
AC 2012-3823: CAPSTONE 101: A FRAMEWORK FOR IMPLEMENTATION OF AN ABET-COMPLIANT CAPSTONE SEQUENCE

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Capstone 101: A Framework for Implementation of an ABET-Compliant Capstone Sequence

Introduction

Accreditation of an engineering or engineering technology degree program depends on the inclusion of a Capstone Design (CD) sequence in the required curriculum. Specifically, ABET Criteria 5 for Accrediting Engineering Programs states, “Students must be prepared for engineering practice through a curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints.” ABET Criteria 5 for Accrediting Engineering Technology Programs states “Baccalaureate degree programs must provide a capstone or integrating experience that develops student competencies in applying both technical and non-technical skills in solving problems.” While the requirement is quite specific, the execution of the requirements is undefined. A CD course is ill suited to traditional lecture format, since the course is about the execution and fusion of the knowledge and skill acquired as a result of passing through a specific curriculum. The CD sequence is not about acquisition of new abilities, but rather a clinical demonstration of ability that will be applied to professional practice in short order after completion of studies ^{(1) (2) (3)}.

ABET guidelines stipulate ⁽⁴⁾:

Engineering programs must demonstrate that their students attain:

- a. an ability to apply knowledge of mathematics, science, and engineering
- b. an ability to design and conduct experiments, as well as to analyze and interpret data
- c. an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
- d. an ability to function on multi-disciplinary teams
- e. an ability to identify, formulate, and solve engineering problems
- f. an understanding of professional and ethical responsibility
- g. an ability to communicate effectively
- h. the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
- i. a recognition of the need for, and an ability to engage in life-long learning
- j. a knowledge of contemporary issues
- k. an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Engineering programs are accredited by the Engineering Accreditation Commission (EAC) of ABET.

Engineering technology programs must demonstrate that graduates have:

- a. an appropriate mastery of the knowledge, techniques, skills and modern tools of their disciplines.
- b. an ability to apply current knowledge and adapt to emerging applications of mathematics, science, engineering and technology.
- c. an ability to conduct, analyze and interpret experiments, and apply experimental results to improve processes.
- d. an ability to apply creativity in the design of systems, components, or processes appropriate to program educational objectives.
- e. an ability to function effectively on teams.
- f. an ability to identify, analyze and solve technical problems.
- g. an ability to communicate effectively.
- h. a recognition of the need for, and an ability to engage in lifelong learning.
- i. an ability to understand professional, ethical and social responsibilities.
- j. a respect for diversity and a knowledge of contemporary professional, societal and global issues.
- k. a commitment to quality, timeliness, and continuous improvement.

Technology programs are accredited by the Technology Accreditation Commission (TAC) of ABET.

The goal of this work is to provide an overview of a successful CD program at a large state university, with enough structural guidance to assist in the establishment of a program where one does not currently exist, or a model for programs that wish to restructure course sequences that are not satisfactory to accreditation entities or to faculty at a particular institution. The content of this work is based on 5 years of research, scholarship, and workshop and implementation experience.

External Customer/Client/Sponsor/Stakeholder

One of the most important lessons that can be transmitted to students during their CD sequence is the nature of relationships with others that will dominate their working lives. Technical competence and even excellence is an assumption by hiring entities. Unfortunately this metric is often used exclusively to reward students during their academic experience (i.e., good grades = success). The reality of the workplace is that the students will be expected to accomplish their work while functioning in a complex environment where drivers not considered in their

coursework (cost, delivery time, relationship building, etc.) may override decisions that are made in the name of technical superiority.

It is for this reason that the authors recommend that no matter what other features are used from this work to implement or improve a CD sequence, incorporation of an external customer should be required for any project that students are allowed to attempt. The realization of this situation for future practitioners is the best way to serve both the students as well as the entities who hire the students upon completion of the CD sequence⁽⁵⁾⁽⁶⁾⁽⁷⁾.

Course Structure

The first basic decision on course structure is CD sequence duration. Some institutions use a single semester experience and some use a two semester sequence. Institutions on the quarter system have another approach. This decision is usually predicated on the number of credit hours that the faculty deem appropriate for the clinical training of their graduates. Once the decision is made, it then drives the content of the course.

Single semester CD sequences are by their nature limited in the scope of what students can be expected to deliver. It is rarely possible for a student or student group to completely design, develop, build and test any type of device/system in a single semester.

The authors recommend a two semester sequence for the CD sequence. This allows ample time for students to experience the entire life cycle of an engineering project, from requirements gathering to conceptual design, detail design and work product realization⁽⁸⁾.

Group versus Single Student Projects

This sequence design decision is a major factor in determining how the balance of the CD experience is constructed. Accreditation is partly based on how students are trained to work in groups. While other courses in a particular curriculum may address group activity, traditional instructional methods tend to dominate the delivery of material in most programs. The CD sequence is a natural place to incorporate group work.

There are cases where individual work may be warranted. Students who aspire to graduate degrees may be best served by a design experience that simulates research activity in academia, such as the design of an experimental investigation, revision of experimental platforms or software or other projects requiring expert level understanding of a particular project. As long as there is an external stakeholder, such as an investigator relying on the student work for successful acquisition of data, the CD sequence can be applied.

There are various schools of thought regarding group size for CD sequence projects. Most published work suggests that group sizes of 3-4 students is the correct balance of student maximum work-load and minimum student involvement for assessment ⁽⁹⁾.

Assignment of students to groups can also present a significant challenge for the CD sequence. Balancing student interest with project staffing needs can be time consuming once the total number of students exceeds about 25 (around 5 projects). This problem is compounded when multidisciplinary teams must be created ^{(10) (11) (12) (13)}.

Instructional Models

Assignment as the instructor of a CD sequence hopefully implies two things: experience as an engineering or engineering technology practitioner, as well as an interest in teaching the design process to students in a clinical setting. Approaching the course as a special topics or independent study type of exercise is helpful in shifting the paradigm of student expectations and performance.

Individual instruction of CD sequences can be a challenge. The open ended nature of design problems requires more student contact and more time consuming types of feedback. This can be mitigated by having all students work on the same project. Unfortunately, it also introduces the temptation for students to collaborate in undesirable ways.

Team teaching the CD sequence is a way to leverage instructor time and effort. This can provide a seamless way to integrate several disciplines into a common experience, or to have a project that all students pursue with cross functional content. This must be balanced with the need for remediation among students with different knowledge bases upon entry into the CD sequence ⁽¹⁴⁾.

Project Sourcing

There are several sources of design projects for use in a CD sequence. At the authors' institution, the students traditionally were allowed to define their design projects. As one can surmise, this led to a large variation in the scope, difficulty and feasibility of projects in any sequence. Student projects are still allowed in the author's program, but the students must recruit a group, find a faculty director for their project and submit a written proposal for their project defining the deliverables. This proposal is reviewed by other faculty prior to revision or approval.

Student competitions are another source of projects for CD sequences. Reference (15) details some of the competitions available. The authors' institution regularly competes in NASA, ASME

and IEEE competitions. Competitions are excellent ways to integrate student organizations with classroom activities and community outreach efforts⁽¹⁶⁾.

More and more students from the current cadre value service learning as a way to expand their education experience as well as to develop their resume for future employment⁽¹⁷⁾. There are several outlets for this type of project. The organization Engineers without Borders has been a source of meaningful projects in the past⁽¹⁸⁾. Goodwill Industries is usually interested in working with college students⁽¹⁹⁾. Some student competitions, such as the NISH AbilityOne Challenge can fulfill this type of need as well⁽²⁰⁾.

Government entities are also sources of projects as well as funding for CD sequences⁽²¹⁾.

Private and corporate entities are also sources of projects and funding. Most Engineering and Engineering Technology programs have external advisory boards which have a vested interest in the success of the program. These board members can be solicited to provide funding, technical support or both to student projects.

The CD sequence at the author's institution accesses all of these sources for project content, funds and technical support.

Deliverables

The deliverables for a CD sequence depend on the duration of the project. The deliverables shown below were designed for a two semester experience. A subset of those shown can be used for a shorter course. These deliverables support the formation of student groups and the subsequent experience of forming teams and working in that structure⁽²²⁾.

Statement of Work

This is a written document that illustrates that the students understand what their project entails and details exactly what work product is to be delivered at the end of the project. This verbiage is chosen specifically to familiarize students with its use in contracts or proposals that may be encountered in the workplace.

Capabilities and Requirements Document

This is a written document; alternately know as a specification, that details the functionality of the work product associated with a student project. This document can be expanded to include test plans and accept / reject criteria for a particular project function.

Project Plan

This document encompasses the project schedule, with deliverables and milestones identified project resources allocation and project tasks assigned. Project dependencies and critical path are identified. This deliverable can be expanded to include a project budget⁽²³⁾.

Conceptual Design Presentation

This deliverable takes the form of a presentation to a faculty/sponsor/stakeholder panel. The students describe their problem, discuss the concepts for solution that they considered, and defend their choice of solution. Concept of operations is presented.

Design Package

This document includes drawings, schematics, work instructions, implementation procedures, written specifications, bill of material or any other document required for the student project to be realized by a competent technology worker without the student's constant supervision.

Interim Report (1st Semester Final Report)

This document provides all project information, design narrative and supporting calculations or other research that would allow a team of competent engineers or engineering technologists to reproduce the student's work to date with no additional effort on the part of the reader.

Progress Report

This document details the student's project status and progress. Progress reports are required on a bi-weekly basis. This report can be expanded to include timekeeping by the students as well as updated project plans with actual hours included.

Prototype Demonstration

This presentation is required at the midpoint of the second semester. Students must demonstrate a functional manifestation of their work product at this time. This is required so that students have ample time for testing and redesign/development of their work product. This exercise is particularly effective at illustrating Murphy's Law and its' many corollaries to inexperienced designers.

Final Report (2nd Semester)

This document provides all project information, design narrative and supporting calculations or other research that would allow a team of competent engineers or engineering technologists to reproduce the student's work to date with no additional effort on the part of the reader. The report should include test data or other performance evaluations and an assessment of how well

the student design accomplished the goals initially described in the Capabilities and Requirements Document.

It should also be noted here that recent changes in United States patent law have rendered the traditional lab notebook obsolete⁽²⁴⁾. Changing from the old “first to invent” to the “first to file” structure prevalent in the rest of the world obviates the need for dated, witnessed and bound records in the protection of intellectual property. The Author’s institution has dropped the notebook as a deliverable for the CD sequence, replacing it with a requirement for students to construct a secure document archive, accessible to the course instructors as well as to industry sponsors and design team members, using commercially available means, such as Google Documents⁽²⁵⁾, Dropbox⁽²⁶⁾ or other modalities of their choice.

Cross Functional Teams

Cross functional teams provide valuable experience to students. Working with new colleagues, who may have different backgrounds than one’s normal academic cohort, is an ability that will serve the students well in actual practice.

ABET specifically requires that students be able to function on multi-disciplinary teams. The CD sequence supplies a framework where students from diverse backgrounds can easily be mixed in groups⁽²⁷⁾.

Assessment

Use of rubrics is helpful in grading the types of deliverables one is likely to encounter during the supervision of a CD sequence. Courses of any appreciable size can’t be handled by a single instructor. External stakeholders can supply valuable feedback for students as well as for faculty course designers^{(28) (29)}.

Peer evaluations, especially when conducted just after a major deliverable is submitted, provide accurate insight into group dynamics.

Clinical Professionalism

Standards of behavior in the workplace are foreign to most students. The CD sequence is an excellent opportunity for students to begin the work habits that will be expected of them from any future employer. This may even extend to a professional appearance at public meetings, presentations and demonstrations.

Enforcement of professional communication standards in any communication with external stakeholders is an important aspect of professionalism.

Both of these issues are incorporated into course rubrics ⁽²⁹⁾ dealing with presentations and public event interaction.

Community Engagement Activity

CD projects tend to show well at events designed to engage the larger University community. A trade show type of atmosphere, with students displaying the results of their project work is recommended as a way to reinforce the communication requirements of a technical degree.

Many competition projects have outreach requirements. NASA competitions require this as a matter of course ⁽³⁰⁾. Community engagement activities can provide venues for outreach that can be more effective than student trips to off-campus facilities alone.

Lessons Learned

A “lessons learned” exploration of the capstone program at UNC Charlotte could constitute an entire publication. The main lessons learned over the 6 year life of the program will be addressed here. Lessons described in the sections above will not be repeated.

Student projects must not appear to be “make-work” or lack realistic expectations – Despite student inexperience in the workplace, they are extremely adept at identifying projects that seem to be unimportant to sponsoring organizations, or projects that do not require the delivery of real engineering content. All projects placed before students for selection or assignment should be formatted in the same way, require deliverables that are defined and achievable and offer the possibility of exploration that goes beyond the undergraduate curriculum. A partial listing of projects from the authors’ program can be seen in Appendix 1.

Multidisciplinary projects prepare the students for practice – Comments on the course from alumni indicate that the interaction students had with those outside their area of expertise prepared them well for their positions after graduation. This is especially true of those students that work in smaller companies, without large technical departments.

Faculty can only mentor a limited number of different projects effectively – In an era of tight budgets and increasing class sizes, this lesson continues to be an issue. In addition to grading deliverables for a CD course, expecting an instructor to keep up with 7-10 individual projects, and offer meaningful guidance is unrealistic, especially if the CD course is counted as a single course assignment in determining teaching load. A practical limit of 3 groups is the limit that the

authors have found for the best of the best capstone instructors who also teach a full load of courses. A more realistic limit is 2 projects per instructor. These limits assume a 30 minute meeting each week, drop in during office hours, purchasing oversight and review of deliverables. This necessitates support from the department and college level to require that other faculty assist with CD project mentoring. The Dean of the College of Engineering at UNC Charlotte has been instrumental in providing this support to the CD program.

Summary of Recommendations for a Capstone Design Sequence

A framework for a capstone design sequence has been presented. It is recommended that the sequence be structured as follows:

- 2 Semesters
- Groups of 3-4 students
- External Stakeholders engaged as project partners
- Deliverables of:
 - Statement of Work
 - Capabilities and Requirements Document
 - Project Plan
 - Conceptual Design Presentation
 - Design Package
 - Interim Report (1st Semester Final Report)
 - Progress Reports
 - Prototype Demonstration
 - Final Report (2nd Semester)

- Cross-functional Teams
- Rubrics for Assessment
- Community Engagement Activities for Project Presentation

This recommended structure should allow a course sequence to succeed and support ABET accreditation of the hosting programs.

Appendix 1 – Representative list of past capstone projects

Title	Sponsor
Modular Reactor Design	AREVA
Turbine Diaphragm Alignment	EPRI
General Dynamics	FPGA / DSP
Irwin Tools	Bar Clamp and Spreader
Stabilus	Gas Spring Quick Disconnect
AFL Telecommunications	Fiber-optic Splice Tray
Chip Ganassi Racing	Race Car Power Management
Eaton	Data Systems and Interfaces
Ingersol Rand	Mechanical Speed Control
Schaeffler Group	Anti-friction Bearing
Shaw	Thermal Storage Enhanced HVAC
Zurn Commercial Brass	Ceramic Flush Valve
Boolean Core Devices	Boolean Core Processor FPGA
Carolinas Medical Center	Chest Simulator for Sternum Closure

Lord Corporation	Magneto-rheological Strut Damper
NASA	CODEC Implementation on FPGA
Charlotte Area Transportation System	Solar Power for Bus Garage Facility
Duke Energy	Steam Valve Position Encoder
NASA	Lunabotics Competition Robot
NISH	Tool Kit for Double Amputee
Carolinas Aviation Museum	Flight 1549 Display Structure
GE Aviation	Turbine Hub Production Optimization
Siemens	Stator Core Assembly Fixture
Westinghouse	Lift Mechanism for Nuclear Power Station
Baldor Electric	Motor Test Fixture with Variable Side Loads
Bosch Engineering	Pedestrian Safety Alert System for Electric Car
Southern Company	Turbine Man-way Cover Removal System
United States Air Force	Combat Climbing Assist Robot
UNC Charlotte Green Initiative	Arcade Game Style Recycling Center

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