

# **Project-Based Learning Incorporating Design and Teaming**

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## ***Abstract:***

Projects that provide inquisitive design and analysis are utilized in a 1<sup>st</sup>-year engineering and science curriculum at the South Dakota School of Mines and Technology to introduce students to experimentation, data collection, analysis, technical report writing, and presentation. Projects allow for construction of numerical models, development of predictions, and corroboration through experimentation. Currently, four student projects are rotated on a yearly basis and include design of a bungee cord, trebuchet, catapult, and SEESat. Design parameters include opportunities for student teams to model, test, and modify the system for optimum performance. In addition, an experimental project involving the measurement of vibration of a cantilever beam is performed each semester. Instrumentation for data collection is utilized during all projects providing true integration between experimentation and analysis. Assessment results indicate students appreciate challenge where there are clearly outlined outcomes and experimentation is performed with informed supervision. Introduction to both design methodology and empowered self-directed teams is provided through these projects adding value to student learning in the first year.

## ***Trends in First Year Engineering Programs:***

With calls for greater accountability in Higher Education and changes in accreditation standards, the engineering education community has proven to be a highly innovative source for curricular reform and improvement. Nowhere has this been more apparent than in innovations in first year engineering programs. Many engineering programs have found substantial gains can be made by reorganizing and integrating curricular components in math, science, and engineering <sup>[1-5]</sup>. Although the Coalitions programs provided rich resource of materials for integrating curricula, such a dramatic reorganization requires a substantial development effort. Other programs found that many of these same gains can be obtained through incorporating freshman design projects and laboratory exercises <sup>[6-11]</sup>. For programs which incorporate vertically integrated teams, newer developments include the use of a service learning component within the design experience <sup>[12-13]</sup>. Most recently, programs are expanding the first year engineering experience to incorporate experiential learning through the co-curriculum. Such programs might collaborate with Student Affairs <sup>[14]</sup>, through freshman grouping in the dormitories, or through formal development of learning communities <sup>[15-16]</sup>.

### ***Program Composition:***

The first-year engineering and science curriculum, GES 115, at South Dakota School of Mines & Technology (SDSM&T) has been a required course in all 10 engineering programs since 2001. Recently, 3 of the science programs have also added GES 115 as a required course. Approximately 400 students per academic year are enrolled in the course, which is offered in both the fall and spring semesters. The curriculum incorporates elements from project-based learning, cooperative learning, and technology-enabled learning <sup>[17]</sup>. Additionally, a rigorous assessment process has been used since 2003 to drive curricular changes and to assess the effectiveness of the program objectives <sup>[18-19]</sup>.

GES 115 curriculum has also been incorporated into a larger campus initiative aimed at improvement in both student learning and retention beyond the 1<sup>st</sup> year. Each fall, 2 of the GES 115 sections has been linked to 2 English 101 sections. Although links between these courses has not yet been achieved at the curricular level, it has been viewed by students as a positive experience. Attendance is almost perfect in both courses throughout the semester (in itself an anomaly) and student teams from GES 115 (which is required) remain seated together in English 101 (which is not required). In addition, GES 115 is an integral component of project FIRST (Freshman Introduction to Real Success at Tech), an initiative aimed at establishing and fostering student cohorts by grouping them together in the newest dorm on campus. As a new program, FIRST is still working through some of the development components but is essentially the first attempt at incorporating elements of a learning community within the first year experience. FIRST attempts to develop student communities through cohort grouping in the dormitory, by incorporating team experiences through the summer orientation program, and by blocked cohort schedules in some freshman courses. Students enrolled in FIRST are blocked in GES 115, mathematics, mentoring, and English 101. In addition, two sections of GES 115 and ENGL 101 are formally linked.

Comparison of grades between linked and non-linked sections show that the students in the linked sections have a higher class-average grade than their non-linked peers. Thus, it is clear that the students have derived added value to their educational experience by these linkages. One possible explanation for this may reside in the fact that participation in the GES 115-English 101 linked sections and project FIRST is by self-selection, thus, may attract more motivated students.

### ***Project-Based Learning:***

Project-based learning, problem-solving, and technology-enabled learning are concepts that have been widely published <sup>[20-23]</sup>. Within this accepted pedagogical structure there remains arenas of challenge to both instructors and students, especially within a 1<sup>st</sup>-year engineering program. Instructors are often forced to perform a subjective balancing act based on the need to effectively provide significant design challenge and experience to students in a way that does not alienate weaker students yet at the same time provides stimulation to more advanced students. The optimum method to achieve this balance would be to separate students into at least 2 programs following models used by Texas A&M or Purdue University <sup>[1]</sup>. In such a program, students are split based either on math/science preparation or on other pre-university performance measures.

However, at SDSM&T, we have a single program that receives all students regardless of their math and other preparatory background. During week 1 of the term, students fill out a survey where they self-rank using a scale of 1-5 (5 being the highest) for their familiarity using several software programs including Excel, Powerpoint, Word, etc. They also list the courses they are currently enrolled in. Instructors use this information to assign student teams to ensure that strong students are distributed as evenly as possible with weaker students. In addition, many section instructors actively utilize strong students as mentors for those students requiring more assistance. This has proven to be a positive developmental and learning tool for all students.

The primary pedagogical structure for that portion of the course related to engineering design is the utilization of projects that incorporate self-empowered student teams that use an engineered device to collect data to be compared to theoretical equations (functions). Preparation and submission of a team technical report is used to assess if the students gained understanding of the significance of the experiment and how mathematical models are used as predictive tools.

This pedagogical structure is based on establishment of a design project library currently consisting of 4 projects, with an ultimate goal of 6 to 8 projects, that can be rotated over a number of years. The 4 large-scale design projects that have been developed and used in the course include: egg bungee, trebuchet, catapult, and SEESat. Each of these projects fill 5 weeks of the course. In addition to these large-scale design projects, a small-scale project, vibrating beam, fills 2 weeks of the course and includes significant exposure to instrumentation, data collection, and analysis. Approximately ½ of the semester is spent on the small-scale and 1 of the large-scale projects. A brief description of each of these projects is given below.

### Vibrating Beam

This project is based on the inherent vibration of natural materials and how this may be problematic in engineering design. From analysis of a damped spring system based on Newton's second law of motion, a simple homogeneous linear differential equation is derived, and without details, is solved and presented as a 5-variable damped exponential cosine function:

$$y(t) = Y_0 e^{-\zeta \omega_n t} \cos(\sqrt{1 - \zeta^2} \omega_n t - \phi_0) + b \quad (1)$$

where:

$y(t)$  = tip deflection as function of time (m)

$Y_0$  = initial displacement (m)

$\zeta$  = damping ratio (dimensionless) =  $\frac{c}{c_c} = \frac{c}{2\sqrt{km}}$

$\omega_n$  = natural frequency (rad/sec) =  $\sqrt{\frac{k}{m}}$

$\phi_0$  = phase shift (rad)

$b$  = initial offset (m)

Variables included as part of the definitions of damping ratio and natural frequency have been defined during the discussion of spring behavior.

Students use a data collection circuit board that is connected to strain gages on a simple cantilever beam to collect vibration data. Cantilevers are of various length and thickness and can be damped by clamping weight on the free end. Interfacing the circuit board to a PC allows the data to be brought into spreadsheets for analysis. Raw bit data are converted to tip deflections using an equation based on the gage constants and material properties. A plot of tip deflection vs. time yields the vibration behavior for that beam (Fig. 1). Modeling of the vibration data involves students having to make initial guesses for the parameters of equation 1 and plotting the results. By making changes to the value of the variables, the model is fit to the data. If parameterization is unsuccessful and does not converge on the correct variable values, students are given 2 values and finding the remaining 3 is then accomplished. Final parameterization is achieved by using the Solver routine in Excel to minimize the sum of the squared errors between the data and the model.

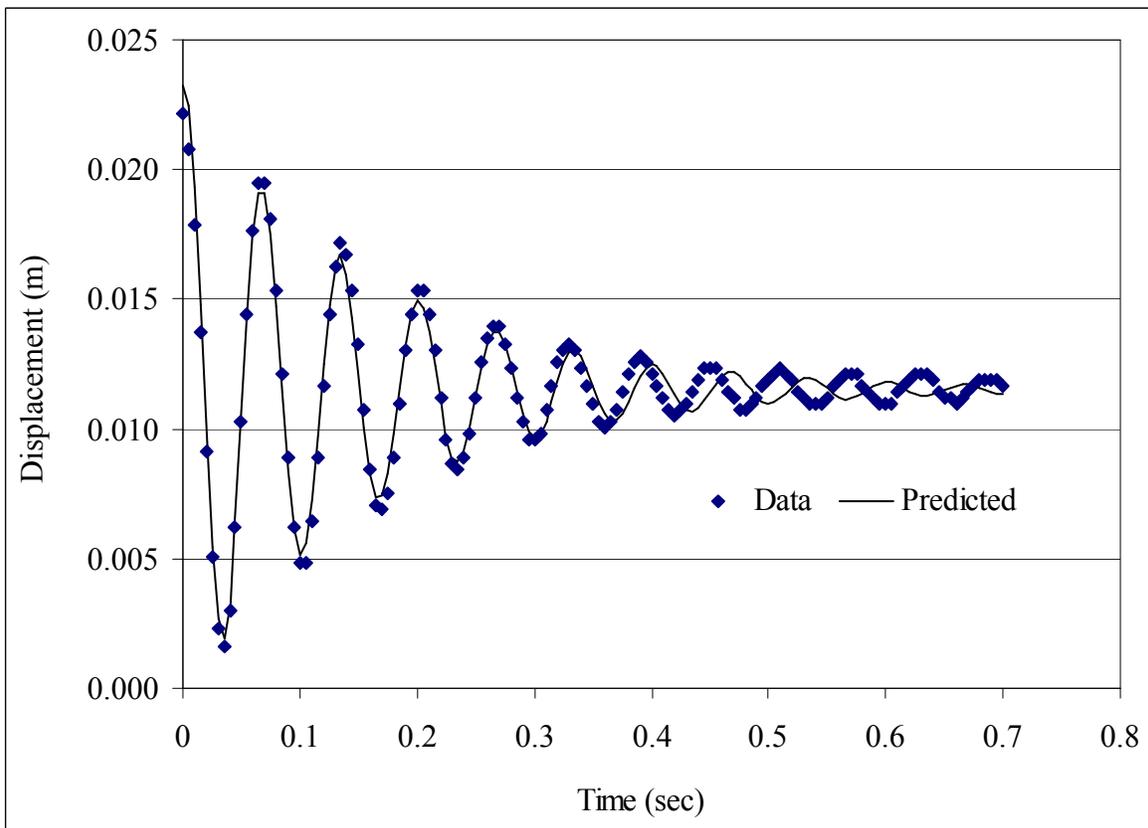


Figure 1. Beam deflection data and model fit using equation 1.

Each team collects 2 to 3 sets of data from 2 different cantilever beam setups and models each for accuracy and repeatability. A team report details their findings where they discuss the significance of the results in terms of the physical experimental setup and their ability to model the vibration correctly.

Initially, some students are intimidated by the development of the differential equation. However, when equation 1 is presented and discussed, they come to realize that the model has

been reduced to fitting variables in a function, an exercise they have already mastered earlier in the course during the problem solving module. These acquired problem solving and function fitting skills are then utilized in the large-scale design projects.

### Egg Bungee

This project is based on a simple analysis of a spring system using Hooke's Law with an overall goal of being able to design a bungee cord that will allow a payload to come as close to the ground as possible without damaging the payload. The basic assumption is that the bungee cord behaves according to Hooke's Law, thus allowing the elasticity constant,  $k$ , to be experimentally derived. Each team is initially provided with 3 strands of bungee cord that are each 3 feet long. Design variables include using stands separately, in parallel, or in series, and payload mass. Drop distance was determined using a sonic motion detector connected to a datalogger from which position, acceleration, and velocity data were collected. From these data, displacement,  $d$ , was determined as a function of mass,  $m$ , gravity,  $g$ , bungee length,  $L$ , and elasticity using:

$$d = \frac{mg}{K} + \sqrt{\frac{m^2 g^2}{K^2} + \frac{2mgL}{K}} \quad (2)$$

A working mathematical model was built from the experimental data that allowed teams to design a bungee cord that estimated the maximum drop distance for a mass. Verification of the model was determined from oscillation damping recorded using the sonic motion sensor in repeated experiments. The culmination of the project involved giving teams an object (an egg) and a drop distance (20 feet) where they had approximately 2 hours to determine the length and number of strands to design a bungee that would drop the egg as close to the ground as possible without breaking the egg. This final analysis also included calculation of maximum force to ensure the egg would not break due to deceleration. Details of the project were written in a technical report and formal presentation by each team specified the bungee model, experimental analysis, and results of the drop.

### Trebuchet

The trebuchet project provided students with fundamentals of both design and physics. The motion of the projectile is a physics problem and the optimization of the throw distance is an engineering problem. All teams were provided a model trebuchet kit that was easily and quickly assembled using bolts. Design options included building either a fixed counter-weight or a hanging counter-weight trebuchet. They also were responsible for the design, materials, and attachment of the sling used to throw the projectile. Wheels could also be attached to the frame for the fixed counter-weight option. All trebuchets were limited to a maximum of 20 lbs. for the counterweight mass, and a maximum projectile mass equal to that of a tennis ball. Variables included sling length, position of the counterweight mass on the throwing arm, and the throwing arm length. Most teams included an optional setting for release angle as needed to maximize the hurl energy into maximum throw distance.

Mathematical models were based on solving for the potential and kinetic energy using variables measured from the actual machine as shown in Figure 2. From kinetic energy, projectile velocity in the vertical and downstream direction were found, and from physics, a range was determined.

Students would make throws with their machine, compare the range to that predicted, and determine a factor that accounted for friction losses. The final model was compared to a table of the actual throw data. A final technical report and presentation detailed the mathematical model predictions, experimental analysis, and the results of the final throw distance for a tennis ball.

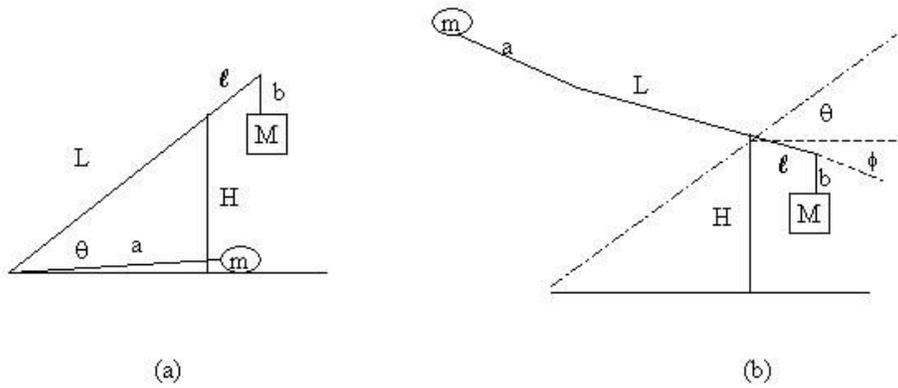


Figure 2. Trebuchet schematic diagram for (a) the cocked position and (b) the release position.

In Figure 1, the following terms are defined as:

- $m$  = mass of the projectile or payload
- $M$  = mass of the hanging counterweight (HCW)
- $L$  = length of the beam from the sling end to the pivot center
- $l$  = length of the beam from the pivot center to the hanging counterweight
- $H$  = height of the trebuchet from the base to the pivot center (axle height)
- $a$  = length of the sling
- $b$  = end of the short arm to the center of gravity for the HCW
- $\theta$  = cocked angle
- $\phi$  = angle from horizontal at which projectile (payload) is released

An additional teaching aspect with the trebuchet project is statistical modeling of the accuracy of the throws. One of the trebuchets was provided to <sup>1</sup>Stat-Ease, Inc., which conducted a statistical experiment involving all of the design parameters and various projectile weights. Their results indicated a ‘sweet spot’ for distance and accuracy when using between 15 and 18 lbs. for the counter-weight throwing a 2.5 ounce payload <sup>[24]</sup>.

### Catapult

The catapult project utilized the frame from the trebuchet where various other parts were built to allow it to be used in a twisted-bundle catapult model. Thus, the frame can be used for either the trebuchet and catapult projects. Catapults are similar to trebuchets in that both operate by energy supplied to an arm that is used to hurl a projectile. The primary difference between the two is the method that energy is supplied, catapults being the more primitive machine. Both machines utilize equations of energy and motion to model throw distance for the projectile, however, the

<sup>1</sup> Use of trade names do not provide product endorsement.

catapult is a much more complicated machine to determine the kinetic and potential energy that is generated.

Design variables for the catapult included material to use in the twisted bundle, design and attachment of a throwing mechanism for the projectile (a tennis ball), and optimization of the release angle.

The energy for the catapult was derived using a twisted rope bundle (students used various types and diameters of rope) wound around the throwing arm. The chapter on the catapult provided 2 methods to determine the amount of torque produced by any bundle, the first being infinitely more complex than the second. The first method models the twisted bundle as a helix and uses an equation of a space curve to determine the amount of tension,  $T$ , produced in the bundle of radius,  $r$ , by cocking the helix by some additional angle,  $\theta$ :

$$T = k\theta\sqrt{r^2 + (L/\theta)^2} \quad (3)$$

where:

- $k$  = elasticity constant for the rope
- $L$  = length of the twisted bundle

Torque was then solved for as a function of the radius of the rope and tension.

The second method utilized a force meter which was assumed to give a direct value for torque when placed at the end of the throwing arm at different cocking angles, thus, eliminating all of the uncertainties associated with using the helix model. Once torque was measured as a function of angle, a plot of torque vs. cocking angle was generated to produce the torque curve. The area under this curve represents the potential energy produced by the twisted bundle. There were 2 methods students used to determine the potential energy, 1 used calculus to integrate a derived equation of the curve and the other used simple geometry estimating the area as the sum of a rectangle and a triangle. Several of the teams having students in calculus opted for the first method. Once the potential energy was found, the modeling of the throw distance was exactly as that used during the trebuchet project (using equations for velocity and position).

A final report and presentation detailed the methods utilized to determine the potential energy and the results of the modeled throw distance vs. the performance from the machine. The model was based on a frictionless system and students were required to detail where friction losses would occur and optimize the model using an experimentally derived friction factor.

The decision to include the helix model method to determine potential energy was made based on past feedback from students who felt they were not adequately supplied with exacting details of the mathematical derivation of the physics involved with the projects. While the faculty agreed that this method was beyond the abilities of most first-year students, they remained sensitive to the desires of the advanced students and included this material. Indeed, many of the faculty began this project at different points and developed either a working theoretical model first or developed experimental data first using the catapult and then modeled that data. Which

ever method ultimately was utilized by the instructors, students were exposed to both experimentation and modeling, thus, fulfilling the project goals.

### SEESat

SEESat (Student Engineered Electronic Satellites) involved construction of an electronic circuit board that was used to collect atmospheric temperature data from the flight of a helium balloon to the outer edges of Earth's atmosphere. The project was based on the Colorado NASA Spacegrant program Starting Student Space Hardware Program II that was attended by one GES 115 faculty member in summer of 2002. Objectives of the program were to provide students an opportunity to work on real satellites and to gain experience with:

- design
- electronic circuitry and soldering
- instrumentation
- data analysis
- introduce students to the rigors of space exploration and the engineering design required to make a successful flight into space

This was from the outset, a non-traditional type of design project. Each student team had their own specific responsibilities (to build and house their circuit) and in addition, there were several other teams comprised of interested students to work on the other areas associated with this project.

Team responsibilities focused around assembly of a SEESat temperature circuit and testing it for several days in varied temperature regimes and then downloading and analyzing the data. All students received detailed instruction and assistance during the soldering portion of the project. Once the circuit was built, students were provided with a small sheet of foam-core board to build their protective housing, which was limited to a maximum volume of  $190 \text{ cm}^3$ . Additional insulation materials were provided to pack the circuit inside the housing. A  $\frac{1}{4}$ " diameter tube was run through the housing that was used to tie all the housings to the payload string.

Supplementary activities for the project were focused in 2 areas: balloon preparation and launch, and tracking and recovery. Students volunteered to become part of a team that was assigned additional responsibilities in these areas. Balloon launch involved all aspects of preparing the balloon for flight including:

- design and construction of a protective housing for the tracking equipment
- determination of payload weight to meet FAA regulations
- final assembly of the payload string
- balloon inflation and launching

Tracking and recovery was centered around the use of a HAM radio transmitter connected to a GPS antenna (flown on the balloon) and receiver (in the chase vehicle). FAA requirements for HAM radio operation specify that each data pack transmitted from the balloon must be accompanied by a valid HAM operators license number. This necessitated acquisition of a HAM operators license and a total of 4 students and 1 instructor took classes and the FAA HAM radio

operators exam during the early part of the semester. Once the balloon was launched, reception of data packets from the flight were received inside the chase vehicle and the information plotted on an interactive mapping program on the notebook PC. The chase vehicle was also equipped with a GPS antenna so both the location of the balloon and chase vehicle were tracked in real time. Ultimately, the chase vehicle recovered the payload after a flight covering approximately 120 miles reaching an altitude of 64,000 feet.

After delivery of the payload back to campus, each team picked up their own SEESat and downloaded the data into a spreadsheet for analysis. A separate program was run to convert the raw bits into temperature data and pressure (altitude) data were provided each team from a single pressure probe that was flown. Figure 3 is a typical temperature-altitude plot from the balloon flight. In addition to the temperature and pressure data, a digital camera was flown that was programmed to take a picture every 3 minutes during the flight.

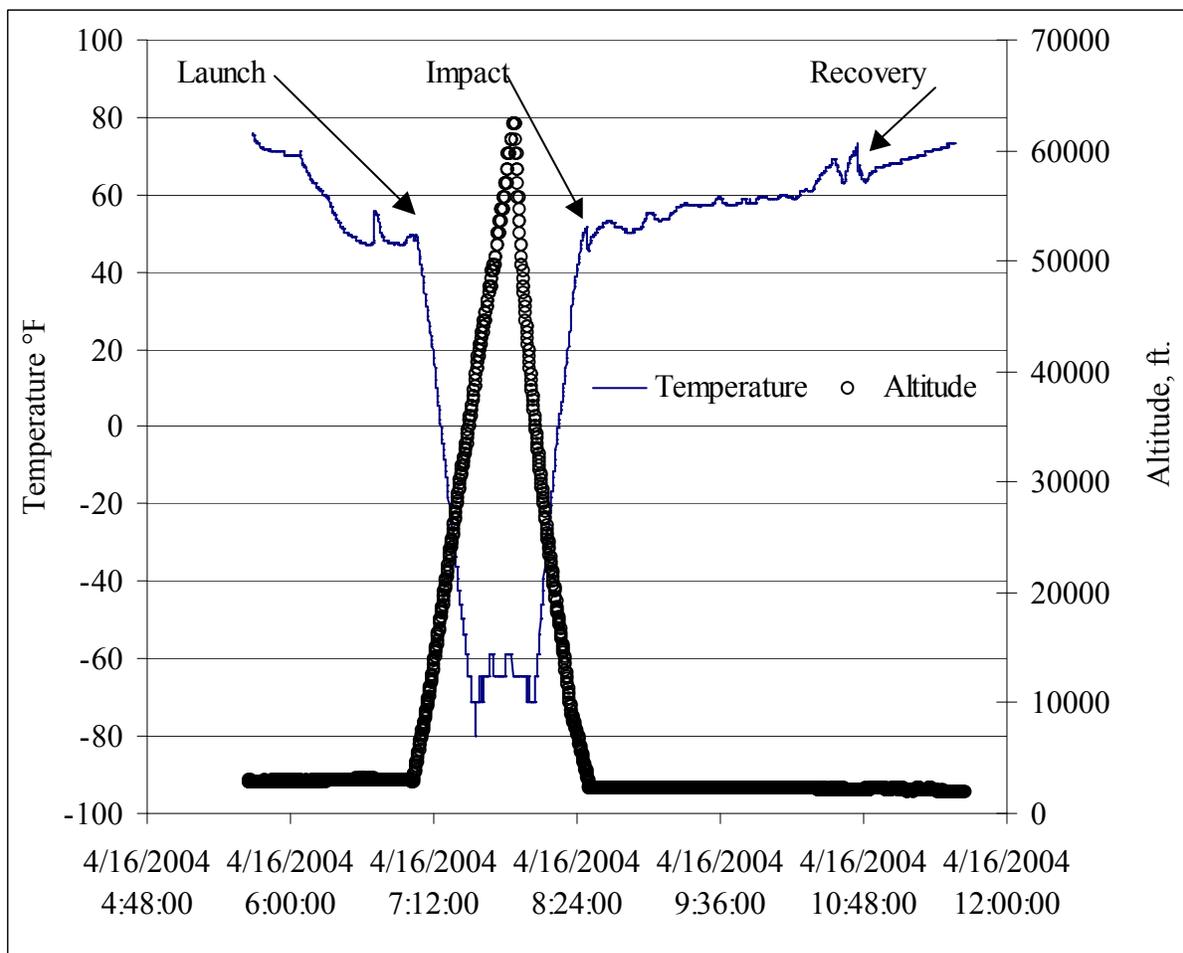


Figure 3. Temperature – altitude plot from SEESat flight of April 2004. Maximum height of 64,000 feet was achieved at a minimum temperature of  $-80^{\circ}$  F.

**Discussion:**

Each of the above described projects are designed to provide students basic training in data collection, analysis, modeling, and technical report writing. Although each project varies in the scope of work required, each incorporates elements of engineering design that are appropriate for first year students. Indeed, these projects have shown themselves to yield excellent results for improving confidence in all students and assessment data indicates that exposure to teaming, problem solving and data analysis techniques, and the projects have been the most important aspects of the course (Fig. 4).

Program assessment has been ongoing as the course has been modified and expanded. Many techniques are currently used for assessment and have been described elsewhere<sup>[18]</sup>. The most recent addition to the assessment protocol has been the inclusion of the Student Assessment of Learning Gains (SALG) that has been administered on a voluntary basis. The SALG is a web-based instrument consisting of statements about the degree of "gain" (on a five-point scale) which students perceive they've made in specific aspects of the class. The survey itself can be easily individualized, provides instant statistical analysis of the results, and facilitates formative evaluation throughout a course. In general, student self-assessment of learning gains is inherently unreliable<sup>[25]</sup>. However, the SALG has been widely tested and has been adopted by the Field-tested Learning Assessment Guide (FLAG)<sup>[26]</sup>. The SALG instrument can spotlight those elements in the course that best support student learning and those that need improvement.

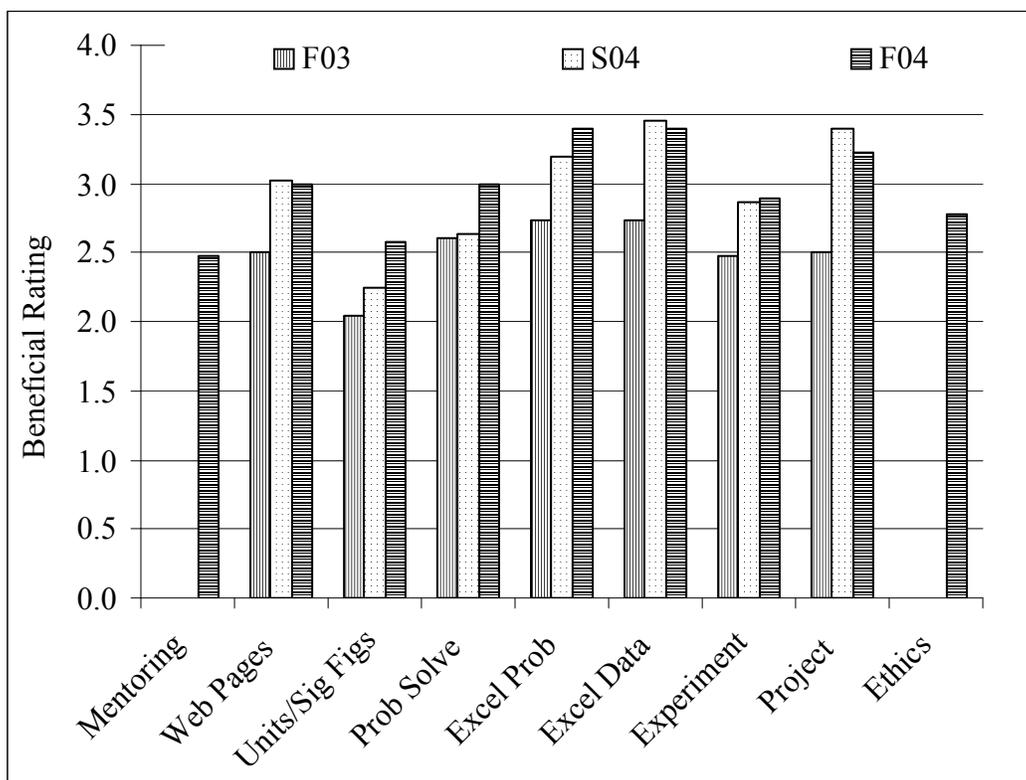


Figure 4. SALG assessment data for course content areas that were rated from 1 (unbeneficial) to 5 (extremely beneficial). Data are from 3 semesters, fall 2003 and spring and fall 2004.

By the end of this course, the large disparity between student preparation that is obvious at the beginning of the term has become invisible at the completion of the course. Those students who

were less prepared academically have been sufficiently challenged and driven to excel through both the curriculum and the more advanced students on the teams. However, such an approach cannot be expected to be successful without a high level of instructor support, which we have strived to provide. Thus, we feel that the problem-based learning approach has not only succeeded in providing a foundation in engineering academics and basic mastery of problem solving techniques but has provided critical personal development as well.

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