The Effects of Solid Modeling and Visualization On Technical Problem Solving

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(ABSTRACT)

This research was undertaken to investigate the effects of solid modeling and visualization on technical problem solving. The participants were 47 students enrolled in solid modeling classes at Southeast Missouri State University. The control and experimental groups consisted of 23 and 24 randomly assigned students respectively.

This study was a posttest only design that used logistic regression to analyze the results. Both groups were required to take the *Purdue Spatial-Visualization Test/Visualization of Rotations* (PSVT/TR). Participants in the control group used only sketching to design their solutions while participants in the experimental group used parametric solid modeling software to design their solutions. All participants then constructed prototypes of their designs. The prototype was evaluated to determine if it successfully met the design specifications.

The findings revealed that visualization was a significant predictor of technical problem solving as defined by successful prototype construction (p=.021). There was no significant difference between the sketching and solid modeling design methods used for technical problem solving (p=.752). The interaction between the method of design, solid modeling or sketching, was analyzed to determine if using solid modeling would offset low visualization scores It was found that the interaction was not significant (p=.393).

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CHAPTER 1

Introduction

As a teaching assistant at Virginia Polytechnic Institute and State University (VPI & SU), I had the responsibility of teaching prospective technology teachers basic drafting and technical graphics skills. The students had very diverse backgrounds and experience levels. Many had no previous experience with drafting or print reading.

During my first year of teaching it was obvious that those with little experience often struggled to visualize objects presented orthographically or two-dimensionally. This was typical of the observations I made as a junior high and high school teacher. The students often struggled to convert objects from three dimensional (3D) or physical objects to two dimensional (2D) representations. When possible, physical parts made of wood, paper, or other materials were used as models with limited success.

During my second year of teaching at VPI & SU, I began using modern parametric solid modeling software. When students were having trouble visualizing simple parts, in a matter of minutes a solid model could be created on the computer for them to look at, rotate, and visualize the object from the various orthographic views. This seemed to work as well if not better than using a physical representation of the object. The students were later taught parametric solid modeling software, and employed it to design projects and solve problems for other classes. Prior to that, I noticed when students used 2D computer aided design (CAD) or manual drafting for designs and solutions, there were often many errors in their reproductions. If parts and assemblies were designed as drawn, they would seldom fit and work without major modifications. After one or two semesters, they had not developed the necessary expertise to interpret several drawings and visualize the entire assemblies as one working unit. They needed more time and exposure to develop those skills, a better approach, or a better methodology.

Using the solid modeling software, the students could design an object they could see in three-dimensions on the computer and test their assemblies to see that the parts would function properly together. Though no formal data were collected, the designs seemed better, more detailed, and more efficient. These observations caused me to wonder if there might be advantages to using solid modeling to solve certain technical design problems.

The *Standards for Technological Literacy* (International Technology Education Association [ITEA], 2000) state “Design is regarded by many as the core problem-solving process of technological development” (p. 90). Technology education and engineering education are placing greater emphasis on problem solving and design. Engineering is transitioning from a more analytical approach to a more applied problem solving based approach (Dearing & Daugherty, 2004). *Standards for Technological Literacy (STL)* includes design as a key component of the standards and devotes all of chapter five (standards 8-11) specifically to design. Though design is a core problem solving process, it is important to remember that design is only one method of problem solving.

“Problem solving is basic to technology” (*STL*, p. 90). Jonassen (2000, p. 63) contends that “most psychologists and educators regard problem solving as the most important learning outcome for life.” There has been a strong focus toward problem solving and application in technology and technology education as teachers strive to promote technological literacy.

Spatial visualization is an important component of the problem solving process, particularly in technical problem solving and design. One must be able to visualize or “see” in one’s mind a mental picture of possible solutions and outcomes to a particular problem. Visual thinking is constantly used and pervades all human activity. For almost all activities we undertake, we create or think visually. (Arnheim, 1974; McKim, 1980). Many cognitive tasks we undertake involve cognitive representations (Zhang, 1997). When you describe driving directions to someone or tell someone what your living room looks like, you see a visual image of those things in your mind. An important aspect of visualization is that it can be improved by practice. (Blade, 1949; Brinkmann, 1966; Cohen, 1981; Rosenfeld, 1985)

Programs that involve the study of technological processes have always taught technical design and other forms of standardized visual communications. The equipment and techniques have changed a great deal in the last few decades. Advancing computer technologies have made it possible to produce complex models using personal computers. The equipment and software for technical design is often very costly and can require a great deal of time and effort to learn its proper use. Current CAD programs have made visualization of designed objects easier by adding true three-dimensional functions and high quality, rendered images of those designs. The trend in industry has shifted greatly from simple 2D designs to these detailed 3D models. A question that remains unanswered is the extent to which these CAD programs aid students in problem solving, designing, communicating, or learning these concepts.

Long (2003) pointed out that increasing graphic realism does not always lead to better learning. “Like many things with technology, just because we can do something may not mean we should” (p. 8). Godfrey (1999) contends that “viewing three-dimensional solid models removes it from its usual two-dimensional form of abstraction and makes it more suitable for use as a method for spatial visual learning”(p. 2).

This research attempted to determine whether or not the use of solid modeling software increases participants’ success in solving a specified technical problem and how visualization affects their ability to solve a technical problem. Little is truly known about how individuals go about solving problems and what tools better equip them to solve certain problems. Jonassen (2003b) concludes, “The potential for research confirming positive relationships between modeling and problem solving is great” (p. 377) and goes so far as to state “no empirical research has examined the effects of using technology tools for representing problems on problem solving performance.” A great deal more research is needed to better understand how problems are solved and what methods and tools best prepare individuals to face future problems.

Visualization

In the last half century, the importance of visualization and visual skills has received growing recognition. Although visualization has not received as much attention as have verbal and numeric abilities, current research is emphasizing the importance of visualization in the traditional fields of engineering, technology, and art, as well as virtually every aspect of life. Visual tasks have often not been considered a measure of intelligence but many proponents are arguing that spatial factors are important aspects of intelligence (Miller & Bertoline, 1991).

Many studies have concluded differences in visualization are often gender-related. In most cases females tend to have weaker visualization scores than males. The cause of these differences has often been related to environmental and social differences but mental differences are being studied and also theorized as legitimate causes. Gender differences need to be addressed effectively in educational settings to maximize students' potential for solving problems.

Visualization is a very broad term that encompasses many meanings and related techniques. The primary focus of this study is on *spatial* visualization. Spatial visualization is the ability to imagine the rotation of depicted objects, the folding or unfolding of flat patterns, the relative changes in position of an object in space, or the motion of machinery (Guilford & Lacey, 1947 as cited in Mack, 1992). This is an important aspect when designing solutions to problems. In a study by Halfin (1973), a Delphi method was used to identify particular aspects of the design process and visualization played a major role in a majority of those processes.

According to Godfrey (1999), as a result of the recent shift from designing using two-dimensional models to three-dimensional models, "the visualization area of study has experienced a 'paradigm shift'" and further research is needed to better understand the changes encountered with solid modeling. Barr and Juricic (1994), claimed that the design process was changing from two-dimensional to three-dimensional.

Problem Solving

STL (ITEA, 2000, p. 5) considers design the primary problem solving approach in technology education. Few, if any, technology education processes have received as much attention in the literature in recent years as has problem solving. The teaching of problem solving has been a goal in technology education since the inception of the field (McCade, 1990; Todd 1999). There are many definitions for problem solving and it can be conducted through various means (Hill, 1997).

Design is not the only problem solving method. Custer (1995) considers design a major subset of technical problem solving. One unique aspect of design problems is that the designer "typically, does not know in advance what the goal state will be, although he [sic] usually has criteria to evaluate potential goal states" (Carroll, Thomas, & Malhotra, 1980, p. 143).

Problem solving is important to technology educators because they are trying to get students to problem solve as a means of doing. McCormick (2004) states that research "shows that action affects thinking, and thinking affects action." (p. 23). Students need to be able to think and act on the problems they face and react to the changes they encounter. He also contends that problem solving is the most important procedural knowledge that occurs in technological activity. Jonassen (2003b) states that "problem solving is at the heart of practice in the everyday and professional contexts.…every secondary and tertiary education course should require students to solve problems" (p. 362).

One challenge when teaching problem solving from a design standpoint is that most students' prior problem solving experiences in education are quantitatively based, procedural story problems (Jonassen, 2003a). When solving these traditional mathematical "word problems," students often do not create mental models of the problem and just plug in values to arrive at a solution. Story problems, the most common form of problem solving in K-16 education, "present a quantitative solution problem within a shallow story context" (Jonassen, 2003a, p. 267) and that research shows this creates a lack of understanding and learning transfer because they follow a procedural algorithm to solve them. (Goldman, 1989; Jitendra, 2002; Jonassen 2003a)

Computer Aided Design and Solid Modeling

Computer aided design has evolved from the simple replacement of traditional drafting equipment to a very sophisticated, highly visual design tool. The earlier CAD programs used the computer to generate lines for 2D drawings. As the software and hardware advanced, these 2D drawings could be converted into 3D objects that the computer recognized as having height, width, and depth. The software used to create these earlier 3D objects was still 2D based; they originated from and were primarily used to draw in two dimensions. Modern software used for solid modeling often functions in the reverse order; the three-dimensional object is drawn and then two-dimensional, orthographic drawings are generated from that model. Advantages are perceived in using this latter order because we live in and interact with a three-dimensional world.

Purposes

The purposes of this study were to determine if:

1. students' visualization skills affect their problem solving ability;

2. the use of 3D modeling software in the design and production of a prototype for a technical design problem is more effective than using sketching; and

3. the use of 3D modeling software offsets any differences in low spatial visualization skills for solving a technical design problem.

Previous research findings show that students can learn and apply CAD, often 2D, to the same degree as conventional or manual drafting (Baird, 1991; Kashef, 1993) and that students' visualization skills can be improved through practice of design or drafting related applications (Blade, 1949; Brinkmann, 1966; Cohen, 1981; Gillespie, 1995; Godfrey, 1999; Rosenfeld, 1985).

Significance

Technology education has placed great emphasis on problem solving, yet little is known about how individuals go about solving problems and what skills or tools are needed to better solve problems. In many cases it is not known if we are effectively measuring problem solving or how to go about doing so. There are no standardized instruments for measuring problem solving ability.

Visualization has been correlated with problem solving (Mack, 1992). Further work must be done to better understand the role of problem solving and the tools that might aid in visualization. Many secondary and post secondary schools are investing heavily to purchase current CAD software and are increasingly teaching solid modeling software before any practical application or problem solving can take place. It is unclear whether these software applications enhance the learning of problem solving and visualization. In short, it is unclear if learning the software is worth the time and effort required for students who are not training to use it vocationally.

The potential exists for students to be able to better visualize problems when designing with 3D representation. Research dealing with assembling objects shows that students tend to do better when they can view a physical or 3D object as opposed to 2D drawings (Pillay, 1998). Few dispute the importance of being able to solve problems, but more information and research is need on how individuals solve technical design problems and what methods, instruction, and experiences can improve this ability.

Research Hypotheses

The following hypotheses were investigated in this study:

$H_0$1: Participants' spatial visualization skills, as measured by the *Purdue Spatial-Visualization Test/Visualization of Rotations*, will not affect their technical problem solving ability.

$H_0$2: Participants using solid modeling software to design solutions to technical problems will not show greater success in the construction of a physical model or prototype than those using sketching.

$H_0$3: Participants with lower visualization skills, as measured by the *Purdue Spatial-Visualization Test/Visualization of Rotations*, will not perform better using solid modeling software than those with equal scores using sketching in the design and production of a prototype for a technical problem.

Assumptions

The following assumptions were made about this study and the circumstances surrounding it.

1. The work performed by each student not influenced by incidental contact with others.

2. The participants understood the design and modeling operations and they possessed the skills necessary to participate in the study.

Limitations of the Study

The following limitation applied to this study:

1. The length of time allotted for both the control and experimental groups was limited to three hours for the design and three hours for the construction of the prototype.

Delimitations of the Study

The following delimitations impose constraints upon the ability to generalize the results of this study to other populations:

1. This study was delimited to the population of 50 Engineering Technology students at Southeast Missouri State University.

2. One specific technical design problem was used for this study; results may vary for different problems and types of problems.

Definitions of Terms

CAD - "the use of a wide range of computer-based tools that assist engineers, architects and other design professionals in their design activities" (Wikipedia, 2006b, ¶ 1).

Finite element analysis (FEA) - a mathematical technique for analyzing structural, thermal, dynamic, fatigue, and fluid factors or stresses, which breaks down a physical structure into substructures called "finite elements." The finite elements and their interrelationships are converted into equation form and solved mathematically.

Model - "a visual, mathematical, or three-dimensional representation in detail of an object or design, often smaller than the original. A model is often used to test ideas, make changes to a design, and to learn more about what would happen to a similar, real object." (ITEA, 2000, p. 240)

Problem solving - "the process of understanding a problem, devising a plan, carrying out the plan, and evaluating the plan in order to solve a problem or meet a need or want." (ITEA, 2000, p. 240)

Solid modeling - a three-dimensional, computer- generated model of an object that resides in three-dimensional space. (Gillespie, 1995, p. 30)

Spatial Visualization - the ability to imagine the rotation of depicted objects, the folding or unfolding of flat patterns, the relative changes in position of an object in space, or the motion of machinery. (Guilford & Lacey, 1947 as cited in Mack, 1992)

The subject of technology - a junior high or high school discipline or class of study developing technological literacy and teaching about technology.

Technology - "the process by which humans modify nature to meet their needs and wants"(Pearson & Young, 2002, p. 3). Technology is more than just artifacts or physical objects, knowledge and processes for operating, manufacturing, and maintaining those products is also technology. (Pearson & Young, 2002)

Technical design – a systematic way of designing a solution to a problem or meeting a particular technical need or want.

Technology education - the preparation of teachers that will teach the subject of technology. It "is the study of technology and its effects on individual, society, and civilization" (Savage & Sterry, 1990, p. 20).

Technical problems solving – "refers to the systematic way of investigating a situation and implementing solutions" (Boser, 1993, p. 12).

Visualization – "the formation of mental images" (Godfrey, 1999, p. 12)

Summary

Problem solving is a basic component of many technological design tasks. Problem solving and technical design are both being used in many technology and engineering technology classes to promote technological literacy and prepare students for future design challenges that they may face. An important aspect of being able to solve technical design problems is being able to visualize objects in different orientations and possible solutions to problems.

This study examined the effects of visualization and solid modeling on solving a specific technical design problem. The purposes of the study were to determine if students' spatial visualization skills affected their problem solving ability, if using 3D modeling software during the design was more efficient than using sketching, and if using solid modeling software offset any differences in spatial visualization ability. Previous studies related to CAD, problem solving, visualization, and cognitive load provide insight that potential benefits of using solid modeling for technical design exist.

Employing CAD for general education purposes in a curriculum is very different from its use in industry or engineering. Industry is typically a profit driven entity. Their main objective is to make money to stay in business. CAD is a more efficient design tool than manual drafting, allowing many designs to be created and modified more easily and quickly. Designs may be transferred directly from a computer model to a rapid prototyping system or computer numerically controlled (CNC) machine to quickly produce a physical part. The time and steps to produce a part can be greatly reduced and profit increased by using CAD based systems. Educators are attempting to teach how to design and solve problems while teaching students current tools and methods used in industry. The skills of design and problem solving need to be learned and developed. The more related strategies students possess regarding a related problem, the more likely they are to solve that problem in an efficient manner.

In education, there is often an attempt to reflect current practices of "the real world." This is often for good reason. It would probably not be practical to teach students concepts and techniques that are not relevant unless their historical value is important. It may not be necessary for technology programs to purchase and use the most current software and equipment when teaching and developing problem solving and design skills. More research is needed to determine how students solve problems and what tools will better prepare them to solve problems in their future. Technology education and engineering technology have placed great emphasis and importance on teaching students how to solve problems and design solutions to problems. Many programs' entire curricula focus on problem solving. Thousands of dollars are spent annually attempting to stay current with the newest technologies. New revisions of CAD software and the equipment needed to run the software are often released annually. Whether or not these new technologies and software are beneficial in educating the students and making them better designers and problem solvers is still uncertain.

The possible benefits and drawbacks of design instruction are still in question. How solid modeling software affects students' ability to design and solve problems needs to be better understood. Previous studies show that students with high visualization skills are often better at design and assembly operations. A primary question addressed by this study is: Does modern solid modeling software provide students with low visualization skills an equal or improved opportunity to solve design problems?

CHAPTER 2

Review of Literature

The components of this study include solid modeling, spatial visualization, problem solving and design, and cognitive load. These components make up an integral and interrelated part of this study. Solid modeling has changed a great deal in the last five to ten years. Have these changes made spatial visualization easier, which could lead to better design problem solving capabilities? Does the use of solid modeling reduce cognitive loads allowing students to learn more from problem solving instruction and be able to better solve design problems?

The focus of technical design instruction has shifted from teaching for total recall and skill development to teaching students to ideate and visualize (Gillespie, 1999). Technology education has undergone a similar change in focus. Problem solving is a way in which to generate ideas, incorporate skills, and require students to think and apply previously learned concepts. Visualization is believed to be an important component of problem solving. Without the ability to visualize a specific problem and “see” possible solutions, it becomes difficult or impossible to solve that problem.

Though problem solving and visualization have been studied for over 50 years, there is still a great deal that is not known about problem solving and its educational benefits. Researchers are just beginning to identify different components and methods of problem solving, and the factors that affect problem solving such as problem structure, transfer, prior knowledge, gender, and cognitive load. There are many other factors that relate to the successful development of technical design solutions such as creativity, cost, and manufacturing. Although such factors are very important in manufacturing or real world scenarios, they were beyond the scope of this research.

There has been very little research conducted that examines technical problem solving, visualization, and solid modeling in technology education and engineering technology. The research that has been conducted is already dated due to the rapid advancement of solid modeling software. For that reason the evolution of solid modeling was briefly reviewed and studies were highlighted that offer some insight to the relationships among problem solving, design, visualization, and solid modeling.

Solid modeling software is often used to create solutions for technical design problems. The intent of this research was to further explore the relationship of visualization and problem solving when solid modeling software is used as the design tool. This study addressed whether or not the use of solid modeling software allows students to better solve technical design problems.

Types of Modeling Software

Solid modeling using computers is a relatively new technology that has only been accessible to most businesses for the last 10 to 15 years. Prior to that, computers and software did not have the capability to handle the complex algorithms required to represent and interpret objects. Earlier three-dimensional (3D) systems used more expensive hardware than two-dimensional (2D) systems and required a great deal of training. Currently, solid modeling software and computers capable of operating the software are each available for less than one thousand dollars. This puts solid modeling within reach of most businesses and educational institutions.

Wireframe Modeling. Three-dimensional modeling has evolved through various stages of progression based on the methodologies and algorithms used to create the models. The earlier forms of 3D modeling software were wireframe models that evolved from 2D CAD (see Figure 1). Edges, vertices, and face information were defined in wireframe models. Wireframe modeling consists of “lines and arcs joined end to end to make up a 3-d model” (Murray, 2003, p. 10). In many cases complex models were impossible to produce. One limitation is that the overall surface of the model is not defined, only the edges. Also, curved surfaces could be represented, but with limitations, particularly in earlier versions of software. An advantage of earlier wireframe models is they were efficient in their data calculation and could be run on slower computers (Bertoline &Wiebe, 2003).

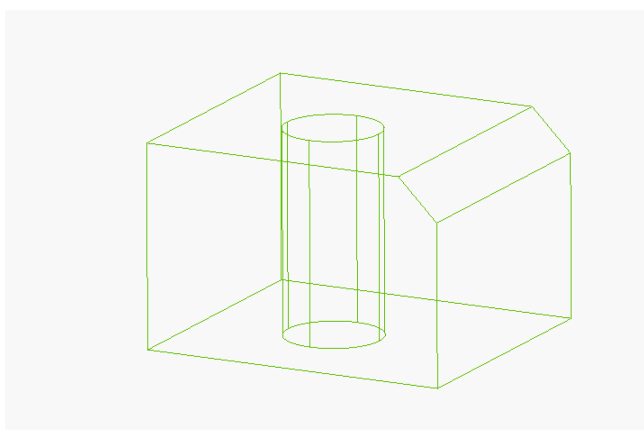

Figure 1. Example wireframe model.

Surface Modeling. Surface modeling software was also a distinctive modeling product. Surface modeling allowed the definition of surface features as well as the edges (see Figure 2). Different types of surface models exist that use different computational geometry for defining curves as well as the degree of the curve. Surface models are still important and widely used in various applications such as an automobile body or ship hull designs in which the surface is the most critical aspect of a product. (Bertoline & Wiebe, 2003)

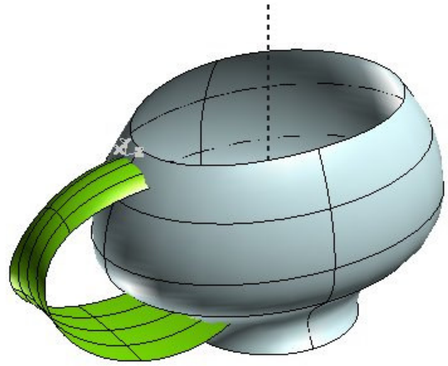

Figure 2. Example surface model.

Solid Modeling. Solid modeling has become the most widely used method of 3D representation (see Figure 3). Earlier versions used primitive shapes such as cubes, cylinders, cones, spheres, and Boolean operations to construct models. The solids have information that describes their outside surfaces as well as internal properties such as volume and mass. Many of the Boolean modelers function differently than parametric modelers. With Boolean modeling, everything originates as a solid part and then these parts can be subtracted from others. Parametric modelers are often much more efficient because they do not require the use of solids for every function. Non-parametric modelers and parametric modelers differ in the way the geometry or dimensions control one another. In non-parametric modelers the geometric shape is constructed and the dimensions are derived based on its shape and size. With parametric modeling the dimensions can be easily changed to affect the geometry or the object. In many cases this allows parametric modelers to be a more efficient and simpler design tools (Murray, 2003; Kurland, 1994).

Murray (2003) identified the following advantages of modern parametric solid modeling software over earlier modeling software:

- Easier to use
- Easier for visualization
- Provides the ability to see the model grow and develop
- Often allows resolving design issues quicker
- Has the ability to determine material properties
- Models are easily converted to other graphic forms for marketing, advertising, etc.
- Finite element analysis (FEA) can be performed on solids.
- Can be linked directly to manufacturing operations such as rapid prototyping and CNC

With all of these advances, computer models cannot always replace physical objects; limitations in hardware and software still exist (Bertoline & Wiebe, 2003; Kurland, 1994).

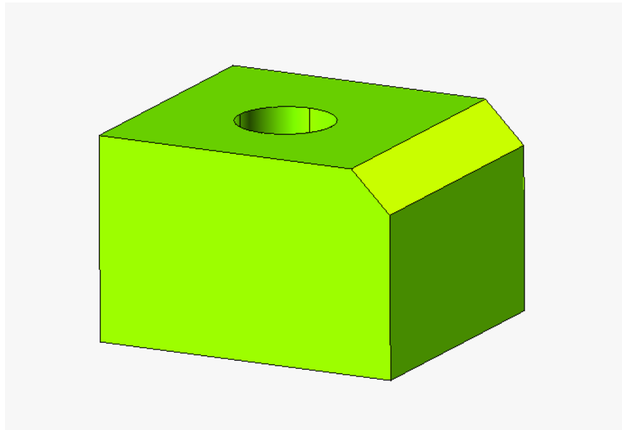

Figure 3. Example parametric solid model.

Spatial Visualization

The term visualization is often used in many different ways, so it is often difficult to understand or interpret the true intent of its use. Visualization research from the late 1800's to the 1970's identified two major factors that appeared from several factorial analyses: spatial visualization and spatial orientation (McGee, 1979; Smith & Strong 2001). McGee (1979) defined spatial visualization as "an ability to mentally manipulate, rotate, twist, or invert pictorially presented visual stimuli" (p. 3) and that spatial visualization involves recognition, retention, and recall.

Guilford and Lacey (1947, as cited by Mack, 1992) define spatial visualization as the ability to imagine the rotation of depicted objects, the folding or unfolding of flat patterns, the relative changes in position of an object in space, or the motion of machinery. Stated somewhat differently by Smith and Strong (2001), "spatial visualization is the ability to manipulate an object in an imaginary 3-D space and create a new representation of the object from a new viewpoint" (p. 2).

Spatial orientation "involves the comprehension of the arrangement of elements within a visual stimulus pattern, the aptitude for remaining unconfused by the changing orientations in which a configuration may be presented…" (McGee, 1979, p. 4). Spatial orientation is the recognition of familiar patterns or scenery such as one might see during navigation. For example an aircraft pilot performing acrobatic maneuvers knowing where the ground is in relation to their present position or a rat knowing its location in a maze are both cases where spatial orientation is needed.

Visualization was not thought of as a reflection or measurement of intelligence and until recently had not received the same emphasis as verbal skills. Spatial visualization and spatial orientation are shown to be more highly correlated with technical, vocational, mathematical, and occupational domains than verbal ability (Bertoline & Wiebe, 2003; Elliot & Smith, 1983; Gillespie, 1994).

The *International Dictionary of Spatial Tests* (Elliot & Smith, 1983) identified three distinct phases of spatial visualization research. Phase one was from 1901-1938, when researchers attempted to identify a single spatial factor. These studies were important for the identification of spatial factors being related to intelligence. In phase two, from 1938-1961, researchers began attempting to identify different spatial factors. In this second phase, two distinct areas evolved; one related to the ability to recognize spatial configurations and another related to mentally manipulating them. The third phase from 1961-1982 attempted to determine relations of spatial abilities with other factors such as age, sex, ability, and previous experience (Gillespie, 1985; Strong & Smith, 2001). A fourth phase may be emerging out of more recent research that focuses on computer technology and its relationship to spatial visualization skills (Strong & Smith, 2001).

Research supports the idea that visualization can be learned and improved through practice. Gillespie (1995) studied the effects of tutorials for teaching solid modeling on visualization. His quasi-experiment examined students enrolled in an engineering graphics course at the University of Idaho. Sixty seven participants, 41 of whom completed the study, were divided into three groups. Each group was pretested using three tests: a mental rotations test; paper folding test; and rotated block test. The rotated block instrument was developed by Gillespie and is similar to the "*Purdue Spatial Visualization Test/Test of Rotations*" (PSVT/TR) used for this study. One group was treated with ten weeks of seventeen modules on solid modeling. The two control groups received traditional 2D graphics instruction. All groups improved their scores from pretest to posttest, and the treatment group improved significantly over the two control groups.

Since Gillespie's study in 1995, solid modeling technology and software have changed a great deal. The software at that time typically involved the use of wireframes, boolean operations, and oftentimes confusing movement of a user coordinate systems (UCS) icon. Modern solid modeling software is simpler and more efficient to use (Kurland, 1994). The images are more realistic with rendered representations. This makes visualization easier and accelerates or improves the advantages of using solid modeling (Devon, Engel, Foster, Sathianathan, and Turner, 1994).

Frey and Baird (2000) studied the effects of using rapid prototyping (RP) on visualization. RP is the production of a physical part directly from a CAD file through an additive process often termed 3D printing. The study included visualization components related to spatial visualization with a physical, rapid prototyped object and how previous CAD experiences affected visualization. Though they found no significant difference when rapid prototyping was used, their data showed increases in scores on the Minnesota Paper Forms Board Test were related to increased drafting experience. The students were divided into four groups based on levels of experience or exposure to drafting and CAD: 1) no drafting experience; 2) some drafting experience; 3) CAD experience; and 4) Rapid prototyping experience. Of the 68 students studied, those with no drafting experience scored the lowest on the visualization test. Those with manual drafting experience scored slightly higher, and students with CAD and solid modeling scored the highest.

Devon, Engel, Foster, Sathianathan, & Turner (1994) examined the effects of solid modeling software on 3D visualization skills. Thirteen sections of an introductory engineering graphics class were examined to determine if using Silver Screen solid modeling software, as opposed to 2D CAD and wireframe modeling, produced higher visualization scores. The “Mental Rotations Test” developed by Vandenburg and Kuse (1978) was used to measure the visualization skills. The six Spring semester sections had significant gains in visualization. This demonstrated that using solid modeling increased the students’ visualization scores over using 2D CAD.

Differences in visualization scores are also attributed to differences in the Silver Screen curriculum, more interest and enthusiasm by the instructors and/or the students, and more attractive display of Silver Screen. With these considerations the researchers suggest they may be examining more of a Silver Screen or software effect than solid modeling effect (Devon et al. 1994).

One concern reported by the researchers was that the pretest scores were very high leaving little room for improvement or limiting the range for improvement. This could hold true of many studies using engineering and technology education students as the participants because they could have higher visualization abilities than the general population by nature of their interests and past experiences.

The study also examined the effect associated with the amount of mechanical drawing or CAD experience participants had in high school. No significant difference was found regarding the amount of mechanical drafting or CAD experience in high school which is consistent with studies by Baenninger and Newcombe (1989) and Sexton (1990 as cited by Devon et al. 1994) but contradictory to other studies (Frey & Baird, 2000).

Godfrey (1999) studied 3D visualization skills using solid modeling among 76 engineering and technology students. The control group received 2D CAD instruction and the treatment group received solid modeling instruction. The PSVT/VR was used as the visualization test at weeks 9 and 16 of the treatments. No significant differences were reported between the groups, but there were differences at the 9 week and 16 week intervals. The solid modeling group showed gains in the first 9 weeks and the 2D group showed gains in the period from week 9 to 16. Godfrey contends that this suggests a logical teaching progression going from solid or 3D modeling to the more abstract 2D CAD.

Importance of Spatial Visualization

Spatial Visualization has been identified as one of the most important skills related to engineering and technical graphics (Gillespie, 1995). “Spatial visualization skills are an important component of engineering because of their direct relationship to the graphical communication associated with design” (Devon et al. 1994, p. 4). Strong spatial visualization skills have been shown to correlate to success, achievement, and retention in engineering programs and success in mathematics (McGee, 1979). In problem solving, a mental model must first be created and regardless of the representation, that mental construction is “most important for problem solving…problem solving requires some activity-based manipulation of the problem space” (Jonassen 2000, p. 65).

Vocational students have had difficulty translating 2D schematics and blueprints into 3D objects and converting 3D objects into 2D representations. This may be due to the lack of development of visualization skills (Rosenfeld, 1985). Visualization is particularly important to engineers because they must be able to solve problems involving abstract objects. They need to be able to communicate those solutions and understand the drawings or solutions of others (Mack, 1992).

Gender Differences. The use of solid modeling curriculum is an effective way to close the gender gap in spatial visualization skills (Devon et al. 1994). Several studies found that differences exist in the spatial visualization abilities of males and females (Branoff,1998; Devon et al. 1994; Gillespie, 1994; McGee, 1979). Studies of younger children showed little or no spatial visualization differences between males and females prior to puberty. After puberty significantly different levels were evident, with males having a higher ability. In studies where differences were evident males typically had stronger visualization skills (McGee, 1979).

Devon et al. (1994) reported no significant gender differences when they examined the Fall and Spring semesters separately. The sections that received extensive solid modeling showed clear gender differences. Possible reasons given for this by the researchers, besides the effects of solid modeling, include: 1) there were more females in those groups; and 2) the lower pretest scores of the females made for larger gains than many of the males.

In Gillespie’s study (1994), gender differences were found to be significant at the .10 level, but this finding was not consistent with many previous studies. He found that the females had higher spatial visualization scores. Possible reasons for this were that the small number of females (5), may not have been a representative sample, and one female had exceptional gains, which skewed the results.

Visual cues regarding the rotation of an object have been shown to offset some of the differences of males and females. Branoff (1998) examined the addition of coordinate axes on mental rotation tasks and found that males scored higher on the preliminary test that did not have coordinates on the samples (see Figure 4). The three dimensional coordinate system (see Figure 5) provides the three physical dimensions of space — height, width, and length (Wikipedia, 2006a) . When coordinates axes were added to the object, the females showed no significant difference from the males. Branoff concluded that males tend to take a more holistic approach to visualization and females more of an analytical approach. By adding a reference, the coordinated axes on the drawings, biases were eliminated.

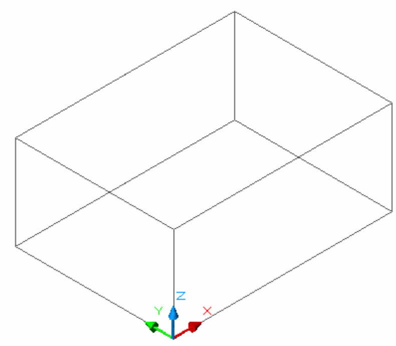

Figure 4. Wireframe model with coordinates displayed.

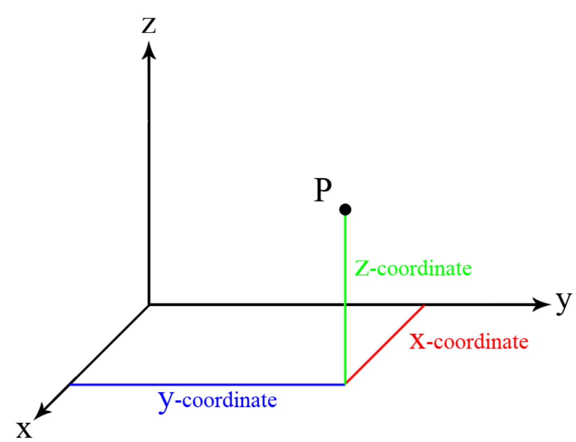

Figure 5. Three dimensional Cartesian coordinate system with the x-axis pointing towards the observer.

Problem Solving and Design

"Problem solving is a critical process skill that involves virtually all aspects of existence" (Wu, Custer, & Dyrenfurth 1996, p. 56). "Virtually everyone, in their everyday and professional lives, regularly solves problems" (Jonassen 2000, p. 63). All problems are not the same and must be approached differently than rote or component skills (Westberry, 2003). Problem solving models need to be further developed and tested to better understand and teach problem solving.

Problem solving and design are often used interchangeably. This is too limiting because problem solving often involves much more than just design; designing is a type of proactive problem solving (McCade 1990). The majority of the design in most classrooms is new product design. New product design is only a small portion of the design that is conducted in real world situations. Most designs require some form of troubleshooting in their development, but troubleshooting can also be a separate component of dealing with existing artifacts and systems.

A majority of design work is the modification of existing designs to meet changing needs and wants, or designs are created to meet open markets. "The best result of a sound problem solving process is often something other than a new product" (Flowers, 1998, p. 2). When an automobile is said to be totally redesigned from the ground up, that does not mean that every part was completely redesigned from scratch. Existing systems, such as the power plant, may have changed little if at all. Changes if any are often minor and based on years of development and previous knowledge. It is still the same internal combustion engine.

Problem Based Learning. Problem-based learning (PBL) is a relatively new and innovative form of instruction (Hung, Bailey, & Jonassen, 2003). One goal of PBL is to prepare students to be able to solve practical problems and continue learning throughout their lives. A drawback of PBL is the lack of short term, immediate, factual knowledge, which can result in poor performance on short-term assessments and standardized tests. PBL has many advantages but there are also several concerns with PBL, including: depth versus breadth of curriculum, higher-order thinking versus factual knowledge acquisition, long-term effects versus immediate learning outcomes, traditional roles of professors versus the roles of PBL tutors, and students' initial discomfort versus their positive attitudes. Numerous studies support the notion that PBL promotes more in-depth understanding of content than traditional methods. One reason for this is increased motivation and interest of students (Hung, et al.).

Components of a Problem. Problem solving is the process of seeking feasible solutions to a problem (Hatch 1988). There are only two critical parts of a problem: 1) an unknown entity in some state; and 2) finding the solution must have some benefit socially, culturally, or intellectually (Jonassen, 2000). The basic unit in problem solving is an action and if more than one solution is available for a certain problem state, a decision has to be made (Zhang, 1997). That decision can be based on learned knowledge, biases, "lookahead", or a combination of these factors.

Problems have at least three distinct components: givens, goals, and operations. Givens are the information provided, goals are the outcomes at which you wish to arrive, and operations are the process you will use to reach the goal. Based on these components, problems may be well-defined or ill-defined, which affects the methodology used for solving the problem (Ormrod, 1999; Jonassen, 2000).

Lookahead refers to the mental imagining or "seeing" of possible solutions for a particular action or decision. A mechanical example would be visualizing that turning a gear in a clockwise direction would result in a mating gear turning in a counter-clockwise direction without having to actually construct and physically test the mechanism. Being able to lookahead and predict outcomes and actions is limited by the complexity of the task, subject matter knowledge, and working memory capacity (Zhang, 1997). Effectively using solid modeling can allow one to lookahead virtually. Complex tasks that require greater prior knowledge and high working memory loads could be broken into smaller tasks or "shorter distances" to lookahead. For example, a possible solution to the problem in this study might be to use a round cam with an arm attached to push the block the required distance. One might not be able to lookahead far enough to determine the best placement and diameter of the cam to allow for the required clearances. Through a combination of analytical reasoning and trials, a solution might be more quickly generated, tested, and verified using solid modeling.

Well-Structured and Ill-Structured Problems. Problems vary based on their structuredness, complexity, and abstractness. Structuredness is whether or not a problem is well-structured or ill-structured. Most problems faced in an academic setting are well-structured. Well-structured problems present all of the needed elements, require a limited number of structured rules organized in a predictive way, and have knowledgeable comprehensive solutions. Ill-structured problems have elements that are unknown, possess multiple solutions, possess multiple criteria for evaluating solutions, and often require learners to make judgments and express opinion. Different methods, thinking, and communication patterns exist or are needed when solving the two different types of problems (Jonassen, 2000). A well-defined process for solving a problem would be considered an algorithm (Ormrod, 1999). This works fine for specific problems such as mathematics problems where there is a definite correct answer and process to arrive at that answer but is less applicable to ill-structured technical design problems.

Complexity is the number of issues, functions, or variables in the problem. Complexity has been shown to affect learners' abilities to solve problems as they become more complex, they naturally become more difficult to solve. Ill-structured problems tend to be more complex than well-structured.

Technical Problem Solving. Childress (1994) defines technical problem solving as:

> The problem solving process… combined with the processes of technology in engineering, architecture, industrial workshops, research and development laboratories, the home, the office, and field, etc., and certainly the technology education laboratory. The processes of technology employed to solve problems of human need or want characterize this method. (p. 94)

McCade (1990) defines technical problem solving similarly but further devides it into three categories: design, troubleshooting, and technology assessment.

Dearing & Daugherty (2004), identified criteria that engineering programs would like to see secondary students attain at the high school level before entering engineering programs. Several of the 64 criteria identified and ranked relate to problem solving and visualization. Those that specifically include problem solving or visualization components include:

- Ability to communicate ideas: verbally, physically, visually, etc.
- Experiences in brainstorming and generating ideas
- Product design assessment: Does a design perform its intended function?

- Troubleshooting of technological devices and systems
- Experiences that lead to Inventiveness/Creativeness
- Mental visualization and manipulation of objects and ideas
- Mechanics: interaction of parts and pieces, and simple machines, kinematics
- Ability to think in abstract form
- Basic practicality/constructability of designs: design limits, manufacturability
- Appearance of designs: aesthetics, prototypes, and models
- General ability to solve basic engineering-related problems
- Ability to use technology to present ideas
- Basic knowledge of computer-aided engineering (i.e., parametric modeling)
- Basic knowledge of spatial construction
- Experiences with the development of basic models and prototypes
- Free-hand sketching ability

Experts and Novices. Experts recognize the different problem states and solutions so they don't need to search through the problem space (Jonassen, 2000). Research shows that concepts typically have to be learned in context for them to be successfully applied by students and that they seldom transfer problem solving schemas to different situations (Westberry, 2003). Experts notice features and meaningful patterns, have acquired greater subject matter knowledge, and can flexibly retrieve important information. Changes in the presentation patterns, grouping, or identification of information can assist novices in retrieval, recognition and problem solving (Bransford, Brown, & Cocking, 2000; Jitendra, 2002). Several studies show that students are unable to solve structurally identical problems because they focus on the face features rather than having an adequate understanding of the root problem. (Bransford et al., 2000; Jonassen, 2003a)

One reason experts are better problem solvers is that they construct better mental representations of problems than novice problem solvers. "Problem representation is the key to problem solving among novice learners as well as experts" (Jonassen, 2003a, p. 365). The more ways a learner is able to represent problems and create successful mental models, that may need to include structural, procedural, reflective knowledge as well as images and metaphors, the more likely they will be able to transfer their skills and knowledge (Jonassen, 2003a).

External Representations and Problem Solving. External representations are a crucial part of many problem solving activities particularly technical design. All forms of external representation are important because "External problem representations, especially those in the form of dynamic models, enable learners to manipulate and test their models" (Jonassen, 2003a, p. 377).

"Relatively little research has been directed toward the nature of external representation in cognition" (Zhang, 1997, p. 179). This is due to the belief that little knowledge about the mind could be gained from external representations. External representations are inputs for the internal mind, and/or because the lack of a suitable method for studying external representations (Zhang, 1997). Internal representations and external representations are interrelated. To be able to interpret and use external representations one must draw on internal knowledge or representations to recall the meaning of symbols, special relations of objects, etc. and function dynamically within external and internal environments.

Zhang (1997) defines external representations as:

> …the knowledge and structure in the environment, as physical symbols, objects, or dimensions (e.g., written symbols, beads of abacuses, dimensions of a graph, etc.), and as external rules, constraints, or relations embedded in physical configurations (e.g., special relations of written digits, visual and special layouts of diagrams, physical constraints in abacuses, etc.). (p. 180)

External representations are shapes and positions of the symbols, the spatial relations of partial products, etc. (Zhang & Norman, 1995). External representations have many functions such as memory aids that extend working memory, archive information, and allow memory to be shared. External representations however are more than just memory aids. They are used in problem solving, reasoning, and decision making and can allow individuals to access knowledge and skills unavailable internally, make inferences, and interpret information (Chambers and Reisberg, 1985; Zhang, 1997). Though external representations can be beneficial in solving problems, Zhang (1997) points out that "externalization can be beneficial if the benefit of using external representations can offset the cost associated with the externalization process" (p. 181).

External representations are used in many other forms of problem solving besides technical design. Mathematics uses mental and graphic representations to promote and enable higher levels of problem solving. Research provides evidence that multiple representations of mathematical problems help students to better grasp and understand concepts (Jiang & McClintock, 2000).Graphic representations can be used to teach students with learning disabilities to be better problem solvers and the evaluation of the math word problem can include examining visual representations such as drawings and diagrams (Jitendra, 2002).

Enhancing Problem Solving with Technology and Integration. Learning, understanding, and problem solving can be enhanced with technology and graphic representations. In a case study by Jiang & McClintock (2000), students were to complete a mathematical probability problem. The participants showed improved problem solving when implementing computer based visual aids. The triangle-probability problem the participants were to solve was *A line segment of length 1 unit is broken into 3 pieces. Find the probability that the resulting line segments are sides of a triangle.* Students used Geometer's Sketchpad software to aid in the visualization and representation of the problem. They also used spaghetti to construct models. The Sketchpad software was able to provide much more dynamic representations and explore all of the possibilities. This allowed them to quickly visualize the probability of the question and establish ratios for comparison through other analytical and numerical means to solve the problem.

Transfer. Problem solving and transfer should be “two of our educational system’s top priorities” (Ormrod 1999, p. 347). Transfer is an important part of problem solving; “The process of learning and the transfer of learning are central to understanding how people develop important competencies” (Bransford et. al., 2000). Problem solving is a form of transfer because previously learned knowledge and skills are often applied to solve problems.

Although problem solving is a form of transfer, “Designing greatly exceeds the normal concept of transfer” (Jonassen, 2000, p. 80) and designers must classify the problem into experience-based schemas that break the problem into meaningful tasks. It was assumed that the processes used to solve well-structured problems were transferred to ill-structured problems but current research differentiates the thinking required for each problem (Jonassen 2003a). “There is so little evidence for transfer, i.e. that problem solving capability developed in one area will transfer to another…” (McCormick, 2004, p. 26).

Ormrod (1999) identifies three related phenomena of the six types of transfer: positive versus negative; vertical versus lateral; and specific versus general. She stated that positive transfer is when learning in one situation aids in learning or performing in another. Negative transfer has the opposite effect and acts as a distracter or hindrance. Vertical transfer is the building on of basic skills or knowledge in a linear fashion and lateral transfer is when there is no requirement to know the earlier knowledge in order to understand the task or concepts at hand. Specific transfer involves being able to apply knowledge and skills to situations that are similar or very much like the context in which they where learned. General transfer is the transfer to very broad underlying concepts.

Based on the various theories of transfer Ormrod (1999) has identified some principles that would help predict or encourage transfer to occur. They include:

- Meaningful learning promotes better transfer than rote learning.
- The more thoroughly something is learned, the more likely it is to be transferred to a new situation.
- The more similar two situations are, the more likely it is that what is learned in one situation will be applied to other situations.
- Principles are more easily transferred than knowledge.
- Numerous and varied examples and opportunities for practice increase the extent to which information and skills will be applied in new situations.
- The probability of transfer decreases as the time interval between the original task and the transfer task increases. (pp. 354-357)

Several others contend that problem solving should include or focus on real world or at least realistic problems (Bransford et. al., 2000; Hill, 1997; ITEA, 2000; McCormick, 1993; Westberry, 2003;). Graduates are rarely prepared to solve real world problems and educators often fail to engage learners in real world, ill-structured problems because of their lack of understanding the breadth of problem solving (Jonassen, 2000). Many of Ormrod’s principles were not intentionally applied or introduced to the students prior to this research because a problem too similar of other situations could make the problem too easy to solve.

Teaching Technical Problem Solving. According to McCade (1990), three basic concepts are involved or needed to teach technical problem solving: 1) A model for problem solving is needed to help students understand the process of problem solving. 2) Because systems and subsystems are often involved, understanding how the systems and sub systems of the problem work, relate, and affect each other is important. 3) Because problem solving is a higher level thinking skill that involves analysis, synthesis, and evaluation appropriate supporting prerequisite knowledge is required.

Several models outline a procedure or process for problem solving. The *Standards for Technological Literacy* (ITEA, 2000) outlines these components:

- Identify and define a problem
- Investigate and research the problem
- Generate multiple solutions
- Select the best solution or solutions
- Model and test the solution, reevaluate the solution until a final design is chosen.

Many contend that problem solving does not work this way in the real world or in the classroom (Williams, 2000; Jonassen 2000). "Meaningful problem solving is impossible without connecting the problem to domain understanding" (Jonassen 2003a, p. 367). To do this the original problem presentation must be related to a construct of meaningful internal representations that can be manipulated. How an individual forms mental representations and relates them to previous representations can have a positive or negative effect on solving the problem.

Some researchers contend that operations and knowledge used to solve a particular problem are domain specific. Domain specificity suggests operations used to solve a problem are specific to the domain in which the problem is situated. Thus, for example, students in engineering learn to focus on different operations than students from business and will most likely be more adept at solving problems from related domains (Jonassen, 2000).

Jonassen (2000) has classified eleven different problem types from studying hundreds of different problems. They include:

- Logical Problems
- Algorithms
- Story Problems
- Rule-Using Problems
- Decision-Making Problems
- Troubleshooting Problems
- Diagnosis-Solution Problems
- Strategic Performance
- Situated Case-Policy Problems
- Design Problems
- Dilemmas

Jonassen (2000) lists several attributes of design problems and considers design problems "among the most complex and ill-structured kinds of problems that are encountered in practice" (p. 80). Attributes that define problems include: 1) the learning activity or what is produces from that learning activity; 2) the inputs or information give as part of the problem statement; 3) the success criteria or what makes the problem successful or the means to assess the problem; 4) the context in which the problem is presented such as a real world context, in the case of design problems; 5) The structuredness of the problems either ill-structured or well-structured; and 6) the abstractness of the problems such as problem situated, case situated, abstract, etc.
The attributes for design problems are:

- Learning Activity - Acting on goals to produce artifact; problem structuring & articulation
- Inputs - Vague goal statement with few constraints; requires structuring
- Success Criteria - Multiple undefined criteria; no right or wrong – only better or worse
- Context - Complex real world; degrees of freedom; limited input & feedback
- Structuredness - Ill structured
- Abstractness - Problem situated

One challenge when relying on solid modeling or sketching in designing solutions to a problem, is that the solution has to fit the capability of the software and the user's skills. For instance, if a student has a solution in mind but does not have the skills to produce a model, or the software is not capable of addressing the problem, the use of that software may not be appropriate for the given situation. The same is true of sketching, using 2D CAD, or any tools. The tools and the skills have to be present and appropriate to effectively and consistently solve the problems. The challenge of dealing with an ill-defined problem is determining the tools to use and how to employ them.

For teaching problem solving and design, Williams (2000) suggested focusing on activities. The problem and the student determine what aspects are needed for a particular problem. The most important aspects he identifies are: evaluation, communication, modeling, generating ideas, research and investigation, producing, and documenting. The majority of these are within the capabilities of many solid modeling programs. Though very similar to many models for problem solving, an issue with most of these models are that they are very linear and suggest that all problems are solved in this linear manner. Research on designing shows both experts and children develop flexible approaches to solving individual problems. When students are forced to follow a teacher-defined process, the students often use their own strategies and then do the required work to meet the teacher's requirements (Williams, 2000).

Hill (1997) contends mental processes of problem solving should be focused on as opposed to specific technologies for solving problems. The technologies change over time but the mental processes are relatively stable. Wu et. al. (1996) studied technological and personal problem solving styles to determine if differences existed between engineering, technology, and humanities college students. The Personal Problem Solving Inventory (PPSI) was used to measure the participants personal problem solving style and an adapted version of the PPSI was used for measuring their technical problem solving style . Wu et. al. found that there were differences between technical problem solving and personal problem solving and that the participants problem solving styles did not change from their freshmen to senior years.

Problem solving typically requires "higher order thinking skills." Students are required to creatively synthesize solutions and analyze them. They must also possess or acquire sufficient content (domain specific) knowledge prior to solving the problem. Knowledge about a particular area or domain is necessary for the problem solver to self-correct or regulate inquiry (Childress, 1994). McCade (1990) uses the example of building materials. Knowledge of plywood, nails, screws etc. does not provide the capability to build a house, but it is essential knowledge used in solving the house building "problem." Pearson and Young's (2002) suggest technology is more than just artifacts or physical objects. Knowledge and processes for operating, manufacturing, and maintaining those products are also technology and an important aspect of design and problem solving when dealing with technology. Expert understanding and use of modeling software is very limited without skills and knowledge that transfer to the particular problem to be solved.

Cognitive Load and Cognitive Skills Acquisition

Studies that examined the relationship between learning and problem solving found that students could often solve problems without learning from the problem or process (Pillay, 1998). The capacity of working memory was often exceeded by the information of the task such as categorizing the information, making comparisons, and comprehending the problem. In learning situations, this cognitive load often is too great to allow effective learning to take place, even if the problems are being solved. If the cognitive load can be reduced and effective cognitive skills acquisition techniques can be employed during the instructional process, learning the desired objectives or skills is more likely to take place.

Products often come in packages that are marked "some assembly required." When attempting to assemble the objects, some individuals follow the instructions and complete it in a step by step manner. The tasks of assembly are broken into small components but the entire object is considered and the pictures on the cover of the box are frequently looked at. Working memory does not have the capacity to store every minute detail of a complex system. We are limited on the amount of information we can store, process, and retrieve. If previous knowledge is to be applied to a given situation, both the problem at hand and the previous knowledge must be in the limited capacity of working memory (Ormrod, 1999). Visualization also requires use of short term memory (Smith & Strong, 2001, p. 2). As more components to a particular problem are added, such as visualizing more objects and retrieving previous knowledge on how other objects were assembled, the cognitive load quickly increases.

Returning the tools used to change a flat tire to their very specifically designed storage area can be difficult. Many would examine one or two components at a time and try to determine how they relate and would fit together. Few, if any, would consider the tool kit at one time. Most individuals do not have the mental capacity for this. Ormrod states, “Problem solving occurs in working memory – a component of the memory system that has a limited capacity for holding and processing information at any single moment” (p. 379). Working memory is very limited. George Miller (1956) proposed the capacity of working memory is seven, plus or minus two, units of information.

Braddeley (1992) contends that working memory has several structures: a central structure that controls information processing and two slave systems. One slave system is for processing visual information (the Visuospatial sketch pad) and the other, the phonological loop, stores and rehearses speech-based information. He states that “the Visuospatial sketch pad is probably intimately related to the processes of visual perception and action” (p. 5). In a study he conducted, Braddeley separately disrupted the spatial and verbal processing of chess players. Chess is considered to be very visually oriented, dealing with recognition of patterns. The participants showed little or no difference in performance when the verbal tasks were disrupted but clear differences where observed when visual tasks were disrupted. This demonstrates that visualization is an integral part of working memory and that its load on students is going to severely limit their germane load or ability to learn while solving design problems.

Pillay (1998) points out that in studies examining learning and problem solving, students could often solve problems but did not learn from those problem solving experiences. If an individual’s mental capacity is exhausted by just solving the problem little or no capacity remains to make connections with existing knowledge and develop schemas for learning (Pillay, 1998; Renkl & Atkinson, 2003). Her analysis found that when students were presented with three-dimensional representations or true 3D objects, cognitive resources were freed and students were more successful at assembly operations.

Students must often be able to acquire the necessary skills or knowledge to solve particular problems within a domain, have the resources to deal with the problem, and have the capacity to process the needed information. Cognitive skill is the “learners’ capabilities to solve problems from intellectual domains such as mathematics, medical diagnosis, or electronics trouble shooting” (Renkl & Atkinson, 2003, p. 16). Halford

(1993) defines cognitive resources as “the individual’s cognitive ability to deal with a task” and cognitive load as “the demand made by a task on the individual’s mental effort for the successful completion of a task” (p. 3).

VanLehn (1996, as cited in Renkl & Atkinson, 2003) identified three distinct phases of skills acquisition. The early phase is when learners gain a basic understanding of the domain. The intermediate phase is when learners focus on how to solve problems. The late stage speed and accuracy are improved through practice. These distinct phases need to be considered during the instruction process when students are learning to solve problems in a particular domain.

Renkl & Atkinson (2003) contend that for well-structured domains such as mathematics, problem solving is not necessarily the best method for learning during the early cognitive skills acquisition, but is superior during later skills. Their study shows that novices tend to learn better with worked-out examples that are forward or backward faded. When forward faded worked out examples are used, the students are given structured problems and the first step in the problems solving process is left out then the next step in the next example. They are required to work through the various steps and complete the missing component in the process. In backward fading, the last step is left out in the first problem a student works.

Sweller, van Merriënboer, & Pass (1998) defined two different types of cognitive loads, intrinsic load and germane load. Intrinsic load is how complex the material is or how many elements have to be dealt with simultaneously. The current level of knowledge of the learner and their cognitive skills for that domain would greatly affect their intrinsic load. If a student were very familiar with 2D drawings, visualizing them as 3D objects may be of little intrinsic load on them. Germane load is the demand on working memory capacity that is imposed by mental activity that contributes directly to learning.

A third type of cognitive load has been identified as extraneous load. Merriënboer & Ayres (2005) state that extraneous cognitive load “is associated with processes that are not directly necessary for learning and can be altered by instructional interventions” (p. 5). Extraneous cognitive load is a load that is unnecessary and so interferes with schema acquisition and automation. Intrinsic and extraneous loads are additive so if intrinsic loads are high the instructional materials need to be taken into account to reduce the total load (Paas, Renkl, & Sweller 2003). Typically, for novice learners the extraneous load needs to be reduced on beginning exercises by often sequencing events from simple to complex (Merriënboer, Kirschner, & Kester 2003).

By mapping mental representations of a problem onto existing cognitive representations the number of mental steps can be reduced, and as problems become more complex, efficient mapping becomes more critical. Research shows that incorporating diagrams or flow charts as well as other graphic representations for complex problems often results in better performance and shorter solution times (Jonassen 2003b). Drawings, diagrams, and models are all forms of external representation that can reduce the cognitive load on the learners. Through the use of technology, feedback can be provided faster (Bransford et.

al., 2000). The saying "a picture is worth a thousand words" may also apply to a learner's cognitive load. "Externally representing problems will decrease the cognitive load in learners, especially while solving complex problems…. providing external representation of the problem components scaffolds working memory by off-loading the need to simultaneously model multiple problem components" (Jonassen, 2003a, p. 377). On the contrary though, mapping mental representations in an inefficient way can hinder problem solving.

In educational settings students are required to focus a portion of their attention and cognitive ability on the instruction itself and a portion on the actual task or problem. When designing and problem solving with software applications, students apply a portion of their mental capacity to using the software, interpreting the object(s) and their relations, and lastly on the problem to be solved. When using 2D representations to solve problems, more mental capacity is used to interpret and understand the image, particularly in individuals not skilled in working with this type of representation or are in the earlier stages of cognitive skills development (Pillay, 1998). This is an important concept for engineering technology and technology education particularly when problem solving is the focus for a particular activity or curricula.

Summary

Several studies have been conducted on visualization and the differences between computer-aided drafting and manual drafting. Presently, advances in computers and design software are far outpacing the research conducted in these areas. There is limited time before software changes. Many softwares are out of date when they are distributed for consumer purchase. There are also a limited number of researchers particularly related to technology education. Care must be taken when making decisions to adopt new, costly softwares and technologies to aid problem solving and technical design. Many researchers suggest focusing on problem solving processes or styles as opposed to the actual technology itself (Halfin, 1973; Hill, 1996; Wicklein, 1996; Wu et. al. 1996). Further studies are needed to verify that solid modeling software does aid the goal of learning or being able to better solve problems, promoting technological literacy and prepare individuals to face future technological problems.

CHAPTER 3

Methodology

Design

The design for this study was an experimental posttest only design. Each participant completed the *Purdue Spatial-Visualization Test/Visualization of Rotations* (PSVT/TR) see Appendix C)). The participants were randomly assigned to either the control group or the experimental group. The control group designed a solution to the design problem using sketching and then physically constructed their prototype with the provided materials. The experimental group participants each used *ProDesktop* solid modeling software and sketching to design their solutions and then constructed a prototype with the provided materials. The physical models or prototypes were then scored as either successful or unsuccessful. A graduate student, who did not know which group the participants were in, scored all of the prototypes.

Purposes. The purposes of this study were to determine if:

1. students' visualization skills affect their problem solving ability;

2. the use of 3D modeling software in the design and production of a prototype for a technical design problem is more effective than using sketching; and

3. the use of 3D modeling software offsets any differences in low spatial visualization skills for solving a technical design problem.

Research Hypotheses. The following hypotheses were investigated in this study:

$H_0$1: Participants' spatial visualization skills, as measured by the *Purdue Spatial-Visualization Test/Visualization of Rotations*, will not affect their technical problem solving ability.

$H_0$2: Participants using solid modeling software to design solutions to technical problems will not show greater success in the construction of a physical model or prototype than those using sketching.

$H_0$3: Participants with lower visualization skills, as measured by the *Purdue Spatial-Visualization Test/Visualization of Rotations*, will not perform better using solid modeling software than those with equal scores using sketching in the design and production of a prototype for a technical problem.

Selection of Participants

The experimental and control groups were each comprised of 25 randomly assigned participants from the Industrial and Engineering Technology Program at Southeast Missouri State University. Specifically, participants were students enrolled in an introductory or advanced computer-aided solid modeling course taught by the researcher. The majority of the participants were technology education, engineering technology, and graphics technology majors in different stages of their academic programs. The remainders were University Studies majors, undeclared majors, or minors in Engineering Technology. Most of the participants had little previous experience with drafting or CAD. Few of the students had any formal exposure to solid modeling software prior to the instruction at Southeast Missouri State University.

Variables

Independent Variables. The independent variables in this study were:
1) The method the participants used to design their prototype; and 2) The participants' spatial visualization ability. Participants in the control group used sketching in the design of their prototype, while experimental group used *ProDesktop* solid modeling software for the design of their prototype. Spatial visualization was measured with the *Purdue Spatial Visualizations Test/ Visualizations of Rotations* (PSVT/TR).

Sketching was selected as the control method because students in technology education are generally required to produce sketches of possible solutions to problems prior to constructing a solution. A survey by Römer, Weißhahn, Hacker, Pache & Lindemann, (2001) of 106 designers indicated that sketching was the dominant external aid for early stages of the design process. Sketching was used significantly more than simple models, complex models, and CAD in the development of solutions. CAD was used more for documentation and complex testing of solutions.

The PSVT/TR test was designed to measure the participants' ability to visualize the rotation of three-dimensional objects. This instrument was chosen because of its higher correlation with similar instruments measuring visualization such as the Shepard-Metzler tests. According to Bodner & Guay (1997), these tests are "among the spatial test least likely to be confounded by analytic processing strategies." (p. 13). The *Minnesota Paper Folding Board Test* is also designed to measure spatial visualization but has a weaker correlation with other spatial visualization instruments and is likely to be confounded by analytic processing (Bodner & Guay, 1997).

The format for the PSVT/TR is thirty questions (see Appendix C). For each question an object is pictured in one position then it is shown, in a second image, rotated to a different position. The participants are shown a second object and given five choices, one of which matches the rotation of the original object example. They are to select the object that shows the same rotation as the original example for that question. A sample PSVT/TR question is shown in Figure 6.

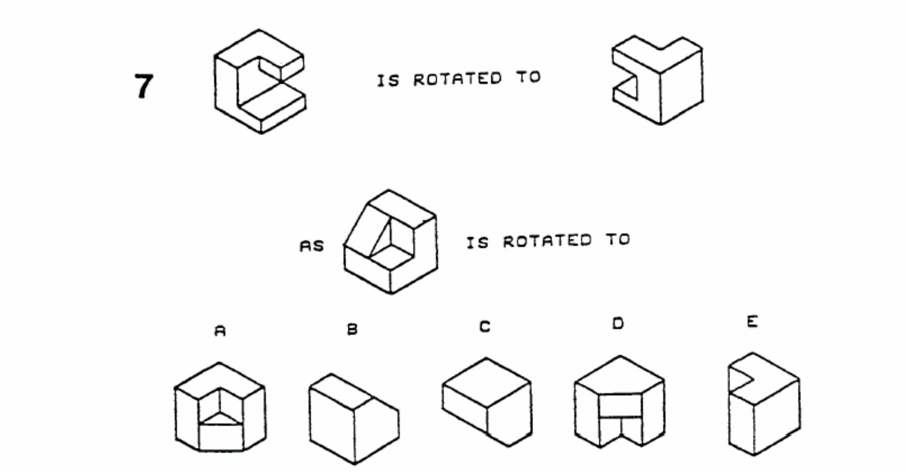

Figure 6. Sample PSVT/TR problem.

Reliability for the PSVT/TR on studies of chemistry students (Bodner & Guay, 1997), report Kruder-Richardson 20 internal consistency test values of .80, .78, and .80 with samples of 758, 850, 1273 respectively. They also reported Split Half reliabilities of .83, .80, .84, .85, .82, and .78 with samples of 757, 850, 127, 1273, 1648, and 158 respectively.

The construct validity for the PSVT/TR is supported by a study of five measures of spatial ability. The highest correlation was between the PSVT/TR and the Shepard-Metzler test ($r=0.61$, $p<0.001$). The lowest correlation was between the PSVT/TR and the Minnesota Paper Form Board (MPFB) test ($r=0.25$, $p<0.01$). The MPFB was the test most likely to be answered by trial-and-error processes or confounded by analytical processing, thus possibly not providing a valid measure of spatial ability. The PSVT/TR also reported significant differences in performance between males and females which have been observed in other spatial visualization measures. Student's scores have also been correlated with highly spatial topics in chemistry. (Bodner & Guay, 1997)

Dependent Variable. The dependent variable was participant performance in solving a technical design problem. The technical design problem used to measure problem solving performance was designed to require a substantial amount of design skill and effort within the limitations of time and resources. The problem selected for the study involved the conversion of rotational motion to reciprocal motion. Such a conversion is fundamental to many applications and can be found in many technical devices and systems such as the internal combustion engine, windmills, and early water-powered devices. The problem also required the consideration of multiple planes or surfaces, adding to its complexity and requiring high level visualization and problem solving skills. Real world examples were not intentionally mentioned to the participants, but it was anticipated that the participants would associate or mentally transfer this problem to devices or mechanisms with which they were familiar. The problem solving activity studied in this research was an ill-defined design problem. That is, there was no set procedure for arriving at a solution and there were many possible solutions.

The problem was also intended to have a cost high enough to benefit from the construction of the solid model for analysis and design purposes. The external representations created using solid modeling exhibit many of the characteristics of physical objects as well as allowing for analysis and manipulation that is not possibly on physical objects.

The participants were instructed to design a mechanism that would convert rotary motion to reciprocal motion and move a block forward a fixed amount within specified tolerances (see Appendices A and B). Upon completion of the design, the participants were instructed to construct a working model or prototype using supplied materials. The materials included:

1. Hot glue gun
2. Glue sticks
3. Double sided tape
4. Wood glue
5. Masking tape
6. Duct tape
7. ¼” dowel rods
8. 3/8” dowel rods
9. ½” dowel rods
10. Foam core board
11. ½” rigid foam
12. Corrugated cardboard
13. ¼” hardboard
14. ½” plywood
15. Assorted nails, screws, bolts, and nuts

The prototype had to successfully advance three 1.5” X 1.5” X 3” blocks a distance of 3.5” with a tolerance of plus or minus $^1/_8$”. The prototypes were dichotomously scored as either successful or not successful. If all three blocks were successfully advanced the required 3” within the $^1/_8$” tolerances in one of two possible attempts, the prototype was scored as a successful solution to the design problem. If the prototype failed to consecutively advance all 3 blocks during the attempts, it was scored as not successful.

This dichotomous value was the dependent variable. This method of evaluation was selected because this and many ill-defined problem solving activities may have multiple, correct solutions. For this problem, the participants were only evaluated on mastering the stated objective. Other aspects of product design and manufacturing, such as creativity, aesthetics, cost, durability, and manufacturability, were not considered within the scope of this research.

Description of Test Administration

The PSVT/TR was used in this study to measure the participants' spatial visualization ability. The 30-item instrument was administered to all participants scored using the key provided by the publisher (Appendix D). The participants were comprised of two classes of students. In each of the classes the students were randomly assigned to either the control group or the experimental group. The control group was given the design problem and instructed to *sketch* a design solution that they would later be required to build. The experimental group was instructed to use *ProDesktop* 3D modeling software to design the prototype that they too would later construct. The participants were given the already constructed fixture (Figure 7) and the blocks that needed to be advanced (Figure 8). The instructions of the problem were read to each group and the animation (see file "Video 1") showing where the blocks were inserted into the fixture and the direction they needed to be advanced. It was also explained to them that the blocks were placed or loaded into the fixture by hand and could be removed by hand once they were advanced.

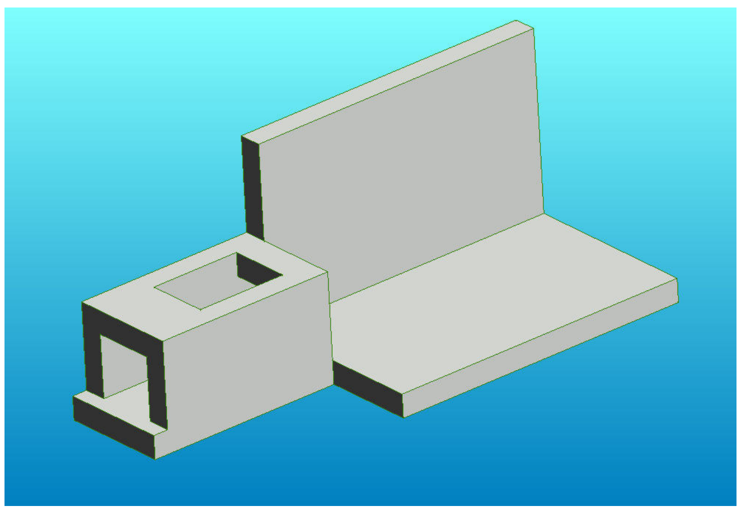

Figure 7. Provided fixture.

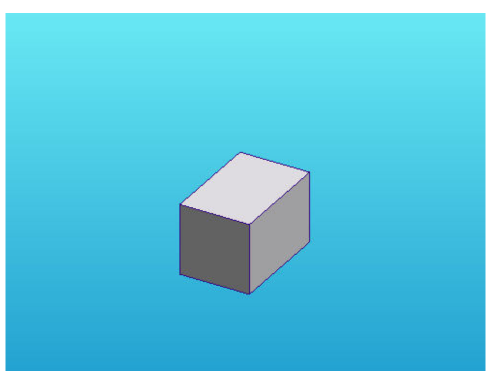

Figure 8. Provided block.

Both groups were limited to three hours for completing the design and three hours for construction of the prototype, but they were not required to use that entire amount of time. Each group completed the design and construction of the prototypes over two consecutive days. During the first three hour session, the participants designed their solutions. The next day, the participants constructed their designed solution. They were instructed that they had to construct the design that they created the previous session and were not allowed to change their designs. This was done to eliminate any influences they may have been exposed to between sessions. The completed prototypes were compared to the designs to verify that they did match.

During the design and prototype construction the individual participants were isolated from one another to limit them from seeing other design ideas and solutions. The classroom and participants were arranged in a manner that would make it very difficult to see the designs of other participants. The participants were spaced out alternately in rows with one participant using sketching, the next using the computer, then sketching, and so on. This was done to minimize or prevent the participants from being able to see the computer monitors of those using the computer to design their solutions. As an added precaution, dividers were placed between the participants.

The participants were spaced out in large room during the construction process of the prototypes to prevent them from observing construction methods or techniques. Although they could not change or deviate from their original designs, this prevented them from gaining ideas for slight design modifications that may assist them in solving the given problem.

Feasibility Test

Prior to conducting this study, 20 Virginia Polytechnic Institute and State University (VPI & SU) students were administered the PSVT/TR and 12 were asked to design and construct a prototype of the problem used in this study as a feasibility test. This feasibility test was conducted to determine if the problem and time allotted were suitable for completion of the design and construction of the prototype. One concern was that perhaps all or none of the participants would successfully complete the prototype. Thus, a feasibility test was conducted to ensure that the problem and times were appropriate and that some variability would likely exist within the population to be used for the study.

The 20 participants used for the feasibility test were enrolled in EDTE 1406 (Teaching Drafting) in VPI & SU's Technology Education Program. The software used was Parametric Technology Corporation's *ProDesktop 2000i*^{2}. An earlier and similar version of the software used in this study. Participants in the feasibility test had similar educational backgrounds to the population from Southeast Missouri State University.

The PSVT/TR was used to measure the spatial visualization of the research participants because of the score variance measured during the feasibility test and the previously established validity and reliability of the instrument. The feasibility study participants had a mean score for the PSVT/TR of 21.8 with a standard deviation of 4.02. This provided evidence that spatial visualization skills of the participants as measured by the PSVT/TR varied somewhat even though the participants had similar educational backgrounds. Several of the participants commented that the test was difficult and that it took a great deal of concentration to determine the correct solutions for the problems.

Twelve participants of the feasibility test were able to complete the design and construction of the prototype. The participants were given three hours to design their solution and four hours to construct them. Due to time constraints and scheduling the four hours had to be broken into two sections over two days. This posed problems with the participants interacting with one another and individuals not participating in the study. Two participants had problems the first day of construction and had designed solutions that did not appear that they would work. They admittedly discussed the problem with others so their changes to their solutions were not considered valid. This reinforced the notion that error had to be reduced by having the participants design and construct their solutions in one session if possible.

All but one of the participants were able to complete their prototypes in the time allotted. Five of the ten prototypes were considered successful. Three of the successful prototypes were designed using *ProDesktop*. The prototypes were simple in design yet effectively met the design requirements. Figures 9-11 show three of the successful solutions. Three more prototypes successfully advanced the block the given distance but failed to use a rotary motion for the mechanism. They used some type of sliding arm (Fig. 12) with the rotational movement not actually functioning to advance the part. This was one of the most common problems or misunderstandings of the feasibility participants.

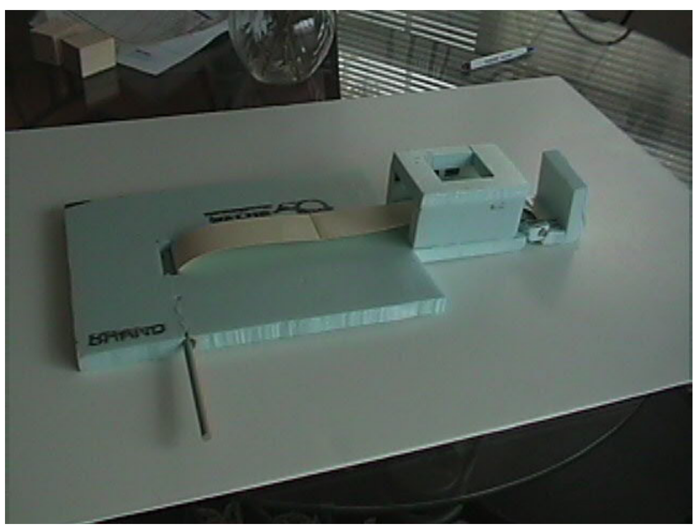

Figure 9. Successful feasibility prototype 1.

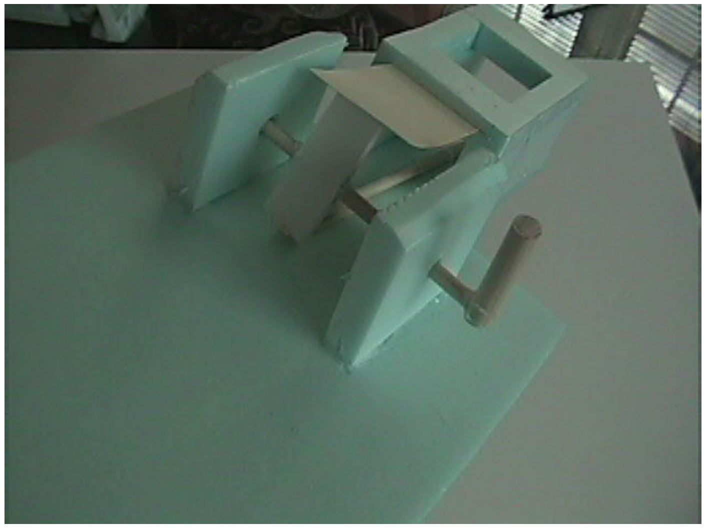

Figure 10. Successful feasibility prototype 2.

Figure 11. Successful feasibility prototype 3.

The other key problem was that the problem they were given was stated as a practical problem. The design problem was a fictitious industry scenario in which they had a motor to provide the rotary motion that would power the device to advance the block. The participants were instructed that they would be powering the device by hand and not a motor. Several of them were unclear of this and asked to see the motor or how their design would hook up to the motor. For this reason the problem description was reworded and did not use the description of a motor to provide power.

Figure 12. Unsuccessful feasibility prototype 1.

The participants commented that the problem was interesting and the ones that had successful solutions said that it was a relatively easy problem. They made references to mechanisms or products that they had seen for solving similar problems such as a conveyor belt or a car engine. They also commented on hesitating to add to the jig or fixture and that it would be helpful to have another surface at 90° to the jig for constructing their mechanism. Based on their comments, the fixture for the study was changed to the shape shown in Figure 13.

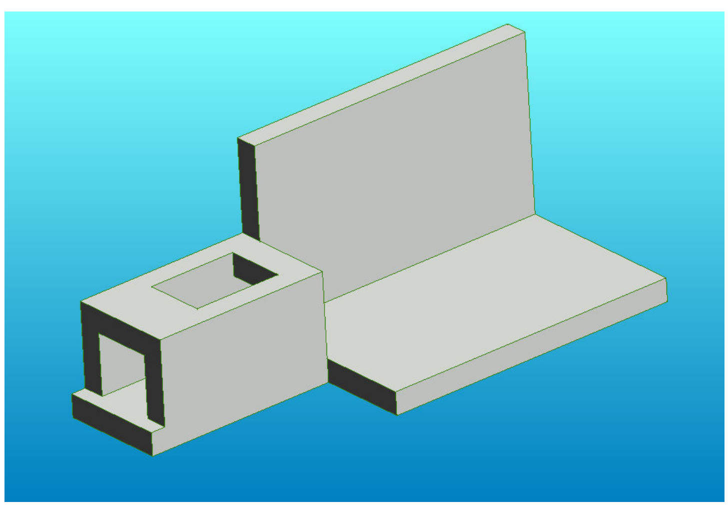

Figure 13. Fixture.

Software

ProDesktop, Version 8 was selected for the three dimension design for this study because of its parametric modeling and visualization capabilities, and because interviews with other instructors and review of their instructional materials demonstrated that all participants received consistent instruction on the use and applications of this software. Both the control and experimental groups had the same exposure and experiences in the courses they participated in as a part of the Industrial and Engineering Technology Program at Southeast Missouri State University. All participants were instructed on the use of the software through completion of the same tutorials and modeling problems.

Data Analysis

The data were analyzed using the logistic regression procedure. This methodology was selected because the dependent variable was dichotomous. The study used one categorical independent variable, the method of design used, and one continuous independent variable, visualization score. Visualization was treated as an independent variable to determine if it affected problem solving ability and if there was interaction between the two independent variables.

Logistic regression was used to determine if significant differences existed between the method of design, visualization, and the successful construction of the prototype/solution. Logistic regression was chosen over linear regression because the latter could result in predicted values greater than one (successful) or less than zero (unsuccessful) when testing dichotomous variables, and the effects of the independent variable could be greatly underestimated (Pedhazur, 1997, p. 715). The data were also analyzed to determine the interaction, if any, between the independent variables: visualization and design method. The overall time used by each participant was recorded to make comparisons of efficiency and to describe the consistency of the designs and finished prototypes.

Summary

This study used a population of 50 students enrolled in technical graphics courses at Southeast Missouri State University. The dependent variable was the construction of a prototype for the given technical problem. The independent variables were visualization, as scored using the PSVT/TR, and the design method used - sketching or 3D solid modeling. This was an experimental posttest only design that utilized logistic regression due to the dichotomous nature of the dependent variable.

CHAPTER 4

Data Analysis

The purposes of this study were to determine if: 1) students' visualization skills affect their problem solving ability; 2) the use of 3D modeling software in the design and production of a prototype for a technical design problem is more effective than using sketching; and 4) the use of 3D modeling software offsets any differences in low spatial visualization skills for solving a technical design problem.

The original population consisted of 50 participants. Each participant completed the *Purdue Spatial Visualization Test/ Test of Rotations* (PSVT/TR). The population was reduced to 47 because three participants were not present for the entire three hours of the prototype construction and did not complete their designs in the time they had available.

Two different variables were analyzed, spatial visualization and the method used to design the solution, to see if they affected the successful completion of the prototype (see Table 1). The variables were also analyzed to determine if there was any interaction between spatial visualization and the method used to design the solution to the problem. For example, could using a particular design tool such as solid modeling software offset differences in visualization scores? The information was process using the logistic regression function of SPSS statistical analysis software to determine if any significant statistical differences existed between the groups.

Table 1.

Description of Variables

Variables	Description
Dependent Variable Successful/Unsuccessful	Scored results of the design problem prototype. Did the prototype successfully meet the requirements stated in the design problem?
Independent Variable Visualization	Spatial Visualization score as measured by the *Purdue Spatial Visualization Test/ Test of Rotations*
Independent Variable Method	The method used to design the solution to the design problem. Sketching-control group Solid Modeling-experimental group
Interaction	Product of the visualization and method used to determine if the variables are homoscedastic or if interaction exists between the variables.

Descriptive Statistics

The control group (sketching as design tool) included 23 participants and the experimental group (*ProDesktop* as design tool) included 24 participants. Both groups completed the PSVT/TR prior to beginning the design problem. The mean score for the PSVT/TR for the 47 participants was 22.26 with a standard deviation of 4.55. The mean score for the 23 participants in the control group was 21.49 with a standard deviation of 4.39. The mean score for the experimental groups 24 participants was 23 with a standard deviation of 4.66. There were 11 successfully constructed prototypes, five from the control group and six from the experimental group
(see Table 2).

Table 2.

Purdue Spatial Visualization Test/Test of Rotations Descriptive Statistics

Group	*N*	*M*	*SD*	Successful completion of prototype
Control Group	23	21.49	4.39	5
Exp. Group	24	23.00	4.66	6

Of the 23 participants that comprised the control group, six were females and one of those females constructed a successful prototype. The experimental group included seven females of which one constructed a successful prototype. Three of the participants that had successful prototypes had completed three semesters of drafting/solid modeling courses. The remaining eight successful participants had only completed two semesters.

Hypotheses Tests

Even though random assignment was used for the control and experimental groups to control for any variation in spatial visualization abilities, the control and experimental groups' visualization scores were analyzed using analysis of variance to ensure that there were no significant differences between the groups spatial visualization abilities as measured by the PSVT/TR. These results revealed that there were no significant differences between the groups, $F(1,45)=1.325$, $p=.256$, $r^2=.029$, indicating the experimental and control groups were equivalent in spatial visualization (see Table 2).

The successful or unsuccessful completion of a working prototype and the visualization scores were processed using logistic regression to determine if any statistically significant differences existed between the groups. They were also analyzed to determine if there was any interaction between the method of design and the visualization scores (see Table 3). The interaction was investigated to determine if using solid modeling software would offset low scores in visualization. It was hypothesized that if using solid modeling reduced a participant's cognitive load, it could possibly make visualization easier for the participants and thus offset any differences in their measured spatial visualization ability.

Table 3.

Summary of Logistic Regression Results for Successful Construction of Prototype (N=47)

Variable	*B*	*B/SE*	Wald	χ^2 (*df*)	*p*
Model 1				7.787(1)*	.005
Constant	-9.018	3.539	6.494		
Visualization*	0.332	0.144	5.313		.021
Model 2				7.977(2)*	.019
Constant	-9.057	3.536	6.559		
Visualization*	0.339	0.146	5.402		.020
Method	-0.242	0.767	0.100		.752
Model 3				8.732(3)*	.033
Constant	-6.671	4.010	2.768		
Visualization	0.239	0.169	1.986		.159
Method	-6.503	7.405	0.771		.380
Interaction	0.256	0.299	0.731		.393

Note. *p<.05

> $H_0 1$: Participants' spatial visualization ability, as measured by the *Purdue Spatial-Visualization Test/Visualization of Rotations*, will not affect their technical problem solving ability.

As suggested in the literature, the analysis indicated that spatial visualization skills were a significant predictor of being able to successfully complete the design problem. The higher the spatial visualization score a participant had the more likely they were to be able to solve the design problem and successfully produce a prototype that met the requirements to be considered successful.

The results from model one (see Table 3) indicated that spatial visualization was a significant predictor of being able to complete this technical design problem. The coefficient on the visualization variable has a Wald statistic equal to 5.313 which is significant at the .05 level (p=.021). The overall model was significant at the .05 level according to the model chi-square statistic. The model predicts 77% of the responses correctly. The null hypothesis was rejected.

Does a participant's visualization ability have an effect on their problem solving ability? The data from this study revealed that visualization ability has an effect on or significantly correlates with the participants being able to solve this technical design problem. The participants' visualization ability, as measured by the PSVT/TR, was a significant predictor of their success for the given technical design problem.

> *$H_0$2:* Participants using solid modeling software to design solutions to technical problems will not show greater success in the construction of a physical model or prototype than those using sketching.

The results from step two indicated that there was no significant difference between participants who used solid modeling and those who used sketching to solve the given design problem. The results of the analysis supported the null hypothesis, thus the null hypothesis failed to be rejected.

Step two of the logistic regression analysis included the addition of the Method variable which takes into account whether the participants used *ProDesktop* solid modeling software and possibly sketching or if they used only sketching. The model was significant at the .05 level (p=.019) with a chi-square statistic of 7.977(df=2). The Method was not significant at the .05 level (p=.752) and a Wald of 0.100. Five participants of the control or sketching only group constructed successful prototypes and six of the experimental or ProDesktop group constructed successful prototypes (see Table 4).

Table 4.

Number of Successful and Unsuccessful Participants

Method	Successful	Unsuccessful	Total (N)	% Successful
Control	5	18	23	21.7
Experimental	6	18	24	25.0

Does the use of solid-modeling software increase students' problem solving ability for technical design problems? It was expected, from the review of previous literature, that using the solid modeling software would reduce the participants' cognitive load or what Sweller et. al. (1998) called intrinsic load and allow participants to better focus on solving the problem. Using ProDesktop provided no significant advantage over sketching alone in solving the given design problem. The use of solid-modeling software did not increase the participants' problem solving ability for the technical design problem. There were six successful solutions from the experimental group out or 24 participants and five successful solutions from the 23 participants in the control group. Table 4 reveals that the experimental group had a slightly higher percent of success, 25% as opposed to the experimental groups 21.7% but that difference is not significant.

> *$H_0$3:* Participants with lower visualization skills, as measured by the *Purdue Spatial-Visualization Test/Visualization of Rotations*, will not perform better using solid modeling software than those with equal scores using sketching in the design and production of a prototype for a technical design problem.

Because there was no significant difference in performance between the two groups and no significant interaction between the method of design and spatial visualizations scores, the null hypothesis failed to be rejected. Using *ProDesktop* to design the solution did not offset differences in the participants' visualization scores (see Table 3). The model was significant at the .05 level (p=.033) with a chi-square statistic of 8.732(df=3). The interaction was not significant at the .05 level (p=.393) and a Wald of 0.731.

The products of the method and the visualization scores or interaction were also analyzed to determine if they were homogeneous. The product was not statistically significant, indicating the regression coefficients were homogeneous. When students have weak visualization skills, is there an advantage to using solid modeling to design a solution to a problem? Using solid modeling did not offer any significant advantage in designing the solution to the technical design problem. A graph of the logistic regression curves for the two methods used, sketching and solid modeling, that shows the predicted probability of successfully solving the problem compared to the visualization score reveals some trends that contradict hypothesis three (see Figure 14).

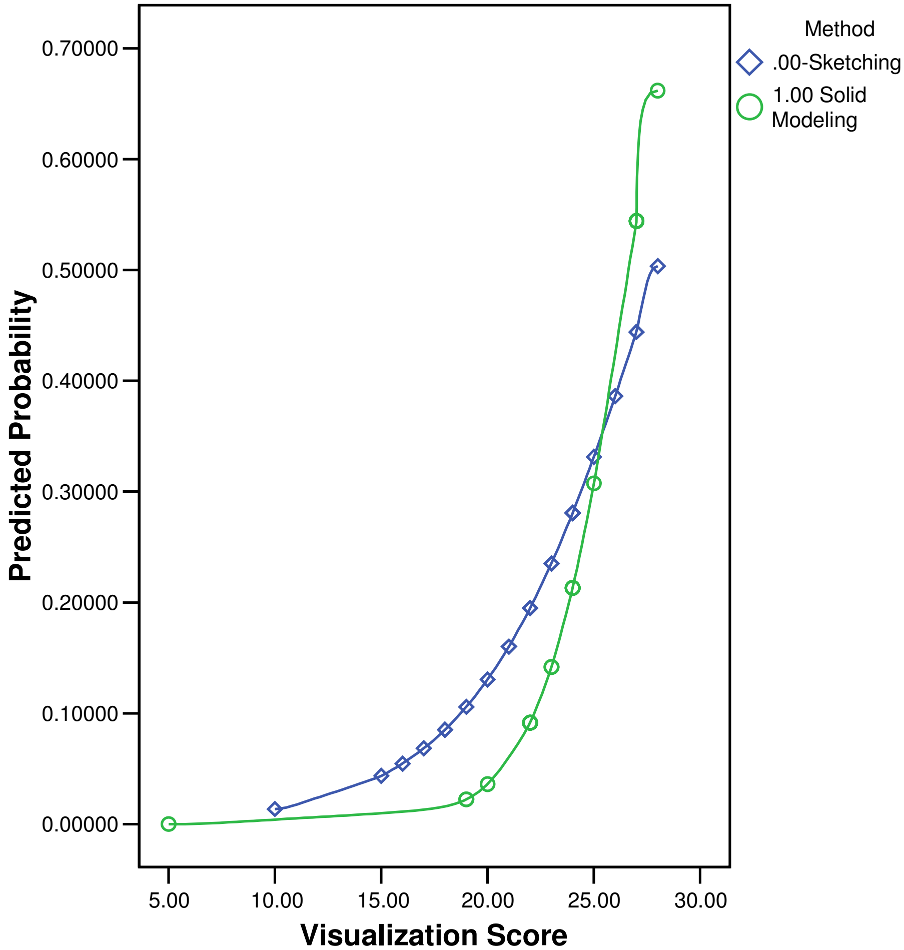

Figure 14. Logistic regression curves for sketching and solid modeling.

Additional Findings

Gender. Though determining differences in spatial visualization ability between genders was not a primary purpose of this study, gender comparisons of spatial visualization are common in the literature. Males have been found in many studies to have higher spatial visualization abilities. The analysis of this study was similar to a minority of others in that it was found that the males did not have significantly higher spatial visualization ability. There were 13 females and 34 males in this study. The males did not show a significant difference in visualization $F(1,45)=3.475$, $p=.069$, $r^2=.072$, from the females' visualization scores (see Table 5). Although, the males did report a slightly higher mean score ($M=23.00$) with a slightly smaller standard deviation ($SD=4.55$) as opposed to the females ($M=20.31$, $SD=5.33$).

Table 5.

ANOVA for Differences in Spatial Visualization and Gender

Group	*N*	*M*	*SD*
Males	34	23.00	4.55
Females	13	20.31	5.33

Visualization Ability. Several researchers reported that visualization can be improved by practice (Baird, 1991; Blade, 1949; Brinkmann, 1966; Cohen, 1981; and Rosenfeld, 1985). For this reason, this study examined the potential impact of visualization practice. The number of mechanical drafting semesters the participants in this study had completed was recorded and analyzed to determine if they showed improvement in their visualization scores.

All of the participants had completed either two or three semesters of mechanical drafting classes at Southeast Missouri State University. The classes do not focus strictly on teaching visualization but the do have many components that relate to visualization. Due to the nature of the subject being taught, drafting and solid modeling, spatial visualization skills are required and practiced throughout the classes. The number of completed semesters of drafting was distributed very evenly with 24 participants having completed two semesters and 23 participants having completed three semesters. The mean number of classes completed was 2.49 with a standard deviation of .505. As reported earlier, the mean visualization score was 22.26 with a standard deviation of 4.55. Contrary to the findings of much of the research, analysis revealed that there was no significant improvement in the visualization scores of those participants who completed a third drafting class, $F(1,45)=.909$, $p=.345$. The results revealed that only 2% ($r^2=.020$) of the variability in the visualization score is related to the number of drafting semesters completed.

Summary

The control groups' mean spatial visualization score was 21.49 with five successfully completed prototypes. The experimental groups' mean spatial visualization score was 23.00 with six successfully completed prototypes. Using logistic regression, the participants' visualization scores, as measured by the PSVT/TR, were found to be significant predictor of successfully completing the prototype. The spatial visualization scores significantly (p=.021) predicted successful completion of a prototype for the given design problem. The first null hypothesis was rejected.

No significant differences were found between the two groups' performances on completing successful prototypes. The results revealed that the group using solid modeling, as opposed to sketching, did not significantly improve their ability to solve the design problem. Thus, the second null hypothesis failed to be rejected.

Because there was not a significant difference between the groups and no interaction between visualization and the design method (solid modeling or sketching) used, lower visualization scores were not offset by the use of the solid modeling design method during the solution of the design problem. The third null hypothesis failed to be rejected.

Additional findings also revealed that the male participants did not score significantly higher on the PSVT/TR than the females. The number of semesters of drafting and solid modeling classes the participants completed was also analyzed to determine if any significant difference existed between spatial visualization scores and the number of semesters completed. It was found that the number of semesters of drafting and modeling classes had no significant difference on their visualization scores.

CHAPTER 5

Summary, Discussion, and Suggestions for Further Research

Summary

The purpose of this study was to investigate the effects of solid modeling and visualization on technical design problem solving. Gillespie (1995), Devon et al. (1994), McGee (1979), and Jonassen (2000) all pointed out the importance of spatial visualization and solving design problems. The participants were 47 industrial engineering technology students enrolled in either an introductory or advanced solid modeling and rapid prototyping class. The participants were randomly assigned to either the control group (sketching) or experimental group (*ProDesktop*). All of the participants completed the *Purdue Spatial-Visualization Test/Visualization of Rotations* (PSVT/TR) to assess their spatial visualization ability. They then designed a solution to the design problem using either sketching only or using *ProDesktop* and sketching. Each participant then constructed a prototype of their design for testing.

The prototype was required to convert rotary motion into reciprocal motion and advance three of the provided blocks 3.5" within a tolerance of plus or minus 1/8". If the prototype met the requirements for advancing the block it was then scored as successful. If the prototype did not meet the requirements it was scored as an unsuccessful solution. The study reviewed the effects of using solid modeling software to solve a technical design problem and the interaction that spatial visualization had on the participants' ability to solve the given problem. A review of previous research indicated there are many factors that influence an individual's ability to solve ill-structured design problems (Jonassen, 2000).

With the recent improvements in solid modeling software it was hypothesized that students would show an increased ability to solve a technical design problem when utilizing solid modeling as a design method as compared to sketching. External and internal representations are a crucial part of technical design. All forms of external representation are important because "External problem representations, especially those in the form of dynamic models, enable learners to manipulate and test their models" (Jonassen, 2003a, p. 377). Jonassen (2003b) concludes, "The potential for research confirming positive relationships between modeling and problem solving is great" (p. 377) and goes so far as to state "no empirical research has examined the effects of using technology tools for representing problems on problem solving performance."

The results of this study revealed that no significant differences in solving the technical design problem existed between the participants who used solid modeling and those who used sketching to design the solution to the problem. A participant's spatial visualization ability was a better predictor of success for this particular type of problem.

The following hypotheses were investigated in this study:

$H_0$1: Participants' spatial visualization skills, as measured by the *Purdue Spatial-Visualization Test/Visualization of Rotations*, will not affect their technical problem solving ability.

$H_0$2: Participants using solid modeling software to design solutions to technical problems will not show greater success in the construction of a physical model or prototype than those using sketching.

$H_0$3: Participants with lower visualization skills, as measured by the *Purdue Spatial-Visualization Test/Visualization of Rotations*, will not perform better using solid modeling software than those with equal scores using sketching in the design and production of a prototype for a technical problem.

Discussion

The tests of hypothesis one indicated that spatial visualization ability as measured by the (PSVT/VR) was a significant predictor of being able to construct a successful prototype. Hypotheses two and three showed no significant differences in the method used to design the solution or any interaction between spatial visualization and the method used. Using ProDesktop to design a solution did not offset any differences in spatial visualization scores or provide the participants any significant advantage over sketching.

Caution must be used when generalizing the results of this study to others because it consisted of only two classes of randomly assigned engineering technology students from Southeast Missouri State University. These classes were chosen because of their similar exposures to drafting, design, and solid modeling. A t-test of the two groups revealed no significant differences in their spatial visualization abilities.

Although examining gender differences related to spatial visualization and problem solving was not a primary purpose, the results of this study were similar to those of the study conducted by Devon et al. (1994) in which the male participants did not show a significant difference. As with the study conducted by Devon et al. (1994), this may be due to the female participants past experiences and interests related to engineering and technology. The populations for this study and the Devon et. al. (1994) study were limited to engineering technology students and not representative of all females. Other studies that examined more diverse populations often found that males had significantly higher visualization scores (Branoff, 1998; Devon et al. 1994; Gillespie, 1994; McGee, 1979). For the actual problem, 26.5% of the males and 15.4% of the females constructed successful prototypes. Further research is needed that focuses on gender differences in solving various technical design problems.

While the findings of this study were affected by the inherent limitations of the study, the following conclusions were inferred:

1. The participants' spatial visualization ability scores as measured by the PSVT/TR were a better indicator of success in solving this type of problem than was the method (solid modeling or sketching) used to solve the problem.

2. The results from this study suggest that using solid modeling as opposed to sketching did not improve the participants' likelihood of solving this particular design problem.

3. The results from this study also suggest that because the interaction between the type of design method and spatial visualization ability did not result in a significant difference, the design method and visualization ability were homoscedastic for this particular problem. Using solid modeling software to design a solution did not offset low spatial visualization scores or offer any advantages to those with high visualization scores. Though the results of the analysis of interaction was not significant Examination of Figure 14 provides some evidence that the opposite might be true.

Examination of the prototypes produced by the participants reinforces several basic strategies regarding design problem solving and ill-structured problem solving activities. Eight non-successful solutions properly advanced the blocks, but they failed to limit the distance to the specified tolerance. Many of the participants seemed to feel that they had successfully completed the problem but overlooked the specific requirements. This points out the importance that the problem and the requirements for the problem be understood and reviewed.

Several simple items could be added or utilized by the participants so they could increase their chances of successfully solving the problem and meeting the requirements for the construction of the prototype. Something as simple as requiring the participants to complete a checklist or mark off the requirements they have completed might have greatly affected the results of this study. Also, because relatively simple materials were used to construct the prototypes and the participants had previously used these materials, it was assumed that they would be able to successfully manipulate them and the tools to be able to produce the design they proposed. For the most part, this appeared to be true. But some participants may have been hindered by their lack of ability to properly build their design with the given materials.

Some participants failed to consider things such as the materials, tools, and time constraints. Looking at the design ideas and the prototypes it is apparent that many participants chose solutions to the problem that may not have matched well with the available materials and tools. Several of the ideas appear to be viable solutions if other materials were used, but not when trying to construct a solution from foam board using a utility knife. Many of the designs tried to incorporate threaded mechanisms and/or gears. The precision needed to produce functional gears and threads cannot easily be reached with the tools and materials provided. Here again, this could relate to a less than thorough understanding of the problem. The participants did not fully understand the materials they had available or how they could best be shaped with the provided tools. The available materials and resources are an important component of any problem and understanding the properties and function of the materials as they relate to the particular design problem is important.

Some of these differences could also be because the participants were novices at solving problems of this nature. Experts are better able to retrieve and distinguish between pertinent information and information or ideas that will off no real advantage to arriving at a solution (Wu et. al. 1996). If they have not experienced problems within this context before they may have experienced difficulty transferring similar schemas to this particular problem (Bransford et al., 2000; Jitendra, 2002; Westberry, 2003).

This study suggests the importance of good problem solving techniques and strategies. Whether it is a technical design problem, mathematical problem, a short answer for a test, what automobile to purchase, etc., when faced with a problem to be solved, one must understand the problem, what criteria need to be met to consider the solution a success or acceptable, and the available resources. Jonassen (2003a) states that problem solving is one of the most important tasks that we do throughout our daily lives and that teaching problem solving should be a top priority of education.

The results of this study suggest that solid modeling did not provide an advantage in solving this technical design problem. Other factors may have influenced participants' success. For example, examination of the designs and constructed prototypes suggests participants did not fully understand the requirements of the problem or the optimal procedures for using the available resources. In further studies, it could prove helpful measure participants' understanding of various aspects of problem solving.

Suggestion For Further Research

Continued research in spatial visualization and technical problem solving is both warranted and needed. This study and related literature suggest relatively little is known about how individuals solve technical design problems and how visualization and the use of technology affect the outcomes. Following are suggestions for further research related to technical design and problem solving, spatial visualization, and solid modeling:

1. The amount of time needed for the design of solutions should be extended. Allowing the participants using solid modeling more time to complete their designs may be needed for them to fully benefit from using the software. All members of the sketching group completed their design solution in the allotted three hours. The designs were good from a conceptual standpoint but it appeared that relatively little time and consideration were given to predict optimal size of the prototype solution and to the predictive analysis as to whether the solution would work effectively. When the control group (sketching) began construction of their prototypes some trial and error was conducted to develop their prototypes based on their sketches. The solid modeling group could have used more time. If the time is expanded, particularly if it went beyond one day, steps would have to be taken to keep subjects from interacting with others and locating other information for their solutions.

2. Because this study found that spatial visualization ability is a better predictor of solving the given design problem, research needs to be conducted to determine if using solid modeling techniques improves the participants spatial visualization skills. Although, improving spatial visualization ability does not necessarily mean that it will improve problem solving ability and this study provided evidence that the spatial visualization ability was merely correlated with solving the technical design problem.

3. Although it was thought that the experimental group participants possessed the skills to effectively use the solid modeling software based on past classes and instruction, in some cases it was not certain if they did poses the needed skills to design the solutions. It would be difficult to pretest their skill level using the solid modeling software for a similar problem without adding testing error to the study. Some type of assessment is needed to ensure that they do posses the need skills to properly operate the software and construct the design they conceive.

4. Measures also need to be taken to ensure that the participants have the skills to construct the prototype. This study used simple materials and tools that should be familiar to all of the participants and the participants had used similar materials on previous assignments. Ensuring a clear understanding of the problem and the limitations of the materials they are using could easily be assessed by requiring the participants to answer some basic questions about the problems and materials.

5. If significant differences, regarding the method used to design solutions, are found in future studies additional data would need to be collected to determine the causes of the differences. The amount of drafting and/or CAD the subjects have completed,

cognitive load scores, software familiarization, etc. would be logical places to begin.

6. Examining various types design problems would allow for more specific understanding and generalizations. It is difficult to identify specific problem solving techniques needed for ill-structured problems because they can have many solutions and methods to reach solutions. If key concepts for solving technical design problems could be identified for various problems, how students apply or use those concepts could be examined with greater detail.

7. Various methods besides the typical paper tests should be developed and explored to better measure spatial visualization. The PSVT/TR uses objects that are represented on 2D paper as isometric drawings. Presenting objects three-dimensionally on the computer as well as using physical objects may provide more information regarding spatial visualization.

8. Research that further examines spatial visualization and cognitive load when using or viewing objects with solid modeling software is warranted to determine if the technology might improve the problem solving or visualization. For novices using solid modeling software, the cognitive load may be increased and reduce the participants likelihood of solving the design problem.

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APPENDIX A: PROCEDURES FOR TREATMENT GROUP

Design Challenge

Problem

You are to design and develop a solution that advances 1.5” X 1.5” X 3” blocks, one at a time, a distance of 3.5” (see figure 1 and the video provided). You must include some type of handle to turn to advance the blocks. The blocks will be fed into the opening one at a time by hand. The mechanism you design must be powered by rotary motion, meaning you must turn or crank the handle to advance the blocks. Sliding a handle back and forth is not acceptable. The fixture that the blocks must fit in and be advanced through is provided.

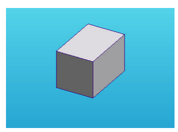


Figure 1. Block

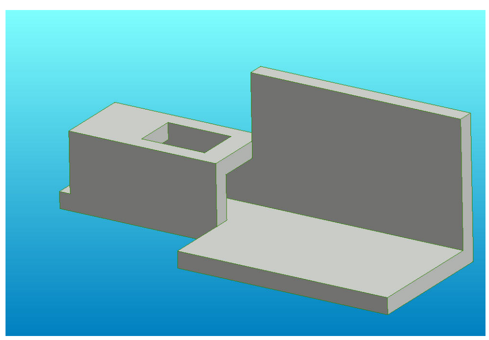


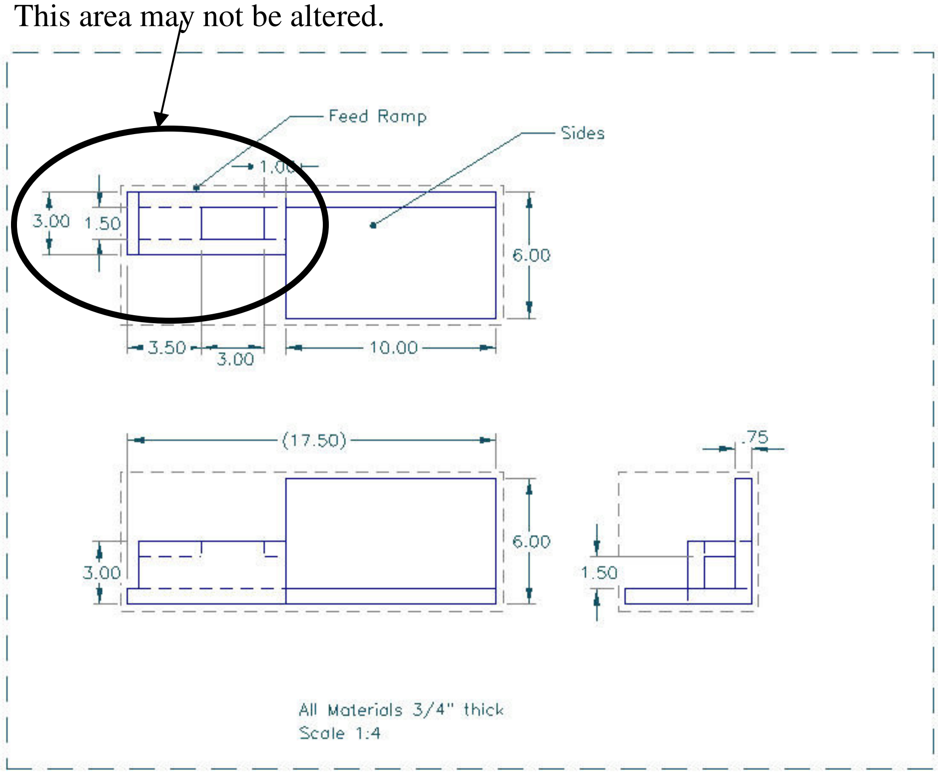
Figure 2. Fixture through which blocks must fit and be advanced

Procedure for the Treatment Group. You will need to design a mechanism that converts rotary motion into reciprocal motion. You are to design the mechanism using ProDesktop. The drawings for the fixture and blocks are already drawn and your instructor will inform you where they are stored on your computer. Once your mechanism is designed you will be constructing a prototype from the materials listed below. The prototype must successfully advance 3 blocks 3-1/2 inches with a tolerance of plus or minus 1/8th of an inch and should be reflective of your drawn design.

Save all of your ProDesktop solution at the instructed location.

You may not alter the feed ramp end but you may alter the sides of the device in any way.

This area may not be altered.



Criteria Used to Evaluate Prototypes/Solutions Developed

1. You have 3 hours to complete your design and 3 hours to construct the prototype/solution.
2. You must include some type of crank that is turned to operate the solution.
3. The device must advance 3 blocks within these tolerances in order to be successful.
4. The blocks must be advanced 3.5" with a tolerance of plus or minus 1/8th of an inch.

Materials Provided From Which Prototypes/Solutions May Be Constructed

Hot glue gun
Glue sticks
Double sided tape
Wood glue
Masking tape
Duct tape
¼" dowel rods
3/8" dowel rods
½" dowel rods
Foam core board
½" rigid foam
Corrugated cardboard
¼" hardboard
½" plywood
Assorted nails, screws, bolts, and nuts

APPENDIX B: PROCEDURES FOR CONTROL GROUP

Design Challenge

Problem

You are to design and develop a solution that advances 1.5” X 1.5” X 3” blocks, one at a time, a distance of 3.5” (see figure 1 and the video provided). You must include some type of handle to turn to advance the blocks. The blocks will be fed into the opening one at a time by hand. The mechanism you design must be powered by rotary motion, meaning you must turn or crank the handle to advance the blocks. Sliding a handle back and forth is not acceptable. The fixture that the blocks must fit in and be advanced through is provided.

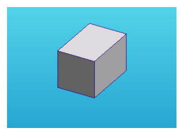


Figure 1. Block

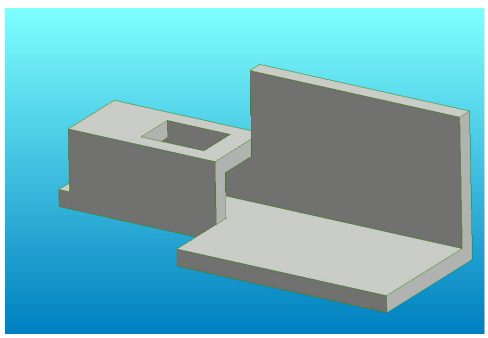
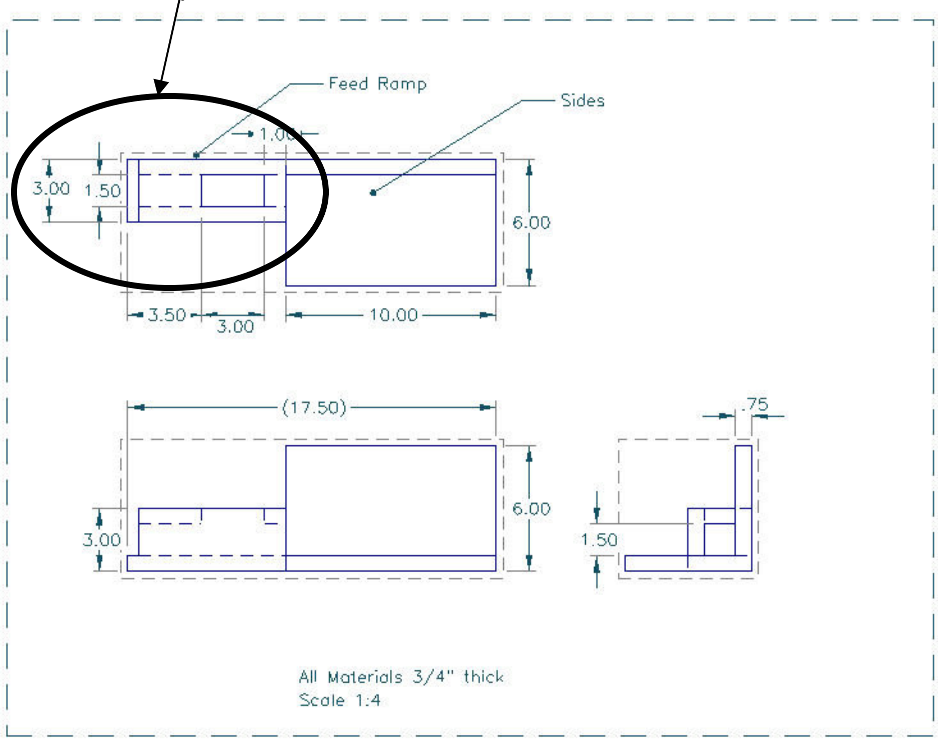


Figure 2. Fixture through which blocks must fit and be advanced

Procedure for the Control Group. You will need to design a mechanism that converts rotary motion into reciprocal motion. You are to design the mechanism by sketching your solution. Once your mechanism is designed you will be constructing a prototype from the materials listed below. The prototype must successfully advance 3 blocks 3-1/2 inches with a tolerance of plus or minus 1/8th of an inch and should be reflective of your drawn design.

You may not alter the feed ramp end but you may alter the sides of the device in any way.

This area may not be altered.



Criteria Used to Evaluate Prototypes/Solutions Developed

5. You have 3 hours to complete your design and 3 hours to construct the prototype/solution.
6. You must include some type of crank that is turned to operate the solution.
7. The device must advance 3 blocks within these tolerances in order to be successful.
8. The blocks must be advanced 3.5” with a tolerance of plus or minus 1/8th of an inch.

Materials Provided From Which Prototypes/Solutions May Be Constructed

Hot glue gun
Glue sticks
Double sided tape
Wood glue
Masking tape
Duct tape
¼” dowel rods
3/8” dowel rods
½” dowel rods
Foam core board
½” rigid foam
Corrugated cardboard
¼” hardboard
½” plywood
Assorted nails, screws, bolts, and nuts

APPENDIX C: PURDUE SPATIAL VISUALIZATION TEST/ TEST OF ROTATIONS

(Permission to use test is freely granted in Bodner & Guay, 1997)

Purdue
Spatial Visualization
Tests

Roland B. Guay

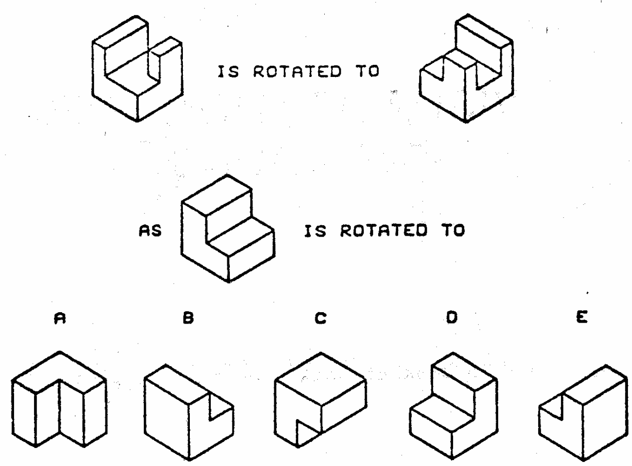
VISUALIZATION OF ROTATIONS

Do NOT open this booklet until you are instructed to do so.

Do NOT make any marks in this booklet.
Mark your answers on the separate answer card.

Directions

This test consists of 30 questions designed to see how well you can visualize the rotation of three-dimensional objects. Shown below is an example of the type of question included in the second section.



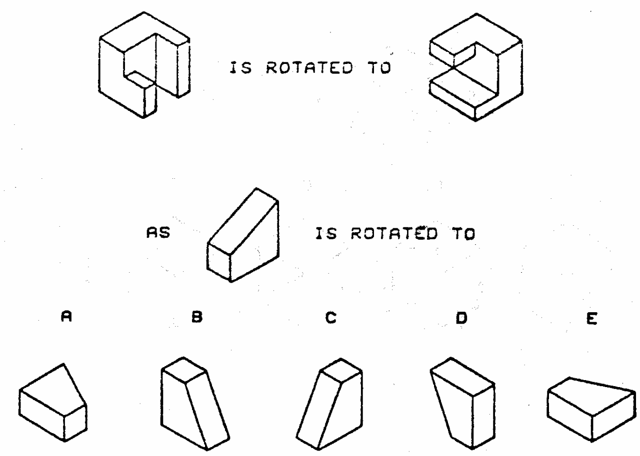
You are to:

1. study how the object in the top line of the question is rotated;
2. picture in your mind what the object shown in the middle line of the question looks like when rotated in exactly the same manner;
3. select from among the five drawings (A, B, C, D, or E) given in the bottom line of the question the one that looks like the object rotated in the correct position.

What is the correct answer to the example shown above?

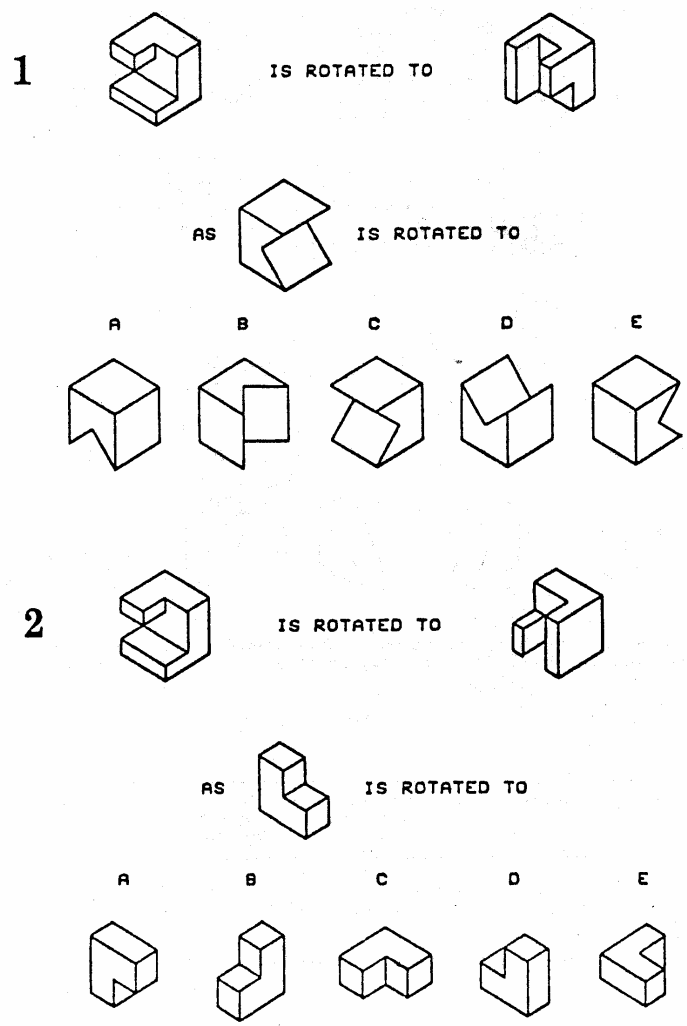
Answers A, B, C, and E are wrong. Only drawing D looks like the object rotated according to the given rotation. Remember that each question has only one correct answer.

Now look at the next example shown below and try to select the drawing that looks like the object in the correct position when the given rotation is applied.



Notice that the given rotation in this example is more complex. The correct answer for this example is B.

Do NOT make any marks in this booklet. Mark your answers on the separate answer card. You will be told when to begin.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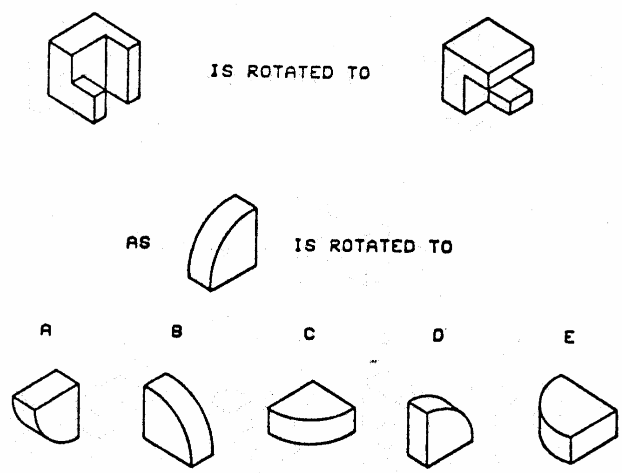
3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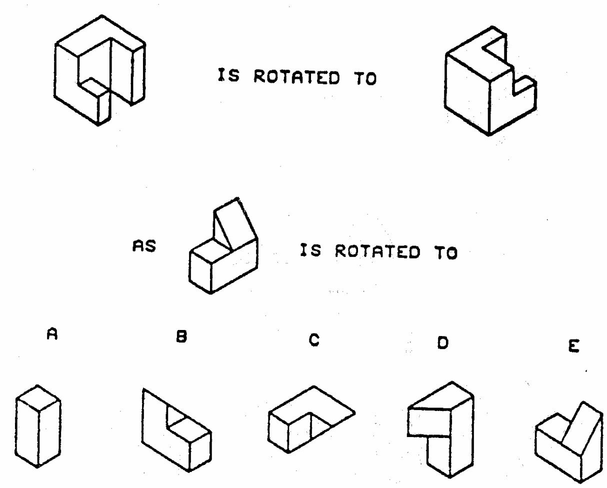
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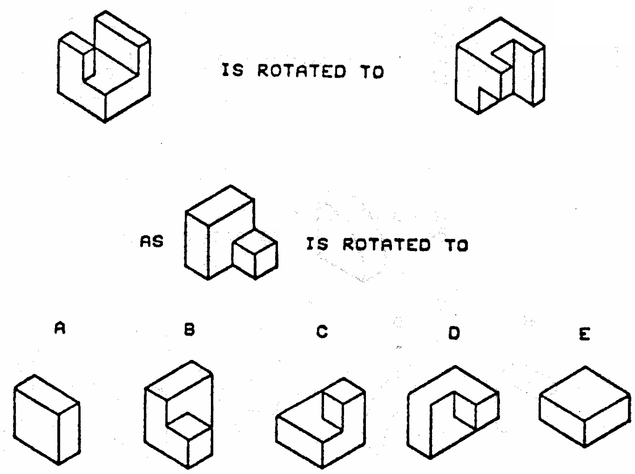
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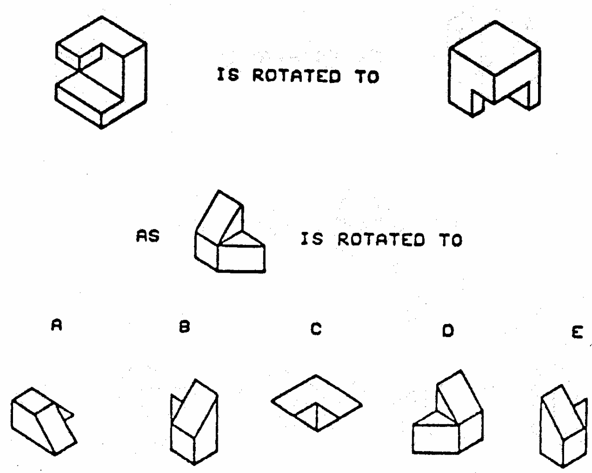
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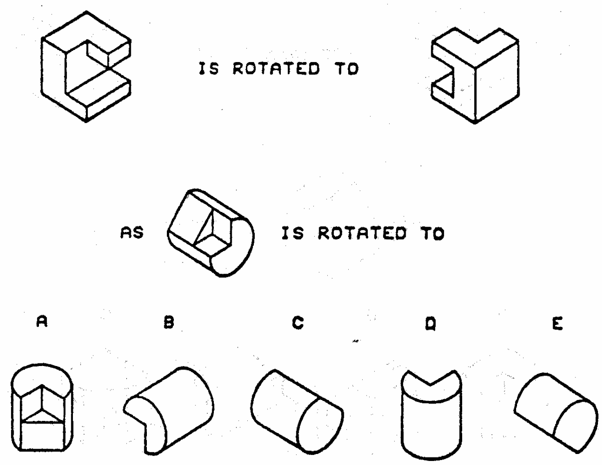
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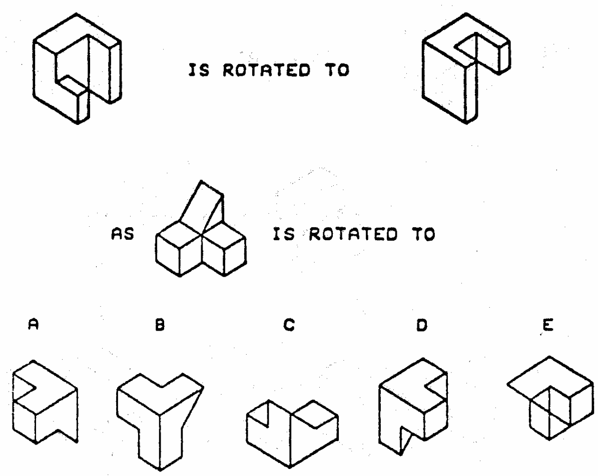
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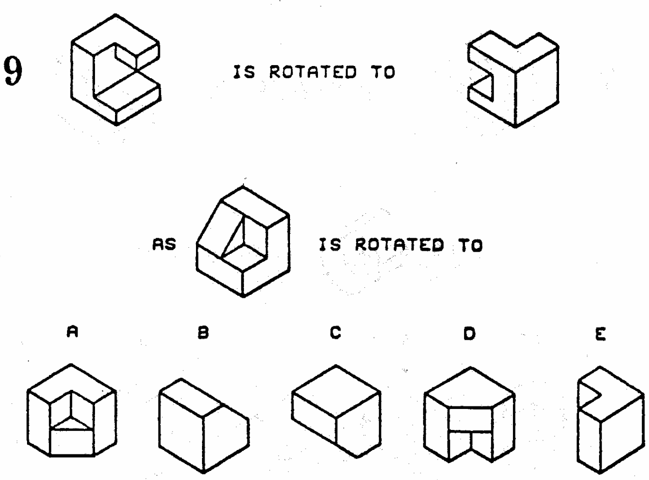
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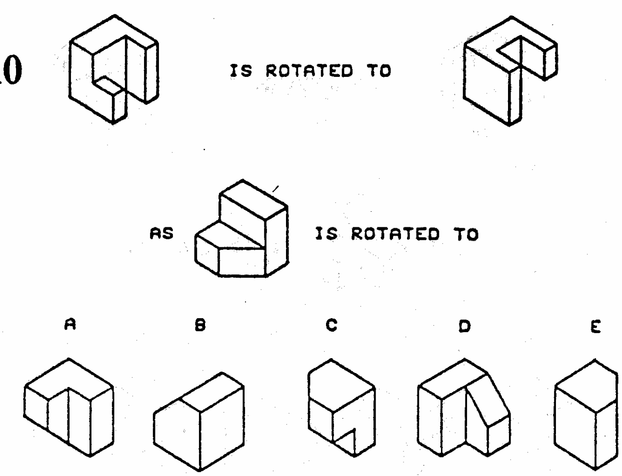
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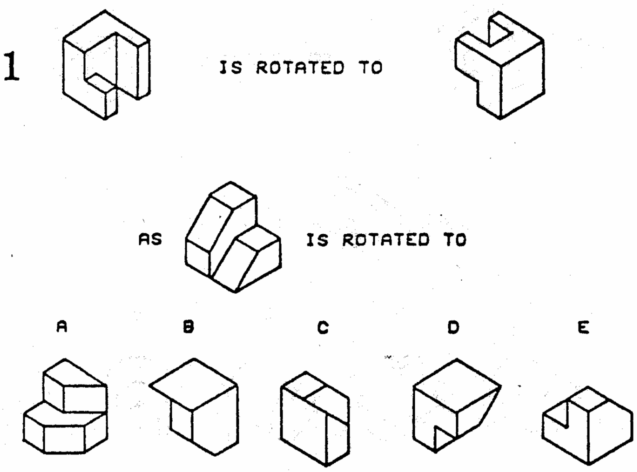
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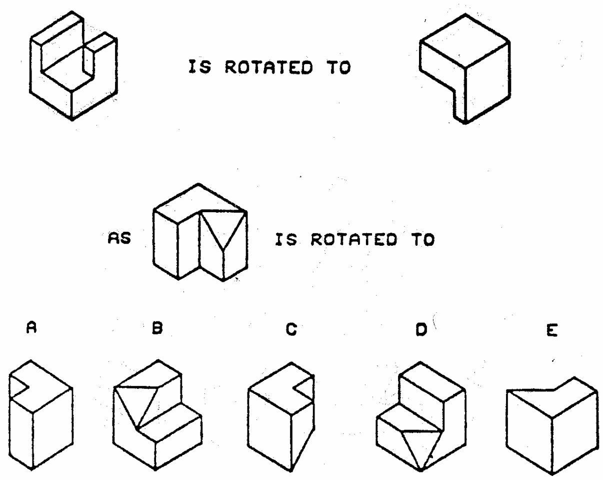
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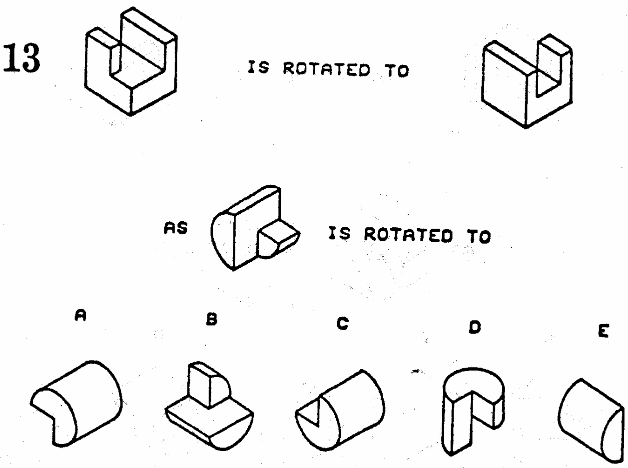
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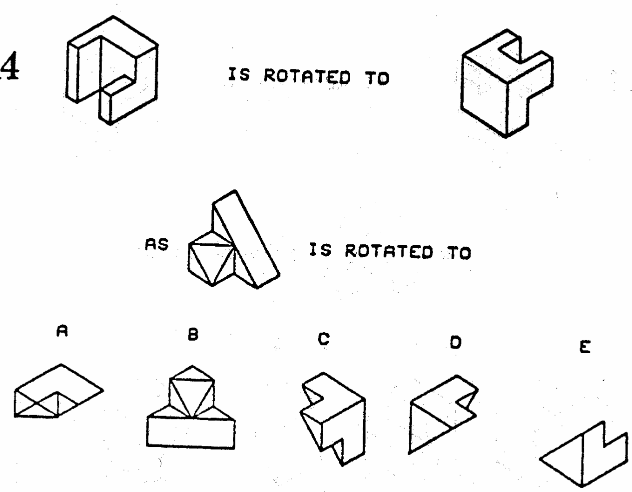
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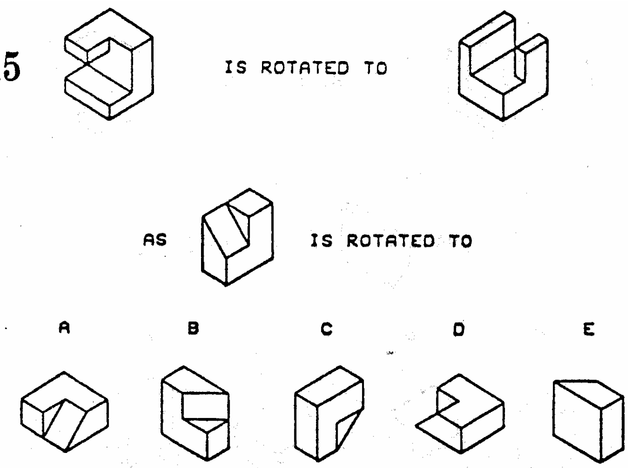
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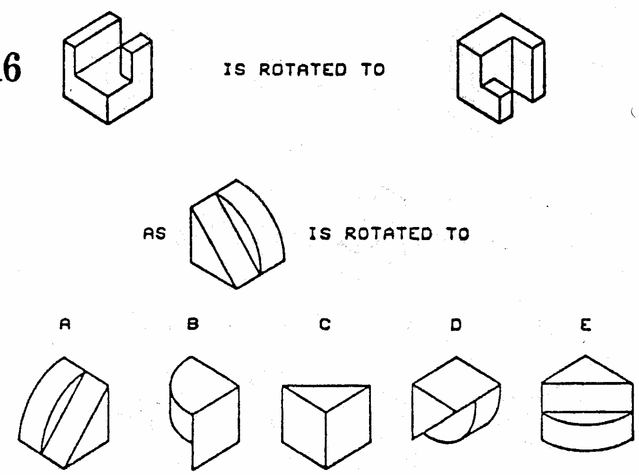
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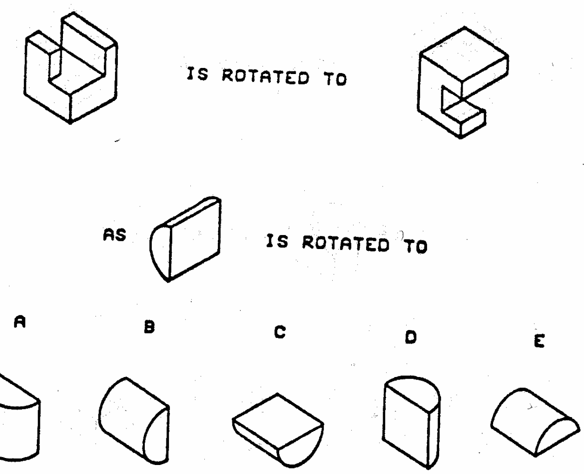
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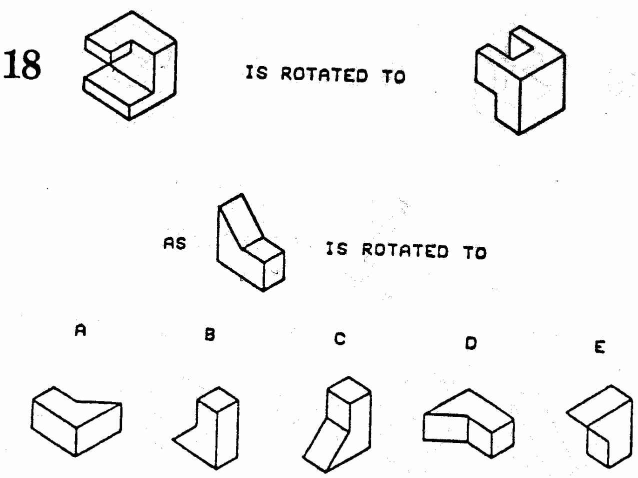
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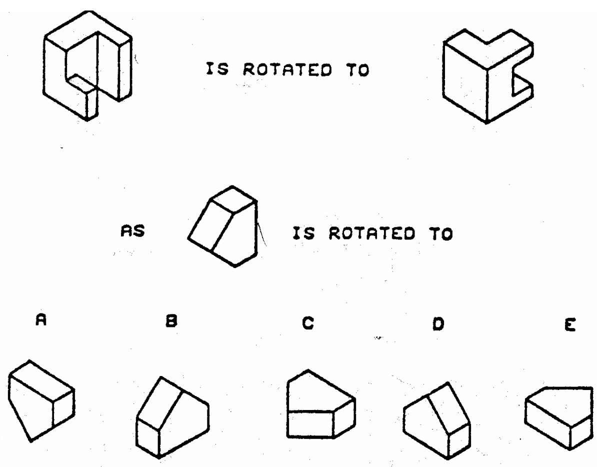
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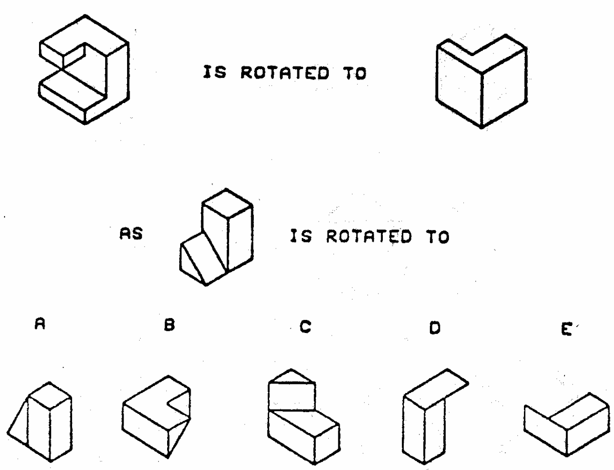
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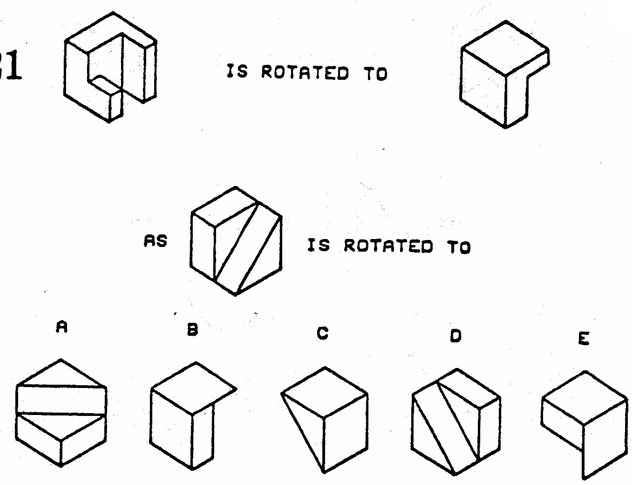
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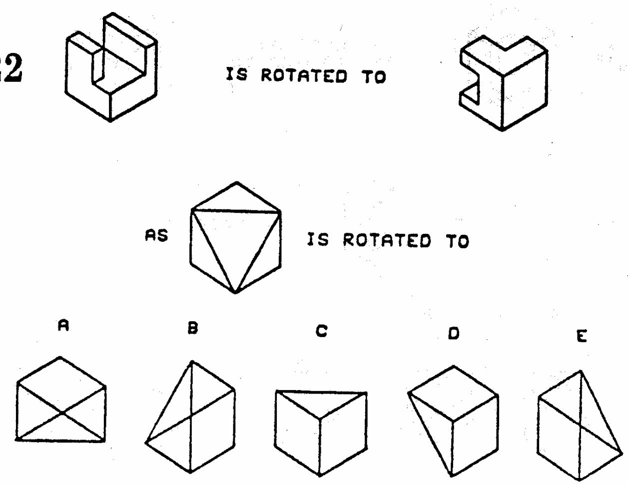
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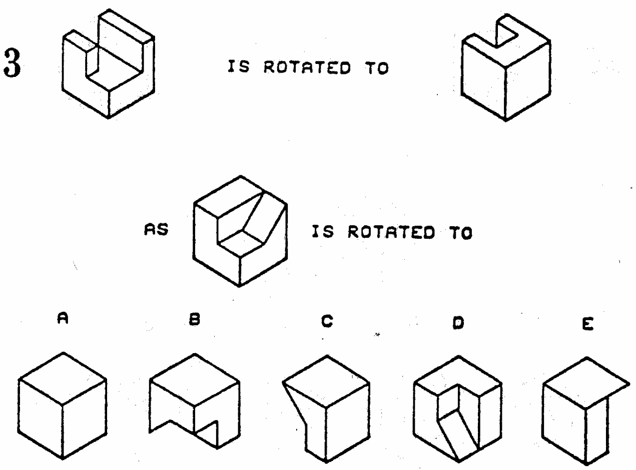
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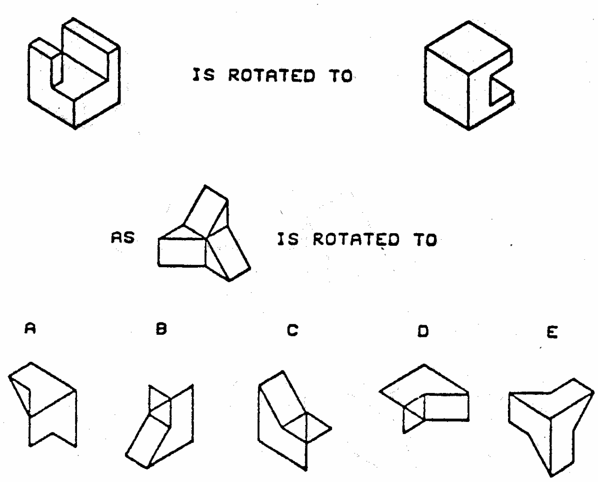
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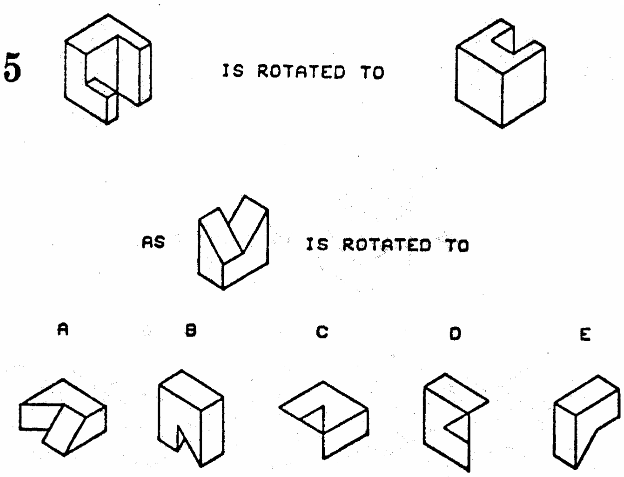
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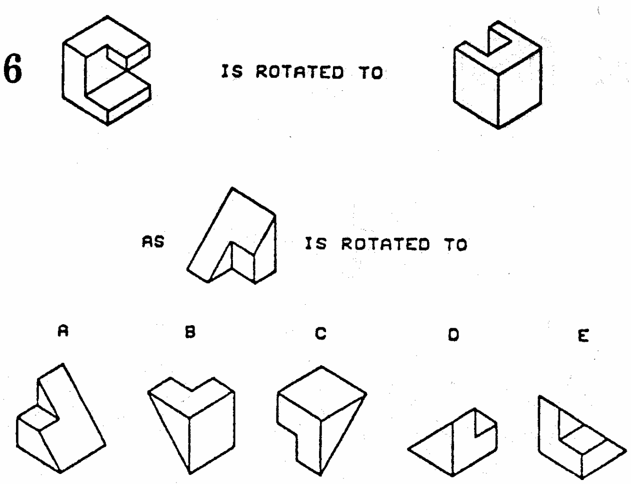
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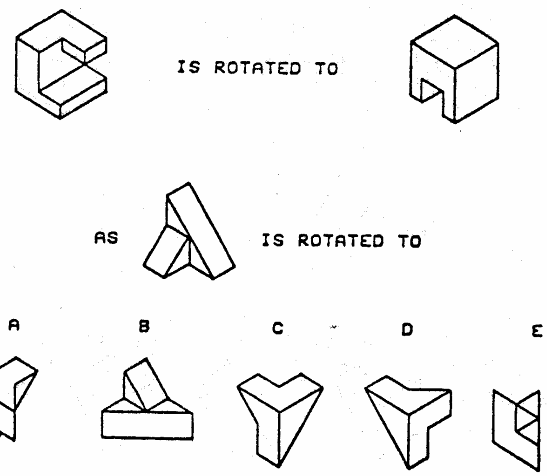
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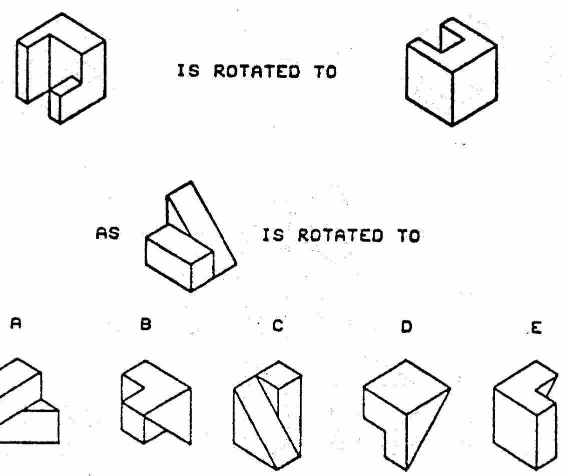
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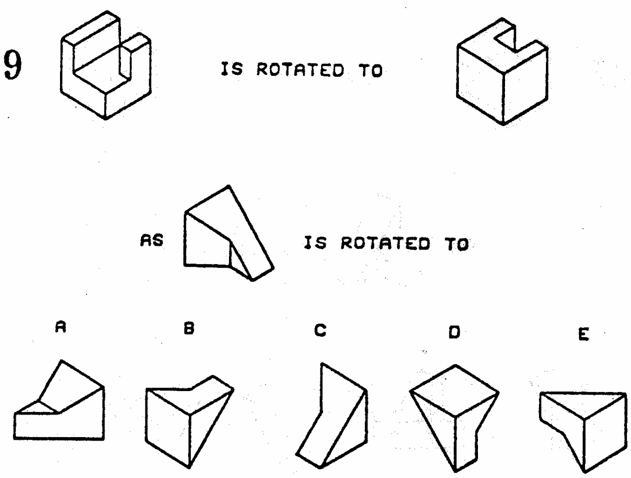
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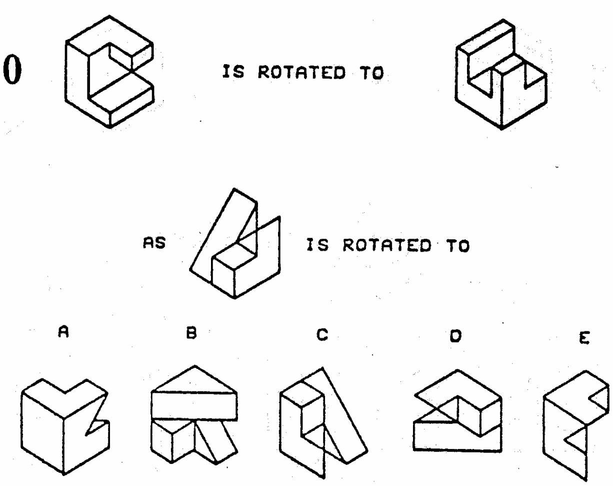
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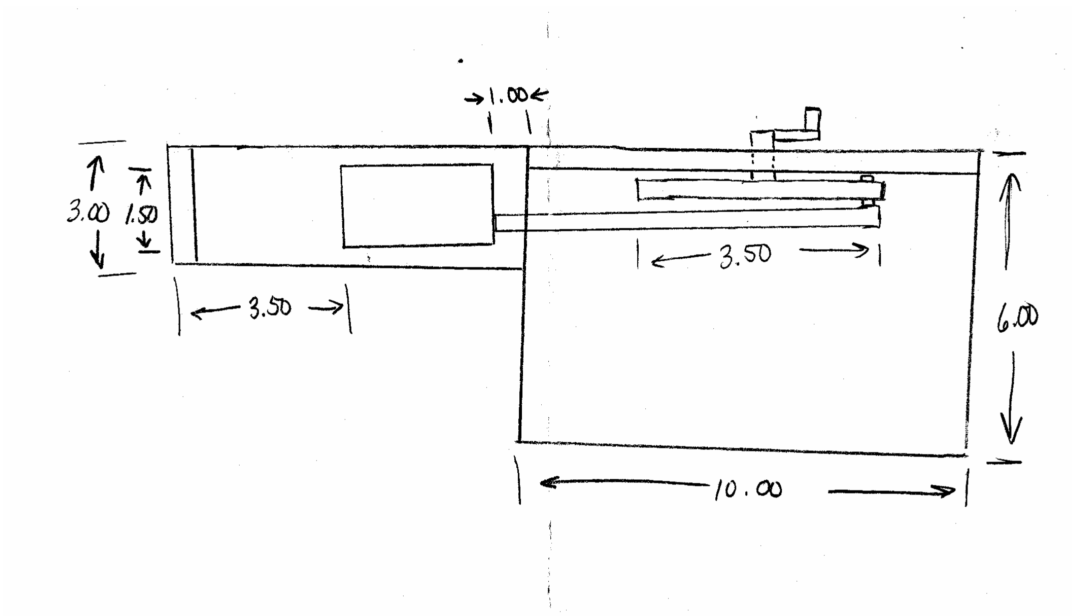
APPENDIX D: PURDUE SPATIAL VISUALIZATION TEST/ TEST OF ROTATIONS ANSWER KEY

Key

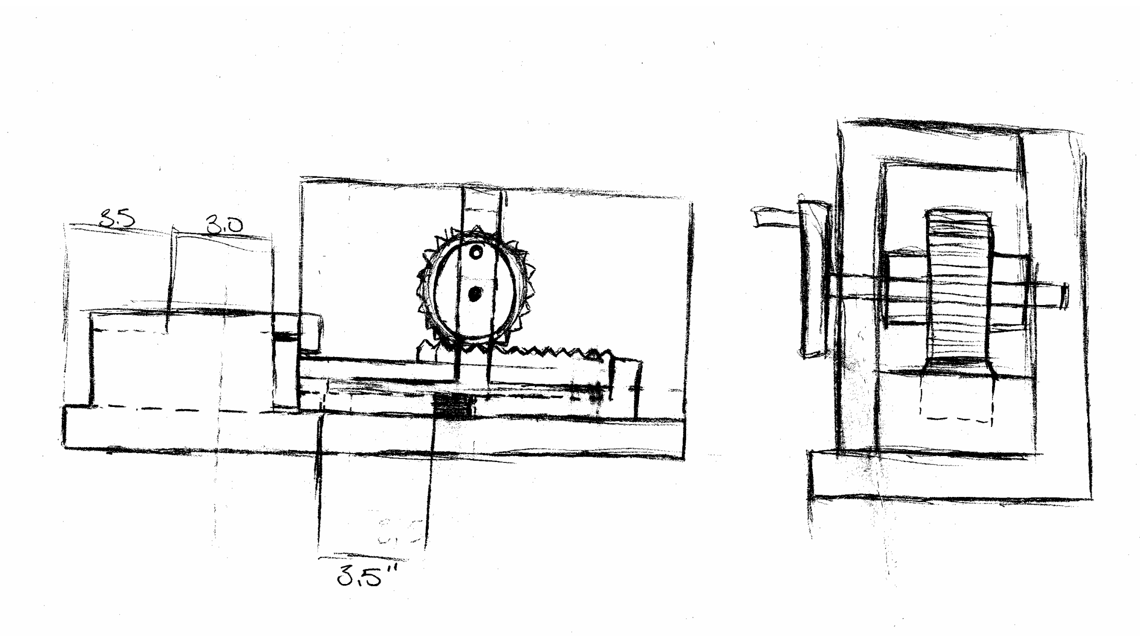
1. A
2. D
3. A
4. B
5. E
6. C
7. C
8. D
9. B
10. E
11. B
12. A
13. C
14. D
15. B
16. E
17. A
18. E
19. D
20. E
21. B
22. C
23. A
24. E
25. B
26. C
27. D
28. D
29. E
30. E

APPENDIX E: EXAMPLES OF SUCCESFUL AND UNSUCCESSFUL PROTOTYPES

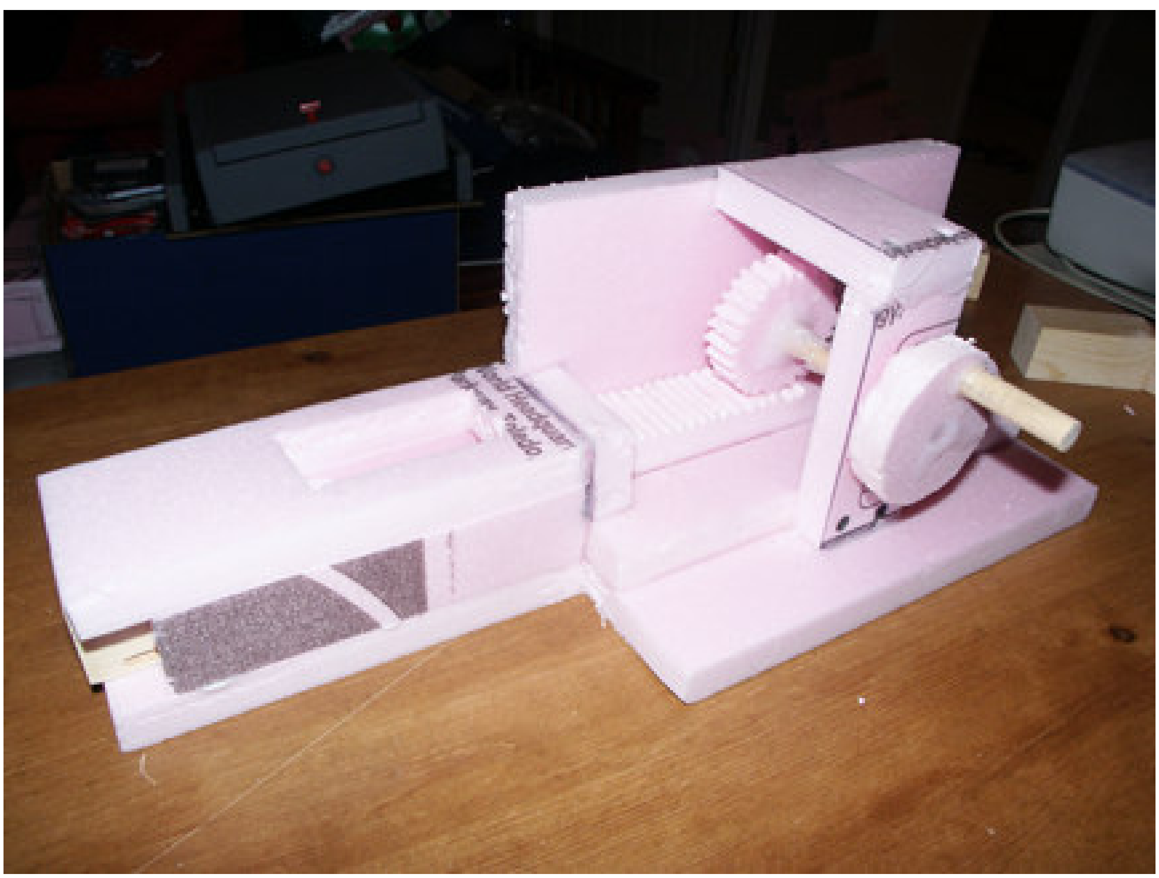


Sketch 1.

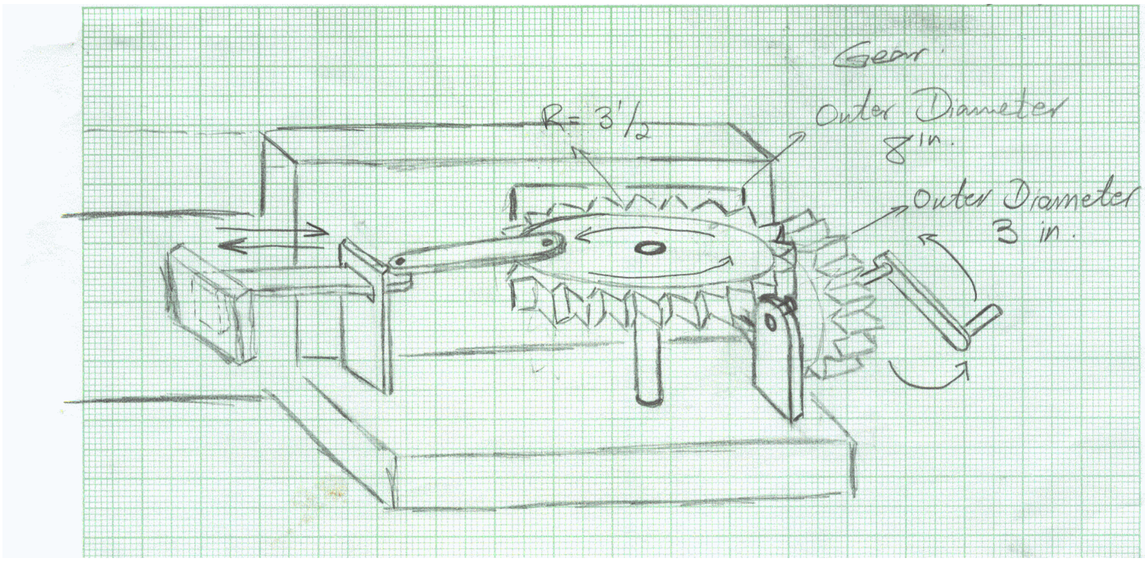
Successfully constructed prototype from sketch 1.



Sketch 2.

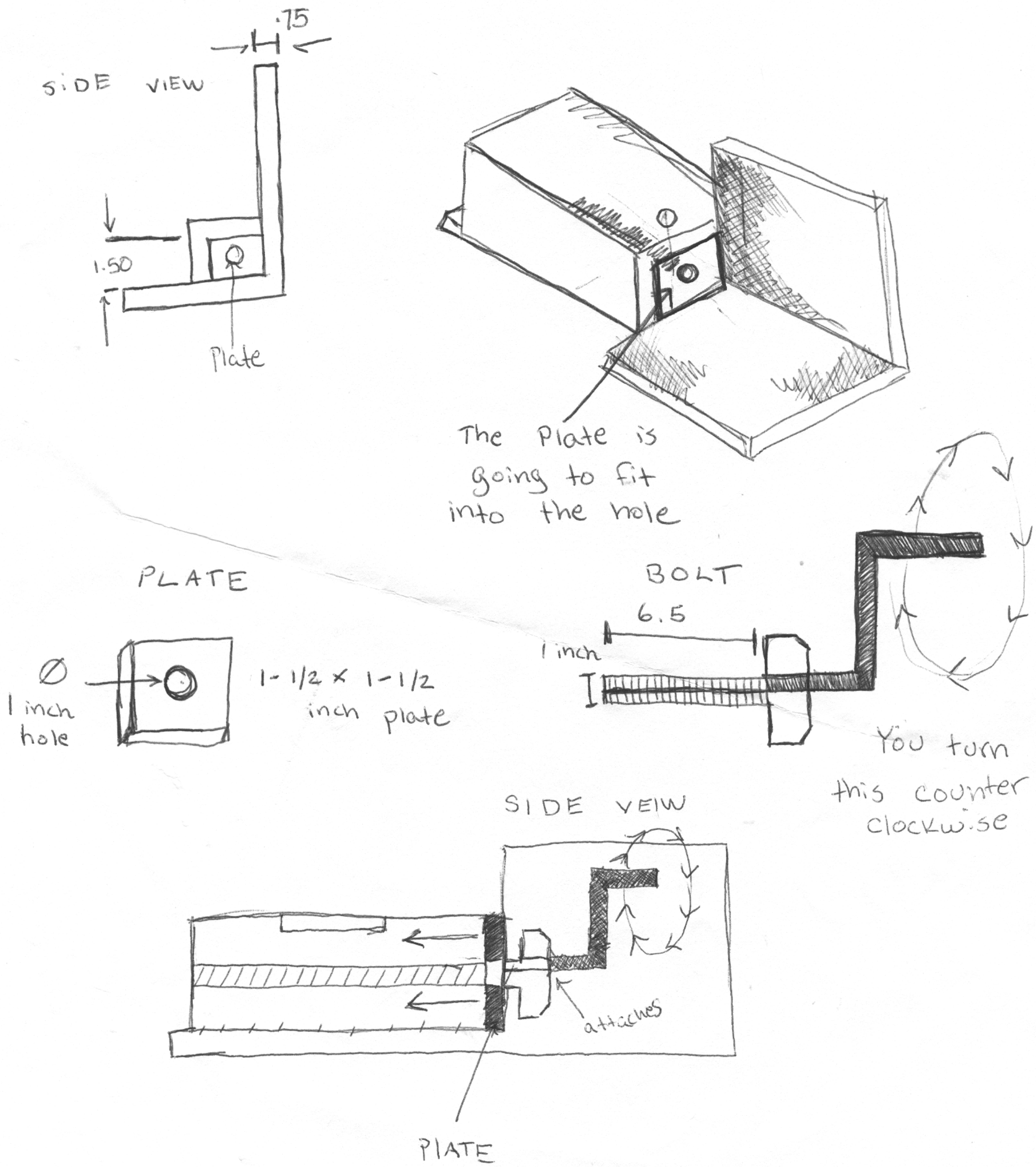


Successfully constructed prototype from sketch 2.

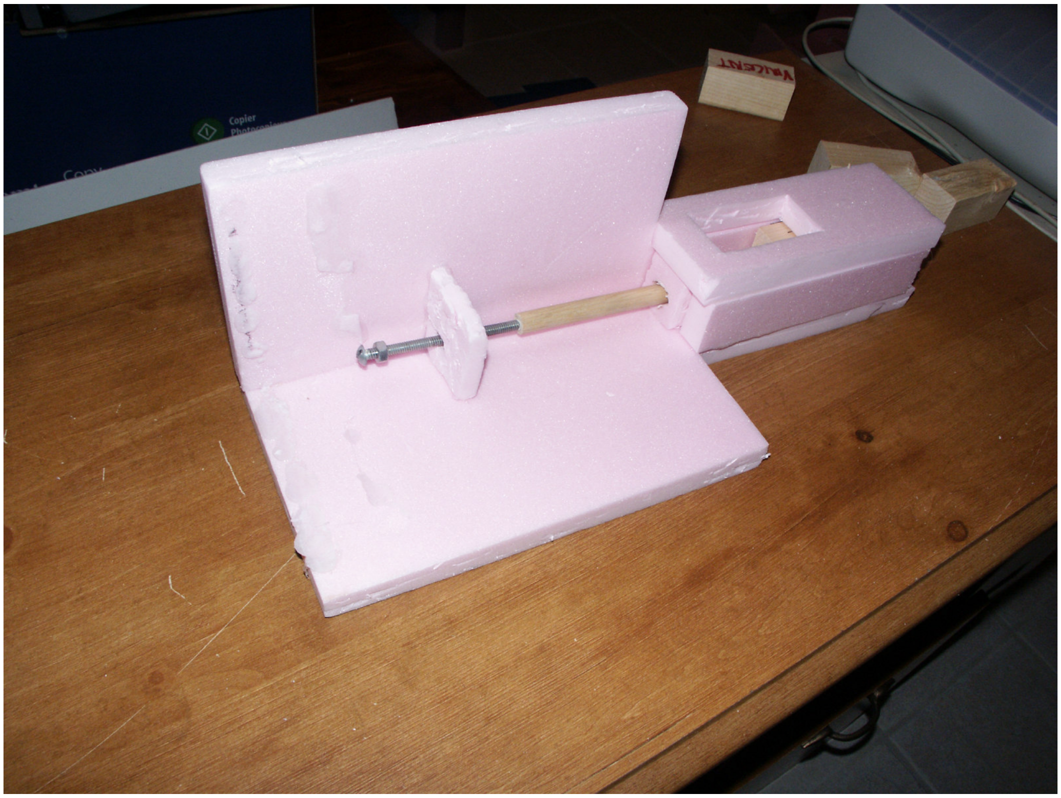


Sketch 3.

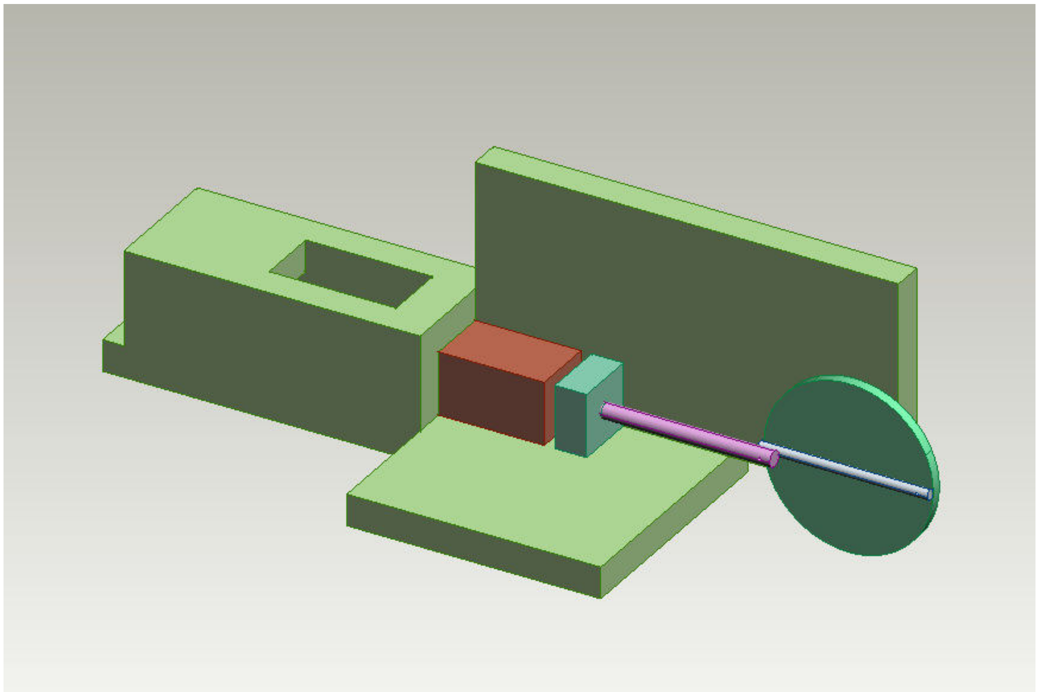
Unsuccessfully constructed prototype from sketch 3.


.75
SIDE VIEW
1.50
Plate
The Plate is going to fit into the hole
PLATE
Ø
1 inch hole
1-1/2 x 1-1/2 inch plate
BOLT
6.5
1 inch
You turn this counter clockwise
SIDE VEIW
attaches
PIATE

Sketch 4.

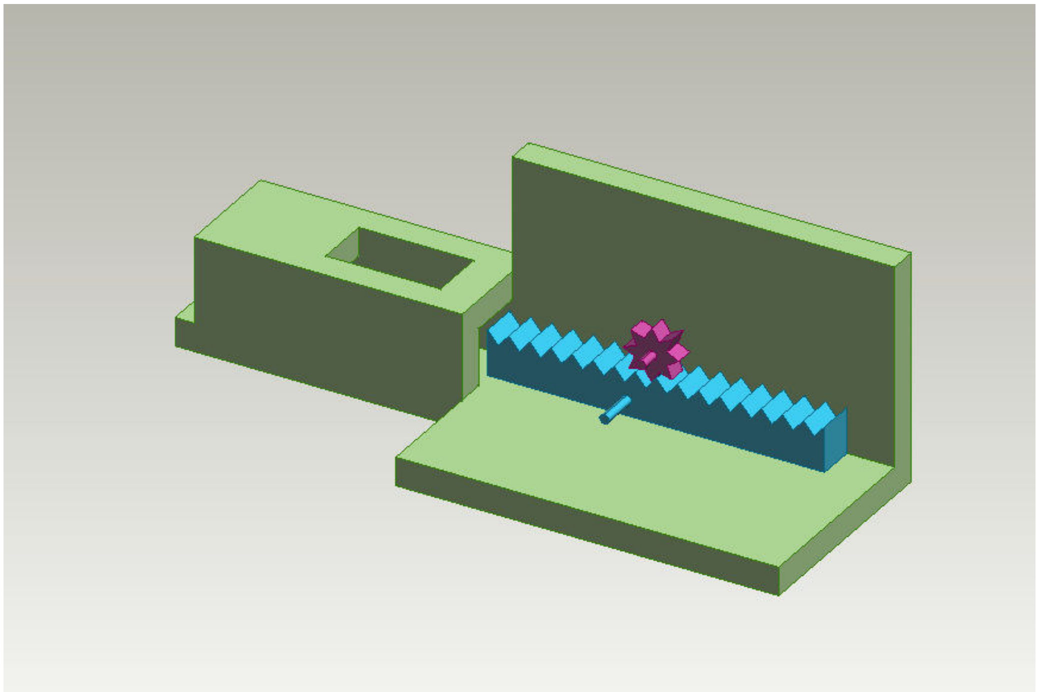


Unsuccessfully constructed prototype from sketch 4.



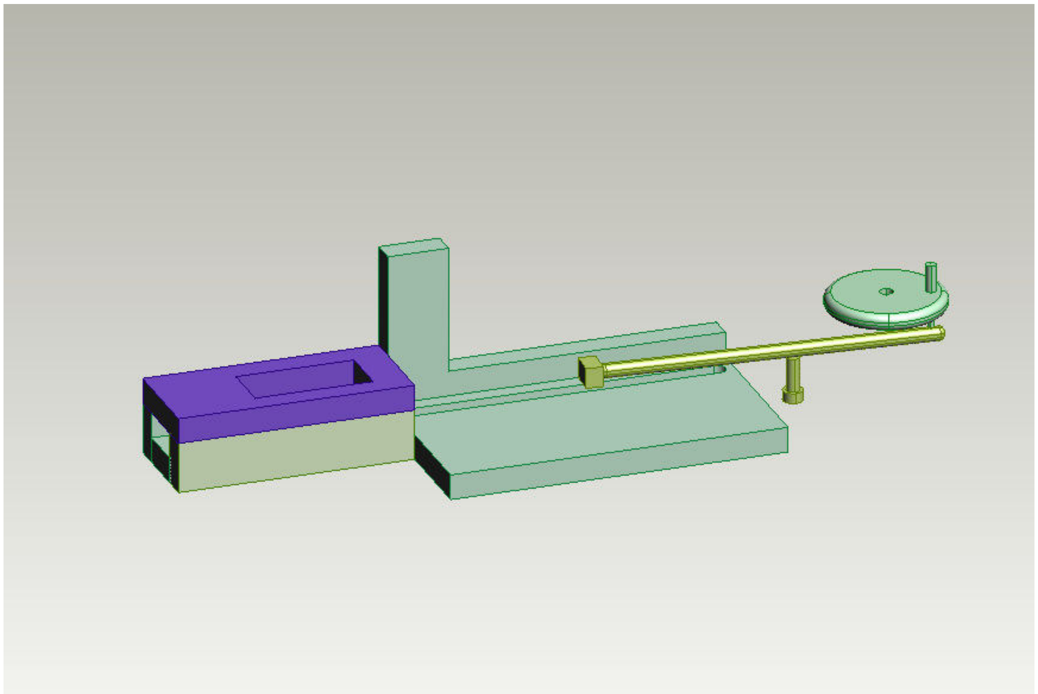
ProDesktop design 1.

Successfully constructed prototype from ProDesktop 1.

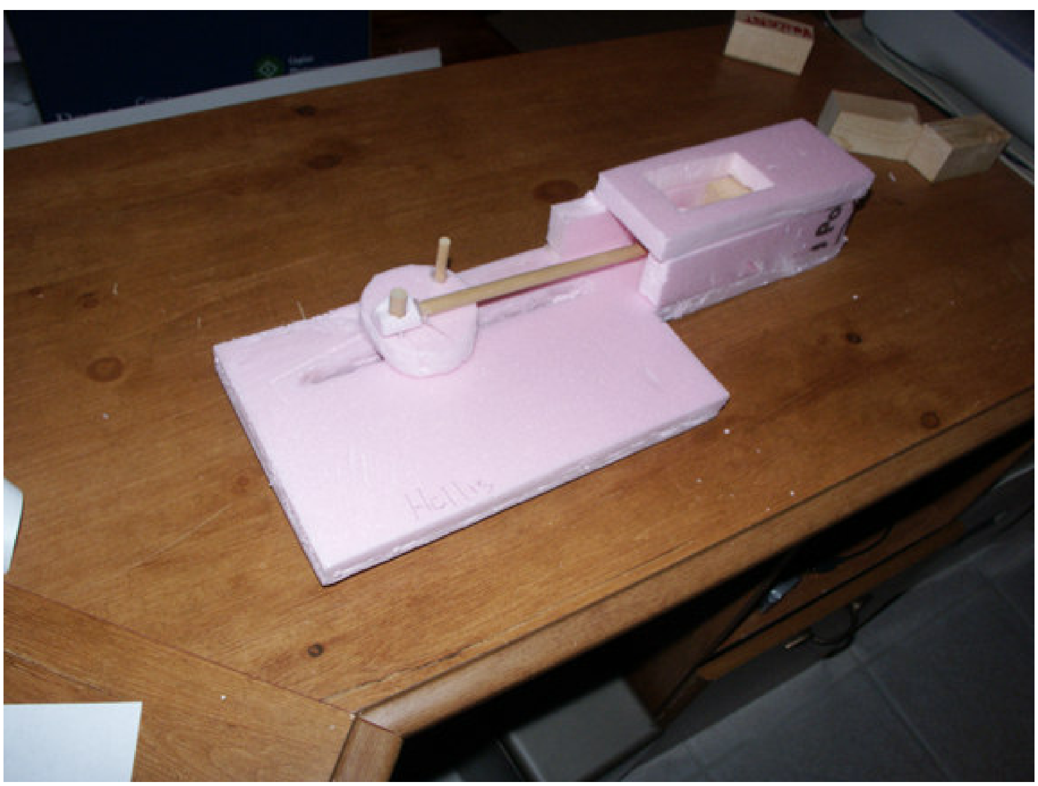


ProDesktop design 2.

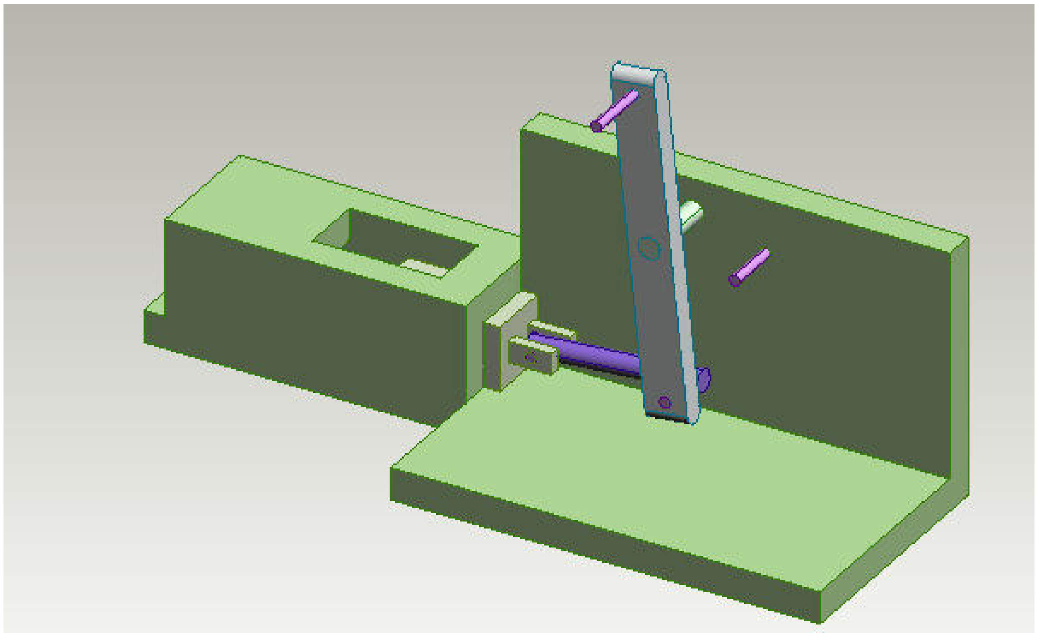
Successfully constructed prototype from ProDesktop 2.



ProDesktop design 3.



Unsuccessfully constructed prototype from ProDesktop 3.



ProDesktop design 4.

Unsuccessfully constructed prototype from ProDesktop 3.

APPENDIX F: IRB APPROVAL FORM

VirginiaTech

Office of Research Compliance
1880 Pratt Drive (0497)
Blacksburg, Virginia 24061
540/231-4358 Fax: 540/231-0959
E-mail: ctgreen@vt.edu
www.irb.vt.edu

FWA00000572(expires 7/20/07)
IRB # is IRB00000667.

DATE: April 11, 2006

MEMORANDUM

TO: Mark E. Sanders
Douglas Koch

FROM: Carmen Green

SUBJECT: **IRB Exempt Approval:** "The Effects of Solid Modeling and Visualization on Technical Problem Solving" , IRB # 06-234

I have reviewed your request to the IRB for exemption for the above referenced project. I concur that the research falls within the exempt status. Approval is granted effective as of April 11, 2006.

As an investigator of human subjects, your responsibilities include the following:

1. Report promptly proposed changes in previously approved human subject research activities to the IRB, including changes to your study forms, procedures and investigators, regardless of how minor. The proposed changes must not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the subjects.

2. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

cc: File

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