Chapter 2
The CDIO Approach

Introduction

The objective of engineering education is to educate students who are "ready to engineer," that is, broadly prepared with both pre-professional engineering skills and deep knowledge of the technical fundamentals. It is the task of engineering educators to continuously improve the quality of undergraduate engineering education in order to meet this objective. Over the past 30 years, many in industry and government have tried to describe these desired outcomes in terms of attributes of engineering graduates. By examining these views, we identified an underlying need: to educate students to understand how to Conceive-Design-Implement-Operate complex value-added engineering products, processes and systems in a modern, team-based environment.

The CDIO approach suggests a pathway for engineering education to meet this underlying need. The approach is built on three premises, which reflect its goals, vision, and pedagogical foundation:

- That the underlying need is best met by setting goals that stress the fundamentals, while at the same time making the process of conceiving-designing-implementing-operating products, processes, and systems the context of engineering education.
- That the learning outcomes for students should be set through stakeholder involvement, and met by constructing a sequence of integrated learning experiences, some of which are experiential, that is, they expose students to the situations that engineers encounter in their profession.
- That proper construction of these integrated learning activities will cause the activities to have dual impact, facilitating student learning of critical personal and interpersonal skills, and product, process, and system building skills, while simultaneously enhancing the learning of the fundamentals.

This chapter outlines the key features of the CDIO approach, beginning with a detailed discussion of the need, goals, vision, and pedagogical foundation, first addressed in Chap. 1. The structure of this first section serves as the framework for

E. F. Crawley et al., *Rethinking Engineering Education*,
DOI: 10.1007/978-3-319-05561-9_2,

many of the remaining chapters of the book. The foundational principle that CDIO is the preferable context of engineering education is discussed in the second section of the chapter. The third part of the chapter describes approaches to adaptation and implementation, and underscores the need to recognize educational reform as a process for organizational change at the university.

Chapter Objectives

This chapter is designed so that you can

- Explain the need, goals, vision, and pedagogical foundation of a CDIO approach
- Describe the authentic context of engineering education
- Describe the basics of the CDIO Syllabus and the CDIO Standards
- Explain how to implement a CDIO approach

The CDIO Approach

CDIO is an approach to the contemporary reform of engineering education. It is founded on a few key ideas, the first two being a restatement of the underlying need for reform of engineering education and a set of goals for engineering education. Central to the CDIO approach is a vision for engineering education that includes the use of the engineering lifecycle process as the context of engineering education. A specific pedagogical foundation supports the realization of this vision. These key ideas are presented in this section.

The Underlying Need

We began by examining the sources of advice from industry that reflected on the needs for the education of engineering students. The input typically was in the form of "lists" that industrial spokesmen and regulatory bodies had developed to summarize the desired attributes of engineers—that they should know the fundamentals, act ethically, communicate effectively, etc. In this format, the lists conveyed the needs, but not the rationale for the needs. As such, they did not have their desired influence. When we tried to synthesize these "lists", we observed that they were driven by a more basic and rational need, that is, the reason society needs engineers in the first place.

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

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

More simply, we must educate engineers who can engineer. Graduating engineers are expected to appreciate engineering tasks, to be able to contribute to the development of engineering solutions, and to do so while working in engineering organizations. Implicit is a fourth expectation that university graduates should be developing as mature and thoughtful individuals. *Conceive-Design-Implement-Operate* is a model of a product, process or system lifecycle, and gives the approach its name. The emphasis is not on this particular lifecycle model—there are many alternatives to this one—but rather that engineers should be able to participate and lead various phases of the lifecycle. Products, processes and systems are proxies for the vast array of solutions and outputs of engineering. We define *value-added* as the additional worth created at a particular stage of development or production. A *modern team-based environment* describes the potentially interdisciplinary and international organization in which engineers work, assisted by modern technology. If we accept this conceive-design-implement-operate restatement of the need, we can then derive more detailed goals for the education.

The Goals

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

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

Let's begin by discussing the goals in some detail.

Goal #1. Engineering education should always emphasize the technical fundamentals. The university is the place where the foundations of subsequent learning are laid. Nothing in our approach is meant to diminish the importance of the fundamentals or of the students' need to learn them. In fact, deep working knowledge and conceptual understanding are emphasized. Conceptual understanding is the ability to apply knowledge across a variety of unencountered instances or circumstances [1]. It is not memorization of facts and definitions, nor is it the simple application of a principle that contains the concept, for example, the application of the First Law of Thermodynamics. Rather, conceptual understanding represents ideas that have lasting value and offers the potential to engage students. Traditional teaching often uses a transmittal approach in which students are assumed to gain knowledge while passively listening to lectures. In a CDIO approach, the goal is to engage students in constructing their own knowledge and in confronting their own misconceptions. The transition to conceptual-change instruction from the long-standing transmittal approach is difficult. Marton and Säljö [2] call this transmittal approach a surface approach to learning, and contrast it with a deep approach to learning. Table 2.1 is an adaptation of Marton and Säljö's seminal work, based on the writings of Gibbs [3], Rhem [4], and Biggs [5]. The statement of the goal of educating

Table 2.1 A surface approach to learning versus a deep approach to learning

A surface approach is encouraged by	A deep approach is encouraged by
An excessive amount of material in the curriculum	Student perceptions that deep learning is required
Relatively high class contact hours	A motivational context
A lack of opportunity to pursue subjects in depth	A well-structured knowledge base
A lack of choice of subjects and methods of study	Learner activity and choices
Threatening and anxiety-provoking assessment	Assessment based on application to new situations
A competitive environment	Interaction with others and collaboration

students who are able to master a deeper working knowledge of the technical fundamentals is meant to contrast this approach with that of the transmittal approach in current practice. This idea is addressed again in Chap. 6.

Goal #2. The second goal is to educate students who are able to *lead in the creation and operation of new products, processes, and systems*. This goal recognizes the need to prepare students for a career in engineering. The need to create and operate new products, processes, and systems drives the educational goals related to personal and interpersonal skills, and product, process, and system building skills. Personal skills and attitudes include modes of thought, for example, analytical reasoning and problem solving, experimentation, system thinking, and critical and creative thinking. Personal attitudes and attributes include integrity, responsibility, curiosity, and a willingness to make decisions in the face of uncertainty. Interpersonal skills encompass communication and teamwork. Product, process, and system building skills and knowledge include conceiving, designing, implementing, and operating products, processes and systems within an enterprise, societal, and environmental context. The more specific learning outcomes that flow from this goal are discussed in a later section and are the main focus of Chap. 3.

Goal #3. The third goal is to educate students who are able to understand the importance and strategic impact of research and technological development on society. Our societies rely heavily on the contributions of scientists and engineers to solve problems. However, research and technological development must be paired with social responsibility and a move toward sustainable technologies. Graduating engineers must have insight into the role of science and technology in society to assume these responsibilities. This goal further recognizes that some students will not become practicing engineers, but will pursue careers as researchers in industry, government, and higher education. Despite different career interests, all students benefit from an education set in the context of product, process, and system development. First, they benefit from fulfillment of the first goal of deep learning of technical fundamentals. Second, engineering researchers need to understand the connection between their efforts and the eventual impact on a product or system. Successful researchers are increasingly recognized for their impact on society in addition to their scholarship. Therefore, it is important for students who embark on careers in research to understand how technology infuses products and processes, and to be able to judge and improve the strategic value of their work.

Goals #1 and #2 represent the tension in engineering education – between stressing knowledge of technical fundamentals versus skills. Most engineering educators agree that these two goals are important, but they disagree about how much time to spend on each. If the model of education is a transmittal process with fixed maximum effective transmittal rate and fixed duration, the tension between technical fundamentals and skills intensifies. The CDIO approach is based on an alternate view of education that helps to relieve that tension. We believe that it is possible to strengthen the learning of the fundamentals and at the same time improve the learning of personal, interpersonal skills, and product, process and system building skills.

The vision

In order to resolve this tension, we have developed a systematic vision for engineering education that encompasses the entire educational program. The CDIO approach envisions an education that stresses the fundamentals, set in the context of conceiving-designing-implementing-operating products, processes, and systems. The salient features of the vision are that:

- Education is based on clearly articulated program goals and student learning outcomes, set through stakeholder involvement.
- A curriculum organized around mutually supporting disciplinary courses with activities interwoven that develop personal and interpersonal skills, and product, process and system building skills.
- Design-implement experiences set in both the classroom and in modern learning workspaces as the basis for engineering-based experiential learning.
- Active and experiential learning, beyond design-implement experiences, that can be incorporated into lecture-based courses.
- A comprehensive assessment and evaluation process

If we succeed in realizing such an education, then the dual outcomes of learning technical fundamentals and broader engineering skills will be met. Students will encounter a sequence of integrated learning experiences, some of which are experiential in that they expose students to the experiences that engineers will encounter in their profession. Proper crafting of these integrated learning experiences will cause them to have dual impact, simultaneously teaching skills and supporting the deeper learning of fundamentals. The sections that follow will expand on these seven features: context, fundamentals, learning outcomes, curriculum, design-implement experiences, active learning and assessment.

Conceiving-Designing-Implementing-Operating as the context. We assert that conceiving-designing-implementing-operating should be the context of engineering education. A context for education is the cultural framework or environment that supports learning. The culture of the education, the skills we teach, and the attitudes we convey should all indicate that conceiving-designing-implementing-operating is the role of engineers in their service to society. There are several important reasons that conceiving-designing-implementing-operating should be the context of education: (1) it is authentic, that is, it is the set of activities that real engineers perform; (2) it is much easier to teach skills in this authentic CDIO context; and (3) context helps to support learning, not only of skills, but also of technical fundamentals. The adoption of conceiving-designing-implementing-operating, or some other engineering lifecycle model, as the context of engineering is so central and foundational to the CDIO approach, that we have identified it as the first of the twelve effective practices, or CDIO Standard 1. This foundational principle is discussed in more detail in the second part of this chapter.

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

The observation that engineers conceive-design-implement-operate and that this should be the authentic context of engineering education seems so self-evident that it forces one to ask why this is not currently the common context of engineering education. Quite simply, it is that engineering schools are not populated by engineer practitioners but by engineering researchers. These researchers develop engineering science knowledge by conducting research with a reductionist approach that largely rewards the efforts of individuals. In contrast, in the engineering context, the focus is on producing engineering products and systems by conducting development with an integrative approach that largely rewards team efforts. At the same time, this desired context must still emphasize a rigorous treatment of the engineering fundamentals. Consequently, what we must recognize is that the transformation of the education from the current to the desired context is one of cultural change.

Some would argue that such a transformation is unimaginable in a university setting. In fact, the current tension in engineering education in many countries is the result of just such a transformation. As recently as the 1950s, and more recently in some countries, university engineering faculty were distinguished practitioners of engineering. Education was based largely on practice. The 1950s saw the beginning of the engineering science revolution, and the hiring of a cadre of young engineering scientists. The 1960s might be called the golden era, in which students were educated by a mix of the older practice-based faculty and the younger engineering scientists. However, by the 1970s, as older practitioners retired, they were replaced by engineering scientists. On average, the culture and context of engineering education took a pronounced swing toward engineering science.

Stressing the fundamentals. The intended consequence of this change was to place the education of engineering students on a more scientific foundation, equipping them to address unknown future technical challenges. Nothing proposed here is intended to minimize the importance of this change, or the vast contributions that engineering science research has produced in the last half-century. However, the unintended consequence of this change was a shift in the culture of engineering education. This shift diminished the perceived value of many of the key skills and

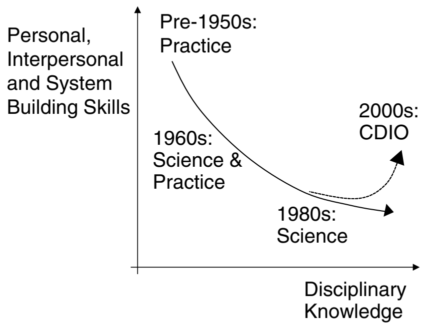

Fig. 2.1 The evolution of engineering education

attitudes that had been the hallmark of engineering education up to that time. It is not a coincidence, therefore, that in much of the developed world, the 1980s became the period in which industry started to recognize the change in the knowledge, skills, and attitudes of graduating students. Industry reacted in the 1980s with observations and expressions of concern. When these expressions did not bring results, industry responded with a more cohesive response in the 1990s, as previously discussed.

This evolution of engineering faculty composition can also be traced to a notional representation of the way in which a balance was struck between the teaching of personal, interpersonal, and process skills, and product and system building skills versus the technical fundamentals. Figure 2.1 illustrates this evolution. Prior to 1950, the context of practice prevailed. By the 1960s, more balance was prevalent. By the 1980s, engineering science dominated with a strong emphasis on technical fundamentals. The trend is shown as a trade-off curve because, assuming that education is an information transferring activity, limitations on bandwidth and time allow only a certain amount of content to be covered. If one accepts this model of education, it forces questions such as "*What must be removed to make room for more teaching of skills?*" We believe that there are alternative educational models to that of information transfer that allow relief from this apparent conflict. In fact, the remaining elements of the CDIO approach, described below, are an attempt to create a vision for an education that allows simultaneous improvement in learning of the disciplines and of the broader skills needed by successful engineers.

Learning outcomes. The first concrete task needed to adapt this vision into a model program was to develop and codify a comprehensive understanding of abilities needed by contemporary engineers. This task was accomplished through the use of stakeholder focus groups comprised of engineering faculty, students and industry representatives. The focus groups were asked "*What is the full set of knowledge, skills, and attitudes that engineering students should possess as they leave university?*" An example of thoughtful input from industry received through this process is that of Ray Leopold, former Vice President and Chief Technology Officer of Motorola's Global Telecom Solutions Sector. (see Box 2.1). Results of the focus groups, plus the views of industry, government, and academia on the expectations of university graduates were organized into a list of learning outcomes, called the CDIO Syllabus. The description, development, and validation of the CDIO Syllabus are the subjects of Chap. 3.

Box 2.1 The Need for CDIO Engineers in Industry

In my estimation, the greatest potential contribution of graduates of CDIO programs is their ability to perform their engineering skills with a more mature appreciation of how a product satisfies real societal needs. This requires project success, broadly defined, which is based on both engineering and non-engineering contributions. The engineer must be able to find not only engineering solutions to a problem, but also economic solutions that have a high potential of being successful. The engineer must define value propositions and find solutions to them. A graduating student must develop the skills not only to create brilliant new ideas, but also to transform those ideas into new realities.

As part of this process, engineering graduates must have a better understanding of the value they add to the organization. They must have better-developed personal skills, and be able to work with other engineers and with colleagues from other disciplines. The maturity of an engineer flows not only from knowledge of the breadth and depth of disciplinary knowledge, but also from the individual's experience in developing personal and professional skills.

Within industry, we generally try to determine what an individual knows, how an individual can contribute, the perspective an individual brings to us, and how well the individual fits into the culture of our organization. We often do not hire high-powered technologists who don't exhibit the people skills to fit into our team environment, or whose perspective seems to be limited to a narrow technical field. We want deep technical expertise, but that expertise must have a context, and the individual needs to be able to work with others. In an interview, I often ask behaviorally oriented questions, such as, "*From your educational experiences, tell me specifically about a time when you had to:*

- *deal with a person who didn't seem to be focused on the team goals*
- *redefine a value proposition*
- *adjust your work plans to meet a schedule.*"

The graduate of a CDIO program should be able to respond more richly to these questions, and their responses should connote an appreciation for the bigger picture while satisfying the problem at hand.

—R. Leopold, The Motorola Corporation

As shown in Table 2.2, the CDIO Syllabus classifies learning outcomes into four high-level categories:

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

Table 2.2 The CDIO Syllabus (v2.0) at the second level of detail

1 DISCIPLINARY KNOWLEDGE AND REASONING	**3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION**
1.1 KNOWLEDGE OF UNDERLYING MATHEMATICS AND SCIENCE	3.1 TEAMWORK
1.1 CORE ENGINEERING FUNDAMENTAL KNOWLEDGE	3.2 COMMUNICATIONS
1.2 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE, METHODS AND TOOLS	3.3 COMMUNICATIONS IN FOREIGN LANGUAGES
2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES	**4 CONCEIVING, DESIGNING, IMPLEMENTING AND OPERATING SYSTEMS IN THE ENTERPRISE, SOCIETAL AND ENVIRONMENTAL CONTEXT—THE INNOVATION PROCESS**
2.1 ANALYTICAL REASONING AND PROBLEM SOLVING	4.1 EXTERNAL, SOCIETAL AND ENVIRONMENTAL CONTEXT
2.2 EXPERIMENTATION, INVESTIGATION AND KNOWLEDGE DISCOVERY	4.2 ENTERPRISE AND BUSINESS CONTEXT
2.3 SYSTEM THINKING	4.3 CONCEIVING, SYSTEMS ENGINEERING AND MANAGEMENT
2.4 ATTITUDES, THOUGHT AND LEARNING	4.4 DESIGNING
2.5 ETHICS, EQUITY AND OTHER RESPONSIBILITIES	4.5 IMPLEMENTING
	4.6 OPERATING
	4.7 LEADING ENGINEERING ENDEAVORS
	4.8 ENTREPRENEURSHIP

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

> understand how to conceive, design, implement, and operate (section 4)
> complex value-added engineering products, processes, and systems (section 1)
> in a modern team based engineering environment (section 3), and
> are mature and thoughtful individuals (section 2).

The knowledge, skills and attitudes outlined in sections 2, 3 and 4 of the Syllabus are referred to as personal skills; interpersonal skills; and product, process, and system building skills. The first section, disciplinary knowledge and reasoning, is program specific, that is, it outlines the content of the specific engineering discipline. Sections 2, 3, and 4 are applicable to any engineering program.

The content of each section was expanded to second, third and fourth levels. Syllabus topics at the second level of detail were validated with subject experts. (Most of these validation studies used CDIO Syllabus v1.0 that did not include 4.7 and 4.8.) To ensure comprehensiveness, the Syllabus was explicitly correlated with documents listing engineering education requirements and desired attributes. We made an attempt to make the CDIO Syllabus a rational and consistent set of skills, derived from an understanding of needs that stakeholders would expect from graduating students. The complete CDIO Syllabus v2.0 is found in the appendix.

The CDIO Syllabus is nothing more than a reference or a template for learning outcome development. Each program must develop its own learning outcomes, perhaps by modifying the content of the Syllabus, and certainly by setting specific learning outcomes for students, validated by program stakeholders. Engineering education has four key stakeholder groups: students, industry, university faculty, and society. The learning outcomes of students in a program should be set in a way that reflects the viewpoints of these four key stakeholder groups. Industry is the ultimate customer for the students who graduate from our programs, and is informed about investments required for long-term benefit. Our graduates and others in industry are therefore a proxy for the long-term interests of the students. Students are the direct beneficiaries of education and the arbiters of consumer needs. University faculty are the developers and deliverers of the knowledge, skills, and attitudes, and they bring their own insights into the needs of students. Broader society, through national standards and accreditation, sets requirements on engineering education, including degree requirements and emphasis on societal goals. Thus, all four stakeholder groups have important views on educational goals. In order to translate the CDIO Syllabus topics and skills into assessable learning outcomes, we proposed methods to engage program stakeholders in order to determine the level of proficiency expected of graduating engineers in each of the Syllabus topics. The approaches are explained in Chap. 3.

The remaining features of the CDIO vision address the question, "*How can we do better at ensuring that students learn these skills?*" Broadly speaking, this requires reform in four major areas: (1) the structure of the curriculum and the content of courses; (2) the learning environment; (3) the way we teach; and, (4) the way in which we assess and evaluate the outcomes.

Curriculum Reform

To achieve the dual goals of deeper working knowledge of technical fundamentals and ability to lead in the creation and operation of new products, processes, and systems, we must improve the engineering curriculum. We cannot expect more resources, longer terms, more years, or other extensions to the curriculum. Consequently, we must re-task existing resources. The challenge is to develop an integrated curriculum. We must find innovative ways to make double duty of teaching time so that students develop a deeper working knowledge of technical fundamentals while simultaneously learning personal, and interpersonal skills, and product, process, and system building skills.

We should not leave this learning to chance, but instead should have an explicit plan for ensuring that students learn these skills. Accomplishing this integration may require changes to curriculum structure that exploit extra- and co-curricular and extra-campus learning opportunities, and the development of new teaching materials. To facilitate curriculum reform, we suggest retaining the disciplinary courses as the organizing structure of the curriculum, while making two substantive improvements. First, the disciplinary courses must work together to be mutually supporting, as they are in practice. Second, education in personal and interpersonal, and product, process and system building skills must be interwoven into the disciplinary education.

Designing a new curriculum requires benchmarking of the current curriculum to identify existing connections among disciplines and places where skills are already taught, and to identify omissions and overlaps. Three specific curricular structures are key elements of an integrated curriculum: (1) an introductory engineering experience that creates the framework for subsequent learning and motivates students to be engineers; (2) conventional disciplinary courses coordinated and linked to demonstrate that engineering requires interdisciplinary efforts; and, (3) a final project course—or capstone—that includes a substantial experience in which students conceive, design, implement, and operate a product, process, or system. With these new structures in place, an explicit plan to overlay skills can be developed. The new curriculum structure also facilitates co-curricular student projects, internships, and placements in industry that can significantly expand the time available for learning skills and enrich the overall learning experience. The result of such curricular reform is an integrated curriculum, which contains a sequence of well-planned learning experiences that help students meet the educational goals. Chapter 4 describes the design and development of an integrated curriculum.

Design-implement experiences and engineering workspaces. Engineers design and implement products, processes, and systems. Providing students with repeated design-implement experiences helps them develop deep working knowledge of the fundamentals and learn the skills to design and implement new systems. Since personal and interpersonal, and product, process and system building skills are derived from engineers' need to work in design teams, design-implement projects provide a natural setting in which to teach students these skills. In a CDIO program, experiences in conceiving, designing, implementing, and operating are woven into the curriculum, particularly in the introductory and concluding project courses. The concluding project course can be re-tasked into one that is closely linked to one or more disciplines and engages students in designing, implementing, and operating a product, process, or system. Aligning theory development with practical implementation gives students opportunities to learn both the applicability and limitations of theory.

If students are to understand that conceiving—designing—implementing—operating is the context of the education, then it is desirable to re-task existing laboratory space by building modern engineering workspaces that are supportive of, and organized around, conceiving—designing—implementing—operating. *Conceive* spaces are designed to encourage people to interact and to understand the needs of others and to provide a venue that encourages reflection and conceptual development. They are largely technology-free zones. *Design* and *Implement* facilities introduce students to digitally enhanced collaborative design and modern fabrication and integration of hardware and software. *Operate* workspaces are more difficult to manage in academic settings. However, students can learn how to operate their own and faculty-assigned experiments. Simulations of real operations, as well as electronic links to real operations environments can supplement the direct student experience. In addition, workspaces must also support other modes of active and hands-on learning, including experimentation, disciplinary laboratories, and social interaction. The space must facilitate and encourage team building and team activities. Design-implement experiences and engineering workspaces are explored in Chap. 5.

Active and experiential learning. Having addressed curriculum issues of what to teach, we now consider the pedagogical issues of how students learn. To meet the dual goals of improved disciplinary learning and skills learning, it is necessary to re-task students' learning time and to employ best practices in teaching and learning throughout the program. To address these learning needs, we recommend improvement in two basic areas: (1) an increase in active and experiential learning, and (2) the creation of integrated learning experiences that lead to the acquisition of both disciplinary knowledge, personal and interpersonal skills, and product, process, and system building skills.

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

To make more effective and efficient use of student learning time, integrated learning experiences are required. Integrated learning refers to learning experiences that lead to the acquisition of disciplinary knowledge concurrently with personal and interpersonal skills, and product, process, and system building skills. This gives the learning experiences dual impact. This learning certainly occurs in design-implement experiences, but is not limited to these experiences. For example, solving problems is an essential skill of engineering. Disciplinary knowledge allows a student *to solve the problem right,* but an integration of broader skills is necessary to teach students *to solve the right problem.* The CDIO approach aims to develop skills in problem formulation, estimation, modeling and solution. A modified problem-based learning format, with strong emphasis on the fundamentals, supports this type of integrated learning. However, there are many other opportunities to integrate learning, for example, coupling communication or teamwork with an assignment, encouraging students to dig deeply into a topic and use specific research and inquiry methods, or discussing the ethical aspects of a technical problem concurrently with its technical aspects. An important subtle aspect of this integrated learning is that students see their role models, namely, the engineering faculty, discussing this wider range of skills, signaling their importance to the profession. Integrated learning and active and experiential learning are the focus of Chap. 6.

Assessment and evaluation. Rigorous assessment and evaluation are required to guide the educational reform process. The learning assessment component measures student learning and monitors achievement of disciplinary, personal, interpersonal, product, process, and system building learning outcomes. The program evaluation component gathers and analyzes data related to the overall quality and impact of the entire educational program.

Effective learning assessment focuses on the intended outcomes for students, that is, the knowledge, skills, and attitudes that students are expected to master as a result of their educational experiences. Student learning assessment measures the extent to which each student achieves specified learning outcomes. Learning assessment methods include written and oral exams, observation and rating of oral presentations and other processes, peer assessment, self-assessment, and portfolios. In a CDIO approach, assessment is learner-centered, that is, it is aligned with teaching and learning outcomes, uses multiple methods to gather evidence of achievement, and promotes learning in a supportive, collaborative environment. Assessment focuses on gathering evidence that students have developed proficiency in disciplinary knowledge, personal and interpersonal skills, and product, process, and system building skills. Learning assessment is the focus of Chap. 7.

Program evaluation is a judgment of the overall quality of a program based on evidence of a program's progress toward attaining its goals. Data collection techniques include best-practice methods of program evaluation, such as entry interviews, student satisfaction surveys, and instructor reflective memos. When evidence and results are regularly reported back to faculty, students, program administrators, alumni, and other key stakeholders, the feedback become the basis for making decisions about the program and its continuous improvement. Program evaluation and continuous improvement are discussed in Chap. 9.

Pedagogical Foundation

Having discussed in some detail the underlying need and the seven features of the vision, we continue with the third key element that supports a CDIO approach – the pedagogical foundation. We believe that reforming engineering education based on the CDIO vision will bring us closer to resolving the tension between the two primary goals of developing deeper learning of the technical fundamentals and the ability to lead in the creation and operation of products, processes, and systems. This belief is based not only on experience, but also on application of theories and models of learning.

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

The CDIO approach is based on experiential learning theory that has roots in constructivism and cognitive development theory. Cognitive development theorists, among whom Jean Piagét is perhaps the most influential [6], explain that learning takes place in developmental stages. The ideas of Piagét and cognitive development theorists who followed him, led to three important principles about learning that bear on engineering education programs:

- The essence of learning is that it involves teaching learners to apply cognitive structures they have already developed to new content.
- Because learners cannot learn to apply cognitive structures they do not yet possess, the basic cognitive architecture must first evolve on its own.
- Learning experiences that are designed to teach concepts that are clearly beyond the current stage of cognitive development are a waste of time for both teacher and learner [7].

Cognitive development theories, in conjunction with social psychology and social learning theory, provide historical precedents for constructivism, a theory that postulates that what is learned is a function of the content, context, activity, and goals of the learner. Constructivists believe that learners build their internal frameworks of knowledge upon which they attach new ideas. Individuals learn by actively constructing their own knowledge, testing concepts on prior experience, applying these concepts to new situations, and integrating the new concepts into prior knowledge. Facilitating the processing of new information and helping students to construct meaningful connections is regarded as the basic requirement for teaching and learning.

The theories of constructivism and social learning have been applied to a number of curriculum and instruction models and practices. The CDIO approach focuses on one of these practices, called experiential learning. Experiential learning can be defined as the process of creating and transforming experience into knowledge, skills, attitudes, values, emotions, beliefs and senses. In his work on experiential learning, Kolb [8] emphasizes six characteristics of experiential learning:

- Learning is best conceived as a process, that is, concepts are derived from and continuously modified by experience.
- Learning is a continuous process grounded in experience, that is, learners enter the learning situation with more or less articulate ideas about the topic at hand, some of which may be misconceptions.
- The process of learning requires the resolution of conflicts between opposing modes of adaptation to the world, that is, the learner needs different abilities from concrete experience to abstract conceptualization, and from reflective observation to active experimentation.
- Learning is a holistic process of adaptation to the world, that is, learning is broader than what occurs in classrooms.
- Learning involves transactions between the person and the real-world environment.
- Learning is a process of creating knowledge, that is, in the tradition of constructivist theories.

In this light, one of the essential features of the CDIO approach—that it creates dual-impact learning experiences—can be better understood. If the experiential learning activities are crafted to support explicit pre-professional behavior, they will facilitate the learning of personal and interpersonal skills, and of product, process and system building skills. More subtly, these learning experiences allow the student to develop a knowledge structure for understanding and learning the abstractions associated with the technical fundamentals. The concrete experiences also provide opportunities for active application that supports understanding and retention. Thus, they provide the pathway to the desired goal—deeper working knowledge of the fundamentals.

The Foundational Principle: CDIO as the Context

The objective of this section is to elaborate the meaning, background and evidence of effectiveness of our belief that conceiving-designing-implementing-operating should be the context of engineering education. This belief is so foundational to the CDIO approach that it is captured as the first principle of effective practice, called CDIO Standard 1.

STANDARD 1—**THE CONTEXT**

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

The standard does not explicitly require "conceiving-designing-implementing-operating" to be the context, but rather the more general framework of product, process, and system lifecycle development and deployment, of which conceiving-designing-implementing-operating is an example. The first part of the discussion below outlines the context of professional engineering practice. Then the specific context of engineering education is discussed. Placing the education of engineering students in context facilitates contextual learning, a well-developed educational model upon which we are building. A brief background in contextual learning is presented, with explanations of its important features and benefits.

The Context of Professional Engineering Practice

Before addressing the context of engineering, we should consider the meaning of the word *context*. One definition of *context* is "the circumstances or events that form the environment within which something exists or takes place, and that help in understanding." The definition has two parts: that there are surroundings, and

Table 2.3 The four activities of the engineering lifecycle

Conceive	Defining customer needs, considering technology, enterprise strategy and regulations, and developing conceptual, technical and business plans
Design	Creating the detailed information description of the design; the plans, drawings and algorithms that describe the system to be implemented
Implement	Transforming the design into the product, process or system, including hardware manufacturing, software coding, testing and validation
Operate	Using the implemented product, process or system to deliver the intended value, including maintaining, evolving, recycling and retiring the system

that the surroundings help with understanding or the interpretation of meaning. An architect might say that to understand a building, one must examine the context of the neighborhood. An observer of an organization might say that to understand a decision made by a team, one must examine the issues and forces that form the organizational context. It is this meaning of context—circumstances and surroundings that aid in understanding—that we use.

CDIO as a model of the engineering lifecycle. In order to understand the context of engineering, we must examine what constitutes engineering. The central task of engineering is to conceive-design-implement-operate products, processes and systems that have not previously existed, and that directly or indirectly serve society or segments of society. We use the terms *products, processes, and systems* to designate the solutions engineers create. Products are any tangible goods or objects that can be transferred; processes are actions or transformations directed toward an aim; and, systems are combinations of objects and processes with some desired outcome. This phrase *products, processes and systems* is a shortened list of more detailed descriptions of what various engineers identify as the solutions they create. Manufacturing, civil, and chemical engineers talk of plants, products, and projects. Bioengineers and chemical engineers create new molecules and larger structures, while materials engineers create new materials. Software, systems, devices, and networks are terms used to describe the outcomes of computer scientists and electrical engineers. In order to simplify and standardize the terminology in this book, the terms *product, process, and system* are consistently used for the solutions that engineers design and implement.

Regardless of the sector, central to the role of engineering is the design and building of these solutions, as shown in Table 2.3. *Design* focuses on creating the plans, drawings, and algorithms that describe what product, process, or system will be implemented. The *Implement* stage refers to the transformation of the design into the delivered solution, including hardware manufacturing, software coding, testing, and validation. Desirably, engineers are also involved in defining the solution, which involves understanding the needs of the customer or society, identifying new technologies that might be infused, and creating the high-level requirements and strategy for the solution. We designate this as *conceiving*, which is the identification of the problem or opportunity to be undertaken. Conceiving

Conceive		Design		Implement		Operate	
Mission	**Conceptual Design**	**Preliminary Design**	**Detailed Design**	**Element Creation**	**Systems' Integration & Test**	**Lifecycle Support**	**Evolution**
• Business Strategy • Technology Strategy • Customer Needs • Goals • Competitors • Program Plan • Business Plan	• Requirements • Function • Concepts • Technology • Architecture • Platform Plan • Market Positioning • Regulation • Supplier Plan • Commitment	• Requirements Allocation • Model Development • System Analysis • System Decomposition • Interface Specifications	• Element Design • Requirements Verification • Failure & Contingency Analysis • Validated Design	• Hardware Manufacturing • Software Coding • Sourcing • Element Testing • Element Refinement	• System Integration • System Test • Refinement • Certification • Implementation Ramp-up • Delivery	• Sales & Distribution • Operations • Logistics • Customer Support • Maintenance & Repair • Recycling • Upgrading	• System Improvement • Product Family Expansion • Retirement

Fig. 2.2 Conceive-design-implement-operate as a lifecycle model of a product, process, project, or system

is central to engineering, and is distinct from design; conceiving is deciding what will be designed.

At the other end of the spectrum, almost all solutions must be operated in order to deliver value. Consumer goods, such as cars and home appliances, are operated by the customer. More complex systems are usually operated by professionals, including engineers who also have a role in maintaining, repairing, upgrading, evolving, recycling and retiring the systems. Even for solutions that do not involve engineers in operations, the design and implementation engineers must be sensitive to the issues of operations. In the CDIO approach, we call this entire post implementation phase *operating*. The span from conceiving to designing, implementing and operating is the product, process or system lifecycle.

These four terms have been chosen because they are applicable to a wide range of engineering disciplines. Details of the tasks that fall into these four main activities—conceiving, designing, implementing, and operating—are found in Fig. 2.2. Note that sequence is not strictly implied by the figure. For example, in spiral development models of product development, there is a great deal of iteration among these tasks.

The most obvious mapping of these four tasks is onto the development of discrete electro/mechanical/information products and systems, such as cars, aircraft, ships, software, computers, and communications devices. Manufacturing engineers actually plan, design, realize, and operate the manufacturing processes for these discrete products and systems. Other engineers envision, design, develop, and deploy networks and systems of these devices, including transportation networks and communication systems. In software, engineers envision, design, write, and operate code. In chemical engineering and similar process industries, engineers conceive, design, build, and operate a plant or facility. But chemical and bio-chemical engineers also produce the vast majority of products by type (as opposed to volume) in batch processes, which create chemical and pharmaceutical products. In civil engineering, similar steps are taken for the planning, design, construction, and operation of a single project.

There is also an analogy for conceiving-designing-implementing-operating for the engineering research process. When a researcher identifies a gap in the established knowledge, and frames a problem or hypothesis, this is "conceiving." Designing the research protocol or experiment naturally follows. Implementing and operating are combined in the execution of the research, the analysis of data, and the reporting of the result. Appropriately interpreted, this common paradigm of conceiving, designing, implementing, and operating covers the essential professional activities of the vast majority of engineers. We use *conceive, design, implement, and operate* for the four major tasks in realizing these products, processes, and systems.

The evolution of a professional engineering context. In addition to the tasks that engineers perform, there is a broader set of aims and activities that form a professional context of engineering that is constantly evolving. It is interesting to note the features that are relatively stable in this environment, and those that are more rapidly evolving. The contextual elements that have not materially changed in the last 50 years include:

- A focus on the problems of the customer and society.
- The delivery of new products, processes and systems.
- The role of invention and new technology in shaping the future.
- The use of many disciplines to develop the "solution".
- The need for engineers to work together, to communicate effectively, and to provide leadership in technical endeavors.
- The need to work efficiently, within resources and/or profitably.

In the last 50 years, we have seen changes in the context of engineering. Some of the evolving factors include:

- Sustainability—a change from mastery of the environment to stewardship of the environment.
- Globalization—international competition and cooperation and distribution of engineering activities
- Innovation—an emphasis on the delivery of new goods and services.
- Leadership—a new emphasis on engineers as leaders in organizations.
- Entrepreneurship—the creation of new enterprises and the regional economic impact that this brings about.

We will discuss each of these evolving contextual elements.

Sustainability. Sustainability refers to the long-term maintenance of wellbeing, which has environmental, economic, and social dimensions. It encompasses the concept of stewardship, that is, the responsible management of resources. Moving towards sustainability is a social challenge that entails, among other factors, international and national law, urban planning and transport, local and individual lifestyles, and ethical consumerism. Ways of living more sustainably can take many forms from reorganizing living conditions, to reappraising work practices, to developing new technologies that reduce the consumption of resources. Today's engineering graduates need to be prepared to address issues of sustainability in the products, processes, and systems that they design and implement. They will need to solve technological problems and use business practices that lead to improved global economic, social, and environmental situations.

Globalization. Globalization refers to the lowering of barriers to form an integrated economy leading to globally complex and fluid systems of communication, production, services and trade. Increasingly, businesses compete and interact on a global scale. They operate across national and international borders with organizational environments that are increasingly complex, dynamic, and have greater interdependencies. As a result, engineers will need not only technical competencies but also an understanding of global conditions and an awareness of, and sensitivity to, differences in cultural environments and work ethics [9]. Employers have expressed the need for undergraduates to have global competence to enable them to function in the corporate environment [10, 11]. Today's engineering graduates not only have to be work-ready, they have to be world-ready, that is, ready to work and ready to address global engineering issues of diverse peoples and environments. The challenge for education programs is to assist students to prepare for this interdependent global environment. A recent study in Australia found that there is a worldwide requirement to increase the internationalization of engineering programs—both content and context—and to support the mobility of engineering students and scholars [12].

Innovation. Innovation is the successful exploitation of new ideas. When used by engineers, innovation implies incorporating new ideas and technologies into new products and services. This requires a team to understand evolving market forces, successfully develop and incorporate new technologies, and design and implement new products, processes and systems, which then must be successfully marketed, sold and supported in the field. The topic of innovation is of great interest because of two parallel trends. From the business perspective, innovation is a route to new markets, large volumes, higher profitability and a more robust future. From the perspective of governments, innovation is a source of economic health and competitiveness.

The engineering and technical aspects of innovation are already highly aligned with the context of engineering practice. The emphasis in innovation on creating *new* things challenges engineers to be more creative and effective at conceiving-designing-implementing-operating, but it does not fundamentally redefine what engineers do. To reflect this alignment, section 4 of the CDIO Syllabus v2.0 (Table 2.2) is called Conceiving, Designing, Implementing, and Operating Systems in the Enterprise, Societal and Environmental Context—the *Innovation Process*. This last phrase emphasizes the inherent nature of engineering practice.

Leadership. Northouse [13] defines leadership as "a process whereby an individual influences a group of individuals to achieve a common goal." Leadership is not fundamentally an issue of position or authority, but of influence, often over those over whom one does not have authority. Leadership is a generic capability and process that manifests itself in business, politics, science and engineering.

Throughout much of history, engineers were the leaders of technical endeavors, because knowledge of engineering was essential to make key decisions. In the later 20th century, a pattern emerged where non-technically-prepared "managers" began making key decisions and taking senior roles in engineering endeavors. Some think this has led to a decrease in the effectiveness of innovation. In many parts of the world, there is a widespread concern for this pattern, and a sense that engineers must re-assume a stronger leadership role in technically based organizations. This does not imply they will become the business leaders or chief executive, but they must have a seat at the table with the business and policy leaders, and they must direct the technical work. As will be seen in Chap. 3, section 4 of the CDIO Syllabus v2.0 has been extended to include issues of engineering leadership.

Entrepreneurship. The word entrepreneurship originally meant the process of undertaking a new task, but has become synonymous with the creation of new business enterprises. Entrepreneurs have the simultaneous tasks of innovation, that is, bringing the first product to market, and of building and financing a new organization. In many regions, entrepreneurship is a significant source of new jobs and economic growth, and is being strongly incentivized by governments and universities. From the perspective of the entrepreneur, entrepreneurship is a high-risk, high-potential reward activity. The role model of many successful high-tech entrepreneurs has particularly excited young engineers in many nations.

Other than the scarcity of resources, lack of established process, and the extreme need to succeed quickly on the first product, the fundamental engineering nature of work in an entrepreneurial firm is not very different than work in other engineering contexts. There are many things that are different about entrepreneurial ventures, including creating an organization and raising capital. These distinct activities associated with an entrepreneurial setting are also discussed in Chap. 3 as an extension of the CDIO Syllabus.

The Context of Engineering Education

Having established the context of professional engineering *practice*, it is now desirable to define an appropriate context for engineering education. In education, context refers to the surroundings and environment that help establish meaning and understanding. Educational context includes the experience base of the students, the factors that motivate learning, and the projections to the ultimate applications of the learned material.

CDIO as the context of engineering education. If we are to base the context of education on the context of professional engineering practice, the implications for engineering education are relatively clear. We should set the education firmly in the timeless aspects of the professional context:

- A focus on the needs of customers.
- Delivery of products, processes and systems.
- Incorporation of new inventions and technologies.
- A focus on the solution, not disciplines.
- Working with others.
- Effective communication.
- Working within resources.

We should make students aware of the new and evolving elements of context, and incorporate them appropriately—sustainability, globalization, innovation, leadership and entrepreneurship. This is the idea that is captured in CDIO Standard 1.

As mentioned earlier, we do not believe that conceiving-designing-implementing-operating should be the content of the education. Almost all agree that at the university, students should learn the fundamental technical knowledge and approaches of an engineering discipline: mechanical engineering, civil engineering, biological engineering, etc. What we assert is that students understand this content better in the appropriate *context*, and that their learning of personal, interpersonal and system building skills is significantly enhanced by placing them in the CDIO context.

Alternative lifecycle contexts. *Conceiving-Designing-Implementing-Operating* is intended to capture a model, not necessarily the only model, of the product, process or system lifecycle. There are alternatives to choosing this particular model as the context of engineering education. Some would argue that design, by itself, is the central activity of engineering. While design activities are certainly important, a focus on them as the exclusive context tends to exclude the important role that engineers have in identifying new products and systems, developing new technologies, implementing, and operations. We would argue that the entire product, process or system lifecycle, encompassing all of the activities of engineering, is a more appropriate context for engineering education.

However, CDIO is not the only possible lifecycle model. It tends to be interpreted as a "top–down" model, in which conceiving new products and systems is driven by customer or societal needs. Often, conceiving is enabled by invention and new technology, which is then matched to societal or customer needs. For example, in the emerging field of biological engineering, educators at MIT have constructed a lifecycle model called MMMM for *Measure-Model-Manipulate-Make*. These are thought of as the essential activities on the pathway to a new biomolecule. First, you measure what nature already gives us as building materials, then you model them. With a model, you can devise and then execute manipulations of the building blocks to create new "solutions". This is an encompassing description that establishes a professional context for students and distinguishes the role of biological engineers from biologists.

It is possible to construct context statements that are more encompassing than conceiving-designing-implementing-operating. Group T in Leuven, Belgium, for example, describes five "E" terms around which their program is built. The first three *E*'s represent the roles engineers play in society: *engineering*, *enterprising,* and *educating.* The remaining two E's are even broader in scope: *environmenting* (embracing all elements of the surroundings) and *ensembling* (transcending and seeing the coherence of things) [14]. Whether it is explicitly conceiving-designing-implementing-operating, a variant such as MMMM, or an extension such as EEEEE, it is important that we place the education of students in the context of product, process, and system lifecycle development and deployment.

Rationale for adopting a lifecycle model as the context. The rationale for adopting the principle that the system lifecycle—conceiving, designing, implementing and operating—is the appropriate context for engineering education is supported by four arguments: (1) it is what engineers do; (2) it is the basis for the desirable skills that industry proposes to university educators; (3) it is the natural context in which to teach these skills; and, (4) it better supports the learning of the technical fundamentals. The first three of these points are discussed quickly in this section, and the fourth, a far more encompassing point, is discussed in the next.

The first of the four points—modern engineers engage in some or all phases of conceiving, designing, implementing, and operating—has been argued above. Students come to us wanting to be engineers, and understand that these are the essential activities of engineering. We actually disappoint them, and reduce their motivation and dedication by not immersing them in the lifecycle context. If we set the engineering education in the context of practice, we reflect to our students what engineers actually do to serve humanity.

The second point is evidenced by the widespread and organized input from industry concerning the skills that students should possess, as discussed in Chap. 1. Industry has articulated the need for a broader emphasis on the skills actually used by engineers in the professional context. What these commentaries by industrialists have in common is that they enumerate the knowledge, skills and attitudes that reflect the professional practice of engineering, always underscoring the importance of engineering fundamentals. The context of professional practice defines the need for knowledge and skills.

The third argument is subtle. In principle, it is possible to teach students the skills and attitudes of engineering while they work by themselves on engineering theory, but this approach may not be very effective. What could be a more natural way to educate students in these skills than to set the education in the context of product, process and system development and deployment, that is, the very context in which students will use the skills?

Pedagogical rationale for the lifecycle context. The fourth point in the rationale for adopting the product, process, and system lifecycle as the context for engineering education is related to more effective learning of technical fundamentals. Learning is more effective when teaching and learning experiences are set within an environment or surroundings that help with understanding and interpretation. In education practice, this is called contextual learning. Contextual learning is a proven concept that incorporates much of the most recent research in cognitive science. According to contextual learning theory, learning occurs when students process new knowledge in such a way that it makes sense to them in their own frames of reference. This approach to learning and teaching assumes that the mind naturally seeks meaning in context, that is, in relation to the person's current environment, and that it does so by searching for relationships that make sense and appear useful [15].

Characteristics of contextual learning. Drawing on its roots in constructivist learning theory, as well as theories of cognition and learning, contextual learning has the following characteristics:

- New concepts are presented in real-life situations and experiences that are familiar to students.
- Concepts in problems and exercises are presented in the context of their use.

- Concepts are presented in the context of what students already know.
- Examples include believable situations that students recognize as being important to their current or possible future lives.
- Learning experiences encourage students to apply concepts and skills in useful contexts, projecting students into imagined futures, e.g., possible careers in unfamiliar workplaces [16].

The rationale for adopting a contextual learning approach is persuasive. This approach encourages students to choose specific careers and remain in their respective career preparation programs. Learning environments and experiences set in professional contexts open students' minds, enabling them to become more thoughtful, participative members of society and the workforce. Moreover, a contextual learning approach assists students in learning how to monitor their own learning so that they can become self-regulated learners.

Benefits and examples of contextual learning. Contextual learning approaches offer several benefits to engineering education. In addition to those already mentioned, this approach increases retention of new knowledge and skills, and it interconnects concepts and knowledge that build on each other. Contextual learning communicates the rationale for the meaning of and the relevance of what students are learning. A few examples of contextual learning may help to illustrate the benefits of contextual learning. In thermodynamics, the study of thermal conductivity might be applied in experiences that measure how the quality and amount of building insulation materials affect the amount of energy required to keep the building heated or cooled. Fieldwork in a hospital research laboratory can provide a stimulating context and rationale for the design of medical devices. Soliciting requests for innovative products and services from community nonprofit organizations can give meaning and relevance to design-implement experiences in engineering programs.

Contextual learning is the basis for adopting the product, process, and system lifecycle as the context for engineering education. This approach underlies our belief that when engineering students acquire knowledge and skills that are relevant to the engineering profession, they are more motivated to learn, learn more effectively, know how to apply what they have learned in meaningful ways, and are encouraged to remain in engineering careers. For these reasons, the adoption of the product, process, and system lifecycle is the foundational principle of the CDIO approach, and the first of the principle of effective practice.

Realizing the Vision

As described earlier in this chapter, the CDIO approach addresses the widely recognized need to educate students who understand how to conceive-design-implement-operate complex value-added engineering products, processes, and systems in a modern team-based environment. The key program goals are to educate students who can master a deeper working knowledge of technical fundamentals, lead in the creation and operation of new products, processes, and systems, and understand the importance and strategic impact of research and technological development on society. We believe these goals are reached when conceiving-designing-implementing-operating products, processes, and systems is the context of the education. The vision includes learning outcomes set through stakeholder engagement, and an education centered on a sequence of integrated experiential learning experiences, set in a curriculum organized around mutually supporting technical disciplinary courses with personal and interpersonal skills, and product, process, and system building skills highly interwoven. The pedagogical foundation supports the premise that with well-planned concrete experiences in engineering and active and experiential learning, the goals can be reached with existing resources.

The challenge in realizing the vision is to transform engineering programs and, in fact, the culture of engineering education. To aid in this transformation, we have adopted a number of techniques to engage engineering faculty, facilitate progress, and ensure quality:

- A rigorous statement of goals for student learning, that is, the CDIO Syllabus.
- A clear set of principles of effective practice, that is, the CDIO Standards.
- Support for organizational and cultural change.
- Enhancement of faculty competence in both engineering skills and in teaching, learning, and assessment methods.
- Shared open-source resources so that, in the steady state, a reformed program is not substantially more resource intensive than a standard program.
- Collaboration of programs for parallel development and approaches to common issues.
- Foundation on engineering educational research and effective practices.
- Alignment with national standards and other major reform initiatives.
- Strategies to attract and motivate students.

The desired outcomes of the CDIO approach are to attract and interest students and to educate engineers who are "ready to engineer." Each of these techniques is described briefly here and explained in more detail in subsequent chapters. The first two—the CDIO Syllabus and the CDIO Standards—constitute the *what* and *how* of educational reform, as suggested by Fig. 2.3.

The CDIO Syllabus

The starting point for educational design and development is the statement of learning outcomes, that is, the capabilities or competencies that students should possess upon completion of a course or program. This statement of learning outcomes is the answer to question, *What is the full set of knowledge, skills, and attitudes that engineering students should possess as they leave the university, and at what level of proficiency?* Clear statements of learning outcomes play a key role in educational design by

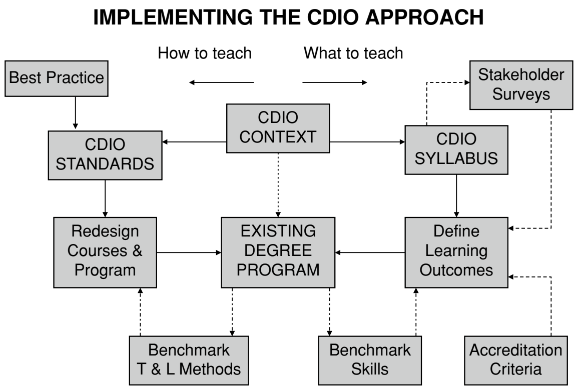

Fig. 2.3 Implementing the CDIO approach

- Formalizing the knowledge, skills, and attitudes that alumni, faculty, industry leaders and society expect from engineering graduates.
- Supporting the design of an integrated curriculum (see Chap. 4), integrated learning experiences (see Chap. 6), and systematic assessment of student learning (see Chap. 7).
- Providing information for current and future students about the program.

The CDIO Syllabus, discussed briefly in this chapter, is explained in detail in Chap. 3.

The CDIO Standards

We have developed 12 principles of effective practice that we call the CDIO Standards. They codify the guiding principles in designing and developing a program. They are the outline of the answer to a second central question, "*How can we do better at ensuring that students learn these skills?*" The Standards serve as guidelines for educational program reform and evaluation, create benchmarks and goals with worldwide application, and provide a framework for continuous improvement.

The 12 CDIO Standards address

- The foundational principle of a lifecycle context of education (Standard 1).
- Curriculum development (Standards 2, 3 and 4).
- Design-implement experiences and workspaces (Standards 5 and 6).
- Methods of teaching and learning (Standards 7 and 8).
- Faculty development (Standards 9 and 10).
- Assessment and evaluation (Standards 11 and 12).

The Standards are also the organizing principle of this book. Each chapter focuses on one or two standards, explaining their meaning and giving examples of their application in existing CDIO programs. Table 2.4 lists the 12 Standards with references to the chapters in which they are discussed. Complete statements of

Table 2.4 The CDIO standards

	CDIO standard	Chapter
1	*The context*	2
	Adoption of the principle that product, process, and system lifecycle development and deployment—Conceiving-Designing-Implementing-Operating—are the context for engineering education	
2	*Learning outcomes*	3
	Specific, detailed learning outcomes for personal and interpersonal skills; and product, process, and system building skills, as well as disciplinary knowledge, consistent with program goals and validated by program stakeholders	
3	*Integrated curriculum*	4
	A curriculum designed with mutually supporting disciplinary courses, with an explicit plan to integrate personal and interpersonal skills, and product, process, and system building skills	
4	*Introduction to engineering*	4
	An introductory course that provides the framework for engineering practice in product, process, and system building, and introduces essential personal and interpersonal skills	
5	*Design-implement experiences*	5
	A curriculum that includes two or more design-implement experiences, including one at a basic level and one at an advanced level	
6	*Engineering workspaces*	5
	Engineering workspaces and laboratories that support and encourage hands-on learning of product, process, and system building, disciplinary knowledge, and social learning	
7	*Integrated learning experiences*	6
	Integrated learning experiences that lead to the acquisition of disciplinary knowledge, as well as personal and interpersonal skills, and product, process, and system building skills	
8	*Active learning*	6
	Teaching and learning based on active and experiential learning methods	
9	*Enhancement of faculty competence*	8
	Actions that enhance faculty competence in personal and interpersonal skills, and product, process, and system building skills	
10	*Enhancement of faculty teaching competence*	8
	Actions that enhance faculty competence in providing integrated learning experiences, in using active experiential learning methods, and in assessing student learning	
11	*Learning assessment*	7
	Assessment of student learning in personal and interpersonal skills, and product, process, and system building skills, as well as in disciplinary knowledge	
12	*Program evaluation*	9
	A system that evaluates programs against these standards, and provides feedback to students, faculty, and other stakeholders for the purposes of continuous improvement	

the CDIO Standards are found in the appendix. For each standard, a description explains the meaning of the standard, highlighting reasons for setting the standard. Rubrics for self-evaluation using the standards have also been developed. As explained in Chap. 9, the standards are also used as the basis of program evaluation and continuous improvement.

Organizational and Cultural Change

Implementing the CDIO approach implies a shift in the nature of engineering education to a more integrated curriculum, in the context of product, process, and system building. This will be a challenge. The current engineering faculty are largely engineering researchers. They tend to think of disciplines in isolation, explain them based on theoretical underpinnings, and focus on the evolution of the discipline, rather than its application or synthesis. A CDIO approach highlights the need for integration of disciplines and the focus on solutions that are part of the context of engineering.

One of the important features of the CDIO approach is a program-level scale of change. This, too, will be a challenge. Many dedicated engineering educators have responded to the needs for reform of engineering education, and many in industry, government, and accrediting bodies have tried to help. However, many of these changes are introduced at the level of a course or module. Universities and funding sources often invest resources in these faculty members to develop new pedagogical approaches based on practice and new content. These faculty members often receive departmental and university awards for teaching, and they are revered by their students. They are important sources of new ideas and form a pool of early adopters in systemic reform efforts. However, experience shows that if the good practices they develop are not incorporated into a program and institutionalized, their impact will fade as instructors tire or rotate to other courses.

The reform of engineering education is best addressed on a department or program level. In this way, common expectations for faculty performance and student responsibility for learning can be set and maintained. The educational program must be viewed as a system in which each element carries both individual and collective learning objects for the program. We observe that any successful attempt at engineering education reform should include most or all of the learning experiences from which a student benefits, and, therefore, must be set and maintained at a program or department level.

The CDIO approach actually calls for a mixture of these two approaches—which might be thought of as "top down" and "bottom up." The bottom up component is the interest and dedication of the individual professors. They must be interested in change and willing to develop or adapt good practice. However, there also must be collective action on the part of those who work in a department or program. Evidence of change in universities indicates this as the more effective approach [17]. Bringing about such a transformation will require more than simply redrafting curricula; it may require cultural change. To be effective in this transformation, we should acknowledge this and be prepared to learn from best practice in organizational and cultural change. This is a central topic of Chap. 8.

Enhancement of Faculty Competence

Part of the change process requires strengthening the competence of faculty in engineering skills and in active and experiential learning and student assessment. There is little reason to expect a faculty that has been recruited as a cadre of researchers to be proficient in many of the skills of engineering practice. And there is no reason to expect that these faculty researchers would be able to teach these skills. Therefore, if we are to successfully support student learning, we must develop approaches to enhancing the skills of engineering faculty. Likewise, faculty have, by and large, been educated using pedagogical styles based on information transmission, such as lectures. If we are to develop a learning-focused education, which relies on active and embedded learning, current faculty must be supported in their personal development and use of these techniques. In both cases-engineering skills and teaching-the transformation will be broader and more effective if there is a well-planned effort to build faculty competence, by bringing individuals with this background to the team and enhancing the competence of the existing team. Enhancement of faculty competence is addressed in Chap. 8.

Open-Source Ideas and Resources

No elements in the CDIO approach are prescriptive. We have developed resources to help engineering programs resolve the essential conflict in engineering education, that is, time and resources for learning both the disciplinary fundamentals and personal and interpersonal skills, and product, process, and system building skills. These resources are intended to facilitate the rapid adaptation and implementation of the CDIO approach into university programs.

To date, the CDIO approach has been implemented in programs that represent differences in goals, students, financial resources, existing infrastructure, university constraints, governmental legislation, industry needs, and professional societies' certification. To accommodate these differences and to acknowledge that our approach is under ongoing development and adaptation, it is codified and documented as an open source. An open accessible architecture for the program materials promotes the dissemination and exchange of ideas and resources. These resources are specifically designed so that university engineering programs can adapt the CDIO approach to their specific needs. Engineering programs can implement the entire approach or choose specific components.

The resources available to engineering programs that wish to adapt and implement the CDIO approach include materials that introduce the model, the CDIO Syllabus, survey tools for investigating stakeholder needs, guidelines for design-implement experiences, support for implementation, start-up advice, and suggested steps for the transition. The transition process and its related tools are addressed in more detail in Chap. 8.

All academic programs exist within an environment of limited resources. We have designed the approach so that a CDIO program can be implemented with a re-tasking of existing resources. However, when entering into a program of education reform, we must differentiate between resources needed in the transition and resources in steady state. It is inevitable that in the reform transition, extra resources will be needed. Change is not without cost. However, in steady state, we cannot expect more resources, and, therefore, must find new approaches that largely re-task existing resources, for example, faculty time, student time, space. Chapter 8 describes resources that help minimize this transitional effort and maximize the benefits of implementing a CDIO program.

Value of Collaboration for Parallel Development

The collaboration of engineering programs in countries worldwide is a fundamental part of our approach to development. Engineering educators around the world struggle with similar issues, for example, the tension between science-oriented goals and practice-oriented skills. Addressing this tension is a challenge for any engineering education designer. The key to effective educational development is not to make minor trade-offs between these two goals, but rather to create a new model for engineering education that encompasses both. This undertaking is difficult for a single program or department.

There are many advantages to working with university consortia when they are properly structured, the principal being acceleration of effort. Consider, for example, a reasonable timeline for systemic education reform: in Year 1, an opportunity for improvement is identified, and an approach developed; in Year 2, the approach is tested; in Year 3 or 4, it is refined and implemented. Now consider the tasks associated with this reform: (a) the curriculum—what will be taught and where; (b) the pedagogical component—how the curriculum will be taught; (c) the evaluation component—how the intended outcomes will be measured and improved; and (d) workspace and logistics—the learning environment. The advantages of a consortium are parallel development and shared tasks. As a team, collaborating universities identify common opportunities for improvement, implement several different approaches simultaneously, and compare results based on common evaluation tools. This collaboration greatly accelerates reform efforts. It also allows the sharing of resources and experience, which reduces the cost of transition and increases the likelihood of success. Engineering education reform that is undertaken by a consortium of programs or departments allows parallel development and the sharing of resources. The consortium of universities that have adopted a CDIO approach is described at http://www.cdio.org.

Foundation on Educational Research and on Effective Practices

There are a growing number of engineering education research programs around the world that seek to identify best practice and to develop new approaches based on learning theory. For example, the National Academy of Engineering in the United

States coordinates a number of research centers and projects through its Center for the Advancement of Scholarship on Engineering Education (CASEE) [18]. Engineering faculty are often unaware of educational theories and practices that could help them accelerate reform efforts. Many of these research-based initiatives have been successful at bringing together interested parties from both engineering and education to build stronger teams. In the CDIO approach, we attempt to build engineering education reform on a well-informed adoption of best practice and understanding of models of learning that are broadly applicable to engineering disciplines.

Alignment with National Standards and Other Change Initiatives

This is an era of increased attention to educational processes in higher education generally, and specifically for engineering. In some cases, national accreditation standards have been revised to reflect an outcomes-based approach to programs. Examples include ABET in the United States [19] and UK-SPEC in the United Kingdom [20]. In other cases, reform of higher education is the result of large-scale regional reform, for example, the Bologna Declaration [21], or the project for the Accreditation of Engineering Programs and Graduates (EUR-ACE) [22]. Recently, the Canadian Engineering Accreditation Board (CAEB) has created a set of guidelines for the evaluation of programs there [23].

We have made every attempt to ensure that the CDIO approach is aligned with these efforts. Chapter 3 discusses the comparison of the CDIO Standards with several national accreditation standards. These comparisons show a similar trend, that is, the CDIO Syllabus is more comprehensive and has a more explicit organization based on the tasks of engineering. Consequently, an engineering education program designed to meet the student learning outcomes set forth in the Syllabus can easily meet its respective national standards. Alignment with the objectives of the Bologna Declaration is discussed in Chap. 11. The CDIO Syllabus outcomes and the 12 CDIO Standards are stretch goals that even the best programs around the world must work diligently to meet. National standards present the rules of what to do. By contrast, the Standards and Syllabus form a best-practice framework that serves as a playbook—the approaches, resources, and community that allow a program to achieve its goals.

Strategies to Attract and Motivate Students

One of the important goals of the CDIO approach is to make engineering more interesting, and, therefore, increase student motivation and retention. In much of the world, there is great concern that more scientists and technologists will be needed in the future, and that current supply is insufficient. We believe that we have incorporated several features that will attract and motivate students. Many students are attracted to engineering by the belief that engineers build things and are disappointed by the first years of traditional engineering education when they are taught theory. By placing early and repeated design-implement experiences in the curriculum, we have appealed to this desire to build and create. Many students complain that engineering education "beats them down" through a demanding schedule of theory-alone education with little reward. By using active and experiential learning techniques and projects, we offer students a chance to develop a sense of empowerment and self-efficacy critical to their perception of self-worth. Projects also provide opportunities to express creativity and demonstrate leadership, with visible signs of accomplishment. These factors are captured in the reaction of several students who have graduated from our programs. Their experiences are framed in Box 2.2.

Box 2.2 Student Views of the Benefit of a CDIO Program

The single reason I picked KTH over another school was the promise of building an aircraft at the end of the program—something the other schools didn't offer. A course where you get to design and build and fly is a great opportunity to try your own wings, to see how much you've actually learned, and to own the whole process. It is much more rewarding to solve your own problem, instead of the professor's problem sets. To practice skills and technical knowledge in a project makes you feel more ready for the real job of engineering.

—H. Grankvist, Former Student,
Royal Institute of Technology (KTH)

One of the major benefits of participating in a CDIO program is that it allows you to develop skills such as engineering reasoning and problem solving. Our profession demands that you have the ability to identify and formulate problems, as well as formulate solutions and recommendations. These are essential skills that a CDIO approach emphasizes. I find that the engineering skills are very important, both for me personally and also for my future employers. The skills of engineering reasoning and problem solving also help bridge the gap between university study and work life, making the transition easier and quicker. A CDIO program creates a supportive environment for today's engineering students as we prepare to be a part of a profession where teamwork and communication skills are essential. In a way, a CDIO program assures a certain level of development in these skills. Consequently, all students, not only the students who are most active in extra-curricular activities, are able to develop these skills during their university years. I believe that we are personally responsible for our own development. By taking part in a CDIO program, we learn the importance of this at an early stage.

—A. Wibring, Former Student,
Chalmers University of Technology

(*Continued*)

Box 2.2 Student Views of the Benefit of a CDIO Program—Cont'd

In my view, the ideal engineering program is well described by the CDIO Syllabus. The emphasis is on technical knowledge and practical methods, which are taught in the context of the real-world requirements of the engineering profession. Teamwork, written communication, and professional ethics, as well as an understanding of the external (e.g., financial, political, environmental) factors that affect today's engineers are important features of the curriculum. During my education, I was able to develop many of the skills a CDIO program is intended to address. Early in my program, coursework emphasized knowledge of the engineering sciences and its application in problem solving. Later courses included more of the "new" elements of the curriculum, such as working in project teams and delivering presentations. In general, these assignments were a valuable part of my engineering studies and have paid dividends since graduation.

—P. Springmann, Former Student,
Massachusetts Institute of Technology (MIT)

Another factor in attracting and motivating students is to show that the education leads to higher quality employment. In fact, in response to industry stakeholders who hire engineering graduates, we should be preparing students who are "ready to engineer." These graduates are more readily hired, have more successful careers, and have more impact in their profession. Preliminary indications are that firms familiar with the CDIO approach are eager to hire graduates of these programs as evidenced by the comments of Billy Fredriksson, former Chief Technology Officer of SAAB, presented in Box 2.3. If we make engineering education more interesting, empowering, and rewarding, and simultaneously increase the learning of both fundamentals and skills, the demand for this education will increase and the needs of society for a technological workforce will be met.

Box 2.3 CDIO Engineers in Industry

Industry would prefer to hire engineers from CDIO programs because they have received excellent training in how to apply their basic theoretical knowledge to the development of practical product- or process-related projects. During their studies, CDIO engineering students get a good introduction to the real practice of engineering. They have learned both the technical skills and also personal and interpersonal skills, and the importance of holistic approaches and systems integration in designing and building products. This means that the CDIO engineers will probably be able to apply their knowledge more quickly when starting work in industry. They can more easily and quickly work productively in engineering teams.

There are several reasons why engineering students graduating from a CDIO program will likely have more options and be more successful in pursuing their careers. I would expect these graduates to start their industrial careers more rapidly, either as a disciplinary specialist or as a project engineer. As disciplinary specialists, they know the importance of taking into account requirements from related areas when integrating results into the product or system. As project engineers or project leaders, they are more prepared for, and understand the importance of, teamwork and other personal and interpersonal skills. They are able to look after and secure the integrated result and performance of the final product, and they recognize the importance of timing to the project. Thus, graduates from CDIO programs will be more attractive to industry and more likely to succeed both personally and in their responsibility to build systems of value to society.

—B. Fredriksson, SAAB

Summary

This chapter presented an overview of the CDIO approach, including its need, goals, vision and pedagogical foundation. It explained the meaning and importance of context, both in the professional practice of engineering and in engineering education. It introduced the CDIO Syllabus and the 12 principles of effective practice, called the CDIO Standards. Finally, this chapter explained ways in which to adapt and implement the CDIO approach, based on principles of organizational and cultural change.

The CDIO approach envisions an education that stresses the fundamentals, set in the context of conceiving-designing-implementing-operating products, processes, and systems. The salient features of the vision are clearly articulated learning outcomes, an integrated curriculum, basic and advanced design-implement experiences, active and experiential learning, and robust learning assessment and program evaluation.

The foundational principle, expressed as CDIO Standard 1, is that product, process, or system lifecycle development and deployment is the context for engineering education. The current context of engineering practice includes such evolving factors as sustainability, globalization, innovation, leadership, and entrepreneurship. The rationale for adopting C-D-I-O as the context is that it describes what engineers do and is the basis for achieving the knowledge, skills, and attitudes desired by stakeholders of engineering education.

In the next chapter, we address the question of what engineering students should learn, that is, the full set of knowledge, skills, and attitudes that engineering students should possess as they leave the university, and at what level of proficiency. The main resource for setting such learning outcomes is the CDIO Syllabus.

Discussion Questions

1. In what ways are you improving engineering education in your own programs?
2. How can the CDIO approach to engineering education be applied to your reform initiatives?

3. Which barriers to educational reform are common to programs around the world? Which may be unique to your program?
4. How do your educational initiatives compare with the CDIO approach and other reform efforts?

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Springer
http://www.springer.com/978-3-319-05560-2

Rethinking Engineering Education
The CDIO Approach
Crawley, E.F.; Malmqvist, J.; Östlund, S.; Brodeur, D.R.; Edström, K.
2014, XVI, 311 p. 38 illus., 6 illus. in color., Hardcover
ISBN: 978-3-319-05560-2