INTRODUCTION

The Massachusetts Institute of Technology (MIT) has collaborated with the government of Singapore to create a new university, the Singapore University of Technology and Design (SUTD); the first SUTD students began classes in May 2012. MIT contributed to the development of SUTD’s undergraduate curriculum, and, as part of that effort, MIT’s Teaching and Learning Laboratory (TLL) identified pivotal concepts and critical skills from what is called SUTD’s “freshmore year,” which encompasses the first three semesters of the students’ course of study. The goal of identifying pivotal concepts and critical skills was to see how they supported learning throughout the SUTD curriculum, generally, and, specifically, how they were connected across disciplines.

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The result of this process was an Engineering Curriculum Map (the Map), which diagrams, for both faculty and students, the crucial ideas and capabilities SUTD students should master in their first three semesters. The Map also visually represents the interdisciplinary connections among concepts that may otherwise appear to be from disparate disciplines (i.e. physics, math, biology, chemistry). The Map relates what can often seem to students as an arbitrary set of topics to the larger context of professional science, engineering, and design.

After the Engineering Curriculum Map was developed, it guided the creation of a set of 15-minute videos narrated by MIT faculty and graduate students, called “concept vignettes.” These videos teach pivotal concepts and critical skills by utilizing animations, visualizations, and/or demonstrations. The Engineering Curriculum Map can be used by any instructor who is interested in designing courses that emphasize the concepts and skills needed to become an expert engineer, architect, or designer.

Chapter 1 of this paper discusses the current research into learning, as well as best practices in instructional design, that we called upon to identify the pivotal concepts and critical skills of an engineering and design curriculum. Chapter 2 describes the Map itself in more detail, as well as secondary Central Concept Maps that more fully develop the ideas in the Engineering Curriculum Map. Chapter 3 outlines how the Engineering Curriculum Map was used to create the concept vignettes and proposes ways in which the Map may be useful to other instructors and curriculum designers. Chapter 4 provides a summary and acknowledges those who contributed to this project.

1 USING RESEARCH AND BEST PRACTICE TO IDENTIFY PIVOTAL CONCEPTS AND CRITICAL SKILLS

Over the last several decades, there have been many calls for reform in engineering education in order to prepare graduates for a constantly changing global workplace [1, 2, 3, 4]. While there is not necessarily a consensus about the specific content knowledge, skills, and attitudes required of graduating engineers, it is often the case that the study of engineering begins with a foundation in math, the physical and life sciences, and information technology; that an understanding of the design processes is considered vital [2, 5, 6, 7]; and that the skills of problem solving, critical thinking, leadership, communication, and teamwork are crucial for today’s engineers and designers [5, 6, 7, 8]. The future engineer/designer is expected to be world-oriented, globally competent, interdisciplinary, flexible, and creative—a life-long learner who can understand the broader implications of his/her work [2, 5, 9, 10, 11].

At the same time, engineering educators are concerned about a curriculum that is becoming increasingly crowded. It is a challenge to reconcile the ever-expanding amount of information that would-be engineers/designers require with the need to devote time in the curriculum to the above-named skills. If educators are going to solve this conundrum, hard decisions will need to be made about what to include—and what to exclude—in the education of future engineers.

A number of engineering educators (as well as educationalists from other disciplines, it should be noted) advocate that the difficult task of constructing a curriculum should begin by thinking about what students should know and be able to do by the time they finish a specific unit of instruction, whether that unit is a single class, a semester-long course, or, as in the case of this project, the first three semesters of a four-year curriculum. John Biggs and Catherine Tang in the U.K. describe this approach as “constructive alignment.” They believe when developing a curriculum, instructors first need to define the students’ intended learning outcomes (ILO) [12]. Flowing from these ILOs are what they call teaching learning activities (TLA) and assessment tasks (AT); they are the means by which students achieve the ILOs and the measurements of the extent to which the ILOs have been mastered, respectively. A similar
methodology, “backward design,” has been created by Grant Wiggins and Jay McTighe in the
U.S. [13]. Wiggins and McTighe also encourage instructors to prioritize content along a
spectrum from “big ideas and core tasks” to “important to know and do” to “worth being
familiar with.” This made our task of defining pivotal concepts and critical skills (the
equivalent of Wiggins and McTighe’s “big ideas and core tasks”) an intellectually challenging
one.

We consulted two other streams in educational research to aid us in identifying the pivotal
concepts and critical skills to include in the Engineering Curriculum Map. First, the literature
on integrated curricula helped us identify the concepts taught in the freshman year that were
truly interdisciplinary or had broad scaffolding potential [14, 15, 16]. Cognitive theory
suggests that one factor that promotes long-term retention of knowledge is practice at
retrieval—including spaced practice and practice within different contexts [17]. Allowing
students to apply the same concept within different contexts helps them construct and re-
construct their mental models and can promote deeper understanding of the concept [18]. If a
course concept was found to have applicability in multiple courses, this added to the
determination that it was pivotal.

We also went to the literature on student misconceptions and misunderstandings; this
literature is quite rich in physics, chemistry, biology, and mathematics [19, 20, 21, 22, 23].
Finally, we examined concept inventories that test for those misconceptions and identify
common stumbling blocks to student learning in the STEM disciplines [24, 25, 26, 27]. If a
course concept was found to have associated misconceptions, this reinforced our decision that
the concept was pivotal. Examining student misconceptions allowed us to recognize concepts
that would provide necessary scaffolding for deep learning, which, in turn, led us to add
missing pivotal concepts. A full list of the references consulted in the development of the
Engineering Curriculum Map can be found on our website (http://mit.edu/tll/teaching-
materials/conceptmap/index.html).

In the end, a concept or skill was identified as pivotal when it satisfied one of two criteria:
(1) it was pre-requisite for multiple concepts that would be taught in upper-level courses;
or (2) it was pervasive across disciplines.

2 BUILDING THE ENGINEERING CURRICULUM MAP

As stated above, we built the Map along the lines advocated by Biggs and Tang, who
recommend beginning the construction of a curriculum with intended learning outcomes, and
by Wiggins and McTighe, who maintain a relatively small number of items should be
classified as “big ideas” or “core tasks.”

We were fortunate in that faculty and instructional staff from MIT had begun the process of
defining SUTD’s curriculum. Most of the courses in the freshman year already had a number
of learning objectives associated with them. We put those learning objectives on individual
strips of paper and laid them out. Then, each member of the TLL team began to organize the
strips into thematically related groups. Through an iterative process that took several weeks,
we were able to group these statements into four major learning objectives, which we call the
“primary learning objectives.” While these objectives were derived from the analysis of
courses in the freshman year, we hypothesize they will serve the four-year SUTD curriculum
well. Specifically, SUTD students will be able to:

1. Analyse a system’s parts and the interactions among those parts.
2. Identify the changing and unchanging components of a system and utilize this
   knowledge to solve problems.
3. Describe systems mathematically.
4. Design a product to solve a problem or fulfil a need.
Eventually, we synthesized these four primary learning objectives into one overarching goal, which, again, we believe can apply to the entire SUTD curriculum: “Students will be able to describe the nature and behaviour of engineering, physical, information, and social systems in order to design, modify, and adapt them.”

Three of these four primary learning objectives support the idea that students should be able to “describe the nature and behaviour” of systems. Engineering curricula help students achieve this goal through the acquisition of basic mathematical and scientific knowledge, and by helping them learn and become comfortable with a variety of representational techniques (e.g., sketching, graphing, use of mathematical symbols). The fourth primary learning objective is targeted towards the “design, modify, or adapt” aspect of the overarching goal. Engineering design is a skill that students develop throughout their entire undergraduate engineering education. However, the development of that skill can begin as early as the first semester as students are exposed to and given practice in developing critical skills related to communication, modelling, problem solving, and teamwork.

Directly supporting the primary learning objectives are 13 “secondary learning objectives.” These secondary objectives were identified by sorting the pivotal concepts and looking for common themes. More specifically, in order to be deemed a secondary learning objective, a concept or skill had to satisfy three requirements. It had to: 1) be interdisciplinary, 2) reappear throughout the curriculum beyond the freshman year, and 3) serve as a conceptual scaffold between the primary learning objectives and the course level pivotal concepts. Visually, the secondary learning objectives were placed in the Map directly under the primary learning objective(s) they connect to. There were two secondary learning objectives that directly supported two primary learning objectives. This is represented on the Map by allowing these secondary learning objectives to span the space underneath both primary learning objectives. Figure 1 illustrates the connections among the overarching goal, the primary learning objectives, and the secondary learning objectives.

We then expanded each secondary learning objective by identifying the course-level subject matter that supports the attainment of the objective. These supporting ideas were organized into Central Concept Maps. One Central Concept Map, for example, is built around the notion that “representations enhance our understanding of a system’s structure, properties, and function”; this Central Concept Map is shown in Figure 2. The idea “mathematics can be used to describe physical systems” supports this notion and appears in courses on classical mechanics, electromagnetism, general chemistry, differential equations, and thermodynamics. The names of courses (many of which are standard for first- and second-year engineering curricula) in which a concept is likely to appear are included on the Central Concept Map. In fact, by scanning the courses that support the topics on this Central Concept Map, it can be seen that the idea “Representations” exists in every course in the freshman year. It is a concept that is pervasive across disciplines. We believe this realization—that the same concept appears in different science and engineering disciplines—is one that should be explicitly stated and reinforced for students.
The Central Concept Maps are not isolated entities. There are connections that exist between them. Figure 2 includes the concept that “vectors represent objects with direction and magnitude that satisfy certain linearity conditions.” This idea is also associated with “Linear Systems,” the subject of another Central Concept Map. The connection between the two Central Concept Maps is depicted visually by the dark blue box that states “see related concept under linear systems” and electronically via a hyperlink. (Please note there is no particular meaning imposed to the horizontal ordering of concepts.)

We used Visual Understanding Environment (VUE), which was created at Tufts University, to draw the maps. This software was developed for concept and digital content mapping and includes features for exporting concept maps as HTML. All the maps are located at http://mit.edu/tll/teaching-materials/conceptmap/index.html, with the Engineering Curriculum Map as the main navigational page. Each Central Concept Map can be reached from this main page through a hyperlink associated with the secondary learning objective.
3 APPLING THE ENGINEERING CURRICULUM MAP AND CENTRAL CONCEPT MAPS

3.1 Developing Concept Vignettes

We used the Central Concept Maps to identify overarching themes around which we built the concept vignettes. As explained above, the concept vignettes are 15-minute videos designed to help students master pivotal concepts and critical skills in the freshman year. To further optimize the design of these videos, we reviewed existing curriculum materials, existing video, and the literature on student difficulties and misconceptions. Because research in cognitive psychology has shown learning is enhanced when information is “re-presented” in different media [17], we incorporated animations, visualizations, and/or demonstrations as well narration and text. Other educational research, which indicates “authentic problems” strengthen learning [28, 29], led us to include examples of how fundamental concepts inform both innovative research and practice.

The concept vignettes were designed to be viewable by students either individually or in groups. As such, they are appropriate for use in large lecture classes, small group recitations, or individually as homework. Specific places to “pause the video” are indicated to give students opportunities to work problems, answer questions, or discuss ideas with each other.
either inside or outside of the classroom. To help with the implementation of the vignettes and mastery of the concepts, instructor guides were developed that include pre- and post-class concept questions, in-class discussion questions, activities, and labs.

The intention of the maps and concept vignettes is to provide students with a coherent educational framework by bringing the central concepts to the forefront of the learning experience. By utilizing video, and including relevant material from both cutting-edge research and professional practice, it is our expectation that the vignettes will promote long-term retention and flexible retrieval of knowledge [17, 30], help students master more difficult material, and ultimately be useful to students in their work as professional engineers and designers.

3.2 Broader Impact

We hope the Engineering Curriculum Map and Central Concept Maps will be of interest to curriculum developers, department chairs, and professors of both introductory and more advanced engineering courses. By highlighting pivotal concepts that reappear throughout the curriculum, our goal is to help instructors and faculty provide additional opportunities for students to revisit these concepts within their courses. We believe that starting the process of curriculum development with what students should know and be able to do offers a model for how engineering educators can negotiate the difficult task of providing students with the knowledge and skills necessary to be creative, robust engineers and designers.

4 SUMMARY AND ACKNOWLEDGMENTS

The Teaching and Learning Lab at MIT proposed that the overarching goal of the curriculum of the Singapore University of Technology and Design should be, “Students will be able to describe the nature and behaviour of engineering, information, physical, and social systems in order to design, modify, or adapt them.” The Engineering Curriculum Map and Central Concept Maps identify learning objectives, pivotal concepts, and critical skills from the first three semesters at SUTD that support the attainment of that goal. These maps were used to develop instructional materials, specifically concept vignettes and instructor guides, which reinforce these learning objectives.

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REFERENCES


