Spring 2007
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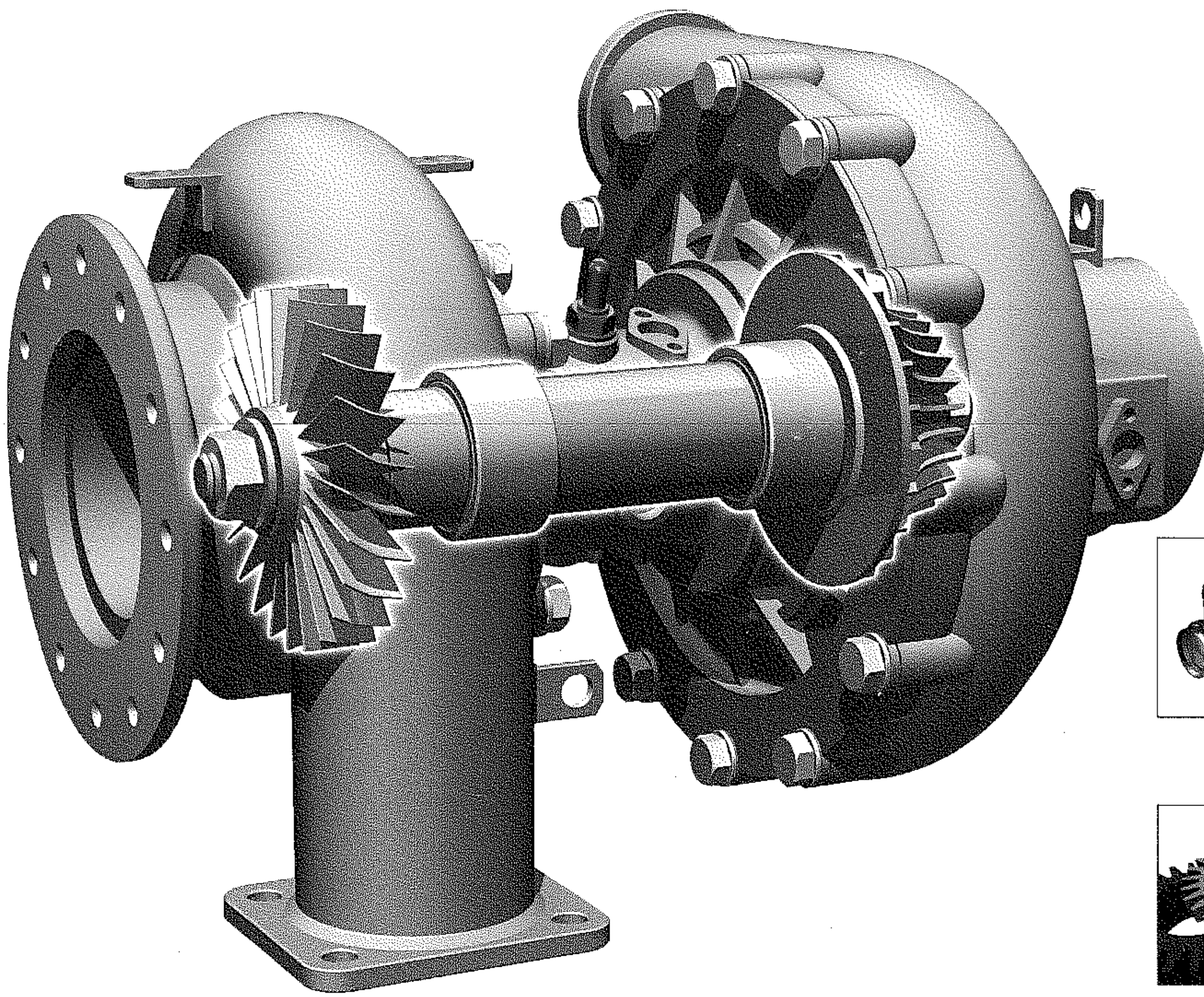
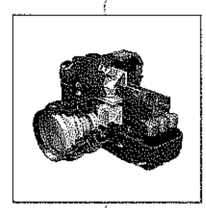
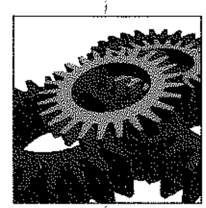
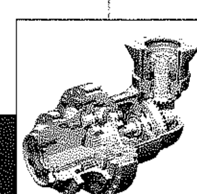
THE ENGINEERING DESIGN GRAPHICS Journal









AMERICAN SOCIETY FOR ENGINEERING EDUCATION

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THE ENGINEERING DESIGN GRAPHICS Journal

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Engineering Design Graphics Journal

About the Journal
The Engineering Design Graphics Journal serves as the official journal of the American Society for Engineering Educators Engineering Design Graphics Division and provides a professional publication for educators and industry personnel associated with activities in engineering, technology, descriptive geometry, CAD, and any research related to visualization and design.

Manuscripts submitted for publication are subject to peer review by the EDG Journal editorial review board. The views and opinions expressed herein are those of authors and do not necessarily reflect the policy or the views of the EDGD.

Manuscript Submission
Please follow the guidelines provided on our website at http://www.edgd.org/. APA Style is required.

Membership and Subscription Information
Information about membership in the EDGD or subscription to the *Engineering Design Graphics Journal* should be directed to Judy Birchman at Purdue University (jbirchman@purdue.edu).

Message from the Editor

Get an Attitude!

By La Verne Abe Harris, Ph.D.
Purdue University

You may have noticed that I did not type "Arizona State University" on my Message from the Editor. That is because I have accepted a position as Associate Professor of Computer Graphic Technology at Purdue University and I am in transit. The one thing I have learned in my life is that you do not always have control over much of what happens in your life, but you do have control of your attitude. So today I am telling you to ***get an attitude!*** -- a creative and innovative attitude.

In today's world it is not enough to be graphic specialists. We must be ***graphic visionaries.*** We must embrace transcending disciplines. We must be open to creative thinking and unique approaches to problem solving. ***We must have attitude.*** Creative and innovative attitude is open to possibilities, accepting of change, and continually striving for improvement. With practice and a renewed sense of shedding suppressive learned behavior, everyone is capable of thinking creatively and innovatively. To improve creative thinking, one must learn how to accept change, be more flexible, be more playful with possibilities, be appreciative of the good things in life, and always want improvement.

Often when we are faced with crisis, we go into survival mode, but that's when we need to change our approach and make an attitude adjustment. There is an Asian symbol for crisis that many believe is the same symbol for danger plus opportunity. When faced with a problem, look at it as being confronted with an opportunity. Holding up the white flag before you begin is a self-fulfilling prophecy.

The world is full of skeptics and they have their role as devil's advocate in problem solving. But without being open to all the possibilities, no imaginative innovation will occur. If creative thinking appears childish or beyond your personal reach, **think again.** If problem solving appears to be out of your realm of expertise, **think again.** The Wright brothers, inventors of the airplane, were bicycle mechanics, not aviation engineers.

I am very pleased to present in this volume of the Engineering Design Graphics Journal three innovative articles focusing on visualization and geometric thinking. Marie Planchard, the Director of World Education Markets from SolidWorks Corporation, is our recipient of the Oppenheimer Award. This award is for the outstanding presentation of the Midyear Conference in San Diego, California in January 2007. Her paper *3D CAD: A Plus for STEM Education* concentrates on the merging of science, technology, engineering, and mathematics principles through three dimensional computer-aided design software across engineering curricula at all levels.

Jianping Yue writes about spatial visualization by isometric drawing. Spatial visualization is a fundamental skill in technical graphics and engineering design. Yue discovers in his research how a popular spatial visualization test is used to show mistakes in isometric views and offers recommendations to improve the tests.

And our last article focuses on a mathematical approach to thinking through cubic symmetry, classic geometry, and elementary vector algebra. Paul Zsombor-Murray's article *Platonic Symmetry and Geometric Thinking* conveys a creative approach to geometric construction.

There is an old time country song that chants, "I may be an old chunk of coal, but I'll be a diamond someday." So to all *you future diamonds ... Get an attitude!*

Elections 2007- Results

VICE CHAIR

Alice Y. Scales
North Carolina State University

\Alice Y. Scales is the Assistant Department Head of the Department of Mathematics, Science, and Technology Education and Coordinator of the Graphic Communications Program at North Carolina State University. She has taught at North Carolina State University since 1988. She has a B.S. in Science Education, a M. Ed. in Industrial Arts Education, and an Ed.D. in Occupational Education. At NC State University, she teaches introductory engineering graphics courses that include CAD, desktop publishing, and website development.

DIRECTOR OF MEMBERSHIP

Judith A. Birchman
Purdue University

Judy Birchman is an Associate Professor in the Department of Computer Graphics Technology at Purdue University. She received her Bachelor of Science and Master of Arts Degrees from Purdue University. A member of the Graphics Department since 1974, she has taught courses in engineering graphics fundamentals, drawing systems, CAD, electronic publishing and multimedia. Professional activities include presentations, papers and workshops on design, graphics and multimedia topics.Professor Birchman served as the Technical Editor and the Editor of the *Engineering Design Graphics Journal.* As a member of the Engineering Design Graphics Division, she has held two elected positions on the executive board serving as Director of Publications and as Chair of the division. She has also served as programs Chair for the ASEE Annual Conference. She is a member of the American Society for Engineering Education (ASEE), the Engineering Design Graphics Division (EDGD) and the International Graphic Arts Education Association (IGAEA).

LIASON COMMITTEE DIRECTOR

Aaron C. Clark
North Carolina State University

Aaron C. Clark is an Associate Professor of Graphic Communications at North Carolina State University in Raleigh, North Carolina. He received his B.S. and M.S. in Technology and Technology Education and earned his doctoral degree in Technology Education from NC State University. He has worked in industry, education, and teacher education including both teaching and administrative positions. His teaching specialties are in engineering drawing, visual theory, 3-D modeling, and technical animation. Research areas include graphics education and scientific/technical visualization. He presents and publishes in both technical/technology education and engineering education. He is currently the PI for an NSF grant titled VisTE: Visualization in Technology Education and has started new research in areas related to visualization within STEM education, gaming, and visual-based material development.

DIRECTOR OF PROGRAMS

Mike Stewart
Georgia Institute of Technology

Michael is currently an Academic Professional in the G.W. Woodruff School of Mechanical Engineering at the Georgia Institute of Technology where he has taught since 2001. Mike has previously taught in Arkansas, South Dakota and Nebraska. Mike served as Director of Liaisons and chaired several committees of the Engineering Design Graphics Division of ASEE before being elected as Vice Chair of the EDG Division. He served then as Chair and then Past Chair. Since that time he has been Program Chair of the 2005-6 Mid-year conference in Ft. Lauderdale, and is currently the Program Chair for the 2007 ASEE annual conference in Hawaii this summer. His research interests are in Geometric Modeling, Parametric Design, Rapid Prototyping, Engineering Design Graphics Curriculum Development and Computer Aided Design software.

Message from the Chair

The World Just Got Smaller for Ted Branoff

Ted Branoff, Ph.D.
North Carolina State University

The one thing I have learned over the last twenty-one years of teaching is that I have a lot more to learn. Like many of my students, I sometimes assume that my experiences are unique and that no one before me or somewhere else has had similar experiences.

In May I gave a talk on the *State of Engineering Design Graphics* in the United States at the ***40th Anniversary of the Japan Society for Graphics Science in Tokyo.*** Also invited were Bing-Shu Tong from Tsinghua University in Beijing, China and Hellmuth Stachel from the Vienna University of Technology in Vienna, Austria. Our talks took place on the morning of May 12. I went first, followed by Professor Tong and then Professor Stachel. I gave an overview of the types of graphics students might see in middle school, high school, community or technical colleges, and universities. I then highlighted the ***Engineering Design Graphics Division*** of ***ASEE*** and talked about commonalities and differences between our programs around the country. Thanks to many of you, I was able to give examples of student work and faculty research activities from around the country. Professor Tong's talk was very similar to mine. The types of activities Chinese students are doing look much like the activities we plan for our engineering and technology students. They have a focus on engineering design using 3D modeling within the context of product lifecycle management. As a mathematician, Professor Stachel's talk was a little different. He began by giving a short history and definition of descriptive geometry and then talked about its importance in the development of 3D spatial visualization. He concluded by summarizing what he believes is obsolete and what is still necessary in modern descriptive geometry education.

On Sunday morning I attended a symposium where five individuals from various areas gave their philosophies on the role descriptive geometry plays in their fields. The talks were all in Japanese, so Emiko Tsutsumi and Kenjiro Suzuki translated key comments in English for me. What I learned is that the ***Japan Society for Graphic Science*** is a little different than our ***EDGD.*** Their Society is made up of faculty and industry professionals from engineering, technology, mathematics, graphic arts, architecture, and fine arts. The common thread through all of these areas is descriptive geometry. Descriptive geometry is treated as a general education topic in Japan, and most students at the university level take at least one course. I also learned that our Japanese colleagues are great hosts. I don't think I have ever been treated so well.

I'm guessing that those of you who have been involved in the ***International Society for Geometry and Graphics*** and have attended the International Conference already knew these things. I will say that after browsing through the conference proceedings, many of the papers looked similar to those in our EDGD conference proceedings. I believe Japanese educators are also feeling pressure to reduce the amount of descriptive geometry that is being offered in favor of what is more popular with students – computer graphics.

So, what did I learn from my trip to Japan?

- First, I have been truly blessed during my life. Many people have helped me personally and professionally to make me who I am. As the current chair of the ***Engineering Design Graphics Division,*** I realize that I was very fortunate to be in the right place at the right time to be asked to make the trip to Japan.

Message from the Chair
continued from previous page

- In the United States, we have learned valuable lessons related to computer graphics curricula issues. I believe our colleagues around the world are interested in our findings.
- We can learn much about how graphics can be used as a problem-solving tool from our international colleagues.
- There is nothing like discussing graphics with someone from a different country. We may struggle to communicate verbally, but graphics is truly an international language.
- I am not as prepared to function internationally as my European and Asian colleagues.
- People appreciate it when you take time to learn a little bit about their language and their culture. I should not be so arrogant to think that everyone speaks English.
- The world is much smaller than I thought.

I know that many of you have done significantly more international traveling than I have and may have learned these things long before me. It is my hope that more of us will be able to take part in international conferences in the future. I can tell you that after talking with several people at the Japan conference (including Gunter Wiess-former president of the ***ISGG***), our European and Asian colleagues would like to see more U.S. participation in the International Society. The 13th International Conference on Geometry and Graphics will be held in Dresden, Germany August 4-9, 2008 (http://icgg2008.math.tu-dresden.de). The Branoffs have already put it on their calendar.

The Schroff Participation Grant (SPG) encourages graduate students and new faculty in engineering graphics and related disciplines to attend and present a paper at the ASEE Engineering Design Graphics Division (EDGD) Mid-Year Conference. The grant is open to graduate students or new faculty, in their first or second year of teaching, in graphics-related programs or courses (for example, Engineering Graphics, Technical Graphics, and Computer Graphics) and have not yet attended an ASEE/EDGD Mid-Year Conference. The grant, funded by Schroff Development Corporation (SDC), provides a maximum of $500 to attend the ASEE/EDGD Mid-Year Conference. The grant must be used for travel, accommodations, and/or conference *registration. Deadline for applications is August 24, 2007. See* http://www.edgd.org/Awards/Schroff/default.aspx for details.

3D CAD: A Plus for STEM Education

Marie Planchard
Director of World Education Market
SolidWorks Corporation

ABSTRACT

At some point in their education, pre-engineering students will take physics and/or calculus. For many freshmen who aren't certain about their career paths, taking these courses is a litmus test to determine whether they have the aptitude or desire to pursue an engineering degree.

Therein lies the challenge for many students in the U.S. Science, technology, engineering and math (STEM) curricula are typically steeped in traditional textbook methods for demonstrating, for example, the velocity of a free-falling object. 2D computer-generated graphs only go so far in showing what forces determine the speed of a calculus textbook dropped out of a third story dorm window. To change the dynamic and increase the chances of piquing student interest in STEM, teachers from middle school through college are starting to use 3D CAD tools in their lesson planning.

Visualizing a wave tank in 3D might help physics students better understand the many different forces that affect surface wave motion. They might also better see the quadratic formula at work, or how they can get the maximum distance from a catapult. Bringing physics, calculus, trigonometry and related subjects to life is a critical step in convincing students of how their knowledge of these subjects will help them in their engineering careers. Additionally, exposing students to 3D CAD technology early will help them begin honing the design skills they'll need in their professional careers.

In this session, attendees will learn how to use 3D CAD technology to fuel student interest in STEM, and potentially grow the pool of skilled engineers in the U.S.

Attendees will learn how to:

- *identify courses where 3D CAD software can help students better understand STEM concepts;*
- *use 3D CAD software to demonstrate practical examples of these concepts in physics, calculus and other subjects;*
- *demonstrate how students can visualize math and science problems more easily in 3D;*
- *show students how they can apply STEM concepts to engineering;*
- *expose students to the engineering fundamentals they will use professionally.*

INTRODUCTION

At some point in their education, pre-engineering students will take physics and calculus base classes. For many freshmen who aren't certain about their career paths, taking these courses is a litmus test to determine whether they have the aptitude or desire to pursue an engineering degree.

Therein lies the challenge for many students in the U.S. Science, technology, engineering and math (STEM) curricula are typically steeped in traditional textbook methods for demonstrating, for example, the velocity of a free-falling object. 2D computer-generated graphs only go so far in showing what forces determine the speed of a calculus textbook dropped out of a third story dorm window. To change the dynamic and increase the chances of piquing student interest in STEM, teachers from middle school through college are utilizing 3D CAD tools in their lesson planning.

OBJECTIVES

The objective of this project was to improve the understanding of STEM principles through 3D CAD software across engineering curricula. In addition, the project's intent was to enhance instructors' skills sets in utilizing 3D CAD to illustrate theory and to provide a community to share resources for STEM related courses across not only college and university levels but also in middle school, high school and technical vocational school.

LESSON CATEGORIES SELECTED

Post-secondary instructors developed lessons for Calculus, Physics, Engineering Graphics, Introduction to Engineering, Engineering Mechanics – Statics, Strength of Materials, Manufacturing, and Fracture Mechanics. Secondary instructors provided lessons for Algebra, Art, Biology, Calculus, Chemistry, Geometry, Robotics, Technology, and Trigonometry. The lesson outline included: the STEM Concepts Addressed, Instructional Period, Grade Level, Objectives, Materials, Procedure, Assessment, Resources Used and Reference to Copyright Materials.

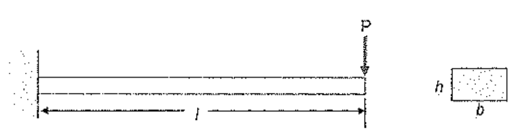
Example 1:

The first example, developed by Professor Herbert Crosby, University of Maine, "Determining Beam Stress and Deflection with COSMOSXpress." explores the theoretical problem of determining stress and deflection for a simply loaded cantilever beam. The results were first found utilizing analytical methods and then found using COSMOSXpress (finite element analysis). The objectives of the lesson were as follows:

Objectives:

1. Learn to calculate maximum stress for a simply loaded cantilever beam.
2. Learn to calculate factor of safety for the same beam.
3. Learn to calculate maximum deflection for the same beam.
4. Learn to determine the same results using COSMOSXpress.
5. Learn the effects of changing beam dimensions.

Engineers often need to determine maximum stress in parts to find if they are safe. Maximum stress is compared with material strength to determine factor of safety. Engineers also need to determine maximum part deflection under load. As an example, consider a simply loaded cantilever beam:



The rectangular cross section cantilever beam is fixed at the wall and has a load P at the right end. Maximum stress occurs at the wall at the top and bottom beam surfaces. The top surface is in tension and the bottom surface is in compression. Maximum beam deflection occurs at the right end of the beam. We can calculate these values for the above case with the following equations:

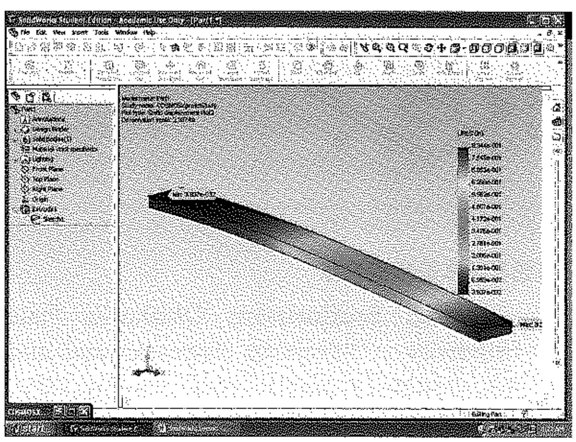
$$\sigma_{\max} = \frac{6Pl}{bh^2}$$

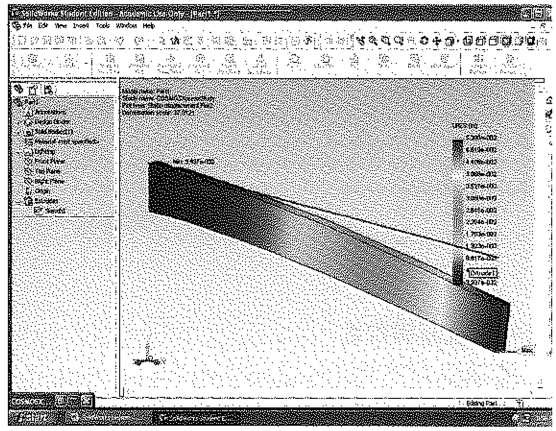
$$F_s = \frac{\sigma_{yp}}{\sigma_{\max}}$$

$$\delta = \frac{4Pl^3}{Ebh^3}$$

P = *load appled at the end of beam, pounds*
l = *beam length, inches*
b = *beam base, inches*
h = *beam height (parallel to load), inches*
F_s = *factor of safety*
σ_{yp} = *material yeild strength, psi*
δ = *deflection at end of beam, inches*
E = *material modulus of elastisity, psi*

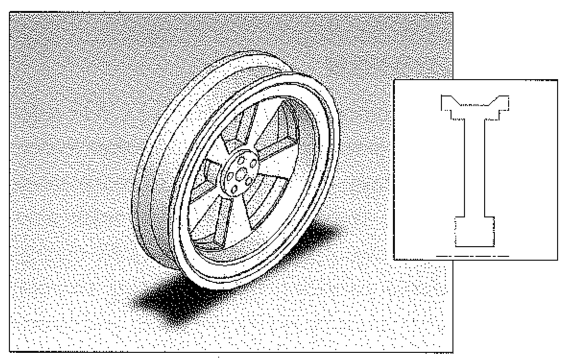
Students modeled two beams with the same rectangular cross section, rotated 90 degrees.



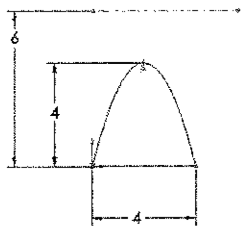


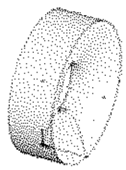
Example 2

The second example, developed by Professor Ric Baugher, Southwestern Oklahoma State University , "Revolving shapes around and axis, creating circular patterns" The objectives of the lesson were to create a wheel by revolving a profile about an axis and utilizing circular patterns in order to locate cuts and holes. The student researches standard dimension required when designing wheels to fit a particular automobile. Emphasis was also placed on developing a production drawing with the correct dimensions.



In a corresponding example, the "Parabola from Algebra to Calculus", students determine the area bounded by the x axis, center of mass and volume of a solid in revolution that is explored in both Calculus II and Engineering Mechanics.





CHALLENGE

To develop a STEM teacher community with the lesson plans faced many challenges. Instructors not only developed text based lessons, but also submitted model files, picture files and movie files. As a result, instead of developing a formal web site, a blog, was created. Because of web security issues, each lesson must be manually reviewed which slows the posting process down.

LESSONS LEARNED

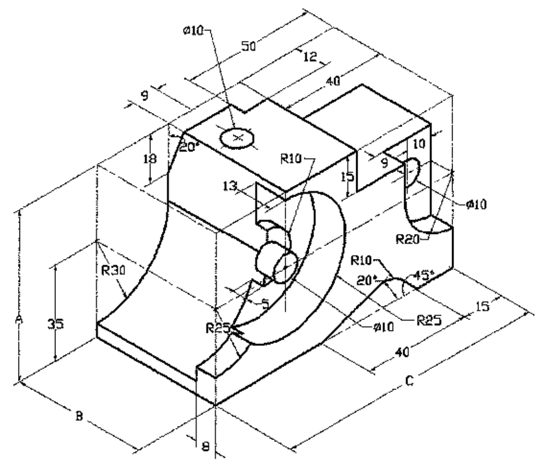
The project grew beyond just physics and calculus and more categories needed to be established. Even for instructors that had no formal 3D CAD training, they were able to follow eLearning exercises and video. With the large number of responses, the lesson submission process needs to become automated in the future.

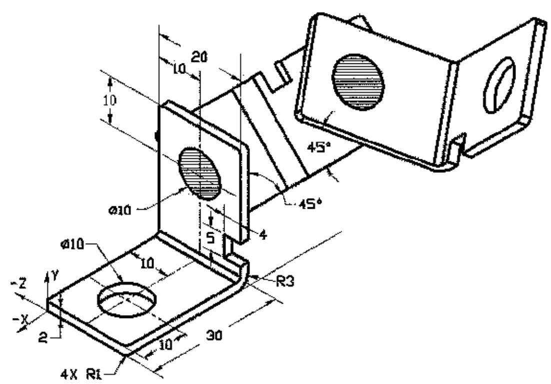
CONCLUSION

For both instructors and students 3D CAD software provides a powerful complement that makes science, technology, engineering, and math more understandable. Industry must work with academia to use technology to make STEM engaging for students considering engineering careers. The instructor must be given the tools and training to develop their 3D skill sets. With their own curricula, instructors develop the virtual illustrations of the theoretical concepts for their own students.

FUTURE DIRECTION

For the engineering and technology instructors and students another goal is to raise the level of 3D CAD competency with the Certified SolidWorks Associate (CSWA) exam. The CSWA exam proves industry readiness focused both on 3D CAD skills and STEM competencies by creating a model from a detailed illustration, applying material to a component, understanding engineering practices, and determining the volume and center of mass.





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Spatial Visualization by Isometric View

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ABSTRACT

Spatial visualization is a fundamental skill in technical graphics and engineering designs. From conventional multi-view drawing to modern solid modeling using computer-aided design, visualization skills have always been essential for representing three-dimensional objects and assemblies. Researchers have developed various types of tests to measure students' spatial visualization abilities, in which most pictorial views of three-dimensional objects are represented by isometric views. Isometric views have many advantages such as being simple to draw, and equally representing the front, top, and side surfaces. However, they are also susceptible to drawing mistakes in spite of their relatively simple construction. This paper discusses the typical styles of visualization tests designed for engineering and technology students. Three formats for spatial visualization tests (developments, rotations, and isometric views) are discussed. A popular spatial visualization test is used as example to show some mistakes in its isometric views. Recommendations are made to improve pictorial views in spatial visualization tests.

INTRODUCTION

Spatial visualization ability has played an important role in civilization, from ancient architectural wonders to modern space exploration. Spatial visualization skills are especially important in engineering and technology fields. From the traditional board drawings of multiviews, sections, and assemblies, to modern solid modeling using computer aided design (CAD) tools, almost all product designs require the visualization of three dimensional (3D) objects. Spatial visualization ability is equally vital in some hot technologies such as geographic information systems (GIS), biomedical information technology, and robotics.

Spatial visualization has long been considered fundamental in engineering graphics courses. In the 1980s, along with the development of microcomputers, CAD was introduced into classrooms. Since then, both computer hardware and software have significantly improved, such that 3D solid modeling CAD has become ubiquitous in industrial applications. Therefore, spatial visualization has become a required skill for engineering and technology students. These developments have revitalized educators' interest in spatial visualization (Miller & Bertoline, 1991; Miller, 1996). In recent decades, many formats have been developed for testing spatial visualization skills. Psychologists have intensively studied spatial visualization from the perspective of cognition and perception. In the early 1970s, Shepard and Metzler (1971) designed a test to investigate the reaction time of visualizing rotated 3D objects. Vandenberg and Kuse

(1978) later developed a test, based on Shepard and Metzler's model, known as the mental rotation test (MRT). Ekstrom, French, and Harman (1976) also included spatial visualization in a set of cognitive tests, which were included in the Educational Testing Service's (ETS) catalog of standardized tests. In the late 1970s, engineering and technology educators also investigated the relationship between spatial visualization ability and technical graphics skills. Among these educators, Guay (1976) developed a test called the Purdue Spatial Visualization Test (PSVT). The PSVT is a multiple-choice test. The test originally consisted of three sections (developments, rotations, and views), each containing twelve problems. The first section is developments (folding 2D flat patterns along fold lines) into 3D objects (surface models). The second section is the orthogonal rotations of 3D objects about the axes of the Cartesian coordinate system. The third section is the isometric views of 3D objects. By adding 18 new problems to the original 12 problems in the second section (rotations) of the PSVT test, Guay (1977) extended it into a 30-problem test on spatial visualization of rotations (PSVT-R). The PSVT-R was included in the ETS test collection and has since been widely used by researchers in engineering and technology fields. An excerpt of the PSVT test was also included in a textbook (Bertoline & Wiebe, 2007), containing the first five problems from each of the three sections of the PSVT test for a total of 15 problems. Sorby (2003) developed a workbook on 3D spatial visualization, which contains a total of 513 problems involving a variety of testing formats in spatial visualization (not counting additional exercises in the bundled software package). Most of the problems are variations of the basic formats in the PSVT test and textbooks. For example, there are 135 problems on orthogonal rotations in the workbook. In addition to the traditional multiple-choice questions on rotated views, there are also multiple-choice and free-form questions relating to degree, direction, and sequence of rotations. Some problems require students to sketch the isometric views after specified orthogonal rotations.

Spatial visualization tests have been used by educators as both teaching and research tools at many colleges. Textbooks include various formats of spatial visualization exercises, quizzes and tests on spatial visualization (Sorby, 2003; Bertoline & Wiebe, 2007). Spatial visualization tests have been commonly used by educators as pre-test and post-test assessments to diagnose and improve students' visualization skills in graphics and CAD courses (Sorby & Baartmans, 1996; Branoff & Connolly, 1999; Yue & Chen, 2001; Czapka, Moeinszdeh, & Leake, 2002; and Study, 2004, 2006). Spatial visualization tests have also been frequently used to assess and improve the retention rate of freshmen, women, and minority engineering and technology students (Sorby & Baartmans, 1996, 2000; Sorby, 2001a; Study, 2004, 2006; Brus, Zhao, & Jessop, 2004; Kinsey, Towle, Hwang, O'Brien, & Bauer, 2006). Educators have used spatial visualization tests to study human visualization behaviors in the context of age, gender, education, training, etc. (Guay, 1978; Sorby & Baartmans, 1996; Sorby, 1999, 2001b; Yue, 2000, 2002a, b; Yue & Chen, 2001). Research has also been done to improve the testing tools for spatial visualization. For example, to help students visualize 3D objects from the approximate and simplified views in visualization tests, some researchers have added reference axes and grids to the views. Branoff (1998a, b) added the Cartesian coordinate axes to the PSVT-R test to highlight the visual relationship between the object and the axes it rotates about. Sorby et al. (1998, 2003) exploded variations of the conventional test formats of pictorial views and used isometric grids to provide dimensions to the features of an object. Recently, educators have used CAD software to create solid models in spatial visualization tests for more realistic 3D views (Sorby, 2003; Ardebili, 2006; Kinsey et al., 2006; Yue, 2007).

Usually, spatial visualization tests represent 3D objects in 2D pictorial views on paper or screen. Due to their simplicity, axonometric views have been dominantly used in spatial visualization tests. Isometric views, a sub set of axonometric views, have been particularly favored by engineering and technology instructors in developing spatial visualization tests. The MRT test (Vandenberg and Kuse, 1978) problems are all axonometric views. The PSVT test (Guay, 1976) consists of 36 problems evenly distributed among developments, rotations, and isometric views. However, all of the problems show pictorial views in isometric. All of the 30 questions in the PSVT-R test (Guay, 1977) are also exclusively in isometric views. Sorby's workbook (2003) has a total of 513 questions involving pictorial views (not counting additional pictorial views in the bundled software package.) All of the views are axonometric and the majority of them (457 or 89%) are in isometric views. This paper discusses the role of the isometric view, especially its pros and cons, in spatial visualization tests. The PSVT-R test is popular in engineering schools. This is probably partly due to the fact that the test uses isometric views for spatial visualization, a simple orthogonal projection method taught in engineering graphics courses. Thousands of engineering and technology students in many colleges and universities have taken the PSVT-R test (Guay, 1978 March, June, 1980; Guay & McDaniel, 1978; Battista, 1981; Sorby & Baartmans, 1996; Branoff, 1998a, b; Branoff & Connolly, 1999; Sorby, 1999, 2001b; Yue, 2000, 2002a, b; Yue & Chen, 2001; Czapka, Moeinszdeh, & Leake, 2002; Study, 2004, 2006; Brus, et al., 2004; Towle, Mann, Kinsey, O'Brien, Bauer, & Champoux, 2005; Ardebili, 2006; Hamlin, Boersma, & Sorby, 2006; Kinsey, et al., 2006;). Due to its popularity and the use of isometric views, this paper will primarily use examples from the PSVT-R test for the discussion of spatial visualization by isometric view.

ISOMETRIC VIEWS IN SPATIAL VISUALIZATION TESTS

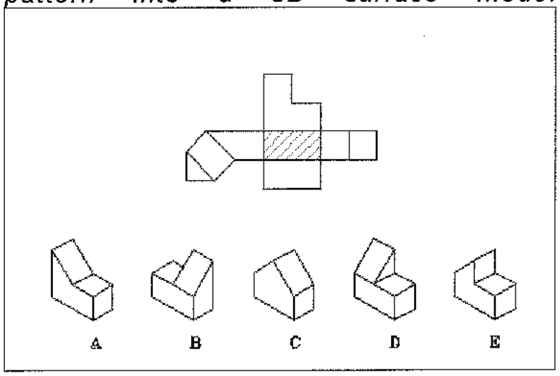
Due to its simplicity in displaying 3D objects, isometric view has been predominant among engineering and technology educators in designing tests for spatial visualizations (Guay, 1976; Sorby, 2003). In the three formats of the PSVT test (Guay, 1976), isometric views were the only pictorial views used to show 3D objects. They were used not only in the format of isometric views, but also to illustrate the rotations and developments. In the variety of spatial visualization tests in Sorby's workbook (2003), isometric view was also the format for pictorial views in almost all formats except for the intersected solids, in which other axonometric views were used to avoid overlapping of edges.

The PSVT and PSVT-R tests (Guay, 1976, 1977) are popular and representative. An abridged PSVT test is readily accessible in a textbook (Bertoline & Wiebe, 2007), and many instructors and students are familiar with the tests. A variety of test formats (Sorby, 2003) may be derived from the PSVT test. Because all pictorial views in the tests are also exclusively in isometric views, this paper introduces the three formats of the PSVT test to discuss the use of isometric views in testing spatial visualization ability.

SPATIAL VISUALIZATION BY DEVELOPMENTS

True development is an un-stretched forming process that bends sheet metals into various shapes. Spatial visualization by developments takes the format of folding a 2D flat pattern into a 3D surface model. As shown in an example with the same format as the PSVT test (Figure 2.1), a 2D flat pattern and five isometric views are given. The five views represent different 3D objects, and only one of them can be developed from the flat pattern. In Figure 2.1, the correct choice is D. To help students visualize the developments, fold lines are usually provided. A suggested base surface, around which adjacent surfaces are folded, is also marked. The marked base surface may be viewed as the bottom of the developed 3D model in contact with the tabletop or ground. In a 2D flat pattern, all interior lines must be fold lines, and all boundary lines must be seam lines. The flat pattern must be folded along the fold lines and then sealed along the seam lines to form the correct choice of the surface model. It is also assumed that the flat pattern is folded upward. The correct answer in Figure 2.1 would be B if it is folded downward.

Figure 2.1: *Spatial visualization by developments of folding a 2D flat pattern into a 3D surface model*

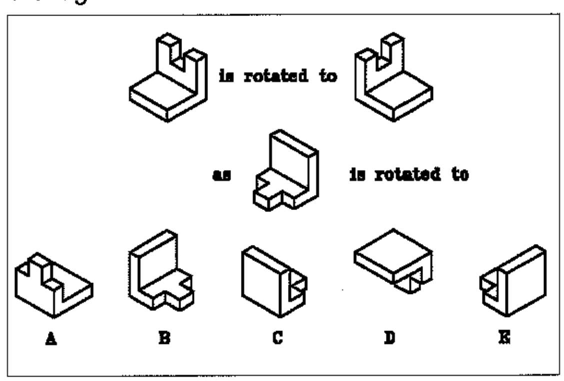


The test of developments may also take the reverse format of unfolding a 3D surface model into its flat patterns. In this case, there is no need to mark the base surface because it is the bottom of the object as it is placed. The seam lines now become cut lines on the 3D surface model along which the edges are cut open and the surfaces are unfolded into the flat pattern. Normally, the edges corresponding to the cut lines are left for the students to figure out, and are not indicated on the 3D surface model. Usually, a surface model may be unfolded into multiple flat patterns. On the other hand, the cut lines must be carefully chosen on the 3D models to form a continuous boundary of a 2D flat pattern. The flat pattern can be made clearer for visualization by using the dashed line type instead of continuous lines for the fold lines. The developments of simple objects are usually fairly easy. For example, a rectangular box requires no more than a maximum of three consecutive folds and all fold lines can be aligned with horizontal or vertical lines on a flat pattern. However, the fold lines for oblique surfaces generally do not follow horizontal or vertical lines on flat patterns. The developments of some complex and embedded surfaces may also require a considerable number of consecutive folds. In these situations, spatial visualization of mentally folding flat patterns into a surface model could be a challenging task.

SPATIAL VISUALIZATION BY ROTATIONS

Another very popular format in spatial visualization tests is rotating a 3D object in its axonometric views. Examples of spatial visualization by rotations include the MRT test (Vandenberg & Kuse, 1978) and the PSVT-R test (Guay, 1977). In the MRT test, students are to recognize an object of ten face-to-face connected cubes after rotating it at an arbitrary angle in axonometric views. In the PSVT-R test, students are to visualize orthogonal (single or multiple 90°) rotations of a 3D object about the Cartesian coordinate axes in isometric views. Figure 2.2 shows an example with the same format as the rotation problems in the PSVT-R test. An object and its rotated view are given as a sample, and then another object is presented with its five different views after various rotations. Students are to choose one view that is resulted from the same manner of rotation as the given example. In Figure 2.2, the correct choice is B. All of the views in the PSVT-R test are regular isometric views, and the five choices (A through E) are rotated views of the same object. The rotations are orthogonal, i.e. multiples of 90° about a single Cartesian axis or multiple axes in sequence.

Figure 2.2: *Spatial visualization by orthogonal rotations*

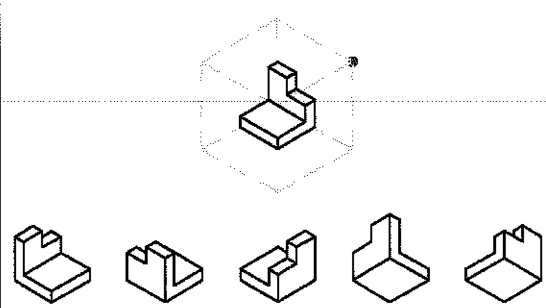


Due to the controllability of limited number of isometric views, as well as due to their simplicity, the format of orthogonal rotations of isometric views has been chosen by many engineering and technology educators.

SPATIAL VISUALIZATION BY ISOMETRIC VIEWS

Another format of applying isometric views in spatial visualization test is to identify the isometric view of a 3D object at a given vertex of its confining rectangular box. Figure 2.3 shows an example with the same format as the isometric view problems in the PSVT test (Guay, 1976). An object is placed inside a confining cube and the point of view is denoted by a dot at one of the vertices of the cube. Then five isometric views of the object are given, and students are to choose one that represents the view from the given point of view. The right choice is C in Figure 2.3.

Figure 2.3: *Spatial visualization by isometric views*



This format of spatial visualization requires a prior knowledge in engineering graphics, such as the concepts of point of view and isometric projection. Therefore, it may not be appropriate for testing a general audience. There are also some problems with the application of the format in spatial visualization. As discussed later, multiple isometric views may exist at each vertex and the available isometric views are limited by imposing constraints to avoid possible ambiguities.

AVAILABLE ISOMETRIC VIEWS FOR SPATIAL VISUALIZATION

Theoretically, there are an infinite number of isometric views. By rotating either the object or the eyes (or camera lens) about the line of view, different isometric views are generated at various orientations. However, due to certain practical constraints, only a very limited number of isometric views are available and have been used in spatial visualization tests. Real objects have various shapes, but any object can be confined in a rectangular box with its size matching the overall width, depth, and height of the object. Therefore, we may use a generic rectangular or cubic object in our discussion of isometric views. If we place a cube on tabletop or ground, keep our heads upright, and look slantwise downward through a diagonal of the cube, we will see a regular bird's-eye isometric view. When the sides of an object or its confining cube are aligned with the axes of a fixed Cartesian coordinate system, there are only a total of 24 bird's-eye isometric views (Figure 3.1). In other words, there are 3 possible isometric views at each vertex of the cube (Figure 3.2) and 8 vertices result in 24 isometric views. In Figure 3.1, each view is denoted by a subscript composed of a letter and a number. The letters indicate the surfaces as an original top surface (T) rotated to bottom (B), front (F), back or rear (R), left side (L), and right side (S). The number in the subscript indicates the number of positive orthogonal rotations about the axis along the surface vector of the specified surface (0 is $0 \times 90^{\circ} = 0^{\circ}$, 1 is $1 \times 90^{\circ} = 90^{\circ}$, 2 is $2 \times 90^{\circ} = 180^{\circ}$, and 3 is $3 \times 90^{\circ} = 270^{\circ}$). For example, the T3 view is obtained by rotating the T0 view 270° about the Z-axis.

Other types of isometric views are also possible. For example, if one craws under a table and looks diagonally upwards at an object on the tabletop (the tabletop must be transparent), a worm's-eye isometric view would be obtained, which shows the bottom and two side surfaces of the object (Figure 3.3b). Similarly, there are also a total of 24 worm's-eye isometric views of any object. However, even if a tabletop is made of glass so that it would not block the sight of the worm's-eye view, people normally would still prefer the bird's-eye views than the worm's-eye views, i.e., stand up rather than craw down. Consequently, if people's viewing preferences or habits are taken into consideration and the object does not move, there are only four practical isometric views at the top vertices of a fixed object (Figure 3.3a). For example, AutoCAD (2006) provides only the four isometric views at the top vertices as direct view options or toolbar buttons, and calls them SW, SE, NE, and NW isometric views.

Figure 3.1: *24 bird's-eye isometric views*

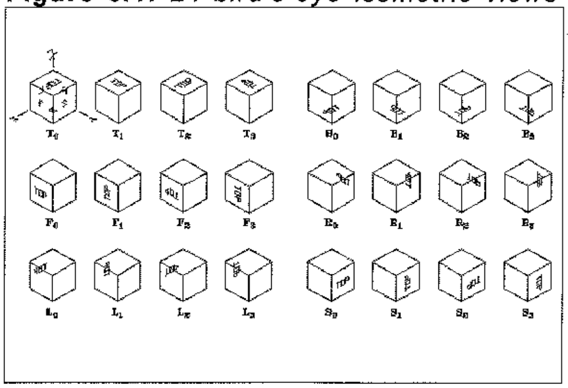


Figure 3.2: *Three possible bird's-eye isometric*

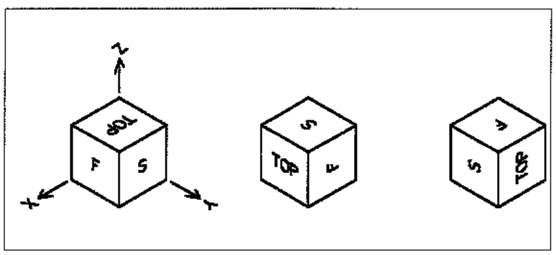
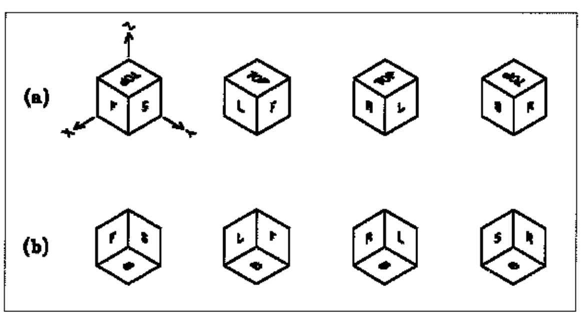


Figure 3.3: *Bird's-eye and worm's-eye isometric*



REPRESENTATION OF ISOMETRIC VIEWS IN SPATIAL VISUALIZATION BY ROTATIONS

The 24 available bird's-eye isometric views (Figure 3.1) may be formed by rotating the object about the Cartesian axes orthogonally, i.e. with 90° angles. Their difficulties of rotation vary depending on the number of axes involved and the degrees of rotations. A well designed visualization test makes an effort to represent all available views and across the spectrum of the difficulty of rotations. Let us look at the PSVT-R test as an example.

REPRESENTATION OF THE ISOMETRIC VIEWS IN EXAMPLE ROTATIONS

In the PSVT-R test (Guay, 1977), two very similar objects are used in the exemplary rotations of all 30 problems to show the rotations you must visualize when selecting the right choice which follows the same rotations. The two objects are both cubes with a central slot on one surface and a cut on one side wall of the slot (one left cut and the other right cut) with a total of 48 isometric views (Figure 4.1.1 and Figure 4.1.2.) If each of the initial and rotated views in the examples of a 30-problem test uses a unique view, it needs a total of 60 different views. There is a shortage of 12 views. Therefore, either some views will be repeated or an additional object is required. Alternately, we may use the same initial view for as many problems as possible and different views or rotations from problem to problem. For example, one object can provide the same initial view and different rotated views for 23 problems, which cover all 24 available isometric views. Two objects would provide 46 problems with different rotations for each object, more than enough for a 30-problem test. Therefore, a 30-problem test with two sample objects is capable of representing all possible isometric views.

Table 4.1 lists the views used in the 30 problems of the PSVT-R test. From Table 4.1, some of the available bird's-eye isometric views are not represented in the PSVT-R test. Only 15 of the 24 (63%) available isometric views have been used for object A, and 12 of the 24 (50%) views for object B. On the other hand, some other views have been used multiple times. The S2 view and F1 view have been used 9 and 6 times respectively for object A, and the T0 view and S1 view 6 and 5 times respectively for object B. In the PSVT-R test, there are also repeated rotations (the same original and rotated views) in two problems (#8 and #10) for object A, and another two problems (#7 and #9) for object B. An improvement is possible in the future design of visualization tests to include more views and to have a better representation of the available isometric views.

Figure 4.1.1: *Twenty-four isometric views by orthogonal rotations for the object A*

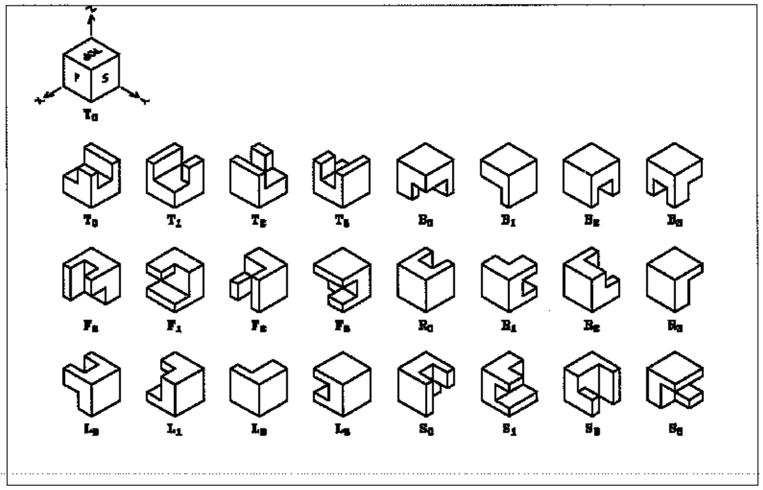


Figure 4.1.2: *Twenty-four isometric views by orthogonal rotations for the object B*

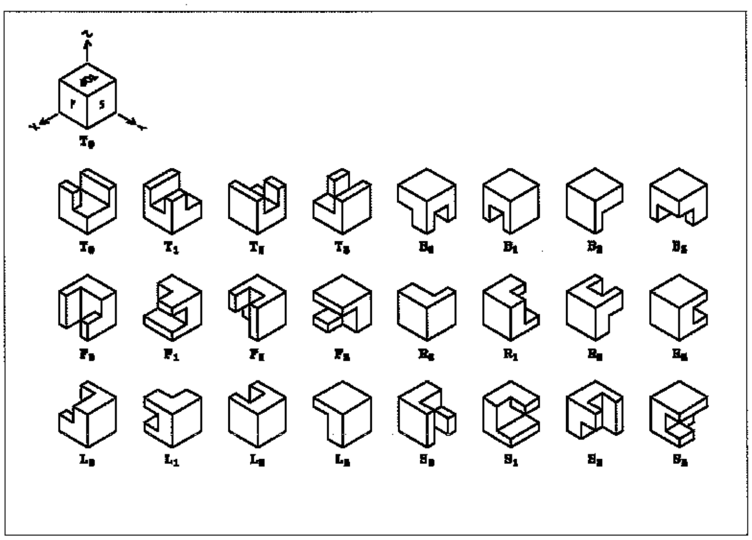


Table 4.1: *Isometric views in the example rotations of the PSVT-R test*

	T_0	T_1	T_2	T_3	B_0	B_1	B_2	B_3	F_0	F_1	F_2	F_3	R_0	R_1	R_2	R_3	L_0	L_1	L_2	L_3	S_0	S_1	S_2	S_3
A_b		3								6													8	
A_a		1			1	1			1		1		2	1	1	1	2		1		2		1	1
B_b	6								2													5		
B_a		1	1			1									1	1		3	3				1	1

Note: Ab and Aa indicate the object A before and after rotations (similar meanings for Bb and Ba.) T0, T1, etc. are the possible isometric views in Figure 4.1.1 and Figure 4.1.2.

REPRESENTATION OF THE DIFFICULTY OF ROTATIONS

The total of 24 bird's-eye isometric views of an object (Figure 3.1) is obtained by orthogonal rotations about the Cartesian axes. They may be sorted into four types of rotations based on the degree of difficulty (Yue, 2004). Each orthogonal or 90° rotation about an axis is a basic unit of rotation. The degree of difficulty is dependent on two factors: the number of axes involved and the number of orthogonal rotations. The four types are Type I: 90° rotation about one axis, Type II: 180° rotation about one axis, Type III: 90° rotation about one axis and 90° rotation about another axis, and Type IV: 90° rotation about one axis and 180° rotation about another axis (Table 4.2.) Clockwise and counterclockwise rotations are treated as the same degree of difficulty. For example, the view T1 is rotated 90° counterclockwise about the Z axis from the initial view T0, and T3 clockwise. Both of them are Type I rotations. Each of the views may be obtained by a number of different combinations of rotations. For example, the view S0 may be obtained from T0 by rotating 90° clockwise about the X axis and then 180° clockwise about the Z axis; or 90° counterclockwise about the X axis and then 180° clockwise about the Y axis; or 90° clockwise about the Y axis and then 90° clockwise about the X axis and finally 90° clockwise about the Z axis; etc. These are the Type IV rotations. If more than one type of rotation produces the same view, the simplest type of rotation always has precedence. The rotations in the PSVT-R test do not represent all 24 available isometric views (Table 4.1.) Therefore, they do not include some rotations. However, they do represent all four types of rotations (Table 4.2.)

Table 4.2: *Types of Orthogonal Rotations*

Type of Rotation	Isometric Views	Number of Views	PSVT-R Views
Type 0: Initial view	T_0	1	
Type I: 90° one axis	T_1, T_3, F_3, R_1, L_0, S_2	6	6
Type I: 180° one axis	T_2, B_0, B_2	3	8
Type III: 90° one axis & 90° another axis	F_0, F_2, R_0, R_2, L_1, L_3, S_1, S_3	8	8
Type IV: 90° one axis & 180° another axis	B_1, B_3, F_1, R_3, L_2, S_0	6	8

PROBLEMS OF USING ISOMETRIC VIEWS IN SPATIAL VISUALIZATION TESTS

Due to its simplicity, isometric view has not only been favored to illustrate pictorial views in engineering and technology textbooks, but also been chosen in designing spatial visualization tests (Guay, 1976, 1977; Sorby, 2003). However, the oversimplifications of the isometric view could also cause problems in its application in spatial visualization tests.

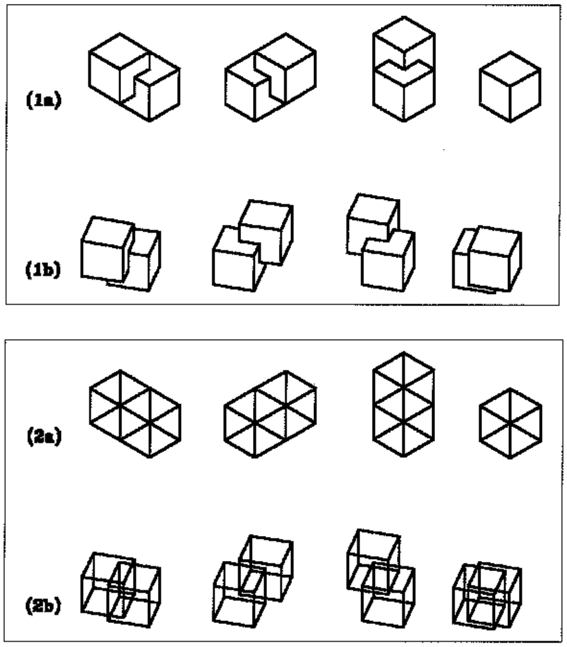
LACK OF 3D FEATURES IN ISOMETRIC VIEWS

Isometric views in technical graphics are far from true or realistic isometric views. A realistic view of a 3D object is composed of many necessary features. These features include dimensions, colors, external lighting and shades, light transmission, surface textures, and perspectives. The dimensions of a 3D object include overall sizes in width, height, and depth, as well as feature sizes and locations. The lighting and shading are affected by the luminance (brightness) of the light sources, whether point or ambient, and their colors (warm or cold). The light transmission may be transparent, translucent, or opaque. The surface textures reflect material properties and finishes such as wood grain, polished metal, and cloth fiber. Obviously, isometric view lacks many of these 3D features. Most importantly, it lacks the perspective effect. The visual rays or projection lines of an isometric view are parallel to each other. As a result, isometric views are distorted and distant features appear significantly enlarged. Isometric view also shows only the unblocked edges or boundary lines of a 3D view without surface features and light effects. An isometric view is constructed with an adjusted proportional ratio. In an isometric projection of a rectangular box, its edges are foreshortened into approximately 82% of their original length. In an isometric view, though, they are usually still drawn as their original length for convenience. Sometimes, the depth dimensions are drawn as half of the original length, known as the cabinet view as opposed to the full length cavalier view. Therefore, isometric views are also distorted in size dimensions. As a matter of fact, isometric view has so many approximations that it may be the simplest to construct among all types of pictorial views. In a spatial visualization test, though, it is necessary to display, as much as possible, realistic pictorial views to help visualize 3D objects. Therefore, the weaknesses of isometric view may impose certain limits on its application in spatial visualization tests.

MISINTERPRETATIONS OF ISOMETRIC VIEWS

Since the hidden lines are not shown in isometric views, blocked rear features are not fully specified and left to the interpretation of the viewer. For example, Figure 5.2.1a shows two intersected cubes from four different points of view. In the first three views, it is very hard to tell whether the blocked portion extends half way or all the way unless we know its size. The fourth view shows a worst-case scenario in which the rear portion is entirely blocked and the object appears as though it were a single cube. In order to clarify rear features, hidden lines are sometimes drawn in isometric views (Figure 5.2.2a.) However, because the parallel edges of an object may overlap, this may cause even more confusion and misinterpretation. In both cases, general axonometric views, such as the trimetric views as shown in Figure 5.2.1b and Figure 5.2.2b, usually can avoid the overlapping and give a much clearer picture. For example, in Sorby's workbook (2003), a small number of problems (approximately 10% of the total problems) are constructions of solid models, such as revolution, union, subtraction, and intersection. In order to make the intersections clearer, hidden lines are drawn in some of the objects, and general axonometric views are also used whenever necessary. In Sorby's workbook, all edges of each individual object shown as continuous lines as if they are visible and the objects are overlapping each other and the intersections of solids are not shown no matter visible or invisible. Figure 5.2.2 illustrates the continuous hidden lines and missing intersection lines similar to the workbook problems. This treatment may highlight features on individual objects, but does not represent realistic joined solids. When it is necessary to show hidden lines in an axonometric view to make the drawing clear, it is still better to draw the hidden lines in dashes as usual.

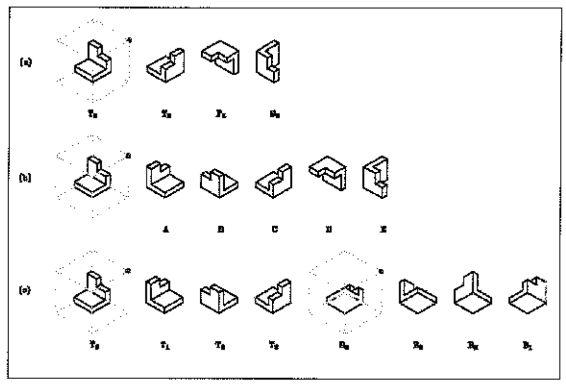
Figure *5.2: Two intersected cubes with hidden lines invisible (1. top) and shown (2. bottom)*



AMBIGUITIES IN SPATIAL VISUALIZATION BY ISOMETRIC VIEWS

One format for applying isometric views in spatial visualization test is to identify the isometric view of a 3D object, seen from a given vertex of its confining rectangular box (Guay, 1976). There are two major problems with this format of spatial visualization. First, multiple isometric views exist at each vertex. Second, when constraints are imposed to avoid the ambiguity, only limited isometric views are available. As discussed above, theoretically there are 3 bird's-eye isometric views possible at each vertex (Figure 3.2), and a total of 24 bird's-eye isometric views (Figure 3.1.) If we include all views in the spatial visualization by isometric views, it would be ambiguous to choose one of the three views at a vertex. For example, an object and its three views at the indicated vertex are shown in Figure 5.3a. If these three views were included in the multiple choices in a test problem, such as the C, D, and E as shown in Figure 5.3b, which one should we choose from? This problem may be solved by adding some constraints to clarify the ambiguity. For example, we could allow only the isometric views for fixed object (Figure 3.3) in this format of spatial visualization test. With this constrain added, there are only a total of 8 regular isometric views, 4 bird's-eye views and 4 worm's-eye views (Figure 5.3c, T0 - T3 and B0 - B3 respectively), available for spatial visualization by isometric views. Back to Figure 5.3b again, the correct choice now is C. Because choices D and E are not isometric views for fixed object, they are no longer valid and can not be used in the test as options. This solution seems to have solved the problem, but it naturally brings up another problem: there are now only very limited views left for use as answer choices.

Figure 5.3: *An example of spatial visualization by isometric views*



LIMITED CHOICES OF ISOMETRIC VIEWS

In order to avoid the ambiguity of multiple isometric views at each vertex, we have limited our views to the 8 isometric views for fixed object (Figure 3.3) in spatial visualization by isometric views. Among the 8 views, the 4 bird's-eye views are more popular than the 4 worm's-eye views due to their similarity to natural human vision. If we limit the isometric views to bird's-eye views, only 4 views are left. After one of the views is used for the initial view, there are only 3 views left for choices, not even enough to make up five multiple choice answers. It seems that we have no choice but to include the worm's-eye views. Even so, we still only have 7 views available for choices. The limited choices available for spatial visualization by isometric views hinder the possible variations of this test format. For example, in the 12 isometric view problems of the PSVT test (Guay, 1976), worm's-eye views are included to boost the number of choices. Except for two view point (TFS and BFS), all other six view points (TRS, TFL, TRL, BRS, BFL, and BRL) are presented in the test both as specified view points and in the multiple choices. Here the three letters denote the surfaces that form the vertex or point of view. The initial views in the PSVT test are all bird's-eye views of TFS, thus can not be used for choices, The BFS is a worm's-eye view and not used in the PSVT test, neither as the initial view nor as multiple choices. In the 5 isometric view problems of the abridged PSVT test (Bertoline & Wiebe, 2007), all specified views are bird's-eye views (TRS, TFL, and TRL).

NECESSARY TRAINING IN VISUALIZING ISOMETRIC VIEWS

An isometric view itself is merely the simplest approximation of a pictorial view of a 3D object. People usually are able to easily visualize isometric views. Most spatial visualization tests choose isometric or axonometric views (Shepard & Metzler, 1971; Vandenberg, & Kuse, 1978; Guay, 1976, 1977; Sorby, 2003). However, because of oversimplifications, some isometric views could be very confusing even to professionals (as discussed in the section below). The test of spatial visualization by isometric view (Figure 2.3) asks students to choose the isometric view that is created by viewing at the given point of view. This format involves more than just looking at isometric views. It addresses several concepts in engineering graphics. The students need to know the concepts of the confining "glass box", the projection plane, the lines of projection, and the point of view. They also need to have some familiarity with the creation of an isometric view. Therefore, the test of spatial visualization by isometric views may not be appropriate for a general audience.

CASE STUDY OF ISOMETRIC DRAWING ERRORS IN SPATIAL VISUALIZATION TEST

Due to its misrepresentation and distortion of a true 3D view, isometric view is prone to drawing errors. For example, in the widely used PSVT-R test (Guay, 1977), the isometric views in seven out of the thirty test questions contain errors (23% error rate). Each of them had at least one or more errors, which accounted for 10 rotated views (with two of them the same object and rotation in the exemplary rotations.) These errors include missing features, misrepresented features, and the inclusion of extra features (Table 6).

Table 6: *Summary of Errors in the PSVT-R Test*

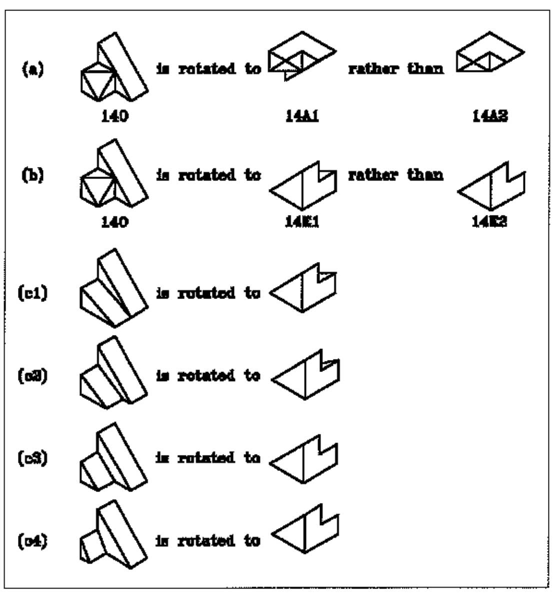
Item	Question Number	Drawing Number	Error
1	8 *	Example rotation	Missing features
2	10 *	Example rotation	Missing features
3	13	Example rotation	Missing features
4	13	A	Extra features
5	13	D	Missing features
6	14	A	Missing features
7	14	E	Missing features
8	15	C	Extra features
9	17	Example rotation	Missing features
10	25	B	Misrepresented feature

* Questions #8 and #10 share the same exemplary object and its rotations.

Question #14 of the PSVT-R test is also the question #17 in the original PSVT test (Guay, 1976), and included in a textbook (Bertoline & Wiebe, 2007. Figure 5.169, p.301, Question E in the part of visualization by rotations). Since question #14 of the PSVT-R test is readily available, it has been chosen as an example to show some details of the errors (Figure 6.1). In question #14 of the PSVT-R test, both the original isometric views of the choices A and E missed some features in the rear part of the views. As shown in Figure

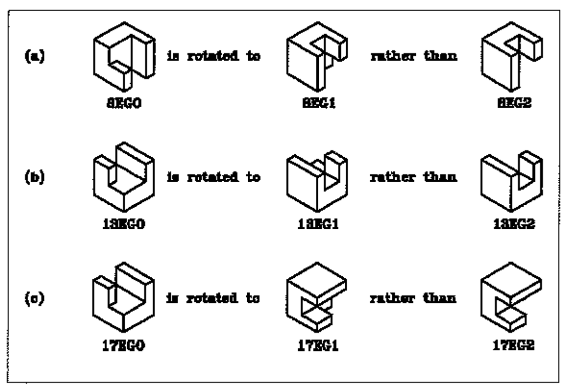
6.1, 14O is rotated to 14A2 and 14E2 in the test, as compared to the correct isometric views 14A1 and 14E1 respectively. Along a particular line of view and at a specific orientation, there is one and only one isometric view of an object, while an isometric view could be the result of different objects even along the same line of view and orientation. As shown in Figure 6.1a and Figure 6.1b, the given object can only be rotated to the correct isometric views 14A1 and 14E1. The erroneous view 14E2 could be the projections of various objects such as the examples shown in Figure 6.1c3 and Figure 6.1c4. The views c1 through c4 in Figure 6.1 show the effects of the change of angle or size of the small wedge to their rotated views. The widths of the wedge change from the full width W to 0.75W, 0.50W, and 0.25W (the views c1 through c4). Through the progressively larger change, we see that different objects can produce the same isometric views as shown in the views 14E1 and c1, and c3 and c4 in Figure 6.1.

Figure 6.1: *Errors in the question #14 of the PSVT-R test*



In the 30 problems of the PSVT-R test, each problem provides a rotation example. Students follow these exemplary rotations to visualize and select from multiple choices the view that has the same manner of rotations. Their errors are critical in that they are likely to lead to student selection of erroneous answer choices and therefore are worthy of discussion. There are two similar objects in the exemplary rotations (A and B in Figure 4.1.1 and Figure 4.1.2). Among the 30 exemplary rotations, 17 of them are object A and 13 are object B. Also among the total of 24 available bird's-eye isometric views for each object (Yue, 2004), 15 views are represented for object A and 12 views for object B. Some of the initial views and/or rotated views are used more than once (Figure 6.2b and 6.2c.) Among the thirty exemplary views, four of them have errors (two for each object), and the error rate is more than 13%. The errors for object A are in the problems #8 and #10 (they share the same exemplary object and rotations), and for object B are in the problems #13 and #17 (Figures 6.2a through 6.2c). In Figure 6.2, the views 8EG1, 13EG1, and 17EG1 are the correct views that should replace the incorrect views of 8EG2, 13EG2, and 17EG2 respectively as given in the PSVT-R test. All errors in exemplary rotations are missing features in the rear part.

Figure 6.2: *Errors in the exemplary rotations of the PSVT-R test*



CONCLUSION

Isometric views have been widely used in spatial visualization tests, especially those tests designed for engineering and technology students. Isometric views may be the simplest of all graphic representations or realistic views of 3D objects. They are usually easy to draw and visualize. However, due to the over simplification and lack of many 3D features in isometric views, they can sometimes also be confusing and prone to drawing errors. As examples, this paper discussed errors occurring in the isometric views of a widely used spatial visualization test, the Purdue Spatial Visualization Test – Visualization of Rotations (PSVT-R). In the total of 30 problems, 7 of them contain errors, an astonishing 23% error rate. These errors are mostly missing features and some are extra features or misrepresented features. Each of the test problems first provides an example of rotations of an object, then gives another object and asks the students to select a view from 5 multiple-choice answers, resulting from the same rotations as the example. Even 4 exemplary rotations have errors. The most erroneous problem contains 3 drawing errors, one in the exemplary view and two in the multiple-choice views. The PSVT-R test was designed in late 1970s and probably drawn by hand, without the precession of today's CAD hardware and software. The discussions of the errors in the PSVT-R test are only intended to show the cons of isometric view that it is prone to drawing errors. With modern computing technology and insights of spatial visualization, we should redesign the testing tools for spatial visualization in order to avoid confusion and better help students to improve their skills in spatial visualization. For example, many CAD software packages are capable of 3D solid modeling. We may avoid potential isometric drawing errors by first creating a 3D solid model and then obtaining its isometric view, rather than using the conventional method of constructing isometric views on a 2D plane with lines. 3D solid models can also provide more realistic views. Therefore, they should be applied in spatial visualization tests to improve the visual effects. Many features of realistic 3D views, such as color, lighting, shading, perspective effect, and surface textures, are also available through rendering solid models. Other supplemental effects, such as animation and audio-visual, may also be included using CAD and multimedia software.

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Platonic Symmetry and Geometric Thinking

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ABSTRACT

Cubic symmetry is used to build the other four Platonic solids and some formalism from classical geometry is introduced. Initially, the approach is via geometric construction, e.g., the ``golden ratio" is necessary to construct an icosahedron with pentagonal faces. Then conventional elementary vector algebra is used to extract quantitative relations among angles and length ratios pertaining to planes and lines as solid boundaries and the relations of these to planes and axes of symmetry. Simple but general and far-reaching notions of symmetry in analysis are mentioned.

INTRODUCTION

Symmetry is the central idea behind all branches of modern applied mathematics, especially engineering math. Its foundations spring from Euclid's Platonic solids. However discussion of these geometric objects, if it appears at all, is restricted, in modern texts on engineering design graphics, e.g., Bertoline & Wiebe (2005), to a brief description and their pictorial illustration. Sometimes a little analysis is included, e.g., Bohne & Klix (1995). In order to pursue the study of more advanced, even multidimensional, geometric notions of symmetry, these five classical polytopes constitute a useful starting point e.g., Coxeter (1973). The following discussion in this article is meant to serve as a reminder concerning the roots of solid modeling and the algebraic geometry upon which they are built.

THE CUBE MODEL

Imagine a cube in front elevation and label the front face near corners counterclockwise from lower left as ABCD. Respectively coincident on the far back face but viewed from the front are the corresponding corners EFGH. Consider the cube is origin centered on a Cartesian frame with edges AB, DC, HG, EF pointing in the positive x-direction, AE, DH, CG and BF pointing in the positive y-direction and AD, EH, FG and BC pointing in the positive z-direction. Furthermore these edges are taken to be 2 units in length. The familiar symmetries of the cube can be conveniently used to build the other four, possibly less familiar, Platonic solids and to analyze their symmetries. Furthermore, by using elementary linear algebra to extract quantitative invariant properties of these solids the student may learn how to use geometric thinking to gain understanding in many areas of engineering math that he or she is compelled to master. In what follows the Platonics will be constructed on the cube, mathematical duality will be introduced and, finally, a systematic procedure to find the angle between the edge of a regular tetrahedron and an axis from a vertex, common to that edge, to the center of the opposite face will be investigated and described.

BUILDING FOUR PLATONIC SOLIDS

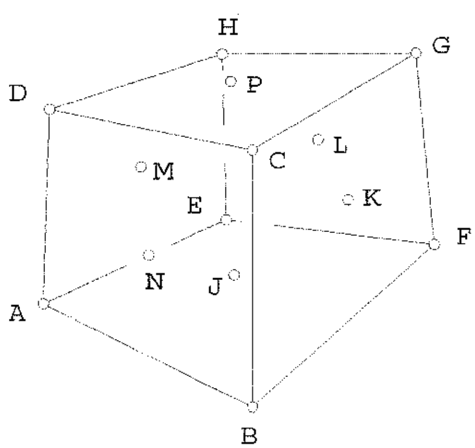
TETRAHEDRON

Referring to the cube model, take the face diagonals DG and BE whose ends form the four vertices. Join D and G to both B and E to complete all six edges and to define the four faces with vertex triplets in right-hand outward-pointing screw sequence BDE, BEG, BGD and DGE. This figure will be recalled later.

OCTAHEDRON

With the cube model in mind, choose points J,K,L,M,N,P each at the center of respective faces, designated in the same manner of outward screw circulation, ABFE, BFGC, EHGF, ADHE, ABCD and CGHD. Now form the twelve edge segments by connecting every one of these face centered points to neighbors on four adjacent faces. The cube with its eight vertices and six face centers, labeled as described above, appear in Fig1.

Figure 1: *Octahedron*



DUALITY AND SCHLÄFLI SYMBOLS

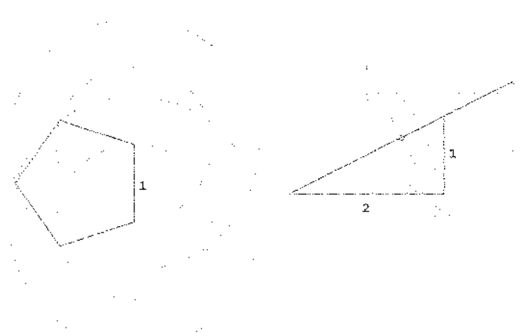
A cube has six faces (planes) and eight vertices (points) while octahedrons have eight faces (planes) and six vertices (points). These two are dual configurations because mathematically points and planes are dual elements in three dimensional space because any theorem stating some relation between points and planes is equally valid if the role of these elements is interchanged. No proof is necessary except to invoke the principle of duality. The octahedron and cube are designated by their respective Schläfli symbols as {4:3} and {3:4} where the first number states how many edges (lines) meet at a corner (point) and the second, how many edges (lines) bound a face (plane). Applying this to the tetrahedron, it is discovered to be self dual, i.e., {3:3}.

ICOSAHEDRON

An icosahedron has twelve faces. Its Schläfli symbol is {3:5} so its faces are regular pentagons. To construct one it is necessary to construct a pentagon. To do that side and diagonal lengths are needed. The ratio of side to diagonal length is known as the golden ratio, a number that has aesthetic properties and is found in nature and has been often used to select dimensional proportions in architectural and artistic design. If a length is chosen to be the length of a pentagon side one forms a triangle whose normal sides are, respectively, this length and twice this length. The hypotenuse is extended by this length and this augmented length is bisected. The golden ratio is the ratio of the pentagon side length to half the augmented length. The construction is shown in Fig.2. If the pentagon side is assigned unit length the ratio is given below.

$$\frac{1}{(\sqrt{5}+1)/2}$$

Figure 2: *Icosahedron*



Let twelve pentagons of side length and diagonal length 2 be placed to correspond to the twelve edges of the cube model and presto, the icosahedron is complete.

DODECAHEDRON

By placing a point at the center of each icosahedral face one may define the vertices of a dodecahedron. Each point is then joined with line segments to five neighboring points on pentagons adjacent to the face containing that point. This dualization is similar to the one used to transform a cube into an octahedron by interchanging the role of point and plane. The Schläfli symbol representing the dodecahedron with 20 faces is, of course, {5:3}.

ANGLE BETWEEN TETRAHEDRON EDGE AND "TENT-POLE"

The cube model is applied to stimulate a little "geometric thinking" and spatial visualization to find the angle between an edge of a regular tetrahedron and a line that extends, from a vertex that belongs to that edge, to the center of the opposite triangular base; a "tent-pole". This sort of problem is somewhat different than finding the angle between, say, adjacent face planes or between a pair of intersecting edges. Furthermore the intent will be to solve the problem with vectors in space rather than with a sequence of exercises in planar trigonometry. To this end, consider the so-called parametric equation of a line segment between two given points.

PARAMETRIC EQUATION OF A LINE

The position vector q locates a given point Q. Similarly, r locates R. Now any point S on that line, before Q, between Q and R or beyond Q can be located by s with a single scalar parameter t, using Eq. 1.

$$s = q + t\,(r-q)$$

This can be expanded to three simultaneous equations in Cartesian point coordinates.

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} + t\left(\begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix} - \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}\right)$$

This gives one an immediate "feel" for where S is located, relative to Q and R, at any specified value of t. If t = 0.5 then S is mid-way between Q and R. If t = -1, S is before Q by a distance equal to that between Q and R, and so on.

CUBE CORNERS AND FACE MIDPOINTS

It is not necessary to draw a picture to write the following Cartesian coordinates.

A(-1,-1,-1), B(1,-1,-1), C(1,-1,1), D(-1,-1,1), E(-1,1,-1), F(1,1,-1), G(1,1,1), H(-1,1,1), J(0,0,-1), K(1,0,0), L(0,1,0), M(-1,0,0), N(0,-1,0), P(0,0,1)

If these were written in column-wise triplets, between square brackets, they would be point position vectors. J and K will be used to get X the midpoint of the tetrahedron face BEG and thereby form the tent-pole DX and hence to obtain the required angle GDX with vertex D.

FACE MIDPOINT

Line segments GJ and EK, since they both bisect the face BEG, intersect on X. Since X is on both lines

$$x = g + g\,(j - g) = e + e\,(k - e)$$

which becomes

$$\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} + g\left(\begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} - \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} -1 \\ 1 \\ 1 \end{bmatrix} + e\left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} -1 \\ 1 \\ -1 \end{bmatrix}\right)$$

or

$$\begin{bmatrix}2\\0\\2\end{bmatrix}+g\begin{bmatrix}-1\\-1\\-2\end{bmatrix}+e\begin{bmatrix}-2\\1\\-1\end{bmatrix}=\begin{bmatrix}0\\0\\0\end{bmatrix}$$

Regardless that all point position and difference vectors are spatial, this line intersection problem is planar, hence there are only two unknown parameters, g and e, and only two of the three simultaneous equations, represented in Eq. 2 are required.

Choosing the first two

$$2-g-2e=0$$

$$-g+e=0$$

The result g = e = 2/3 is obtained. Of course, this satisfies the third simultaneous equation 2-2g-e=0 and one can proceed to find x on line segment GJ with Eq.2.

$$\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}=\begin{bmatrix}1\\1\\1\end{bmatrix}+\frac{2}{3}\begin{bmatrix}-1\\-1\\-2\end{bmatrix}=\begin{bmatrix}1/3\\1/3\\-1/3\end{bmatrix}$$

ANGLE COSINE VIA INNER PRODUCT OF UNIT VECTORS

Consider vectors g – d and x – d along DG and DX, respectively, divided by their magnitudes

$$\|g-d\|=\sqrt{(g_1-d_1)^2+(g_2-d_2)^2+(g_3-d_3)^2}$$

,

$$\|x-d\|=\sqrt{(x_1-d_1)^2+(x_2-d_2)^2+(x_3-d_3)^2}$$

to obtain the unit vectors uDG and uDX.

$$g-d=\begin{bmatrix}1\\1\\1\end{bmatrix}-\begin{bmatrix}-1\\-1\\-1\end{bmatrix}=\begin{bmatrix}2\\2\\0\end{bmatrix},\|g-d\|=2\sqrt{2}$$

$$x-d=\begin{bmatrix}1/3\\1/3\\-1/3\end{bmatrix}-\begin{bmatrix}-1\\-1\\1\end{bmatrix}=\begin{bmatrix}4/3\\4/3\\-4/3\end{bmatrix},\|x-d\|=\frac{4}{\sqrt{3}}$$

$$u_{DG}=\begin{bmatrix}1/\sqrt{2}\\1/\sqrt{2}\\0\end{bmatrix},u_{DX}=\begin{bmatrix}1/\sqrt{3}\\1/\sqrt{3}\\-1/\sqrt{3}\end{bmatrix}$$

The angle ϕ desired is given by Eq.3.

$$\phi=\cos^{-1}(u_{DG}\cdot u_{DX})$$

so ϕ is about 35.26°

CONCLUSION

"Geometric thinking" was used to visualize the familiar cube and label its features in order to discuss symmetry in terms of the five Platonic solids. The tetrahedron and octahedron were immediately derived from the cube using these features. Constructing the icosahedron required the construction of a regular pentagon and this led to the introduction of the golden ratio. The fifth Platonic, the dodecahedron was then formed as the dual of the icosahedron. Symmetries of polytopes were discussed in terms of Schläfli symbol notation. An exercise to find the angle between an edge of a tetrahedron and its intersecting axis of symmetry was performed to show how three dimensional visualization is used to formulate vector algebra problems. This provided opportunity to introduce the parametric equation of a line in space and to relate any point on it to two points that were used to define that line.

OBSERVATIONS

Engineering design graphics is about more than just learning to use various popular CAD softwares to help students, by being "industry-user-ready," to find summer employment or a first job after graduation. Notwithstanding that students generally enjoy the CAD learning experience and those, talented with spatial visualization ability, quickly develop impressive CAD drafting skill, it is our primary job to enhance inherent ability by augmenting it with tools that the student is unlikely to acquire unaided. Furthermore "geometric thinking" is more than an aid to interpreting and creating intricate aesthetic and useful shape. It is a means by which mathematics may be learned and applied more fully. It gives life and intuitive meaning, --dare one say beauty?-- to ugly things like basis sets, null spaces and eigenvectors, via notions like symmetry and duality, not necessarily among the restricted set of Platonic solids, between points and planes and between a line on a plane pair and a line on a point pair.

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CONFERENCES

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