Using Design to Teach Freshman Engineering

Nicole C. DeJong, Ph.D., Kenneth W. Van Treuren, Ph.D.,
Donald R. Farris, Ph.D., Cynthia C. Fry, M.S.
Baylor University

Abstract

Most freshmen enter the university with a limited understanding of what engineering is and what engineers do. Baylor University's first-semester freshman Introduction to Engineering course informs the students about the engineering profession and equips them with some of the basic skills and tools necessary for success. These skills include technical drawing, use of spreadsheets, and data collection and analysis. The students ultimately develop their confidence in problem solving and design skills using a balsa wood bridge design project. The skills, tools, and techniques developed during the semester in class and in laboratories are applied to the design and construction of the bridge. Students, operating in teams of three to five, also learn to work with their peers. The teams are given a Request for Proposals (RFP) and allowed to exercise creativity within the scope of the RFP. Students progress through the design process (concept, preliminary, and final phases) using both written and oral communication. The final grade of the design process is based on their prototype and on written and oral presentations. At the conclusion of the semester, the teams test their bridges to destruction to determine which bridge holds the maximum load. A student peer assessment of the project is used and feedback is given to each student. The design project reinforces skills taught in the classroom and labs and motivates the students to pursue engineering as a career.

Overview

The Introduction to Engineering course offered at Baylor University is intended to provide an overview of the profession of engineering, the engineering educational experience, and the engineering program at Baylor University. It also provides students with some skills and tools needed as they progress through the program. The course seeks to accomplish these purposes through discussions, demonstrations, laboratory activities, interaction between faculty and students, engineering problem solving, and the use of engineering analysis and design techniques. The objectives of the course are

- To provide career guidance and motivation for new engineering students
- To build a sense of community among engineering students and faculty
- To provide students with experience in engineering problem solving
- To develop some basic analytical and design skills needed by engineers, and
- To introduce Computer Aided Design (CAD)

The design project reinforces many of the topics in the course. Its completion is the culmination of the semester's work, and it is a first introduction to the engineering design process, as well as to team building, project planning and scheduling, and presentation. Details on the course curriculum and syllabus are available on the internet and can be accessed at any time by the students. This paper will discuss in detail the freshman engineering design project, which accounts for one-fourth of the total grade for this course, and the way in which it reinforces the other course activities and contributes to the course objectives.

Request for Proposal

Approximately a fourth of the way through the semester, the freshmen are divided into three- to five-member design-build teams. Students interested in functioning as team leaders e-mail their instructors with their qualifications. If an insufficient number of students volunteer, team leaders are chosen based on previous performance and leadership in class. Team leaders attend a special meeting in which such topics as team building, motivation of one’s peers, and scheduling are discussed. Each team acts as a company, developing its own name and logo. Teams are grouped by class ranking to place people of relatively equal ability in each team. In that way, poor students have less of a chance to “coast” by letting the good students in the group complete their portion of the work.

The teams are given a Request For Proposals (RFP) for a balsa wood truss structure along with an overview of the project. The RFP covers the scope of the project, the system description, design directives, a listing of owner-supplied materials, a detailed discussion of the required submittals, the judging procedures, and a list of the points of contact (for questions, comments, clarification). The teams are required to submit a proposed design to the Department of Engineering, also known as the “Owner.” A prototype structure is constructed by the design teams and subsequently tested to destruction by the owner. The goal of the project is to build a bridge that supports the greatest load, as tested by the owner.

The balsa wood structure must span a gap of 15.25 inches between two wooden support blocks (see Figure 1). The support blocks have dimensions of 3” x 9”. Prior to loading, no portion of the structure may lie below the horizontal plane containing the top surface of the support blocks. The structure accepts a dead weight load on its top at its midspan. The load is suspended beneath the structure by a rod (less than 3/8” diameter) that must pass vertically upward through the center of the structure and attaches to an owner-furnished 3” x 9” wooden bearing block. The bearing block is positioned by the design team. Design teams must incorporate in their bridge designs a structure to accept the bearing block.

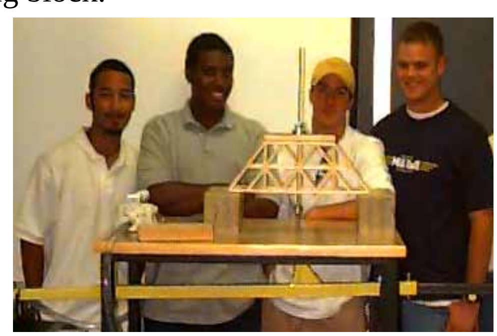

Figure 1: Bridge testing Spring 1999

The prototype structures are constructed from owner-furnished balsa wood and glue. Other construction materials are not permitted. Materials such as straight pins, binder clips, paper clips, and tape may be used as aids to construction but must be removed from the prototype structure prior to submittal to the owner. Failure to comply with these first two requirements results in the immediate disqualification of the design team from the testing phase of this project. The balsa wood sheet is 1/8" x 4" x 36". This sheet must be cut into strips of 1/8" x 1/2" x 18". These strips may then be further cut as desired. It is not required that all of the specified material be used in the construction of the prototype structure.

The following material is supplied to each design team by the owner:

- Balsa Wood, 1 sheet (1/8” x 4” x 36”)
- Superglue, ¼ ounce
- Hobby Knife
- 18” Straight Edge
- Cutting Board

As part of the requirements for this design project, the design teams are required to submit four deliverable items: a conceptual design submittal (along with a presentation of each concept to the entire class), a preliminary design submittal, a final design submittal, and a prototype structure. The details of each of these submittals will be discussed in later sections.

Several procedures are used to judge the balsa wood structure designs. First, entries are judged on construction practices, aesthetics, and conformance to final design drawings. Second, the owner tests each prototype structure to destruction to determine the load capacity in pounds. These tests take place during the last week of classes for the semester and are open to the public. Team members are expected to be present for the testing of their designs. Pictures from past destructive tests can be found on the world-wide web[1].

Conceptual Design

High school graduates entering the university as freshmen engineering students have some experience with analytical tools and techniques. They are accustomed to “solving” problems that yield a single answer. Their work is generally judged to be either right or wrong, depending on comparison with that right answer. As they progress through an engineering curriculum, they learn that the problems they are asked to solve are different. While there will certainly be many instances of determining the single right answer, the larger problems – the design problems – do not have a single right answer. They are of an open-ended nature, allowing many possible solutions, and those solutions vary in quality and desirability. Perhaps the first place they encounter these open-ended problems is in the conceptual design phase of the balsa wood bridge design project.

The design process model and the relationship it has with the elements of the freshman-engineering course are shown in Figure 2. After the Statement of Need and Specifications have been discussed in class and presented in the RFP, the students begin the conceptual design phase.

The task given them is to create and analyze several potential bridge designs that meet the requirements outlined in the RFP.

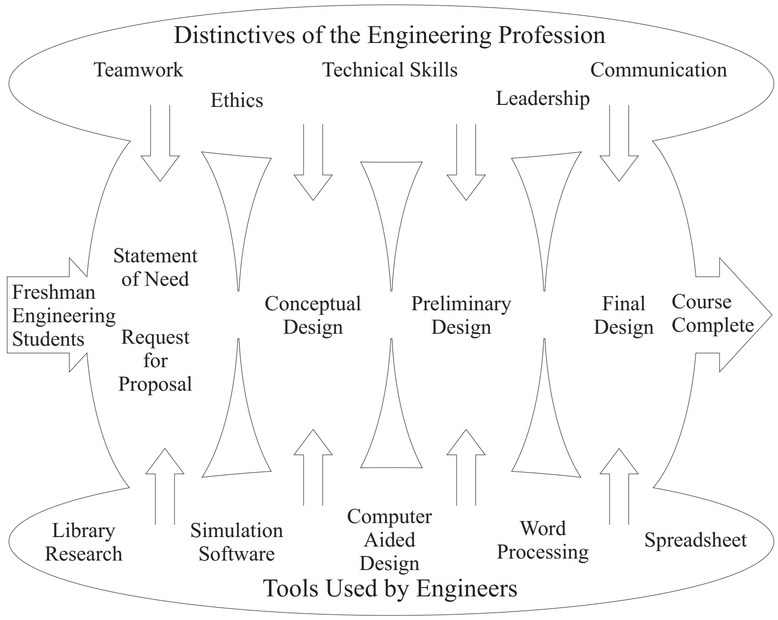

Figure 2: The design process model

The design teams of three to five people prepare the potential designs. To facilitate their bridge design creation, several tools and resources are made available. Where needed, instruction on their use is also provided. The primary tools and resources and their use throughout the semester are described below.

At the beginning of the year a survey determining the skills and tools the students bring to the course is performed. They are asked to evaluate their ability in these skills on a 1 to 5 scale with a 5 corresponding to an expert and 1 corresponding to little experience. This Beginning of Course (BOC) survey shows the students enter the course with a wide variety of skills and a varied experience level in those skills. One aim of the course is to have students achieve an acceptable level of ability in each of these areas. Approximately 87% of the 68 students in the course in the fall of 1999 indicated they had word processing experience with a 4 rating for their ability. In addition to design project submittals, the students use word processing for two laboratories and some homework assignments. Usually, the students divide the task of writing various report sections for the design submittals, and the team leader is then responsible for integrating the report. The quality of the report is generally a reflection of the team's planning. Teams that allow themselves adequate time to finish the report generally do a good job. Some teams are busy trying to compile the report minutes before it is to be turned in. These teams generally do not have a coherent report. Teams are encouraged to have several team members read reports for content and clarity prior to submission.

The ability of our students to use a CAD tool varies greatly as they enter the course. The BOC student survey indicated that 24% of the students had some CAD experience in the fall of 1999. The average experience level was 1. In addition, 31% of the students had experience with drafting, but again, the experience level was 1. Three CAD laboratories are accomplished early in the course. In the first laboratory the students learn how to use the CAD program and basic presentation format by preparing a simple drawing. In the next laboratory, the students prepare a multi-view drawing, again using a simple geometry. The last laboratory requires drawing a more complex object, and proper dimensioning is emphasized. These CAD laboratories, reinforced with classroom lectures, stress the basics of drawing, orthographic projection, isometric projection, and dimensioning.

The use of spreadsheets is taught in three laboratories and used in several homework assignments as well as in the design project. The BOC survey indicated that 53% of the students had previous experience with spreadsheets, and the ability level was evenly split among all five categories. The first spreadsheet laboratory has an electrical engineering emphasis and looks at circuit state variables over time. Students perform simple calculations and graph their results. The next laboratory emphasizes the presentation and format of engineering results. The vehicle for this laboratory is a linear regression analysis with matrix mathematics. The last lab is an analysis of pressure data taken on a cylinder in a wind tunnel. The students use numerical integration to determine the drag of the cylinder. Format for the submission of this lab is not specified, and the students apply what they learned from the previous two laboratories.

The students are also introduced to technical research. They are encouraged to use the university library, examine textbooks on statics and bridge design, discuss their ideas with professors, and browse the internet. Ways to determine the reliability of internet sources are presented. To encourage use of the library, one of the engineering librarians is invited to present the library's resources to the class.

The students gain simulation experience through an elementary truss analysis program. The program allows a quick graphical means of preparing a model, and it simulates loading to failure. It then offers some elementary analysis results that display the location of the failure and the total load borne by the bridge. The design teams use the truss analysis program to perform some elementary optimization of their bridge designs.

The design teams have about two weeks to prepare their conceptual designs in response to the RFP. Each team member is responsible for one design that is substantially different from those of the other team members. At the conclusion of the conceptual design phase, each team makes a four-minute presentation of their designs to the entire class. This presentation not only encourages the students to think thoroughly through their designs, but it also provides an opportunity to gain experience speaking before an audience. In addition to the oral presentations, each team presents a written package that contains

- A summary of their research that applies to the project
- A narrative describing each design
- Single-line orthographic drawings of each design
- A tabulation of the amount of wood required for the design
- An organizational structure describing the duties of each team member
- A timeline showing scheduled meetings and deadlines for the entire project

With the conceptual design phase completed, the student design teams move on to the preliminary design phase.

Preliminary Design

The preliminary design phase of the project requires the students to select one design from among their conceptual designs or some combination of their conceptual designs and to optimize that design. No major design changes are allowed following the preliminary design phase. Included in the preliminary design submittal are the following:

- A narrative describing their method of selection
- A tally sheet to aid in their design selection
- A one-half size three-view drawing with dimensions of their selected design
- A spreadsheet containing a piece-by-piece listing of the wood used and a comparison with the total amount available

The choice of design is the most important aspect of this phase. Class time is spent discussing design trade-offs in real engineering applications, such as the trade-offs between allowable design time and the quality and cost of the product. The students, with guidance from the faculty, discuss the types of factors that should influence the choice of design. Examples include functionality, economic factors, spatial compatibility, safety, and reliability. The effects of ethical considerations on design are also presented. The faculty moderate class discussions of National Society of Professional Engineers ethical case studies and disaster case studies (such as the Challenger and Chernobyl accidents) in which engineers were required to determine a course of action – whether in design or in other situations – while in the midst of an ethical dilemma.

After lectures and discussions concerning factors influencing design choices, the students apply their new knowledge to their bridge designs. The first step is for them to determine what criteria are important in their design selection, and the second is to determine weighting factors for each criterion. Each criterion is weighted to carry a certain percentage of the decision. The weighting factors for the criteria must add up to 100%. Typical selection criteria include load capacity, ease of construction, and material allocation. The goal of the project is to build the bridge that holds the greatest load, and thus load capacity typically has the highest weighting factor. The students have a limited amount of time to build their bridges, and their prototypes must match their drawings. Therefore, ease of construction is a typical choice for the second-highest weighting factor. Finally, the students build their bridges out of a 36"x4"x1/8" piece of plywood and ¼ ounce of glue. Preliminary bridge designs that use somewhat less than the maximum amount of wood and glue are desirable because the excess can then be used to strengthen weak portions of their design discovered during testing of their prototypes. This factor typically receives a smaller weighting factor than load capacity and ease of construction.

Once selection criteria and weighting factors have been chosen, the students develop tally sheets. A typical tally sheet is shown in Figure 3. Students rank each bridge in each category from one to ten based on some qualitative measure. In this example, the best bridge in each category has been given a 10, and the other bridges are scored in comparison with that standard. Each score is multiplied by its weighting factor, resulting in a certain number of points. The points for each category for each bridge are summed, and the bridge receiving the highest total number of points is chosen. While other, more complicated decision-making methods are shown to the students, the tally sheet works well for these simple designs and illustrates the desired concepts. With the tally sheets, the students are required to write a narrative explaining their decision-making process – how they chose their criteria, weighting factors, and scores. While all of the groups typically are able to develop appropriate tally sheets, the narratives show a wide range of reasoning abilities. Some groups are unable to clearly explain the logic behind their choice of scores for each bridge and do not clearly explain the reasons for their choice of selection criteria. However, with feedback from the professors, the narratives accompanying each submittal typically improve by the time the final design submittal has been reached. Not only does this exercise teach the students how to logically make a decision based on many factors, it also teaches the students how to clearly and logically communicate and defend their engineering decisions.

Selection Criteria	Weighting Factor (%)	Design 1	Design 2	Design 3	
load capacity	60	10	6	5	score
		600	360	300	points
ease of construction	25	2	6	10	score
		50	150	250	points
material allocation	15	3	7	10	score
		45	105	150	points
Total Points		695	615	700	

Rating Scale	
Best	10
Very Good	7-9
Acceptable	4-6
Poor	1-3

Figure 3: An example of a tally sheet

Either in the preliminary or final design phase, each group builds a prototype and tests it. The students then optimize their designs by strengthening the members or joints that failed. The students must design their own testing apparatus for this first test. Many load the top with textbooks or suspend a garbage can underneath the bridge and then slowly fill it with water.

The next important component of preliminary design is a one-half size three-view drawing of the selected design. This drawing applies the drawing and dimensioning skills the students learned in class and in the CAD drawing labs. In addition, throughout the semester, as the students make the transition from high school to university, the faculty teach the students to pay close attention to detail. These complicated drawings contribute to this process.

The final segment of the preliminary design is a piece-by-piece listing of the wood used in the design and a comparison of the wood used in their designs with the maximum allowed. In this presentation they apply the knowledge of spreadsheets that they gained in three labs. It also leads them to examine if they are making efficient use of available materials.

Final Design

The final design phase is an opportunity for the design teams to prepare formal final design submittal packages using all of the computer resources available. At this point in the process the design of the bridge is basically fixed (only small changes are allowed), and the students are documenting the process used to develop the bridge. Elements of the previous conceptual and preliminary design submittals are incorporated into the final submittal, so the report tells the "story" of the bridge design from beginning to end. The report is not just a step-by-step description but includes the results of research, how the team functioned and how team building was addressed. A justification for the final design is also presented. The final design submittal "wraps up" the project and has the students reflect on what they learned during the project.

Included in the final submittal are

- Executive summary of the design – summary of the design process including research, team-building, the decision-making process at each stage of the design, and the features of the final design
- Fully dimensioned three-view orthographic CAD drawing of the final balsa wood structure
- Isometric drawing of the structure
- Full scale drawing of the front of the structure for comparison with the model
- Bill of Materials using a spreadsheet accounting for wood and glue
- Estimate of man-hours for construction of the structure using a spreadsheet
- Estimate of load capacity using the truss analysis software and actual testing
- An appendix that includes the conceptual and preliminary design submittals

The executive summary is the heart of the report. Emphasis is on the analysis and justification of their design. A good design is of no use without successful communication of the idea. The executive summary must be professionally developed using a word processor.

The three drawings are done using CAD. The requirement for CAD drawing in the project has an impact on the bridge design. Teams that look ahead to the CAD requirement simplify their designs because they realize they will have to reproduce the designs on paper. Teams with more complex designs have difficulty accomplishing this portion of the design. The full-size front view drawing is an aid for the instructor to determine if the drawing of the bridge matches the dimensions of the actual bridge. Students turn in the actual structure along with the final design report, and they are graded on both construction and the degree to which the structure conforms to the drawings.

The Bill of Materials and man-hours estimate are accomplished using spreadsheets. The students are not given a specified format for either of these two areas in the final design project other than the requirement to present the results in a complete and professional manner. Teams with more complex designs have difficulty clearly accounting for the amount of wood used. The number of man-hours is presented in a tabular format. A conscious effort has been made to teach spreadsheets in this freshman course because of the students' limited computer experience and the wide availability of spreadsheets. Other courses in the engineering program frequently require mathematics-type programs.

The load capacity estimate is based on two items. First, the students are encouraged to build a prototype and test it to destruction. Based on the prototype, small final changes can be made and incorporated into the final design. They are encouraged to also use the truss analysis software to make a prediction of load capacity. Since the software assumes balsa wood members that are smaller than those the students use, it will not exactly model the structure. However, it still gives a helpful indication of the load carrying capability. This number is used for comparison with the actual load the bridge carries.

The conceptual and preliminary design submittals are attached to the final design submittal as appendices. The final submittal is archived. This keeps the project from being widely circulated for the next semester. It also allows the students to make references to their previous reports in the final report. Turning previous submittals in with the final also allows the instructor to determine if suggestions on previous reports have been incorporated in the final report.

Assessment

Several methods of assessment are used in conjunction with the final design project. As previously stated, the BOC survey provides the instructors with an indication of ability level in the different skills and tools needed for the project. Instructors use this information as a gauge when teaching the skills and tools in the course. Traditional grading of labs, exams, and homework provide feedback on the students' progress towards learning the skills and tools throughout the course. Since the course is team-taught, the instructors discuss grading policies extensively to ensure that each instructor applies the same standard across the course. The design project is worth 25% of the final grade for the course. The breakdown of the grades for the project is as follows:

- Conceptual Design – 15%
- Conceptual Design Presentation – 5%
- Preliminary Design – 15%
- Final Design – 35%
- Team Participation – 10%
- Prototype Structure – 20%

Conceptual design is evaluated on content, including such items as a timeline for project completion, organizational structure, research on bridge design, drawings, and descriptions of the designs. Approximately 15% of this grade is for communication and grammar. The truss analysis software is available during this phase of the project to help compare conceptual designs.

Each team's conceptual design presentation is limited to four minutes and is done in class. It presents the team's conceptual designs and the conclusions from these designs. The students are given training in PowerPoint and presentation methods. Only 63% of the students indicated they were familiar with PowerPoint at the beginning of class and then only at Level 1. Because of the limited presentation time, students have to plan their time and rehearse their presentations. The time period is strictly enforced, and when it expires they are asked to stop. In Fall 1999, all but two groups out of seventeen finished at or before the time limit. The student teams are evaluated in three categories: visual aids, organization, and oral communication. A total score is compiled and the teams ranked. Student teams are required to evaluate each of the other presentations under the same categories. Each team discusses each presentation and decides on scores as a team. Surprisingly, the student teams' average for all the presentations was only 4.5% different from the instructors' average for all the presentations in Fall 1999. The three instructors had approximately a 50% greater standard deviation in the scores, indicating the instructors were more discriminating. The instructors and the students did not entirely agree on the rankings of the team. In all, this is a good experience for students to improve their presentation skills and for student teams to evaluate each other.

Preliminary design emphasizes two main areas -- the narrative and the drawings -- totaling 65% of the grade for this portion of the project. The narrative is a description of the process used to reduce the conceptual designs to one design. This process involves setting evaluation criteria, weighting the criteria, and using a tally sheet to determine the outcome. Some calculations are made for wood usage. Grammar and communication accounts for 10% of the grade, and the remaining 25% accounts for the tally sheet and presentation of wood used.

Final design has a stronger emphasis on professional presentation and quality. Communication and grammar have a slightly higher percentage of the final score (15%). Since drawing is a large requirement, it also has a heavy emphasis on the grade (50%). More in-class work sessions are given for this part of the project.

Team participation is evaluated by a peer review of contributions to the project accomplished by each team. Motivation of peers is a difficult task for the team leaders. Each individual group member is asked to rank the contributions of the other members of the group in the following areas using a five-point scale:

- Engineering Judgment
- Contribution to Project Effort
- Contribution to Project Quality
- Leadership Contribution
- Performance Under Stress
- Oral Communication Skills
- Written Communication Skills
- Professional Attitude
- Human Relations

Space is allocated for comments to the team member. These comments are compiled and given anonymously to the individual. An additional space is provided for comments only the instructor will see. Each student is given 100 points to distribute among the other team members to indicate their relative levels of contribution. This information, along with instructor observation, determines the team participation score. Since team participation accounts for ten percent of the final project grade, grades of team members may vary by as much as a full letter grade.

Finally, 20% of the project grade is determined by the actual construction of the test structure and how well it matches the full-scale drawing.

Summary

The heart of engineering is the ability to solve problems using an organized design process. There is no better time to present this to prospective engineering students than in the Introduction to Engineering course taught at Baylor University. The course is highly successful in accomplishing its objectives, and this is due in a large part to the challenging but fun design project. The course, with the introduction to the design process and design teams (and the dynamics involved therein) as well as the construction of a prototype, gives the students a balanced first view of the engineering profession and an encouragement to pursue engineering as a career.

Bibliography

1. URL: http://ecswww.baylor.edu/faculty/fry/EGR1301.S98/BridgePicts.html, http://ecswww.baylor.edu/faculty/fry/EGR1301.F98/BridgePicts.html

NICOLE DEJONG
Nicole DeJong is an Assistant Professor in the Department of Engineering at Baylor University. She received her B.S. in Engineering from Calvin College in Grand Rapids, Michigan and her M.S. and Ph.D. in Mechanical Engineering from University of Illinois at Urbana-Champaign. She teaches courses in the areas of heat transfer and thermodynamics as well as freshman engineering, and her research area is experimental convective heat transfer.

KEN VAN TREUREN
Ken Van Treuren is an Associate Professor in the Department of Engineering at Baylor University. He received his B. S. in Aeronautical Engineering from the USAF Academy and his M. S. in Engineering from Princeton University. After serving as USAF pilot, he completed his DPhil in Engineering Sciences at the University of Oxford, UK, and returned to the USAF Academy to teach heat transfer and propulsion systems. At Baylor he teaches courses in laboratory techniques, fluid mechanics, energy systems, and propulsion systems, as well as freshman engineering. His research interests include experimental convective heat transfer.

DON FARRIS
Donald R. Farris is a Professor in the Department of Engineering at Baylor University. He received his B.S. in Electrical Engineering from Texas Tech University and his M.S. and Ph.D. in Electrical Engineering from Southern Methodist University and is a registered Professional Engineer in Texas. His industrial/research experience includes work at Los Alamos National Laboratory and General Dynamics (now Lockheed). In addition to the freshman engineering class, he teaches courses in electrical circuits and networks, communications systems, and automatic control.

CINDY FRY
Cynthia C. Fry is a Lecturer in the Department of Computer Science and the Department of Engineering at Baylor University. She received her B.S. in Industrial Engineering from Texas A&M University in College Station, Texas. While working for NASA's Marshall Space Flight Center in Huntsville, Alabama, she earned her M.S. in Systems Engineering from the University of Alabama in Huntsville. In addition to teaching engineering and computer science classes, she is the owner of Systems Engineering Services, a computer systems software consultation firm.