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A Rube Goldberg Approach to Teaching Dynamics of Machine Elements

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ABSTRACT

Dynamics of Machine Elements is a junior-level course in mechanical engineering that covers the kinematics (motion) and kinetics (causes of motion) of machine elements such as linkages, cams, and gear trains. This paper describes the results of adding a Rube Goldberg Machine Contest® project to the course to address student concerns over the lack of interactivity in the previous lecture-only format. The goals of the project were to give students experience designing, analyzing and implementing a variety of machine elements in a hands-on manner. On a post-survey, many students reported that the open-ended nature of the project was very challenging yet did not help them learn the content, but it did help them develop other skills, such as manufacturing and design, and helped them learn to work with new people. Peer evaluation scores on contributing to the team's work, keeping the team on track, and expecting quality improved significantly over the term.

Key words: Design project, Kinematics, Machine Elements, Rube Goldberg

INTRODUCTION

Dynamics of Machine Elements is a junior-level course in mechanical engineering at Louisiana Tech University that covers the kinematics (motion) and kinetics (causes of motion) of machine elements such as linkages, cams, and gear trains. Previously, the course has used a lecture-only format that left students frustrated with the lack of interactivity, as evidenced by senior exit surveys listing the course as the worst in the program. This paper describes the results of a Winter 2013–2014 pedagogical innovation to add a Rube Goldberg Machine Contest® project to the course.

This course was built on the philosophy that hands-on project-based pedagogy will motivate students to learn the technical concepts necessary to complete their projects, and that they will develop a strong visual and physical understanding of real-world engineering problems. This approach has an added advantage in that it adds a junior-year design experience that emphasizes divergent thinking. A common problem in design is that students commit to a particular solution too early, before considering a wide array of options (Sheppard et al. 2008). Since the Rube Goldberg Machine Contest® rewards excessive complexity and unusual steps, students have an added incentive to divergently explore a variety of ideas. Rube Goldberg projects have been used in K-12 (Jordan and Pereira 2009) and collegiate (Graff et al. 2011) classrooms for decades to teach STEM. For example, Pierson and Suchora (2002) had undergraduate freshman engineering students design Rube Goldberg-inspired timer devices. Other faculty have used Rube Goldberg to teach engineering dynamics (Berg 2015) and as an introduction to Vex Robotics (Sirinterlikci and Acharya 2010). Jordan et al. (2012) used Rube Goldberg designs as a context for a design swapping experiment.

The goal of the project was to give students an opportunity to gain experience in designing, analyzing, implementing, and integrating a variety of machine elements to accomplish a task. Most tasks would traditionally have a simple, closed-ended solution, so a Rube Goldberg-style approach was utilized to maximize the design space and promote creativity. The 2014 challenge was to design and build a device that will zip a zipper. The class project required that students adhere to all competition rules (including designing as many steps as possible into their machine), with an added requirement that each team use at least four different mechanisms and provide a thorough kinematic and kinetic analysis of each step, including computational simulations where appropriate. The simulations integrated concepts learned in a pre-requisite course, Computer-Aided Modeling.

Project-Based Learning

Project-based learning is a constructivist pedagogical technique where students are introduced to open-ended problem solving (Prince 2004) "to carry out one or more tasks that lead to the production of a final product" (Prince and Felder 2006). Project-based learning environments have the following five key features: (1) they start with a problem to be solved; (2) students explore the problem by engaging in situated inquiry; (3) students and teachers collaborate to find solutions; (4) learning technologies are used to support student inquiry; and (5) students create a tangible product that solves the problem (Blumenfeld et al. 1991; Krajcik et al. 1994; Krajcik, Czerniak, and

Berger 2002). Project-based learning is typically used in capstone design courses (Pembridge and Paretti 2010), but some universities emphasize it throughout their undergraduate curriculum (e.g., Olin College (Bourne 2001), Harvey Mudd College (Phillips 2000), and the Arizona State University Polytechnic School (Danielson et al. 2005; Roberts and McHenry 2004; Roberts et al. 2007)). Some university engineering programs (such as Arizona State University's Polytechnic School) implement project-based learning in order to meet ABET engineering accreditation outcomes including "an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics", "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors", "an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives", and "an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions" (ABET Engineering Accreditation Commission 2018). Project-based learning has been found to motivate students by engaging students in authentic problems (Blumenfeld et al. 1991), and is called for in Sheppard et al.'s *Educating Engineers: Designing for the Future of the Field* (Sheppard et al. 2008).

Context

Mechanical Engineering at Louisiana Tech University

Louisiana Tech University is a four-year, selective admission, public research university that awards bachelor's, master's, and doctoral degrees and is located in northern Louisiana. In 2013, the total enrollment was over 11,000 students, with 2,376 in the College of Engineering and Science. The College of Engineering and Science consists of eight engineering programs (biomedical, chemical, civil, cyber, electrical, industrial, mechanical, and nanosystems engineering), two engineering technology programs (construction and electrical engineering technology), and four science programs (chemistry, computer science, mathematics, and physics). Mechanical engineering is the largest of the engineering programs at Louisiana Tech University.

In their first year, all engineering students take the "Living with the Lab" Integrated Curriculum (livingwiththelab.com) where they work in self-selected pairs and teams to learn fundamental engineering, science, and math concepts and implement them using student-owned labs. Instead of purchasing a textbook, students purchase an Arduino® microcontroller, a parts kit to construct a robot, a multimeter to test electronic circuits, safety glasses, a dial caliper, software and other tools. Students use, maintain, and "live" with this lab throughout the year, later adding a 4x20 character LCD panel, drill bits, a breadboard and a few other supplies. Replacement or supplemental sensors and LEDs are available 24/7 from a vending machine in the main engineering building. In their sophomore year, students continue taking core engineering courses and start to branch off into coursework within their discipline. In their junior and senior years, students primarily take mechanical engineering courses, including a year-long industry-sponsored senior capstone.

This paper focuses on the junior-year Dynamics of Machine Elements course, which examines the kinematics and kinetics of machine elements such as linkages, cams, and gear trains. Pre-requisite courses are Computer-Aided Modeling and Dynamics. The course is not a pre-requisite for any other courses, so students have the option to postpone it to their senior year. Louisiana Tech is on a quarter academic calendar, but the unit of academic credit awarded is the semester credit hour (SCH). This is accomplished in a 10-week quarter (as opposed to a 15-week semester) by increasing the amount of contact time per class meeting. Three quarters (Fall, Winter, Spring) equals two semesters. On the quarter calendar, eight SCH is considered full-time and 12 SCH is the maximum a student may take without special permission. Dynamics of Machine Elements is a 3-SCH class that met for 75 minutes Monday, Wednesday, and Friday for 10 weeks in the Winter quarter (December-February). Students successfully completing the course should be able to:

1. Define terms associated with motion and constraints in machine components and apply these definitions to determine the mobility of planar kinematic chains
2. Calculate the position, linear velocity, and acceleration of any point in a planar mechanism and the position, angular velocity, and acceleration of rigid body components of the mechanism using graphical and computer tools
3. Synthesize mechanisms that will achieve required position configurations.
4. Generate cam follower motions and disk cam profiles that generate required lifts subject to specified acceleration constraints
5. Analyze the velocity ratios of simple, compound, and planetary gear trains
6. Compute inertial forces on moving components of mechanisms and the resulting shaking force transmitted to the foundation
7. Calculate the masses that must be added to thin and thick rotors to achieve static and dynamic balance
8. Analyze the inertial forces associated with single and multi-cylinder reciprocating engines

As shown in Table 1, the course began with the classification of mechanisms and their mobility (degrees of freedom), followed by the synthesis and analysis of linkages. There were three exams worth a total of 65%, homework worth 10%, and the Rube Goldberg project discussed in this paper was worth 25% of the overall grade.

Table 1. Weekly Schedule of Topics.

Week	Topics
Week 1 (partial week)	Mobility, Classification of Mechanisms, Position Synthesis of Linkages
Week 2	Position Synthesis
Week 3	Position Analysis, Exam 1
Week 4	Velocity Analysis
Week 5	Acceleration Analysis
Week 6 (partial week)	Cam Design
Week 7	Gear Intro, Exam 2, Project Time
Week 8	Gear Trains
Week 9	Dynamic Force Analysis
Week 10	Balancing, Engine Dynamics, Rube Goldberg Machine Contest®
Week 11 (partial week)	Multi-Cylinder Engines, Final Report due, Exam 3

The course included a semester-long project where students designed Rube Goldberg machines and entered them into a Rube Goldberg Machine Contest®, described below.

Rube Goldberg Machine Contest®

The Rube Goldberg Machine Contest® is an international competition devoted to the design and demonstration of contraptions that complete a simple everyday task in an absurdly complex manner. The contest promotes STEAM (Science, Technology, Engineering, Arts, and Math) education in a team project-based competition setting. The competition was inspired by Rube Goldberg, a Pulitzer Prize-winning cartoonist who was best known for his sketches of crazy inventions that parodied how technology and government sometimes unnecessarily overcomplicates our lives. Rube Goldberg graduated from University of California – Berkeley with a degree in engineering and worked as a sewer engineer for the City of San Francisco prior to pursuing cartooning full-time with the San Francisco Chronicle and later with Hearst Corporation in New York City (George et al. 2013; Marzio 1973; Wolfe, 2000). The estimated 50,000 cartoons he drew during his life earned him the honor of being the only person to be listed as an adjective in the Merriam Webster Dictionary ("Rube Goldberg" n.d.).

Each year, the competition challenges both pre-college and college students to design and build machines that complete a simple task defined by Rube Goldberg, Inc. Previous tasks include inflating and popping a balloon, watering a plant, juicing an orange, and teeing up a golf ball. During the time of the Dynamics of Machine Elements course, the task to be completed by all machines entering the competition was to zip a zipper. Teams are given a set of specifications, including a minimum machine complexity (measured in "steps"), maximum physical size of each machine, and limits on the number of power and water sources running to the machine. Machines must also be safe and not use hazardous materials, explosives, or flames. Machines can use mechanical, electrical, and chemical steps as long as they fall within the required specifications.

During the competition, teams have 2 minutes to give a verbal presentation of their machine, followed by 2 – 3 demonstrations of their machine for the judges. Machines are judged prior to the demonstration on the presentation of the steps in a written step list, the inclusion of a theme or story, comedic value, absurd complexity, team communication and chemistry, and the use of everyday items. During the demonstrations, teams are judged on their verbal presentation of the machine and machines are judged on the inclusion of Rube Goldberg-style steps, the overall flow of the machine, and both the functionality and success in completing the task (to zip a zipper) during 2 demonstrations. Penalties are assessed for human interventions and objects leaving the boundaries of the machine during judged demonstrations. More information on the competition is available at rubegoldberg.com.

METHODS

Participants

A total of 64 students completed the Dynamics of Machine Elements course, consisting of 58 males and 6 females. The course is required for all mechanical engineering students, and most students in the course were majoring in mechanical engineering. For biomedical engineering students who choose biomechanics as their concentration, the course is a common choice to fulfill their mechanical engineering requirement. Dynamics of Machine Elements is typically taken in the junior year, but as it is not a pre-requisite for any other course, students may postpone it until their final year. As noted in Table 2, less than 10% of the participants were female. When classified by credit hours, 55 were considered seniors, however, only 24 were enrolled in a senior design class.

All students were asked to complete a team formation survey at catme.org so that the instructor could assign them into their teams based on their skill set and schedules. One of the most important factors contributing to the success of student design teams is having a common meeting time. According to Layton, Loughry, Ohland, and Ricco (2010, 21), "regardless of what challenges a team faces, team members must interact to address them." Many students were unhappy about being assigned to a team, but since they are allowed to self-select their teams in every other team in the ME curriculum, the instructor felt that it was important for them to experience working with new people at least once. The criteria for selecting teams were:

1. *Similar GPAs*. The student with the highest GPA in a team had at least one teammate with a similar GPA. This ensured that no student would feel dragged down by their teammates.
2. *Common time*. All team members had common free time multiple days each week.

Table 2. Student participant characteristics.

Characteristic	Students
Sex	
Male	58
Female	6
Major	
Mechanical Engineering	61
Biomedical Engineering	3
Classification by credit hours	
Junior	9
Senior	55
Classification by enrollment in Senior Design	
Junior	40
Senior	24
Total	**64**

3. *Different skills*. Fabrication, computational modeling, and writing skills were spread across teams.

There were a total of 16 teams in the class, each with 3 – 5 members. Each team was also assigned to a 16-person "superteam". The instructor tried to accommodate requests for students to be on a superteam with their friends/roommates/senior design team to encourage more interaction between the four-person teams. This setup was selected to keep the team size manageable while guaranteeing that as long as each team developed at least five steps, the superteam would meet the minimum requirement of twenty steps to complete the task. It also confirmed that there would be at least four teams for the competition.

This work was completed in accordance with Lousiana Tech University's Human Subjects Protocol HUC 1282. Unless otherwise noted, photos and videos are from the course website on which students published their work.

Term Project: A Rube Goldberg Machine

The Rube Goldberg Project was presented to the students in the first week of class. Each superteam was asked to create a Rube Goldberg machine that would complete the task of zipping a zipper in at least 20 steps and within a 6' x 6' x 6' space. The Rube Goldberg Machine Contest FAQ defines a step as "a transfer of energy from one action to another action" (Rube Goldberg, Inc. 2013, 8). There were four superteams, each composed of four teams of 3 – 5 members each, for a total of four machines entered in the end-of-term Rube Goldberg Machine Contest®. The steps of the design process are described next.

Write a Story

The Rube Goldberg Machine Contest® rules require that all machines have an observable theme and/or story integrated throughout the machines. Stories provide a narrative helpful in describing machines to audiences, in addition to providing an additional design constraint. The instructor met with Dr. Kenneth Robbins, director of the School of Performing Arts and award-winning author, to discuss successful story-writing techniques. Dr. Robbins suggested the "backwards and forwards" technique for dissecting stories and plays (Ball 1983) to help scaffold the machine story-writing activities. The technique is called backwards and forwards because the reader begins at the end of the play and works backwards to identify the preceding action that directly led to the final event, and then the action that led to the semifinal action. Once the reader reaches the beginning of the play, they can then see the chain of events going forward more clearly. To make use of this technique, student superteams were asked to compose the "story" of their machine by starting at the end. In class, each superteam was given a giant notepad and marker and asked to brainstorm as many types or uses of zippers as they could. Once each superteam had a list, they were asked to pick one zipper idea around which to build a story. This allowed the instructor to make sure no two superteams would have similar stories. Next, superteams were asked to come up with an event that might have immediately preceded the zipping of their chosen zipper. The process of picking an event that immediately preceded the previous event continued until each superteam had constructed an entire story from the end to the beginning, with at least 20 steps. Once the story was complete, the superteam divided responsibility among the 4-person teams to design machine modules for parts of the story.

Design and Build the Machine

Teams were given free rein to design, build, and test in whatever order they chose, as long as they could show progress at each of three reporting points. They were encouraged to order parts and prototype as early as possible and to save time at the end of the term for testing and troubleshooting. Teams were given a $50 budget from an internal instructional innovation grant to purchase small items. Larger items were purchased by the instructor with the intent of building a small inventory of parts that could be reused for future projects. Igus®, a plastic parts company that has a "Young Engineers' Support Program (www.igus.com/info/company-about-yes-ca)," gave a presentation on campus one evening and donated some parts for the projects. 3D printing filament was also made available for the teams to use to print custom parts. Students were encouraged to use the on-campus rapid prototyping lab, machine shop, and an interdisciplinary, collaborative makerspace on campus named the Thingery (https://thingery.org).

Progress Reports

Each four-person team was required to submit three progress reports documenting their progress on the machine. Progress Report 1 was a standard written report outlining their preliminary plans. It included: 1) the overall machine story (which was the same for all four teams on each superteam); 2) a more detailed description of the steps for which the team was responsible; 3) a description of the machine itself, identifying the types of mechanisms that would be used and including appropriate sketches; 4) required materials and plans for acquisition of parts (buy/borrow/build); and 5) a discussion of team roles, including who would liaise with other teams at the connection points between the steps, how work was divided, and who was and/or would be trained on the necessary tools in order to build each step.

The second and third progress reports were more open-ended and took the form of postings to a class Google site. Each team was given access to a page from which they could create and edit subpages as desired. Teams were asked to include descriptions, pictures, and short videos documenting their progress. The motivation for this format was twofold – first, it kept students from becoming buried in paper when they had a relatively short timeframe to complete a complex project, and second, it provided the instructor and event host with electronic media that could be used to promote the Rube Goldberg Machine Contest®. Guidance for reports 2 and 3 was as follows:

Progress Report 2- What has been accomplished so far? What plans have changed? Include sketches and analyses. Timeline and roles for the remainder of the project.

Progress Report 3- This should be a nearly final analysis of your team's portion of the project. From here on, you should be working with other teams to perfect the connections.

Demonstrate Machines at the Rube Goldberg Machine Contest®

The competition was held on the Louisiana Tech campus and was co-hosted with the Thingery on-campus makerspace. The event was open to the public and was promoted using a Facebook page and a Google Site. The judges for the competition included a biology professor, a music composition professor, a communication design professor, and the chief innovation officer of the Thingery.

Final Report

One way in which this project differed from the Rube Goldberg Machine Contest® requirements was in the final report and the analysis of each step expected in order to align with the learning objectives of the Dynamics of Machine Elements course. It can be difficult to provide clear guidelines for students doing open-ended projects. However, documenting and analyzing real-life messy design processes is a valuable skill. Students were given a template with guiding questions to scaffold their documentation experience to align with the learning objectives of the course. An abbreviated version of the final report template is shown in Table 3.

Table 3. Final Report Guidelines (abbreviated)

Project Story

This should be the same for all teams on a project. Explain the overarching theme and main ideas
(1 paragraph)

Team Step List

Explain your team's role in the story *(1 paragraph)* and describe your steps in detail *(1 - 3 sentences each)*, including what each symbolizes, if applicable. Include at least one picture or diagram and reference it in the text.

Design and Analysis

Analysis of each step. This could vary but should include plenty of explanation. I would expect a minimum of one page per step, probably more for some steps.

- For a four-bar mechanism: how did you synthesize the linkage? Did you start with two positions? How would you classify your result? Is it Grashof? Is it a quick-return? If it has a motor, what is the input speed? What is the velocity of a key point? If it works on gravity, what are the forces and accelerations? What is the maximum transmission angle?
- For gears: what is the gear ratio? Diametral pitch? Pitch diameter? Pressure angle? Addendum? Dedendum? Contact area?
- For things that fall or slide analyze the forces – estimate parameters as necessary and indicate how you made those estimates
- For things that roll or rotate estimate the moment of inertia and radius of gyration. Calculate energy transfer.
- If you are not sure if you are doing an appropriate analysis…ask!

Include figures from linkages or SolidWorks where appropriate, but EXPLAIN them.

If you include hand sketches, please SCAN them rather than take a picture. The quality is much better.

In every step, be sure to state all assumptions and design decisions! How reliable was the step? What are the ways it could go wrong?

Team Roles

Each team member, report on what you believe were your most significant contributions. Did you stretch yourself? On what skills/concepts/ideas do you think you need the most improvement?
(1 paragraph each)

Together, reflect on how you worked as a team. What did your team do well? What could you as a team do better?
(1 paragraph)

Machine Performance

Did your machine perform as planned? If not, talk about what happened. Did you get any ideas from the other projects that could potentially be incorporated into your machine? *(1 paragraph)*

Assessment

Feedback on the Rube Goldberg Machine Contest® project was solicited on the Course Objectives and Outcomes Survey administered to students at the end of the quarter. Students were asked whether the project helped them learn the course content better, learn to work with new people, and learn other engineering skills such as manufacturing and design.

Team project grades were composed of progress reports (10% each), final report (45%), and superteam machine performance at the competition (25%). Individual project grades were then adjusted according to team member contribution based on three peer evaluations. At each peer evaluation, CATME provides an adjustment factor with and without the student's self-rating. An average of the three peer ratings without the self-rating was used. A student's first rating was dropped if they improved their team participation over the course of the term.

RESULTS AND DISCUSSION

The Machine Stories

Each superteam selected a unique theme and story for their project, which ended with zipping of a different type of zipper:

- The "Late for Class" machine told the story of a student waking and carrying out a morning routine. The machine completed the task by zipping a sandwich into a Ziplock® bag. Click https://sites.google.com/a/email.latech.edu/dome/projects/late-for-class for more details on the machine.
- "The Life and Times of Elvis Presley" machine highlighted the highs and lows of the life of Elvis. While this team initially planned to complete the task by zipping Elvis' body bag, they instead chose to zip up a leather sign that said, "Elvis has left the building." Click https://sites.google.com/a/email.latech.edu/dome/projects/the-life-and-times-of-elvis-presley for more details on the machine.
- "The Handy Man" machine used a construction theme to tell the story of Handy Manny, a cartoon handyman with a can-do spirit. After a long day of work painting fences, hammering nails, and repairing electrical wires, Handy Manny zipped up his tool bag to go home. Click https://sites.google.com/a/email.latech.edu/dome/projects/the-handy-man for more details on the machine.
- "A Dawg's Life" machine chronicled the life of a Louisiana Tech University Mechanical Engineering student. The four sides of the machine represented the four years of the degree program, from freshman classes through senior design. The machine completed the task by zipping up a graduation gown. Click https://sites.google.com/a/email.latech.edu/dome/projects/a-dawg-s-life or read on for more details on the machine.

Project Example: "A Dawg's Life"

"A Dawg's Life," shown in Figure 1, won the Rube Goldberg Machine Contest®. The judges noted that the superteam pulled together for a strong comeback after a first-round failure. The second run was flawless. This project will be described in more detail as an illustrative example of how students learned Dynamics of Machine Elements content in the context of the project.

Figure 1. "A Dawg's Life" Team and Machine (photo by Estevan Garcia).

The Louisiana Tech mascot is a bulldog, so the title of the machine refers to the life of a Louisiana Tech student, specifically one in mechanical engineering. The team selected a graduation gown as their zipper of choice, and many of the steps represented classes or experiences in the curriculum. Each team chose a year of the 4-year degree program to represent with their part of the machine. The superteam came up with a plan to make a four-sided display that spectators could walk around (Figure 1). Each side represented a curriculum year and transitions happened at the corners. Wires and other inner workings of the machine were hidden inside the display.

The Freshmen Frustration

The first side of the machine represented the freshman year. The steps are shown in Figure 2 and given below in the students' words (underlines added). ENGR 120, 121, and 122 are the core of the Living with the Lab Engineering Problem Solving series that all engineering students take as freshmen. A video of these steps is available here: http://youtube/2rm36dPhwJI.

1. *Setting a tool bag down onto a lever attached to a string. The tool bag is used because all freshman engineering students are required to purchase a tool bag and tools and bring them to class.*

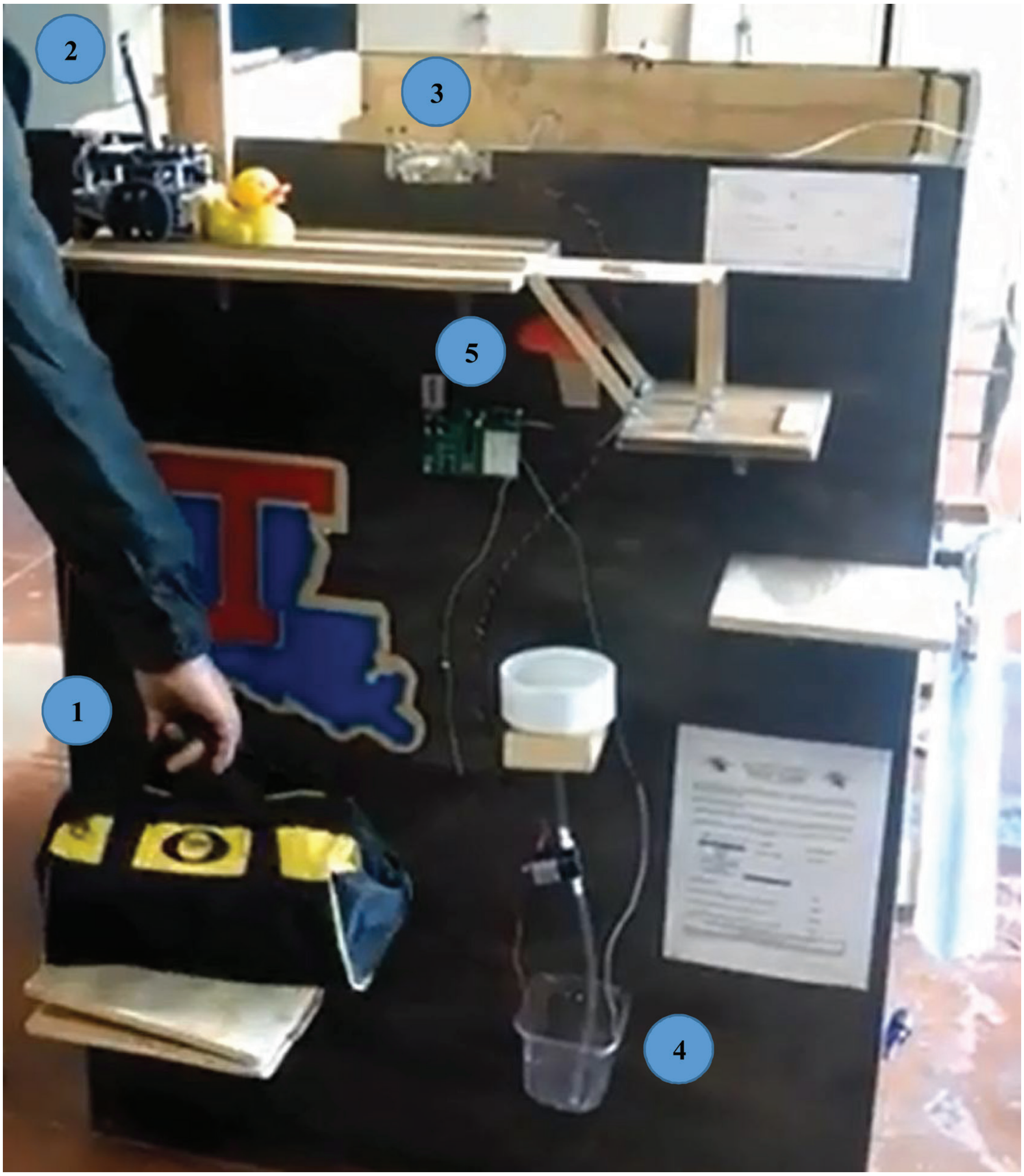


Figure 2. The Freshmen Frustration (numbers added to help identify steps).

2. *The string is attached to a weight depressing the reset button on a Boe-Bot. Once the weight is lifted, the Boe-Bot is released. The lever/string/weight system represents the basic statics portion of ENGR 122.*
3. *Once the weight is lifted, the Boe-Bot is programmed to travel down tracks for a set distance, pushing a duck onto a four-bar mechanism. Along the way, the Boe-Bot flips a switch engaging a solenoid*

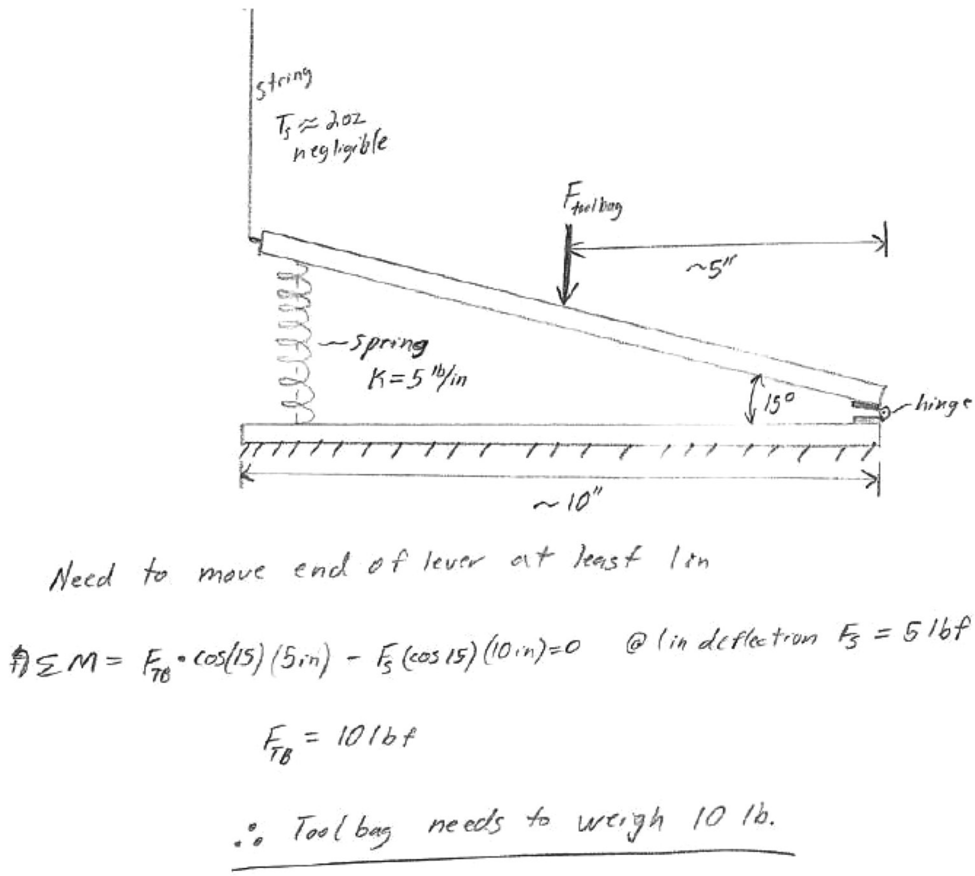


Figure 3. Lever analysis to determine the weight of tool bag.

valve. The Boe-Bot, including its microcontroller, is the centerpiece and platform of the ENGR 120 series. The duck is representative of the "Duck Challenge" ENGR 120 students have to complete.

4. *The open solenoid valve drains saltwater from a holding tank into a secondary tank. The secondary tank contains two wire leads connected to a microcontroller. The circuit is completed by the saltwater signaling the microcontroller to engage the cam. The saltwater tank system represents the "Fish Tank" project from ENGR 121.*
5. *The cam is mounted against the four-bar mechanism. Once engaged, the cam topples the four-bar mechanism.*
6. *Upon the falling of the four-bar mechanism, the duck slides off, impacting a lever to begin the Sophomore team's sequence.*

This team incorporated multiple mechanisms discussed in class (four-bar linkages, cams) and provided appropriate analyses to demonstrate understanding of the concepts. For the lever in step 1,

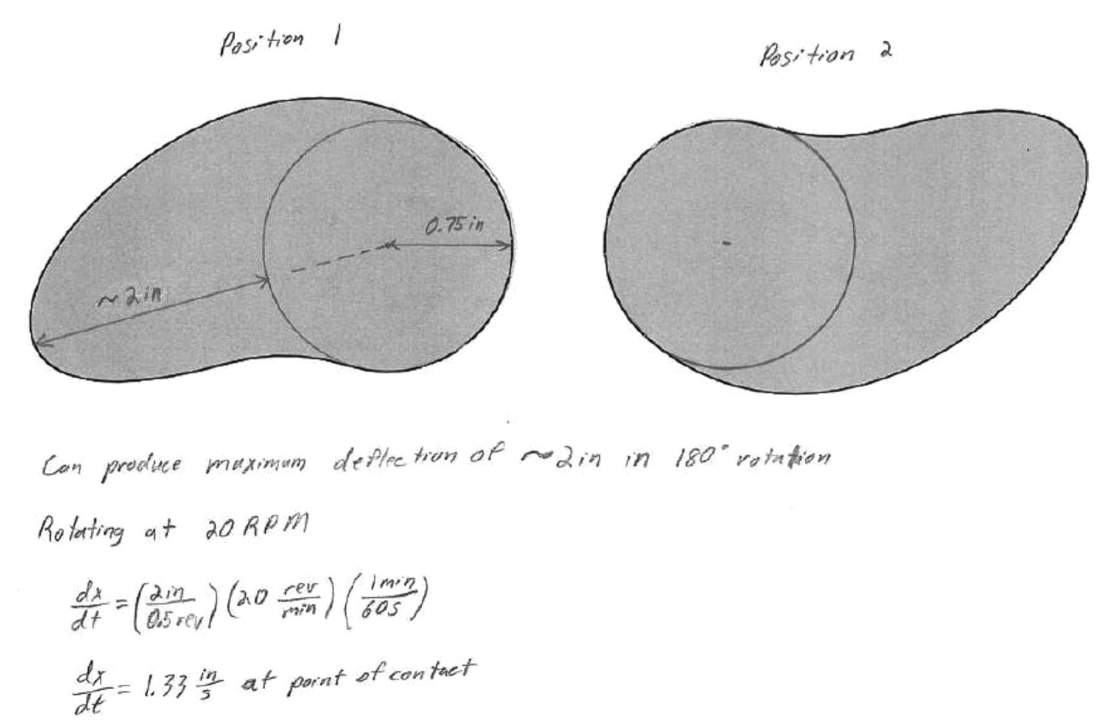


Figure 4. Analysis of Cam.

a simple static analysis was sufficient to determine the required weight of the tool bag (Figure 3). There is a slight inconsistency in their work: in their calculation, they treated the weight of the tool bag as if it was 5" up the ramp, but in the diagram, they showed 5" as the horizontal distance. Fortunately, the difference is less than 5%.

The Freshmen Frustration team was the only team to implement a cam (Figure 2, step 5). The analysis of it (Figure 4) was rather simplistic compared to what was taught in the course, but the design was sufficient to accomplish the task of toppling the four-bar linkage. This team missed an opportunity to plot and discuss the displacement, velocity, acceleration, and jerk profiles. Instead, they computed an average velocity based on what appears to be an arbitrary rise and base circle radius.

The synthesis of the four-bar linkage was more on par with coursework - they used a graphical technique to produce a linkage that would pass through two specific positions (see Figure 5). This diagram was posted on the website for a midterm report but did not make it into the final report. Other hand-written analyses were included in the report, but in general, were not very effective at communicating the calculations. The implementation (see Figure 6) was impressive, even including burning the school logo onto the platform. This step, in particular, allowed students to see first-hand that many problems they think are three-dimensional can be easily solved in two dimensions. While

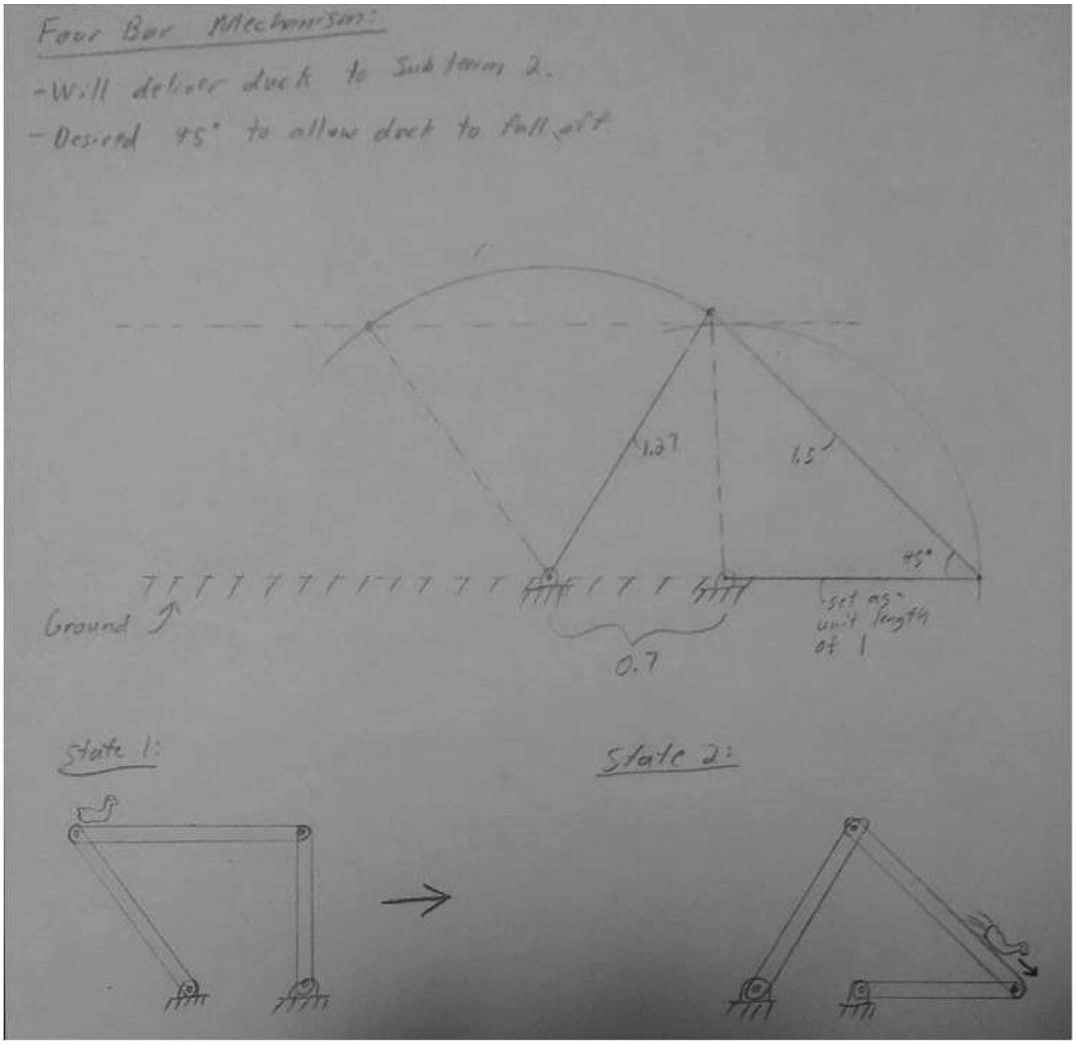


Figure 5. Four-bar synthesis.

Figure 6. Four-bar implementation.

the final product is a three-dimensional object, the motion all occurs in two directions, and so the 2-D linkage generated on paper can be duplicated and extruded to produce depth.

Sophomore Slump

The second stage of the machine, shown in Figure 7, is best summarized by the students:

Our section of the machine takes you through the "sophomore slump" where the worlds of statics, circuits, and thermodynamics take their toll on unsuspecting students. There are many defining moments in sophomore year that makes it an unforgettable experience: from breaking trusses in … Statics and Mechanics of Materials class to building intricate circuits in … Introduction to Circuit Analysis labs and let's not forget … [the] epic adventure through Thermodynamics. Each of these experiences will be captured in creative ways in our mechanisms before finally passing over to the "Jam-Packed Junior Year". After all, you can never make it to junior year without making it past these classes… or the countless nights without sleep while studying in Bogard Hall.

Step List:

0. *(Transition step) The ending mechanism of "The Freshmen Frustration" involves dropping rubber duck. The duck will land on a balance mechanism and tip over a truss that is rest-*

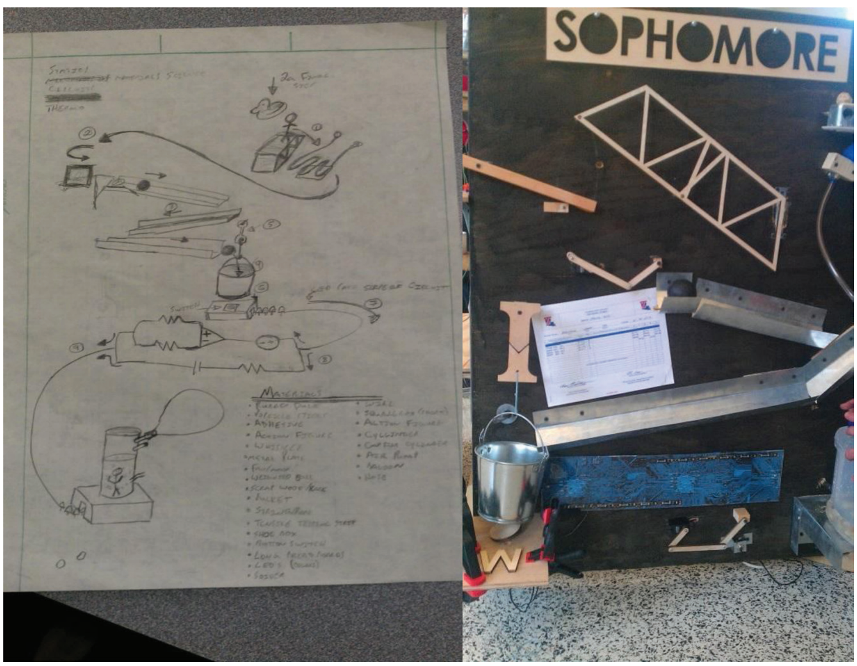


Figure 7. Overview of the Sophomore Slump.

ing on the opposite end symbolizing the pushing through into a new world [of] statics and mechanics.

1. *The tipping of the truss causes a switch to flip.*
2. *The switch completes a circuit that starts a four-bar mechanism.*
3. *Four-bar mechanism rotates and hits a weighted ball.*
4. *The ball rolls down a path and falls into a bucket representing the student rolling along and getting a handle of things.*
5. *The bucket is attached to a tensile testing strip held together by magnets. The weight of the ball breaks the testing piece and causes the bucket to fall on to a switch. The breaking of the tensile testing piece represents the students separating from general engineering to their major concentration courses.*
6. *The falling bucket flips a switch that starts an identical four-bar mechanism from step 3 and also triggers a switch that lights up a circuit board. The lighting of the circuit board is symbolic of the elaborate circuits the students create and analyze in the circuits labs of [Introduction to Circuit Analysis].*
7. *The four-bar mechanism rotates and activates a switch.*
8. *The switch starts an air pump that pumps air into a rigid vessel container that is filled with enough water to cover "Dawg" figure's head. This symbolizes the student being submerged into Thermodynamics.*
9. *The incoming air flows to the top of the vessel where a hose is attached from the vessel to a balloon by a hose. The air blows up the balloon using boundary work as discussed in the [Thermodynamics] lectures. The balloon … triggers the start of the "Jam-packed Junior Year".*

This team also used a four-bar linkage (Figure 8) and used Excel to calculate position, velocity, and acceleration at each crank position. They choose to place the linkage such that it hit the weighted ball with maximum velocity in the x-direction. Several short video clips are available on their page: https://sites.google.com/a/email.latech.edu/dome/projects/a-dawg-s-life/dawg-ii.

Jam-Packed Junior Year

The third team took a more narrative approach to their step list in their report but provided the summarized step list shown below for judging. Figures from their report and website have been added for clarity. Their part of the machine in action can be seen here: http://youtu.be/H0_461xaSwk.

*The **Jam-Packed Junior Years** will take you through the junior year ("Round 1") of a Mechanical Engineering student. Their portion of the machine will incorporate the following*

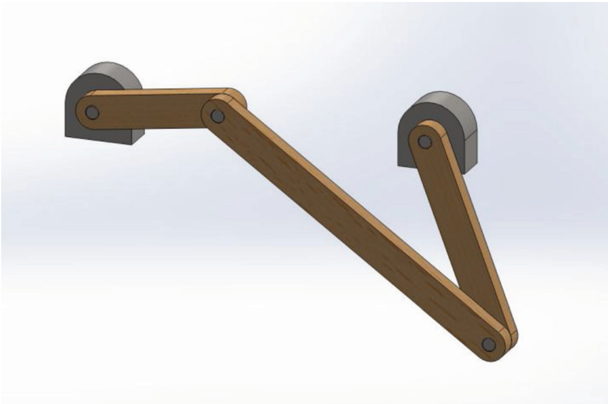
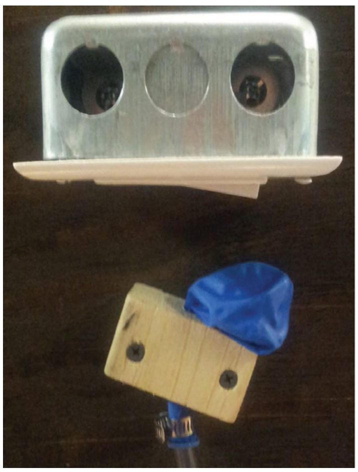


Figure 8. Sophomore Slump Linkage.

common junior year mechanical engineering classes: Dynamics of Machine Elements, "Elementary" Fluid Mechanics, "Basic" Measurements, and Computer-Aided Modeling. The classes will be incorporated into the contraption by using various mechanisms, sensors, and props that are related to the classes.

Steps

1. *Balloon presses light switch (Figure 9, left).*
2. *Light switch starts motor.*
3. *Motor turns four-bar mechanism (Figure 9, right). Four-bar mechanism symbolizes Dynamics of Machine Elements.*



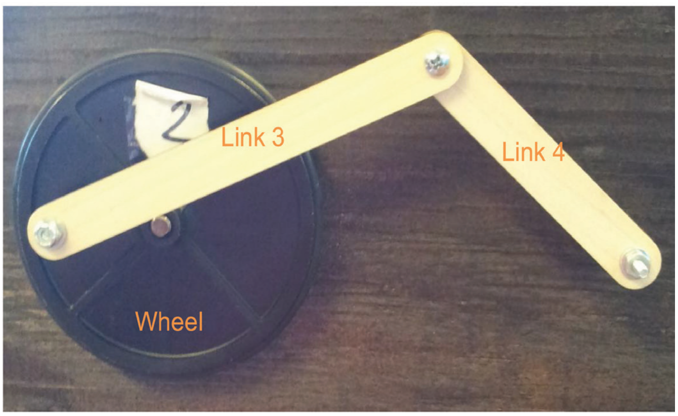


Figure 9. Balloon Switch (left) and four-bar linkage (right).

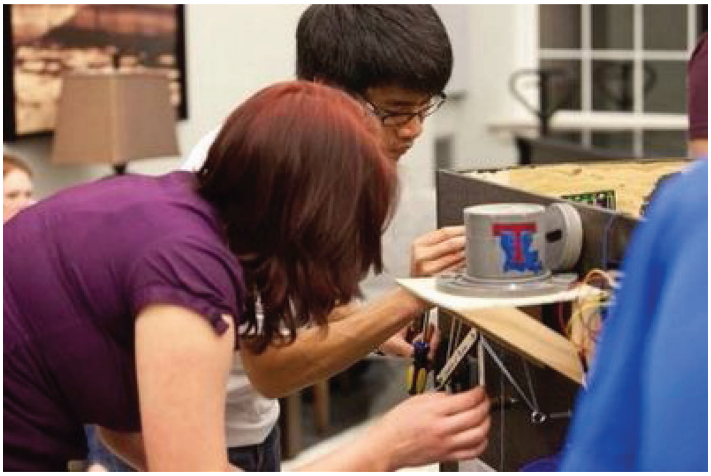


Figure 10. Students working on the water tower plug.

4. *Four-bar linkage removes rubber stopper (Figure 10).*
5. *Water flows into container on seesaw (Figure 11, left). Water flow symbolizes Fluid Mechanics.*
6. *Seesaw tilts and presses switch. Uses of switches and sensors symbolizes basic measurements.*
7. *Switch starts servo.*
8. *Servo reels twine to open laptop (Figure 11, right).*
9. *Opening laptop knocks off screwdriver. Laptop with CAD model and prototype symbolizes Computer-Aided Modeling.*

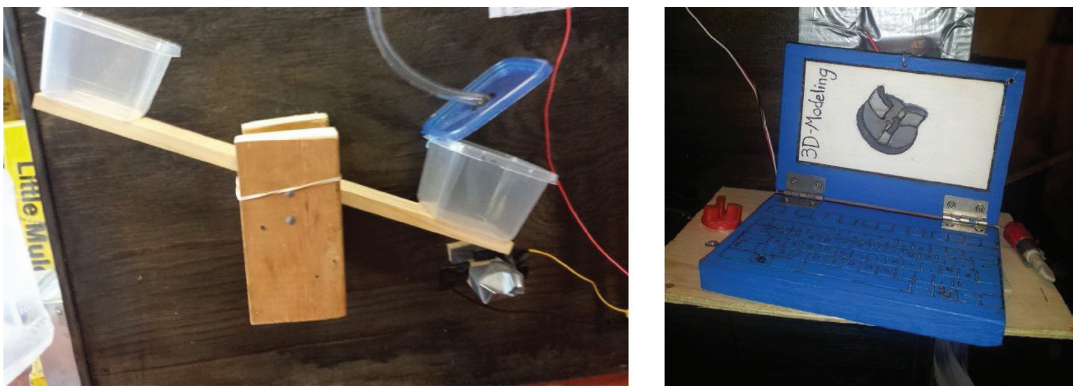


Figure 11. See-saw (left) and laptop (right).

The Final Stretch

The last team represented the senior year and life after graduation. This team did a particularly good job of communicating their work. The report included several labeled images like the one below (see Figure 12).

1. *Senior Year Parking Sticker Slap - The machine began with the screwdriver falling off of the Junior team's last step, which triggered the mousetrap seen in [Figure 12] below. The mousetrap has a 4th parking sticker on it, which symbolized the last year at [Tech], as a student in general and an engineering student as well. This parking sticker was slapped on to a rotatable shelf, which had a hacky sack sitting on it, waiting to be knocked off to trigger the next step.*

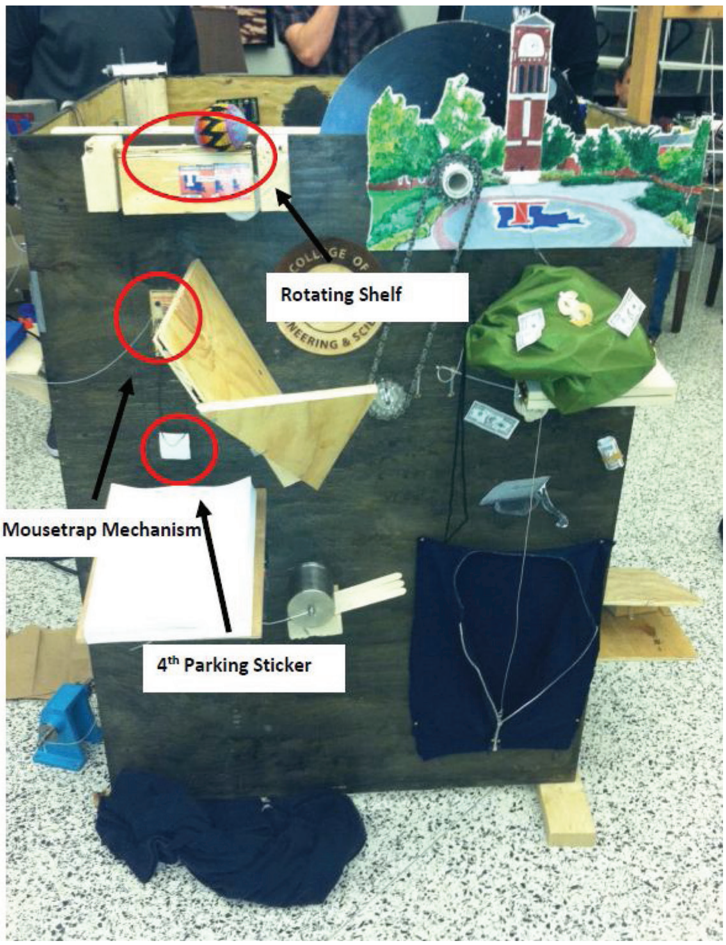


Figure 12. The Final Stretch with step 1 labeled.

$p := 0.5\ in \qquad \omega_{motor} := 60\ rpm$

$N_{motor} := 15 \qquad N_{wheel} := 17 \qquad N_{chain} := 68 \qquad r_{sun} := 6.75\ in$

$C_{pmotor} := N_{motor} \cdot p = 7.5\ in \qquad D_{pmotor} := \frac{C_{pmotor}}{\pi} = 2.387\ in$

$C_{pwheel} := N_{wheel} \cdot p = 8.5\ in \qquad D_{pwheel} := \frac{C_{pwheel}}{\pi} = 2.706\ in$

$L_{chain} := N_{chain} \cdot p = 34\ in$

$D_{center} := 0.5 \cdot \left(L_{chain} - 0.5 \cdot \left(C_{pmotor} + C_{pwheel}\right)\right) = 13\ in$

$R_{gear} := \frac{N_{motor}}{N_{wheel}} = 0.882 \qquad \omega_{wheel} := \frac{\omega_{motor}}{R_{gear}} = 68\ rpm$

$V_{sun} := r_{sun} \cdot \omega_{wheel} = 48.066\ \frac{in}{s}$

Figure 13. Chain analysis and photo

The remainder of the steps were:

2. *Hacky sack falls off platform and knocks away support beneath lab report. Falling reports represents the completion of the endless thermal design lab reports.*
3. *Lab report falls on switch.*
4. *Switch turns on "day/night" wheel. Endless turning of wheel represents endless days and nights dedicated to senior design.*
5. *Wheel pulls the money bag off shelf. The money bag represents the acceptance of a full-time job offer.*
6. *Money bag pulls up zipper of "graduation gown." Zipping of graduation gown represents the completion of the degree.*

This team employed a chain and sprockets driven by a motor, which allowed them to select appropriate gear ratios so that the day-and-night wheel would not turn too quickly or too slowly (Figure 13).

Finally, an additional benefit of this particular project is that the students reflected on their past coursework and experiences and looked forward to the rewards of earning their degree.

Rube Goldberg Machine Contest®

All four superteams presented a functional project at the Rube Goldberg Machine Contest®. A team of judges rated each machine on two trials. They selected "A Dawg's Life" as the winner because after a catastrophic failure in the first trial, the team banded together to make the necessary repairs and had a perfect second trial. "Late for Class" was selected as the runner up. Although the winning team was eligible to compete in the national competition, driving the large machine up to Ohio would have caused them to miss multiple classes, so they opted not to compete nationally. The course Google site documents each team's progress and also includes photos and videos of the final projects (https://sites.google.com/a/email.latech.edu/dome/home).

Assessment Outcomes

Course Survey

An anonymous online Course Objectives and Outcomes survey was administered near the end of the term. The survey asked students the extent to which they believe they achieved each course outcome. Additionally, three questions were asked about the Rube Goldberg project. On the survey, 36 out of 52 students responding disagreed or strongly disagreed that the project helped them learn the course content better and another 14 were neutral. However, 38 agreed or strongly agreed that the project helped them learn to work with new people (9 neutral). Twenty-nine agreed or strongly agreed that the project helped them learn other engineering skills such as manufacturing and design (11 neutral). These results are shown in Figure 14. While students do not believe the project helped them to learn the course content, they do generally believe it helped them learn to work with new people. This seems to be a common outcome. Blumenfeld et al. (1991, 374) noted that "students do not necessarily respond to high-level tasks with increased use of learning strategies." Graff and colleagues list teamwork as the number one goal of their longstanding Rube Goldberg project (Graff

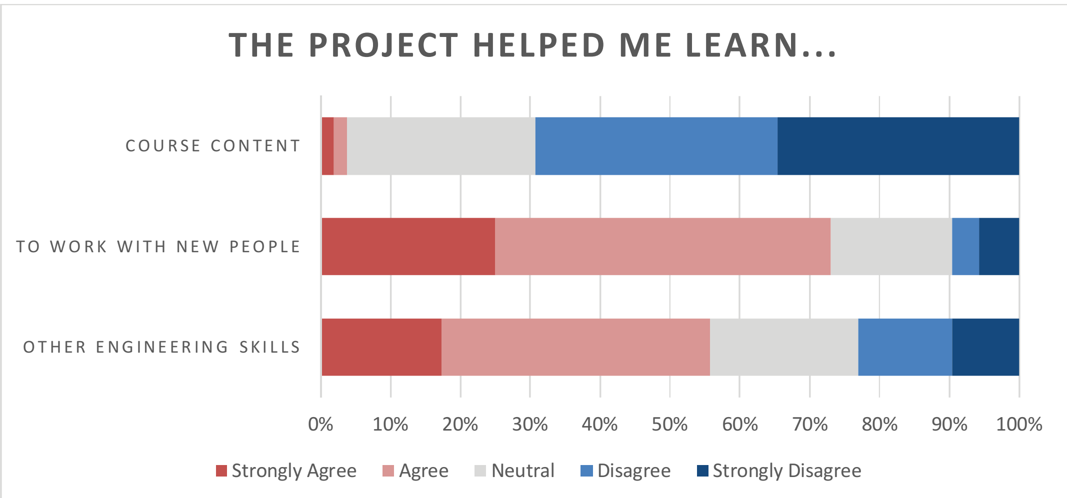


Figure 14. Anonymous course survey results

et al. 2011). DeBartolo and Robinson (2007) have also emphasized teamwork and communications as skills practiced in a Rube Goldberg project, as well as time management and experimentation. Although many students said the project helped them learn other engineering skills, there was no follow-up question to determine which engineering skills they had learned.

After the competition, several students expressed their unexpected enjoyment of the project to the instructor. Some of these sentiments, positive, negative, and mixed, were captured in the survey:

- "I feel like the project did not have much to do with the class. That said, it was a fun project. If this is done next year, I think the class should be changed to a lab with class time set aside to work on the project. With Senior Design and Mechatronics [at the same time], it was really hard to complete all my projects."
- "I just thought the project was a little too short on time to accomplish the goal of applying [Dynamics of Machine Elements] concepts, but I thought it was a fun project. I just think there needs to be a little tweaking and prep for next time."
- "I love the project and I learned many things"
- "Despite how much time and effort this project required, I enjoyed crafting it and was very proud of the end result."
- "Learned a lot more through the project than the class. Also enjoyed being in a team and a sub-team. Although I enjoyed the project in the end, I strongly disagree with requiring us to analyze everything single component and step in the report (One [Dynamics of Machine Elements] analysis per four-person team would be appropriate). The report should be more focus on information to help someone replicate the contraption since the project had little to do with [Dynamics of Machine Elements]. The project competition took much time from the class when the class material become (sic) much more difficult in addition to the report."
- "I feel like the project took a tremendous amount of time, without adding a great deal of instructional benefit. It was fun at times, but did not add to my understanding of the course material. It took time away from the class."
- "The project assigned was too big of a problem with very little parameters and guidelines to follow…"
- "It is a nice notion, and the project would be fun if there wasn't too much going on in the class already. We almost literally covered a chapter a day in there. That's too much with expecting us to do the project work as well. Also, realize who takes this class and when it is offered. Winter quarter is a [certain professor] class for juniors, and the most intensive quarter of senior design for seniors. I don't feel it helped with any understanding of classwork."
- "I think the project turned out a lot better than I anticipated. It seemed somewhat unorganized at the beginning which is understandable since this is the first time doing the project for you

as a teacher and us as students. I believe that next year it will be much better, because the groups have a realistic idea of what they are trying to achieve. Also, we don't have to waste as much time trying to figure out what to buy, because you will already have some material that they can use. Again, this project turned out a lot better than I expected throughout the quarter and enjoyed working on something different, but it just took us a while to bring it all together since we weren't sure what an actual project was supposed to look like."

The most frequent complaint was the time the project took. Many students did not see the value in the report and analysis. There was also evidence of frustration over the open-ended nature of the project. On the positive side, some students found the hands-on, creative aspect to be enjoyable and fun. These comments are similar to those reported by Berg (2015), who also mentioned the challenges of collaboration in student teams. Other than the initial displeasure of not being allowed to choose their teams, complaints about collaboration were largely absent from the comments in this case. This could be due to smaller team size, taking schedule into consideration when forming teams, or frequent peer evaluation.

Peer Evaluations

The CATME system was used for students to evaluate themselves and their team members on five categories of team contribution identified by Loughry, Ohland, and Moore (2007): contributing to the team's work; interacting with teammates; keeping the team on track; expecting quality; and having relevant knowledge, skills, and abilities. The average score for all students is shown in Figure 15 for each category of team contribution at the beginning (Peer Evaluation 1), middle (Peer Evaluation 2) and end (Peer Evaluation 3) of the project.

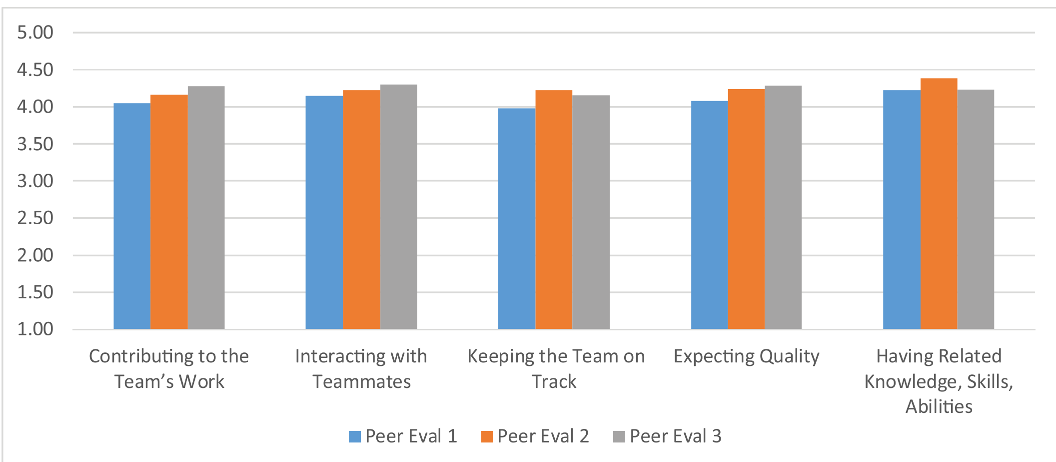


Figure 15. Peer evaluation of individual contributions to the team.

Table 4. Paired t-test of team contribution scores, Peer Evaluation 3 – Peer Evaluation 1 (n=64).

Category	Mean Difference (PE3-PE1)	Std Dev	Std Err	p (2-tailed)	Effect Size (Cohen's d)
Contributing to the team's work	0.232	0.678	0.085	* 0.008	0.34 small
Interacting with teammates	0.150	0.698	0.087	0.091	0.21 small
Keeping the team on track	0.176	0.539	0.067	* 0.011	0.33 small
Expecting quality	0.210	0.597	0.074	* 0.007	0.35 small
Having relevant knowledge, skills, and abilities	0.012	0.587	0.073	0.874	0.02

* p <0.05

To test the significance of the change in peer ratings, the difference between each student's average score at Peer Evaluation 3 and Peer Evaluation 1 was computed in SPSS® for a paired/dependent samples t-test (Table 4). Not all students completed all peer evaluations (50, 57, and 47 for Peer Evaluations 1, 2, and 3, respectively), but every student was evaluated by at least one team member at each time point, and thus n=64. On Peer Evaluation 1, four students were only evaluated by one team member.

In every category, a Shapiro-Wilk test rejected the null hypothesis that the difference scores were normally distributed (Ghasemi and Zahediasl 2012). However, histograms all showed a clear peak and a two-tailed t-test is robust to violations of the normality assumption for sample sizes greater than 10 (Miller 1998). Boxplots and nonparametric analysis are included in the appendix.

The mean difference between each student's average score at Peer Evaluation 3 and Peer Evaluation 1 was significantly different from zero (two-tailed) for contributing, keeping the team on track, and expecting quality, according to a paired t-test (Table 4). These effect sizes ranged from 0.33 to 0.35 standard deviations, indicating they were small but meaningful effects (Cohen 1988). Interacting with teammates showed a small but not statistically significant change in the positive direction. The change in having relevant knowledge, skills, and abilities was neither statistically significant nor practically meaningful (effect size less than 0.2).

Similar to the individual survey results, students did not perceive improvement in their team members' "relevant knowledge, skills and abilities." However, they did perceive positive changes in other teamwork skills.

CONCLUSION

Adding a Rube Goldberg machine design project to the Dynamics of Machine Elements class was a valuable learning experience for both the students and the instructor. As there are few papers describing Rube Goldberg projects at an upper-class level, this paper contributes to the project-based learning literature by providing evidence-based best practices for successful implementation that could be used at other institutions.

Suggestions for future implementations are summarized below:

- Students sometimes get distracted by exciting design projects and do not naturally make connections between their projects and course content. Therefore, make connections between design projects and course content explicit, even if they seem obvious to the instructor.
- Encourage students to create and test prototypes early and often, by incorporating intermediate design project goals and checkpoints including analysis into classwork and homework.
- Reinforce technical content learning objectives by requiring analysis of each component before fabrication begins.
- Make plans for the complete life-cycle of the projects, knowing that it can be difficult to get student help after the term ends.
- Keep the physical scale of projects in mind to make them more portable and reduce logistical concerns.
- To make a nationally competitive team at a school with a quarter system, an extracurricular program would provide more sufficient time.
- It is important that students have an experience working with a non-self-selected team at least once in their academic career. Although students resisted this at first (in part due to the campus culture of selecting your own project teams), by the end, most recognized that it helped them learn an important skill.

Implementing and assessing project-based learning is always a challenge. While most students did not perceive that the Rube Goldberg project had a significant effect on their learning of course content, they did perceive their own growth in terms of working with new people and other engineering skills. Further, their peer-evaluated contributions to the team improved over the term.

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APPENDIX

As the data were not strictly normally distributed, a nonparametric test, the Related-Samples Wilcoxon Signed Rank test, was also run (Table A1). Results were similar except that in the signed rank test, the positive change in interacting with teammates reached significance, while it did not in the more conservative t-test.

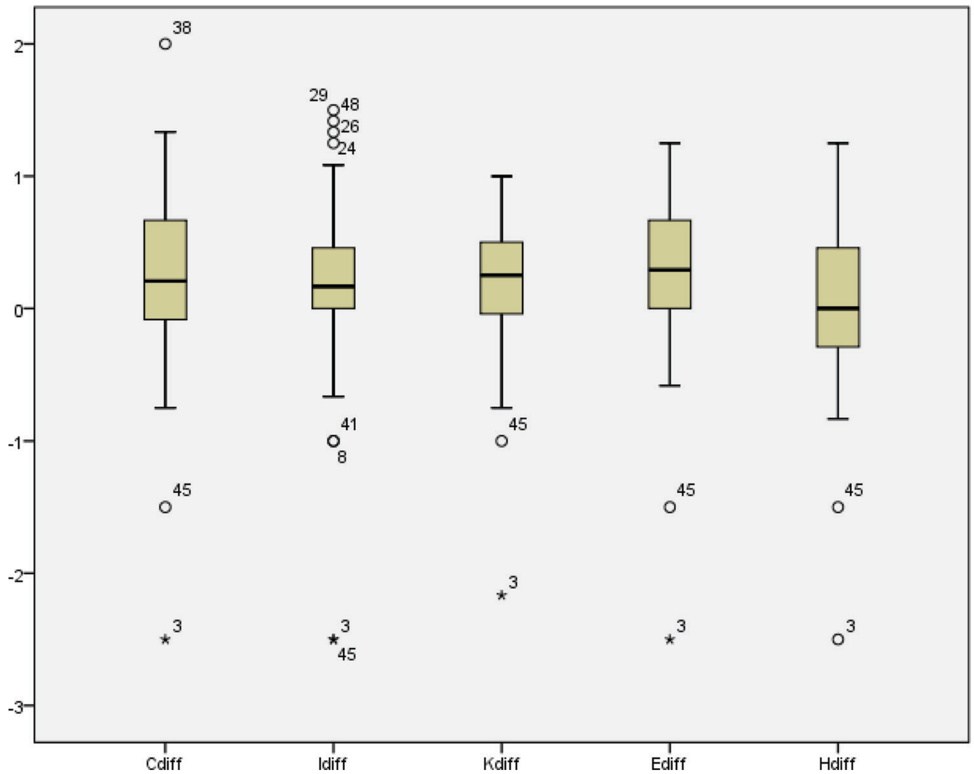

Figure A1. Boxplot of difference scores for the five categories of team contribution. All are generally normally distributed with some outliers.

Table A1. Related-Samples Wilcoxon Signed Rank t-test of team contribution scores.

Category	Z	p (2-tailed)
Contributing to the team's work	–3.215	* 0.001
Interacting with teammates	–2.799	*0.005
Keeping the team on track	–3.117	* 0.002
Expecting quality	–3.605	* <0.001
Having relevant knowledge, skills, and abilities	–0.609	0.543

* $p < 0.05$