These four papers were downloaded on 30 Nov 2003 from
www.cdio.org/papers/papers.html

They seem a good introduction to the concept e.g. read first the introduction only of the first paper; then the second paper for an overview of the initiative; then all of them.

CDIO stands for Conceive, Design, Implement, Operate.
It is an approach to designing engineering undergraduate education. It could be seen as an improvement to PBL.

CREATING THE CDIO SYLLABUS, A UNIVERSAL TEMPLATE FOR ENGINEERING EDUCATION

Edward F. Crawley[1]

Abstract *¾ This paper details how a team at the Massachusetts Institute of Technology identified and codified a set of goals for engineering education, which can serve as the basis for curricular improvement and outcome based assessment. The result of two years of scholarship, these goals are embodied in* The CDIO Syllabus, A Statement of Goals for Undergraduate Engineering Education.

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

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

Index Terms ¾ CDIO, syllabus development, undergraduate education.

INTRODUCTION

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

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

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

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

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

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

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

The emphasis on the product/system lifecycle (Conceive ¾ Design ¾ Implement ¾ Operate) gives the program and the Syllabus its name. Once the CDIO premise is accepted as

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

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

STRUCTURE OF THE TOPICAL CDIO SYLLABUS

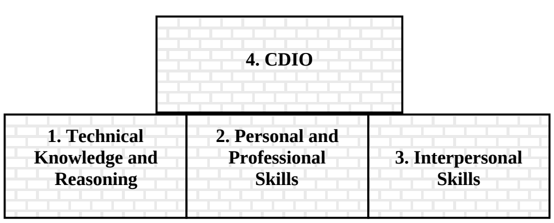
In assembling and organizing the Syllabus content our goal was threefold: to create a structure whose rationale is apparent; to derive a comprehensive high level set of goals correlated with other sources; and to develop a clear, complete, and consistent set of detailed topics that facilitate implementation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

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

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

FIGURE.1

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



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

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

Parts 2 of the Syllabus is *Personal and Professional Skills and Attributes*. The three modes of thought most practiced professionally by engineers are Engineering Reasoning and Problem Solving (2.1), Experimentation and Knowledge Discovery (2.2) and System Thinking (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." 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). The subset of personal skills that are not primarily used in a professional context, and are not interpersonal, are Personal Skills and Attitudes (2.4).

In Part 3, the *Interpersonal Skills* are outlined. The *Interpersonal Skills* are a distinct subset of the general class of personal skills, and divide into Teamwork (3.1) and Communications (3.2). Our international collaborators have added Communications in a Foreign Language (3.3) to this part of the Syllabus.

Part 4, *Conceiving, Designing, Implementing, and Operating Systems in the Enterprise and Societal Context,* presents a view of how product or system development moves through four metaphases, Conceiving (4.3), Designing (4.4), Implementing (4.5), and Operating (4.6). The chosen terms are descriptive of hardware, software and process industries. Conceiving runs from market or opportunity identification through high level or conceptual design, and includes development project management. Designing includes aspects of design process, as well as disciplinary, multidisciplinary, 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 work and enterprises exist within a larger Societal and External Context (4.1). An understanding of these frameworks is essential to the successful practice of the engineering profession.

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

SOURCING AND CORRELATING THE CDIO SYLLABUS

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

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

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

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

Each second level (X.X) section of the Syllabus was then peer reviewed by several domain experts. Combining the results of the peer review, and a check of additional sectional references, we completed the final topical version of the Syllabus.

To ensure comprehensiveness and to facilitate comparison, the contents of the Syllabus were explicitly correlated with the four comprehensive source documents. As an example, the correlation with ABET’s EC2000 accreditation is presented in Table 1. EC2000 states that accredited engineering programs must assure that its graduates have developed 11 specific attributes. While coverage by the CDIO Syllabus of ABET’s attributes is strong, the Syllabus is more comprehensive. For example, ABET omits any reference to System Thinking (2.3), and lists only item (i), “an ability to engage in lifelong learning,” from among the many desirable Personal Attributes (2.4). (ABET omits initiative, perseverance, flexibility, creative and critical thinking, etc.)

TABLE. 1
ABET 2000 REQUIREMENTS CORRELATED WITH THE CDIO SYLLABUS

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

● Strong Correlation □ Good Correlation

The Syllabus has two advantages over EC2000, one minor and one major. The minor advantage is that it is arguably more rationally organized because it is more explicitly derived from the functions of modern engineering.

This might not allow a better understanding of *how* to implement change, but it certainly will create a better understanding of *why* to implement change. The major advantage is that it contains more levels of detail. While EC2000 is an evaluation criteria, the CDIO Syllabus is a guide. Both are needed.

DETERMINING PROFICIENCY LEVELS

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

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

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

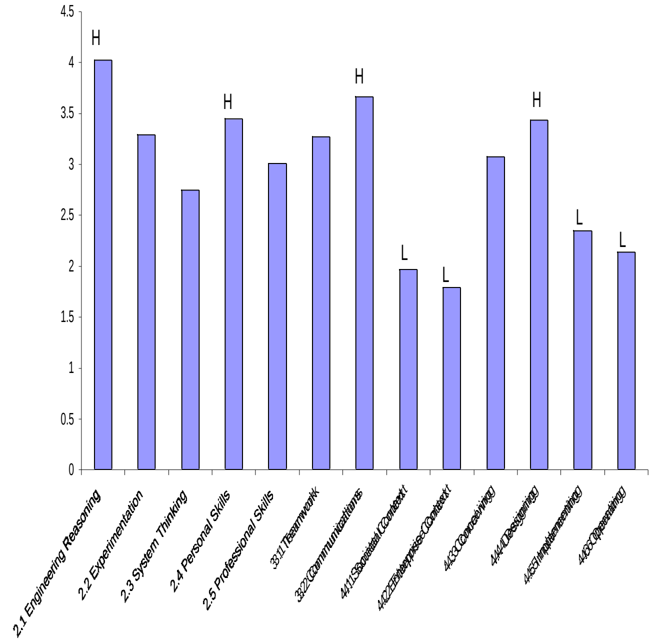
The scale is intended to be absolute; i.e., the most experienced engineers in practice would be able to "lead and innovate" in, for example, design. This expected proficiency on this scale can then be mapped to learning objectives expressed in any of several educational taxonomies. However we found that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

The second step was conducting the survey. We surveyed four groups: faculty from within and outside our university, mid- to upper-level leaders of industry, recent alumni (about five years from graduation) and older alumni (about 15 years from graduation). The alumni groups were chosen so that the respondents were young enough to still recall their education in some detail, yet old enough to be able to reflect on it.

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

TABLE. 2

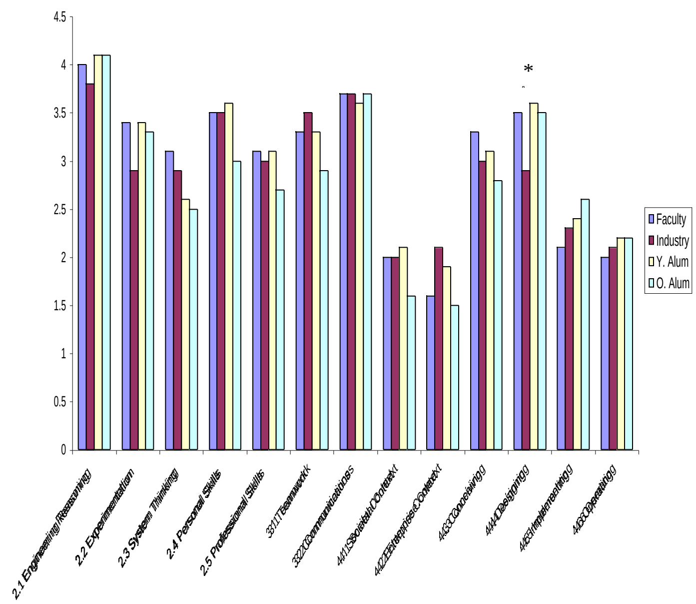
MEAN PROFICIENCY LEVEL FOR ALL GROUPS COMBINED. H AND L INDICATE STATISTICALLY HIGH AND LOW COMPARED TO AVERAGE PROFICIENCY



The most significant result of our survey was the unexpected similarities in opinion among the four stakeholder groups, as show in Table 3. When asked specific well posed questions, and given a quantitative scale for responses, the faculty, industry leaders and alumni were all in agreement. It settled all arguments about the desired level of proficiency we now expect in our graduating students.

TABLE .3

PROFICIENCY EXPECTATION BY SURVEY GROUP. ASTERISK DESIGNATES STATISTICAL DIFFERENCES.



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

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

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

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

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

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

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

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

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

APPENDIX
THE CDIO SYLLABUS (CONDENSED)

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

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

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

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

CDIO: An International Initiative for Reforming Engineering Education

CDIO: An International Initiative for Reforming Engineering Education

Karl-Frederick Berggren, Doris Brodeur, Edward Crawley, Ingemar Ingemarsson, William Litant, Johan Malmqvist, Sören Östlund

ABSTRACT:
With support from the Knut and Alice Wallenberg Foundation, the Royal Institute of Technology (KTH), Linköping University, and Chalmers University of Technology, of Sweden; and the Massachusetts Institute of Technology of the US, launched the CDIO Initiative to improve undergraduate engineering education in their countries, and, eventually, worldwide. The Initiative is an open-architecture endeavour designed to be adaptable and adoptable by any undergraduate engineering program. In 2002, the Technical University of Denmark joined the Initiative, and, in 2003, other schools in Canada, South Africa, the United Kingdom, and the US were aligning themselves as well. CDIO is a closely coordinated program with parallel efforts at participating schools. The Initiative's vision is to provide students with an education stressing engineering fundamentals set in the context of conceiving – designing – implementing – operating (CDIO) real–world systems and products. This paper describes the Initiative's launch, progress and impact
.

INTRODUCTION
With support from the Knut and Alice Wallenberg Foundation of Sweden, four Swedish universities — Chalmers University of Technology (Chalmers) in Göteborg, the Royal Institute of Technology (KTH) in Stockholm, Linköping University (LiU) in Linköping — and the Massachusetts Institute of Technology (MIT)) in the US formed an international collaboration in October 2000 to improve undergraduate engineering education in Sweden, the United States, and worldwide.[1] Three overall goals direct the alliance endeavours. They are to educate students to:

- master a deep working knowledge of technical fundamentals
- lead in the creation and operation of new products and systems
- understand the importance and strategic value of their future research work

The project vision is to provide students with an education that stresses engineering fundamentals set in the context of Conceiving – Designing – Implementing – Operating real–world systems and products. Thus, the project became known as the CDIO Initiative.

The Initiative's strategy to implement CDIO has four themes:

- *curriculum* reform to ensure that students have opportunities to develop the knowledge, skills, and attitudes to conceive and design complex systems and products
- improved *teaching and learning* necessary for deep understanding of technical information and skills
- experiential learning environments provided by *laboratories and workshops*
- effective *assessment* methods to determine quality and improve the learning process.

From its start, the Initiative's product was designed as open architecture. It would be freely available to any and all schools that offer undergraduate engineering education, to take CDIO methodologies, products and templates, and readily adapt and adopt them to their own programs. While the collaborating schools shared a common vision of an education set in the context of CDIO, and they would work in close cooperation on the four main themes, they chose to implement the Initiative in four different professional areas. Success in a variety of engineering education disciplines would help ensure CDIO's universality and adaptability. KTH is developing its program in vehicle engineering, MIT in aerospace, Chalmers in mechanical engineering, and LiU in applied physics and electronics.

Each participating school has an overall CDIO director and at least one representative on each of the four theme areas. Student representatives from each school participate in the four theme areas, as well as contribute as a separate student group.

The four original CDIO collaborators maintain a steering committee of engineering deans and industry representatives, which helps guide the Initiative and serves as liaison to the Wallenberg Foundation. An external review board evaluates the project biennially.[2]

CDIO–based undergraduate engineering education features:

- a curriculum organised around the disciplines and interwoven with CDIO activities
- student projects complemented by internships in industry
- multidisciplinary instruction, and active and experiential group learning
- networked classroom, workshop, and laboratory settings
- robust assessment and evaluation processes

The context for this undergraduate engineering education is a generalized description of a complete system life cycle, called in this project, *Conceive – Design – Implement – Operate*.

The *Conceive* stage includes defining the need and technology, considering the enterprise strategy and regulations, developing the concept, architecture, and business case. The second stage, *Design*, focuses on creating the design, that is the plans, drawings, and algorithms that describe what will be implemented. *Implement* refers to the transformation of the design into the product, including manufacturing, coding, test and validation. The final stage, *Operate*, uses the implemented product to deliver the intended value, including maintaining, evolving and retiring the system

At the outset of the collaboration, each of the four theme areas identified specific tasks for joint investigation and development with parallel efforts at each school. *Curriculum* initiatives include defining and validating the outcomes of an engineering program, early engineering experiences, disciplinary linkages, integrated design–build experiences, and CDIO skills education. *Teaching and Learning* tasks are concrete (hands–on) learning, problem formulation, active learning, feedback, and research into teaching and learning approaches. The *Laboratories and Workshops* group focuses on models for building and furnishing workshops and laboratories, and research into best practices in the use of laboratories for engineering education. *Assessment* reform includes identification of clear goals and outcomes, CDIO skills assessment, creative skills assessment, and programmatic evaluation.

Intended program outcomes have been identified for each of the four themes at both programmatic and student experience levels. (See Figure 1)

	Curriculum	Teaching and Learning	Laboratories & Workshops	Assessment
Program	Models for curriculum structure and design	Understanding and addressing barriers to student learning	Models for the design and use of labs/workshops	Tools and processes for program evaluation
Student Experience	Curricular materials for CDIO education	Active, experiential learning with enhanced feedback	Workshop–based educational experiences	Tools and processes for assessing student achievement

Figure 1. Intended CDIO Outcomes

CURRICULUM

New curriculum models and designs are based on an organised list of learning outcomes identified as critical in the education of new engineers. Each institution conducted surveys of its faculty, students, alumni, and industrial representatives to validate the importance of these outcomes.[3] This list, now called the CDIO Syllabus, may be found at http://www.cdio.org.

The CDIO Curriculum Theme proposed a curriculum model in which

- disciplines are the organising principle interwoven with design–build experiences
- design–build experiences motivate and reinforce learning and teach system building
- clear connections of learning to utility exist throughout the curriculum
- rigor and breadth of coverage are preserved
- students are well prepared to be leading engineers as well as researchers with a clear understanding of the strategic value of their area

The integration of these features into existing and new curriculum is left to each institution. Three integration models are proposed for local adaptation. A *block* model fully integrates disciplinary content and CDIO skills into one or more courses. In a *linked* model, two or more subjects are taught separately and concurrently, and eventually merge with CDIO skills as the main link. In an *umbrella* integration model, subjects and courses are taught separately, and are connected by some coordinating CDIO activity.

In the design of new curriculum, each institution is also focusing on its introductory courses. These initial experiences are designed to motivate students to study engineering, to provide personal experiences that foster deeper understanding of fundamentals, and to provide early exposure to system building. Chalmers has revised its Introduction to Mechanical Engineering, KTH its Perspectives on Vehicle Engineering, and MIT its Introduction to Aerospace and Design. LiU has developed a new introductory course, Engineering Projects–Y, for its program in electronics and applied physics.

At the same time, each partner is working on one or more projects that enhance disciplinary linkages, including a machine elements design and manufacture project and a mechatronics course at Chalmers, a solar–powered aircraft at KTH, an electronics course at LiU, and an electric aircraft in a Unified Engineering course at MIT.

The Curriculum Theme is taking the lead in the design and development of Instructor Resource Modules (IRMs) to provide faculty with teaching and learning resources for integrating CDIO skills education into the curriculum. Four prototype guides are under development: oral and written communication, communication in foreign languages, teamwork, and professional ethics. Additional guides will be developed in subsequent years of the collaboration. The IRMs will be freely available on the Web.

Other recent Curriculum Theme activities include:

- major redesigns of each participating school's curricula to integrate the CDIO model. For example, KTH introduced four new/revised programs for 2003
- a revised Web–based Syllabus survey has been designed
- LiU has developed and implemented the Lightweight Interactive Project Management model in CDIO project–based courses for student years 1, 3 and 4

TEACHING AND LEARNING

The main goal of the Teaching and Learning Theme is to increase student learning through

- problem formulation
- increased active learning experiences
- immediate feedback
- improved instructor skills

In the first year, each institution conducted interviews and surveys of its respective instructional staff to determine what teaching methods were in use. In addition to more traditional methods of lecture, recitation, and problem sets, instructors promote learning through student presentations, teamwork, laboratory exercises, hands–on projects, and design–build experiences.

As a result of the CDIO Initiative, instructors engaged in joint projects to improve teaching and learning. For example, instructors at all four institutions introduced "muddiest–part–of–the–lecture" cards[4] to encourage interaction in lecture–based classes and improve immediate feedback of students' conceptual understanding. LiU and MIT are working with personal response systems[5] and other new technologies, both for independent study and class interaction.

Examples of progress by the Teaching and Learning Theme are:

- a new Problem Based Learning course at Chalmers, Environmentally Adapted Product Development and Manufacturing, developed, given, evaluated and reported
- a new method for increasing student conceptual understanding in the Signals and Systems course at MIT developed and preliminary report presented
- the report "Assessing & Enhancing Conceptual Understanding" presented
- workshops on both student and teacher education presented

As the Initiative continues, the Teaching and Learning Theme is

- organising additional faculty and student workshops

- publishing technical briefs on innovative teaching methods
- expanding the use of electronic response systems
- continuing to develop problem formulation and case study approaches
- investigating and testing new instructional technologies

WORKSHOPS AND LABORATORIES

The main objectives of the Workshops and Laboratories Theme are to:

- develop the infrastructure and facilities to support educational initiatives
- introduce design–build experiences within existing courses
- promote active, team–based, hands–on project work

First–year projects were largely devoted to single–institution endeavours. For example, Chalmers designed a new prototyping workshop and virtual design studio, KTH introduced a new creativity lab–workshop in its redesigned aeronautics and lightweight structures courses, LiU introduced labs and workshops in its electronics and computer technology courses, and MIT built its Learning Laboratory for Complex Systems.

The Workshops and Laboratories Theme identified 12 modes of instruction for effective use of laboratories in engineering education. These varied uses help to determine the requirements of laboratory spaces. They are:

- Class Lab Mode: occasional use, short duration, storable
- Large Systems Mode: year–long project, design intensive, dedicated space, product thrust, close connectivity to outside
- Design Product Mode: large–scale project, term length, virtual design, dedicated space, breakout–report spaces
- Tinkering Mode: occasional, temporary work space
- Experiment Mode: desktop project, one to two terms, student developed
- Research Design Support Mode: in and out capacity, temporary team design space, weeks to months in duration
- Graduate Thesis Mode: one or more years, equipment needs, dedicated space, in and out capacity
- Large Student–Project Mode: large–scale project, dedicated space, large physical components, after hours
- Linked Projects Mode: multidisciplinary, one term or less, multi–use lab experiments, joint labs and designs
- Teaching in Labs Mode: occasional, presentation area, demonstrations
- Income–Generating External Mode: ongoing, in and out testing, days or weeks duration, dedicated space
- Outreach Mode: weekly, accommodate visits, lectures, presentations

Most recently in the Workshops and Laboratory Theme, MIT has refined its Learning Laboratory, new labs have opened at Linköping and at KTH and Chalmers prototyping lab has been reconstructed.

New design–build–test experiences have been implemented at the Swedish schools. Examples of products that have been developed in these courses are a solar-powered aircraft at KTH, and a race car at Chalmers. In the coming years, the Laboratory and Workshops Theme will outfit and operate the labs designed in the first year, create new courses with design–build opportunities, expand the current laboratories and workshops, coordinate with other educational projects and development efforts, and support capstone design experiences.

ASSESSMENT

In the first year, the Assessment Theme engaged in activities in four main areas: creating learning objectives, assessing CDIO skills, course evaluation, and program evaluation. Chalmers, KTH, and LiU held faculty workshops on writing and classifying learning objectives. The team focused on communication skills, creative and affective skills, and alternative assessments in mathematics. All four institutions examined and described their procedures for end–of–course evaluations by students, and LiU and MIT initiated Web–based course evaluations. In the area of program evaluation, LiU implemented an approach called The Balanced Scorecard[6], and MIT evaluated its program using ABET's EC 2000[7].

The theme developed new tools for assessing technical courses and for assessing design-build-test experiences. The former address the proper formulation of learning objectives, utilize oral exams and concept questions to assess deep understanding and develop concept maps of student learning. The latter include adapted scoring guides, the use of oral presentations and techniques for peer and self-assessment.

New methods for evaluating educational programs were developed including the use of baseline interviews, longitudinal studies and portfolios for assessing student learning during the whole program, use of Balanced Scorecards to display program status and a range of techniques for course evaluations such as Web–based course evaluation questionnaires, course panels and instructor reflective memos.

CDIO EXPANSION

By the Initiative's second year, with CDIO development and application well underway[8], the original partners began an outreach effort to encourage CDIO adoption by a select number of additional schools. These early potential adopters were approached based on their commitment to apply the CDIO concept, the diversity of their programs, their potential for contributing new ideas to the benefit of the all Initiative members, their enthusiasm for joining the collaboration and their willingness to secure resources to support their participation. The first school to join the original partners was the Technical University of Denmark. Other institutions laying the groundwork for joining are located in Canada, Finland, Ireland, and the US. In addition, the South African Ministry of Education has a high–ranking representative closely involved with the CDIO Initiative to explore the introduction of CDIO in that country. This diverse and growing collaboration will ensure the continued evolution and improvement of this project.

SUMMARY

The international collaboration of the CDIO Initiative has resulted in an exemplary partnership of professionals committed to the reform of engineering education. It is fostering the learning and sharing of ideas, projects, and materials bridging programs, institutions, languages, and national boundaries.

CDIO is an open architecture endeavour . It is specifically designed for, and offered to, all university engineering programs to adapt to their specific needs. It is an ongoing development effort. Participating universities will develop materials and approaches to share with others. Many already have unique capabilities that could enrich other programs. Therefore, we are developing an open, accessible architecture for the program materials, for disseminating and exchanging resources.

In designing and administrating CDIO, its creators reached beyond the traditional walls of engineering institutions to assemble a unique development team of curriculum, teaching and learning, assessment, design and build, and communication professionals. They are available to provide information and assist others who want to explore adopting CDIO in their institutions. There is a wealth of development material available ranging from model surveys, to assessment tools, to reports from institutions that have implemented the CDIO Initiative.

To contact the CDIO team, email info@cdio.org. For more information on the CDIO Initiative, visit www.cdio.org

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The Conceive-Design-Implement-Operate Initiative: A New Outcomes Based Approach for the Reform of Higher Engineering Education

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Introduction

Recognising South Africa´s high international status on engineering education that is based on the membership of the Washington Accord and International Engineers` Mobility Forum Agreement, this paper aims to update South Africans on the latest developments regarding the skills required by the international engineering job market and endeavours made by the world´s leading universities and industry through the current reforms on engineering education. Outcomes-based-educational (OBE) approaches through the Conceive-Design-Implement-Operate (CDIO) Initiative is the key word for the current reforms on higher engineering education that are led by Massachusetts Institute of Technology (USA), Chalmers University of Technology, Linköping University and The Royal Institute of Technology of Stockholm (all of Sweden). New members of the Initiative are Denmark Technical University (Denmark), US Naval Academy (US) and Queens University (Northern Ireland). Some of the questions that are emerging centre around engineering science versus engineering practice based approaches, what effect and influence would this new international trend have for countries that have declared OBE as national educational policy and whether the CDIO Initiative would be the ultimate educational philosophy to bridge the technological advancement gap that currently exists between developed and developing countries.

A Brief History of International Engineering Education on Skills Required by the Job Market

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. In North America, King (1944) called for the development of additional non-traditional skills such as those needed for good oral and written communications, planning and working successfully in organisations. Also, the honing of personal attributes, such as a propensity towards action, integrity and self-reliance was called for.

With the advent of the modern engineering science based approach to engineering in the 1950s, 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 engineering practice. Gordon (1984) clearly enumerated the skills required for contemporary practice. By the late 1980s, a few universities had begun to examine this issue and made tentative statements of the appropriate goals of undergraduate education.

By the mid 1990s, industry in the United States began a concerted effort to close the gap between engineering education and engineering 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 and created joint working groups to facilitate exchange of views. The Accreditation Board of Engineering and Technology (ABET 2000) developed a list of high level goals traceable back to the writings of the past 50 years.

European engineering is directed to developing, providing and maintaining infrastructures, goods and services for industry and the community. Creative problem solving and designing technical artefacts are still perceived as the core of engineering but the range of activities connected and identified with engineering is far bigger. Engineering as an academic discipline is continuously undergoing a process of rapid expansion and diversification currently significantly characterised by interdisciplinary approaches. Engineering as a profession has to deal with scientific and technological matters, but increasingly also with economical and political matters as well as with ethical, societal and environmental aspects (Varin, 1999).
An engineer has to be educated and trained to work in permanently changing technological, social and working environments, contributing to a great deal to these changes, and must be prepared to take over

different functions as an employee in industry or in the public service sector, as well as as an entrepreneur, researcher, educator or politician. Education, practical training and professional development of engineers must therefore reflect these conditions and demands.

A general profile for a good engineer in the learning society of the new millennium is built on the ability and willingness to learn, on solid knowledge of the basic natural sciences, and on good knowledge of some field of technology. Other skills include general human values and the communication and leadership capacities needed in modern working life. Engineering graduates in a modern society must be able and willing to learn, have solid basic knowledge of the natural sciences, have basic engineering skills, have good knowledge of one's major technical discipline, have commitment to quality, have internationalisation oriented skills, have good communication skills, be able to work in teams, be able to lead and manage resources, demonstrate professional and ethical responsibility, and be able to deal with uncertainty and ambiguity (Varin, 1999).

The Conceive-Design-Implement-Operate Initiative

The CDIO Initiative is an innovative outcomes - based educational framework for producing the next generation of engineering leaders. It is based on a simple concept that as graduating engineers are expected to appreciate engineering *processes,* to be able to contribute to the development of engineering *products,* and to do so while working in an engineering *organisation,* whilst developing as *whole, mature and thoughtful individuals,* the approach to the CDIO Syllabus is based on the essential functions of engineering that graduating engineers should be able to **c**onceive-**d**esign-**i**mplement-**o**perate complex value-added engineering systems and products in a modern team-based environment.

The need for the CDIO Initiative

As stated above, industry leaders began to find that graduating students, while technically adept, lacked many abilities required in real world situations. To delineate their needs, some major companies created lists of abilities they wanted their engineers to possess. The CDIO Initiative is aimed at encouraging schools and departments of engineering to meet real world needs and rethink their educational designs. . The strategy to implement the CDIO Initiative has four themes.

1. The engineering education reform must take place in the CDIO skills based *curriculum* first, which is underpinned by a deeper working knowledge of technical fundamentals, to ensure that it addresses the appropriate material necessary to conceive and build successful systems and products. The curriculum is guided by three innovative curriculum structures, namely; the <u>cornerstone</u> that motivates students to be engineers by introducing engineering experiences and giving exposure to essential early skills that lead students to build something; the <u>conventional disciplinary subjects</u> that are better coordinated and linked to demonstrated practice required by engineering; and the <u>capstone</u> that includes a substantial experience in which students design, build and operate a product or system. Student projects, internships and co-ops become more integrated extensions of the overall learning experience.

2. Second, an improved *pedagogy* that takes into account the students´ prior experience and its effects on learning must complement the new curriculum. Increase in active and hands-on learning, emphasis on problem formulation and solution, and an increased emphasis on concept learning and enhancement of learning feedback mechanisms are areas that the CDIO Initiative concentrates on Third, it has been recognised that the key to educational improvement is to develop an effective *assessment* scheme so that the progress of students and improvement in the quality of the education provided can be tracked. The CDIO Syllabus codifies 80 identifiable attributes as important assessment statements of learning objectives for graduating engineers. The assessment tools embrace creativity, design and entrepreneurship and include portfolios, design reviews and desk critiques while students become more responsible for not only learning but also for self and peer assessment. Attitudinal change and skill progression are assessed. Assessment takes cognisance of both the university and workplace based instructions and experiences These references seem to have nothing to do with CDIO assessment

Finally, as in the CDIO Initiative engineers design and build products and systems to enhance integrated theory-practice or knowledge-application concepts, *modern engineering workshop/laboratories* that are conducive to this approach must be developed. By providing students with repeated authentic design-build experiences, they develop and reinforce a deep working knowledge of the fundamentals and learn the skills to design and develop new products and systems. Experiences in conceiving, designing, implementing and operating are woven into the curriculum, particularly in the introductory cornerstone and concluding capstone.Two types of workshop/laboratories are a basic requirement for a successful CDIO Initiative based approach. First, the creation and staffing of *browsing laboratories* provides areas where preassembled experiments can be operated by students with technical supervision to reinforce or supplement concepts learned in the classroom. Second, the Industrial Design Engineering (*IDE) - expand Studio*, a laboratory for supporting teams working with virtual prototypes and a physical prototype workshop where engineering projects of significant scope are developed by students, is an essential element in the Conceive-Design-Implement-Operate approach of systems and products.

The CDIO Syllabus

Educating students in an increasing broad range of technologies (technical knowledge) while simultaneously developing learners' personal, interpersonal and system-building skills are two high level objectives within contemporary engineering education. The CDIO Syllabus´s general objective is to summarize formally a set of knowledge, skills and attitudes desired and can be used to define expected outcomes in terms of learning objectives of the personal, interpersonal and system/product building skills necessary for modern engineering practice. The specific objective is to create a *rational, complete*, *universal* and *generalisable* set of goals for engineering education.

As engineers recognize that a product/process will meet the needs of the customer if designed to a well developed set of requirements, the following approach to the CDIO Syllabus is highly recommended:

1. Technical Knowledge and Reasoning	1.1 Knowledge of Underlying Sciences 1.2 Core Engineering Fundamental Knowledge 1.3 Advanced Engineering Fundamental Knowledge
2. Personal and Professional Skills And Attributes	2.1 Engineering Reasoning and Problem Solving 2.2 Experimentation and Knowledge Discovery 2.3 System Thinking 2.4 Personal Skills and Attitudes 2.5 Professional Skills and Attitudes
Interpersonal Skills	2.6 Teamwork 2.7 Communications
3. Conceiving, Designing, Implementing and Operating Systems in the Enterprise and Societal Contexts	3.1 External and Societal Context 3.2 Enterprise and Business Context 3.3 Conceiving and Engineering Systems 3.4 Designing 3.5 Implementing 3.6 Operating

The formulation of the functions of an engineer from which the CDIO Syllabus is derived, does not in any way diminish the role of engineering science or engineering research. On the contrary, it should be recognised that the undergraduate students are being educated to be engineers. Therefore, 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, designing, implementation and operation* of systems and products.

Structure of the CDIO Syllabus

Engineers engineer, that is, they build systems and products for the betterment of humanity. Simply stated, graduating engineers should appreciate the engineering *process,* be able to contribute to the development of engineering *products,* and do so while working in engineering *organisations.* 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 organisation of the CDIO Syllabus as illustrated below:

4. CDIO
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*

1. Technical Knowledge and Reasoning	2. Personal and Professional Skills	3. Interpersonal Skills
1.1 Advanced Engineering Fundamentals *1.2 Core Engineering Fundamentals* *2.3 Scientific Knowledge*	*2.1 Engineering Reasoning and Problem Solving* *2.2 Experimentation and Knowledge Discovery* *2.3 System Thinking* *2.4 Personal Skills and Attributes* *2.5 Professional Skills and Attitudes*	*3.1 Team work* *3.2 Communications*

Above tables are a repetition of table on bottom of previous page, just shown differently

A mature individual interested in technical endeavours possesses *Personal and Professional Skills* which are central to the practice. In order to develop value-added engineering systems, students must have mastered the appropriate *Technical Knowledge and Reasoning.* In order to work in a modern team-based environment, students must have developed *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.*

How the CDIO Syllabus is Organised

The CDIO Syllabus is organised at the first two levels in a manner that is rationale. The first level reflects the function of an engineer, who is a well developed individual, involved in a process which is embedded in an organisation, and with the intent of building products. The second level reflects much of the modern practice and scholarship on the profession of engineering. 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. analyse the audience). This level of details has many benefits for faculty members as it gives allowance to gain insight into content and objectives, to contemplate the deployment of these skills into a curriculum, and to prepare lesson and assessment plans.

Implications for South African Engineering Education

In support of the National HRD Strategy (RSA 5000 2001) that states that the South African people will be provided with a solid educational foundation for social participation, and will also be empowered to develop the relevant and marketable skills at further and higher education levels, the **National Plan of Higher Education (DOE 2001)** states:

> ``It is crucial to equip all graduates with the skills and qualities required for participation as citizens in a democratic society and as workers and professionals in the economy. This should not be seen in a simplistic vocational sense as there is increasing evidence to suggest that narrowly technical skills are becoming less important than knowledge management and organisational skills. What evidence there is suggests that employers, in addition to technical skills, want graduates who can demonstrate a strong array? of analytical skills and a solid grounding in writing, communication and presentation skills``.

The Plan adopts Gibbons' (1998) skills requirements that must underpin all graduate education in South Africa, and the skills required are computer literacy, knowledge reconfiguration skills, information management, problem-solving in the context of application, team building, networking, negotiation/mediation competencies and social sensitivity. Not relevant to the CDIO Initiative

Conclusion

In my continued search for the most relevant higher engineering education programme to equip engineering educators with the necessary required skills and from the experience drawn from my PhD study on the Cognitive Science Philosophy, Mbanguta (2000) I am most convinced that the Conceive-Design-Implement-Operate Philosophy will meet the expectations and will also equip the next generation of graduate engineers with the necessary skills required by industry and society. As an increasing number of institutions are gaining the CDIO Initiative membership and abiding by the basic infrastructural requirements, this is an assurance that a more uniform approach to higher engineering education is adopted. If an increasing number is gained from developing countries as well, the sharing of program offerings in accordance with each university's strength, will receive high priority to ensure that steps towards bridging the skills and technological gap that exists between North and South are taken. However, mutual respect and recognition as equal partners is of utmost in this partnership. The moving around of students to both North and South countries in program attendance will enrich students, faculty and countries immensely. An institution that has the required infrastructure will offer the full CDIO Initiative skills based program.

The introduction of the CDIO Initiative will be phased in at credit-based masters and doctoral degree programs for the primary aim of retraining educators to equip them with the CDIO skills. The admission requirement will be a B Eng or B Sc (Eng) or B Tech (Eng). The retraining of educators first will ensure that the necessary reforms focussing on the education of a new engineering graduate are well executed. The overall development and implementation of the CDIO based curriculum will be phased in at the same time.

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Student involvement in principled change: Understanding the student experience

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Abstract

The CDIO Initiative is an international collaboration to reform engineering programs of each participating institution. Student representatives are actively involved in the process together with faculty and staff. In order to better represent a majority of students the student representatives initiated and carried out a survey of learning experiences among their peers. In the three participating Swedish engineering programs students were interviewed about their study experiences.

The student representatives discovered that they lacked a framework to interpret the interview data, and they were unsure how findings could be used to improve education. They teamed with pedagogical staff involved in the CDIO Initiative to link survey data to concepts from literature.

Frank quotes from the interviews are used to illustrate concepts such as deep and surface approaches to learning, assessment effects on learning, hidden curriculum, cue-seeking, motivation factors etc. This shows that theory is relevant to understand our context and improve education.

Based on evidence from the interviews we show how several aspects of course design affect student experiences of learning, and recommendations are made regarding changes. A separate “Top 10 list” of concrete recommendations was distilled in order to maximise potential dissemination.

1. Introduction

1.1 About the CDIO Initiative
The CDIO Initiative is an international collaboration to reform engineering education. The CDIO Syllabus[1] is a set of goals for engineering education, explicitly including personal, interpersonal and professional skills. It is the basis for curricular improvement in constructive alignment.

Members of the CDIO Initiative are Massachusetts Institute of Technology, Chalmers University of Technology, Linköping University, Royal Institute of Technology (KTH), Queen's University, Belfast, Technical University of Denmark and United States Naval Academy. Each institution is reforming at least one program.

1.2 Background of the study
In the CDIO Initiative, student representatives are working actively in the change process together with faculty and administrators. In order to better represent a majority of students, the CDIO student representatives initiated and carried out a survey of learning experiences. The same survey was done in the three participating Swedish engineering programs, Vehicle Engineering at KTH, Mechanical Engineering at Chalmers and Applied Physics at Linköping University.

However, after conducting and transcribing the interviews, the student representatives discovered that they lacked a framework to interpret the data. Most of all, they were unsure how findings could be used to improve education. The solution was to team with staff members involved in the CDIO Initiative. Together we have linked survey data to concepts from literature and to a previous survey[2] with the teachers of the same three engineering programs.

The aim with the collaboration was
- to help the students develop a framework to analyse student experiences and make well-founded suggestions for changes in course design.
- to send the message about necessary change from the students.
- to show that theories on teaching and learning are appropriate to describe our own students’ experiences in our own programmes, and can be used to improve practise.

2. Method

2.1 About the interviews
The participating students were picked randomly from year one and four. In total 56 students were interviewed by the student representatives. Interviews lasted about one hour.

The interviews at Chalmers and KTH were done in groups, and the group interviews were audio recorded and transcribed. In Linköping the interviews were done one-on-one and recorded by taking notes. It turned out that the answers were very consistent among the three universities, independent of the interview format.

2.2 Questions

Questions were developed with the aim to make the interviewed students reflect on their own learning.

1. Describe your program: How do the courses generally work? What methods of teaching have you experienced?

2. What methods do you use to learn outside scheduled hours and how do they work?

3. What motivates you in your studies? What influences/decides - how much you study? – when you study? – the kind of study task you do?

4. What do you feel is the focus of learning in your classes now? Does this focus help you? Do you feel that you can apply your knowledge afterwards? What kind of focus would improve your learning?

5. What is it that defines the course to you? How do you know what to study and when you have succeeded? What if different sources say different things? What are most important?

6. How does the assessment influence your way of studying?

7. Do you feel efficient while you study or do you think you could do more/better? If so, what could change your way of studying?

8. Have you had any classes that have especially inspired and motivated you? How did the class accomplish this? Did it enhance your learning in that subject area?

9. What changes or other learning methods would you like to see implemented in classes to improve your learning?

3. Analysis and selection of topics

Upon reading the interview transcripts, we noticed that certain topics permeated the students' answers. **Assessment** was the dominating topic - in fact**,** it didn't matter much what the original question was, the answers almost always concerned some aspect of assessment. The second most common topic was **Motivation**. We also identified the topics **What defines the curriculum**, **Approaches to and quality of learning**, **Interaction** and **Time/Planning.** The analysis of the topics **Interaction** and **Time/Planning** are not included in this paper. All these topics are of course interdependent.

For each topic we looked for theory to provide a framework for interpreting the students' statements. We chose to read literature which was fairly accessible to engineering students with a keen interest but without any formal education in pedagogy:

- John Biggs, Teaching for Quality Learning at University (1999)
- Graham Gibbs, Improving the Quality of Student Learning (1992)

- Graham Gibbs, Using Assessment Strategically to Change the Way Students Learn (from Assessment Matters, ed. Brown & Glasner 1999)

4. Topic: What defines the curriculum?

4.1 Summary from literature

How do students decide what defines the course? Do they read the course objectives and other official information about the course, note what is said in lectures, read the literature, do the coursework or study old exams? What sources are most important?

The extent to which students were cued in to the assessment system is a strong predictor of their overall performance. **Cue-seeking** or cue-conscious students will work out hints about examination, they will find out what is the hidden curriculum.

Students quickly learn to see behind the formal curriculum (as expressed in the course objectives) and orient themselves to **the hidden curriculum**, which is defined by what counts in assessment. It can be very different from the official curriculum, which often aims at a higher level of understanding.

In summary: It is not curriculum which shapes assessment; it is assessment that shapes the curriculum. Or even: **Unless assessment tasks mirror the curriculum, they will erode it**.

4.2 Results from interviews

The **course objectives are not used** as guidance by the students. This result was expected, as most courses in these programs had objectives written in formats like: "students should be able to understand...". The course objectives are considered "fuzzy" and the students aren't able to determine when they have reached the objectives. Instead, they focus on other sources that are more important to them:

- The course objectives are very unclear and they don't give that much [guidance]. It's pretty hard to know what 'good knowledge' is. By testing yourself on previous exams you get a clear picture of what you know.
- The course objectives are so huge; the lecturers bring up what is most important.

The **course literature** is mentioned by a few students who have a special interest in the subject, but many do not read the text books. Many students follow the **coursework schedule** (recommended problems to solve each week). But it is overwhelmingly clear from the interviews that **what really counts is the assessment**. Assessment shapes what the students are oriented towards in their learning. The exam has the **overriding importance** over anything else, be it the course objectives or the recommended coursework. Many students report that they are cue-seekers, trying to **find out what will be assessed**, in order to concentrate on that. Cue seeking is also done **collaboratively**. All students **study exams from the previous years** in order to understand what is important in the course. Lectures are also an important source of cues.

- You focus on the exam. If you know what the exam will be about, you will study that.
- I look in old exams for typical exam tasks and learn those.

- If you don’t go to the lectures, you’ll miss what is considered important. Then you have to study all of it.
- The goal is set by what will be on the exam, which in turn is based on what the lecturer says during lectures.
- Before the exams it feels good to work together so you know that you don’t do the wrong things.

In summary, students strategically orient themselves towards **the hidden curriculum**, which is defined by assessment. This would not be a problem if assessment was properly aligned to the objectives, but in reality the hidden curriculum can be **very different from the official curriculum**.

- I’m sorry. The exams aren’t always so difficult and you can actually make it through [university] without knowing very much.
- To get a higher grade you need to be able to solve the problems that are different each year, but to pass you only need to practice on five previous exams.

5. Topic: Assessment

5.1 Summary from literature

Assessment dominates in several ways what students are oriented towards in their learning. It affects student learning by

- Communicating, or rather: defining, the intended learning outcomes.
- Generating time on task.
- Distributing the time spent working during the length of the course.
- Generating the kinds of learning activity the students will do.
- Providing feedback on progress.
- Affecting what learning strategy students will adopt (deep or surface).

Constructive alignment is when teaching and assessment are in harmony with the objectives. That means that the strong influence that assessment has on student learning is used as a positive force. Assessment will support student learning in a beautiful way when the assessment tasks generate appropriate learning activities, help students getting started and keep working across the course, give early success which drives motivation, and provide timely feedback that the students pay attention to.

On the other hand, badly designed assessment will be a strong negative force. **Unless assessment tasks mirror the official curriculum they will erode it**. The **hidden curriculum** is shaped by the assessment requirements. This can be very different from the official curriculum, if the assessment system rewards a lower level of understanding than the intended learning outcomes.

5.2 Results from interviews

Students reported that final exams made them **postpone their studying** until the last moment. A previous survey[2] has shown that all courses in these programs have final exams (with only a few exceptions in Linköping). The message came through very clearly:

- In a course with a final exam you feel that learning the content can wait, and then you don't spend so much time.
- Some courses you neglect until the week of the exam. You can actually cram in some courses in a few days.
- I think final exams are hard, because then I think that it's not until six weeks later that I need to know this, and I can relax until then.
- I can think that this time I will start early and do a little each day. But it has never happened so far. (student in the fourth year)

Assessment tasks early in the course help students **getting started** with their own work in the course. Giving the necessary igniting spark is an important function of assessment. Many students report that continuous assessment helps them **spend more time** on the course. The pressure from deadlines makes the students keep up. Students also report that they **learn better** from doing coursework during the course than from intense cramming for exams. We think this is because they spend more time on task, but probably also because coursework seems to lead to more effective study habits.

- Tasks that you have to do during the course makes you start studying and you get into the subject earlier.
- If you have deadlines all the time, then you spend time on the subject.
- When assessment is spread over the whole duration of the course you learn better.

In summary, continuous assessment tasks helped students get started, made them spend more time on the course and also learn better. However, some students feared that the **total workload could be overwhelming** if parallel courses have continuous assessment.

- If you would have three courses in parallel which don't have final exams you would be totally burnt out.

How the assessment is designed will also **affect the kind of work** the student will do. One example which is mentioned is **aids in exams.** Examples of aids are textbooks, books with formulae, or the student's own notes. An **exam where aids are not allowed can encourage students to adopt a surface approach**, because they focus on memorisation instead of understanding. Being allowed to bring aids will change how and what students do to study before the exams, as memorisation is no longer necessary or relevant. Another important consequence is of course that the teacher cannot construct the same kinds of questions for open book exams.

- In the first years you are mostly not allowed to bring any aids to the exams. Then you don't focus on being able to apply this knowledge afterwards, but more on what you are supposed to learn in the course.
- I once wrote an exam where you were allowed to bring 'everything'. There you had to first understand the problem, and then how to solve it. I think that feels more useful.

6. Topic: Motivation

6.1 Summary from literature

The expectancy-value theory of motivation cites two factors that make students want to learn:

1. They must perceive the topic to be important; it must have some **value** to them
2. They must expect that it is possible to accomplish the task; they must **expect success**.

Motivation is the result of these factors multiplied. If either of them is zero, then motivation is zero. There are four dimensions of value that the learner can assign to the task:

- **Intrinsic motivation**: performing the task driven by their own interest. The task itself can bring immediate satisfaction, or it will contribute to future satisfaction. Intrinsic motivation is strongly related to a deep approach to learning. Students experience a need to know; they have ownership over their own learning; it matters to them.
- **Social motivation**: performing the task in order to please others whose opinions are important to them. Social motivation is a good precursor to intrinsic motivation. Teachers can create social motivation, and the social dimension of many learning situations can increase motivation, as it is important to students to look good in front of peers and teachers.
- **Extrinsic motivation**: performing the task because of the value they attach to what the outcome brings. The outcome itself is more important than learning. The task is something that has to be got out of the way in order to pass the course, receive the student loan etc.
- **Achievement motivation**: performing the task in order to compete and win. Here, learning is less important than winning, and the task must be handled as grade-effectively as possible.

What about the second factor then? What will influence a learner to expect success or failure? **Previous experience** will influence expectations. After success, the student will expect to succeed again, if the conditions that are believed to lead to success are the same. **Clear goals and criteria** are important to make it possible for students to expect success. Students must know where they are going, and know what work they have to do in order to get there. Expectancy is at risk if the course communicates unclear or unreasonable goals, for instance when trying to cover too much content. Giving students **feedback on progress** early in the course is important. Formative assessment will help students get started and keep working, and offer a chance of "early success" which, in turn, enhances motivation.

6.2 Results from interviews

It is clear from the interviews that an **early success** in a course will spur motivation.

- If you get the right answer on a calculation assignment you continue with the next one and it gets fun. If it's difficult you get unmotivated and you spend less time on it. One should really put more time into things that work badly but it doesn't work that way.
- When it works well it's easier to study and then the whole course feels more meaningful.

Two kinds of motivation seem to matter most to the students: **intrinsic motivation** and **social motivation** are mentioned very frequently. Intrinsic motivation is very satisfactory. Some students bring intrinsic motivation with them when entering the course, but students note that it can as well be created during the course.

- The interest for the subject is the most important. It can be a prior interest or it can be created during the course.
- With some courses I can feel ‘Oh no not another math course’. But then you get some understanding for something in that course and then it suddenly feels great fun in a way.
- I spend much more time on courses that feel relevant to me, but at the same time less, because it’s easier for me to pass these exams.

Reaching a deeper level of **understanding** is clearly desirable to the students. What is mentioned above all is **being able to apply** knowledge. This clearly gives a sense of ownership. On the other hand**,** rote learning is perceived as boring.

- Knowledge is motivating. Being able to answer a question makes you feel motivated and you think it’s fun.
- [These] courses are interesting because we solve problems. Then you learn better and it’s more fun. They are also better connected to what I want to work with and that’s why they become more interesting.
- Some courses are very theoretical and based on rote learning. They tend to be very boring.
- In the fourth year courses focus more on problem solving, which is very satisfying to be able to do on your own.

The influence of **the teacher** is considered extremely important. A “good” teacher is often mentioned when the students are asked to describe a course that especially inspired and motivated them.

- In [one course] the teachers were carefully chosen and really wanted to share what they were doing. Then it was so fun that you almost want to go on over the break and just hear more. In other courses the teacher seems almost forced to stand there.
- Some lecturers made you interested in their subject. Some failed completely, so you thought that you never want to take that subject.
- It depends totally on how the lecturer is, the subject itself can be so and so.

In many cases, the social motivation also comes from **peers**.

- Having study mates helps you getting up in the morning to go to school.
- In one course we had calculations as homework twice a week. Every time the teacher picked a student at random who had to present the week’s homework. This gave motivation [to prepare], because you did not want to stand up and say that you couldn’t do it.

When all else fails, **extrinsic** motivation is also present.

- Totally honestly, you often study just to pass the exams. Sometimes the subjects are interesting but not enough to give the energy it takes to learn all of it.
- When you start on a job you will do completely other things anyway and the education is just to prove that you are able to learn and understand things.
- You study just to get the credits so the money keeps coming.
- In certain courses you feel that you don’t want to learn more than what it takes to pass. I feel that there is nothing in [course] which I will have used for and that I find interesting.

7. Topic: Approaches to learning / Quality of learning

7.1 Summary from literature

Students have different intentions driving their learning. Trying to achieve different things, make them go about their learning differently. Two extreme approaches to learning are identified: surface and deep approach.

In **surface approach** the intention is to reproduce the subject matter, typically in an exam. The focus is on isolated facts; items treated independently of each other. This prevents students from grasping the meaning and structure of the subject; they see trees, not woods. Emotionally, learning becomes a drag, a task to get out of the way. Memorisation is a surface approach when used to fake understanding. Knowledge is poorly structured, and rapidly forgotten. It is possible to achieve a good grade using the surface approach, as long as the assessment system rewards rote learning. But exam results do not predict long term retention. The reason for this can be that intensive revision for exams involves a surface approach.

In **deep approach** the intention is to make sense of what is learned. The focus is on underlying meaning: on main ideas, themes, principles or successful application. This requires a sound foundation of relevant prior knowledge, so students will naturally try to learn the details, as well as making sure they understand. When using a deep approach in handling a task, students have positive feelings. A deep approach is likely to result in long-term retention. Coursework results are a good predictor of long term recall.

An approach is not the same thing as a skill or characteristic of the student. Instead, **most students can adopt both surface and deep approaches** to their learning, responding strategically to the perceived demands of the course or task. Inappropriate course design, teaching methods and assessment can foster a surface approach.

7.2 Results from interviews

Many students describe using **a surface approach.** They describe **ineffective study habits** when concentrating their studies to the end of the course or when they study old exams. Memorisation is used as a substitute for understanding. This is bad for motivation and long-term retention.

- Most courses are based on learning by heart. In the first years you are mostly not allowed to bring any aids to the exams. Then you don’t focus on being able to apply this knowledge afterwards, but more on what you are supposed to learn in the course.

- Take away rote learning, you loose it quickly anyway. More understanding!

For a majority of students **the route to understanding is through application**, not through derivations and theory. The focus of many courses is seen as mainly theoretical, and many students point out that **theory is memorised for the exam** rather than applied and understood. Interviews[2] with teachers have shown that practically all courses have a bottom-up approach, starting with theory, and only after that problem-solving and practical application. Apparently this is badly received by the students:

- In some courses you are supposed to know every little step of the derivations. It feels unnecessary, it would be better to know how to arrive at something than learning it by memorisation.
- We should move the focus more to application, to get a grip on what it's all about. I don't feel that I can apply the knowledge I have.
- Connection to real problems is good. You don't want to sit there with a theory cake which you cannot eat from.
- What the teachers want to know is you've studied the theory. You often study for the exam and then forget. Instead of focusing on why and how you do something, it is much rote learning.
- The new [course] really got an understanding approach and you're allowed to bring books on the exam. Knowing by heart is really useless. It is much more fun if you understand, and you remember much more.
- I want to see the practical use before theory, because that motivates the theory.

One quote shows that the same student can use **both a deep and surface approach** in the same course. Here the strategy adopted **depends on the assessment task**: coursework is done with a deep approach and cramming for the exam is done with a surface approach. This student also observes how a deep approach results in long-term retention:

- The things I remember from a course are the parts we had assignments on. Then I really sat down with the problem and worked out the solution myself. If you work on old exams you check up the correct answer too quickly and then move on without really learning.

Another reason to take a surface approach is **time pressure** due to **content overload**, which the students think is very common.

- I think they want us to learn a lot of unnecessary things 'just in case'.
- Many courses dig too deeply into a subject for [the amount of] credits. They include too much and you only have time brush against the surface of a huge subject.
- Of course you should really know all of it to be a good engineer, but it just isn't possible.

Some of the students, especially in their fourth year, have clearly found intrinsic motivation. It seems that their **deep approach to learning is effective**.

- This is really my dream education because I want to design vehicles. I spend much more time on the courses which feel relevant to me, but at the same time less time, because I pass the exams easier.
- In year four you understand more about what you're doing, you absorb knowledge much better when you know how it can be used.

8. Conclusions and recommendations

The results show that concepts from theory are indeed appropriate to interpret student experiences. We have let frank interview quotes illustrate the concepts, to show that the theory is relevant in our context. By applying the concepts we also improve our own understanding of them. Based on the evidence from the interviews, we have identified certain problematic practises in the education programmes. Supported by the literature we then recommend some changes to the courses. A separate "Top 10 list" (Appendix A) of concrete recommendations regarding changes was distilled in order to maximise potential dissemination. We have focused on such changes that are within the power of an individual teacher.

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Appendix A. Top 10 recommendations

1. **Set clear objectives that are relevant to the engineer: "After this course you will be able to..."**
   This will increase motivation.

2. **Design assessment tasks and teaching that are relevant to the objectives.**
   This will define the course objectives to the students and engage them in the appropriate learning activities. Motivation is strong when students experience a need to know things in order to carry out tasks that matter to them.

3. **Focus on working knowledge of basic concepts and provide connections to reality. Application is the road to understanding theory.**
   This will encourage a deep approach to learning by increasing intrinsic motivation, giving better understanding and long-term retention.

4. **Prioritise. Remember: coverage is the enemy of understanding.**
   This will reduce time stress, which is an important reason why students adopt a surface approach to learning.

5. **Set an assessment task early in the course.**
   This will help students getting started and provide an opportunity for early success, which is a motivation factor. Getting feedback in a timely, effective manner, will help students learn.

6. **Set assessment tasks regularly during the course.**
   This will help students spend time on tasks and keep up the pace of work. Getting feedback and responding in a timely, effective manner, will help students learn.

7. **Produce explicit criteria for assessment. Make sure students know exactly what is expected of them.** This will take away the hidden curriculum and reduce the cue-seeking game.

8. **Design tasks and activities with built-in interaction. Use both peer interaction and student-teacher interaction.**
   This will increase social motivation and encourage deeper understanding.

9. **Make a realistic plan for the time the students spend on the course. Get regular feedback on the actual time spent on tasks. Coordinate deadlines and workload with parallel courses.**
   This will reduce time stress.

10. **Show with your enthusiasm that the course and its tasks are worth doing.**
    This will promote social motivation.