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Progressive Curricular Structure for STEM Programs

Ivana Milanovic, University of Hartford, USA
Tom Eppes, University of Hartford, USA
Fred Sweitzer, University of Hartford, USA

Abstract: In many undergraduate STEM programs, design and research experiences are delayed until the senior year. As a consequence students often lack the creativity, initiative and ability to develop robust design solutions. This paper describes a curricular strategy that improves the full range of skill sets critical to capstone success. Students successively and in parallel encounter courses that strengthen key liberal education skills: critical thinking, quantitative reasoning, teamwork, communications and information literacy.

In response, a progressive curricular structure called Capstone Performance Recovery (CPR) was developed and implemented within a course sequence in the undergraduate Mechanical Engineering Technology (MET) Program. Strategically positioned in core topical areas, CPR courses gradually introduce challenging and open-ended assignments that foster integration of knowledge and skills. Students work independently in seeking and synthesizing information and ultimately emerge better prepared to tackle the rigors of design. In addition, each course contains embedded assessments that mirror those in the capstone course. CPR also liberates the instructor to become a mentor whose focus is on fostering higher level skills as students assume greater responsibility for their learning experience.

At a course level, students gradually progress toward an open-ended design. CPR successfully engages students in inquiry and learning, gradually building toward intellectual and practical challenges without pre-determined outcomes. To accomplish this, each course contains a cluster of interconnected laboratories organized in a pyramidal block-like system. These blocks are: (1) classical experiments, (2) jigsaw experiments, and (3) design of an experiment. This structure delivers an array of experiences, builds on already existing skills and knowledge, and connects them in a logical way. CPR facilitates development of problem solving skills as students become active participants in discovery.

Keywords: design of an experiment, capstone, open-ended design.

Introduction

This paper describes a progressive curricular structure that was developed and implemented within a course sequence in the undergraduate Mechanical Engineering Technology (MET) Program. Capstone Performance Recovery (CPR) successfully engages students in inquiry and learning, gradually building toward intellectual and practical challenges without pre-determined outcomes. The primary learning objective of CPR is to improve the full range of skill sets critical to capstone success. Students successively and in parallel encounter courses that strengthen key liberal education skills: critical thinking, quantitative reasoning, teamwork, communications and information literacy.

In conventional undergraduate engineering (E) and engineering technology (ET) curricula, design and research experiences are delayed until the capstone project. The consequence is that many students lack the creativity, initiative and ability to develop robust design solutions. In most E/ET laboratory courses, students are required to perform and document

work on 10-12 experiments during the semester. Instructions are specific and detail what is to be constructed, measured and calculated. The primary learning objectives are to: operate the measurement equipment, take meaningful data, reduce the data, compare data to a theoretical model and draw reasonable conclusions. Consequently, the main challenges to students are scope and quantity of work. Instructors function as overseers who assist students with staying on task.

In this conventional laboratory structure, problem solving and critical thinking skills are not fostered because instructions are to be followed rigorously and laboratory reports largely consist of duly recorded outcomes and conclusions. This approach is an unimaginative one and denies students the opportunity to build experiments and models from scratch, experience difficulties, be resourceful and explore different avenues while making decisions along the way. Instructors of upper-level courses generally observe that students have great difficulty when open-ended design problems are posed. Consequently, there is a strong pedagogical need to address the shortcomings that stem from the overuse of well-defined experiments.

A literature survey found that other educators have drawn similar conclusions with regard to the pre-capstone experience, and recent papers report successfully evaluating new avenues of teaching design preparedness. Truax (2004) introduced teamwork and experimental design within an Environmental Lab course prior to the capstone experience. This work illustrated the need for more open-ended problem solving. Farahbakhsh et al. (2007) developed and introduced a Mass Transfer Operations course in the Environmental Engineering curriculum that abandoned the traditional well-defined approach and replaced it with one in which students designed, built and tested experiments themselves. Willis (2006) identified in an Electrical Circuit Theory course the value of incorporating a progressively challenging set of exercises as the semester went on. Truax (2004) and Farahbakhsh (2007) created a new course around the concept of a single semester-long design of experiment team project. On the other hand, Willis (2006) understood the need for a transitional approach within a single course to better prepare for open-ended design. Butler et al. (2005) went so far as to test both well-defined and open-ended laboratory structures simultaneously; however, no impact to students' grades in the capstone project was observed. It is worth noting that in each case a single-course solutions was tested which speaks to the need for a holistic solution.

CPR addresses the aforementioned need by offering a curricular solution built on an innovative set of teaching and learning strategies. CPR was initially conceived for use in the thermo-fluids area and successfully piloted in a single fluids course (Milanovic & Eppes, 2008). Within the course, CPR is organized as a progressive set of interconnected laboratories configured in a modular fashion: (1) classical experiments with prescribed outcomes, (2) higher level jigsaw experiments, and (3) a student-centric design of an experiment (DoE). This new laboratory structure builds on already existing skills and knowledge, connects them in a logical way and engages students in inquiry and learning, gradually building toward intellectual and practical challenges without pre-determined outcomes.

Such CPR courses, strategically placed across core topical areas, contain open-ended design problems that foster greater independence and instil higher level intellectual and practical skills. Students enter the senior year better prepared to tackle the rigors of capstone design. Instructors become mentors as students self-monitor, reflect and assume greater responsibility for their learning experience.

Alternatively, CPR may be viewed as a sequence of exercises in undergraduate research. In the words of Settles, research is analogous to a jigsaw puzzle (Settles, 2003). Even if the final

picture is known, the task of putting the pieces together is not a predictable one and progress cannot be forecast. Early on, only a few pieces may fit, and progress may be painfully slow. Discovery is one of twists, turns and outright dead-ends; however, useful information is always gained. During the most frustrating moments, a breakthrough may be just around the corner, and no matter how the journey ends, students are better prepared for the next design challenge.

While earlier work advanced the idea of a course-based solution, CPR advocates a broader curricular approach. Students successively encounter courses that successively and in parallel strengthen their skills prior to the capstone project. At a course level, students gradually progress towards an open-ended problem. One by-product of CPR is the creation of new experiments chosen from quality DoEs.

Motivation for Change

The University of Hartford, a private institution, serves a diverse constituency of both full- and part-time, graduate and undergraduate students. The College of Engineering, Technology, and Architecture (CETA) has a population of about 800 undergraduates. CETA is primarily located in the recently-completed Integrated Science, Engineering, and Technology (ISET) complex. When ISET was opened in 2005, it provided newly renovated as well as some additional space; however, the project did not include major capital equipment purchases or a multi-year plan to replenish the infrastructure.

The ongoing challenges faced by CETA are to:

- Maximize the effectiveness of the laboratory experience
- More efficiently use space, equipment and faculty resources
- Modernize teaching-based laboratory equipment

Prior to CPR, thermo-fluids courses in the MET program were taught mostly from a theoretical perspective without sufficient hands-on experience. The mechatronics area, important for both the MET and Electronic Engineering Technology (EET) programs, had an instrumentation laboratory that was under-equipped and the faculty was exploring new ways to expand experiential learning using virtual laboratories.

Faced with continuing equipment needs and static budgets, an inventory revealed deficiencies particularly in some topical areas. To leverage resources in the thermo-fluids area, students were tasked to construct models in the machine shop (Milanovic & Eppes, 2008). In the mechatronics area, the use of virtual experiments was undertaken, and a distance laboratory system called ALTE (Advanced Laboratory Test Environment) was developed and successfully piloted. However, ALTE soon evolved into a complement to the hands-on laboratory not a replacement as reported by Eppes & Schuyler (2005) and Eppes & Schuyler (2006).

Beyond the cost of equipment and facilities, the development of quality experiments is a time-consuming process. This responsibility normally falls on the faculty who teach laboratory-based courses and is not shared equally. Laboratory courses are under-credited for the amount of work and time that must be invested (Truax, 2004). CPR offers a teaching strategy that transforms the laboratory into a more rewarding student-centric environment promoting autonomy and self-expression and easing the reliance on equipment technology as the primary focus of learning.

Structure of CPR

Many E/ET laboratory courses are held captive by a form of linear thinking that perpetuates the use of procedurally-based exercises with well-defined outcomes. This conventional approach exposes students to measurement techniques and enhances their understanding of the fundamental laws of the discipline. However, students struggle with the problems inherent in capstone design such as facing uncertainty, overcoming difficulties and improvising solutions. Consequently, the drawbacks of this approach are:

- Critical thinking and problem solving skills are not fostered
- Faculty oversee rather than mentor the learning process (Truax, 2004)
- Ongoing investment is required to sustain the equipment base

CPR reorganizes a laboratory course into three progressively challenging modules as shown in Table 1. Each module contains one or more experiments that are performed sequentially during the semester.

In Module 1: Classical Experiments (weeks 1-4) familiarize students with the lab facilities and measurement equipment. Working in teams, students are provided with a set-up and procedure to be followed by data acquisition, analysis and a written report. This is often the first time students are required to adhere to a technical documentation standard (e.g. American Society of Mechanical Engineers).

In Module 2: Jigsaw Experiments (weeks 5-8) are transitional exercises that contain some design components. The Jigsaw has defined objectives; however, some instructions are intentionally left out leaving students to synthesize the set up and data collection to successfully acquire relevant and meaningful data. Although the experimental goal is given, the task of filling in the missing pieces is the challenge. A properly designed jigsaw is carefully crafted so students can complete the work in the time available, usually two weeks. For many students, this is their first experience where completing set up must be done before the experiment can be performed.

In Module 3: DoE (weeks 9-14) is the culminating experience in which teams of students identify, design and perform a relevant experiment of their choosing. Each team proposes, plans and executes the DoE within a limited budget and timeframe. In an end-of-the-semester event, formal oral presentations are given to a group of judges consisting of alumni, faculty and industry representatives.

Table 1. CPR components, activities and deliverables

Module	Outline of Activity	Deliverables
Classical Experiments	Experiments with conventional set up and procedures provided	Written report
Jigsaw Experiments	Experiments with defined objectives but without a complete set of instructions	Written report
DoE	Creative exercise in which student teams propose and execute a project within a limited budget and timeframe	Formal oral presentation

Within a single course, CPR progressively challenges students during the semester. In Module 1, teams perform well-defined experiments with established procedures and goals. Transitional exercises of Module 2 introduce design uncertainty as students must synthesize the missing elements of an experiment. In the DoE of Module 3, success is measured by integrating subject matter, inquiry-based learning, coping with adversity and group problem solving.

CPR modules occur sequentially beginning with Classical Experiments where students perform two labs that span two weeks each with written reports. The learning outcomes of Classical Experiments are to:

- Familiarize students with lab facilities and measurement equipment
- Provide experience in data acquisition, analysis and data interpretation
- Logically structure experimental work
- Acquaint students with reporting requirements

The two Jigsaw Experiments each span a two-week period including written reports. A Jigsaw is similar to the Classical Experiment since it has defined objectives; however, some set up and/or instructions are intentionally left out requiring students to first synthesize missing information in order to collect meaningful data. Consequently, the goal of the Jigsaw is to prepare students for more independent work prior to entering the DoE where critical thinking and problem solving skills are essential. The learning outcomes are to:

- Construct models, create a simulation, or design a test bed
- Gather and utilize relevant information
- Develop a specific data acquisition plan
- Synthesize a successful experimental set up
- Justify, validate, and document the results

The DoE is the culminating experience within a CPR course in which teams of students work for five weeks to identify, design and perform an original and relevant experiment of their choosing. Students are expected to integrate prior experiences into an independent research project appropriate for the course and budgeted funds. Each team brainstorms and prepares a project proposal that adequately summarizes the purpose of the DoE. To be acceptable, a project must meet the following criteria:

- Relevant to one or more course topics
- Suitable in scope of work
- Original and not a copy
- Limited in time and budget

At an end-of-the-semester event, each design team delivers a formal oral presentation to a group of judges made up of faculty, alumni and an outside panel, some of whom are practicing engineers drawn from local industry. The learning outcomes of the DoE are to:

- Generate concepts and filter down to a single proposal
- Gather and utilize relevant information
- Evaluate alternatives within the construct of the experiment
- Synthesize, design, and conduct the experiment
- Manage the project within time and budget constraints
- Report project status in writing on a weekly basis
- Develop a specific data acquisition plan
- Collect and perform data visualization
- Justify, validate, and document the results

- Deliver a formal oral presentation to a panel of judges
- Assess team skills of peers

As the semester unfolds, students become more engaged in inquiry and learning as they face the intellectual and practical challenges contained in a CPR course. An integrated sequence of laboratory modules builds on skills and knowledge already gained so that students gradually learn to perform at more complex levels of experimental design.

CPR transforms the role of the faculty from one who oversees the successful execution of pre-planned experiments to that of a mentor. CPR liberates the instructor to focus on fostering higher level skills as students are challenged to assume a greater responsibility for their learning experience. By reducing the number of pre-planned experiments and introducing a progressive pathway towards discovery, students become better equipped to work independently and become more effective in seeking and synthesizing information.

Teaching Strategies

The learning objective of CPR is to improve key liberal education skills in within a program. To achieve this objective, the curricular teaching strategy is to embed CPR courses within one or more topical areas of a discipline that follow Science, Technology, Engineering, and Mathematics (STEM) fundamentals and precede the capstone design. Within the MET program, the topical areas of mechatronics and thermo-fluids first appear during the third year.

The course teaching strategy employs a three module structure that advances students through a sequence of challenge and discovery experiences. Using pre-existing knowledge, students perform a set of interconnected experiments and gradually progress toward solving an open-ended problem referred to as the DoE.

CPR creates a mentored environment that engages students in inquiry and learning, gradually building toward intellectual and practical challenges to better prepare for the capstone experience. Students explore avenues of choice, build experiments and models from scratch, face uncertainty, experience difficulties, utilize their own resourcefulness and synthesize different solutions. Students learn to self-monitor, reflect and assume greater responsibility.

A useful by-product of CPR courses is a set of quality DoEs developed by previous generations of students. From time to time, some DoEs have been found to be helpful in the development of new Classical or Jigsaw experiments. In this sense, CPR functions as a net supplier of learning materials that are feasibility tested and qualified by prior student teams. The transplanting of learning materials across topical areas becomes a cyclical change engine within the curriculum. Each area benefits by mutually sourcing experiments from the others forming a continuous improvement process within a course or topical bundle.

Outcome Assessment

CPR assessment takes place on two levels: attainment of course objectives and evaluations of student achievement. Course objectives are measured using both quantitative and qualitative student/faculty surveys. At the end of each semester, the course evaluation format provides a reflective opportunity to examine improvements in student problem solving and critical thinking skills, the role of faculty (overseer vs. mentor) and the value of experiments created by students in the DoE.

To assess student learning outcomes and level of achievement, four course deliverables are used: technical reports, team skills rubric, status reports and communication skills rubric. This structure and means of deliverable assessment is the same for each CPR course and is precisely repeated in the capstone. Table 2 illustrates how each deliverable maps to one or more of the liberal education skills that comprise the course outcomes.

Table 2. Course deliverables

Deliverable	Critical Thinking	Quantitative Reasoning	Team Work	Comm. Written	Comm. Oral	Info. Literacy
Technical Reports	✓	✓	✓	✓		✓
Status Reports	✓	✓		✓		
Team skills rubrics			✓			
Comm. skills				✓	✓	

Technical reports are submitted by each team following an experiment. The format is as follows: Table of Contents, Abstract, Nomenclature, Introduction, Experimental Setup, Procedure, Results & Discussion, Conclusion, Acknowledgements, References, and Appendices. A qualitative assessment rubric is used that focuses on the areas of critical thinking, quantitative reasoning, written communication and information literacy. Students receive feedback and are expected to correct mistakes and improve the quality of future work. A numerical grade is assigned to each report based on overall achievement.

Accompanying the technical reports, student teams evaluate members using a team skills rubric. Quantitative data is solicited in the areas of gathering information, fulfilling duties, sharing workload and listening to others. In addition, qualitative feedback is collected in the form of commentary. Team skill results are used along with the technical report score to synthesize a grade for each student. Teams skill results may reduce a technical report score, but it cannot raise it.

During the DoE phase, teams are required to submit a weekly status report. A worksheet, available online, describes the structure and content: scheduled tasks and accomplishments, problems encountered and approach to solution, changes to objectives, future activities, needed support, and schedule concerns. Status reports are not graded and factored into assessment; however, at the discretion of the instructor, a team may be sanctioned and/or penalized for failure to report progress on a timely basis. The same status worksheet is used in the capstone.

At the end of the semester, a formal DoE team presentation is given in which an outside judging panel evaluates both oral and written skills. The evaluation rubric is based on rhetorical concepts emphasized in previous communication courses: appropriate for audience, organization, graphics, English conventions and delivery. Separate scores for oral and written communications are produced. The communication rubric is again the same as that used in the capstone.

Conclusion

There is a strong pedagogical need to address the shortcomings that stem from the overuse of well-defined experiments. Other educators have drawn similar conclusions with regard to the laboratory experience, and recent papers report successfully evaluating new DoE courses. However, only single-course solutions were put forth, hence the need for a holistic approach. CPR addresses the aforementioned need by offering an embedded curricular solution built on an innovative teaching strategy.

The DoE component was first implemented in Fall 2002 within the MET program. This led to the development of one complete CPR course (fluid mechanics) in Fall 2005. Changes were made in the capstone to mirror the assessment structure of CPR in 2006-08, and a second CPR course (thermodynamics) was added in 2009.

Over this time, we have experienced the full range of benefits and directly observed the development of skills largely gained by designing and successfully performing experiments from scratch. Several projects have been featured at the University's undergraduate research colloquium, and CPR has successfully exported models and/or experiments to other courses.

CPR has been found to yield the following transformational benefits to students, instructors, laboratory courses, and the curriculum:

- Students self-monitor, reflect and assume greater responsibility
- Instructors move from being overseers to mentors
- CPR laboratory structure sequentially builds critical thinking and problem solving skills
- Knowledge and skills are better integrated across topical areas (e.g. thermo-fluids with control systems)
- The curriculum better reconciles the undergraduate experience with capstone expectations

CPR may be expanded to include simulation and virtual experimentation and has the broader potential to offer similar benefits to other STEM programs and disciplines.

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