The Cornerstone Course: Projects and Progress

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Abstract - In the Fall of 2014, Northeastern University taught 2 pilot sections of what is now being called the Cornerstone of Engineering course, as support of the "Cornerstone to Capstone" approach in the College of Engineering's curriculum. The first 2 pilot sections integrated 2 existing 4-credit first year engineering courses in an intense 1-semester, 8-credit format. After the pilot sections were completed and reviewed, 4 sections of this 1-semester, 8-credit course were offered in 2015-2016. In addition, 13 sections of the cornerstone course were "split" into two 4-credit courses over the Fall and Spring semesters in order to address logistical and pedagogical issues with the intense 1-semester format. The results of student feedback following the cornerstone approach are discussed in other papers, with more data currently becoming available.

The goal of the cornerstone approach was the integration of design, programming, graphical communication, and engineering analysis through real world, hands-on design projects previously taught in two separate courses. This paper will present some of the mechanics of offering the cornerstone approach, focusing on the projects themselves. Some examples of these are robot swarms that seek a chemical source and inform of the danger, museum-type exhibits that teach topics related to sustainability, open-ended robot designs for many goals such as working in dangerous areas or disasters, efficient energy transfer devices, sustainable home designs, and input devices for games that are tested on actual users. This paper's purpose is to present the themes and projects used in the cornerstone courses to date with sufficient detail and support to be considered by others and to show the success of this approach by the student built project results.

Introduction - The goal of teaching these classes with a cornerstone approach was to directly support the interdisciplinary, student-centered approach recommended by the National Academy of Engineering's *Educating the Engineer of 2020* report.[2] Other motivation for the cornerstone approach included student feedback, the changing profile of first year students, and increased access to affordable technologies such as programmable microcontroller kits and 3D printing. Specifically, feedback from students' was that they were focused on hands-on engineering experiences, and wanting more real-world challenges. First year students are enrolling with more Advanced Placement credit and interested in accelerating through the first year program to begin courses in their major by taking courses at an accelerated pace.

As further motivation for restructuring the course with more hands-on, real world, open-ended projects, there is a variety of support in other universities and in the literature for this approach. One resource showed that project-based learning increases retention of engineering students and that there is a clear need to increase the number of faculty who can teach engineering design and to create facilities and design studios to support project-based design courses. This work was done by Dym, Agogino, Eris, Frey and Liefer at Harvey Mudd College, University of California Berkley, Stanford University and Massachusetts Institute of Technology, who conducted their own literature review of project-based learning.[3] Northwestern University described an interdisciplinary, project-based cornerstone course where students acquire skills in communication, design and teamwork as they learn that engineering with an iterative and creative problem-solving process.[4] California Polytechnic State University used a constructivist design model to develop a project-based cornerstone course and found that the pilot course was an empowering experience for the students.[5] The work in project-based learning is not new, the authors built on their knowledge and experiences, along with the literature to inform the design of the curriculum and the projects used in the cornerstone course. In Fall of 2016, all 650 incoming first-year students will be enrolled in a cornerstone course. The themes will be robotics, sustainability, game design, energy systems, security, bioengineering, and engineering and music. Courses will have the same content integration and learning outcomes, the projects will be different. All of the sections will have established milestones where students will present research, proposals, prototypes and final designs. The students are required to work in teams, along with working on other professional skills. The next section of this paper shows the details of the milestones for different cornerstone themes and the resulting projects that were built.

The course centered on a number of theme-specific design-and-build projects with the core outcomes of:

- Application of the design process.
- Design and construction to specifications.
- Engineering a solution to a real problem.
- Graphical Communication and 3D printing.
- Professional oral and written communication.

- Computational programming skills: C++, Matlab, programmable microcontrollers.
- Focus on sensing and input/output.
- Numerical analysis and calibration of sensors.

In order to free up class time for project work, many of the course elements were flipped. The flipped classroom model allows more time for hands on activities, team project work, and in-class feedback from the professor. Additional advantages to the cornerstone model are that the students are able to design projects with a systems approach, and to simulate real projects with complex solutions. Core course concepts such as applications of programming, graphics and the design process are integrated naturally and are not forced. This gives immediate confirmation that the topic is relevant as they have to apply it in order to solve their problem. Finally, students can explore and research engineering principles due to their interest and the project requirements which leads to further fulfillment of effort.

Figure 1 shows a conceptual framework for the cornerstone experience. This model helps visualize how this program weaves together three content areas into an integrated design experience. From left to right, we see that the learning objectives include students being able to evaluate and interpret designs, conceptualize and prototype them, and communicate them in diverse ways. This visualization of cornerstone allows the program instructors to organize learning objectives together, which can help in planning, teaching, and assessment purposes.

Project-based cornerstone has, as one of its challenges, the ability to have incongruent learning of course content due to the nature of problem solving. By highlighting the fact that engineering problem solving brings together groups of competencies in a networked fashion rather than in a linear fashion, we increase the quality of instruction for all students, showing them that this incongruence is acceptable. Specifically, the emphasis here is that cornerstone is a lens by which engineering learning can come together to develop practical applications to solving problems. By representing cornerstone as a ring that brings together three content areas, the conceptual framework focuses on the notion that it blends together seemingly separate aspects into a useful weave of skills in a problem solving context.

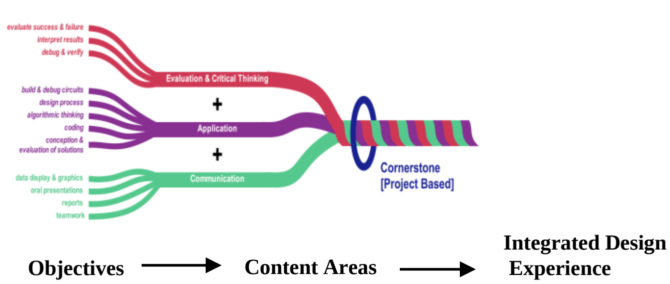

Figure 1 - Conceptual Model of Cornerstone Course.

Cornerstone Courses and Projects - For each of the different themes, milestones and projects support the course objectives with appropriate, real world application-inspired end goals. These are done in a similar order across the sections, but not all sections use the same course structure and approach. Since the focus of this paper is the theme-based projects and the steps taken to achieve them, the discussion here is mostly on the project activities rather than the course materials, evaluations or other content of the course itself. The purpose of this section is therefore two-fold: first, to give examples of themes and projects that support those themes, and second, to provide some detail on how to get to the final outcomes and projects.

Robotics - Eight sections of the cornerstone course with the theme of Engineering Robotics Applications were offered in the Fall of 2015 (Cornerstone 1) and Spring of 2016 (Cornerstone 2). The teams were formed at the beginning of the Fall semester (2nd week). In the Fall semester, each team had three members in order to give maximum practice to all participants. The teams were changed in the Spring and had three or four members based on the class size. There were team building activities in the first semester along with use of a web-based team rating system to help facilitate team functioning. In both semesters, the projects and reports required students to

- Draw a sketch of the system/model using Autocad/Solidworks.
- Build a prototype or a simple model using some 3D element printed via a Solidworks sketch.
- Integrate C++ and/or Matlab programing for data collection and analysis.
- Make Power Point Slides to present the work.
- Write a technical report of the work.

The following milestones supported the overall course learning objectives and accomplished the project goals:
Semester 1:

1. Research project: Students were required to research an area of robotics related to the engineering majors of their team. They prepared a draft presentation that was reviewed with feedback, a short presentation in class and a research paper..
2. Sumo Robot Project 1: Students built a robot from a kit that contained an aluminum frame, wheels, 2 motors and a mounted breadboard. They had sensors to detect a line and a distance sensor to detect other robots. Their first project was to have an autonomous robot programmed to stay in a ring for longer than its opponent, using only logic. The robots were identical in physical design. They also submitted a report with reflection.
3. Sumo Robot Project 2 – Using the design process and what was learned from Sumo 1, the students created robots with improved programming and design additions to make their robots competitive, within given constraints. They wrote a more

complete report detailing the use of the design process and implementation in the competition, with reflection on both programming, design and what was learned.

Semester 2:

1. Robot Proposal – Students were given a list of suggested problems where robotics would be a part of the solution, then selected a problem from the list or created their own problems. Examples of the problems were exploration of Mars, exploration of a disaster area or hazardous area, manufacturing area application or approved themes of their own such as an automatic cat teaser, beverage delivery system and radiation detector robot. The students wrote a proposal and presented to the class, this had a peer review process. Teams wrote proposal reports starting to outline the purpose of the robot and possible designs.
2. Prototype Robot – The teams gave a demonstration of a working prototype of their robot design. This included revisions from the proposal, reasons for the revisions and description of remaining work.
3. Final Robot Design – At the conclusion of the second semester, the teams gave a demonstration of the final working robot. They wrote a final design report that included all work from the semester including drawings, design ideas, material choices, testing of designs and parts and the final design along with reflection on the design process, the programming and the robot itself.

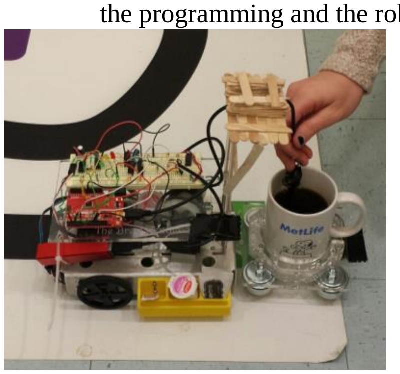

Figure 2 – Final design robot example.

Efficient Energy (production/Transfer) System" Cornerstone - Two sections of the cornerstone course with the theme "Efficient Energy (production/Transfer) System" were offered in the fall of 2015. This section was a full cornerstone which is an 8 credit 1 semester course as opposed to the previous robotics cornerstone which was a split version of 4 credits taken over two semester in the Fall and Spring. The teams were formed at the beginning of the semester (2nd week). Each team had four or five members based on the class size. Team activities were given to build team interaction, including a case study project on energy systems.. In this project, team task and requirements as engineers were:

- To identify a system and write a proposal based on the case study of Efficient Energy (Production/Transfer) System.
- Draw a sketch of the system/model using Autocad/Solidworks.
- Build a prototype or a simple model using some 3D element printed via solidworks sketch.
- Integrate C++ and/or Matlab programing for data collections and analysis.
- Make Power Point Slides to present the work to the public
- Write a technical report of the work.

After brainstorming, teams choose the following titles:

Project titles

- Energy Production Efficiency with Stirling Engines
- Rooftop Wind Turbines
- Tidal Energy
- Regenerative Braking Elevator
- Airborne Wind Generation
- Seabed Carpet for Wave Energy Absorption
- Gorlov Helical Turbine and Generator:
- Renewable Energy Generation from Frequent Human Activity (published at the ASEE-NE2006 Conference)
- Alternative Windmill Design: Research on a Hybrid Turbine Design on a Scaled Down Model
- Alternative Transportation and Energy Production: Regenerative Pedaling Systems
- Solar Powered Winch
- Vertical-axis wind turbines (VAWTs)

In addition, the following team activities were integrated with the course work. These concepts were expected to aid the final design project.

- Efficient Energy Transfer System Design
- Wind Fan Design and Analysis
- Strong I-Arms Design and Measurements

The first activity was to help students to design and calculate energy loss and system efficiency, which is an important aspect of the course theme. The second was designed to aid students to gain basic knowledge in the wind turbine structure and design, which are common concepts in many wind/water based energy related designs. The third activity was to learn the fundamentals of designing strong structures to withstand high wind speed and earthquake. As a course requirement the following milestones were set to complete the project:

- Team Formation week 2
- Case Study Presentation on energy system week 4
- Cornerstone Final Team Project Proposal and presentation week 5
- Cornerstone Final Team Project Progress 1 presentation (P1) week 9
- Cornerstone Final Team Project Progress 2 presentation (P2) week 11
- Initial Prototype/Model demo (P3) week 12
- Optimized Prototype/Model demo (ID1) week 13
- Formal Presentations/demo/ final reports week 14

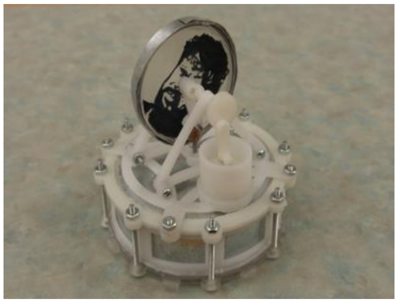

Figure 3 – Final design example - The completed Stirling engine without solar reflecting panels.

Games and Virtual Reality - One section of the cornerstone course with the theme of Games and Virtual Reality was offered in the Fall of 2015 (Cornerstone 1) and Spring of 2016 (Cornerstone 2). The project in the Fall semester was to create a mini-golf hole based on a science or math theme (i.e. friction, gravity, Pythagorean's Theorem). The teams were formed during the third week of the fall semester. Each team had four members in the fall and the teams were changed in the Spring and had three or four members based on the class size. There were team building activities in the first semester along with use of a web-based team rating system to help facilitate team functioning. In both semesters, the projects and reports required students to complete milestones:

Week	Mini-Golf Project Milestones (Fall)
6	**Design Proposal:** The design proposal was comprised of background, an AutoCAD drawing of the design, and a project management plan.
8	**Rough prototype:** The first prototype did not have any electronics or sensors and was meant to show off the theme and follow the specifications.
8	**Rough Prototype Testing:** During this testing session students had to test each other teams project and data was collected on the average number of strokes.
10	**Final Prototype Design:** The final prototype required the implementation of sensors and electronics to give the player feedback. Teams revamped their original proposals to include circuit diagrams and a bill of materials as well as an updated CAD drawing.
14	**Final prototype testing:** Final testing was performed and students had to rate the hole based on which one was the most enjoyable.
15	**Final presentation and Report:** Each team was required to give a 10-minute presentation on their project. They also had to compile all their work into a cohesive report.

The Spring project was to create an input device for use with video games and virtual reality. Teams could choose between three different types of input devices:

1. One handed design: a fully functioning input device that was usable with just one hand.
2. Fitness/health: an input device that uses health or fitness sensing as part of its operation.
3. Education: an input device that uses STEM education as part of its design.

The teams were once again tasked with milestones:

Week	Input Device Project Milestones (Spring)
4	**Design Proposal:** Based on the type of input device the students chose they had to write a document with a competitor analysis, background and patent search, and preliminary design plan.
5	**Rough prototype:** The first input device prototype had to be made using paper, cardboard, clay and other simple materials. It needed to have enough inputs to play Tetris.
9	**Rough Prototype testing;** The testing consisted of each student playing Tetris using each team's device. The tests were timed and the score was recorded along with a survey.
10	**Test Data presentation:** The data from the test had to be put into MatLab by the teams and then analyzed. The teams then presented their findings.
12	**Final prototype design:** The final prototype had to use 3D printing and include a SolidWorks model as well as a bill of materials and more controls.
14	**Final prototype testing:** Testing was performed by each student in a game of their choosing. User survey data was collected and provided to the teams for analysis.
15	**Final presentation and Report:** Each team was required to create a PowerPoint presentation and give a 10-minute presentation on their project. They also had to compile all their work into a cohesive report.

Figure 4 – Final design examples – Mini Golf Holes and input devices.

Sustainability theme - In the sustainability themed full cornerstone taught in the Fall of 2014, there was one semester long design project and three minor design projects given throughout the semester. These project were done in groups of 4. The object project was to design a sustainable and independent home in Greater Boston by completely eliminating the use of energy and water from outside sources (grid) and utilize local and/or sustainably harvested/produced materials. Students used AutoCAD to design their homes which had to be drawn to scale with piping and electrical systems incorporated. There were bi-weekly milestones that the students needed to complete as a group for the semester long sustainable home design project.

Research Client Needs: Knowing your home location – do some research on the culture and temperature of this region.

Examine Energy Needs for a home: List all the energy needs of a home, along with alternatives. In a spreadsheet, calculate energy usage of each item. Examine the energy supply issues considering peak energy demand and energy storage. In energy generation, 3 new, ground breaking methods and 3 older methods were researched for

Integrated Design

environmental impact, economy for the house and if the home can be off the grid.

Examine Household Water Guidelines and needs: Consider water usage, water collection and efficiency of the water used.

Materials Guidelines: Search patents, insulation and any other sources for materials that will help contain energy, and make the home more efficient.

Alternative Designs, Synthesis, and Decision Making: Students designed a sustainable home using brainstorming techniques to stimulate creativity and generate at least 1 improvement then performed a decision analysis.

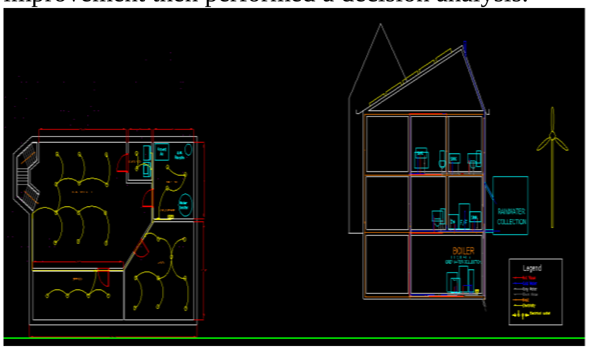

Figure 5 - Example of AutoCAD of group's Sustainable Home.

The three minor design projects were used to learn and build on the idea of sustainability and sustainable buildings. These projects were hands-on where the students designed, tested, and analyzed data from their designs and were able to use that data to redesign and improve upon their original designs.

The first hands-on minor design project was to design and build a solar water heater that provided the warmest water for the longest time compared to others groups in the class. The students had to collect and analyze data using Matlab from their first design, report their findings to the class, and use that data to help them redesign a better solar water heater. The second minor design project was to build a thermostat using Arduino microcontroller boards. They had to make a thermostat using temperature sensors and an LCD screen and write code so the Arduino run thermostat would turn on and off to simulate conserving energy in a home. Lastly, the third minor design project was to design a passive solar box with the goal to maintain the temperature inside the box between 65ºF and 85ºF for the longest time possible compared to other groups in the class. This project was to help students understand how heat transfer from the sun can affect a home by specifically maximizing the sun's solar radiation heat to decrease the use of electrical heating systems in a home. The students had to determine which materials and how much should be used as a thermal mass within their passive solar boxes. The students again measured the temperature inside the boxes over 5 days and analyzed the data using Matlab and C++ to determine how to best design their boxes.

Figure 6- Student's Passive Solar Boxes tested on the roof.

Security - Four sections of the cornerstone course with the theme of Security were offered in the Fall of 2015 (Cornerstone 1) and Spring of 2016 (Cornerstone 2). Project teams of, generally, four students were formed at the beginning of each semester, with the teams scrambled between the Fall and Spring semesters. The web-based teaming and peer evaluation system implemented in other Cornerstone sections was used in the Spring semester. All of the projects required students to:

- conceive a solution that matches the need of a client with needs very different from that of the typical student in the class,
- draw a sketch of the system using Autocad and/or Solidworks,
- build and demonstrate a prototype for peer review in advance of the actual demonstration,
- make Power Point Slides to present the work to the public, and write a technical report of the work.

By the end of the Spring semester, as the students progressed, the projects required

- the use of a significant and functional part that was conceived by the students, created in Solidworks, and built with a 3D printer,
- an original C++ program that controlled the action of the microcontroller-based solution,
- a numerical model of their project's performance implemented in MATLAB, of sufficient complexity that the output of the model could be compared to the actual measured performance at the demonstration, and
- the implementation and use of technical components for which instruction was not given by the instructor.

One unique aspect used in the Spring semester of these sections was a system of class "patents." Intellectual property is a course objective, so the class patent system was designed to support that learning goal. In the system, student teams could, at any time, submit a patent application to the instructor with an idea for their project that they believed was "novel, non-obvious, and useful." If the instructor agreed, the team was given a class patent. The team's patent was placed on the section's course management system website so that all students could see it and learn from it, and no other team was allowed to use that idea for 6 weeks (timed so that all patents awarded before the milestone presentation were free for use by any team at the final presentation). To motivate the submission of a class patent, the Spring milestone and final projects were made somewhat competitive, with a winning team project getting those students a small bonus on their grade. Students quickly saw the benefits of an intellectual property system, and were indeed spurred to innovate faster, resulting in teams working harder on their projects from the first day!

The following projects supported the overall course learning objectives:

Semester 1: The Launch Box: The focus of this first project was a device/system that fulfilled relatively simple goals in terms of function, but that was designed to a client with unusual objectives for the design. Specifically, teams built a small device that enabled a single person to launch a small payload into the air with as little notice as possible. In other words, this was a James Bond-like mechanism for a "secret agent" to collect data in a crowd. Groups could choose between a few different (simulated) payloads, with different height and mass requirements. Teams demonstrated creativity in the means by which the device and the launch itself were made unnoticeable to others in the surroundings.

That's a Fugazi – Student teams had to design, construct, program, and present in both oral and written reports an Arduino-based device/system that enabled a border control officer to quickly and easily test whether received goods are valid or counterfeit. Each team chose what manner of good was to be tested by their device and demonstrated with examples of valid and counterfeit goods. The device had to use at least two sensors chosen by the students to detect the validity of the good being tested. For example, a counterfeit item might have had a different weight and a weaker magnet than the valid samples. The device had to be simple to operate and interpret, and had to look like a professional, durable device that matched a typical border control agent's sense of on-the-job aesthetic appeal.

Semester 2: Students were given a base system that included a SparkFun RedBoard, a motor controller, a robot platform, and a set of basic sensors and actuators. Each team had to design, construct, program, demonstrate, and present in both oral and written reports a robot that autonomously found and alerted to the presence of a simulated threat. The only interaction a student could have with their robot was pushing a button to have it begin moving. Each team had to design and 3D print for their robot a bump sensor to prevent damage from a collision.

Hide and Seek, Milestone – For the milestone demonstration, the simulated threat was a spot of light in a dim room. The robot was expected to search for the illuminated location, moving until it stopped in the vicinity of the brightest location on the floor. The team with the fastest time in each section received bonus.

Hide and Seek, Final – For the final demonstration, all of the robots in each section were placed around the periphery of a 40 x 20 foot room that contained a few wall-like obstacles. The goal was for the robots to find as quickly as possible a simulated chemical weapon in the form of an open container of isopropanol. Each group was given a single alcohol vapor sensor. Robots were to come to a stop within a few feet of the container and give some kind of alarm notice that the "weapon" has been found. All robots in a class section searched simultaneously. Rewards in the form of bonus points were given to not just the fastest team within each section but also to the entire section that had the shortest median time. In this way, there was incentive to build a robot that is both fast and cooperative, and the fastest section was able to implement a light-based communication system that caused all of their robots to swarm on the chemical source once one robot found it.

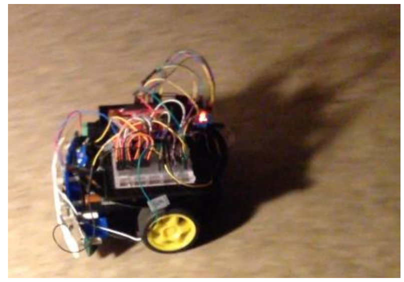

Figure 7 – A robot from the Hide and Seek, Milestone project has autonomously directed itself toward the light source. A 3D printed bump sensor designed by the team is in white and forms the front of the robot.

Conclusions - The focus of this has been on the projects as representative of the course outcomes. Before the Cornerstone approach, the outcomes of the first semester design course were a small, simple minor design and build project and a larger design proposal for a more complex, real world problem. In the second problem solving and computations course which focused on programming the outcome was a small project programming a microcontroller on a breadboard and a separate programming project using both C++ and Matlab. There were homework and application problems using AutoCAD, Solidworks, the design process, flow charts, in the 2 courses, with successful design and programming projects. The projects from cornerstone reflect a different focus and show the integrated design experience along with the competence in the content areas. What is hard to capture is the level of commitment the groups demonstrate as they struggle to solve technical problems, build working prototypes and then the resulting pride and enthusiasm when the teams achieve success. The project quality and amount of integrated programming and design by the end of the 2 semesters (or 8 credits) is evident to all of the instructors and observers.

Future plans include student purchased Arduino and/or Sparkfun kits to support the projects. Due to the large variety of projects, the teaching team has created a custom component kit to support the cornerstone courses that the students can then retain, hopefully to be useful in future courses and projects. The course will replace the separate courses completely in Fall 2016, so there are new themes planned such as bioengineering and engineering of musical instruments. In addition, there will be continued improvement of the course organization, project design and implementation resulting from assessment data and feedback from students and instructors. Cornerstone has provided the integrated design experience while maintaining the course content integrity, these were the desired outcomes, and will be the first-year experience moving forward.

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