CREATING THE CDIO SYLLABUS, A UNIVERSAL TEMPLATE FOR ENGINEERING EDUCATION

Edward F. Crawley[1]

Abstract *— This paper details how a team at the Massachusetts Institute of Technology identified and codified a set of goals for engineering education, which can serve as the basis for curricular improvement and outcome based assessment. The result of two years of scholarship, these goals are embodied in* The CDIO Syllabus, A Statement of Goals for Undergraduate Engineering Education.

The specific CDIO (Conceive — Design — Implement — Operate) Syllabus objective is to create rational, complete, universal and generalizable goals for undergraduate engineering education. The Syllabus focuses on personal, interpersonal and system building skills, and leaves a placeholder for the disciplinary fundamentals appropriate for any specific field of engineering. It complements and significantly expands on ABET's criteria. The process of adapting the Syllabus to a degree program includes a survey step to determine the desired level of proficiency in the designated skills that is, by consensus, expected of program's graduates.

With rationale, detail and broad applicability, the CDIO Syllabus' principal value is that it can be generalized to serve as a model from which any university's engineering programs may derive specific learning outcomes. A work in progress, we encourage examination, comment and potential adoption. Widespread adoption of the Syllabus will facilitate sharing of the best curricular and pedagogic approaches, and it will promote the development of standardized assessment tools.

Index Terms — CDIO, syllabus development, undergraduate education.

INTRODUCTION

In contemporary undergraduate engineering education, there is a seemingly irreconcilable tension between two growing needs. On one hand, there is the ever-increasing body of technical knowledge that graduating students must command. On the other hand, there is a growing recognition that young engineers must possess a wide array of personal, interpersonal, and system building knowledge and skills that will allow them to function in real engineering teams and to produce new products and systems.

To resolve these seemingly irreconcilable needs, the MIT Aeronautics and Astronautics Department is creating a new concept for undergraduate education. We are developing this by applying *the engineering problem solving paradigm*. This entails first creating and codifying a comprehensive understanding of the skills needed by the contemporary engineer. Then, pedagogical and curricular approaches are developed to enhance the learning of these skills. Simultaneously, new assessment techniques are introduced to provide the feedback necessary to improve the educational process. Collectively, these activities comprise the CDIO Program.

The first tangible outcome of this initiative was the CDIO Syllabus, a codification of contemporary engineering knowledge, skills and attitudes. The Syllabus essentially constitutes a *requirements document* for undergraduate engineering education. It is both a template and an associated process. The process can be used to capture the opinions of industry, alumni and faculty, and customize the Syllabus to a set of learning objectives appropriate for any specific undergraduate engineering program.

The required skills of engineering are best defined through the examination of the practice of engineering. In fact, from its conception as a profession until the middle of the 20th century, engineering education was based on practice. With the advent of the engineering science-based approach, the education of engineers became based on a more fundamental and generalizable set of analysis tools. Unfortunately, engineering education also began to disassociate from practice, as engineering research became the culture of engineering schools.

Over the past decade, industry in the United States began a concerted effort to close the gap between engineering education and practice. It did this in part by issuing statements of high-level goals. Yet these admonitions have not made the kind of fundamental impact their authors desired. We feel that the two root causes for this lack of convergence between engineering education and practice are an absence of *rationale*, and an absence of *detail*.

Our approach was to reformulate the underlying need to make the rationale apparent. We assert that graduating engineers should be able to:

conceive-design-implement-operate
complex value-added engineering systems
in a modern team-based environment.

The emphasis on the product/system lifecycle (Conceive — Design — Implement — Operate) gives the program and the Syllabus its name. Once the CDIO premise is accepted as

[1] Edward F. Crawley, Massachusetts Institute of Technology, Aeronautics and Astronautics Department, 33-207, 77 Massachusetts Ave., Cambridge, MA 02139

the *context* of engineering education, more detailed goals can be re-derived.

In the discussion that follows, the structure of the Syllabus and its origins are presented, followed by a brief correlation with other source documents. The process to adopt the Syllabus to a particular program is then outlined.

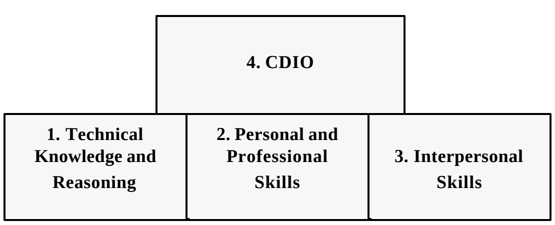
STRUCTURE OF THE TOPICAL CDIO SYLLABUS

In assembling and organizing the Syllabus content our goal was threefold: to create a structure whose rationale is apparent; to derive a comprehensive high level set of goals correlated with other sources; and to develop a clear, complete, and consistent set of detailed topics that facilitate implementation and assessment. The outcome of this activity is the CDIO Syllabus, shown in condensed form in the Appendix.

The departure point for the derivation of the CDIO Syllabus' content is the simple statement that *engineers engineer*; that is, they design and build systems and products for the betterment of humanity. Graduating engineers should appreciate engineering *process*, be able to contribute to the development of engineering *products*, and do so while working in engineering *organizations*. Implicit is the additional expectation that engineering graduates should develop as whole, mature, thoughtful individuals.

These high level expectations correlate directly to the highest level organization of the CDIO Syllabus. Figure 1. Examining the mapping of the first level Syllabus items to these four expectations, we can see that a mature, thoughtful individual interested in technical endeavors possesses a set of *Personal and Professional Skills*, which are central to the practice. In order to develop complex value-added engineering systems, students must have mastered the fundamentals of the appropriate *Technical Knowledge and Reasoning*. To work in a modern team-based environment, students must have developed the *Interpersonal Skills* of teamwork and communications. Finally, to create and operate products and systems, a student must understand something of *Conceiving, Designing, Implementing, and Operating Systems in the Enterprise and Societal Context*.

FIGURE.1
BUILDING BLOCKS OF KNOWLEDGE, SKILLS AND ATTITUDES NECESSARY TO CONCEIVE, DESIGN, IMPLEMENT AND OPERATE SYSTEMS IN THE ENTERPRISE AND SOCIETAL CONTEXT



Part 1 of the Syllabus is *Technical Knowledge and Reasoning*. Modern engineering professions rely on a necessary core Knowledge of Underlying Sciences (1.1). A body of Core Engineering Fundamental Knowledge (1.2) builds on that science core, and a set of Advanced Engineering Fundamentals (1.3) moves students *toward* the skills necessary to begin a professional career. This is the curriculum that engineering school faculty usually debate and define. Therefore, the CDIO Syllabus merely leaves a placeholder here, since the Part 1 details will vary from field to field.

In the remainder of the Syllabus, we have endeavored to include the knowledge, skills and attitudes that *all* engineering graduates might require.

Part 2 of the Syllabus is *Personal and Professional Skills and Attributes*. In Part 3, the *Interpersonal Skills* are outlined. Part 4, *Conceiving, Designing, Implementing, and Operating Systems in the Enterprise and Societal Context*, presents a view of how product or system development moves through four metaphases, Conceiving (4.3), Designing (4.4), Implementing (4.5), and Operating (4.6). The chosen terms are descriptive of hardware, software and process industries.

Products and systems are created and operated within an Enterprise and Business Context (4.2), and engineers work and enterprises exist within a larger Societal and External Context (4.1). An understanding of these frameworks is essential to the successful practice of the engineering profession.

It is important to note that the full CDIO Syllabus (as opposed to the condensed version in Appendix) exists at up to five levels of detail. This decomposition is necessary to transition from the high level goals (e.g., all engineers should be able to communicate) to the level of teachable and assessable skills (e.g., a topic in attribute 3.2.1, "analyze the audience"). The detail allows instructors to gain insight into content and objectives, contemplate the deployment of these skills into a curriculum, and prepare lesson and assessment plans.

SOURCING AND CORRELATING THE CDIO SYLLABUS

The process used to arrive at the detailed content of the CDIO Syllabus blended elements of a product development user need study with techniques from scholarly research. The Syllabus' detailed content was derived through focus group discussions, document research, surveys, workshops and peer reviews.

The first step in gathering the detailed content of the Syllabus was interviewing focus groups that included faculty, current students, industry leaders and senior academics from other universities. To ensure applicability to all engineering fields, we included individuals with varied engineering backgrounds, generalized concepts whenever possible, and we used relatively universal terminology. The groups were presented with the question, “What, in detail, is the set of knowledge, skills and attitudes that a graduating engineer should possess?” Not surprisingly, each group produced varied responses.

We organized results of the focus groups, plus the topics extracted from four principal comprehensive source documents into a preliminary draft, which contained the first four-level organization of the content. The principle source documents used represent the views of industry, government and academia on the expectations for a university graduate. They included the ABET EC2000 criteria, Boeing’s “Desired Attributes of a Graduating Engineer,” and two MIT goal documents. [1]-[4]

This preliminary draft needed extensive review and validation. To obtain stakeholder feedback, a survey was conducted among four constituencies: faculty, senior industry leaders, young alumni (average age 25) and older alumni (average age 35). The qualitative comments from this survey were incorporated, improving the Syllabus’ organization, clarity and coverage.

TABLE. 1
ABET 2000 REQUIREMENTS CORRELATED WITH THE CDIO SYLLABUS

CDIO SYLLABUS SUB-SECTION	ABET CRITERIA MET										
	a	b	c	d	e	f	g	h	i	j	k
1.1	✔										
1.2	✔										
1.3	✔										✔
2.1					✔						✔
2.2		✔									
2.3			✔								
2.4									✔		
2.5						✔					✔
3.1				✔							
3.2							✔				
4.1								✔		✔	
4.2											
4.3			✔								
4.4			✔								
4.5			✔								
4.6			✔								

Each second level (X.X) section of the Syllabus was then peer reviewed by several domain experts. Combining the results of the peer review, and a check of additional sectional references, we completed the final topical version of the Syllabus. To ensure comprehensiveness and to facilitate comparison, the contents of the Syllabus were explicitly correlated with the four comprehensive source documents. As an example, the correlation with ABET’s EC2000 accreditation is presented in Table 1. EC2000 states that accredited engineering programs must assure that its graduates have developed 11 specific attributes. While coverage by the CDIO Syllabus of ABET’s attributes is strong, the Syllabus is more comprehensive. For example, ABET omits any reference to System Thinking (2.3), and lists only item (i), “an ability to engage in lifelong learning,” from among the many desirable Personal Attributes (2.4). (ABET omits initiative, perseverance, flexibility, creative and critical thinking, etc.)

The Syllabus has two advantages over EC2000, one minor and one major. The minor advantage is that it is arguably more rationally organized because it is more explicitly derived from the functions of modern engineering. This might not allow a better understanding of *how* to implement change, but it certainly will create a better understanding of *why* to implement change. The major advantage is that it contains more levels of detail. While EC2000 is an evaluation criteria, the CDIO Syllabus is a guide. Both are needed.

DETERMINING PROFICIENCY LEVELS

To translate our list of topics and skills into learning objectives, we needed a process to determine the level of proficiency expected of graduating engineers in each of the Syllabus topics. This process must include stakeholder input and encourage consensus. Constructing a well formulated survey, conducting the surveys among appropriate stakeholder groups, and reflecting on the results achieved this.

The first step was the construction of the survey. The survey questionnaire was clear and concise and asked questions on the desired proficiency in such a way that information was collected for each topical Syllabus item. Each respondent was asked to rate the expected level of proficiency of a graduating engineer on the following five point proficiency scale:

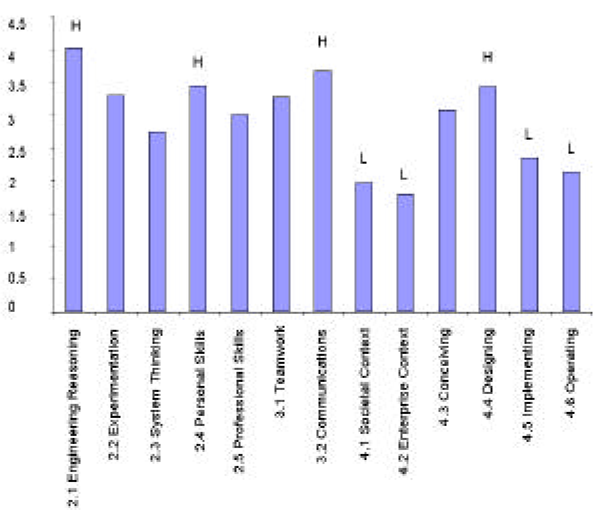
1. to have experienced or been exposed to
2. to be able to participate in and contribute to
3. to be able to understand and explain
4. to be skilled in the practice or implementation of
5. to be able to lead or innovate in

The scale is intended to be absolute; i.e., the most experienced engineers in practice would be able to “lead and innovate” in, for example, design. This expected proficiency on this scale can then be mapped to learning objectives expressed in any of several educational taxonomies. However we found that in soliciting input from stakeholders, the simpler activity based scale was more easily understood.

The second step was conducting the survey. We surveyed four groups: faculty from within and outside our university, mid- to upper-level leaders of industry, recent alumni (about five years from graduation) and older alumni (about 15 years from graduation). The alumni groups were chosen so that the respondents were young enough to still recall their education in some detail, yet old enough to be able to reflect on it. The survey was sent to approximately 40 faculty, with N = 22 respondents; approximately 40 industry leaders with N = 16 respondents; approximately 160 young alumni; with N = 34 respondents; and approximately 180 older alumni with N = 17 respondents. Except for older alumni, we considered these returns rates quite high.

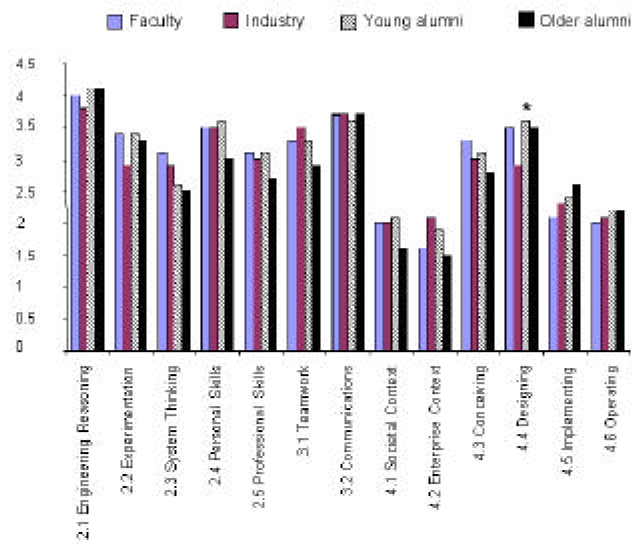
The third step was the analysis of the responses. The mean of survey inputs for each of the four stakeholder groups was calculated, and is presented in Figure 2. Statistical tests (such as pairwise Student's T) were used to determine if differences in the means were meaningful. It is hoped that from this survey and analysis process, consensus will emerge, or substantive differences can be identified and resolved by a further process.

FIGURE. 2
MEAN PROFICIENCY LEVEL FOR ALL GROUPS COMBINED. H AND L INDICATE STATISTICALLY HIGH AND LOW COMPARED TO AVERAGE PROFICIENCY



The most significant result of our survey was the unexpected similarities in opinion among the four stakeholder groups, as show in Figure 3. When asked specific well posed questions, and given a quantitative scale for responses, the faculty, industry leaders and alumni were all in agreement. It settled all arguments about the desired level of proficiency we now expect in our graduating students. Note that of all the possible pair-wise comparisons, there were only two where a statistically significant difference occurred, both in the same section. Industry respondents believe a graduating senior should be *less* proficient at the design process than did the two alumni groups. This may a result of the fact that the alumni in the age groups surveyed are primarily concerned with design processes and emphasize proficiency in that area, while the industry respondents are at a higher level in the organization where the detailed skills of design are less important.

FIGURE .3
PROFICIENCY EXPECTATION BY SURVEY GROUP. ASTERISK DESIGNATES STATISTICAL DIFFERENCES.



SUMMARY

We have derived a statement of goals for undergraduate engineering that is:

- rationalized against the modern practice of engineering, so the intent of the goals flows naturally from the actual roles of engineers
- comprehensive of other high level documents which attempt to outline the goals of engineering education
- complete and consistent; all of the knowledge, skills and attitudes that could be rationally expected to be possessed by a graduating engineer are included
- presented in sufficient detail that the specific topics that are to be taught and learned are enumerated, laying the foundation for curriculum planning and outcome based assessment
- linked to a survey process that will set broadly agreed upon levels of proficiency that would be expected of a graduating engineer

Any educational program can adapt the Syllabus to its specific needs by following these suggested steps:

- Add or delete topics based on the program's needs, changing terminology as necessary
- Survey stakeholders on expected proficiency using the five-point scale above
- Examine survey data, resolve discrepancies, assign to each topic a proficiency rating

We recognize that the Syllabus is a draft document. With the support of the Wallenberg Foundation, we have formed a partnership with three leading Swedish engineering schools; Chalmers, the Royal Technical Institute, and Linköping University, and we are implementing CDIO syllabi in those institutions. We invite others to study and adapt the CDIO Syllabus, and supply comments and feedback. Working together, we can make the Syllabus into a universal document, and shape the future of engineering education.

REFERENCES

[1] Accreditation Board of Engineering and Technology, "Criteria for Accrediting Engineering Programs: Effective for Evaluations During the 2000-2001 Accreditation Cycle," 2000.

[2] The Boeing Company, "Desired Attributes of an Engineer: Participation with Universities," 1996.

[3] Massachusetts Institute of Technology School of Engineering Committee on Engineering Undergraduate Education, "Eight Goals of an Undergraduate Education," Cambridge, MA, 1988.

[4] Massachusetts Institute of Technology, Task Force on Student Life and Learning, *Task Force Report, 22 April 1998,* Cambridge, MA, 1988.

APPENDIX
THE CDIO SYLLABUS (CONDENSED)

1 TECHNICAL KNOWLEDGE AND REASONING
- 1.1 KNOWLEDGE OF UNDERLYING SCIENCES
- 1.2 CORE ENGINEERING FUNDAMENTAL KNOWLEDGE
- 1.3 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES
- 2.1 ENGINEERING REASONING AND PROBLEM SOLVING
  - 2.1.1 Problem Identification and Formulation
  - 2.1.2 Modeling
  - 2.1.3 Estimation and Qualitative Analysis
  - 2.1.4 Analysis With Uncertainty
  - 2.1.5 Solution and Recommendation
- 2.2 EXPERIMENTATION AND KNOWLEDGE DISCOVERY
  - 2.2.1 Hypothesis Formulation
  - 2.2.2 Survey of Print and Electronic Literature
  - 2.2.3 Experimental Inquiry
  - 2.2.4 Hypothesis Test, and Defense
- 2.3 SYSTEM THINKING
  - 2.3.1 Thinking Holistically
  - 2.3.2 Emergence and Interactions in Systems
  - 2.3.3 Prioritization and Focus
  - 2.3.4 Tradeoffs, Judgment and Balance in Resolution
- 2.4 PERSONAL SKILLS AND ATTITUDES
  - 2.4.1 Initiative and Willingness to Take Risks
  - 2.4.2 Perseverance and Flexibility
  - 2.4.3 Creative Thinking
  - 2.4.4 Critical Thinking
  - 2.4.5 Awareness of One's Personal Knowledge, Skills and Attitudes
  - 2.4.6 Curiosity and Lifelong Learning
  - 2.4.7 Time and Resource Management
- 2.5 PROFESSIONAL SKILLS AND ATTITUDES
  - 2.5.1 Professional Ethics, Integrity, Responsibility and Accountability
  - 2.5.2 Professional Behavior
  - 2.5.3 Proactively Planning for One's Career
  - 2.5.4 Staying Current on World of Engineer

3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION
- 3.1 TEAMWORK
  - 3.1.1 Forming Effective Teams
  - 3.1.2 Team Operation
  - 3.1.3 Team Growth and Evolution
  - 3.1.4 Leadership
  - 3.1.5 Technical Teaming
- 3.2 COMMUNICATION
  - 3.2.1 Communication Strategy
  - 3.2.2 Communication Structure
  - 3.2.3 Written Communication
  - 3.2.4 Electronic/Multimedia Communication
  - 3.2.5 Graphical Communication
  - 3.2.6 Oral Presentation and Interpersonal Communication
- 3.3 COMMUNICATIONS IN FOREIGN LANGUAGES
  - 3.3.1 English
  - 3.3.2 Languages of Regional Industrial Nations
  - 3.3.3 Other Languages

4 CONCEIVING, DESIGNING, IMPLEMENTING AND OPERATING SYSTEMS IN THE ENTERPRISE AND SOCIETAL CONTEXT
- 4.1 EXTERNAL AND SOCIETAL CONTEXT
  - 4.1.1 Roles and Responsibility of Engineers
  - 4.1.2 The Impact of Engineering on Society
  - 4.1.3 Society's Regulation of Engineering
  - 4.1.4 The Historical and Cultural Context
  - 4.1.5 Contemporary Issues and Values
  - 4.1.6 Developing a Global Perspective
- 4.2 ENTERPRISE AND BUSINESS CONTEXT
  - 4.2.1 Appreciating Different Enterprise Cultures
  - 4.2.2 Enterprise Strategy, Goals and Planning
  - 4.2.3 Technical Entrepreneurship
  - 4.2.4 Working Successfully in Organizations
- 4.3 CONCEIVING AND ENGINEERING SYSTEMS
  - 4.3.1 Setting System Goals and Requirements
  - 4.3.2 Defining Function, Concept and Architecture
  - 4.3.3 Modeling of System and Ensuring Goals Can Be Met
  - 4.3.4 Development Project Management
- 4.4 DESIGNING
  - 4.4.1 The Design Process
  - 4.4.2 The Design Process Phasing and Approaches
  - 4.4.3 Utilization of Knowledge in Design
  - 4.4.4 Disciplinary Design
  - 4.4.5 Multidisciplinary Design
  - 4.4.6 Multi-objective Design
- 4.5 IMPLEMENTING
  - 4.5.1 Designing the Implementation Process
  - 4.5.2 Hardware Manufacturing Process
  - 4.5.3 Software Implementing Process
  - 4.5.4 Hardware Software Integration
  - 4.5.5 Test, Verification, Validation and Certification
  - 4.5.6 Implementation Management
- 4.6 OPERATING
  - 4.6.1 Designing and Optimizing Operations
  - 4.6.2 Training and Operations
  - 4.6.3 Supporting the System Lifecycle
  - 4.6.4 System Improvement and Evolution
  - 4.6.5 Disposal and Life-End Issues
  - 4.6.6 Operations Management