Gravity Powered Block Transport: A Freshman Design Project.

Clark T. Merkel, Patricia Brackin,
Department of Mechanical Engineering
Rose-Hulman Institute of Technology

Introduction:

This paper describes a project used for a mechanical engineering, freshmen design course. Its focus is on how this project was used to introduce design methodology through practice with a project-based implementation. Four sections of a freshman design course with approximately 32 students each were divided into 4 person teams and were all given the same design task: design a device which would use a dropping weight to transport a small wooden block while attempting to optimize a number of other design constraints. The design course was structured to introduce and walk the students through the design process, thereby demonstrating systematic examination of the design problem, generation of design ideas, analysis and comparison of different designs, and the process of narrowing down and making the final selection of a design. The design project was capped by having each team construct their final design and compete against each other in a contest to determine which team designed and built the superior project. This paper explains the design problem used and how the design steps were integrated with the project to develop both teaming skills and an understanding of the design process. The paper concludes with subjective feedback on the effectiveness of this design project and its implementation from both student and instructor feedback.

The Freshman Design Course:

Like many other engineering programs, our mechanical engineering program at Rose-Hulman Institute of Technology attempts to include design experiences throughout the curriculum. As part of this overall emphasis, a 2 credit course is currently offered during the spring quarter of the freshmen year. Its primary focus is to offer students their first formalized introduction to the process and methods of design as applied in an engineering context. A wide variety of design methods and team oriented experiences are included in this course to help students learn ways to formalize such diverse skills as idea generation, team building, communication, time management, consensus building, modeling, design evaluation, design selection, working with machine tools, device specification, and documentation. The approach which we have adopted for this course is to choose one main design problem to be addressed across the design spectrum. The students are assigned to teams in the class and work through a number of design steps and activities to find an acceptable solution to the design problem. Near the end of the quarter, the devices that they design are built and pitted against each other in a competition to determine which team created the best design and built the best device.

The Project:

The project chosen for the class offered during the spring of 2002 was to design a device which could transport a 1-1/2" wooden cube through as large a horizontal displacement as possible using only the potential energy source of an elevated, water-filled, 3-liter bottle. Additional design requirements were added to limit the scope of the designs. These design requirements included:

1) The design needed to fit within a 3' x 3' x 3' volume prior to assembly.
2) Any assembly or set-up needed to be completed within 5 minutes after the group was called to demonstrate.
3) The cube was required to start from rest and not be more than 1 foot above the floor surface in its starting position.
4) The maximum height of any portion of the 3 liter bottle could be no more than 8 feet..
5) Each group was to be given two chances to demonstrate their design. The better performance was used for the device performance grade.
6) An performance equation was developed and provided to quantify the performance of the group project. The elements that made up this performance grade will included:

Distance cube traveled from the start position
Weight of design
Creativity of the solution
Aesthetic appeal of the design

7) Penalties for failing to comply with design requirements were also included in the performance grade equation to enforce limits on such items as

Unassembled volume
Setup time
Initial cube over-height
Initial bottle over-height

The exact performance formula to determine the performance of the design was not provided to the students until later in the design process because we wished to encourage an unlimited and unrestrained exploration process of idea generation. This design performance criteria given to the teams during the fourth week of the quarter was

$$Score = 30a + 35\frac{d}{D} + 25\frac{W}{w} + C + S - P$$

where:

a = 1 if the cube movement is at least 12 inches in the horizontal direction
0 if the cube movement is less than 12 inches
d = the distance from the cube's start to finish location (in.)
D = average distance of the top 15% of designs (in.)
w = weight of vehicle (lb.)
W = minimum weight of all designs (lb.)
C = score for creativity (5 points max)
S = score for aesthetics (5 points max)
P = penalty points for violating contest rules

- 1 point for every second over 5 minutes of set-up time
- 5 points for every inch over allowed heights
- 40 points if volume constraint is not met (note: the 3 liter bottle must fit within the volume constraint and is counted when the design is weighed.)

The Design Activities:
To the students, getting the device built for competition may have seemed to be the most important aspect of the project. However, the real purpose of the project was primarily to have them work through a set of design practice activities, exposing them to different design techniques…learn by doing. A short description of the techniques and activities that were completed as either in-class or out-of-class activities associated with the main design project are discussed. In class, these activities were usually introduced by showing an example of how the activities would be used for some example other than the design project. Then each of the teams would be assigned to work through the same steps or techniques for their project. These activities included:
Brainstorming: After introducing the rules of brainstorming using an anecdotal form, and emphasizing the noncritical aspect of brainstorming, the student teams were prompted to work through several rounds of idea generation using the trigger method, thereby generating a wide variety of ideas and subsequencially building on top of existing ideas.
Functional Analysis: A morphological listing was generated which showed different step processes which could be used to convert the bottle's potential energy to horizontal displacement of the cube. Each step in the process was then examined to determine different ways to accomplish each step. These ideas were all put into a matrix structure which allowed different combinations of steps and methods to be examined. This was done as an exercise by the entire class working together using the ideas that each team had produced during their brainstorming sessions.
Design Selection: Teams were given several methods which could be used to eliminate or narrow down the number of ideas to be examined in more detail. The teams were assigned to use the technique of multivoting to reduce the number of design ideas down to their best seven or eight. These ideas would undergo additional development and refinement before being narrowed down to the top three. Later on in the process the teams would use a decision matrix to select the best of the remaining designs.
Design Evaluation: Using the performance measure formula as a starting point, each team was to come up with a set of objectives and constraints that their potential designs should try to meet. A weighting factor was to be associated with each objective. Using these objectives and constraints, a decision matrix was developed which would later be used to evaluate and compare the team's different developed designs.
Task Planning: Teams were given the due dates for the project, including dates when progress reports were due, the competition date, and the presentation dates. They were assigned to develop a list of tasks that needed to be completed prior to each due date and then develop an approximate order and amount of time needed for the completion of each task.
Scheduling: Working from the task list they had developed, student teams were required to come up with a Gantt chart showing the projected completion steps that the team was expected to follow and the time line for carrying them out. This was to be updated as part of their weekly progress reports. The final chart would be part of their final report.
Project Management: Each team was assigned to fill out a member responsibility form which formalized which member would take primary responsibility for overseeing each of the tasks to be completed. Taking responsibility of the task did not mean they were

responsible to complete that task as an individual, but to ensure that the team was working to complete that task in some manner.

Meeting Skills: During Weeks 5 to 9 of the quarter, teams were assigned to have weekly meetings with different members being responsible for leading and creating an agenda, submitting a progress report, and taking meeting minutes for each meeting. All of these items were to be submitted to the instructor for review. Additionally, during one of the weekly meetings, the instructor would attend and provide feedback on the procedure used to conduct the meeting.

Project modeling: Each team was expected to attempt some type of modeling of their top three designs. Modeling could be done using a variety of methods such as modeling their design mathematically, graphically, using simulation programs, or building a small physical model. The model was to be used to make a prediction of the performance measure before actually building their final design. An explanation of the modeling process was a required part of the final report for the project.

Project Construction: The students were responsible for building their own design and having it ready for the competition. Early in the quarter, the students had been assigned an individual machining project to introduce them to machine shop and the tools that were available for their use. Most designs developed for this project did not require advanced construction skills so most teams had little difficulty building them. Many teams did find, however, that upon construction and testing, many of their devices required some additional redesign work.

Project Competition: Our competition was held on a weekend in the large in-door track facility on our campus. It was treated in some respects similar to a track meet competition. Each team would have two attempts to assemble and demonstrate their device. The specific rules of the competition day and the scoring sheet are included at the end of this paper as Addendum 1 and 2. Each team was required to provide one volunteer to help run the competition. This provided the officials to measure and record time, distance, weight, and size which were used to determine the performance of each design. Awards in the form of certificates and trophies were created for the competition. Team photos were a compulsory part of the competition schedule.

Presentation: During the final week of the quarter, each team gave a PowerPoint presentation on their project. The primary purpose was to give the teams practice with presentation skills. Since there were a wide variety of designs, it also provided a forum to reinforce the concept that there are often many different, yet successful, ways to solve the same problem. It also gave the teams insight into how their team might have approached the problem differently.

Team assessment: All team members were required to complete an assessment of their team members and themselves. This was done twice during the quarter. The first assessment was done early enough in the quarter to determine if any team was dysfunctional, thereby giving the instructor's time to provide intervention, if needed. The assessment also helped track individual member's performance and was particularly useful to determine if any team member was working below the team's expectations. The final assessment was also used to assign small shifts in grade depending upon if a member excelled or was deficient in the opinions of their teammates. A copy of the team citizenship form used for this assessment is included as Addendum 3.

Project assessment: During the final two weeks of the quarter, all students were asked to provide feedback on their teaming and design experience. The questionnaire given during week 9 is provided as Addendum 4. Additionally, during week 10, they were asked to provide a reflective essay in their lab books which responded to the following two statements.

1) *Identify three or more, items, things, or aspects about your project, your team, or your design process that worked well and that you were happy with. Discuss why each of these items pleased you.*

2) *You are also to identify three items, aspects, or concerns about your project, your team, or your design process that didn't go well as you would have liked and could be improved. Discuss why each of these items was less than ideal, and discuss what could have been done to give a better result.*

Project Documentation: Throughout the quarter, students were responsible for keeping a log book. This was to detail the progress made on the design project as well as other in-class exercises and assignments. In addition to the documentation of activities already described, other documentation included creating preliminary drawings and descriptions of possible exploratory designs, CAD drawings of their final design, a final report, and a PowerPoint presentation. The requirements for the final report that the students were required to submit during week 10 of the quarter are included in the Addendum 5.

Results:

As a whole, this choice of design project worked very well for a freshman design class. Each of the 33 teams who worked on the project designed and constructed a device which successfully exceeded the minimum motion requirement. Even better, the 33 teams produced a reasonable variety of solutions to this design problem. These designs have been categorized as seven different varieties of solution. These included:

- 14 Throwing Devices (different variety of catapults)
- 6 Flinging Devices (similar to trebuchets or variations)
- 6 Impact Devices (typically a pendulum used to collide with block)
- 4 Pulling Devices (wheel or pulley systems used to pull the block back towards the device)
- 1 Spring Activated Device (stretching of elastic cords and release)
- 1 Gravity Powered Vehicle (carried block, bottle, and structure together)
- 1 Rotational Spin and Release Device.

The wide variety of solutions demonstrated that many teams had taken the brainstorming and idea generation activities to heart, producing some innovative and creative ways of solving the design problem. Even within the most common category (the throwing devices), there were a number of unique and creative ideas developed and used. Best of all, from an instructor's point of view, one of the nonobvious solutions turned out to be the best design for this problem. The top two overall devices in our competition were ones that used wheels to pull the cube instead of tossing it. Comments from some of the student's project assessment essays during the final week of class indicated that some groups selected their final design choice at a very early stage of the process, and never seriously considered alternative designs even as they worked through the design activities which were to help them to do just that. Jumping to too a quick conclusion is a common and bad design habit, and this project provided one example where additional insight and creativity did, in fact, produce a better solution than the most commonly preconceived solution. From the student's essay comments, the success of the nonobvious designs validated the effort it took to work through the in-class activities and the design steps. Overall, students seemed genuinely interested and enthused about designing and constructing this project and getting ready for the competition against each other. While there were some complications during the competitive event due to poor event planning, the comments show that the overall experience was positive.

Students also expressed that they felt that they had gained teaming skills. In analyzing the teaming evaluations from the 33 teams, only 5 of the 33 teams had serious problems. The major problem in each of these 5 teams was a group member that did not want to work with the team. In three of the five cases, there was one unmotivated individual. During group meetings we discussed methods for motivating students, but three students just did not want to work on the project. In one case, the group member was an excellent student who did not trust the others and insisted that his ideas be followed. Repeated suggestions by the instructor also went unheeded. As it turned out, his ideas were not the best and each of the group members learned a lesson: the two members who did not stick up for their ideas are resolved to do so in the future and the excellent student has indicated he will be more willing to listen to others next time. In the final case, the student was from another culture and had a hard time stating his ideas, particularly if they were different from others. He and his group members indicated that he improved tremendously throughout the quarter, but he will need to continue to work in this area.

On the flip side, not all students acknowledged the value of the formalized design exercises and steps. A number of students indicated in their project feedback assignments that they felt the design exercises they were assigned to work through slowed them down and wasted their time. It was commented that much of the design process was really common sense and by completing it, time that might have been used to fine tune their final design was short. Others students found that the most challenging aspect of the design problem was learning how to work with a team of individuals who often seemed to be working toward different goals or not communicating very well.
In fact, lack of communication was the most common comment in the student's reflection essay about what they could have been done better.

As to the results of our actual design competition, the maximum block displacement achieved by the top team was 292 ft. The average distance based on the 33 teams that competed was 218 ft. The lightest design weighed 10.25 lbs. Using the weighted design performance criteria described in this paper, the best design performance was scored at 97.7, the minimum performance score was 47.7, and the average performance score of the 33 projects was 65.6. The wide distribution of performance indicated that the project was challenging, but not overwhelming to the students. The majority of the top groups indicated that they had followed the design process and found it beneficial to their project's success.

Conclusion:

This design project which used a water filled bottle to cause the displacement of small wooden cube turned out to be a challenging and successful project for a freshman level design course in mechanical engineering. The project offered a wide variety of different possible solutions which students were able to design and construct with their current skills. It also proved to be an effective method for demonstrating the design process and introducing teaming skills. By the instructors estimation, around 85% of the groups functioned as successful teams and indicated that they had learned teaming skills. 60% of the projects were judged as good or excellent by the instructors. Even students who did not value the design process were aware of the phases of the process.

The project was characterized by a number of attributes which made it a good project for this class. These attributes included:

--not too technical (to match students skills at freshman level)
-- limited in scope (able to be completed in 8 to 10 weeks)
-- provided opportunities to introduce and practice design activities
-- allowed simple designs which were able to be constructed by student efforts
-- required team participation to construct and test
-- not too expensive to build
-- open to solution by different conceptual methods
-- readily modeled with simple mathematical and other modeling methods
-- easily adapted to competitive testing and performance
-- fun yet challenging

The range of group performance obtained on this project indicates that the difficulty of the project was appropriate. There were designs that clearly outperformed the others and students saw that the nonobvious solution was superior in this instance, thus emphasizing the need for exploring alternatives. This particular project has been used only one quarter, so far, but the authors have found it to be a good design choice for their freshman design class. It provided a robust vehicle which supported an introduction to the varied and diverse skills and processes of engineering design.

Examples of the Gravity Powered Cube Displacement Designs:

Top Left: A wheeled block-pull device.
Top Right: A flinging device
Bottom Left: A transport vehicle.
Bottom Right: A spin-and-release device

Addendum 1: Competition Rules

<u>Cube Displacement Competition Rules and Procedure:</u>

Date: Sunday, May 5
Time: 1:00 p.m. to 4:00 p.m.
Location: SRC main floor

Sign In: Table in front of Wrestling Room
Weigh In: Wrestling Room
Set Up: Along East wall of Main Room SRC.

There is a not strict starting time for your competition. Sometime between the hours of 1:00 and 3:00 p.m, your team will need arrive at the SRC, sign in, and compete with your device.

Upon arrival, each team needs to sign-in at the table outside the wrestling room.
At the table you will need to fill out two forms:

1) EM103 Cube Displacement Documentation Form:
2) EM103 Information Display Sheet:

Take both completed sheets with you to the wrestling room, where your design will be tested for both volume compliance and weight. Have the Weight and Volume Compliance recorded on both sheets by the weighing official.

Proceed into the main room and locate a spot to set up your device along the east wall.

When you are ready to proceed with assembly, turn your <u>EM103 Cube Displacement Documentation Form</u> in at the sign-in table. Display your <u>EM103 Information Display Shee</u>t on or near your project. Projects will be processed in the order by which the <u>EM103 Cube Displacement Documentation Form</u>s are submitted.

Do not begin assembly until a site official indicates for you to begin. You will have 5 minutes to assemble your device before a penalty will be applied. If you successfully complete assembly within 5 minutes on your first attempt and <u>do not modify</u> your design between attempts, you will <u>not</u> have to reassemble your design for the second attempt.

After assembly, the maximum bottle height and maximum cube height will be measured before activation of the device. Initial location of the cube will be marked. After activation, the displacement of the cube will be measured along a straight, horizontal line.

After your second attempt, if your cube is not visible, you will need to demonstrate that the object that was displaced did contain a cube.

Before disassembling your design, you need to

a) Get a picture taken of your design which clearly shows the completed EM103 Information Display Sheet.

b) Have a faculty site official verify that all the information required has been measured and have them initial your <u>ME103 Cube Displacement Documentation Form</u>..

c) Turn in your <u>EM103 Information Display Sheet</u> at the sign-in table.

Top Teams will be determined for each section by the determination of the maximum Score.

Addendum 2: Competition Documentation Form

EM103 Cube Displacement Documentation Form:

Section:_____________ Team Number:__________________________

Team Members present at testing:	Team Members not present at testing:
_________________________________	_________________________________
_________________________________	_________________________________
_________________________________	_________________________________
_________________________________	_________________________________
_________________________________	_________________________________

Generic description of device: ____

Device will be assessed by the metric:

$$\text{Score} = 30\,a + 35\frac{d}{D} + 25\,\frac{W}{w} + C + S - P$$

where a = 1 if cube displacement is more than 12 inches, otherwise a = 0
d = is horizontal distance from starting point to center of cube
D = average distance of top 15% designs
w = weight of prototype (including bottle and cube)
W =minimum weight of all designs
C = Creativity Score (5 pts max)
S = Aesthetics Score (5 pts max)
P = penalty points for rules violations

Total Weight:		Performance		Score:		
		Attempt 1	Attempt 2	1	2	Max
Cube movement (more than 12 inches)		Yes No	Yes No			y=30 n=0
Total cube displacement (from start to finish) [12*ft]						35 max
Total Weight (including Bottle and Cube) [lbf]						25 max
Creativity (5 pt scale) very-5 above-4 average-3 below-2 little-1 none- 0						5 max
Aesthetics (5 pt scale) very-5 above-4 average-3 below-2 little-1 none- 0						5 max
Penalty Points:	Total Assembly Time (TT):					0 if t<300s t-300 if t>300
	Bottle Over Height					5*OH
	Cube Over Height:					5*OH
	Exceed Volume:	Yes No	Yes No			y=40 n=0

Total:___ ___

Picture taken _____ Measurements complete: _______

Comments:

Addendum 3: Peer Assessment Form

Team Citzenship Rating Form: Name: ___________________________

EM103 Introduction to Design Date: ________________

Rose-Hulman Institute of Technology

Please write the names of all the members of your team, INCLUDING YOURSELF, and rate the degree to which each member fulfilled his or her responsibilities. Such responsibilities include:

1. Respect for Others	4. Responsibility
2. Communication	5. Leadership
3. Cooperation	6. Participation
4. Organization	8. Motivation

Your responses are used to assign individual grades from the group grades. Your responses are confidential. The possible ratings are:

Excellent	Consistently went above and beyond; tutored teammates, carried more than his or her fair share of the load.
Very good	Consistently did what he or she was supposed to do, very well prepared and cooperative.
Satisfactory	Usually did what he or she was supposed to do, acceptably well prepared and cooperative.
Ordinary	Often did what he or she was supposed to do, minimally well prepared and cooperative.
Marginal	Sometimes failed to show up or complete tasks, rarely prepared.
Deficient	Often failed to show up or complete tasks, rarely prepared.
Unsatisfactory	Consistently failed to show up or complete tasks, unprepared.
Superficial	Practically no participation.
No show	No participation at all.

These ratings should reflect each individual's level of participation, effort, and sense of responsibility to achieving team goals, not his or her academic ability.

Name of team members (including yourself)	Rating
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________
______________________________	______________________________

Your signature ____________________________________

Ref. 1. Kaufman, D.B., Felder, R.M., and Fuller H., Peer ratings in cooperative learning teams, in proc. *ASEE Annual Conf.*, Charlotte (Jun 1999).

2. Layton, R.A. and Ohland, M.W., Peer ratings revisited: focus on teamwork, not ability, in proc. *ASEE Annual Conf.,* Albuquerque (Jun2001).

Addendum 4: Project Feedback Questionnaire:

EM103: Teamwork Feedback Survey:

1) Approximately how many different solutions do you believe your team seriously considered?

2) Did you analyze all alternative design ideas without bias? Did your team members?

3) Were all group members given the chance to participate equally?

4) Did any team member become dysfunctional or was ostracized by the other team members?
If so, why?

5) Do you feel your use scientific principle and analysis tools were used appropriately and gave an accurate model?

6) Did your team stick to the timelines that were set up?

7) Did your team stick to the budget guidelines that were set up?

8) Compare your current teamwork experience, with previous teaming experience. Were the tools introduced in this class successful in improving how well your team was able to function together or was there little value in the tools? Which tools would you use again?

9) What has been a major weakness, difficulty, or failure of your team?

10) How do you see your teammates? Try to predict each of your teammates main Interpersonal Style. List their names below and select the one style that you feel best describes them: Dominant, Influential, Conscientious, or Steadiness

____________________________ ____________________________

____________________________ ____________________________

Addendum 5: Final Report Requirements

Final Documentation
EM 103 Introduction to Design
Department of Mechanical Engineering
Spring 2002

The final documentation for your project includes 5 components:

Lessons Learned: The purpose of doing a design project is to allow you to learn about the design process, teaming, fabrication and testing. Your team should submit a paragraph detailing what you have learned. Record anything you learned during the project that might help you avoid problems on future projects. Often the lessons learned include at least as much discussion of organizational, personnel, procurement, and scheduling problems as it does discussion of purely technical problems.

Gantt Chart: Include a final Gantt Chart that details the activities and the **actual hours** that your team spent on the project.

Decision Matrix: Include a copy of your decision matrix. Write a brief description that indicates your rationale for rating the projects as you did. For example, "We rated our 100 ft track idea a '2' in weight because it would be much heavier than our other solutions."

Detail Drawings: Describe your final design in sufficient detail that a skilled craftsman could duplicate your device. This will likely include part and assembly drawings. Be sure to use a professional package (AutoCad, Mechanical Desktop, IronCad, etc.) to produce your drawings.

Mathematical Models: Provide a summary of the methods you used to design, model, and predict the behavior of your final project design. Indicate what methods you used and give additional details explaining your modeling techniques. If you created a Working Model simulation include screen snap shots of the simulation and indicate any parameters set in the simulation. If you modeled it using mathematical equations, show your equations, parameters used, and any detail drawings needed to understand your calculations. If you built a scaled down physical model, take digital photos of your prototype and discuss how you were able to experiment with it to refine and improve your design. Whichever method(s) you used to model your project, we will be looking for evidence that you created a model that allowed you to modify different parameters of your project design to test and improve your design performance before actually building the project. After final testing your project, you are to compare how well your model or simulation predicted your final performance outcome.

Due Date for Final Documentation: Friday, 5 p.m. of 10th Week.