

# **Assessment of First-Year Engineering Students' Spatial Visualization Skills**

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Dissertation submitted to the Faculty of the  
Virginia Polytechnic Institute and State University  
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy  
in  
Engineering Education

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March 30<sup>th</sup>, 2012  
Blacksburg, Virginia

Keywords: concept inventory, spatial visualization, assessment,  
engineering graphics, pedagogy

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## ABSTRACT

This research was undertaken to investigate the assessment of the spatial visualization skills of first-year engineering students. This research was conducted through three approaches: (1) a review of cogent research framed by a spatial visualization matrix, (2) the development and validation of an Engineering Graphics Concept Inventory, and (3) an investigation into the relationship into the correlations between 3D modeling skills and performance on the Purdue Spatial Visualization Test: Rotations (PSVT:R) and the Mental Cutting Test (MCT).

The literature reviewed spans the field of published research from the early 1930's to the present. This review expands and provides a new direction on published research as it is viewed through the lenses of the four common pedagogical approaches to teaching spatial visualization: the standard approach, the remedial approach, computer-aided design, and the theory-informed approach. A spatial visualization matrix of criteria was developed to evaluate each of the methods. The four principle criteria included: learning outcomes, active and engaged learning, stage of knowledge, and explanatory power. Key findings from the literature review indicate the standard method is not the most effective method to teaching spatial visualization while the theory-informed method as evaluated by the matrix is the most effective pedagogical approach of the four methods evaluated.

The next phase of this research focused on the two-year development, validation, and reliability of an Engineering Graphics Concept Inventory given to over 1300 participants from three universities. A Delphi method was used to determine the key concepts identified by the expert panel to be included in the inventory. A student panel of 20 participants participated in the pilot study of "think aloud" protocols to refine inventory test items and to generate the appropriate distractors. Multiple pilot studies coupled with a detailed psychometric analysis provided the feedback and direction

needed for the adjustment of test items. The reported Cronbach's  $\alpha$  for the final instrument is .73, which is within the acceptable range. The inventory is ready to be implemented and the predictability of the instrument, in reference to students' spatial visualization skills, to be researched.

The final chapter of this research was a correlational study of the relationship between first-year engineering student's 3D modeling frameworks and their performance on the PSVT:R and the MCT. 3D modeling presence in graphical communications has steadily increased over the last 15 years; however there has been little research on the correlations between the standard visualization tests and 3D modeling. 220 first-year engineering students from Embry-Riddle Aeronautical University participated in the study in the fall of 2011. The main findings from this research indicate there is no significant correlational relationship between the PSVT:R and a student's 3D modeling ability, but there is one for the MCT. The significant correlational factors reported for the MCT and modeling aptitude for the three assignments are:  $r = .32$  ( $p < 0.05$ ),  $.36$  ( $p < 0.01$ ), and  $.47$  ( $p < 0.01$ ). These findings may be used by undergraduate educators and course administrators to more effectively organize engineering graphics education to yield students with deeper, more meaningful knowledge about engineering graphics and its inherent connection throughout the engineering curriculum.

Together these three studies represent a sequential exploratory mixed methods approach that intertwines qualitative interviews and observations to frame the quantitative instrument and data collection. Results of this study can be used to guide the assessment of incoming freshmen engineering students, and the modification and development of engineering graphics courses.

## Acknowledgements

The published pages of this dissertation contain much more than the culmination of my years of study. These pages reflect the diverse community of inspiring and supportive people that have generously guided me through my doctoral work. Each has contributed to my development as a scholar and a teacher.

Deepest thanks to my advisor, Dr. Lisa McNair, a patient mentor who allowed me the latitude and space to find my own way through this work. The support, guidance, and patience she demonstrated through her edits and revisions were above and beyond the call of duty. I am privileged to have had the opportunity to work with her for the last few years and I look forward to continued collaborations.

To my committee members, Dr. Maura Borrego, Dr. Richard Goff, and Dr. Dave Pedersen for their encouraging words, thoughtful critiques, time, and attention during busy semesters. The quality of this work is a direct reflection of the care and direction of my committee – how fortunate I was to have such a strong, supportive committee with such clarity of purpose.

To Dr. Marie Paretti for showing me by example and through challenging, interesting coursework: how to think, teach, and to teach others to think. I am honored to count her as a friend and a colleague.

To the invaluable network of my Embry-Riddle family who was supportive and generous throughout and without whom I could not have completed much less started this rite of passage.

To Dr. James Ladesic for whom a mere thank you will never be enough; your steadfast encouragement, support, and mentoring throughout my professional career has been most undeserved. You have encouraged me to grow both professionally and academically.

To Dr. Timothy Wilson who started the conversation about me pursuing my PhD in Engineering Education and planted the seed with the Dean of the College at Embry-Riddle. Your kindly smile always made this process a bit lighter.

To Dr. and Mrs. Johnson who always asked me about my progress, offered guidance, and most importantly believed in my success.

To Dr. Irene McReynolds who showed me there were many more people rooting for me than I ever truly knew.

I am indebted to all of my colleagues in the College of Engineering whose genuine interest and concern gave me the impetus to continue – thank you.

I owe much gratitude to all of the students who willingly participated in every aspect of this research by dedicating their time, energy, and opinions to help to improve engineering graphics education.

To my mother Dolores, my two brothers, Bruce and Eric, for their understanding though this long, arduous process, and to my father, William, for instilling the stubbornness required not to quit.

To Paikea and Theo your countless hours of unquestioning companionship, warmth, and friendly faces made this experience much less dark.

Last and certainly by no means least, my last defense against the outside world and my lifelong friend, Raul. Neither one of us knew of the path ahead nor the challenges that awaited when this adventure started four years ago; thank you for leaving the door open and the light on so I could find my way home again.

It has taken a village.

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# Chapter 1

## Dissertation Introduction

Engineering graphics has been a part of the U.S. undergraduate engineering curriculum since it was first introduced at West Point in 1807 (Barr & Juricic, 1994) and most modern engineering graphics can be directly traced to scientific method first introduced in 1827 by Monge in his *Geometrie Descriptive*. While there is an enduring history and tradition governing the instruction of engineering graphics that is resistant to change from within the community of graphics educators, since 1955 the prominence of engineering graphics has experienced a steady decline. This can be attributed to several factors: (1) the Grinter report (Grinter, 1955), (2) patterns of research funded by U.S. government (Seeley, 1999), (3) a reduction of the available credit hours for engineering graphics due to a misunderstanding of engineering graphics function within the engineering curriculum (Meyers, 2000), (4) the steady integration of Computer-Aided Modeling and Design, and (5) the misclassification of CAD's pedagogical impact (Lortie, 1975). Compounding the reduction in available curriculum hours is the low spatial visualization skill level of incoming first-year engineering students. Quite often students are matriculating into engineering graphics—considered one of the gateway courses in engineering—without the basic skills required to be successful in the course and in engineering overall (Lubinski, 2010; Strong & Smith, 2002; Wai, Lubinski, & Benbow, 2009).

This dissertation explores the teaching of engineering graphics, assessment of misconceptions about engineering graphics concepts, and assessment of 3D modeling skills with two well-known validated instruments. The first manuscript, *A Comparison of Current Teaching Pedagogies for Engineering Graphics with Standardized Evaluation Criteria*, frames the review of the research literature around the four common methods for teaching engineering graphics, the standard approach, the remedial approach, the 3D modeling approach, and the theory informed approach. Four principle criteria are used to evaluate each method – learning outcomes, active and engaged learning, stage of knowledge, and explanatory power. The second manuscript, *Development and Validation of Engineering Graphics Concept Inventory*, documents the Delphi method I utilized to create the concept inventory and presents the psychometric results from 1300 students from three universities. The final manuscript, *The Predictive Ability of the*

*PSVT:R and the MCT for Students 3D Modeling Skills*, demonstrates a correlation between high performance on the MCT and maturity of 3D modeling frameworks.

The three overarching research questions that frame this research are presented in detail in Table 1 and are summarized here:

1. Which of the primary four pedagogical methods for teaching engineering graphics are more effective when evaluated with standard criteria?
2. What elements and criteria are necessary in a reliable and valid concept inventory for engineering graphics?
3. How strongly does a student's performance on two visualization instruments correlate to their ability to develop robust 3D modeling frameworks?
  - a. The Purdue Spatial Visualization Test of Rotations
  - b. The Mental Cutting Test

The purpose of this research is: (1) to develop an evaluation matrix from a detailed literature review assessing the four more common pedagogical approaches to teaching engineering graphics providing some clarity to the field; (2) to develop a validated and reliable concept inventory for graphical communications; and (3) to confirm that two of the standard tests for pencil-and-paper visualization, the PSVT:R<sup>1</sup> and the MCT<sup>2</sup>, are also valid for measuring and predicting 3D modeling abilities. These topics are explored in detail in the subsequent chapters 2-4.

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<sup>1</sup> The Purdue Spatial Visualization Test: Rotations

<sup>2</sup> The Mental Cutting Test

**Table 1: Summary of Research Questions, Data Collection and Analysis for Chapters 2 - 4**

Chapter	Title of Article	Purpose or Research Question	Data Source and Collection	Data Analysis
2	Evaluation of Current Teaching Pedagogies with Standardized Criteria	1. Which of the primary four pedagogical methods for teaching engineering graphics are more effective when evaluated with standard criteria?	<ul style="list-style-type: none"> <li>• Extensive Literature Review</li> </ul>	<ul style="list-style-type: none"> <li>• Pedagogical Method Matrix</li> </ul>
3	Development and Validation of Graphical Communication Concept Inventory	1. What elements and criteria are necessary in a reliable and valid concept inventory for engineering graphics?	<ul style="list-style-type: none"> <li>• PSVT:R Pre</li> <li>• MCT Pre</li> <li>• CI Pre – given to three institutions</li> </ul>	<ul style="list-style-type: none"> <li>• Delphi Method</li> <li>• “Think Aloud” Protocols</li> <li>• Item Analysis</li> <li>• Reliability Analysis per University</li> <li>• Validity Analysis per University</li> </ul>
4	The Predictive Ability of the PSVT:R and the MCT for Students 3D Modeling Skills	<p>1. How strongly does a student’s performance on the PSVT:R correlate to their ability to develop robust 3D modeling framework?</p> <p>2. How strongly does a student’s performance on the MCT correlate to their ability to develop robust 3D modeling framework?</p>	<ul style="list-style-type: none"> <li>• PSVT:R Pre</li> <li>• MCT Pre</li> <li>• 3D Modeling Frameworks from three modeling assignments</li> </ul>	<ul style="list-style-type: none"> <li>• Correlational</li> </ul>

## **Background and Rationale for the Dissertation**

Spatial visualization is a fundamental skill required for students to be successful engineers and is considered the primary language of engineering (Orth, 1941; Rising, 1948; Svensen, 1948) . The ability to visualize objects and situations in one's mind, and to manipulate those images, is a cognitive skill vital to many career fields. By one estimate, there are at least 84 different careers for which spatial skills play an important role (I. M. Smith, 1964). It is also an essential skill for the Science, Technology, Engineering, and Mathematics (STEM) fields (Bruer, Benbow, & Wilson, 2010). Simoneau, Fortin, and Ferguson posit that engineering graphics is essential for two fundamental reasons: “to teach the technical language” and “to develop the students’ ability to visualize and solve problems in three dimensions” (1987, p. 5). Spatial abilities have been widely studied and are known to be fundamental to higher-level thinking, reasoning, and creative processes.

However, there have been certain developments in the engineering graphics curriculum that pose problems for students. Three of the primary challenges are: the need for effective, high-quality instruction, an assessment that provides guidance to student misperceptions about engineering graphics, and the pervasiveness of 3D modeling in the curriculum. Engineering graphics courses have either been steadily reduced if not outright eliminated as the undergraduate engineering curriculum has shifted to accommodate an increased emphasis on the engineering design process. As such many of the freshmen engineering courses, e.g. engineering graphics and programming, have been eliminated and replaced with a comprehensive introduction to engineering course. Given the reduced number of hours currently allocated to the teaching of engineering graphics it is essential that the instruction be high-quality and that professors have a clear understanding of what preconceptions their students have about engineering graphics. An additional challenge is the increased presence of 3D modeling in the engineering graphics curriculum and how to best organize the curriculum to meet the students’ skills. The three manuscripts of this dissertation address these problems.

## Theoretical Frame

The theories of pedagogy of engineering graphics, instrument development using the Delphi method, assessment, and the theory of Computer-Aided Modeling provide the theoretical frame.

To provide some clarity to the wide field of engineering graphics research publications, the pedagogy of engineering graphics was used to frame the literature review. To further clarify the organization of the review the stages of knowledge achieved by each method was incorporated. Specifically the stages of knowledge used for this research were correlated to Bloom's Taxonomy (Bloom, Englehart, Furst, Hill, & Krathwohl, 1956), Perry's Scheme (Perry, 1979), and Baxter Magolda's Stages of Intellectual Development (Baxter Magolda, 1992).

The development of the Engineering Graphics Concept Inventory was guided by the Delphi method and the theory of assessment. A panel of experts was utilized to generate and rank the concepts for the instrument and a panel of students generated the distractors for the test items. The instrument was revised and refined by comprehensive psychometric analysis.

To successfully complete an engineering graphics course students must now be able to proficiently hand-sketch and construct intelligent, robust 3D solid models; it is essential that both of these skills are accurately measured to ensure student success within the course and ultimately within the overall program of engineering. A possible way to address this is to investigate how well the PSVT:R and the MCT relate to construction of 3D solid models. While the PSVT:R has been used to measure spatial visualization since the late 1970's and the MCT since the 1930's, and both can provide a baseline for measuring different aspects of spatial visualization, neither was developed to specifically address the concepts taught in an engineering graphics course.

The theory of Computer-Aided Modeling—specifically how the solid model is created as is demonstrated by the organization of the specification tree—is used to structure this correlational study.

It is quite possible that many engineering graphics courses are improperly organized for the skill set of their students. Without effective, accurate instruments in place, first-year engineering students may continue to be improperly prepared for engineering graphics and inadequately equipped for the remainder of their engineering curriculum. In order to reduce the attrition of engineering students due to poor visualization skills, the engineering education

community needs to appreciate the significance of the spatial visualization within the engineering curriculum and its impact on problem solving. Finally, the engineering education community needs to understand the importance of properly assessing students' skill levels and providing them with the appropriately structured coursework to improve and deepen their understanding of the course material.

## **Organization of the Dissertation**

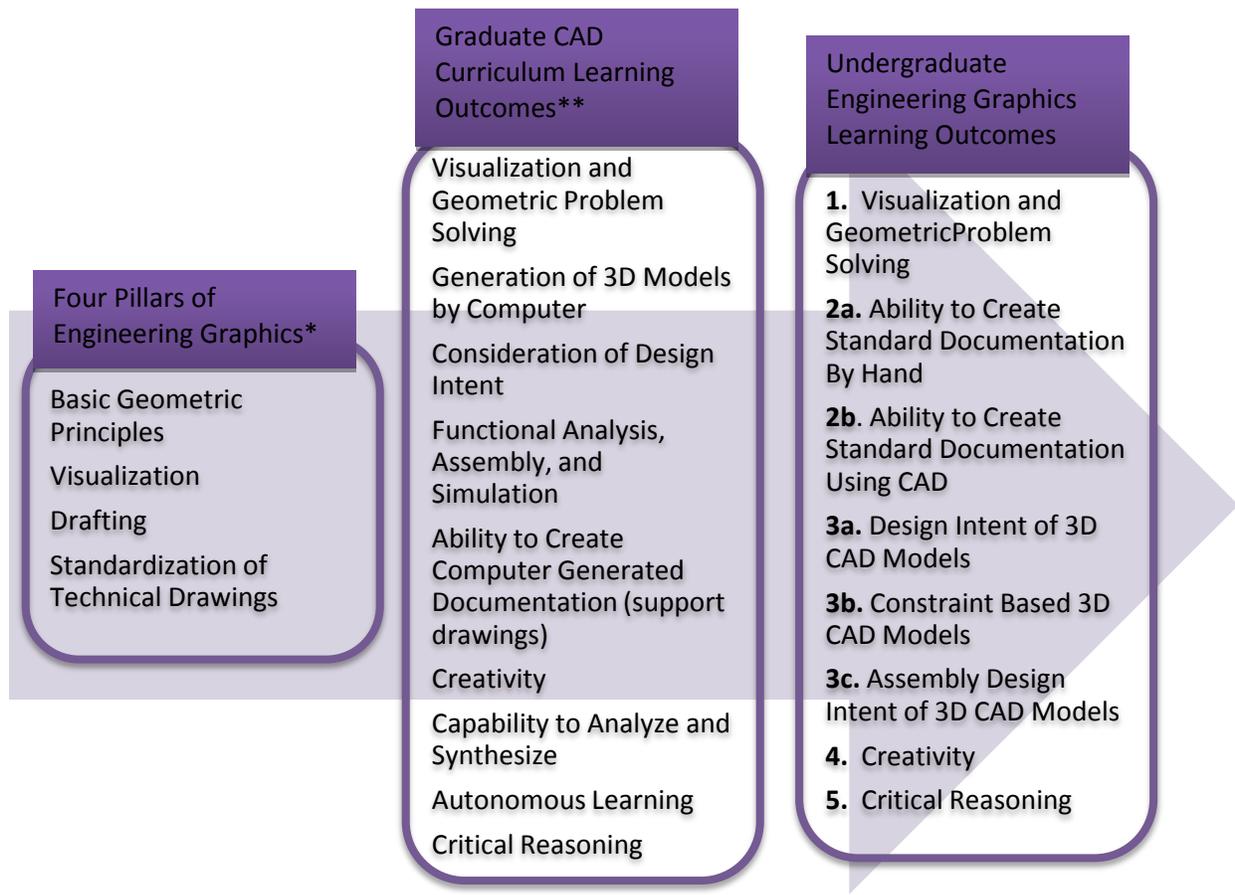
### **Chapter Two: *A Comparison of Current Teaching Pedagogies for Engineering Graphics with Standardized Evaluation Criteria.***

Research on graphical communication and spatial abilities was first published over 100 years ago (Miller, 1996; Mohler, 2008). The amount of published research is overwhelming, as there have only been two literature reviews published the first by Miller in 1996 and the second by Mohler in 2008. While both do provide some organization to the field – Miller has an excellent review of early publications pre-1950 and Mohler organizes his review around four themes, both have limitations. Miller's literature review is limited to the research published in *Engineering Graphics Design Journal* and Mohler's literature review is framed about the primary psychological themes in spatial visualization research. Neither provides a review of research within the pedagogical context of engineering graphics. Over the past decade the curriculum of many engineering graphics courses have been reduced. Educators for engineering graphics are under pressure to teach the critical and fundamental skills of spatial visualization with less time. Another challenge compounding the reduced curriculum is the unequal level of spatial visualization ability of incoming college students (Jenkins & Burtner, 2007). This literature review provides a detailed and systematic comparison of the most common instruction methods, identifies the pedagogical strengths and weaknesses, and contributes an overview of the spatial visualization pedagogy for the engineering education community.

The methodology for the literature review included the use of Engineering Village, IEEE Xplore Digital Library, ERIC, Dissertation and Theses (ProQuest), and EBSCOhost databases to locate research published on spatial visualization research since 1930. Next, criteria for evaluating pedagogical approaches were determined based on the literature, and finally each

pedagogical approach was rated using the established criteria. The literature review began by locating and reviewing all the research articles presented in both Miller's (1996) and Mohler's (2008) publications. These two articles provided a baseline from which to structure my own literature review, Miller's research provided clarity of the spatial visualization publications prior to WWII and demonstrated the impact of the Grinter report on the undergraduate engineering curriculum in the United States especially engineering graphics. Mohler's study provided insight into the engineering graphics research using themes from psychology as a lens.

Identification of the learning outcomes was based on the works of —Sorby et al. (2000) and Barbero and Garcia (2011). Using Sorby et al. (2000) four pillars of undergraduate engineering graphics: basic geometric principles, visualization, drafting, and standardization of technical drawings as a guide. Barbero and Garcia's graduate CAD curriculum outcomes were used to complement principles outlined in Sorby's work. The learning outcomes identified for this research are: geometric problem solving, ability to create standard documentation by hand and using CAD, 3D modeling skills (design intent, constraint based, and assembly design, creativity, and critical reasoning. Figure 1 lists Sorby's four pillars, Barbero and Garcia's graduate CAD learning outcomes, and the undergraduate engineering graphics learning outcomes identified for this research.



**Figure 1: Learning Outcomes Based on Sorby's and Barbero's Work**

A comprehensive review of the engineering graphics textbooks and associated course syllabi provided the structure for identifying the four more common pedagogical approaches to teaching, the standard approach, the remedial approach, the 3D modeling approach, and the theory informed approach.

Next each of the four pedagogical methods was evaluated for aspects of active and engaged learning. Deep, meaningful and lasting learning is achieved through an active, engaged process (Barkley, 2010). For students to truly understand an idea, they must be able to complete a variety of applications involving the particular concept to be learned, and they should examine, question and relate the new information to their existing knowledge. The foundation of active, engaged learning, as defined by Karl Smith is “a situated, social activity requiring ambiguity and unlearning,” (2006, p. 16), Chickering and Gameson (1987, p. 4) offered “students talking about what they are learning, writing about it, relating it to past experiences, and applying to their daily lives,” Felder and Brent provided: “anything course-related that all students in a class session are called upon to do other than simply watching, listening, and taking notes” (2009, p.

2), and Prince provided: “any instructional method that engages students in the learning process...requires students to do meaningful learning activities and think about what they are doing” (2004, p. 223). The pedagogical methods utilizing active, engaged learning are more likely to foster deeper, meaningful, and lasting learning.

Finally, each pedagogical method of engineering graphics was judged for its explanatory power. Explanatory power is attributed to a theory and how effectively that theory explains the subject matter to which it pertains (Rapoport, 1972; Timmer, 2006; Verleysen, 2002). Further, theories which possess explanatory power “serve as intellectual frameworks that link and make sense of what would otherwise be a dissociated collection of facts” (Timmer, 2006, p. 1). Explanatory power additionally, “is the degree to which, in the light of theory, unexpected events become expected ones” (Rapoport, 1972, p. 324). The methods which meet the learning objectives; contain active, engaged learning; achieve conceptual, procedural, and strategic knowledge are more likely to have explanatory power.

### **Chapter Three:** *Development and Validation of an Engineering Graphics Concept Inventory*

The literature indicates that the problem of student conceptual misunderstanding is deeper than misinterpretation and confusion; rather, students acquire *and retain* fundamental misconceptions (Olkun, 2003). While there are several well-known tests for spatial visualization: the Purdue Spatial Visualization Test of Rotation, the Mental Cutting Test, the Mental Rotations Test, and the Flat Pattern Test, all of these assessments only provide information about an individual’s understanding. None of them provide any guidance or feedback about an individual’s misperceptions when an incorrect answer is selected, a concept inventory provides summary of students’ understanding and more importantly about their misunderstandings. In addition to dealing with academic time constraints, educators may lack the pedagogical content knowledge – the blending of content and pedagogy into an understanding of how specific topics, problems, and issues are arranged, presented, and organized for the diverse abilities and interests of their learners (Shulman, 2005). To ensure the effective, proper structure of the course material, faculty must have an initial summary of their students’ skills and knowledge. A standardized concept inventory would allow for the precise identification of the key areas of student misconceptions, the depth of the identified misconceptions, and aid faculty members in addressing and correcting them (Streveler, Olds,

Miller, & Nelson, 2003). Another outcome would be the assignment into the appropriate skill level course – remedial versus the standard engineering graphics. The purpose of this research is to develop a validated and reliable concept inventory for graphical communication.

The mixed methods methodology for this project included a Delphi study, think-aloud protocol interviews, and quantitative analysis of student scores. The first stage of the research for the development of the concept inventory was the identification of the expert panel; six experts were identified and asked to participate in the study fitting with both Atkins, Tolson, and Cole (2005) and Clayton's (1997) findings that panel size is a function of the diversity of the participants. The panel of experts was asked to identify all concepts that were considered fundamental to engineering graphics, and then the experts were asked to rank the difficulty of the concepts.

Next a panel of 20 students who had completed the introductory engineering graphics course was asked to participate in "think-aloud" protocols as each participant completed four of concept inventory items. Participant feedback was used to modify item wording and to generate distractors for each of the items.

During 2010 and 2011 the concept inventory was then implemented for two pilot studies at Embry-Riddle Aeronautical University. The results from each of these field studies was used to refine and reword test items as needed.

In September of 2011 the concept inventory was implemented at three institutions: Embry-Riddle Aeronautical University, Virginia Tech, and North Carolina State University. The results indicated that the instrument is reliable independent of institution. The reported reliability, Cronbach's  $\alpha$  for the multiple institution implementations ranged between .71 and .73. The concept inventory is ready to be implemented as a pre- and post-test assessment to measure student learning gains and possible course effectiveness across different instructors.

#### **Chapter Four:** *The Predictive Ability of the PSVT:R and the MCT For Students 3D Modeling Skills*

Over the last 25 years there has been a steady integration of 3D modeling software into the engineering design graphics curriculum (Anand, Aziz, & Agrawal, 1987; Devon, Engle, Foster, Sathianathan, & Turner, 1994; Miller, 1992; Sexton, 1992; Sorby, 1999; Wiley, 1990). Originally thought to be a complementary instructional aid for developing students' spatial

abilities, 3D software has displaced much of the formal lecture on engineering graphics theory. However, merely providing 3D software without scaffolding or the appropriate contextualization does not significantly improve students' visualization skills or abilities (Barbero & Garcia, 2011). Two of the standard pencil-and-paper tests used to benchmark student spatial visualization are the PSVT:R – Purdue Spatial Visualization Test: Rotations, developed by Guay (1977) and the MCT –the CEEB Special Aptitude Test in Spatial Relations, developed by the College Entrance Examination Board (1939). The results from both of these tests, independently, have been used to predict the success of students' visualization strategies for solving problems on paper-based problems. The purpose of this research is to investigate the transferability of the PSVT:R and the MCT to predict the success of students' visualization strategies for solving 3D solid modeling problems. As engineering graphics educators strive to keep course delivery current with industry standards, teachers will need reliable methods for identifying the skills for both hand sketching and 3D modeling of their students. It is no longer enough to establish a baseline for just students' hand sketching visualization skills; a baseline for their 3D modeling abilities is also needed.

During the first week of classes in the fall semester of 2011, 220 students enrolled in the introductory engineering graphics course at Embry-Riddle Aeronautical University completed a pre-test of the PSVT:R and the MCT. Additional data collected from all participants were three common 3D modeling projects. The specification trees for each of the common modeling projects were evaluated by three experienced evaluators using a standardized solid model rubric. Correlation factors between student performance on the PSVT:R, performance on the MCT, and the three project grades were determined. The results indicated there is correlation between a student's performance on the MCT and 3D modeling ability. There was a significant relationship between the MCT and modeling aptitude for the three assignments are:  $r = .32$  ( $p < 0.05$ ),  $.36$  ( $p < 0.01$ ), and  $.47$  ( $p < 0.01$ ). It appears that the both the PSVT:R and the MCT are needed as a comprehensive pre-test of incoming student skills and abilities. The PSVT:R is rather effective at measuring the traditional spatial visualization skills in graphical communication while the MCT is quite capable of assessing 3D modeling skills.

## **Chapter Five: Dissertation Conclusion**

This chapter summarizes and interweaves the findings from the literature review, the mixed methods data collection which guided the creation and validation of the Engineering Graphics Concept Inventory, and the correlational study between student performance on both the PSVT:R and the MCT and their 3D parametric solid modeling ability. These findings provide guidance to faculty to better assess their students' initial skill level, evaluate student misperceptions about engineering graphics, appraise initial 3D modeling skill, and to measure course learning gains. The findings also offer pedagogical guidance for engineering educators and administrators for the development or restructuring of engineering graphics courses. Recommendations for future work to expand the base of this research are provided.

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A Comparison of Current Teaching Pedagogies for Engineering Graphics with  
Standardized Evaluation Criteria

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*This article would be submitted to the Engineering Design Graphics Journal and would summarize the graphics communication and spatial visualization research as completed since Miller's 1996 and Mohler's 2008 published review.*

“We can conclude that during the last decades we appreciate some changes in the contents of the engineering graphics discipline, but barring some exceptions, spatial abilities are still considered as a secondary goal that simply is achieved through the learning of other concepts” (Contero, Company, Saorin, & Naya, 2006, p. 1).

## Abstract

The first historical review of spatial visualization research was conducted by Craig Miller in 1996, which provided a complete summary of all the theoretical and applied spatial visualization publications from the *Engineering Design Graphics Journal*. Twelve years later James Mohler completed an expanded review. This article parsed spatial visualization research into four phases: 1880-1940 the spatial factor independent from general intelligence, 1940-1960 multiple spatial factors through psychometric studies, 1960-1980 the emergence of developmental research guided by the cognitive domain, and after 1980 the effect of technology and emergence of information processing research. While both reviews provide an excellent summary of spatial visualization publications neither present the research as framed by an educational perspective. To provide a new direction on both Miller's and Mohler's works, this article presents the literature as viewed through the lens of the four most common approaches to spatial visualization education – the standard approach, the remedial approach, computer-aided design, and the theory-informed approach. Strengths and weaknesses for each of these methods are presented as framed by four principle criteria – learning outcomes, active and engaged learning, stage of knowledge, and explanatory power. The spatial visualization matrix—a tool to aid graphics educators integrating active learning into their courses—is also presented.

## Introduction

This article furthers current knowledge on spatial visualization in engineering education research by performing a comparative analysis, i.e., a detailed and systematic comparison of the most common instruction methods to identify pedagogical strengths and weaknesses. Each method is assessed by four principle criteria: learning outcomes, active and engaged learning, state of knowledge, and explanatory power. It is intended for this literature review to contribute an overview of spatial visualization pedagogy for the broader engineering education community.

This analysis presents several unique lines of investigation in the field of spatial visualization research. First, it is a synthesis of germane literature on spatial visualization, encompassing both a broader literature review of pedagogical methods and a systematic comparison of those methods. Second, it is the third such comprehensive review to be written on spatial visualization research, but the first to include a comparative analysis on the different methods. Miller's (1996) review solely focused on the research published in the *Engineering Design Graphics Journal*. Mohler's (2008) review complements Miller's work by encompassing a broader field of publications on spatial visualization research and when combined with Miller's provides a more rounded summary of the field. This analysis will provide recommendations clearly supported by the findings of the comparative analysis; it will clearly identify both the importance of the inclusion of spatial visualization in undergraduate education and the importance of the pedagogical method selected.

Thirty years of research has clearly indicated that spatial visualization is a challenging and complex skill to obtain and that students arrive at college with unequal levels of spatial visualization ability (Jenkins & Burtner, 2007). Numerous researchers have found that weak spatial visualization skills can be strengthened through the proper application of curriculum content, and that interactive, dynamic, computer-based training modules can be more effective than the traditional paper-based, lecture-centered paradigm.

Connolly (2009), Contero, et al. (2006), Onyancha, et al. (2008), Holliday-Darr, et al. (2000), and Uria and Mujika (2008) have all explored the initial visualization skills of first-year engineering students as a predictor for success in engineering. Miller concluded that a "successful engineer must have strong spatial abilities in order to specifically visualize design solutions" (1996, p. 12). Nagy-Kondor (2007) found the pre-test spatial visualization scores of

first level mechanical engineers were indicative of lower than expected levels and needed to be addressed through the completion of their introductory course. Uria and Mujika (2008) and Holliday-Darr et al. (2000) both reported several additional positive outcomes – fewer drop-outs of students successfully completing the spatial visualization course and links between visualization skills, student confidence levels, and retention in undergraduate programs. In terms of student engagement, Cotrell (2005) considered the influence of the integration of design into the graphical communication course for engineering technology students and found that participants reported a greater satisfaction with the course.

In spite of these reported findings spatial visualization instruction has been steadily marginalized if not outright eliminated from many programs' undergraduate engineering curriculum. This article seeks to present and compare the methods of spatial visualization pedagogy to provide some clarity on the complex issue and propose a possible direction forward.

This article begins with a literature review of spatial visualization research that clarifies the current challenges associated with the integration of spatial visualization in the undergraduate curriculum and then briefly describes the four common educational approaches (standard, remedial, computer-aided design, and theory-informed). Next, the Methods section presents the comparative analysis method in detail, including definitions of the criteria (learning outcomes, active, engaged learning, stages of knowledge, explanatory power) and process used to evaluate the four educational approaches. The Results section then describes the use of the evaluative criteria and presents the spatial visualization pedagogy matrix that shows rankings of each educational approach. The article concludes with the implications for future research on teaching spatial visualization.

## **Literature Review**

### **Spatial Visualization Can Be Developed**

The research has indicated that – regardless of nationality and academic year (high school, undergraduate, and graduate) – spatial visualization skills can be improved through thoughtful, pedagogically structured lectures and training modules. A common misconception is that spatial visualization cannot be taught or improved; numerous research studies have indicated the contrary. Bertoline, Bowers, McGrath, Pleck, and Sadowski (1990) demonstrated that high

visualization ability was achieved when nurtured and developed through carefully planned stages incorporating both planned and unplanned experiences. For example, Akash and Alias (2006) and Rafi, Samsudin, and Said (2008) investigated improvement of spatial visualization skills of Malaysian engineering students. Akash and Alias (2006) were able to bridge the gap between novice and expert within a semester, and Rafi, et al. (2008) demonstrated that interactive, online, spatial visualization modules were more effective than the traditional lecture method. Nagy-Kondor (2010) demonstrated that the spatial abilities of Hungarian first level engineering students could be strengthened through a structured learning process. Fleisig, et al. (2004) measured the spatial visualization abilities of Canadian engineering students, and found that a combination of technical sketching, 3D modeling, and design dramatically improved performance. Lane and Seery (2010) and Lane, Seery, and Gordon (2009) studied the effect of freehand artistic sketching on the visualization abilities of Irish technical high school students and found a positive association. Barbero and Garcia (2011) defined, identified, and implemented the fundamental principles needed to undergird the teaching of 3D modeling skills for the development of the visualization skills of Spanish Master's engineering students.

### **Spatial Visualization is a Key Skill for Success in STEM**

Independent of educational level or national background spatial visualization is a central skill required for success in STEM (science, technology, engineering, and math) courses. Strong spatial visualization skills are not just correlated to increased success in engineering courses but to a wide field of topics ranging from math to science to medicine (Lubinski, 2010). Deno (1995) found that students who completed hands-on courses in high-school (wood shop or automotive repair) had a higher skill level than those who did not. Smith (2009) revealed that students who had high spatial visualization abilities performed better in a fundamental electronics course than those who had weaker spatial visualization skills. Strong and Smith (2002) reported on selected research findings on spatial visualization skills from 1967 to 2000, finding correlations between spatial visualization ability and higher math capability, increased facility with computers, and greater completion rate in engineering. Trafton, Trickett, and Mintz (2005) explored how scientists use mental imagery, or internal mental representations to aid them in identifying the correct solutions. Tseng (2009) examined for a correlation between spatial visualization and complexity in mechanism design, finding a negative correlation that

indicated that the stronger the spatial visualization skill the simpler the design. The effect of spatial visualization skills is not limited to engineering graphics or engineering design courses, but rather has a direct correlation on student success in STEM subjects as well. Wai, Lubinski, and Benbow (2009) found a correlation between higher spatial visualization skills and advanced education credentials and occupations in STEM.

### **Weaker Spatial Visualization Skills of Underrepresented Students**

Underrepresented students are at a much higher risk of having weaker developed spatial visualization skills as compared to the general population of engineering undergraduates. Sorby and Baartmans (1996) established a statistical difference in the spatial visualization abilities between male and female freshmen engineering students, but also showed that disparity could be addressed through the completion of a remedial spatial visualization course. Study (2005) explored the impact of participation in a corrective visualization course on black students' spatial visualization skills and found that post-test scores improved to the control group's pre-test scores. Veurink, et al. (2009) measured the spatial visualization ability in female and minority engineering students as compared to white male students across eight different institutions located across the continental United States. All eight institutions reported improvement in the individual post-test averages of the three visualization tests (the Purdue Spatial Visualization Test: Rotations, the Mental Cutting Test and the Lappan Test) equaling those of the pre-test averages of the control group, indicating the experimental group had increased their spatial skills to equal those of the control group. Yue (2002) studied the spatial visualization ability as a function of educational level – a majority of which were minority students, high school students, and high school teachers. The results indicated spatial skill level steadily improved as the educational level increased. Spatial visualization research has studied a diverse range of participants and the research indicates spatial visualization skills can be improved regardless of ethnic or educational background.

Not all research has yielded clear cut and evident results as to the relationship between spatial visualization ability and improved performance within an engineering course. In addition, there may be a difference in spatial visualization ability between engineering and non-engineering students. For example, Connolly and Holliday-Darr (2006) conducted a two university study between engineering and non-engineering students and between computer-based

instruction and paper-based instruction. Their results were inconclusive, but indicated that the non-engineering students actually performed better than the engineering students on the multi-view drawing post-test. Ferguson, Ball, McDaniel, and Anderson (2008) examined and compared spatial visualization ability levels in STEM and non-STEM students across several treatment levels. Nothing definitive emerged from the analysis: the STEM and non-STEM students performed too similarly to yield any clarification. While not all research has been able to identify an obvious cause and effect much of it has clearly indicated a direct correlation to spatial visualization skills and improved performance and motivation in engineering courses.

### **CAD and Spatial Visualization**

Research has demonstrated that CAD offers a contextualized application to develop spatial visualization skills. Barr and Juricic (1994) predicted that CAD would need to be purposefully integrated into the engineering graphics curriculum if it is to be effective. Hamlin, Boersma, and Sorby (2006) found there was a correlation between spatial visualization and CAD modeling abilities and that sketching needed to be taught before the introduction of 3D modeling in the curriculum. Interestingly, Barbero and Garcia (2011) explored a possible relationship between spatial visualization and CAD modeling abilities, and found that the pedagogical frame for teaching CAD had a greater effect on the quality of modeling approaches than visualization skills. Much of the research published on the relationship between 3D modeling and spatial visualization has found a strong correlation between the purposeful and deliberate integration of 3D modeling techniques into the curriculum as having a significant influence on spatial visualization skills (Anand, Aziz, & Agrawal, 1987; Hamlin et al., 2006; Hart, 2003; Jenkins & Burtner, 2007; Jerz, 2002; Kinsey, Towle, & Onyanca, 2008; Onyanca et al., 2008; Rafi, Samsudin, & Ismail, 2006; Scales & Kirby, 2001; Sexton, 1992; Sorby, 1999b; Study, 2005; Uria & Mujika, 2008; Watkins, 2005; Yip-Hoi, 2010). It appears that 3D modeling scaffolds spatial visualization skills similar to hand sketching and that students need to be taught the theory of hand sketching in parallel with 3D modeling skills.

### **Reduced Engineering Graphics Curriculum**

In spite of the positive correlation that researchers have found between spatial ability and success in pursuing and completing an engineering degree (Bodner & Guay, 1997; Sorby, 2001;

Study, 2005), many undergraduate engineering programs have considerably reduced the amount of spatial visualization instruction in the curriculum. This has been in response to two factors: the pressure to cap credit hours while maintaining the number of engineering science courses taught in the program, and the mistaken assumption engineering students already have this critical skill or can easily acquire the skill indirectly in other courses. Quite often graphical communication courses have been completely removed from the curriculum and, in replacement, integrated into a few lectures on graphics and modeling into an introductory first-year design class. The mistake in this revised structure is the assumption that first-year engineering students are entering college with strong enough spatial visualization skills to adequately meet the integral visualization component required for engineering design, when in fact many are not (Ardebili, 2006; Sorby, 2001; Will & Johnson, 2004). Faculty must now scramble within the limited time allowed to teach the complex and challenging skill of spatial visualization and students must further scramble to assimilate and understand the very information that comprises the foundation of their engineering design visualization knowledge. Given the greater time constraint to teach this critical skill, it is essential that faculty utilize the most effective pedagogical approaches.

### **Challenges in Spatial Visualization Instruction**

An additional challenge to the instruction of spatial visualization is that the pedagogical method most commonly employed is the traditional, lecture-based, instructor centered paradigm. Spatial visualization is not a skill that can be learned or improved through passively observing a lecture or relentlessly taking notes to be reviewed later. For students to truly learn the theory and to improve their skill they must be actively engaged with the material (Barkley, 2010; Felder & Brent, 2003; Felder, Woods, Stice, & Rugarcia, 2000; Prince, 2004; Rugarcia, Felder, Woods, & Stice, 2000; K. A. Smith, Shepard, Johnson, & Johnson, 2005). Hake (1998) reports that for high school, college, and university students the best student gains in a lecture-based course are at the lower end of the student gains in an interactive-based course.

The field is rich in active learning on engineering education and its positive impact on student learning. The literature can be overwhelming to filter through and parse into more salient information. This paper addresses this issue by surveying the more common approaches to visualization pedagogy and providing a concise analysis of each in terms of learning

outcomes, active and engaged learning, stages of knowledge, and explanatory power, so that engineering graphics educators may better integrate active learning methods into their courses.

### **Common Instructional Methods Associated with Spatial Visualization**

The approaches affiliated with the pedagogy of visualization presented in this literature review are the standard approach, the remedial approach, the computer-aided modeling approach, and the theory-informed approach. The standard method is a teacher-centered lecture that is based on a textbook that has been framed on an improper assumption that students possess a deeper previous knowledge. Students have little opportunity to apply and understand the material presented, nor do they have enough time to construct their mental model of the material. The remedial approach utilizes a better balance of teacher led lecture and student engagement with the material but only presents the basics of visualization techniques. To aid students in the structured development of their skills they are provided with an interactive CD, sketching plates, and snap blocks. Each major topic is prefaced by an animated and interactive module on the CD followed by a brief lecture by the instructor. The computer-aided modeling approach can utilize either a teacher centered lecture or a more student engaged lecture but often is lacking in alignment to the theory of hand sketching so critical for success. The final method presented is the theory-informed approach, which has the potential to be the most effective and impactful pedagogically. The theory-informed approach utilizes a combination of active learning and instructor guidance while maintaining a focus on theory. Following a brief overview lecture, students solve a drafting plate in parallel with the instructor. As the drafting plate is solved students are asked to explain the theory behind each identified surface, with guidance proffered by the instructor as needed. This approach provides students with the time and interaction needed to develop their mental frame of spatial visualization theory.

### **Methods**

Four criteria are used to evaluate the effectiveness of these pedagogical methods, including learning outcomes, active and engaged learning, stage of knowledge, and explanatory power. These criteria were applied to the methods following a thorough review of the published

research and descriptions of engineering graphics courses. These criteria are defined in the following sections.

### **Learning Outcomes**

Learning outcomes as defined by ABET “are the narrowly defined descriptions of what students are expected to know and to be able to do – the skills, knowledge, and behaviors to be acquired” (2009, p. 2). The learning outcomes identified to evaluate the pedagogy are derived from Sorby’s et al. (2000) previous work. The first section in Figure 1 identifies the four pillars they developed. Recognizing these four pillars did not address any specific learning outcomes for Computer Aided Design within the context of engineering graphics, Barbero and Garcia (2011) expanded the four pillars into nine learning outcomes to address the identified shortcoming. The second section in Figure 1 presents the expanded learning outcomes for a graduate computer-aided design course. It is important to note that Barbero and Garcia developed these nine outcomes to address pedagogical shortcomings for a Master’s level course in solid modeling and as such several of these outcomes are not appropriate for a first-year undergraduate course in engineering graphics. To better fit within the purview of this research the list of learning outcomes has been modified. The third section in Figure 1 lists the more course appropriate learning outcomes for an introductory course. These five learning outcomes will be used to evaluate the four pedagogical methods for teaching engineering graphics. Of the five learning outcomes identified, the last two, creativity and critical reasoning, are the more difficult to achieve and measure. Many first-year students are still well ensconced in Baxter Magolda’s (1992) absolute learning stage in which students perceive learning to be about reciting facts and expect instructors to be absolute authorities.

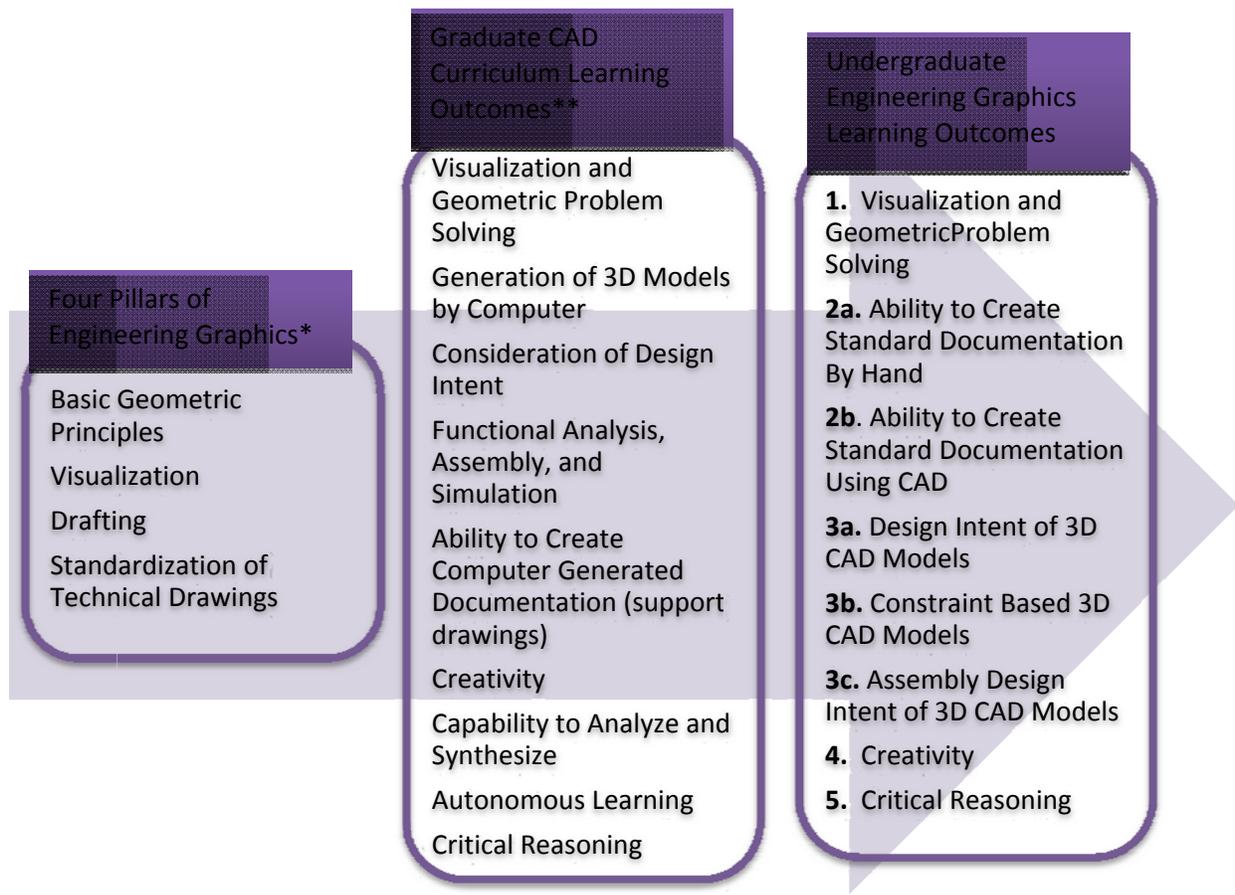


Figure 1: Learning Outcomes Based on Sorby’s and Barbero’s Previous Work \*(Sorby et al., 2000), \*\*(Barbero & Garcia, 2011)

### Active, Engaged Learning

The second criterion for evaluating the method of teaching spatial visualization is active learning. As active, engaged learning has been defined differently by many people it lacks a unified, universally accepted meaning; following are the definitions from well-known engineering education literature. Karl Smith (2006, p. 16) identified the foundations of engaged learning as “a situated, social activity requiring ambiguity and unlearning.” Chickering and Gameson (1987, p. 4) characterize active learning as “students talking about what they are learning, writing about it, relating it to past experiences, and applying to their daily lives.” Felder and Brent offered this definition of active learning: “anything course-related that all students in a class session are called upon to do other than simply watching, listening, and taking notes” (2009, p. 2). Prince provided the following definition: “any instructional method that engages students in the learning process...requires students to do meaningful learning activities and think about what they are doing” (2004, p. 223). Barkley (2010, p. 6) provides a similarly worded definition that draws from Bonwell and Eison (1991): “doing what we think and thinking

about what we are doing.” All of the above definitions have the recurring theme of “thinking about what they are doing,” and this is the definition of active learning for this research.

For students to truly understand an idea, they must be able to complete a variety of applications involving the particular concept to be learned, and they should examine, question and relate the new information to their existing knowledge. Deep, meaningful and lasting learning is achieved through this active, engaged process (Barkley, 2010). Bonwell and Eison (1991) found in their review of active learning research that it leads to better student attitudes and improved student thinking and writing. McKeachie (1972) found that students had improved retention which in turn increased their motivation and thinking skills. Several pedagogical approaches foster this type of student learning and include, problem-based learning and collaborative learning (Barkley, 2010; Chickering & Gameson, 1987; Felder & Brent, 2003, 2009; Felder et al., 2000; Prince, 2004; K. A. Smith et al., 2005), which require students to be actively learning as they are engaged in specific tasks of the discipline.

### **Stage of Knowledge**

The third benchmark is the stage of learning achieved by the teaching methodology. The stages of learning to be considered are conceptual knowledge, procedural knowledge, and strategic knowledge (Barbero & Garcia, 2011; Schwartz, 2008).

Conceptual knowledge is defined by knowledge or understanding of concepts, e.g., types of surfaces or methods for the creation of auxiliary views. This is most similar to the knowledge level in Bloom’s Taxonomy (Bloom, Englehart, Furst, Hill, & Krathwohl, 1956) or the remembering level in the revised Bloom’s Taxonomy (Anderson & Krathwohl, 2001). At this level learners are capable of recalling facts, methods, processes, or patterns. The dualism category as defined in the Perry (1979) scheme of intellectual and ethical development would be comparable to conceptual knowledge. Learners believe that truth is absolute and view the world in a dualistic fashion, i.e. Black-White, Good-Bad, and all uncertainty is merely temporary. Baxter Magolda’s (1992) stage of absolute knowing is quite similar to Perry’s dualistic category, where learners believe that absolute answers exist in all areas of knowledge and to transitional knowing, learners are beginning to accept some uncertainty, and they need to understand not just acquire knowledge.

Procedural knowledge is the knowledge of the commands, rules, or algorithms needed to solve a problem (Barbero & Garcia, 2011), e.g., dimensioning guidelines, the capability to determine the tools needed to complete a particular step in CAD or the particular procedure needed to solve an oblique surface. The comprehension level as defined by Bloom, or the understanding level as renamed by Anderson and Krathwohl, where information is used for translation or extrapolation (Bloom et al., 1956) is complementary to how procedural knowledge is being defined for this research. The multiplicity category in Perry's scheme, where all have a right to their own opinion, and those opinions have equal importance including those of an authority (Perry, 1979), is parallel to this stage. Baxter Magolda's framework includes a similar category: independent learning. Independent knowers have an opinion, are beginning to think through the concepts, regard their peers as having useful contributions, and expect teachers to provide the context for exploration (Baxter Magolda, 1992).

Strategic knowledge is the ability to identify alternate methods by which the task or problem may be completed (Schwartz, 2008), e.g., the ability to recognize that multiple, procedural processes can be utilized to create a solid model or solve an incomplete view. The application or applying level in Bloom's taxonomy, in which learners are able to use the information in new ways and contexts (Anderson & Krathwohl, 2001; Bloom et al., 1956), best aligns with strategic knowledge. The relativism category in Perry's scheme is comparable to this, where the learner recognizes that knowledge is contextual and relative (Perry, 1979). The highest level of knowledge described by Baxter Magolda is contextual knowledge. Here learners understand knowledge is to be constructed, opinions are to be supported by evidence, and teachers are partners in the development of knowledge (Baxter Magolda, 1992).

Table 1 summarizes the relationship between the stages of knowledge and correlation with Bloom's Taxonomy of Educational Objectives, Perry's Scheme of Intellectual and ethical development, and Baxter Magolda's Stages of Intellectual Development. Each category is identified.

**Table 1: Comparison of Stages of Knowledge**

<b>Stages of Knowledge</b>	<b>Bloom’s Taxonomy</b>	<b>Perry’s Scheme</b>	<b>Baxter Magolda Stages of Intellectual Development</b>
<b>Conceptual</b>	Knowledge/Remembering	Dualism	Absolute
<b>Procedural</b>	Comprehension/Understanding	Multiplicity	Independent
<b>Strategic</b>	Application/Understanding	Relativism	Contextual

**Explanatory Power**

The final measure applied to the pedagogical methods of engineering graphics is explanatory power. Traditionally explanatory power is attributed to a theory and how well the theory explains the subject matter to which it pertains (Rapoport, 1972; Timmer, 2006; Verleysen, 2002). Timmer further states that theories which possess explanatory power, “serve as intellectual frameworks that link and make sense of what would otherwise be a dissociated collection of facts” (2006, p. 1). Rapoport offers that explanatory power, “is the degree to which, in the light of theory, unexpected events become expected ones” (1972, p. 324). In this particular context it is how well the method explains the varied subject matter of spatial visualization.

**Results—Comparative Analysis of Four Learning Approaches**

**Evaluation Process**

Table 2 presents a summary of how effectively the four different approaches meet the evaluation criteria. These rankings were assigned following a detailed and exhaustive review of course syllabi, course descriptions, associated course textbooks, and published research. The final column provides the overall effectiveness of each method, the methods range in effectiveness from low (✓-) to high (✓+).

Table 2: Pedagogical Approach Evaluation Matrix

Pedagogical Approach	Learning Outcomes	Active, Engaged Learning	Stage(s) of Knowledge	Explanatory Power	Overall
Standard	Low	Inadequate	Procedural	Low	✓-
Remedial	Moderate	Excellent	Conceptual	Moderate	✓
CAD	High	Very Good	Conceptual, Procedural, and Strategic	High	✓+
Theory-Informed	High	Very Good	Conceptual, Procedural, and Strategic	High	✓+

### Standard Approach

Table 3 presents an individual evaluation matrix for the standard approach to teaching spatial visualization. All too often the limited time within the curriculum and the primary instructional approach add to students’ misperceptions and misunderstandings about spatial visualization. The standard teaching approach often entails a “drive-by” experience to the engineering graphics curriculum; this is especially true when engineering graphics is no longer a stand-alone course and is merely a module embedded within another course. In this type of approach the learning outcomes are not often met well if at all. The structure for this approach is a teacher-centered lecture of the day’s topic that relies heavily on a textbook which more than likely has been written with the mistaken assumption that students have obtained the basic visualization skills and therefore do not need a detailed, structured explanation. Students are expected to passively take notes or to simply watch the derivation of the partial solution. At best students will only reach the stage of procedural knowledge, able only to follow specific instructions and unable to extrapolate beyond the lesson. Coupled with the lower stage of knowledge is low explanatory power, as many of the students are lacking the basic knowledge and therefore not able to easily utilize the knowledge presented, and therefore do not really understand spatial visualization significantly better.

Table 3: Standard Approach Summary

Pedagogical Approach	Learning Outcomes*	Active, Engaged Learning	Stage of Knowledge	Explanatory Power	
Standard	Outcome	Inadequate	Procedural Only	Low	
	1				Maybe
	2a				Maybe
	2b				No
	3a				No
	3b				No
	3c				No
	4				No
5	No				

\*1. Visualization and Geometric Problem Solving; 2a. Ability to Create Standard Documentation By Hand; 2b. Ability to Create Standard Documentation Using CAD; 3a. Design Intent of 3D CAD Models; 3b. Constraint Based 3D CAD Models; 3c. Assembly Design Intent of 3D CAD Models; 4. Creativity; 5. Critical Reasoning

### Low learning outcomes.

A fundamental weakness in the standard approach to teaching spatial visualization is the textbooks. The very structure and organization of most engineering graphics textbooks sustains this overestimation of incoming students' visualization skills, further compounding the problem. Additionally, engineering graphics textbooks continue to present classical content that is no longer taught due to the limited space available in the curriculum and the expanding integration of computer aided design. Often textbooks do not provide detailed, thorough explanations for the solutions of orthogonal or isometric views, static concepts, theories, and offer no interpretation of spatial data. These books have been written with the assumption that students already have a solid understanding of spatial visualization and therefore do not require much guidance or detailed presentation of the foundational concepts of spatial visualization for the solutions provided. It is mistakenly assumed that students will be able to overcome the mental challenge of solving the incomplete isometric and orthographic drafting plates, and assemble the spatial puzzle to arrive at the correct solution (Birchman & Sadowski, 2005). Students are given final solutions without having been provided the required knowledge to bridge the gaps in their own knowledge and skills.

This method of lectures guided by inadequate textbooks contributes little to the development of visualization and geometric problem solving (learning outcome 1) for many of the students enrolled in this type of course. The few students who do benefit from this type of

course arrive already having the conceptual spatial visualization skills to decode the information provided by the lectures.

A complementary skill to the ability to decode 3D isometric views into 2D orthographic views is the creation of engineering documentation by hand (Jerz, 2002; Koretsky, 1998; Watkins, 2005; Wright, 1990) or using CAD software (learning outcomes 2a and 2b). Students lacking the appropriate fundamental spatial visualization skills are simply unable to produce these drawings in accordance with either ISO, International Standards Organization, or ANSI, American National Standards Institute, standards (Barr & Juricic, 1991, 1992; Jerz, 2002; Leach & Matthews, 1992). At the end of this type of standard instruction the average student's ability to generate documentation is not much improved. If the standard method does not develop most students' conceptual spatial knowledge which is required to disassemble, reassemble, and mentally rotate the requested solid model, the method cannot provide students with the skills needed to create the support documentation, as the two are inextricably linked.

Depending on the structure of the course, CAD may or may not be a formal topic in the course curriculum. If there are CAD lectures integrated into the standard lecture format of the standard teaching of graphical communication, students will have the same disadvantage. Several studies (Ardebili, 2006; Barbero & Garcia, 2011; Birchman & Sadowski, 2005; Devon, Engle, Foster, Sathianathan, & Turner, 1994; Koch, 2006; Sorby, 2007a) have reported the importance of including formal learning outcomes and engaged learning activities for 3D modeling.

However, the ability to understand CAD (learning outcome 3a) and develop the required strategic knowledge to produce the solid models and the appropriate documentation are firmly rooted in a student's ability to visualize the part from the provided views and associate those views to the completed solid model (Barbero & Garcia, 2011; Mohler, 2007; Sorby, 2007a). Several studies have shown that merely providing students with the material (drafting plates), with minimal, structured guidance and intermittent feedback does not significantly improve their performance. For instance, Contero, et al. (2006) found that merely "picking and clicking" through CAD applications did not significantly impact or improve visualization abilities; and Fleisig, et al.'s (2004) found that the lack of clearly defined learning outcomes contributed to students' frustration and lack of understanding.

Robust solid models have addressed the design intent, are constraint based, and are easily updateable (learning outcome 3b) (N. W. Hartman & Branoff, 2005; Wiebe, Branoff, & Hartman, 2003). To achieve this type of solid model a good deal of forethought must guide the construction of the model (Rynne & Gaughran, 2007). Design intent embeds intelligence in the solid through the proper integration of parametric and geometric constraints that define the fit and function of the part (Wiebe et al., 2003). Standard spatial visualization instruction does not usually improve the average students' ability to create robust solid model, as it does not develop most students' conceptual and procedural spatial knowledge which is required to disassemble, reassemble, and mentally rotate the requested solid model in order to "see" how to build it (N. Hartman, Connolly, Gilger, & Bertoline, 2006).

Of the five learning outcomes identified from Barbero and Garcia's work (2011) for evaluating the pedagogical approaches, creativity (learning outcome 4) and critical reasoning (learning outcome 5), are the more difficult to achieve. Many first-year students are still well situated in the absolute learning state defined in Baxter Magolda's (1992) work or the dualistic category established by Perry's (1979) work. In this stage students perceive learning to be about reciting facts and expect instructors to be absolute authorities. Unfortunately, the standard or typical method of teaching engineering graphics only serves to reinforce this lower level of learning, which is in direct contradiction with students achieving either creativity or critical reasoning.

This standard type of pedagogical approach has several undesired outcomes. The first one is the reduced importance that students place on engineering graphics in their mental map of the undergraduate engineering curriculum. Spatial visualization is a fundamental skill to *all* of engineering, but this is often not conveyed well by this method. Orth (1941), Rising (1948), and Svensen (1948) identified the importance of graphical communication by positing that it is the *language* of engineering. It is quite unrealistic to expect first-year freshmen to develop the level of knowledge needed to become fluent in this language when the topic is given only passing acknowledgement in current pedagogical structure. Contero, et al. (2006, p. 4) clearly describe the relationship between design, visualization and drawing, "design is done essentially in the mind and drawings are pictorial extensions of the mind."

The second unintentional outcome is poor learning. The lack of instruction, the lack of student engagement, and the lack of proper contextualization all contribute to minimal student

learning. It is clear that the standard approach to teaching this vital skill does not provide students with the skills needed nor does it achieve most of the learning outcomes.

### **Inadequate active, engaged learning.**

The standard lecture format is not conducive to active, engaged learning as it is not usually structured to be participatory or learner centered. For learning to be effective students must be involved in meaningful activities that foster their critical engagement with the material (Prince, 2004). Students are expected to take notes and to apply the gathered information later when solving the drafting plates assigned for homework. It has been demonstrated that this specific lecturing paradigm is ineffective and inefficient (Barkley, 2010; Birchman & Sadowski, 2005; Prince, 2004). Not surprisingly this particular pedagogical approach is also not conducive for student questions or much student learning (Uria & Mujika, 2008).

Guidance is available to the few students confident enough to ask, but many students instead will turn to their peers for an explanation or help. When provided in a well-framed context peer help is often touted as an excellent way for students to learn and to better understand the material (Fleisig et al., 2004). However of the few students who have strong spatial visualization skills few of them possess the needed expertise and pedagogical ability to quantify the method well to their peers. Stronger students are able to provide the completed solution but not the overarching theory. This only puts the weaker student at an even further disadvantage, for once the solution has been presented they no longer are required to visualize the missing information, and the opportunity to develop their skills has been lost (Craig & Craig, 2003, p. 1). Bransford, Brown, and Cocking (2000, p. 28) found a negative effect on student performance when non-expert tutors are used; an expert must have “both a deep and broad foundation of factual knowledge.” When pressed for an explanation from the student who does not understand, the stronger student will often offer the explanation “that is just the way it looks.” Left alone, without a well-structured explanation from their peers, minimal contextualized activities, or readily available help, students with weaker visualization skills can become anxious and frustrated, which can interfere with their spatial thinking and all but overcome their motivation (Mohler, 2007).

### **Stages of knowledge – procedural only.**

The standard method of teaching does not allocate much space in the curriculum to the teaching of rudimentary concepts as it is incorrectly assumed that students arrive knowing the conceptual knowledge of spatial visualization. Conceptual knowledge is an understanding of the types of surfaces and an understanding the relationship between isometric (3D) and orthographic (2D) views. Procedural knowledge is constructing an isometric view from the provided orthographic views. Strategic knowledge is creating the best procedure to solve the provided challenge. No matter how well organized the curriculum, teaching only the later (procedural and strategic) stages of knowledge in problem solving all but ensures failure of the deep and robust learning desired. Brown, Collins, and Duguid (1989) define learning as a function of knowing and doing within an appropriately contextualized social situation. Further, knowledge is a function of situations *and* activity. However, many institutions treat knowledge as if it is not connected to doing, that knowledge “is theoretically independent of the situation in which it is learned and used” (Brown et al., 1989, p. 32). At its lowest level, graphical communication is perceived as a tool of engineering; Brown, et al. (1989, p. 33) eloquently argue, “because tools and the way they are used reflect the particular accumulated insights of communities, it is not possible to use a tool appropriately without understanding the community or the culture in which it is used.” Appropriate and *understandable* contextualized applications are essential for building a deep well of knowledge. Similarly, Barkley argues “that to truly learn, we need to make an idea, a concept, or a solution our own by working it into our personal knowledge and experience” (2010, p. 16). Often in the standard method of teaching visualization, students are expected to develop a deep understanding of information that has been removed from its proper context (engineering applications). Many students have no prior knowledge of or experience with engineering applications, and are expected to extrapolate from this decontextualized theory to highly specific and contextualized applications. It is not surprising that many students do not find much success with this method.

### **Low explanatory power.**

At the end of this type of facilitated course, students exit with little to no improvement in their visualization skills, with little to no understanding of the theory behind the visualization approach (Uria & Mujika, 2008), and with the mistaken belief that visualization is an innate

entity (Jerz, 2002; Lane & Seery, 2010; Lane et al., 2009; Mohler & Miller, 2008) – one that cannot be taught or improved through instruction and practice. Students also are missing the critical connection between spatial visualization and engineering; they still hold the mistaken belief that they are discrete, isolated topics. Students have gained little explanatory power.

### Remedial Approach

Table 4 presents the individual evaluation matrix for the remedial approach to teaching spatial visualization. The remedial course meets learning outcomes visualization and geometric problem solving, ability to create standard documentation by hand, and begins fostering critical thinking. At the end of this course students are able to perform these tasks. The remedial course developed by Sorby (1996) incorporates excellent active learning. Her original course included a brief lecture, hands-on sketching, supplemental snap blocks, and an animated CD. The snap blocks and the animated CD are an interesting addition to the graphics curriculum, which traditionally relied heavily on lecture and drafting plates. This type of course offered a strong foundation in conceptual knowledge of engineering graphics students learn about the different types of surfaces and the relationship between 2D and 3D representations. The course begins to introduce procedural knowledge, decoding cutting planes, multiple axes of rotation, and combining solids. Finally, students gain moderate explanatory power as they only achieve three of the learning outcomes and just begin to learn the procedural knowledge.

Table 4: Remedial Approach Summary

Pedagogical Approach	Learning Outcomes*	Active, Engaged Learning	Stage of Knowledge	Explanatory Power	
Remedial	<b>Outcomes</b>	Excellent	Conceptual Basic Procedural	Moderate	
	1				Yes
	2a				Partially
	2b				No
	3a				No
	3b				No
	3c				No
	4				No
	5				Yes

\*1. Visualization and Geometric Problem Solving; 2a. Ability to Create Standard Documentation By Hand; 2b. Ability to Create Standard Documentation Using CAD; 3a. Design Intent of 3D CAD Models; 3b. Constraint Based 3D CAD Models; 3c. Assembly Design Intent of 3D CAD Models; 4. Creativity; 5. Critical Reasoning

### **Moderate Learning Outcomes.**

The curriculum of the remedial approach is guided by the overarching principle that spatial skills can be taught and improved through proper training. This method does an excellent job of providing students with the tools to help develop their basic visualization skills (learning outcome 1). Students are given snap blocks, an interactive CD, and a drafting workbook to help develop their skills. Students are first presented with an interactive lecture on the CD provided with multiple examples. These examples link the paper-based views back to a solid model created with the snap blocks, and a brief, overarching lecture can be provided to connect the pieces together. Following the brief lecture students are asked to complete the provided sketching examples. A limitation to this course is the absence of inclined, cylindrical, and oblique surfaces – only normal surfaces are presented in detail.

The primary focus of the remedial course is the development of spatial visualization skills and as such does not provide a specific lecture on creating engineering documentation (learning outcome 2a). This method does include one chapter on the development of orthographic views, and the cd provides an excellent animated tutorial on the relationship between isometric and orthographic views. The tutorial also clearly explains and demonstrates the rules associated with the creation of a multi-view orthographic drawing. However, engineering documentation is more than creation of orthographic views. At a minimum the concept of scaling, a title block, border, and dimensions are required; none of this information is covered in this approach. After completing this course students would be able to complete the basic four view, three orthographic and one isometric layout but would not be able to add the additional information required to complete the engineering documentation.

The remedial approach does not address any of the outcomes associated with the creation of CAD solid models as it does not include any formal or informal CAD instruction so none of the learning outcomes associated with CAD are met. Students who complete this course will not have had any proper introduction to creation of solid models, identifying design intent (learning outcome 3a), the implementation of constraints (learning outcome 3b), or the creation of multiple parts within an assembly (learning outcome 3c).

This approach fosters the development of basic spatial ability; students are given the opportunity to see and build an understanding between the 2D and 3D paper-based representations and the model constructed of snap blocks. The course does provide students

many occasions to develop creative solutions (learning outcome 4) to the posed challenges, as they can arrive at the solution using the snap blocks, reviewing the interactive video, sketching a coded plan or isometric view, or reading the workbook.

As Dr. Sorby's reported findings indicate (1999a, 2001, 2003, 2007a, 2009; S. A. Sorby & B. Baartmans, 1996; S. A. Sorby & B. J. Baartmans, 1996), the course does an excellent job of developing the spatial visualization skills of weaker students. These students can now begin to generate and critically evaluate (learning outcome 5) multiple solutions.

It is important to note this course is not a suitable replacement for the standard course, since it does not present all of the desired learning outcomes needed. It only covers the very basics of spatial visualization and does not teach any of the theory of surfaces behind visualization. Students are only presented with the building, rotating, and sketching of 2D profiles and normal (oriented horizontally or vertically only) surfaces. Students do not learn about the concept of scaling, inclined, oblique, or cylindrical surfaces, nor do they learn about auxiliary or section views, or about dimensioning. Finally, the course does not teach students about the connection between 2D spatial visualization and how it is inherently connected to the construction of 3D solid models.

#### **Excellent active, engaged learning.**

The snap blocks are an excellent addition to the curriculum. The snap blocks address the findings of Tracy (1987), Deno (1995), and Leopold, Sorby, & Gorska (1996) the correlation between certain childhood activities; Lego's, tinker toys, Lincoln Logs, and stronger spatial visualization skills. The snap blocks engage the learner on several levels, visually, haptically, and cognitively. As several researchers have concluded, people only remember 15% of what they hear, and 25% of what they see or watch, but they remember 60% of what they interact with (Endestad, Magnussen, & Helstrup, 2004; McBride & Doshier, 2002; Stenberg, 2006). For students who struggle with the transition from 2D orthographic views to 3D isometric views back to 2D orthographic views, snap blocks facilitate the transition. Students are able to see the constructed model of snap blocks and map it to the 2D images on the page – constructing knowledge and bridging the gap in their spatial visualization abilities. The snap blocks provide students with a concrete model to connect to the visualized conceptual model.

The interactive CD is also a great complement to the curriculum. Students are able to engage with the material at any time which is convenient for them. They can also review the material as many times as needed until they truly understand the concept being presented. The animations provided on the CD are organized and presented well. Multiple formats are presented in parallel: isometric solid, isometric grid, and the orthographic views. Activities range from multiple choice to constructing the solution on a 3D grid. When an incorrect solution is selected the correct one is not provided; instead, an explanation as to why that particular selection does not meet the criteria is given, and students are then prompted to try again. From a pedagogical standpoint this approach actively engages students and enables them to learn and grow from their mistakes. This type of effective low-stakes formative assessment is often missing from the traditionally taught visualization class.

### **Stages of knowledge – conceptual and beginning procedural.**

The structure of this course focuses on teaching students the building concepts of spatial visualization: revolution of 2D profiles about an axis, symmetry, 3D construction of normal surfaces, 2D decomposition of 3D views, cutting planes, and flat patterns. Students are not taught much of the procedural knowledge or the theory that governs these procedural algorithms for solving complex problems; instead they are given a very light, very cursory introduction. Students who complete this course have learned the prerequisite conceptual knowledge needed to continue on to the traditional course, but they will have little procedural knowledge and no strategic knowledge.

### **Moderate explanatory power.**

A gap in the curriculum is the single chapter presentation between the development of multi-view orthographic drawing and the isometric representation. This limited opportunity to explore and grow their understanding between the isometric and orthographic projections through hand sketching is not enough to develop a permanent framework of orthographic and isometric projections (Watkins, 2005). A major weakness of this course is the absence of learning about the inherent connection between the construction of 3D solid models and 2D spatial visualization skills. Research has found that students are not able to extrapolate and make the theoretical leap from 2D and 3D hand sketching to the development of solid models on their

own (Ardebili, 2006; Devon, Engel, Foster, & Sathianathan, 1994; Hamlin et al., 2006; Jerz, 2002; Sorby, 1999b; Yue, 2008). This remedial course by no means replaces graphics communication and design in the engineering curriculum; it prepares students to successfully transition into the graphics communication course.

The findings generated from Sorby's research have impacted the way engineering students are tested and the way they are taught spatial visualization (Sorby, 1999a, 1999b, 2001, 2003, 2007a, 2007b, 2009; S. A. Sorby & B. J. Baartmans, 1996; Sorby & Young, 1998). Sorby has consistently reported a significant improvement (from 56% to 80%) on post-test performance of the Purdue Spatial Visualization Test: Rotations (PSVT:R), improved overall GPA, and better four-year retention of the students who completed the remedial visualization course. Sorby has indicated through multiple research studies (1999a, 2001, 2003, 2007a; S. A. Sorby & B. J. Baartmans, 1996) that the visualization skill of the students who complete this course equals that of the average visualization skill of the general engineering population. This approach to teaching spatial visualization can be quite effective in remediating students with lower level visualization skills.

### **Computer-Aided Modeling Design (CAD) Approach**

Table 5 presents the individual evaluation matrix for the computer-aided modeling design approach to teaching spatial visualization. When properly and thoughtfully integrated into the curriculum the CAD approach is a very effective way to teach engineering graphics. It is important to note that the CAD approach does not completely eliminate or replace hand sketching activities. The CAD course meets all learning outcomes. This type of course also has very good active learning, as students are able to build the solid models in parallel with learning the sketching theory. Students are able to approach learning the theory through multiple venues – instructor lectures, hand sketching activities, and building solid models with interactive software. This type of course provides a solid base of conceptual knowledge – students learn about the types of surfaces and the transition from 2D to 3D. Students also have the opportunity to develop and implement procedural knowledge – developing the approaches for the creation of models, solving orthographic views from isometric views and vice-versa. Finally, the higher level students will have the opportunity to build and test strategic knowledge – building their own unique approach to constructing solid models or to solving incomplete orthographic views.

Students can gain high explanatory power. They are able to accomplish most if not all learning outcomes and can achieve all three stages of knowledge.

**Table 5: Computer-Aided Design Approach Summary**

Pedagogical Approach	Learning Outcomes*	Active, Engaged Learning	Stage of Knowledge	Explanatory Power	
<b>Computer-Aided Modeling</b>	<b>Outcome</b>				
	1	Yes			
	2a	Yes			
	2b	Yes			
	3a	Yes	Very Good	Conceptual, Procedural, and Strategic	High
	3b	Yes			
	3c	Yes			
	4	Yes			
5	Yes				

\***1.** Visualization and Geometric Problem Solving; **2a.** Ability to Create Standard Documentation By Hand; **2b.** Ability to Create Standard Documentation Using CAD; **3a.** Design Intent of 3D CAD Models; **3b.** Constraint Based 3D CAD Models; **3c.** Assembly Design Intent of 3D CAD Models; **4.** Creativity; **5.** Critical Reasoning

Computer-aided design, CAD, uses computer technology for the process of design, documentation, assembly, animation, analysis, and fabrication. Within the last 15 years, computer-aided modeling has been steadily integrated into the engineering graphics curriculum. However, Watkins (2005) reported that while most of the responding institutions in their research used CAD for part of their engineering graphics education, less than nine percent reported using it for the entirety of the course.

Although the vast majority of drawing and design work done today is performed by computer, the skills involving the use of pencil and paper sketching must not be removed from the curriculum. When sketching skills are appropriately aligned with CAD instruction, computer aided modeling provides an excellent context in which to develop those 2D skills (Pan, Kuo, & Strobel, 2010; Sorby, 2003; Will & Johnson, 2004).

There is no one unified approach to teaching CAD in engineering graphics. This diversity can be attributed to many factors: different program expectations about CAD, presence of a relationship with industry (The Boeing Company, Ford Motor Company, etc.) (Branoff, Hartman, & Wiebe, 2003; Meznarich, Shava, & Lightner, 2009; Ye, Peng, Chen, & Cai, 2004), inertia or impetus within the department to significantly revamp an existing course (Condoor, Boyer, & Jayaram, 2008), level of instructor knowledge with the CAD software (Clark & Scales,

2005), uncertainty about how to properly align CAD with the learning outcomes of hand sketching (Condoor et al., 2008), misconceptions about the importance of CAD and its position within the engineering graphics curriculum (Jenkins & Burtner, 2007), or lack of space within the existing engineering graphics course.

It is important to note that the CAD approach should not entirely replace the hand sketching theory and activities; instead, it should be thoughtfully integrated throughout the engineering graphics curriculum. Merely showing students how to “pick and click” through the software will contribute nothing towards desired learning gains. Deciding to eliminate the theory of 2D hand sketching from the curriculum – because software packages are capable of generating 2D artifacts – and replacing it solely with CAD instruction would be equivalent to no longer teaching the strength of materials because finite element software packages can now perform virtually any needed analysis. This type of logic leads to “garbage in – garbage out” solid models and the supporting documentation. Even though the computer will “cognitively process” and generate the solution, students clearly still need a solid and thorough understanding of the visualization process to generate robust, correct solid models (Pan et al., 2010). Students who do not possess the knowledge of how to create a drawing by hand will be unable to evaluate and diagnose the computer generated artifact as they will not possess the correct frame of reference for evaluation purposes. Students unfamiliar with the connection between 2D profiles and their associated 3D representation will not be able to create a concise, properly constrained, parametrically linked solid model.

In order to achieve this ideal complement of curricular blending, educators must become familiar with the computer based drawing, modeling, and design tools (Will & Johnson, 2004) and how these are best aligned within the theory of hand sketching. When properly structured by spatial visualization learning outcomes and presented with an appropriate context a CAD course can improve a student’s spatial visualization ability (Ardebili, 2006; Baxter & Mandigo, 2005; Condoor et al., 2008; N. W. Hartman & Branoff, 2005; Pan et al., 2010). In this type of course computer-aided design or modeling is a very effective tool for the development of spatial skills. Students will not learn the outcomes of graphical communication as a by-product of unstructured exposure to either 2D hand sketching or 3D solid modeling; the curriculum must be intentionally designed to address each of the outcomes (Akash & Alias, 2006; Mohler, 2007).

### High learning outcomes.

CAD offers students the opportunity to see the relationship between the 3D solid model and its associated orthographic views helping to develop their visualization and geometric problem solving (learning outcome 1). Many students struggle with the visualization leap between 2D and 3D and can often become frustrated when they are not able to quickly or correctly develop the solution when sketching. Seeing the solid model emerge from 2D sketches, figure 3, affords students another approach to seeing the connections between the 3D isometric (represented by the solid model), figure 2, and the 2D orthographic (represented by the construction sketches).

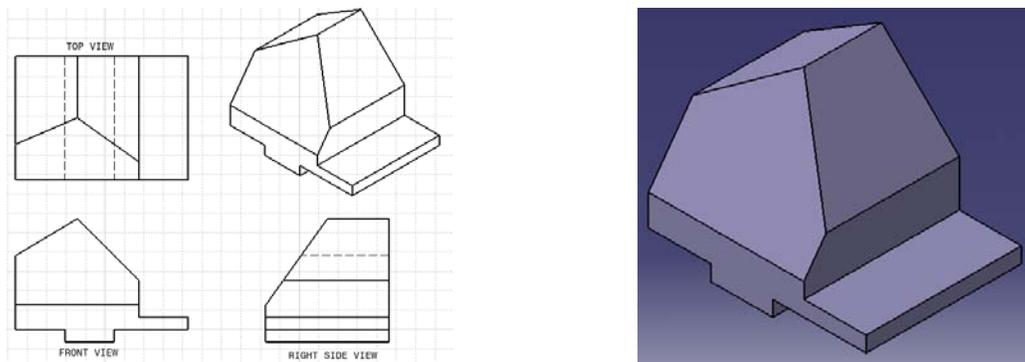


Figure 2: Standard Documentation and the Generated Solid Model

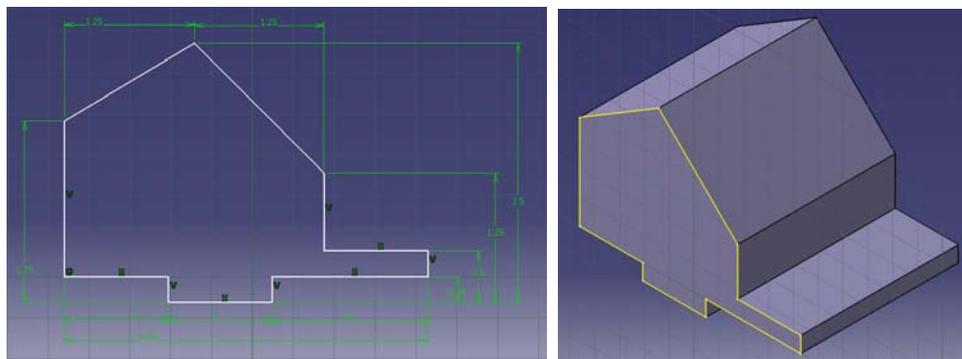


Figure 3: Sketch Profile and the Extruded Solid Model from the Sketch Profile

As students begin to build solid models they are developing their visualization skills and strengthening the connections between the 2D and the 3D representations – independent of the format in which they are created.

While CAD can improve spatial visualization skills to do so it must be coupled with the appropriate learning outcomes and structured so that students learn the theory of solid modeling in parallel with the theory of spatial visualization. The integration of CAD itself may not directly improve a student's ability to create an engineering drawing (learning outcomes 2a and 2b) as the creation of engineering drawings are governed by rules independent of CAD. If these guidelines are not incorporated into the curriculum CAD cannot provide them.

The overarching learning objective for CAD can be described as students who have mastered the solid modeling skill through the development of their own unique, artistic style (Condoor et al., 2008). The theory of solid modeling must be presented as students are learning to navigate through the software package. Design intent (learning outcome 3a), parametric and constraint based modeling (learning outcome 3b) are not only the fundamentals of robust solid modeling but also complement the theory of orthographic and isometric projection. Students learn to look at the solid model and decompose it into the steps that would construct most logical and editable specification tree or model browser, figure 4.

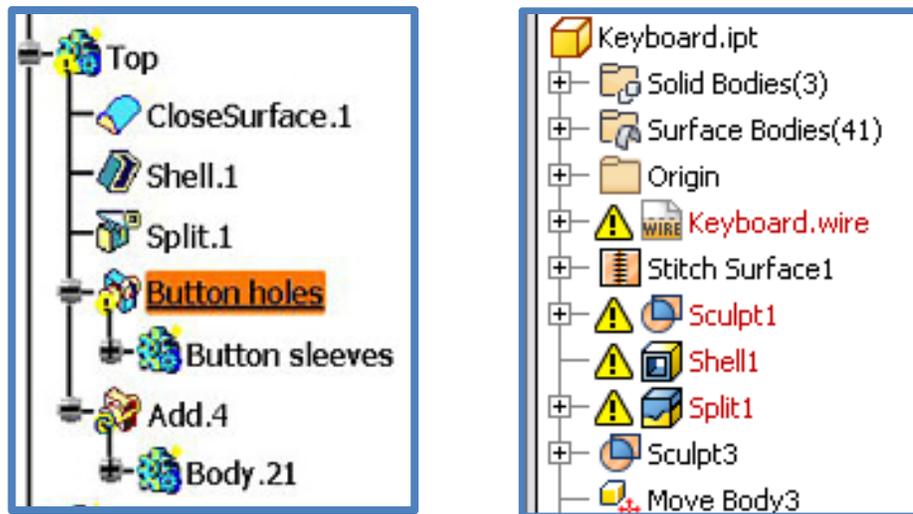


Figure 4: (Left) CATIA Specification Tree and (Right) AutoCAD Model Browser

Experience with this type CAD pedagogy foster students' development with a strong understanding of design intent and the inherent connection between constraint based design and 2D to 3D view development.

The CAD approach to teaching engineering graphics can provide many excellent opportunities for students to exercise and mature their creative thought processes (learning

outcome 4). Students are able to quickly try different commands and approaches to determine the most effective model, through this process of trial and error students begin to build their own unique modeling style. Students are able to easily see the cause and effect of certain design choices early as well as downstream the design path. It is essential that students are encouraged to explore many commands available and the many options available within each command, as this will contribute greatly to the creative development of their personal modeling strategies.

The criterion of an elegant and robust solid model is not how the solid model appears on the screen, but rather the approach taken to create it, this is an excellent indication of critical thinking (learning outcome 5). This is reflected in the structure and organization of the specification tree (CATIA) or the model browser (AutoCAD). The creation of these robust solid models can only be accomplished if students have fundamentally learned and applied the spatial visualization skills taught in engineering graphics. The outcomes for hand sketching and CAD in engineering graphics are not to be viewed as mutually exclusive, but rather they are complementary to each other. These two concepts presented together in an integrated fashion serve to reinforce and to strengthen each other's pedagogical impact.

### **Very good active, engaged learning.**

CAD has the potential to effectively engage students – especially the higher end application such as CATIA, Pro-E, and Solid Works – with the engineering graphics curriculum. Sorby (1999b, 2003), Jerz (2002), Watkins (2005), Hamlin, et al. (2006), and Pan, et al. (2010), all reported an increase in student satisfaction with the course after the purposeful integration of CAD into engineering graphics curriculum. 3D modeling affords students the opportunity to immediately apply and participate in the day's lecture. They are no longer passively taking notes to be applied at some future date. Instead they are able to try and get immediate feedback from the software, their peers, and the instructor. Students are able to manipulate and modify models which in turn can help students further develop their visualization skills – but only if they are meta-cognitively engaged with the material.

Under ideal circumstances, the approach can motivate and engage students in ways the paper based hand-sketching cannot. However, it is greatly dependent upon the instructor, the instructor's familiarity with the software, the pedagogical structure (Ye et al., 2004), and intent of the lecture/activities (Company, Gomez-Fabra, Agost, & Vergara, 2007).

### **Stages of knowledge – conceptual, procedural, and initial strategic.**

As CAD instruction varies so will the stages of knowledge desired by educators and achieved by students. At its worst students are merely “picking and clicking” through the construction of the solid model with minimal cognitive engagement. At the end of this type of instruction students may be able to build solid models that “appear” correct but closer inspection will reveal the cursory, superficial knowledge used to create them. Students will develop only the lower levels of conceptual knowledge through this method and as such their modeling abilities will be immature, contain limited logical structure, and be unwieldy. At its best CAD instruction will provide students with properly contextualized applications that provide the opportunity to learn conceptual knowledge, develop and refine procedural knowledge, and foster the beginning stages of strategic knowledge. Students who develop the appropriate procedural and strategic model frames will possess modeling abilities that are mature, and have elegant, robust modeling strategies.

When teaching CAD, Barbero and Garcia (2011) stress the importance of teaching CAD theories and applications over merely teaching the commands. Providing students with problems that are open-ended, with multiple design approaches will encourage modeling creativity. Students need to learn the concepts of solid modeling: organization of data, types of workbenches, and the application of commands, before they can begin to develop an understanding of the procedural knowledge. Ultimately, students should achieve the beginning level of strategic knowledge and are able to recognize there is no one right solution instead there are multiple approaches for each solution.

### **High explanatory power.**

The explanatory power gained by a course taught with a balanced approach between the theory of CAD and the theory of surfaces is quite good. Engineering is a combination of process and knowledge - specialized knowledge that enables and fuels the problem solving process. Spatial abilities relate to a “students’ ability to disembed relevant information from a complex drawing” or to restructure the given information (Bodner & Guay, 1997, p. 5). Students are provided opportunity to develop their spatial visualization skills through multiple outlets – hand sketching and the creation of 3D models. Students are able to see the connection

between 2D hand sketching and the creation of 2D profiles for the elements of the 3D solid model.

This is a skill fundamental to all of engineering not to just decoding spatial visualization problems. Students are able to recognize the importance about the link between spatial visualization and engineering; how engineers use sketching to think/work through a problem (Watkins, 2005). Students are better equipped to approach, dismantle, and solve open-ended problems more typically associated with engineering – whether in the classroom or in industry. This finding was supported by Mohler (2007, p. 11) in his qualitative research in which he found “the major difference between the high and low spatial ability participants was their ability (or lack thereof) in deconstructing spatial representations into simpler, more manageable pieces so that they could solve them.” Bodner & Guay (1997) also found a correlation between chemistry students’ spatial ability and their problem-solving skills. The effect size was increased when the questions were novel to the students, i.e., ones that were markedly different from previous questions presented in textbooks, covered in lectures, or assigned as homework.

Most importantly, students are able to see that solutions are open-ended and that personal creativity coupled with fundamental understanding of the theory produce the most robust models (Koretsky, 1998). Students who are able to see the flexibility implemented in the creation of 3D solid models can also be used in generating the solutions for posed hand sketching problems. At the end of this type of course students have achieved strong explanatory power.

### **Theory Informed Approach**

Table 6 presents the individual evaluation matrix for the theory informed approach to teaching spatial visualization. The final approach to teaching engineering graphics is the theory of surfaces, which provides students with the context to more richly mature their understanding of 2D and 3D spatial development. It is important to note the theory-informed course does not exclude CAD but integrates it throughout the curriculum. The theory informed course does an excellent job of meeting all learning outcomes. Much of the content is structured with active learning, with guided mentored sketches, integrated CAD activities, dyad group work, and structured lab time. Students are able to approach the material through different but complementary methods. Students are presented with the fundamentals of the engineering graphics, and are given the chance to practice procedural knowledge through the development of

standard drawings and the creation of solid models. It is possible for students to start developing strategic knowledge through the construction of multiple approaches. At the end of this course, students can achieve high explanatory power; as they have attained all the learning outcomes and all the stages of knowing.

**Table 6: Theory-Informed Approach Summary**

Pedagogical Approach	Learning Outcomes*	Active, Engaged Learning	Stage of Knowledge	Explanatory Power	
<b>Theory Informed</b>	<b>Outcome</b>	Very Good	Conceptual, Procedural, and Strategic.	High	
	1				Yes
	2a				Yes
	2b				Yes
	3a				Yes
	3b				Yes
	3c				Maybe
	4				Yes
5	Yes				

\***1.** Visualization and Geometric Problem Solving; **2a.** Ability to Create Standard Documentation By Hand; **2b.** Ability to Create Standard Documentation Using CAD; **3a.** Design Intent of 3D CAD Models; **3b.** Constraint Based 3D CAD Models; **3c.** Assembly Design Intent of 3D CAD Models; **4.** Creativity; **5.** Critical Reasoning

**High learning outcomes.**

The theory-informed approach provides students with the opportunity to create the emerging solution in parallel with the lecture, to develop their visualization and geometric problem solving skills (learning outcome 1). This method permits students to engage with the material and to fit it within their existing knowledge structure. Connolly and Holliday-Darr (2006) found that appropriate instruction could improve visualization skills of both engineering and non-engineering students. Because students are afforded the chance to develop the solution along with lecture they are able to identify areas of misperceptions and ask for immediate guidance, thereby correcting and refining their visualization schema. It is important that the drawing activities are not abstracted activities but are context or discipline specific Mohler & Miller (2008) and Akash & Alias (2006), relevant to the engineering graphics concepts presented. Lane, et al. (2009) found that appropriate, detailed feedback helped to improve students’ sketching abilities and their perceptions about those abilities; and Mohler and Miller

(2008) found that providing students with a lecture in parallel to solving a drafting plate improved their visualization skills significantly.

This approach can improve visualization skills especially the connections between 2D orthographic and 3D isometric views, enabling students to generate standard engineering documentation (learning outcomes 2a and 2b). Students are able to disassemble the 3D object into the appropriate 2D views needed to create an engineering drawing. Given the opportunity to generate drawings under guidance and in groups, students learn to identify the appropriate orthographic views from the provided isometric view. Coupled with this firm understanding students are now also able to identify and provide key dimensions required to build the part.

Once students have achieved a firm understanding of spatial visualization they have the skills and knowledge needed to create solid models that address the appropriate design intent and are properly constraint based (learning outcomes 3a and 3b). In order to properly create a solid model, students must be able to deconstruct the 3D image into the appropriate 2D elements. The theory-informed course enables students to develop the appropriate visualization skills needed to craft solid models. Since students are able to construct models along with the instructor, they are able to ask for immediate guidance when they encounter challenges. When the CAD activities are appropriately contextualized within the structure of the course they can also improve visualization abilities (Sexton, 1992; Tang, Xue, & Wang, 2010; Wiebe et al., 2003; Yip-Hoi, 2010).

The structure of this course encourages students to develop the solutions to the posed problems during the lecture and provides them the opportunity to try multiple approaches in a low stakes situation encouraging creativity and critical thought (learning outcomes 4 and 5). Students are able to see which methods and approaches work and are able to receive immediate, corrective feedback which reduces the potential for frustration and disengagement from the material. Felder and Brent state: “the only way a skill is developed –skiing, cooking, writing, critical thinking, or solving thermodynamics problems–is *practice*: trying something, seeing how well or poorly it works, reflecting on how to do it differently, then trying again and seeing if it works better” (2003, p. 282).

Uria & Mujika (2008), in their study about spatial visualization problem-solving affirmed that when students reason, different aspects of inter-related knowledge are put to work. As such, students need to be given problems which require thoughtful analysis to complete; this

contributes to the development of their creativity and critical reasoning skills. As students develop the general abilities required for a particular subject they begin to create particular ways of reasoning in that subject (Donald, 2002). Students are able to explore different approaches and begin making connections across topics enabling them to develop a much deeper understanding of the material. Streveler, et al. (2008, p. 1) quoting Bransford, et al., indicated that “learning with understanding can enhance the transfer of knowledge to new problems”. This cross connection of the material affords them the depth of knowledge to utilize various approaches in creating the solution to the posed problem.

### **Very good active, engaged learning.**

In a theory informed course, students are taught the supporting theory by the course instructor while developing and completing the drafting plates in parallel with the teacher. Students are able to see how the theory guides and governs the narrowing of choices available as the students and the instructor create the solution in parallel. The theory informed course cognitively engages the students with the material in three different ways: they *see* the solution developing on both their and the instructor’s plate, they *hear* the theory as it is applied to the developing solution, and they are *creating* the emerging solution as it is formed by the theory. Prince (2004) states that activities imbedded within the lecture foster deep understanding of the critical ideas to be learned and also significantly improve the recall of knowledge. Brown, et al. suggests that students, who are quite similar to apprentices, “must enter the community and its culture to learn how to use tools as the practitioners do” (1989, p. 33). Students are able to watch and hear the instructor as they solve the problem. Students (or the apprentice) experience the expert’s (or the practitioner’s) approach to solving the problem providing the student with the much needed enculturation.

The theory informed approach emphasizes student engagement, and transitions the pedagogical method from an instructor centered lecture to a student centered one. Students are provided with the logic behind the behavior of surfaces and they are also provided the opportunity to apply and try this logic during guided hands-on lectures. A supplementary benefit is real-time feedback. Student misperceptions can be quickly identified and corrected. Mohler and Miller (2008) found this method led to significant increases in their students’ ability to *see*

(in real time), their thinking about spatial problems, and their approaches to spatial problems when “mentored sketches” were integrated into the pedagogy.

### **Stages of knowledge conceptual, procedural, and strategic.**

The theory informed process aids students in learning the terminology and having a realistic understanding, conceptually, of how to accomplish the required tasks (Mohler, 2007). Examples of required tasks would be: solve a missing or incomplete view, apply the appropriate dimensions for given views, generate an auxiliary or a section view, and create a 3D solid model. The theory-informed course establishes a firm foundation by providing students with the required conceptual knowledge needed.

The theory informed method provides students the opportunity to start developing their creative and critical thinking skills. This is achieved through active learning techniques – the guided or “mentored” lectures. Students are taught the supporting theory of surfaces and how that theory is connected to visualization techniques. Students solve the provided assignments in parallel with the instructor; students are provided guiding questions at key junctions to help them connect the theory to the application. “Mentored” lectures provide students with a direct application of the procedural knowledge needed to solve the posed visualization problems. Students are able to develop their own procedural knowledge from the “mentored” lectures in theory informed course and subsequently are able to begin refining their critical thinking.

As their own knowledge and facility increases students are to question and critique the provided procedures, and they are able to take ownership of them and develop procedures of their own. As students develop their own methodologies they take ownership of their learning and now are able to start weighing which method would be more effective and are now employing strategic knowledge. An example of this would be determining which method would be utilized to solve a missing view problem – choosing to solve the isometric view first and then completing the associated orthographic views, choosing to create the solid model in a software program to determine the associated orthographic views, choosing to solve the orthographic views first to determine the isometric, or choosing to solve the isometric and orthographic views in parallel. Students can now vary the approach based on the complexity of the problem and their comfort level with the specific problem affording them the skill level of experts, the application of strategy.

### **High explanatory power.**

The explanatory power gained by the theory informed course with a balance between the theory of CAD and the theory of surfaces is fairly high. Engineering is a combination of process and knowledge - specialized knowledge that allows and drives the problem solving process, the theory informed course is structured with process and knowledge combined. Spatial abilities relate to a “students’ ability to disembed relevant information from a complex drawing” or to restructure the given information (Bodner & Guay, 1997, p. 5). This is a skill fundamental to all of engineering not to just decoding spatial visualization problems. At the end of this type of course students are better equipped to approach, dismantle, and solve open-ended problems more typically associated with engineering – whether in the classroom or in industry. This finding was supported by Mohler (2007, p. 11) in his qualitative research in which he found “the major difference between the high and low spatial ability participants was their ability (or lack thereof) in deconstructing spatial representations into simpler, more manageable pieces so that they could solve them.” Students are also afforded the opportunity to attempt problems alongside peers accompanied with guidance provided by an expert. This pedagogical approach prepares students to be more successful in other engineering environments beyond the classroom. The theory informed course shows students how to learn and fundamentally understand one of the enduring concepts of the engineering design process – problem solving.

### **Future Directions for Research**

Bodner and Guay (1997) found a correlation between spatial ability and performance on solving problems requiring multistep synthesis. Mohler (2007) identified a difference in decomposition skill between high and low skill spatial abilities. Mohler and Miller (2008) found correlation between increased student understanding and mentored sketching. Uria and Mujika experienced similar results as Mohler and Miller, when they integrated a new teaching strategy for part visualization. There has been some research on 3D modeling and the impact of hand sketching on modeling skills. Ardebili (2006), Devon, Engle, et al. (1994), Hamlin et al. (2006) Newcomber, Raudebaugh, McKell, and Kelley (1999), Rafi et al. (2006) reported an improvement of students’ spatial abilities when solid modeling and interactive media are

incorporated into the engineering graphics curriculum. However, Sorby (1999b) found that merely working with 3D modeling software did not improve a person's spatial skill as much as sketching. And Contero et al. (2006) replaced traditional pencil and paper hand sketching with sketching on tablets and demonstrated the student's visualization skills were improved – regardless of the sketching method. Barr and Juricic (1997) found student satisfaction improved as did student self-assessment in regards to learning to think for themselves. However, none of the published research addresses the impact of the theory informed course on the development and structure of 3D solid models. The purpose of this research was to provide a frame within which the methods of engineering graphics can be compared so educators may better understand the challenges and complexities associated with each these pedagogical methods: standard, remedial, computer-aided design, and theory-informed.

In spite of the reported findings that spatial visualization is an essential skill for student success in engineering and that it contributes to increased retention and higher engineering self-efficacy, it has been steadily reduced if not outright eliminated from the undergraduate engineering curriculum (Bertoline, Wiebe, Hartman, & Ross, 2007). This article presented and compared the methods of spatial visualization pedagogy to provide some clarity on this complex issue and to provide a possible direction forward.

## **Conclusion**

As the review of the existing research has shown, there are four common methodologies for teaching graphical communication: the traditional method, the remedial method, and possibly the CAD method have rather serious limitations. The traditional method is predicated on the improper assumption of student's skill level and is structured around a paradigm that is not conducive to active learning. The remedial method addresses both of these shortcomings quite effectively but doesn't cover all of the basic conceptual knowledge and does not incorporate any CAD instruction. When properly implemented the computer-aided modeling approach addresses the shortcomings of both the traditional and the remedial method. However this type of course is not common in the engineering graphics curriculum (Watkins, 2005) and instead CAD is often added at the end of a traditional course with minimal scaffolding back to 2D visualization. The theory-informed course does address the shortcomings identified in the traditional, remedial, and CAD methods. As reported by Mohler & Miller (2008) and Uria & Mujica (2008), the theory

informed approach develops the spatial ability and improves the problem-solving strategies of students; therefore those students will develop better organized, and more logically structured 3D solid models than those students who are not taught to visualize using the theory informed approach. Students will be able to discern the connection between 2D sketching theory and the creation of 3D solid models. Further, these students will be able to better identify how to break a more complex part into appropriately manageable chunks to properly solve the given drawing or the given solid model.

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Development and Validation of an Engineering Graphics  
Concept Inventory

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*This article will be submitted to the Engineering Design Graphics Journal and would document the development and validation of the concept inventory. A portion of this research was presented at the ASEE 2011 Annual Conference in Vancouver, BC. A second portion of this research was presented at the Research in Engineering Education Symposium in Madrid, Spain.*

## **Abstract**

One fundamental component in the development of competence and expertise in engineering is learning spatial visualization concepts in engineering graphics, enabling students to transfer this knowledge to new situations. Effective assessment is essential to confirm learning outcomes are achieved. Concept inventories are an excellent method of assessing conceptual understanding and providing formative feedback. Currently, there are no validated concept inventories available for engineering graphics. This article describes the development of an engineering graphics concept inventory and reports on the psychometric analysis of the inventory results of 1300 students from three universities. The Delphi method was used to guide an expert panel of experienced engineering faculty to achieve consensus about the fundamental concepts of engineering graphics particularly challenging to students. Drawing on the expert's rich experience the fundamental concepts and typical student errors in engineering graphics, multiple choice questions were devised to probe students' understanding. A panel of twenty engineering students participated in a pilot study and "think aloud" protocols to refine test item wording and to generate the appropriate distractors for the test items. Following the initial pilot study problem test items were identified and modified. Problem test items had either a very high or very low item difficulty index, negatively impacted overall instrument reliability, or had a negative biserial correlation. The results for each field study are presented. Reliability of the graphics concept inventory was established by the conclusion of the third field study. The concept inventory is ready to be implemented and the predictability of the instrument to be researched.

## Introduction

### Typical Development of Concept Inventory

The Force Concept Inventory, FCI, developed by Hestenes, Wells, and Swackhamer (1992) is considered the seminal work in the field of concept inventory development and assessment. The FCI was derived from prior work by Halloun and Hestenes (1985) on their Mechanics Diagnostic Test (MDT), which was developed to measure the discrepancies between student held beliefs and Newtonian force concepts. Recognizing that dedication and subject matter expertise were not enough for effective instruction in addressing these deeply held student misconceptions, and that educators must also know how their students think and learn, Hestenes, et al. (1992) set about to develop an instrument to aid teachers in identifying their learners' preconceived commonsense misconceptions about introductory physics. The distractors, or incorrect answers, for the force concept inventory were deliberately structured around the most commonly held student misperceptions, and as such educators are able to gain a richer understanding of their students pre-existing knowledge through their distractor choices. In addition to identifying the concepts misunderstood by students, the inventory also categorizes the *why* behind the incorrect choices. The FCI provides physics educators with a clearer picture of their students' beliefs (both correct and incorrect) the distractors provided for each item on the FCI are selected from the incorrect written answers from students during instrument development (Halloun & Hestenes, 1985). Physics educators are now able to tailor their coursework to address the shortcomings in their specific students' knowledge base. Implemented as a pre and post-test, educators could track student learning gains and gauge the effectiveness of individual educator pedagogy. Reliability and validity of the FCI has been well documented through the 18 years of implementation in high schools and universities.

In the 18 years since the development of the FCI there have been no less than 15 concept inventories for engineering and engineering related fields: electromagnetics, strength of materials, systems and signals, thermodynamics, circuits, fluid mechanics, engineering materials, chemistry, computer engineering, dynamics, electronics, heat transfer, thermal science, transport science, and statistics (Evans et al., 2003). The majority of these concept inventories were developed and organized around the same structure as the Force Concept Inventory. This procedure will be discussed in detail over the next few paragraphs.

Documented by faculty observations and supported by findings in the literature, many science and engineering students do not conceptually know or understand the fundamentals in engineering and science (John T. Demel, Meyers, & Harper, 2004; Halloun & Hestenes, 1985; Hestenes et al., 1992; Miller, Streveler, Nelson, Geist, & Olds, 2005; Newcomber & Steif, 2008; Olds, Streveler, & Miller, 2004; Santiago-Romain, Streveler, & DiBello, 2010; Steif & Dantzler, 2005; Steif & Hansen, 2007; Stone et al., 2003; Streveler, Litzinger, Miller, & Steif, 2008; Streveler, Olds, Miller, & Nelson, 2003). The literature further suggests the problem is deeper than misunderstanding or confusion; instead, much of students' constructed knowledge is based upon incorrect inferences drawn from their daily lives (Halloun & Hestenes, 1985; Hestenes et al., 1992; Olds et al., 2004; Steif & Dantzler, 2005; Streveler et al., 2008). These misconceptions are based on "common sense" and as such are deeply held. In order to develop the curriculum to address these misconceptions, faculty must first identify which concepts students don't understand, and a well-developed concept inventory can provide faculty with this essential information.

The first step to creating a concept inventory is identification of the fundamental concepts associated with the particular engineering or science field that are traditionally challenging for students to understand or for which they have deeply held misconceptions. This is most often achieved through the implementation of a Delphi study. The Delphi method was developed by Dalkey and Helmer (1962) for the RAND corporation to forecast the impact of technology on warfare (Custer, Scarcella, & Stewart, 1997), and is a "structured process for collecting and distilling knowledge from a group of experts with controlled opinion feedback" (Streveler et al., 2003, p. 2). Through the use of anonymous solicitation from multiple subject-matter experts, the Delphi method attempts to address the known flaws of the following methods: use of a single expert, round table discussion, and group average (Evans et al., 2003; Miller et al., 2005; Olds et al., 2004; Steif & Dantzler, 2005; Streveler et al., 2003). The use of only one expert places too much emphasis on a single person's opinion; the round table discussion is unpredictable as some members may unduly influence the decision of others; and group average is less than ideal as "individual experts have neither the opportunity to provide their most thoughtful input nor have the benefit of hearing others' responses that might encourage the refinement of their contributions" (Clayton, 1997, p. 3). Since the responses provided through the Delphi method

are anonymous, all participants have equal social capital and influence, and only the strength of the logic in their argument can influence the decisions of the other participants.

It is important to note there have been faults identified with the Delphi method, most markedly by Sackman (1974). He cited the following shortcomings: “the conventional Delphi does not satisfactorily meet the numerous experimental and methodological standards cited for test design, item analysis subject sampling, reliability, validity, administration, interpretation of findings, and warranted social use” (Sackman, 1974, p. 5). Sackman’s most strident criticism is that “the conventional Delphi neglects virtually every major area of professional standards for questionnaire design, administration, application and validation” (1974). However, if the primary goal is the identification, categorization, and ranking of concepts based upon expert consensus (Clayton, 1997, p. 17), then the Delphi method is well suited for the development of concept inventories.

A panel of experts is first identified and established. The size of the panel is often a function of “the complexity and expertise required” Clayton (1997) and as such panel size can range from five to over a 1000 experts (Atkins, Tolson, & Cole, 2005). The panel is then asked to generate a list of fundamental concepts that students either find challenging or which they often have strongly held misconceptions. Once the panel has reached consensus on the concepts, they are asked to rate each concept along two scales: 1) the importance of the particular concept and 2) the difficulty in understanding of the particular concept. The process is repeated until ratings for each concept reach stability and the experts are in agreement. Stability is often reached after three iterations.

Next, the questions for the instrument are generated from the list of concepts. The experts may either be asked to generate the questions or to critique questions created by the researchers. During this stage, the questions are closely evaluated and compared to the list of identified fundamental concepts, ensuring each concept has been appropriately addressed. This process is repeated until expert consensus is reached. Usually, at this point only the questions have been created and evaluated, the distractors will be created later in the process.

Then, the instrument, without distractors, is pilot tested with the appropriate populations. The pilot study allows the researchers to identify problem items and to gather the appropriate distractors from participant generated responses, as the participants are given the instrument without distractors and are asked to write in their answers. The distractors for the inventory are

then taken from the recurring incorrect answers. However, this method is not ideal, as the researcher does not have a clear idea as to *why* the participant provided the answer they did (whether they misunderstood the question or if they misunderstood the concept being tested). To address this critical shortcoming participants can be interviewed and asked to provide a description or a “think aloud” of their interpretation and solution to the given question. From these interviews, researchers are able to rewrite the items using the terminology of the students and to greatly reduce misinterpretation of the question. The interview “think aloud” protocol ensures the distractors selected most accurately reflect the knowledge, beliefs, and the misconceptions of the population to be tested. These pilot studies are often implemented over several semesters at several institutions to ensure a complete cross section.

Finally, the concept inventories are extensively field tested to evaluate the instrument’s reliability and validity. Reliability is the repeatability of the instrument while validity is the accuracy of the instrument (Moskal, Leydens, & Pavelich, 2002; Steif & Dantzler, 2005). To properly investigate reliability these field studies are often implemented across several different institutions. Content validity is addressed through several means: careful selection of the expert panel, researcher familiarity with the concepts under investigation, and detailed analysis of student responses. Criterion validity is the predictive ability between the instrument and another performance score (Moskal et al., 2002; Steif & Dantzler, 2005). If another test does not exist (which is often the case with concept inventories) a comparison between instrument and overall course performance can be used to partially demonstrate the predictive ability of the inventory. Construct validity can be established through confirmatory factor analysis, which calculates how well the items “hang together” (Messick, 1995), and can be supported by the Goodness of Fit Index, the Comparative Fit Index, Chi Squared, and the Root Mean Square Approximation (Steif & Dantzler, 2005).

While not all engineering concept inventories have followed the procedure described in the preceding paragraphs, many of them have. Evans, et al. (2003) provides an excellent summary of the eleven engineering concept inventories developed in the last 10 years, five of which clearly describe employing the Delphi Method.

The next section provides a description of the development process of the Engineering Graphics Concept Inventory, placing particular emphasis on the description and explanations of any differences in the method implemented for this research.

## Method

### Description of the Development of the Engineering Graphics Concept Inventory, (EGCI)

The Delphi method was utilized for the development of the Engineering Graphics Concept Inventory. The primary stages for this research were: expert selection, concept identification and rating, item creation, pilot study of items, participant interviews with “think-aloud” protocols, item revision, initial field study of instrument for validity and reliability, instrument revision, second field study of the instrument for validity and reliability, instrument revision and data analysis, multi-institution implementation and data analysis. Figure 1 documents the major milestones for the development of this concept inventory.

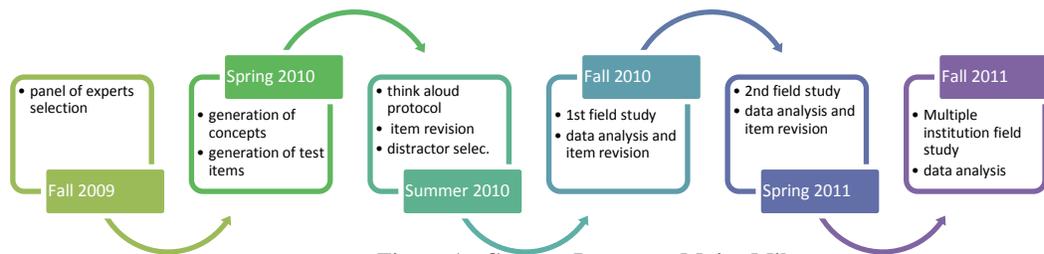


Figure 1 - Concept Inventory Major Milestones

### *Expert Selection*

The Delphi panel participants were selected based upon their level of experience teaching Graphical Communications. Six experts were asked to participate, each expert has taught a minimum of two sections Graphical Communication per year for the last five years, one of the experts is the course coordinator, a second expert has developed supplemental study guides for the course, and a third expert has taught eight sections per year for the last 15 years. All participants were ensured their responses would be kept confidential. The panel created for this Delphi method is a bit different than most others created, in that all of the experts are from the same institution, and as Atkins (2005) and Clayton (1997) both indicate, the size of an acceptable panel is a function of the diversity of the participants. While all experts teach the same course, their approaches and emphases vary greatly from each other. As such it was deemed for the development of the instrument their opinions and experiences would be diverse enough to

provide a complex and rich list of concepts. While this could be considered a validity limitation, the multiple institution implementations addressed this.

### *Concept Identification and Ranking*

The panel participated in rounds: 0, 1, 2, and 3. In round 0, the experts were asked to simply identify the concepts students traditionally found difficult. The 50 generated responses were then coded and organized into 15 distinct concepts. For round, 1 the experts were asked to rate each concept along two scales: difficulty in student learning (0-7) and importance of concept (0, 5, or 10). For round 2, experts were asked to rank the 15 concepts again. They were also provided with the median response from round 1 along with the two quartile range. If experts ranked a concept outside of the provided quartile range, they were requested to provide an explanation for their choice. In round 3, the experts were asked to rank the 15 concepts. They were provided with the median response, the two quartile range, and the comments provided from Round 2. From this the final concepts (theory of surfaces – normal, inclined and oblique, section views, auxiliary views, dimensioning, scales, and line-types) were selected to develop the concept inventory.

### *Test Item Development*

The instrument items were developed next; these items were created by Steinhauer and provided to the expert panel for review. At this point, no answers or distractors had been created. The experts were only provided with the individual test items. There were three rounds of expert review and comments on the instrument items. For each round the panel of experts was asked to identify which category each question specifically addressed, how to improve the wording if needed, or if the question should be completely removed and replaced. At the end of this stage, there were 16 questions to be tested for the pilot study.

### *Pilot Study and Participant Interviews*

Twenty students agreed to participate in the pilot study. To be selected for the study they must have completed the Engineering Graphics course within the last year. There were four participants selected from each instructor of Engineering Graphics to ensure equal

representation. Table 1 maps the pilot study participation across experts and questions. Each participant completed four questions of the concept inventory by writing in their answers.

**Table 1: Distribution of Pilot Study Participants**

<b>Test Items</b>	<b>Expert 1</b>	<b>Expert 2</b>	<b>Expert 3</b>	<b>Expert 4</b>	<b>Expert 5</b>
<b>1-4</b>	Student 1	Student 5	Student 9	Student 13	Student 17
<b>5-8</b>	Student 2	Student 6	Student 10	Student 14	Student 18
<b>9-12</b>	Student 3	Student 7	Student 11	Student 15	Student 19
<b>13-16</b>	Student 4	Student 8	Student 12	Student 16	Student 20

Each participant was interviewed and asked to read the question back using their own wording and terminology, they were asked to describe their approach using the “think-aloud” protocol. Instrument items were reworded to better match participant language and to increase the clarity of the questions. Distractors were developed from the incorrectly written responses and the “think-alouds.”

*Initial Field Study of Concept Inventory*

The subsequent stage of the concept inventory development is the field study. In August 2010, 10 sections of an engineering graphics course completed the EGCI as a pre-test; 217 students agreed to participate. The data collected from this field was used to identify problem items. Several of the items had more than one correct answer, but the provided instructions failed to clarify this. Those items have been reworded so that there is now only one correct answer per item. Two of the items had a distractor bold-faced; this formatting error has been corrected. One item had a distractor that was too similar to the correct answer; this distractor has been removed and replaced with a more distinct choice. Preliminary reliability results show that measures needed to be taken for improvement: Cronbach’s  $\alpha$  for the instrument is 0.55; the minimum acceptable value is 0.70. Out of a possible 16 points, the averages across the sections for the pre-test are consistent (ranging from 6.9 to 8.2), indicating, on average, students’ understanding is at the appropriate level to be in an introductory engineering graphics course.

### *Second Field Study of Concept Inventory*

The revised EGCI was implanted in January 2011 to eight sections of engineering graphics. One hundred twenty four students agreed to participate. The data collected from this second field study verified that the rewording impacted distractor selection. Preliminary reliability results showed that Cronbach's  $\alpha$  for the instrument was 0.67 closer to the .70 minimum. The averages across the sections for the pre-test were consistent (ranging from 7.1 to 7.8), replicating the findings from the August field study, and that their entry-level understanding was appropriate for an introductory visualization course.

### *Multiple Institution Implementations*

The revised EGCI was implemented in September 2011 at two large public universities located southeastern United States. Twenty-eight sections of Exploration of Engineering Design at Virginia Tech, 850 students agreed to participate. The data collected from this field study verified that the rewording impacted distractor selection. Preliminary reliability results showed that Cronbach's  $\alpha$  for the instrument was 0.71. Four hundred students from 10 sections of Foundations of Graphics at North Carolina State University agreed to participate. Results showed that Cronbach's  $\alpha$  for the instrument was 0.73. The averages across the sections for the pre-test for both institutions are consistent (ranging from 7.2 to 8.1) replicating the findings from the January 2011 field study, and that their entry-level understanding is appropriate for an introductory visualization course.

It is important to acknowledge here that most other concept inventories were pilot and field tested at several institutions. While that is the ideal approach, as it can demonstrate the generalizability of the instrument, this was not a readily available option of the pilot implementation for this concept inventory. Many of the other concept inventories have been developed through a consortium supported by funding provided through an NSF grant as described by Evan, et al. (2003), with the inter-institution connections already well established. This inventory was pilot tested only at the home institution, but was field tested at several other institutions during the fall of 2011. One university is a large, public, land-grant university located in the south eastern United States. The other institution is a mid-size university, public university located in the south. Each institution approaches teaching engineering graphics very differently. One has eliminated the course entirely and has integrated the major concepts into a

two semester introduction to engineering design sequence, while the other has maintained a fairly rigorous stand-alone engineering graphics course.

The procedure implemented for the development of the concept inventory closely follows the procedure identified in the development of the majority of engineering concept inventories, with one exception: the selection criteria of the panel of experts. Given the diverse viewpoints and teaching approaches utilized by the instructors of Engineering Graphics it was deemed their viewpoints would offer a rich, diverse, and detailed concept list. The possible limitations and impact on the generalizability of this research are addressed in detail in the limitations section of this paper.

The next section of this paper discusses the concepts associated with visualization skills and how these map to Guay's Purdue Spatial Visualization Test: Rotations, PSVT:R, and the College Entrance Examination Board's, CEEB, Mental Cutting Test, MCT.

### **Visualization Tests: Guay's PSVT:R, and CEEB's MCT**

Graphical communication has undergone a significant transformation over the last 15 years, due in large part to the introduction of computer aided modeling and design. Combined with the reduction of available credit hours for graphical communication, this trend has increased the importance of efficient and effective delivery of course information (Croft, Demel, & Meyers, 2001; J. T. Demel, Croft, & Meyers, 2002; John T. Demel et al., 2004; Meyers, 2000). The development of a concept inventory would aid graphics educators in identifying the misconceptions of their students and properly adjusting the curriculum to better reflect their students' knowledge.

Two tests are commonly used for the measurement of spatial ability: Guay's (1977) PSVT:R (Purdue Spatial Visualization Test: Rotations) and CEEB's (1939) MCT (Mental Cutting Test). According to Branoff (2000), and Bodner and Guay (1997), both the PSVT:R and the MCT have high construct validity in the area of spatial visualization. The skills developed in a graphical communication course are student's spatial visualization, therefore both the PSVT:R and the MCT lend themselves well to measuring this ability.

### *Purdue Spatial Visualization Test: Rotations*

PSVT:R was developed by Guay (1977) at Purdue University. In this timed 30 item test participants are asked to visualize the direction and rotation of the provided sample model; next they are to visualize what the second object would appear as if it were rotated the same as the sample; and then they are to select the correct image from the five options provided. A sample question from the PSVT:R is provided in Figure 2 (the correct answer is D). The reported reliability, KR-20 of the PSVT:R has been .87, .89, and .92 for university students (Bodner & Guay, 1997; R. B. Guay, 1980; Sorby & Baartmans, 1996).

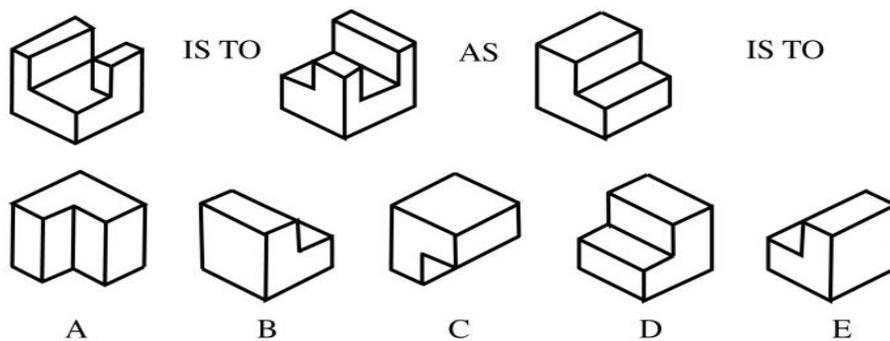


Figure 2: Sample Question from PSVT:R

### *The Mental Cutting Test*

The MCT, the Mental Cutting Test, was developed for the College Entrance Examination Board (CEEB, 1939). The MCT is a 20 minute test containing 25 items divided into two categories of test items. The first category has 19 pattern recognition problems; the correct answer is determined by identifying the correct pattern (or shape) of the profile (Tsutsumi, 2004). The second category has six dimension specification problems; the correct answer is determined by identifying the correct pattern (or shape) and the correct dimensional relationships of the object (Tsutsumi, 2004). Each item contains one test solid and associated cutting plane, one correct cross section, and four distractor cross sections. Participants are asked to identify the correct cross section for the given solid. One sample question from the MCT is provided in Figure 3 (the correct answer is D). The reported reliability, Cronbach's  $\alpha$ , of the MCT has been reported .87 and .92 for undergraduate chemistry and engineering students (Branoff, 2000; Caissie, Vigneau, & Bors, 2009).

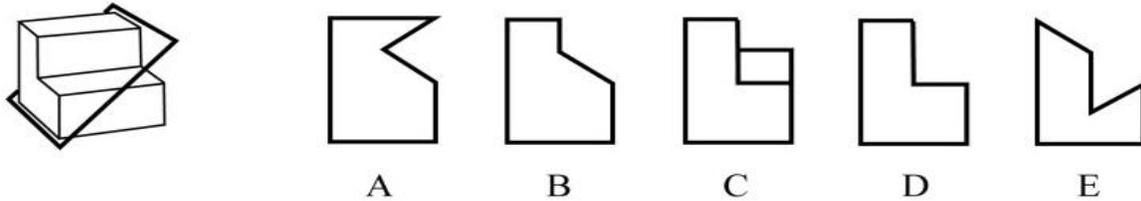


Figure 3: Sample Question from MCT

*Alignment Between Concept Inventory, the PSVT:R and the MCT*

The concepts selected for the concept inventory testing visualization skills are: dimensioning, orthographic projection theory (normal, inclined, and oblique surfaces), scales, section views, auxiliary views, and line-types. These topics were similar to a list generated by Croft, et al. (2001) and Meyers (2000) when identifying the particular skills they deemed vital to the graphical communication curriculum. The PSVT:R and the MCT measure spatial ability; this ability is commonly defined as the ability to view, conceive, and manipulate objects or ideas within the “mind’s-eye.” The concepts taught in graphical communication overlap these. The following concepts: orthographic projection theory (normal, inclined, and oblique surfaces), dimensioning, sectioning, and auxiliary views, all require students to mentally view, conceive, manipulate, and process either 2D or 3D information to arrive at the correct solution. It is to be expected that students who perform well on the PSVT:R and the MCT will easily learn and apply the spatial visualization concepts taught in graphical communication.

**Field Study Results**

The initial concept inventory, developed in Summer2010, had a low reported reliability, .47. To correct for the low reliability a detailed analysis of the instrument was conducted. Reliability, item difficulty, and biserial correlation for each question on the test were determined. Reliability is a measure of the consistency of the assessment’s measurements and is to be independent of when the test is scored or who scored the response (Moskal et al., 2002). Item difficulty, often called the p-value, is the percent of examinees who correctly answered the item (Richardson, Steif, Morgan, & Dantzler, 2003), the higher the value the more examinees who answered the question correctly. Biserial correlation is the degree to which responses on a particular item rank order examinees in the same way as total scores on the remaining items (Costa, Oliveria, & Ferrao, 2009). Biserial correlation was selected instead of point-biserial

correlation because biserial correlation is not constrained to having item difficulty be greater than .50. By January 2011, the instrument had been refined through multiple field trials that yielded concept inventory reliability values of .71 and .73.

*Pilot Testing and Item Analysis – August 2010*

A total of 217 students participated in the pilot study; due to missing data responses only 181 were included in the item analysis. Participants responded to 16 multiple choice questions. The concept inventory was administered as a paper based test, and there were no time restrictions placed on the participants. JMetrik was used to conduct the item analysis. Following the item analysis, the reliability, Cronbach’s  $\alpha$ , of the inventory was low at .47; the generally accepted minimum for reliability is around .70. Nine of the inventory items contributed to the low reported reliability, so it was apparent these items of the inventory would be need to revised and the instrument retested before the instrument could be formally implemented as an ABET program objectives assessment. In the following section, all revisions to the original inventory are explained in detail, including the original distractors along with item totals, and the revised distractors included for each of these items. The test level descriptive statistics are provided in Table 2. The results of the item analysis and recommendations for each test item are discussed in the following section.

**Table 2: August 2010 Test Level Descriptive Statistics**

<b># of Items</b>	<b># of Participants</b>	<b>Mean</b>	<b>Median</b>	<b>Standard Deviation</b>	<b>Minimum</b>	<b>Maximum</b>
16	181	5.9116	6.000	23133	1	11

The item analysis resulted in a reliability coefficient ( $\alpha = .47$ ), item difficulties ranged from .1203 to .6512, and the biserial correlation with totals ranged between -.0068 and .4666. The item difficulty for each test item of the EGCI is shown in Figure 4, item difficulty identifies if there are a disproportionate number of test items that are too easy or too hard. The dark lines on the figure indicate the three areas easy ( $\leq .15$ ), moderate ( $.15 \leq x \leq .7$ ), and hard ( $\geq .7$ ) questions. As this instrument is to be criterion-referenced it needs to have several challenging test items – with an item difficulty of .15 or lower. Test items Q 2, Q 4, Q 6, Q 9b, and Q 10a

fall into this range, while the 11 remaining test items are considered less challenging. Finally, biserial correlation is the degree to which responses on a particular item rank order examinees in the same way as total scores on the remaining items (Costa et al., 2009), for this instrument the biserial correlation need only to be positive.

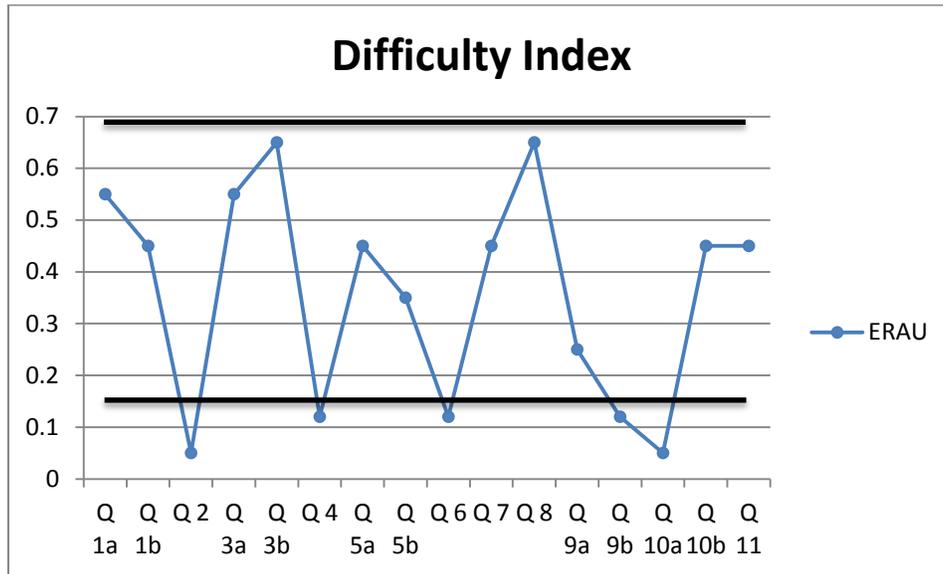


Figure 4: August 2010 Item Difficulty Index (Pilot Study)

Table 3 shows the test question distribution as a function of difficulty, the item difficulty was well distributed between less challenging and more challenging with more of the items placed towards the less challenging end of the spectrum: 2 items were in the .10-.20 range (highest difficulty); 2 items were in the .21-.30 range; 3 items were in the .31-.40; 1 items was in the .41-.50 range; and 4 items were in the .51-.60 range; and 4 item was in the .61-.70 range (least difficulty), this arrangement desired for a criterion-referenced instrument.

Table 3: August 2010 Item Difficulty Range



	.00 - .01	.11 - .20	.21 - .30	.31 - .40	.41 - .50	.51 - .60	.61-.70
<b>Item Numbers</b>	2 10a	4 6 9b	9a	5b	1b 5a 7 10b 11	1a 3a	3b 8

Table 4 provides the item analysis for item 2. Based on the item difficulty and the biserial correlation with total, the original question for item 2 was revised for the final inventory. Upon reviewing the item totals of the four distractors, it was decided the distractors needed to be significantly reworded, these numbers are provided in the parenthesis. The original five distractors along with their item totals are listed below.

- A (.4360), an inclined line
- B (.1047), a surface
- C (.0581), a horizontal line
- D (.3488)\*, either A and B
- E (.0465), none of the above

Please note that all correct answers are indicated by an asterisk.

Table 4: Item 2: If Surface A was an inclined surface it would appear as what in the Right Side View?

Item Difficulty	Standard Deviation	Biserial Correlation with Total	Cronbach's $\alpha$	Cronbach's $\alpha$ if Item is Deleted	Decision About Item
.3488	.4780	.0292	.4715	.4866	Revise

The question's distractors were poorly written and confusing as indicated by several factors. Both A and B were correct answers and option D included both of these, however the

item totals demonstrated the students did not recognize this, as 54% choose either distractor A or B, only 35% selected the correct answer D, and 5% selected C and E respectively.

The original and revised distractors and correct answers are included below:

Original	Revised
A: an inclined line	A: a surface or a vertical line
B: a surface	B: a surface or a horizontal line
C: a horizontal line	C: a surface or an inclined line*
D: Either A or B*	D: an inclined line or a vertical line
E: None of the Above	

Table 5 provides the item analysis for item 4. Based on the item difficulty, the bi-serial correlation with total, and the Cronbach’s  $\alpha$  if item is deleted, item 4 was not deleted, but distractor C has been re-worded for the final version of the inventory. 39% of the students selected distractor C, 23% selected distractor B, 17% selected distractor A and only 23% selected the correct answer. Distractor C was originally worded as “an angled line in one and a surface in the other.” It was determined that the inclusion of inclined edge was confusing to students as oblique surfaces are a specific type of inclined surface. To eliminate this confusion inclined edge was replaced with vertical edge.

**Table 5: Item 4: If Surface C was an oblique surface it would appear as what in the Top and Right Side Views?**

<b>Item Difficulty</b>	<b>Standard Deviation</b>	<b>Biserial Correlation with Total</b>	<b>Cronbach’s <math>\alpha</math></b>	<b>Cronbach’s <math>\alpha</math> if Item is Deleted</b>	<b>Decision About Item</b>
<b>.2093</b>	<b>.4080</b>	<b>-.0665</b>	<b>.4715</b>	<b>.4957</b>	<b>Revise</b>

Table 6 provides the item analysis for item 5a. Based on the item difficulty, the bi-serial correlation with total and the Cronbach’s  $\alpha$  if item is deleted, item 5a was not revised but was kept in its original form for the final inventory.

**Table 6: Item 5a: Based on the part's geometry the most appropriate section view would be:**

<b>Item Difficulty</b>	<b>Standard Deviation</b>	<b>Biserial Correlation with Total</b>	<b>Cronbach's <math>\alpha</math></b>	<b>Cronbach's <math>\alpha</math> if Item is Deleted</b>	<b>Decision About Item</b>
<b>.4186</b>	<b>.4948</b>	<b>.0174</b>	<b>.4715</b>	<b>.4898</b>	<b>Revise</b>

Table 7 provides the item analysis for item 5b. Based on the item difficulty, the bi-serial correlation with total, and the Cronbach's  $\alpha$  if item is deleted, item 5b was not deleted, but distractor E has been removed and distractor F has been re-worded for the final version of the inventory. 11% of the students selected distractor E, 39% selected distractor F, and only 23% selected the correct answer. Upon close examination of the provided part (which is not symmetrical) and a discussion with other experts, it was determined that students are quite familiar with the concepts of symmetry and non-symmetry, so it was decided to eliminate those distractors. Original distractors along with the item totals are included below:

- E: (.1105), the part is symmetrical
- F: (.3837), the part is not symmetrical
- G: (.2267)\*, the part contains non-planer internal details
- H: (.2733), the part contains an inclined surface

The correct answer is identified by an asterisk, the distractor to be removed is E, and distractor F has been reworded. The revised distractors are listed below:

- E: the part is contains internal circular details
- F: the part contains non-planer internal details\*
- G: the part contains an inclined surface

**Table 7: Item 5b: Because**

<b>Item Difficulty</b>	<b>Standard Deviation</b>	<b>Biserial Correlation with Total</b>	<b>Cronbach's <math>\alpha</math></b>	<b>Cronbach's <math>\alpha</math> if Item is Deleted</b>	<b>Decision About Item</b>
<b>.2267</b>	<b>.4199</b>	<b>.0394</b>	<b>.4715</b>	<b>.4818</b>	<b>Revise</b>

Table 8 provides the item analysis for item 6. Based on the item difficulty, the bi-serial correlation with total, and the Cronbach's  $\alpha$  if item is deleted, item 6 was not deleted, however

the distractors have been revised for the final version of the inventory. Question 6 originally had one correct answer (B) and five distractors. Due to a formatting/editing error the last two distractors (E and F) were mistakenly included; these were deleted from the final version of the concept inventory.

**Table 8: Item 6: The most appropriate view for generating an auxiliary view for Surface A is:**

<b>Item Difficulty</b>	<b>Standard Deviation</b>	<b>Biserial Correlation with Total</b>	<b>Cronbach's <math>\alpha</math></b>	<b>Cronbach's <math>\alpha</math> if Item is Deleted</b>	<b>Decision About Item</b>
.1395	.3475	.1139	.4715	.4708	Revise

Table 9 provides the item analysis for item 7. Based on the item difficulty, the bi-serial correlation with total, and the Cronbach's  $\alpha$  if item is deleted, item 7 was not deleted; however distractor E (none of the above) has been removed for the final inventory, as only 9% selected it as a distractor. The original distractors and their Item totals are included below:

- A (.1105), 1.5; 2.0; 3.8; and 4.3
- B (.4302)\*, 1.50; 2.00; 3.75; and 4.25
- C (.2209), 1 ½; 2; 3 ¾; and 4 ½
- D (.1395), 1.5; 2; 3.75; and 4.5
- E (.0988), none of the above

Due to this low number of students, less than 10%, who selected E, it has been removed from the distractor pool.

**Table 9: Item 7: When dimensioning an engineering drawing, primary units are in inches, select the appropriate series of dimensions:**

<b>Item Difficulty</b>	<b>Standard Deviation</b>	<b>Biserial Correlation with Total</b>	<b>Cronbach's <math>\alpha</math></b>	<b>Cronbach's <math>\alpha</math> if Item is Deleted</b>	<b>Decision About Item</b>
.4302	.4966	.2518	.4715	.4443	Revise

Table 10 provides the item analysis for item 8. Based on the item difficulty, the bi-serial correlation with total, and the Cronbach's  $\alpha$  if item is deleted, item 8 was not deleted; however

distractors A and B have been revised for the final version of the inventory, as only 10% of the students selected them.

The original distractors and their item totals and the revised distractors are included below:

Original	Revised
A (.0349), 2 = 1	A: 2/1
B (.0756), 1 = 2	B: 1/2
C (.3663), 2 : 1	C: 2 : 1
D (.5233)*, 1 : 2	D: 1 : 2*

**Table 10: Item 8: When dimensioning an engineering drawing, primary units are in mm, select the appropriately written half scale:**

Item Difficulty	Standard Deviation	Biserial Correlation with Total	Cronbach's $\alpha$	Cronbach's $\alpha$ if Item is Deleted	Decision About Item
.5233	.5009	-.0685	.4715	.5064	Revise

Table 11 provides the item analysis for item 9a. Based on the item difficulty and the biserial correlation with total, the original question for item 9a was revised for the final inventory. Upon reviewing the item totals of the four distractors, it was decided the distractors needed to be significantly reworded. The original five distractors along with their item totals are listed below.

- A: (.1105), the dimension is dimensioning an element that is not true size
- B: (.2500), the dimension is a duplicate dimension and not required
- C: (.1686)\*, the dimension is not placed in the most descriptive location
- D: (.1628), the dimension format is incorrect for dimensions that are in inches
- E: (.3028), the dimension as provided is correct

**Table 11: Item 9a: Dimension A in the Front View is incorrect because:**

Item Difficulty	Standard Deviation	Biserial Correlation with Total	Cronbach's $\alpha$	Cronbach's $\alpha$ if Item is Deleted	Decision About Item
.1686	.3755	-.1017	.4715	.4967	Revise

The question's distractors were poorly written and confusing as this was indicated by several factors. C was the correct answer; however the item totals demonstrated the students did not recognize this, as 30% chose distractor E, 25% chose distractor B, only 17% selected the correct answer D, and 11% selected A. Distractor B could have been interpreted as a correct option if students did not properly understand the provided image; based on this ambiguity, the distractor B was eliminated. The revised distractors and correct answer is included below:

Revised

- A: the dimension is dimensioning an element that is not true size
- B: the dimension is not placed in the most descriptive location\*
- C: the dimension format is incorrect for dimensions that are in inches
- D: the dimension as provided is correct

Table 12 provides the item analysis for item 10a. Based on the item difficulty and the biserial correlation with total, the original question for item 10a was revised for the final inventory. Upon reviewing the item totals of the six distractors, it was decided several distractors needed to be significantly reworded and an additional one needed to be deleted. The original six distractors along with their item totals are listed below.

- A (.0581), the dimension is dimensioning an element that is not true size
- B (.1628), the dimension includes information that is not needed
- C (.2849), the dimension is not placed in the most descriptive location
- D (.0814), the dimension as provided is correct
- E (.0814), both A and B
- F (.1860)\*, both A and C
- G (.1458), both B and C

**Table 12: Item 10a: Dimension B in the Right Side View is incorrect because:**

<b>Item Difficulty</b>	<b>Standard Deviation</b>	<b>Biserial Correlation with Total</b>	<b>Cronbach's <math>\alpha</math></b>	<b>Cronbach's <math>\alpha</math> if Item is Deleted</b>	<b>Decision About Item</b>
<b>.1806</b>	<b>.3903</b>	<b>.0240</b>	<b>.4715</b>	<b>.4822</b>	<b>Revise</b>

The question's distractors were not clearly written and confusing as this was indicated by several factors. Both A and C were correct answers and option F included both of these; however the item totals demonstrated the students did not recognize this, as 33% choose either distractor A or C, and only 18% selected the correct answer.

The revised distractors and correct answer are included below:

- A: the dimension is dimensioning an element that is not true size\*
- B: the dimension includes information that is not needed
- C: incorrectly combines three dimensions into one
- D: none of the above, the dimension as provided is correct.

The August 2010 pilot test identified several weaknesses with the concept inventory a lower than hoped-for reliability of .47, several items with unclear or confusing distractors, and unclear test protocol – as indicated by the high number of incomplete concept inventories. Based on these findings the questionable items were revised and a more detailed and structured test protocol was developed.

#### *Pilot Testing and Item Analysis – January 2011*

The revised concept inventory was implemented at the original institution in January of 2011. It was determined that keeping all other parameters the same—implementing the instrument at the same institution with the same population—would yield the most clear indication that the revisions had addressed the problems identified in the pilot study. The reliability, Cronbach's  $\alpha$ , of the revised inventory is .67; the generally accepted minimum for reliability is around .70. While still a bit low, it is a marked improvement from reliability of the August 2010 pilot study. This improvement to reliability is supported by the fact that only two inventory items' biserial correlations are negative (ideally none of the test items should have a negative biserial correlation). However, since it is not clear why these two items have a negative value, the items were unmodified and reviewed again after the field test in September 2011.

There were a total of 125 students who participated in this pilot study. Only one inventory needed to be removed due to missing data. Participants responded to 16 multiple choice questions. The concept inventory was administered as a paper based test, and there were no time restrictions placed on the participants. JMetrik was used to conduct the item analysis. The instrument had a reliability of .67. Due to the marginal impact of the two negatively scoring items the inventory was not revised. The inventory was field tested a final time in August 2011 at the original institution as well as at several others.

The test level descriptive statistics of the January 2011 field test are included in Table 13. The item analysis resulted in a reliability coefficient ( $\alpha = .67$ ), item difficulties ranged from .1290 to .6371, and the biserial correlation with totals ranged between .0785 and .4755. The reported numbers were much better. All 16 items now have a reported positive biserial correlation; the items flagged in the August 2010 field test were corrected.

**Table 13: January 2011 Test Level Descriptive Statistics**

<b># of Items</b>	<b># of Participants</b>	<b>Mean</b>	<b>Median</b>	<b>Standard Deviation</b>	<b>Minimum</b>	<b>Maximum</b>
<b>16</b>	<b>124</b>	<b>7.3226</b>	<b>7.000</b>	<b>2.7246</b>	<b>0</b>	<b>16</b>

The item difficulty was well distributed between less challenging to more challenging with more items placed towards the less challenging end of the spectrum, and the higher the item difficulty the more people who selected the correct answer: 2 items were in the .10-.20 range; 1 item was in the .21-.30 range; 2 items were in the .31-.40; 2 items were in the .41-.50 range; and 8 items were in the .51-.60 range; and 1 item was in the .61-.70 range.

*Field Testing and Item Analysis – September 2011 – Virginia Tech*

In an effort to address external reliability, the concept inventory was also implemented at Virginia Tech (VT). Virginia Tech was selected because there are few similarities between ERAU and VT. The stand-alone graphics course at VT has been eliminated and the concepts have been integrated into a two semester introduction to engineering design course unlike at ERAU where the course is a rigorous stand-alone course. Also, the engineering student population at VT is much more diverse than that at ERAU. The reliability, Cronbach’s  $\alpha$ , of the inventory is .71; the generally accepted minimum for reliability is around .70. While still a bit low it is an improvement from reliability of the January 2011 pilot study. This improvement to reliability is supported by the fact that all of the test items have a positive biserial correlation and the item difficulties are well distributed.

There were a total of 850 students who participated in this pilot study. Twenty three inventories needed to be removed due to missing data. Participants responded to 16 multiple

choice questions. The concept inventory was administered as a paper based test, there were no time restrictions placed on the participants. JMetrik was used to conduct the item analysis. The instrument had a reliability of .71.

The test level descriptive statistics of the September 2011 field test are included in Table 14.

**Table 14: September 2011 Test Level Descriptive Statistics**

<b># of Items</b>	<b># of Participants</b>	<b>Mean</b>	<b>Median</b>	<b>Standard Deviation</b>	<b>Minimum</b>	<b>Maximum</b>
<b>16</b>	<b>827</b>	<b>7.4196</b>	<b>8.000</b>	<b>2.2647</b>	<b>2</b>	<b>15</b>

The item analysis resulted in a reliability coefficient ( $\alpha = .71$ ), item difficulties ranged from .1282 to .6929, and the biserial correlation with totals ranged between .0012 and .4666. All 16 items continue to have a reported positive biserial correlation.

Figure 5 compares the item difficulty for each test item for the August 2010 pilot test at Embry-Riddle Aeronautical University and the September 2011 field test at Virginia Tech. Interestingly, only two test items Q 9b and Q 10a were challenging to the students at Virginia Tech, all other questions fell within the easy and moderate range. Those two questions specifically refer to dimensioning concepts, a topic most students find challenging. The three questions Q 2, Q 4, and Q 6 refer to surface behavior and it would appear that the test item revisions from the pilot study have addressed the unclear test items.

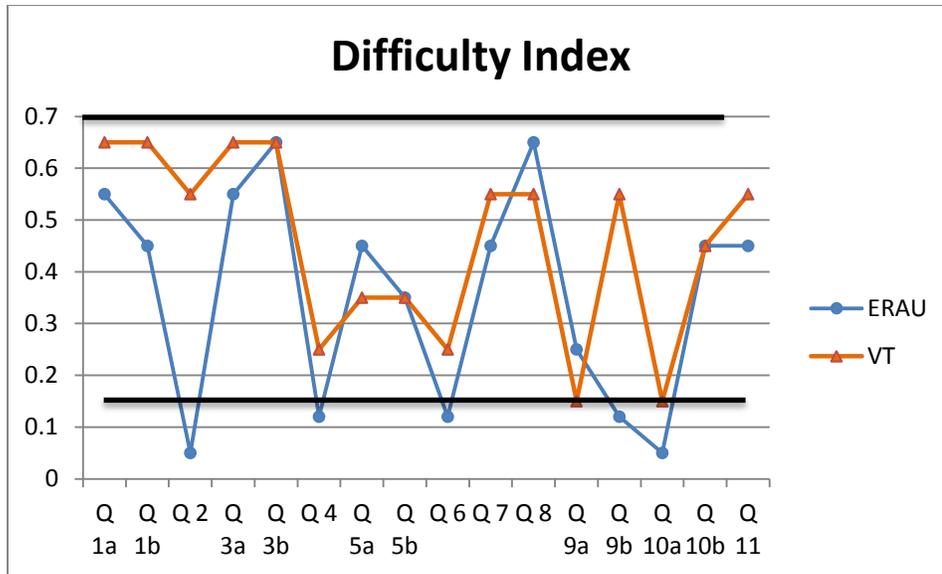


Figure 5: August 2010 and September 2011 Item Difficulty Indices

Table 15 shows the test question distribution as a function of difficulty which is well distributed between less challenging and more challenging with more items placed towards the less challenging end of the spectrum.

Table 15: September 2011 Item Difficulty Range

	<div style="display: flex; align-items: center; justify-content: center;"> <div style="text-align: center; margin-right: 10px;"><b>Most Challenging</b></div> <div style="flex-grow: 1; text-align: center;"> </div> <div style="text-align: center; margin-left: 10px;"><b>Least Challenging</b></div> </div>					
	.11 - .20	.21 - .30	.31 - .40	.41 - .50	.51 - .60	.61 - .70
<b>Item</b>	9a	4	5a	9b	2	1a
<b>Numbers</b>	10a	6	5b	10b	8	3a
					11	3b

*Field Testing and Item Analysis – September 2011 – North Carolina State University*

In an effort to address external reliability the concept inventory was also implemented at North Carolina State University, NCSU. The graphics course taught at NCSU is more closely aligned to the course taught at ERAU, in that both are stand-alone, semester long courses. However the university environment is more closely aligned to VT, as both are large land

grant research institutions. The reliability, Cronbach’s  $\alpha$ , of the inventory is .73; the generally accepted minimum for reliability is around .70. While still a bit low it is an improvement from reliability of the January 2011 pilot study.

There were a total of 402 students who participated in this pilot study. Eight inventories needed to be removed due to missing data. Participants responded to 16 multiple choice questions. The concept inventory was administered as a paper based test, and there were no time restrictions placed on the participants. JMetrik was used to conduct the item analysis. The instrument had a reliability of .73.

The test level descriptive statistics of the September 2011 field test are included in Table 16.

**Table 16 : September 2011 Test Level Descriptive Statistics**

<b># of Items</b>	<b># of Participants</b>	<b>Mean</b>	<b>Median</b>	<b>Standard Deviation</b>	<b>Minimum</b>	<b>Maximum</b>
<b>16</b>	<b>394</b>	<b>7.3959</b>	<b>8.000</b>	<b>2.3132</b>	<b>2</b>	<b>13</b>

The item analysis resulted in a reliability coefficient ( $\alpha = .73$ ), item difficulties ranged from .1294 to .6853, as detailed in Table 17. The biserial correlation with totals ranged between .0015 and .5374, all items continue to have a reported positive biserial correlation.

Figure 6 compares the item difficulty for each test item for the August 2010 pilot test and the September 2011 field tests at NCSU and VT. Test items Q 4 and Q 10a were challenging to the students at NCSU, all other questions fell within the easy and moderate range. One of the items refers to a surface theory question and the other refers to dimensioning concepts.

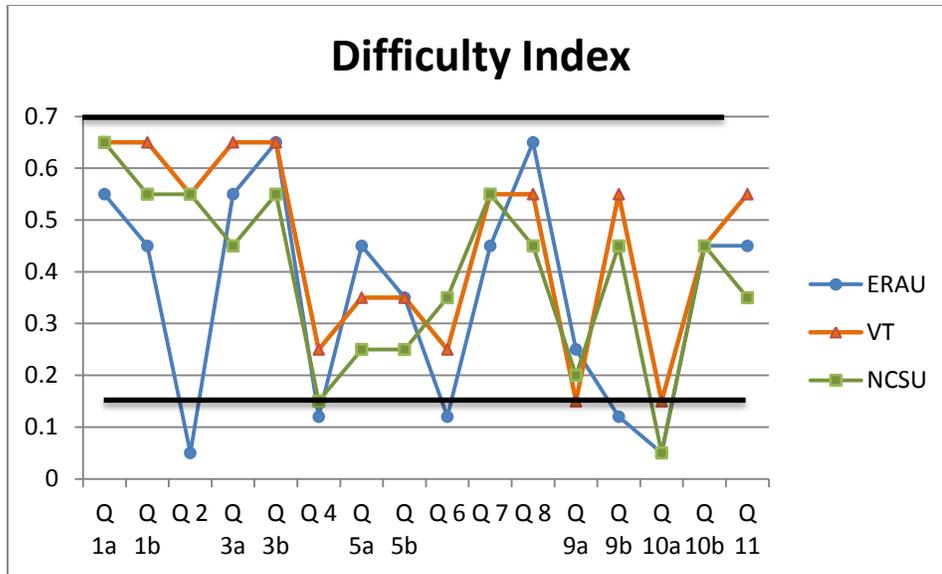


Figure 6: August 2010 and both September 2011 Item Difficulty Indices

Table 17 shows the test question distribution as a function of difficulty which is well distributed between less challenging and more challenging with more items placed towards the less challenging end of the spectrum.

Table 17: September 2011 Item Difficulty Range

	<div style="display: flex; align-items: center; justify-content: center;"> <div style="text-align: center; margin-right: 10px;"><b>Most Challenging</b></div> <div style="flex-grow: 1; text-align: center;"> </div> <div style="text-align: center; margin-left: 10px;"><b>Least Challenging</b></div> </div>					
	.11 - .20	.21 - .30	.31 - .40	.41 - .50	.51 - .60	.61 - .70
<b>Item Numbers</b>				3a	1b	
	4		6	9b	2	1a
	9a	5a	11	10b	3b	
	10a	5b		8	7	

The item difficulty continues to be well distributed between less challenging and more challenging with more items placed towards the less challenging end of the spectrum.

## **Limitations**

### *Expert Selection*

The panel of experts came from the same department at one university, and while this can be identified as a significant weakness, there are several factors which mitigate this. First, the experts range in educational background and professional experience. Several experts worked for several years in the aerospace industry, taught undergraduate engineering courses for at least five years, and have earned graduate degrees. Others have worked in the civil engineering industry and have taught undergraduate engineering courses for more than 20 years. Finally, the remainder of the experts have earned Ph.D.'s in engineering and have taught undergraduate engineering courses for over five years. The education of the experts is also diversified from aerospace engineering to civil engineering to mechanical engineering – providing a rich background of engineering graphics knowledge to draw from. Another contributing factor to the strength of this panel of experts is the diversity of cultural backgrounds represented; only two of the experts were American, one was from Africa, one was from China, one was from Venezuela, and one was from France. While it is less than ideal to have all experts from the same department – the diversification represented by the faculty does mitigate this limitation.

### *Initial Low Reliability of Concept Inventory*

The low reliability of the August 2010 field study was addressed with the January 2011 and two September 2011 field tests. This improvement can be attributed to several factors. First, all professors who proctored the concept inventory were given a detailed written test protocol. The instructions specified the specific dates and times to implement the inventory and professors were asked to give the inventory at the start of the class. The instructions also provided an explanation to the students that the field test was not testing their specific knowledge rather it was testing the instrument itself. Of the 125 concept inventories given 124 were completed, and this was also a vast improvement.

### *Different Testing Locations*

One weakness still present is implementing the inventory during the first week of classes when students have yet to become situated and comfortable with the class structure and environment. This unfamiliarity with the actual testing environment may interfere with student

focus and as such negatively impact their performance. Nor were the classroom settings and locations uniform across the sections. Some classrooms had limited writing space and students had to juggle placement of the test while completing it. This inconvenience may also have interfered with student focus or prompted students to rush completing it.

### *Sample Size*

The sample size in the January field test was smaller than hoped—only 124 were analyzed. This small sample size was addressed with the September 2011 field tests, in which over 1300 were implemented. Finally, the January 2011 field study was only implemented at one institution but in the fall 2011 field study was implemented at two different universities.

In the final field study of over 1300 students implemented in September 2011, 825 participants were from Virginia Tech, and 394 participants were from North Carolina State University. This final field study addressed two of the major weaknesses – a limited number of participants and the single institution implementation. In January of 2012 the concept inventory has been implemented as a pre-test in all sections of EGR 120 at Embry-Riddle Aeronautical University, post-test data will also be formally collected in April 2012 from the same sections of EGR 120.

## **Conclusion**

### *Review of Concept Inventory Development*

In the fall of 2009 experts were contacted to participate on the panel. The test concepts were generated and the test items were created throughout the following semester. The pilot study over the summer of 2010 provided rewording for test items and the distractors for the test items. The concept inventory was implemented for the next two semesters at ERAU, item difficulty, bi-serial correlation, and reliability analysis were calculated, and the concept inventory revised. In the fall of 2011, the concept inventory was implemented at other institutions.

### *Validity and Reliability*

Throughout the process of developing the concept inventory very close attention was paid to both validity and reliability. Content validity was addressed through: careful selection of the expert panel, researcher familiarity with the concepts under investigation, and detailed analysis

of student responses. Criterion validity, the predictive ability of the instrument, has not been investigated with this research. When no other test exists, criterion validity can be addressed by comparing the results to overall course performance or some other appropriate measure (Moskal et al., 2002; Steif & Dantzler, 2005). Overall course performance was not collected from any of the participants who completed the concept inventory prior to January 2011. However, criterion validity of the concept inventory will be available in May 2012 as overall course performance will be available from all subsequent participants.

Messick (1995) defined that construct validity has five types of evidentiary support: content, substantive, structural, generalization, and external. The five aspects of construct validity have been established. Content-related evidence concerns how well the instrument items reflect the content of the domain; the instrument was developed through a detailed test blue print that was derived from the panel of topics identified by the panel of experts. Substantive evidence is the relation between the data collected from the instrument and the theory. As demonstrated from the item analysis, the data generated is consistent with the theory. Structural evidence is indicated by how well the scores reflect the complexities of the theoretical model; this has been established by the item difficulty indices. Generalization has been addressed as the concept inventory has been given to freshmen engineering students from three distinct institutions. Finally, external evidence has been addressed by the multiple institution implementation of the graphics concept inventory. Reliability was addressed through multiple field studies across several different institutions and through the detailed item analysis of the inventory questions. The final reported reliability for the concept inventory is .73, which is above the baseline minimum.

### *What Wasn't Done*

The concept inventory has not been implemented as post-test, nor has student performance on the concept inventory been compared to final exam or final course grade. The predictability of the instrument has yet to be investigated. The primary focus of the research has been to create and establish a reliable engineering graphics concept inventory utilizing the Delphi method has been achieved

### *Future Research*

The next stage in this research is to implement the Engineering Graphics Concept Inventory as a pre- and post-test to 10 sections of engineering graphics at ERAU in Spring 2012. Data to be collected from this phase of the study are: tracking the gains on the concept inventory, comparing final exam performance to post-test score on the concept inventory, comparing the overall course grade to the post-test score on the concept inventory, and comparing student performance across different section. It is expected the concept inventory will be made available following the conclusion of the next phase of research when the criterion validity will have been established.

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The Predictive Ability of the PSVT:R and the MCT For Students' 3D Modeling Skills

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*This article would be submitted to the Journal of Engineering Education and would detail the predictive ability of the PSVT:R and the MCT for students 3D modeling skills. Parts of this research were presented as REES 2011 in Madrid, Spain and at the 2012 Engineering Graphics Mid-Year Conference in Limerick, Ireland.*

## Abstract

The emergence of stable, fast, affordable 3D modeling platforms such as CATIA, Pro-E, and AutoCAD have ameliorated some of the pedagogical challenges in teaching engineering graphics while providing a few new ones. Engineering graphics has historically been viewed as a challenging course to teach. A successful student must arrive with the suitable level of spatial visualization skill. Nevertheless many students are not and as such struggle with the basic concepts. 3D modeling platforms offer students the opportunity to manipulate a completed solid model in space – enabling them to actually see information not traditionally available in a standard engineering drawing, helping them to flesh out their understanding. However, simply completing 3D models will not properly develop spatial visualization skills, the software must be thoughtfully integrated into the curriculum so it complements the theories of spatial visualization. Two of the more common assessment instruments for spatial visualization are the Purdue Spatial Visualization Test: Rotations (PSVT:R) and the Mental Cutting Test (MCT). There has been little research on the predictive relationship between either of these two tests and the person's 3D modeling ability and maturity. There has been no research that has compared the relationship between the PSVT:R, the MCT, and the specification tree/model browser of 3D solid models. This article presents the results of such a study. 220 first year engineering students participated, and three CATIA projects were evaluated and compared to pre-test scores of the PSVT:R and the MCT. A significant relationship was found between high performance on the MCT and modeling ability, there was no correlation between the performance on the PSVT:R and modeling skill.

## Introduction

Undergraduate engineering students who have strong spatial visualization skills tend to be more successful in engineering (Miller, 1996). Until the mid-1990's, engineering graphics was a standard introductory course in many freshmen engineering curricula, due to shifting emphasis engineering graphics has been marginalized (Doyle, Smith, & Ieta, 2011). This modification is based on the mistaken assumption that most college freshmen are arriving already possessing the appropriate level of spatial visualization and are properly prepared to be successful in engineering, when in fact most are not (Jenkins & Burtner, 2007). Compounding this challenge is the addition of 3D solid modeling software into the limited engineering curriculum.

Spatial visualization is a skill fundamental to success in many technical fields including engineering and is often one of the gateway courses into engineering (Lubinski, 2010; Strong & Smith, 2002; Wai, Lubinski, & Benbow, 2009). Before the introduction of solid modeling, engineering students traditionally completed a two semester course sequence that allowed those with weaker visualization skills enough time to properly develop them. The challenges generated when 3D solid modeling was introduced into the curriculum are two-fold. First, time allocated to spatial visualization development needed to be reduced even further to generate space for solid modeling in the curriculum. Second, without solid visualization skills to aid in the decoding of solid models, students are unable to build a fundamental understanding of 3D modeling theory. This type of course organization may leave students frustrated, doubting their engineering abilities, and unprepared for the remainder of their math, science, and engineering curriculum.

Assessing student's spatial visualization skills has been a topic of interest in the field of engineering education research since the 1930's (CEEB, 1939; R. Guay, 1977; Heacock, 1938; Orth, 1941). Today, it is perhaps even more critical that incoming students' visualization skills are properly identified, given the limited space in the curriculum. Two of the more common instruments are The Purdue Test of Spatial Visualization: Rotations (PSVT:R) and the Mental Cutting Test (MCT). Since the 1970's the PSVT:R has been utilized for measuring spatial visualization abilities. Traditionally, this test has been used to predict a student's ability to solve hand-sketching problems; there is over thirty years of research to support this instrument's validity in that particular respect (R. B. Guay, 1980). There has been some limited research on

the PSVT:R and 3D modeling ability, none have found a significant relationship (Ardebili, 2006; Hamlin, Boersma, & Sorby, 2006; Sorby, 1999, 2000). Since the 1930's the MCT has been employed for measuring the ability to discern a 2D cross section of the provided 3D shape. This instrument also has decades of research supporting the instrument's validity. There has been very limited research on the relationship between performance on the MCT and modeling ability there have been some significant findings (Feng, Morgan, & Ahmed, 2004; Hamlin et al., 2006; Sorby, 1999, 2000; Tsutsumi, 2010). This is not surprising as to construct solid models one must be able to discriminate the 2D cross section from the provided 3D information.

While there have been many studies which have looked into the relationship of the PSVT:R and spatial abilities as well as the relationship of the MCT and spatial abilities, this research is no longer the most appropriate to the current engineering graphics course structure and organization. Students are now expected to develop two sets of distinct skills- spatial visualization and 3D modeling in engineering graphics. To better prepare engineering graphics courses to student skills and knowledge students need to be evaluated for both skills.

The purpose of this research is to focus on the relationship between the PSVT:R, the MCT, and 3D modeling abilities. Of particular interest is whether either instrument is more strongly correlated to 3D modeling abilities. It is proposed that both instruments will need to be implemented to fully evaluate the potential for success in engineering graphics as both are measuring different skills the PSVT:R is measuring the ability to rotate an unknown object in space and the MCT is measuring the ability to identify the appropriate 2D profile of a given solid.

### **Background of Engineering Design Graphics Education**

Engineering drawing has been the primary method of conveying design intent and structure for the past two centuries in the United States (Mohler, 2007). Until 1955, following the publication of the Grinter Report (1955), freehand sketching was identified as the language of engineering (Orth, 1941; Rising, 1948; Svensen, 1948) and as a major contributor to the engineering design process (Barr & Juricic, 1994; Sorby, 1999). The United States Military Academy is credited with the formal introduction of engineering design graphics education into the undergraduate curriculum with course titled "Drawing" in 1807 followed by "Descriptive Geometry" in 1816 (Barr & Juricic, 1994).

Monge's scientific projection method, as described in his 1795 published work *Geometrie Descriptive*, continues to underpin the theoretical structure of the graphics curriculum. So influential was Monge's work that textbooks still use it *today*. There is a deep sense of history and tradition embedded in the instruction of engineering design graphics that is resistant to revision and change. By 1900 drawing standards had been established, a curriculum developed that would provide the theoretical frame for modern engineering graphics education, and textbooks were written and refined.

1900 to 1950 marked the formative stage for engineering design graphics education. In the five decades that followed there was a steady growth of collegiate institutions that taught engineering design graphics (Barr & Juricic, 1994; Harris & Meyers, 2007; Meyers, 2000; Sorby, 1999).

In the 1950's, the U.S. government along with several universities, in particular Massachusetts Institute of Technology, MIT, began developing and testing giant computers, the basis of which eventually would become graphics-based workstations. All modern Computer-Aided Design CAD/Computer-Aided Manufacturing CAM software can be linked back to three independent sources: Arizona State University, MIT, and McDonnell Douglas. In 1957, an Arizona State University graduate developed the first commercial computer-aided manufacturing software system, PRONTO (CADAZZ.com, 2007). "Sketchpad" was developed by MIT's Lincoln Laboratory in 1960, and is considered the first computer-aided design software (CADAZZ.com, 2007). Also in 1960, McDonnell Douglas developed two dimensional simple algorithms which laid the groundwork for their in-house 3D modeling software (Harris & Meyers, 2007).

However, it was not until the early 1980's and the parallel development of personal computers and AutoCAD that computer-aided design became an affordable, mainstream option for undergraduate education in the United States (Barr & Juricic, 1994; Harris & Meyers, 2007).

Due to a forward thinking and progressive business plan AutoCAD led in sales and in industry preference from the mid 1980's to the mid 1990's (CADAZZ.com, 2007). Computer-aided design software, most commonly AutoCAD, began to be integrated into the undergraduate graphics curriculum during the mid-1990's. The software was often mistakenly categorized as a modern drafting tool, analogous to the drafting board and T-square. It was not viewed as an integral or complementary part of the engineering design graphics curriculum, nor as part of the

engineering design process, and therefore was not thought to require any specific pedagogical development from the faculty. For many years CAD has primarily been taught driven by a “pick and click” mentality instead of being formed by legitimate CAD theory.

This critical misjudgment can be attributed to several sources: the Grinter Report, the background and education of the engineering professors themselves, the research selected for funding by the U.S. government, and the very structure of AutoCAD. Published post WWII, the Grinter Report (1955) called for engineering education to adopt a more analytical science-based approach with less emphasis on “skills” based courses. While engineering graphics was not specifically targeted for removal, its position in the undergraduate curriculum was notably diminished. Having been displaced by more math and science curricula, engineering graphics was no longer recognized as the scaffold to the design process (Meyers, 2000). Second, the push behind the Grinter report was not to address any specific shortcoming in collegiate education rather it was to support military research. Therefore to be competitive for federal research grants, universities needed to emphasize engineering science over practice-based engineering (Seeley, 1999). Third, most educators teach as they themselves were taught (Lortie, 1975), and many teaching in the late 1980’s and 1990’s were educated with the analytical engineering science based paradigm defined by the Grinter Report. Few would recognize the far reaching and revolutionary impact that computer-aided design software could have on the engineering design graphics curriculum and engineering design because of what they were taught to educationally value and respect – analytic science based applications over practice-based skills. Instead, CAD was merely viewed as a tool, an extension or modernization of the drafting board (Barr & Juricic, 1994). Few faculty learned the software beyond the rudimentary navigation skills which further hindered the impact of the software on the graphics curriculum. Finally, AutoCAD’s early success (Harris & Meyers, 2007) and modeling platform (it was a 2D instead of a 3D platform) contributed to the misclassification of its educational potential. The original software’s true strength was its stability in 2D drafting and not 3D applications, and the transition from 2D elements to 3D solids in AutoCAD was not transparent or easily accomplished. In fact, it would be two decades before AutoCAD would modernize its modeling platform.

In the late 1990’s and early 2000’s computer-aided design underwent a significant change. Moderately priced, easy to use, and stable PC based, 3D solid modeling programs began

to emerge: ProE, Unigraphics, and CATIA. Until then, the market had been dominated by software with primary 2D modeling platforms: AutoCAD, AutoSketch, and MicroStation. It seems that with a few exceptions (Michigan Technological University, North Carolina State University, Ohio State University, and Purdue University), these new modeling programs were simply added into the graphics courses as the 2D programs were in the 1990's with little thought to their impact or effect. They were simply viewed as the most recent drafting "tool." The limited amount of research from 1990 until present indicates how the misclassification of 3D modeling programs' pedagogical potential continues to this day.

CATIA is the 3D parametric modeling software selected for this research. A brief description of CATIA its development and history is provided in the following paragraph.

Originally named CATI, CATIA was developed in 1967 by Dassault Aviation to meet specific aviation requirements: aerodynamics and stress analysis through theoretical computation and numerical control machining of parts (CATIA.IN, 2012). In 1975, Dassault Aviation acquired CADAM the 2D drafting program developed by Lockheed providing CATIA with a 2D drafting platform to complement the nascent 3D modeling platform (Bernard, 2003). This is an important milestone in the development of software. AutoCAD and AutoSketch will not provide a combined 2D/3D platform until 20 years later (CADAZZ.com, 2007) and provides CATIA the opportunity to develop an extremely robust, powerful, and efficient software capable of producing dimensionally accurate digital mock-ups well before any other company. By the mid-1990's CATIA had become the software of choice for the Boeing Corporation, General Dynamics Electric Boat Corporation, BMW, Grumman, and Daimler-Benz. Today CATIA is the premier parametric 3D modeling software; it provides a seamless transition between 2D drafting and interactive 3D modeling many competitor's software does not (Bernard, 2003).

## **Review of Current Literature**

A comprehensive review of the literature in the field identified the primary areas of focus as: the importance of spatial visualization, the definition of spatial ability, spatial visualization as predictor for success in STEM, gender differences in spatial visualization abilities, correlation between spatial visualization skills and specific childhood activities, the assessment of spatial visualization instruments, and the interaction between spatial visualization and 3D modeling structures. Each of these primary areas of research are summarized in the following sections.

### Importance of spatial ability

Spatial visualization is a fundamental skill to *all* of engineering, but this is often not recognized in the academy. Orth (1941), Rising (1948), and Svensen (1948) identified the importance of visualization by positing that it is the *language* of engineering. McKim's (1980) model of spatial visualization, Figure 1, presents three overlapping circles seeing, imagining, and drawing. The overlapping areas can be seen as symbiotic. When seeing and drawing overlap, seeing is facilitated by drawing and drawing strengthens seeing. Where drawing and imagining overlap, "drawing stimulates and expresses imagining, while imagining provides impetus and material for drawing" (McKim, 1980, p. 6). When imagining and seeing overlap, imagination provides direction for seeing and seeing provides the 'raw material' for imagining. McKim theorizes that the deepest visual thinking occurs when seeing, imagining, and drawing "merge into active interplay" (1980, p. 6), represented by the shaded black area; where seeing facilitates drawing, drawing stimulates and expresses imagining, and imagining provides the direction for seeing.

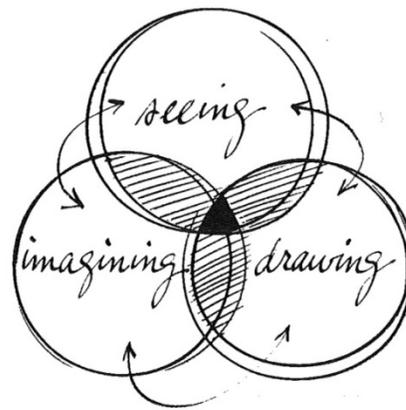


Figure 1: McKim's Model for Visual Thinking (McKim, 1980)

The Grinter Report (1955) even acknowledged that "graphical expression is both a form of communication and a means for analysis and synthesis....The emphasis should be on spatial visualization, experience in creative thinking, and the ability to convey ideas, especially by free-hand sketching, which is the normal mode of expression in the initial stages of creative work" (p. 16). Contero, et al. (2006, p. 4) explain the relationship between design, visualization and drawing as, "design is done essentially in the mind and drawings are pictorial extensions of the mind." Mackenzie and Jansen (1998) that "[as] the vernacular of industry, technical design,

drafting, and drawings are essential to the curricula of all technology, engineering, and design programs” (p 61). Bertoline, Wiebe, Miller, and Mohler (2002) describe that the design process as 92% graphically based, with the remaining 8% divided between mathematics and written and/or verbal communication. The published research indicates that spatial visualization is an essential skill for all engineering students and possibly provides a critical overarching connection between the broad concepts of engineering often incorrectly viewed as disaggregate, isolated pieces of their engineering education.

### Definition of spatial ability

There are three well-accepted definitions of spatial ability, Guttman’s Radex Model of Intelligence (1954), Smith’s Hierarchical Structure of Human Abilities (1964), and McGee’s refinement of spatial visualization and spatial orientation (1979). Guttman (1954) using Thurstone’s (1950) work as a guide created the radex model of intelligence, Figure 2. He placed spatial ability with equal prominence as verbal and numerical intelligence. Spatial ability was divided into three factors of intelligence,  $S_1$ ,  $S_2$ , and  $S_3$ . The general factor of intelligence,  $g$ , is located at the center of the radex.

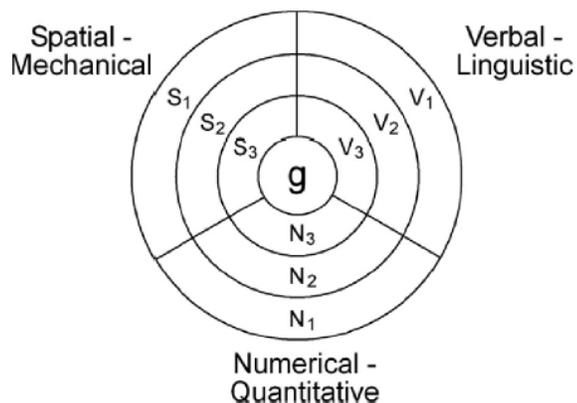


Figure 2: Example of the radex model of intelligence (Guttman, 1954)

Smith (1964) is credited with further classifying the factors as ( $S_1$ ) mental rotation – the ability to recognize an object if moved to different orientation or angles; ( $S_2$ ), spatial visualization – the ability to recognize the parts of an object if they were moving or displaced from their original position; and ( $S_3$ ) spatial perception – the ability to use one’s body orientation to relate to questions regarding spatial orientation. These are situated in the specific factors

region in Figure 3. Unlike Guttman’s radex arrangement, Smith presented his in a hierarchical model. The verbal-numerical factor is identified as v:ed and the spatial-mechanical-practical factor is labeled as k:m.

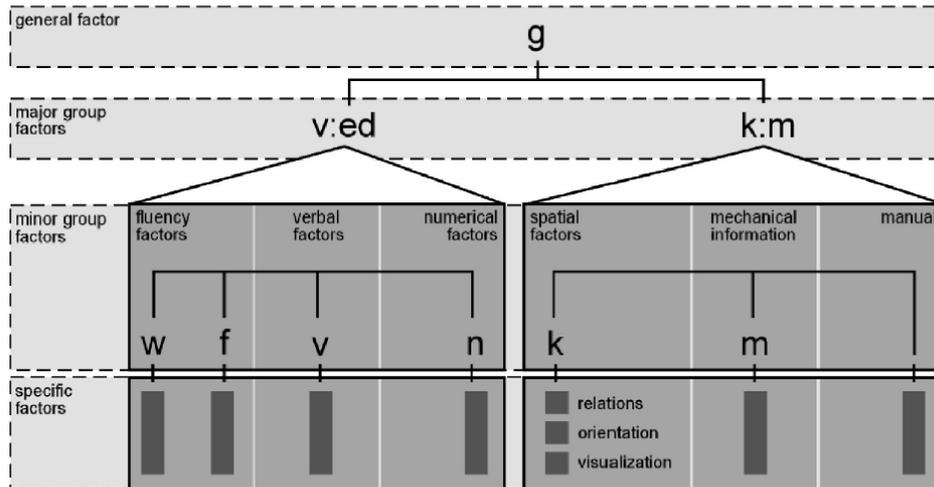


Figure 3: Hierarchical structure of human abilities (Smith, 1964)

McGee (1979) refined the definition of spatial orientation and spatial visualization. He defined spatial *orientation* as “the comprehension of the arrangement of elements within a visual stimulus pattern, the aptitude for remaining unconfused by the changing orientations in which the configuration may be presented, and the ability to determine the spatial relations in which the body orientation of the observer is an essential part of the problem” (McGee, 1979, p. 4). He defined *spatial visualization* as “the ability to manipulate, rotate, twist, or invert pictorially presented visual stimuli. The underlying ability seems to involve a process of recognition, retention, and recall of a configuration in which there is movement among the internal parts of the configuration, or of an object manipulated in three-dimensional space, of the folding or unfolding of flat patterns....” (1979, pp. 3-4).

These models of spatial visualization provide an overview of the timeline for the development of the theory of spatial visualization. Guttman (1954) and Thurstone (1950) placed spatial visualization with equal importance as numerical and linguistic intelligences. Smith (1964) refined the three spatial factors and provided a better organizational structure to defining the relationship of human intelligence. Lastly, McGee (1979) contextualized the

classifications of spatial visualization and orientation providing the seminal definitions for the field.

### **Spatial visualization as a predictor for STEM success**

While spatial visualization has been long believed to be a successful predictor in math, science, and engineering coursework, the published research indicates the relationship is not so easily demonstrated. Smith (1964) theorized in his book that spatial visualization skills directly impact mathematical, science, and social abilities. Shea, Lubinski, and Benbow (2001) found that spatial ability was more accurate in predicting students' selection of math-science in high-school and college courses, and for a career than either the math or verbal sections of the SAT's. Webb, Lubinski, and Benbow (2007) were able to replicate Shea, et al. (2001) findings that spatial ability is a better predictor than the SAT's for high-school STEM course preference, STEM college major selection, and intended STEM occupation. Wai et al. (2009) also found that through their analysis of the data collected for the longitudinal study, project TALENT, that spatial ability is a salient psychological characteristic among adolescents who would eventually earn advanced educational and occupational credentials in STEM.

Bishop (1978) used the Piagetian visualization scheme (1954, 1960) as a frame for his meta-analysis of the spatial visualization research publications to describe the challenges elementary, middle, and high school students encountered when attempting to conceptualize posed three dimensional scientific models and to provide recommendations. Piaget believed that spatial skills are developed in three periods. The first phase, topological skills are primarily two-dimensional and are acquired by children aged three to five. The second stage, projective spatial ability, is three-dimensional and involves visualizing familiar objects and perceiving how they would appear from different angles. This is usually acquired by adolescence. In the third period of development, people are able to visualize the concepts of area, volume, distance, translation, rotation, and reflection; they are able to combine measurement concepts with their projective skills.

Do (2002) found a relationship between improved science and engineering understanding and spatial skills and provided recommended classroom activities to foster the growth of spatial skills. Tracy (1990) also found a significant relationship between fifth graders who had high spatial ability and higher science achievement scores. Bodner and Guay (1997) demonstrated a

correlation between increased problem-solving skills and higher spatial visualization abilities of college chemistry students. It appears the research on the relationship between science and spatial visualization has been more successfully demonstrated than the relationship between mathematics and spatial visualization.

Battista, Wheatley, and Talsma (1982) did not find a significant relationship between spatial visualization skills and achievement in geometry. Nor did Peters, Chisholm, and Laeng (1995) find a correlation between academic performance in mathematics and better spatial visualization. However, Shea et al. (2001) conducted a longitudinal study on high performing 13 year-olds and did find that spatial ability did significantly contribute overall success in mathematics at 5, 10, and 20 years after initial identification.

While the research on the relationship between STEM and spatial visualization do not provide unambiguous findings it does appear that longitudinal studies are more reliable in demonstrating a connection.

### **Gender differences in spatial visualization**

Through the 1960's and 1970's much of the research on spatial abilities focused on the apparent performance difference between males and females as primarily a function of gender (Medina, Gerson, & Sorby, 1998; Nemeth & Hoffmann, 2006; Peters et al., 1995). Veurink et al. (2009) reported that while females are weaker than males in rotation tasks they are equal in other tasks and even outperform males in spatial memory activities. Sorby and Baartmans (1996) found that more females than males entering college had not yet developed their spatial skills to the level to be successful in engineering. Sorby and Baartmans addressed this by creating a course to foster their spatial skill development and have reported successful results for the last 15 years (Sorby & Veurink, 2010). While Janssen and Geiser (2010) demonstrated no gender difference in performance when solving the Mental Rotation Test and Cube Comparison Test, their research did indicate a difference in solution strategies utilized by males and females. Females tended to prefer the analytic method, which involved comparing individual details of the stimulus, while the males preferred the holistic method which involved comparing the whole stimulus. In 1979, when McGee published a literature review on the field of psychometric studies on spatial visualization, research at the time mostly centered on two aspects 1) defining the facets of spatial visualization and 2) exploring the relationship between gender, environment,

and spatial visualization. McGee's findings (1979) laid the foundation that spatial visualization was influenced by environmental factors and the activities children choose to pursue instead of gender.

### **Spatial visualization skills and childhood activities**

By the mid 1980's the locus of research on spatial visualization shifted from gender as the primary factor for performance difference to the impact of childhood activities. Tracy (1987) questioned whether specific childhood activities better fostered improved spatial skills, and conducted a literature review of the field, her results indicated a weak connection between play with Lego's, tinker toys, and transportation toys. Tracy cautioned these findings were tenuous at best, and additional research needed to be conducted to strengthen the argument. In 1990, Tracy conducted a correlation study and did find a connection between certain childhood activities, higher spatial visualization skills, and higher achievement in science. Deno (1995) developed a Spatial Experience Inventory that contained 312 items divided among academic subjects, non-academic activities, and sports. Deno found a correlation between Lego play, Tinker Toys, Erector sets, watching Sesame Street and higher spatial visualization skills. Medina et al. (1998) only found a significant correlation between play with Lego's and stronger spatial visualization skills. Allam (2009) replicated previous findings that play with construction toys, Lego's, tinker toys, and Erector sets strengthened spatial skills.

### **Development and assessment of spatial visualization instruments**

This research will focus on the development of two of the better known instruments, the Purdue Spatial Visualization Test: Rotations (R. Guay, 1977), and the Mental Cutting Test (CEEB, 1939). After the completion of a thorough review of the salient research on spatial visualization tests these two instruments were selected as they best aligned with the area of focus defined within this research.

When first released the PSVT:R developed by Guay in 1977 received some critiques about validity. In 1980, Bodner and Guay published a detailed rebuttal addressing these critiques. They identified six factors supported by the literature which strongly indicate the PSVT:R is measuring exactly what Guay intended: precision of the mean and standard deviation when given to different groups of the sample population, the strong correlation between the

PSVT:R and the MCT, the continued presence of differences in performance by gender as demonstrated by other spatial visualization measures, a correlation between the PSVT:R and student performance on highly spatial tasks, a correlation between the PSVT:R and problem solving tasks requiring cognitive restructuring and disassembling strategies, and the results of the PSVT:R has been shown to be the least likely to be complicated by analytical processing. Figure 4 is a sample problem from the PSVT:R.

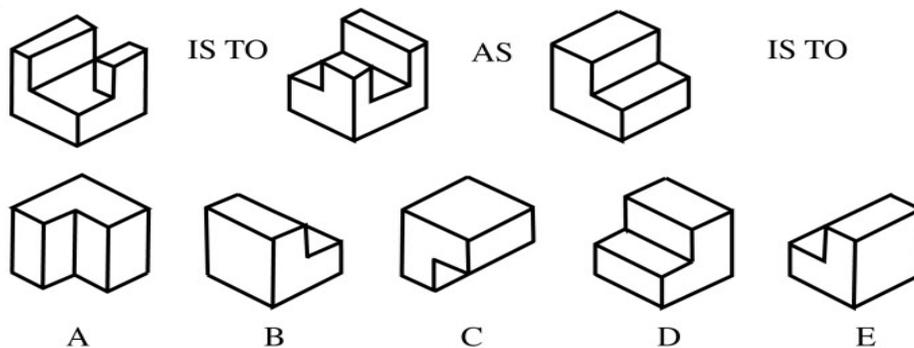


Figure 4: Sample Question from PSVT:R

Branoff and Connolly (1999) added coordinate axes to the images and replicated Guay's findings. Yue (2006; 2008) added an isometric project box around the target figure and provided redrawn, cleaner images for all the figures. Yue's results for both studies also replicated previous published results. Nearly 30 years after Bodner and Guay's rebuttal Gorska and Sorby (2008) echo their argument that the PSVT:R assesses a person's ability to visualize rotated solids.

The Mental Cutting Test (MCT) was developed for the College Entrance Examination Board (CEEB, 1939). The reported reliability, Cronbach's  $\alpha$ , of the MCT has been reported .87 and .92 for undergraduate chemistry and engineering students (T. J. Branoff, 2000; Caissie, Vigneau, & Bors, 2009). Tsutsumi has conducted research with the MCT for the last 10 years using the MCT as a predictor of spatial ability – she has repeatedly shown that students who do not perform well on the MCT cannot “see” the solid in their minds-eye to ever discern the resultant cross-section. She has replicated these results with Japanese female college students (Tsutsumi, 2004; Tsutsumi et al., 1999) and with Austrian and German college students (Tsutsumi, 2005; Tsutsumi, Schroecker, Stachel, & Weiss, 2005). Figure 5 is a sample problem from the MCT.

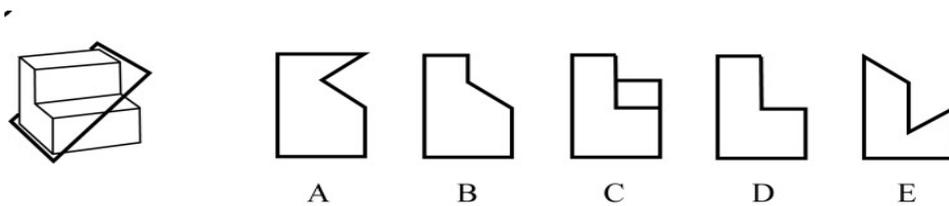


Figure 5: Sample Question from MCT

### **Interaction between spatial visualization and 3D modeling structures**

Publications on 2D sketching activities, spatial ability, and the possible interaction with 2D/3D modeling began appearing in 1994. Each article is briefly summarized and presented chronologically.

Norman (1994) cautioned that computer-aided modeling needed to be integrated slowly and thoughtfully into the engineering graphics curriculum. He warned that while it may provide an additional tool to aid students in developing their spatial visualization skills, it may also prove to be a hindrance and that may further divide high performing and low performing students. He proposed that the most promising integration of CAD would be twofold: “the development of interfaces that 1) make apparent hidden links and logical contingencies and 2) that allow the user to perform spatial and intermediate operations on the interface rather in the head” (Norman, 1994, p. 203). Interestingly the 3D modeling software available today provides this exact type of interface.

Devon, Engle, Foster, Sathianathan, and Turner (1994) implemented 3D software into their graphical communication class. They used the Mental Rotation Test as a pre- and post-test, while there was an improvement in overall scores, they were not statistically significant for any of the three trials. The authors reported that while the statistics did not support the claim, they believed it was the integration of 3D into the curriculum that improved the scores, citing increased student interest in 3D modeling. A weakness in this study is the lack of analysis on any modeled artifacts.

Duesbury and O'Neil (1996) studied the effect of manipulating 2D and 3D wireframe models on students visualization skills. Participants completed four types of visualization tests: Test of Paper-Folding, Surface Development Test, Test of 3D Shape Visualization and the Flanagan Industrial Test-Assembly. Reported results indicated statistical significance between

the experimental and control groups, indicating that spatial ability can be improved through practice that enables the learner to see the relationship between 2D and 3D features. However these results were tied to a self-report survey and again no student produced models were evaluated and compared back to test performance.

In the late 1990's Sorby (1999) conducted a study to ascertain whether there was a connection between a student's spatial ability and aptitude for 3D solid modeling software/2D drafting software. To establish their baseline spatial ability, students were given three tests: the PSVT:R, the MRT, and the MCT. Students were asked to complete a difficulty/time required questionnaire for the solid modeling project; however Sorby did not evaluate the structure or approach students used to construct their solid models. Instead she used the students' self-assessment from the questionnaires to determine whether or not a relationship existed. The findings of her study included: (1) the MCT is a better predictor for students 3D solid modeling ability, (2) none of the three tests administered were a good predictor for students 2D drafting (software) ability, and (3) working with 3D modeling software without proper instruction and guidance does not improve spatial abilities as well as completing hand sketching activities.

Scales and Kirby (2001) explored the connection between 3D modeling, previous modeling experience, and engineering graphics sketching ability. They compared the final CAD project grade, student performance on the sketching portion of the final exam, and student score on a post-test questionnaire about the modeling software. The CAD final project was not assessed on the modeling approach used to create the solid model; instead it was evaluated on 2D based criteria: a generated multi-view drawing, the correctness of the titleblock, and ANSI appropriate dimensions. They did not directly evaluate the 3D modeling abilities of their students, rather they evaluated their students' abilities to generate 2D artifacts with the modeling program. This is a clear example of the misclassification of the proper application of 3D modeling software (using it mostly as a 2D application) and its possible connection with spatial ability. They found no significant relationship between spatial ability and the quality of the generated 2D artifacts.

Elrod and Stewart (2004) encountered a connection between hand sketching, 2D CAD, and 3D modeling when they redesigned their freshmen engineering graphics course. They originally arranged the course to teach only hand sketching (4 weeks) and 3D modeling (8 weeks) but found students were not able to make the intellectual leap from 2D hand sketching to

identifying the 2D profiles needed for the creation of 3D solid models. Based on this anecdotal data they recognized the course needed to be restructured into the three primary topics of hand sketching (4 weeks), 2D CAD instruction (4 weeks), and 3D CAD instruction (4 weeks). While Elrod and Stewart acknowledge the importance of the connection between 2D and 3D by specifying one of the three final course outcomes to be “freehand sketches and CAD are used to model 3D objects” (Elrod & Stewart, 2004), this decision was based on anecdotal data and not formal research.

Feng, et al. (2004) found in their research that the difficulties encountered by many students with 3D modeling could be directly related to weak spatial visualization skills. They used a web-based interactive tutorial to help first year engineering students improve their spatial visualization skill, and student performance gains were tracked with a pre- and post-test assessment with the Mental Rotation Test (MRT), and the Mental Cutting Test (MCT). They did not look at the structure of the solid models the students created; instead they simply compared student performance on the MRT and the MCT. They extrapolated that strengthening students’ spatial visualization skills would improve their 3D modeling skills as the two skills are innately intertwined.

Ardebili (2006) integrated 3D modeling software to specifically address students’ abilities to visualize orthographic projection, rotation about one or more axes, reflection and symmetry. The PSVT:R was implemented as a pre- and post-test for both the experimental and control group, and statistically significant differences are identified. The authors cautioned that merely picking and clicking through modeling software would not improve students’ skills, echoing Sorby’s (1999) earlier sentiment. Student performance was only compared through performance on the PSVT:R and not any analysis of any student created solid models.

Contero, et al. (2006) used the Mental Rotations Test (MRT), to gauge student learning gains. Students identified with weaker visualization skills were given six hours of remedial, web-based, interactive, 3D solid models, and tutoring during the first week of the semester. The sketching activities however were not paper based. They were completed with a Tablet-PC. This research, while using some 3D modeling in its intervention, did not consider the possible connection between the 2D sketching activities and the development of the 3D solid models. Students only completed 2D sketches on a tablet – no solid models were created.

Hamlin, et al. (2006) specifically set out to research the influence of spatial ability on their ability to 3D model. They used the PSVT:R and the MCT to test students' levels of spatial ability. Students were given five 90 minute classes dedicated to hand sketching activities and three classes dedicated to teaching the 3D software package. Students were asked to complete a questionnaire on the following topics: previous 2D and 3D CAD experience, amount of time required to complete the assignment, amount of help needed to complete the assignment, how they rated the assignment, and how they compared their modeling abilities against their peers. Again the actual modeling structure and approach was not evaluated, only student self-reports were compared against the MCT and the PSVT:R. They did not find a relation between spatial ability as measured by the PSVT:R and 3D modeling ability. They did however find that a student's spatial ability as measured by the MCT did significantly influence their ability to learn and use 3D solid modeling software.

Tsutsumi (2010), using the Mental Cutting test as a pre- and post-test for Japanese college females reported correlation between higher scores on the MCT and performance on certain 3D CAD modeling assignments. Tsutsumi found a correlation in terms of cognitive abilities relating to 3D objects drawn in a 2D plane (isometric views) and higher performance on the MCT pre-test, higher increase on the MCT post-test, increased project grades, and better overall course grade. What is unclear in the publication is the evaluation criteria for the modeling assignments and what specifically was identified as a comparison.

As indicated by this review, the published research, while beginning to address the importance of 3D solid modeling and its relationship with spatial visualization skills, has not truly evaluated the 3D artifact as produced by the student. Much of the research is either focused on the produced 2D article or based on students' self-assessment. This can be traced to how CAD was initially viewed by faculty and subsequently integrated into the engineering graphics curriculum- as a tool, an extension, or replacement of the drafting board. This is additionally compounded by the lack of understanding between 3D modeling software and how a student's spatial ability governs their structuring of a 3D solid model.

The type of research that needs to be conducted is exploring the relationship between 2D spatial visualization skills and 3D solid modeling abilities. While there has been some research (Feng et al., 2004; Hamlin et al., 2006; Sorby, 1999; Tsutsumi, 2010) that has brushed up against this relationship, none of it has directly investigated it. Instead of focusing on 2D generated

artifacts, and self-reported data focusing on the amount of time required and perceived difficulty, the research needs to quantify the solid model itself. While on the surface quantifying the solid model can seem overwhelmingly complex – as there is more than one correct way to create a solid model. However thoughtful construction of an evaluation rubric based on a solid understanding of the theory of CAD and 3D modeling can go a long way to identifying the overarching concepts indicative of a higher order modeling framework. Using the MCT as a pre-score assessment would help to establish the baseline modeling abilities.

The research reported in this manuscript will investigate this relationship between 2D spatial ability and 3D modeling skills. The MCT and PSVT:R will be used to establish a pre-test baseline. Typically both of these tests are strictly timed. The time limit simply parses between students who use either the analytic or holistic method for solving visualization problems. The analytic method involves rotating the object in stages or in parts while the holistic method involves rotating the image as an organized whole in one step. The holistic method is indicative of quicker visualization skills; however research (Janssen & Geiser, 2010) has indicated that the holistic method is not any more accurate than the analytic method when the time constraint is removed. Students were asked to mark on their tests how far they were able to complete the test under the standard time limit. They were then allowed enough time to complete the rest of the test. Student performance on the PSVT:R and the MCT (untimed) were compared against the 3D solid model generated. Models were evaluated for approach, structure, accuracy, parity, and creativity.

The review of literature seems to indicate a relationship between the MCT and 3D modeling skills. In 2004, Feng et al. theorized a connection between performance on the both the Mental Rotation Test and the Mental Cutting Test and 3D modeling skills of first year engineering students. While their research did not directly report a connection, it laid the initial foundation for the MCT as a predictor in 3D modeling performance. Hamlin et al. (2006) demonstrated that the MCT was more effective than the PSVT:R in measuring a student's ability to learn and use 3D modeling software. Finally, Tsutsumi (2010) used the MCT as a pre- and post-test evaluation to track Japanese female college students improvement on 3D modeling assignments and did find a positive correlation between the score on the MCT and quality of 3D model produced. Using the previous research as a guide the following research questions have been identified:

1. How strongly does a student's performance on the PSVT:R correlate to their ability to develop robust 3D modeling framework?
2. How strongly does a student's performance on the MCT correlate to their ability to develop robust 3D modeling framework?

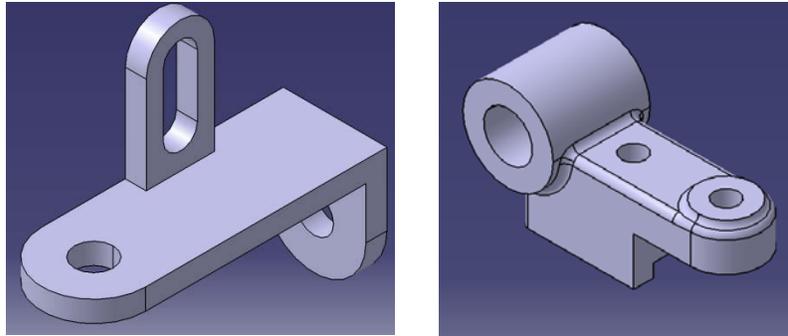
## **Methods**

### *Present Study*

To investigate the correlation between a person's performance on the MCT, the PSVT:R, and the quality of their 3D modeling structure (the specification tree\the model browser), a study was conducted at Embry-Riddle Aeronautical University in the fall of 2011. This research comprised students enrolled in an introductory graphical communications course, EGR 120.

### *Task*

In addition to the regularly assigned CATIA solid modeling assignment students were asked to complete two common modeling assignments for this study, Figure 6. The first solid model was given during the first week of modeling instruction and the second was given during the fifth week of modeling instruction. These two solid models were chosen for several factors. The first model, the image on the left, while not being overly complex had several elements, the two concentric holes, the three rounded ends, and the elongated hole on the top vertical surface, that would quickly reveal the level of modeling maturity and understanding. The second model, the image on the right, incorporated several features from the original model the two concentric holes and the rounded ends but also had several new elements the raised boss, embedded, elongated cylinder, lower channel, and the finishing fillets which again would reveal the modeling maturity.



**Figure 6: Individual CATIA Solid Modeling Projects Provided for this Study**

Students were also given a common CATIA final project to complete as shown in Figure 7. While the first two modeling projects were able to examine a student's level of modeling maturity and knowledge in reference to individual parts, it was important to also explore a student's modeling approach to building and managing a multi-part assembly. The individual parts were evaluated and students received feedback, for this research only the modeling intent and structure of the assembly's specification tree were assessed.



**Figure 7: CATIA Final Project Provided for this Study**

These two models and the common final project were given as part of the students' regular assignments; only the course instructors knew these three projects were to be evaluated for the purposes of this study. For each assignment, the specification tree was of particular interest and was appraised closely for it documents the modeling approach and structure. Figure 8 shows two specification trees for the first CAD project. The image on the left denotes a lower level understanding of modeling as they divided the model into three distinct pieces and all detail

features, such as the corner fillets and holes, are embedded in the base sketches. This type of modeling indicates a cursory understanding of the software, as many of the more direct modeling commands were not selected. This type of approach does not lend itself well to modification and revision and is often fraught with update errors.

The image on the right depicts a much higher level understanding of modeling and organization, this can be observed by the placement of the details as features on the specification tree instead of embedded in the lower level sketches. It can also be seen by the order of the steps indicating a thorough understanding of the modeling process and how to best leverage it. All three projects were evaluated using the solid modeling rubric consisting of five primary sections and is shown in Figure 9. The rubric was previously developed and refined over several semesters by Steinhauer to evaluate student homework for prior courses of EGR 120.

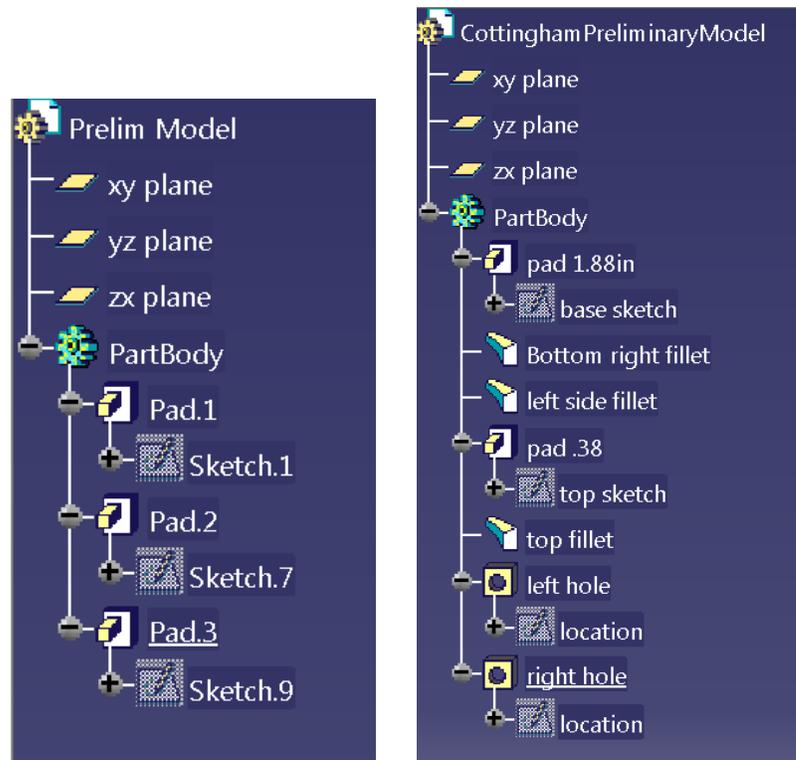


Figure 8: Two Sample Specification Trees for First CAD Project

Solid Model Rubric					
	1	2	3	4	Score
<b>Approach:</b> 1 <sup>st</sup> sketch profile and orientation	Base sketch is a simple base profile and/or is on the wrong primary plane	Base sketch is less than 50% comparable to the front view/on the wrong plane	Base sketch is less than 80% comparable to the front view/on the wrong plane	Base sketch is comparable to the front view and is on the correct plane	
<b>Structure:</b> order of detail steps/dress-up features	Specification Tree has extra step/ branches  Solid model contains none of the appropriate dress-up features	Specification Tree has extra step/ branches  Solid model contains less than 60% of the appropriate dress-up features	Specification Tree has extra step/ branches  Solid model contains less than 100% of the appropriate dress-up features	Specification Tree is well organized has no extra branches  Solid model contains of the appropriate dress-up features	
<b>Accuracy:</b> Correct dimensions and size	Less than 25% of the dimensions are correct	Less than 60% of the dimensions are correct	Less than 100% of the dimensions are correct	All of the dimensions are correct	
<b>Robustness:</b> placement of constraints and cross sketch associativity	Less than 25% of the sketches are properly constrained and associated to the solid model	Less than 60% of the sketches are properly constrained and associated to the solid model	Less than 100% of the sketches are properly constrained and associated to the solid model	All sketches are fully constrained and associated back to the solid model	
<b>Creativity:</b> overall approach and implementation	Less than 25% of the correct commands have been used and very little to no preplanning	Less than 60% of the correct commands have been used and some preplanning	Less than 100% of the correct commands have been used and moderate preplanning	All the correct commands have been used and significant preplanning	
Total					

Figure 9: Solid Model Rubric

### *Participants*

The data for this research came entirely from students in a sixteen-week Graphical Communication course offered in the fall 2011 semester in the Freshmen Engineering (FE) Department at Embry-Riddle Aeronautical University (ERAU). Students were pretested at the beginning of the course with two different tests designed to assess their spatial abilities. These tests included the Purdue Spatial Visualization Test: Rotations (PSVT:R), and the Mental Cutting Test (MCT). The reported reliability, Cronbach's  $\alpha$ , of the MCT has been reported .87 and .92 for undergraduate chemistry and engineering students (T. J. Branoff, 2000; Caissie et al., 2009).

The Graphical Communication course at ERAU teaches hand sketching and 3D solid modeling and is organized around six topics: theory of surfaces, orthographic and isometric view projection, auxiliary and section views, dimensioning, formal engineering drawings, and 3D modeling. The order of the material presented is different than from traditional textbooks, both dimensioning and 3D modeling concepts are integrated throughout the course instead of presented as isolated lectures. The course is a combination of lecture, guided sketching, and hands-on activities with homework, quizzes, a mid-term project, a final project, and a final exam. All nine sections of EGR 120 taught in the fall of 2011 were assigned a CAD based final project.

Twenty-six 2 hour classes are dedicated to engineering graphics concepts via hand sketching and 3D modeling; topics include scales, isometric and orthographic sketching, orthographic projections, auxiliary and section views, dimensioning, and formal drawing creation. Solid modeling is covered in eight sessions using CATIA. Topics comprise sketching and constraining 2D profiles, parametric based solid models, development and management of assemblies, and creation of engineering drawings. The concepts of solid modeling were presented in parallel with the hand-sketching activities and not as isolated, individual lectures. There were a total of 220 participants in the study.

### Data Collection

The PSVT:R and MCT was given to students during the first of classes in the fall 2011 semester and the scores were collected using Scantron sheets. The two visualization tests were implemented by Steinhauer.

Each of the three course instructors were asked to collect the completed CATIA solid models and submit the files to a data repository. For each of the three modeling projects assignments were randomly sorted and assigned to one of three evaluators. Each rater was assigned approximately one-third of each assignment from each instructor, and given one week to evaluate all of their assigned models for the first project and to post their completed rubric grades. All the evaluations for the first solid modeling project were compiled and inter-rater reliability calculated. Given the high inter-rater reliability for the first project,  $r = .918$ , it was agreed to continuing following the grading protocol for the second and final modeling project, the summary of inter-rater reliability are in Table 2. The process was repeated for the second and third modeling projects.

### Results

The average age of the participants was 19.0 for the MCT and 19.1 for the PSVT:R, there is a slight difference as one female participant completed the MCT but did not complete the PSVT:R. Descriptive statistics for the population sample are included in Table 1.

**Table 1: Descriptive Statistics for Population Sample Segregated by Gender**

		<b>Avg. Score</b>	<b>Number</b>	<b>Age</b>
<b>MCT</b>	Female	4.8	40 (18%)	18.4
	Male	5.3	180 (82%)	19.1
	Combined	5.2	220	19.0
<b>PSVT:R</b>	Female	19.0	39 (17.8%)	18.3
	Male	21.9	180 (82.2%)	19.1
	Combined	21.4	219	19.0

The mean score for MCT (combined) was 5.2 out of 10 or 52%. This average was compared to the reported pre-score average and was found to be similar to the 54% reported by Sorby (1999), the 57% reported by Hamlin et al. (2006), and the 52% reported by Tsutsumi (2010). The score distribution is shown in Figure 9.

The mean score for PSVT:R (combined) was 21.35 out of 30 or 71%. This average was compared to the reported pre-score average and was found to be similar to the 76% reported by Maeda and Yoon (2011), the 74% reported by Sorby (1999), and the 73% reported by T. J. Branoff (2000). The score distribution is shown in Figure 10.

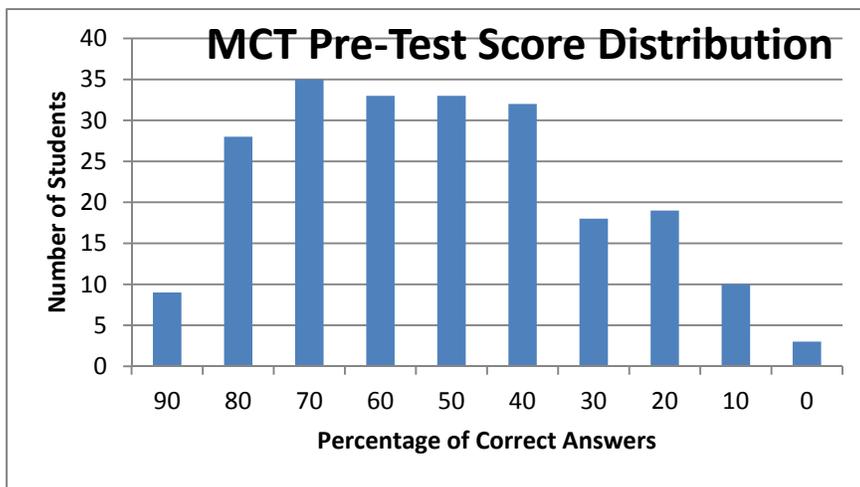


Figure 10: MCT Pre-Test Score Distribution

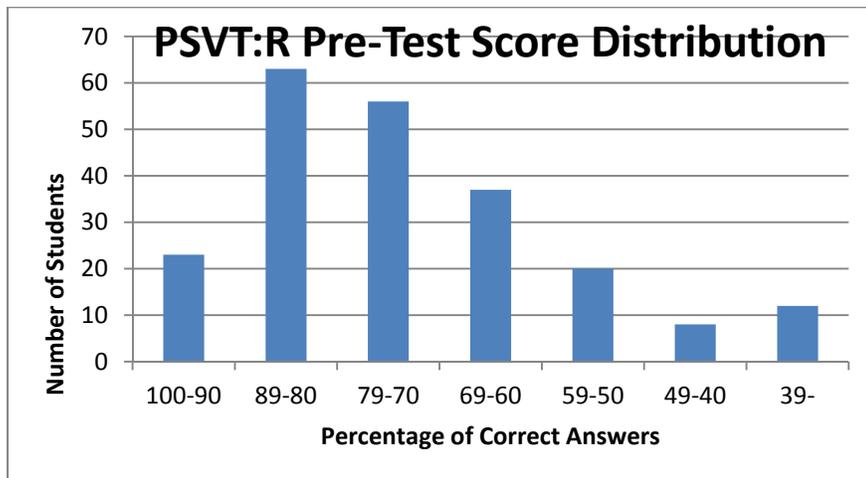
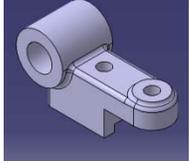
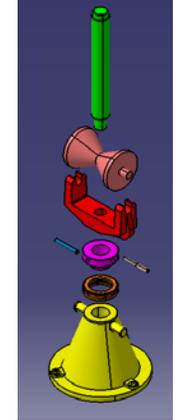


Figure 11: PSVT:R Pre-Test Score Distribution

Both of the individual modeling projects and the final CAD project were scored using the solid modeling rubric, Figure 9. The scoring of the rubrics was completed by Steinhauer and two graduate teaching assistants. The two assistants have worked as Steinhauer’s CATIA lab assistants and as course graders for the last two years and are quite familiar with the rubric and the intent of each of the five sections. Prior to grading any projects Steinhauer and both assistants met to discuss grading guidelines and expectations. Several sample CATIA models were provided and the team discussed their assessments of the models paying strict attention to the criteria defined in the rubric. The inter-rater reliability, the Pearson correlation, for the two individual modeling projects and the final assembly project was determined using SPSS 20, and are presented in Table 2.

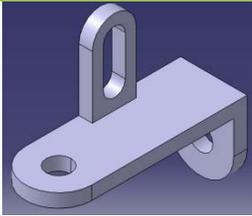
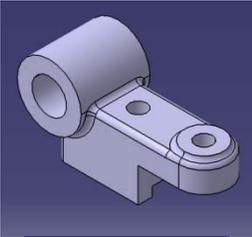
**Table 2: Inter-Rater Reliability**

Assignment	Pearson Correlation
	$r = .918$
	$r = .924$
	$r = .936$

Correlations between student scores on the MCT (n= 220), the PSVT:R (n= 219), individual modeling projects, and the CAD final project were calculated using SPSS 20 and are shown in Table 3. There was a statistically significant medium correlation between MCT pre-

score and final project score, MCT pre-score and both solid modeling projects. There was a statistically significant small correlation between the PSVT:R pre-score and the final project score but there was no correlation between PSVT:R pre-score and either of the solid modeling projects. Statistical significance of  $p < 0.05$  is denoted by \* and  $p < 0.01$  is denoted by \*\*.

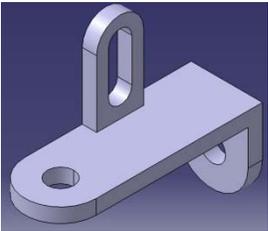
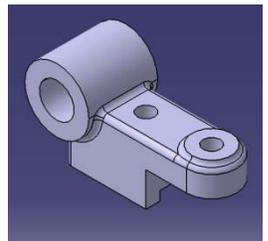
**Table 3: Correlation between Pre-Test Scores, Two CAD Projects, and CAD Final Project**

	MCT (n = 219)	PSVT:R (n = 220)
	$r = 0.32^*$	$r = 0.08$
	$r = 0.36^{**}$	$r = 0.10$
	$r = 0.30^{**}$	$r = 0.12^*$

Results from the rubrics were recorded for both of the common assignments. Values for each of the sections of the rubric were input as numerical values. A Principal Component Analysis was performed on the rubric section scores using SPSS 20. With this analysis, multipliers for each section of the rubric were obtained so that the composite score for each

student on a particular rubric could be determined. Use of these multipliers accounted for more than 50% of the variability between the rubrics. A Principal Component Analysis was performed for all three rubrics. Correlations were computed between the rubric scores, the final project score, and scores on both of the spatial visualization tests. The computed correlations are presented in Table 4. Statistical significance of  $p < 0.05$  is denoted by \* and  $p < 0.01$  is denoted by \*\*.

**Table 4: Correlation Factors between Solid Models, MCT, and PSVT:R**

Solid Models	Rubrics	MCT	PSVT:R
	<b>First Solid Model</b>		
	Approach	$r = 0.3933^*$	$r = 0.0618$
	Structure	$r = 0.1865^*$	$r = 0.1395$
	Accuracy	$r = 0.4182^{**}$	$r = 0.0746$
	Robustness	$r = 0.2457^{**}$	$r = 0.0090$
	Creativity	$r = 0.2108^*$	$r = 0.1286$
	<b>Second Solid Model</b>		
	Approach	$r = 0.3001^{**}$	$r = 0.0568$
	Structure	$r = 0.1782^*$	$r = 0.1034$
	Accuracy	$r = 0.3910^*$	$r = 0.1025$
	Robustness	$r = 0.2994^{**}$	$r = 0.0493$
	Creativity	$r = 0.3654^*$	$r = 0.1106$
	<b>CAD Final Project</b>		
	Approach	$r = 0.4007^{**}$	$r = 0.1407$
	Structure	$r = 0.3175^*$	$r = 0.1764$
	Accuracy	$r = 0.2293^*$	$r = 0.1087$
	Robustness	$r = 0.1568^{**}$	$r = 0.1821$
	Creativity	$r = 0.1397^*$	$r = 0.0652$

## Discussion

The correlation factors in Table 3 are the correlations between student performance on either test and overall grade for each project. All three of the modeling projects had a medium positive correlation with the MCT, indicating that students who performed better on the MCT had better, more mature 3D modeling frameworks than those students who did not perform well on the MCT. These findings support Hamlin et al.'s (2006) and Tsutsumi's (2010) previous research which also suggest the MCT may be a better predictor of students' 3D modeling skill than the PSVT:R. This may be because the MCT requires students to identify the 2D cross section of a provided solid model while the PSVT:R requires to students to identify the proper orientation of an unknown solid, of these two tasks the MCT more closely relates the theory of solid modeling.

The correlation factors presented in Table 4 are the correlations between student performance on either test and each of the five section grades per project. There was no significant correlation between student performance on the PSVT:R and the project section grades, however there was significant relationship between performance on the MCT and the project section grades. These results support the findings of Hamlin et al. (2006) where they only found a correlation between the MCT and the capability to learn and use 3d modeling software. These findings are also supported by the presented results in Tsutsumi's (2010) work. These results may be indicative of the close relationship between the skill measured by the MCT and creating solid models, both require the ability to discern the correct 2D profiles associated with a solid model.

The literature does suggest a connection between the MCT and 3D modeling ability, and it appears that this research has identified the same association. However, none of the previous research has included a detailed and structured analysis on the specification tree as a measure of modeling approach. Instead much of the published literature has compared other factors against student performance on the MCT. This is the first time this type of analysis has been conducted. The remainder of the presented findings do lend support to the findings published by Hamlin et al. (2006) and Tsutsumi(2010) in the general sense. Nevertheless the research is too dissimilar to draw a direct comparison between the detailed analysis conducted on the five aspects of the specification tree in this research and the findings from the published literature.

The correlation was strongest between approach and performance on the MCT for all three modeling projects, .3933, .3001, and .4007, respectively. Approach is perhaps the most important factor when creating a solid model, this is defined by the base, or first, sketch – is it on the correct primary plane? Is it overly simplistic? Or it is a profile not readily associated with the finished solid model? All of these are indicative of a low understanding of the solid model and how to effectively parse it into a meaningful sequence of steps.

Another significant correlation was between accuracy and overall MCT score, the correlation factors were, .4182, .3910, and .2293. Accuracy is measured comparing the final part dimensions to the provided handout. It is interesting to note that accuracy was much lower for the assembly than for the individual parts. This may be attributed in part to the amount of time students were provided to complete the project. While several parts of the assembly were reasonably simple to complete, the stock support base (the yellow model), support roller bracket (the red model), and adjusting screw nut (the magenta model) were quite complex and required students to leverage knowledge from dimensioning, tolerancing, and thread call-outs to complete. Students were given several weeks to complete this project, however, it fell at the end of the semester along with other final projects and final exams. It is possible students were not able to dedicate as much time as required to create a completely, dimensionally accurate assembly. This is certainly an area that bears future closer inspection.

The correlation for structure and performance on the MCT for all of the modeling projects were .1865, .1782, and .3175. Structure is measured by the organization and detail included in the specification tree - are there extra, unneeded branches in the specification tree? Are dress-up features embedded as sketch details? Are steps organized to facilitate understanding? These types of choice are symptomatic of a low level understanding of modeling.

Robustness is indicated by the type of constraints placed in the base sketch and in the subsequent detail sketches. A solid model which is robustly modeled will contain no update errors or errors that waterfall down the specification tree if an earlier branch is modified. There was a significant correlation between student performance on the MCT and robustness of the three modeling projects .2457, .2994, and .1568. Of interest is the lower level of correlation of the assembly project, it may be attributed to the difference between modeling approaches when creating an assembly or an individual part. Or it may be an indication of the complexity of integrating constraints properly across the solid models within a specific assembly. That

particular concept may not have been presented or emphasized clearly during the course lectures. It is also quite possible that students had very limited exposure to developing assemblies and as such are still constructing that specific portion of their modeling framework.

Finally, the correlation between creativity and performance was also explored. A small correlation was determined for each of the modeling projects, .1286, .1106, and .1397. Creativity is indicated by selection of modeling commands and the order in which they are executed. Examples of poor creativity - using the pocket command to place holes, failing to use the rectangular pattern for regularly spaced geometric details, using an edge fillet in place of a tritangent fillet - all of these choices indicate a lack of preplanning and minimal understanding of 3D modeling. Again, the correlation is the weakest for the assembly project. This may relate back to the instruction provided in the classroom and how much time students had prior to completing this final project to develop their understanding of 3D assemblies. Data management within the assembly workbench is quite different from the workbench used to create individual parts. Students may not have been able to extrapolate across salient modeling theory across the two workbenches.

It appears that performance on the MCT is a more effective predictor of student success in 3D modeling than the PSVT:R. Certainly an area of future research would be student's modeling frameworks and performance on the MCT. The limitations and future work are presented in the following section.

### **Limitations/Future Work**

Although this research has indicated a relationship between a student's ability to learn and use 3D modeling software and their performance on the MCT it is not without a few limitations.

Due to time constrictions both of the visualization tests, the PSVT:R and the MCT, were only implemented as a pre-test. It was the original intent of this research to give both tests as a post-test, however due to time restrictions it was not possible to implement and collect the post-tests. Tsutsumi (2010) was also able to measure improvement in student performance on the MCT as function of the 3D modeling since they implemented the MCT as a pre- and post-test. For the next phase of this research both of the visualization tests will be implemented as a post-test in addition to the pre-test, this could yield additional insight into the skills of spatial visualization and 3D modeling performance and tracked performance on the MCT.

A second weakness is the absence of qualitative data from the students. While close inspection of the specification trees does provide detailed, step-by-step summary of the part's construction and the student's approach it does not provide specific insight into the student's mindset as they made deliberate design choices to complete the solid model. This could provide some additional insight to what was happening with the assembly project in respect to both accuracy and robustness. The implementation of a think aloud protocol and the capture of student's narrated description as they complete the provided solid models could provide a wealth of information to better understand the relationship between the MCT and student 3D modeling aptitude.

A final limitation is the variance in course instruction, during the fall of 2011, EGR 120 was taught by three different instructors. While each instructor was briefed as to the importance of how and when CATIA is presented into the curriculum they were not given a specific, structured protocol to follow. This is especially true in reference to the assembly workbench and it is suspected that it may have contributed to the decreasing correlation factors for the final project. For additional studies it is recommended that a structured CATIA concept protocol be provided to all of the course instructors so to better standardize and align the learning experiences for all of the participants.

## **Conclusion**

It would seem that a person's 3D spatial ability as measured by the MCT correlates to their ability to produce a robust and creative solid model. This relationship was determined through a unique approach to data collection instead of focusing on self-reported performance or reviewing a 2D dimensional artifact data collection focused on the arrangement and order of the specification tree for each solid model.

3D spatial skills measured by the PSVT:R do not correlate to a person's ability to create a robust and thoughtful solid model. This is a thought-provoking finding as the PSVT:R has long been shown to be a significant predictor of student performance in traditional engineering graphics courses. In 1998, Sorby and Young, and in 2006, Ardebili both found that a person's score on PSVT:R was a significant predictor of student success in an introductory engineering graphics course.

As engineering graphics courses have begun to change so must the assessment tools. Many engineering graphics courses today dedicate a significant portion of time to presenting 3D solid modeling software in addition to teaching the traditional hand sketching concepts. These findings may be an indication that the PSVT:R may no longer be enough to predict a student's success in a graphics communication course as the curriculum is shifting to encompass more of the 3D solid modeling techniques and assessment needs to shift also to include modeling along with spatial visualization. Engineering graphics courses now require skills in spatial visualization as measured by PSVT:R and 3D modeling skills as measured by the MCT. The results indicate that a more effective assessment strategy would be to implement both the PSVT:R and the MCT as a pre-test.

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## Chapter 5

### Summary and Conclusions

#### Summary

This research investigated four of the pedagogical approaches to teaching engineering graphics, assessment of engineering graphics through the development and validation of a reliable concept inventory, and the exploration of the correlation between two well-known spatial visualization instruments and 3D modeling skills. First, the literature review provided a detailed and systematic comparison of the most common instruction methods, identified the pedagogical strengths and weaknesses, and contributed an overview of the spatial visualization pedagogy for the engineering education community. The literature review was framed about four common methods for teaching engineering graphics: the standard approach, the remedial approach, the 3D modeling approach, and the theory informed approach. Each method was evaluated by four principle criteria—learning outcomes, active and engaged learning, stage of knowledge, and explanatory power. A summary of the findings for each of the four methods are presented in Table 1.

**Table 1: Pedagogical Approach Summary Evaluation Matrix**

<b>Pedagogical Approach</b>	<b>Learning Outcomes</b>	<b>Active, Engaged Learning</b>	<b>Stage(s) of Knowledge</b>	<b>Explanatory Power</b>	<b>Overall</b>
<b>Standard</b>	Low	Inadequate	Procedural	Low	✓-
<b>Remedial</b>	Moderate	Excellent	Conceptual	Moderate	✓
<b>CAD</b>	High	Very Good	Conceptual, Procedural, and Strategic	High	✓+
<b>Theory-Informed</b>	High	Very Good	Conceptual, Procedural, and Strategic	High	✓+

These findings can be used by undergraduate engineering graphics educators, department and university administrators as educators are under pressure to teach the critical and fundamental skills of spatial visualization with less time to students who have unequal skills

levels. These findings may also be used to aid in the development of the appropriate pedagogical content knowledge needed for the teaching of engineering graphics. These results can be used to create an engineering graphics course that can better meet the challenge of a reduced presence in the curriculum while still addressing the weaker spatial visualization skills of undergraduate engineering students.

In an effort to better understand the prior knowledge and misconceptions students are bringing into the engineering graphics course, this research developed a valid and reliable concept inventory. Developed over two years and administered at three different universities in the United States and resulting in more than 1300 participants.

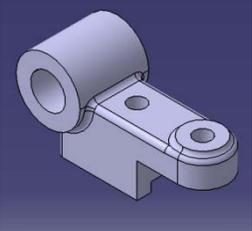
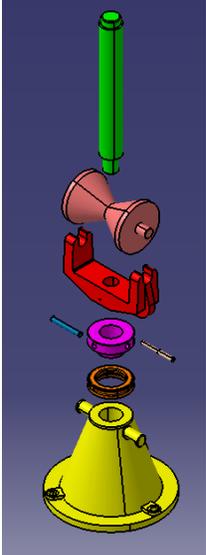
The mixed methods for this research encompassed a Delphi study to identify and rank the concepts, think-aloud interviews to generate the distractors and to better word the questions, and a quantitative analysis of the student scores. The final reported reliability for each of institutions was: Embry-Riddle Aeronautical University  $\alpha = .67$ , Virginia Tech  $\alpha = .71$ , and North Carolina State University  $\alpha = .73$  which demonstrate the instrument is reliable independent of institution.

The criterion validity of the concept inventory is now ready to be verified; the pre- and post-test scores on the concept inventory, final course grade, and final exam grades will be compared. Following the conclusion of the criterion validity analysis the concept inventory will be made available. This concept inventory can be used to measure student learning gains and the consistency of overall course performance across multiple sections of the course – per semester and annually.

The final manuscript investigated the correlation between a student's performance on the PSVT:R and the MCT and their ability to learn and use a 3D parametric solid modeling software, specifically investigating students modeling strategies. Traditionally, both the PSVT:R and the MCT have been used to predict student's spatial visualization abilities for solving paper-based problems. Simply establishing a baseline of students' hand sketching skills no longer provides enough feedback to address incoming student skill sets. 3D modeling has been steadily integrated into the engineering graphics curriculum often displacing some of the formal lectures on engineering graphics theory. A baseline for students' 3D modeling needs to be established at the start of the semester, too.

During the first week of the fall 2011 semester, 220 engineering graphics students from Embry-Riddle Aeronautical University completed a pre-test of the PSVT:R and the MCT. Throughout the semester students completed three common modeling projects. The specification tree from each were evaluated and compared to the pre-test performances. The results indicate there is a correlation between a student's performance on the MCT and 3D modeling strategy; the correlations are presented in Table 2.

**Table 2: Correlation between Pre-Test Scores, Two CAD Projects, and CAD Final Project**

	MCT (n = 219)	PSVT:R (n = 220)
	$r = 0.32^*$	$r = 0.08$
	$r = 0.36^{**}$	$r = 0.10$
	$r = 0.30^{**}$	$r = 0.12^*$

The findings from this research can be used to better identify student skills and abilities and can be used to develop courses which better reflect student requirements. These results indicate that while the PSVT:R still is an appropriate instrument for measuring students' spatial

visualization skills in reference to hand-sketching, it is not an appropriate measure for students' 3D modeling. The MCT does appear to measure a student's ability to learn and use 3D parametric solid modeling software.

### **Future Work**

The results of this research and the discussion of the findings identify several paths for furthering the work in the field of assessment of engineering graphics. Future work should be focused on implementing the Engineering Graphics Concept Inventory as a post-test to address criterion validity aspect, collecting post-test data on the student performance on the PSVT:R and the MCT, gathering qualitative data from students through "think-aloud" protocols about the development of 3D modeling frameworks, and implementing the correlational study to other universities.

#### *Implement Engineering Graphics Concept Inventory as Post-Test*

While all other aspects of validity were addressed through the development and refinement of the Engineering Graphics Concept Inventory criterion validity was not. One approach to address this is through a comparison of the student performance on the concept inventory to another instrument known for measuring the same construct. Since there is not another published engineering graphics concept inventory or another validated and reliable instrument available, criterion validity must be established another way. Criterion validity can also be established by comparing performance on the concept inventory to another metric measuring the construct, e.g. a final exam.

Once criterion validity has been addressed, the predictability of the concept inventory to measure student success in engineering graphics should be measured. An investigation on student performance on the pre-test of the concept inventory and final exam grade could provide this. An additional area of interest for additional investigation would the correlation between student performance on the Engineering Graphics Concept Inventory, performance on the PSVT:R and the final exam grade for the course. Such an examination may yield refinements to the measurements of the concept inventory perhaps broadening its application in the assessment of engineering graphics.

The concept inventory could then be used to measure incoming student skill level into engineering graphics, providing course instructors with valuable information about student's pre-existing knowledge and misperceptions. Performance on the concept inventory could also provide earlier insight and identification of students who are at higher risk of failure to instructors thereby decreasing student attrition from the course and ultimately the program.

#### *Collect Post-Test Data For the PSVT:R and the MCT*

While this study included a preliminary examination into the connection between a student's performance on the both pre-tests of the PSVT:R and the MCT and their ability to learn and use 3D parametric modeling software, a post-test performance of both instruments was not investigated. Future research should also utilize post-test scores in addition to the pre-test scores. This additional information may provide additional clarity on the correlation found between a student's performance on the MCT and 3D modeling ability.

#### *Gather Qualitative Data about 3D Modeling Frameworks*

This research studied the development of students' 3D modeling frameworks by reviewing the organization and structure of the specification tree for each model submitted. While the specification tree often provided enough insight to discern students' modeling choices there were times when design choices and modeling approaches simply were not clear. Future examinations should include qualitative data collection in addition to the quantitative data provided by the rubrics. A suggested approach would be implementing a think-aloud protocol and the capture of the student's narrative description as they complete the solid models. In addition to offering a wealth of descriptive information simply not provided by a rubric, it provides the opportunity to ask for further clarification in parallel with the solid model being created. In addition to conducting the think-aloud protocols would be to complete the modeling rubric in parallel with the think-aloud protocols, so that the assessment of the modeling is occurring real time instead of days or weeks after the fact. Completing the rubric in parallel with the think-aloud protocols may provide a richer understanding of students 3D modeling development and maturation.

### *Implement the PSVT:R and MCT Study at Other Universities*

A final recommendation for this research is to broaden the generalizability by implementing this study at other universities. While a significant correlation was found with the first-year engineering graphics students at Embry-Riddle Aeronautical University utilizing CATIA, these results need to be replicated in courses similar to engineering graphics taught at other institutions using different 3D parametric modeling software such as AutoCAD, Pro-E, and Solidworks. It is essential that future research continue to examine the specification tree in parallel with conducting the student's own description of the development of their solid models.

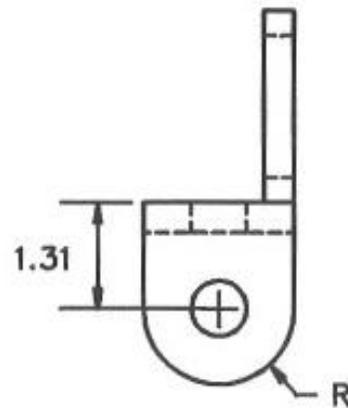
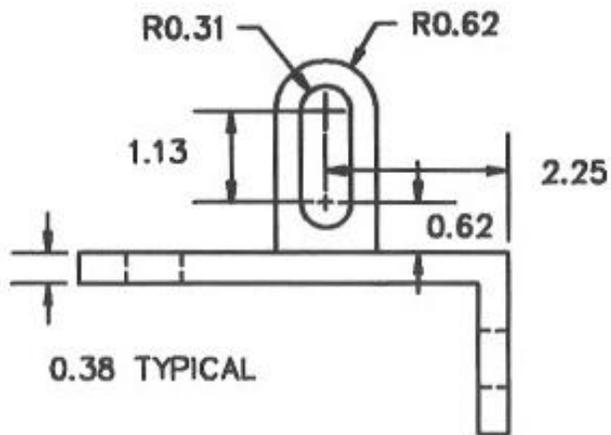
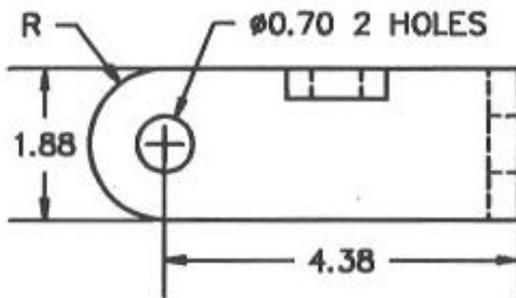
### **Conclusion**

These three studies have provided a progressive exploratory mixed methods approach that combined qualitative interviews and observations that framed the development of the concept inventory and the data collection. The results may be used to provide pedagogical insight and pedagogical content knowledge for developing or revising an engineering graphics course. The findings may also offer guidance to faculty for the types of assessment needed to most effectively evaluate their students' initial skill level and course learning gains.

In summary, this research provides several paths for addressing a few of the challenges associated with teaching engineering graphics from most effective teaching method to identifying incoming student misperceptions about engineering graphics to measuring students' modeling strategies for 3D parametric modeling software.

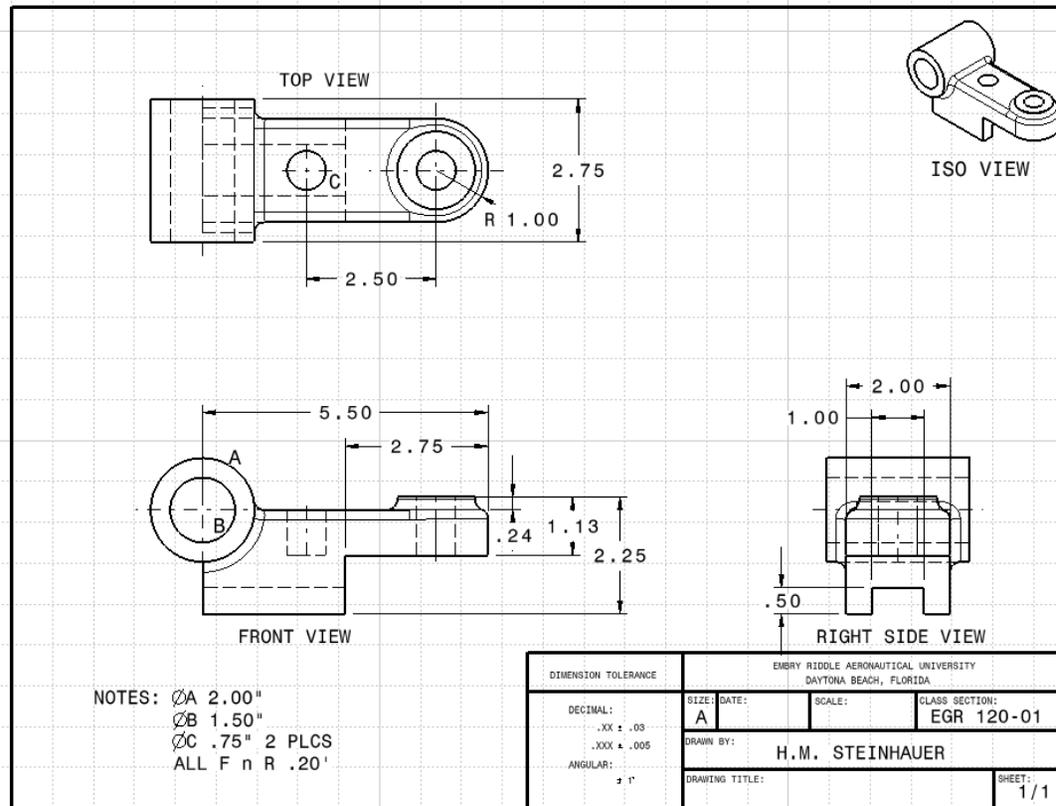
Appendix A  
Detailed Handout of CAD project One

1. Given the top, front, and right side orthographic views of a solid model
2. The units are in inches
3. Using CATIA create the solid model
4. The project is due by the start of the next class, Thursday September 22<sup>nd</sup> 2011
5. Post the completed solid model through the link on blackboard labeled First Modeling Project



## Appendix B Detailed Handout of CAD Project Two

1. Given the top, front, and right side orthographic views of a solid model
2. The units are in inches
3. Using CATIA create the solid model
4. The project is due by the start of the next class, Thursday October 13<sup>th</sup> 2011
5. Post the completed solid model through the link on blackboard labeled Second Modeling Project



## Appendix C

### Detailed Handout of CAD Final Project

Due Tuesday the 29<sup>th</sup> of November 2011

Create solid models of the following parts:

1. Stock Support Base
2. Support Roller Bracket
3. Adjusting Screw Nut
4. Stock Support Roller
5. Support Adjusting Screw
6. Adjusting Screw Guide
7. Adjusting Nut Handle
8. Thrust Bearing
9. Taper Pin
10. Hex Jam Nut

Place all of the files in the folder named: your last name Stock Bracket.

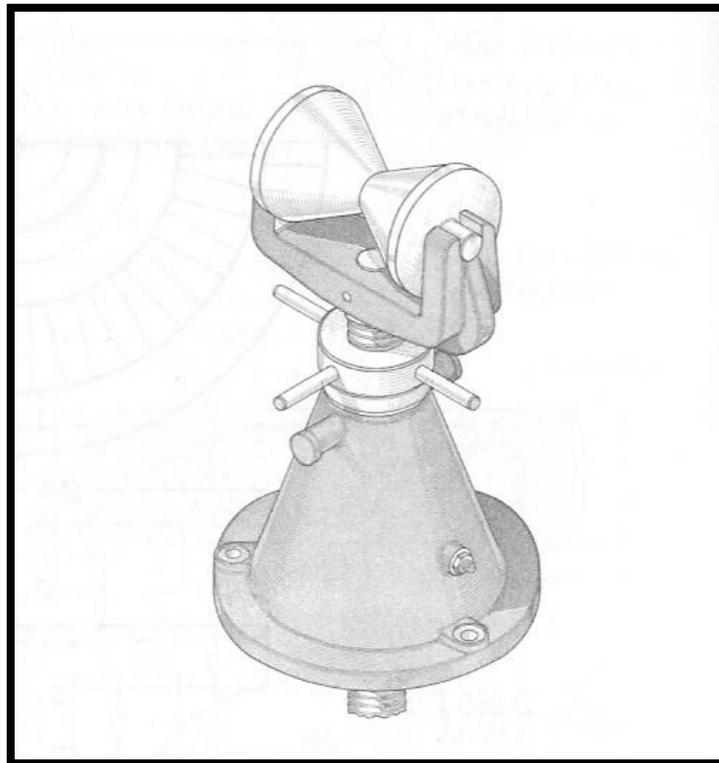
- There will be 11 part files in this directory:
  - One product file renamed to your last name Stock Bracket Assembly.CatProduct
  - 10 part files named:
    1. Your Last name Support Roller Bracket
    2. Your Last name Adjusting Screw Nut
    3. Your Last name Stock Support Roller
    4. Your Last name Support Adjusting Screw
    5. Your Last name Adjusting Screw Guide
    6. Your Last name Adjusting Nut Handle
    7. Your Last name Thrust Bearing
    8. Your Last name Taper Pin
    9. Your Last name Hex Jam Nut
- There will also be 11 drawing files in this directory:
  - One B size drawing renamed to your last name Stock Bracket Assembly.CatDrawing
  - 10 A size drawing files named:
    1. Your Last name Support Roller Bracket
    2. Your Last name Adjusting Screw Nut
    3. Your Last name Stock Support Roller
    4. Your Last name Support Adjusting Screw
    5. Your Last name Adjusting Screw Guide
    6. Your Last name Adjusting Nut Handle
    7. Your Last name Thrust Bearing
    8. Your Last name Taper Pin
    9. Your Last name Hex Jam Nut

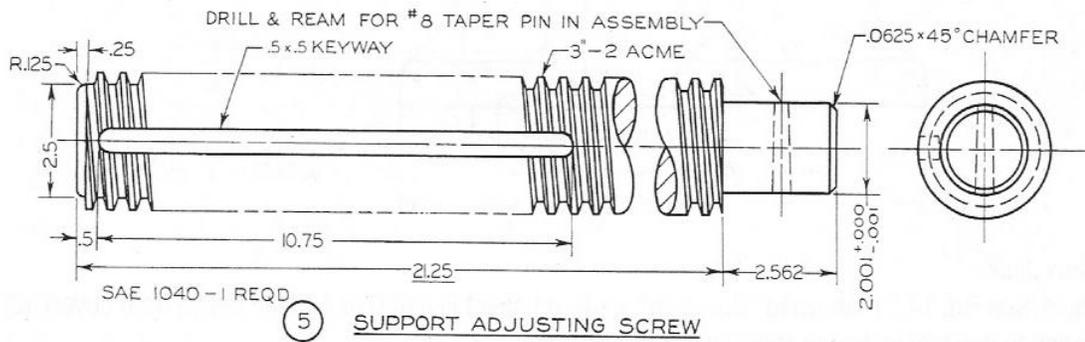
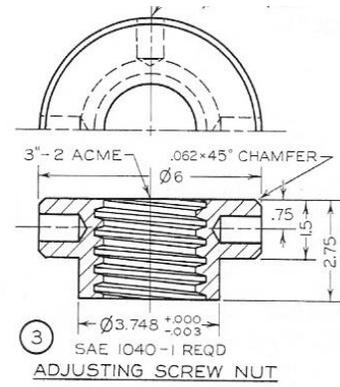
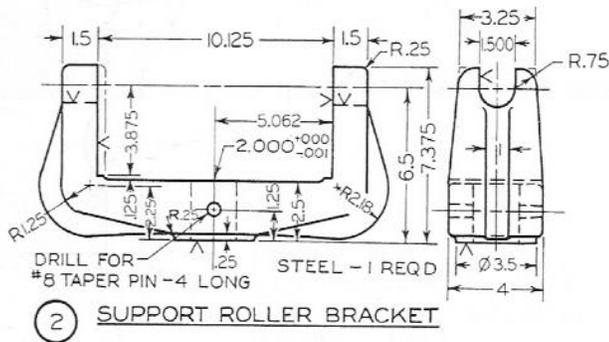
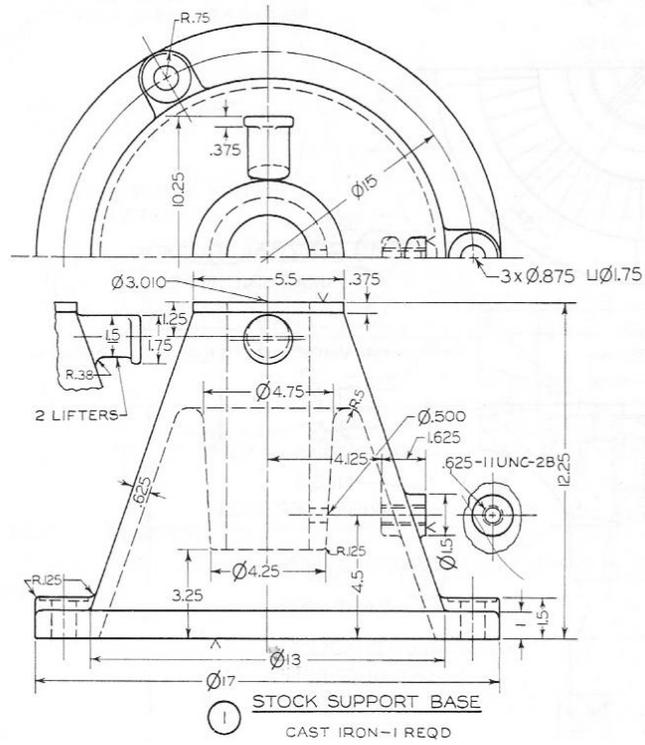
All part and drawing files are to be zipped together and posted through the link on blackboard labeled Final CAD Project.

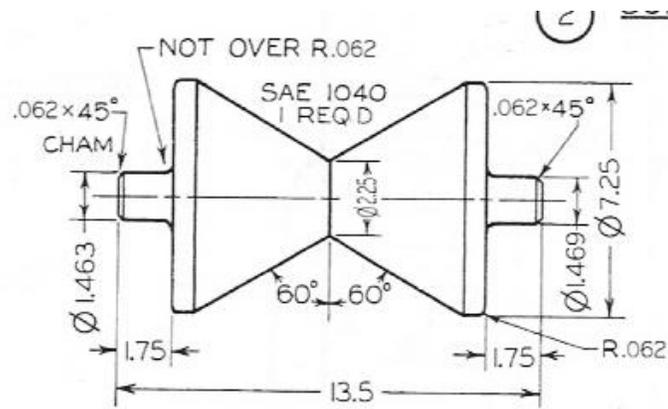
You will be graded on the quality of the modeling process for all of the solid models, i.e. number of steps, extra sketches, part orientation, accuracy of the solid models, etc.

You will be graded on the quality of the final CATIA assembly, i.e. the number of constraints required, proper orientation, quality of fit and alignment, **ability to follow provided instructions**, etc.

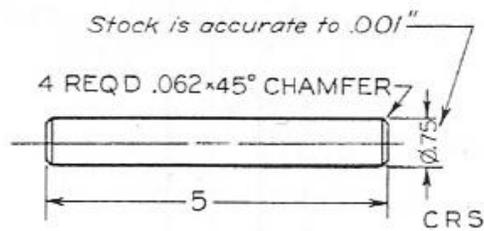
You will be graded on the quality of the final drawings, i.e. the number of views included in the drawings, the overall layout, spacing, and organization, the appropriateness of dimensions, choice of orthographic scales, supplemental views (e.g. auxiliary views, and section views), and proper information included in the titleblock.



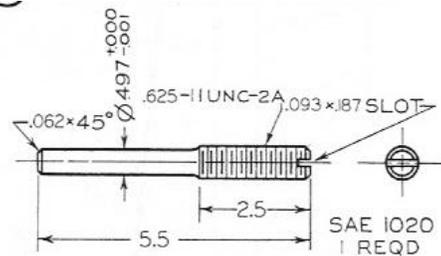




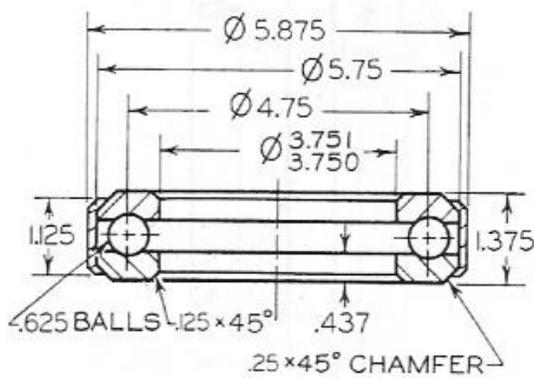
④ STOCK SUPPORT ROLLER  
9=



⑦ ADJUSTING NUT HANDLE



⑥ ADJUSTING SCREW GUIDE



⑧ THRUST BEARING

STOCK ITEMS

- ⑨ 1-#8 TAPER PIN  
4" LENGTH
- ⑩ 1-.625 FIN. HEX JAM NUT