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Sophomore Engineering Design: Back to the Future*

JEFFREY S. BURMEISTER[1], TIMOTHY FOUTZ[2] AND SIDNEY THOMPSON[2]
[1] *School of Engineering and Computer Science, University of the Pacific, Stockton, CA 95211, USA. Email: jburmeister@pacific.edu*
[2] *Biological and Agricultural Engineering Department, The University of Georgia, Athens, GA 30602, USA.*

Design is a critical component of any engineering curriculum. It is possible to integrate a sophomore engineering design course focused on the theory of design and its application with the curriculum found in an elementary (K–5) school. The primary objective was to design science demonstrations for local elementary schools as part of a sophomore design course at The University of Georgia. This joint venture proves to be valuable for both sophomore engineers and elementary science students.

Keywords: Engineering; design; sophomore engineering design; elementary school science projects; K–5 design; customers; constraints

INTRODUCTION

DESIGN IS A CRITICAL TOPIC in any engineering curriculum, and the application of design is a critical skill needed by graduates entering the engineering profession. A literature search provides numerous writings dedicated to the subject of design. Some of which report: the thought processes used by students during the design process [1]; methods to facilitate interdisciplinary design education [2, 3]; student-design team dynamic [4, 5]; and tools for assessing the student's skills in design [6, 7]. These efforts typically are direct responses to ABET's [Accreditation Board of Technology] mandate that an accredited engineering programme must incorporate one and one-half years of open-ended design experiences in the curriculum and that [this] design experience must be found throughout the curriculum and must culminate in a major project that

- requires the knowledge and skills acquired in earlier course work and
- incorporates engineering standards and realistic constraints that include the following considerations: economics, environmental, sustainability, manufacturability, ethical, health and safety, social and political.

Design is also a critical topic to the technology curricula found in the USA K–12 education system. The design process is used to develop students' problem solving skills, to demonstrate the iterative processes needed in critical thinking, and to incorporate technology-based topics into the K–12 education system [8, 9, 1, 10, 11]. The State of Georgia Department of Education Academic Standards for Technology Education now mandates that by the end of the fifth grade, students will

1. define and discuss technological literacy;
2. define technology;
3. describe the difference between invention and innovation;
4. investigate the concepts of technological resources;
5. describe the impacts of technology on careers.

In this mandate, technology is defined as 'An ability to cut, shape or put together materials to change the world to suit us better'. However, a review of the specifics of these Performance Standards show that Science, Technology and Mathematics (STM) are taught as distinct topics with little crossover of any STM topic with other topics such as social science. In contrast, the Performance Standard for Economics and for Social Science was well integrated. Studies [12, 13, 14] indicate that the lack of this integration is not meeting the needs of today's society and industry. Gorham [15] presents an argument that ABET's criteria for design matches perfectly with the State of Georgia's mandate for technology education and can be used by teachers to integrate topics in their curricula. Gorham outlines how engineering educators should become involved in technology education and the preparation of science teachers in the understanding of design.

Thus there are certain requirements pertaining to the integration of a sophomore engineering design course focused on the theory of design and its application with the curriculum found in an elementary (K–5) school. Specifics relate to

a) selecting projects;
b) selecting design teams;
c) using elementary school students and faculty as customers.

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And ultimately how well this joint venture worked for providing hands-on experiences for both the college and elementary student.

BACKGROUND

At The University of Georgia, design theory and methodology are taught in a sophomore core curriculum course. Lectures focus on the principles behind axiomatic design [16] as well as approaches to customer-driven design. Course requirements such as design analysis, product fabrication, prototype testing are based on a background expected of a sophomore. Since the structure of the University's engineering programmes allow students to wait until their junior year before declaring an engineering area of emphasis, the enrolled sophomores have interest in biomedical, biochemical, structural, environmental, mechanical, electrical, computer systems and agricultural engineering applications. This diverse group of engineering students allows for the formation of cross-disciplinary design teams. However, this course has consistently challenged the instructors in locating projects that:

1. are challenging but not overly difficult for undergraduates with such a diverse engineering interest and background:
2. have enough customers for the diverse set of projects needed.

The course learning objectives of the Design Methodology course are to develop the student's fundamental knowledge of methodical approaches to solving open-ended problems:

- understanding and appreciation of the iterative nature of design;
- appreciation of customer-driven design;
- critical thinking skills;
- ability to formulate and logically evaluate conceptual solutions;
- fundamental understanding of the application of the mathematical, natural and engineering sciences for transforming conceptual solutions into real solutions;
- knowledge of techniques used to verify engineering solutions and their results;
- ability to document engineering activities;
- ability to communicate and explain engineering activities;
- ability to locate and use information not found in the curriculum.

The underlying philosophy of this course is to expose the undergraduate to real-world problems where solutions are open-ended and do not have a single correct answer. Students must interview and work directly with customers who test a prototype of the developed solution. Students also must work directly with a machinist who will fabricate the prototype. In-the-classroom assignments are used to create a learning environment that allows the students to compare and contrast their solutions with those of other students. An outline of the course lectures are given in Table 1.

To show that they understand the design process, the specific activities they must successfully complete are

- Understanding the problem which involves the transformation of the often nebulous facts and needs expressed in by a statement of work into a coherent problem definition or 'what is needed'.
- Generation of concepts which involves the creative process that transforms the defined problem or 'what is needed' into conceptual solutions or a proposal of 'how to solve the need'.
- Analysis and optimization which takes the conceptual solution and refines it in a detailed solution; an activity may result in the need to review the previous two activities.
- Construction which involves the preparation of accurate engineering drawings and the transformation of the detailed solution into an actual product.
- Testing which involves checking the solution to

Table 1. Outline of lectures in ENGR 2920 Design Methodology

1. Definition of design	9. Managing information to learn interactions of constraints and functional requirements
2. Types of design	10. Functional Decomposition
3. The human element in design	11. Conceptual Design
4. Team management and collaboration	a. Use of Functional Decomposition
5. ISO 9001 and 14001	b. Brain Storming for functions
6. Engineering Documentation	12. Concept Evaluation
7. Project Scheduling	a. Feasibility Analysis
8. Problem Identification verse Problem Definition	b. Technology Readiness
a. Who are stakeholders	c. Go-No Go
b. What are the scientific principles related to the problem	d. Decision Matrix
c. Problem Definition	13. Use of ISO process
d. Stakeholder Definitions	14. Optimization
e. Benchmarking	15. Science, Engineering Analysis and Calculations
f. Engineering Definitions	16. Concurrent Design
i. Constraints	17. Final Solution Evaluation
ii. Functional Requirements	18. Production
	19. Liability, standards, ethics

the original problem definition confirming assumptions made during analysis/optimization activity and identifying problems related to use and production, and an activity involving computational simulation, prototyping and field testing.
- Implementation which relates to the construction of the solution and eventually the release of the solution for the benefit of society.

A suitable partner was identified which satisfied the need for diverse design projects, provided a real customer base, as well as opportunities for prototype testing. This partner was Barrow Elementary School, Clarke County School District, Georgia, one of 13 elementary schools in this district with a student enrolment of approximately 420. Barrow offers curricula from kindergarten to fifth grade, has a pre-K programme, is staffed with 29 faculty members (teachers and administrators), and is accredited by both the Southern Association of Colleges and Schools (SACS) and the Georgia Accrediting Commission (GAC). This school is conveniently adjacent to The University of Georgia and thus is easily visited by engineering undergraduates. The Barrow Science Coordinator was the 2001 Georgia Regional Science Teacher of the Year and the K–5 science curriculum covers the topics specified by The State of Georgia Performance Standards. These topics and learning objectives are:

- Earth and the Universe
  Learning Objective: students should develop an inventory of the variety of things in the universe and learn about the relationship of earth to the universe.
- Structure of matter
  Learning Objective: students should design and build objects that require different properties of materials and should be able to measure those properties (such as the conduction of heat).
- Motion and forces
  Learning Objective: students should understand periodic motion, force-motion relationships, the relationship between vibration and materials and material property effects on motion and forces.
- Energy transformation
  Learning Objective: students should understand energy in various forms, flow and the importance of energy flow to society.
- Diversity of life
  Learning Objective: students should learn about the increasing variety of living organisms, be aware of schemes for classifying organisms, animal behaviour and other features related to the life of an animal (e.g. habitat).
- Cells
  Learning Objective: students should understand cell growth, how cells relate to organisms and nutritional needs of cells.

The State of Georgia standards and the Clarke County School District emphasize hands-on experiences to develop the student's basic knowledge of these topics and scientific thinking skills. Development and fabricating hands-on science/technology exercises are used as the basis for projects in the engineering design course.

IMPLEMENTATION

Selection of projects

The instructors structure the course to work as a consulting firm where the instructors are owners and the engineering majors will serve as employed engineers. Teachers of Barrow Elementary School are customers who have hired the consulting firm to design and build science projects that fit the K–5 curriculum. The engineering majors will have to respond to the 'owners' and customers through oral reports, three written reports and other documentation that follow ISO 9001/14001 procedures. The engineering majors will be responsible for all aspect of the design solution from development to implementation.

Two months before implementation, the instructors meet the principal and science coordinator and determine the set of mandated science topics that will be used while meeting the objectives of the engineering course. Based on this set of topics, the instructor interviews the science coordinator and teachers and identifies resources needed for the project. Two sentence descriptors of each project are given to the participating undergraduates after lectures concerning problem definition. The following are example descriptors written for science needs:

- Design a device that demonstrates the rotation of the solar system.
- Design a device that explains principles of electrical energy flow.
- Design a device that explains the transfer of loading on bridges.
- Design a device that explains simple machines.
- Design a device that explains the tension in soap bubbles.
- Design a device that demonstrates the biological processes associated with composting.
- Design a device that explains the flow of blood through the heart.

Student responsibilities

Once the projects are identified, the entire engineering class meets the Barrow faculty and students. The purpose of this meeting is to become acquainted with the limitations of K–5 classroom instruction, the learning styles of K–5 students and the resource needs and limitation of the school. After this class meeting, the class is given a brief period, typically two days, to research each project and understand how personal skills and goals match specific projects. The actual method for assigning individual students to a project is given below.

Once the engineering majors are grouped into teams (see section below), each team will be assigned to a customer group that includes elementary students, noting several grades may be involved with a single engineering team. Before any other activity, each team prepared a strategic plan of action for approval by the 'owners'/instructors. Next the team interviewed and interacted with the customers and developed:

1. a problem statement that guided the team's activities;
2. define customer groups' wants and needs and prioritize those wants and needs;
3. transform the customer wants and needs to functions and quantifiable constraints.

These activities typically were completed after 15 lecture periods that focused on developing the functional requirements and constraints of an engineering design project. A written report on the students' work and findings was required.

Once the problem had been fully defined, the team was allowed to develop concepts and then logically selected the concept which had the greatest potential to solve the problem. It should be noted that several iterations between problem definition to final concept development are needed. Next, each team prepared a written design proposal and made a short presentation justifying concept selection. This proposal included a budget, a review by the customer and 'owners'/instructors whose final approval was also required. These activities were completed just before the mid-point of the semester. Again, specific aspects of these activities coincided with lectures.

After the proposed concept was approved, the team developed a paper design solution which was presented to the customer and 'owners'/instructors for approval. The paper solution including machine drawings were then given to a craftsman for fabrication. During fabrication, the student team was required to observe key activities, gain knowledge about the fabrication process and be readily available to the craftsman in order to correct mistakes on the machine drawings. Assembly of parts was the responsibility of the team members and not the craftsman.

Once the design is fabricated, the team was required to develop a field-testing process that includes allowing Barrow Elementary students to use the device/system/design. From these tests, improvements of the design were suggested and incorporated into the final design. A final presentation was made to all involved parties including other engineering faculty.

Selection of teams

In our experience, the maximum team size should be no more than five persons, with three to four person teams considered optimal. With teams of this size, it is felt that each team member must take an active part in the design in order for each group to meet the project deadlines in this class. The following three step process was used to identify teams. First, nominations were taken for team captains, who were assigned to a specific project and who would be responsible for assigning other students to that project. Students were permitted to nominate themselves. In situations where more than one student was nominated to be a team captain for a single project, elections were held. The potential captains were given a specified period of time (typically 5 min/person) to identify their qualifications and/or desires for being a captain. These individuals were then asked to leave the room and anonymously voted on by their peers. The captains were decided by majority vote and immediately told the results.

The second step involved identifying the interest areas of other members in the class. During this the remaining students are granted a specified period of time (typically 3 min/person) to identify their qualifications and/or desires for preferred projects. Note that there is no guarantee that they will receive their first choice. The captains took notes during this step to identify possible team members. Non-captains were then asked to leave the room.

Finally, the third step involved the captains drafting their team. The draft order was determined randomly and was reversed with each successive round. The drafting method has several advantages over, say, instructor assigned teams and/or random teams. Drafting provides a 'sense of ownership' both to the individual and the team as a whole. This method has the added benefit of public speaking for individuals who have to make a case in front of their peers. For example, successful arguments appear to revolve around previous coursework, work experience or inherent interest (e.g. hobbies) in a certain topic. Confidentiality is critical throughout the process particularly in the draft results. Although the team captains know the draft order, it is particularly important that this be kept confidential. Thus far, this has not been an issue.

Based on instructor observations of group interactions, it appears that this draft method works extremely well in promoting teamwork and ultimately positive peer interactions [17]. Therefore, this initial relatively labour intensive method of determining teams yields significant dividends over the course of the semester for everyone concerned.

School relationships

The instructors meet on a regular basis with the Barrow School principal and science director throughout the school year. The purpose of these meetings is to discuss interactions between the engineering major and teacher, between the engineering major and student, between the engineering faculty and teachers. Guidelines for these interactions are set and changed as needed to meet the regulations of the school district and state. The instructors also meet the K–5 science directors of all of the school district's elementary and middle schools.The purpose of this district-wide meeting is to inform and disseminate the design solutions developed by the engineering major.

EXPERIENCES AT THE UNIVERSITY OF GEORGIA

ABET emphasizes engineering design methodology throughout the engineering curriculum. Ideally, this will include the first and second years culminating in the capstone senior design course. However, the paradox of incorporating engineering analysis into lower level design courses exists because the upper level analysis courses have not yet been completed. Therefore, elementary school science projects provide the appropriate level of analysis for the sophomore level engineer. At this level much of the analysis is related to those concepts learned in statics—strength of materials, physics and lower level mathematics.

Planned interactions between the undergraduate and K–6 students

Following project and group selection a field trip is arranged in which the students meet interested teachers as well as a sample cross-section of different aged elementary students at Barrow School. During this activity the sophomore engineering design students have an opportunity to interview elementary aged school students in order to gain a deeper understanding of various science topics. Based on these interviews the design students are then better able to identify the background and knowledge level of their customer as well as identifying potential engineering constraints as dictated by the customer. For each project not only is a mechanism or device produced by each group, but also a learning activity which might include a simple class exercise and a list of related questions which the school age children must answer about the subject area. This learning activity needs to be designed for the appropriate age and grades of the customer. Following these interviews each group is then required to write a well-thought out statement about the design problem in their science topic.

Expectations of the undergraduate

Once the undergraduate has met K–6 students and teachers as well as other experts identified during the 'understanding the problem phase', the student conducts a benchmark study of existing educational products associated with his or her science topic, identify the importance of each customer, also any important customer constraints. For each constraint the student team is required to set all engineering specifications and goals. During the concept phase, the students communicate often with their customers (Barrow Elementary Teachers) seeking their opinions on the relative importance of each design constraint and on possible design solutions. The product is often a challenging design problem. For example, storage and portability are common constraints that can pose real challenges to the design students. Cost is always a constraint. Because these projects are actually built, funding is required in this class over and beyond normal funding levels in other lecture classes. These funds have been obtained in the past from either laboratory fees or small minigrants from the university. Typically, these projects require less than £100 with four hours of departmental shop resources provided for fabrication purposes.

At the end of the concept phase each group is required to submit a design solution and budget as well as other potential concepts which were considered but not adopted by the course instructors (project managers/owners). The instructors then review each project for its potential to address the science principle in question and the techniques which each group used in selecting a design solution using engineering design methodology. The instructors then meet each group to discuss the proposed project as well as the suggested level of funding. During this meeting the group is told if their project was:

1. approved with additional budget funding;
2. approved with the budget as suggested;
3. approved with a reduced budget;
4. disapproved.

During this meeting the groups are given the opportunity to further 'sell' their ideas to the instructors. While for many groups having their project disapproved or provided with a large budget reduction is rather traumatic, it reinforces the hard fact to everyone in the class that engineering is a very competitive field in which firms vie for design jobs based on their design solutions and price. If a design solution is not approved by the instructors, then the group is normally given a deadline to come back with either an entirely new concept or a project based on a more fully developed idea from one of the concepts previously considered and rejected by the design group.

The budget determination is an effective means of highlighting that there is rarely if ever a 'blank cheque' in the development of a product. Any additional manufacturing time above the provided four hours is billable at the going hourly rate. It is important that the students understand that the amount of funding is directly proportional to the quality of the proposed design such that not every team necessarily receives equal funding. This infuses a certain element of competition earlier on into the design process because funding is not uniform, but contingent on the justifiable needs of the team as determined by the instructors.

After the concept phase students use their analytical tools to optimize the conceptual solution into a fully developed product which will be fabricated later. Instructor/owner approval of this developed product is required and the team must produce a detailed set of engineering drawings. Because this product is to be fabricated, the students learn the importance of producing correct/logical/accurate engineering drawings and the importance of these in conveying their desired manufacturing accuracy to fabricators. During this phase the students also research vendor information and talk with technical representatives from companies. Students also communicate with technical support in the departmental fabrication shop concerning potential manufacturing techniques. At this time the technical staff in the departmental research shop also counsel each design group on possible alternative design or manufacturing techniques for construction of the product. Many of these students are not familiar with manufacturing principles and techniques and do not have a comprehension of required fabrication time, techniques or the accuracy whereby many products are manufactured. In this phase appropriate engineering analysis for selected aspects of the project as dictated by the level of expertise of the student is also required.

At the end of the Analyse and Optimize phase, the students hand to the course instructors a materials list, parts and estimated cost list, vendor list and a set of engineering drawings and move into the Construction phase. Based on these documents materials are ordered and the product is manufactured. At any time during purchasing or manufacturing if problems exist, because of misinformation associated with their parts list or engineering drawings, then construction of that project ceases and that group is immediately notified of the problem. Often these problems are associated with not providing enough information in the documentation for someone to even to find the correct item to purchase. This helps to stress the communications requirements of engineering and the need for the student to provide accurate product specifications. At the end of the allocated four hours manufacturing period, progress is noted and the technical staff then keeps track of the time required to finish manufacturing in order to better gauge the 'true' cost of the project. This extra manufacturing time is then added into their budget as a cost to the project. During the last two years of this class, the students have had available for use a rapid prototype machine as well as a CNC machine. Groups are encouraged to provide the technical support staff with 3-dimensional CAD drawings of those parts which will be manufactured 'in-house'. During the last two years, assembly of the projects has been performed by each design group rather than by the technical staff. This also reinforced to each group the importance of producing accurate engineering drawings in the manufacturing process.

At the end of the Construction phase the students then present the prototype to their customers at Barrow School. During this presentation, the design groups are encouraged to either have a formal set of questions related to customer satisfaction or record accurately any comments made about their mechanism during their presentation. Prototype testing helps provide the students with feedback on the good and bad aspects of their design solution. This interaction with the customer, both the teachers and students at Barrow School, allows the students to critically ask themselves questions concerning:

1. does the product meet the customers expectations, (both students and teacher)?
2. does the product teach the intended science principle?
3. did the project meet budget requirements?
4. does the project conform to engineering specifications as proposed in the concept generation phase of the project?

At the end of the semester students provide the instructors of this class with a final report, documenting how their group utilized engineering design methodology to develop and manufacture their mechanism, as well as a corrected set of engineering drawing and parts list. Throughout the semester each individual student was also required to keep a design notebook. This design notebook documented their individual contribution to the group such as concepts generation, analysis and other work performed. The design notebook makes a critical contribution to each student's final grade and helps to reinforce throughout the semester the idea of communication skills and record keeping as important aspects of engineering design. Proper techniques for keeping a design notebook are covered during the first few weeks of class and the design notebooks are periodically checked throughout the semester to make sure that the students document their work correctly. During this presentation it is emphasized that the design notebook is an official record and can be used in patent applications and even court proceeding involving litigation. Grading techniques for each student are based on:

1. daily work (quizzes and homework related to lectures on design);
2. group activities (each design report as well as the final report) and then individual contributions (based on the design notebook).

Grades for the group activities are not based on the quality of the mechanism but rather how the groups utilized the engineering design process to arrive at the final product. Students are reminded of that throughout the course that the process is what we are primarily looking at and not the artefact. While the usefulness of the product is a major concern of their customer, the instructors are more concerned with the engineering design process.

One of the greatest challenges faced by the students is to fabricate and field test the project in a time frame that allows the results to be included in the final report. To help the student with this time management issue, the instructors set, three weeks before the end of the semester, a deadline for submitting the mechanical drawings to the fabrication shop. If this deadline is met, the instructors guarantee that fabrication and field testing can be completed before writing the final report. The requirement of this deadline is that a complete set of mechanical drawings previously reviewed by the fabricator must be submitted and all needed corrections made. If the deadline is not met, the instructors do not guarantee that fabrication can be completed in a manner that allows enough time for field testing.

Almost all student teams have a completed project before the end of the semester, however only about 75% of the teams meet the deadline described above. Over the last three years, only three projects (out of 24+) have not been completed. Points from the course final grade are deducted for incomplete projects.

On a bi-weekly basis, team members use a team assessment form to rate the performance of each team member. This assessment form is the primary document used by the instructors to identify problems which might be occurring between individual team members. If problems are identified, the instructors mediate a team session and find a solution to the problem. On occasions the solution is to remove a team member who is not providing meaningful contributions to the project or who is causing conflict within the team. In such situations, the student is assigned an individual project.

The instructors must intervene on at least one project per semester. This intervention typically is due to the lack of performance from an entire team. The instructors will arrange for a meeting with the team; all work documented in the design notebooks is reviewed for quality of work and the team members are given a 'potential' course grade. Only once in the last three years has poor team performance continued after such a meeting. In this case, the instructors disbanded the team and each team member was given an individual course project. Points from the course final grade are deducted when such actions are taken.

Participant reaction

The partnership that exists between the sophomore design class and Barrow School has been in our opinion a very positive experience for both parties. Barrow School provides a very diverse set of engineering design problems on a yearly basis which satisfies the wants and needs of the class while also providing a customer base with which students are allowed to interact. The mechanisms and artefacts which the engineering students produce for Barrow School satisfy this school's needs in many different areas for hands-on experiences in science and technology. As with most local school systems, budgets are tight, and projects like this help make use of equipment which they have. Projects like this also provide benefits to the local community and provide a method whereby engineering is highlighted to elementary teachers as well as the parents and students at Barrow School.

Barrow teacher comments have been very positive. The science coordinator for the elementary school indicated that

- The simple machine device was very usable, easily understood and loved by all the students.
- The solar system is very adaptable for different grades—I loved it; but I was surprised it fit your requirements for the engineering course.
- The kids liked the electricity one, but 3rd graders do not understand it.
- The plate techtonics was good, adaptable to various skills—I thought that was creative.

Two 5th grade science teachers provided the following observations:

- Working on an elaborate project like that seemed to be a struggle for one group of engineering students but they were all proud of the product in the end.
- Most of the engineering students did a good job of familiarizing themselves with the appropriate subject matter in order to understand the project.
- Sometimes it seemed as though the engineering students wanted guidance and ideas from me, rather than leading the project and justifying their own ideas to each other.
- The model was great, the kids enjoyed cranking the earth and looking to see the shadow patterns.
- Lots of interactive time for my students to 'show what they know' and also problem solve some things they didn't already know.

Course evaluations from the participating engineering undergraduates included comments to the following questions

- What things in the course do you think were done particularly well to enhance your professional development?
  - Developing team work skills.
  - Making a project that represented a real engineering situation.
  - Think for myself.
  - The design experience was challenging.
  - We were treated as employees would be on a tight deadline.
  - Hands-on learning, interaction with product completion.
  - Learned what might be expected at our professional job. We kept a design notebook which really helped our professional development.
  - Real world environment (frustrating, challenging, deadlines).
- What things in this course could be changed to enhance your professional development?
  - More control on what project I work on.
  - More workshop in class.
  - Learned R&D process.
  - The workload is not proportional to the credit hours.

– Good course content, but seemed a little ambiguous at times.
– Begin the project earlier.

CONCLUSIONS

Designing elementary science demonstrations has proved to be appropriate and effective as projects for sophomore engineering students. The 'draft' method for determining student teams also has proved beneficial. Ultimately the elementary student is the end user. A critical step in the design process is when the engineering students meet elementary students to identify their constraints (background, K–9 curriculum etc.). The highlight of the course is the sophomore engineering team presentation of the final design to the elementary school students. The benefits to the community are tangible. The intangible benefit of having sophomore engineers influencing elementary school students may yield dividends in future engineering enrolment.

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J. S. Burmeister is currently Director of Bioengineering at the University of the Pacific and Assistant Professor. He was a co-instructor (with the coauthors) of this sophomore design course while at The University of Georgia as a Postdoctoral Teaching Fellow.

Timothy Foutz is currently Professor, Biological and Agricultural Engineering, University of Georgia. He conducts research in biological systems and biomechanical response of tissue; soft tissue healing and repair; analysing and improving medical techniques in veterinary medicine; materials used for tissue grafting. He teaches courses in engineering dynamics, fluid mechanics, biomaterials, biomechanics, design methodology and non-destructive testing of tissues.

Sidney Thompson is currently Professor, Biological and Agricultural Engineering, University of Georgia. He conducts research in the storage of granular materials; physical properties of granular materials; design of agricultural structures; studies in stress and strain; computer modelling and graphics. He teaches courses in strength of materials, agricultural structure design, engineering design of residential structures, instrumentation for engineering research and design methodology.