The CDIO Syllabus

A Statement of Goals for Undergraduate Engineering Education

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1 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 it is felt 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 real products and systems.

In order to resolve these seemingly irreconcilable needs, we must develop a new vision and concept for undergraduate education. At MIT we are developing this new educational concept by applying the *engineering problem solving paradigm*. This entails first developing and codifying a comprehensive understanding of the skills needed by the contemporary engineer. Next we are developing new approaches to enable and enhance the learning of these skills. Simultaneously we are exploring new systems to assess technical learning, and to utilize this assessment information to improve our educational process. Collectively these activities comprise the CDIO program at MIT.

The first tangible outcome of this program is the CDIO Syllabus, the sought after codification of the skills of contemporary engineering. The Syllabus essentially constitutes a requirements document for undergraduate engineering education. It is presented here as a *template* plus a *process*, which can be used to customize the Syllabus to any undergraduate engineering program. The template lists the generic topical content of an engineering education, and serves as a reference from which customized versions can be obtained. The process draws in faculty, alumni, students, and industry in a consensus building activity which arrives at a common understanding of the level of competence which should be achieved in each of the topics.

The general objective of the CDIO Syllabus is to summarize formally a set of knowledge, skills, and attitudes that alumni, industry, and academia desire in a future generation of young engineers. The Syllabus can be used to define expected outcomes in terms of learning objectives of the personal, interpersonal, and system building skills necessary for modern engineering practice. Further, the Syllabus can be utilized to define new educational initiatives, and it can be employed as the basis for a rigorous assessment process, such as is required by ABET.

The required skills of engineering are best defined through the examination of the *practice* of engineering. In fact, from its conception as a profession, through the development of formal engineering education in the 19th century, until the middle of the 20th century, engineering education was based on practice. Even in this earlier era, there were writings which attempted to codify the "non-traditional" skills an engineer must possess. One such effort is called the *Unwritten Laws of Engineering* (King 1944). When translated into modern terms, it calls for the development of skills such as those needed for good oral and written communications, planning, and working successfully in organizations. In addition, it calls for the honing of personal attributes, such as a propensity towards action, integrity, and self-reliance. This list sounds as current today as it did when written in 1944.

With the advent of the modern engineering science based approach to engineering education in the 1950's, the education of engineers began to become disassociated from the practice of engineering. Fewer faculty members had worked as engineers (the norm of the earlier era), and engineering science became the dominant culture of engineering schools. By the 1980's, some began to react to this widening gulf between engineering education and practice. For example, the essay by Bernard Gordon (inventor of the analog to digital converter and winner of the Medal of Technology) entitled *What is an Engineer?* (Gordon 1984) clearly enumerates the skills required for contemporary practice. By the late 1980's, a few universities had begun to examine this issue, and make tentative statements of the appropriate goals of undergraduate education.

By the mid 1990's, industry in the United States began a concerted effort to close the gap between engineering education and practice. Companies such as Boeing published lists of desired attributes (Boeing 1996), and leaders of industry wrote essays urging a new look at the issues (Augustine 1996). American industry successfully lobbied the National Science Foundation to fund reform of education, lobbied the professional societies to change accreditation standards (ABET 2000), and created joint working groups to facilitate exchange of views. ABET, in its EC 2000, instantiated a list of high level goals traceable back to the writings of the past 50 years.

These various statements of high level goals, written in part by those outside the academic community, have probably not made the kind of fundamental impact that was desired by their authors. At MIT we examined this issue, and decided there were two root causes for this continued lack of convergence between engineering education and practice: an absence of rationale, and an absence of detail.

The "lists," as presented, were derived requirements, which failed to make a convincing statement of the rationale for *why* these were the desired attributes of a young engineer. Our approach was to reformulate the underlying need to make the rationale more apparent:

> *Graduating engineers should be able to*
> *conceive-design-implement-operate*
> *complex value-added engineering systems*
> *in a modern team-based environment.*

This is essentially just a restatement of the fact that it is the job of engineers to be able to engineer. If we accept this conceive-design-implement-operate premise as the *context* of engineering education, we can then rationally re-derive more detailed goals for the education.

The second barrier is the fact that the "lists," as written, lack sufficient detail and specificity to be widely understood or implemented. Therefore we composed the CDIO Syllabus to provide the necessary level of detail.

The specific objectives of the CDIO Syllabus are to create a clear, complete, and consistent set of goals for undergraduate engineering education, in sufficient detail that they could be understood and implemented by engineering faculty. These goals form the basis for rational design of curricula (i.e. they are a requirements document), as well as the basis for a comprehensive system of assessment. Our goal was to create a list which is rationalized against the norms of contemporary engineering practice, comprehensive of all known other sources, and peer-reviewed by experts in the field. Further, we sought to develop a listing that was prioritized, appropriate to university education, and expressed as learning objectives.

It should be pointed out that our formulation of the functions of an engineer, from which the Syllabus is derived, does not in any way diminish the role of engineering science or engineering research. On the contrary, engineering science is the appropriate basis for engineering education, and engineering research is the process of adding new knowledge to that base. Most of us involved in this project are engineering scientists and researchers. However we recognize that our undergraduate students are being educated to be engineers. Whether their careers evolve so that they become practicing engineers, or engineering researchers, their background will be *strengthened* by setting their undergraduate experience in the context of the conception, design, implementation, and operation of systems and products.

In codifying the Syllabus, we have created both a template for the detailed topical objectives, and a process to customize it to any particular engineering program. The approach used to derive and customize the document had three main steps. As summarized in Part 2, the first step was to create the comprehensive list of topics and to structure the lower level topics into identifiable headings and categories. However, lists of topics are not requirements. Part 3 describes how the topics can be converted into requirements, using a survey process to gauge desired levels of competence of engineers from a specific university or program. In Part 4, the topics are then reformulated into learning objectives using a formal specification language for learning, based on Bloom's Taxonomy (Bloom 1956). In Parts 3 and 4, the process is demonstrated by customizing the topical Syllabus to create a form for a specific undergraduate program at MIT. Part 5 summarizes the effort, and gives a roadmap of how an equivalent syllabus can be derived for any undergraduate engineering program.

2 Content of the Topical CDIO Syllabus

The first challenge in composing the CDIO Syllabus was to assemble and organize the *content*. Our goal in composing the content 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 topics in order to facilitate implementation and assessment. The outcome of this activity is the CDIO Syllabus shown in condensed form in Table 1. The fully expanded topical Syllabus is listed in Appendix A.

2.1 Structure of the CDIO Syllabus

The point of departure for the derivation of the content of the CDIO Syllabus is the simple statement that *engineers engineer*, that is, they build systems and products for the betterment of humanity. In order to enter the contemporary profession of engineering, students must be able to perform the essential functions of an engineer:

> *Graduating engineers should be able to*
> *conceive-design-implement-operate*
> *complex value-added engineering systems*
> *in a modern team-based environment.*

Stated another way, 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, as university graduates and young adults, engineering graduates should be developing as whole, mature, and thoughtful individuals.

These four high level expectations map directly to the highest, first or "X" level organization of the CDIO Syllabus, as illustrated in Figure 1. Examining the mapping of the first level Syllabus items to these four expectations, we can see that a mature 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*. In order to work in a modern team-based environment, students must have developed the *Interpersonal Skills* of teamwork and communications. Finally, in order to actually be able 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*. We will now examine each of these four items in more detail.

The second or "X.X" level of content of Part 1 *Technical Knowledge and Reasoning* of the Syllabus is shown diagrammatically in Figure 2. Modern engineering professions often 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 towards the skills necessary to begin a professional career. This section of the CDIO Syllabus is, in fact, just a placeholder for the more detailed description of the disciplinary fundamentals necessary for any particular

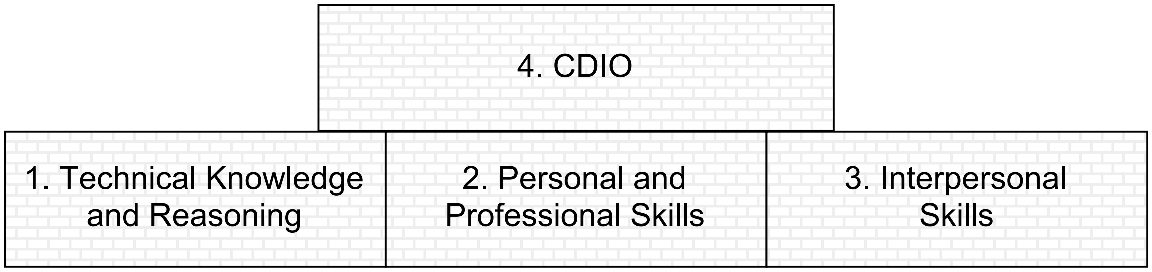

Figure 1: Building blocks of knowledge, skills, and attitudes necessary to Conceive, Design, Implement, and Operate Systems in the Enterprise and Societal Context (CDIO).

engineering education. The details of Part 1 will vary widely in content from field to field. The placement of this item at the beginning of the Syllabus is a reminder that the development of a deep working knowledge of technical fundamentals is, and should, be the primary objective of undergraduate engineering education.

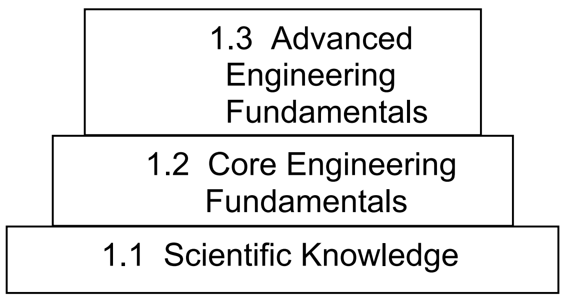

Figure 2: Hierarchy of Technical Knowledge and Reasoning.

Unlike Part 1 *Technical Knowledge and Reasoning*, the remainder of the Syllabus is, arguably, common to all engineering professions. Engineers of all types use approximately the same set of personal and interpersonal skills, and follow approximately the same generalized processes. We have endeavored in the remaining three parts of the Syllabus to be inclusive of all the knowledge, skills, and attitudes that engineering graduates might require. In addition, we have attempted to use terminology which would be recognizable to all professions. Local usage in different engineering fields will naturally require some translation and interpretation.

The second level content of Part 2 *Personal and Professional Skills and Attributes* and Part 3 *Interpersonal Skills* are shown schematically in the Venn diagram of Figure 3. Starting from within, the three modes of thought most practiced professionally by engineers are explicitly called out: Engineering Reasoning and Problem Solving (2.1), Experimentation and Knowledge Discovery (2.2), and System Thinking (2.3). These might also be called engineering thinking, scientific thinking, and system thinking. The detailed topical content of these sections at a third or "X.X.X" level is shown in Table 1, and a fourth or implementable level is given in Appendix A. There is parallelism in these three sections (2.1- 2.3). Each starts with a subsection which is essentially "formulating the issue," moves through the particulars of that mode of thought, and ends with a section which is essentially "resolving the issue."

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

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES
- 2.1 ENGINEERING REASONING AND PROBLEM SOLVING [e]
  - 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 [b]
  - 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 Trade-offs, Judgment and Balance in Resolution
- 2.4 PERSONAL SKILLS AND ATTRIBUTES
  - 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 [i]
  - 2.4.7 Time and Resource Management
- 2.5 PROFESSIONAL SKILLS AND ATTITUDES
  - 2.5.1 Professional Ethics, Integrity, Responsibility, and Accountability [f]
  - 2.5.2 Professional Behavior
  - 2.5.3 Proactively Planning for One's Career
  - 2.5.4 Staying Current on World of Engineering

3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION
- 3.1 TEAMWORK [d]
  - 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 COMMUNICATIONS [g]
  - 3.2.1 Communications Strategy
  - 3.2.2 Communications Structure
  - 3.2.3 Written Communication
  - 3.2.4 Electronic/Multimedia Communication
  - 3.2.5 Graphical Communication
  - 3.2.6 Oral Presentation and Inter-Personal Communications
- 3.3 COMMUNICATION 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 [h]
  - 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 [j]
  - 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 [c]
  - 4.3.1 Setting System Goals and Requirements
  - 4.3.2 Defining Function, Concept and Architecture
  - 4.3.3 Modeling of System and Insuring Goals Can Be Met
  - 4.3.4 Development Project Management
- 4.4 DESIGNING [c]
  - 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 (DFX)
- 4.5 IMPLEMENTING [c]
  - 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 [c]
  - 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

Table 1: Condensed CDIO Syllabus, showing first, second, and third level content.

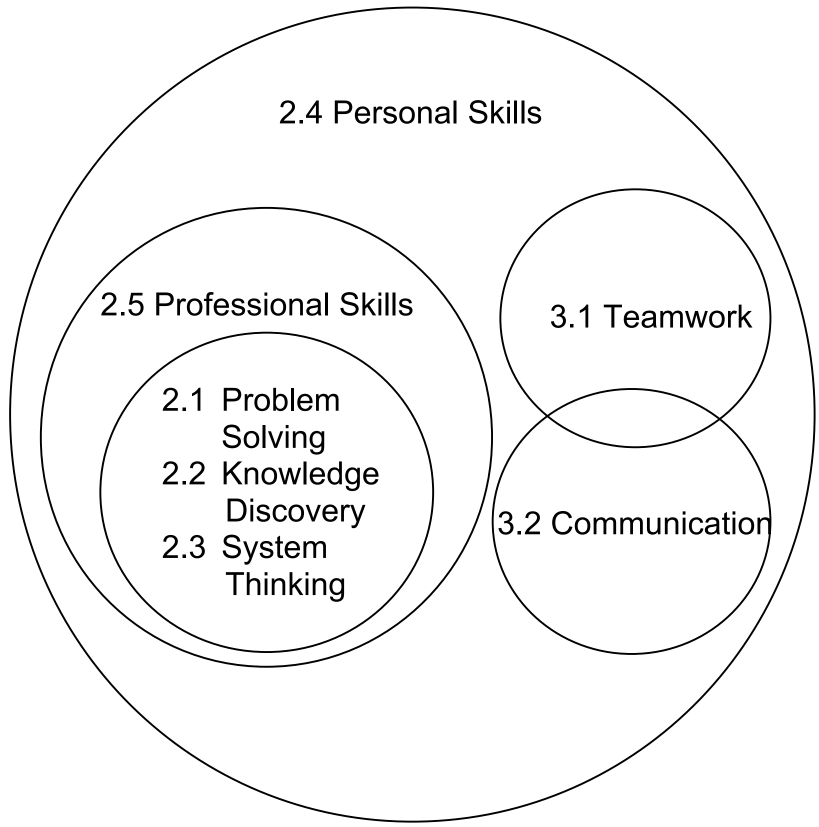

Figure 3: Venn diagram of Personal and Professional and Interpersonal skills.

As indicated by Figure 3, those personal skills and attributes, other than the three modes of thought, which are used primarily in a professional context are called Professional Skills and Attitudes (2.5). These include professional integrity and professional behavior, and the skills and attitudes necessary to plan for one's career, as well as stay current in the world of engineering.

The subset of personal skills which are not primarily used in a professional context, and are not interpersonal, are simply labeled Personal Skills and Attitudes (2.4). These include the general character traits of initiative and perseverance, the more generic modes of thought of creative and critical thinking, and the skills of personal inventory (knowing one's strengths and weaknesses), curiosity and lifelong learning, and time management.

The *Interpersonal Skills* are a somewhat distinct subset of the general class of personal skills, and divide into two overlapping sets called Teamwork (3.1) and Communications (3.2). Teamwork is comprised of forming, operating, growing, and leading a team, along with some skills specific to technical teamwork. Communications is composed of the skills necessary to devise a communications strategy and structure, and those necessary to use the four common media: written, oral, graphical, and electronic. If appropriate, the command of a foreign language would be in Section 3.2 as well.

Figure 4 shows an overview of Part 4 *Conceiving, Designing, Implementing, and Operating Systems in the Enterprise and Societal Context.* It presents a modern view

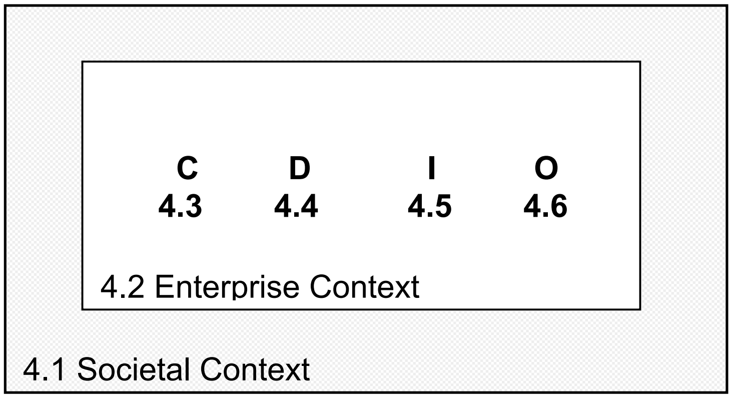

Figure 4: Conceiving, Designing, Implementing, and Operating products and systems, which occurs in the framework of an Enterprise and Societal Context.

of how product or system development moves through four meta-phases, Conceiving (4.3), Designing (4.4), Implementing (4.5), and Operating (4.6). The terms are chosen to be descriptive of hardware, software, and process industries. Conceiving runs from market or opportunity identification though high level or conceptual design, and includes development project management. Designing includes aspects of design process, as well as disciplinary, multi-disciplinary, and multi-objective design. Implementing includes hardware and software processes, test and verification, as well as design and management of the implementation process. Operating covers a wide range of issues from designing and managing operations, through supporting product lifecycle and improvement, to end-of-life planning.

Products and systems are created and operated within an Enterprise and Business Context (4.2), and engineers must understand these sufficiently to operate effectively. The skills necessary to do this include recognizing the culture and strategy of an enterprise, and understanding how to act in an entrepreneurial way within an enterprise of any type or size. Likewise enterprises exist within a larger Societal and External Context (4.1). An understanding of which includes such issues as the relationship between society and engineering, and requires a knowledge of the broader historical, cultural, and global context.

It can be seen that the CDIO Syllabus is organized at the first two levels in a manner which is rational. The first level reflects the function of an engineer, who is a well developed individual, involved in a process which is embedded in an organization, with the intent of building products. The second level reflects much of the modern practice and scholarship on the profession of engineering.

It is important to note that the CDIO Syllabus exists at four (and in some cases five) levels of detail. This decomposition is necessary in order 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"). Although perhaps overwhelming at first, this level of detail has many benefits for engineering faculty members, who in many cases are not experts in some of these topics. 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.

2.2 Correlation with other Comprehensive Source Documents

One of our explicit goals in creating the Syllabus was to ensure that it is comprehensive in its statement of the desired knowledge, skills and attitudes of a graduating engineer. In an attempt to ensure this, the Syllabus is compared explicitly with four other similar primary source documents, is reviewed against a longer list of sources, and is correlated with the expected career tracks of an engineering professional.

To ensure comprehensiveness and to allow easy comparison, the contents of the Syllabus (at the second or X.X level) are explicitly correlated with four principal comprehensive source documents that describe the desired skills and attributes of graduating engineers (Appendix D). These four are reviewed in the approximate chronological order of the appearance: the goals of the 1988 MIT Commission on Engineering Undergraduate Education (Table 2a), the ABET EC 2000 accreditation criteria (Table 3a), Boeing's Desired Attributes of an Engineer (Table 4a), and the goals of the 1998 MIT Task Force on Student Life and Learning (Table 5a). These four sources are representative of the views of industry, government and academia on the expectations for a university graduate.

In 1988, the MIT School of Engineering's Commission on Engineering Undergraduate Education set forth eight goals of an undergraduate education, as listed in Table 2a. This document is notable in that it precedes the other three by almost a decade. The goals, as stated, were meant to stretch and shape the evolving view of undergraduate education. For example, the wording "have *begun* to acquire a working knowledge of current technology" was meant to signal a potential shift towards viewing the Master's degree as the professional engineering degree. Items (c) and (h) were meant to explicitly acknowledge the broader education necessary to be a leading engineer. Comparison with the CDIO Syllabus sections reveals substantive correlation (Table 2b). Every item in the MIT CEUE goals shows a "strong correlation" with the Syllabus, but the reverse is not true. For example, Engineering Reasoning and Problem Solving (2.1), System Thinking (2.3), Conceiving (4.3), Implementing (4.5) and Operating (4.6) are barely hinted at in item (f). As we will see with the other three source documents, each of the four contains many similar themes, but differs in some details. Even at the second or X.X level, none of the four is as comprehensive as the CDIO Syllabus.

By the mid 1990's, the Accreditation Board for Engineering and Technology (ABET) had proposed new accreditation standards for engineering programs meant to focus on measurable outcomes. Mandatory by the year 2000, the ABET EC 2000 states that for an engineering program to be accredited, it must assure that its graduates have developed the knowledge, skills, and attitudes listed in Table 3a. Again the coverage by the CDIO Syllabus of the ABET points is strong,

a. Have obtained a firm foundation in the sciences basic to their technical field.

b. Have begun to acquire a working knowledge of current technology in their area of interest.

c. Have begun to understand the diverse nature and history of human societies, as well as their literary, philosophical, and artistic traditions.

d. Have acquired the skills and motivation for continued self-education.

e. Have had an opportunity to exercise ingenui ty and inventiveness on a research project.

f. Have had an opportunity for engineering synthesis on a design project.

g. Have developed oral and written communication skills.

h. Have begun to understand and respect the economic, managerial, political, social, and environmental issues surrounding technical development.

Table 2a: Goals of Engineering Undergraduate Education (MIT, 1988)

		CEUE Goal Met							
CDIO Syllabus Sub-Section		a	b	c	d	e	f	g	h
1.1	*Knowledge of Underlying Sciences*	●							
1.2	*Core Engineering Fundamental Knowledge*		●						
1.3	*Advanced Engineering Fundamental Knowledge*		●						
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*								○
3.1	*Teamwork*						○		
3.2	*Communications*							●	
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*						○		

● Strong Correlation ○ Good Correlation

Table 2b: Correlation of MIT CEUE goals with the CDIO Syllabus.

but the Syllabus is more comprehensive as shown in Table 3b. 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.). Likewise ABET lists only item (f), "an understanding of professional and ethical responsibility," from among several important Professional Skills and Attitudes (2.5). The ABET document comes closer than most to capturing the full involvement in a product lifecycle by specifying in item (c) the "ability to design a system, component or process to meet desired needs." A "system…to meet a desired need" hints at the spirit of Conceiving and Engineering Systems (4.3) in the CDIO Syllabus. The phrase "designing … a component" of course maps to Designing (4.4), and "designing … a process" could be construed to include Implementing (4.5) and Operating (4.6). To facilitate direct comparison with ABET EC 2000, the condensed form of the Syllabus in Table 1, and the topical form of Appendix A are annotated with the letters [a] to [k] to show the items of strongest correlation between the two documents.

Except for these noted discrepancies, the CDIO Syllabus is well aligned with the ABET criteria. However the Syllabus has two advantages, one minor and one major. The minor one 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 certainly will create a better understanding of *why* to implement change. The major advantage is that it contains two or three more levels of detail than the ABET document. It penetrates into enough detail that phrases which are quite general, such as "good communication skills," take on substantive meaning. Furthermore, it goes as far as defining implementable and measurable goals, which are necessary to carry out the ABET curricular design and assessment processes.

For completeness, two other source documents are correlated with the CDIO Syllabus. In 1996, Boeing identified a list of "basic, durable attributes into which can be mapped specific skills reflecting the diversity of the overall engineering environment in which we in professional practice operate," listed in Table 4a. Again, inclusion of the Boeing attributes by the CDIO Syllabus is excellent (Table 4b). Among the four principal references, the Boeing document uniquely and explicitly calls out System Thinking (2.3) (item (c)) and an appreciation of the Enterprise and Business Context (4.2) (in item (d)). The Boeing document misses Engineering Reasoning and Problem Solving (2.1), Experimentation and Knowledge Discovery (2.2), and interestingly for a company so involved in it, Operating (4.6).

Finally it is interesting to compare the CDIO Syllabus with one document intended to set educational goals for a wider audience, those receiving a general technically based education. The MIT Task Force on Student Life and Learning evaluated MIT's educational processes to assess what attributes will distinguish educated graduates in the 21st century. In 1998, the Task Force concluded that MIT's educational goal is to produce educated individuals who possess the reasoning, knowledge and wisdom listed in Table 5a. Again the CDIO Syllabus provides excellent coverage of the MIT Task Force items, when they are

a. An ability to apply knowledge of mathematics, science, and engineering.

b. An ability to design and conduct experiments, as well as to analyze and interpret data.

c. An ability to design a system, component, or process to meet desired needs.

d. An ability to function on multi-disciplinary teams.

e. An ability to identify, formulate, and solve engineering problems.

f. An understanding of professional and ethical responsibility.

g. An ability to communicate effectively.

h. The broad education necessary to understand the impact of engineering solutions in a global and societal context.

i. A recognition of the need for, and an ability to engage in life-long learning.

j. A knowledge of contemporary issues.

k. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Table 3a: ABET 2000 accreditation requirements (ABET, 1998).

CDIO Syllabus Sub-Section		ABET Criteria Met										
		a	b	c	d	e	f	g	h	i	j	k
1.1	*Knowledge of Underlying Sciences*	●										
1.2	*Core Engineering Fundamental Knowledge*	●										
1.3	*Advanced Engineering Fundamental Knowledge*	○										●
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*						●					○
3.1	*Teamwork*				●							
3.2	*Communications*							●				
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*			●								

● Strong Correlation ○ Good Correlation

Table 3b: Correlation of ABET 2000 requirements with the CDIO interpreted for engineering (Table 5b). Understandably there are Syllabus sections that do not explicitly appear in the Task Force list, notably those associated with the enterprise context and system building – areas somewhat unique to the business of engineering.

Stepping back and comparing the CDIO Syllabus with the other four source documents, it can be seen that the Syllabus meets its goal of comprehensiveness. The Syllabus covers all of the items listed in the union of the other four documents, but more items than any of the four individually. It is somewhat specialized to engineering, but arguably not specialized to any type of engineering, and not far from enumerating the goals of a modern "liberal" technical education. In a final check for comprehensiveness, the CDIO Syllabus was compared with six other high level comprehensive documents (see Appendix D). By and large, the Syllabus covered all topics that we feel are appropriate to a university education contained in these six additional documents.

As an independent check on comprehensiveness, it can be observed that the Syllabus implicitly identifies a generic set of skills needed by all engineers, as well as more specific sets needed by different professional career tracks (Figure 5). The generic skills applicable to all tracks include: Engineering Reasoning and Problem Solving (2.1), Personal and Professional Skills and Attitudes (2.4 and 2.5), Teamwork (3.1), Communications (3.2), and External and Societal Context (4.1). There are at least five different professional tracks which engineers can and do follow, according to individual talents and interests. The tracks, and sections of the Syllabus which support them, are:

1. The Researcher –Experimentation and Knowledge Discovery (2.2)
2. The System Designer –System Thinking (2.3), Conceiving and Engineering Systems (4.3)
3. The Device Designer/Developer –Designing (4.4), Implementing (4.5)
4. The Product Support Engineer/Operator –Operating (4.6)
5. The Entrepreneurial Engineer/Manager –Enterprise and Business Context (4.2)

Of course, no graduating engineer will be expert in all of these potential tracks, and in fact may not be *expert* in any. However, the paradigm of modern engineering practice is that an individual's role will change and evolve. The graduating engineer must be able to interact in an informed way with individuals in each of these tracks, and must be educated as a generalist, prepared to follow a career which leads to any one or combination of these tracks.

The second or X.X level of the Syllabus has been shown to be topically inclusive of four principal comprehensive statements of expectations of graduating students, and has been reviewed against six others. Sections of the Syllabus enumerate the skills needed by five different engineering career tracks. It is therefore reasonable to conclude that the CDIO syllabus is a comprehensive set

a. A good understanding of engineering science fundamentals: Mathematics (including statistics), Physical and life sciences, Information Technology (far more than "computer literacy").

b. A good understanding of design and manufacturing processes. (i.e., understands engineering).

c. A multi-disciplinary, *systems* perspective.

d. A basic understanding of the *context* in which engineering is practiced: Economics (including business practices), History, the environment, customer and societal needs.

e. Good communication skills: written, verbal, graphic and listening.

f. High ethical standards.

g. An ability to think both critically and creatively - independently and cooperatively.

h. Flexibility. The ability and self-confidence to adapt to rapid or major change.

i. Curiosity and a desire to learn for life.

j. A profound understanding of the importance of teamwork.

Table 4a: Boeing's desired attributes of an engineer (Boeing, 1996).

		Boeing Criteria Met									
CDIO Syllabus Sub-Section		a	b	c	d	e	f	g	h	i	j
1.1	*Knowledge of Underlying Sciences*	●									
1.2	*Core Engineering Fundamental Knowledge*	○									
1.3	*Advanced Engineering Fundamental Knowledge*										
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*						●				
3.1	*Teamwork*							○			●
3.2	*Communications*					●					
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*										

● Strong Correlation ○ Good Correlation

Table 4b: Correlation of Boeing's desired attributes with the CDIO Syllabus.

a. Possess well-developed faculties of critical and rational reasoning.

b. Understand the scientific method and other methods of inquiry and hence are able to obtain, evaluate, and utilize information to pose and solve complex problems in life and work.

c. Have a strong grasp of quantitative reasoning, and have the ability to manage complexity and ambiguity.

d. Have a sound foundation of knowledge within a chosen field and have achieved some depth and experience of practice in it.

e. Are able to relate this knowledge to larger problems in society, and have an appreciation for the interaction between science, technology, and society.

f. Are able to relate this knowledge to larger problems in society, and have an appreciation for the interaction between science, technology, and society.

g. Are intellectually curious and motivated toward continu ous learning.

h. Possess the qualities associated with the best in the human spirit: a sense of judgment, an aesthetic sensibility, and the flexibility and self-confidence to adapt to major change.

i. Have a knowledge of history and an understanding of the spectrum of human culture and value systems.

j. Combine this knowledge with a strong sense of judgment to think critically about moral and ethical issues.

Table 5a: Goals of undergraduate education (MIT, 1998)

		MIT Goal Met									
CDIO Syllabus Sub-Section		a	b	c	d	e	f	g	h	i	j
1.1	*Knowledge of Underlying Sciences*				●						
1.2	*Core Engineering Fundamental Knowledge*				●						
1.3	*Advanced Engineering Fundamental Knowledge*				●						
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*										●
3.1	*Teamwork*										
3.2	*Communications*										
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*				○						

● Strong Correlation ○ Good Correlation

Table 5b: Correlation of MIT's goals with the CDIO Syllabus.

of goals for engineering education, and written at the X.X level, is universal to all fields of engineering.

2.3 Development of the Detailed Content

In addition to comprehensiveness, the CDIO Syllabus aims to be complete, consistent, and clear, i.e. to describe the knowledge, skills, and attitudes expected of a graduating engineer in sufficient detail that curricula can be planned and implemented, and student learning assessed. While there is general agreement about the high level view of these expectations among the comprehensive source documents cited, they lack the detail necessary to actually plan instruction and assess learning. We set out to develop and refine the necessary detailed content in the CDIO Syllabus.

Since a complete topical listing of the Syllabus itself (Appendix A) stretches over many pages, a discussion of the detailed content is impossible in any concise form. The Syllabus stands on its own in this regard, and is meant to be fairly explicit and understandable. However a brief review of the process used to arrive at the detailed content is warranted. The process blends elements of a product development user need study with techniques from scholarly research. The detailed content was derived through multiple steps, which included a combination of focus group discussions, document research, surveys, workshops, and peer reviews (Figure 6).

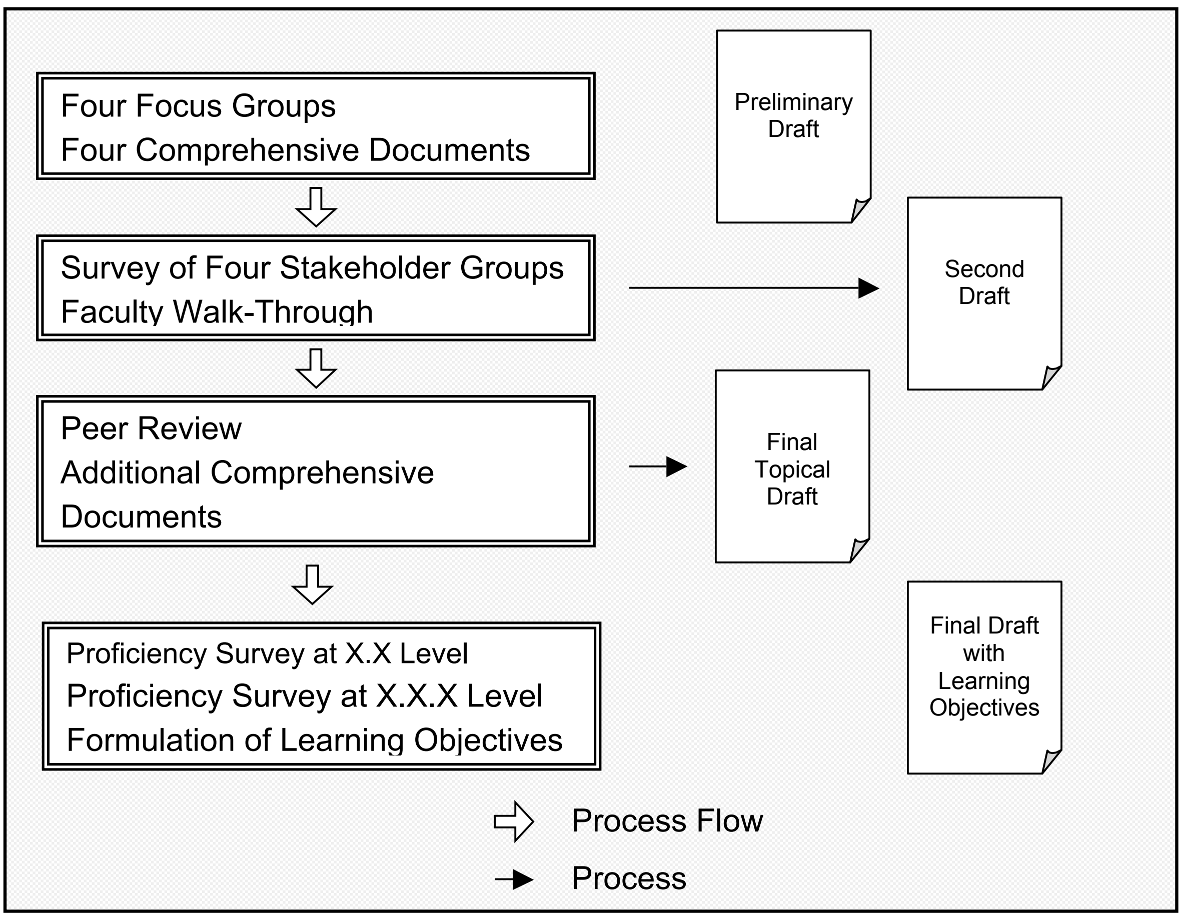

Figure 6: Development of detailed Syllabus content.

In this process, the intent was to produce a topical Syllabus with a broad applicability to all fields of engineering. The focus groups, surveys, and workshops primarily involved individuals with an affiliation to aerospace. However there are several reasons to believe that the content at the third, or X.X.X, level, and the lowest level, is relatively universal. We actively tried to make it so by drawing in individuals with varied engineering backgrounds, generalizing concepts to the extent possible, and using relatively standard and universal topics and terminology.

The first step in gathering the detailed content of the Syllabus was a set of four focus groups. The groups included: the faculty of the Department of Aeronautics and Astronautics; a group of current students; a group of industrial representatives; and a broadly based external review committee. This external review committee, known as the Visiting Committee of the MIT Corporation, included junior and senior alumni, leaders of industry from inside and outside of aerospace, and senior academic leaders from other universities. Each of the four focus groups was chosen for its unique and diverse perspective on the undergraduate curriculum. The groups were presented with the question: *What, in detail, is the set of knowledge, skills and attitudes that a graduating engineer should possess?* These four groups, which included representatives of most of the important stakeholders in the undergraduate education, produced a rich and varied view of expectations for graduating students.

The several hundred detailed topics which resulted from the focus groups, plus the topics extracted from the four principal comprehensive source documents (Tables 2 to 5), were then gathered and organized into a preliminary draft. This draft contained the first four-level organization of the content.

This preliminary draft needed extensive review and validation. To obtain feedback from our stakeholders, a survey was conducted among four constituencies: the faculty, senior leaders of industry, young alumni (average age 25) and older alumni (average age 35). Each group was asked to supply both quantitative inputs and qualitative comments on the preliminary draft of the Syllabus. The quantitative feedback will be discussed below. The qualitative comments from the survey were incorporated, improving the organization, clarity, and coverage of the Syllabus.

The resulting draft was then reviewed in a faculty workshop. In a type of review known as a requirements "walk through," each section within the document was examined and discussed. Repetition was removed, and topics were rearranged to present a more coherent and consistent structure. The incorporation of comments from the faculty workshop, as well as from the survey, resulted in a second draft of the CDIO Syllabus.

However, it was clear that more specific and expert input was still needed, particularly to ensure that the view of the various fields, which had been created by generalists, coincided with the view of experts. The second draft of each of the thirteen second level (X.X) sections in Parts 2 through 4 of the Syllabus was sent to several disciplinary experts for review. Appendix G contains the list of the various reviewers who responded.

Through the faculty and expert reviews we identified six other comprehensive source documents (listed in the References of Appendix D), as well as detailed references appropriate for each section (listed in the Bibliography of Appendix D). Combining the results of the peer review, and the check of additional comprehensive and detailed sectional references, the final topical version of the Syllabus was completed (Appendix A).

The topical Syllabus is a reasonably clear, consistent, and complete listing of the attributes that should be possessed by a contemporary engineer. An attempt has been made to describe topics in relatively standard American English, so that the Syllabus is mostly free of jargon, and uses terms that are at least recognizable by engineers in most fields. The process of having expert reviewers critique the document ensures that the listings are reasonably complete and coordinated with the way specialists in the disciplines view the content of their domain. Internal reviews have ensured that the document is reasonably consistent, both in style and content.

There is an open issue as to the universality of the Syllabus at the lower levels of detail. Despite attempts to the contrary, a bias toward the kind of engineering of modest volume, complex electro-mechanical-information systems, typical of aerospace, may be present in the document. The Syllabus at the lower levels should therefore be considered a reference and point of departure for customization.

Any educational program that seeks to use the Syllabus will have to adapt it to the needs and objectives of the specific local program and disciplinary field. A suggested process to adapt the topical Syllabus would be to review its content (Appendix A) and add or delete topics based on the perceived needs of the particular program. Changes in terminology might be needed in order to match the vernacular of the profession, and some changes in organization at the third (X.X.X) level, or at the lowest level may be necessary as well.

3 Determining the Appropriate Levels of Student Proficiency for Syllabus Topics

The topical Syllabus is a detailed list of skills in which a graduating engineer should, in principle, have developed some level of proficiency. However, in order to translate this list of topics and skills into learning objectives, we must establish a process to determine the level of proficiency that is expected in a graduating engineer. This process must capture the inputs and opinions of all the potential stakeholders of the educational program and encourage consensus building based on both individual viewpoints and collective wisdom. It has been our experience that this can be most effectively achieved by conducting well formulated surveys. The faculty then reflects on the survey results and makes informed decisions.

Such a generic survey process will be described below, followed by the specific implementation of the process for the program in Aeronautics and Astronautics at MIT. In actuality, the specific example of the survey process was conducted first, and then generalized, with lessons learned, to the generic one described below. Therefore the details of the MIT implementation will vary slightly from the recommended process. The detailed results of the MIT survey will also be presented. They are of course unique to this program and university, but are typical of the kind of results that a survey will generate.

3.1 Recommended Survey Process for Defining Desired Levels of Proficiency

The recommended survey process for determining the desired level of proficiency of the second (X.X) and third (X.X.X) level Syllabus topics is described below.

Identify the stakeholder communities to survey. Undergraduate education has a large number of stakeholder communities who might be included in the survey and consensus process. These will certainly include the faculty, and under ABET guidelines, should reach outside the university. One can consider including alumni groups of various ages, industry representatives, and peers at other universities. Standing and *ad hoc* advisory boards, administrators and faculty in other departments at the same university can also be included. Depending on local culture, current undergraduate students can be surveyed as well.

Our recommendation is to survey faculty, mid- to upper-level leaders of industry, a set of relatively young alumni (perhaps five years or so from graduation) and a set of older alumni (perhaps 15 years from graduation). These alumni will still be young enough to remember what they learned as undergraduates, yet have some maturity to reflect on the importance of undergraduate education and its role in their career. It is interesting to survey students to determine the degree to which their views change as they mature at the university and after they enter the workforce. However, the data from current students should probably be kept separate in the analysis from that of other stakeholder groups.

Conduct the survey to determine expected levels of proficiency. A survey questionnaire must be constructed and the survey actually conducted. The questionnaire must be clear and concise and ask questions on the desired levels proficiency in such a way that information is collected for each item in the topical

Syllabus at the second, or X.X, level, and at the third, or X.X.X, level. Both quantitative and qualitative responses should be solicited. A set of rubrics or definitions must be used to insure reasonable consistency of quantitative responses.

A recommended approach is to ask the respondent to rate the expected level of proficiency of a graduating engineer on a five point activity based scale, developed for this use at MIT. The proficiency scale was devised to anchor the responses in easily understood rubrics. Table 6 shows the scale, which is based

1.	To have experienced or been exposed to
2.	To be able 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

Table 6: MIT activity based proficiency scale.

on "activities", and ranges from "To have experienced or been exposed to" at level 1, to "To be able to lead or innovate in" at level 5. These levels were meant to resemble the progressive development of skills in a professional engineer, from those of an apprentice to those of a senior leader.

The CDIO Syllabus contains 16 items at the second (X.X) level, 13 of which are in Parts 2 through 4. These latter parts arguably contain the topics for which outside opinion is most useful in establishing expected levels of competence. These 13 items contain 67 attributes at the third (X.X.X) level. A meaningful survey can be constructed around 13 questions, but not 67. Therefore a two step process is recommended.

In the first step, the respondent is asked to rate, on the absolute five point activity based scale, "the expected level of proficiency of every graduating student in …", followed by the thirteen X.X level topics. An opportunity for the respondents to comment qualitatively on each X.X section should also be provided.

In the second step, within each X.X section the respondent is asked to pick one or two subsection topics at the X.X.X level for which a relatively higher level of proficiency should be expected. Relatively higher should be interpreted as one step higher on the activity based proficiency scale. Likewise the respondent is asked to pick an equal number (one or two) subsection topics for which a relatively lower level of proficiency is acceptable. This question must be asked in such a way that the pluses and minuses cancel and the mean level of proficiency is not raised or lowered.

Sample survey forms tailored for the purpose of asking these two questions are found in Appendix H. It is also recommended that the entire topical Syllabus, as well as other information on the program be sent or made available to respondents as background reading. A survey group of 20 to 30 representative individuals is usually shown to capture all of the important trends in stakeholder opinion.

Compile the data from the survey and examine it. Qualitative and quantitative data on the 13 second level and the 67 third level topics will be obtained from respondents in two or more stakeholder groups. The qualitative comments should be examined for trends and used in the updating of the customized syllabus. The quantitative responses should be used to guide the determination of the expected levels of proficiency of students at graduation.

The quantitative responses can be analyzed for their mean and variance. The mean of all inputs will give a consensus indicator of the level of proficiency expected of graduating students. Comparison of the means of the different stakeholder groups will indicate the degree of consensus. Statistical tests, such as ANOVA and Student's t tests, can be used to determine if differences in the means are significant.

One of the interesting outputs of this data phase is a sense of the degree of agreement on the expected levels of proficiency. If all stakeholder groups are in agreement, then it is obvious that consensus has been reached. If, on the other hand, there is significant disagreement on the expected level of proficiency on a Syllabus topic, then follow up discussions, closer reading of the qualitative inputs, and debate may be necessary to come to consensus. Use the survey data as guidance in assigning final levels of expected proficiency to the X.X and X.X.X topics, but make choices that align with the context and local program goals. Be cautious about setting the goals at too high a level.

The final result of the survey and consensus process is an expected proficiency rating of each of the 67 attributes at the third level of the topical Syllabus found in Appendix A.

A clearer understanding of the process will be derived by examining the example shown below of customizing the topical Syllabus for the program in Aeronautics and Astronautics at MIT.

3.2 Example: Establishing the Desired Levels of Proficiency for Graduating MIT Engineers at the CDIO Syllabus Second Level

When developing a customized version of the CDIO Syllabus for the program in Aeronautics and Astronautics at MIT, three surveys were conducted. The first established the desired levels of *proficiency* at the second, or X.X, level, and the second established the same information at the X.X.X level. Note that two separate surveys were conducted, unlike the recommended procedure described above.

An additional survey was also conducted simultaneously with the first, which asked respondents to rank the relative *importance* of a second level (X.X) topic, as measured by the resources that should be dedicated to its teaching. These responses are presented and discussed in Appendix E. Note that, *a priori*, there is no reason to believe that respondents would answer similarly to the resource vs. proficiency questions. However it was found that both surveys contained essentially the same information, and therefore an independent question on importance is not warranted.

Following the procedure recommended above, the stakeholder groups were first chosen. These included faculty, industry leaders, and two alumni groups. In the surveys, the “faculty” are primarily the faculty of the Department of Aeronautics and Astronautics at MIT, with a few respondents from other engineering departments. The “industry” respondents are primarily mid- to upper-level leaders and managers in the aerospace industry. Many hold positions which put them in contact with universities, usually in an advisory, liaison, or review capacity. A few teach part time. The two alumni groups consist of the “older alumni” of the Department, who are 14, 15, and 16 years from graduation with a Bachelor’s Degree, and the “younger alumni”, who are 4, 5, 6, and 7 years from graduation. The groups were chosen to be about a decade apart to determine if there was any significant shift in opinions with increased professional experience.

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 the older alumni, these return rates are considered quite high.

The survey packet included a description of the CDIO Syllabus, the Syllabus itself, excerpts from the four primary comprehensive documents correlated with the Syllabus (Tables 2 to 5) and the survey forms. Respondents were asked to use the five-level scale to indicate the expected level of proficiency (Table 6). The specific question we asked of respondents was:

> *For each set of the attributes, please indicate which of the five levels of proficiency you desire in an engineering student graduating from MIT. Feel free to include a brief statement elaborating this level of proficiency.*

Figure 7 shows the results of the survey, with the four respondent groups indicated. The data is also summarized in Appendix F (Table F2). The asterisk in Figure 7 indicates statistically significant differences among the respondent groups within any topic. Note that of the 78 (13x6) possible pair-wise comparisons performed using Student’s t test, there were only two where a statistically significant difference (□<0.05) occurred, both in the same section. Industry respondents believe a graduating senior should be *less* proficient at the design process than the two alumni groups. This may be a result of the fact that 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.

The most significant result of this survey is the uncanny similarities in opinion among the groups. This degree of agreement was unexpected. It essentially settles all arguments about the desired level of proficiency we now expect in our graduating students.

Because the responses of the groups were so similar, the four data sets were combined and the average expectation in proficiency was determined. The

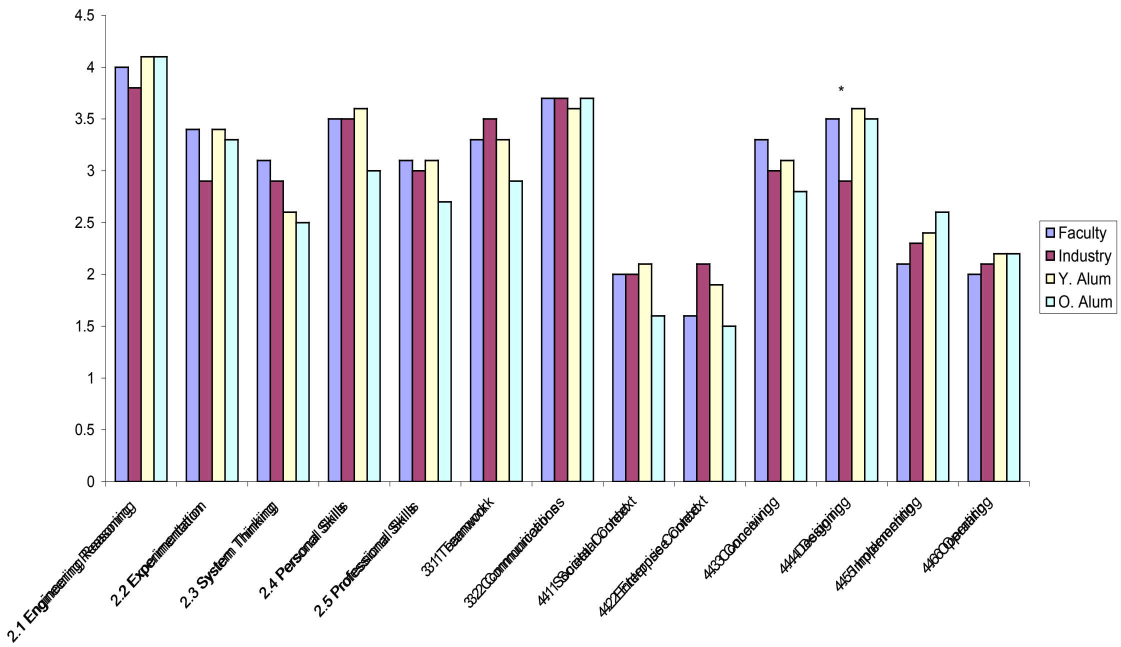

Figure 7: Proficiency expectation by survey group. Asterix designates statistical differences.

average proficiency is shown in Table 8, in Appendix F, and is indicated in parentheses in the customized form of the Syllabus, found in Appendix C. In order to determine the areas in which students are expected to have relatively higher, or lower, levels of proficiency, the mean for each attribute was compared with the mean for all responses, again using a Student's t test. Figure 8 displays the results, indicating those with statistically higher levels of expected proficiency with an "H" and lower levels with an "L."

In this comparison of expected proficiency, Engineering Reasoning and Problem Solving (2.1), Communication (3.2), Designing (4.4), and Personal Skills and Attitudes (2.4) fell in the "high" category, with proficiency levels between 3.4 and 4. These three topics appear consistently in various documents as among the most important skills of engineering, and their high ranking is not a surprise. These correspond to an ability "to be skilled in the practice" of these topics.

The Societal Context (4.1), the Enterprise and Business Context (4.2), Implementing (4.5) and Operating (4.6) are rated quite "low," with proficiency levels near 2 (corresponding to "an ability to contribute"). The low ranking on the Societal Context (4.1) and the Business Context (4.2) were not clarified by reading respondents comments. Comments by respondents did specifically indicate that the low rankings on Implementing (4.5) and Operating (4.6) are indicative of the fact that these topics may be better learned on the job, or may be too domain-specific to teach at a university.

Type of Topic	Activity Based Proficiency Level						
	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
Cognitive	a b c	Recall Recall Recall	Describe/define Describe/define List/recognize/ state	Discuss/explain Interpret/translate Locate & classify/ identify	S1 S2 S3 S4 S5 E1 E2 E3 E4	Apply Choose/select Demonstrate/execute/practice Employ/use/utilize Prepare/schedule Analyze/examine/appraise Compare/discriminate/reconcile Elicit/question Experiment/test	formulate/construct formulate/construct formulate/construct formulate/construct synthesize/plan/create evaluate evaluate estimate evaluate
Cognitive Process		Recall	Describe/define	Discuss/explain		demonstrate/execute/practice	evaluate
Affective		Has been exposed to the idea of (exposed to)	Accepts the need for (accepts)	Engages in discussions regarding (discusses)		Demonstrates belief in (demonstrates)	Resolves conflicting issues in (resolves)

Table 8: Bloom Verb Patterns used in the CDIO Syllabus

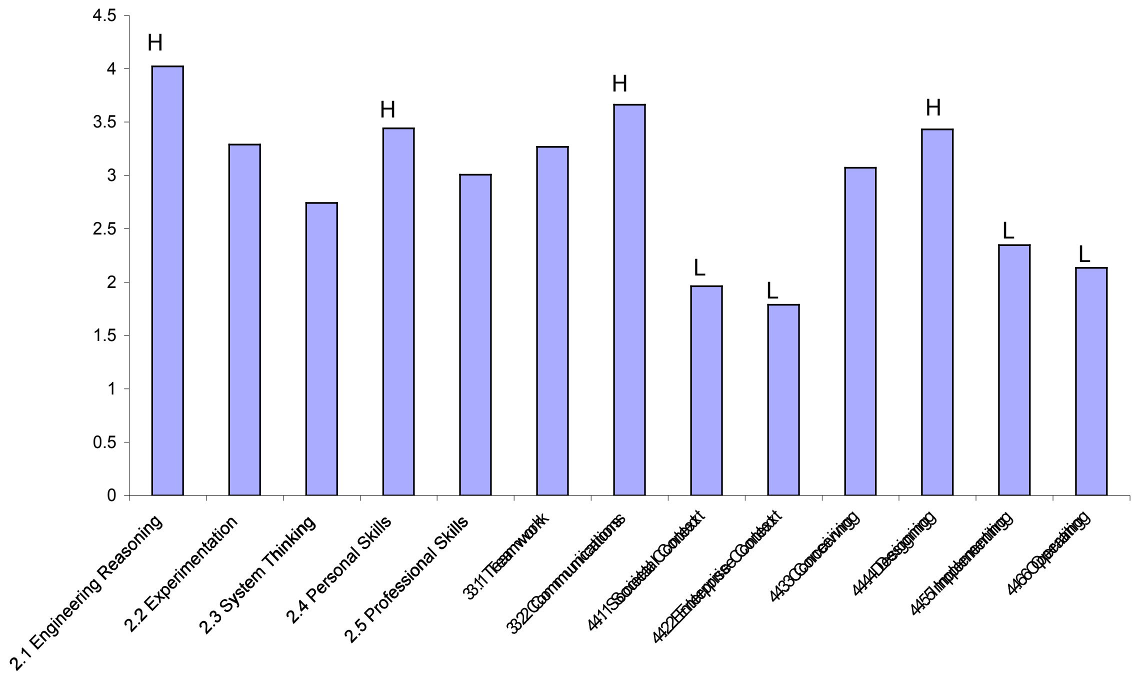

Figure 8: Mean proficiency levels for all groups combined. H and L indicate statistically high and low compared to the average proficiency.

3.3 Example: Establishing the Desired Level of Proficiency for Graduating MIT Engineers at the Syllabus Third Level

A second, separate survey was later conducted to gain more detailed insight into the proficiency expected in third-level (X.X.X) Syllabus attributes. Specifically, survey participants were asked to consider which third-level attributes required a higher (or lower) level of proficiency than its parent second level (X.X) topic. The task posed in this survey was:

> *For each X.X topic of sections 2 through 4 of the Syllabus, identify one (or two) of the X.X.X attributes for which you think that students should develop a relatively higher level of competence than the mean indicated for the corresponding X.X level topic. Likewise identify one (or two) attributes for which it is sufficient that students achieve a relatively lower level of competence.*

Survey participants were instructed to assign one plus (+) to indicate the one X.X.X attribute that they felt should be developed at one level higher in proficiency than the X.X section rating, using the activity-based scale (Table 6). Respondents were also instructed to assign one minus (-), indicating a skill to be developed at a relatively lower level of proficiency, in order to avoid changing the section's mean level of proficiency. In sections with five or more X.X.X attributes, respondents were allowed to assign a maximum of two pluses and two minuses. A refined version of the survey form, which combines the X.X and X.X.X surveys, is shown in Appendix H.

The 44 respondents were classified into two groups. The first group consisted of 26 MIT Department of Aeronautics and Astronautics faculty members, and the second consisted of 18 industry representatives. Of these industrial representatives, 11 were mid- to senior- career technical leaders of their enterprises. Seven additional respondents had significant life-long industry or government experience and, in addition, had some part-time or short-time affiliation with the MIT faculty. This latter group was asked to respond to the survey from the perspective of industry, and hence their responses were grouped with the industry representatives. (The survey responses were also analyzed with these seven respondents grouped with the faculty. No qualitative differences were found with the results reported below.)

Survey results were analyzed with two purposes in mind: 1) to identify those attributes for which there was significant disagreement in expected levels of proficiency between the two groups surveyed; and 2) to determine which third-level attributes survey participants felt required an increased or decreased level of proficiency relative to the level of proficiency assigned to the attribute's second level (X.X) topic.

In order to identify attributes for which there was disagreement between the MIT faculty and industry representatives, comparisons for significant differences were made. This was accomplished first by assigning a value of 1 to each plus response, and –1 to each minus response. A t-test was used to determine whether the difference of the means was significantly different than zero ($\alpha < 0.05$). A summary of all the data is given in Appendix F. The tests revealed that there was statistically significant disagreement for only 9 of the 67 third level attributes. Of those nine, shown in Figure 9, only four indicated what we

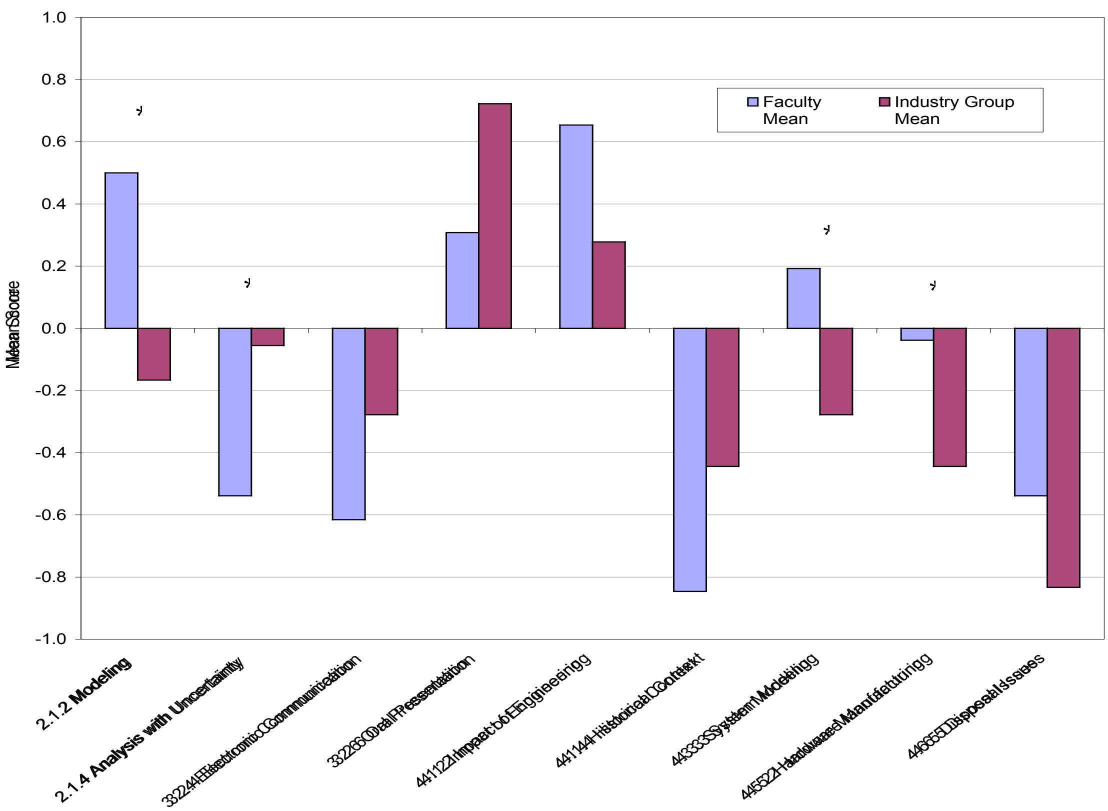

Figure 9: Third level syllabus attributes for which there was significant statistical disagreement between two survey groups. Asterisk signifies a qualitative disagreement.

consider real qualitative disagreements, and are marked with "RD". We judged that a real qualitative disagreement arose when one group thought the proficiency for an attribute should remain unchanged or decrease, while the other group thought it should increase (or vice versa). For the other five attributes for which there were statistically significant disagreements, the difference was only in the *amount* the proficiency should be increased (or decreased).

We believe these four items of qualitative disagreement do reveal some differences in values between the faculty and industry. For example, in section 2.1 Engineering Reasoning and Problem Solving, there were two disagreements. On attribute 2.1.2 Modeling, the faculty rated the desired proficiency as increased (relative to the mean for section 2.1), while the industry representatives rated it as unchanged. In contrast, in the same section, attribute 2.1.4 Analysis with Uncertainty, the faculty rated it as decreased, while industry rated it unchanged. This probably reflects a real difference in values: the faculty valuing modeling, while industry valuing the ability to deal with uncertainty. This difference over the value of modeling appeared again in section 4.3 Conceiving, where the faculty rated attribute 4.3.3, Modeling of System and Ensuring Goals can be Met, as unchanged, while industry rated it as decreased. The qualitative disagreement over attribute 4.5.2 Hardware Manufacturing is more difficult to understand, and is discussed below.

Opening up the interpretation of the data to allow for examination of trends, i.e. cases where $0.05 < \square < 0.15$, reveals some further interesting biases. Industry has relatively more interest: in Formulating Hypotheses (2.2.1), in contrast with faculty interest in Experimental Inquiry (2.2.3); in Leadership (3.1.4), in contrast with faculty interest in Team Operation (3.1.2); in Setting System Goals and Requirements (4.3.1) and Defining Function, Concepts and Architecture (4.3.2), in contrast with faculty interest in Modeling (4.3.3); and in Hardware/Software Integration 4.5.4, in contrast with faculty interest in Hardware Manufacturing (4.5.2). On the other hand, the faculty has relatively more interest in Critical Thinking (2.4.4), in contrast with industry interest in Perseverance Flexibility (2.4.2).

Overall an image emerges that the faculty are slightly more interested in detailed, deterministic, and analytic processes, while industry is slightly more interested in higher level, more conceptual processes in the face of uncertainty. Based on the differences in culture between industry and academia, these minor differences are understandable. However the main conclusion of the two surveys is that there is overwhelming agreement between faculty and industry on the expected levels of student proficiency, and relatively few statistically significant, qualitatively important differences in opinion. Having noted these, we feel confident in using the mean of the faculty plus industry sample as a basis for setting the expected levels of expected proficiency for our students in the 67 third level X.X.X attributes of the CDIO Syllabus.

The results of the means of the survey data suggest that some adjustments to the levels of proficiency are required for third-level attributes in order to determine the *absolute* levels of proficiency expected of each student for every X.X.X level attribute. This was achieved by a relatively simple algorithm. The mean change in level of competence for each X.X.X attribute (obtained from the later more detailed survey) was added to the desired level of competence for the X.X level topic (obtained from the earlier survey) to obtain an interim average target level of proficiency for the X.X.X attribute. This sum was then rounded to the nearest integer, to obtain the final level of competence for the X.X.X level attribute. These interim and final levels of proficiency are listed in Table F3, and are indicated on the customized Syllabus of Appendix C in parenthesis for each X.X.X item, in the format (interim level/final level).

The net result of this two phase survey process was an overwhelming agreement among the interested stakeholders (alumni, faculty, and industry) on the average levels of proficiency expected of graduating engineers in each of the 67 third level attributes. The few and minor qualitative differences of opinion are understandable, and can be considered when deriving detailed learning objectives. At this point we have arrived at the desired goal - a complete, concise and consistent set of attributes desirable in a graduating engineer, with a consensus on the expected level of proficiency for each.

4 Formulation of the Syllabus as Learning Objectives

Having determined the desired level of proficiency for each CDIO Syllabus topic at the second and third level, there still remains the task of formulating the related learning objectives. This formulation requires the following three steps:

1. Choosing a taxonomy for learning objectives
2. Developing a correspondence between the chosen taxonomy and the activity based proficiency scale
3. Writing learning objectives for each of the most detailed topics in the Syllabus, corresponding to the taxonomy and the appropriate proficiency rating.

Details on these process steps are given below. Following the discussion of the process, an example is given of developing a complete learning objective form of the CDIO Syllabus.

4.1 The Process for Formulating the Syllabus as Learning Objectives

The first step in formulating the Syllabus as learning objectives is to choose an appropriate taxonomy. From among the several possibilities, the one chosen is the one authored by Bloom and colleagues (Bloom 1956, Krathwohl, Bloom, Masia 1964). This taxonomy is in widespread use, and can be easily explained to engineering faculty as a formal specification language for learning objectives.

Bloom's taxonomy divides learning into three potentially overlapping domains. The cognitive domain covers knowledge and reasoning, while the affective domain treats values and attitudes, and the psychomotor domain describes skills with a motor component. For each domain there is a five or six step scale, which represents lower to higher levels of development. Associated with each scale are rubrics and verbs that are meant to connote a specific and measurable learning behavior. A short guide to Bloom's taxonomy is found in Appendix B.

In order to define specific learning objectives at a level commensurate with the proficiency rating, a correspondence must be developed between Bloom's taxonomy and the activity based proficiency scale. By considering the levels of cognitive, affective, and psychomotor skills that underlie a certain activity based proficiency, a correspondence can be drawn, as shown in Table 7. For example, there is no cognitive skill associated with the first proficiency level, "to have experienced or been exposed to." The second level, "participation," implies at least "knowledge," the first Bloom level in the cognitive domain. "Comprehension," as defined by Bloom, specifically includes "explaining." Likewise, "skill in the practice" arguably implies the ability to "apply knowledge" and "analyze." Finally, the ability to "lead and innovate" requires an ability to "synthesize and evaluate." Similar approximate correspondences can be drawn to the affective and psychomotor domains.

The final step in converting the topical CDIO Syllabus of Appendix A into specific learning objectives is to choose the correct Bloom verb for each detailed item of knowledge, skill or attitude. This requires three sequential choices: consider real qualitative disagreements, and are marked with "RD." We judged

MIT Proficiency Based Scale	Cognitive Domain	Affective Domain	Psychomotor Domain
1. To have experienced or been exposed to	--------	--------	Perception, Set
2. To be able to participate in and contribute to	Knowledge	Receiving	Guided Response
3. To be able to understand and explain	Comprehension	Responding	Mechanism
4. To be skilled in the practice or implementation of	Application, Analysis	Valuing	Complex Overt Response Adaptation
5. To be able to lead or innovate	Synthesis, Evaluation	Organization, Characterization by a Value	Origination

Figure 7: Correspondence of MIT activity based proficiency and Bloom" scales.

choice of domain; choice of object/process construction; and finally, choice of verb corresponding to the desired level of proficiency.

The domain choice implies that verb must make sense in the context of the topic, and be chosen from the appropriate taxonomy domain, i.e. cognitive, affective, or psychomotor. Examining the list of Syllabus topics, there are only a handful of lowest level skill items that are in the psychomotor domain, for example "sketching and drawing" in attribute 3.2.5 Graphical Communications. Since even these often have an important cognitive component, it was decided to not use the psychomotor domain verbs, but instead, for these skills, consistently use the cognitive verbs. On the other hand, there are a significant number of affective traits in the Syllabus, such as "one's ethical standards" in attribute 2.5.1 Professional Ethics, Integrity, Responsibility, and Accountability. Here it was found that the use of the affective domain verbs sometimes lent additional clarity to the learning objective. When an affective domain verb was used, the topic is marked with the symbol {A}, for affective, in Appendix C. It is interesting to note that some items have both a cognitive and affective character. For example "the goals and roles of the engineering profession" (in 4.1.1 Roles and Responsibility of Engineers) could be *analyzed* in the cognitive sense, without any belief in them whatsoever. Alternatively they could be *embraced* in the affective sense. In these cases, judgement was used in selecting the appropriate Bloom verb.

A second issue in assigning verbs is the semantic choice of an object or process construct for the learning objective. A topical item can often be considered a cognitive object, so that the learning objective is constructed as:

Bloom verb + cognitive object

Alternatively, the same item can often be worded as a process, so the learning objective is constructed as:

Bloom verb +cognitive process

For example, the first item of attribute 2.1.1 can be thought of as "data and symptoms" (a cognitive object), which gives

Evaluate + data and symptoms

Doing so places this item at the fifth level (be able to lead or innovate) on the activity based proficiency scale. Alternatively, the same item could be thought of as "data and symptom evaluation" (cognitive process), which gives

Execute + data and symptom evaluation

This formulation corresponds to at the fourth level (to be skilled in the practice or implementation of) on the activity based scale.

The latter formulation is felt to allow too much flexibility and ambiguity in choosing the relationship between the proficiency and the Bloom verb. In all cases where it did not distort the meaning of the item, the Bloom verb + cognitive object formulation was used. Only in a limited number of cases was the cognitive process formulation used. These are marked with the notation {CP}, for cognitive process, in Appendix C.

The third issue in choosing a verb is to correlate the learning objective with the appropriate proficiency rating for the third (X.X.X) level subsection. A great deal of judgement is necessarily applied at this stage. The activity rating to Bloom taxonomy correspondences (Table 7) are approximate. The ratings are therefore used as guidance, with some degree of flexibility necessary. On average, the level of proficiency of the items within a subsection should be matched to the subsection rating, but individual items may deviate upwards or downwards to make sense in context. In choosing the verbs in any X.X.X subsection, some attention was also paid to the interim, as well as final, proficiency target, to preserve some sense of where the proficiency had been rounded up or down.

When these decisions on how to write the learning objectives have been made, the entire Syllabus can be converted, in principle, into a *menu* of learning objectives. As an example, attribute 2.1.1, Problem Identification and Formulation (under section 2.1 Engineering Reasoning and Problem Solving), can be used to illustrate how specific learning objectives can be derived from the topical list. Consider the following options for the five Bloom verbs for each entry:

2.1.1 Problem Identification and Formulation
Recall/Recognize/Identify/Analyze/Evaluate data and symptoms
Recall/Describe/Explain/Analyze/Evaluate assumptions and sources of bias
Recall/Describe/Discuss/Demonstrate/Evaluate issue prioritization { CP}
Recall/Describe/Interpret/Choose/Formulate a plan of attack …

where the five verbs indicate, respectively, the first through fifth activity based proficiency level (Table 6). The verb "recall," among the weakest of the Bloom equivalent verbs for "knowledge," is used to connote the result of an exposure. "Recognize," "describe" and "define" are representative of "being able to participate," etc. up through the fifth level, where "evaluate" and "formulate" are verbs which connote the ability to "lead or innovate."

If this process were written out for all the low level entries, the net would be a complete "menu form" of the Syllabus. However in the interest of conciseness, this form is not shown in this printed report, but is only implied by the annotations in Appendix C. Each lowest level topic in the Appendix C form of the Syllabus has associated with it an annotation, marked in brackets. The annotation links the entry with a pattern of Bloom verbs, which are listed in Table 8. As discussed above, the annotation {A} implies affective domain, the annotation {CP} implies cognitive process. Each has associated with it one pattern of verbs. All affective entries can be linked to the pattern of Bloom verbs:

> *Has been exposed to/Accepts the need for/Engages in discussion of/Embraces/Resolves conflicting issues in*

where the entries map to activity based proficiency levels 1 through 5. Likewise all cognitive processes fit with:

> *Recall/Describe/Discuss/Demonstrate/Evaluate*

These two patterns are listed, along with some common synonyms, in Table 8.

The vast majority of the low level entries in the Syllabus are cognitive objects. These require a richer set of Bloom verb patterns. Through several iterations it was found that all entries fit with about 27 patterns, which are made up of three patterns for verbs in activity based proficiency levels 1 through 3, combined with nine options in levels 4 and 5. The three patterns for levels 1 through 3 are designated "a" through "c" in Table 8. The nine patterns for levels 4 and 5 are made up of five application/synthesis pairs (designated S1 through S5 in Table 8) and four analysis/evaluation pairs (designated as E1 to E4 in Table 8). Each low level topic in Appendix C has affixed a designator in brackets for its appropriate pattern, which is made up of the letter a to c, followed by S1 to S5 or E1 to E4.

The implied 27 patterns can be used as the basis for the process of setting the objectives for knowledge, skill, and attitude learning for any given degree program. Each engineering program will assign different levels of proficiency to each of the 67 attributes as fits their culture, professional focus, and degree of expectation for their graduates. The level of proficiency is then loosely correlated with the Bloom learning level (Table 7) and the appropriate verb pattern is noted from Appendix C, and appropriate verb selected from the designated pattern (Table 8).

4.2 Example: Formulating the MIT Aero/Astro Syllabus as Learning Objectives

As an example of this process, Appendix C contains the Syllabus customized to the MIT Department of Aeronautics and Astronautics. The level of proficiency, on the activity scale, is shown for each X.X.X subsection. One of the learning verbs, which corresponds approximately to this level of proficiency, is selected from the appropriate pattern, and entered together with the topical phrase of

Appendix A. To illustrate this process, consider the entries in subsection 2.1.1, with the topical form annotated by the verb pattern:

2.1.1 Problem Identification and Formulation (4.4/4)
Data and Symptoms {c-E1}
Assumptions and sources of bias {a-E1}
Issue prioritization {CP}
A plan of attack {b-S2}

This is in a section with an interim proficiency level of 4.4, and a final rating of 4. Therefore Bloom verbs should be drawn from level 4, but if appropriate one or two might be drawn from level 5. After some discussion, it was felt that handling data and symptoms and plans of attack were relatively more important than the other two entries, so these were set at proficiency level 5. The final result, as it appears in Appendix C, is:

2.1.1 Problem Identification and Formulation (4.4/4)
Evaluate data and symptoms {level 5 of c-E1}
Analyze assumptions and sources of bias {level 4 of a-E1}
Demonstrate issue prioritization… {level 4 of CP}
Formulate a plan of attack … {level 5 of b-S2}

Note that here and in Appendix C, the verbs have been shaded in those topics for which the verb chosen does not exactly coincide with the final desired proficiency level.

By carefully reviewing and discussing the topics and their associated proficiency rating, Bloom verbs were chosen for all the low level topics of the Syllabus in a similar manner. The result is a comprehensive set of learning objectives, consistent with the expectations for proficiency.

We observed that the rigorous process of assigning Bloom verbs in this way tended to set lower expectations on student proficiency than would have resulted from a less well structured process. The tendency discovered in this work was that the formulation chosen by most respondents identified a topical skill level associated with that of a *highly* experienced engineer. For example, if not somehow constrained and guided, a typical alumnus, faculty member, or leader of industry might have expressed the expected proficiency in subsection 2.2.1 as:

2.1.1 Problem Identification and Framing
Evaluate data and symptoms (proficiency level 5)
Evaluate assumptions and sources of bias (proficiency level 5)
Prioritize issues… (CP) (proficiency level 5)
Formulate a plan of attack …(proficiency level 5)

Since the expected proficiency level of this section is 4.4/4, such an unconstrained statement is not far from the actual expectation. However, in attributes with lower expected proficiency ratings, the difference can be significant. If such high expectations were set consistently over the broad range of 67 attributes present in the CDIO Syllabus, this would produce a set of expectations that no single professional engineer, no matter how experienced, could possibly meet. To expect this level of proficiency from a graduating engineer is completely unrealistic.

5 Conclusions and Recommendations

The conclusions and recommendations fall into three categories, those associated with: the CDIO Syllabus as a generalized statement of goals; the process used in deriving specific versions for local program needs; and the insights gained in deriving the local version for the MIT Department of Aeronautics and Astronautics.

5.1 The CDIO Syllabus as a Generalized Statement of Goals for Undergraduate Engineering Education.

We have attempted to derive a statement of goals for undergraduate engineering that has the following properties:

- It is rationalized against the modern practice of engineering, so the intent of the goals flows naturally from the actual roles of engineers.
- It is comprehensive of all other high level documents which attempt to outline the goals of engineering education.
- It is complete and consistent, in that all of the knowledge, skills, and attitudes that could be rationally expected to be possessed by a graduating engineer are included.
- It is 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.
- It is linked to a survey process that will set broadly agreed upon levels of proficiency that would be expected of a graduating engineer.
- It is expressed in terms of a formal specification language for learning objectives, which should lead to consistent and assessable interpretation of the desired level of proficiency.

The Syllabus is presented in two forms, one in which the items are listed topically (Appendix A), and a second in which a set of Bloom verb options are implicitly presented for each topic (Appendix C).

5.2 The Process for Deriving Specific Versions of the Syllabus for Local Program Needs

Any educational program that seeks to use the Syllabus will have to adapt it to the needs and objectives of the specific local program and disciplinary field. A suggested process of accomplishing this is as follows:

- Review the content of the topical Syllabus (Appendix A) and add or delete topics based on the perceived needs of the particular program. Changes in terminology might be needed in order to match the vernacular of the profession, and some changes in organization at the third (X.X.X) level, or at the lowest level may be necessary as well. We feel that the first and second levels are more universal, and their close mapping to ABET EC 2000 suggest this is true.
- Identify the stakeholder communities, and conduct the surveys on expected proficiency at the second, or X.X, level, and at the third, or X.X.X, level, using the five-point proficiency scale discussed above. Sample survey forms tailored for this purpose are found in Appendix H.
- Compile the data from the two surveys, and examine it for agreement and statistically significant disagreement among the stakeholders. Where there is

disagreement, resolve it in an appropriate manner. Assign to each X.X.X level attribute a rating on the five point proficiency scale. Be cautious about setting the goals at too high of a level.

- Assign a level of proficiency for each low level topic in the form of the Syllabus in Appendix A. Use the survey data as guidance, but make choices that align with the context and local program goals. Based on the level of proficiency set, and the Bloom verb pattern suggested by the annotation in Appendix C, choose an appropriate Bloom verb from Table 8. Combining the Bloom verb with the topic will give a statement of the learning objective consistent with the expected level of proficiency.

5.3 The Insights Gained in Deriving the Customized Syllabus for the MIT Department of Aeronautics and Astronautics

In preparing the CDIO Syllabus and conducting the surveys that led to the version customized for the Department of Aeronautics and Astronautics at MIT, we developed several important insights:

- The various high level statements of goals of engineering education, written over the last 55 years, are remarkably consistent. The barriers to the implementation of programs which would more fully meet these goals are therefore probably some combination of: a lack of understanding, context, or intent of the goals; a lack of specificity of the goals; or a lack of an educational concept which would allow meeting these goals without "sacrificing" the fundamentals. We feel that the CDIO Syllabus makes a step toward resolving the first two of these barriers.
- The agreement among the faculty, leaders of industry, young and mid-career alumni on the expected levels of proficiency of graduating engineers was overwhelming and unexpected. In only a handful of cases were the differences statistically significant and qualitative. Even in these cases, the differences were modest and easily rationalized.
- The minor differences in expectations indicate that the faculty are slightly more interested in detailed, deterministic, and analytic processes, while industry is slightly more interested in higher level, more conceptual processes in the face of uncertainty. This is understandable in view of the cultures and context in which these two groups operate.
- The survey indicates that the skills for which the proficiency expectations are the highest include engineering reasoning, personal attributes, communications, and design. These four skills are consistently among those cited as most important in a young engineer. On the other hand, the survey identified the social and enterprise context, implementing, and operating as requiring lower proficiency. This is likely due to the fact that these are more domain specific, and/or more appropriately acquired after graduation in a professional context.
- The rigorous survey process led to setting levels of learning objectives that were significantly lower than would probably have been selected by either the faculty or leaders of industry in a more informal process. However, in aggregate, even the levels of expected proficiency established in the CDIO Syllabus set a high standard for engineering graduates and pose an enormous challenge to educational design.

5.4 Summary and Benefits

A reasonable attempt at a rational, comprehensive, complete, and consistent set of goals for modern undergraduate engineering education has been developed, along with a process to customize the goals to any particular university program. The benefits of the Syllabus accrue to individual faculty, students, and the larger academic community:

- The detail in the Syllabus allows individual faculty to gain detailed insight into its content and objectives, contemplate the deployment of these skills into a curriculum, and prepare lesson and assessment plans.
- Adopting the CDIO Syllabus will faciltiate more comprehensive and rigorous education in its topics, to the benefit of students who will enter the practice of engineering, and also to the benefit of those who will go on to be researchers.
- Widespread adoption of the Syllabus will also facilitate the sharing of best curricular and pedagogic approaches and it will promote the development of standardized assessment tools, which will allow easier and better outcome based assessment.

We recognize that the Syllabus is only a draft. We invite comments and feedback from those who study and apply it. Working together, the Syllabus will evolve into a more universal document, and shape the future of engineering education.

Appendix A. The CDIO Syllabus in Topical Form (v 4.2.3)

1 TECHNICAL KNOWLEDGE AND REASONING

1.1 KNOWLEDGE OF UNDERLYING SCIENCES [a]

1.1.1 Mathematics (including statistics)
1.1.2 Physics
1.1.3 Chemistry
1.1.4 Biology

1.2 CORE ENGINEERING FUNDAMENTAL KNOWLEDGE [a]

1.3 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE [k]

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES

2.1 ENGINEERING REASONING AND PROBLEM SOLVING [e]

2.1.1 Problem Identification and Formulation
- Data and symptoms
- Assumptions and sources of bias
- Issue prioritization in context of overall goals
- A plan of attack (incorporating model, analytical and numerical solutions, qualitative analysis, experimentation and consideration of uncertainty)

2.1.2 Modeling
- Assumptions to simplify complex systems and environment
- Conceptual and qualitative models
- Quantitative models and simulations

2.1.3 Estimation and Qualitative Analysis
- Orders of magnitude, bounds and trends
- Tests for consistency and errors (limits, units, etc.)
- The generalization of analytical solutions

2.1.4 Analysis With Uncertainty
- Incomplete and ambiguous information
- Probabilistic and statistical models of events and sequences
- Engineering cost-benefit and risk analysis
- Decision analysis
- Margins and reserves

2.1.5 Solution and Recommendation
- Problem solutions
- Essential results of solutions and test data
- Discrepancies in results
- Summary recommendations
- Possible improvements in the problem solving process

2.2 EXPERIMENTATION AND KNOWLEDGE DISCOVERY [b]

2.2.1 Hypothesis Formulation
- Critical questions to be examined
- Hypotheses to be tested
- Controls and control groups

2.2.2 Survey of Print and Electronic Literature
- The literature research strategy
- Information search and identification using library tools (on-line catalogs, databases, search engines)
- Sorting and classifying the primary information
- The quality and reliability of information
- The essentials and innovations contained in the information
- Research questions that are unanswered
- Citations to references

2.2.3 *Experimental Inquiry*

The experimental concept and strategy
The precautions when humans are used in experiments
Experiment construction
Test protocols and experimental procedures
Experimental measurements
Experimental data
Experimental data vs. available models

2.2.4 *Hypothesis Test, and Defense*

The statistical validity of data
The limitations of data employed
Conclusions, supported by data, needs and values
Possible improvements in knowledge discovery process

2.3 SYSTEM THINKING

2.3.1 *Thinking Holistically*

A system, its behavior, and its elements
Trans-disciplinary approaches that ensure the system is understood from all relevant perspectives
The societal, enterprise and technical context of the system
The interactions external to the system, and the behavioral impact of the system

2.3.2 *Emergence and Interactions in Systems*

The abstractions necessary to define and model system
The behavioral and functional properties (intended and unintended) which emerge from the system
The important interfaces among elements
Evolutionary adaptation over time

2.3.3 *Prioritization and Focus*

All factors relevant to the system in the whole
The driving factors from among the whole
Energy and resource allocations to resolve the driving issues

2.3.4 *Trade-offs, Judgement and Balance in Resolution*

Tensions and factors to resolve through trade-offs
Solutions that balance various factors, resolve tensions and optimize the system as a whole
Flexible vs. optimal solutions over the system lifetime
Possible improvements in the system thinking used

***2.4* PERSONAL SKILLS AND ATTITUDES**

2.4.1 *Initiative and Willingness to Take Risks*

The needs and opportunities for initiative
The potential benefits and risks of an action
The methods and timing of project initiation
Leadership in new endeavors, with a bias for appropriate action
Definitive action, delivery of results and reporting on actions

2.4.2 *Perseverance and Flexibility*

Self-confidence, enthusiasm, and passion
The importance of hard work, intensity and attention to detail
Adaptation to change
A willingness and ability to work independently
A willingness to work with others, and to consider and embrace various viewpoints
An acceptance of criticism and positive response
The balance between personal and professional life

2.4.3 *Creative Thinking*

Conceptualization and abstraction
Synthesis and generalization
The process of invention
The role of creativity in art, science, the humanities and technology

2.4.4 *Critical Thinking*

The statement of the problem
Logical arguments and solutions
Supporting evidence
Contradictory perspectives, theories and facts
Logical fallacies
Hypotheses and conclusions

2.4.5 *Awareness of One's Personal Knowledge, Skills and Attitudes*

One's skills, interests, strengths, weaknesses
The extent of one's abilities, and one's responsibility for self-improvement to overcome important weaknesses
The importance of both depth and breadth of knowledge

2.4.6 *Curiosity and Lifelong Learning* **[i]**

The motivation for continued self-education
The skills of self-education
One's own learning style
Developing relationships with mentors

2.4.7 *Time and Resource Management*

Task prioritization
The importance and/or urgency of tasks
Efficient execution of tasks

2.5 PROFESSIONAL SKILLS AND ATTITUDES

2.5.1 *Professional Ethics, Integrity, Responsibility and Accountability* **[f]**

One's ethical standards and principles
The courage to act on principle despite adversity
The possibility of conflict between professionally ethical imperatives
An understanding that it is acceptable to make mistakes, but that one must be accountable for them
Proper allocation of credit to collaborators
A commitment to service

2.5.2 *Professional Behavior*

A professional bearing
Professional courtesy
International customs and norms of interpersonal contact

2.5.3 *Proactively Planning for One's Career*

A personal vision for one's future
Networks with professionals
One's portfolio of professional skills

2.5.4 *Staying Current on World of Engineer*

The potential impact of new scientific discoveries
The social and technical impact of new technologies and innovations
A familiarity with current practices/technology in engineering
The links between engineering theory and practice

3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION

3.1 TEAMWORK [d]

3.1.1 *Forming Effective Teams*

The stages of team formation and life cycle
Task and team processes
Team roles and responsibilities
The goals, needs and characteristics (works styles, cultural differences) of individual team members
The strengths and weakness of the team
Ground rules on norms of team confidentiality, accountability and initiative

3.1.2 *Team Operation*

- Goals and agenda
- The planning and facilitation of effective meetings
- Team ground rules
- Effective communication (active listening, collaboration, providing and obtaining information)
- Positive and effective feedback
- The planning, scheduling and execution of a project
- Solutions to problems (team creativity and decision making)
- Conflict negotiation and resolution

3.1.3 *Team Growth and Evolution*

- Strategies for reflection, assessment, and self-assessment
- Skills for team maintenance and growth
- Skills for individual growth within the team
- Strategies for team communication and writing

3.1.4 *Leadership*

- Team goals and objectives
- Team process management
- Leadership and facilitation styles (directing, coaching, supporting, delegating)
- Approaches to motivation (incentives, example, recognition, etc)
- Representing the team to others
- Mentoring and counseling

3.1.5 *Technical Teaming*

- Working in different types of teams :
  - Cross-disciplinary teams (including non-engineer)
  - Small team vs. large team
  - Distance, distributed and electronic environments
- Technical collaboration with team members

3.2 COMMUNICATIONS [g]

3.2.1 *Communications Strategy*

- The communication situation
  - Communications objectives
  - The needs and character of the audience
  - The communication context
- A communications strategy
  - The appropriate combination of media
  - A communication style (proposing, reviewing, collaborating, documenting, teaching)
  - The content and organization

3.2.2 *Communications Structure*

- Logical, persuasive arguments
  - The appropriate structure and relationship amongst ideas
  - Relevant, credible, accurate supporting evidence
  - Conciseness, crispness, precision and clarity of language
  - Rhetorical factors (e.g. audience bias)
- Cross-disciplinary cross-cultural communications

3.2.3 *Written Communication*

- Writing with coherence and flow
- Writing with correct spelling, punctuation and grammar
- Formatting the document
- Technical writing
- Various written styles (informal, formal memos, reports, etc)

3.2.4 *Electronic/Multimedia Communication*

- Preparing electronic presentations
- The norms associated with the use of e-mail, voice mail, and videoconferencing
- Various electronic styles (charts, web, etc)

3.2.5 Graphical Communication

Sketching and drawing
Construction of tables, graphs and charts
Formal technical drawings and renderings

3.2.6 Oral Presentation and Inter-Personal Communications

Preparing presentations and supporting media with appropriate language, style, timing and flow
Appropriate nonverbal communications (gestures, eye contact, poise)
Answering questions effectively

3.3 COMMUNICATIONS IN FOREIGN LANGUAGES

3.3.1 English
3.3.2 Languages of Regional Industrialized 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 [h]

4.1.1 Roles and Responsibility of Engineers

The goals and roles of the engineering profession
The responsibilities of engineers to society

4.1.2 The Impact of Engineering on Society

The impact of engineering on the environment, social, knowledge and economic systems in modern culture

4.1.3 Society's Regulation of Engineering

The role of society and its agents to regulate engineering
The way in which legal and political systems regulate and influence engineering
How professional societies license and set standards
How intellectual property is created, utilized and defended

4.1.4 The Historical and Cultural Context

The diverse nature and history of human societies as well as their literary, philosophical, and artistic traditions
The discourse and analysis appropriate to the discussion of language, thought and values

4.1.5 Contemporary Issues and Values **[j]**

The important contemporary political, social, legal and environmental issues and values
The process by which contemporary values are set, and one's role in these processes
The mechanisms for expansion and diffusion of knowledge

4.1.6 Developing a Global Perspective

The internationalization of human activity
The similarities and differences in the political, social, economic, business and technical norms of various cultures
International inter-enterprise and inter-governmental agreements and alliances

4.2 ENTERPRISE AND BUSINESS CONTEXT

4.2.1 Appreciating Different Enterprise Cultures

The differences in process, culture, and metrics of success in various enterprise cultures:
- Corporate vs. academic vs. governmental vs. non-profit/NGO
- Market vs. policy driven
- Large vs. small
- Centralized vs. distributed
- Research and development vs. operations
- Mature vs. growth phase vs. entrepreneurial
- Longer vs. faster development cycles
- With vs. without the participation of organized labor

4.2.2 *Enterprise Strategy, Goals, and Planning*
- The mission and scope of the enterprise
- An enterprise's core competence and markets
- The research and technology process
- Key alliances and supplier relations
- Financial and managerial goals and metrics
- Financial planning and control
- The stake-holders (owners, employees, customers, etc.)

4.2.3 *Technical Entrepreneurship*
- Entrepreneurial opportunities that can be addressed by technology
- Technologies that can create new products and systems
- Entrepreneurial finance and organization

4.2.4 *Working Successfully in Organizations*
- The function of management
- Various roles and responsibilities in an organization
- The roles of functional and program organizations
- Working effectively within hierarchy and organizations
- Change, dynamics and evolution in organizations

4.3 CONCEIVING AND ENGINEERING SYSTEMS [c]

4.3.1 *Setting System Goals and Requirements*
- Market needs and opportunities
  - Customer needs
  - Opportunities which derive from new technology or latent needs
- Factors that set the context of the requirements
  - Enterprise goals, strategies, capabilities and alliances
  - Competitors and benchmarking information
  - Ethical, social, environmental, legal and regulatory influences
  - The probability of change in the factors that influence the system, its goals and resources available
- System goals and requirements
  - The language/format of goals and requirements
  - Initial target goals (based on needs, opportunities and other influences)
  - System performance metrics
  - Requirement completeness and consistency

4.3.2 *Defining Function, Concept and Architecture*
- Necessary system functions (and behavioral specifications)
- System concepts
- The appropriate level of technology
- Trade-offs among and recombination of concepts
- High level architectural form and structure
- The decomposition of form into elements, assignment of function to elements, and definition of interfaces

4.3.3 *Modeling of System and Ensuring Goals Can Be Met*
- Appropriate models of technical performance
- The concept of implementation and operations
- Life cycle value and costs (design, implementation, operations, opportunity, etc.)
- Trade-offs among various goals, function, concept and structure and iteration until convergence

4.3.4 *Development Project Management*
- Project control for cost, performance, and schedule
  - Appropriate transition points and reviews
  - Configuration management and documentation
  - Performance compared to baseline
- Earned value recognition
- The estimation and allocation of resources
- Risks and alternatives
- Possible development process improvements

4.4 DESIGNING [c]

4.4.1 The Design Process

Requirements for each element or component derived from system level goals and requirements
Alternatives in design
The initial design
Experiment prototypes and test articles in design development
Appropriate optimization in the presence of constraints
Iteration until convergence
The final design
Accommodation of changing requirements

4.4.2 The Design Process Phasing and Approaches

The activities in the phases of system design (e.g. conceptual, preliminary, and detailed design)
Process models appropriate for particular development projects (waterfall, spiral, concurrent, etc.)
The process for single, platform and derivative products

4.4.3 Utilization of Knowledge in Design

Technical and scientific knowledge
Creative and critical thinking, and problem solving
Prior work in the field, standardization and reuse of designs (including reverse engineer and redesign)
Design knowledge capture

4.4.4 Disciplinary Design

Appropriate techniques, tools, and processes
Design tool calibration and validation
Quantitative analysis of alternatives
Modeling, simulation and test
Analytical refinement of the design

4.4.5 Multidisciplinary Design

Interactions between disciplines
Dissimilar conventions and assumptions
Differences in the maturity of disciplinary models
Multidisciplinary design environments
Multidisciplinary design

4.4.6 Multi-Objective Design (DFX)

Design for:
- Performance, life cycle cost and value
- Aesthetics and human factors
- Implementation, verification, test and environmental sustainability
- Operations
- Maintainability, reliability, and safety
- Robustness, evolution, product improvement and retirement

4.5 IMPLEMENTING [c]

4.5.1 Designing the Implementation Process

The goals and metrics for implementation performance, cost and quality
The implementation system design:
- Task allocation and cell/unit layout
- Work flow
- Considerations for human user/operators

4.5.2 Hardware Manufacturing Process

The manufacturing of parts
The assembly of parts into larger constructs
*T*olerances, variability, key characteristics and statistical process control

4.5.3 *Software Implementing Process*
- The break down of high level components into module designs (including algorithms and data structures)
- Algorithms (data structures, control flow, data flow)
- The programming language
- The low-level design (coding)
- The system build

4.5.4 *Hardware Software Integration*
- The integration of software in electronic hardware (size of processor, communications, etc)
- The integration of software with sensor, actuators and mechanical hardware
- Hardware/software function and safety

4.5.5 *Test, Verification, Validation, and Certification*
- Test and analysis procedures (hardware vs. software, acceptance vs. qualification)
- The verification of performance to system requirements
- The validation of performance to customer needs
- The certification to standards

4.5.6 *Implementation Management*
- The organization and structure for implementation
- Sourcing, partnering, and supply chains
- Control of implementation cost, performance and schedule
- Quality and safety assurance
- Possible implementation process improvements

4.6 OPERATING [c]

4.6.1 *Designing and Optimizing Operations*
- The goals and metrics for operational performance, cost, and value
- Operations process architecture and development
- Operations (and mission) analysis and modeling

4.6.2 *Training and Operations*
- Training for professional operations:
  - Simulation
  - Instruction and programs
  - Procedures
- Education for consumer operation
- Operations processes
- Operations process interactions

4.6.3 *Supporting the System Lifecycle*
- Maintenance and logistics
- Lifecycle performance and reliability
- Lifecycle value and costs
- Feedback to facilitate system improvement

4.6.4 *System Improvement and Evolution*
- Pre-planned product improvement
- Improvements based on needs observed in operation
- Evolutionary system upgrades
- Contingency improvements/solutions resulting from operational necessity

4.6.5 *Disposal and Life-End Issues*
- The end of useful life
- Disposal options
- Residual value at life-end
- Environmental considerations for disposal

4.6.6 *Operations Management*
- The organization and structure for operations
- Partnerships and alliances
- Control of operations cost, performance and scheduling
- Quality and safety assurance
- Possible operations process improvements
- Life cycle management

Appendix B: Bloom's Taxonomy of Educational Objectives

In 1956, educational psychologist Benjamin Bloom chaired a committee of College and University Examiners who were charged with the development of a classification system that would capture the intellectual behavior important in learning. This classification system was to delineate the "intended behavior" of students - the ways in which individuals are to act, think or feel as a result of participating in a unit of instruction expressed in measurable observable formats (learning objectives). This became known as Bloom's Taxonomy. The committee identified three overlapping domains: the cognitive, affective, and psychomotor.

In the discussion below, these three domains will be discussed, and the levels of learning in each enumerated. Verbs that are typically used to describe learning objective in these domains will be presented, along with examples from the Syllabus. Unlike a generic discussion of Bloom's Taxonomy, this one has been specialized and expanded to include the kinds of verbs used to describe learning objectives typically encountered in an engineering education. These verbs are listed in Table B1.

In the process of converting the topical Syllabus of Appendix A to a set of learning objectives, it is convenient to identify patterns of Bloom verbs that naturally accompany technical topics. Table 7 shows such patterns of verbs that correspond to the five levels in the MIT activity based proficiency scale (Table 6).

B.1 The Cognitive Domain

The cognitive domain encompasses a complex, hierarchical series of intellectual skills involving the acquisition and use of knowledge that ranges from simple recall to the ability to judge and evaluate learned material. Bloom (1956) identified six levels within the cognitive domain.

1. ***Knowledge*** refers to those behaviors and situations that emphasize remembering, either by recognition or recall, of specifics and ideas, of terms and materials, and of abstraction and phenomena. Students have the ability to store in their mind certain information and later to remember and recall it, often with slight alteration.

Verb examples that represent intellectual activity on this level include: *describe, list, match, and recognize.*

Examples from the Syllabus:
- *Describe* data and symptoms
- *List* assumptions and sources of bias
- *Recognize* conceptual and qualitative models

2. ***Comprehension*** refers to those objectives, behaviors, or responses that represent an understanding of the literal message contained in a communication, without necessarily relating it to other material. In coming to this understanding, the student may change the communication in his / her mind, or in overt responses, to reflect a parallel form more meaningful to him / her.

Verb examples that represent intellectual activity on this level include: *classify, explain, extrapolate, interpolate, locate, translate.*

Examples from the Syllabus:
- *Locate and classify* essential results of solutions and test data
- *Interpret* bounds and trends
- *Explain* discrepancies in results

Table B1: Bloom Cognitive Verbs Appropriate for Technical Topics

Level	Group	Verbs	**Verbs not used**
Knowledge			
	Recognize	*label, name, **recognize**, **recall**, underline*	*outline*
	List	***list,** record, repeat, reproduce, **state***	*knows, recite*
	Describe	***define, describe***	*identify, select*
	Match	*arrange, match, order, relate*	
Comprehension			
	Locate and classify	*arrange, **classify, identify**, indicate, **locate**, sort*	*predict, describe*
	Explain	***discuss, explain**, express, give examples, report, summarize*	*defend*
	Translate	*convert, **interpret**, paraphrase, restate, **translate***	*distinguish, rewrite*
	Interpolate	*interpolate, infer*	*comprehend, estimate*
	Extrapolate	*extend, extrapolate, generalize*	
Application			
	Prepare	***choose, prepare, schedule, select,** sketch*	*produce, relate*
	Use	***apply,** change,* **employ**, *manipulate, modify, operate, **use**,* **utilize**	*discover*
	Practice	***demonstrate,*** **execute,** *illustrate, **practice,** show*	*predict*
	Resolve	*compute, measure, solve*	*construct*
Analysis			
	Analyze and test	***analyze, appraise**, calculate,* **elicit,** ***examine, experiment, question, test***	*identify, point out*
	Categorize	*breakdown, categorize, diagram, inventory, outline, separate, subdivide*	*infer, relate, select*
	Discriminate	***compare**, differentiate, distinguish, **discriminate**,* **reconcile**	*illustrate, deconstruct*
Synthesis			
	Plan	*collect, **plan**, propose*	*categorize, prepare*
	Create	*compose, **create,** design, devise,* **formulate**, *generate, set up, tell, write*	*explain, conduct*
	Construct	*arrange, assemble, **construct,** combines, compiles, manage, organize, **synthesize**, set up*	*relate*
	Rearrange	*modify, rearrange, reconstruct, reorganize, revise, rewrite*	*summarize*
Evaluation			
	Assess	*assess, conclude, **estimate**, predict, rate, score*	*appraise, explain, summarize*
	Evaluate	*attack, criticize, critique, **evaluate**, value*	*compare, interpret, appraise*
	Defend	*argue, defend, justify, support*	*contrast, relates, select describe, discriminate*

3. ***Application*** is the ability to use previously learned material in situations which are either new, or contain new elements, as compared to the situation in which the abstraction was learned. This means that the problem should be drawn from material the student is not likely to have yet had contact with, or be a problem known to the student, but having a different slant that he/she is unlikely to have thought of.

Verb examples that represent intellectual activity on this level include: *practice, prepare, resolve, use*.

Examples from the Syllabus:
Prepare margins and reserves
Practice engineering cost-benefit and risk analysis
Use assumptions to simplify complex systems and environments

4. *Analysis* is the breakdown of material into its constituent parts and detection of the relationship of the parts and of the way they are organized. While clear lines can be drawn between analysis and comprehension or analysis and evaluation, it is useful to think of it as an aid to more complete comprehension and as a prelude to evaluation.

Verb examples that represent intellectual activity on this level include: *analyze, categorize, discriminate, test*.

Examples from the Syllabus:
Analyze possible improvements in the problem solving process
Discriminate hypotheses to be tested
Test hypotheses and conclusions

5. *Synthesis* is defined as the putting together of elements and parts so as to form a whole. This is the category in the cognitive domain that Bloom tells us most clearly provides for creative behavior on the part of the learner, but within the limits set by the framework.

Verb examples that represent intellectual activity on this level include: *construct, create, plan, rearrange*.

Examples from the Syllabus:
Plan evolutionary adaptation over time
Create one's professional portfolio
Construct the abstractions necessary to model the system

6. *Evaluation* is the making of judgments about the value, for some purpose, of ideas, works, solutions, methods, material, etc. It involves the use of criteria and standards for appraising the extent to which particulars are accurate, effective, or satisfying. It may be quantitative or qualitative.

Verb examples that represent intellectual activity on this level include: *assess, defend, evaluate*.

Examples from the Syllabus:
Assess one's skills, interests, strengths and weaknesses
Evaluate supporting evidence

A way in which to view the structure of the Bloom verbs is shown in Table B1, which gives the six levels, and identifies three to five key verbs within each level. Some common synonyms for those key verbs are also listed. Verbs in Italics of Table B1 are commonly used Bloom verbs, and those in regular font were added to better fit with technically oriented topics of the Syllabus. The verbs in the column to the far right of Table B1 are commonly used Bloom verbs that we recommend *not* be used with the Syllabus. This is because the verbs either appear at two levels, and therefore are ambiguous, or because they have a technical connotation apart from their common meaning, which causes them to be misplaced in terms of level. Entries in bold will be used in the Bloom verb patterns discussed below.

B.2 The Affective Domain

The affective domain relates to the emotional component of learning. It emphasizes a feeling, tone, an emotion, or a degree of acceptance or rejection. Affect encompasses a range from simple attention to organization and characterization of complex, but internally consistent, qualities of character and conscience. Krathwohl, Bloom and Masia (1964) developed five levels in the affective domain.

1. ***Receiving*** *(attending)*: Receiving speaks to an awareness that a learner is conscious of something, that he / she take into account a situation, phenomenon or state of affairs. It also addresses the learner's willingness to receive information. In other words the climate must be set so that students attention is grabbed and directed in a particular manner.

Verb examples which represent intellectual activity on this level include: *ask*, *accept*, *hold*.

Examples from the Syllabus:
Accepts the need for a commitment to service
Accepts the goals and roles of the engineering profession

2. ***Responding:*** At the responding level, students are sufficiently motivated that they are not just willing to attend, but are actively attending. It involves a continuum from acquiescence in responding, to willingness to respond, to satisfaction in response. In other words, it is active participation by the students in their own learning.

Verb examples that represent intellectual activity on this level include: *answer, assist, discuss.*

Examples from the Syllabus:
Discuss the motivation for continued self-education
Discuss the importance of both a depth and breadth of knowledge

3. ***Valuing:*** Simply put, something has value or worth. At this level, behavior is sufficiently consistent and stable as to be characterized as a belief or attitude. The student is perceived as holding a value. This level ranges from acceptance of a value, to preference, to commitment to a value.

Verb examples that represent intellectual activity on this level include: *demonstrate a belief in, embrace, follow, join, share, value.*

Examples from the Syllabus:
Embrace one's responsibility for self improvement
Value a willingness to work independently

4. ***Organization*** refers to the process learners go through after they internalize values and are faced with situations for which more than one value is relevant. This necessitates the organization of values into a system, determining the relationship among them, and establishing dominant and pervasive values. The emphasis is on comparing, relating, and synthesizing values.

Verb examples that represent intellectual activity on this level include: *alter, combine, complete, integrate, order, organize, relate, synthesize .*

Example from the Syllabus:
Integrate the potential benefits and risks of an action

5. ***Characterization by a value or value complex:*** At this level the individual acts consistently in accordance with the values he/she has internalized. A behavior is pervasive, consistent, predictable, and characteristic of the student. Student beliefs, ideas, and attitudes are integrated into a total philosophy or view of the world.

Verb examples that represent intellectual activity on this level include: *discriminate, display, influence, presuppose, qualify, resolve, solve, verify*.

Example from the Syllabus:
Resolves conflicting issues in the balance between personal and professional life

B.3 The Psychomotor Domain

The psychomotor domain emphasizes physical skills. It involves muscular or motor skill, some manipulation of materials and objects, or some act which requires a neuromuscular coordination. It captures the complexity of grace, strength, and speed that is often involved in physical activity or skill acquisition.

While there are a few examples in the CDIO Syllabus that touch on the psychomotor domain, these topics all have an important cognitive component as well. Therefore the cognitive verbs are consistently used for these topics, and the psychomotor categories are not used in the Syllabus.

For completeness, it is worth outlining the breakdown of this domain by Simpson (1972) into seven levels.

1. ***Perception*** is defined as the ability to use sensory cues to guide motor activity.

2. ***Set*** refers to the readiness to take a particular course of action. This includes physical and emotional set as well as mental.

3. ***Guided Response:*** refers to imitation and trial and error in which the adequacy of the performance is judged by the instructor or by a defined set of criteria.

4. ***Mechanism:*** describe learned responses that have become habitual, movements can be performed with some confidence and proficiency.

5. ***Complex Overt Responses:*** is the skillful performance of motor acts that involve complex movement patterns. Proficiency is indicated by a quick, accurate, and highly coordinated performance, requiring a minimum of energy. In this category, responses are automatic.

6. ***Adaptation:*** is the level at which skills are so well developed that the individual can modify movement patterns to fit special requirements or to meet a problem situation.

7. ***Origination*** is the creation of new movement patterns to fit a particular situation or specific problem. Outcomes at this level emphasize creativity based upon highly developed skills.

B.4 Bloom Verb Patterns for the CDIO Syllabus

In specializing the CDIO Syllabus to any particular program and thereby creating a framework of learning objectives, one Bloom verb must be selected for each of the over 300 lowest level topics in the

Syllabus. The Bloom verb chosen should correspond to the expected proficiency level of a graduating engineer, developed through the survey and consensus process. The activity based proficiency rating can be translated to a Bloom verb domain and level using the rough equivalence listed in Table 8.

In order to simplify this process, we tried to create a *menu* of Bloom verbs for each of the over 300 entries. In this way, a faculty specializing the Syllabus could simply choose the Bloom verb for each topic that corresponded to the designated level of proficiency.

As an example of creating such a menu, consider subsection 2.1.1, Problem Identification and Formulation (under section 2.1 Engineering Reasoning and Problem Solving). The following Bloom verb menu options can be created for each entry:

2.1.1 Problem Identification and Formulation
Recall/Recognize/Identify/Analyze/Evaluate data and symptoms
Recall/Describe/Explain/Analyze/Evaluate assumptions and sources of bias
Recall/Define/Discuss/Demonstrate/Evaluate issue prioritization …{CP}
Recall/Describe/Interpret/Choose/Formulate a plan of attack …

where the five verbs indicate, respectively, the first through fifth activity based proficiency levels (Table 6). The verb *recall*, among the weakest of the Bloom verbs for knowledge, is used to connote the result of an exposure, the lowest activity based proficiency. *Recognize, describe* and *define* are representative of "being able to participate", the second activity based proficiency level. At the third activity based level, *identify, explain, discuss* and *interpret* connote "being able to understand and explain". *Analyze, practice* and *choose* denote skills of a person who is "skilled in the practice of", the fourth acvity based level. Finally, at the fifth level, *evaluate* and *formulate* are verbs which connote the ability to "lead or innovate".

In attemping to create the equivalent five verb menu for each of the low level entries in the Syllabus, it became obvious that there were a relatively small number of underlying patterns, rather than 300 odd unique menus. Those patterns as summarized in Table 7. The patterns were determined by simple reverse engineering. First the specific verbs were assigned for the customized MIT version of the Syllabus listed in Appendix C. Then all the verbs actually used, listed in bold in Table B1, were examined for patterns.

First a pattern was chosen for the relatively small set of affective topics, which carry the annotation {A}. It was found that all affective entries can be linked to the pattern of Bloom verb:

Has been exposed to/Accepts the need for/Engages in discussion of/Embraces/Resolves conflicting issues in

Where the entries map to activity based proficiency levels 1-5.

Likewise all cognitive processes, which are annotated {CP}, fit with the pattern:

Recall/Describe/Discuss/Demonstrate/Evaluate

These two patterns are listed, along with some common synonyms, in Table 7.

The vast majority of the low level entries in the Syllabus are cognitive objects. These require a richer set of Bloom verb patterns. Through several iterations, it was found that all entries map to about 27 patterns. These patterns are made up of 3 patterns for verbs in activity based proficiency levels 1-3, combined with 9 options at levels 4 and 5, as shown in Table 7. There are a relatively small number of verbs at the lower levels which make sense when combined with engineering topics and learning objectives. At the fourth activity based level, "to be skilled in the practice or implementation of", a major split occurs. Some topics are primarily outside of the control of engineers. For these topics, the appropriate verbs are some form of *analyze*. The fifth level which corresponds to an analysis task tends to be *evaluate*. In contrast, for topics which tend to be under the control of engineers, the appropriate fourth level verb tends to be *apply*. The corresponding fifth level verb is some form of *synthesize*.

The structure of the menu implied in Table 7 reflects these trends. For any lowest level Syllabus topic, there is one of the three verb sets from levels 1-3, denoted with a letter a,b or c, plus one of the nine patterns from levels 4 and 5, which tend to be either a Synthesis or Evaluation pattern. Synthesis patterns are designate S1 through S5, while Evaluation patterns are designated E1 through E4. The annotation in brackets is just the notation for one of a-c, followed by the notation for one of the nine higher level patterns

Again, refering to the example in the text, we can consider the patterns for the subsection:

2.1.1 Problem Identification and Formulation
- Data and symptoms {c-E1}
- Assumptions and sources of bias {a-E1}
- Issue prioritization {CP}
- A plan of attack {b-S2}

The topic "data and symptoms" is ultimately evaluated by engineers (at least as a part of Problem Identification and Formulation), and so carries the pattern {c} at the 1-3 levels, and the pattern {E1} at the 4-5 level. Issue prioritization is a cognitive process, and maps to that pattern in Table 7. "A plan of attack" is ultimately synthesized by an engineer, and therefore is a pattern {S2} at the 4-5 level.

Using Table 7 and the annotation in Appendix C, a five-verb Bloom pattern is therefore suggested for each low level topical entry in the Syllabus.

Appendix C: The CDIO Syllabus Customized for the MIT Department of Aeronautics and Astronautics (v 4.2.3)

1 TECHNICAL KNOWLEDGE AND REASONING

1.1 KNOWLEDGE OF UNDERLYING SCIENCES [a]

1.1.1 Mathematics (including statistics)
1.1.2 Physics
1.1.3 Chemistry
1.1.4 Biology

1.2 CORE ENGINEERING FUNDAMENTAL KNOWLEDGE [a]

1.2.1 Fluid Mechanics
1.2.2 Solid Mechanics and Materials
1.2.3 Dynamics
1.2.4 Signals and Systems
1.2.5 Thermodynamics
1.2.6 Control
1.2.7 Computers and computation

1.3 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE [k]

1.3.1 Aerodynamics
1.3.2 Structural Mechanics
1.3.3 Structures and Materials
1.3.4 Jet and Rocket Propulsion
1.3.5 Flight and Advanced Aerospace Dynamics
1.3.6 Computational Techniques
1.3.7 Estimation and Navigation
1.3.8 Human and Supervisory Control
1.3.9 Digital Communications
1.3.10 Software Engineering
1.3.11 Autonomy
1.3.12 Digital Circuits and Systems

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES

2.1 ENGINEERING REASONING AND PROBLEM SOLVING (4.0) [e]

2.1.1 Problem Identification and Formulation (4.4/4)

Evaluate data and symptoms {c-E1}
Analyze assumptions and sources of bias {a-E1}
Demonstrate issue prioritization in context of overall goals {CP}
Formulate a plan of attack (incorporating model, analytical and numerical solutions, qualitative analysis, experimentation and consideration of uncertainty) {b-S2}

2.1.2 Modeling (4.3/4)

Employ assumptions to simplify complex systems and environment {c-S4}
Choose and *apply* conceptual and qualitative models {c-S2, c-S1}
Choose and *apply* quantitative models and simulations {c-S2, c-S1}

2.1.3 Estimation and Qualitative Analysis (4.0/4)

Estimate orders of magnitude, bounds and trends {b-E3}
Apply tests for consistency and errors (limits, units, etc.) {c-S1}
Demonstrate the generalization of analytical solutions {CP}

2.1.4 Analysis With Uncertainty (3.7/4)

Elicit incomplete and ambiguous information {c-E3}
Apply probabilistic and statistical models of events and sequences {b-S1}
Practice engineering cost-benefit and risk analysis {b-S3}
Discuss decision analysis {a-S3}
Schedule margins and reserves {c-S5}

2.1.5 Solution and Recommendation (3.8/4)

Synthesize problem solutions {b-S2}
Analyze essential results of solutions and test data {c-E1}
Analyze and *reconcile* discrepancies in results {a-E1a, a-E2}
Formulate summary recommendations {b-S2}
Appraise possible improvements in the problem solving process {a-E1}

2.2 EXPERIMENTATION AND KNOWLEDGE DISCOVERY (3.3) [b]

2.2.1 Hypothesis Formulation (3.4/3)

Select critical questions to be examined {c-S2}
Formulate hypotheses to be tested {c-S2}
Discuss controls and control groups {a-S4}

2.2.2 Survey of Print and Electronic Literature (3.0/3)

Choose the literature research strategy {a-S2}
Demonstrate information search and identification using library tools (on-line catalogs, databases, search engines) {CP}
Demonstrate sorting and classifying the primary information {CP}
Question the quality and reliability of information {a-E3}
Identify the essentials and innovations contained in the information {c-E2}
Identify research questions that are unanswered {c-E2}
List citations to references {c-E1}

2.2.3 Experimental Inquiry (3.6/4)

Formulate the experimental concept and strategy {a-S2}
Discuss the precautions when humans are used in experiments {a-S3}
Execute experiment construction {CP}
Execute test protocols and experimental procedures {b-S3}
Execute experimental measurements {c-S3}
Analyze and *report* experimental data {b-E1}
Compare experimental data vs. available models {a-E2}

2.2.4 Hypothesis Test, and Defense (3.3/3)

Discuss the statistical validity of data {a-E1}
Discuss the limitations of data employed {a-E1}
Prepare conclusions, supported by data, needs and values {b-S5}
Appraise possible improvements in knowledge discovery process {a-E1}

2.3 SYSTEM THINKING (2.8)

2.3.1 Thinking Holistically (2.9/3)

Identify and *define* a system, its behavior, and its elements {c-E1}
Use trans-disciplinary approaches that ensure the system is understood from all relevant perspectives {a-S4}
Identify the societal, enterprise and technical context of the system {c-E1}
Identify the interactions external to the system, and the behavioral impact of the system {c-E1}

2.3.2 Emergence and Interactions in Systems (2.6/3)

Discuss the abstractions necessary to define and model system {a-S2}
Identify the behavioral and functional properties (intended and unintended) which emerge from the system {c-E1}
Identify the important interfaces among elements {c-S2}
Recognize evolutionary adaptation over time {c-S5}

2.3.3 Prioritization and Focus (2.7/3)

Locate and classify all factors relevant to the system in the whole {c-E2}
Identify the driving factors from among the whole {c-E2}
Explain resource allocations to resolve the driving issues {a-S5}

2.3.4 Trade-offs, Judgement and Balance in Resolution (3.1/3)

Identify tensions and factors to resolve through trade-offs {c-E2}
Choose and employ solutions that balance various factors, resolve tensions and optimize the system as a whole {b-S2, b-S4}
Describe flexible vs. optimal solutions over the system lifetime {a-S2}
Appraise possible improvements in the system thinking used {a-E1}

2.4 PERSONAL SKILLS AND ATTITUDES (3.4)

2.4.1 Initiative and Willingness to Take Risks (3.4/3)

Identify the needs and opportunities for initiative {c-E1}
Discuss the potential benefits and risks of an action {A}
Explain the methods and timing of project initiation {CP}
Demonstrates leadership in new endeavors, with a bias for appropriate action {A}
Practice definitive action, delivery of results and reporting on actions {CP}

2.4.2 Perseverance and Flexibility (3.8/4)

Demonstrate self-confidence, enthusiasm, and passion {A}
Demonstrate the importance of hard work, intensity and attention to detail {A}
Demonstrate adaptation to change {A}
Demonstrate a willingness and ability to work independently {A}
Demonstrate a willingness to work with others, and to consider and embrace various viewpoints {A}
Demonstrate an acceptance of criticism and positive response {A}
Discuss the balance between personal and professional life {A}

2.4.3 Creative Thinking (3.6/4)

Demonstrate conceptualization and abstraction {CP}
Demonstrate synthesis and generalization {CP}
Execute the process of invention {CP}
Discuss the role of creativity in art, science, the humanities and technology {a-E2}

2.4.4 Critical Thinking (3.8/4)

Analyze the statement of the problem {b-E1}
Choose logical arguments and solutions {c-S2}
Evaluate supporting evidence {c-E1}
Locate contradictory perspectives, theories and facts {c-E2}
Identify logical fallacies {c-E4}
Test hypotheses and conclusions {c-E4}

2.4.5 Awareness of One's Personal Knowledge, Skills and Attitudes (2.9/3)

Describe one's skills, interests, strengths, weaknesses {a-E1}
Discuss the extent of one's abilities, and one's responsibility for self-improvement to overcome important weaknesses {A}
Discuss the importance of both depth and breadth of knowledge {A}

2.4.6 Curiosity and Lifelong Learning (3.1/3) **[** i **]**

Discuss the motivation for continued self-education {A}
Demonstrate the skills of self-education {a-S3}
Discuss one's own learning style {a-S3}
Discuss developing relationships with mentors {CP}

2.4.7 Time and Resource Management (3.3/3)

Discuss task prioritization {CP}
Explain the importance and / or urgency of tasks {a-E2}
Explain efficient execution of tasks {CP}

2.5 PROFESSIONAL SKILLS AND ATTITUDES (3.0)

2.5.1 Professional Ethics, Integrity, Responsibility & Accountability (3.7/4) **[f]**

Demonstrate one's ethical standards and principles {A}
Demonstrate the courage to act on principle despite adversity {A}
Identify the possibility of conflict between professionally ethical imperatives {c-E2}
Demonstrate an understanding that it is acceptable to make mistakes, but that one must be accountable for them {A}
Practice proper allocation of credit to collaborators {a-S3}
Demonstrate a commitment to service {A}

2.5.2 Professional Behavior (2.7/3)

Discuss a professional bearing {a-S3}
Explain professional courtesy {a-S3}
Identify international customs and norms of interpersonal contact {c-S3}

2.5.3 Proactively Planning for One's Career (2.7/3)

Discuss a personal vision for one's future {a-S4}
Explain networks with professionals {a-S4}
Identify one's portfolio of professional skills {c-S5}

2.5.4 Staying Current on World of Engineer (2.9/3)

Discuss the potential impact of new scientific discoveries {a-E2}
Describe the social and technical impact of new technologies and innovations {a-E2}
Discuss a familiarity with current practice / technology in engineering {a-S3}
Explain the links between engineering theory and practice {a-E2}

3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION

3.1 TEAMWORK(3.3) [d]

3.1.1 Forming Effective Teams (3.4/3)

Identify the stages of team formation and life cycle {c-S5}
Interpret task and team processes {b-S2}
Identify team roles and responsibilities {c-S2}
Analyze the goals, needs and characteristics (works styles, cultural differences) of individual team members {c-E1}
Analyze the strengths and weakness of the team {c-E1}
Discuss ground rules on norms of team confidentiality, accountability and initiative {a-S1}

3.1.2 Team Operation (4.0/4)

Choose goals and agenda {b-S2}
Execute the planning and facilitation of effective meetings {CP}
Apply team ground rules {b-S1}
Practice effective communication (active listening, collaboration, providing and obtaining information) {CP}
Demonstrate positive and effective feedback {a-S3}
Practice the planning, scheduling and execution of a project {CP}
Formulate solutions to problems (creativity and decision making){b-S2}
Practice conflict negotiation and resolution {CP}

3.1.3 Team Growth and Evolution (2.7/3)

Discuss strategies for reflection, assessment, and self-assessment {a-S1}
Identify skills for team maintenance and growth {c-S3}
Identify skills for individual growth within the team {c-S4}
Explain strategies for team communication and writing {a-S4}

3.1.4 Leadership (3.4/3)

Explain team goals and objectives {a-S2}
Practice team process management {CP}
Practice leadership and facilitation styles (directing, coaching, supporting, delegating) {CP}
Explain approaches to motivation (incentives, example, recognition, etc) {a-S4}

Practice representing the team to others {CP}
Describe mentoring and counseling {CP}

3.1.5 Technical Teaming (3.0/3)

Describe working in different types of teams {CP}:
Cross-disciplinary teams (including non-engineer)
Small team vs. large team
Distance, distributed and electronic environments
Demonstrate technical collaboration with team members {CP}

3.2 COMMUNICATIONS (3.6) [g]

3.2.1 Communications Strategy (3.5/4)

Analyze the communication situation {b-E1}
Choose communications objectives {c-S2}
Analyze the needs and character of the audience {b-E1}
Analyze the communication context {b-E1}
Choose a communications strategy {c-S2}
Choose the appropriate combination of media {c-S2}
Choose a communication style (proposing, reviewing, collaborating, documenting, teaching) {c-S2}
Select the content and organization {c-S2}

3.2.2 Communications Structure (3.8/4)

Construct logical, persuasive arguments {c-S2}
Construct the appropriate structure and relationship amongst ideas {c-S4}
Choose relevant, credible, accurate supporting evidence {c-S2}
Practice conciseness, crispness, precision and clarity of language {a-S3}
Analyze rhetorical factors (e.g. audience bias) {c-E1}
Identify cross-disciplinary cross-cultural communications {c-S3}

3.2.3 Written Communication (3.9/4)

Demonstrate writing with coherence and flow {CP}
Practice writing with correct spelling, punctuation and grammar {CP}
Demonstrate formatting the document {CP}
Demonstrate technical writing {CP}
Apply various written styles (informal, formal memos, reports, etc) {b-S1}

3.2.4 Electronic/Multimedia Communication (3.1/3)

Demonstrate preparing electronic presentations {CP}
Identify the norms associated with the use of e-mail, voice mail, and videoconferencing {c-S1}
Apply various electronic styles (charts, web, etc) {c-S1}

3.2.5 Graphical Communication (3.4/3)

Demonstrate sketching and drawing {CP}
Demonstrate construction of tables, graphs and charts {CP}
Interpret formal technical drawings and renderings {b-E1}

3.2.6 Oral Presentation and Inter-Personal Communications (4.1/4)

Practice preparing presentations and supporting media with appropriate language, style, timing and flow {CP}
Use appropriate nonverbal communications (gestures, eye contact, poise) {b-S4}
Demonstrate answering questions effectively {CP}

4 CONCEIVING, DESIGNING, IMPLEMENTING AND OPERATING SYSTEMS IN THE ENTERPRISE AND SOCIETAL CONTEXT

4.1 EXTERNAL AND SOCIETAL CONTEXT (2.0) [h]

4.1.1 Roles and Responsibility of Engineers (2.2/2)

Accepts the goals and roles of the engineering profession {A}
Accepts the responsibilities of engineers to society {A}

4.1.2 The Impact of Engineering on Society (2.5/3)

Explain the impact of engineering on the environment, social, knowledge and economic systems in modern culture {a-E1}

4.1.3 Society's Regulation of Engineering (1.7/2)

Accepts the role of society and its agents to regulate engineering {A}

Recognize the way in which legal and political systems regulate and influence engineering {c-E1}

Describe how professional societies license and set standards {b-S3}

Describe how intellectual property is created, utilized and defended {b-S3}

4.1.4 The Historical and Cultural Context (1.4/2)

Describe the diverse nature and history of human societies as well as their literary, philosophical, and artistic traditions {a-E2}

Describe the discourse and analysis appropriate to the discussion of language, thought and values {a-S3}

4.1.5 Contemporary Issues and Values (2.2/2) **[j]**

Describe the important contemporary political, social, legal and environmental issues and values {a-E1}

Define the process by which contemporary values are set, and one's role in these processes {a-S3}

Define the mechanisms for expansion and diffusion of knowledge {a-S3}

4.1.6 Developing a Global Perspective (2.1/2)

Describe the internationalization of human activity {a-S3}

Recognize the similarities and differences in the political, social, economic, business and technical norms of various cultures {c-E2}

Recognize International inter-enterprise and inter-governmental agreements and alliances {c-S1}

4.2 ENTERPRISE AND BUSINESS CONTEXT (1.8)

4.2.1 Appreciating Different Enterprise Cultures (1.6/2)

Recognize the differences in process, culture, and metrics of success in various enterprise cultures: {c-E2}

Corporate vs. academic vs. governmental vs. non-profit / NGO
Market vs. policy driven
Large vs. small
Centralized vs. distributed
Research and development vs. operations
Mature vs. growth phase vs. entrepreneurial
Longer vs. faster development cycles
With vs. without the participation of organized labor

4.2.2 Enterprise Strategy, Goals, and Planning (2.2/2)

State the mission and scope of the enterprise {c-S1}

Recognize an enterprise's core competence and markets {c-S2}

Recognize the research and technology process {c-S3}

Recognize key alliances and supplier relations {c-S4}

List financial and managerial goals and metrics {c-S1}

Recognize financial planning and control {c-S1}

Describe stake-holder relations (with owners, employees, customers, etc.) {b-S4}

4.2.3 Technical Entrepreneurship (1.8/2)

Recognize entrepreneurial opportunities that can be addressed by technology {c-S2}

Recognize technologies that can create new products and systems {c-S2}

Describe entrepreneurial finance and organization {a-S3}

4.2.4 Working Successfully in Organizations (1.8/2)

Define the function of management {b-S3}

Describe various roles and responsibilities in an organization {b-S4}

Describe the roles of functional and program organizations {b-S4}

Describe working effectively within hierarchy and organizations {CP}
Describe change, dynamics and evolution in organizations {CP}

4.3 CONCEIVING AND ENGINEERING SYSTEMS (3.1) [c]

4.3.1 Setting System Goals and Requirements (3.2/3)

Identify market needs and opportunities {c-E3}
Elicit and *interpret* customer needs {c-E3, b-E1}
Identify opportunities which derive from new technology or latent needs {c-S2}
Explain factors that set the context of the requirements {a-E1}
Identify enterprise goals, strategies, capabilities and alliances {c-E1}
Locate and classify competitors and benchmarking information {c-E1}
Interpret ethical, social, environmental, legal and regulatory influences {b-E1}
Explain the probability of change in the factors that influence the system, its goals and resources available {a-E3}
Interpret system goals and requirements {b-S2}
Identify the language / format of goals and requirements {c-S1}
Interpret initial target goals (based on needs, opportunities and other influences) {b-S2}
Explain system performance metrics {a-S1}
Interpret requirement completeness and consistency {b-E3}

4.3.2 Defining Function, Concept and Architecture (3.2/3)

Identify necessary system functions (and behavioral specifications) {c-S2}
Select system concepts {b-S2}
Identify the appropriate level of technology {c-S2}
Analyze trade-offs among and recombination of concepts {CP}
Identify high level architectural form and structure {c-S2}
Discuss the decomposition of form into elements, assignment of function to elements, and definition of interfaces {CP}

4.3.3 Modeling of System and Ensuring Goals Can Be Met (3.1/3)

Locate appropriate models of technical performance {c-S2}
Discuss the concept of implementation and operations {a-S3}
Discuss life cycle value and costs (design, implementation, operations, opportunity, etc.) {a-E1}
Discuss trade-offs among various goals, function, concept and structure and iteration until convergence {CP}

4.3.4 Development Project Management (3.0/3)

Describe project control for cost, performance, and schedule {CP}
Explain appropriate transition points and reviews {a-S3}
Explain configuration management and documentation {CP}
Interpret performance compared to baseline {b-E2}
Define earned value process {CP}
Discuss the estimation and allocation of resources {CP}
Identify risks and alternatives {c-E1}
Describe possible development process improvements {a-S2}

4.4 DESIGNING (3.4) [c]

4.4.1 The Design Process (3.9/4)

Choose requirements for each element or component derived from system level goals and requirements {c-S2}
Analyze alternatives in design {a-E1}
Select the initial design {c-S2}
Use prototypes and test articles in design development {a-S4}
Execute appropriate optimization in the presence of constraints {CP}
Demonstrate iteration until convergence {CP}
Synthesize the final design {b-S5}
Demonstrate accommodation of changing requirements {CP}

4.4.2 The Design Process Phasing and Approaches (2.9/3)

Explain the activities in the phases of system design (e.g. conceptual, preliminary, and detailed design) {a-S2}

Discuss process models appropriate for particular development projects (waterfall, spiral, concurrent, etc.) {a-S1}

Discuss the process for single, platform and derivative products {a-S3}

4.4.3 Utilization of Knowledge in Design (3.4/3)

Utilize technical and scientific knowledge {c-S4}

Practice creative and critical thinking, and problem solving {CP}

Discuss prior work in the field, standardization and reuse of designs (including reverse engineer and redesign) {a-S4}

Discuss design knowledge capture {CP}

4.4.4 Disciplinary Design (3.4/3)

Choose appropriate techniques, tools, and processes {c-S2}

Explain design tool calibration and validation {a-S3}

Practice quantitative analysis of alternatives {CP}

Practice modeling, simulation and test {CP}

Discuss analytical refinement of the design {CP}

4.4.5 Multidisciplinary Design (3.4/3)

Identify interactions between disciplines {c-E1}

Identify dissimilar conventions and assumptions {c-E2}

Explain differences in the maturity of disciplinary models {a-E2}

Explain multidisciplinary design environments {a-S4}

Explain multidisciplinary design {CP}

4.4.6 Multi-Objective Design (DFX) (3.5/4)

Demonstrate design for: {CP}

Performance, life cycle cost and value
Aesthetics and human factors
Implementation, verification, test and environmental sustainability
Operations
Maintainability, reliability, and safety
Robustness, evolution, product improvement and retirement

4.5 IMPLEMENTING (2.3) [c]

4.5.1 Designing the Implementation Process (2.3/2)

State the goals and metrics for implementation performance, cost and quality {c-S2}

Recognize the implementation system design: {c-S2}

Task allocation and cell / unit layout
Work flow
Considerations for human user / operators

4.5.2 Hardware Manufacturing Process (2.1/2)

Describe the manufacturing of parts {a-S5}

Describe the assembly of parts into larger constructs {a-S5}

Define tolerances, variability, key characteristics and statistical process control {a-S4}

4.5.3 Software Implementing Process (2.4/2)

Explain the break down of high level components into module designs (including algorithms and data structures) {CP}

Discuss algorithms (data structures, control flow, data flow) {a-S1}

Describe the programming language {a-S1}

Execute the low-level design (coding) {a-S3}

Describe the system build {a-S3}

4.5.4 Hardware Software Integration (2.4/2)

Describe the integration of software in electronic hardware (size of processor, communications, etc) {a-S5}

Describe the integration of software integration with sensor, actuators and mechanical hardware {a-S5}
Describe hardware / software function and safety {a-E1}

4.5.5 *Test, Verification, Validation, and Certification (2.7/3)*
Discuss test and analysis procedures (hardware vs. software, acceptance vs. qualification) {a-S3}
Discuss the verification of performance to system requirements {a-S3}
Discuss the validation of performance to customer needs {a-S3}
Explain the certification to standards {a-S3}

4.5.6 *Implementation Management (2.0/2)*
Describe the organization and structure for implementation {a-S2}
Discuss sourcing, partnering, and supply chains {a-S2}
Recognize control of implementation cost, performance and schedule {c-S3}
Describe quality and safety assurance {b-S4}
Describe possible implementation process improvements {c-S2}

4.6 OPERATING (2.2) [c]

4.6.1 *Designing and Optimizing Operations (2.6/3)*
Interpret the goals and metrics for operational performance, cost, and value {b-S2}
Explain operations process architecture and development {a-S2}
Explain operations (and mission) analysis and modeling {CP}

4.6.2 *Training and Operations (2.2/2)*
Describe training for professional operations: {CP}
Simulation
Instruction and programs
Procedures
Recognize education for consumer operation {a-S3}
Describe operations processes {a-S3}
Recognize operations process interactions {c-E1}

4.6.3 *Supporting the System Lifecycle (2.4/2)*
Explain maintenance and logistics {a-S5}
Describe lifecycle performance and reliability {a-E1}
Describe lifecycle value and costs {a-E1}
Explain feedback to facilitate system improvement {CP}

4.6.4 *System Improvement and Evolution (2.4/2)*
Define pre-planned product improvement {a-S5}
Recognize improvements based on needs observed in operation {c-S5}
Recognize evolutionary system upgrades {c-S5}
Recognize contingency improvements / solutions resulting from operational necessity {c-S4}

4.6.5 *Disposal and Life-End Issues (1.5/2)*
Define the end of life issues {b-E1}
List disposal options {c-S5}
Define residual value at life-end {b-E1}
List environmental considerations for disposal {c-E2}

4.6.6 *Operations Management (2.3/2)*
Describe the organization and structure for operations {a-S2}
Recognize partnerships and alliances {c-S2}
Recognize control of operations cost, performance and scheduling {c-S3}
Describe quality and safety assurance {b-S4}
Define life cycle management {a-S3}
Recognize possible operations process improvements {a-S2}

Appendix D: Source Documents and Bibliography for the CDIO Syllabus

Comprehensive Documents Used in Developing CDIO Syllabus

Principal Comprehensive Source Documents

Accreditation Board of Engineering and Technology (ABET). (2000). *Criteria for Accrediting Engineering Programs: Effective for Evaluations During the 2000-2001 Accreditation Cycle*. Revised March. (http://www.abet.org)

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Appendix E: Results of the Survey for Resource Allocation

Within the same survey that asked respondents to rate the expected level of *proficiency* of graduating engineers at the X.X level of the Syllabus, a second question was asked. This second question sought to establish the relative *importance* of a second level (X.X) topic, as measured by the resources that should be dedicated to its teaching. Note that, *a priori*, there is no reason to believe that respondents would answer similarly to the resource and proficiency questions.

The respondents were asked to answer the following question:

· Please assign 100 "resource points" to items 2.1-4.6 (i.e. do not include items 1.1-1.3) to indicate your feeling of relative importance. Use the comment space to identify any topic within the item that you want to emphasize as being of particular importance.

The question was deliberately worded to create a fixed resource game, at least among the CDIO Syllabus items that encompass personal, interpersonal and system building skills (Parts 2-4). Since the importance and proficiency questions were physically contained in the same survey, the respondents in the two surveys were identical, and a direct side-by-side comparison of the results can be made.

The results of the resource survey were then compiled and analyzed. The first step in analyzing the data was determining whether there were any statistically significant differences between the means for each respondent group for each second level section rating. Student's t-test was performed pair-wise on the data sets, after those responses that fell outside of 3-sigma in any given set were removed. Due to the relatively small sample size, it was important to have good data to isolate real differences that may be concealed by unusually large variances. The summary of the data is listed in Appendix F.

Figure E1 shows the mean resource point allocation for each topic, broken down by respondent group. The asterisk "*" marks those groups that showed statistically significant variations between groups. The overall result is one of substantial agreement. In the 78 (13x6) possible pair-wise comparisons, there are only eight instances of statistically significant ($\alpha < 0.05$) disagreement among the groups:

· In Experimentation (2.2), the faculty rating is high relative to the industry.

· In System Thinking (2.3), the industry rating is high relative to the younger alumni and the older alumni, and the faculty rating is high relative to the older alumni.

· In Societal Context (4.1), the industry and faculty ratings are high relative to the older alumni

· In Business Context (4.2), the industry rating is high relative to the faculty and older alumni.

This relatively small number of differences can be rationalized. One would expect the faculty, made up primarily of engineering scientists, to put more resources into Experimentation and Knowledge Discovery (2.2). As academics, they value the understanding of the Societal Context (4.1), but place less importance on understanding the Enterprise and Business Context (4.2). The industry representatives, who are more senior managers, allocate more resources to System Thinking (2.3), the Societal Context (4.1) and the Business Context (4.2). It is interesting that these latter differences are not primarily with the faculty, but rather with the older alumni, who are also primarily in industry. Presumably these older alumni are still at a low enough level in their organizations that technical, rather than system / societal / business issues dominate their work.

By comparison with the proficiency survey, there is relatively more variance of opinion among the four groups, but in an absolute sense, this would have to be considered substantial agreement. Once this

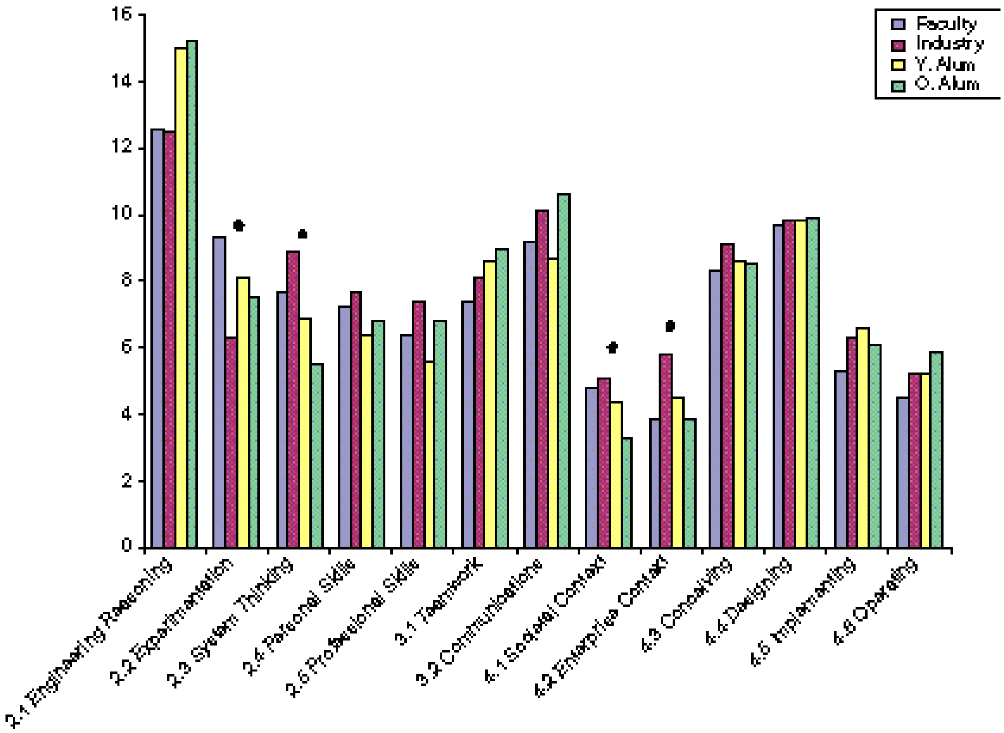

Figure E1: Mean resource points allocated by each survey group. Asterisk designates statistical differences.

agreement among stakeholder groups was established, the data were combined and a relative ranking of resource allocation was computed for each second level section (Figure E2).

The mean proficiency level for each topic was then compared to the overall mean to determine which if any were statistically higher or lower than an even distribution of resource points (which would be 100/13= 7.7 points for each). In addition to showing the means for each topic, Figure E2 marks those that are statistically higher (H) or lower (L) than an even distribution. Engineering Reasoning and Problem Solving (2.1), Designing (4.4), and Communications (3.2) are high as expected. The Societal Context (4.1) and the Business Context (4.2) are ranked quite low. This could be interpreted as reflecting a feeling that these are unimportant, or alternatively that there are other means to learn about these issues (such as humanities, arts and social science requirements on campus, or on-the-job learning after graduation). Personal Skills and Attitudes (2.4) and Professional Skills and Attitudes (2.5) rated somewhat lower than the even distribution. An explanation for this will be given below.

It is interesting to cross-correlate the responses in the importance and proficiency surveys. A comparison of Figures 8 and E2 indicates that many of the topics that the survey indicates should be allocated high levels of resources are the same in which students should be expected to demonstrate higher proficiency. To illustrate the comparison between resource allocation and proficiency, Figure E3 shows the cross plot of the two data sets, in which the second level Syllabus topics are reordered in term of descending resource point allocation.

The resource and proficiency data line up well, except in the areas of Personal Skills and Attitudes (2.4) and Professional Skills and Attitudes (2.5). The proficiency expected in these areas is relatively high, while the resources allocations are low. The comments on many of the surveys seem to explain this

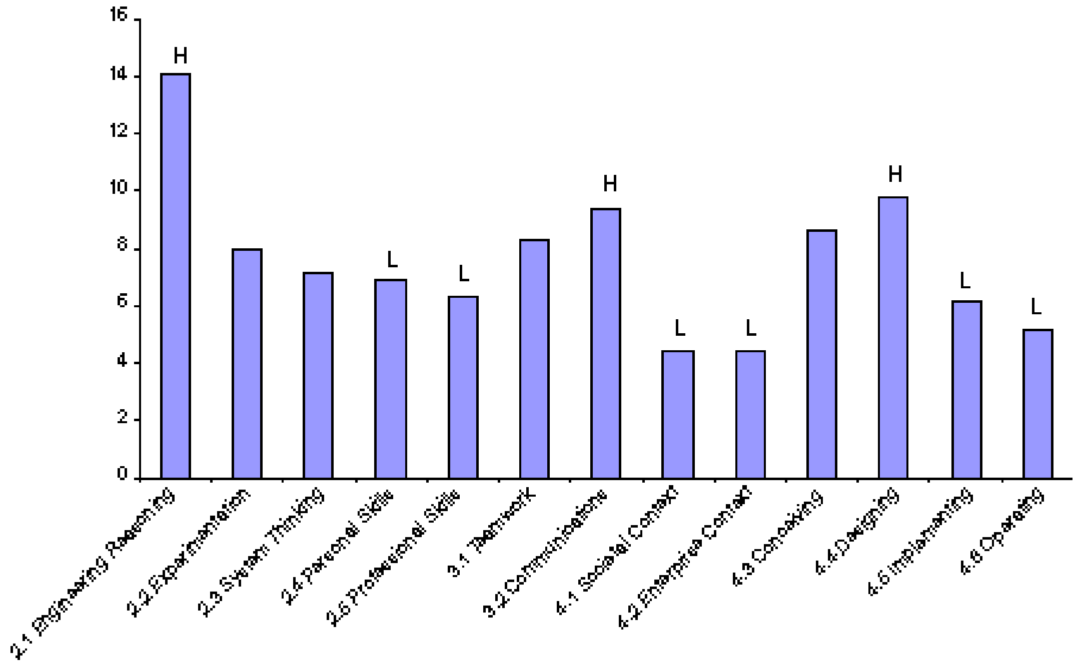

Figure E2: Mean resource point allocation for all groups combined. H and L indicate statistically high and low compared to an even distribution.

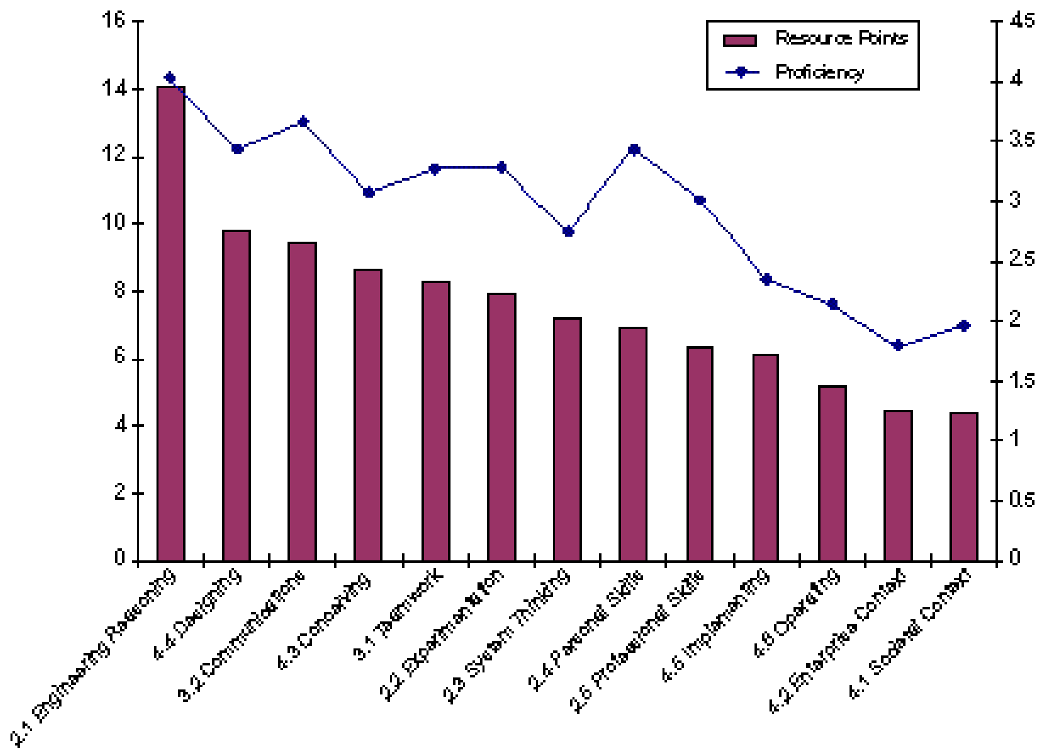

Figure E3: Cross-correlation of means of all groups for resources and proficiency, rank ordered by resources.

difference. Students are expected to demonstrate strong personal and professional attributes, but they are supposed to either have them upon entering MIT or gain them through their own life experiences while at school. An interpretation of this result is that these are important attributes of a graduating engineer, but are difficult to explicitly teach.

Note that there are some other, more minor, but notable differences in the two sets of responses. While Engineering Reasoning and Problem Solving (2.1) is the highest ranking item in both resource allocation and proficiency, the margin by which it exceeds the closest comparable item is lower in proficiency than in resources. Also Conceiving (4.3), while ranked seventh in proficiency, is ranked fourth in resources, indicating the respondents thought this might require more resources to teach.

Aside from these subtleties, the trends in the responses to the two surveys are substantially the same. There does not seem to be sufficient new information in the resource allocation responses to support the decision to ask both questions independently. In the recommended process for customizing the CDIO Syllabus, the resource/importance question is therefore omitted from the survey process.

Appendix F: Data Summaries

Table F1: Resource Point Allocation Survey

Section	Name	Faculty (F) Mean	Industry (I) Mean	Younger Alumni (YA) Mean	Older Alumni (OA) Mean	Pairs with Statistically Significant Differences	Total Survey Mean	Trend Type *
2.1	Engineering Reasoning and Problem Solving	12.58	12.53	14.97	15.18	-	14.05	H
2.2	Experimentation and Knowledge Discovery	9.33	6.27	8.06	7.47	F-I	7.94	-
2.3	System Thinking	7.73	8.93	6.88	5.53	F - OA, I - YA, I - OA	7.16	-
2.4	Personal Skills and Attitudes	7.23	7.73	6.39	6.80	-	6.92	L
2.5	Professional Skills and Attitudes	6.36	7.36	5.64	6.82	-	6.34	L
3.1	Teamwork	7.36	8.07	8.65	9.00	-	8.30	-
3.2	Communications	9.18	10.07	8.70	10.63	-	9.42	H
4.1	External and Societal Context	4.78	5.08	4.35	3.33	F - OA, I - OA	4.38	L
4.2	Enterprise and Business Context	3.86	5.79	4.53	3.86	F - I, I - OA	4.46	L
4.3	Conceiving and Engineering Systems	8.32	9.13	8.63	8.50	-	8.61	-
4.4	Designing	9.73	9.80	9.75	9.88	-	9.78	H
4.5	Implementing	5.27	6.31	6.64	6.12	-	6.13	L
4.6	Operating	4.50	5.23	5.16	5.94	-	5.16	L

* Statistically significant difference between Total Survey Mean and the mean of the Total Survey Means
H - Positive Difference, L - Negative Difference

Table F2: Proficiency Level Survey

Section	Name	Faculty (F) Mean	Industry (I) Mean	Younger Alumni (YA) Mean	Older Alumni (OA) Mean	Pairs with Statistically Significant Differences	Total Survey Mean	Trend Type *
2.1	Engineering Reasoning and Problem Solving	3.95	3.75	4.06	4.12	-	4.02	H
2.2	Experimentation and Knowledge Discovery	3.43	2.87	3.38	3.33	-	3.29	-
2.3	System Thinking	3.11	2.94	2.62	2.47	-	2.74	-
2.4	Personal Skills and Attitudes	3.50	3.50	3.59	3.00	-	3.44	H
2.5	Professional Skills and Attitudes	3.09	3.00	3.09	2.71	-	3.01	-
3.1	Teamwork	3.25	3.50	3.26	2.87	-	3.27	-
3.2	Communications	3.73	3.69	3.62	3.71	-	3.66	H
4.1	External and Societal Context	2.00	2.00	2.06	1.59	-	1.96	L
4.2	Enterprise and Business Context	1.62	2.06	1.91	1.53	-	1.79	L
4.3	Conceiving and Engineering Systems	3.30	3.00	3.09	2.81	-	3.07	-
4.4	Designing	3.45	2.94	3.62	3.53	I - YA, I - OA	3.43	H
4.5	Implementing	2.14	2.25	2.44	2.65	-	2.35	L
4.6	Operating	2.00	2.06	2.24	2.18	-	2.13	L

* Statistically significant difference between Total Survey Mean and the mean of the Total Survey Means
H - Positive Difference, L - Negative Difference

Table F3: XXX Level Survey

Sub-Section	Name	Faculty Mean	Industry Mean	α	Trend Type *	Total Survey Mean	Interim Profi-ciency	Final Profi-ciency
2.1.1	Problem Identification	0.35	0.44	0.6098	A	0.39	4.4	4
2.1.2	Modeling	0.50	-0.17	0.0023	RD	0.23	4.3	4
2.1.3	Estimation	0.04	-0.06	0.6981	A	0.00	4.0	4
2.1.4	Uncertainty	-0.54	-0.06	0.0490	RD	-0.34	3.7	4
2.1.5	Solution	-0.23	-0.17	0.7695	A	-0.20	3.8	4
2.2.1	Hypothesis	0.00	0.28	0.1444	A	0.11	3.4	3
2.2.2	Literature	0.46	0.17	0.1804	A	0.34	3.0	3
2.2.3	Experiment	-0.27	-0.44	0.4069	A	-0.34	3.6	4
2.2.4	Defense	-0.04	0.06	0.6208	A	0.00	3.3	3
2.3.1	Holistics	0.19	0.06	0.4592	A	0.14	2.9	3
2.3.2	Emergence	-0.15	-0.22	0.7511	A	-0.18	2.6	3
2.3.3	Focusing	-0.19	0.00	0.3157	A	-0.11	2.7	3
2.3.4	Trade-Offs	0.19	0.33	0.4607	A	0.25	3.1	3
2.4.1	Initiative	-0.04	0.22	0.1763	A	0.07	3.4	3
2.4.2	Perseverance	0.31	0.61	0.1140	A	0.43	3.8	4
2.4.3	Creative Thinking	0.12	0.22	0.6140	A	0.16	3.6	4
2.4.4	Critical Thinking	0.50	0.17	0.0757	A	0.36	3.8	4
2.4.5	Personal Awareness	-0.42	-0.56	0.5217	A	-0.48	2.9	3
2.4.6	Lifelong Learning	-0.23	-0.33	0.6354	A	-0.27	3.1	3
2.4.7	Time Management	-0.04	-0.22	0.4129	A	-0.11	3.3	3
2.5.1	Ethics	0.77	0.61	0.3168	A	0.70	3.7	4
2.5.2	Professional Behavior	-0.38	-0.11	0.0734	A	-0.27	2.7	3
2.5.3	Career Planning	-0.31	-0.22	0.6393	A	-0.27	2.7	3
2.5.4	Currency	-0.08	-0.17	0.6600	A	-0.11	2.9	3
3.1.1	Forming Teams	0.19	0.00	0.3688	A	0.11	3.4	3
3.1.2	Team Operations	0.81	0.50	0.0730	A	0.68	4.0	4
3.1.3	Growth Operations	-0.62	-0.50	0.5274	A	-0.57	2.7	3
3.1.4	Leadership	-0.04	0.39	0.0791	A	0.14	3.4	3
3.1.5	Technical Teams	-0.31	-0.39	0.7464	A	-0.34	3.0	3
3.2.1	Communication Strategy	0.00	-0.22	0.3537	A	-0.09	3.5	4
3.2.2	Communication Structure	0.35	-0.06	0.1083	A	0.18	3.8	4
3.2.3	Written Communication	0.42	0.17	0.1666	A	0.32	3.9	4
3.2.4	Electronic Communication	-0.62	-0.28	0.0433	SD	-0.48	3.1	3
3.2.5	Graphical	-0.27	-0.11	0.4461	A	-0.20	3.4	3
3.2.6	Oral	0.31	0.72	0.0401	SD	0.48	4.1	4

Sub-Section	Name	Faculty Mean	Industry Mean	α	Trend Type *	Total Survey Mean	Interim Profi-ciency	Final Profi-ciency
4.1.1	Roles of Engineers	0.27	0.17	0.6269	A	0.23	2.2	2
4.1.2	Impact of Engineering	0.65	0.28	0.0236	SD	0.50	2.5	3
4.1.3	Regulation of Engineers	-0.19	-0.33	0.5621	A	-0.25	1.7	2
4.1.4	Cultural Context	-0.85	-0.44	0.0273	SD	-0.68	1.4	2
4.1.5	Contemporary Issues	0.19	0.11	0.6466	A	0.16	2.2	2
4.1.6	Global Perspective	0.00	0.17	0.5128	A	0.07	2.1	2
4.2.1	Enterprise Culture	-0.23	-0.22	0.9660	A	-0.23	1.6	2
4.2.2	Strategy	0.35	0.39	0.8331	A	0.36	2.2	2
4.2.3	Entrepreneurship	-0.04	0.00	0.8345	A	-0.02	1.8	2
4.2.4	Organizations	-0.12	0.06	0.3653	A	-0.05	1.8	2
4.3.1	System Goals	0.04	0.28	0.0911	A	0.14	3.2	3
4.3.2	Concepts	-0.04	0.28	0.1477	A	0.09	3.2	3
4.3.3	Modeling	0.19	-0.28	0.0008	RD	0.00	3.1	3
4.3.4	Management	-0.19	0.06	0.3358	A	-0.09	3.0	3
4.4.1	Design Process	0.62	0.44	0.3495	A	0.55	3.9	4
4.4.2	Process Phasing	-0.62	-0.39	0.2440	A	-0.52	2.9	3
4.4.3	Knowledge Utilization	0.04	0.06	0.9358	A	0.05	3.4	3
4.4.4	Disciplinary Design	0.00	0.11	0.6173	A	0.05	3.4	3
4.4.5	Multidisciplinary Design	0.08	-0.17	0.1810	A	-0.02	3.4	3
4.4.6	Design For X	0.12	0.11	0.9855	A	0.11	3.5	4
4.5.1	Implementation Process	-0.04	-0.06	0.9437	A	-0.05	2.3	2
4.5.2	Manufacturing	-0.04	-0.44	0.0457	RD	-0.20	2.1	2
4.5.3	Software	0.12	0.11	0.9833	A	0.11	2.4	2
4.5.4	HW/SW	-0.04	0.28	0.1077	A	0.09	2.4	2
4.5.5	Test, Verification	0.27	0.61	0.0723	A	0.41	2.7	3
4.5.6	Implementation Management	-0.27	-0.28	0.9712	A	-0.27	2.0	2
4.6.1	Operations Procedure	0.46	0.28	0.3379	A	0.39	2.6	3
4.6.2	Training/ Operations	-0.12	0.06	0.3938	A	-0.05	2.2	2
4.6.3	Support	0.12	0.28	0.4262	A	0.18	2.4	2
4.6.4	Improvements	0.27	0.11	0.4686	A	0.20	2.4	2
4.6.5	Disposal	-0.54	-0.83	0.0432	SD	-0.66	1.5	2
4.6.6	Operations Management	-0.23	0.17	0.0876	A	-0.07	2.3	2

* A - Agreement ($\alpha > .05$)
SD - Statistical Disagreement ($\alpha <= .05$), difference only in magnitude.
RD - Real Disagreement ($\alpha <= .05$), qualitative difference in change.

Appendix G: Syllabus Reviewers

2.1 Engineering Reasoning and Problem Solving

Manual Martinez-Sanchez – Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology

Ian Waitz – Associate Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology

Amedeo Odoni - Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology

Eugene Covert - Professor Emeritus, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology

2.2 Experimentation and Knowledge Discovery

Jack Kerrebrock - Professor Emeritus, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology

Eileen Dorschner – Librarian, Department of Aeronautics & Astronautics, Massachusetts Institute of Technology

Peter Hamel – Director, Institute for Flight Mechanics, German Aerospace Research Center (DLR) Braunschweig, Germany

2.3 Systems Thinking

Andrew P. Sage -- Founding Dean Emeritus / First American Bank Professor, Systems Engineering and Operations Research Department, George Mason Univiersity

Billy Fredriksson – Vice President of Engineering, Technical Director, Saab Scania AB / Saab Military Aircraft

Dan Roos – Professor, Associate Dean of Engineering for Engineering Systems, School of Engineering, Massachusetts Institute of Technology

William Ballhaus – President, The Aerospace Corporation

Eberhardt Rechtin – Professor Emeritus, University of Southern California

2.4 Personal Attributes and Abilities

Peter Hexner – Former executive technical director of Braun, a division of Gillette

Donna Qualters -- Director, Center for Effective University Teaching, Northeastern University

Leon Trilling - Professor Emeritus, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology

2.5 Professional Attributes and Abilities

Robert Seamans - Professor Emeritus, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, former Secretary of the Air Force

John Keesee – Senior Lecturer, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Col USAF

3.1 Multi-disciplinary Teamwork

Bonnie Burrell – Lecturer, Department of Chemical Engineering, Massachusetts Institute of Technology

3.2 Communications

Lori Breslow – Senior Lecturer, School of Management (Teaching and Learning Center) , Massachusetts Institute of Technology

4.1 External and Societal Context

Richard DeNeufville – Chairman, Technology and Policy Program, Professor of Civil Engineering, Department of Civil and Environmental Enginnering, Massachusetts Institute of Technology

Daniel Hastings - Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology, former USAF Chief Scientist

Chris Bates -- Administrative Officer, Department of Science, Technology and Society, Massachusetts Institute of Technology

Dan Schwinn – President, Avidyne Corporation

4.2 Enterprise and Business Context

Mark Lundstrom – President and CEO, Ripcord Systems, Inc

Brian Hughs – Chairman of the Board, SafeScienco, Inc

D. Nightingale - Professor of Practice, Lean Aerospace Initiative, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology

Dave Staelin – Associate Director, Lincoln Laboratory

4.3 Conceiving and Engineering Systems

Ray Leopold -- Vice President, Chief Technology Officer for Global Telecommunications Solutions Sector, Motorola

Pete Young - Senior Lecturer, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Col USAF (retired)

Gerhard Schulmeyer – President and CEO, Siemens Corporation, Professor of the Practice, Sloan School of Management, Massachusetts Institute of Technology

Bernard Lloyd – Partner, McKinsey & Company, Inc

Jack Kerrebrock - Professor Emeritus, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology

4.4 The Design Process

Steve Eppinger -- Co-Director, CIPD / GM LFM Associate Professor of Management, Sloan School of Management, Massachusetts Institute of Technology

Bradford Parkinson – Professor, W. W. Hansen Experimental Physics Laboratory, Stanford University

4.5 Implementing

Nancy Leveson -- Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology

James Jamieson – Executive Vice President, The Boeing Company

Tim Gutowski -- Professor of Mechical Engineering and Director, Laboratory for Manufacturing and Production, Massachusetts Institute of Technology

4.6 Operating

Col John Kukonis – Commander of Air Force ROTC detachment 365, Massachusetts Institute of Technology

Bill Lenoir – Vice President, Booz Allen & Hamilton, Inc.

Appendix H: Sample Survey

The specific objectives of the CDIO Syllabus are to create a clear, complete, and consistent set of goals for undergraduate engineering education, in sufficient detail that they could be understood and implemented by engineering faculty. These goals can form the basis for rational design of curricula (i.e. they are a requirements document), and as the basis for a comprehensive system of assessment. Our goal was to create a list which is rationalized against the norms of contemporary engineering practice, comprehensive of all known other sources, and peer-reviewed by experts in the field. Further, we sought to develop a listing that was prioritized, appropriate to university education, and expressed as learning objectives.

To accomplish the prioritization we used a two-step process. In the first step we provided the list of topics from the syllabus to our review group. They were asked to identify the proficiency or competence level expected of a graduating senior for each topic. As noted in the text, the consistency of desired proficiency among the diverse members of our survey participants was remarkable.

To further refine the desired level of proficiency for each sub-topic we asked the survey participants to go through the syllabus a second time. In this pass they adjusted the desired level of proficiency for the sub-topics relative to the selected proficiency at the topic level. They were allowed to identify at most one (or two, when there a large number of subtopics) subtopic that required a higher level of proficiency than the overall topic. If they chose to elevate the proficiency of sub-topics they were required to identify a matching number of sub-topics to reduce the desired level of proficiency so that the average level matched the overall level for that topic.

The following survey is a template that implements this two step process.

	Circle one level of proficiency for each topic				
	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	5. To be able to lead or innovate in

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES

2.1 ENGINEERING REASONING AND PROBLEM SOLVING [e] ***Problem Identification and Formulation*** ***Modeling*** ***Estimation and Qualitative Analysis*** ***Analysis With Uncertainty*** ***Solution and Recommendation***	1	2	3	4	5
2.2 EXPERIMENTATION AND KNOWLEDGE DISCOVERY [b] ***Hypothesis Formulation*** ***Survey of Print and Electronic Literature*** ***Experimental Inquiry*** ***Hypothesis Test, and Defense***	1	2	3	4	5
2.3 SYSTEM THINKING ***Thinking Holistically*** ***Emergence and Interactions in Systems*** ***Prioritization and Focus*** ***Trade-offs and Balance in Resolution***	1	2	3	4	5
2.4 PERSONAL SKILLS AND ATTRIBUTES ***Initiative and Willingness to Take Risks*** ***Perseverance and Flexibility*** ***Creative Thinking*** ***Critical Thinking*** ***Awareness of One's Personal Knowledge, Skills and Attitudes*** ***Curiosity and Lifelong Learning*** [i] ***Time and Resource Management***	1	2	3	4	5
2.5 PROFESSIONAL SKILLS AND ATTITUDES ***Professional Ethics, Integrity, Responsibility and Accountability*** [f] ***Professional Behavior*** ***Proactively Planning for One's Career*** ***Staying Current on World of Engineer***	1	2	3	4	5

	Circle one level of proficiency for each topic				
	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

3 Communication

3.1 TEAMWORK [d] ***Forming Effective Teams*** ***Team Operation*** ***Team Growth and Evolution*** ***Leadership*** ***Technical Teaming***	1	2	3	4	5
3.2 COMMUNICATIONS ***Communications Strategy*** ***Communications Structure*** ***Written Communication*** ***Electronic/Multimedia Communication*** ***Graphical Communication*** ***Oral Presentation and Inter-Personal Communications***	1	2	3	4	5

	Circle one level of proficiency for each topic				
	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

4 OPERATING SYSTEMS IN THE ENTERPRISE AND SOCIETAL CONTEXT

4.1 EXTERNAL AND SOCIETAL CONTEXT [h] ***Roles and Responsibility of Engineers*** ***The Impact of Engineering on Society*** ***Society's Regulation of Engineering*** ***The Historical and Cultural Context*** ***Contemporary Issues and Values*** [j] ***Developing a Global Perspective***	1	2	3	4	5
4.2 ENTERPRISE AND BUSINESS CONTEXT ***Appreciating Different Enterprise Cultures*** ***Enterprise Strategy, Goals, and Planning*** ***Technical Entrepreneurship*** ***Working Successfully in Organizations***	1	2	3	4	5
4.3 CONCEIVING AND ENGINEERING SYSTEMS [c] ***Setting System Goals and Requirements*** ***Defining Function, Concept and Architecture*** ***Modeling of System and Insuring Goals Can Be Met*** ***Development Project Management***	1	2	3	4	5
4.4 DESIGNING [c] ***The Design Process*** ***The Design Process Phasing and Approaches*** ***Utilization of Knowledge in Design*** ***Disciplinary Design*** ***Multidisciplinary Design*** ***Multi-Objective Design (DFX)***	1	2	3	4	5
4.5 IMPLEMENTING [c] ***Designing the Implementation Process*** ***Hardware Manufacturing Process*** ***Software Implementing Process*** ***Hardware Software Integration*** ***Test, Verification, Validation, and Certification*** ***Implementation Management***	1	2	3	4	5
4.6 OPERATING [c] ***Designing and Optimizing Operations*** ***Training and Operations*** ***Supporting the System Lifecycle*** ***System Improvement and Evolution*** ***Disposal and Life-End Issues*** ***Operations Management***	1	2	3	4	5

Now, within each topic you may select sub-topics that should have a higher level of proficiency relative to the others in that topic and sub-topics that should have a lower proficiency. A "+" indicates one step up in the activity-based proficiency scale. A "-" indicates one step down. The number of "+"s must equal the number of "-"s.

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES

2.1 ENGINEERING REASONING AND PROBLEM SOLVING [e]

2.1.1 Problem Identification and Formulation	+	-	Choose one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
2.1.2 Modeling	+	-	
2.1.3 Estimation and Qualitative Analysis	+	-	
2.1.4 Analysis With Uncertainty	+	-	
2.1.5 Solution and Recommendation	+	-	

Comments:

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2.2 EXPERIMENTATION AND KNOWLEDGE DISCOVERY [b]

2.2.1 Hypothesis Formulation	+	-	Choose one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
2.2.2 Survey of Print and Electronic Literature	+	-	
2.2.3 Experimental Inquiry	+	-	
2.2.4 Hypothesis Test, and Defense	+	-	

Comments:

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2.3 SYSTEM THINKING

2.3.1 Thinking Holistically	+	-	Choose one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
2.3.2 Emergence and Interactions in Systems	+	-	
2.3.3 Prioritization and Focus	+	-	
2.3.4 Trade-offs and Balance in Resolution	+	-	

Comments:

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2.4 PERSONAL SKILLS AND ATTRIBUTES

2.4.1 Initiative and Willingness to Take Risks	+	-	Choose two, one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
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 [i]	+	-	
2.4.7 Time and Resource Management	+	-	

Comments:

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2.5 PROFESSIONAL SKILLS AND ATTITUDES

2.5.1 Professional Ethics, Integrity, Responsibility and Accountability [f]	+	-	Choose one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
2.5.2 Professional Behavior	+	-	
2.5.3 Proactively Planning for One's Career	+	-	
2.5.4 Staying Current on World of Engineer	+	-	

Comments:

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3 Communication

3.1 TEAMWORK [d]

3.1.1 Forming Effective Teams	+	-	Choose one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
3.1.2 Team Operation	+	-	
3.1.3 Team Growth and Evolution	+	-	
3.1.4 Leadership	+	-	
3.1.5 Technical Teaming	+	-	

Comments:

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3.2 COMMUNICATIONS

3.2.1 Communications Strategy	+	-	Choose one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
3.2.2 Communications Structure	+	-	
3.2.3 Written Communication	+	-	
3.2.4 Electronic/Multimedia Communication	+	-	
3.2.5 Graphical Communication	+	-	

Comments:

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4 OPERATING SYSTEMS IN THE ENTERPRISE AND SOCIETAL CONTEXT

4.1 EXTERNAL AND SOCIETAL CONTEXT [h]

4.1.1 Roles and Responsibility of Engineers	+	-	Choose two, one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
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 [j]	+	-	
4.1.6 Developing a Global Perspective	+	-	

Comments:

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4.2 ENTERPRISE AND BUSINESS CONTEXT

4.2.1 Appreciating Different Enterprise Cultures	+	-	Choose one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
4.2.2 Enterprise Strategy, Goals, and Planning	+	-	
4.2.3 Technical Entrepreneurship	+	-	
4.2.4 Working Successfully in Organizations	+	-	

Comments:

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4.3 CONCEIVING AND ENGINEERING SYSTEMS [c]

4.2.1 Setting System Goals and Requirements	+	-	Choose one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
4.2.2 Defining Function, Concept and Architecture	+	-	
4.2.3 Modeling of System and Insuring Goals Can Be Met	+	-	
4.2.4 Development Project Management	+	-	

Comments:

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4.4 DESIGNING [c]

4.4.1 The Design Process	+	-	Choose two, one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
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 (DFX)	+	-	

Comments:

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4.5 IMPLEMENTING [c]

4.5.1 Designing the Implementation Process	+	-	Choose two, one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
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	+	-	

Comments:

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4.6 OPERATING [c]

4.6.1 Designing and Optimizing Operations	+	-	Choose two, one or zero of these sub-topics to increase the proficiency level relative to the others in this topic. Then choose an equal number to reduce so the average remains the same.
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	+	-	

Comments:

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