The Development of a Concept Inventory for Engineering Graphics

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy
in the Graduate School of The Ohio State University

By

Steven Yasuto Nozaki

Graduate Program in Education Teaching & Learning

The Ohio State University

2017

Dissertation Committee:

Dr. Sheryl Sorby, Advisor

Dr. Paul Post, Committee Member

Dr. Lin Ding, Committee Member

Dr. Kathleen Harper, Committee Member

Copyrighted by
Steven Yasuto Nozaki
2017

Abstract

Graphics education has been a central component in the engineering course of study. As technology advances, so have the methods in which graphics are expressed and practiced. Though the media of graphics education have evolved, the concepts of the field remain relatively consistent. Tools are needed to measure students' comprehension, regardless of current instructional practices. Concept inventories are an example of such a tool that can be used in graphics education to provide a stable mechanism of gauging student understanding. Concept inventories are assessment instruments that can be used to help identify concepts that students understand, and identify which misconceptions are most prevalent.

Concept inventories can also be used in an evaluative manner to aid in course design and assessment. Concept inventories have been developed for other fields and have found to lead to curriculum and pedagogical reform. Currently, there is no widespread agreed upon and validated instrument to use in engineering graphics and related courses to assess learning of fundamental concepts.

This study describes the first recorded attempt at the development of a concept inventory for engineering graphics on a national scale. Using established methods for instrument development as guidelines, a concept inventory for engineering graphics was created. The final version of the instrument consists of thirty items that measure

understanding across five fundamental concepts. Additional statistical analysis of the data will provide guidance on efficient use of the instrument in the future.

Dedication

To Sid and Sue.
Thank you.

Acknowledgments

Family: Mom and Dad; Grandparents; Scott; all the aunties, uncles, and cousins; friends old and new

OSU Faculty: Dr. S. Sorby; Dr. P. Post; Dr. L. Ding; Dr. K. Harper; Dr. F. Croft; Dr. R. Gustafson

OSU Staff: Dr. J. Merrill; E. Callahan; S. Lindeboom; D. Vehr and staff; L. Corrigan

OSU Athletic Staff: W. Stephens; T. Galligan; T. Lewis; M. Nicholson; D. Patko

Colleagues: Dr. M. Sadowski; Dr. H. Steinhauer; Dr. N. Study, Dr. R. Miller; Dr. Y. Allam; Dr. L. Long; G. Duffy; Dr. S. Yoon; R. Loffing; J. Niese; R. Kohatsu; V. Lakes

Classmates: D. Lan; E. Hathaway; A. Jayakumar

The author gratefully acknowledges the support of the National Science Foundation for this project through collaborative grants DUE-1432280 and DUE-1432288.

Vita

2016	M.A. Education, College of Education and Human Ecology, <i>The Ohio State University</i>
2012	M.S. Civil Engineering, College of Engineering, <i>The Ohio State University</i>
2010	B.S. Civil Engineering, College of Engineering, <i>The Ohio State University</i>
2005	Waiakea High School – Hilo, Hawaii
2014-2017	Graduate Research Associate, First Year Engineering Program, <i>The Ohio State University</i>
2015-2016	Instructor of Record, First Year Engineering Program, <i>The Ohio State University</i>
2010-2015	Graduate Teaching Associate, First Year Engineering Program, <i>The Ohio State University</i>

Publications

- Nozaki, S.,** Study, N., Steinhauer, H., Sorby, S., Sadowski, M., & Miller, R. (2016). Development of a Concept Inventory for Engineering Design Graphics. American Society for Engineering Education Annual Conference and Exposition, New Orleans, LA.
- Nozaki, S.,** Study, N., Steinhauer, H., Sorby, S., Sadowski, M., & Miller, R. (2015). Development of CAD-Related Items for a Concept Inventory for Engineering Graphics. American Society for Engineering Education, Engineering Design Graphics Division 70th Midyear Conference, Daytona Beach, FL.

Nozaki, S., Study, N., Steinhauer, H., Sorby, S., Sadowski, M., & Miller, R. (2016). The Development of a Concept Inventory for Engineering Graphics. Frontiers in Education Annual Conference, Erie, PA.

Abrams, L., Shoger, S., Corrigan, L., **Nozaki, S.**, Narui, M., & Jayakumar, A. (2016). Empowering Male Students as Allies for Gender Equity Within an Engineering College. American Society for Engineering Education Annual Conference and Exposition, New Orleans, LA.

Corrigan, L., Kecskemety, K., & **Nozaki, S.** (2016). Using Frequent Low-Stakes Assessment (FLA) in a First-Year Engineering Class. First Year Engineering Experience Conference, Columbus, OH.

Duffy, G., Sorby, S., Bowe, B., & **Nozaki, S.** (2016). Exploring the Role of Spatial Cognition in Problem Solving. IEEE Frontiers in Education Annual Conference, Erie, PA.

Fields of Study

Major Field: Education Teaching & Learning

Program: STEM (Engineering) Education

Table of Contents

Abstract.....	ii
Dedication.....	iv
Acknowledgments.....	v
Vita.....	vi
Table of Contents.....	viii
List of Tables	xiii
List of Figures.....	xvii
Chapter 1: Introduction.....	1
1.1 Statement of the Problem	1
1.2 Why the Problem is Important.....	2
1.3 Approach to the Problem.....	2
1.4 Purpose of the Study.....	3
1.5 Research Aims.....	4
1.6 Limitations.....	5
1.7 Organization of the Document	6

Chapter 2: Literature Review.....	7
2.1 Educational Assessment	7
2.2 Engineering Graphics	8
2.3 Concept Inventories	9
2.4 A Concept Inventory in Engineering Graphics	10
2.5 Methodology for Development	10
2.6 Assessment Triangle.....	11
2.7 Cognition	13
2.8 Observation.....	14
2.9 Interpretation	15
2.10 Psychometrics	15
2.11 Classical Test Theory	16
2.12 Item Response Theory	17
2.13 Data Analysis.....	18
2.13.1. Difficulty Score.....	18
2.13.2. Discrimination Index.....	19
2.13.3. Kuder-Richardson Formula 20.....	21
2.14 Concept Maps	23
2.15 Delphi Study.....	23

Chapter 3: Research Population and Pilot Study	25
3.1 Research Population	25
3.2 Item Creation	27
3.3 Distribution and Data Collection.....	30
3.4 Open Ended Items Coding.....	35
3.5 Likert Item Responses	40
3.6 Distractor Creation	41
3.7 Removal of Concepts.....	43
Chapter 4: Alpha Version	47
4.1 Alpha Version Methods.....	47
4.2 Concept Maps	48
4.3 Alpha Version Results	53
Chapter 5: Beta Version.....	58
5.1 Beta Version Methods	58
5.2 Item Selection and Distribution.....	58
5.3 Beta Version Results	60
Chapter 6: Validity Study	62
6.1 Validity Study Methods.....	62
6.2 Validity Study Results	67

Chapter 7: Gamma Version	68
7.1 Item Selection	68
7.2 Gamma Version	70
Chapter 8: Discussion and Conclusion	75
8.1 Item Difficulty and Discrimination	75
8.2 Alignment of Corners	75
8.2.1. Relationship between Cognition and Observation	76
8.2.2. Relationship between Interpretation and Cognition	76
8.2.3. Relationship between Observation and Interpretation	77
8.3 Scoring	77
8.4 Addressing Research Aims	79
8.5 Conclusions	81
8.6 Future Work	82
References	84
Appendix A : Concepts and Topics from Delphi Study	91
Appendix B : Pilot Study Item Mapping	95
Appendix C : Selected Open Ended Items from Pilot Study	98
Appendix D : Selected Responses from Pilot Study	104
Appendix E : Alpha Version Item Mapping	109

Appendix F : Selected Items and Statistics from Alpha Version.....	112
Appendix G : Selected Items and Statistics from Beta Version	121
Appendix H : Items from Final Version	127
Appendix I : Item Mapping from Final Version.....	144
Appendix J : Selected Items from Validity Study	162
Appendix I: Selected Statistics from Validity Study	173

List of Tables

Table 1 Ranges of difficulty scores for use in CI	19
Table 2 Ranges of discrimination indices	21
Table 3 Definitions of concepts	24
Table 4 Participating institutions	25
Table 5 Coding for open ended item 0006.....	36
Table 6 Open ended codes for Item 0006	36
Table 7 Open ended codes for Item 0033.1	39
Table 8 Original open ended codes for Item 0033.1	40
Table 9 Revised open ended codes for Item 0033.1	40
Table 10 Likert scores from Item 0006.....	41
Table 11 Descriptive statistics for Item 0006 on alpha version.....	54
Table 12 Descriptive statistics for alpha version editions	55
Table 13 Item measures for alpha version	56
Table 14 Item map for beta version	59
Table 15 Beta version participants by institution	61
Table 16 Comparative statistics for editions on beta version	61
Table 17 Roles of experts in validity study	63
Table 18 Experience of experts in validity study.....	63

Table 19 Validity study Item 0013	64
Table 20 Validity study Item 0022	65
Table 21 Validity study Item 0055	66
Table 22 Concepts by version.....	69
Table 23 Count of items by concept on final version	71
Table 24 Item description for final version.....	71
Table 25 Concept list for gamma version	78
Table 26 Item Mapping for Pilot Version – Groups of Five.....	96
Table 27 Item Mapping for Pilot Version – Groups of Three	97
Table 28 Item Map for Alpha Version.....	110
Table 29 Alpha Version Items - Sorted by Concept	113
Table 30 Validity Study Participant Role	174
Table 31 Validity Study Participant Role	175
Table 32 Validity Study - Participant Years of Experience in Graphics	175
Table 33 Validity Study Item 0001	175
Table 34 Validity Study Item 0006.....	176
Table 35 Validity Study Item 0013.....	176
Table 36 Validity Study Item 0014.....	176
Table 37 Validity Study Item 0015.....	176
Table 38 Validity Study Item 0017.....	177
Table 39 Validity Study Item 0021	177
Table 40 Validity Study Item 0022.....	177
Table 41 Validity Study Item 0027.....	178

Table 42 Validity Study Item 0028.1.....	178
Table 43 Validity Study Item 0028.2.....	178
Table 44 Validity Study Item 0028.5.....	179
Table 45 Validity Study Item 0031.2.....	179
Table 46 Validity Study Item 0039.....	179
Table 47 Validity Study Item 0040.....	180
Table 48 Validity Study Item 0042.....	180
Table 49 Validity Study Item 0043.2.....	180
Table 50 Validity Study Item 0045.2.....	180
Table 51 Validity Study Item 0047.1.....	181
Table 52 Validity Study Item 0047.4.....	181
Table 53 Validity Study Item 0048.2.....	181
Table 54 Validity Study Item 0049.1.....	181
Table 55 Validity Study Item 0055.....	182
Table 56 Validity Study Item 0056.....	182
Table 57 Validity Study Item 0057.....	182
Table 58 Validity Study Item 0058.....	182
Table 59 Validity Study Item 0063.....	183
Table 60 Validity Study Item 0064.....	183
Table 61 Validity Study Item 0066.....	183
Table 62 Validity Study Item 0069.....	183
Table 63 Validity Study Item 0071.....	184
Table 64 Validity Study Item 0072.....	184

Table 65 Validity Study Item 0073.1.....	184
Table 66 Validity Study Item 0073.3.....	184
Table 67 Validity Study Item 1012.....	185
Table 68 Validity Study Item 1014.....	185
Table 69 Validity Study Item 1016.....	185
Table 70 Validity Study Item 1026.....	185
Table 71 Validity Study Item 1027.....	185
Table 72 Validity Study item 1029.....	186
Table 73 Validity Study Item 1030.....	186
Table 74 Validity Study Item 1045.....	186
Table 75 Validity Study Item 1067.....	186
Table 76 Validity Study Item 1068.....	186
Table 77 Validity Study Item 1158.....	187
Table 78 Validity Study Item 1167.....	187

List of Figures

Figure 1 Assessment triangle	13
Figure 2 Sample item from pilot study	29
Figure 3 Student response to sample item (correct response).....	29
Figure 4 Student response to sample item (incorrect response)	30
Figure 5 Sample open ended item from pilot study	31
Figure 6 Intended solution for Item 0006	32
Figure 7: Sample open ended student response	33
Figure 8 Sample open ended student response	34
Figure 9: Sample open ended student response	34
Figure 10 Sample open ended student response	35
Figure 11 Sample open ended student response	38
Figure 12 Item from alpha version with distractors.....	43
Figure 13 Example solid modeling response	44
Figure 14 Example solid modeling response	44
Figure 15 Example solid modeling response	45
Figure 16 Proposed item for engineering methodologies	46
Figure 17 Item from concept of section views.....	48
Figure 18 Individual concept map A	50

Figure 19 Individual concept map B.....	51
Figure 20 Individual concept map C.....	51
Figure 21 Final concept map.....	52
Figure 22 Item from validity study	64
Figure 23 Item from validity study	65
Figure 24 Validity study item	66
Figure 25: Difficulty vs. discrimination for items on gamma version.....	72
Figure 26 Gamma version Item 0001	72
Figure 27 Gamma version of Item 0006	73
Figure 28 Gamma version of Item 0017	73
Figure 29 Final version of Item 0047.4	74
Figure 30 Final version of Item 0073.1	74
Figure 31: Item 0001 Final Version.....	128
Figure 32 Item 0006 Final Version.....	128
Figure 33 Item 0008 Final Version.....	129
Figure 34 Item 0009 Final Version.....	129
Figure 35 Item 0013 Item from Final Version.....	130
Figure 36 Item 0017 Final Version.....	130
Figure 37 Item 0021 Final Version.....	131
Figure 38 Item 0022 Final Version.....	131
Figure 39 Item 0027 Final Version.....	132
Figure 40 Item 0028.2 Final Version.....	132
Figure 41 Item 0028.4 Final Version.....	133

Figure 42 Item 0039 Final Version.....	134
Figure 43 Item 0040 Final Version.....	134
Figure 44 Item 0042 Final Version.....	135
Figure 45 Item 0043.2 Final Version.....	136
Figure 46 Item 0045.2 Final Version.....	136
Figure 47 Item 0047.1 Final Version.....	137
Figure 48 Item 0047.4 Final Version.....	137
Figure 49 Item 0047.5 Final Version.....	138
Figure 50 Item 0052 Final Version.....	138
Figure 51 Item 0056 Final Version.....	139
Figure 52 Item 0058 Final Version.....	139
Figure 53 Item 0063 Final Version.....	140
Figure 54 Item 0066 Final Version.....	140
Figure 55 Item 0068 Final Version.....	140
Figure 56 Item 0069 Final Version.....	141
Figure 57 Item 0071 Final Version.....	141
Figure 58 Item 0072 Final Version.....	142
Figure 59 Item 0073.1 Final Version.....	142
Figure 60 Item 0073.3 Final Version.....	143

Chapter 1: Introduction

1.1 Statement of the Problem

Methods in Engineering graphics instruction continue to change with technological advances and the needs of industry. What was once best represented using paper and pencil techniques has now been replaced with design accomplished using the latest in software. Although a focus on modern tools is appropriate, as educators, it is important to keep in mind the underlying concepts and skills crucial to engineering graphics. Just as the methods of graphical representation have changed since today's instructors were in school, such will be the case for the students in their classes as well. Thus, it is important to keep in mind the fundamentals and concepts in engineering graphics so that students can adapt to the new methods of the future.

Educational assessment includes the interpretation of data to advance student learning. A common means of collecting data are tests, which vary depending on the application and subject matter. One of the variety of tests used to measure conceptual understanding in a content area is concept inventories. Currently, there are no concept inventories that are oriented toward the area of engineering graphics. Concept inventories are educational instruments used to identify students' knowledge and misunderstandings. The availability of such an instrument could help instructors identify concepts students are having trouble understanding, as well as identifying possible areas

for pedagogical improvements. Having a standardized instrument in engineering graphics that can identify errors in application of fundamental concepts would be a valuable pedagogical resource of interest to a significant national audience.

1.2 Why the Problem is Important

Engineering graphics is an integral part of engineering and many other STEM (Science, Technology, Engineering, Mathematics) courses of study (Meyers, 2004; S. Sorby, Casey, Veurink, & Dulaney, 2013; S. A. Sorby, 2009). Included at multiple levels of education, engineering graphics reaches a significant number of students each year. Having a tool that spans educational levels can help establish continuity in design and assessment of classes that incorporate graphics. Without such means, it can be left to individual educators to try to interpret performance of students. With a standardized instrument, stable measurement associated with graphics coursework is available.

1.3 Approach to the Problem

This study developed an instrument that measured student's understanding of concepts in engineering graphics while meeting acceptable standards for validity and reliability. The instrument is a standardized means to help link students' understanding to instruction. Experts in the graphics field have been consulted in the development of the instrument. The instrument will serve as an extension of pedagogical methods available to engineering graphics instructors. The intended use of the instrument will be to assess students' understanding of engineering graphics concepts.

The instrument can be used in a variety of experimental designs. Using it for pretest-posttest group design (Gay, Mills, & Airasian, 2006), will allow for monitoring of changes in performance in a population. It can also be used for applications like case-study observation design, which often are held at the end of an instructional module to assess final understanding. A goal of the instrument is to be nationally accepted and utilized. Rigorous statistical analysis will ensure that the instrument is suitable for widespread use. Appropriate dissemination of instrument use and application is needed to insure appropriate administration and interpretation of results. Revising the instrument as topics for engineering graphics change might also be needed to keep the instrument relevant and up to date.

1.4 Purpose of the Study

There has been extensive work done in many areas of engineering graphics education. A widely accepted field, it is considered by many to be an essential topic in the STEM curriculum. There have been several studies that focus on methods of graphics instruction (Branoff & Devine, 2015; Chen, Chi, Hung, & Kang, 2011; Khan, 1994; Marunic & Glazar, 2013; Potter et al., 2009; Santo, 1986; Ullman, Wood, & Craig, 1990), graphics pedagogy (S. Sorby et al., 2013; S. A. Sorby & Bulleit, 2006), and improving graphics ability (Contero, Naya, Company, Saorfa, & Conesa, 2005; Crown, 2001; Serdar & deVries, 2015). There is limited work being done in the areas of assessment within engineering graphics education. One tool that shows potential application in the field of engineering graphics are concept inventories, as they have been effective in other fields as a means of influencing pedagogy (Singer & Smith, 2013;

Smith & Tanner, 2010). Results from student performance on concept inventories have provided the impetus that moved educators to utilize different pedagogical methods (Hake, 1998; Von Korff et al., 2016). Regardless of methods, there are “core” concepts and skills that graphics experts deem foundational to a content area (M. A. Sadowski & Sorby, 2015; M. Sadowski & Sorby, 2013; M. Sadowski & Sorby, 2014). Having an instrument to quantify graphics understanding will be a meaningful tool in engineering graphics education.

1.5 Research Aims

The study addresses the following research aims:

1. *Identify fundamental consensus concepts within engineering graphics.*

There are many topics considered to be important to the area of engineering graphics. To have a valid instrument, it is necessary to identify concepts that are largely agreed upon as important. The concepts should be specific to engineering graphics, and comprehensive enough to allow for lasting use of the instrument in the engineering graphics community.

2. *Creation of reasonable distractors.*

It is important that the instrument be grounded in practice. The distractors in the instrument should be based on student performance rather than solely on expert opinion. As graphics education methods change, it is not unreasonable to conceive that items will also evolve. The distractors may also need to be updated to reflect the emerging misconceptions of students and/or the changes in technology used in engineering graphics education.

3. *Develop items that are statistically reliable and valid*

The instrument will have items that are both highly reliable and valid. Validity will be achieved by having items that accurately measure the concept they intend to. One of the goals for the instrument will be its reliable use across different populations at different levels of education. It is important for the instrument to be reliable enough to make meaningful interpretations across various populations who are taught by different instructors.

1.6 *Limitations*

Resources and logistical issues account for many of the limitations of the project. The following elements are limitations that were considered in the design of the study. These are the conditions that cannot be controlled for and place restrictions on the methodology and conclusions.

- Access to certain student populations may influence the trends in responses.
- Due to the timing and nature of course offerings, there is a restriction on how often iterations of the instrument can reasonably be tested.
- The format of the instrument may prove to constrain the format in which students express their misconceptions or misunderstandings.
- The researcher will use proctors at institutions other than the researcher's own to administer the instrument, and must trust in the decisions made by them. Even with steps in place to assure consistency in application, there may be variation attributed to the differences in setting.

1.7 Organization of the Document

This chapter explains the nature of the study and provides an overview. Chapter 2: is a review of the literature. Chapters 3 through 6 cover the stages of instrument development. Chapter 3: addresses the pilot study, Chapter 4: the alpha version, Chapter 5: the beta version, Chapter 6: a validity study, and Chapter 7 covers the final version of the instrument, referred to as the gamma version. Chapter 8: discusses the findings and implications resulting from the study.

Chapter 2: Literature Review

This chapter describes the development and utilization of concept inventories as related to the field of engineering graphics. It will cover educational assessment as it pertains to engineering graphics, methodology used for concept inventory development, psychometrics used in analysis, and the use of concept maps. Simple scores and figures are provided when available.

2.1 Educational Assessment

Educational assessment is the use of empirical evidence to determine how well students are learning (Allen, 2006). Assessment is a necessary part of learning, as it provides feedback on the educational process. The idea of tests or testing is commonly associated with assessment, though it encompasses much more than simple procurement of scores (National Council on Measurement in Education, 2016).

Modern learning theories emphasize how knowledge is represented in the mind. Emphasis is also placed on the social dimensions of learning, including participatory activities that support how a person understands. This field of study suggests that assessment practices should go beyond appraising skills and memorization; they should aim to cover higher levels of student thinking and performance (Pellegrino, Chudowsky, & Glaser, 2001).

Studies in the differences between experts and novices show important differences in ability. These differences are one area which assessment can focus on. Students bring with them unique understandings and interpretations of knowledge. When students learn, this understanding is transformed and applied in a context applicable to the subject area. Assessment can be used to further this progression by making students' thoughts and understanding identifiable. Skills are commonly developed in a contextualized setting, making transfer of knowledge one indicator of understanding. The constructivism theory of learning advocates that learning occurs through doing and interacting with others (National Council on Measurement in Education, 2016; Vygotskiĭ & Cole, 1978). This interaction often occurs in the classroom and includes the development of skills specific to a subject area. Assessments then examine how students apply those skills when presented with new and varied contexts, such as the challenges presented on a test. Much of what is known about exploring and interpreting students' knowledge comes from the field of cognitive psychology. Accordingly, many of the processes used by cognitive scientists to make judgments about learning are applicable to the development of a useful educational assessment instrument (National Research Council Panel on Undergraduate Engineering Education, 1986).

2.2 Engineering Graphics

It is common for engineering or engineering technology programs to incorporate a graphics component into the course of study, as spatial and graphical skills have been associated with success in many engineering or technology curricula (Baartmans &

Sorby, 1996; S. Sorby et al., 2013). These skills are also important in the practical application of many engineering and technical fields (Lieu & Sorby, 2009).

2.3 *Concept Inventories*

The impetus for creating a concept inventory can be traced to the work of Halloun & Hestenes (1985) on an instrument that would become known as the Force Concept Inventory, or FCI, a test that looked at students' problems understanding of Newtonian force. These problems were attributed to misconceptions held by the students. In the development of the FCI, the instrument was written with terminology and in a context easily understood by students. The items on the instrument had a prompt that posed a question to students, usually had a diagram, and five options for responses. Each choice, or distractor, was created using commonly held misconceptions about the given topic. This initial assessment test evolved into the FCI over time, the first true "concept inventory". The FCI has been used consistently across institutions and in numerous studies since its creation (Halloun & Hestenes, 1985; Hestenes, Wells, & Swackhamer, 1992).

The successful creation of the FCI has helped contribute to educational reform in many science and engineering areas, and concept inventories (CI or CIs) have been created for additional areas in STEM. Selected CIs that have been completed or are being worked on include the areas of statistics (Allen, 2006), electricity and magnetism (Ding, Chabay, & Beichner, 2006a), heat transfer (Jacobi, Martin, Mitchell, & Newell, 2003), fluid mechanics (Martin, Mitchell, & Newell, 2004), and transport science

(Streveler et al., 2011). Databases have been created to consolidate the range of CIs in STEM (The Foundation Coalition, 2008).

2.4 A Concept Inventory in Engineering Graphics

Concept inventories are instruments used to identify understandings and misconceptions regarding a set of related conceptual ideas. Misconceptions are typically deeply rooted beliefs, and can be problematic for instruction. The constructs that students have difficulty with need to be identified to address these misconceptions during instruction. The use of a quality concept inventory may provide instructors with the data they need to alter their instruction to counteract the misconceptions.

An engineering graphics concept inventory (EGCI) will largely follow the format of other validated assessment instruments. The common format of a concept inventory is a multiple-choice examination consisting of items focused on key concepts. A stem (question) is presented to the student that relates to a conceptual construct. The choices for responses contain a correct answer and several alternative incorrect answers, or distractors. These distractors are often solutions based on common misconceptions held by students. Well-designed distractors can provide insight into students' reasoning and previously held beliefs or understandings (Adams & Wieman, 2011; Allen, 2006). Distractors can be created in a variety of ways; expert opinions, student interviews, and speculation have all been methods used in the past (Treagust, 1988).

2.5 Methodology for Development

To develop a valid and reliable concept inventory for engineering graphics, it was important to first examine the process used in developing other established instruments. Publications documenting the creation and revisions of accepted instruments such as the Force Concept Inventory (FCI) (Clement, 2008; Goldman, Schoner, & Pentony, 1980; Hestenes & Wells, 1992) demonstrate procedures that resulted in valid and accepted means of assessment for their specific content domain.

There are several studies documenting the creation and development of concept inventories (Aslanides & Savage, 2013; Hoe, 2013; Kalas, O'Neill, Pollock, & Birol, 2013), but limited publications regarding suggested methodologies to follow for instrument development. One report that documents procedures for concept inventory development informed by contemporary theory and methods, is by Streveler et. al. in *Rigorous Methodology for Concept Inventory Development: Using the 'Assessment Triangle' to Develop and Test the Thermal and Transport Science Concept Inventory (TTCI)* (Streveler et al., 2011). It describes the creation and analysis of the TTCI using the framework of the 'assessment triangle' as described by the National Research Council (Pellegrino et al., 2001). This study shows how the TTCI was developed using current practices. It stated that for the TTCI to be a robust and quality instrument, it needed to keep the three foundational ideas of the assessment triangle in mind - observation, cognition, and interpretation.

2.6 *Assessment Triangle*

The goal of this project was to develop a reasonably reliable and valid instrument for use in assessing conceptual understanding in engineering graphics. The framework

for Streveler's (2011) test development was primarily influenced by using the 'assessment triangle' as described in *Knowing What Students Know: The Science and Design of Educational Assessment* (Pellegrino et al., 2001). Streveler et. al. suggests keeping the ideals of the triangle in mind while constructing educational assessment instruments. The assessment triangle has been used in the development of multiple concept inventories in STEM, including instruments such as the Introductory Molecular and Cell Biology (Shi et al., 2010), Thermal and Transport Science Concept Inventory (Streveler & Smith, 2006), and Geoscience Concept Inventory (Libarkin & Anderson, 2006).

The assessment triangle describes the underlying beliefs of what assessment should address. The three integral parts of cognition, observation, and interpretation, form a triangle, represented in Figure 1 (Pellegrino et al., 2001). The triangle not only serves as a figure of speech; it also represents the interconnectivity of the three elements in successful assessment design. For an assessment to be useful, all parts of the triangle must be considered and connected. A linear or sequential attention to the elements would 'unfold' the triangle, thus failing to include qualities that are uniquely shared by any two sides of the triangle. The descriptions of each of the sides of the triangle come from Pellegrino et al (2001) and Streveler et al (2009) unless otherwise cited.

Figure 1 Assessment triangle

2.7 Cognition

Cognition describes a set of theories or beliefs about how students represent knowledge. A theory of learning is needed before creating an assessment. The content area that is being addressed by the instrument is referred to as the target domain. The cognition corner of the triangle considers how students learn about the target domain. When considering CI development, this corner can manifest itself by considering the misconceptions and confusion students might have in regards to the target domain. Finding out what students are consistently having trouble with is an indicator of learning or not learning, as the case may be (Gollub, 2002).

One method to identify concepts that students may be having problems understanding is to consult experts. The Delphi method of identifying topics for inclusion is an appropriate choice for a CI. The Delphi method uses moderated groups of experts who generate information and reach consensus over a series of rounds (Coates, 1975; Dalkey & Helmer, 1963; Linstone & Turoff, 1975). When creating a new CI,

utilizing the findings from a Delphi study is an accepted method for gaining an understanding of important concepts that students have difficulty in learning.

2.8 *Observation*

The observation corner represents the kinds of activities or items that make up the assessment itself. The questions used to measure student understanding should not be uninformed and left to chance, and should be reasonable related to the concepts identified in the cognition corner. The activities used to observe the abilities of students should pertain to identified concepts and abilities.

Characteristics of quality items on a CI are is that they are straightforward and easily understood by participants, do not involve extensive computations; and contain distractors are representative of student held misconceptions. The first two qualities can be partially addressed by instrument developers working on their own. Additional work with students must be done to produce distractors that represent common student misconception when creating a new CI. One effective technique in creating items for CIs follow the steps below (Lane, Raymond, & Haladyna, 2016)

1. Draft open ended items
2. Collect student responses
3. Use the responses to inform creation of multiple choice items that are based on open ended items
4. Test the multiple-choice items
5. Solicit expert reviews of items
6. Revise items based on appropriate numerical evaluation
7. Repeat field testing and revision as necessary.

2.9 *Interpretation*

The interpretation corner focuses on how the researcher tries to understand the results of testing the instrument with appropriate student populations. Inferences into information gathered in the observation corner can justify the attainment of knowledge in the target domain (Pellegrino et al., 2001). For an instrument with intended large scale or broad applications, the interpretation corner includes statistical modeling which helps describe observed trends in observations. For a concept inventory, the results should be valid, reliable, and identify the misconceptions held by students. Interpretation methods should thus look to identify and explain traits in the data.

2.10 *Psychometrics*

Psychometrics refers to the part of psychology that deals with measurement, which includes quantifying, understanding, proficiency, and attitudes of participants (Kaplan & Saccuzzo, 2013; Murphy, 1999). Two focus areas of the field are the creation of instruments and procedures of measurement, and the improvement of theories regarding measurement. Psychometrics have been used extensively in educational assessment in areas such as standardized testing and college entrance exams (Messick, 1995; Pellegrino et al., 2001; Treagust, 1988). Two of the theories used in instrument development are Classical Test Theory (CTT) and Item Response Theory (IRT). CTT and IRT are both models for the design and evaluation of test results.

2.11 Classical Test Theory

Classical Test Theory (CTT) is an approach used to describe student performance on an instrument. It is based on the idea that an individual's score on an instrument will be the result of genuine performance ability plus an error (Engelhardt, 2009; Kuder, 1937). The equation for modeling a score with CTT is shown in Equation 1. Where X is the observed score from the instrument, T is a measurement of the true ability of the individual, and E is the error introduced by measurement (Brennan, 2011; Crocker & Algina, 1986).

Equation 1: CTT Modeling

$$X = T + E$$

CTT's primary concern is to improve the reliability of the test by reducing the error. The assumption is that the true score of an individual, T , can never truly be measured (Brennan, 2011). Thus, other measures must be utilized to estimate E . An error estimate can be made using a statistical measure called Cronbach's alpha.

Cronbach's alpha has been used to provide an indicator of how well a group of items measures a single latent uni-dimensional construct (Bechger, Maris, Verstralen, Huub H. F. M., & Béguin, 2003). If an instrument has items that are scored dichotomously, i.e. a response is either correct or incorrect with no ambiguity, a special case of Cronbach's alpha can be used called Kuder-Richardson's Formula 20 (KR20). KR20 measures the internal consistency of an instrument, and can range from [0-1]. The higher the value, the more homogenous a test is thought to be. Homogeneity in an instrument suggests the

tendency to observe a single latent construct. Thresholds for acceptable ranges for KR20 in practice are set by professional opinion, and have few statistical underpinnings (Nunnally & Bernstein, 1994).

2.12 Item Response Theory

Item Response Theory (IRT) describes the application of mathematical models to the results of administration of assessment instruments designed to measure abilities, attitudes, or other latent traits (Ndalichako & Rogers, 1997). IRT can be used to statistically monitor the development of instruments. The underlying philosophy of IRT is that the probability of an individual generating a correct response to an item is the result of the latent characteristic being measured (Bechger et al., 2003; Ding & Beichner, 2009; Streveler & Smith, 2006). This suggests that an individual with a higher ability is more likely to respond correctly to a specific item on a given instrument.

The mathematical models of IRT provide a foundation for instrument and item evaluation. Because IRT focuses on items instead of the entire instrument as with CTT, it can approximate an individual's ability on a given latent trait in addition to the error (Fan, 1998). Measures obtained using methods from IRT can be objectively compared, whereas scores using CTT methods need a comparison group to be evaluated (Baker, 1992). The primary measures from each theory is difficulty score from CTT, and discrimination index in IRT.

2.13 Data Analysis

The approaches governing item and instrument analysis in this study were largely based on Classical Test Theory (CTT). CTT is a significant part of the underpinning of contemporary measurement models and is still used as part of instrument development (Allen, 2006; Ding & Beichner, 2009; Streveler & Smith, 2006). Several statistical methods have been based on CTT that examine individual item performance and entire instrument analysis (Doran, 1980). For individual item performance, two measures were used; Difficulty Score (P) and Discrimination Index (D) (Ding, Chabay, & Beichner, 2006; Ding & Beichner, 2009). Internal instrument reliability was calculated using Kuder-Richardson's Formula 20.

2.13.1. Difficulty Score

An item's Difficulty Score, P, is a measure of how difficult an item is, and is measured as the percentage of the total population that correctly responded to the item. It can be operationalized and thought of as being an item's "easiness" score. Equation 1 Equation 2 shows the formula for calculating an item's Difficulty Score

$$P = \frac{N_1}{N}$$

Equation 2 Difficulty Score

Where N_1 is the number of correct responses for an item, and N is the total number of responses for the item. Values for P can range from [0,1], with 0 indicating

that there was no one who got the item correct, and 1 meaning that all participants responded correctly to the item. The acceptable range of difficulty scores varies. Sources suggest that there is an upper and lower limit for items to be included on concept assessments, from about 0.25 to 0.85 (Ding & Beichner, 2009; Streveler & Smith, 2006). For this instrument, values adopted from Tamil (Tamil, 2015) were used to classify items, and shown in Table 1. Items that scored below 0.20 (too difficult) or above 0.80 (too easy) were set aside for revision or removed from consideration for the subsequent version of the CI.

Table 1 Ranges of difficulty scores for use in CI

Range	Difficulty Level
[.00, .20]	Very Difficult
[.21, .40]	Difficult
[.41, .60]	Medium Difficulty
[.61, .80]	Easy
[.81, 1.00]	Very Easy

2.13.2. Discrimination Index

The second measure regarding item analysis used in this study was the calculation of the discrimination index. The discrimination index is a metric that suggests how well an item discriminates between high and low performing students (Crocker & Algina, 1986; Gronlund, 1985; Oosterhof, 2001; Sax, 1980; Thorndike & Thorndike, 1991). The discrimination index was calculated using Equation 3.

$$R = \frac{(H - L)}{N_{27\% \text{ of group size}}}$$

Equation 3 Discrimination Index

Where H = number of correct responses in the high scoring group, L = number of correct responses in the low scoring group, and N = size of the upper or lower group.

Participants are sorted by overall performance on the instrument, and predetermined thresholds indicate the ranges of students to be included in each group. The ranges and methods that determine how H and L are defined can vary. It can be “internally” established using a criterion based on instrument performance, or “externally” established using an outside corresponding measure (Doran, 1980). An example of internal criteria would be to use students’ performance on the instrument itself to determine the high-performing group. An example of external criteria would be sorting students by their performance using their course grades. Most instruments, including the EGCI, use internal criteria. A common threshold is to use quartiles to determine H and L . In this manner, students’ whose scores are in the in the top 25% are considered for H , and scores from the bottom 25% of students are included in L . For this study, 27% of the number of responses for an item was used because this proportion has been found to yield the most reliable results in instrument creation. (Nunnally & Bernstein, 1994).

The discrimination index is useful in making inferences into how participants are interpreting items, because it can be used to determine which alternatives are being selected by the high-scoring participants. The range of item discrimination indices is from -1.00 to +1.00. Positive discrimination indices signify the tendency for higher

performing participants to select a correct response to the item, while lower performing participants will select incorrect responses. A score close to +1.00 means high performers are responding correctly and low performers are not. A score that is close to zero suggests that either high or low performers have a similar chance of selecting an incorrect option, which is not desirable. Items with discrimination indices that are negative should be examined carefully, because this suggests that more low-scoring participants are getting the answer correct compared to high-performers. An item with a negative discrimination index is not only ineffective at determining performance, but is decreasing the validity of the instrument as a whole (Adkins, 1974). The ranges for item classification based on discrimination index can be found in Table 2. For this study, a floor of 0.20 was used as the threshold for item inclusion when considering item discrimination.

Table 2 Ranges of discrimination indices

Range	Description of Discrimination
[-1.00, .08]	Discard and/or Re-design
[.09, .19]	Poor Item
[.20, .29]	Fair Item
[.30, .39]	Good item
[.40, 1.00]	Very Good Item

2.13.3. Kuder-Richardson Formula 20

Internal consistency or reliability refers to the relationship between individual items on an instrument (Ding & Beichner, 2009). Reliability gauges the extent to which items that are designed to measure the same construct produce similar scores. In this study, the construct being measured was student understanding of key concepts in

engineering graphics. Thus, a reliable instrument should have good scores from high performing students across all the concepts being measured, regardless of the items selected for inclusion.

To quantitatively verify internal consistency of the different editions and versions of the instrument, Kuder-Richardson's Formula 20 (KR20) was used. KR20 is a coefficient of consistency that measures how well a group of items measure a single, unidimensional latent trait (Kuder & Richardson, 1937). Homogeneity in instrument constructs is an assumption, not a conclusion of using KR20. KR20 is a specific variation of Cronbach's alpha for use with items that have dichotomous choices; that is, items when scored will receive a value of 1 (correct) or 0 (incorrect), regardless of distractor choice. Equation 4 shows how KR20 was calculated.

$$\rho_{KR20} = \frac{k}{k-1} \left(1 - \frac{\sum_i^k P_i(1 - P_i)}{\sigma^2} \right)$$

Equation 4 Kuder-Richardson Formula 20

In Equation 4, k is the number of items on the instrument, P_i is the difficulty of item i , and σ^2 is the variance of all the total scores as measured by the instrument. An accepted KR20 value of 0.7 is considered reliable for instruments measuring groups; a KR20 greater than 0.8 is considered reliable for instruments measuring individuals (Doran, 1980). Through monitoring changes in KR20, varying the items to be included on the instrument can alter its reliability. For the EGCI, a value of 0.7 was the minimum desired value for KR20.

2.14 Concept Maps

Concept maps are graphical representations that show the arrangement of information within a subject (Greitzer, Soderholm, Darmofal, & Brodeur, 2002). To help clarify the relationships of topics in engineering graphics, concept maps were chosen to provide structure. In a concept map, individual concepts or topics are shown in a box or similar enclosed shape. Lines or arrows on the map represent the relationships between the concepts/topics. Arrows are an important feature of a concept map, as they imply hierarchy or direction. Having a concept map for engineering graphics helped researchers frame items and instrument during the latter stages of instrument development. For an instrument to be valid, it must have an acceptable level of breadth and depth of topics measured (Moskal, Leydens, & Pavelich, 2002). Aligning the items with the concept map allowed the team to ensure appropriate coverage of the identified topics in engineering graphics.

2.15 Delphi Study

This study utilized work completed in a previous project that aimed to identify fundamental concepts in engineering graphics (M. A. Sadowski & Sorby, 2015). The researchers in that study utilized the Delphi method to generate a preliminary list of concepts that could be included in a concept inventory for engineering graphics. The Delphi method is a systematic surveying technique that relies on a group of experts to reach consensus regarding items of importance (Armstrong, 2001; Dalkey & Helmer, 1963; Linstone & Turoff, 1975).

The resulting list of concepts from this Delphi Study can be found in Table 3.

These ten concepts were identified as core ideas in engineering graphics and were used as the basis of the current study. Abbreviated definitions are shown Table 3 and the unabridged descriptions can be found in Appendix A.

Table 3 Definitions of concepts

	Concept	Definition
1	Visualizing in 2D and 3D	Understating the relationship between orthogonal views of geometry.
2	Mapping between 2D and 3D	Representing, converting, creating and interpreting drawings from 2D to 3D, and 3D to 2D
3	Planar Geometry	The ability to place a plane in space that serves a particular function
4	Sectional views	Establishment of a plane for the purpose of showing interior and exterior features of an object
5	Engineering Methodologies for Object Representation	Representing the 3D world using 2D visual methods using engineering graphic techniques
6	Projection theory	Viewing an object with a transparent plane placed between the observer and the object
7	Parallel Projection Methodologies	Graphically representing 3D objects in a 2D medium based on a line of sight and a plane of projection
8	Drawing Conventions	Conventional methods for expressing a graphical description
9	Dimensioning	The process of providing an accurate, clear, complete and readable, description of an object.
10	Solid Modeling	A consistent set of principles for mathematical and computer modeling of three-dimensional solids which supports the creation, exchange, visualization, animation, interrogation, and annotation of digital models of physical objects.

Chapter 3: Research Population and Pilot Study

3.1 Research Population

The research population of the study was undergraduate engineering students in entry level engineering and technology classes. These students were chosen primarily because of the timing of graphics instruction in most engineering and technology programs. All classes in the study where the instrument was administered have graphics as a part or the sole focus of a first year introductory or entry level course. Courses at each of the institutions were housed in a department affiliated with engineering or engineering technology. A total of four institutions took part in the study. Table 4 shows the number of responses collected from students at each stage of the study at the participating institutions.

Table 4 Participating institutions

Institution	Pilot	Alpha Ed. A	Alpha Ed. B	Alpha Ed. C	Beta Ed. Red	Beta Ed. Blue	Total
Institution A	0	226	188	197	233	229	1073
Institution B	225	28	77	45	55	61	491
Institution C	48	0	21	26	29	29	153
Institution D	215	58	48	60	107	116	604
Total	488	312	334	328	424	435	2321

Having multiple institutions included in the study increases the validity of the instrument, as any patterns that emerge across populations help show that the instrument

can produce repeatable results (Gay et al., 2006). The research sample consisted of approximately 3000 students from the four institutions over the various stages of item development. The total of 2,231 in Table 4 represents the number of responses that remained after raw data was filtered.

Institution A is a large, public, research, 4-year institution in the Midwest. It has relatively large and prominent engineering and technology schools. Students from majors outside of engineering that have a graphics requirement enroll in a dedicated graphics course through the College of Technology. Both engineering and technology students enroll in the same graphics course which focuses on graphical languages used to communicate design ideas and an introduction to computer graphics applications.

Institution B is a large, public, research, 4-year university in the Midwest. The first-year engineering program at Institution B has three tracks for students: honors, transfer, and standard. All tracks feature a multiple course plan, consisting of either two or three classes to complete the sequence. Only students from the standard first year engineering course were selected for this study. Students receive graphics instruction as a part of the second of two required classes in the standard track. The graphics portion in this course is principally ordered in two stages, graphics fundamentals and hand-sketching followed by Computer Aided Design (CAD). The graphics portion of this course is completed midway through the semester.

Institution C is a medium, public, 4-year institution in the mid-Atlantic region. The students from this institution were enrolled in a mechanical engineering technology program and were in a graphics class that focused on the development of visualization skills and on introductory CAD modeling techniques.

Institution D is a medium, private, 4-year institution in the southeast US with a significant part of the student body comprised of STEM students. Students from Institution D were first-year engineering students taking a module on introductory graphics in their first-year program, and technology students in a course focused on computer graphics.

Students under the age of 18 were not included in the study. To encourage participation among students, course credit was given for completion of the instrument when possible. When the instrument was used for course credit, participants were always given the option to not have their data be analyzed in the study if desired. Time limits were given to students at each stage of the instrument development. Exact parameters varied between instrument iterations, but were held constant whenever possible within a stage.

3.2 Item Creation

The fundamental concepts for engineering graphics were identified through a previous Delphi study. Thus, the current study focuses solely on the creation of the items to be included on the final CI and not on the Delphi Study. The first step in the process of instrument creation was to draft open-ended items for use in a pilot study. Seminal engineering graphics texts were consulted as a starting point for item creation (Giesecke, 2004; Lieu & Sorby, 2009; Meyers, 2004). Exercises from chapters that corresponded closely with the defined concepts were identified and accumulated. Once each concept had an adequate assortment of exercises, those that seemed to best reflect the definitions of concepts were chosen. A total of sixty items were selected as this stage in the process.

The exercises were adapted and constructed to be in an open-ended format. The items included a stem, a standardized title block, and space for students to work on the exercise (Adams & Wieman, 2011). Participants were instructed to respond to the stem in any manner they saw fit. This included responding directly to the instructions, as well as commenting on the structure of the item itself. To gain an understanding of participants' understanding and the perceived difficulty of the items, two seven level Likert scale items were included with each graphics item (Lavrakas, 2008). The first Likert item asked about students' understanding. It stated "I understood what the question was asking" and the scale ranged from "1-Strongly Agree" to "7-Strongly Disagree". The second Likert item asked about the perceived difficulty of the graphics item. It stated "I feel that this question was:" and scale ranged from "1-Very Easy" to "7-Very Difficult". Figure 2 shows a sample open ended item. In this item, the standard orthographic views of an object are presented in third angle projection (Lieu & Sorby, 2009) along with a sectional view. The stem instructs the participant to draw an appropriate cutting plane line that would result in the provided section view. The Likert scale questions are placed in a location out of the way of the area for student response. Figure 3 and Figure 4 shows examples of student responses to the item in Figure 2.

Draw the cutting plane line, in the proper view, that would result in the section view shown in the front view below.

I understood what the question was asking:
Strongly Agree — Strongly Disagree
1 2 3 4 5 6 7

I feel that the question was:
Very Easy — Very Difficult
1 2 3 4 5 6 7

SolidWorks Student Edition.
For Academic Use Only.

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0021	Scale: N/A	Author: SS	Units: Inches	Item #: 0021
	Drawn By: SYN		Topic: 04	Version: 2.0	Date: 03/22/2015

Figure 2 Sample item from pilot study

Draw the cutting plane line, in the proper view, that would result in the section view shown in the front view below.

I understood what the question was asking:
Strongly Agree — Strongly Disagree
1 2 3 4 5 6 7

I feel that the question was:
Very Easy — Very Difficult
1 2 3 4 5 6 7

SolidWorks Student Edition.
For Academic Use Only.

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0021	Scale: N/A	Author: SS	Units: Inches	Item #: 0021
	Drawn By: SYN		Topic: 04	Version: 2.0	Date: 03/22/2015

Figure 3 Student response to sample item (correct response)

Figure 4 Student response to sample item (incorrect response)

3.3 Distribution and Data Collection

The pilot study was done using hardcopies of test items. Packets of items were compiled and distributed to instructors at each of the participating institutions. Instructors were given written instructions regarding instrument administration, and a script was provided to read before administering items from the pilot study. Instructions for participants were attached to every packet of items. Depending on the institution and amount of time instructors were willing to allot to the exercise, participants were given either 3 or 5 open ended items to complete in either 15 or 25 minutes, respectively. Appendix B shows the mapping for all editions administered during the pilot study. All items were as evenly and randomly distributed as possible. The packets were compiled so that any one participant would receive items from a variety of concepts. Results were sorted by item and by institution. For each of the 60 open ended items in the pilot study,

there were between 25 and 30 useful responses. In total, nearly 2000 individual responses were collected and coded to consider in distractor creation.

A second example item from the pilot study is shown in Figure 5. It shows Item 0006, which is intended to measure the concept of Mapping Between 2D and 3D. A more extensive list of items drafted for the pilot study can be found in Appendix C. Figure 6 shows the solution for Item 0006 as intended by the author.

Figure 5 Sample open ended item from pilot study

Figure 6 Intended solution for Item 0006

Item 0006 asks the student to produce the isometric view of the object, when provided with the three standard third angle orthographic views. To aid in coding, a reference point (“A”) was labeled on the views provided and on the isometric grid. In coding student responses, elements of a correct response were correct orientation of the object, accurate size and shape of features, presence of all visible features, and general neatness.

There were 31 responses for Item 0006. Figure 7 through Figure 10 show examples of student responses. Figure 7 is incorrect. It is missing the wedge shape towards the back of the object, and does not show the hole through the top of the object. Figure 8 shows the inclined plane as a pyramid and is incorrect. Figure 9 has the wedge feature placed incorrectly, and has too many visible edges on the front face of the object.

Figure 10 is missing a feature completely. Of the features that are present, the wedge is improperly sized and located, and the through hole is incorrectly shown.

Figure 7: Sample open ended student response

Given the three complete views, sketch an isometric view of the given object.

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory Item Title: Open Ended Item 0006 Scale: N/A Author: SS Units: Inches Item #: 0006
 Drawn By: SYN Topic: 02 Version: 2.0 Date: 03/20/2015

I understood what the question was asking:
 Strongly Agree — Strongly Disagree
 1 2 3 4 5 6 7

I feel that the question was:
 Very Easy — Very Difficult
 1 2 3 4 5 6 7

Figure 8 Sample open ended student response

Given the three complete views, sketch an isometric view of the given object.

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory Item Title: Open Ended Item 0006 Scale: N/A Author: SS Units: Inches Item #: 0006
 Drawn By: SYN Topic: 02 Version: 2.0 Date: 03/20/2015

I understood what the question was asking:
 Strongly Agree — Strongly Disagree
 1 2 3 4 5 6 7

I feel that the question was:
 Very Easy — Very Difficult
 1 2 3 4 5 6 7

Figure 9: Sample open ended student response

Figure 10 Sample open ended student response

3.4 Open Ended Items Coding

All responses from the pilot study were coded to quantify the types of responses students gave to the open-ended questions. Table 5 shows the coding done for Item 0006. Once all items were coded, they were sorted into categories. Attention was given to make sure enough categories were created to account for the different types of responses, while still allowing for a meaningful number of responses in each category. Table 6 shows the number of responses in each of the established groups for Item 0006.

When reviewing the responses, three raters were used to ensure inter-rater reliability. At least two coded the response for each item. Frequent communication by coders helped to keep ratings consistent through the open-ended responses. Trends in response type were looked for, and if there were potential candidates for distractor creation, they were included for further discussion.

Table 5 Coding for open ended item 0006

Response	Understood	Difficulty	School	Coder A	Coder B	Coder C
61	1	1	D	Missing One Line on Diagonal Object	Missing Edge, Wrong Shape	Correct
62	1	3	D	Correct	Correct	Correct
63	1	3	D	Diagonal Object in Wrong Place	Wrong Edge Interpretation	Side Feature
64	1	1	D	Wrong Shape on Side Object	Wrong Shape	Side Feature
65	1	1	D	Wrong Shape on Side Object	Wrong Edge Interpretation	Side Feature
66	1	1	D	Correct	Correct	Correct
67	1	7	D	Missing All Features of Piece	Wrong Shape	Missing Feature
68	3	4	D	Missing Diagonal Object	Wrong Shape	Missing Feature
69	1	2	D	Correct	Correct	Correct
70	7	2	D	Correct	Correct	Correct
71	1	3	D	Drawn on Wrong Orientation	Wrong Orientation	Orientation
72	2	2	D	Diagonal Object in Wrong Place	Wrong Edge Interpretation	Side Feature
73	1	2	D	Correct	Correct	Correct
74	6	3	D	Correct	Correct	Correct
75	2	2	D	Correct	Correct	Correct
76	1	1	D	Correct	Correct	Correct
77	1	2	B	Correct	Correct	Correct
78	1	1	B	Correct	Correct	Correct
79	2	6	B	Diagonal Object and Base Wrong Shape	Wrong Shape	Side Feature
80			B	Missing Diagonal Object	Wrong Shape	Missing Feature
81	1	2	B	Missing Hole	Missing Hole and Edge	Missing Feature
82	6	4	B	Missing One Line on Diagonal Object	Wrong Edge Interpretation	Side Feature
83	7	1	B	Missing Diagonal Object and Base	Wrong Shape	Missing Feature
84			B	Missing Home; Diagonal Object Too Wide	Wrong Shape	Missing Feature
85	1	2	B	Correct	Correct	Correct
86	2	4	B	Correct	Correct	Correct
87	1	3	B	Correct	Correct	Correct
88	7	3	B	Correct	Correct	Correct
89	1	2	C	Correct	Missing Edge	Correct
90	1	1	C	Correct	Correct	Correct
91	1	2	C	Correct	Correct	Correct

N=31

Table 6 Open ended codes for Item 0006

Response Coding	Count	Percentage
Correct	18	58%
Side Feature	6	19%
Missing feature	6	19%
Orientation	1	3%
Total	31	100%

To avoid expert blind spot, one rater was recruited from outside the discipline of engineering graphics. Expert blind spot happens when a subject matter expert miscalculates the resources needed for a student to complete a task which the expert considers to be uncomplicated (Ambrose, 2010; Nathan & Koedinger, 2000). This could be problematic in coding, as a subject matter expert might easily overlook certain types of responses or issues in the item structure.

Conversely, a concern regarding expert blind spot was that the non-expert coder might have difficulty with nuances associated with the subject area. An example of this was in the conventions of engineering graphics. Line weights, hatching, and view orientations are all examples of features in graphics that have established conventions (Giesecke, 2004). The non-expert rater questioned many of the conventions as they applied to the items being developed and revised. This in turn, made researchers pay extra attention to the details in each item. An example of potentially overlooked subject matter knowledge was with item stems. For the pilot study, all the items were drafted by content experts, including the stems. Instructions that seemed clear to experts were ambiguous to the non-expert, and required revision. Having a non-expert involved in the coding process proved to be worth the effort of familiarizing them with the content, as details that were overlooked by experts were given full consideration.

Originally, all responses were considered part of a single sample population. This was discarded in favor of having some degree of cross referencing by institution and selected response. It seemed that there were patterns in responses by institutions that could have been attributed to possible differences in content and coverage of graphics in the curriculum between each institution. Variations in content, timing within the

semester, and pedagogical approaches were all speculated as reasons for institutional trends in responses where they were observed. When considering the sample size from each participating school, the locations with larger sample sizes have the potential to greatly influence trends in responses. In addition to a frequency count, the percentage of response was also tabulated for each item by institution. This helped to show a more standardized distribution between institutions and helped when making decisions about what kind of responses to include as distractors. Options that were prominent at an institution with a smaller sample size could then be evaluated and discussed for distractor inclusion.

Figure 11 Sample open ended student response

Table 7 Open ended codes for Item 0033.1

Response	Understanding	Difficulty	Institution	Rater 1	Rater 2
654	2	2	D	direction of section line	direction of section line
655	7	2	D	correct	correct
656	1	5	D	missing labels	missing labels
657	1	3	D	correct	correct
658	1	3	D	missing labels	missing labels
659	1	2	D	correct	correct
660	7	2	D	correct	correct
661	1	1	D	missing labels	missing labels
662	4	4	D	correct	correct
663	1	1	D	correct	correct
664	1	4	D	missing labels	missing labels
665	1	1	D	direction of section line	direction of section line
666	1	2	D	correct	correct
667	1	1	D	correct	correct
668			D	no attempt	no attempt
669	1	3	D	correct	correct
670	1	1	D	missing labels	missing labels
671	1	1	D	missing labels	missing labels
672	1	2	D	single straight section line	single straight section line
673	5	7	B	single straight section line	single straight section line
674	2	5	B	no attempt	no attempt
675	2	4	B	multiple section lines, no direction	multiple section lines
676			B	single straight section line, no direction	single straight section line
677	1	1	B	missing labels	missing labels
678	7	6	B	no attempt	no attempt
679	1	7	B	single straight section line	single straight section line
680	7	3	B	missing labels, no direction	missing labels
681	2	2	B	missing labels	missing labels
682	1	1	C	correct	correct
683	6	5	C	correct	correct
684	1	1	C	correct	correct

Figure 11 shows an item whose responses in the pilot study illustrates the possible effects of sample sizes in the study. Table 7 shows the coding of the item with correct responses in bold. Table 8 and Table 9 show the coding breakdown for Item 0033.1. Every single student from institutions C and D who attempted the item got the placement of the cutting line correct, which is the focus of the problem, and not a single student from institution B got the problem correct in its entirety. Table 8 shows the initial

coding, and suggests that there are certain categories that had enough responses to consider being included for distractor choices. When disregarding the conventions aspect of the problem, the distribution changes drastically, and is shown in Table 9. Using the revised codes, the item had an overwhelming correct response and an insufficient number of distractors to warrant further refinement of responses into distractors, and the item was eliminated from further consideration.

Table 8 Original open ended codes for Item 0033.1

Response Coding	n	%
direction of section line	2	7%
<i>correct</i>	12	40%
missing labels	9	30%
no attempt	3	10%
single straight section line	4	13%
multiple section lines	1	3%

Table 9 Revised open ended codes for Item 0033.1

Response Coding	n	%
<i>correct</i>	23	77%
single straight section lines	4	13%
multiple section lines	1	3%
no attempt	3	10%

3.5 *Likert Item Responses*

Responses to the Likert questions were scored and compiled alongside the open-ended coding and were used as part of the process in distractor creation. The first Likert item stated “I understood what the question was asking” and asked students to match their perceptions on a scale “1-Strongly Agree” to “7-Strongly Disagree”. The second

Likert item stated “I feel that this question was:” and asked students to rate on a scale from “1-Very Easy” to “7-Very Difficult”.

Table 10 Likert scores from Item 0006

	Understanding	Difficulty
Responses Collected	31	31
Likert Scale Responses	29	29
Average Likert Rating	2.17	2.45
Median Likert Rating	1.00	2.00
Std. Dev. Likert Rating	2.12	1.48

Likert Level	Number of Responses	
1 (Understood/Very Easy)	19	8
2	4	10
3	1	6
4	0	3
5	0	0
6	2	1
7 (Did not understand/ Very Difficult)	3	1

Descriptive statistics for the Likert questions in Item 0006 are shown in Table 10.

It shows the number of responses that were used for coding and the number that responded to the Likert items. Observing the frequency of responses was helpful in the revisions of an items’ stem. It was helpful to compare the coded open ended response to any trend in the perceived difficulty or understanding for each item. For example, perceived vague or unclear instructions may have been the cause for a tendency of certain incorrect responses in the open-ended items.

3.6 Distractor Creation

With an understanding of the kinds of responses that were generated for each item, work could begin on drafting distractors. In keeping with suggested methods of

instrument development and other examples of established concept inventories (Allen, 2006; Ding et al., 2006), items were revised to be in multiple choice format. A total of 4 choices were created for each item. One was the correct response, and three were distractors based on students' responses to the open-ended items. Prevalent incorrect responses served as the primary factor in distractor creation. Comments made by the participants were considered for revisions to item's stems and images were adjusted to meet graphic conventional standards. Graphics experts who had many years' experience in teaching graphics, were consulted to provide ideas for additional distractor options when inadequate options were available through the pilot testing for a given item.

Once distractors were identified, complete items were constructed. Stems were corrected for grammar and rewritten for use in a multiple-choice format. Components for the open-ended responses, such as the grids and locating points, were removed. Where applicable, question marks were included to reduce ambiguity on the figures regarding what was being asked for in the item. Several of the open-ended items had more than one potentially correct response. For the statistical methods selected for analysis later in the study, it was necessary for items to be scored dichotomously. From this point forward, each item had one and only one correct response. A completed version of Item 0006 is shown in Figure 12. The correct intended response is choice "A".

Figure 12 Item from alpha version with distractors

3.7 Removal of Concepts

Two of the concepts were removed during the pilot study stage of the project. The two concepts that were removed were “Engineering Methodologies for Object Representation”, and “Solid Modeling”. Engineering Methodologies were removed before the pilot study, and Solid Modeling was removed after it.

During the coding of the open-ended items, problems arose when trying to code the Solid Modeling (also referred to as CAD for Computer Aided Design) items. The CAD items asked students to describe solid modeling strategies they would use to create a given object. The resulting descriptions turned out to be extremely varied, and were difficult to code effectively. One difference with the CAD items was with the idea of “design intent” in evaluating the participant’s response. For example, in other concepts, it was relatively evident when a participant either did, or did not, understand the task or application of skill. With the CAD items, however, many of the varied approaches led to a correct response. When coding and looking for responses that were either “right” or “wrong” this became problematic. How could one answer be “more right” or “more

wrong” than another? Figure 13 through Figure 15 show examples of the variety of responses for Solid Modeling.

Figure 13 Example solid modeling response

Figure 14 Example solid modeling response

Figure 15 Example solid modeling response

The initial analysis of the CAD items suggested that they could be the focus of an entire separate study. (Steinhauer, 2012) suggests that the skills needed for effective CAD design are embedded in the understanding and application of basic graphics skills. In addition, although the experts identified CAD concepts as “important” in the Delphi study, they did not indicate these were particularly “difficult” (M. Sadowski & Sorby, 2013; M. Sadowski & Sorby, 2014). Thus, the items for Solid Modeling concept were removed from inclusion in the instrument after the pilot study.

A similar problem occurred with the concept of “Engineering Methodologies”, in that it was difficult to find items that were suitable for use in the EGCI. Per the definition developed in the Delphi study, Engineering Methodologies dealt with the integration of multiple graphical entities. For example, Figure 16 was a proposed item for the Engineering Methodologies concept. It instructs the participant to describe the assembly

process for the item shown using a suggested methodology. It became increasingly apparent that appropriate items would be difficult to develop for this concept for use on a concept inventory. This realization occurred before the pilot testing and items for this concept were not included in open-ended testing. With the exclusion of CAD and Engineering Methodologies, eight of the original ten concepts were carried over to the first round of distractor testing with multiple choice items, the alpha version of the instrument.

<p>Describe in general terms how you would create an assembly of this table using a top down assembly method, starting with the table top. There are nine total components in the complete assembly, the table top, 4 legs, 2 front rails, and 2 side rails.</p> <p>Describe in general terms how you would create an assembly of the same table using a bottom up assembly method, starting with the table top.</p>
--	--

Figure 16 Proposed item for engineering methodologies

Chapter 4: Alpha Version

4.1 Alpha Version Methods

The next stage of development for the concept inventory would be testing the items with distractors. The initial multiple choice version of the instrument was referred to as the alpha version. All four of the schools participated in the alpha version testing. The alpha version was administered near the end of the semester, a few weeks before final exams. All graphics material for the surveyed sections had been completed at that time. Administration of the alpha version was done electronically.

The alpha version of the instrument was administered simultaneously at all participating institutions. Ideally, each participant would take all of the items on the alpha version; however, having volunteers take a large number of items (50+) would not have been a good research practice, because it would increase the likelihood of cognitive fatigue (P. L. Ackerman & Kanfer, 2009; P. Ackerman, Kanfer, Shapiro, Newton, & Beier, 2010; Sievertsen, Gino, & Piovesan, 2016). Furthermore, it would have been logistically difficult to request a volunteer participant to complete 50+ items with accuracy. To address this, multiple editions of the alpha version were created with the surviving items. Three editions of approximately 22 questions each were developed. Using a scale as identified by Streveler et. al. (Streveler, Litzinger, Miller, & Steif, 2008), items were sorted by difficulty as demonstrated by participant responses in the Pilot

Study. Each of the editions contained items representing all concepts and a range of difficulties and concepts with fewer items were included on multiple versions. In similar fashion to the pilot study, completion of the instrument was made compulsory in given classes when feasible to encourage sufficient responses for each item. Appendix E shows the item distribution on each edition of the alpha Version of the EGCI. Between the three editions, 974 students took the alpha version of the test. The editions were distributed randomly and regularly, which resulted in approximately 325 students completing each edition.

Figure 17 Item from concept of section views

4.2 Concept Maps

The topics in engineering graphics overlap, and there is debate regarding whether a certain type of problem belongs in one concept area or another (M. Sadowski & Sorby, 2013). For example, consider Item 0013 as shown in Figure 17. The item was created with the intention to measure the concept of Sectional Views. When evaluated by experts, it was also considered to possibly measure the concepts of Visualizing in 2D, Planar Geometry, and Drawing Conventions. With respects to the concepts as defined in

this study, one can see a case being made for the item's inclusion into any one of these concepts. The requirement of a concept to be a primary focus of an item, while still acknowledging the inherent connectivity between concepts, warranted the use of concept maps as an organizational tool.

Concept maps were chosen to help define relationships between the concepts. With a concept map, concepts are shown in a box or similar enclosed shape. Lines or arrows on the map represent the relationships between the concepts. Using arrows is an important feature of a concept map, because this implies hierarchy or direction. Verbs are used on the arrows to indicate the nature of the relationship between the concepts. For this study, a concept map would help provide structure for the instrument as it was developed. Aligning the items on the EGCI with those on the concept map ensured adequate coverage of the important concepts.

Several concept maps were created using the ten concepts identified by Sadowski and Sorby (2013) for engineering graphics. Each researcher on the project generated a concept map independently. At an in-person meeting of the research group, the individual maps were compared and combined into a single map. An integrated scoring rubric as described by Besterfield-Sacre et.al (2004) was used to guide the merging of the individual maps. The rubric describes qualities of concept maps, as well as the interpretation of assigned scores. Examples of qualities are structure, organization, and correctness. Having an established rubric permitted a focused discussion among the members of the research team. Consensus was achieved after open discussion between all members. Frequent re-examination of the rubric allowed intermittent checking of the emerging consensus map. Figure 18 through Figure 20 show examples of individual

concept maps as generated by the research team. Figure 21 shows the final version of the concept map produced by the researchers.

Figure 18 Individual concept map A

Figure 19 Individual concept map B

Figure 20 Individual concept map C

Figure 21 Final concept map

One can see how the initial individual concept maps contributed to the final version. The most significant change in the final version was in the resulting number and names of concepts in the final map. It was decided that an overarching theme of “Conventions” informed the concepts of Dimensioning and Sectional Views. The final concept map utilized one way arrows and has a distinct hierarchal nature to it. This implied the importance or underpinnings of certain ideas, and how an understanding of a concept closer to the top of the map would be necessary for application to concepts lower in the map. This flow supports the distribution of items on the instrument amongst the topics. For example, the ability to understand and apply the concepts of Sections relies

on an individual understanding of Parallel Projection Methods, Planar Geometry, and the ability to Visualize and Translate between 2D and 3D

Having a clearer, agreed upon understanding of the concepts that were included in the instruments and the relationships between them was a critical step in the development of the concept inventory. For an instrument to be valid, it must have an acceptable level of breadth and depth of topics measured (Moskal, Leydens, & Pavelich, 2002). The utilization of the concept map helped ensure this by providing a basis for evaluation of individual items to ensure coverage of all concepts on the instrument.

One advantage of a well-constructed concept map was in the validity testing of the instrument. Comparing the depth and extent to which included items address the concepts was more effective with the relationships between the concepts clearly articulated. Another way the map could be used was in the analysis the instrument. Patterns emerged in the data that revealed tendencies for students to have trouble with certain areas in the hierarchy. For example, if a participant does poorly on items within the “Parallel Projections Methodology” concept, one might look at his/her performance in the “Projection Theory” and “Planar Geometry” concepts to indentify possible insights into confounding factors.

4.3 Alpha Version Results

Each item in the alpha version had a sample size of approximately 300 from students from participating schools. The data was compiled from all editions and coded. Only participants that completed an edition in its entirety was included for analysis. Responses that appeared to have been filled out in haste were eliminated from data

processing. For example, a student who took significantly less time to complete the instrument while getting a very low score, or a student providing the same response for all items were eliminated from the analysis.

Difficulty scores and discrimination indices were calculated for each item. Internal reliability for the editions was measured using KR20 with a value of above 0.7 as the desired value. An example of the descriptive statistics calculated for an item can be found in Table 11. Additional selected statistics from each edition of the alpha version can be found in Appendix F.

Table 11 Descriptive statistics for Item 0006 on alpha version

VERSION	A
RESPONSE	Item 0006
	Frequency
A	26
B	60
C	17
D	209
n-TOTAL	312
ITEM DIFFICULTY	0.67
MEAN TIME [s]	53.4
n-School A	28
n-School B	226
n-School C	0
n-School D	58
% Correct School A	57%
% Correct School B	64%
% Correct School C	
% Correct School D	83%

**Correct response is D*

Table 11 shows the performance for Item 0006 for all participants surveyed. It shows the frequency of distractor selection, difficulty score, average time spent on the item, the number of responses from each institution, and the percent correct at each

school. It was important to have a sense of the number of students at each school as a school with a larger sample population could possibly skew results.

Distractor choices were tabulated to observe trends in incorrect response selection. Incorrect responses across multiple institutions were considered likely areas of student misunderstanding (Streveler & Smith, 2006). Items were coded dichotomously as either correct or incorrect, regardless of response. Table 12 shows the descriptive statistics for the three editions of the alpha version. The total in terms of variance, mean score, standard deviation, and standard error of measurement are shown for each edition. Of significance are the KR20 measures. All versions are approaching or above the accepted level of internal reliability. All the KR20 values are also within .05 of each other. This suggests that a subset of the items can produce an instrument that is not only sufficiently reliable, but also of a steady reliability level irrespective of items chosen. To have equal representation of concepts covered in each edition, eight items were repeated in the editions.

Table 12 Descriptive statistics for alpha version editions

	Edition A	Edition B	Edition C
Number of items	25.00	25.00	22.00
Variance (σ^2)	18.28	16.86	15.55
Mean Score	12.82	15.44	12.46
St. Dev. of Score	4.28	4.11	3.94
KR20*	0.74	0.74	0.69
Std. Error or Measurement	2.16	2.09	2.18

To make comparisons between items covering each concept, the discrimination indices and difficulty scores were charted together. Items were sorted by concept to

show item behavior and assisted in item selection for the subsequent version (beta). Table 13 shows the item statistics for the alpha version. Items that are listed twice were assigned on multiple editions of the alpha version. Failure to consider difficulty and discrimination concurrently could result in a decrease in instrument quality. Without a range of difficulties, the instrument would at best result in a binary sorting system, classifying students into high- or low-performing depending on where the threshold was set. Not having items without suitable discrimination could result in an instrument that was unreliable, as the items would not indicate the likelihood of a student getting the question correct due to ability rather than chance.

It was helpful to see items grouped by concept as the ranges of difficulty and discrimination were readily compared. Continuing to operate under the assumption that items within a concept measured the same latent ability or trait, decisions on item selection could be made more objectively by using the metrics of difficulty score and discrimination index.

Table 13 Item measures for alpha version

Item No.	Alpha Concept	Difficulty Score	Discrimination Index	Edition
0017.0	Dimensioning	0.63	0.54	A
0045.2	Dimensioning	0.72	0.47	C
0073.1	Dimensioning	0.53	0.61	A
0073.2	Dimensioning	0.73	0.45	B
0073.3	Dimensioning	0.40	0.47	C
0046.1	Dimensioning	0.80	0.32	B
0046.2	Dimensioning	0.74	0.51	C
0008.0	Drawing Conventions	0.17	0.15	A
0016.0	Drawing Conventions	0.73	0.29	B
0053.0	Drawing Conventions	0.28	-0.13	A
0053.0	Drawing Conventions	0.24	0.17	C
0004.0	Mapping BT 2D and 3D	0.43	0.45	B
0004.0	Mapping BT 2D and 3D	0.55	0.51	C
0006.0	Mapping BT 2D and 3D	0.68	0.43	A

Continued

Table 13 continued

0010.0	Mapping BT 2D and 3D	0.85	0.24	B
0027.0	Mapping BT 2D and 3D	0.65	0.43	C
0031.1	Mapping BT 2D and 3D	0.37	0.40	A
0039.2	Mapping BT 2D and 3D	0.80	0.41	A
0039.2	Mapping BT 2D and 3D	0.84	0.30	B
0039.2	Mapping BT 2D and 3D	0.70	0.56	C
0040.0	Mapping BT 2D and 3D	0.84	0.36	B
0044.0	Mapping BT 2D and 3D	0.65	0.59	C
0045.1	Mapping BT 2D and 3D	0.83	0.40	A
0047.1	Mapping BT 2D and 3D	0.58	0.67	B
0047.2	Mapping BT 2D and 3D	0.46	0.41	C
0047.4	Mapping BT 2D and 3D	0.32	0.50	A
0047.5	Mapping BT 2D and 3D	0.65	0.33	B
0048.1	Mapping BT 2D and 3D	0.71	0.41	C
0048.2	Mapping BT 2D and 3D	0.40	0.50	A
0049.1	Mapping BT 2D and 3D	0.69	0.31	B
0062.0	Mapping BT 2D and 3D	0.69	0.50	A
0063.0	Mapping BT 2D and 3D	0.26	0.54	B
0064.0	Mapping BT 2D and 3D	0.69	0.56	C
0065.0	Mapping BT 2D and 3D	0.36	0.34	A
0066.0	Mapping BT 2D and 3D	0.65	0.58	B
0067.0	Mapping BT 2D and 3D	0.26	0.08	C
0068.0	Mapping BT 2D and 3D	0.19	0.27	A
0069.0	Mapping BT 2D and 3D	0.55	0.49	B
0070.0	Mapping BT 2D and 3D	0.26	0.17	C
0071.0	Mapping BT 2D and 3D	0.39	0.44	A
0015.0	Parallel Projection Methodologies	0.75	0.36	A
0049.4	Parallel Projection Methodologies	0.89	0.22	A
0049.4	Parallel Projection Methodologies	0.87	0.37	C
0072.0	Parallel Projection Methodologies	0.70	0.56	B
0072.0	Parallel Projection Methodologies	0.71	0.61	C
0042.0	Planar Geometry	0.29	0.32	A
0042.0	Planar Geometry	0.38	0.40	B
0042.0	Planar Geometry	0.30	0.41	C
0051.0	Planar Geometry	0.38	0.23	C
0052.0	Planar Geometry	0.65	0.61	A
0055.0	Planar Geometry	0.36	0.39	B
0056.0	Planar Geometry	0.29	0.40	B
0001.0	Projection Theory	0.55	0.58	A
0014.0	Projection Theory	0.83	0.33	B
0028.1	Projection Theory	0.64	0.40	C
0028.2	Projection Theory	0.53	0.71	A
0028.3	Projection Theory	0.71	0.39	B
0028.4	Projection Theory	0.45	0.36	C
0028.5	Projection Theory	0.72	0.46	A
0039.0	Projection Theory	0.78	0.45	B
0061.0	Projection Theory	0.55	0.29	C
0013.0	Sectional Views	0.24	0.28	A
0022.0	Sectional Views	0.65	0.52	B
0043.2	Sectional Views	0.29	0.32	B
0043.2	Sectional Views	0.38	0.39	C
0057.0	Sectional Views	0.28	0.22	C
0058.0	Sectional Views	0.43	0.57	A
0060.1	Sectional Views	0.14	0.14	B
0060.2	Sectional Views	0.43	0.72	C
0004.0	Visualizing in 2d/3d	0.52	0.45	A
0009.0	Visualizing in 2d/3d	0.24	0.41	B
0009.0	Visualizing in 2d/3d	0.41	0.38	C
0021.0	Visualizing in 2d/3d	0.52	0.65	A
0021.0	Visualizing in 2d/3d	0.73	0.35	B

Chapter 5: Beta Version

5.1 *Beta Version Methods*

Following the analysis of the alpha version, the next iteration served as a chance to further refine items and evaluate the instrument in its entirety. The concepts of “Visualizing in 2d/3d” and “Drawing Conventions” were consolidated into other concepts after again utilizing concept maps, which left 6 concepts remaining. Items from these six concepts were compiled into a beta version of the instrument that was administered at all four institutions. The beta version was given approximately two thirds of the way through the semester at each institution when the graphics portion of the curriculum had already been completed in each surveyed course.

5.2 *Item Selection and Distribution*

The objective of the beta version was to make revisions of the items selected from the alpha version. Since a 30-item instrument was planned as the final concept inventory, it was also an opportunity to remove any items from the alpha version that seemed problematic or redundant. Any revisions in format to items were made before including in the beta version for testing. Revisions were made to elements such as alignment of distractors, drawing conventions, language of item stems, and items’ appearance in electronic format.

Item selection for the beta version followed a similar procedure for the alpha version. Table 14 shows the item distribution for the beta version of the instrument combined with the psychometric statistics from the alpha version that were used for item selection. A lower bound of 0.20 was used as the threshold for item inclusion when considering discrimination and range of 0.20 to 0.80 was used for difficulty. Like the administration of the alpha version, the items on the beta version were divided into multiple editions to help with the data collection process. The two editions of the beta version, red and blue, had 38 items distributed across all concepts. Twenty of the items appeared on both editions, and the remainder were split and unique to one edition. Concepts with fewer items appeared on both editions.

Table 14 Item map for beta version

Item	Concept	Alpha Diff.	Alpha Disc.	Red	Blue
0001.0	Projection Theory	0.55	0.58	x	x
0009.0	Projection Theory	0.41	0.38	x	x
0014.0	Projection Theory	0.83	0.33		x
0028.1	Projection Theory	0.64	0.40	x	
0028.2	Projection Theory	0.53	0.71		x
0028.3	Projection Theory	0.71	0.39		x
0028.4	Projection Theory	0.45	0.36	x	x
0028.5	Projection Theory	0.72	0.46	x	
0039.0	Projection Theory	0.78	0.45	x	
0021.0	Planar Geometry	0.52	0.65	x	
0042.0	Planar Geometry	0.38	0.40	x	x
0052.0	Planar Geometry	0.65	0.61		x
0055.0	Planar Geometry	0.36	0.39	x	x
0027.0	Parallel Projection Methodologies	0.65	0.43		x
0072.0	Parallel Projection Methodologies	0.71	0.61	x	
0073.1	Parallel Projection Methodologies	0.53	0.61	x	x
0006.0	Mapping b/t 2D and 3D	0.68	0.43		x
0015.0	Mapping b/t 2D and 3D	0.75	0.36		x
0031.1	Mapping b/t 2D and 3D	0.37	0.40	x	x
0039.2	Mapping b/t 2D and 3D	0.80	0.41		x
0040.0	Mapping b/t 2D and 3D	0.84	0.36	x	
0047.1	Mapping b/t 2D and 3D	0.58	0.67		x
0047.4	Mapping b/t 2D and 3D	0.32	0.50	x	

Continued

Table 14 continued

0047.5	Mapping b/t 2D and 3D	0.65	0.33	x	x
0048.1	Mapping b/t 2D and 3D	0.71	0.41	x	
0048.2	Mapping b/t 2D and 3D	0.40	0.50	x	
0049.1	Mapping b/t 2D and 3D	0.69	0.31	x	
0063.0	Mapping b/t 2D and 3D	0.26	0.54		x
0064.0	Mapping b/t 2D and 3D	0.69	0.56		x
0066.0	Mapping b/t 2D and 3D	0.65	0.58	x	
0068.0	Mapping b/t 2D and 3D	0.19	0.27	x	x
0069.0	Mapping b/t 2D and 3D	0.55	0.49		x
0071.0	Mapping b/t 2D and 3D	0.39	0.44	x	
0013.0	Conventions - Sectional Views	0.24	0.28	x	x
0022.0	Conventions - Sectional Views	0.65	0.52	x	x
0043.2	Conventions - Sectional Views	0.38	0.39	x	x
0056.0	Conventions - Sectional Views	0.29	0.40	x	x
0057.0	Conventions - Sectional Views	0.28	0.22	x	x
0058.0	Conventions - Sectional Views	0.43	0.57	x	x
0008.0	Conventions - Dimensioning	0.17	0.15	x	x
0016.0	Conventions - Dimensioning	0.73	0.29	x	x
0017.0	Conventions - Dimensioning	0.63	0.54	x	x
0045.2	Conventions - Dimensioning	0.72	0.47	x	x
0073.3	Conventions - Dimensioning	0.40	0.47	x	x
1029.0	Cad Sweep	0.55	0.63	x	
1030.0	Cad Sweep	0.70	0.51		x
1016.0	Cad Revolve	0.80	0.43	x	
1045.0	Cad Revolve	0.73	0.40		x
1067.0	Cad Planes	0.78	0.52	x	
1068.0	Cad Planes	0.65	0.72		x
1026.0	Cad Loft	0.55	0.53	x	
1027.0	Cad Loft	0.44	0.52		x
1012.0	Cad Extrude	0.84	0.42		x
1014.0	Cad Extrude	0.82	0.33	x	
1158.0	Cad Constraints	0.64	0.43	x	
1167.0	Cad Constraints	0.60	0.56		x
				38	38

5.3 Beta Version Results

All four institutions participated in testing the beta version. A breakdown of participants and their scoring can be found in Table 15. Table 16 Shows the comparative statistics for the Red and Blue editions of the beta version.

Solid-modeling (CAD) items were re-introduced in the beta version. During the pilot study, difficulties with CAD items were identified and they were not included in the alpha version. External advisers to the project suggested the inclusion of CAD items in a new format for the beta version. Multiple choice CAD items were adapted from an

existing instrument designed to assess CAD proficiency at the high school level. Several of these items were included in the beta version of the CI.

Table 15 Beta version participants by institution

Institution	N-Blue	Average Score on Blue Edition	N - Red	Average Score on Red Edition
Institution A	229	22.06	233	22.70
Institution B	61	18.20	55	18.35
Institution C	29	27.07	29	25.86
Institution D	116	24.43	107	25.07
Overall	435		424	

Table 16 Comparative statistics for editions on beta version

	Red Edition	Blue Edition
N (Items)	38	38
Mean	23.47	22.51
Median	24.00	23.00
Standard Deviation	7.33	6.88
Variance (Σ^2)	53.61	47.17
KR20	0.8507	0.8408

Concepts were again re-aligned using concept maps. There were six concepts used in the beta version down from the eight that were included in the alpha version. “Drawing Conventions” was distributed into its dependent concepts, and “Mapping between 2D/3D” was absorbed by its preceding concepts of “Projection Theory” and “Planar Geometry”. By revisiting the concept map, items could be reevaluated for placement into alternative categories. Concepts in graphics are inherently connected and difficult to separate. Thus, an item belonging to more than one category plausible.

Chapter 6: Validity Study

6.1 Validity Study Methods

There are several measures of validity that attest to different aspects of the cogency of an instrument. One measure that has been used in creating concept inventories was face validity. Face validity of an instrument is the extent to which an instrument appears to measure the constructs that it intends to measure (Gay, Mills, & Airasian, 2006). The guiding question used to determine the face validity was “Do the items on the EGCI represent the graphics concepts identified through the Delphi study determine students understanding of these core concepts?” (Crocker & Algina, 1986). Frequent consulting with experts throughout the life of the project suggested that the items were answering this question positively. To further verify this claim, a study was done to verify the validity of the items being developed.

The structure of the face validity study was to solicit a group of experts and pose the question to them. Experts from within the engineering graphics education community were solicited for participation. Several of these participants had also contributed to the Delphi study. The self-identified roles and experience of the experts are shown in Table 17 and Table 18 (M. Sadowski & Sorby, 2013; M. Sadowski & Sorby, 2014).

Table 17 Roles of experts in validity study

Participant Role	N
Graphics Professional	1
Instructor / Professor	16
Researcher	2
Total	19

Table 18 Experience of experts in validity study

Years of Experience	N
0-2 years	2
3-5 years	0
6-10 years	3
Over 10 years	14
Total	19

Items from the beta version were used in the validity study. Items and the concept the item was intending to measure were shown to participants. Descriptions of the concepts were provided to the participants and were available throughout the survey. The participants were asked if they agreed that the item appeared to measure the proposed concept. If they did not agree, then participants could indicate what concept from the list seemed more appropriate. All items from the beta version were used in the validity study. Figure 22 through Figure 24 are examples of the question layout. Additional items from the validity study are given in Appendix J. It was important to indicate that feedback on item structure was not being sought (i.e. conventions, whether the item was correct, etc.). Experts were to only indicate whether they thought being able to respond to the item correctly was characteristic of understanding the given concept.

Item #: 0013

Given the front and top views of the object, select the option that shows the correct section view.

A. **B.** **C.** **D.**

The above question is intended to measure the Concept of:
SECTIONAL VIEWS.

Do you agree that this is what is measures?

YES ☐ **NO** ☐

Which Concept should this instrument measure?

☐ MAPPING BETWEEN 2D AND 3D
 ☐ PROJECTION THEORY
☐ PARALLEL PROJECTION METHODOLOGIES
 ☐ SECTIONAL VIEWS
☐ PLANAR GEOMETRY
 ☐ DIMENSIONING
☐ OTHER (please indicate):
☐ CAD CONCEPTS

Figure 22 Item from validity study

Table 19 Validity study Item 0013

Response	N - Item 0013
Yes	18
No	1
Planar Geometry	1
Total	19

Item #: 0022

Select the option that shows the correct section view A-A.

?

A.

B.

C.

D.

The above question is intended to measure the Concept of:
SECTIONAL VIEWS.

Do you agree that this is what is measures?

YES ☐ NO ☐

Which Concept should this instrument measure?

☐ MAPPING BETWEEN 2D AND 3D ☐ PROJECTION THEORY

☐ PARALLEL PROJECTION METHODOLOGIES ☐ SECTIONAL VIEWS

☐ PLANAR GEOMETRY ☐ DIMENSIONING

☐ OTHER (please indicate): ☐ CAD CONCEPTS

Figure 23 Item from validity study

Table 20 Validity study Item 0022

Response	N - Item 0022
Yes	18
No	1
Other (please indicate)	1
Total	19

Item #: 0055

Select the option that shows the correct cutting plane that produces section A-A.

A.

B. SECTION A-A

C.

D.

The above question is intended to measure the Concept of:
PLANAR GEOMETRY.

Do you agree that this is what is measures?

YES ☐ NO ☐

Figure 24 Validity study item

Table 21 Validity study Item 0055

Response	N - ITEM 0055
Yes	4
No	15
Sectional Views	14
Other (please indicate)	1
Total	19

6.2 *Validity Study Results*

Nineteen subject matter experts provided input on all 58 items from the beta version. Any item selected to be on the final version of the instrument would thus have a validity rating associated with it. All items had at least a 50% agreement rate, often going into the 70-80% range. For the items that did have several experts in disagreement with the measured concept, the declared responses of the participants were never the majority of the responses or greater than the number of participants who agreed with the stated concept. Table 19 through Table 21 show the responses for the example items from the validity study. Responses for all items in the validity study can be found in Appendix J. Items served as a control to monitor participants' behavior where the intended concept was intentionally labeled incorrectly. For these items, the overwhelming consensus was that the item did not measure the stated concept. Based on the results from the face validity study, it seems that the items on the instrument are measuring the concepts they were designed to measure.

Chapter 7: Gamma Version

7.1 Item Selection

With the beta version complete and the data analyzed, items could be selected for inclusion for the final version of the instrument. Keeping with naming conventions for previous versions, the final version is referred to as the gamma version and may be used interchangeably in this document with the term “final version”. The items on the beta version had now undergone at least two series of revisions and field testing. Item selection for the gamma version was a similar process to that followed for the alpha and beta versions. For the gamma version, items were selected whose difficulty and discrimination indices would have thorough range as possible to cover an appropriate span of values.

Concept maps were revisited again to re-classify items and sort into categories where appropriate. After item and concept reorganization, there were five concepts that made it to the Gamma version, excluding the CAD items. The list of concepts as covered in each version of the instrument appears in Table 22. With the same psychometric calculations being performed twice for each item (alpha and beta versions), an additional facet could be considered when selecting items. This resulted in an opportunity to check for reliability by looking at the instrument’s test-retest reliability. Test-retest reliability is the extent to which an assessment tool produces stable and consistent results (Cozby &

Bates, 2012; Moskal, Leydens, & Pavelich, 2002; Tukey, 1991). Measures of item performance across time could be compared for additional insight into item behavior.

Table 22 Concepts by version

Pilot	Alpha	Beta	Gamma
Mapping between 2D and 3D	Mapping between 2D and 3D	Mapping between 2D and 3D	Mapping between 2D and 3D
Planar Geometry	Planar Geometry	Planar Geometry	Planar Geometry
Sectional views	Sectional views	Sectional Views (Conventions)	Sectional Views (Conventions)
Projection theory	Projection Theory	Projection Theory	Projection Theory
Dimensioning	Dimensioning	Dimensioning (Conventions)	Dimensioning (Conventions)
Parallel Projection Methodologies	Parallel Projection Methodologies	Parallel Projection Methodologies	
Drawing Conventions	Drawing Conventions		
Visualizing in 2D and 3D	Visualizing in 2d/3d		
Engineering Methodologies for Object Representation			
Solid Modeling		CAD	CAD
10 Concepts	8 Concepts	6 Concepts + CAD	5 Concepts + CAD

Consistency or improvement in difficulty or discrimination was interpreted as an indicator of the reliability of the items. Based on the method for calculating item discrimination and difficulty, comparisons between items from the alpha and beta versions could not be made because on both the alpha and beta versions, the number of items on any given edition was different. There were three editions in the alpha version and two editions in the beta version, and none had the same set of items. This compromised any ability to make any direct comparisons for items that were in both versions. Item discrimination considers the performance of a given item as they relate to the instrument as a whole in the formula, thus any disparity in what items were included

may lead to differences in calculations. Even though direct comparisons could not be made between versions, discrimination index was a helpful metric to keep in mind when selecting items for the gamma version. Discrimination indices were especially useful in certain cases where a large difference in item performance occurred between versions, as one would expect a quality item would remain relatively stable in a similar instrument administered under similar conditions.

The descriptive statistics for the alpha and beta versions are similar. Both have mean scores of just below 60% and KR20 scores within a few points of each other (see Table 12 and Table 16). Based on these it is reasonable to assume that the gamma version will be reasonably reliable.

7.2 *Gamma Version*

The final 30 items and their respective measures are in given in Table 24. Figure 25 graphically shows the range of difficulty and discrimination indices for items on the gamma version of the instrument. Each of the concepts on the gamma version is represented by a different type of point on the graph (see legend for details). The dashed vertical lines represent the upper and lower thresholds for item difficulty as used in the study. The dashed horizontal line shows the minimum acceptable level of discrimination for the items. Similar figures for each concept are shown in 144Appendix I. Sample items from the final version are shown in Figure 26 to Figure 30.

Table 23 gives the number of items per concept. The distribution follows the concept map created for the study, in that concepts that are higher up on the chart tend to

have more items. For example, “Mapping Between 2D and 3D” concept has the most items, and is the concept at the “source” of the concept map.

Table 23 Count of items by concept on final version

Concept	Number of Items
Mapping b/t 2d and 3d	10
Projection theory	8
Planar geometry	3
Sectional views (Conventions)	5
Dimensioning (Conventions)	4
Total	30

Table 24 Item description for final version

Item	Concept	Difficulty	Discrimination
0013.0	Sectional Views (Conventions)	0.25	0.26
0022.0	Sectional Views (Conventions)	0.66	0.58
0043.2	Sectional Views (Conventions)	0.35	0.38
0056.0	Sectional Views (Conventions)	0.30	0.23
0058.0	Sectional Views (Conventions)	0.52	0.41
0001.0	Projection Theory	0.54	0.58
0009.0	Projection Theory	0.42	0.36
0027.0	Projection Theory	0.63	0.51
0028.2	Projection Theory	0.67	0.46
0028.4	Projection Theory	0.51	0.45
0039.0	Projection Theory	0.73	0.59
0072.0	Projection Theory	0.67	0.66
0073.1	Projection Theory	0.67	0.67
0021.0	Planar Geometry	0.72	0.38
0042.0	Planar Geometry	0.40	0.50
0052.0	Planar Geometry	0.75	0.62
0006.0	Mapping b/t 2D and 3D	0.67	0.43
0040.0	Mapping b/t 2D and 3D	0.75	0.53
0047.1	Mapping b/t 2D and 3D	0.60	0.54
0047.4	Mapping b/t 2D and 3D	0.39	0.47
0047.5	Mapping b/t 2D and 3D	0.61	0.47
0063.0	Mapping b/t 2D and 3D	0.33	0.48
0066.0	Mapping b/t 2D and 3D	0.65	0.65
0068.0	Mapping b/t 2D and 3D	0.21	0.23
0069.0	Mapping b/t 2D and 3D	0.57	0.57
0071.0	Mapping b/t 2D and 3D	0.52	0.54
0008.0	Dimensioning (Conventions)	0.35	0.47
0017.0	Dimensioning (Conventions)	0.71	0.49
0045.2	Dimensioning (Conventions)	0.65	0.53
0073.3	Dimensioning (Conventions)	0.38	0.40

Figure 25: Difficulty vs. discrimination for items on gamma version

Figure 26 Gamma version Item 0001

Item #: 0006

Given the front, side, and top views of the object, select the option that shows the correct isometric view.

Figure 27 Gamma version of Item 0006

Item #: 0017

Select the correctly dimensioned object from the object given below.

Figure 28 Gamma version of Item 0017

Figure 29 Final version of Item 0047.4

Figure 30 Final version of Item 0073.1

Chapter 8: Discussion and Conclusion

8.1 *Item Difficulty and Discrimination*

The values for discrimination indices and difficulty scores were used to select items to be included in the subsequent versions of the instrument. To be considered for inclusion on the next version, items needed to have appropriate scores on both discrimination and difficulty. Keeping in mind the goal of having items across a range of difficulties and of adequate discrimination, it was not practical to consider difficulty and discrimination independently or for one to take precedence over another. Doing so might have caused unwarranted elimination of items. For example, eliminating items below a certain threshold on discrimination index might have removed several items with satisfactory difficulty scores. Conversely, selecting items across the range of difficulty scores failing to incorporate the discrimination index, might have resulted in items that have insufficient discriminatory ability. Thus, both measures were considered when selecting items for inclusion.

8.2 *Alignment of Corners*

The finished instrument should consider all elements of the assessment triangle. The three elements should be reinforcing each other instead of dominating or working

against one another (Pellegrino et al., 2001). The relationship between each of the corners of the triangle are described subsequently.

8.2.1. Relationship between Cognition and Observation

When utilizing the assessment triangle as a framework to facilitate instrument development, tasks (observations) should be grounded in beliefs about how students misconceive concepts in the subject matter (cognition) (Streveler & Smith, 2006). One connection between cognition and observation is the association between the concepts and expert opinion. The findings from Sadowski & Sorby (2014) came from experts who identified the core concepts in engineering graphics. The Delphi study also had experts determine the importance and perceived difficulty of the concepts. Concepts that were considered difficult and important were used to guide the creation of items for the instrument, ensuring a direct link between the two corners.

Another connection between the two corners can be found in how the distractors were developed. Student incorrect responses to open ended items were used to inform distractor creation. Student responses gave insight into the misconceptions of how skills and concepts were being applied to engineering graphics problems.

8.2.2. Relationship between Interpretation and Cognition

Experts identified important concepts and developed concept maps (cognition) that were used to help explain trends in responses (interpretation). In the Delphi study, experts rated the concepts in terms of students' perceived difficulty. When looking for patterns in student performance after administration of the alpha and beta versions, this

expert difficulty rating was considered for items that might have had irregular or especially low performance in a particular version. It is reasonable to expect the items covering concepts that are difficult to be the ones with fewer correct scores. When factoring in student informed distractors, one could expect the trend to be exacerbated, because the misconceptions are held by a wide range of students.

8.2.3. Relationship between Observation and Interpretation

Keeping in practice with methods for concept inventory development, each item on the EGCI has one correct response. Any alternative responses are considered uniformly erroneous. The dichotomous scoring of the EGCI (observation) makes techniques from CTT and IRT applicable (interpretation). The difficulty scores and discrimination indices are a sensible method for construing meaning from student performance and for selection of surviving items for the final instrument.

8.3 Scoring

For the gamma version, the survey tool employed in this project produces a total score on the instrument, as well as sub-scores for each concept. A maximum score on the instrument is 30 points, followed by the individual sub scores in a predetermined order: Mapping between 2D and 3D, Projection Theory, Planar Geometry, Sectional Views, and Dimensioning. A perfect score would thus be thirty, followed by the sub-scores in each concept; 30(11-8-3-5-4). Concepts with a smaller number of items in the gamma version may be harder to make inferences from, because each item represents a larger percentage of the total score of the concept. A proposed further refinement of concepts is shown in

Table 25. The concepts with the subheading of “conventions” have been merged, as well as the concepts of “projection theory” & “planar geometry”. These combinations are in line with the practices that have been used throughout the instrument development. The three surviving concepts follow the hierarchy and relations set forth in the final concept map described earlier. With this grouping scheme, the three concepts now have a similar number of items. This could likely make comparisons of sub-scores more meaningful and useful.

Table 25 Concept list for gamma version

Existing Concept	Number of Items	Proposed Concept for Scoring	Number of Items
Mapping b/t 2d and 3d	10	Mapping b/t 2d and 3d	10
Projection theory	8	Projection theory & Planar geometry	11
Planar geometry	3		
Sectional views (Conventions)	5	Conventions: Sectional views & Dimensioning	9
Dimensioning (Conventions)	4		
Total	30		30

In most cases, a single total score will likely be sufficient. The instrument was developed with the intent that all items are measuring the same latent trait of ability in engineering graphics. This would be useful in assessments of groups of students, as sample size tends to negate outliers in measurement (Gay et al., 2006). For things with higher stakes, such as individual assessment and evaluating curricula, it may be more beneficial to account for sub-scores. For example, consider students A, B, and C with identical scores of 18 out of 30. As a group, they represent a certain strata of student performance. If sub-scores are considered, the students may tell a different story. Using the proposed scoring system in Table 29, possible scores are: Student A with a score of

18:10-9-0, Student B with 18:6-6-6, and Student C with 8-3-7. Some inferences can be made about the students' performances. Students A and C seem to be high scoring except on certain concepts. Student B seems to be a more well-rounded student, with even marks throughout. If the scenario was changed and the sub-scores represented class averages, this would likely be an indicator for further scrutiny of pedagogical practices and coverage of topics in a graphics class.

8.4 Addressing Research Aims

Research Aim 1 - Identify fundamental consensus concepts within engineering graphics.

This study largely built on the previous work of the Delphi study conducted by Sadowski and Sorby for the identification of fundamental concepts in engineering graphics (M. Sadowski & Sorby, 2013; M. Sadowski & Sorby, 2014; M. A. Sadowski & Sorby, 2015). Their study provided a foundation on which to begin the current study. The participants in the previous Delphi study helped to demonstrate the interest of the engineering graphics community and potential for the final instrument to be widely adopted by practitioners.

The concepts identified by the Sadowski and Sorby work were a useful starting point for this project. Changes were made to the concepts as the development of the instrument progressed. There were 10 concepts at the start of the pilot study and initial drafting of items. Field testing, expert consultation, and statistical analysis contributed to amending the scope of concept definitions and usage and to the non-inclusion of certain concepts on the EGCI. Concept maps proved to be particularly useful in the organization of concepts. Establishing the relationship between concepts helped distill underlying

ideas relating to the scope of the study. The final list for concepts in the instrument consider the ideas identified by Sadowski and Sorby in the Delphi Study.

Research Aim 2 -Creation of reasonable distractors

Well-crafted distractors are designed to appeal to those who do not accurately understand the concepts being tested. Based on the methods used in this study, there is evidence to suggest that the distractors created are reasonable for use in a concept inventory. Distractors in the EGCI were based on the type and frequency of student incorrect responses. The high number of responses from a variety of in the alpha and beta versions suggests reliability in the distractors.

Research Aim 3 - Develop items that are statistically reliable and valid

Established statistical psychometrics were used to evaluate the reliability and validity of the items. Measures such as item difficulty and discrimination index verified the performance of the items on the instrument and justified their inclusion on this educational assessment tool. Multiple rounds of testing showed consistent performance on these metrics. Difficulty and discrimination scores were above acceptable levels for all items that were included on the final version of the instrument.

The multiple editions of the alpha and beta versions consistently had high KR20 scores. Editions within each version also had KR20 scores that were close to one another, often within a few hundredths of a point. This suggests that the items developed were likely reliably measuring the single latent trait of engineering graphics conceptual understanding.

The face validity study provided evidence to show that the items on the instrument appear to measure the intended concepts. All the items used in the face validity study had a high number of participants (at least half or more) who agreed that the item was measuring the intended concept. Findings from other validity studies confirm that test items with high face validity tend to be more technically accurate (Holden & Jackson, 1985). Face validity generally has a positive, stable relationship with other types of validity. High levels of face validity reported by the participants in this study likely indicate a satisfactory level of other types of validity in the items.

8.5 Conclusions

Based on the study design, a concept inventory for engineering graphics has been developed. The concepts being measured are representative of the field of engineering graphics. Distractors for the items included on the instrument were based on student misconceptions. Accepted methods for establishing the reliability and validity of assessment items were used throughout the development process to sustain a reasonable level of instrument quality.

The instrument is the first step in filling a gap in engineering education research regarding assessment in engineering graphics. A standardized instrument can help assessment across a wide range of settings and populations. The final version of the ECGI developed in this study will be readily available to engineering graphics educators to assess student learning in their classes.

Concept inventory creation is not a static process. Items always have room for improvement in regards to the traits of validity and reliability. As the context for

instrument administration changes, it is likely that the EGCI will also need to change to stay relevant. Population, technology, and location are examples of factors that can alter the structure of the instrument.

8.6 Future Work

The creation of the thirty items on the EGCI is the beginning of a larger body of work. Further data collection will be needed to facilitate rigorous statistical analysis to effectively analyze the instrument. Additional procedures can further determine validity and reliability of the instrument and the items. Point-biserial coefficient, Cronbach's Alpha, concurrent reliability, additional construct validity, and factor analysis, are all examples of measures in psychometrics used to validate instruments (Adams & Wieman, 2011; Ding & Beichner, 2009; Messick, 1995; Streveler et al., 2011; Thorndike & Thorndike, 1991).

Testing the instrument in different contexts should also be considered. The data collection for the gamma version should provide adequate insights using the populations at the four participating institutions. If possible, the instrument should be tested at additional institutions and it should also be tested at different levels. The instrument was designed to be used at different levels, including high schools and community colleges. Before making inferences about the instrument's validity and reliability across age, gender, institution, and ability, analysis must be done in additional settings.

The CAD items examined in the study may also be the source of future work. CAD items were included in the pilot study, removed in the alpha version, tested in the beta version, and not included in the gamma version. Further work will need to be done

to determine the reliability and validity of CAD items in a conventional concept inventory format. After the analysis of the data in the beta version, it was decided that CAD items were not appropriate to include on the CI. In the beta version, the tested items for CAD produced overwhelmingly low difficulty scores, and consequently low discrimination indices. Considering the goals of the instrument, it would not be fitting to include items with such a profile on the instrument. If CAD items were the subject of a standalone study, work could be done to develop items that represent a better range of psychometric properties and be suitable for assessment purposes

References

- Ackerman, P. L., & Kanfer, R. (2009). Test length and cognitive fatigue: An empirical examination of effects on performance and test-taker reactions. *Journal of Experimental Psychology*, 15(2), 163-81.
- Ackerman, P., Kanfer, R., Shapiro, S., Newton, S., & Beier, M. (2010). Cognitive fatigue during testing: An examination of trait, time-on-task, and strategy influences. *Human Performance*, 23(5), 381-402.
- Adams, W. K., & Wieman, C. E. (2011). Development and validation of instruments to measure learning of Expert-Like thinking. *International Journal of Science Education*, 33(9), 1289-1312.
- Adkins, D. C. (1974). *Test construction; development and interpretation of achievement tests*. Columbus, Ohio: C.E. Merrill Pub. Co.
- Allen, K. (2006). *The statistics concept inventory : Development and analysis of a cognitive assessment instrument in statistics* Available from /z-wcorg/.
- Ambrose, S. A. (2010). *How learning works: Seven research-based principles for smart teaching*. San Francisco, CA: Jossey-Bass.
- Armstrong, J. S. (2001). *Principles of forecasting: A handbook for researchers and practitioners*. Boston, MA: Kluwer Academic.
- Aslanides, J., & Savage, C. (2013). Relativity concept inventory: Development, analysis, and results. *Phys. Rev. ST Phys. Educ. Res*, 9(1), 010118.
- Baartmans, B. G., & Sorby, S. A. (1996). Making connections: Spatial skills and engineering drawings. *Mathematics Teacher*, 89(4), 348-57.
- Baker, F. B. (1992). *Item response theory: Parameter estimation techniques*. New York: M. Dekker.
- Bechger, T. M., Maris, G., Verstralen, Huub H. F. M., & Béguin, A. A. (2003). Using classical test theory in combination with item response theory. *Applied Psychological Measurement*, 27(5), 319-334.

- Besterfield-Sacre, M., Gerchak, J., Lyons, M. R., Shuman, L. J., & Wolfe, H. (2004). Scoring concept maps: An integrated rubric for assessing engineering education. *JEE Journal of Engineering Education*, 93(2), 105-115.
- Branoff, T. J., & Devine, K. L. (2015). Engineering design graphics instruction through a lens of cultural-historical learning theory. *Proceedings of the ASEE Annual Conference & Exposition*,
- Brennan, R. L. (2011). Generalizability theory and classical test theory. *Applied Measurement in Education*, 24(1), 1-21.
- Chen, Y. -, Chi, H. -, Hung, W. -, & Kang, S. -. (2011). Use of tangible and augmented reality models in engineering graphics courses. *Journal of Professional Issues in Engineering Education and Practice*, 137(4), 267-276.
- Coates, J. F. (1975). In defense of Delphi: A review of Delphi assessment, expert opinion, forecasting, and group process by H. Sackman. *Technological Forecasting & Social Change*, 7(2), 193-194.
- Contero, M., Naya, F., Company, P., Saorfa, L. J., & Conesa, J. (2005). Improving visualization skills in engineering education. *IEEE Computer Graphics and Applications*, 25(5)
- Cozby, P. C., & Bates, S. (2012). *Methods in behavioral research*. New York, NY: McGraw-Hill.
- Crocker, L. M., & Algina, J. (1986). *Introduction to classical and modern test theory*. New York: Holt, Rinehart, and Winston.
- Crown, S. W. (2001). Improving visualization skills of engineering graphics students using simple JavaScript web based games. *JEE Journal of Engineering Education*, 90(3), 347-355.
- Dalkey, N., & Helmer, O. (1963). An experimental application of the DELPHI method to the use of experts. *Manuscript of Management Science*, 9(3), 458-467.
- Ding, L., & Beichner, R. (2009). Approaches to data analysis of multiple-choice questions. *Physical Review Special Topics - Physics Education Research*, 5(2), 020103-1--020103-17.
- Ding, L., Chabay, R., & Beichner, R. (2006). Evaluating an electricity and magnetism assessment tool: Brief electricity and magnetism assessment. *Physical Review Special Topics - Physics Education Research*, 2(1), 010105-1--010105-7.

- Doran, R. L. (1980). *Basic measurement and evaluation of science instruction*. Washington, D.C.: National Science Teachers Association.
- Engelhardt, P. V. (2009). An introduction to classical test theory as applied to conceptual multiple-choice tests. In C. Henderson, & K. A. Harper (Eds.), *Getting started in PER ()*. College Park, MD: American Association of Physics Teachers. Retrieved from <http://www.per-central.org/items/detail.cfm?ID=8807>
- Fan, X. (1998). Item response theory and classical test theory: An empirical comparison of their item/person statistics. *Educational and Psychological Measurement*, 58(3), 357.
- Gay, L. R., Mills, G. E., & Airasian, P. W. (2006). *Educational research: Competencies for analysis and applications*. Upper Saddle River, N.J.: Pearson Merrill Prentice Hall.
- Giesecke, F. E. (2004). *Engineering graphics*. Upper Saddle River, NJ: Prentice Hall.
- Gollub, J. P. (2002). *Learning and understanding: Improving advanced study of mathematics and science in U.S. high schools*. Washington, DC: National Academy Press.
- Gronlund, N. E. (1985). *Measurement and evaluation in teaching*. New York; London: Collier Macmillan.
- Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics. *American Journal of Physics*, 66(1)
- Hoe, D. H. K. (2013). Development of a concept inventory for microelectronics courses. *2013 IEEE Frontiers in Education Conference (FIE)*, 1078-1080. doi:10.1109/FIE.2013.6684993
- Holden, R. R., & Jackson, D. N. (1985). Disguise and the structured self-report assessment of psychopathology: I. an analogue investigation. *Journal of Consulting and Clinical Psychology*, 53(2), 211-22.
- Kalas, P., O'Neill, A., Pollock, C., & Birol, G. (2013). Development of a meiosis concept inventory. *CBE Life Sciences Education*, 12(4), 655-64.
- Kaplan, R. M., & Saccuzzo, D. P. (2013). *Psychological testing: Principles, applications, & issues*. Belmont, CA: Wadsworth, Cengage Learning.
- Khan, H. (1994). Objective based instruction for learning outcomes of engineering/technical design graphics and computer aided design. *Proceedings - Frontiers in Education Conference*, 482.

- Kuder, G. F., & Richardson, M. W. (1937). The theory of the estimation of test reliability. *Psychometrika*, 2(3), 151-160.
- Lane, S., Raymond, M. R., & Haladyna, T. M. (2016). Twelve steps for effective test development. *Handbook of test development* ()
- Lavrakas, P. J. (2008). Encyclopedia of survey research methods.
- Lieu, D. K., & Sorby, S. A. (2009). *Visualization, modeling, and graphics for engineering design*. Clifton Park, NY: Delmar Cengage Learning.
- Linstone, H. A., & Turoff, M. (1975). *The Delphi method: Techniques and applications*. Reading, Mass.: Addison-Wesley Pub. Co., Advanced Book Program.
- Marunic, G., & Glazar, V. (2013). Spatial ability through engineering graphics education. *International Journal of Technology and Design Education*, 23(3), 703-715.
- Messick, S. (1995). Validity of psychological assessment: Validation of inferences from persons' responses and performances as scientific inquiry into score meaning. *American Psychologist*, 50(9), 741-49.
- Meyers, F. D. (2004). *Technical graphics*. [New York]: [John Wiley & Sons].
- Moskal, B. M., Leydens, J. A., & Pavelich, M. J. (2002). Validity, reliability and the assessment of engineering education. *JEE Journal of Engineering Education*, 91(3), 351-354.
- Murphy, C. (1999). Factor analysis. *Atlantic Monthly* (10727825), 284(5)
- Nathan, M. J., & Koedinger, K. R. (2000). An investigation of teachers' beliefs of students' algebra development. *Cognition and Instruction*, 18(2), 209-37.
- National Council on Measurement in Education. (2016). Glossary of important assessment and measurement terms. Retrieved from http://www.ncme.org/ncme/NCME/Resource_Center/NCME/Resource_Center/Glossary1.aspx?hkey=8bd573bd-a7b4-498a-93b9-3e0081c557c0
- National Research Council Panel on Undergraduate Engineering Education. (1986). Engineering undergraduate education.
- Ndalichako, J. L., & Rogers, W. T. (1997). Comparison of finite state score theory, classical test theory, and item response theory in scoring multiple-choice items. *Educational and Psychological Measurement*, 57(4), 580-89.

- Nunnally, J. C., & Bernstein, I. H. (1994). *Psychometric theory*. New York: McGraw-Hill.
- Oosterhof, A. (2001). *Classroom applications of educational measurement*. Upper Saddle River, N.J.: Merrill.
- Pellegrino, J. W., Chudowsky, N., & Glaser, R. (2001). *Knowing what students know: The science and design of educational assessment*. Washington, DC: National Academy Press.
- Potter, C., Kaufman, W., Delacour, J., Mokone, M., Van der Merwe, E., & Fridjhon, P. (2009). Three-dimensional spatial perception and academic performance in engineering graphics: A longitudinal investigation. *Sapsyc South African Journal of Psychology*, 39(1), 109-121.
- Sadowski, M. A., & Sorby, S. A. (2015). Engineering graphics concepts: A Delphi study. *ASEE Annual Conference and Exposition, Conference Proceedings, 122nd ASEE Annual Conference and Exposition: Making Value for Society*
- Sadowski, M., & Sorby, S. (2013). Update on a Delphi study for developing a concept inventory for engineering design graphics. *Engineering Design Graphics Division 68th MidYear Meeting Proceedings*, Worcester, MA.
- Sadowski, M., & Sorby, S. (2014). Defining concepts for an engineering concept inventory: A Delphi study. *Proceedings of the 69th Midyear Meeting of the Engineering Design Graphics Division of ASEE*, Normal IL. 67-72.
- Santo, H. P. (1986). ENGOL—Engineering-graphics-oriented language: The core of a “Computational engineering graphics” implementation. *CAE Computers & Education*, 10(1), 101-114.
- Sax, G. (1980). *Principles of educational and psychological measurement and evaluation*. Belmont, Calif.: Wadsworth Pub. Co.
- Serdar, T., & deVries, R. H. (2015). Enhancing spatial visualization skills in engineering drawing course. *Proceedings of the ASEE Annual Conference & Exposition*,
- Shi, J., Wood, W. B., Martin, J. M., Guild, N. A., Vicens, Q., & Knight, J. K. (2010). A diagnostic assessment for introductory molecular and cell biology. *CBE - Life Sciences Education*, 9(4), 453-461.
- Sievertsen, H. H., Gino, F., & Piovesan, M. (2016). Cognitive fatigue influences students' performance on standardized tests. *Proceedings of the National Academy of Sciences of the United States of America*, 113(10), 2621-4.

- Singer, S., & Smith, K. A. (2013). Discipline-based education research: Understanding and improving learning in undergraduate science and engineering. *Journal of Engineering Education*, 102(4), 468-471.
- Smith, J. I., & Tanner, K. (2010). The problem of revealing how students think: Concept inventories and beyond. *CBE Life Sciences Education*, 9(1), 1-5.
- Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education*, 31(3), 459-480.
- Sorby, S. A., & Bulleit, W. M. (2006). *An engineer's guide to technical communication*. Upper Saddle River, NJ: Pearson Prentice Hall.
- Sorby, S., Casey, B., Veurink, N., & Dulaney, A. (2013). The role of spatial training in improving spatial and calculus performance in engineering students. *Learning and Individual Differences Learning and Individual Differences*, 26(5??6), 20-29.
- Steinhauer, H. M. (2012). Assessment of first-year engineering students' spatial visualization skills.
- Streveler, R. A., Miller, R. L., Santiago-Roman, A. I., Nelson, M. A., Geist, M. R., & Olds, B. M. (2011). Rigorous methodology for concept inventory development: Using the 'assessment triangle' to develop and test the thermal and transport science concept inventory (TTCI). *International Journal of Engineering Education*, 27(5), 968-984.
- Streveler, R. A., Litzinger, T. A., Miller, R. L., & Steif, P. S. (2008). Learning conceptual knowledge in the engineering sciences: Overview and future research directions. *JEE Journal of Engineering Education*, 97(3), 279-294.
- Streveler, R. A., & Smith, K. A. (2006). Conducting rigorous research in engineering education. *Journal of Engineering Education*, 95(2), 103-105.
- Tamil, A. M. (2015). Calculating difficulty, discrimination and reliability index/standard error of measurement. Retrieved from <https://ppukm.org/2015/04/02/calculating-omr-indexes/>
- The Foundation Coalition. (2008). Concept inventory assessment tools. Retrieved from <http://fc.civil.tamu.edu/home/keycomponents/concept/>
- Thorndike, R. M., & Thorndike, R. L. (1991). *Measurement and evaluation in psychology and education*. New York: Macmillan Pub. Co.

- Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education International Journal of Science Education*, 10(2), 159-169.
- Tukey, J. W. (1991). The philosophy of multiple comparisons. *Statistical Science*, 6(1), 100-116.
- Ullman, D. G., Wood, S., & Craig, D. (1990). The importance of drawing in the mechanical design process. *Computers & Graphics Computers & Graphics*, 14(2), 263-274.
- Von Korff, J., Heckendorf, T., Shepherd, C., Archibeque, B., Gomez, K. A., Sayre, E. C., McKagan, S. B. (2016). Secondary analysis of teaching methods in introductory physics: A 50 K-student study. *American Journal of Physics*, 84(12), 969-974.
- Vygotskiĭ, L. S., & Cole, M. (1978). *Mind in society: The development of higher psychological processes*. Cambridge: Harvard University Press.

Appendix A : Concepts and Topics from Delphi Study

1. Visualizing in 2D and 3D

Understating the relationship between orthogonal views of geometry.

- a. **Edge View** – Orthographically, an edge view is achieved when a plane surface is perpendicular to the plane on which it is projected.
- b. **Normal** – A plane perpendicular to the line of sight. Appears as a true line or true shape plane
- c. **True Shape and Size** – Features shown in an engineering drawing are true shape and size if the line of sight is perpendicular to the feature.
- d. **View Alignment** - Orthographic drawings are aligned horizontally and vertically. Every point or feature in one view must be aligned on a parallel projector in any adjacent view
- e. **View Direction** – Arrangement of the principal orthographic views around the front view.

2. Mapping between 2D and 3D

Representing, converting, creating and interpreting drawings from 2D to 3D, and 3D to 2D.

- a. **Interpretation** – reading and understanding standard information on an engineering drawing.
- b. **Creation** – Making 2D and 3D images using the appropriate tools

3. Planar Geometry

The ability to place a plane in space that serves a function

- a. **Cutting Plane** – Imaginary plane which passes through an object, used to divide the object and reveal interior features
- b. **Datum Plane** – Geometric reference point for parametric dimensions
- c. **Reference Plane** – Used as a basis for measurement that locks the principle dimension of the object into a fixed relationship. The central view of a referential plane is perpendicular to the line of sight.
- d. **Projection Plane** – Representation of a line or line, figure, or solid on a given plane as it would be seen from a direction or in accordance with an accepted set of rules

4. Sectional views

Establishment of a plane for the purpose of showing interior and exterior features of an object

- a. **Full section** – section view that shows the part cut entirely through, typically along the centerline
- b. **Half section** – view obtained when the cutting plane passes halfway through a symmetrical object to expose the interior of half the object and the exterior of the other half
- c. **Removed Section** – Used when only a partial section of a view is needed to expose the interior shapes

- d. **Revolved Section** – View obtained when the shape of the cross section of a bar, arm, spoke or other elongated object is shown by revolving the feature
- e. **Offset section** – Used when sectioning irregular objects. The cutting plane is offset rather than straight allowing it to cut through and show different features of the object.
- f. **Aligned Section** – The cutting plane passes through angled arms, holes, or other features located around a central cylindrical shape and the section view is rotated into a single plane that shows features in the section true size.

5. Engineering Methodologies for Object Representation

Representing the 3D world using 2D visual methods using engineering graphic techniques

- a. **Assembly** – Presentation of a product together, showing all parts in their operational positions
- b. **Exploded** – View that shows an assembly's components separated and positioned to show the relationship or order of assembly of the parts
- c. **Isometric** – type of axonometric projection in which three of the axes are measured on the same scale and are at the same angle relative to each other

6. Projection theory

Viewing an object with a transparent plane placed between the observer and the object

- a. **Auxiliary Views** – Orthographic view of an object using a different direction of sight other than one of the six basic views (front, top, right-side, bottom, rear, left-side); used to show a surface that is not parallel to any of the principal viewing planes.
- b. **Edge View** – Normal lane surface perpendicular to the plane on which it is projected and appears as an edge in two of the three orthogonal views.
- c. **Line of sight** – Vector path for the viewer to a particular point on an object
- d. **Inclined Surface** – Flat tilted surface at an angle with one end higher than the other, a plane whose angle to the horizontal is less than a right angle.
- e. **Plane of Projection** – View of an object that has been projected onto a plane. In an orthographic drawing the top view is projected onto the horizontal plane, the side profile on a profile plane.
- f. **True Length** – Perpendicular to the line of sight.

7. Parallel Projection Methodologies

Graphically representing 3D objects in a 2D medium based on a line of sight and a plane of projection

- a. **Isometric** – Type of axonometric projection in which three of the axes are measured on the same scale and are at the same angle relative to each other
- b. **Orthogonal** – Two-dimensional graphic representation of an object formed by the perpendicular intersections of lines drawn from points on the object to a plane of projection.

8. Drawing Conventions

Conventional methods for expressing a graphical description

- a. **Annotations and notes** – Dimensions, tolerances, information, text, or symbols placed on an engineering drawing that give additional information to the reader.
- b. **Callouts** – Local notes that convey information about specific geometric features

9. Dimensioning

The process of providing an accurate, clear, complete and readable, description of an object.

- a. **Dimension Placement** – Studied placement of size, location, and notes and symbols for the unambiguous description of geometry and process.
- b. **Location Description** – Dimension that specifies the position of a geometric entity relative to another geometric entity.
- c. **Shape Description** – Dimensions that will define overall height, width, and depth of an object and its features
- d. **Size Description** – Dimensions used to describe the overall size, as well as the size, width, and depth of object features.

10. Solid Modeling

A consistent set of principles for mathematical and computer modeling of three-dimensional solids which supports the creation, exchange, visualization, animation, interrogation, and annotation of digital models of physical objects.

- a. **Extrusion** – Normal profile can generate a solid of uniform cross-section by projecting it along a straight line with successive cross-sections all parallel
- b. **Features** – Prominent region or portion of a part often associated

Appendix B : Pilot Study Item Mapping

Table 26 Item Mapping for Pilot Version – Groups of Five

Packet	Item	Corresponding concept number									
		1	2	3	4	5	6	7	8	9	10
1	0001.0						x				
	0004.0			x							
	0048.3		x								
	0047.5		x								
	0013.0				x						
2	0006.0			x							
	0049.1		x								
	0010.0		x								
	0050.5										x
	0015.0							x			
3	0016.0								x		
	0049.2		x								
	0018.0										x
	0021.0				x						
	0048.1		x								
4	0022.0				x						
	0025.0						x				
	0027.0		x								
	0039.2	x									
	0045.2								x		
5	0028.0						x				
	0031.1		x								
	0033.1				x						
	0050.2										x
	0031.2		x								
6	0034.0						x				
	0039.0						x				
	0040.0		x								
	0042.0				x						
	0050.4										x
7	0043.2				x						
	0044.0		x								
	0049.4							x			
	0045.1		x								
	0046.1									x	
8	0047.1		x								
	0058.0				x						
	0046.2									x	
	0047.2		x								
	0014.0						x				
9	0047.3		x								
	0047.4		x								
	0051.0				x						
	0056.0			x							
	0008.0								x		
10	0020.0						x				
	0057.0				x						
	0048.2		x								
	0053.0				x						
	0007.0									x	
11	0061.0						x				
	0049.5		x								
	0052.0				x						
	0050.3										x
	0055.0				x						
12	0060.1				x						
	0017.0									x	
	0050.1										x
	0060.2				x						
	0009.0	x									
Total		2	18	3	14	0	8	2	3	4	6

Table 27 Item Mapping for Pilot Version – Groups of Three

Packet	Item	1	2	3	4	5	6	7	8	9	10
1	0001.0						x				
	0004.0			x							
	0048.3		x								
2	0006.0			x							
	0008.0								x		
	0049.1		x								
3	0010.0		x								
	0013.0				x						
	0050.5										x
4	0015.0							x			
	0016.0								x		
	0049.2		x								
5	0018.0										x
	0021.0				x						
	0048.1		x								
6	0022.0				x						
	0025.0						x				
	0027.0		x								
7	0028.0						x				
	0031.1		x								
	0033.1				x						
8	0031.2		x								
	0034.0						x				
	0039.2	x									
9	0039.0						x				
	0040.0		x								
	0042.0				x						
10	0043.2				x						
	0044.0		x								
	0045.2								x		
11	0045.1		x								
	0046.1									x	
	0047.1		x								
12	0046.2									x	
	0047.2		x								
	0049.4							x			
13	0047.3		x								
	0058.0				x						
	0014.0						x				
14	0047.4		x								
	0050.2										x
	0051.0				x						
15	0047.5		x								
	0020.0						x				
	0057.0				x						
16	0048.2		x								
	0053.0				x						
	0061.0						x				
17	0049.5		x								
	0050.4										x
	0052.0				x						
18	0055.0				x						
	0056.0			x							
	0007.0									x	
19	0060.1				x						
	0050.3										x
	0017.0									x	
20	0050.1										x
	0060.2				x						
	0009.0	x									
Total		2	18	3	14	0	8	2	3	4	6

Appendix C : Selected Open Ended Items from Pilot Study

Indicate the location of Surface A in the top and side views.

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0009	Scale: N/A	Author: SS	Units: Inches	Item #: 0009
	Drawn By: SYN		Topic: 01	Version: 2.0	Date: 03/20/2015

For the object shown in orthographic projection below, construct an isometric in the space provided.

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0045-1	Scale: N/A	Author: SS	Units: Inches	Item #: 0045-1
	Drawn By: SYN		Topic: 02	Version: 1.0	Date: 03/08/15

Sketch the section view that would result from cutting line A-A.

SECTION A-A

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0056	Scale: N/A	Author: SS	Units: Inches	Item #: 0056
	Drawn By: SYN		Topic: 03	Version: 2.0	Date: 03/20/2015

A half section of an object is shown below. Draw cutting line A-A in the proper view.

SECTION A-A

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0042	Scale: N/A	Author: SS	Units: Inches	Item #: 0042
	Drawn By: SYN		Topic: 04	Version: 1.2	Date: 03/20/2015

Indicate on the table, in which view(s) each line is shown at its true length.

	Front View	Top View	Side View
A			
B			
C			
D			
E			

SolidWorks Student Edition.
For Academic Use Only.

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0028 Drawn By: SYN	Scale: N/A	Author: SS Topic: 06	Units: Inches Version: 1.1	Item #: 0028 Date: 03/20/2015
---	---	------------	-------------------------	-------------------------------	----------------------------------

For the object shown, sketch the orthographic multi-view drawing which shows the top, front, and side views properly aligned.

SolidWorks Student Edition.
For Academic Use Only.

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0015 Drawn By: SYN	Scale: N/A	Author: SS Topic: 07	Units: Inches Version: 1.1	Item #: 0015 Date: 03/20/2015
---	---	------------	-------------------------	-------------------------------	----------------------------------

Add generic dimensions without values to fully define the object.

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0008	Scale: N/A	Author: SS	Units: Inches	Item #: 0008
	Drawn By: SYN		Topic: 08	Version: 2.0	Date: 03/23/2015

Add generic dimensions without values to fully define the object.

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0017	Scale: N/A	Author: SS	Units: Inches	Item #: 0017
	Drawn By: SYN		Topic: 09	Version: 2.0	Date: 03/20/2015

Describe with sketches and words the steps necessary to create the object shown below using solid modeling software.

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0018	Scale: N/A	Author: SS	Units: Inches	Item #: 0018
	Drawn By: SYN		Topic: 10	Version: 2.0	Date: 03/23/2015

Given the object below, describe in general terms how you would create it using a CAD system. You may use sketches to help your explanation.

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0050.4	Scale: N/A	Author: SS	Units: Inches	Item #: 0050.4
	Drawn By: SYN		Topic: 10	Version: 2.0	Date: 03/20/2015

Appendix D : Selected Responses from Pilot Study

Draw the cutting plane line, in the proper view, that would result in the section view shown in the front view below.

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0021	Scale: N/A	Author: SS	Units: Inches	Item #: 0021
	Drawn By: SYN		Topic: 04	Version: 2.0	Date: 03/22/2015

Draw the cutting plane line, in the proper view, that would result in the section view shown in the front view below.

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0021	Scale: N/A	Author: SS	Units: Inches	Item #: 0021
	Drawn By: SYN		Topic: 04	Version: 2.0	Date: 03/22/2015

Draw the cutting plane line, in the proper view, that would result in the section view shown in the front view below.

SECTION A-A

???

I understood what the question was asking:
Strongly Agree — Strongly Disagree
1 2 3 4 5 6 7

I feel that the question was:
Very Easy — Very Difficult
1 2 3 4 5 6 7

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0021	Scale: N/A	Author: SS	Units: Inches	Item #: 0021
	Drawn By: SYN		Topic: 04	Version: 2.0	Date: 03/22/2015

Draw the cutting plane line, in the proper view, that would result in the section view shown in the front view below.

SECTION A-A

I understood what the question was asking:
Strongly Agree — Strongly Disagree
1 2 3 4 5 6 7

I feel that the question was:
Very Easy — Very Difficult
1 2 3 4 5 6 7

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0021	Scale: N/A	Author: SS	Units: Inches	Item #: 0021
	Drawn By: SYN		Topic: 04	Version: 2.0	Date: 03/22/2015

Draw the cutting plane line, in the proper view, that would result in the section view shown in the front view below.

SECTION A-A

I understood what the question was asking:
Strongly Agree — Strongly Disagree
1 2 3 4 5 6 7

I feel that the question was:
Very Easy — Very Difficult
1 2 3 4 5 6 7

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0021	Scale: N/A	Author: SS	Units: Inches	Item #: 0021
	Drawn By: SYN		Topic: 04	Version: 2.0	Date: 03/22/2015

Draw the cutting plane line, in the proper view, that would result in the section view shown in the front view below.

SECTION A-A

I understood what the question was asking:
Strongly Agree — Strongly Disagree
1 2 3 4 5 6 7

I feel that the question was:
Very Easy — Very Difficult
1 2 3 4 5 6 7

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0021	Scale: N/A	Author: SS	Units: Inches	Item #: 0021
	Drawn By: SYN		Topic: 04	Version: 2.0	Date: 03/22/2015

Draw the cutting plane line, in the proper view, that would result in the section view shown in the front view below.

I understood what the question was asking:
Strongly Agree — Strongly Disagree
1 2 3 4 5 6 7

I feel that the question was:
Very Easy — Very Difficult
1 2 3 4 5 6 7

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0021	Scale: N/A	Author: SS	Units: Inches	Item #: 0021
	Drawn By: SYN		Topic: 04	Version: 2.0	Date: 03/22/2015

Draw the cutting plane line, in the proper view, that would result in the section view shown in the front view below.

I understood what the question was asking:
Strongly Agree — Strongly Disagree
1 2 3 4 5 6 7

I feel that the question was:
Very Easy — Very Difficult
1 2 3 4 5 6 7

**SolidWorks Student Edition.
For Academic Use Only.**

Engineering Graphics Concept Inventory	Item Title: Open Ended Item 0021	Scale: N/A	Author: SS	Units: Inches	Item #: 0021
	Drawn By: SYN		Topic: 04	Version: 2.0	Date: 03/22/2015

Appendix E : Alpha Version Item Mapping

Table 28 Item Map for Alpha Version

Item	Concept on Alpha Version	Edition A	Edition B	Edition C
0001.0	Projection Theory	x		
0004.0	Visualizing in 2d/3d	x		
0006.0	Mapping b/t 2d and 3d	x		
0008.0	Drawing Conventions	x		
0009.0	Visualizing in 2d/3d			x
0010.0	Mapping b/t 2d and 3d		x	
0013.0	Sectional views	x		
0014.0	Projection Theory		x	
0015.0	Parallel Projection Methodologies	x	x	
0016.0	Drawing Conventions		x	
0017.0	Dimensioning	x		
0021.0	Visualizing in 2d/3d		x	
0022.0	Sectional views		x	
0027.0	Mapping b/t 2d and 3d			x
0028.1	Projection Theory			x
0028.2	Projection Theory	x		
0028.3	Projection Theory		x	
0028.4	Projection Theory			x
0028.5	Projection Theory	x		
0031.1	Mapping b/t 2d and 3d	x		
0039.0	Projection Theory		x	
0039.2	Visualizing in 2d/3d	x		
0040.0	Mapping b/t 2d and 3d		x	
0042.0	Planar Geometry		x	x
0043.2	Sectional views			x
0044.0	Mapping b/t 2d and 3d			x
0045.1	Mapping b/t 2d and 3d	x		
0045.2	Drawing Conventions			x
0046.1	Dimensioning		x	
0046.2	Dimensioning			x
0047.1	Mapping b/t 2d and 3d		x	
0047.2	Mapping b/t 2d and 3d			x
0047.4	Mapping b/t 2d and 3d	x		
0047.5	Mapping b/t 2d and 3d		x	
0048.1	Mapping b/t 2d and 3d			x
0048.2	Mapping b/t 2d and 3d	x		
0049.1	Mapping b/t 2d and 3d		x	
0049.4	Parallel Projection Methodologies	x		x
0049.5	Mapping b/t 2d and 3d			x
0051.0	Planar Geometry			x
0052.0	Planar Geometry	x		
0053.0	Drawing Conventions	x		
0055.0	Drawing Conventions		x	
0056.0	Planar Geometry		x	
0057.0	Sectional views			x
0058.0	Sectional views	x		
0060.1	Sectional views		x	
0060.2	Sectional views			x

Continued

Table 28 continued

0061.0	Projection Theory			x
0062.0	Mapping b/t 2d and 3d	x		
0063.0	Mapping b/t 2d and 3d		x	
0064.0	Mapping b/t 2d and 3d			x
0065.0	Mapping b/t 2d and 3d	x		
0066.0	Mapping b/t 2d and 3d		x	
0067.0	Mapping b/t 2d and 3d			x
0068.0	Mapping b/t 2d and 3d	x		
0069.0	Mapping b/t 2d and 3d		x	
0070.0	Mapping b/t 2d and 3d			x
0071.0	Mapping b/t 2d and 3d	x		
0072.0	Parallel Projection Methodologies		x	x
0073.1	Dimensioning	x		
0073.2	Dimensioning		x	
0073.3	Dimensioning			x
Total		23	22	22

Appendix F : Selected Items and Statistics from Alpha Version

Table 29 Alpha Version Items - Sorted by Concept

Item	Concept on Alpha Version	A	B	C
0017.0	Dimensioning	x		
0046.1	Dimensioning		x	
0046.2	Dimensioning			x
0073.1	Dimensioning	x		
0073.2	Dimensioning		x	
0073.3	Dimensioning			x
0008.0	Drawing Conventions	x		
0016.0	Drawing Conventions		x	
0045.2	Drawing Conventions			x
0053.0	Drawing Conventions	x		
0055.0	Drawing Conventions		x	
0006.0	Mapping b/t 2d and 3d	x		
0010.0	Mapping b/t 2d and 3d		x	
0027.0	Mapping b/t 2d and 3d			x
0031.1	Mapping b/t 2d and 3d	x		
0040.0	Mapping b/t 2d and 3d		x	
0044.0	Mapping b/t 2d and 3d			x
0045.1	Mapping b/t 2d and 3d	x		
0047.1	Mapping b/t 2d and 3d		x	
0047.2	Mapping b/t 2d and 3d			x
0047.4	Mapping b/t 2d and 3d	x		
0047.5	Mapping b/t 2d and 3d		x	
0048.1	Mapping b/t 2d and 3d			x
0048.2	Mapping b/t 2d and 3d	x		
0049.1	Mapping b/t 2d and 3d		x	
0049.5	Mapping b/t 2d and 3d			x
0062.0	Mapping b/t 2d and 3d	x		
0063.0	Mapping b/t 2d and 3d		x	
0064.0	Mapping b/t 2d and 3d			x
0065.0	Mapping b/t 2d and 3d	x		
0066.0	Mapping b/t 2d and 3d		x	
0067.0	Mapping b/t 2d and 3d			x
0068.0	Mapping b/t 2d and 3d	x		
0069.0	Mapping b/t 2d and 3d		x	
0070.0	Mapping b/t 2d and 3d			x
0071.0	Mapping b/t 2d and 3d	x		
0015.0	Parallel Projection Methodologies	x		
0015.0	Parallel Projection Methodologies		x	
0049.4	Parallel Projection Methodologies	x		
0049.4	Parallel Projection Methodologies			x
0072.0	Parallel Projection Methodologies		x	
0072.0	Parallel Projection Methodologies			x
0042.0	Planar Geometry		x	
0042.0	Planar Geometry			x
0051.0	Planar Geometry			x
0052.0	Planar Geometry	x		
0056.0	Planar Geometry		x	
0001.0	Projection Theory	x		
0014.0	Projection Theory		x	
0028.1	Projection Theory			x
0028.2	Projection Theory	x		
0028.3	Projection Theory		x	
0028.4	Projection Theory			x

Continued

Table 29 continued

0028.5	Projection Theory	x		
0039.0	Projection Theory		x	
0061.0	Projection Theory			x
0013.0	Sectional views	x		
0022.0	Sectional views		x	
0043.2	Sectional views			x

0057.0	Sectional views			x
0058.0	Sectional views	x		
0060.1	Sectional views		x	
0060.2	Sectional views			x
0004.0	Visualizing in 2d/3d	x		
0009.0	Visualizing in 2d/3d			x
0021.0	Visualizing in 2d/3d		x	
0039.2	Visualizing in 2d/3d	x		
Total		23	22	22

Item: 0004

Item #: 0004

Given the front and right views of the object, select the option that shows the correct top views.

?

A.

B.

C.

D.

Concept:

Visualizing in 2D/3D

Topic:

1.3 True Shape and Size

Notes:

VERSION	A
	Item 0004
RESPONSE	C
A	39
B	48
C	158
D	67
E	0
n-TOTAL	312
ITEM	
DIFFICULTY	51%
MEAN TIME [s]	65.3
n	226
n	0
n	58
n	28
%	48%
%	
%	53%
%	64%

VERSION	B
	Item 0004
RESPONSE	C
A	50
B	54
C	150
D	70
E	0
n-TOTAL	324
ITEM	
DIFFICULTY	46%
MEAN TIME [s]	41.8
n	68
n	21
n	48
n	187
%	53%
%	62%
%	50%
%	41%

VERSION	C
	Item 0004
RESPONSE	C
A	57
B	38
C	176
D	50
E	0
n-TOTAL	321
ITEM	
DIFFICULTY	55%
MEAN TIME [s]	37.8
n	43
n	26
n	57
n	195
%	51%
%	81%
%	54%
%	52%

Item: 0021

Item #: 0021

Select the option that shows the correct cutting plane that produces Section A-A.

Concept: Visualizing in 2D/3D
Topic: 4.3 Offset Sections

Notes:

VERSION	A
	Item 0021
A	
RESPONSE	
A	151
B	68
C	26
D	34
E	9
n-TOTAL	288
ITEM	
DIFFICULTY	52%
MEAN TIME [s]	22.5
n	202
n	0
n	58
n	28
%	46%
%	
%	57%
%	89%

VERSION	B
	Item 0021
A	
RESPONSE	
A	250
B	57
C	18
D	9
E	0
n-TOTAL	334
ITEM	
DIFFICULTY	75%
MEAN TIME [s]	32.1
n	77
n	21
n	48
n	188
%	66%
%	95%
%	67%
%	78%

Item: 0039.2

Item #: 0039.2

Given the front and top views of the object, select the option that shows the correct right side view.

Concept: Visualizing in 2D/3D
Topic: 1.5 View Direction

Notes:

VERSION	A
	Item 0039.2
+	D
RESPONSE	
A	7
B	10
C	43
D	242
E	0
n-TOTAL	302
ITEM	
DIFFICULTY	80%
MEAN TIME [s]	20.6
n	216
n	0
n	58
n	28
%	77%
%	
%	91%
%	82%

VERSION	B
	Item 0039.2
+	D
RESPONSE	
A	2
B	8
C	35
D	286
E	0
n-TOTAL	331
ITEM	
DIFFICULTY	86%
MEAN TIME [s]	28.9
n	74
n	21
n	48
n	188
%	92%
%	100%
%	85%
%	83%

VERSION	C
	Item 0039.2
+	D
RESPONSE	
A	7
B	22
C	65
D	227
E	0
n-TOTAL	321
ITEM	
DIFFICULTY	71%
MEAN TIME [s]	19.0
n	43
n	26
n	57
n	195
%	86%
%	96%
%	75%
%	63%

Item: 0042

Item #: 0042

Select the option that shows the correct cutting plane that produces section A-A.

Concept: Sectional Views
Topic: 4.2 Half Sections

Notes:

VERSION A	
Item 0042	
A	
RESPONSE	
A	83
B	50
C	45
D	101
E	10
n-TOTAL	289
ITEM	
DIFFICULTY	29%
MEAN TIME [s]	24.6
n	203
n	0
n	58
n	28
%	24%
%	
%	29%
%	61%

VERSION B	
Item 0042	
A	
RESPONSE	
A	136
B	33
C	60
D	100
E	0
n-TOTAL	329
ITEM	
DIFFICULTY	41%
MEAN TIME [s]	51.3
n	72
n	21
n	48
n	188
%	42%
%	52%
%	29%
%	43%

Item: 0009

Item #: 0009

Select the set of views where Surface A is labeled correctly.

Concept: Visualizing in 2D/3D
Topic: 1.1 Edge View

Notes:

VERSION	B
	Item 0009
	A
RESPONSE	
A	87
B	151
C	46
D	39
E	0
n-TOTAL	323
ITEM DIFFICULTY	27%
MEAN TIME [s]	61.1
n	67
n	21
n	48
n	187
%	31%
%	24%
%	33%
%	24%

VERSION	C
	Item 0009
***	A
RESPONSE	
A	131
B	121
C	39
D	37
E	0
n-TOTAL	328
ITEM DIFFICULTY	40%
MEAN TIME [s]	92.8
n	45
n	26
n	60
n	197
%	40%
%	38%
%	47%
%	38%

Item: 0043.2

Item # 0043.2

Select the option that shows the correct section view A-A.

Concept: Sectional Views
Topic: 4.6 Aligned Sections

Notes:

VERSION B	
Item 0043.2	
C	
RESPONSE	
A	65
B	30
C	106
D	122
E	0
n-TOTAL	323
ITEM	
DIFFICULTY	33%
MEAN TIME [s]	32.8
n	67
n	21
n	48
n	187
%	33%
%	48%
%	29%
%	32%

VERSION C	
Item 0043.2	
*** C	
RESPONSE	
A	51
B	35
C	125
D	117
E	0
n-TOTAL	328
ITEM	
DIFFICULTY	38%
MEAN TIME [s]	44.4
n	45
n	26
n	60
n	197
%	31%
%	35%
%	48%
%	37%

Appendix G : Selected Items and Statistics from Beta Version

Item #: 0021

Select the option that shows the correct cutting plane that produces Section A-A.

Count of Q3.8 - Item 0021		Column La				
Row Labels		A	B	C	D	Grand Total
		18	84	2	3	107
			29			29
		45	165	9	14	233
		21	26	6	2	55
Grand Total		84	304	17	19	424

Qualtrics	Version	Item	Topic	α DIFF.	β DIFF.	α DISC.	β DISC.
Q3.8	RED	0021.0	PLANAR GEOMETRY	52	72	0.65	0.38

Item #: 0042

Select the option that shows the correct cutting plane that produces section A-A.

Count of Q2.19 - Item 0042					
Column L					
Row Labels	A	B	C	D	Grand Total
	51	14	20	31	116
	17	1	4	7	29
	92	29	37	71	229
	12	19	16	14	61
Grand Total	172	63	77	123	435

Count of Q3.16 - Item 0042					
Column La					
Row Labels	A	B	C	D	Grand Total
	55	8	21	23	107
	16	2	4	7	29
	83	31	47	72	233
	12	18	17	8	55
Grand Total	166	59	89	110	424

Qualtrics Questic	Version	Item	Topic	α DIFF.	β DIFF.	α DISC.	β DISC.
Q2.19	BLUE	0042.0	PLANAR GEOMETRY	38	40	0.40	0.50
Q3.16	RED	0042.0	PLANAR GEOMETRY	38	39	0.40	0.45

Item #: 0009

Select the set of views where Surface A is labeled correctly.

Count of Q2.5 - Item_0009					
Row Labels	A	B	C	D	Grand Total
	16	32	48	20	116
	1	9	15	4	29
	31	92	73	33	229
	9	27	16	9	61
Grand Total	57	160	152	66	435

Count of Q3.4 - Item_0009					
Row Labels	A	B	C	D	Grand Total
	16	24	51	16	107
	5	8	15	1	29
	22	71	118	22	233
	6	24	18	7	55
Grand Total	49	127	202	46	424

Qualtrics Question	Version	Item	Topic	α DIFF.	β DIFF.	α DISC.	β DISC.
Q2.5	BLUE	0009.0	PROJECTION THEORY	41	35	0.38	0.39
Q3.4	RED	0009.0	PROJECTION THEORY	41	48	0.38	0.32

Item #: 0028.4

Given the set of views above, choose the option where 4 is at it's true length.

- A. Side View, Front View
- B. Side View
- C. None
- D. Front View

Count of Q2.15 - Item 0028.4	Column L				
Row Labels	A	B	C	D	Grand Total
	29	5	78	4	116
	8		19	2	29
	82	13	127	7	229
	24	9	25	3	61
Grand Total	143	27	249	16	435

Count of Q3.11 - Item 0028.4	Column La				
Row Labels	A	B	C	D	Grand Total
	46	4	54	3	107
	13	3	11	2	29
	107	20	98	8	233
	19	9	23	4	55
Grand Total	185	36	186	17	424

Qualtrics Questio	Version	Item	Topic	α DIFF.	β DIFF.	α DISC.	β DISC.
Q2.15	BLUE	0028.4	PROJECTION THEORY	45	57	0.36	0.44
Q3.11	RED	0028.4	PROJECTION THEORY	45	44	0.36	0.45

Item #: 0043.2

Select the option that shows the correct section view A-A.

Count of Q2.20 - Item 0043.2		Column L				
Row Labels		A	B	C	D	Grand Total
		40	8	10	58	116
		12	1	5	11	29
		96	17	45	71	229
		19	13	13	16	61
Grand Total		167	39	73	156	435

Count of Q3.17 - Item 0043.2		Column La				
Row Labels		A	B	C	D	Grand Total
		36	5	15	51	107
		14	1	2	12	29
		99	16	52	66	233
		16	9	15	15	55
Grand Total		165	31	84	144	424

Qualtrics Questio	Version	Item	Topic	α DIFF.	β DIFF.	α DISC.	β DISC.
Q2.20	BLUE	0043.2	SECTIONAL VIEWS (CONVENTIONS)	38	36	0.39	0.43
Q3.17	RED	0043.2	SECTIONAL VIEWS (CONVENTIONS)	38	34	0.39	0.33

Appendix H : Items from Final Version

Figure 31: Item 0001 Final Version

Figure 32 Item 0006 Final Version

Figure 33 Item 0008 Final Version

Figure 34 Item 0009 Final Version

Item #: 0013

Given the front and top views of the object, select the option that shows the correct section view.

Figure 35 Item 0013 Item from Final Version

Item #: 0017

Select the correctly dimensioned object from the object given below.

Figure 36 Item 0017 Final Version

Figure 37 Item 0021 Final Version

Figure 38 Item 0022 Final Version

Figure 39 Item 0027 Final Version

Figure 40 Item 0028.2 Final Version

Item #: 0028.4

Given the set of views above, choose the option where 4 is at true length.

- A.** Side View, Front View
- B.** Side View
- C.** None
- D.** Front View

Figure 41 Item 0028.4 Final Version

Figure 42 Item 0039 Final Version

Figure 43 Item 0040 Final Version

Item #: 0042

Select the option that shows the correct cutting plane that produces section A-A.

Figure 44 Item 0042 Final Version

Item #: 0043.2

Select the option that shows the correct section view A-A.

Figure 45 Item 0043.2 Final Version

Item #: 0045.2

Given the drawing below, select the correct meaning of the callout.

- A. 0.375" diameter thru all, countersink of diameter 0.625" to a depth of 0.25"
- B. 0.375" radius hole thru all, counterbore diameter of 0.625" to a depth of 0.25"
- C. 0.375" diameter hole thru all, spot face diameter of 0.625" to a height of 0.25"
- D. 0.375" diameter hole thru all, counterbore diameter of 0.625" to a depth of 0.25"

Figure 46 Item 0045.2 Final Version

Figure 47 Item 0047.1 Final Version

Figure 48 Item 0047.4 Final Version

Item #: 0047.5

Given the top and right views of the object, select the option that shows the correct front view.

Figure 49 Item 0047.5 Final Version

Item #: 0052

Select the option that shows the correct cutting plane that produces Section A-A.

Figure 50 Item 0052 Final Version

Figure 51 Item 0056 Final Version

Figure 52 Item 0058 Final Version

Figure 53 Item 0063 Final Version

Figure 54 Item 0066 Final Version

Figure 55 Item 0068 Final Version

Figure 56 Item 0069 Final Version

Figure 57 Item 0071 Final Version

Figure 58 Item 0072 Final Version

Figure 59 Item 0073.1 Final Version

Item #0073.3

Select the view with the properly dimensioned incline depth (1.00).

- A.** A
- B.** B
- C.** C
- D.** D

Figure 60 Item 0073.3 Final Version

Appendix I : Item Mapping from Final Version

ITEM DIFFICULTY VS. DISCRIMINATION INDEX FOR "MAPPING BETWEEN 2D AND 3D"

ITEM DIFFICULTY VS. DISCRIMINATION INDEX FOR "DIMENSIONING"

Item #: 0001

Given the orthographic views, select the option that shows the correct auxillary view.

Item #: 0006

Given the front, side, and top views of the object, select the option that shows the correct isometric view.

Item #: 0008

Select the correctly dimensioned object from the options given below.

Item #: 0009

Select the set of views where Surface A is labeled correctly.

A.

B.

C.

D.

Item #: 0013

Given the front and top views of the object, select the option that shows the correct section view.

A.

B.

C.

D.

Item #: 0017

Select the correctly dimensioned object from the object given below.

Item #: 0021

Select the option that shows the correct cutting plane that produces Section A-A.

Item #: 0022

Select the option that shows the correct section view A-A.

Item #: 0027

Select the option that shows all the standard views of the object correctly aligned in orthographic projection.

Item #: 0028.2

Given the set of views above, choose the option where 2 is at true length.

- A. Top View
- B. Front View
- C. Top View, Front View
- D. None

Item #: 0028.2

Given the set of views above, choose the option where 2 is at true length.

- A. Top View, Front View
- B. Front View
- C. Top View
- D. None

Item #: 0028.4

Given the set of views above, choose the option where 4 is at true length.

- A. Side View, Front View
- B. Side View
- C. None
- D. Front View

Item #: 0039

Select the set of views that has Surface A labeled correctly.

Item #: 0040

Select the option that shows the correct orthographic projection of the object shown.

Item #: 0042

Select the option that shows the correct cutting plane that produces section A-A.

Item #: 0043.2

Select the option that shows the correct section view A-A.

Item #: 0045.2

Given the drawing below, select the correct meaning of the callout.

- A. 0.375" diameter thru all, countersink of diameter 0.625" to a depth of 0.25"
- B. 0.375" radius hole thru all, counterbore diameter of 0.625" to a depth of 0.25"
- C. 0.375" diameter hole thru all, spot face diameter of 0.625" to a height of 0.25"
- D. 0.375" diameter hole thru all, counterbore diameter of 0.625" to a depth of 0.25"

Item #: 0047.1

Given the front and top views of the object, select the option that shows the correct right side view.

?

A.

B.

C.

D.

Item #: 0047.4

Given the front and right views of the object, select the option that shows a correct top view.

?

A.

B.

C.

D.

Item #: 0047.5

Given the top and right views of the object, select the option that shows the correct front view.

?

A.

B.

C.

D.

Item #: 0052

Select the option that shows the correct cutting plane that produces Section A-A.

A.

B.

C.

D.

Item #: 0056

Select the option that shows the correct section view A-A.

?

SECTION A-A

A.

SECTION A-A

B.

SECTION A-A

C.

SECTION A-A

D.

SECTION A-A

Item #: 0058

Select the option that shows the correct section view A-A.

Item #: 0063

Given the front and right side views, select the correct top view.

Item #: 0066

Given the top and front views, select the correct right side view.

Item #: 0068

Given the orthographic views, select the correct pictorial view.

Item #: 0069

Given the orthographic views, select the correct pictorial view.

Item #: 0071

Given the orthographic views, select the correct pictorial view.

Item #: 0072

Select the option that shows the correct form of orthographic projection.

Item #0073.1

Select the option that contains the top view.

- A.** A
- B.** B
- C.** C
- D.** D

Item #0073.3

Select the view with the properly dimensioned incline depth (1.00).

- A.** A
- B.** B
- C.** C
- D.** D

Appendix J : Selected Items from Validity Study

Item #: 0001

Given the orthographic views, select the option that shows the correct auxiliary view.

The above question is intended to measure the Concept of:
PROJECTION THEORY.

Do you agree that this is what it measures?

- ☐ Yes
☐ No

Which Concept should this instrument measure?

☐ MAPPING BETWEEN 2D AND 3D	☐ PROJECTION THEORY
☐ PARALLEL PROJECTION
METHODOLOGIES	☐ SECTIONAL VIEWS
☐ PLANAR GEOMETRY	☐ DIMENSIONING
☐ OTHER (please indicate):	☐ CAD CONCEPTS

Item #: 0022

Select the option that shows the correct section view A-A.

The above question is intended to measure the Concept of:

SECTIONAL VIEWS.

Do you agree that this is what is measures?

YES

NO

Which Concept should this instrument measure?

☐ MAPPING BETWEEN 2D AND 3D

☐ PROJECTION THEORY

☐ PARALLEL PROJECTION
METHODOLOGIES

☐ SECTIONAL VIEWS

☐ PLANAR GEOMETRY

☐ DIMENSIONING

☐ OTHER (please indicate):

☐ CAD CONCEPTS

Item #: 0028.1

Given the set of views above, choose the option where A is at true length.

- A. Side View, Top View
- B. Side View
- C. Top View
- D. None

The above question is intended to measure the Concept of:
PROJECTION THEORY.

Do you agree that this is what is measures?

YES
☐

NO
☐

Which Concept should this instrument measure?

☐ MAPPING BETWEEN 2D AND 3D	☐ PROJECTION THEORY
☐ PARALLEL PROJECTION
METHODOLOGIES	☐ SECTIONAL VIEWS
☐ PLANAR GEOMETRY	☐ DIMENSIONING
☐ OTHER (please indicate):	☐ CAD CONCEPTS

Item #: 0063

Given the front and right side views, select the correct top view.

The above question is intended to measure the Concept of:
MAPPING BETWEEN 2D AND 3D.

Do you agree that this is what is measures?

YES
☐

NO
☐

Which Concept should this instrument measure?

☐ MAPPING BETWEEN 2D AND 3D	☐ PROJECTION THEORY
☐ PARALLEL PROJECTION METHODOLOGIES	☐ SECTIONAL VIEWS
☐ PLANAR GEOMETRY	☐ DIMENSIONING
☐ OTHER (please indicate):	☐ CAD CONCEPTS

Item #0073.1

Select the option that contains the top view.

- A. A
- B. B
- C. C
- D. D
- E. E

The above question is intended to measure the Concept of:
PARALLEL PROJECTION METHODOLOGIES.

Do you agree that this is what is measures?

YES
☐

NO
☐

Which Concept should this instrument measure?

☐ MAPPING BETWEEN 2D AND 3D	☐ PROJECTION THEORY
☐ PARALLEL PROJECTION METHODOLOGIES	☐ SECTIONAL VIEWS
☐ PLANAR GEOMETRY	☐ DIMENSIONING
☐ OTHER (please indicate):	☐ CAD CONCEPTS

Item #: 0047.4

Given the front and right views of the object, select the option that shows a correct top view.

The above question is intended to measure the Concept of:
MAPPING BETWEEN 2D AND 3D.

Do you agree that this is what is measures?

YES
☐

NO
☐

Which Concept should this instrument measure?

☐ MAPPING BETWEEN 2D AND 3D

☐ PROJECTION THEORY

☐ PARALLEL PROJECTION
METHODOLOGIES

☐ SECTIONAL VIEWS

☐ PLANAR GEOMETRY

☐ DIMENSIONING

☐ OTHER (please indicate):

☐ CAD CONCEPTS

Item #: 0049.1

Given the orthographic views, select the option that shows the correct isometric view of the object.

The above question is intended to measure the Concept of:

MAPPING 2D AND 3D.

Do you agree that this is what is measures?

YES
☐

NO
☐

Which Concept should this instrument measure?

☐ MAPPING BETWEEN 2D AND 3D

☐ PROJECTION THEORY

☐ PARALLEL PROJECTION
METHODOLOGIES

☐ SECTIONAL VIEWS

☐ PLANAR GEOMETRY

☐ DIMENSIONING

☐ OTHER (please indicate):

☐ CAD CONCEPTS

Item #: 0056

Select the option that shows the correct section view A-A.

?

SECTION A-A

A.

SECTION A-A

B.

SECTION A-A

C.

SECTION A-A

D.

SECTION A-A

The above question is intended to measure the Concept of:
SECTIONAL VIEWS.

Do you agree that this is what is measures?

YES
☐

NO
☐

Which Concept should this instrument measure?

☐ MAPPING BETWEEN 2D AND 3D

☐ PROJECTION THEORY

☐ PARALLEL PROJECTION
METHODOLOGIES

☐ SECTIONAL VIEWS

☐ PLANAR GEOMETRY

☐ DIMENSIONING

☐ OTHER (please indicate):

☐ CAD CONCEPTS

Item #: 0057

Select the option that shows the correct Section A-A.

?

SECTION A-A

A.

SECTION A-A

B.

SECTION A-A

C.

SECTION A-A

D.

SECTION A-A

The above question is intended to measure the Concept of:
SECTIONAL VIEWS.

Do you agree that this is what is measures?

YES
☐

NO
☐

Which Concept should this instrument measure?

☐ MAPPING BETWEEN 2D AND 3D

☐ PROJECTION THEORY

☐ PARALLEL PROJECTION
METHODOLOGIES

☐ SECTIONAL VIEWS

☐ PLANAR GEOMETRY

☐ DIMENSIONING

☐ OTHER (please indicate):

☐ CAD CONCEPTS

Item_1014

Using **only one feature or command**, the solid model of the object below can be created with:

- A. Extrude only
- B. Revolve only
- C. Stamp only
- D. Either extrude or revolve

The above question is intended to measure the Concept of:
Computer Aided Design - REVOLVE.

Do you agree that this is what is measures?

- ☐ YES
- ☐ NO

If "No", which Concept should this instrument measure?

- ☐ CAD - EXTRUDE
- ☐ CAD - LOFT
- ☐ CAD - PLANES
- ☐ CAD - LOFT
- ☐ CAD-SWEEP

Appendix I: Selected Statistics from Validity Study

Table 30 Validity Study Participant Role

Institution	Participant N
Buena Vista University	1
Bullis School	1
Carter Fuel Systems	1
Central Connecticut State University	1
CGT, Purdue University	1
College of Lake County	1
Colorado School of Mines	1
East Carolina University	1
Embry-Riddle Aeronautical University	1
Hudson Valley Community College	1
Ivy Tech Community College	1
JF Drake State Community & Technical College	1
KSU	1
Messiah College	1
NC State University	2
Old Dominion University	2
Purdue	3
Purdue University northwest	1
Red Rocks Community College	1
Rose-Hulman Institute of Technology	1
San Antonio College	1
South Newton High School	1
St. Louis Community College	1
UC San Diego	1
UNC Charlotte	1
University of Detroit Mercy	1
University of Maine	1
University of Texas at Austin	1
University of Udine	1
University of Washington	1
Utah State University	2
Washington State University	1
Whatcom Community College	1
Total	39

Table 31 Validity Study Participant Role

Participant Role	N
Graduate Student, Instructor / Professor	1
Graphics Professional	1
Instructor / Professor	29
Instructor / Professor, Graphics Professional	1
Instructor / Professor, Other (Please Specify):	1
Instructor / Professor, Researcher	4
Researcher	2
Total	39

Table 32 Validity Study - Participant Years of Experience in Graphics

Years of Experience	N
0-2 years	2
3-5 years	1
6-10 years	4
Over 10 years	32
Total	39

Table 33 Validity Study Item 0001

Response (Ver1)	N
Yes	19
Total	19
Response (Ver2)	N
Yes	18
No	2
Other (please indicate)	2
Total	20

Table 34 Validity Study Item 0006

Response	N - Item 0006
Yes	19
Total	19

Table 35 Validity Study Item 0013

Response	N - Item 0013
Yes	18
No	1
Planar Geometry	1
Total	19

Table 36 Validity Study Item 0014

Response	N - Item 0014
Yes	11
No	8
Mapping between 2D and 3D	4
Parallel Projection Methodologies	3
Planar Geometry	1
Total	19

Table 37 Validity Study Item 0015

Response	N - Item 0015
No	2
Mapping between 2D and 3D	1
Other (please indicate)	1
Yes	17
Total	19

Table 38 Validity Study Item 0017

Response (Ver1)	N - ITEM 0017
Yes	19
Total	19

Response (Ver2)	N - ITEM 0017
Yes	19
No	1
Other (please indicate)	1
Total	20

Table 39 Validity Study Item 0021

Response (Ver1)	N - Item 0021
Yes	5
No	14
Planar Geometry	1
Sectional Views	12
Other (please indicate)	1
Total	19

Response (Ver2)	N - Item 0021
Yes	9
No	11
Sectional Views	11
Total	20

*Ver2 Was set up as a “check”
with reversed responses*

Table 40 Validity Study Item 0022

Response	N - Item 0022
Yes	18
No	1
Other (please indicate)2	1
Total	19

Table 41 Validity Study Item 0027

Response	N - ITEM 0027
Yes	14
No	5
Mapping between 2D and 3D	3
Projection Theory	1
Other (please indicate)	1
Total	19

Table 42 Validity Study Item 0028.1

Response	N - ITEM 0028.1
Yes	16
No	3
Mapping between 2D and 3D	2
Sectional Views	1
Total	19

Table 43 Validity Study Item 0028.2

Response (Ver1)	N - ITEM 0028.2
Yes	16
No	3
Mapping between 2D and 3D	2
Sectional Views	1
Total	19

Response (Ver2)	N - ITEM 0028.2
Yes	15
No	5
Total	20

Table 44 Validity Study Item 0028.5

Response	N - ITEM 0028.5
Yes	15
No	5
Mapping between 2D and 3D	2
Planar Geometry	1
Other (please indicate)	2
Total	20

Table 45 Validity Study Item 0031.2

Response (Ver1)	N - ITEM 0031.2
Yes	9
No	10
CAD Concepts	1
Parallel Projection Methodologies	5
Planar Geometry	1
Projection Theory	3
Total	19

Response (Ver2)	N - ITEM 0031.2
Yes	11
No	9
Parallel Projection Methodologies	5
Projection Theory	2
Sectional Views	1
Other (please indicate)	1
Total	20

Table 46 Validity Study Item 0039

Response	N - ITEM 0039.0
Yes	15
No	4
Mapping between 2D and 3D	2
Parallel Projection Methodologies	1
Sectional Views	1
Total	19

Table 47 Validity Study Item 0040

Response	N - ITEM_0040
Yes	13
No	6
Parallel Projection Methodologies	2
Projection Theory	3
Other (please indicate)2	1
Total	19

Table 48 Validity Study Item 0042

Response	N - ITEM_0042
Yes	19
Total	19

Table 49 Validity Study Item 0043.2

Response (Ver1)	N - ITEM_0043.2
Yes	18
No	1
CAD Concepts	1
Total	19

Response (Ver2)	N - ITEM_0043.2
Yes	19
Total	19

Table 50 Validity Study Item 0045.2

Response (Ver1)	N - ITEM_0045.2
Yes	17
No	2
Other (please indicate)	2
Total	19

Response (Ver2)	N - ITEM_0045.2
Yes	19
Total	19

Table 51 Validity Study Item 0047.1

Response	N - ITEM 0047.1
Yes	12
No	7
Parallel Projection Methodologies	2
Planar Geometry	1
Projection Theory	4
Total	19

Table 52 Validity Study Item 0047.4

Response	N - ITEM 0047.4
Yes	13
No	6
Parallel Projection Methodologies	2
Planar Geometry	1
Projection Theory	3
Total	19

Table 53 Validity Study Item 0048.2

Response	N - ITEM 0048.2
Yes	12
No	7
Parallel Projection Methodologies	1
Planar Geometry	2
Projection Theory	3
Other (please indicate)	1
Total	19

Table 54 Validity Study Item 0049.1

Response	N - ITEM 0049.1
Yes	19
Total	19

Table 55 Validity Study Item 0055

Response	N - ITEM 0055
Yes	4
No	15
Sectional Views	14
Other (please indicate)2	1
Total	19

Table 56 Validity Study Item 0056

Response	N - ITEM 0056
Yes	19
Total	19

Table 57 Validity Study Item 0057

Response	N - ITEM 0057
Yes	18
No	1
Mapping between 2D and 3D	1
Total	19

Table 58 Validity Study Item 0058

Response	N - ITEM 0058
Yes	18
No	1
Projection Theory	1
Total	19
Response	N - ITEM 0058
Yes	19
Total	19

Table 59 Validity Study Item 0063

Response	N - ITEM_0063
Yes	11
No	8
Parallel Projection Methodologies	4
Planar Geometry	1
Projection Theory	2
Other (please indicate)	1
Total	19

Table 60 Validity Study Item 0064

Response	N - ITEM_0064
Yes	11
No	8
Parallel Projection Methodologies	3
Planar Geometry	1
Projection Theory	4
Total	19

Table 61 Validity Study Item 0066

Response	N - ITEM_0066
Yes	11
No	8
Parallel Projection Methodologies	2
Planar Geometry	1
Projection Theory	4
Other (please indicate)	1
Total	19

Table 62 Validity Study Item 0069

Response	N - ITEM_0069
Yes	19
Total	19

Table 63 Validity Study Item 0071

Response	N - ITEM_0071
Yes	19
Total	19

Table 64 Validity Study Item 0072

Response	N - ITEM_0072
Yes	17
No	2
Mapping between 2D and 3D	1
Projection Theory	1
Total	19

Table 65 Validity Study Item 0073.1

Response (Ver1)	N - ITEM_0073.1
Yes	15
No	4
Mapping between 2D and 3D	1
Planar Geometry	1
Projection Theory	2
Total	19

Response (Ver2)	N - ITEM_0073.1
Yes	17
No	2
Projection Theory	1
Other (please indicate)	1
Total	19

Table 66 Validity Study Item 0073.3

Response	N - ITEM_0073.3
Yes	17
No	2
Projection Theory	1
Other (please indicate)	1
Total	19

Table 67 Validity Study Item 1012

Response	N - ITEM_1012
Yes	19
Total	19

Table 68 Validity Study Item 1014

Response	N - ITEM_1014
Yes	5
No	14
CAD - Extrude	13
Other (please indicate)	1
Total	19

Table 69 Validity Study Item 1016

Response	N - ITEM_1016
Yes	19
Total	19

Table 70 Validity Study Item 1026

Response	N - ITEM_1026
Yes	19
Total	19

Table 71 Validity Study Item 1027

Response	N - ITEM_1027
Yes	16
No	3
Other (please indicate)	2
CAD - Sweep	1
Total	19

Table 72 Validity Study item 1029

Response	N - ITEM_1029
Yes	18
No	1
Other (please indicate)	1
Total	19

Table 73 Validity Study Item 1030

Response	N - ITEM_1030
Yes	17
No	2
CAD - Loft	1
Other (please indicate)	1
Total	19

Table 74 Validity Study Item 1045

Response	N - ITEM_1045
Yes	16
No	3
Other (please indicate)	3
Total	19

Table 75 Validity Study Item 1067

Response	N - ITEM_1067
Yes	18
No	1
Other (please indicate)	1
Total	19

Table 76 Validity Study Item 1068

Response	N - ITEM_1068
Yes	18
No	1
Other (please indicate)	1
Total	19

Table 77 Validity Study Item 1158

Response	N - ITEM 1158
Yes	18
No	1
Other (please indicate)2	1
Total	19

Table 78 Validity Study Item 1167

Response	N - ITEM 1167
Yes	19
Total	19