Session 3253

INHANCING STUDENT CREATIVITY AND RESPECT FOR THE LINKAGES BETWEEN ANALYSIS AND DESIGN IN A FIRST YEAR ENGINEERING COURSE

Alfred J. Bedard Jr.
University of Colorado
Aerospace Engineering Sciences Department
Campus Box 429
Boulder, Colorado 80309

Abstract

There is great value in introducing hands-on components to first year student courses and providing them with opportunities to nurture their creative talents. A risk is to develop a reflex that trial and error can solve most problems and reduce student respect for the analytical component of engineering. Radish and Steinberg[1] in a 1999 paper expressed similar concerns. In order to create an environment where the seamless interplay between analysis and the execution of a design concept is emphasized, a series of projects attempt to underline this natural connection. The goal of these projects is to preserve open ended, creative problem solving components while also including theory requirements. Three projects address this goal. Two are given concurrently in an effort to also develop project management skills. These are the design and construction of a Rube Goldberg device and the creation of a craft propelled and suspended on a water surface using surface tension forces. The third project involves reverse engineering an engineered device. Each of these projects has a strong analysis component built into the requirements. For the Rube Goldberg, the final report has to include the analysis of one segment and a comparison between theory and practice. The students are also required to review the elements of their design and indicate, which were driven by trial and error and which were guided by theory. They are encouraged to use their courses in math and physics as resources for this. For the surface tension design a series of equations with text is provided to assist the design process. This includes information on how to determine the amount of weight that can be suspended, and equations valuable for designing a propulsion system, the craft size and shape, and other design details. In their final report they need to summarize how each of the analytical relationships guided their design. A racing competition is an element of this project. Finally, the reverse engineering project includes a requirement for an analysis of one portion of the design including a comparison with quantitative testing. Project details will be reviewed in this paper and experiences summarized.

1. Introduction

Over the last five years a new first year engineering projects course[2] (First Year Engineering Projects) developed at the University of Colorado provided valuable experiences introducing students to design and hands on engineering. The course in the fall 1998 semester included eight sections of about thirty first year students, typically working in teams of 4 or 5. Although the various sections share a structure of common exercises, the main projects differ between sections. This paper is based upon my personal experiences with student responses to three projects. Students are given the learning goals, the grading criteria, and expected products for each project, which all have embedded analysis requirements. Preliminary attempts to encourage direct connections between concurrent analytical courses and design projects produced valuable interactions between students and professors teaching chemistry and physics. An effort to link analysis with simple hands on experimentation at the junior and senior level[3] also underlined the need to bridge gaps between theory and practice.

1. Rube Goldberg Design Project

The Rube Goldberg project requires student teams to design and construct a device that performs a simple function (e.g. turning on a light switch) using a series of complex, multi-disciplinary steps in the spirit of the famous cartoonist. The fact that the project is quite open ended provides a wide range of opportunities for individual students to demonstrate their existing skills, as well as to appreciate and develop additional skills. A series of "just in time" short (1 to 2 hour) introductory workshops given throughout the semester (e.g. tool safety, machine shop techniques, CAD, electronics) are resources for their project work.

Students propose the purpose and details of their project, which are subject to a preliminary design review (PDR) and critical design review (CDR). They report frequently both orally and in writing on all projects. Design reviews include management plans, time lines, analysis goals and budgeting. The students are each expected to contribute a total of up to fifty dollars to their three projects, of which the Rube Goldberg is typically the most costly. Teams produce lists of needed parts for their projects and are encouraged to help other teams with components or special skills in an effort to reduce costs. The learning goals for the Rube Goldberg project are summarized below.

The project learning goals include:

- Learn how to identify the project: problem definition
- Introduction to the philosophy of design
- Learn and experience the design process
- Dealing with and closing open-ended problems
- Encouraging creativity
- Translation of theory into practice
- Application of analysis to guide design

- Appreciation of multi-disciplinary approaches in design
- Packaging, completing details, closure
- Time management
- Operating within constraints
- Budgeting, financial management
- Technical writing, oral presentations

1.0 Constraints and Grading

This exercise in its' original form in 1995 was quite open ended with essentially no constraints except safety and appropriateness. The initial Rube Goldberg projects tended to be large and often incorporated portions of the classroom in the design (e.g. blackboards, overhead projector, door/entryway). There was a requirement for including results from a simulation program, but this was more often relegated to the status of a footnote in project reports. When the number of sections increased in 1997 with the opening of a new laboratory (the Integrated Teaching and Learning Laboratory) there was considerable pressure on space and facilities. This laboratory included two classrooms specifically designed and reserved for the first year engineering projects course. The number of students enrolled in the course increased until, during the fall 1998 semester each classroom was used by four sections (about 120 first year students total).

At first, students designing Rube Goldberg projects in this new facility wished to continue the tradition of building large, extended devices, some even proposing to use great portions of the teaching laboratory in their projects. This was clearly not possible and a series of changes were made. From 1997 as a result, more quantitative requirements, constraints and structure have increased the value of the Rube Goldberg project as an engineering design exercise. Also, more detailed definitions of the grading criteria have increased student focus on important design elements.

The design constraints and requirements are:

- Maximum footprint -- three feet by three feet
- Maximum height -- six feet
- Easily disassembled for storage
- Easily transported
- Safe
- Multi-disciplinary
- Reliable
- Include analysis
- Demonstrate Creativity/ingenious problem solving
- Short repetition time
- Professional appearance

The grading structure is reflective of these requirements and reinforces the students need to address each of these areas in their design work. The scoring sheet includes each of ten areas weighted equally at ten points. The areas are:

1. Safety

1. Multi-disciplinary
1. Reliable
1. Analysis component
1. Creativity
1. Problem solving
7. Short repetition time
1. Professional Appearance
1. Presentation
1. Report and graphics

Students are given additional explanatory information and examples for each of the grading areas.

1.0 Examples of Student Analyses

To date, the effort to incorporate analysis into the Rube Goldberg project has been encouraging. Initially, projects emphasized functionality, creativity, and the use of multiple disciplines. The designs usually involved elements of hydraulics, electronics, kinematics, aeronautics, and chemical reactions. The themes often involved food, sleep, everyday jobs and leisure activities. Examples of some of the earlier projects range from providing sustenance (hot chocolate, cold drinks, pop dispenser, a birthday machine lighting candles and cutting a cake) to performing everyday tasks (e.g. sharpening a pencil, screwing in a light bulb, assisting a professor in grading). Many of these projects were truly elegant, but were too often driven in large by trial and error implementation.

The more quantitative requirements, constraints, and structure outlined above have improved this project into a more complete design exercise. Yet, the open ended, creative nature of the exercise seems intact as evidenced by the recurrence of similar themes and imaginative designs. Currently, an analysis requirement is an integral part of the project; and in retrospect should have been more strongly emphasized from the first use of this project. Table 1 below includes some examples of the Rube Goldberg design functions and the element analyzed. Students are required to analyze one segment of their design and compare theory and actual operation in a critical way. They are also asked to review their entire design and document the extent to which trial and error as well as analysis drove the final form of each segment. These elements are treated both in the PDR and CDR presentations.

In addition, students are asked to provide names of professors teaching analytical courses who they feel would be interested in their projects. These were then contacted, told about the purpose of the projects course, the goals of more strongly connecting analysis with design, and invited to become involved. Several professors assumed the role of informal advisors, and others participated as judges in a design exposition where the projects were showcased. A hope is that with time the numbers of those connecting with the projects course can be broadened.

Table 1 Examples of Rube Goldberg Projects and Elements Analyzed

FUNCTION	ANALYSIS
1. Re-light a candle	Compute the torque required to start a ball rolling
2. Start a ball rolling and return it to the starting position after many sequences.	Analyze a centrifugal ball launcher and the resultant trajectory.
3. Create mouse trap: but the mouse is fed cheese and wine.	Volume of liquid released from a container as a function of hydraulic head. Also analyzed other segments.
4. Physics machine	Demonstrated and analyzed conservation of energy/spring compression, centripetal acceleration, conservation of momentum/projectile collisions.
5. Putting a golf ball into a hole	Velocity of a ball at the base of a ramp.
6. Flush a toilet	Time/height trajectory of a ball on a track.
7. Rubber stamping a piece of paper	Minimum height necessary for a ball to traverse a loop-the-loop.
8. Press a snooze button on an alarm clock	Force produced by a fan on a sail. Force gauge measurements compared with theory.
9. Open a soda and pour it into a glass.	The operation of an electromagnet.

1. Surface Tension Craft

This project is introduced with the Rube Goldberg project; and both projects run concurrently as a project management challenge. This surface tension based design is an especially attractive project if there are constraints on space for construction or storing materials. Many student teams do preliminary testing in dorm rooms with simple, readily available materials. The goal is to build a craft that is suspended on a water surface by surface tension and also race the craft in a competition using surface tension to propel the craft. For the tournament "race tracks" we cut a ten foot length of one foot diameter PVC pipe in half and sealed both ends. The length of the race tracks is eight feet with an additional one foot starting and finish zone. We race two craft at a time in a double elimination. We are very careful in cleaning the half cylinders after each race to eliminate all traces of contaminating surfactants. Following sections contain detailed, analytical background describing concepts students can use in designing their craft. A goal here was to provide enough detail so that other instructors can evaluate and possibly make use of this project. This exercise is usually introduced by having the student teams estimate the wetted perimeter necessary to permit an average person to walk on water using surface tension alone. The answer indicates a length of about 10 kilometers, but they are challenged to devise methods of somehow making an "walk-on-water" device in practical form. Many teams suggest the approach of using a screening material to increase the wetted perimeter per unit area, which could be exploited in the design of their craft.

This design exercise is interesting in that it has a number of learning goals and is an introduction to the process of balancing conflicting design requirements. The learning goals include:

a. providing examples of the valuable guidance provided by analysis to design projects,

b. providing a project intended to run concurrently with a second project to build and exercise time management and project management skills,

c. providing clear, visible evidence of forces at the molecular level and how these forces can be harnessed and manipulated,

d. providing an introduction to system design and the art and science of integrating various design elements, while balancing conflicting constraints, and

e. providing a simple and yet potentially elegant construction challenge.

The elements to consider include: payload limits, developing a propulsion system, and the various forms of drag. Practical considerations will also have to be contended with: e.g. race start deployment, directional stability, interaction with surface waves, and the racetrack walls. It may be possible to explore any lessons nature has to offer on using surface tension[4,5,6].

3.1 Design Considerations

3.1.1 Suspending the craft on a liquid surface using surface tension

This requires that there be a balance of forces between the surface tension force holding the craft at the free surface and the gravitational force tending to pull the craft through the free surface.
Thus-

$$mg = \sigma L$$

Where m is the mass of the craft, g is the local gravitational acceleration, σ is the surface tension, and L is the wetted perimeter. This relation will allow you to make an estimate of the limits of craft mass for a given wetted perimeter.

3.1.2 Propelling the craft using surface tension

There are a variety of possibilities for propelling a craft using surface tension. These include, but are not limited to:

a. Creating a differential surface tension force across the craft. This could be done by
- The use of surfactants
- Introduction of temperature changes
- The use of electric fields

b. Using surface tension as a prime mover to for example operate a drive train

c. Use the release of potential energy stored by surface tension to for example create a jet

3. Drag forces

The force you create with your propulsion system will be limited by drag forces and you will need to take these into account in your design which should attempt to minimize these. These are several distinct processes contributing to drag and producing energy losses. These include:

a. Form Drag - The drag force is proportional to the surface area. The craft surface in contact with the free surface will usually be of primary concern.

b. Wave Drag - This drag force occurs as you exceed the speed of capillary waves and energy is radiated by the free surface waves. This is the analog to supersonic flight. Since the speed of capillary waves increases as the wavelength becomes smaller, this could be an argument for creating craft of small size.

c. Vortex Drag - This form of drag occurs when you lose energy shedding eddies. A streamlined craft will be less susceptible to this form of drag.

The form drag force on a ship can be written

$$F_d = \rho (UL)^2$$

where:

ρ is the liquid density,
L id the craft characteristic dimension, and
U is the speed.

If you assume you are propelling your craft using surface tension and the driving force, F, and the form drag forces are in equilibrium,

F surface tension = F form drag, or

$$\sigma L_d = \rho (UL)^2$$

Thus, the terminal velocity is

$$U_t = \left(\sigma L_p / \rho (L)^2\right)^5$$

L_p is the perimeter involved with driving the craft. The terminal velocity for several different craft areas (2, 4, and 6 square centimeters) ranges from 5 to 25 centimeters per second.

To increase the speed (considering only the form drag):

- increase the differential surface tension,
- increase the wetted perimeter contributing to the driving force,
- reduce the area

3.1.4 Speed of motion of a surface tension disturbance on a free surface

Another consideration is the speed of motion of a surface tension disturbance (e.g. from the
release of a surfactant at the rear of the craft) compared with the speed of motion of the craft itself. If the speed of expansion of the surfactant is large, a region of low surface tension could propagate in front of the craft and possibly sink it. This has in fact happened during past student competitions to the designers surprise and frustration.

Thus, optimum design for this competition requires a balanced consideration of all of the factors leading to success with careful regard to the interplay between competing processes.

You can find that the time scale for the expansion of a surface tension disturbance, T, is

$$T = r^{4/3} / \left[\sigma^2 / (\rho^2 \nu)\right]^{1/3}$$

Where r is the expansion radius,
sigma is the surface tension,
rho is the fluid density, and
nu is the kinematic viscosity of the fluid.

The speeds of propagation of these surface tension disturbances typical fluids used as surfactants is in the range 5 to 20 centimeters per second. This is in the speed range of many craft designed. Students are guided to you look in the Handbook of Chemistry and Physics or similar resources for the properties of fluids.

3.1.5 Wave Drag Caused by Capillary Waves

The speed of capillary waves, c , can be related to the wavelength, lambda, using the following expression:

$$c = \left| 2\pi\sigma / (\rho\lambda) \right|^{1/2}$$

Students can estimate the speed at which a craft will go "supersonic" for a particular size craft using this relationship. You may substitute a craft characteristic dimension (either length or width and see which works best) for the wavelength. Unlike ocean gravity waves (important for ships at sea) which increase speed with increasing wavelength, capillary waves increase speed with smaller wavelengths. Thus, the strategy of large tankers increasing their lengths to reduce wave drag will not work in the same way for surface tension craft. "Supersonic is in the range of speeds from 10 to 30 centimeters per second.

5. Directional Stability

Students could create an exceptionally fast craft, but if it will not keep to the desired course (stay straight), they risk embarrassment as it spins in small circles. If the force you create with surface tension is not aligned with the axis of your craft, you risk having such directional stability problems. An example of a cause of directional instability is the non-uniform application of a surfactant to the rear of a craft inducing a turning moment. Also, lack of symmetry in the construction of a craft can cause similar problems.

1.0 Comments on Grading Criteria and Student Responses

The teams are required to contrast the design of their craft with each of the theoretical criteria provided. This is a key element of the grading criteria outlined below in Table 2.

Table 2 Summary of Grading Criteria

GRADING ELEMENTS	COMMENTS/QUESTIONS
1. Propulsion	On what principles were the propulsion system designed?
2. Form drag	Did the team exploit the predicted relationship between speed and form drag. Did they compare their craft performance with this result?
3. Vortex drag	Was the craft designed to reduce this form of drag? How was this done?
4. Wave drag	Did the craft go fast enough to make wave drag a factor? What steps were taken to reduce this form of drag?
5. Stability	Was the craft stable? How was stability achieved?
6. Analysis	Did the report compare the various aspects of theoretical performance elements with actual performance?
7. Testing	How was the final design chosen? What series of tests guided the evolution of the design?
8. Integration	Did the final design represent an optimal balance between conflicting design considerations?
9. Competition	This element with a maximum value of 10 is weighted by multiplying 10 by the ratio of the best time in the race to the best time of a particular team.
10. Short report	Did the report address the key design elements.?

1 Reverse Engineering Project

In this project students propose to study an engineered object and determine the design details (How was it made? How does it function?). It is used as the final project of the semester. As with the Rube Goldberg and surface tension projects, teams are expected to include a strong analytical component in their study and perform quantitative testing. Although the time allotted is relatively short (about 3 weeks), at this point in the semester, teams should be working efficiently and a high quality of performance is required.

The study of engineered objects around us can lead to important insights about design and the design process. Reverse engineering usually involves the methodic disassembly and re-assembly of a device taking care to document, test, analyze, and report on the study of its' function. Stanford University[7] offers a "mechanical dissection" course based upon this concept. Whereas, the mystery artifact challenge was a capsule introduction to reverse engineering of assigned artifacts, the reverse engineering project is open-ended; requiring students to choose an engineered device and perform a broad and detailed study of the factors and constraints that dictated its' final form. The reverse engineering project can provide an interesting, valuable experience and challenge to integrate and apply growing skills. The process of reverse engineering a well-designed product can uncover a wealth of subtle innovations, which can lead to a lasting respect and wonder about "simple" objects around us. Often a superficial simplicity keeps us from appreciating design elegance.

1.0 Reverse Engineering Project Learning Goals

Responding to the project challenges will provide a range of valuable experiences. The fact that the objects usually represent evolutionary designs means that students can not only analyze an object in its' present form, but also can study the dynamics causing design changes with time. Also, the needs for testing and analyzing will confront teams with the challenge of inventing methods for study, within constraints of time and available resources.

Reverse engineering brings to bear skills of analysis, design of investigative approaches, and testing methodology, documentation, data taking, use of spread sheets, graphical representation, and creative design. This is accomplished in a framework of sensitivity to manufacturing and marketing factors.

The reverse engineering project learning objectives are quite broad. These are summarized below:

- Documentation of design
- Analysis of design
- Learn about design by example
- Design and execute quantitative tests
- Discovery of design principles by understanding the design attributes producing its' functions
- Analysis of consumers of the device
- Create an add or TV commercial, becoming sensitive to the elements of a product emphasized for a specific audience
- Design for manufacturing
- Packaging for customers
- Improving on design, making things better
- Green design- Can it be redesigned to be more environmentally friendly?
- Universal design- Can it be redesigned to be accessible to all people?
- Reinforce lessons learned from course design experiences
- Apply tools, techniques, and team methodologies developed during courses.

4.2 Examples of Conclusions and Results from Past Reverse Engineering Projects

Students are given a series of examples and background information to help guide their project work. For example, a book by H. Petroski[8] (Invention by Design) reviews several simple objects from a reverse engineering perspective. The design history of the simple paper clip emphasizes that when engineers study an object, they tend to see the imperfections and also potential design improvements and solutions to problems. There have been several hundred patents issued for bent wire paper clips over the past century. The author challenges readers to reverse engineer a Gem paper clip, design an improved clip, and objectively measure the gripping forces. The second object studied by Petroski is the pencil. He points out that often it is the analysis of design failures or limitations that leads to improved products. Such a failure analysis study based upon reverse engineering of a spectrum of manufactured pencils led to significant design improvements.

The zipper is a third object reviewed and the design history is developed, including the discovery of Velcro by the Swiss inventor George de Mestal and the development of reclosable plastic bags. This wonderful book also covers aluminum cans, the 777 aircraft, and a variety of structures.

The students are given additional examples, including the fact that the National Transportation Safety Board has "GO" teams on call to be dispatched at a moments notice to the scene of a transportation accident. They apply reverse engineering to go backwards from the evidence at a crash site to determine the cause. Numerous design weaknesses uncovered in this way have helped make our transportation systems safer. Similarly, forensic atmospheric science is used to analyze the aftermath of destructive severe weather events (e.g. hurricanes and tornadoes) to estimate the magnitude and structure of the wind fields causing damage. We emphasize that these analyses have led to improved building codes to help mitigate future damage.

Some examples of the methods and findings from past student projects appear below.

1. Aluminum Can

   Procedures: Measure dimensions
   Weight
   Flow rates (open mouth, closed mouth)
   Force (force required to open)
   Load (to deform and to explode) They used the Civil Engineering "Smash Lab" for these tests.

   Results/Conclusions:
   Requires 550 to 600 pounds to deform
   Requires 725 to 790 pounds to explode
   Wide mouth 8.3 seconds to empty
   Narrow mouth 13.6 seconds to empty
   Ease of recycling is a big advantage
   Calculated that you can stack cans 617 high without damaging the bottom can. This is important for storage and shipping.

1. The Match

Procedures: Historical review

Burn time of matches of different lengths as a function of orientation.
Critical angle to hold a match in the wind. They used a fan for this.
Striking force and match angle They used an air track for these tests.

Results/Conclusions:

Held horizontally a short match burned about 1.7 inches in 30 seconds.
Held at 45 degrees a short match burned about 1.4 inches in 12 seconds.
In a wind it is best to point a match straight down.
The best striking angle was between 35 and 40 degrees from the surface.

1. Fly Swatter

Procedures: Comparative testing of a variety of flyswatters

Measured the pressures on an impact surface from a “swat”. They used a sensitive pressure gage connected to a hole in a flat plate.

Results/Conclusions:

The larger swatters and the ones with a few smaller or no holes produce the largest pressure changes and will give a fly an early warning.
It is better to use smaller swatters with a porous surface.

1. Horner Harmonica

Procedures: History

Measure frequencies of blow holes. They used a spectrum analyzer.
Measure minimum pressure required to produce a clear note.
Constructed a simple U-tube water manometer tp do this measurement.

Results/Conclusions:

Frequency is inversely proportional to the length of the metal strips.
The low-frequency and high-frequency notes require the most pressure.
The range of pressures required is from 1 to 2.5 inches of water.

1. The Toaster

Procedure: Dissection

Dimensions
Temperature as a function of setting
Measure electrical resistance

Results/Conclusions:

The time for toasting ranges with settings from 20 to 34 seconds, if the toaster is cooled between tests.
The time for toasting ranges with settings from 4.7 to 11.7 seconds, if the toaster is not cooled down between tests. Therefore, if you wish quick response let the toaster go through a cycle before you place the toast in.
The toast compartments taper in width from top to bottom. The team Theorized that this would permit smaller, thicker items to be toasted without falling down.

These are samples of a few past projects. There were many others that did excellent jobs of reverse engineering devices of various kinds. One additional one that comes to mind, because of the elegant simplicity of their test method, was a comparative study of the “sweet spots” of tennis racquets. They took video of tennis balls marked with chalk falling from a fixed height and measured the height after impact as a function of the impact position. They were able to create three-dimensional plots of these data which vividly displayed the forms of the sweet spots (which were quite complex).

4.3 Student Products and Grading

The products for the reverse engineering project include a number of elements outlined below. These are addressed in final reports. Most student teams decide to produce a video commercial.

- Documentation of background
  This could include areas of use and a characterization of typical users.

- Where did it come from?

- Was there an evolution with time? Where there distinct transitions of form or use?

- Describe the typical function.

- Summary of any documentation provided

- A definition of goals and methodology

- Document the test methodology created.

- Documentation of the reverse engineering systematic analysis. This could include:
- A list of major components
- Definition of the dissection sequence (if required)
- Description of interactions between components
- Summary of working guesses concerning functions.
- Summary of equations or physical processes that determine the function

- Documentation of procedures

- Summary of results and recommendations

- Identify a market and marketing approach. Creation of an advertisement or possibly a user’s manual.

The grading elements emphasize the close connection between analysis and hands on work (this project usually required a physical dissection). The grading elements appear below.

Reverse Engineering Grading Elements

Report (Total 60)	
Project Goals	------(10)
Background	-----(10)
Test/Analysis Procedures	-----(10)
Dissection Details	------(10)
Results	------(10)
Graphs/Figures	------(10)
Presentation	-----(15)
Commercial	------(15)
Suggestions for Improvement	------(10)

1. Concluding Remarks

The series of three projects are presented to students in the context of exercises and resource opportunities that continue to emphasize the valuable connections between analysis and design throughout the semester. If these projects were presented individually or without this context the impact would certainly be lessened. We continue the work to build bridges between analytical and design courses.

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ALFRED J. BEDARD JR.
Al Bedard is an adjunct associate professor at the University of Colorado, Boulder. He is also a supervisory physicist with the Environmental Technology Laboratory of the National Oceanic and Atmospheric Administration where he researches acoustic, air safety, and severe weather problems. He received his masters and Ph.D from the Aerospace engineering department at the University of Colorado

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