Integrating Design, Analysis, and Problem Solving in an Introduction to Engineering Curriculum for High School Students

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Abstract

The current paper describes an *Introduction to Engineering* class that was taught to a group of high school students in the summer of 1997. The class was offered through an outreach program at the University of California at Berkeley called the Academic Talent Development Program (ATDP), and was designed to give students an overview of the diverse field of engineering. In order to learn what engineers actually do, the students engaged in a variety of projects and hands-on activities to find out how things work and to practice their own engineering skills. This paper will provide an overview of the syllabus and goals of the course. Specific activities and design projects will also be documented such as the mechanical and computer engineering design challenges, teamwork and student presentations, and the on-line web-based assignments. Detailed examples of student work and student feedback will be reported. The quality of student work, as well as the positive feedback about the class, indicates that these high school students were not only motivated by the subject matter but were also capable of fundamental engineering design and problem solving.

I. Introduction

Over the past few decades our society has become increasingly technologically advanced. This societal change has required a more technologically savvy workforce and has produced an increasing demand for skills such as a capacity with open-ended problem solving, a facility with computers, an ability to manage and make sense of large amounts of data and information, and an ability to work in interdisciplinary teams to solve increasingly complex problems. Since these are skills that are typically associated with the practice of engineering, there has been a great deal of interest in introducing engineering to students at the pre-college level. Introducing the practice of engineering to students earlier in their career may potentially provide them with a head-start on the abilities they will need to be competitive in the workplace.

The *Introduction to Engineering* course described in this paper was developed to meet the growing interest for pre-engineering curricula appropriate for high school students. The course was designed to combine engineering skills and content with a firm pedagogical and instructional foundation. The main goals of the course are to familiarize students with the practice of engineering and to engage students in engineering analysis, design and problem solving. These goals were accomplished by designing lessons and activities that not only contain engineering skills and content, but also are consistent with research described in the education literature. The design of the course was influenced by two main areas of research in the education community; 1) collaborative learning[1] and 2) scaffolded knowledge integration[2].

Collaborative learning refers to students working together where they share and distribute the responsibilities of 'learning'. The students support each other through questioning and elaboration, providing alternative points of view, and sharing expertise[3]. Research has shown that cooperative settings produce positive results in elaboration of ideas, analysis, and problem solving[1]. Therefore aspects of a collaborative learning environment were incorporated into the lessons and activities in the *Introduction to Engineering* curriculum.

Aspects of the scaffolded knowledge integration (SKI) framework also guided the design of the course. Two specific features of SKI that are embedded into the design of the lessons are 1) the emphasis on developing independent and autonomous learners and 2) the practice of making thinking visible[2]. The SKI framework advocates that students learn to be independent and autonomous. This is supported in the SKI instructional framework, as well as in the engineering class, through making thinking visible and by providing social supports similar to those found in collaborative learning environments.

While research in the education community helped to guide the development of the classroom learning environment, other factors helped to guide the selection of engineering activities and content. Specifically we based many of the engineering activities on the learning goals defined by the Synthesis Coalition. The Synthesis Coalition is a National Science Foundation funded Engineering Education Coalition of which the University of California at Berkeley is a member.

The Synthesis Coalition has defined five qualities which are expected of their graduating engineers; 1) ability with open-ended problem solving, 2) familiarity with multi-disciplinary content and design, 3) teamwork skills, 4) facility with hands-on activities, and 5) ability to communication effectively[3]. Since these qualities are defined as important to the engineering community, as well as coincide with the new Accreditation Board of Engineering and Technology (ABET) criteria established for accrediting undergraduate engineering programs[4], an effort was made to include activities in the *Introduction to Engineering* course that would help students to develop these skills.

The current paper provides an overview of the goals and content of the course and describes two specific activities in detail; the straw and pin design challenge and the computer redesign project. Examples of students' work from these activities are presented and discussed. In addition, two methods that were used to obtain student feedback, as well as some of the student comments, are described.

The paper is divided into seven sections. Section II provides a brief background of the class and students, and Section III provides an overview of the course goals and content. The straw and pin design challenge is described in Section IV and Section V discusses the computer design project.

The student feedback and comments are presented in Section VI. Finally, the summary is given in Section VII.

II. Background of the Class

The *Introduction to Engineering* class was offered through an outreach program at the University of California at Berkeley called the Academic Talent Development Program (ATDP). ATDP is administered through UC Berkeley's Graduate School of Education and is designed to provide challenging academic experiences to elementary and secondary school students. The program also maintains a commitment to serving gender, ethnic, and socio-economic diversity in its student population. Each summer the program offers roughly 50 different courses to students who have completed grades 7 through 11.

The summer of 1997 was the inaugural year for the *Introduction to Engineering* class. Since there was no past experience which could guide the format of the class, we decided to try a variety of activities to get a feel for what would work best with the students. The basic outline of the class was designed to give students an overview of the diverse field of engineering. The six disciplines we investigated included mechanical engineering, electrical engineering, civil engineering, chemical engineering, computer engineering, and aeronautical engineering. Due to the time constraint of a six week session, not every discipline was given the same depth of coverage. For example, we spent four class sessions on electrical engineering and only one on chemical engineering.

The class met twice a week for six weeks and each class session was for 3 hours. This is almost equivalent in time to a three credit, one semester university class. The class consisted of 16 students, 5 female and 11 male. The students ranged in age from 13-16 and had just completed grades 8 through 10. The ethnicities that were represented were; 12% Latino, 12% African-American, 19% Caucasian, and various Asian ethnicities. Ann McKenna, one of the co-authors, was the instructor of the class. She holds an M.S. in Mechanical Engineering and is presently in an interdisciplinary program between education and engineering at UC Berkeley.

Decisions regarding which engineering subjects were taught, and how much time was spent on each subject, were governed by a variety of logistical factors such as material, resources, the instructor's familiarity with the content, and time. While these constraints played a practical role in the selection of activities, the major contributing factor in the development of the lessons and activities was to facilitate authentic engineering practice.

III) Overview of Course Goals and Content

The main goals of the course were to familiarize students with the practice of engineering and to engage students in engineering analysis, design, and problem solving. These are two very broad goals that warrant further explication. In order to familiarize students with the field of engineering, the activities were designed to simulate authentic engineering practice. It should be noted that, in this case, authentic practice refers to the activities or skills embedded in the project, not to the actual products that were built. For example, an actual engineer may not ever build a structure made of straws and pins (described in Sec. IV) but he or she would likely engage in the practices the students used to solve the problem. Some of these practices include communicating with others, brainstorming, and learning through trial and error.

The lessons were designed to engage the students in engineering analysis, design, and problem solving. Specifically, the lessons were organized around particular design challenges. Depending on the day's challenge, the class activities were structured in order to support the students' completion of the design. The use of supporting activities, or scaffolding, is part of the instructional framework for promoting knowledge integration as described by Linn[2] and is also part of the collaborative instructional framework of cognitive apprenticeship[5].

The class was organized around several different engineering disciplines. As the class progressed, and new disciplines were introduced, the lines between each of the discipline began to blur. The class extracted engineering skills that are consistent across disciplines, and recognized the interdisciplinary nature of the design of various products. For example the design of a computer may require computer engineers, electrical engineers, mechanical engineers, as well as supporting staff such as technicians, administrators, etc. The outline of the course syllabus, organized around the six disciplines that were covered, is given in Figure 1.

Introduction to Engineering 1634 Syllabus

Date	Class Topic
Week 1	
June 16	Introductions, Technical Drawing
June 19	Mechanical Engineering: Build straw structures, use LEGOs to investigate strength and flexibility of different shapes, intro to MacLab in 3116 Etcheverry
Week 2	
June 23	Mechanical Engineering: Simple machines computer and LEGO activities in Maclab
June 26	Electrical Engineering: Dr. Mark Jeffery visits and gives lecture on electrical theory, visit Cory Hall. Start the flashlight dissection activity. Dr. Jeffery and Anu Bhat explain their research and show their lab that designs and builds high speed superconducting circuits.
Week 3	
June 30	Electrical Engineering cont'd: Flashlight dissection, build electromagnet, tours of Laser Lab and Robotics Lab
July 3	Electrical Engineering cont'd: Oscillations and sound, learning to solder and Parallel and Series Resistors
Week 4	
July 7	Electrical Engineering Completed: Build Burglar Alarm!
July 10	Civil Engineering: Visit civil engineering labs in Davis Hall; boat building activity
Week 5	
July 14	Chemical Engineering: Field trip to Chevron Oil Refinery
July 17	Computer Engineering: disk drive CD ROM and dissection. Computer design activity.
Week 6	
July 21	Aeronautical Engineering: Airplane Building and Investigation.
July 24	Wrap-Up: What did we learn? Enter data onto class web site.

Figure 1. Syllabus for Introduction to Engineering 1634; ATDP Summer 1997.

IV) The Straw and Pin Design Challenge

The students were given various design projects throughout the course and this section will describe one of these projects; the 'straw and pin design challenge'[6]. The challenge posed to the students is given below:

> You are given 20 pins and 20 straws, build the tallest structure that will hold an egg at the top.

The students were divided into teams of four and were given approximately 30 minutes to work on the project. After completing the project each structure was 'tested' with an egg and each team explained their design. The teams compared designs and determined the features which resulted in the 'best' design. The students were exposed to a variety of designs and approaches by the other teams and the class discussed the merits and drawbacks of each. The majority of the responsibility for analyzing the designs rested with the students in an effort to develop autonomy. As described in the SKI framework, autonomous learning was facilitated by having the students serve as social supports for each other through sharing design ideas, providing feedback, and critiquing each other's designs[2].

Self-reflection was also achieved through the sharing of designs and ideas. Since the activity was structured in a collaborative learning environment, individual student self-reflection became voiced through the group discourse. Therefore, the students' thinking became 'visible' throughout the class demonstrations and discussions. As described in SKI, self-reflection and making thinking visible is beneficial to student understanding because once ideas are brought to the surface they can be discussed, debated, compared, and refined[1, 2]. Many of the activities of this project were included to encourage students to make their thinking visible through self-reflection and the sharing of ideas.

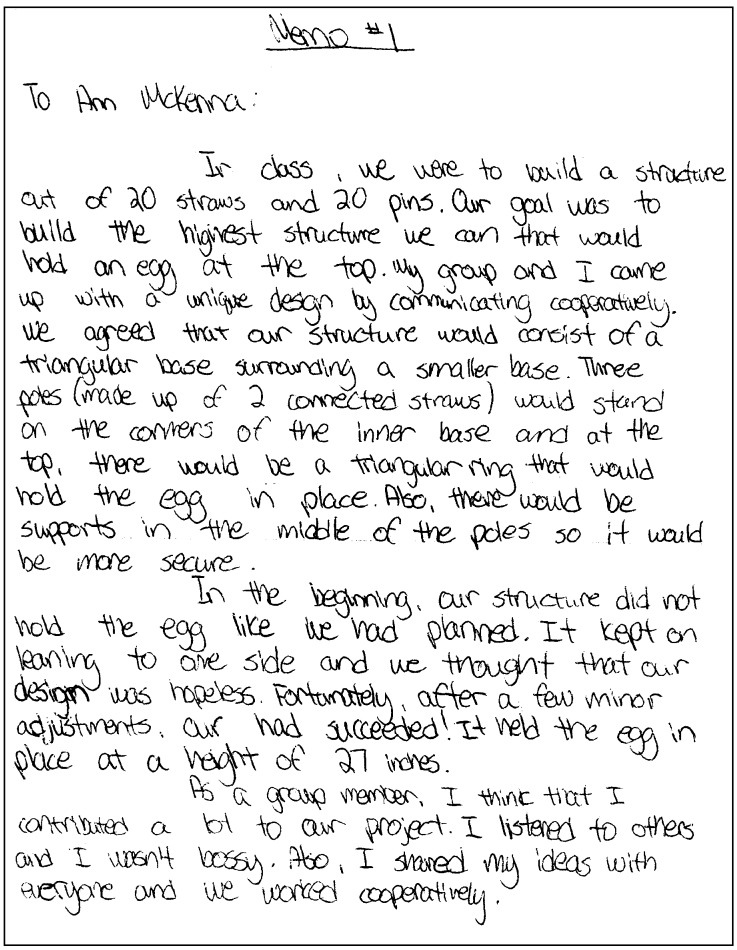
Specifically, self-reflection took place in the class by having students demonstrate and explain their designs, by having students analyze the various approaches, and through reflection on their performance as a team. After completion of the project, students were asked to reflect on what they did as a team in order to solve the problem, and then we related these reflections to the practice of engineering. For example, some of the things students reported were; 'we listened to each other', 'we made mistakes', 'we argued', and 'we had to explain our ideas'. The class then engaged in a discussion about how these activities are all part of the practice of engineering.

The other feature of this project which encouraged reflection was the memo writing exercise. The students were given homework assignments where they had to write memos to their 'boss' about the day's activities. The actual memo assignment for the straw and pin design challenge is given below.

> Write a memo to your boss (in this case teacher) explaining the design you built in class today. Include the design specifications regarding the amount and types of materials, and a description of the problem you were trying to solve. Explain in the memo how your team came up with the design and why you chose to make it

the way you did. If your design worked, explain why you think it worked and if it didn't, explain what your plan would be to fix it so that it will. Also, describe in the memo what your contribution to the team was.

Examples of student memos are shown in Figures 2 and 3. Almost every memo was accompanied by a sketch but the sketches are not included due to space considerations. These two memos are representative of the student work that was submitted. There are two main aspects of the memos that indicated the assignment and activity were a success. First, based on the detail in the memos, the students devoted time and effort analyzing, building, and revising their designs. This indicates student motivation but, more importantly, it suggests that the students were engaged in the process of discovering and understanding. Second, the memos indicate that the students actively engaged in working as a team to solve the problem. We found comments such as; 'I listened to others and I wasn't bossy' and 'My group came up with a unique design by communicating cooperatively' as wonderful examples of collaborative work. At the very least these student comments suggest an appreciation and value of others ideas.


Memo #1

To Ann McKenna:

In class, we were to build a structure out of 20 straws and 20 pins. Our goal was to build the highest structure we can that would hold an egg at the top. My group and I came up with a unique design by communicating cooperatively. We agreed that our structure would consist of a triangular base surrounding a smaller base. Three poles (made up of 2 connected straws) would stand on the corners of the inner base and at the top, there would be a triangular ring that would hold the egg in place. Also, there would be supports in the middle of the poles so it would be more secure.

In the beginning, our structure did not hold the egg like we had planned. It kept on leaning to one side and we thought that our design was hopeless. Fortunately, after a few minor adjustments, our had succeeded! It held the egg in place at a height of 27 inches.

As a group member, I think that I contributed a lot to our project. I listened to others and I wasn't bossy. Also, I shared my ideas with everyone and we worked cooperatively.

Figure 2. 'Brett's[1]' memo on the straw and pin assignment.

[1] Students were given pseudonyms to protect their identities.

The purpose of the memo was to have students reflect on the activity but it also served as a means to develop written communication skills. In addition, the memo served as a culminating event for the students' engineering design project. The students therefore participated in many stages of the engineering design process. Specifically, the students began with the conception of a design idea, they then proceeded with analysis and construction of the design, followed by a presentation of their work, and the process concluded with a report (memo) of their work to superiors.

MEMORANDUM

DATE: June 19, 1997

TO: Ms. McKenna

FROM:

RE: Egg Support Structure

In teams we were assigned to build the tallest structure that would support the weight of an egg. This structure was to be constructed using only 20 straws and 20 pins. Our group, and I, created two structures.

Our first structure had a rectangular base with 2 straws put together at each corner. we were unable to create a place to hold the egg. This structure did not work because the base was unstable. It was falling apart and could not hold the weight of straws. Also, we put more thought on height and less of the purpose of the structure when we should have been thinking of both equally.

Our second structure had a triangular base with 2 straws put together connecting to each corner. These three straws connected to the corners of a smaller triangle at the top. This triangle was where tho egg would be held. This structure worked because the weight of the egg was evenly distributed. The stress on each straw was equal and the structure supported the egg.

We came up with these ideas because we knew we needed a strong base. This base needed to hold the structure together and be able to support the egg. After to base was built we built for height. We did not build too high because of the weight it would hold. Then we created a place for the egg so that if the structure could hold the weight of the egg, it would not fall off.

My main contribution to the team was I made a new base and came up with a new idea when our first one did not work. I helped put together both structures but did more work on the second. I also contributed my scissors. I cleaned up after the entire project was over.

Figure 3. 'Rita's' memo on the straw and pin assignment.

The straw and pin design activity lends itself to authentic engineering practice by having students engage in the design process, work together in teams on a solution, engage in hands-on work, as well as having them compare and analyze the efficacy of their designs. These skills have been identified both by the Synthesis Coalition and the ABET as essential attributes of a successful engineer. Therefore, this activity was structured to maximize both engineering process as well as content.

V) Computer Design Project

The design challenge discussed in this section is the computer re-design activity. This project was part of a series of activities that were covered for the discipline of Computer Engineering. The instructions and specifications for the project are given in Figure 4. Since the design challenge required familiarity with the components and construction of a computer, the class lesson plan included a variety of supporting tasks to assist the student in the completion of the design assignment. This project, through the use of supporting technical and social activities, was also designed to encourage the students to become autonomous learners as described in the SKI instructional framework.

For example, the students worked through a disk-drive dissection activity where they took apart actual disk-drives[7]. This activity was included so that students could investigate the parts and function of the disk drive. The dissection activity was supported by an interactive CD-ROM that explained all of the parts and their functions[8]. As the students dissected the actual drive they could refer to the CD-ROM in order to obtain information about the device. The students worked in pairs on the dissection exercise, and at all times throughout the course were instructed to help each other in answering questions.

Next, the students took apart actual computers and investigated the components contained inside. Again this activity was supported by an on-line web site which described the parts inside a computer[9]. Once the students were familiar with the components of the computer, they proceeded to the computer re-design project. The project was designed to incorporate all five of the Synthesis Coalition’s engineering education goals; open-ended problem solving, multi-disciplinary design, hands-on activities, teamwork, and communication. While the completed design had to meet certain specifications, the students were encouraged to be creative and original in their thinking.

Computer Design Project

Your reputation as an awesome design engineering team has spread through the engineering community. Because your team is known for its great creativity, it has been hired to design the new '21st-century-portable-computer-pack'. Your task is to design the new casing which will hold all of the 'insides' of the computer. The new packaging should be designed to encase the motherboard, the power supply, the memory and the disk drives. (Refer to either your handout or the actual computer you took apart to see what these parts look like.)

Here are your design specifications:

1) The size of your new design must be no more than 1/2 the original volume of the current computer 'box'.

2) The customer is really bored with the same old square box design. They want something that is unique and different BUT still must be able to house all the parts.

3) The minimum number of expansion slots you need is 3.

4) You can change the shape of the motherboard BUT it still must be able to connect all of the parts to it.

5) Assume you can get a power supply that is half the size of the original one.

Your team assignment:

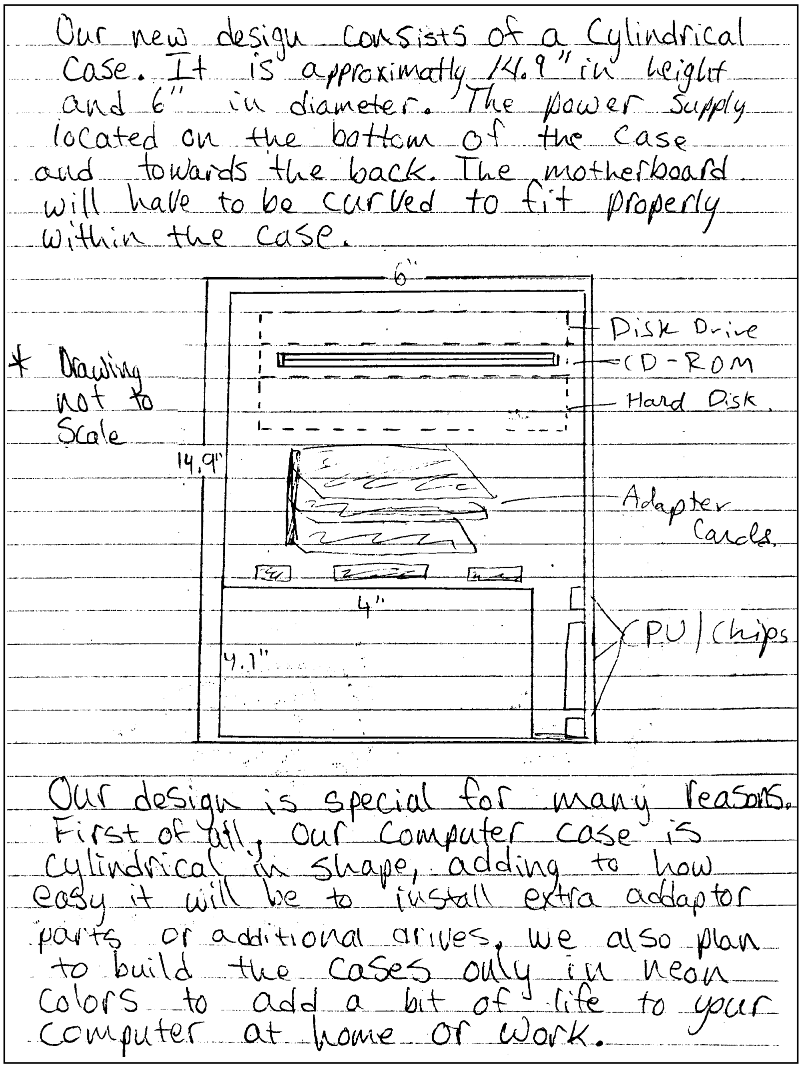
- Design the new packaging
- Make a sketch of the design. Include dimensions, size, shape, etc. Label the computer components.
- Explain where all of the parts will go.
- Tell us what makes your design original.
- Report the type of material you used.
- Give a presentation at the end!

Your team will be expected to give a presentation of the design to the company (the class). For your presentation you will be given two overhead transparencies to use where you can record your data (pictures, dimensions, size, shape, etc.). You can use these during your presentation.

Figure 4. Instructions and specifications for the computer design activity.

The students were separated into teams of three or four and at the completion of the project the teams gave presentations to the class. The students were told that the presentations would follow official engineering conference formats where they would get a short time to present (in this case 5 min.) followed by questions from the audience. The presentations were very enjoyable to watch since the students took their roles as engineers very seriously. They asked relevant questions and audience members double-checked the presenters' calculations to make sure they were accurate. If inconsistencies were found, they were pressed to explain their work in more detail. Overall we were pleased to see the students engaged in authentic engineering practice and impressed with the work the students produced. One of the proposed computer designs is shown in Figure 5.

An additional goal of the computer project was to have students learn about the computer and its components through the process of actively engaging in a design activity. The students needed to learn about the various computer parts in order to work them into their design. The example shown in fig. 5 shows that the students did indeed become familiar with the hardware and used the proper terminology in their description of the design.


Our new design consists of a Cylindrical Case. It is approximatly 14.9" in height and 6" in diameter. The power supply located on the bottom of the case and towards the back. The motherboard will have to be curved to fit properly within the case.

Our design is special for many reasons. First of all, our computer case is cylindrical in shape, adding to how easy it will be to install extra adaptor parts or additional drives. We also plan to build the cases only in neon colors to add a bit of life to your computer at home or work.

Figure 5. Example of one team's redesign of the computer casing.

VI) Student Feedback and Comments

The students were given regular opportunities to provide feedback about the class. The feedback was used to gauge student interest in the class activities, to indicate what students were learning, and to monitor for any unanticipated consequences of the curriculum. In addition, since the *Introduction to Engineering* class is considered to be a work-in-progress, the student feedback was used to implement continuous improvement of the course. Two particular methods that we used to collect student responses were an on-line web posting form and an end of course questionnaire.

The on-line web posting form is part of the class' web site[10]. The class web site contains sections for each of the six disciplines that were covered. Each discipline section contains a CGI script and form that allows students to post what they learned in each of the classes. All of the comments that are submitted are sent and saved to a separate web page that can be referenced by the students. This feature was included to provide a space for the students to share their discoveries with the class. Having the students report what they learned served three main purposes: 1) it encouraged the students to self-reflect on their learning, 2) it contributed to the collective knowledge of the class by making each student's thinking visible, and 3) it served as an assessment tool. Again the activities of making thinking visible and self-reflection encourage students to become self-sufficient learners as well as contribute to a more robust understanding[2, 11].

The following comments are taken from one of the on-line posting sections found in the 'Mechanical Engineering Notebook' web page[12]. They correspond to the mechanical engineering activities, specifically the straw and pin design challenge.

> Name: Rita
> What I learned:
>
> I have learned that there are many steps before you can reach what you want to accomplish. While doing activities like designing the structure that could hold the weight of an egg, I have learned that communication, hard work, and trial and error are the only ways to reach your goals. I also got a better idea of the kind of problems that engineers try to solve.
>
> Name: Steve
> What I learned:
>
> I learned much about mechanical engineering in this class. First, I learned how to recognize, visualize, and finally draw orthographic projections...I learned how to write memorandums with information about something I was researching or building. I learned how to build structures that were to hold a certain amount of weight which helped me learn how to accept failure and learn from my mistakes, and from the class' findings. Overall, I did learn a lot, and I hope that whatever I learned will come in handy in the future...

We were very excited about the responses the students submitted, and these comments indicate that the students clearly reflected on what they did and learned. Both Rita's and Steve's comments suggest that the students developed an understanding of engineering as a *process* instead of as a static, fixed body of knowledge. We considered comments such as "communication, hard work, and trial and error are the only ways to reach your goals" as indicators of a successful activity and lesson.

Additional comments related to the computer design activity were taken from the on-line posting section of the 'Computer Engineering Notebook' web page[13]. Some of the student responses are given below.

> Name: Tom
> What I learned:
>
> This was also one of my favorites. In this class, I learned about the components of a computer. About all the little itty bitty pieces of silicon and the drives in the computer. The activity was designing a disk drive in the computer simulation. That was my favorite. On my first try, my partner and I achieved the requirements right away!
>
> Name: Chad
> What I learned:
>
> I learned about the system and the terms that go along with it. Such as the harddrive and disk drive. I also noticed that a lot of soldering was involved in the building of the computer, which means it takes a lot of time to build. I like the presentation in front of the class we had to do in regards to the design problem because it gave me experience for what I might have to do in the future.

Once again, we were excited about the quality of comments submitted by the students. These responses not only suggest that students are becoming familiar with engineering content, but they also suggest a fairly high level of student interest and engagement.

Finally, at the end of the course, a questionnaire was given to the students which included open-ended questions about what the students liked most/least about the class. Some of the responses the students gave about what they liked most about the class are given below.

> Chad: I enjoyed the building projects such as the straw structure...the most because it was a tangible way to see the lesson. I can't really explain why I enjoy building so much, other than the fact it is fun to see the thing transform from its raw materials to the final product.
>
> Alan: I enjoyed the chance to work with other people to solve problems. These projects gave a feeling of team work. It helped develop my ability to work with others.

Many of the activities and projects in the *Introduction to Engineering* course emphasized hands-on building and working with others to solve problems. Both Alan's and Chad's comments are wonderful examples of how the students perceived the relevance of these activities.

VII) Summary

This paper provided an outline and description of an *Introduction to Engineering* class that was offered in the Summer of 1997 through an outreach program at the University of California at Berkeley. The class consisted of 16 students that ranged in age from 13 to 16. The class learning environment was influenced by two main instructional frameworks described in the education literature; collaborative learning and scaffolded knowledge integration. In addition, the engineering content was based on the learning goals defined by the Synthesis Coalition. The learning environment and engineering content were combined to engage students in authentic engineering practice. Specifically, the course emphasized creative and analytical problem solving, hands-on building, design and teamwork.

The paper described two specific design activities that the students completed; the straw and pin design challenge and the computer redesign project. Examples of student work from these two projects were presented and discussed. In addition, two methods for obtaining student feedback were also described. The class made use of an on-line web posting form and an end of class questionnaire. One of the main purposes for eliciting student feedback was to provide information to the course designer and instructors in order to implement continuous improvement of the class. The on-line web activities were also used to encourage students to self reflect on their learning. Student comments obtained from both these methods were also given.

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