THE EDUCATION OF FUTURE AERONAUTICAL ENGINEERS: CONCEIVING, DESIGNING, IMPLEMENTING AND OPERATING

Edward F. Crawley, Doris R. Brodeur, Diane H. Soderholm
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge Massachusetts USA

Keywords: education, engineering, CDIO, best practice

Abstract

This paper will outline answers to the two central questions regarding improving engineering education:

- *What is the full set of knowledge, skills, and attitudes that engineering students should possess as they leave the university, and at what level of proficiency?*
- *How can we do better at ensuring that students learn these skills?*

The suggested answers lie within an innovative educational framework, the CDIO (conceive-design-implement-operate) Initiative. This initiative will be described along with the needs it meets, its goals, context, vision and pedagogical foundation. The first question is answered by the CDIO Syllabus and the process for reaching stakeholder consensus on the level of proficiency that students should attain in a given program. The second question is addressed through a best practice framework, which discusses curriculum design, design-implement experiences, teaching and learning, student assessment, program evaluation and faculty competence. Examples are provided of the implementation of best practices within the CDIO program in Aeronautics and Astronautics at the Massachusetts Institute of Technology (MIT).

1 Introduction

Aerospace engineers build and operate things that serve society – aircraft, airports, air transport systems and space launch and space-based systems. To quote the founder of ICAS, Theodore von Kármán [1], "Scientists discover the world that exists; engineers create the world that never was." Modern engineers lead or are involved in all phases of an aerospace system lifecycle; they Conceive, Design, Implement, and Operate. The *Conceive* stage includes defining customer needs; considering technology, enterprise strategy, and regulations; and developing conceptual, technical, and business plans. The second stage, *Design*, focuses on creating the design, that is, the plans, drawings, and algorithms that describe what system will be implemented. The *Implement* stage refers to the transformation of the design into the product, including hardware manufacturing, software coding, testing, and validation. The final stage, *Operate*, uses the implemented product or system to deliver the intended value, including maintaining, evolving, recycling, and retiring the system.

The task of higher education is to educate students to become effective modern engineers—able to participate and eventually to lead in aspects of conceiving, designing, implementing, and operating systems. It is widely acknowledged that we must do a better job at preparing engineering students for this future, and that we must do this by systematically reforming engineering education.

Any approach to improving engineering education must address two central questions:

- What is the full set of knowledge, skills, and attitudes that engineering students should possess as they

leave the university, and at what level of proficiency?
- How can we do better at ensuring that students learn these skills?

These are essentially the *what* and *how* questions that engineers commonly face. Focusing on the first question, there is a seemingly irreconcilable tension between two positions in engineering education. On one hand, there is the need to convey the ever-increasing body of technical knowledge that graduating students must master. On the other hand, there is growing acknowledgment that engineers must possess a wide array of personal and interpersonal skills; as well as the system building knowledge and skills required to function on real world engineering teams to produce real world products and systems.

This tension is manifest in the apparent difference of opinion between engineering educators and the broader engineering community that ultimately employs engineering graduates. University-based engineers traditionally strike a balance that emphasizes the importance of a body of technical knowledge. However, beginning in the late 1970s and early 1980s, and increasingly in the 1990s, industrial representatives began expressing concern about this balance, articulating the need for a broader view that gives greater emphasis to the personal and interpersonal skills; and product, process, and system building skills. What commentaries by industrialists have in common is that they always underscore the importance of engineering science fundamentals and engineering knowledge, but then go on to list a wider array of skills that typically include elements of design, communications, teamwork, ethics, and other personal skills, and attributes.

This paper will outline an approach to answering the two questions posed above – what should students learn, and how can we assure that they do so. Our approach is called CDIO, as it adopts this system lifecycle as its context. We begin with a short discussion of the origin and logic of CDIO, and then describe a best practice framework consisting of twelve CDIO Standards. These CDIO Standards can guide a program or university to implementing an improved education. Each of the Standards is illustrated with a brief example of how it was implemented in the Department of Aeronautics and Astronautics at MIT.

2 The CDIO Initiative

In October 2000, the Massachusetts Institute of Technology, Chalmers University of Technology, the Royal Technical University (KTH), and Linkoping University launched a project to reform undergraduate engineering education. This reform effort has now expanded to more than 23 programs worldwide. More information can be found at http://www.cdio.org. The CDIO Initiative is founded on four key ideas: a statement of the needs of our students, a set of goals, a vision or concept for engineering education, and a pedagogical foundation that ensures that the vision is realized. These key ideas are presented in this section.

Analysis of the needs for engineering education

We developed the CDIO Initiative in response to requirements and advice from industry and other stakeholders with respect to the desired knowledge, skills, and abilities of future engineers. When we tried to synthesize lists of desired attributes proposed by industry, we observed that they were driven by a more basic need, that is, the reason society needs engineers in the first place.

Therefore, the starting point of our CDIO Initiative was a restatement of the underlying *need* for engineering education. We believe that every graduating engineer should be able to:

Conceive-Design-Implement-Operate
complex value-added engineering products, processes, and systems
in a modern, team-based environment

More simply, we must educate engineers who can engineer. The responsibilities of engineering are these: to execute a sequence of tasks, in order to design and implement a product, process, or system within an organization. This emphasis on the product or system lifecycle (Conceive-Design-Implement-Operate) gives the initiative its name.

The goals of the CDIO Initiative

The CDIO Initiative has three overall goals: *To educate students who are able to:*

1. *Master a deeper working knowledge of technical fundamentals*
2. *Lead in the creation and operation of new products, processes, and systems*
3. *Understand the importance and strategic impact of research and technological development on society*

We believe that these three goals are best met by making the context of engineering education one of conceiving, designing, implementing and operating. Let's begin by discussing the goals in some detail.

A CDIO-based education always begins by emphasizing the technical fundamentals. University is the place where the foundations of subsequent learning are laid. Nothing in a CDIO program is meant to diminish the importance of the fundamentals, or students' need to learn them. In fact, deep working knowledge and conceptual understanding is emphasized to strengthen the learning of technical fundamentals.

The second goal is to educate students who are able to *lead in the creation and operation of new product, processes, and systems*. This goal recognizes the need to prepare students for a career in engineering. The need to create and operate new products, processes, and systems drives the educational goals related to personal and interpersonal skills; and product, process, and system building skills.

The third goal is to educate students who are able to *understand the importance and strategic impact of research and technological development on society.* Our societies rely heavily on the contributions of scientists and engineers to solve problems, ranging from healthcare to entertainment, and to ensure the competitiveness of nations. However, research and technological development must be paired with social responsibility and a move toward sustainable technologies. Graduating engineers must have insight into the role of science and technology in society to assume these responsibilities. This goal further recognizes that a small percentage of students will not become practicing engineers, but will pursue careers as researchers in industry, government, and higher education. Despite different career interests, all students benefit from an education set in the context of product, process, and system development.

The first two goals represent the historic and contemporary tension in engineering education, that is, between knowledge of technical fundamentals and professional skills. Most engineering educators agree that these two goals are important, but they disagree about how much time to spend on one versus the other. If the model of education is a transmittal process with fixed maximum effective transmittal rate and fixed duration, the tension between technical fundamentals and skills intensifies. The CDIO Initiative has an alternate view of education that helps to relieve that tension. We assert that it is possible to strengthen the learning of the fundamentals and at the same time, improve the learning of personal, interpersonal and system building skills.

The vision of CDIO

In order to resolve this tension, a new vision for engineering education is needed. This education needs to be based on a scholarship of learning and on best practices of engineering education. It should be integrated and comprehensive, that is, encompassing the entire educational program.

The CDIO Initiative envisions an education that stresses the fundamentals, set in the context of Conceiving — Designing — Implementing—Operating products, processes, and systems. The salient features of the vision are that:

- A CDIO education is based on clearly articulated program goals and student learning outcomes, set through stakeholder involvement.

- Learning outcomes are met by constructing a sequence of integrated learning experiences, some of which are experiential, that is, they expose students to the experiences that engineers will encounter in their profession.
- A curriculum organized around mutually supporting disciplinary courses with CDIO activities highly interwoven, forming the curricular structure for the sequence of learning experiences
- Design-implement and hands-on learning experiences set in both the classroom and in modern learning workspaces as the basis for engineering-based experiential learning
- Active and experiential learning, beyond design-implement experiences, that can be incorporated into disciplinary courses
- A comprehensive assessment and evaluation process

We must find ways to realize this vision by strengthening the collective skills of the faculty, by re-tasking existing resources, while largely using existing resources.

Pedagogical foundation

To understand the CDIO Initiative's pedagogical foundation, we must consider what we know about how students learn. Many engineering students tend to learn from the concrete to the abstract. Yet, they no longer arrive at universities armed with hands-on experiences from tinkering with cars or building radios. Likewise, the engineering science educational reforms of the latter half of the 20th century largely removed many of the hands-on experiences that engineering students once encountered at university. As a result, contemporary engineering students have little concrete experience upon which to base engineering theories. This lack of practical experience affects students' ability to learn abstract theory that forms much of the engineering fundamentals, and also hampers their ability to realize the applicability and practical usefulness of a good theory.

The CDIO model of engineering education and its associated teaching and learning methods are based on experiential learning theory, which is an instructional theory with roots in constructivism and cognitive development theory. [2] Constructivists believe that learners build their internal frameworks of knowledge upon which they attach new ideas. Individuals learn by actively constructing their own knowledge, testing concepts on prior experience, applying these concepts to new situations, and integrating the new concepts into prior knowledge. Facilitating the processing of new information and helping students to construct meaningful connections is regarded as the basic requirement for teaching and learning.

The theories of constructivism and social learning have been applied to a number of curriculum and instruction models and practices. The CDIO model focuses on one of these approaches, called experiential learning. Experiential learning can be defined as active learning in which students take on roles that simulate professional engineering practice. Experiential learning engages students in critical thinking, problem solving and decision making in context that are personally relevant and connected to academic learning objectives by incorporating active learning. This approach requires the making of opportunities for debriefing and consolidation of ideas and skills through reflection, feedback and the application of the ideas and skills to new situations. [3]

The essential feature of CDIO is that it creates *dual-impact* learning experiences that promote deep learning of technical fundamentals and of practical skill sets. CDIO uses modern pedagogical approaches, innovative teaching methods, and new learning environments to provide concrete learning experiences. These concrete learning experiences create a cognitive framework for learning the abstractions associated with the technical fundamentals, and provide opportunities for active application that facilitates understanding and retention. Thus these concrete learning experiences are of *dual-impact*. More obviously, they impart learning in personal and interpersonal skills and product, process, and system building skills. More subtly, at the same time they provide the pathway to deeper working knowledge of the fundamentals.

The objective of educational design is therefore to craft a series of concrete learning experiences, including design-implement exercises, which will both teach the skills, and at the same time promote the deeper understanding of the fundamentals, and thus allow the two CDIO goals to simultaneously be met.

3 The CDIO Initiative

A CDIO Standard describes an essential characteristic of an engineering program that has adopted the CDIO model of engineering education reform. As such, they constitute a best practice framework for educational reform. The twelve standards were developed in response to requests from industrial partners, program leaders, and alumni for attributes of graduates of CDIO programs. That is, they wanted to know how they would recognize CDIO programs and their graduates. As a result, these CDIO Standards

- define the distinguishing features of a CDIO program
- serve as guidelines for educational program reform
- create benchmarks and goals that can be applied world wide
- provide a framework for self-evaluation and continuous improvement

Taken individually, the CDIO Standards add little new knowledge of effective engineering education research and practice. However, taken as a whole, the twelve CDIO Standards provide a comprehensive approach to the reform and improvement of engineering programs.

The twelve CDIO Standards address program philosophy (Standard 1), curriculum development (Standards 2, 3 and 4), design-implement experiences and workspaces (Standards 5 and 6), new methods of teaching and learning (Standards 7 and 8), faculty development (Standards 9 and 10), and assessment and evaluation (Standards 11 and 12). Each standard is described, the rationale for setting the standard is provided, and a brief explanation is given of how it is met in the undergraduate program of the Department of Aeronautics and Astronautics at MIT. Note that we at MIT have collaborated with universities in more than 15 countries, so that educational reforms at MIT represent a collective accomplishment, with contributions from colleagues worldwide. Seven of the CDIO standards, marked by an asterisk (*) in the title, are considered to be the distinctive features of a CDIO program. The other five are supplementary good practice, and strengthen the learning experience of the students.

Standard 1 – The Context*

Adoption of the principle that product, process, and system lifecycle development and deployment -- Conceiving, Designing, Implementing and Operating -- are the context for engineering education

A CDIO program is based on the principle that product, process, and system lifecycle development and deployment are the appropriate context for engineering education. *Conceiving--Designing--Implementing--Operating* is a model of the entire product, process, and system lifecycle. The product, process, and system lifecycle is considered the *context* for engineering education in that it is the cultural framework, or environment, in which technical knowledge and other skills are taught, practiced and learned. The principle is *adopted* by a program when there is explicit agreement of faculty to transition to a CDIO program, and support from program leaders to sustain reform initiatives.

Beginning engineers should be able to *Conceive--Design--Implement--Operate* complex value-added engineering products, processes, and systems in modern team-based environments. They should be able to participate in engineering processes, contribute to the development of engineering products, and do so while working in engineering organizations. This is the essence of the engineering profession.

It is important to note that we assert that the product or system lifecycle should be the *context*, not the *content*, of the engineering education. Not every engineer should specialize in product development. Rather, engineers should be educated in disciplines, *that is*, mechanical, electrical, chemical, or even engineering science. However, they should be educated in those disciplines in a context that will give them the skills and attitudes to be able to design and implement things.

At MIT, we examined what engineers, and in particular aerospace engineers, actually do. We listened to the input from our alumni and leaders of industry, obtained through over 60 interviews. The department faculty voted to accept this conceive-design-implement-operate premise as the *context* of engineering education, We then rationally derived more detailed learning outcomes for the education of our students.

The rationale for adopting the principle that the system lifecycle—conceiving, designing, implementing and operating—is the appropriate context for engineering education is supported by the following arguments:

- It is what engineers do.
- It is the underlying need and basis for the “skills lists” that industry proposes to university educators.
- It is the natural context in which to teach these skills to engineering students.

The first point has been argued above—what modern engineers do is engage in some or all phases of conceiving, designing, implementing, and operating. The second point is evidenced by the widespread, consistent and organized reaction from industry in the last few decades. The third point is more subtle. In principle, it is possible to teach students the skills and attitudes of engineering while they work by themselves on engineering theory, but this may not be very effective. What could be a more natural way to educate students in these skills than to set the education in the context of product and system development and deployment, that is, the very context in which students will use the skills?

The adoption of the context is cited in the mission statement of the MIT Department of Aeronautics and Astronautics, the goals of our undergraduate education, and the description of our programs in print and web based material available to the public.

Standard 2 – Learning Outcomes *

Specific, detailed learning outcomes for personal and interpersonal skills, and product, process, and system building skills, as well as disciplinary knowledge, consistent with program goals and validated by program stakeholders

The knowledge, skills, and attitudes intended as a result of engineering education, *i.e.*, the *learning outcomes*, are codified in the *CDIO Syllabus*. These learning outcomes detail what students should know and be able to do at the conclusion of their engineering programs. *Personal* learning outcomes focus on individual students' cognitive and affective development, for example, engineering reasoning and problem solving, experimentation and knowledge discovery, system thinking, creative thinking, critical thinking, and professional ethics. *Interpersonal* learning outcomes focus on individual and group interactions, such as, teamwork, leadership, and communication. *Product, process, and system building* skills focus on conceiving, designing, implementing, and operating systems in enterprise, business, and societal contexts.

Learning outcomes are reviewed and validated by key *stakeholders*, groups who share an interest in the graduates of engineering programs, for consistency with *program goals* and relevance to engineering practice. In addition, stakeholders help to determine the expected level of proficiency, or standard of achievement, for each learning outcome.

Setting specific learning outcomes helps to ensure that students acquire the appropriate foundation for their future. Professional engineering organizations and industry representatives have identified key attributes of beginning engineers both in technical and professional areas. Moreover, many evaluation and accreditation bodies expect engineering programs to identify program outcomes in terms of their graduates' knowledge, skills, and attitudes.

The first task of turning the vision into a model program at MIT was to develop and codify a comprehensive understanding of abilities needed by contemporary engineers. This task was accomplished through the use of stakeholder focus groups comprised of engineering faculty, students, industry representatives, university review committees, alumni, and senior academicians. The focus groups were asked the first of the two central questions that must be addressed in the reform of engineering education, "*What is the full set of knowledge, skills, and attitudes that engineering students should possess as they leave university?*" Results of the focus groups, plus topics extracted from the views of industry, government, and academia on the expectations of university graduates were organized into a list of learning outcomes, called the CDIO Syllabus.

The CDIO Syllabus classifies learning outcomes into four high-level categories:

1. Technical knowledge and reasoning
2. Personal and professional skills and attributes
3. Interpersonal skills: teamwork and communication
4. Conceiving, designing, implementing, and operating systems in the enterprise and societal context

These four headings map directly to the underlying need for CDIO identified in an earlier section of this paper, *that is*, to educate students who can:

understand how to conceive, design, implement, and operate (Section 4)

complex value-added engineering products, processes, and systems (Section 1)

in a modern team based engineering environment (Section 3), and

are mature and thoughtful individuals (Section 2).

The knowledge, skills and attitudes outlined in Sections 2, 3 and 4 of the CDIO Syllabus are referred to as *personal and interpersonal skill; and product, process, and system building skills*, or briefly as skills. The first section, *Technical Knowledge and Reasoning*, is program-specific, *that is*, it outlines major concepts of a specific engineering discipline. Sections 2, 3, and 4 are applicable to any engineering program.

The content of each section was expanded to second, third and fourth levels. Syllabus topics at the second level of detail were validated with subject experts and key stakeholders. To ensure comprehensiveness, the Syllabus was explicitly correlated with documents listing engineering education requirements and desired attributes. As a result, the CDIO Syllabus is a rational and consistent set of skills, derived from an understanding of needs, that stakeholders would expect from graduating students. It is comprehensive, peer reviewed, and forms the basis for program design and assessment. Table 1 is the CDIO Syllabus at the second level of detail. [4]

TABLE 1

THE CDIO SYLLABUS AT THE SECOND LEVEL OF DETAIL

1 TECHNICAL KNOWLEDGE AND REASONING 1.1 KNOWLEDGE OF UNDERLYING SCIENCE 1.1 CORE ENGINEERING FUNDAMENTAL KNOWLEDGE 1.2 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE	**3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION** 3.1 MULTI-DISCIPLINARY TEAMWORK 3.2 COMMUNICATIONS 3.3 COMMUNICATIONS IN FOREIGN LANGUAGES
2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES 2.1 ENGINEERING REASONING AND PROBLEM SOLVING 2.2 EXPERIMENTATION AND KNOWLEDGE DISCOVERY 2.3 SYSTEM THINKING 2.4 PERSONAL SKILLS AND ATTITUDES 2.5 PROFESSIONAL SKILLS AND ATTITUDES	**4 CONCEIVING, DESIGNING, IMPLEMENTING, AND OPERATING SYSTEMS IN THE ENTERPRISE AND SOCIETAL CONTEXT** 4.1 EXTERNAL AND SOCIETAL CONTEXT 4.2 ENTERPRISE AND BUSINESS CONTEXT 4.3 CONCEIVING AND ENGINEERING SYSTEMS 4.4 DESIGNING 4.5 IMPLEMENTING 4.6 OPERATING

To translate the CDIO Syllabus topics and skills into measurable learning outcomes, we developed a survey of program stakeholders to determine the level of proficiency expected of graduating engineers in each of the Syllabus topics. The completely unexpected result was that, by and large, our stakeholders were in complete agreement as to the expected level of proficiency of students graduating from the Aeronautics and Astronautics program at MIT. Similar stakeholder agreement has been found at other universities. [5] As a result of the surveys, we have a stakeholder-based, comprehensive answer to the first of the two central questions posed at the beginning of this chapter, "*What is the full set of knowledge skills and attitudes that engineering students should possess as they leave the university, and at what level of proficiency?"*

The remaining CDIO Standards address the second central question, "*How can we do better at ensuring that students learn these skills?*"

Standard 3 -- Integrated Curriculum *

A curriculum designed with mutually supporting disciplinary courses, with an explicit plan to integrate personal and interpersonal skills, and product, process, and system building skills

An integrated curriculum includes learning experiences that lead to the acquisition of *personal and interpersonal skills, and product, process, and system building skills* (Standard 2), interwoven with the learning of disciplinary knowledge. Disciplinary courses are *mutually supporting* when they make explicit connections among related and supporting content and learning outcomes. An *explicit plan* identifies ways in which the integration of skills and multidisciplinary connections are to be made, for example, by mapping the specified learning outcomes to courses and co-curricular activities that make up the curriculum.

The teaching of personal and interpersonal skills, and product, process, and system building skills should not be considered an addition to an already full curriculum, but an integral part of it. To reach the intended learning outcomes in disciplinary knowledge and skills, the curriculum and learning experiences have to make dual use of available time. Faculty play an active role in designing the integrated curriculum by suggesting appropriate disciplinary linkages, as well as opportunities to address specific skills in their respective teaching areas.

An effective approach for us has been to re-task existing curricular resources at MIT. The challenge was to develop an *integrated curriculum*, that is, to find innovative ways to make teaching time have *dual-impact*, so that students develop a deeper working knowledge of technical fundamentals while simultaneously learning personal, and interpersonal skills; and product, process, and system building skills. We developed an explicit plan for ensuring that students learn these skills.

To facilitate curriculum reform, we retained the disciplinary course as the organizing structure of the curriculum, while making two substantive improvements. First, we found ways for the disciplinary courses to work together to be mutually supporting. Second, we wove education in CDIO skills into the disciplinary education.

This involved first benchmarking the teaching of the skill enumerated in the CDIO Syllabus, revealing that there was a great deal of cursory or introductory treatment of many of these skills, but few places where instructors actually took responsibility for ensuring that learning of the skills took place. This led to much inefficiency, with both underlaps and overlaps.

To counteract this inefficiency, we identified three specific curricular structures as key elements of a CDIO curriculum: 1) an *introductory engineering experience* that creates the framework for subsequent learning and motivates students to be engineers; 2) conventional disciplinary subjects coordinated and linked to demonstrate that engineering requires interdisciplinary efforts; and, 3) a final project course—or capstone—that includes a substantial experience in which students design, build, and operate a product, process, or system. One of these structures was the refinement of *Unified Engineering*, a block of four courses normally taught in the second year. In Unified Engineering, the central underlying engineering science disciplines are taught in a way that shows their intellectual connections, and their common application to the solution or aerospace "systems problems." We also created a multi-semester sequence to serve as a hands-on design-implement subject for our astronautics option.

With these new structures in place, an explicit plan to overlay CDIO skills was developed. The essence of this plan is to first develop the sequence of teaching of the skills, and then match it to the opportunities to teach. The result was a matrix of responsibilities for skills learning assigned to the courses, and a more integrated disciplinary preparation.

Standard 4 -- Introduction to Engineering

An introductory course that provides the framework for engineering practice in product, process, and system building, and introduces essential personal and interpersonal skills

The *introductory* course, usually one of the first required courses in a program, provides a framework for the practice of engineering. This *framework* is a broad outline of the tasks and responsibilities of an engineer, and the use of disciplinary knowledge in executing those tasks. Students engage in the *practice of engineering* through problem solving and simple design exercises, individually and in teams. The course also includes personal and interpersonal skills knowledge, skills, and attitudes that are *essential* at the start of a program to prepare students for more advanced product, process, and system building experiences. For example, students can participate in small team exercises to prepare them for larger development teams.

Introductory courses aim to stimulate students' interest in, and strengthen their motivation for, the field of engineering by focusing on the application of relevant core engineering disciplines. Students usually elect engineering programs because they want to build things, and introductory courses can capitalize on this interest. In addition, introductory courses provide an early start to the development of the essential skills described in the *CDIO Syllabus*.

In the MIT introduction to engineering course, called an Introduction to Aerospace Engineering and Design, students are immersed in the hands-on, lighter-than-air (LTA) vehicle design project that culminates in a race at the end of the semester. The students work in teams of five to six, and design, build, and fly a remote-controlled blimp. By randomizing the design teams, many of the students develop teamwork skills for the first time. The design aspect of the competition gives the students the opportunity to show their creativity and ingenuity in developing a flight vehicle. The goal is to achieve an active learning environment for acquiring a conceptual framework as well as problem-solving skills. The connections between theory and practice become real in the LTA vehicle design. The first year students are empowered by the challenge, and it is the instructor's job to assure that all teams successfully accomplish the design project.

Participating students prepare an electronic design portfolio. The goal of the portfolio assignment is to actively engage students in the design process and to allow them to watch it take shape throughout the semester via their individual efforts and team designs.

Based on the lecture material and the LTA project, the first-year students receive a preview of what lies ahead in the next three years of their education, a preparation for it, as well as a rudimentary systems perspective, so important in aerospace engineering. The first year students have a fun, hands-on engineering design experience during their first year of college that excites them for a career in engineering. Most importantly, for the past two years we have ensured that all teams succeed in flying a LTA vehicle by race day, an empowering experience for the first year students. [6]

Standard 5 -- Design-Implement Experiences*

A curriculum that includes two or more design-implement experiences, including one at a basic level and one at an advanced level

The term *design-implement experience* denotes a range of engineering activities central to the process of developing new products and systems. Included are all of the activities described in Standard One at the *Design* and *Implement* stages, plus appropriate aspects of conceptual design from the *Conceive* stage. Students develop product, process, and system building skills, as well as the ability to apply engineering science, in design-implement experiences integrated into the curriculum. Design-implement experiences are considered *basic* or *advanced* in terms of their scope, complexity, and sequence in the program. For example, simpler products and systems are included earlier in the program, while more complex design-implement experiences appear in later courses designed to help students integrate knowledge and skills acquired in preceding courses and learning activities. Opportunities to conceive, design, implement, and operate products, processes, and systems may also be included in required co-curricular activities, for example, undergraduate research projects and internships.

Design-implement experiences are structured and sequenced to promote early success in engineering practice. Iteration of design-implement experiences and increasing levels of design complexity reinforce students' understanding of the product, process, and system development process. Design-implement experiences also provide a solid foundation upon which to build deeper conceptual understanding of disciplinary skills. The emphasis on building products and implementing processes in real-world contexts gives students opportunities to make connections between the technical content they are learning and their professional and career interests.

The MIT Department of Aeronautics and Astronautics has developed a sequence of three design-implement experiences in its curriculum. The first is the one described above as the Introduction to Engineering. The second occurs in the second year as a part of the integrated Unified Engineering. This course includes a mandatory semester long aircraft based design-implement project in which students build a kit plane, and then learn design through redesign. They select some part of the plane (wing, propeller, tail, etc.), redesign and then fly the modified aircraft in a competition. MIT has taken the scope of the third, a summative capstone design course, beyond the norm, to provide students with experience in not only the design, but also in the prototyping, testing, fabrication, and operation of a complex aerospace system.

The goal of the capstone course is to immerse undergraduates in all aspects of the lifecycle development of an engineering product and thereby expose students to important aspects of systems engineering that are not experienced in conventional laboratory and design courses. The three semester sequence, which started with students in the second term of their third year, allowed students to develop a basic concept for a satellite formation flight laboratory to be operated on the International Space Station, build a high fidelity prototype of that laboratory, and operate it for short periods of micro-gravity on NASA's KC-135. In addition, they experienced the formal reviews, carrier integration, customer communication, systems integration, procurement practices, industry collaboration, hardware qualification and many other stages in the evolution of an aerospace product. By experiencing the full lifecycle, the students gain a better appreciation for how decisions made early in the design impact downstream activities.

By conducting the development over three semesters, the students gain four very important experiences. First, they are provided with the time to make and learn from mistakes. If students are continuously guided towards the correct decision, they never have the opportunity to learn to recognize bad decisions or, more importantly, learn how to recover from bad decisions. Second, the length of the project allows the students to work through interpersonal conflicts and, as a result, develop into a very cohesive team that not only works well together but also has the confidence to assume responsibility and guide the development of the product. Third, the students are exposed to various forms and iterations of technical communications. By conducting several reviews and writing multiple revisions of design documents for the same project allows the students to build upon their work thereby not only strengthening the design but also their communications skills. Fourth, the duration allows the students to take the design to a higher level of quality than a conventional one or two semester sequence would allow. Since quality is an essential element of any aerospace product, this experience is invaluable to their future careers. [7]

Standard 6 -- Engineering Workspaces

Workspaces and laboratories that support and encourage hands-on learning of product and system building, disciplinary knowledge, and social learning

Workspaces and laboratories support the learning of product and system building skills concurrently with disciplinary knowledge. They emphasize hands-on learning in which students are directly engaged in their own learning, and provide opportunities for social learning, that is, settings where students can learn from each other and interact with several groups. The creation of new workspaces, or remodeling of existing laboratories, will vary with the size of the program and resources of the institution.

Workspaces and other learning environments that support hands-on learning are fundamental resources for learning the process of designing, building, and testing products and systems. Students who have access to modern engineering tools, software, and laboratories have opportunities to develop the knowledge, skills, and attitudes that support product and system building competencies. These competencies are developed in workspaces that are student-centered, user-friendly, accessible, and interactive.

At MIT we took the view that if students are to understand that conceiving— designing—implementing—operating is the context of the education, then it is desirable to re-task existing laboratory space by building modern engineering workspaces that are supportive of, and, organized around C, D, I, and O. In such *CDIO workspaces*, the *Conceive* spaces are designed to encourage people to interact and to understand the needs of others and to provide a venue, which encourages reflection and conceptual development. They are largely technology-free zones. *Design* and *Implement* facilities introduce students to digitally enhanced collaborative design and modern fabrication and integration of hardware and software. *Operate* workspaces are more difficult to manage in academic settings. However, students can learn how to operate their own and faculty-assigned experiments. Simulations of real operations, as well as electronic links to real operations environments can supplement the direct student experience.

There are some small numbers of essential educational modes through which students will learn in a learning environment. For an engineering workspace, there are about four higher-level modes. The first is the conceiving, designing, implementing and operating mode described above. The second is experimentation, in which students build and test experiments, preferably of their own design, to seek new knowledge, or verify the performance of systems. The most traditional mode of laboratory use is reinforcement of disciplinary knowledge, in which students execute (or worse witness the execution of) prepared experiments. If these modes are successfully enabled, the students will be drawn to the space, allowing social learning, the fourth mode.

As we started to develop concepts for the space, we identified a set of *themes* that are desirable aspects of the concepts. In brief, we determined that the environment must be *flexible* easily reconfigured, *accessible* whenever needed, *scaleable* to accommodate projects of all physical sizes, *sustainable* within a normal operating budget, *wired* (or *wireless*) for optimal power and data access, *coordinated* with and not duplicative of MIT facilities and not replicate them, and *supportive* of several large facilities (e.g., our low speed and supersonic wind tunnels).

There are four main spaces associated with the workshop/laboratory, which opened in September 2000 within a renovated 1927 building on the main MIT campus. On the second floor is the Digital Design Studio. On the first floor is the Seamans Laboratory, which houses the Library, a multi-purpose Concept and Management Forum, and a large open space for social interaction and operations, as well as academic support offices. One floor below is the Gelb Laboratory, which is the main implementation space, with electronics, mechanical and specialty fabrication facilities, as well as open area for project construction. Adjoining the older building is new construction — the Newman Hangar — which is a large open space for the execution of large projects and the housing of the two student wind tunnels. [8]

Standard 7 -- Integrated Learning Experiences *

Integrated learning experiences that lead to the acquisition of disciplinary knowledge, as well as personal and interpersonal skills, and product, process, and system building skills

Integrated learning experiences are pedagogical approaches that foster the learning of disciplinary knowledge simultaneously with personal and interpersonal skills, and product, process, and system building skills. They incorporate professional engineering issues in contexts where they coexist with disciplinary issues. For example, students might consider the analysis of a product, the design of the product, and the social responsibility of the designer of the product, all in one exercise. Industrial partners, alumni, and other key stakeholders are often helpful in providing examples of such exercises.

The curriculum design and learning outcomes, prescribed in Standards 2 and 3 respectively, can be realized only if there are corresponding pedagogical approaches that make dual use of student learning time. Furthermore, it is important that students recognize engineering faculty as role models of professional engineers, instructing them in disciplinary knowledge, personal and interpersonal skills, and product, process, and system building skills. With integrated learning experiences, faculty can be more effective in helping students apply disciplinary knowledge to engineering practice and better prepare them to meet the demands of the engineering profession.

One example of integrated learning at MIT is the integration of communication instruction and practice in the capstone course, Flight Vehicle Design. The course provides the students a lifecycle experience with a hardware-related, complex aerospace system. The students are part of a large team environment, which emphasizes communication, teamwork, planning, and responsibility.

The course has a strong communication component. Students receive brief instruction in writing and in oral presentation just as those specific skills are required. Drafting and rehearsal and revision are key elements of the instruction cycle. Thus students may meet individually with the communication instructor for feedback on their draft before the final document is submitted, and "dry runs" are done several days before the formal presentations. In these conferences and "dry runs", students reflect on and revise the technical graphics and the organization and substance of the written information. Often teams may work together on revisions as faculty emphasizes the link between collaboration and communication in the complex design process.

The written and oral assignments are not artifacts of the process, produced long after the design choices have been made. These assignments are integrated into the substantive design process as students make the evaluative choices common to design process. Assignments are evaluated for technical content as well as communication skill. Faculty use rubrics that assess performance at both the technical and the communication levels so that students see that technical abilities are integrated closely with their ability to communicate. At the end of the semester, the communication grade comprises 25% of the final course grade.

Standard 8 -- Active Learning

Teaching and learning based on active experiential learning methods

Active learning methods engage students directly in thinking and problem solving activities. There is less emphasis on passive transmission of information, and more on engaging students in manipulating, applying, analyzing, and evaluating ideas.

By engaging students in thinking about concepts, particularly new ideas, and requiring some kind of overt response, students not only learn more, they recognize for themselves what and how they learn. This process of metacognition helps to increase students' motivation to achieve program learning outcomes and form habits of lifelong learning. With active learning methods, instructors can help students make connections among key concepts and facilitate the application of this knowledge to new settings.

Educational research [10] confirms that active learning techniques significantly increase student learning. Active learning occurs when students are more involved in manipulating, applying, and evaluating ideas. Active learning in lecture-based courses can include pauses for reflection, small group discussion, and real-time feedback from students about what they are learning. Active learning becomes experiential when students take on roles that simulate professional engineering practice, that is, design-implement projects, simulations, and case studies. CDIO's emphasis on widespread use of active and experiential learning is a major aspect of our commitment to develop deeper working knowledge of the technical fundamentals. The desired outcome is an understanding of the underlying technical concepts, as well as their application. This is understood to be a precursor to innovation.

Active and experiential learning methods have transformed an advanced course in aerodynamics in the CDIO program at the Massachusetts Institute of Technology. Prior to 1999, the course was a traditional undergraduate engineering course with lectures, recitations, weekly homework assignments, a small end-of-semester design project, and written exams. The current course includes several active and experiential learning activities, the most innovative of which is concept-based lectures with real-time feedback. In this approach, two or three multiple-choice concept questions are given in a typical one-hour lecture. These questions are designed to include the important concepts of the subject and their common misconceptions. After a few minutes of independent reflection, students use handheld remote-control devices to select an answer. A computer charts responses in real-time and projects them on a screen for all to see. Depending on the responses, students are given time to interact with each other to discuss their answers, or the instructor clarifies misconceptions.

In addition, students are given weekly (graded) homework due prior to class lecture and discussion. Traditionally, engineering courses assign homework after concepts have been presented in class. To increase the effectiveness of concept-based lectures, students need prior engagement with the concepts and ideas. Without this prior engagement, students may not have sufficient background to understand the conceptual questions being asked. In Aerodynamics, students complete homework assignments and related readings prior to in-class discussion. With this preparation, the classroom becomes an interactive environment where students have developed a common language to discuss the conceptual difficulties they have encountered.

At the end of the semester, students are given oral examinations. Student learning assessment is aligned with concept-based lectures and design project experiences. Oral examinations take an active approach to assessment of student learning. They provide insight into how students understand and relate concepts. Furthermore, practicing engineers are faced daily with the real-time need to apply rational arguments based on fundamental concepts. By using oral exams, it is possible to assess a student's ability to construct sound conceptual arguments. [11]

Standard 9 -- Enhancement of Faculty Skills Competence *

Actions that enhance faculty competence in personal and interpersonal skills, and product, process, and system building skills

CDIO programs provide support for faculty to improve their own competence in the *personal and interpersonal skills, and product, process, and system building skills* described in Standard 2. They develop these skills best in contexts of professional engineering practice. The nature and scope of faculty development vary with the resources and intentions of different programs and institutions. Examples of *actions that enhance faculty competence* include: professional leave to work in industry, partnerships with industry colleagues in research and education projects, inclusion of engineering practice as a criterion for hiring and promotion, and appropriate professional development experiences at the university.

If faculty are expected to teach a curriculum of personal and interpersonal skills, and product, process, and system building skills integrated with disciplinary knowledge, as described in Standards 3, 4, 5, and 7, they need to be competent in those skills themselves. Many engineering professors tend to be experts in the research and knowledge base of their respective disciplines, with only limited experience in the practice of engineering in business and industrial settings. Moreover, the rapid pace of technological innovation requires continuous updating of engineering skills. Faculty need to enhance their engineering knowledge and skills so that they can provide relevant examples to students and also serve as role models of contemporary engineers.

In the Department of Aeronautics and Astronautics at MIT, we recognized that part of the change process would require strengthening the competence of faculty in skills. There is little reason to expect a faculty that has been recruited as a cadre of researchers to be proficient in many of the skills of engineering practice. And there is absolutely no reason to expect that these faculty researchers would be able to teach these skills. We adopted a multi-part strategy to enhance the collective skills competence of our faculty. First, we recruited three Professors of the Practice to our staff, all of who were distinguished practitioners from industry. Secondly, we sponsored several short courses on product development for our faculty, and offered time for them to take other courses elsewhere. We also encouraged leaves that would allow faculty members to work in industry. Finally, we gave all new faculty members who had not worked in industry a one year leave prior to starting teaching, to work in industry and develop some appreciation of engineering practice.

Standard 10 -- Enhancement of Faculty Teaching Competence

Actions that enhance faculty competence in providing integrated learning experiences, in using active experiential learning methods, and in assessing student learning

A CDIO program provides support for faculty to improve their competence in *integrated learning experiences* (Standard 7), active and experiential learning (Standard 8), and assessing student learning (Standard 11). The nature and scope of faculty development practices will vary with programs and institutions. Examples of *actions that enhance faculty competence* include: support for faculty participation in university and external faculty development programs, forums for sharing ideas and best practices, and emphasis in performance reviews and hiring on effective teaching methods.

If faculty members are expected to teach and assess in new ways, as described in Standards 7 8, and 11, they need opportunities to develop and improve these competencies. Many universities have faculty development programs and services that might be eager to collaborate with faculty in CDIO programs. In addition, if CDIO programs want to emphasize the importance of teaching, learning, and assessment, they must commit adequate resources for faculty development in these areas.

Faculty have, by and large, been educated using pedagogical styles based on information transmission—lectures and the like. If we are to develop a learning-focused education, which relies on active and experiential learning, current faculty must be supported in their personal development and use of these techniques. In both cases, CDIO skills and the pedagogic skills, the transformation will be broader and more effective if there is a well planned effort to build faculty competence, by bringing individuals with these skills to the team and enhancing the skills of the existing team.

At MIT there are a number of resources that are available to assist faculty with gaining and developing skills in active and experiential teaching methods, and course design. At the university level, the Teaching and Learning Laboratory is staffed with educational experts whose goals are to partner with faculty to strengthen the quality of instruction; better understand the process of learning in science and engineering; and aid in the creation of new and innovative educational curricula, pedagogical methods, technologies, and methods of assessment. The Lab offers individual consultations, group seminars and workshops, and sponsors invited speakers on current topics of interest. In the Aeronautics and Astronautics Department, two educational professionals have been available to collaborate with individual faculty members to design and implement the teaching, learning and assessment methods best suited to the course, the learning objectives, and the faculty member. Also offered are workshops and presentations on various pedagogical, student assessment, and course evaluation techniques, tailored to the department and to CDIO. An informal faculty-to-faculty mentoring network has been operating as faculty members who have tried and succeeded with new techniques share their results with other faculty and offer to help; at times the mentoring is an informal coaching session, and sometimes it results in a team-teaching experience.

Standard 11 -- Learning Assessment *

Assessment of student learning in personal and interpersonal skills, and product, process, and system building skills, as well as in disciplinary knowledge

Assessment of student learning is the measure of the extent to which each student achieves specified learning outcomes. Instructors usually conduct this assessment within their respective courses. Effective learning assessment uses a variety of methods matched appropriately to learning outcomes that address disciplinary knowledge, as well as personal and interpersonal skills, and product, process, and system building skills, as described in Standard 2. These methods may include written and oral tests, observations of student performance, rating scales, student reflections, journals, portfolios, and peer and self-assessment.

If we value personal and interpersonal skills, and product, process, and system building skills, and incorporate them into curriculum and learning experiences, then we must have effective assessment processes for measuring them. Different categories of learning outcomes require different assessment methods. For example, learning outcomes related to disciplinary knowledge may be assessed with oral and written tests, while those related to design-implement skills may be better measured with recorded observations. Using a variety of assessment methods accommodates a broader range of learning styles, and increases the reliability and validity of the assessment data. As a result, determinations of students' achievement of the intended learning outcomes can be made with greater confidence.

As an example, in the aerospace program at MIT, we have developed new assessment tools to assess students' competence in preparing and delivering oral technical briefings. These presentations can be given by individuals or groups, and are usually supported with tables, charts, and other electronic graphic media. The assessment tools include criteria for technical accuracy and significance, as well as communication clarity and style. Rating scales are straightforward and user friendly. Assessment instruments are completed by presenters' themselves, their peers, course instructors, other instructional staff, and sometimes by industrial and research sponsors. We use this assessment tool with students in the introductory course and later in the capstone courses to try to determine students' progress in developing their communication skills. We have a great deal of anecdotal evidence that students have improved their communication skills beyond the effects of maturation alone. We have developed similar instruments and processes to assess teamwork in project-based courses.

Standard 12 -- Program Evaluation

A system that evaluates programs against these twelve standards, and provides feedback to students, faculty, and other stakeholders for the purposes of continuous improvement

Program evaluation is a judgment of the overall value of a program, based on evidence of a program's progress toward attaining its goals. A CDIO program should be evaluated relative to these twelve CDIO Standards. Evidence of overall program value can be collected with course evaluations, instructor reflections, entry and exit interviews, reports of external reviewers, and follow-up studies with graduates and employers. The evidence can be regularly reported back to instructors, students, program administrators, alumni, and other key stakeholders. This feedback forms the basis of decisions about the program and its plans for continuous improvement.

A key function of program evaluation is to determine the program's effectiveness and efficiency in reaching its intended goals. Evidence collected during the program evaluation process also serves as the basis of continuous program improvement. For example, if in an exit interview, a majority of students reported that they were not able to meet some specific learning outcome, a plan could be initiated to identify root causes and implement changes. Moreover, many external evaluators and accreditation bodies require regular and consistent program evaluation.

We use a variety of data gathering methods to evaluate the aerospace program at MIT: interviews of students when they begin and complete the program, student evaluations of all courses taught each semester, senior exit surveys conducted in alternate years by the School of Engineering and by the overall Institute. One of the most useful program evaluation activities in the aerospace program is the use of reflective memos that faculty complete each term for each of the courses for which they are responsible. Instructors reflect on, and summarize in a memo, the learning outcomes that students have achieved, the teaching and assessment methods that have been most effective in student learning, the areas that need improvement, and the instruction staff with whom they will share their reflective memos.

Summary

This paper has given an overview of the CDIO Initiative, the needs it meets, its goals, context, vision and pedagogical foundation. We have also outlined the answers provided by the CDIO Initiative to the two central questions that any approach to improving engineering education must address:

- *What is the full set of knowledge, skills, and attitudes that engineering students should possess as they leave the university, and at what level of proficiency?*
- *How can we do better at ensuring that students learn these skills?*

The first question is answered by the CDIO Syllabus and the process for reaching stakeholder consensus on the level of proficiency that students should attain in a given program. The second question is addressed by Standards 3 through 12, which discuss curriculum design, design-implement experiences, teaching and learning, student assessment, program evaluation and faculty competence.

Attracting and motivating students who are “ready to engineer”

One of the important outcomes of the CDIO initiative is to make engineering more interesting, and therefore increase student motivation and retention. In much of the developed world, and in the developing world as well, there is great concern that more scientists and technologists will be needed in the future, and that current supply is insufficient. We believe that we have incorporated several features into CDIO that will attract and motivate students.

Many students are attracted to engineering by the belief that engineers build things and are disappointed by the first years of traditional engineering education, when they are taught theory. By placing early and repeated design-implement experiences in the curriculum, we have appealed to this desire to build and create. Many students complain that engineering education "beats them down" through a demanding schedule of concept-rich education with little reward and few chances to actually "engineer." By using active and experiential learning techniques and projects, CDIO offers students a chance to develop a sense of empowerment and self-efficacy critical to their perception of self-worth. Projects also provide outlets for creativity and leadership, with visible signs of accomplishment.

Another factor in attracting and motivating students is to show that the education leads to higher quality employment. In fact, by responding to the input of industry stakeholders who hire our students, we should be preparing students who are "ready to engineer"—more readily hired, have more successful careers, and more impact in their profession. Preliminary indications are that firms familiar with CDIO are eager to hire graduates of these programs.

Acknowledgements

The authors would like to acknowledge the contributions made to this paper by the work of many of our colleagues, including Professors Dava Newman, David Darmofal, David Miller, and by Ms. Jennifer Craig, Dr. Cory Hallam, Mr. Steven Imrich, and Mr. William T.G. Litant.

REFERENCES

[1] von Kármán, T. In A. L. Mackay, *Dictionary of Scientific Quotations,* London, 1994.

[2] Jarvis, P., Holford, J., and Griffin, C. *The Theory and Practice of Learning*, Kogan Page, London, 1998.

[3] Kolb, D.A. *Experiential Learning*. Prentice-Hall, Upper Saddle River, NJ, 1984.

[4] Crawley, E.F. *The CDIO Syllabus Report – A Statement of Goals for Undergraduate Engineering Education*, Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, Cambridge, Massachusetts, 2001.

[5] Bankel, J., Berggren, K-F., Blom, K., Crawley, E., Östlund, S., and Wiklund, I. The CDIO Syllabus: A comparative study of expected student proficiency. *European Journal of Engineering Education*, Vol. 28 No. 3, 2003.

[6] Newman, D. and Amir, A. Innovative Aerospace Design Course at MIT, *Proceedings of the 1998 American Society of Engineering Education Annual Conference and Exposition*, Seattle, Washington, USA, 1998.

[7] Miller, D.W. and Brodeur, D.R. The CDIO Capstone Course: An Innovation in Undergraduate Systems Engineering Education, *Proceedings of the 2002 American Society of Engineering Education Annual Conference and Exposition*, Montréal, Quebec, Canada, 2002.

[8] Crawley, E. F., Hallam, C. R. A., and Imrich, S. Engineering the engineering learning environment. *Proceedings of the 2002 European Society of Engineering Education Annual Conference*, Florence, Italy, 2002.

[9] Craig, J. Internal memo. Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, Cambridge, Massachusetts, 2006.

[10] Bonwell, C. and Eisen, J. *Active Learning: Creating Excitement in the Classroom. ASHE-ERIC Higher Education Report 1.* The George Washington University, School of Educationa nd Human Development, Washington, DC, USA, 1991.

[11] Darmofal, D.L. Enhancing Conceptual Understanding. *M.I.T. Faculty Newsletter*, TeachTalk column, Volume XV, No. 2, November 2002.