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Rethinking Engineering Education

The CDIO Approach

Second Edition

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Foreword to the First Edition

Authors' Note

When the first edition of Rethinking Engineering Education: The CDIO Approach *was published in 2007, Charles M. Vest had stepped down from a fourteen-year tenure as president of the Massachusetts Institute of Technology. Subsequently, he served as president of the U. S. National Academy of Engineering. President Vest died on December 12, 2013. The worlds of engineering and engineering education have lost a true visionary and champion. We have chosen to publish his foreword unchanged because his thoughts remain as relevant and important today as when they were first written.*

Educating Engineers for 2020 and Beyond

Most of my career was played out in the twentieth century—the century of physics, electronics, and high-speed communications and transportation. And now, we all—and especially our students—have the privilege of living through the transition to the twenty-first century—presumably the century of biology and information.

As this transition occurs, it is an appropriate time to rethink engineering education. When I look back over my 35-plus years as an engineering educator, I realize that many things have changed remarkably, but others seem not to have changed at all. Challenges that have been with us for the past 35 years include making the first university year more exciting, communicating what engineers actually do, and bringing the richness of human diversity into the engineering workforce. Students must learn how to merge the physical, life, and information sciences at nano-, micro-, and macro-scales, embrace professional ethics and social responsibility, be creative and innovative, and write and communicate well. Our students should be prepared to live and work as global citizens, understanding how engineers contribute to society. They must develop a basic understanding of business processes, be adept at product development and high-quality manufacturing, and know how to *conceive*, *design*, *implement*, and *operate* complex engineering systems of appropriate complexity. They must increasingly do this within a framework of sustainable development, and be prepared to live and work as global citizens. That is a tall order . . . perhaps even an impossible order.

But is it really? I meet students in the hallways of MIT and other universities who can do all of these things—and more. So, we must keep our sights high. But how are we going to accomplish all this teaching and learning? What has stayed constant, and what needs to be changed?

As we think about the challenges ahead, it is important to remember that some things are constant. Students, for example, are driven by passion, curiosity, engagement, and dreams. Although we cannot know exactly what they should be taught, we focus on the environment and context in which they learn, and the forces, ideas, inspirations, and empowering authentic situations to which they are exposed.

Another constant is the need for students to acquire a sound basis in science, engineering principles, and analytical capabilities. In my view, a deep understanding of the fundamentals is still the most important thing we provide. Much of our current view of the engineering fundamentals was shaped by what is commonly termed the "engineering science revolution." This revolution was spawned largely by faculty at MIT who, building on their experiences gained by developing radar systems during World War II, created a radically different way to practice and teach engineering. A towering legacy of this era, with contributions from many major universities, was a new world of engineering education that was built on a solid foundation of science more than on traditional macroscopic phenomenology, charts, handbooks, and laboratories. However, the creators of this new vision of engineering education did not mean to displace the excitement of engineering, the opportunity for students to design and build, or the need for teamwork and ethics, meant to enrich the student experience. Along the way, something got lost. We need to rethink engineering education, and find a new balance.

Perhaps I am so old fashioned I still believe that masterfully conceived, well-delivered lectures are still wonderful teaching and learning experiences. They still have their place. But even I admit there is a good deal of truth in what my extraordinary friend, Murray Gell-Mann, Winner of Nobel Prize in Physics in 1929, likes to say, "We need to move from the sage on the stage to the guide on the side." Studio teaching, team projects, open-ended problem solving, experiential learning, engagement in research, should be integral elements of engineering education.

The philosophy of the CDIO approach to engineering education captures these essential features of a modern engineering education—excitement about what engineers do, deep learning of the fundamental skills, and the knowledge of how engineers contribute to society. It is taught in a way that captures our students' passion.

I encourage you to read about this integrated approach and consider how it might influence the practice of engineering education at your university.

Charles M. Vest
President, U. S. National
Academy of Engineering

Foreword to the Second Edition

Since the publication of *Rethinking Engineering Education: The CDIO Approach,* the number of universities that have adopted a CDIO approach in at least one of their engineering programs and joined the collaboration of the CDIO Initiative has increased fourfold. While the approach retains the same basic principles, its application is now found in a much broader range of engineering disciplines, for example, chemical engineering, biological engineering, and mining engineering. Moreover, the general framework of the approach is now being applied in programs in business management and other professional programs.

The key documents of the CDIO approach have been updated. The *CDIO Syllabus v2.0* has added two new sections on leadership and entrepreneurship, and given more emphasis to certain topics that were previously subsumed under other headings, for example, ethics, social responsibility, and sustainability. The *CDIO Standards v2.0* now includes distinct rubrics for each standard to facilitate self-evaluation. The general structure of the chapters remains the same in that they parallel the CDIO Standards. The chapters on implementation, history of engineering, and outlook have also been updated since the first edition.

Chapter 1 introduces the CDIO approach as a way of comprehensively reforming engineering education worldwide. It highlights some of the key features of the approach: the importance of learning in the context of engineering practice, the specification of intended learning outcomes for students, the need for curriculum and teaching methods that integrate disciplinary content with personal and professional skills and attitudes, and a framework of research-based practices that significantly improve the quality and nature of undergraduate engineering education. As such, this chapter serves as an executive summary of the book. There are two key changes in this edition. The section on "Motivation and Change" has been moved from Chap. 2 to Chap. 1 to support the rationale for a new approach to engineering education—the CDIO approach—and the need for this book. Secondly, the term *The CDIO Initiative* has been clarified. It is now used exclusively to mean the organization of more than 100 universities worldwide that collaborate in the implementation of the CDIO approach in their respective programs. The CDIO Initiative (the organization) is first described in Chap. 8 in the section on resources that support implementation of the CDIO approach.

As in the first edition, Chap. 2 explains the key features of the CDIO approach, beginning with a detailed discussion of the underlying need, and the goals, vision, and pedagogical foundation of the approach. The chapter introduces the basics of the CDIO Syllabus, the CDIO Standards, and approaches to adaptation and implementation, all of which are addressed in later chapters. The title has been changed from "Overview' to "The CDIO Approach" to reflect that the approach is described in more detail that the word *overview* would suggest. Secondly, the section on the "Requirements for the Reform of Engineering Education" has been streamlined. A new section explains the foundational principle of the CDIO approach, that is, that CDIO is the context of engineering education. Finally, the chapter introduces five new themes that have influenced the CDIO approach in explicit ways since the first edition: sustainability, globalization, innovation, leadership, and entrepreneurship.

Chapter 3 describes the development and content of the CDIO Syllabus, that is, the codification of contemporary engineering knowledge, skills, and attitudes that constitute the foundation for the reform of university engineering education programs. It explains the rationale for specifying learning outcomes in personal and interpersonal skills, and product, process and system building skills, as well as in technical disciplines. There are three key changes to this chapter. The first is related to the updating and extension of the CDIO Syllabus v2.0. The second is the extension of the discussion of ways in which the five contemporary themes addressed in Chap. 2 are included in the CDIO Syllabus v2.0. Finally, the last section of the chapter has been updated and reorganized to describe a process for establishing proficiency levels and learning outcomes based on the CDIO Syllabus. The examples of the stakeholder surveys found in the first edition are retained, but significantly abbreviated. Our colleague, Perry J. Armstrong of Queen's University Belfast, who contributed to this chapter in the first edition, has subsequently died. We have retained his name as a contributor because of his significant influence on the topics in this chapter. We are grateful to Peter J. Goodhew of the University of Liverpool for updating *Box 3.1 Comparison of the CDIO Syllabus with UK-SPEC*.

Chapter 4 describes the rationale for a curriculum that integrates the learning of engineering skills with disciplinary fundamentals. Furthermore, it lays the foundation for curriculum design by benchmarking an existing curriculum, recognizing pre-existing conditions, and describing the process for design and implementation of an integrated curriculum. A new figure in Box 4.1 illustrates the components of an integrated program description, emphasizing the importance of integration and progression in learning. A new box written by colleagues at Singapore Polytechnic (Box 4.4) gives an example of an integrated curriculum that includes all programs for an entire university. Many of the figures have been revised for increased clarity.

The objectives of Chap. 5 are rephrased with greater precision. A section describing the design-implement experiences with respect to related pedagogical models has been added. Overall, the chapter has been revised in light of the knowledge and experience gained since 2007. An effort has also been made to generalize the message and avoid implicit references and links to mechanical and aerospace engineering, unless such examples are specifically intended. A new section provides a clearer connection of design-implement experiences with current pedagogical models of problem-based and project-based learning. Greater emphasis is placed on the progression of complexity and the formation of engineering skills and attitudes in the sequence of design-implement experiences, with less focus on distinguishing between basic and advanced experiences, as such. For the sake of clarity, some examples are explained in less detail or omitted altogether. In particular, *Box 5.1 The Linköping Project Management Model* is omitted because it overlaps with its description in Chap. 4. The section on workspaces now emphasizes function and learning, with less discussion of the physical space and equipment requirements.

The overall aim of Chap. 6 is to discuss the implementation of integrated learning at the course level. It sets the context by identifying students' perspectives of their educational experiences. It introduces a constructive alignment model and gives examples of active and experiential learning approaches. Finally, the chapter describes the ways in which more stimulating learning experiences can contribute to the attractiveness of engineering education to more widely diverse audiences. The term *personal, interpersonal, product, process and system building skills* has been replaced by the term *professional skills*, except when the term is referenced in CDIO Standards 7 and 8 or when a specific meaning is intended. Discussions of concept tests and electronic response systems are now merged into a section on the peer instruction method, consistent with current research and practice. The section on faculty support for integrated learning has been moved to a later chapter and merged with an overall approach to the enhancement of faculty skills.

Chapter 7 emphasizes the meaning of learning assessment and the alignment of assessment methods with learning outcomes and teaching methods. Learning assessment methods are illustrated with a number of examples. A few changes have been made to this chapter to improve clarity and to make more explicit connections to the previous chapter on teaching and learning. The constructive alignment of curriculum, teaching, and assessment, introduced in Chap. 6, is repeated here with an emphasis on assessment. A sample rubric to assess a reflective journal now replaces the box that described the use of a reflective portfolio at a specific institution, hopefully with broader application. The chapter concludes by addressing the connection between assessment results and continuous improvement, as well as the key benefits and challenges to sound learning assessment.

Chapter 8 describes the key success factors that influence change in an organization and the development of a CDIO program as an example of cultural change. Activities are suggested to help change leaders to enhance faculty competence in personal and interpersonal skills, and product, process, and system building skills, and enhance faculty competence in teaching, learning, and assessment methods. The chapter also describes resources that facilitate the adoption and implementation of a CDIO approach in engineering programs. There are two additional case studies illustrating the ways that the change factors discussed in the chapter were addressed in institutions where the CDIO approach was adopted at college and university system levels.

Chapter 9 discusses the purpose and value of a standards-based approach to program evaluation as a way to determine if programs are successfully implementing a CDIO approach. It focuses on the characteristics of a standards-based approach to program evaluation, key questions that guide program evaluation, descriptions of a variety of evaluation methods, the connections between results, continuous program improvement and quality assurance, and the overall impact of programs that have implemented a CDIO approach. A brief description of student self-efficacy studies has been added to the section of program evaluation methods. The key change is related to the updating of the CDIO Standards document with rubrics customized for each standard.

As in the first edition, Chap. 10 provides a historic framework for the reform ideas included in the CDIO approach. It outlines some of the foundational and continuing discussions of the objectives, content, and structure of engineering education. Engineering institutions and educational approaches are outlined with emphasis on national differences as well as controversies on the balance between practice and theory. The chapter ends with an outline of contemporary challenges to engineering education, and the problems related to a science orientation to education and the need for communication and teamwork skills that support interdisciplinary cooperation and design activities. The chapter includes a discussion of new competencies that are demanded of engineers in the areas of climate and environment, built environments, user involvement, globalization, and entrepreneurship. The ways in which engineering schools respond in their disciplinary and pedagogical approaches differ by country or culture, emphasizing the flexibility embedded in the CDIO approach that allows it to be adapted to various situations.

The final chapter summarizes the changes in the CDIO approach since 2007 and highlights the growth and expansion in the number of collaborating universities that have adopted a CDIO approach. As in the previous edition, it identifies factors that continue to drive change in engineering education. The section on the future development of the CDIO approach and the anticipated growth of the CDIO Initiative (the organization of universities that have adopted a CDIO approach in at least one engineering discipline) examines achievements in areas identified in 2007 and projects potential emphases and directions for the future.

We are grateful for the contributions of our colleagues to each of the chapters and for their case studies and examples that form the "boxes" in each chapter. As always, we welcome your comments and encourage you in your endeavors to reform engineering education.

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Chapter 1
Introduction and Motivation

Rationale

The purpose of engineering education is to provide the learning required by students to become successful engineers—technical expertise, social awareness, and a bias toward innovation. This combined set of knowledge, skills, and attitudes is essential to strengthening productivity, entrepreneurship, and excellence in an environment that is increasingly based on technologically complex and sustainable products, processes, and systems. It is imperative that we improve the quality and nature of undergraduate engineering education.

In the last two decades, leaders in academia, industry, and government began to address the necessity for reform by developing views of the desired attributes of engineers. Through this endeavor, we identified an underlying critical need—to educate students who are able to Conceive-Design-Implement-Operate complex, value-added engineering products, processes and systems in a modern, team-based environment.

Within these pages, we identify twelve effective practices that can help engineering education programs to meet this critical need. The first of these effective practices is to make the authentic practice of engineering—conceiving, designing, implementing, and operating products, processes, and systems—the context for engineering education. The second is to solicit stakeholder input to identify the learning needs of the students in a program. In order to fulfill these learning needs, we have identified ten additional effective practices that collectively provide a comprehensive and broadly applicable approach to improving curriculum, teaching and learning, and engineering learning workspaces that is supported by robust assessment and change processes. By these means, we seek to significantly improve the quality and nature of undergraduate engineering education worldwide.

E. F. Crawley et al., *Rethinking Engineering Education*,
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Motivation for Change

What Modern Engineers Do

Engineers build things that serve society. To quote Theodore von Kármán [1], "*Scientists discover the world that exists; engineers create the world that never was*." The 1828 charter of the British Institution of Civil Engineers [2] states that engineering is "the art of directing great sources of power in nature for the use and convenience of man." While we might change this today to include man's responsibility to be a steward of nature, it is clearly true that the creation of new products, and intelligent and sustainable utilization of natural resources remain the tasks of engineers today.

Modern engineers are engaged in all phases of the lifecycle of products, processes and systems that range from the simple to the incredibly complex, but all have one feature in common. They meet a need of a member or members of society. Good engineers observe and listen carefully to determine the needs of the member of society for whom the benefit is intended. They define the scope of the device or system, and help to create the concept. We say they are involved in *conceiving* the device or system. Modern engineers *design* products, processes, and systems that incorporate technology. Sometimes this is state-of-the-art technology, pushing new frontiers, and creating new capabilities, or applying and adapting existing technology to meet society's changing needs. Engineers lead, and in some cases, execute the *implementation* of the design to actual realization of the product, process, or system. All engineers should design so that their systems are implemented easily and in a sustainable way. In order to deliver a benefit to a member of society, engineering devices and systems must be *operated*. Consumer products, such as stoves, cars, or laptop computers, are operated by private users. More complex systems, such as, industrial furnaces, aircraft, or communication networks, are operated by professionals. All engineers should consider and plan for the operation of the product, process, or system as an integral part of design.

In order to conceive, design, implement and operate products, processes and systems, good engineers work in teams and communicate effectively. They think creatively and critically and act responsibly, and use an array of other personal and professional skills.

The Need for Reform of Engineering Education

The task of higher education is to educate students to become effective modern engineers—able to participate and eventually to lead in aspects of conceiving, designing, implementing, and operating systems, products, processes, and projects. To do this, students must be technically expert, socially responsible, and inclined to innovate. Such an education is essential for achieving productivity, entrepreneurship, and excellence in an environment that is increasingly based on technologically complex systems that must be sustainable. It is widely acknowledged that we must do a better job at preparing engineering students for this future, and that we must do this by systematically reforming engineering education.

There is a seemingly irreconcilable tension between two positions in engineering education. On one hand, there is the need to convey the ever-increasing body of technical knowledge that graduating students must master. On the other hand, there is growing acknowledgment that engineers must possess a wide array of personal and interpersonal skills, as well as the product, process, and system building knowledge and skills required to function on real engineering teams to produce real products and systems.

This tension is manifest in the apparent difference of opinion between engineering educators and the broader engineering community that ultimately employs engineering graduates. University-based engineers traditionally strike a balance that emphasizes the importance of a body of technical knowledge. However, beginning in the late 1970s and early 1980s, and increasingly in the 1990s, industrial representatives began expressing concern about this balance, articulating the need for a broader view that gives greater emphasis to personal and interpersonal skills, and product, process, and system building skills.

In this era, engineers in industry and government, along with university program leaders, began to discuss improvements in the state of engineering education. In this process, they considered the proficiencies of engineering graduates of recent years and developed lists of the desired attributes of engineers. Common among these lists was an implicit criticism of current engineering education for prioritizing the teaching of theory, including mathematics, science, and technical disciplines, while not placing enough emphasis on laying the foundation for practice, which emphasizes skills such as design, teamwork, and communications.

This criticism reveals the tension between two key objectives within contemporary engineering education: the need to educate students as *specialists* in a range of technologies—each with increasing levels of knowledge required for professional mastery—while at the same time teaching students to develop as *generalists* in a range of personal, interpersonal, and product, process, and system building skills.

Engineering programs in many parts of the world that exemplify this tension are the products of the evolution of engineering education in the last half century. Through those years, programs moved from a practice-based curriculum to an engineering science-based model. The intended consequence of this change was to offer students a rigorous, scientific foundation that would equip them to address unknown future technical challenges. The unintended consequence of this change was a shift in the culture of engineering education that diminished the perceived value of key skills and attitudes that had been the hallmark of engineering education until that time. Thus evolved the tension between theory and practice.

An early reaction to this shift was the Finiston Report of 1978 in the United Kingdom [3]. A few years later in 1984, Bernard M. Gordon, the inventor of the analog-to-digital converter, winner of the U.S. National Medal of Technology, and benefactor of the Gordon Prize for Engineering Education of the U.S. National

Academy of Engineering, stated bluntly that "society…around the world…is not entirely pleased with the current state of general [engineering] education" [4]. Box 1.1 is an excerpt of his address to the annual conference of the European Society for Engineering Education (SEFI). It remains relevant more than 25 years later.

Box 1.1 What Is An Engineer?

It is apparent that society around the world, particularly, the western world, is not entirely pleased with the current state of general education. Its displeasure is reflected in the barrage of criticism leveled at the graduate who cannot read effectively, cannot write effectively, and cannot master moderately complex arithmetic. The well-publicized question, "Why can't Johnny read?" sums up the societal concerns.

A parallel question, "Why can't Mr./Dr. Engineer engineer effectively?" is now increasingly being asked, and sums up the frustration of engineering supervisors and of the public who suffer from the failures of inadequate designs. Critics of engineering education often cite the following inadequacies among the complaints about the educational system's "product":

- Disproportionately low and increasingly poor economic return for the amount of employed engineering resources.
- Limited formal training in, and exposure to, a breadth of basic technical knowledge.
- Inadequate training and orientation to a meaningful depth of engineering skills.
- Inadequate understanding of the importance of precise test and measurement.
- Insufficient competitive drive and perseverance.
- Inadequate communication skills.
- Lack of discipline and control in work habits.
- Fear of taking personal risks.

Therefore, it is appropriate that we re-examine our perceptions of real engineering to focus our attention on the content in terms of what we want engineers to do in their careers, while we are exploring the application of new technology to the methods of education.

Definition

I propose to define a REAL, that is, professional, ENGINEER as *one who has attained and continuously enhances technical, communications, and human relations knowledge, skills, and attitudes, and who contributes effectively to society by theorizing, conceiving, developing, and producing reliable structures and machines of practical and economic value.*

The greater the breadth of knowledge, the more varied and accomplished the skills, and the more dedicated the attitude of any individual engineer, the more significant will be the accomplishment, resulting in proper recognition as a role model, teacher, and leader.

Knowledge

Knowledge for a real engineer is more than acquired data, and certainly much more than acquired engineering data. The cognitive process is different from the acquisitive process. While today's engineer may use information technology to make any of the world's data instantly available, the real engineer has developed a relational understanding of the data and will have learned how to recall and correlatively process relevant data in order to synthesize new information to solve problems.

The areas of required knowledge are not limited to those of science or technology, as consideration of the role of the engineer as leader will reveal. An understanding of societal evolution through study of history, economics, sociology, psychology, literature, and arts will enhance the value of the engineering contribution. And, in the shrinking world that the new communications technology is producing, we should not forget the study of foreign languages—an item often ignored on the western side of the Atlantic.

Skills

A real engineer's skills are essentially scheduled problem solving techniques of design, in which the concentrated disciplines of science and technology are exercised with the personal creativity and judgment developed from training and experience. In addition, because engineering accomplishments are achieved in a group environment, communication skills are critical to the roles of follower and leader.

These skills can be acquired only by doing: the practice may be on simulated problems, or, as for the entry-level medical doctor, on real cases under expert supervision. However, no amount of case study can replace the practice in learning how to debug a design, for example. The case study technique may be useful, but it is not sufficient to qualify the real engineer.

Attitudes

A real engineer's attitudes will directly affect the quality of his design solutions, whatever the problem. The real engineer is a leader of a team of resources: financial, personal, and material, at all levels of engineering activity. Successful team leadership implies a degree of self-criticism, where egotism and humility have counterbalancing influences. It requires a spirit of curiosity and courage that leads to creativity and innovation. Successful leadership is characterized by a forcefulness that gives orders, as well as receives orders, and accepts the challenges of competition in the marketplace with a perseverance to succeed. Leadership exhibits a loyalty downward as well as loyalty upward, and requires the earning of respect of project team members for personal competence, tolerance, and supervisory guidance.

—B. M. Gordon, Analogic Corporation

By the 1990s, this trend of criticizing university engineering education spread widely. For example, The Boeing Company in the United States organized an effort to influence university engineering education by setting forth its list of desired attributes of an engineer, as listed in Box 1.2. More broadly, the reaction of industry in the developed world included industry-led workshops and programs on engineering education and industry influence on accrediting and professional bodies. It also included direct industry and foundation funding of educational initiatives and industry influence on government to create resources and incentives for change. This was not a random or ill-coordinated effort, but a coherent reaction to what industry considered a major threat to its human resource flow from universities. What these and other commentaries by industrialists have in common is that they always underscore the importance of engineering science fundamentals and engineering knowledge, but then go on to list a wider array of skills that typically include elements of design, communications, teamwork, ethics, and other personal skills and attributes.

Box 1.2 Desired Attributes Of An Engineer

- A good understanding of engineering science fundamentals
  - Mathematics (including statistics)
  - Physical and life sciences
  - Information technology (far more than computer literacy)
- A good understanding of design and manufacturing processes
- A multi-disciplinary systems perspective
- A basic understanding of the context in which engineering is practiced
  - Economics (including business practices)
  - History
  - The environment
  - Customer and societal needs
- Good communication skills
  - Written, oral, graphic, and listening
- High ethical standards
- An ability to think both critically and creatively—independently and cooperatively
- Flexibility, i.e., the ability and self-confidence to adapt to rapid or major change
- Curiosity and a desire to learn for life
- A profound understanding of the importance of teamwork.

—**The Boeing Company**

Many individuals, programs and universities have heard, processed, and responded to these needs expressed so clearly by industry. However, the challenge from industry, and increasingly from government, still remains: to increase the quality of engineering education. Added to this input is increasing pressure to increase the quantity of graduating engineers. We seek to enhance the preparation of engineering students through the development of a systematic reform of engineering education, based on adaptations of the CDIO approach in university programs.

Overview of the CDIO Approach

The CDIO approach meets this challenge by educating students as well-rounded engineers who understand how to Conceive-Design-Implement-Operate complex, value-added engineering products, processes, and systems in a modern, team-based environment. The approach addresses three overall goals.

To educate students who are able to:

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

This education stresses the fundamentals, and is set in the *context* of conceiving, designing, implementing, and operating products, processes, and systems. We seek to develop programs that are educationally effective and more exciting to students, attracting them to engineering, retaining them in the program and in the profession.

A learning context is the set of cultural surroundings and environments that contribute to understanding, and in which knowledge and skills are learned. Conceiving, designing, implementing and operating should be the *context*, but not the *content*, of engineering education. Choosing the learning context as conceiving, designing, implementing, and operating is appropriate both because it is the professional role of engineers and because it provides the natural setting in which to teach key pre-professional engineering skills and attitudes. Within that context, we develop an integrated approach to identifying students' learning needs and we construct a sequence of learning experiences to meet them.

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

A rigorous engineering process has been applied to the design of the CDIO approach to ensure that it achieves its goals. We build an integrated approach to identifying the learning needs of the students in a program, and construct a sequence of learning experiences to meet those needs. These two elements are captured in a framework of effective practice, consisting of the CDIO Syllabus and the CDIO Standards.

Specific learning outcomes are codified in the CDIO Syllabus. This taxonomy of learning outcomes is a rational, consistent and detailed statement of the possible set of skills for an engineer. The Syllabus was derived from needs assessments and source documents, and tested by peer review. The proficiency expectations for graduating students are set with stakeholder input. These learning outcomes then form the basis for communicating goals and outcomes to both students and instructors, for program benchmarking and design, and for student learning assessment.

The CDIO Standards are an attempt to capture in one framework the effective practices of successful engineering education. We have identified these through benchmarking of programs worldwide, and correlated them with scholarship on engineering learning. The first Standard states the underlying principle that conceiving, designing, implementing and operating should be the context of engineering education. The second emphasizes that a broad set of learning outcomes should be set and validated by stakeholders. Curriculum should be organized around mutually supporting technical disciplines with personal and interpersonal skills, and product, process, and system building skills highly interwoven. An introduction to engineering should greet and inspire students early in their education, and lay the foundation for disciplinary learning. Programs should be rich with student design-implement experiences conducted in modern workspaces. They should feature active and experiential learning, and the learning of skills should be integrated into the technical learning. Instructors should be adequately prepared, both in teaching and learning, and in engineering skills. Our programs should be continuously improved through assessment of student learning across the spectrum of learning outcomes, and through a quality evaluation process. These characteristics are formalized in twelve CDIO Standards that serve as guidelines for educational program reform, create benchmarks and goals with worldwide application, and provide a framework for continuous improvement.

Development and implementation of the CDIO approach was initiated at three universities in Sweden—Chalmers University of Technology (Chalmers) in Göteborg, the Royal Institute of Technology (KTH) in Stockholm, Linköping University (LiU) in Linköping —and the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, USA. The number of programs known to be using the approach has expanded to more than 100 universities worldwide.

Little in our approach has been invented out of whole cloth. We have built upon research and best practices found within our collaborating universities and many other universities around the world who are seeking to improve engineering education. Many have made important contributions. For example, the development of learning outcomes and the use of problem-based learning and project-based learning are central to the CDIO approach. The CDIO approach incorporates these into a broader framework that is applicable to the entire design and operation of an engineering education program. The CDIO approach seeks to build on and systematize this international body of work, to develop a set of broadly applicable shared approaches and open-source resources that guide and accelerate engineering education reform. We recognize that, for most programs, extensive financial and personal resources are not available. We encourage the use of shared open-source resources and parallel coordinated efforts to facilitate continuous improvement.

Nothing in our approach is prescriptive. The CDIO approach must be adapted to each program—its goals, university, national, and disciplinary contexts. It is aligned with many other movements for educational change, but unlike national accreditation and assessment standards that state objectives, we provide a pallet of potential solutions to the comprehensive reform of engineering education. Many programs around the world are working on aspects of this issue and making important contributions. Many have already developed along the lines of the twelve CDIO Standards independently. But we can all do better, improve where we are weaker, contribute to others where we have strength, and constantly keep ahead of the changing needs of our students and society.

The Book

We have written this book to serve as an introduction to the CDIO approach. It is a practical guide with enough information to acquaint you with the high-level rationale, philosophy, and key ideas, and how they have evolved in a historical and societal context. The book points to more detailed resources that are contained in other publications, in workshops, and on the web.

Chapter 2 continues with an overview of the CDIO approach. It gives the reader an understanding of the need for change, the goals, vision, and pedagogical foundation of the approach, and the essential elements of implementation. Chapter 3 explains the process for identifying the desired skills of an engineer and the learning outcomes for students in a program. Chapters 4 through 6 then describe in some detail the curricular, workspace, and teaching and learning aspects of the approach. Chapters 7 through 9 discuss student assessment, implementation and change processes, and program evaluation. The book concludes with a historical perspective of engineering education, in order to provide the reader with the background to understand the context of change and an informed outlook to the future.

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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

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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

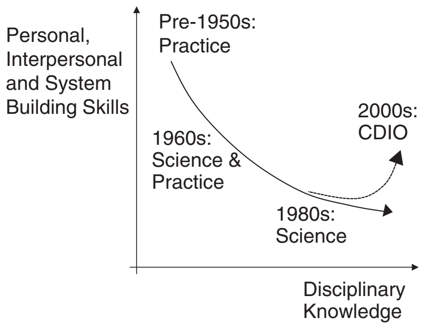

Fig. 2.1 The evolution of engineering education

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 20th century largely removed many of the hands-on experiences that engineering students once encountered at university. As a result, contemporary engineering students have little concrete experience upon which to base engineering theories. This lack of practical experience affects students' ability to learn 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

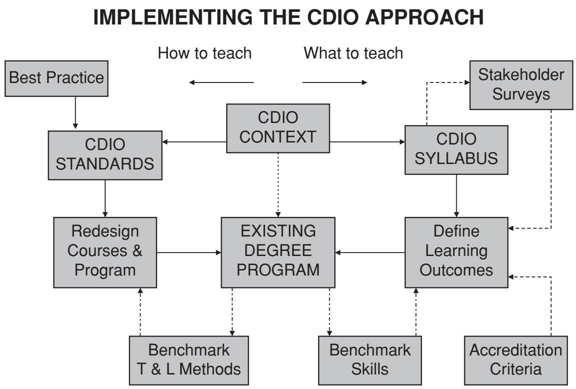

Fig. 2.3 Implementing the CDIO approach

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

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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Chapter 3
The CDIO Syllabus: Learning Outcomes for Engineering Education

Introduction

We will now develop a comprehensive approach to answering the first question central to the reform of engineering education, posed in Chap. 2:

> 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?

Said another way, what are the desired learning outcomes for engineering education? This question highlights the tension between two apparently conflicting needs. It is our responsibility as university educators to give students a solid foundation in a broad body of disciplinary knowledge. On the other hand, engineers must possess a wide array of personal and interpersonal skills, and product, process and system building skills that will allow them to function on real engineering teams in order to produce tangible benefits to society. The CDIO approach attempts to resolve this tension and to address the complete needs of students. We do this by first developing a comprehensive understanding of the knowledge, skills, and attitudes needed by the contemporary engineer, that is, the desired learning outcomes. The development of this understanding is the subject of this chapter. The curricular, pedagogical, and assessment strategies to facilitate meeting these learning outcomes are addressed in Chaps. 4, 5, 6, 7, 8, 9.

This chapter describes the development and content of the CDIO Syllabus, a codification of contemporary engineering knowledge, skills, and attitudes that constitute the foundation for the reform of university engineering education programs. Engineers might view the Syllabus as a requirements document for engineering education. For education specialists, it can be viewed as a comprehensive statement of learning outcomes. Both are equally valid interpretations. It is our aim that we move toward a resolution of the tension in contemporary engineering education by providing a complete enumeration of the knowledge and skills that graduating students should possess. This enumeration should be sufficiently general to allow it to be applied to all branches of engineering. On the other hand, it should be

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sufficiently detailed to be useful in curriculum planning and learning assessment. The first half of the chapter describes the development of the Syllabus, addressing the first part of the central question, "*What is the full set of knowledge, skills, and attitudes that engineering students should possess as they leave the university?*"

Traditionally, the second part of the central question—*at what level of proficiency?*—is decided internally by university faculty, by consensus, or by the choice of individual instructors. We advocate an approach that includes stakeholders from among students, faculty, university staff, alumni, and industry representatives working together to set the expected level of proficiency for each learning outcome.

Chapter Objectives

This chapter is designed so that you can

- Explain how the content of the CDIO Syllabus is derived from engineering practice.
- Describe the content and structure of the Syllabus.
- Explain the rationale for specifying learning outcomes in personal and interpersonal skills, and product, process and system building skills, as well as in technical disciplines.
- Describe how to engage stakeholders within and outside the university in the development of detailed learning outcomes.
- Outline a process for developing learning outcomes for engineering education that can be generalized to all disciplines.

The Knowledge and Skills of Engineering

The required knowledge and skills of engineering are best defined through the examination of the practice of engineering. In fact, from its conception as a profession early in the 19th century until the middle of the 20th century, engineering education was based on engineering practice. As explained in Chap. 1, the last half-century of engineering education saw its development move from a practice base to an engineering-science base. We now are observing a renewed interest in developing a third approach that merges the best of the engineering-science and practice viewpoints. This third approach requires a re-examination of the needs of modern engineering practice.

Required Engineering Knowledge and Skills

As early as the 1940s, attempts were made to codify the nontraditional skills an engineer must possess. One such attempt, the *Unwritten Laws of Engineering* [1], called for the development of such skills as oral and written communication, planning, and

Table 3.1 Evident shortcomings of graduating engineers with respect to skills and abilities [4]

Most important abilities with respect to EMPLOYMENT	Greatest deficits in abilities with respect to EDUCATION
Work effectively as a team	Business approach
Analyze information	Management skills
Communicate effectively	Project management methods
Gather information	Methods for quality assurance
Learn independently	Ability to communicate effectively
	Knowledge of marketing principles
	Sense of ethical and professional responsibilities

the ability to work successfully in organizations. In addition, the *Unwritten Laws* emphasized the importance of personal attributes, such as propensity toward action, integrity, and self-reliance. In many ways, this list of skills remains as valid for today's engineers as it was over a half century ago.

With the advent of the modern engineering-science approach in the 1950s, the education of engineers became more disassociated from the practice of engineering. Engineering science became the dominant culture of engineering schools, where fewer faculty members worked as engineers prior to teaching. By the 1980s, engineering educators and industrialists began to react to this widening gulf between engineering education and practice. For example, in the essay entitled *What is an Engineer?*, Bernard M. Gordon clearly enumerates the knowledge and skills required for contemporary engineering practice [2] (see Box 1.1 in Chap. 1).

The past decade has seen a concerted effort to close the gap between engineering education and practice. Major engineering companies, for example, The Boeing Company, published lists of desired attributes, and leaders of industry urged a new look at the issues related to the qualifications of engineers [3]. One might ask if these lists are particular to the United States, a specific field of engineering, or the needs of a decade? It is interesting that 10 years after these lists appeared, the World Chemical Engineering Council produced the 2004 list of the evident shortcomings of engineering graduates with respect to important skills of engineering graduates [4], as shown in Table 3.1. Comparison of this list with those produced by Boeing (see Box 1.2 in Chap. 1), and the Accreditation Board for Engineering and Technology (ABET) [5]—as well as other sources spanning 50 years, yields a remarkably consistent image of the desired attributes of young engineers. The required knowledge, skills, and attitudes that companies desire in their engineers consistently include an understanding of engineering fundamentals, design and manufacturing, the context of engineering practice, and abilities to think critically and creatively, to communicate, and to work on teams.

Based on this consistency, industrial leaders in the United States successfully lobbied government agencies to fund science and engineering education reform, persuaded professional societies to revise accreditation standards, and created joint working groups to facilitate the exchange of viewpoints. Other industrialized countries around the world initiated similar educational reforms. Despite good intentions, most of these initiatives did not have the fundamental impact on education originally desired.

Importance of Rationale and Levels of Detail

Two key reasons account for the lack of convergence between engineering education and engineering practice: (1) an absence of rationale, and (2) an absence of detail. Previous lists of skills were derived requirements that failed to make convincing statements of the rationale for why these were the desired attributes of an engineer. As explained in Chap. 2, the CDIO approach reformulates the underlying need to make the rationale more explicit. 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.

The rationale is essentially a restatement of the fact that it is the job of engineers to be able to engineer. If the conceive-design-implement-operate premise is accepted as the context of engineering education, it is possible to derive more detailed goals and learning outcomes for engineering education that are understandable within this rationale. We use this restatement of the underlying need to organize the content of the Syllabus.

The second limitation is the fact that other existing lists of skills lack sufficient detail to be widely understood or implemented. The CDIO Syllabus was developed to address this limitation by creating a clear, complete, and consistent set of goals for engineering education, in sufficient detail that they can be understood and implemented by engineering faculty. This set of detailed goals forms the basis for rational design of the curriculum and a comprehensive system of assessment.

The formulation of the functions of an engineer, from which the Syllabus is derived, does not in any way diminish the role of engineering science or engineering research. On the contrary, engineering science is the appropriate basis for engineering education, and engineering research is the process of adding new knowledge to that base. Although most university professors who adopt a CDIO approach are engineering scientists and researchers, their programs educate students, the vast majority of whom will go on to become professional engineers. This is true even at research-intensive universities, such as MIT in the United States, KTH in Sweden, and Tsinghua University in China. Whether students become practicing engineers or engineering researchers, setting their educational experiences in the context of the conception, design, implementation, and operation of systems and products strengthens their backgrounds.

The CDIO Syllabus

The CDIO Syllabus is a list of knowledge, skills, and attitudes desired of graduating engineers. It is rationalized against the norms of contemporary engineering practice, comprehensive of all known skills lists, and reviewed by experts in many fields. The principal value of the Syllabus is that it can be applied across a variety of programs and can serve as a model for all programs to derive specific learning outcomes.

The second principle of effective practice, called CDIO Standard Two, emphasizes the importance of the Syllabus in engineering education reform.

Standard 2—Learning Outcomes

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

Note that the standard does not require the use of the Syllabus at all. It calls more generally for the setting of learning outcomes for the wide range of personal, interpersonal, and product, process, and system building skills consistently cited as necessary for engineering practice. It calls for these outcomes to be set in a way that they are consistent with the goals of the local program and validated by the program's stakeholders. In principle, this could be done without any reference to the Syllabus at all, but with reference to some other comprehensive set of learning outcomes as perhaps supplied by a national accreditation or evaluation process.

The CDIO Syllabus is a resource and reference document for programs trying to implement this principle of effective practice. The knowledge, skills, and attitudes desired as a result of engineering education, that is, the learning outcomes, are codified in the CDIO Syllabus. These learning outcomes detail what students should know and be able to do at the conclusion of their engineering programs. In addition to learning outcomes for disciplinary knowledge (Section 1), the Syllabus specifies learning outcomes as personal, interpersonal, and product, process and system building skills. Personal learning outcomes (Section 2) focus on students' cognitive and affective development that includes analytical reasoning and problem solving, experimentation, investigation and knowledge discovery, system thinking, creative thinking, critical thinking, professional ethics and other responsibilities. Interpersonal learning outcomes (Section 3) focus on individual and group interactions such as teamwork, leadership, and communication. Product, process, and system building skills (Section 4) focus on conceiving, designing, implementing, and operating products, processes, and systems in enterprise, societal and environmental contexts.

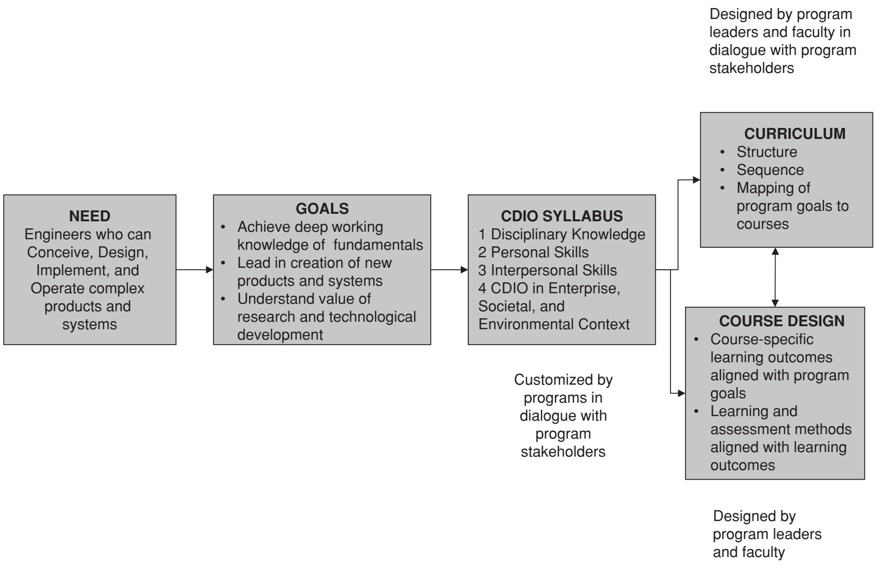

Fig. 3.1 Development and integration of the CDIO Syllabus

Learning outcomes are reviewed and validated by key stakeholders, that is, groups who share an interest in the graduates of engineering programs, for consistency with program goals and relevance to engineering practice. In addition, stakeholders help to determine the expected levels of proficiency, or standards of achievement, for each learning outcome. The process of validating the Syllabus with stakeholders is discussed later in this chapter.

Development and Integration of the CDIO Syllabus

The content and structure of the Syllabus is the focus of this chapter. Content and structure are motivated, in part, by an understanding of how the Syllabus is used. Customized with results of stakeholder surveys, the Syllabus lays the foundation for curriculum planning and integration, teaching and learning practice, and outcomes-based assessment. Figure 3.1 illustrates the development of the CDIO Syllabus from needs to goals, its customization to program goals, and the integration of program goals into the curriculum. More details on this process are given in later chapters. The process of integrating the Syllabus into a program's curriculum is the subject of Chap. 4. Approaches to teaching and learning the content of the Syllabus are described in Chap. 6. Student assessment of learning outcomes is the focus of Chap. 7.

The CDIO Syllabus was developed through focus groups comprised of various stakeholders, by reference to other documentation of the time, and through peer review. As a result of this development process, what we now call the CDIO Syllabus version 1.0 emerged in 2001 [6]. Originally intended to help programs fulfill Standard Two, the CDIO Syllabus v1.0 has proven to be a useful framework document in over 100 programs worldwide for setting program goals, planning curricula, and evaluating student learning. It has been translated into Swedish, French, Spanish, Vietnamese and Chinese.

Since the CDIO Syllabus v1.0 was drafted, it has been a remarkably stable document. However, there have been pressures to change the Syllabus. These pressures have two primary sources. The first pressure arises from the development of new taxonomies of knowledge that surface new issues that should be considered. These new taxonomies have arisen both from other universities, for example, the 5E Model of Group T in Belgium [7] and from national accreditation or evaluation bodies, for example, the Canadian Engineering Accreditation Board [8]. Another source of pressure comes from questions asked by users of the Syllabus looking for clarification or for knowledge and skill areas that seem to be missing.

A thorough review of these issues was conducted in 2010 and 2011, yielding the CDIO Syllabus version 2.0 that is described below. The original Syllabus v1.0 is extensively documented in reports and the first edition of this book, and remains a useful taxonomy. Version 2.0 largely extends and clarifies the taxonomy, building on the original document. Of course, the Syllabus is just a reference document; it is not prescriptive. If programs feel that the Syllabus is not appropriate for their programs, or needs to be expanded, they can modify it in any way desirable to them. As these documents are only resources, an academic program can choose to work with either version of the Syllabus or with their own modifications.

Content and Structure of the CDIO Syllabus

Three goals motivated the choice of content and structure of the Syllabus. These goals were to

- Create a structure whose rationale is clearly visible.
- Derive a comprehensive high-level set of goals that correlated with other respected sources.
- Develop a clear, complete, and consistent set of topics to facilitate implementation and assessment.

The point of departure for the derivation of the content of the Syllabus is the simple statement that engineers engineer, that is, they build products, processes, and systems for the betterment of humanity. In order to enter the contemporary profession of engineering, students must be able to perform the essential functions of an engineer. As described previously, graduating engineers should be able to conceive-design-implement-operate complex value-added engineering products, processes, and systems in a modern, team-based environment. Stated another way, graduating engineers should appreciate the engineering process; be able to

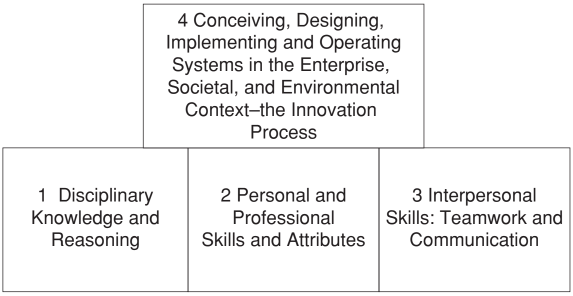

Fig. 3.2 The CDIO Syllabus at the first level of detail

contribute to the development of engineering products, processes, and systems; and do so while working in engineering organizations. Implicit is the additional expectation that, as university graduates and young adults, engineering graduates should be mature and thoughtful individuals.

These high-level expectations map directly to the first-level, or X-level, organization of the Syllabus, as illustrated in Fig. 3.2. The mapping of the first-level Syllabus items to the four expectations illustrates that a mature individual interested in technical endeavors possesses a set of *Personal and Professional Skills and Attributes*, central to the practice. In order to develop complex, value-added engineering systems, students must have mastered the fundamentals of the appropriate *Disciplinary Knowledge and Reasoning*. In order to work in modern, team-based environments, students must have developed the *Interpersonal Skills* of teamwork and communication. Finally, in order to create and operate products, processes, and systems, students must understand something of *Conceiving, Designing, Implementing, and Operating Systems in the Enterprise, Societal and Environmental Context*, which is the innovation process.

An independent validation of this mapping is the universal educational taxonomy developed by UNESCO [9]. They have proposed that all education should be organized around four fundamental types of learning:

- Learning to Know, that is, acquiring the instruments of understanding.
- Learning to Do, so as to be able to act creatively on one's environment.
- Learning to Live Together, so as to cooperate with other people.
- Learning to Be, an essential progression that proceeds from the previous three.

The organization of the CDIO Syllabus can be described as an adaptation of the UNESCO framework. Technical Knowledge and Reasoning (Section 1) is akin to UNESCO's Learning to Know. Conceiving, Designing, Implementing and Operating Systems in the Enterprise, Societal and Environmental Context (Section 4) is the application of UNESCO's Learning to Do to engineering. Interpersonal Skills: Teamwork and Communication (Section 3) is very close to UNESCO's Learning to Live Together. Finally, Personal and Professional Skills and Attributes (Section 4), placing emphasis on individual development, is equivalent to UNESCO's Learning to Be. Although the UNESCO framework

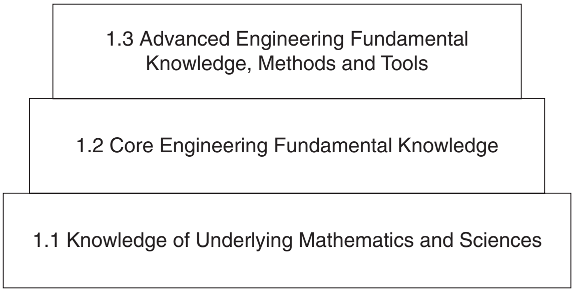

Fig. 3.3 The CDIO Syllabus: technical knowledge and reasoning

precedes the first draft of the CDIO Syllabus by several years, the original drafters of the Syllabus did not know of its existence. Thus, UNESCO and CDIO independently arrived at the same fundamental structure of these main types of learning.

The second level of detailed content, or X.X, was shown in Table 2.3, and will now be presented in some detail. The second level content of Section 1 *Disciplinary Knowledge and Reasoning* is shown in Fig. 3.3. Modern engineering relies on *Knowledge of Underlying Mathematics and Sciences* (1.1). A body of *Core Engineering Fundamental Knowledge* (1.2) builds on that science core, and a set of *Advanced Engineering Fundamental Knowledge, Methods and Tools* (1.3) moves students towards the skills necessary to begin a professional career. This is the disciplinary curriculum that engineering faculties usually debate and define. This section of the Syllabus is, in fact, a placeholder for the more detailed description of the disciplinary fundamentals necessary for engineering education. The details of Section 1 vary widely in content from field to field. The placement of *Disciplinary Knowledge and Reasoning* at the beginning of the Syllabus is a reminder that the development of a deep working knowledge of disciplinary fundamentals is, and should, be the primary objective of engineering education. The remainder of the Syllabus addresses the more generic knowledge, skills, and attitudes that all engineering graduates should possess.

Engineers of all types use approximately the same personal and interpersonal skills, and follow approximately the same generalized processes. In the remaining three parts of the Syllabus, we tried to be inclusive of all the knowledge, skills, and attitudes that engineering graduates might require. In addition, we attempted to use terminology recognizable to all professions. Local usage in different engineering fields will require some translation and interpretation.

The second-level content of Section 2 *Personal and Professional Skills and Attributes* is shown with Section 3 *Interpersonal Skills* in Fig. 3.4. The innermost circle highlights the three modes of thought most practiced by engineers: *Analytical Reasoning and Problem Solving* (2.1), *Experimentation, Investigation and Knowledge Discovery* (2.2), and *System Thinking* (2.3). These might also be called engineering thinking, scientific thinking, and system thinking. Each mode of thinking is further detailed into formulation of issues, the process of thinking, and

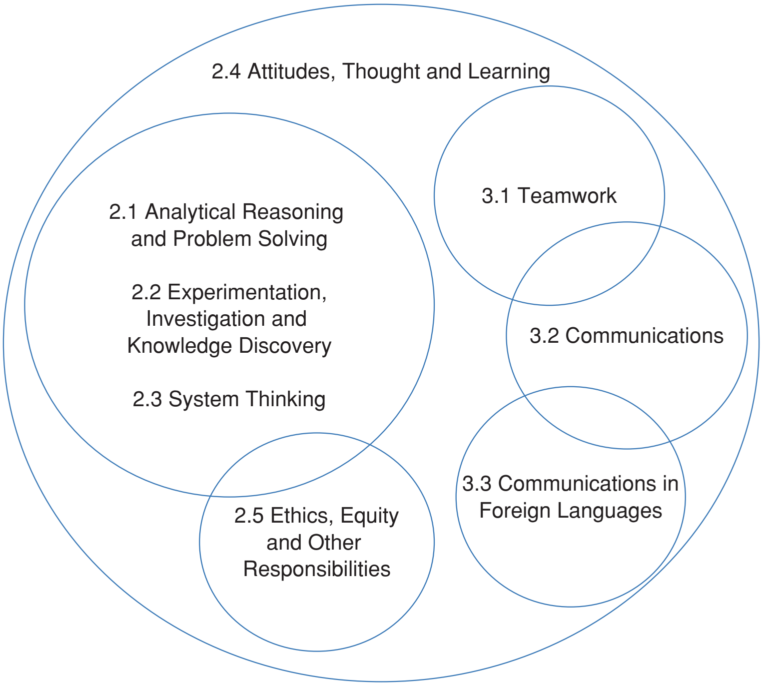

Fig. 3.4 The CDIO Syllabus: personal, professional, and interpersonal skills

resolution of issues. The detailed topical content of these sections at the third level is shown in Table 3.2, and a fourth or implementable level is given in the appendix.

Those personal values and attitudes that are used primarily in a professional context and that reflect responsibility are called *Ethics, Equity and Other Responsibilities* (2.5). These include ethics, integrity and social responsibility, professional behavior, the skills and attitudes necessary to plan for careers, and lifelong learning in the world of engineering. Other responsibilities such as equity and loyalty are also discussed. *Attitudes, Thought and Learning* (2.4) includes general character traits of initiative and perseverance, the more generic modes of thought of creative and critical thinking, and the skills of self-awareness, lifelong learning and educating, and time management.

Interpersonal Skills are a distinct subset of personal skills that divide into three overlapping subsets: *Teamwork* (3.1), *Communications* (3.2) and *Communications in Foreign Languages* (3.3). Teamwork is comprised of forming, operating, growing, and leading technical and multidisciplinary teams. Communications includes the skills necessary to devise a communications strategy and structure, and to use four common modes of communication: written, oral, graphic, and electronic. It also includes more informal communication: listening, negotiation, advocacy and networking. *Communications in Foreign Languages* includes traditional skills associated with foreign language learning and applications made specifically for technical communications.

Table 3.2 Condensed CDIO Syllabus v2.0 at the third level of detail

1 DISCIPLINARY KNOWLEDGE AND REASONING
1.1 KNOWLEDGE OF UNDERLYING MATHEMATICS AND SCIENCE
1.2 CORE ENGINEERING FUNDAMENTAL KNOWLEDGE
1.3 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE, METHODS AND TOOLS
2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES
2.1 ANALYTICAL REASONING AND PROBLEM SOLVING
- 2.1.1 Problem Identification and Formulation
- 2.1.2 Modeling
- 2.1.3 Estimation and Qualitative Analysis
- 2.1.4 Analysis with Uncertainty
- 2.1.5 Solution and Recommendation

2.2 EXPERIMENTATION, INVESTIGATION AND KNOWLEDGE DISCOVERY
- 2.2.1 Hypothesis Formulation
- 2.2.2 Survey of Print and Electronic Literature
- 2.2.3 Experimental Inquiry
- 2.2.4 Hypothesis Test and Defense

2.3 SYSTEM THINKING
- 2.3.1 Thinking Holistically
- 2.3.2 Emergence and Interactions in Systems
- 2.3.3 Prioritization and Focus
- 2.3.4 Trade-offs, Judgment and Balance in Resolution

2.4 ATTITUDES, THOUGHT AND LEARNING
- 2.4.1 Initiative and the Willingness to Make Decisions in the Face of Uncertainty
- 2.4.2 Perseverance, Urgency and Will to Deliver, Resourcefulness and Flexibility
- 2.4.3 Creative Thinking
- 2.4.4 Critical Thinking
- 2.4.5 Self-awareness, Metacognition and Knowledge Integration
- 2.4.6 Lifelong Learning and Educating
- 2.4.7 Time and Resource Management

2.5 ETHICS, EQUITY AND OTHER RESPONSIBILITIES
- 2.5.1 Ethics, Integrity and Social Responsibility
- 2.5.2 Professional Behavior
- 2.5.3 Proactive Vision and Intention in Life
- 2.5.4 Staying Current on World of Engineering
- 2.5.5 Equity and Diversity
- 2.5.6 Trust and Loyalty

3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION
3.1 TEAMWORK
- 3.1.1 Forming Effective Teams
- 3.1.2 Team Operation
- 3.1.3 Team Growth and Evolution
- 3.1.4 Team Leadership
- 3.1.5 Technical and Multidisciplinary Teaming

3.2 COMMUNICATIONS
- 3.2.1 Communications Strategy
- 3.2.2 Communications Structure

(Continued)

Table 3.2 (Continued)

3.2.3 Written Communication
3.2.4 Electronic/Multimedia Communication
3.2.5 Graphical Communication
3.2.6 Oral Presentation
3.2.7 Inquiry, Listening, and Dialog
3.2.8 Negotiation, Compromise, and Conflict Resolution
3.2.9 Advocacy
3.2.10 Establishing Diverse Connections and Networking
3.3 COMMUNICATIONS IN FOREIGN LANGUAGES
3.3.1 English
3.3.2 Languages of Regional Commerce and Industry
3.3.3 Other Languages

4 CONCEIVING, DESIGNING, IMPLEMENTING, AND OPERATING SYSTEMS IN THE ENTERPRISE, SOCIETAL AND ENVIRONEMENTAL CONTEXT—THE INNOVATION PROCESS

4.1 EXTERNAL, SOCIETAL, AND ENVIRONMENTAL CONTEXT
4.1.1 Roles and Responsibilities of Engineers
4.1.2 The Impact of Engineering on Society and the Environment
4.1.3 Society's Regulation of Engineering
4.1.4 The Historical and Cultural Context
4.1.5 Contemporary Issues and Values
4.1.6 Developing a Global Perspective
4.1.7 Sustainability and the Need for Sustainable Development
4.2 ENTERPRISE AND BUSINESS CONTEXT
4.2.1 Appreciating Different Enterprise Cultures
4.2.2 Enterprise Stakeholders, Strategy, and Goals
4.2.3 Technical Entrepreneurship
4.2.4 Working in Organizations
4.2.5 Working in International Organizations
4.2.6 New Technology Development and Assessment
4.2.7 Engineering Project Finance and Economics
4.3 CONCEIVING, SYSTEM ENGINEERING, AND MANAGEMENT
4.3.1 Understanding Needs and Setting Goals
4.3.2 Defining Function, Concept, and Architecture
4.3.3 System Engineering, Modeling, and Interfaces
4.3.4 Development Project Management
4.4 DESIGNING
4.4.1 The Design Process
4.4.2 The Design Process Phasing and Approaches
4.4.3 Utilization of Knowledge in Design
4.4.4 Disciplinary Design
4.4.5 Multidisciplinary Design
4.4.6 Design for Sustainability, Safety, Aesthetics, Operability, and other Objectives
4.5 IMPLEMENTING
4.5.1 Designing a Sustainable Implementation Process
4.5.2 Hardware Manufacturing Process
4.5.3 Software Implementing Process
4.5.4 Hardware Software Integration

(continued)

Table 3.2 (Continued)

4.5.5 Test, Verification, Validation, and Certification
4.5.6 Implementation Management
4.6 OPERATING
4.6.1 Designing and Optimizing Sustainable and Safe Operations
4.6.2 Training and Operations
4.6.3 Supporting the System Lifecycle
4.6.4 System Improvement and Evolution
4.6.5 Disposal and Life-End Issues
4.6.6 Operations Management

Figure 3.5 shows an overview of Section 4 *Conceiving, Designing, Implementing, and Operating Systems in the Enterprise, Societal and Environmental Context—the Innovation Process.* It illustrates the way the development of a product, process, or system moves through four phases: *Conceiving, System Engineering, and Management* (4.3), *Designing* (4.4), *Implementing* (4.5), and *Operating* (4.6). The terms are chosen to be descriptive of hardware, software, systems, and process industries. *Conceiving, Systems Engineering, and Management* takes the process from market or opportunity identification through high-level conceptual design and includes the system engineering of the product or process and project management. *Designing* includes aspects of the design process, as well as disciplinary, multidisciplinary, and design for sustainability, safety, aesthetics, operability and other objectives. *Implementing* includes hardware and software processes, test and verification, as well as design and management of the implementation process. *Operating* covers a wide range of issues from designing and managing operations, through supporting the product, process, and system lifecycle and improvement, to end-of-lifecycle planning.

Products, processes, and systems are created and operated within an *Enterprise and Business Context* (4.2) that engineers must understand to operate effectively. The skills necessary to do this include recognizing the culture and strategy of an enterprise and understanding how to act in an effective and entrepreneurial way within a small, large or international organization. Also covered in this section are skills of new technology development and project finance. Enterprises exist within a larger *External, Societal and Environmental Context* (4.1). Knowledge and skills in this area include acknowledgment of the relationship between society and engineering, and an understanding of the broader historical, cultural, and global context, and a deep appreciation for the need for sustainable development.

In summary, the Syllabus is organized at the first two levels in rational manner. The first level, or X level, reflects the functions of an engineer, who is a well-developed individual, involved in a process that is embedded in an organization, with the intent of building products, processes, and systems. The second level of detailed content, or X.X level, reflects contemporary practice and scholarship of the engineering profession.

The Syllabus is defined to third level (X.X.X) and fourth level of detail, respectively. These fine-grain details are necessary to transition from high-level goals to

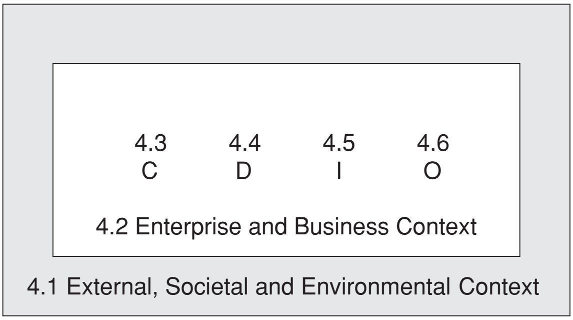

Fig. 3.5 The CDIO Syllabus: conceiving, designing, implementing, and operating

teachable and assessable learning outcomes. Although it could seem overwhelming at first, the detailed Syllabus has many benefits for engineering faculty who may not be experts in some of the Syllabus topics. The details provide insight into content and learning outcomes, the integration of these skills into a curriculum, and the planning of teaching and assessment. Table 3.2 is a condensed version at the third level of detail. The complete CDIO Syllabus v2.0 at the fourth level of detail is found in the appendix.

Validation of the CDIO Syllabus

The process used to arrive at the detailed content of the CDIO Syllabus v1.0 in 2001 blended elements of user-need studies in product development with techniques used in scholarly educational research. It included focus-group discussions, document research, surveys, and peer review. A first draft included the results of the focus groups and topics extracted from four principal, comprehensive source documents: ABET's *Criteria for Accrediting Engineering Programs*, Boeing's *Desired Attributes of an Engineer*, and two internal documents from the Massachusetts Institute of Technology, reporting on the goals of engineering undergraduate education. Qualitative comments from stakeholder surveys were incorporated, improving the Syllabus' organization, clarity and coverage. Subsequently, several domain experts reviewed each second-level, or X.X level, Syllabus topic. Combining the results of the expert reviews and additional references, a final version of the Syllabus v1.0 was produced.

In 2010, a similar process was used to update the Syllabus to produce version 2.0. Comparison with a number of accreditation and evaluation documents was conducted, including the updated ABET criteria, the criteria of the Canadian Engineering Accreditation Board, the UK Standards for Professional Engineering Competence [10], the Dublin Descriptors [11], the Swedish national engineering degree requirements [12], and the European EUR-ACE framework standards for accreditation of engineering programs [13]. In addition, extensive input from users of the Syllabus was incorporated. The changes

Table 3.3 The CDIO Syllabus correlated with ABET's evaluative criterion 3

CDIO Syllabus	**ABET's Evaluative Criterion 3**										
	a	b	c	d	e	f	g	h	i	j	k
1.1 Knowledge of Underlying Mathematics, Science	■										
1.2 Core Engineering Fundamental Knowledge	■										
1.3 Adv. Engr. Fund. Knowledge, Methods, Tools	▒										■
2.1 Analytical Reasoning and Problem Solving					■						▒
2.2 Exper. Investigation and Knowledge Discovery		■									
2.3 System Thinking			▒								
2.4 Attitudes, Thought, and Learning									■		
2.5 Ethics, Equity, and Other Responsibilities						■					▒
3.1 Teamwork				■							
3.2 Communications							■				
3.3 Communication in Foreign Languages											
4.1 External, Societal, and Environmental Context			▒					■		■	
4.2 Enterprise and Business Context			▒					■			
4.3 Conceiving, Systems Engr., and Management			■								
4.4 Designing			■								
4.5 Implementing			▒								
4.6 Operating			▒								
	■	Strong Correlation					▒	Good Correlation			

to the Syllabus were made in part to add missing skills and in part to clarify nomenclature and make the Syllabus more explicit and more consistent with national standards.

To ensure comprehensiveness and to facilitate comparisons, the Syllabus version 2.0 was correlated with many of the comprehensive source documents referred to earlier. For example, the Syllabus topics at the second level were correlated with ABET's Evaluative Criteria 3a to 3 k (see Table 3.3). ABET states that accredited engineering programs must ensure that its graduates can demonstrate 11 specific skills. All 11 skills explicitly appear in the Syllabus. In fact, the Syllabus is more comprehensive. For example, the Evaluative Criteria do not explicitly address *System Thinking* (2.3), and list only *an ability to engage in life-long learning* (3i) from among the many desired attributes in *Attitudes, Thought and Learning* (2.4) of the Syllabus, missing for example, initiative, perseverance, and critical thinking. Likewise, the Evaluative Criteria list only *an understanding of professional and ethical responsibility* (3f) from among several important attributes in *Ethics, Equity and Other Responsibilities* (2.5).

The ABET document comes closer than other source documents to capturing the full involvement in a product lifecycle by specifying item (3c) *the ability to design a system, component, or process to meet desired needs, within realistic constraints, such as economic, environmental, social, political, ethical, health and safety, manufacturability and sustainability.* Designing *a system to meet desired needs* hints at the spirit of *Conceiving, System Engineering, and Management* (4.3) in the Syllabus. *Designing a component or process* maps to *Designing* (4.4), and *designing for … manufacturability and sustainability* at least references the need to consider *Implementing* (4.5) and *Operating* (4.6).

Comparing the CDIO Syllabus with ABET's Evaluative Criterion 3, the Syllabus has two advantages, one minor and one major. The minor advantage is that the Syllabus is more rationally organized. It is explicitly derived from the functions of modern engineering. Although this organization might not provide a better understanding of how to implement change, it creates a better understanding of the reasons to change. The major advantage is that the Syllabus contains more levels of detail than the ABET document. It penetrates into enough detail that general phrases such as *good communication skills* take on substantive meaning. Furthermore, it defines measurable goals that are critical to curriculum design and assessment.

Similar comparisons have been made of the CDIO Syllabus with accreditation standards in other countries. Box 3.1 compares it with standards for engineering programs in the United Kingdom.

Box 3.1 Comparisons of the CDIO Syllabus with UK-SPEC

The CDIO Syllabus has been compared with accreditation criteria published in 2004, and updated most recently in 2011, for engineering programs in the United Kingdom. The Engineering Council [www.engc.org.uk] in collaboration with the UK Quality Assurance Agency [QAA, www.qaa.ac.uk] publish the criteria. They make the Master of Engineering (MEng) degree the minimum academic qualification for becoming a Chartered Engineer (CEng). Students graduating with the less academically demanding Bachelor of Engineering (BEng) degree become Incorporated Engineers (IEng), unless they undertake one year of postgraduate study to match the educational attainment of MEng graduates.

The set of requirements are called UK-SPEC, and are detailed in two principal documents which focus on the threshold standards of competence required for registration as a Chartered or Incorporated Engineer (*UK Standard for Professional Engineering Competence*) and the accreditation of engineering degree programs (*The Accreditation of Higher Education Programs*). Both can be downloaded from the Engineering Council web site at http://www.engc.org.uk. The accreditation criteria are expressed in the form of a list of required learning outcomes, which are presented under the headings *General Learning Outcomes* and *Specific Learning Outcomes*.

A. General Learning Outcomes
   1. Knowledge and Understanding
   2. Intellectual Abilities
   3. Practical Skills
   4. General Transferable Skills

B. Specific Learning Outcomes
   1. Underpinning Science and Mathematics, and Associated Engineering Disciplines
   2. Engineering Analysis
   3. Design
   4. Economic, Social, and Environmental Context
   5. Engineering Practice

In UK-SPEC, an initial set of learning outcomes is provided for BEng programs; then, supplementary outcomes are stipulated under most headings for MEng programs. The learning outcomes are more detailed than the 11 found in the ABET Evaluative Criteria. As an illustration, 26 separate learning outcomes are listed under *Specific Learning Outcomes* for a BEng program, with a further 14 for an MEng program. However, in a number of cases, outcomes lack precision and clarity. In part, this is a consequence of the system in the United Kingdom where degree programs are not accredited by a central body but by individual engineering institutions, for example, the Institution of Mechanical Engineers, the Institution of Engineering and Technology (IET) or the Institution of Civil Engineers (ICE). There are more than 30 licensed institutions, many of which have produced interpretive documents in order to customize the accreditation criteria for their particular disciplines.

The outcomes listed as *General Learning Outcomes* in UK-SPEC are, in most cases, reproduced and expanded in the *Specific Learning Outcomes*. The exception is *General Transferable Skills* where reference is made to the *higher-level key skills*, defined by the Qualifications and Curriculum Development Agency (formerly the QCA). This body provides extensive guidance on the development of key skills in six areas: application of number, communication, information, and communication technology, improving one's own learning and performance, problem solving, and working with others. Levels of attainment are set for all areas of the education system in the UK, including university education. However, the university-level key skills are generic, and do not specifically relate to engineering education.

There is a relatively weak correlation between the UK-SPEC accreditation criteria and the UK-SPEC standards for professional registration. In particular, the required learning outcomes do not mirror registration standards relating to leadership, interpersonal skills, and communication in a professional setting. In part, this is a result of the decision to delegate responsibility for defining transferable skills to the Qualifications and Curriculum Development Agency [QCDA, www.qcda.gov.uk], although this

(*Continued*)

Box 3.1 Comparisons of the CDIO Syllabus with UK-SPEC —CONT'D

body is to close under 2011 government reforms. It may also reflect a view that professional skills and attitudes can be acquired only when graduates enter employment as practicing engineers.

As indicated in the list, UK-SPEC devotes a specific group of learning outcomes to design. Within the group, there are some references to the conceptual phase that precedes design. However, the contention that engineering education should cover the complete product or system lifecycle is not fully reflected in UK-SPEC. One learning outcome states that graduates should have the *ability to ensure fitness for purpose for all aspects of the problem including production, operation, maintenance and disposal*. While this statement echoes our thinking, it is included in the design section and effectively refers to multi-objective design (Design for X). It can therefore be argued that UK-SPEC does not fully recognize that all engineers need to know how to implement their designs in the form of physical products or systems. In addition, UK-SPEC makes no specific mention of the operational phase of the product or system lifecycle, apart from the need to promote sustainable development.

UK-SPEC recognizes that some aspects of UK higher education are different in Scotland, and offers guidance about how to approach these. The Engineering Council can also authorize the award of the EUR-ACE label to approved engineering programs. The EUR-ACE framework aligns with the HE qualification framework agreed as part of the Bologna process, thus widening the international standing of UK degree awards.

From the foregoing discussion, it is apparent that the CDIO Syllabus has several advantages over UK-SPEC, the most obvious of which are the following:

- Although UK-SPEC contains more learning outcomes than the ABET criteria, it still lacks the fine detail of the CDIO Syllabus.
- UK-SPEC is not self-contained, that is, it delegates responsibility for important personal and interpersonal skills to the Qualifications and Curriculum Development Agency, which provides guidance on a limited set of skills that are not specifically those required by engineering graduates.
- There is limited coverage of professional skills in UK-SPEC compared with the CDIO Syllabus. Although formal training in employment, which used to be widespread in the United Kingdom, is now rare, employers expect graduates to have at least some of the professional skills needed to move directly into positions of responsibility.
- UK-SPEC does not reflect the need for competence in all aspects of the product or system lifecycle. The implementation and operational phases, in particular, are not addressed by appropriate learning outcomes.

> It may be argued that UK-SPEC is less helpful than it could be because it limits itself to listing a series of learning outcomes. Although topic-based, the CDIO Syllabus is supported by a rationale, a set of standards and a process for developing program-specific learning outcomes. The comprehensive nature of the Syllabus also means that it will invariably cover any learning outcomes required for accreditation purposes. However, when combined with its other elements, a CDIO approach achieves a more fundamental objective, which is to indicate clearly how an engineering program can be improved, and not simply accredited.
>
> —**P. J. Armstrong, Queen's University Belfast**
> —**P. Goodhew, University of Liverpool**

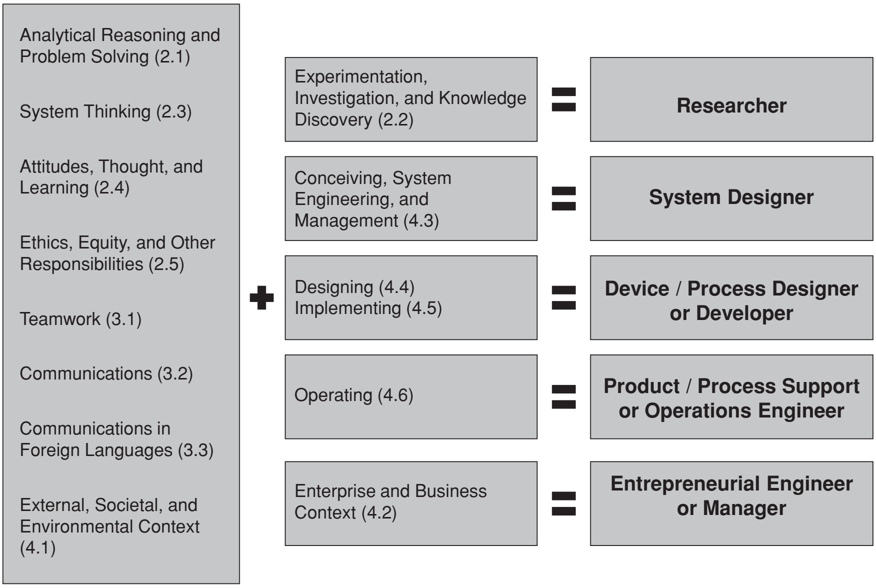

Fig. 3.6 Professional engineering career tracks implicitly identified in the CDIO Syllabus

As an independent check on the comprehensiveness of the CDIO Syllabus, it was compared with generic skills needed by engineers in five different career tracks. The generic skills applicable to all tracks include: 2.1 *Analytical Reasoning and Problem Solving*, 2.3 *System Thinking*, 2.4 *Attitudes, Thought, and Learning*, 2.5 *Ethics, Equity, and other Responsibilities*, 3.1 *Teamwork*, 3.2 *Communications*, 3.3 *Communications in Foreign Languages*, and 4.1 *External, Societal, and Environmental Context*. There are at least five professional tracks that engineers can and do follow, according to their individual talents and interests. The tracks, and sections of the Syllabus that support them, are shown in Fig. 3.6.

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

Contemporary Themes in Engineering: Sustainability, Innovation, and Globalization

The CDIO Syllabus was written with the intent of creating a long-lived, stable enumeration of the knowledge and skills required of an engineer. At the same time, contemporary themes emerge that are important for both engineering and engineering education. As discussed in Chap. 2, the themes of sustainability, innovation and globalization fall in this category and are discussed in this section. In the next section, we discuss the increasing role that engineers play as leaders and entrepreneurs. These themes did not appear explicitly in the higher-level organization of the Syllabus v1.0, but many of the constituent knowledge and skills that support these themes were present. However, in the drafting of the Syllabus v2.0, these themes were strengthened and made more explicit, allowing the Syllabus to be a complete reference document of the skills and knowledge of contemporary engineers.

During the last decade, the importance of sustainable development has become widely recognized. Future engineers need to be able to mitigate the negative environmental consequences of current energy and production systems, and create new ones that are essentially carbon neutral. Syllabus v2.0 makes this more explicit by referencing the environmental context in the headings of Sections 4 and 4.1, by adding a Section 4.1.7 entitled *Sustainability and the Need for Sustainable Development*, and by making sustainability a more prominent issue in design (4.4), implementation (4.5) and operations (4.6).

However, it could also be argued that CDIO is already fundamentally aligned with the ideas of sustainability; engineers are said to conceive, design, implement and operate complex technical systems with the entire product/process/system lifecycle in mind. Moreover, sustainability is a complex concept. It includes three main dimensions: economic, environmental, and social sustainability, including both subject matter and judgmental aspects, such as, ethics and decision-making [14]. There are many places in the CDIO Syllabus that emphasize the lifecycle perspective, for example, requirements should cover all phases of the lifecycle; analyses should be made of lifecycle values and costs; and product retirement should be planned ahead. With this broader perspective in mind, links between sustainability principles and CDIO Syllabus topics can be identified [15].

An excellent guide for the teaching of engineering for sustainable development was produced by the Royal Academy of Engineering in the United Kingdom, which describes sustainability as the constructive intersection of technocentric,

Table 3.4 Principles of sustainability compared with the CDIO Syllabus topics

	Sustainability principle		The CDIO Syllabus
1	Look beyond your own locality and the immediate future	4.1.1	Roles and responsibilities of engineers
		4.1.2	The impact of engineering on society and the environment
		4.1.6	Developing a global perspective
2	Innovate and be creative	2.4.3	Creative thinking
3	Seek a balanced solution	2.3.4	Trade-offs, judgment and balance in resolution
4	Seek engagement from all stakeholders	4.2.2	Enterprise stakeholders, strategy and goals
5	Make sure you know the needs and wants	4.3.1	Understanding needs and setting goals
6	Plan and manage effectively	4.3.4	Development project management
7	Give sustainability the benefit of any doubt	4.1.7	Sustainability and the need for sustainable development
8	If polluters must pollute, then they must pay as well	4.4.6	Design for sustainability, safety, aesthetics, operability, and other objectives
9	Adopt a holistic 'cradle-to-grave' approach	2.3.1	Thinking holistically
		4.3.3	System engineering, modeling, and interfaces
10	Do things right, having decided on the right thing to do	2.5.1	Ethics, integrity, and social responsibility
11	Beware cost cutting that masquerades as value engineering	2.4.4	Critical thinking
		4.3.4	Development project management
12	Practice what you preach	2.5.1	Ethics, integrity, and social responsibility

sociocentric, and ecocentric concerns [16]. A scan of the Syllabus for these three categories of concerns reveals a great deal of discussion of issues of appropriate development and use of technology, environmental issues, and an engineer's responsibility to consider societal and environmental issues in design. In this report, the Royal Academy defines twelve guiding principles of engineering for sustainable development. Table 3.4 compares these twelve principles with the corresponding topics of the Syllabus. In almost all cases, the Syllabus contains the skills or knowledge associated with the principle. Thus, both in terms of high-level visibility and alignment, and in terms of detailed content, the Syllabus v2.0 is the foundation for an education in sustainable engineering.

A second contemporary theme in engineering is the role that engineers play in innovation. In its Innovation Survey, the Confederation of British Industry (CBI) defines innovation broadly as "the successful exploitation of new ideas [17]." The specific role that engineers play in innovation is in the development and introduction into the market of new goods and services. In this sense, innovation is just the market-oriented view of what the CDIO Syllabus defines in Sections 4.2 through 4.6—Conceiving, System Engineering, and Management (4.3), Designing (4.4), Implementing (4.5), and Operating (4.6), within an enterprise (4.2). To emphasize this point, the phrase *the innovation process* has been added to the title of Section 4. In version 2.0, the Syllabus has also been strengthened in topics specifically associated with innovation, by adding or expanding discussion of stakeholders, new technology development and engineering project finance in Section 4.2, and of understanding needs and setting goals in Section 4.3.

There is another view of innovation, which focuses more on the capabilities of an innovator: a deep conceptual understanding of fundamentals, the skills to exploit ideas, and a sense of self-empowerment. Said another way, these are the knowledge to innovate, the skills to innovate, and a positive attitude towards taking the risks necessary for innovation. When comparing this model with the CDIO Syllabus, we find the knowledge of a technical discipline listed in Section 1. The skills required to exploit ideas include most of Section 4, as well as communications (3.2 and 3.3), and teamwork (3.1). The character traits that underlie an inclination to innovate include a willingness to take risk (2.4.1), perseverance (2.4.2), creative thinking (2.4.3) and critical thinking (2.4.4). From both a process and capabilities perspective, the Syllabus v2.0 includes a thorough discussion of the skills required of engineers in innovation.

With increasing international accords and trade, we are in a period of internationalization and mobility of workforce. Engineers increasingly work with international partners at a site, in multinational companies, and with companies, suppliers or markets in different lands. The engineering workforce itself is more mobile, and it is not uncommon for engineers to work in nations other than the one in which they received their training. In order to prepare students for this future, the Syllabus v2.0 includes *Developing a Global Perspective* (4.1.6), and *Working in International Organizations* (4.2.5), which in concert with *Communications in Foreign Languages* (3.3) and reference in 2.5.2 to international norms, prepare a student for mobility and international efforts.

Contemporary Themes in Engineering: Leadership and Entrepreneurship

In modern society, engineers are increasingly expected to move to positions of leadership and to take on additional roles as entrepreneurs. *Leadership* refers to the role of helping to organize effort, create vision, and facilitate the work of others. *Entrepreneurship* in this context refers to the specific activity of creating and leading a new enterprise. Engineering leadership and entrepreneurship are not orthogonal to the skills already contained in the CDIO Syllabus. After all, the goal of the CDIO approach is "To educate students who are able to: … Lead in the creation and operation of new products, processes, and systems…" The knowledge, skills, and attitudes needed in the creation and operation of new products, processes, and systems should, therefore, already be contained in the CDIO Syllabus. In fact, there is a broad overlap, both between leadership and entrepreneurship, and between the two of them and the skills already in the Syllabus (see Fig. 3.7). In this section, we discuss engineering

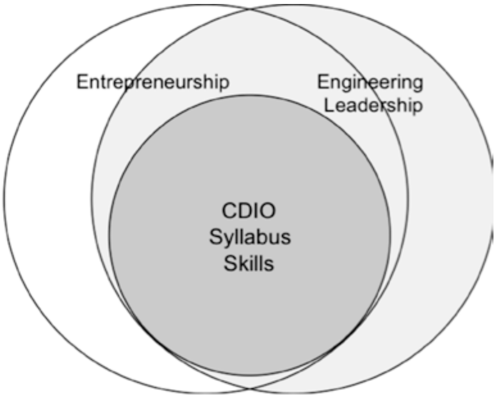

Fig. 3.7 The relationship between the knowledge, skills and attitudes in the CDIO Syllabus, engineering leadership, and entrepreneurship

Table 3.5 Extension of the CDIO Syllabus v2.0

4.7 LEADING ENGINEERING ENDEAVORS	4.8 ENTREPRENEURSHIP
Creating a Purposeful Vision	4.8.1 Company Founding, Formulation, Leadership, and Organization
4.7.1 Identifying the Issue, Problem or Paradox	4.8.2 Business Plan Development
4.7.2 Thinking Creatively and Communicating Possibilities	4.8.3 Company Capitalization and Finances
4.7.3 Defining the Solution	4.8.4 Innovative Product Marketing
4.7.4 Creating New Solution Concepts	4.8.5 Conceiving Products and Services around New Technologies
Delivering on the Vision	4.8.6 The Innovation System, Networks, Infrastructure, and Services
4.7.5 Building and Leading an Organization and Extended Organization	4.8.7 Building the Team and Initiating Engineering Processes
4.7.6 Planning and Managing a Project to Completion	4.8.8 Managing Intellectual Property
4.7.7 Exercising Project/Solution Judgment and Critical Reasoning	
4.7.8 Innovation—the Conception, Design and Introduction of New Good and Services	
4.7.9 Invention—the Development of New Devices, Materials or Processes that Enable New Goods and Services	
4.7.10 Implementation and Operation—the Creation and Operation of the Goods and Services that will Deliver Value	

leadership as the skills beyond those already reflected in the CDIO Syllabus, and engineering entrepreneurship as those additional skills beyond the Syllabus and leadership.

We recognize that many programs that use the CDIO Syllabus do not address leadership and entrepreneurship in their programs. For this reason, we created an extension of the CDIO Syllabus for Leadership and Entrepreneurship, with the additional content discussed below (see Table 3.5). At some point in their careers, many engineers will move to positions of engineering leadership, ranging from being a leader of a small team, to being the technical leader of an entire enterprise. Leadership is explicitly discussed in Section 3.1.4 of the CDIO Syllabus, but this topic discusses the skills needed in leading small groups, and is only a placeholder for the wider set of skills that an engineer leader is required to have.

Much has been written over the years about the qualities of a leader. In contemporary scholarship, leadership is closely studied by those in organizational behavior groups, often at schools of business or management, for example, the Four Capabilities Leadership Framework was developed at the Sloan School of Management at MIT [18]. It begins with four assumptions: (1) that leadership is distributed; (2) that it is personal; (3) that it continues to develop throughout one's career and thus changes over time; and, (4) that each individual invents his/her own framework for how he/she will lead. It then identifies four essential capabilities: sensemaking, relating, visioning and delivering on the vision (inventing). The Gordon—MIT Engineering Leadership Program customized this model to engineering, and extended it to include the attitudes of leadership and a foundation of technical fundamentals [19]. The customized engineering leadership model has six central skills, some of which overlap with topics already in the Syllabus v2.0:

1. The Attitudes of Leadership, Core Personal Values, and Character: initiative, the will to deliver, resourcefulness, integrity, and loyalty. These are largely covered in the Syllabus v2.0 in *Attitudes, Thought and Learning* (2.4), and in *Ethics, Equity and Other Responsibilities* (2.5)
2. Relating to Others: developing trusted relationships with diverse individuals, using inquiry to know how to communicate effectively, and leadership through advocacy, even if one is not a formal leader. These are contained in *Teamwork* (3.1), *Communications* (3.2) and potentially *Communications in Foreign Languages* (3.3)
3. Making Sense of the Context: making sense of the context of the changing world around us. This employs topics already in *External, Societal and Environmental Context* (4.1), *Enterprise and Business Context* (4.2) *Conceiving, Systems Engineering and Management* (4.3) and *System Thinking* (2.3)
4. Creating a Purposeful Vision: both to create a vision for oneself and to convey that vision to others
5. Realizing the Vision: engineering leaders need to invent ways to think through situations, and create ways of organizing their work with others
6. Technical Knowledge: the foundation of technical knowledge and skills that separate an engineer from other professions. This is the knowledge and skill set contained in *Disciplinary Knowledge and Reasoning* (1.0).

In order to develop the topics that are not within the main body of the Syllabus, a new Section 4.7 *Leading Engineering Endeavors* was added to the CDIO Syllabus v2.0. This new section defines the remaining topics in *Creating a Purposeful Vision* (4.7.1 to 4.7.4) and *Realizing the Vision* (4.7.5 to 4.7.10) (see Table 3.2 and the CDIO Syllabus v2.0 in the appendix). These sections enumerate specific engineering leadership skills, such as identifying the issue or problem, thinking creatively and defining a solution concept, building and leading a technical organization, and exercising technical judgment. Many of these skills, like the entrepreneurial skills in the discussion below, require significant professional experience to develop and will be a challenge to address in a university education. They are included in the extended Syllabus v2.0 as a guide, taxonomy and set of challenging goals for programs seeking these educational outcomes.

We call *entrepreneurship* the specific skills associated with business formulation, beyond those of engineering and engineering leadership (see Fig. 3.7). These were touched on in Section 4.2.3 of the Syllabus, but are expanded in the new Section 4.8. In the view of classical economics, entrepreneurship involves the redirection and mobilization of capital and human resources to form a new economic activity. Today, the term *entrepreneurship* generally refers exclusively to starting a new company, while launching a radically new line of business within an existing firm is sometimes called *intrapreneurship* or, more simply, innovation [20].

Preparation for entrepreneurship, that is, the starting of a new company, involves unique competencies that can be learned [21]. There are parallels with skills needed within an existing company, such as the similarity between recognizing new opportunities enabled by advancing technology, or writing business plans for a new product. However, there is an array of skills that engineers in an established company might never face, such as finding and hiring an entire company of talented professionals willing to accept risk, using equity to motivate innovation, or creating a new company culture where none existed.

In order to capture these additional skills of entrepreneurship, Section 4.8 was added to the Syllabus v2.0. This new section includes the following topics: company founding, formulation, leadership and organization; business plan development; company capitalization and finances; innovative product marketing; conceiving products and services around new technologies; the innovation system, networks, infrastructure, and services; building the team and initiating engineering processes (conceiving, designing, implementing, and operating); and managing intellectual property (see Table 3.5 and the CDIO Syllabus v2.0 in the appendix).

Learning Outcomes and Student Proficiency Levels

The CDIO Syllabus is a detailed list of knowledge and skills in which a graduating engineer should have developed some level of proficiency. It comprehensively addresses the first part of the central question posed at the start of this chapter:

> What is the full set of knowledge, skills, and attitudes that engineering students should possess as they leave the university, and at what level of proficiency?

However, Standard Two on learning outcomes calls for more than a mere listing of topics. It requires that a program set *specific, detailed learning outcomes for personal and interpersonal skills, and product, process, and system building skills*

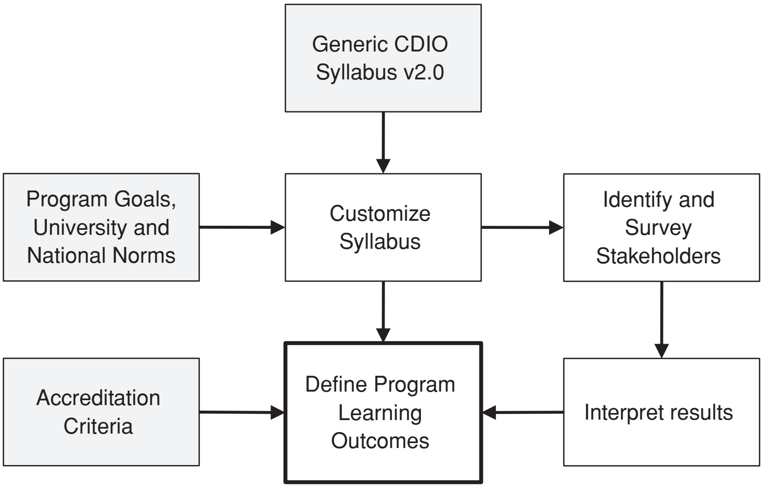

Fig. 3.8 Process for defining program learning outcomes based on the CDIO Syllabus

consistent with program goals and validated by program stakeholders. In order to translate this list of knowledge, skills, and attitudes into learning outcomes, detailed levels of expected proficiencies need to be established for all of the topics in the Syllabus. It is highly desirable to capture the opinions of representative stakeholders of the educational program, and to encourage consensus of both individual viewpoints and collective wisdom. This is the intent of the phrase *validated by program stakeholders* in Standard Two.

Figure 3.8 illustrates a process for establishing proficiency levels and learning outcomes based on the CDIO Syllabus:

1. Review the CDIO Syllabus v2.0 and make modifications or additions to customize it for a specific program within its university and national context.
2. Identify the important stakeholders of the program, both internal and external to the university, including faculty, graduates, representatives of industry, and others.
3. Determine a means of engaging stakeholders and summarizing their opinions. This could include surveys, focus groups, interviews or workshops.
4. Conduct faculty discussions to interpret the results of stakeholder input. These discussions can lead to consensus on expected levels of proficiency.
5. Translate the expected levels of proficiency into more formally stated educational objectives and learning outcomes that are the basis for instructional design and student learning assessment.

We now address each of these five steps in detail and give several examples of the process.

To give an example of the process of establishing proficiency levels and learning outcomes, we describe the experience of four universities. Early in the development of the CDIO approach, the mechanical engineering program of Chalmers University of Technology (Chalmers), the systems (electronics) engineering program at Linköping University (LiU), the vehicle engineering program at the Royal

Institute of Technology (KTH), and the aeronautics and astronautics program at the Massachusetts Institute of Technology (MIT) conducted parallel studies to set the expected levels of proficiency in the topics of the CDIO Syllabus with their respective program stakeholders [22]. To allow more direct comparison of the results, the four universities agreed to focus on Sections 2, 3, and 4, and use the generic form of CDIO Syllabus v1.0 without alteration (although the Swedish universities translated the document into Swedish).

Customizing the Syllabus for a Specific Program

As a university or program begins the curriculum design process, it can choose to use the generic CDIO Syllabus 2.0 or customize it for its own program. The Syllabus provides a valuable resource for enumerating the knowledge, skills and attitudes that should be considered. While every effort was made to make Sections 2, 3, and 4 of the CDIO Syllabus applicable to all engineering programs, it was inevitable that some customization would be required.

There are several major decisions to be made when customizing the Syllabus. The first is whether to customize Sections 2, 3, and 4 at all or use them as is. The advantage of customization is that it makes the knowledge, skills, and attitudes more relevant to the views of faculty and other stakeholders, and the local and national context within which the program and university operates. The customized Syllabus should be aligned with the mission and goals of the university and program. National regulation, evaluation or accreditation issues must also be considered. The process of customizing the Syllabus also promotes ownership of the document by the faculty and other stakeholders.

As a note of caution, a program should be careful about customizing Sections 2, 3, and 4, since the words there have been carefully chosen by experts to explain and contrast specific ideas. When engineering faculty with less expertise in personal, interpersonal, and process, product, and system building skills edit the document, these distinctions may become blurred. For example, an ethicist would see a strong distinction between Section 2.5.1 *Ethics, Integrity, and Social Responsibility*, which is about ethical issues and dilemmas, and Sections 4.1.1 to 4.1.3, which address the specific responsibility of engineers to society. However, many engineering faculty would miss this distinction.

Faculties must also decide if they want to gather data on the topics in Section 1 *Disciplinary Knowledge and Reasoning.* Not doing so focuses the effort more on the personal, interpersonal and system building skills, and produces a simpler stakeholder engagement. Doing so gathers a great deal of information that is useful in curriculum design, and often surprises faculty as to how much stakeholders value the skills in Sections 2, 3, and 4 versus Section 1. Of course, this would require deriving a list of the knowledge implied in Section 1, but most programs already have such lists.

There may be significant additions or subtractions of topics in Sections 2, 3, and 4 as well. Experience has shown that particularly in areas that deal with social responsibility and values, the local role of the university and society influence the choice of Syllabus topics. There is a great deal of material in the Syllabus and a faculty or program may want to omit some parts. The program must also decide what, if any, of the leadership and entrepreneurship skills to include.

The customized version will reflect the needs and terminology of the specific engineering discipline involved. Departments and programs should alter the terms used, particularly in Section 4, to reflect the professional terms of a discipline. For example, in architecture, *Conceiving* might be *Programming*, while in software engineering, *Implementation* might be *Programming*. Different disciplines will use different words to describe the same generic activity; the most appropriate words should be used in the customized document.

Identifying the Program Stakeholders

As a preparatory step in establishing learning outcomes, it is important to establish the level of proficiency graduates should be able to demonstrate in the knowledge, skills, and attitudes listed in the customized version of the CDIO Syllabus. Opinions on this question should clearly be sought from all stakeholders. Stakeholders are those who have a stake or interest in the outcomes, results and graduates of the program. Most importantly, stakeholders include graduates who are aware of both the levels of proficiency they achieved at university and the levels of proficiency they subsequently needed as graduates. Other key stakeholders include faculty, direct employers, and leaders of industry. Peers at other universities, advisory boards, administrators, and faculty in other departments might also be included. Depending on local culture, students can be surveyed as well.

In the studies conducted by Chalmers, LiU, KTH, and MIT, we focused on the same groups of stakeholders:

- University faculty.
- Mid- to upper-level industry leaders.
- Alumni about 5 years past graduation.
- Alumni about 15 years past graduation.

We chose alumni groups who were young enough to recall their education in some detail, yet old enough to be able to reflect on it with meaningful perspective. We selected the two groups to determine whether the opinions of alumni changed over time.

Engaging Stakeholders and Capturing Their Opinions

There are several alternatives for gathering stakeholder input, including interviews, focus groups and workshops. Surveys also are common and produce quantitative data on reactions. Whatever method is used, two design features of

Table 3.6 Expected levels of proficiency in CDIO Syllabus knowledge and skills

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

the engagement should be considered: (1) the level of detail; and (2) the method of prioritization. Experience has shown that stakeholders will respond best when asked about the Syllabus content at the second or X.X level, where there are usually between 13 and 16 topics, depending on how a program has customized the Syllabus. Asking about the first or X level is too generic, and asking at the third or X.X.X level is too fine and creates too many topics—nearly 100. In seeking responses about topics at the second level, information from the Syllabus at the third level should be given in order to explain the meaning and content of the topics. The survey instrument contains roughly the information in Table 3.2.

Whatever alternative is used, stakeholders must be posed a question that does not allow them to respond that all items are equally important. Several questions can be asked, including "What level of proficiency should the students achieve as they graduate?" An alternative question is "What is the relative importance of these topics?", assuming that students should be more proficient at more important tasks. A third way to ask is "Relatively how much time should be spent on this topic?" Experience shows that all of these will give about the same result. The first is more directly transferable to learning outcomes, and is, therefore, the recommended question.

Programs should specifically ask about the outcomes for their program and university. Not all universities fulfill the same role in society, and there are different expectations for their students. The responses will be much more coherent when asking about the outcomes for the Y program at Z university, than asking more generic questions. This is why the responses from program graduates are most important, as they will reflect directly on their experiences in the program. In contrast, general statements from national bodies about what is relatively more important must be used cautiously, as they do not reflect the role played by any given program.

In the example of the four universities, the survey process used a questionnaire to collect data from stakeholders about the expected proficiency levels of CDIO Syllabus v1.0 topics. The survey instrument asked questions in such a way that information was collected for each item in the Syllabus at the second, or X.X, level of detail. Both quantitative and qualitative responses were solicited. Respondents were given a set of definitions based on the third level of detail (Table 3.2) to ensure reasonable consistency of interpretation and increase the reliability of the responses. Respondents were also given the CDIO Syllabus at the fourth level of detail and background reading on the program.

For each second-level (X.X-level) Syllabus topic, respondents were asked to indicate an expected proficiency level using a 5-point scale. Table 3.6 shows the rating scale. Scale points designate absolute levels of proficiency expected in the activities or experiences of engineers. They are not relative measures of skills compared with other graduating engineers. For example, *5 To be able to lead or innovate in* requires a level of proficiency attained by experts in a particular discipline or area. In addition, respondents were encouraged to include brief statements elaborating on their ratings.

Qualitative and quantitative data were gathered on the 14 second-level Syllabus topics (Sections 2.1 to 4.6) from respondents in each of the stakeholder groups. For each of the four programs, mean responses for each of the stakeholder groups were calculated. The qualitative comments of the respondents were examined to determine if they led to any generalizations of the understanding of the trends and differences among different stakeholder groups.

Interpreting Results and Arriving at Consensus

With the results from the stakeholder input, the faculty must interpret the results in order to arrive at consensus. This is probably best done in a setting that allows careful deliberation and reflection, adequate time, and includes as many of the members of the program faculty as possible, in order to have buy-in and long-term ownership. The group should be careful not to over-interpret the results. Fine distinctions are probably not important. Faculty should be looking for major trends, for example, most proficient or important, somewhat, less, etc. Three to five levels of distinction are sufficient for setting learning outcomes, designing curriculum, and assessment student learning.

Two trends in stakeholder engagement may help the consensus process. One trend deals with the observed agreement among the stakeholders in a program, and the second with the overall trends among programs. Often, the various professional stakeholder groups are in relatively good agreement about the proficiency desired in graduates of that program. This remarkable result requires the following factors: (1) stakeholders, including program graduates, leaders of industry, and faculty, have a deep knowledge of the program; (2) questions are specific to the customized Syllabus; (3) a rubric, such as the one in Table 3.6, is used. With these factors, there will likely be broad agreement among the stakeholder segments. When this is the case, the consensus process is greatly simplified [22].

In our continuing example, Fig. 3.9 shows the results of the proficiency-level surveys at MIT. Four stakeholder groups are included: faculty, industry leaders, and two groups of alumni (5 and 15 years after graduation). The most striking outcome of the MIT survey is the statistical agreement on all but one topic among the four professional stakeholder groups (Design, Section 4.4). This result was totally unexpected (Skills related to 3.3 *Communications in Foreign Languages* were not included in the MIT customized Syllabus at the time of this survey).

There is a weaker pattern that shows some correlation in the results between programs at different universities and nations, at least among those that are more research-intensive and prepare students for careers centered on research and design. Usually, the most highly ranked skills are *Analytical Reasoning and Problem Solving* (2.1), *Communications* (3.2), and *Attitudes, Thought and Learning* (2.4), which

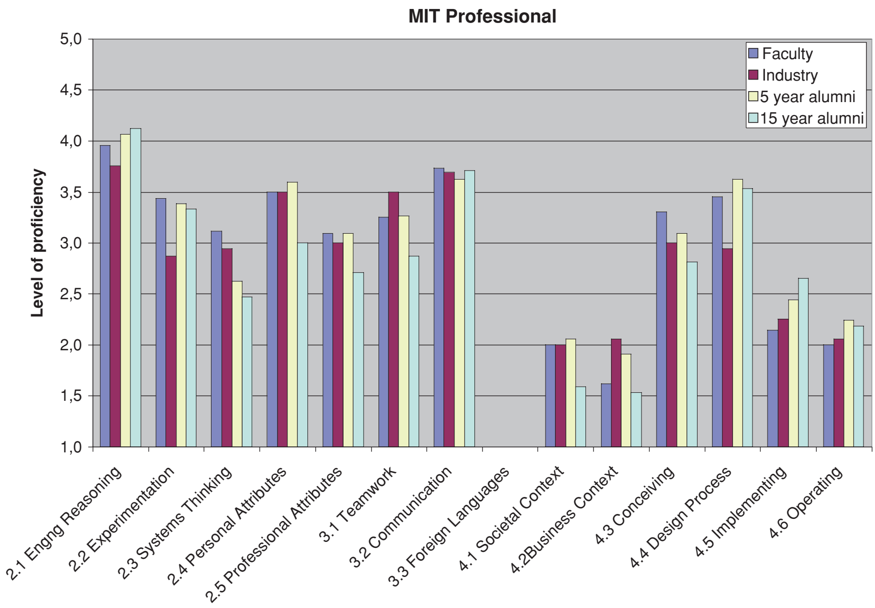

Fig. 3.9 Expected proficiency levels reported by stakeholder groups at MIT

includes critical and creative thinking. *Designing* (4.4), *System Thinking* (2.3), *Teamwork* (3.1), and *Communications in Foreign Languages* (3.3) are often rated at an upper-middle level. *Experimentation, Investigation and Knowledge Discovery* (2.2), *Ethics, Equity and Other Responsibilities* (2.5), and *Conceiving, System Engineering, and Management* (4.3) are perceived to be at a lower-middle level of desired proficiency. This leaves *External, Societal and Environmental Context* (4.1), *Enterprise and Business Context* (4.2), *Implementing* (4.5) and *Operating* (4.6), which tend to be rated lower than others. This general trend was seen in the mean responses given by the professionals in the three surveys conducted at Chalmers, LiU, and KTH. Box 3.2 describes the stakeholder survey conducted at Queen's University Belfast that showed similar trends. This pattern is sufficiently common that it appears in Passow's meta-analysis of learning outcomes for engineering education [23].

It is interesting that the most generic and lifelong engineering skills, for example, problem solving, communicating, and thinking critically and creatively rise to the top of the list consistently. Of course, there will be variations in this pattern from university to university, and nation to nation. In programs where the native language is English, the importance of communications in foreign languages seems to drop. In nations where engineering is found in the service sector, the importance of implementing and operating increase. Beyond these understandable variations, the consistency between universities, and particularly among the stakeholders within a university program, are apparent and useful in curriculum design.

Box 3.2 Stakeholder Survey at Queen's University Belfast

The School of Mechanical and Manufacturing Engineering at Queen's University Belfast (QUB) conducted a survey of expected proficiency levels. Using the process steps suggested in this chapter, the design of the study was:

- The generic CDIO Syllabus v1.0 was used for Sections 2, 3, and 4. In addition, the survey asked alumni about topics in engineering science, mathematics, management, economics, law, electronics, and computer programming. Information on the careers pursued by graduates was also gathered (As in the MIT survey, 3.3 *Communications in Foreign Languages* was not included.).
- The most important category of stakeholders for the QUB survey was QUB alumni. As graduates, they are familiar with QUB's programs, and, as experienced professionals, they know how well the knowledge and skills acquired during their studies prepared them for their careers. About 800 alumni, who had graduated between 5 and 30 years ago, were invited to participate in the survey. About 200 hundred alumni responded—a strong response rate for a postal survey.
- Queen's University used a survey instrument, but did not use the 5-point scale found in Table 3.6. Instead, a 5-point level-of-importance scale was used. The scale ranged from *1 Of no importance* to *5 Essential.* The scale was changed mainly because the importance scale was more suitable to a greater number of items in their questionnaire.
- Means were calculated for the items related to Sections 2, 3, and 4 of the Syllabus, for comparison with results from alumni at MIT. Figure 3.10 shows the comparison of mean responses from QUB alumni with MIT alumni. The general agreement found between the MIT, Chalmers, LiU, and KTH is repeated in the comparison of QUB and MIT (This assumes correspondence between the proficiency and importance scales.).

A close examination of the results in Fig. 3.10 for Sections 3 and 4 reveals some interesting differences, however. For example, *Enterprise and Business Context* (4.2) is rated significantly higher by the QUB alumni, compared with their MIT counterparts. This is undoubtedly a reflection of the fact that a relatively high percentage of QUB graduates are employed in small companies that dominate the local economy. In such companies, professional engineers tend to be involved in the general running of the company, and have to take on management and financial responsibilities. Likewise MIT alumni felt that the proficiency level in implementation should be much lower than design, while QUB alumni thought that implementation was just as important as design, again probably reflecting the relative importance of preparing students in implementation for aerospace graduates from MIT versus mechanical and manufacturing engineers in Northern Ireland. These differences in the details of the survey results provide a justification for each university to conduct its own survey.

In the section of the questionnaire on additional subjects, twenty subjects were listed. The results indicated that alumni regarded manufacturing, management, and business courses as particularly important. Control received a lower rating, which may be a reflection on the theoretical nature of control courses in universities. However, the lowest rating was given to computer programming, a result that was of particular interest to the School of Engineering since some faculty questioned the need to teach computer programming. Their argument was that in view of the range of software applications now available, mechanical and manufacturing engineers are unlikely to need programming skills. The views of the alumni were taken into account and after further debate, computer programming was removed from the curriculum.

Overall, the QUB surveys were highly valuable in the course of curriculum design. The results obtained for Sections 2, 3, and 4 of the Syllabus provided useful input on the emphasis to be placed on each area. In addition, results highlighted areas where faculty and students have opinions that do not correspond to alumni's more authoritative views. The extended questionnaire also assisted decision-making on topics to be covered in mathematics and the additional subjects to be included in the curriculum. However, a striking result of the survey is the support it provides for a CDIO approach to engineering education. QUB graduates regard an understanding of fundamental principles as very important, and fully support the allocation of additional time to design-build experiences and the development of skills and attitudes. This result is a timely endorsement of the university's use of the CDIO approach.

– P. Armstrong, Queen's University Belfast

Translating Expected Levels of Proficiency into Learning Outcomes

Having determined the expected level of proficiency for each CDIO Syllabus topic at the second and third levels of detail, the remaining task is to formulate corresponding learning outcomes. This formulation requires three steps:

- Choosing a taxonomy of learning outcomes.
- Developing a correspondence between the taxonomy and the rating scale used to determine expected levels of proficiency.
- Specifying a learning outcome for each of the most detailed topics in the Syllabus, corresponding to the taxonomy, and the appropriate proficiency rating.

The first step in formulating learning outcomes is to choose an appropriate taxonomy. From among several possibilities, the one most widely used by our

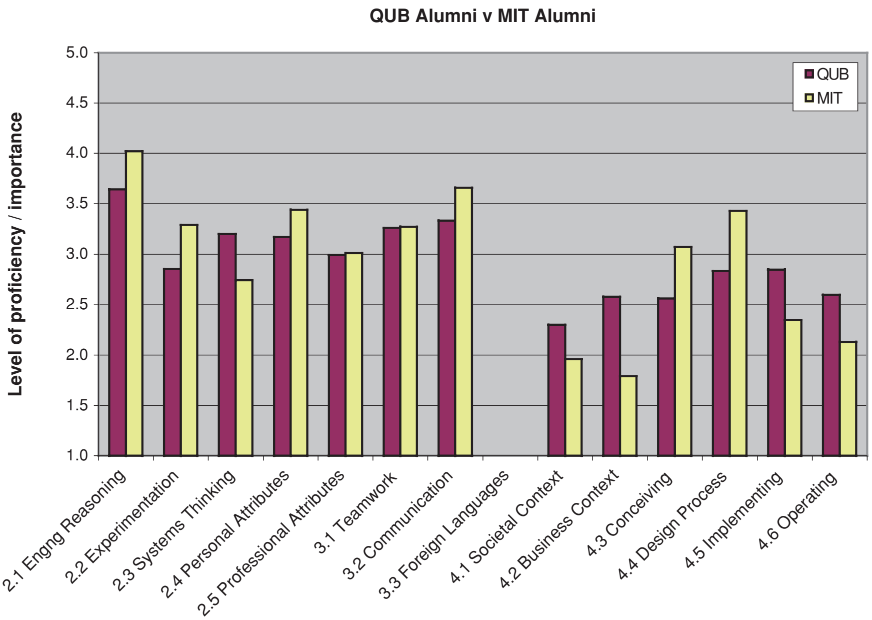

Fig. 3.10 Comparison of results for QUB and MIT Alumni

programs is the cognitive domain of Bloom et al. [24]. Briefly, Bloom's taxonomy divides learning into three domains: (1) the cognitive domain addresses knowledge and reasoning; (2) the affective domain includes attitudes and values; and, (3) the psychomotor domain describes skills requiring mobility and manipulation. Each of the three domains is classified into five or six hierarchical levels.

In order to specify learning outcomes derived from the Syllabus, a correspondence must be developed between Bloom's taxonomy and the rating scale used to determine expected levels of proficiency. Table 3.7 illustrates such a correspondence. For example, in Bloom's cognitive domain, there is no skill that corresponds with a rating of *1 To have experienced or been exposed to*. Looking further, however, a rating of *2 To be able to participate in and contribute to corresponds* to Knowledge; a rating of *3 To be able to understand and explain* is associated with Comprehension; a rating of *4 To be skilled in the practice or implementation of* maps to two levels, Application and Analysis; and finally, a rating of *5 To be able to lead or innovate* corresponds to Bloom's highest cognitive levels of Synthesis and Evaluation. Similarly, approximate correspondences can be drawn to the affective and psychomotor domains.

The final step in converting Syllabus topics into specific learning outcomes is to associate each topic phrase with a verb that best describes the level of proficiency determined by program stakeholders. Each level of Bloom's taxonomy can be expressed with specific verbs. For example, Synthesis in the cognitive domain includes such skills as *formulate, create, construct,* and *reorganize*. Table 3.7 gives

Table 3.7 Correspondence of proficiency rating scale and Bloom's taxonomy

Proficiency rating scale	Bloom's taxonomy-cognitive domain	Examples of learning outcomes based on the CDIO Syllabus
1. To have experience or been exposed to		
2. To be able to participate in and contribute to	Knowledge	List assumptions and sources of bias
3. To be able to understand and explain	Comprehension	Explain discrepancies in results
4. To be skilled in the practice or implementation of	Application	Practice engineering cost-benefit and risk analysis
	Analysis	Discriminate hypotheses to be tested
5. To be able to lead or innovate	Synthesis	Construct the abstractions necessary to model the system
	Evaluation	Make reasonable judgments about supporting evidence

examples of specific learning outcomes derived from the Syllabus presented at the appropriate levels of expected proficiency. While it is possible to specify program learning outcomes without stakeholder input, the rigorous survey process used to set expected levels of proficiency enabled us to set more realistic learning outcomes for engineering students.

Summary

This chapter focused on defining the CDIO Syllabus v2.0, describing its structure and development, and showing how the Syllabus can be used as the basis for determining stakeholder consensus on expected levels of proficiency of the knowledge, skills, and attitudes desired of engineering graduates. The Syllabus is a generalized statement of goals for engineering education that flows directly from the actual roles of engineers. It is comprehensive in that it includes all of the knowledge, skills, and attitudes expected of a graduating engineer.

Although the Syllabus is a generalized statement, it can be customized to meet local program needs. The process of customization includes the definition of disciplinary content for Section 1 *Disciplinary Knowledge Reasoning* and adjustments to the rest of the Syllabus. Surveys and other forms of engagement gather input from program stakeholders about the expected levels of proficiency, or importance, of each Syllabus topic. Results provide guidance for curriculum design and learning assessment.

Surveys conducted by representative programs yielded some interesting results. The agreement among the faculty, industry leaders, and alumni on the expected levels of proficiency of graduating engineers was significant and unexpected. Surveys indicated that the skills for which the proficiency expectations are the highest include engineering reasoning, personal attributes, communications, and design. These four skills are consistently among those cited as most important in a graduating engineer.

The CDIO Syllabus, customized with results of stakeholder surveys, lays the foundation for specific learning outcomes, curriculum planning and integration, teaching and learning practice, and outcomes-based assessment. The process of integrating the Syllabus into a program's curriculum is the subject of Chap. 4. Approaches to teaching and learning the content of the Syllabus are described in Chap. 6. Student assessment of these learning outcomes is the focus of Chap. 7.

Discussion Questions

1. How would you rate the proficiency levels in the knowledge, skills, and attitudes expected of graduates of your program?
2. How do your ratings compare with those of the programs described in this chapter?
3. In what ways can you implement the suggested processes to define your program learning outcomes and validate them with your program stakeholders?

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Chapter 4
Integrated Curriculum Design

Introduction

We have now reached a transition point in our discussion. In Chap. 2, we posed the two central questions that any approach to improving engineering education must address:

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

As discussed in the previous chapters, there are compelling reasons for university engineering programs to educate students in a broad set of personal and interpersonal skills, and product, process, and system building skills, as well as to instruct them in the technical disciplines. To accomplish this, the CDIO approach proposes that: (1) we stress the fundamentals and set the education in the context of conceiving-designing-implementing-operating products, processes, and systems (the essence of CDIO Standard 1); (2) students be expected to achieve a set of learning outcomes as defined by the CDIO Syllabus; and, (3) learning outcomes be comprehensive, be consistent with program goals, and be validated by program stakeholders (the essence of Standard 2). The first three chapters laid out a process to answer the first of the two central questions.

The next three chapters discuss the resolution of the second central question—*How can we do better at ensuring that students learn these skills?* Engineering programs need to provide an education that is better at supporting students in learning, not only disciplinary fundamentals, but also personal and interpersonal skills, and product, process, and system building skills. In most cases, we need to do better with allotted resources. In order to reach these goals, a program re-tasks the available resources to get more out of them, that is, it re-tasks the curriculum and workspaces and restructures the learning experiences. This chapter

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discusses the way a program is built around an integrated curriculum that incorporates an introduction to engineering. Chapter 5 explains how a program also incorporates two or more experiential design-implement exercises, often in a modern engineering workshop. Chapter 6 describes how the CDIO approach incorporates integrated learning activities that simultaneously teach disciplinary knowledge, personal and interpersonal skills, and product, process, and system building skills, and uses active and experiential methods to support student learning. Therefore, as we begin this chapter, we transition from the *what* implied by first central question to the *how* implied by the second.

An integrated curriculum is characterized by a systematic approach to teaching personal and interpersonal skills, and product, process, and system building skills, as defined in the CDIO Syllabus. To emphasize the fact that these learning outcomes are necessary for preparing graduates for engineering practice, and for simplicity, we refer to these skills as professional engineering skills or professional skills. In general, an integrated curriculum has the following attributes:

- It is organized mainly around the engineering disciplines. However, the curriculum is re-tasked so that these disciplines are shown to be connected and mutually supporting, in contrast to being separate and isolated.
- The professional engineering skills are highly interwoven into mutually supporting courses, exploiting the synergistic relationship between technical disciplines and professional skills.
- Every course or learning experience sets specific learning outcomes in disciplinary knowledge, and in professional skills, to ensure that students acquire the appropriate foundation for their futures as engineers.

Said another way, the integrated curriculum forms an education that has an impact greater than the sum of its parts. The curriculum is coordinated, with mutually supporting elements, each taking on a well-defined function. The elements work together to enable students to reach program learning outcomes. An important part of an integrated curriculum is an introductory course in engineering, which creates excitement about engineering, teaches some early key skills, defines a set of concrete engineering experiences on which students can base subsequent learning, and suggests the framework of the education to follow. As with any well-defined system, the curriculum must be designed with an appropriate balance of flexibility and efficiency.

This chapter describes the CDIO approach for developing and implementing an integrated curriculum. The process respects pre-existing conditions and available resources that characterize each individual program, but suggests approaches and alternatives to curriculum design to support the intended student learning. The first part of this chapter underscores the importance of an integrated curriculum, as defined in Standard 3. It is followed by discussions and examples of systemic approaches to curriculum design. The second part of this chapter discusses the task of introducing students to engineering, and gives examples of how to do this in an introductory course, as defined in Standard 4. Design-implement experiences and pedagogical aspects of integrated learning are discussed in Chaps. 5 and 6, respectively.

Chapter Objectives

This chapter is designed so that you can

- Explain the rationale for a curriculum that integrates learning and establishes learning outcomes that require integration of professional engineering skills and disciplinary fundamentals.
- Lay the foundation for curriculum redesign by benchmarking an existing curriculum and recognizing pre-existing conditions that influence curriculum design in your current setting.
- Describe the process for designing and implementing an integrated curriculum.
- Describe the purpose and benefits of an introductory course in an engineering curriculum.

The Rationale for an Integrated Curriculum

Two major learning processes characterize engineering education: (1) the acquisition of disciplinary knowledge and understanding, and (2) the development of professional skills. The rationale behind the integrated curriculum is that these two processes are interrelated. The value of disciplinary knowledge and understanding is created by expressing and applying knowledge in practice. The development of professional engineering skills is based on the integration and application of disciplinary knowledge and understanding in engineering working modes. In addition to applications of theory, professional engineering skills also promote the capacity for informed judgment and idea generation. Therefore, an integrated curriculum is characterized by a systematic approach to teaching professional skills, that is, personal and interpersonal skills, and product, process, and system building skills, integrated with engineering disciplinary fundamentals. Another aspect of the integrated curriculum is that disciplinary courses should also make explicit connections among related content and learning outcomes. Furthermore, an explicit plan identifies ways in which the integration of engineering skills with multidisciplinary connections is to be made. This integrated approach to curriculum is the focus of Standard 3.

> STANDARD 3—INTEGRATED CURRICULUM
>
> **A curriculum designed with mutually supporting disciplinary courses, with an explicit plan to integrate personal and interpersonal skills, and product, process, and system building skills**.

Disciplinary courses are mutually supporting when they make explicit connections among related content and learning outcomes. An explicit plan identifies ways in which the integration of personal and interpersonal skills, and product, process, and system building skills with multidisciplinary connections are to be made. It is important to recognize that an integrated curriculum requires a dynamic and meaningful integration throughout the curriculum. Students are not empty vessels that first must be filled with content before they get to practice engineering skills. This assumption can create problems with motivation and retention in programs because it can take years before students encounter a course that reminds them of the reasons they wanted to study engineering in the first place. It also creates problems with retention of knowledge because when students finally get to the point in their education when they need to apply the knowledge, they have forgotten or cannot retrieve the information. Learning based solely on theoretical knowledge is not necessarily connected to reality and engineering practice. Instead, we need to see students as beginning engineers who develop into professional engineers through the acquisition of disciplinary knowledge integrated with engineering skills.

Practical Reasons

There are both practical and pedagogical reasons for constructing an integrated curriculum. In an already existing engineering curriculum, it is often difficult to add more content or time, and, thus, there are few options available other than to re-task the available time and resources. The strategy is to make dual use of time and resources within disciplinary courses, capitalizing on the synergy of the simultaneous learning of professional skills and disciplinary knowledge.

Pedagogical Reasons

In addition, there are sound pedagogical reasons for integrating students' development of professional skills with disciplinary knowledge:

- Personal and interpersonal skills, and product, process, and system building skills depend on the context in which they are taught and used.
  In engineering education, personal and interpersonal skills, such as teamwork and communication, are often called generic skills. They are generic in the sense that lawyers, doctors, and other professionals need to communicate and work in teams. However, the personal and interpersonal skills, and product, process, and system building skills used by engineers are practiced in specific technical contexts. For example, communication proficiency in a technical field depends on being able to apply disciplinary concepts, examine problems at different levels of abstraction, make connections, and explain technical issues for different audiences.

- Learning experiences for engineering skills are opportunities for students to develop deeper working knowledge of engineering fundamentals.
  The process of learning professional skills in a disciplinary context has the potential to reinforce students' understanding of disciplinary content. The integrated learning experiences provide a way to apply and express technical knowledge, and in doing so, disciplinary knowledge is transformed from abstract ideas into working knowledge. As a result, disciplinary knowledge and professional skills are mutually supporting.

Characteristics of an Integrated Curriculum

An integrated curriculum is characterized by:

- Program learning outcomes that systematically flow down to learning outcomes in each of the educational components, for example, courses, modules, or other units of instruction.
- Educational system components that mutually support the learning of disciplinary fundamentals, and the achievement of desired levels of professional skills.
- An explicit curriculum plan that is adopted and owned by the entire faculty. An example of such a plan is described in Fig. 4.1.

This last characteristic is vital for the success of the integrated curriculum. Since an engineering curriculum is generally owned by the teaching faculty as a whole, and executed largely in individual components, faculty and leaders of all components must be aware of the role and the function of their components in the curriculum as a whole.

An integrated program description (IPD) that describes the goals, content, and structure of an educational program, as well as how these are connected, is an efficient tool in curriculum design [1]. The intent is to provide key stakeholders of the program design process with a documented set of tools that can facilitate the design process. Figure 4.1 also shows the relationships between the components of an IPD.

A program design process that is aligned with the contents of an integrated program description typically starts with the statement of the program purpose, followed by the development and validation of the program goals. The next step is to formulate the program idea, i.e., the fundamental principles and considerations that underlie the program design. The program plan then implements the program idea by defining the included courses, their credits, and their placement in the curriculum. The role of the program design matrix is then to interconnect the program goals with the courses, assuring that no program goal is neglected and that there is a deliberate learning progression in the program. Finally, the course plans are developed by refining the program goals assigned to the course and selecting pedagogical and assessment approaches.

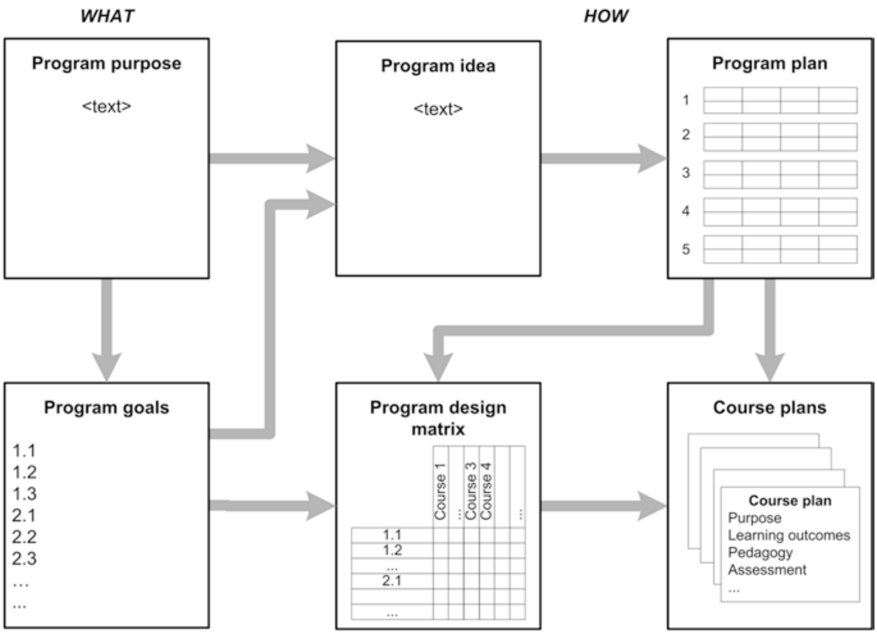


Fig. 4.1 Components of an integrated program description

The assignment of goals for the learning of professional skills needs to be done in a combined top-down and bottom-up dialogue between the program chair and the faculty in order to achieve commitment and to transfer ownership for such goals. An IPD is an effective tool for visualization of the curriculum design, and the development of the IPD itself is an important component in the design process. It also enables faculty to appreciate the contributions to the program learning outcomes from every course in the program.

Faculty Perceptions of Professional Skills

When planning an integrated curriculum, it is important to recognize that faculty members may have different perceptions of the value and place of personal and interpersonal skills, and product, process, and system building skills as part of the curriculum. Faculty who think that these skills are of secondary importance or that they should be taught separately from disciplinary content may be unwilling to integrate them into their courses. According to Barrie [2], for example, faculty perceptions of generic attributes fall into four hierarchical categories: enabling, translating, complementary, and precursory (see Table 4.1). The categories are not

Table 4.1 Faculty perceptions of generic skills

Enabling	Generic attributes are integral to disciplinary knowledge, infusing and enabling scholarly learning and knowledge	Integrated
Translating	Generic attributes let students use and apply disciplinary knowledge. They interact with disciplinary knowledge through application, potentially changing and translating knowledge, and are in turn shaped by this disciplinary knowledge. They are closely related to disciplinary learning outcomes	Integrated
Complementary	They are useful additional skills that complement disciplinary knowledge. They are part of the syllabus, but separate and secondary to disciplinary knowledge	Associated
Precursory	They are necessary basic precursor skills and abilities, and may need remedial teaching of such skills at university	Not part of the curriculum

mutually exclusive, but hierarchical, that is, a category includes all the categories below it.

The perceived relationship between the skills and the disciplinary content will affect the way that faculty think the curriculum should be designed. Using this classification, Standard 3 emphasizes upgrading our view on the learning of skills from the *Not-part-of-the-Curriculum* and *Associated* categories to the *Integrated* categories, focusing on the interaction of skills and disciplinary knowledge. For example, the teaching of communications as part of a disciplinary topic might be seen as *Translating*, while the teaching of design could well be considered at the *Enabling* level, since it enables and reinforces knowledge. In both cases, they must be genuinely integrated into the curriculum.

Faculty may also need the opportunity to discuss the arguments for an integrated curriculum and reflect on these issues over time. Such discussions may serve to identify relevant combinations of professional skills and disciplinary content in preparation for the curriculum design process. At this point, stakeholder input on the importance of these skills can be critical to developing consensus.

Integrated Curriculum Design Process

We use an engineering problem-solving process to structure the design of the engineering education. The starting point for the curriculum design process may differ considerably among programs. Redesigning an existing program into a CDIO program implies that a number of initial conditions need to be considered. The design of an entirely new program does not necessarily involve so many

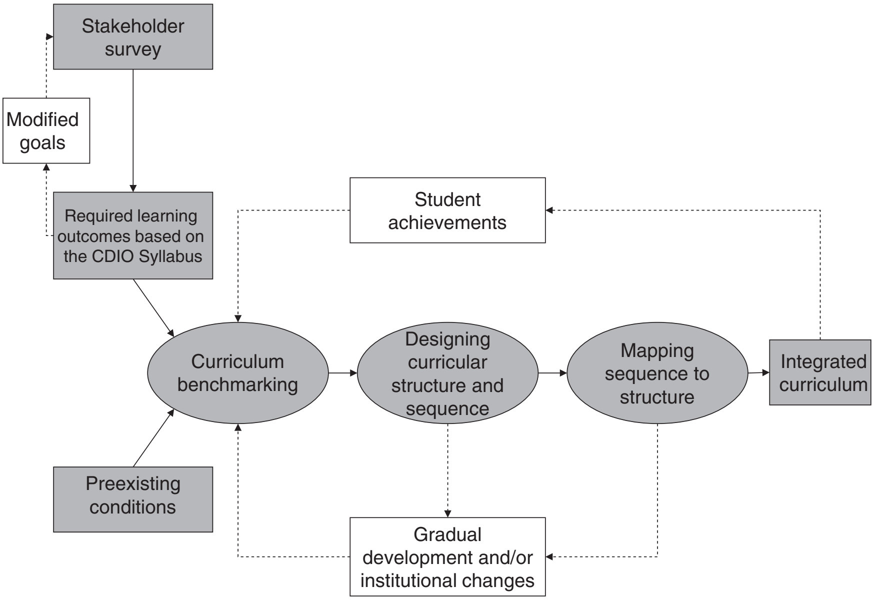


Fig. 4.2 Integrated curriculum design process model

pre-existing conditions. Irrespective of the starting point, the word *design* is used here to describe the creation of new programs and the transformation of existing programs.

The Curriculum Design Process Model

Figure 4.2 illustrates a model for the design of an integrated curriculum. The model calls for a translation of the CDIO vision into a formal set of goals that will provide a foundation for curriculum design. This translation is informed by the desired learning outcomes, pre-existing conditions, and curriculum benchmarking. Curriculum design itself is then defined as the projection of these goals onto the courses and associated learning experiences that formally constitute a curriculum.

The starting points are the process of setting the expected learning outcomes and the examination of pre-existing conditions, including factors such as program purpose and length, high-level program design, and underlying structure of the curriculum. These in turn are informed by national standards, university rules, and program tradition. As a departure point for curriculum design, a benchmarking exercise examines the existing curriculum to see how it compares with the expectations, that is, the intended learning outcomes. The scope of the benchmarking activity includes all parts that contribute to the educational experience.

To some extent, the benchmarking activity can be carried out in parallel with the stakeholder survey of expected proficiencies that was described in the previous chapter. Once the program goals are clearly established, the pre-existing conditions understood, and the existing curriculum has been benchmarked, curriculum design can truly begin.

Curriculum design proper begins with two parallel interactive steps: (1) the design of the curriculum structure, and (2) the determination of the appropriate instructional sequence for each topic. With the structure and sequence established, the last step in design is the mapping of the sequence onto the elements of the structure so that each element carries well-defined responsibilities for student learning in an integrated, mutually supporting, and coordinated design. Design is an iterative process with several feedback loops, indicated by the dashed lines in Fig. 4.2. Continuous improvement and refinement of the curriculum design is driven by results of student learning assessment, changes in required learning outcomes over time, and institutional changes, such as development funding, altered resources, and faculty re-assignments. In the sections that follow, each of the steps in the integrated curriculum design process model is discussed in more detail.

Curriculum Content and Learning Outcomes

The foundation of curriculum design is the delineation of the desired curriculum content and the specification of learning outcomes. Disciplinary curriculum content includes fundamentals of mathematics and the sciences, engineering science, and other technical knowledge, as well as university requirements, such as humanities and social sciences. In a CDIO program, learning outcomes are specified for disciplinary content as well as for the engineering skills. The CDIO Syllabus outlines in detail the personal and interpersonal skills, and product, process, and system building skills. Stakeholder surveys identify the expected proficiency of graduating engineers in each of the topics, and potentially for the disciplinary content as well. The process of translating topics into intended learning outcomes is explained in Chap. 3. Learning outcomes and expected proficiency levels, both for disciplinary topics and skills, form the foundation of curriculum design.

Pre-existing Conditions

The curriculum design process begins with the need to reflect on pre-existing conditions and the existing connectivity of the curriculum. Pre-existing conditions are the set factors regarding the current curriculum, including accreditation standards, university rules, program tradition, and requirements of local, regional, and national groups. Three pre-existing conditions strongly influence the amount of flexibility available to the design process: program purpose and length, high-level program design, and the underlying structure of the curriculum.

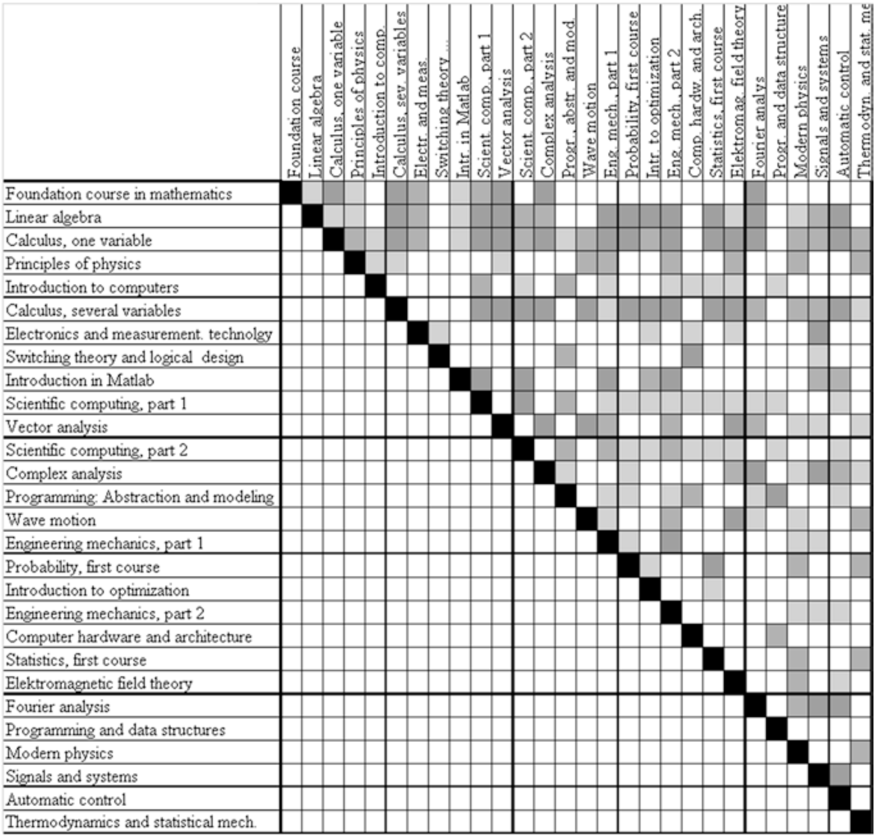
Program purpose and length. Programs usually fall into two groups based on their purpose: those leading to a terminal pre-professional degree for engineering, and those intended to be followed by a subsequent terminal pre-professional degree. This distinction is often reflected in the length and structure of the programs. Curriculum design must acknowledge and accommodate these constraints.

High-level program design. Institutions often set high-level designs for programs. Some programs are divided into upper-level and lower-level courses. In engineering programs, it is common to find four phases: (1) mathematics and science fundamentals, (2) engineering fundamentals, and (3) specialized courses and electives, and (4) summative experiences. This high-level design can affect faculty teaching responsibilities and the degree to which program leaders can influence each of the phases. For example, in many universities, science faculties are responsible for science fundamentals and are not directly influenced by the work of engineering curriculum designers. On the other hand, engineering fundamentals are often taught in required core courses that can be directly influenced. Specializations or electives that may or may not be explicitly recognized as formal curriculum options are in general taught by faculty with engineering backgrounds. A specific elective course is often easy to influence but will not affect the learning experience of all students to the same extent as required courses. Summative experiences, such as final year projects, design-implement experiences, and theses, can provide opportunities to incorporate common requirements so that specializations and electives contribute to the integrated curriculum.

Underlying structure of the curriculum. Virtually all universities have an underlying structure that dictates the length of the university school year, the length and intensity of the terms or semesters, and the atomic unit of instruction, which is referred to as a *course* in this book. Established academic units and total number of allowable units can limit the flexibility of a curriculum plan.

Program's disciplinary content. Another form of pre-existing condition is the program's disciplinary content and the degree to which it is fixed. It is important to understand the connections among the topics, that is, existing interactions or isolation of the disciplinary topics within the courses. Written program plans for student pathways through the program can provide a curriculum with mutually supporting disciplinary subjects, as called for in Standard 3. However, the most reliable means of understanding disciplinary structure is to interview program faculty. As an example, Box 4.1 describes the results of a survey of pre-existing conditions in the Applied Physics and Electrical Engineering program at Linköping University. Typically, results show a high degree of connection among the topics. Not surprisingly in the Linköping example, mathematics courses are used by many subsequent courses. The matrix also reveals other key courses, such as *Scientific Computing*, which are used by many courses. This information is important for the design team as they begin to consider how the curriculum might be restructured.

Box 4.1 Connections Between Mandatory Courses in Applied Physics and Electrical Engineering, Linköping University



A survey of faculty members was conducted at Linköping University to document the pre-existing disciplinary connections within the Applied Physics and Electrical Engineering program. The purpose of the survey was to investigate and clarify the connections between the mandatory courses, that is, those in the first three years of the program. Hence, the survey covers mathematics, science, and engineering courses. The survey asked faculty members responsible for each course to provide a measure of the connections between their courses and the courses that preceded them in the program. Note that in such surveys, faculty are much more aware of the connection with previous courses than with subsequent courses. Each connection was rated on a four-level scale, ranging from *No immediate connection* (white box) to

(*Continued*)

Box 4.1 Connections Between Mandatory Courses in Applied Physics and Electrical Engineering, Linköping University—Cont'd

Strong connection (dark gray box). A row in the matrix illustrates how the content of a particular course is used in subsequent courses. A column in the matrix shows the extent to which a particular course uses knowledge from previous courses.

—T. Karlsson, Linköping University

Benchmarking of the Existing Curriculum

The purpose of benchmarking is to document how an existing curriculum addresses the expectations and proficiency levels of the professional engineering skills and to serve as an important starting point for subsequent design. Engineering programs, in general, already include many activities that relate to professional skills, but they are not necessarily well designed, well coordinated, and comprehensive. Benchmarking identifies the existing committed resources and highlights ways that a curriculum can make better use of time. Bankel et al. [3] propose a benchmarking tool for this purpose of identifying the existing activities.

In benchmarking studies, instructors are asked about the extent to which specific learning outcomes are addressed in their respective courses. For each of the topics at the second level of the CDIO Syllabus, for example*, 2.1 Analytical reasoning and problem solving*, faculty are asked about how these topics are addressed in their courses. The aim is to identify learning outcomes and the way they are implemented in the course design.

Teaching activities are categorized as Introduce (I), Teach (T) or Utilize (U), based on intent, time spent, and explicit linkages to learning outcomes, assignments, and assessment criteria. The operational definitions for Introduce, Teach, and Utilize are shown in Table 4.2. The decision to make distinctions among Introduce, Teach, and Utilize was made after observing that the word *teach* is used to describe a great variety of activities occurring within courses.

Bankel et al. [3] suggest face-to-face interviews with instructors responsible for each course in the program. Responses are analyzed to illuminate patterns of teaching. It is not possible to equate expected proficiency levels of CDIO learning outcomes directly with teaching activity levels. However, it is possible to make some comparisons, to identify weaknesses and strengths in the existing curriculum, and to identify learning outcomes that require more (or perhaps less) emphasis across the curriculum. It is also possible to identify skills that are introduced multiple times without any instructor taking responsibility for actually teaching and assessing them. Results of benchmarking studies provide important information for curriculum design. Describing teaching activities using the

Table 4.2 Definitions of introduce, teach, and utilize

	Learning outcomes	Learning activities	Assessment
Introduce	Probably not an explicit outcome	Topic is included in an activity	Not assessed
Teach	Must be an explicit learning outcome	Included in a compulsory activity. Students practice and receive feedback	Students' performance is assessed. May be graded or ungraded.
Utilize	Can be a related learning outcome	Used to reach other intended outcomes	Used to assess other outcomes

Table 4.3 Excerpt of a program design matrix for an engineering curriculum

	Course 1	Course 2	Course 3	Course 4	Course 5
2.1.1 Problem identification and formulation	T	I	T	T	T
2.1.2 Modeling	T	T	T	T	T
2.2.2 Survey of print and electronic literature		I			
2.2.3 Experimental inquiry		T	T		
2.4 Attitudes, thought and learning	T	T		U	
3.1 Teamwork		T	U		
3.2.3 Written communication	U	T		U	
3.2.4 Electronic/multimedia communication		I		T	
3.2.5 Graphical communication		T	U		
3.2.6 Oral presentation	U	T			

Introduce-Teach-Utilize (ITU) categories for the different sections and subsection of the CDIO Syllabus leads to the use of program design matrices of the form illustrated in Table 4.3 as a tool for curriculum benchmarking. Different approaches to the design and development of such matrices have been proposed since the first results were presented in 2005.

Gunnarsson et al. [4] compare the use of such program design matrices at Linköping University (LiU) and the Technical University of Denmark (DTU). One notable difference between the two different approaches is that the matrices used at LiU use the ITU categories as a way to characterize the teaching activities in the program but not the expected levels of proficiency, while those used at DTU describe progression in terms of the proficiency levels defined by Bloom's taxonomy, but do not characterize the teaching activities.

Curriculum Structure

Curriculum structure is the arrangement of content and associated learning outcomes into instructional units, e.g., courses, to facilitate intellectual connections among the courses. The requirements for curricular structure in a CDIO program follow

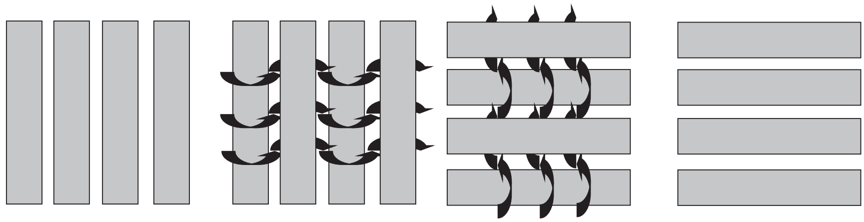


Fig. 4.3 Four approaches to curriculum organization

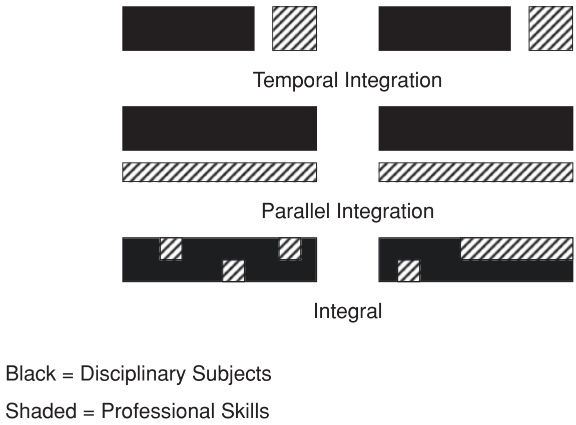
from Standard 3. The curriculum structure must allow the disciplinary courses to be mutually supporting, and it must allow the professional skills to be interwoven in the curriculum. The CDIO approach aims to reform the curriculum to make dual use of time so that students develop both a deeper working knowledge of the fundamentals and the necessary professional skills. Several levels of decisions must be made about curriculum structure to support implementation of a CDIO approach. These include choosing the organizing principle, the master plan for integration, the use of block course structures, and a curriculum concept.

Organizing Principle

The highest-level choice in integrated curriculum design is that of the organizing principle of the curriculum. Figure 4.3 shows four approaches to curriculum organization. In the figure, disciplines run vertically, and projects and skills run horizontally. A strict disciplinary organization is depicted at the far left, with the disciplinary topics in isolated "stovepipes." Students learn a sequence of topics, with few linkages or interactions and little integration of skills. In contrast, at the far right of Fig. 4.3 is a traditional apprenticeship model in which a student works as an apprentice on a first project, then a second, moving on with little or no formal organization around disciplinary learning.

The middle two options for organization allow integration. The problem-based curriculum uses problems or projects as the organizing principle, integrating disciplinary content on a need-to-know basis, through both formal and informal instruction. Several universities, notably Aalborg University in Denmark [5], are successful with this curriculum model, and it merits examination. While it is possible to design a curriculum on this model, many universities have a pre-existing disciplinary organization, making it difficult to transform an existing program to

Fig. 4.4 Alternative integration plans for curriculum structure



one with a comprehensive problem-based organization. There is also a concern that this organizing principle may de-emphasize the technical disciplines.

In the CDIO approach, the organizing principle for an integrated curriculum is the model indicated in Fig. 4.3, with mutually supporting disciplines interwoven with projects and skills. This curriculum structure promotes the learning of disciplinary content and allows several flexible structures for integrating project work and design-implement experiences.

Master Plan

All good designs require a master plan of how disciplinary content and learning outcomes will be integrated into the curriculum. Again, several alternatives are possible. Figure 4.4 illustrates an academic year from left to right in two terms. The black shading represents disciplinary concepts and the diagonal shading represents professional engineering skills. The greatest degree of integration occurs in the *integral* model where the learning of personal and interpersonal skills, and product, process and system building skills is totally embedded in the disciplinary courses. All teaching is dual use, strengthening disciplinary knowledge and professional engineering skills.

A second master plan is called *parallel integration* model. Here a segment of the learning experience in one or more terms is organized around projects or skills where disciplinary content is taught in parallel with professional skills. Design-implement courses that span one or several terms would be an example. A third master plan is *temporal integration* model in which a block of time is set aside for intensive work in projects and skills. In general, some combination of the different master plans is appropriate, and the choice depends largely on local pre-existing conditions. The fact that in the temporal and parallel integration plans the project

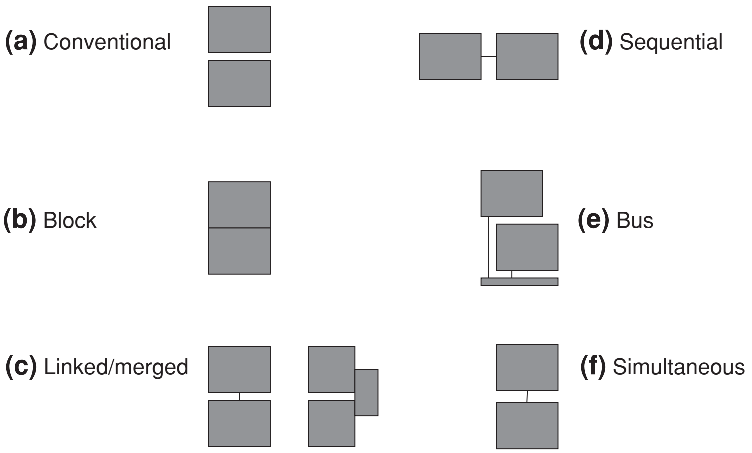


Fig. 4.5 Alternative block course structures

and skills activities are separate does not imply they do not have dual impact. Well-designed projects and other experiential learning activities can motivate and reinforce disciplinary learning even if they are in separate modules of the curriculum. A challenge to the curriculum design team is to determine ways in which extra-curricular activities can enrich the learning of both disciplinary knowledge and skills without making participation a requirement.

Block Course Structure

Virtually all universities segment the curriculum into some form of modules or block course structures. Faculty and program managers tend to take this structure for granted because they have limited influence over it. The curriculum is built of instructional units of a specified length of time with a specified number of hours. This conventional structure is shown schematically in Fig. 4.5a. Often, the only recognizable connection among courses is determined by prerequisites, that is, courses that must be taken chronologically before others. Sometimes universities allow co-requisites, that is, courses that must be taken before or in the same term as other courses. These are weak temporal structural linkages that do not necessarily reflect real integration between the courses.

Working within the pre-existing conditions of common university policies and regulations, curriculum designers have identified several approaches to building more flexibility into curriculum structure. Figure 4.5(b through f) illustrates these alternatives to the conventional structure (a).

Block structure (b). Perhaps the strongest of these alternatives is the block structure in which the time and content allotted to two courses is combined into one course (Fig. 4.5b). Either one instructor teaches an integrated course, or more commonly, two or more instructors teach together in a closely coordinated fashion. This structure allows a great deal of intra-disciplinary linkages, that is, connections within the course, and tends to make learning experiences across topics more flexible and more common.

Linked or merged structures (c). The linked or merged structure allows a disciplinary connection that is almost as strong as the block structure (Fig. 4.5c). In this structure, two instructors start the term teaching independently, but at some point, the two courses flow together and work in common. This is most effective when the common work is associated with a design project or end-of-term problem that requires the integration of content from both courses.

Sequential structure (d). A variant of the merged structure is the sequential structure in which the time and content allotted to two courses are tightly combined into two consecutive terms (Fig. 4.5d). Here, two instructors teach as a team or alternate over the entire length of the two terms in such a way as to present a more integrated view of the whole. This structure has the benefit of fostering the kind of mature understanding of linkages that is facilitated by exposure over a longer time.

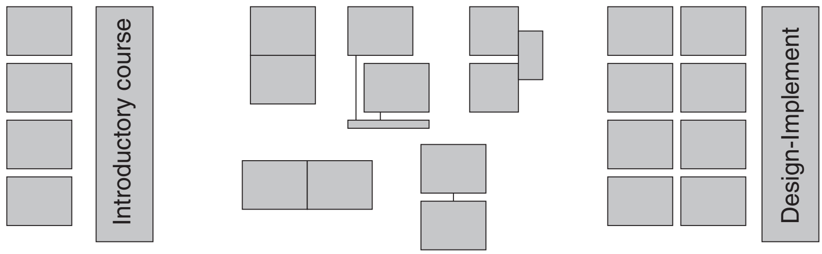
Bus structure (e). Another structure shown in Fig. 4.5e is the bus structure. The idea is that two or more courses connect to an element that acts as a "bus" for the courses. The bus may be a project, such as a design-implement project, or a set of integrating lectures or seminars. Homework assignments and lectures in the connecting courses can be directly related to the bus. One advantage with this design is that students can take the conventional courses without necessarily participating in the "bus" experiences.

Simultaneous structure (f). The weakest linkage is found in the simultaneous structure (Fig. 4.5f). In this structure, two instructors teach two separate, parallel courses. Through good communication and cooperation, they point out, in real time, how learning in one of the courses can influence that in the other. In addition, they individually create exercises that require knowledge and application from both courses.

Using a variety of structures offers curriculum designers flexibility to make disciplinary linkages within the curriculum, and provide opportunities for integrated learning experiences. In implementing any curriculum connections it is important not to impose too many constraints on the flexibility in the path a student takes through the program. Consequently, linkages are easier to implement in those parts of the curriculum that are more or less required or standardized. Linkages within a curriculum also place increasing demands on faculty because they require substantial cooperation and adjustments of course content in order to achieve the desired connections.

CDIO Curriculum Concept

Depending on pre-existing conditions and choices of organizing principle, integration plan and block structures, a concept for the structure of the integrated curriculum will have evolved. Below, four types of elements are discussed in relation



Framework:
a first-year course to lay the foundation in skills; accompanies other foundational courses; may involve innovative structures

Engineering core:
various innovative curricular structures to carry skills as a part of the regular curriculum

Elective and specialization courses:
accompanied by a summative design-implement course; may also use innovative structures

Fig. 4.6 Example of a curriculum concept for a CDIO program

to their role in the integrated curriculum: the introductory course, disciplinary courses, design-implement experiences, and summative experiences.

An example of a developed concept for curricular structure is illustrated in Fig. 4.6.

Introduction to engineering. The introductory course is an early engineering course that aims to establish the framework in which engineers work and contribute to society. It serves to stimulate students' interest in, and strengthen their motivation for, the field of engineering. There is often a big difference in the experiences of engineering among the new students; thus, it is important to provide a general overview of the field and strengthen the motivation for the studies. In addition, introductory courses provide an early start to the development of the personal and interpersonal skills, and product, process, and system building skills described in the CDIO Syllabus. More details about the motivation for including an introductory course in the curriculum, the challenges related to the implementation of such a course, and some examples are found in a later section of this chapter.

Disciplinary courses. The disciplinary courses are often organized in a common or required core with a specialization toward the end of the program. These learning experiences should be mutually supporting, that is, organized and sequenced to support students in making connections within the disciplinary learning outcomes. Because the disciplinary courses constitute a major part of the curriculum, it is vital that these courses make substantial contributions to the development of personal and interpersonal skills, and product, process and system skills together with disciplinary learning outcomes. This can be achieved in ways that strengthen the working knowledge of disciplinary fundamentals. The design of integrated learning experiences on a course level (Standard 7) is discussed in more detail in Chap. 6.

Design-implement experiences. One of the best practices identified in the CDIO approach is the weaving of a sequence of project-based courses into the

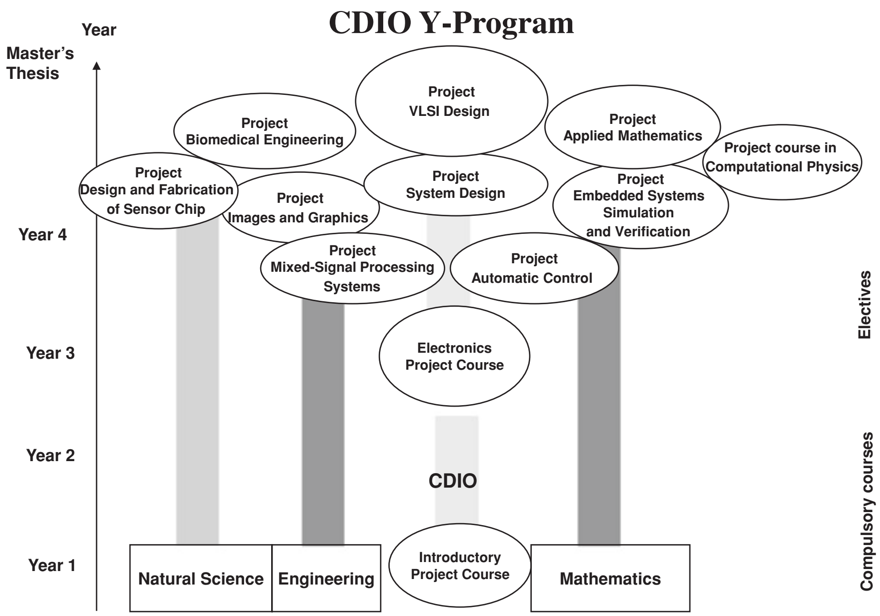


Fig. 4.7 Concept for a curriculum structure at Linköping University

curriculum. The aim is to provide appropriate learning experiences by allowing students to tackle realistic problems in working modes that are aligned with professional engineering practice. The intended learning outcomes for such courses will emphasize the development of engineering skills, such as communication, teamwork, and skills in developing products, processes and systems, as well as the integration and application of technical knowledge. Design-implement experiences are discussed in more detail in Chap. 5.

Summative Experiences. Many engineering programs include one or more summative experiences in the form of thesis work or capstone projects. In a two-level program, such as in several European countries that have adopted the Bologna model [6], there could be one thesis at the end of the first level (bachelor thesis) and another thesis at the end of the second level (master thesis). The disciplinary content of such thesis work is individually chosen and ranges in engineering programs from product development to research-oriented activities. Therefore, it is difficult to assign disciplinary learning outcomes to a thesis, but these summative experiences offer excellent opportunities for training and assessment of professional engineering skills. For example, thesis work requires planning and application of personal and professional skills, including communication skills.

Figure 4.7 illustrates an example from Linköping University of a curriculum structure using different curricular elements.

Sequence of Content and Learning Outcomes

The next curriculum design issue to consider is the sequence of content and learning outcomes. Sequence is the order in which student learning progresses. If sequence is properly developed, learning follows a pattern in which one experience builds upon and reinforces the previous ones. In well-established academic disciplines, content sequence is fairly well understood. For the most part, these sequences have been derived from the experiences of faculty who teach and write engineering textbooks. Distinctions center on the spectrum between specialization and generalization. In newer fields, there is more variation. For example, in computer science, significant debate takes place about whether it is best to start with the teaching of a programming language, the theory of computation, or the operations of computing machines.

For professional engineering skills, the appropriate learning sequence may be less established. The CDIO Syllabus uses a topical organization to suggest what should be taught, but does not give guidance on the sequence of topics and skills or the number of repetitions required for proficiency. For example, no sequence is given to teach teamwork. Should the first teamwork exercise be leaderless, with an appointed leader, an elected leader, or a self-selected leader? Should it have a specific deliverable? When should students be taught how to diagnose and negotiate conflict resolution in a team—early or late in their experience? By answering questions such as these, learning sequences for each professional skill can be developed during the curriculum design process, to be used for the next step, that of mapping the skills onto the curriculum.

A high level of proficiency is often expected of certain complex skills, including design, communication and teamwork. These skills have to be developed in several courses across the program. For example, in the Vehicle Engineering Program at The Royal Institute of Technology (KTH), several courses in the program integrate teamwork. The sequence of teamwork learning activities is coordinated so that experiences in one course build upon previous experiences and prepare students for the next experiences in the sequence. At KTH, the sequence of learning experiences for a specific learning outcome is called a *development route*. Two of these development routes, for written communication and communication in English, are shown in Fig. 4.8.

Coordination of learning outcomes and experiences is necessary both to achieve an appropriate progression of learning and to use resources and time effectively. For example, while students are learning report writing, they benefit from the repeated use of the same standards for writing technical reports across multiple courses. After they have mastered these standards, they can benefit from increased variation in styles of technical report writing. Joint development between courses gives instructors opportunities to share teaching approaches, feedback forms, and assessment instruments. In addition, with development routes, instructors are more aware of the entire program and the contributions of their respective courses to the whole. Appointing development route "champions" could be useful for supporting

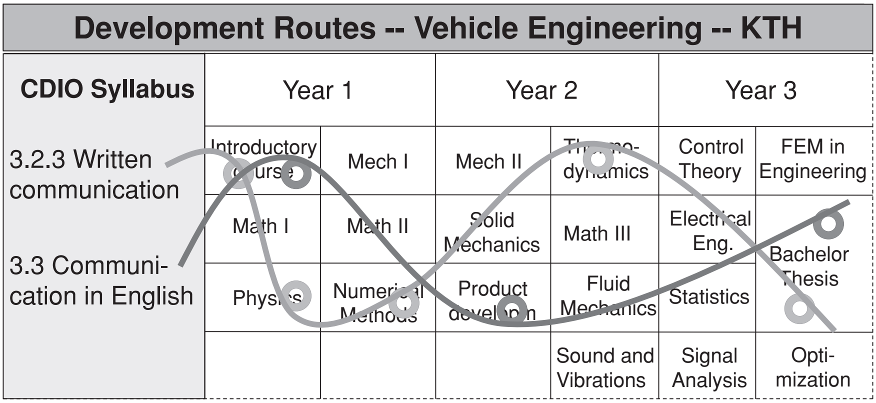


Fig. 4.8 Integrating communication skills into the curriculum

Table 4.4 Excerpt of program design matrix for curriculum mapping

Course	1	2	3	4	5
1.1 Knowledge of underlying mathematics and sciences					
1.2 Core engineering fundamental knowledge					
1.3 Advanced engineering fundamental knowledge, methods, and tools					
2.1 Analytic reasoning and problem solving					
2.2 Experimentation, investigation, and knowledge discovery					
2.3 System thinking					
2.4 Attitudes, thought, and learning					
2.5 Ethics, equity, and other responsibilities					
3.1 Teamwork					
3.2 Communications					

the faculty in course development and for monitoring student progress. Champions can be either subject experts or faculty members with special interest in the specific skills.

Mapping Learning Outcomes

Once the curriculum structure and learning sequences have been developed, learning outcomes are mapped to the learning activities. Standard 3 calls for an explicit plan to integrate personal and interpersonal skills, and product, process, and system building skills. This plan illustrates the ways in which responsibilities for developing professional skills are explicitly assigned to the courses. Curriculum mapping results in a matrix where one axis lists the program learning outcomes and the other axis lists the individual courses in the program. Table 4.4

is an excerpt from a generalized program design matrix for a curriculum mapping where the CDIO Syllabus second-level topics are mapped to the courses. The matrix is filled in with appropriate entries of where each topic will be integrated into the curriculum. Learning sequences and levels of proficiency, which were suggested by stakeholder surveys, determine the appropriate entries.

At this point in the curriculum development, it is important that the faculty involved in teaching the courses be engaged in the planning process. They provide insight into the feasibility of integrating specific skills with the disciplinary content for which they are responsible. They also validate the intended sequence of those outcomes. By being part of the curriculum design throughout its many iterations, faculty develop ownership of the new integrated curriculum.

Guidelines help in deciding which skills to integrate into each course:

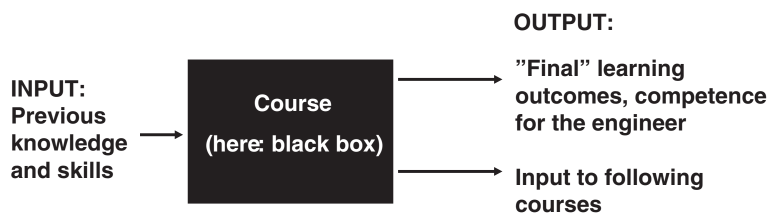
- Identify natural and obvious combinations of disciplinary content and engineering skills.
- Build on the strengths of the existing curriculum. If a professional skill is already addressed in a course, this learning experience can be reinforced through improved assessment tools.
- Take advantage of where the course is taught in the sequence of the program.
- Start with instructors who are willing and able to develop their courses in this direction. They can set examples and create early successes that can serve as proof-of-concept to other instructors.

Box 4.2 describes an exercise to facilitate coordination between courses. This exercise can be helpful in identifying and improving linkages between courses for both disciplinary and skills learning outcomes.

Box 4.2 The Black Box Exercise: Facilitating Coordination Between Courses

In an integrated curriculum, it is vital that the responsibility of each course toward the program learning outcomes is made explicit, that the interfaces between courses be well defined, and that the understanding of the curriculum and its elements be understood by all the faculty. In the Black Box exercise, the whole faculty team reviews the curriculum and its required courses. To keep focus, courses are discussed only in terms of its input and output of knowledge and skills. Before the meeting, instructors are asked to prepare a presentation on their respective courses, stating the specific knowledge and skills that students should have as they enter the course and the specific knowledge and skills students should be able to bring to the respective future courses. These expectations are expressed as intended learning outcomes. With this preparation, it is possible to identify the sum of the course learning outcomes as well as the connections between courses, or lack thereof. The discussions that follow aim to adjust any inconsistencies, redundancies, and gaps; improve timing; remove obsolete content; and, reveal places where a course may have drifted from its intent.

This exercise enhances the dialogue among the faculty, increasing shared awareness of the aims of the whole curriculum as well as the roles and responsibilities of each course. Development routes for disciplinary and professional skills learning outcomes are made visible to everyone. The exercise makes it easier to contact a colleague to discuss actions when they address problems where there is common agreement. Benefits of this exercise increase when the findings are well documented. Experience shows that this exercise can spark productive discussions, and it is well worth it to allocate an extended block of time to benefit fully from this exercise.



The result of the integrated curriculum design process should be a curriculum that meets the learning objectives and goals for the program. Integrated curriculum design requires the three desired features discussed in the introduction to this chapter: mutually supporting disciplinary courses, highly interwoven learning of professional skills, and well-defined learning outcomes for each course in both professional engineering skills and disciplinary knowledge. Box 4.3 describes an example of the implementation of an integrated curriculum at Singapore Polytechnic. The curriculum design also establishes the environment in which integrated learning experiences that make dual use of time can be executed. Integrated learning experiences are discussed further in Chap. 6.

Box 4.3 Integrated Curriculum Examples at Singapore Polytechnic

At Singapore Polytechnic (SP), curriculum designers recognized that successful curriculum integration, including the development of integrated learning activities, would require clear articulation of the

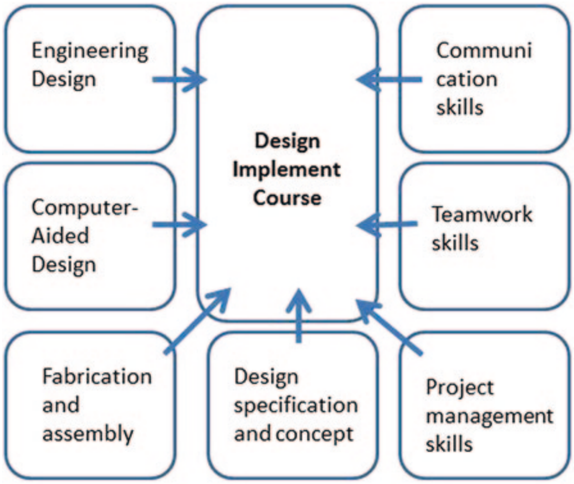
(*Continued*)

Box 4.3 Integrated Curriculum Examples at Singapore Polytechnic—Cont'd

CDIO skills at specific learning outcome and proficiency levels for the polytechnic. From the basis of a CDIO curriculum customized for SP, selected CDIO skills could be more easily and appropriately integrated into the technical knowledge and skills framework of programs. Within this context, *Personal and Professional Skills and Attributes* and the *Interpersonal Skills* of *Teamwork* and *Communication* were selected for initial implementation because faculty were more familiar with them and perceived their relevance in the engineering workplace. For example, through the clear articulation of critical and creative thinking skills in the learning outcomes, faculty were able to craft integrated learning activities that infused content knowledge and skills with these desirable but often elusive process skills. Critical thinking skills such as analysis, comparison, inference, interpretation, and evaluation, as well as creative thinking involving the generation of novel possibilities, were systematically infused in real-world learning activities that required conceiving, designing, implementing and operating. Similarly, teamwork skills were made explicit and facilitated by getting students to enact them in real teamwork contexts, e.g., setting ground rules, identifying the strengths and weaknesses of team members, formulating team goals, handling conflicts, etc., while working on real-world projects.

Knowledge and skills of related courses were also clustered and integrated through real-world learning activities. In the School of Mechanical and Aeronautical Engineering's Introduction to Engineering in Year One, knowledge and skills learned in two separate courses were integrated to conceive, design, and build a model racing car. Students machined the chassis from a given set of blueprints and applied creative thinking to conceive, design, and model the car's body. They then assembled and raced their cars. Teamwork and communication skills, as well as basic *Conceive*, *Design*, and *Implement* skills were introduced and woven into the activity.

In Year Two, to reinforce the integration of CDIO skills with technical disciplinary content, two existing courses, Engineering Design (ED) and Computer-Aided Design (CAD), were merged to become the Design-Implement course, illustrated in the figure below. The Design-Implement course exposed students to the various stages of machine design, such as conceptualization of design specifications, drawing, designing, fabrication, assembly, and commissioning of the machine.

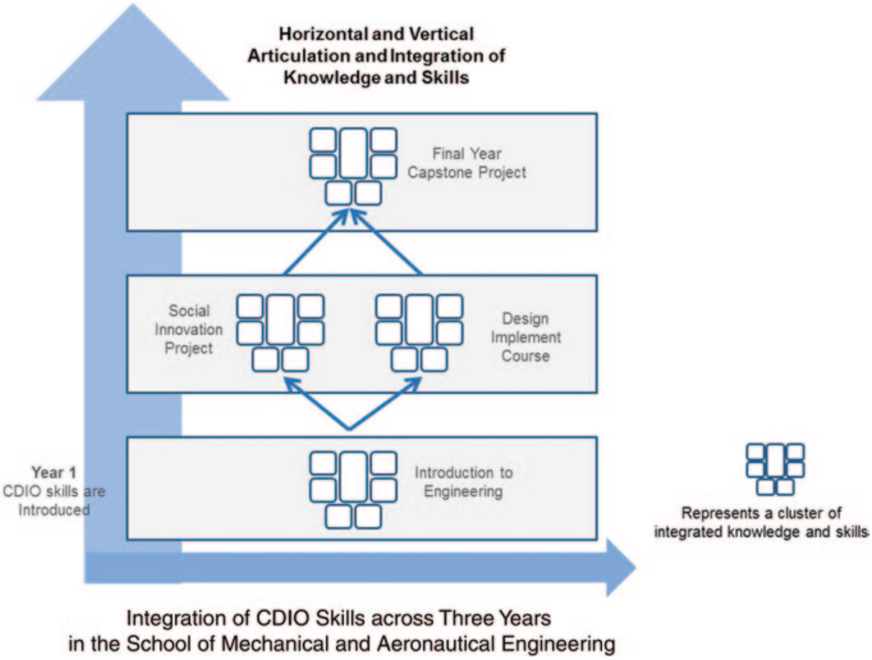


Cluster of Integrated Knowledge and Skills for the Year Two Design-Implement Course

To further reinforce the *Conceive*, *Design*, and *Implement* skills in Year Two, a social innovation project course required that students identify and prototype solutions for social endeavors. Students applied a design thinking process and tools to identify user needs, brainstorm solutions, and co-create their solutions with a selected community. In the process, they used competencies like questioning, critical and creative thinking, visual communication, and teamwork. Finally, teamwork and communication skills, as well as the skills of conceive, design, and implement introduced in the Year One Introduction to Engineering course and reinforced in the Year Two Design-Implement course, were practiced in the Year Three capstone project, as illustrated in the figure below.

(*Continued*)

Box 4.3 Integrated Curriculum Examples at Singapore Polytechnic—Cont'd



—H. Leong and D. Sale, Singapore Polytechnic

Introductory Engineering Course

As described earlier in this chapter, an integrated curriculum consists of four parts: the introductory course, disciplinary courses, design-implement experiences, and summative experiences. The introductory course is an early engineering course that aims to establish the framework in which engineers work and contribute to society. It serves to stimulate students' interest in, and strengthen their motivation for, the field of engineering. In addition, introductory courses provide an early start to the development of the personal and interpersonal skills, and product, process, and system building skills described in the CDIO Syllabus. Standard 4 highlights the importance of an introductory course.

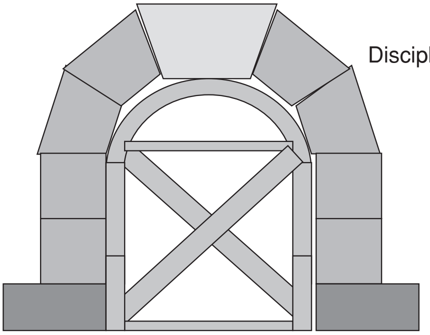


Fig. 4.9 Metaphor of an integrated curriculum structure

STANDARD 4—INTRODUCTION TO ENGINEERING

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

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

The metaphor of building a vault is used to illustrate the role of the introductory course in an integrated curriculum (see Fig. 4.9). The introductory course is the arch-shaped wooden form, or centering, used to support a stone arch made from the disciplinary courses as they are laid in place. When the arch is nearing completion, the capstone, or summative design-implement and/or thesis experiences, lock the structure into place. Once the capstone has been added, that is, all disciplinary courses completed, the centering can be removed. Building a real arch without centering is impossible. The introductory course is similar to centering in that it gives students a quick insight into engineering practice and the roles of engineers. Like the centering, it gives an early idea of the finished shape. The introductory course teaches some essential skills, provides a set of early authentic personal experiences that motivate the need for the disciplinary concepts, and allows early fundamentals to be learned more deeply. This aspect will be discussed further as part of experiential learning in Chap. 6.

Although found in various forms in CDIO engineering programs, introductory courses have a number of common denominators. They are among the first building blocks of their respective curricula. All employ some sort of authentic experience. Some use case studies to discuss historical or contemporary engineering issues. Others use "dissection," that is, taking apart an engineering device, such as a car, to understand how it works. However, most introductory courses include a design-implement experience of some kind that is carried out by student teams of two to six members. In these cases, design-implement experiences tend to account for at least 50 % of the total time devoted to the course. The courses and projects can focus on different stages of product or process development. Some concentrate on one or two stages, for example designing, or conceiving and designing. Others address all phases of development, from conceiving through operating. According to West [7], it is important for students in these courses to see that their projects actually operate. Therefore, several programs provide student workshops that permit students to build prototypes as part of their introductory courses.

Experience from our introductory courses supports the idea that design-implement projects improve students' comfort level working on technical problems that have no clear solutions. Moreover, students are able to demonstrate an understanding of how to design and build a device from an unidentified assortment of parts [8]. Students welcome opportunities to develop their own ideas in a project, and they appreciate the possibility of seeing something that they themselves have conceived become a reality. Box 4.4 describes an introductory course at Linköping University.

Box 4.4 An Introductory Course at Linköping University

The Applied Physics and Electrical Engineering Program at Linköping University created an introductory course called Engineering Project Y. It has now been conducted successfully for more than ten years, and the format of the course has been adopted by other engineering programs at Linköping University. The course has approximately 150 participants each year, runs over the entire first semester, and corresponds to about 25 % of a student's workload. This introductory course consists of three main parts: a series of lectures and seminars, project work, and a project conference.

Lectures and seminar

The series of lectures and seminars address topics related to the role of an engineer, group dynamics, oral and written communication, information retrieval, and introduction to the project management model used in the course. In addition, representatives of industry give a number of guest lectures.

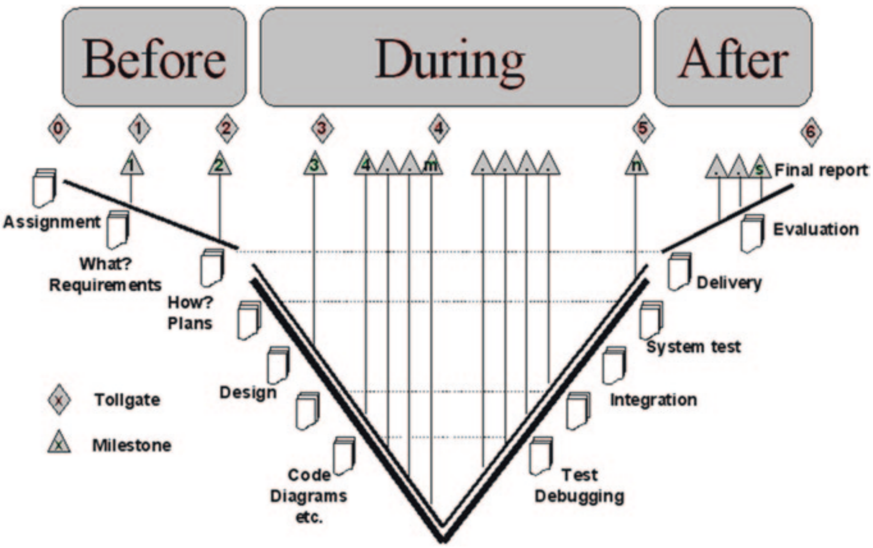
Project work

Project instructors assign students to groups of five or six students to carry out the project work. Each group is assigned a project task defined by a requirement specification. Each year there are approximately ten different project tasks, covering a wide range of subjects, assigned by five different disciplinary departments. Representative projects include the web-based supervision of indoor climate, the detection of moving objects in an image sequence, and a control system for optimal performance of a model car. Project work is managed by a project management approach, called LIPS, that was developed at Linköping University [9]. The LIPS project model is shown in this box.

Starting from the requirement specification, the first step in the project work is to create a project and time plan. The project customer must approve these plans before the project work can start. In many cases, group members agree on a group contract that specifies the rules for the work in the group and ways to handle conflicts. During the project work, groups have regular meetings, and they deliver project results to the customer according the requirement specification. At the final delivery, experts in oral and written communication assess group presentations and give feedback and advice to the groups concerning their communication skills. When the customer approves delivery, each group writes a reflection document in which they evaluate their work, both in terms of the technical results and the group work.

Project conference

The course ends with a final conference in which the groups present their work. The conference is organized in parallel sessions with faculty members acting as session chairs. The conference gives students practice in speaking in front of large audiences.



—T. Svensson, Linköping University

Summary

An integrated curriculum is characterized by a systematic approach to teaching professional engineering skills, also referred to as personal and interpersonal skills, and product, process, and system building skills. The curriculum is organized around, and integrated with, mutually supporting disciplinary courses. This integrated approach promotes deeper working knowledge through application of engineering concepts and emphasizes the importance of skills in engineering practice. Designing an integrated curriculum begins with setting learning outcomes based on stakeholder input, and an examination of pre-existing conditions such as program purpose and length and university policies and culture.

The curriculum design process itself focuses on three key components: structure, sequence, and mapping. Examples from CDIO programs illustrate the application of these components. The result of the design process is an integrated curriculum comprised of an introductory course, disciplinary courses, specializations, and design-implement experiences rich with professional skills learning outcomes. Introductory courses serve to convey the framework of engineering practice, engage and motivate students, teach early skills, and create a set of personal experiences that strengthen disciplinary learning. Introductory courses often include design-implement experiences, which are discussed in more detail in Chap. 5. The issues of designing an integrated curriculum reappear in Chap. 6 where the challenges of integrated teaching and learning are addressed.

Discussion Questions

1. What pre-existing conditions, such as program structure, facilitate or hinder the design of an integrated curriculum in your program?
2. In what ways can you integrate skills learning outcomes into your existing curriculum?
3. Of the many alternative curriculum structures presented in this chapter, which are feasible for your program?
4. How can an existing introductory course be modified to address the purposes of introductory courses in CDIO programs?

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Chapter 5
Design-Implement Experiences and Engineering Workspaces

Introduction

In this chapter, we continue our discussion of the resolution of the second question central to the improvement of engineering education—*How can we do better at ensuring that students learn these skills?* In Chap. 4, we examined how the curriculum can be restructured and re-tasked in order to strengthen the links between the disciplines and weave the necessary skills into the curriculum plan. In this chapter, we examine perhaps the most important device to meet the demands placed on an integrated engineering curriculum, namely, design-implement experiences.

Design-implement experiences involve practical hands-on activities in which students design, implement (build, create, produce), test, and operate an actual product, process or system, or some reasonable surrogate thereof. In disciplines where students develop artifacts, such experiences are sometimes called design-build or design-build-test activities. In software development, students design and then write code. There are also examples of courses related to competitions involving aspects of design-create-compete. In contrast to traditional "paper" design courses, the essential feature of design-implement experiences is that students actually realize their design and verify its performance.

Design-implement experiences are key features of a CDIO program in that they

- Complement theory to support efficient and deep learning.
- Have dual impact since they teach students engineering skills, i.e., personal and interpersonal skills, and product, process, and system building skills, and at the same time reinforce disciplinary knowledge.
- Strengthen the learning of fundamentals through repetition within a curriculum, first, by introducing concepts and motivating learning, and later, by providing opportunities for application and specialization.

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- Involve both active learning in which students manipulate, apply, and evaluate ideas, and experiential learning in which students take on roles that simulate professional engineering practice.
- Can be motivating, attracting students to engineering and helping to retain them within the program once they have enrolled.
- Foster self-confidence and encourage leadership in engineering design and development.

Because of this important role in engineering education, design-implement experiences should not be optional, but carefully integrated into the curriculum. Students need to be engaged in a sequence of design-implement experiences during their education in order to support progressive learning of professional engineering skills.

An important complementary aspect of a CDIO program is that it also provides workspaces to facilitate hands-on project-based learning. This need not be new space created for this purpose, but can be a re-tasked space previously used for classroom or traditional engineering laboratory exercises.

This chapter discusses educational means for planning and conducting design-implement experiences. We include experiences from programs that have adopted the CDIO approach. The learning environments, denoted *engineering workspaces*, that enable these design-implement experiences are also discussed. Descriptions include key attributes of effective workspaces and suggestions for modifying existing facilities to accommodate design-implement experiences.

Chapter Objectives

This chapter is designed so that you can

1. Recognize the importance of design-implement experiences and supporting engineering workspaces in the educational infrastructure.
2. Share examples of design-implement experiences and their appropriate learning spaces.
3. Find examples of design-implement experiences in different educational contexts.
4. Appreciate the benefits and challenges with design-implement experiences.
5. Adapt existing facilities and resources to improve design-implement experiences and engineering workspaces.

Rationale for Design-Implement Experiences

A design-implement experience is an activity in which learning takes place through the development of a product, process, or system. Students are thus engaged in applying and developing their knowledge and skills while working on an authentic engineering task, in working modes resembling professional engineering practice. Because it is intended to provide engineering practice in a relevant field, the detailed nature of a design-implement experience depends largely on the engineering discipline and can take many different forms. The key criterion for such an experience is that the solution is designed and implemented to a state at which it is operationally testable by the students. In this testable state, students should be able to verify that the product, process, or system meets its requirement in order to evaluate their work and identify possible improvements, both regarding the result and the process that brought them to the result.

Design-implement experiences can be designed to include several elements and activities that are recognized as strong drivers for deep learning. The act of first designing and then practically realizing the result provides immediate feedback of progress and success (or the opposite). Students are likely to reflect on what works and what does not work, how, when and why. Driven by curiosity, they may explore how different elements are related and how certain changes or manipulations affect the properties or performance of a system, or for that matter, the performance of a group. By carrying projects all the way through to implementing and testing solutions, students become more comfortable in translating between models and physical reality, in understanding the implications of assumptions and estimations, and in becoming accustomed to keeping one foot in analysis and the other in the physical world. Since this relationship is the essence of engineering, it should also be the emphasis of engineering education.

Characteristics of Design-Implement Experiences

We use the term *design-implement experience* to signify a range of engineering activities central to the process of developing new products, processes, and systems. These experiences enable students to work through most or all of the activities in the product, process, or system lifecycle model. As mentioned in Chap. 2, *Conceiving* includes defining customer needs; considering technology, enterprise strategy, and regulations; and, developing conceptual, technical, and business plans. *Designing* focuses on creating the plans, drawings, and algorithms that describe the product, process, or system to be implemented. *Implementing* refers to transforming the design into a real product, including for example hardware manufacturing, software coding, testing, verification and validation. The final lifecycle stage, *Operating*, uses the implemented product, process, or system to deliver the intended value, including maintaining, evolving, and retiring the system. Ideally, students would be exposed to aspects of actual operation as well, but experience has shown that it is difficult to orchestrate in an academic setting for all but the simplest devices. Therefore, for both pedagogical and practical reasons, we focus primarily on conceiving, designing and implementing as the key activities about which students should learn, including verification in the implementing phase.

The intended outcome from the design can consist of hardware, software, substances, or combinations thereof. Media or materials used to realize the results need to be carefully chosen, but this does not mean that the product has to be implemented in its final form. Depending on the level of the course, the object of design can be anything from a simple functional model and a complex near-production prototype. If the outcome is a more complex system or process, it may be impossible to actually implement the entire system or process, but alternatives include implementing elements of it, an analog, a scaled model, or a digital model. Regardless of the details, the result must meet the basic criterion of being designed, implemented, and verified. Only then does it serve as a source of direct feedback to students on the success of their work and provide opportunities for valuable reflection.

Distinguishing Design-Implement Exercises

Although the CDIO approach is not exclusive, there may be reasons to distinguish CDIO design-implement activities from other activities and particular pedagogical models. For instance, the term *project-based learning* is often used for activities where a number of students are grouped together to perform a certain task collectively, during a limited period of time and with given resources and constraints. Such activities may or may not involve design-implement experiences as outlined in this chapter, and may or may not be contextual or authentic. Neither does project-based learning necessarily generate real-world verifiable results. On the other hand, lab experiments and projects, while being authentic, do not inherently belong to the category design-implement experiences, but could very well do so if their scope includes the design of the experiment as well as its conduct and evaluation.

Problem-based learning is an established pedagogical model where the program or course content is primarily delivered through inductive or exploratory work where instructors pose problems, the solutions of which will facilitate student learning. At some institutions, entire programs are delivered this way, although now even some of the most ardent supporters of problem-based learning have backed away somewhat from this philosophy. As an example, the newest problem-based learning model at Aachen University embraces a balance between problem-based learning courses and more traditional disciplinary courses [1]. Problem-based learning rests on a foundation of motivating students to acquire knowledge out of curiosity and a desire to solve a particular problem. Design-implement experiences focus on developing professional engineering skills and competencies while applying and reinforcing knowledge.

Role and Benefit of Design-Implement Experiences

Design-implement experiences play a key role in an integrated curriculum since they can enable dual-impact learning, that is, when a single learning event simultaneously teaches skills and reinforces the understanding of fundamentals. From the skills perspective, it is in these design-implement experiences that students learn how to develop and build products, processes, and systems, and in addition, they develop personal and interpersonal skills, such as teamwork and communication skills. From the perspective of fundamentals, design-implement experiences strengthen the foundation upon which deeper conceptual understanding of disciplinary and multidisciplinary knowledge can be built. Earlier design-implement experiences lay this base by engaging students in problem solving and emphasizing the need for analysis. Ideally, they prepare students to learn theory and help them to understand the implications. In addition, students find themselves in situations where they need to test the validity of theories, methods, and assumptions, and examine reasons for discrepancies. Design-implement experiences allow students to apply their theoretical learning, and therefore, such experiences promote both deep understanding and long-term retention of knowledge.

Because of their importance, design-implement experiences are the focus of CDIO Standard 5.

Standard 5—Design-Implement Experiences

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

The standard proposes a sequence of design-implement experiences from basic to advanced levels in terms of scope and complexity. An iterative approach reinforces students' understanding of product, process, and system development. More importantly, design-implement experiences should be deliberately structured and sequenced to reinforce the learning of fundamentals. The first design-implement experience in the curriculum could be a concrete experience that introduces students to particular phenomena or challenges in the field, getting them acquainted with the subject, generating curiosity, and stimulating reflection. Students may then become better motivated to learn theory and abstractions in more formal coursework. The next design-implement experience may involve an application of the previously learned technical knowledge. This increasing spiral of knowledge is the reason that Standard 5 requires a sequence of design-implement experiences. In a simple idealized example, a 1st-year design-implement experience would expose students to a problem that requires limited disciplinary theory to solve; a 2nd-year course would involve certain theoretical knowledge; and a 3rd- or 4th-year design-implement experience would require true application of such theory.

In Chap. 4, the concept of introductory courses was presented and explained. Introductory courses may include elements of design-implement experiences provided that they do not rely on specific technical disciplinary knowledge. In fact, we recommend that students encounter their first design-implement experience in an introductory course since it is a good way of introducing disciplinary content and professional engineering skills and attitudes. At the same time, the design-implement experiences can be motivating to students and build good social relations among 1st-year students.

In addition to teaching students skills and strengthening the understanding of fundamentals, design-implement experiences

- Add realism and diversity to the curriculum.
- Illustrate connections between engineering disciplines.
- Highlight complexity that calls for informed choices rather than "finding *the* right answer".
- Foster students' creative abilities.
- Provide authentic engineering experiences that may strengthen students' self-efficacy.
- Can be fun and motivating both for students and instructors.

To summarize, authentic engineering experiences, in working modes similar to real-world engineering contexts, give students opportunities to reinforce fundamental knowledge and simultaneously develop professional engineering skills and attitudes. Thus, design-implement experiences both contribute to insights about the technical content, and explore and develop skills that benefit students' professional lives and careers.

Early Design-Implement Experiences

As explained in Chap. 4, an integrated curriculum includes early design-implement experiences. As also mentioned above, introductory courses are most helpful if they include basic design-implement experiences. These early experiences have significant positive effects on beginning students. Students are introduced to structured engineering problem solving with opportunities to apply fundamental engineering principles. In addition, they learn to work in teams and communicate their progress and results. These early experiences also provide excellent means to introduce disciplinary content that will be taught in succeeding semesters. Early introduction to disciplinary knowledge is effective in building students' enthusiasm for engineering since students can be creative and can share the experience with others. Such activities can make students more aware of, and curious about, different engineering disciplines and some of their main challenges, prior to choosing an area of specialization.

Basic design-implement experiences have benefits for instructors, as well. From these experiences, instructors become familiar with the personalities, maturity, dependability, and unique skills of students at an early stage in their education. Because they get to know students better, instructors are able to recognize individuals and their learning styles, in ways that are not always possible in more traditional classrooms. This enhanced personal contact with individual students can facilitate more effective advising, teaching activities, mentoring, and assessment.

Advanced Design-Implement Experiences

In contrast, advanced design-implement experiences are usually planned for upper-level students. They provide opportunities to analyze, design, build, test, and potentially operate real-world engineering systems that function at higher levels of sophistication than earlier design-implement experiences. Where basic experiences may have multiple small teams applying a fairly limited breadth of engineering knowledge, advanced project teams are usually larger and require a wider scope of engineering abilities. An advanced project can involve teams of more than ten students working on a single project over one or several academic semesters. Tasks for such projects could, for example, deal with research questions, cooperative work with industry, or global societal challenges.

Advanced design-implement experiences are technically challenging at several levels. The work includes design and implementation of student-developed components, as well as integration, testing, verification, and validation in conjunction with commercially available components or those developed by other students. The technical tasks involved are typically at a level that students might encounter in their professional careers. The need for both the technical knowledge and the skills outlined in the CDIO Syllabus increases as the complexity of the task becomes evident to students.

Development of Design-Implement Experiences

The development and realization of design-implement experiences can be more complex than traditional course development and teaching. The planning and organization of these experiences require consideration of a number of factors, particularly in selecting relevant projects and managing resources. Moreover, the quality of the learning experience depends on the synergistic combination of appropriate activities, workspaces, and adequate faculty support. The detailed nature of a design-implement experience depends on the engineering discipline from which it is derived. However, what is vital and common for all disciplines is that the design-implement experiences should be designed to meet specific desired learning outcomes. Some common essential and desirable attributes of effective design-implement experiences were identified by Andersson, Malmqvist, Knutson Wedel, and Brodeur, and are listed in Table 5.1 [2].

Table 5.1 Essential and desirable attributes of design-implement experiences

Essential attributes	It is essential that design-implement experiences • Resemble engineering practice in the field of the discipline • Are realistic enough to challenge students when relating theory to practice • Develop working modes relevant for students' professional development • Are aligned with a set of explicitly formulated learning outcomes primarily related to – Integrating, applying, and reinforcing disciplinary knowledge – Developing engineering skills, such as product, process and system design and implementation skills – Developing personal and interpersonal professional skills, such as teamwork and written, oral and graphical communication • Emphasize and assess these learning outcomes rather than the project goals per se • Include aspects of design, implementation, and verification • Are open-ended and allow alternative paths to alternative solutions • Are fully integrated into the curriculum
Desirable attributes	It is desirable that design-implement experiences • Provide students with practical hands-on experience in – Building and operating small, medium, and large systems – General prototype fabrication, testing, and redesign – Handling and use of authentic tools and equipment • Are problem-led rather than discipline-led • Build community and increase students' motivation for engineering

Design-Implement Experiences Throughout the Curriculum

We have observed that a single design-implement experience, no matter how well planned, is insufficient to provide students with a proper understanding of the design-implement process. Mastering these skills, like any other skills, requires practice. Just as in any other training activity, the level of complexity and challenge should be increased gradually and iteratively. An effective strategy is to include a sequence of design-implement experiences in the curriculum, and plan for systematic variation across each instance. Early projects introduce basic concepts, design strategies and tools. In later experiences, more complex projects help students integrate knowledge and skills acquired across the entire curriculum. One project might emphasize creativity while another might address manufacturability or issues concerning multidisciplinary integration. Figure 5.1 illustrates a plan where design-implement experiences are integrated throughout a five-year curriculum.

First-Year Activities

In the first year, the design-implement experience can be part of an introductory course that emphasizes the fundamental principles of the design process, for example,

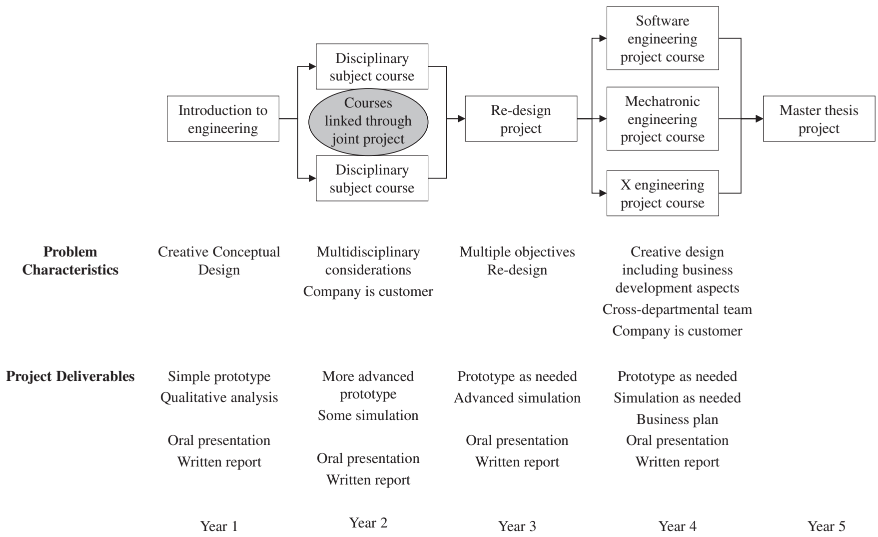

Fig. 5.1 A plan to integrate design-implement experiences throughout a curriculum

concept generation and selection. Creativity is encouraged through practical exercises. The prototypes are simple, yet enable students to go through the process from identifying user needs to building and testing their designs. The design might include analysis based on fundamentals learned previously. The cost of required materials and equipment is kept to a minimum through proper design of the task. Students typically work in groups of three to five, practicing communication and teamwork skills. A simple project management model, such as the Linköping Project Management Model (LIPS) [3], can be introduced with specific milestones, nomenclature, and templates for project documentation.

Second-Year Activities

In the second year, a design-implement experience can be used to integrate the knowledge acquired in diverse disciplinary courses, as suggested by Fig. 5.1. One approach is to pair two engineering disciplines. Another option is to pair a disciplinary subject with one that focuses on producibility, software engineering, or some other topic. Students might design and implement a prototype based on an industrial commission, adding a degree of realism to the task. At this point, students are able to base their design decisions on the technical knowledge they have gained during their first year of study. They may be able to consider manufacturability of their prototype in order to obtain cost-effective solutions. Simulations can be used to a higher degree than in earlier courses, and simple prototypes can be made.

In a 2nd-year design-implement project at Queen’s University in Belfast, classes are divided into groups of six to undertake the design, construction, and testing of a one-meter beam in three-point bending. The aim is to achieve the highest failure load per unit weight. This experience requires application of theory introduced in the first year and developed in the second year. Box 5.1 is a description of this design-implement experience at Queen's University.

Box 5.1 Beam Design Lab At Queen's University Belfast (QUB)

The beam design laboratory at Queen's University Belfast (QUB) is a team-based competition designed to reinforce the fundamentals of basic beam theory. The lab is intended for 2nd-year mechanical engineering students. Design and manufacture take place over a three-week period with a competition at the end of term to find the team with the highest *load at failure-to-mass* design. Each lab period is 3 h long, so the complete exercise takes no longer than 12 h.

Design and Implementation

During the first week, each team of students produces concepts for a beam with specific geometric constraints, without recourse to any calculations. After discussing the concepts with a teaching assistant, the groups choose three designs to build as their prototypes. The prototypes are manufactured from cardboard and tape, and are tested to destruction in three-point bending. On the basis of these results, students choose a final design to be constructed in medium-density fiberboard (MDF). The second week involves marking out a sheet of MDF in preparation for the cutting and assembly of the final design. While engaged in preparation, student teams must consider the likely mode of failure and calculate the maximum load at which the beam will fail. In the third week, student teams assemble their beams from the MDF components. The groups have workbenches, some basic hand tools, and PVA glue to construct their beams. Sixteen teams participate in the beam design laboratory. The groups' activities are staggered over a ten-week period to maximize resource utilization. All the teams come together at the end of term for the competition, which now tests the MDF beams in three-point bending until failure.

Student Assessment

Student assessment is a combination of beam performance at the competition (50 %), a group report (30 %), and a supervisor's evaluation (20 %). Beam performance is characterized as the strength/mass ratio of the beams, with maximum credit assigned to the winners, and credit assigned to the other teams on a pro-rata scale. The group report is an ongoing exercise over the term of the laboratory. During the first week, groups sketch their final design and explain the rationale behind it. In the second week, the groups present the calculated mass and predicted load at failure, and explain how they arrived at the figures. The final stage of the report is a reflection, in which groups discuss how the predicted performance of the beam compared with actual performance, and also how the performance of the design could be improved. The supervisor's grade is based on construction quality, design originality, and group dynamics. The final laboratory grade constitutes 10 % of the total credit for the statics course, of which the beam design lab is a part.

The beam design laboratory is a new type of learning activity for students in the first three years and has been judged by students to be quite a success. The lab provides a good mix of teamwork, hands-on experience, and applied theory in an authentic setting. Not only has it fulfilled its initial goal of reinforcing the fundamentals of beam theory, but it has also increased student enthusiasm and improved their perceived relevance of the statics course overall.

—**G. Cunningham, Queen's University Belfast**

Third-Year and Fourth-Year Activities

In the 3rd- and 4th-years of study, students are given tasks of increased complexity and authenticity. For example, in the third year, they might be asked to redesign existing industrial products in order to improve performance or to decrease environmental load or cost. Analyzing trade-offs among multiple goals is now explicitly considered. At this point, students are able to make decisions using more situation-adapted strategies, selecting prototypes and simulation methods as needed to support the development processes (see Fig. 5.1).

In 4th-year projects, the scope can be widened to include business development aspects. Teams consist of larger groups, typically about eight to ten students from one or several engineering departments and possibly additional students, for example, from a business program. Customer and market surveys can then be included in the work. Communication skills and project management models are further refined and developed. Working in large groups requires organized project management, continuous documentation, and follow-up of decisions for successful project completion. Conflicts of interest and multiple optional approaches to given tasks might generate challenges, both technically and from a group dynamics perspective.

The project deliverable in the fourth year is typically an operable prototype or an advanced model that demonstrates real performance. For example, in a fourth-year design-implement experience at the Massachusetts Institute of Technology (MIT), students designed two autonomous 2-kg robots meant to communicate with each other in space. About 15 students participated in this project intended to complement an existing research program. Students designed, prototyped, and then built or acquired subsystems providing propulsion, navigation, autonomy, and communications. Then they assembled and verified the system. Figure 5.2 illustrates the operational testing of the autonomous robots by students and their instructor in microgravity conditions aboard NASA's KC-135A research aircraft.

Fig. 5.2 The SPHERES project at MIT: testing autonomous robots in “0-gravity”

Another example of a 4th-year design-implement experience comes from KTH — Royal Institute of Technology in Stockholm. In the Department of Aeronautical and Vehicle Engineering, a design-implement project course is offered jointly for students specializing in Lightweight Structures and Naval Architecture, and spans two full semesters. Project tasks are assigned collectively to student groups of from 10 to 15 students, some from the structures program and some from the naval program. Within the groups, there is freedom to define and distribute project sub-tasks, based on the individual interest and expertise of group members. Each student is expected to contribute with technical work in several sub-tasks, and to the management of the overall project. The size of the groups creates the need for planning, documentation, information sharing, communication, and team building. The importance of attending to such management issues becomes obvious to students during the course of the work.

The project task is carefully designed with respect to Conceiving-Designing-Implementing-Operating:

C The project deliverable is unconventional in the sense that students have limited prior experience with similar products. A pioneering situation enhances the *conceiving* phase and encourages students to engage deeply in the main technical challenges and approaches. Because the course involves students from different curriculum tracks, the projects are also crossdisciplinary. Different perspectives and incompatible solutions are likely to occur, creating the need for compromises and trade-offs between conflicting desirable features of the product. Consequently, holistic thinking is brought about naturally and in an authentic context.

D The task is difficult enough to be a true challenge to students, yet possible to solve if the work is organized and carried out well. One of the main objectives of the course is to encourage students in applying theory, analysis tools, and methodologies learned in other courses, thereby solidifying their knowledge and gaining confidence in their role as engineers.

I The size and complexity of the product will entail teamwork and coordination, and provide opportunities to obtain practical experience from real manufacturing on a prototype level.

O The task is formulated in such a way that the assessment of the results involves operation of the product and evaluation of its performance with respect to technical specifications.

The task is defined by a brief requirement specification of a technical system, typically some kind of vehicle, where the expected performance is described together with constraints, in terms of cost, size, weight, power supply, or other factors. The idea is that the requirements are very clearly specified early in the course but the approach to the task is by no means obvious. How the final product will come out is still very open. A shared site is used for documentation and information sharing within the project. In this way, all information is continuously updated and always available within the project group. An open website also enables interested people outside the project group to monitor the progress of the work.

Challenges of Design-Implement Experiences

Providing effective and motivating design-implement experiences for students poses five key challenges for engineering programs.

1. *Learning outcomes for design-implement experiences need to distinguish between product performance and learning performance.*
   Learning outcomes—what students will know and be able to do as a result of the design-implement experience—need to distinguish success in acquiring personal and interpersonal skills, and product, process, and system building skills, from successful performance of the product, process, or system that is designed. It is possible to have substantial learning benefits even if the project is not a complete success in terms of a functional product.
2. *The task of the design-implement experience must be sufficiently complex, yet limited in scope, to ensure successful outcomes for students.*
   Instructors and students sometimes see the achievement of a good technical solution as the real learning outcome. Failure in the task can be perceived as failure in learning. If the task is too difficult, the result may be an impressive product that is essentially instructor-designed, with students merely acting as implementers. A task that is too simple might fail to motivate students or to build the kind of confidence that results from having met a

challenge. Students' time spent on the task needs to be carefully monitored in order to maintain a balance with other activities competing about the students' attention.

3. *Design-implement experiences require teaching and assessment practices that are different from traditional instruction.*
   With design-implement experiences, instructor roles change from lecturer and dispenser of information to mentor and coach. In a less-constrained learning environment, students are encouraged to discuss, reason, and explore issues with support from instructors. The successful instructor-coach is a mentor providing support, a mediator between the students and their "clients", and a manager guiding team and design processes [4]. It may be challenging for some instructors to switch from a teacher-centered style to a student-centered one. Methods for teaching and assessing design-implement experiences are addressed in further detail in Chaps. 6 and 7.
4. *Few instructors are prepared to assume responsibility for technically challenging projects.*
   In a typical engineering department, only a small fraction of faculty and staff have personal, practical experience of developing complex systems. Many programs depend on the talents and skills of one or a few key individuals. The introduction of design-implement experiences requires adequate faculty resources to ensure stable and sustainable operation. Some engineering programs hire graduate teaching assistants involved in research projects that have goals and objectives supporting the intended design-implement experiences. This approach supplies valuable technical assistance to students, while also accomplishing pre-established graduate research goals. Other programs use technical advisors from industry who are interested in specific student projects. The challenge for teachers to lead design-implement experiences should not be overestimated but it helps if a few enthusiastic souls are available. Faculty development to enhance competence in training engineering skills is addressed in Chap. 8.
5. *Design-implement experiences need to be cost-effective.*
   Reluctance to include design-implement experiences in engineering education is frequently rooted in suspicions that such experiences are highly resource intensive. On average, design-implement experiences cost about 1.5 times that of a traditional lecture course, with a range of 1.0–2.5 [5]. With some creativity, it is possible to develop lower-cost design-implement experiences without compromising educational outcomes. One university's internal study of the return-on-investment of an advanced-level design-implement-test project concluded that the success of an ambitious project was a key factor in the university's bidding for, and winning of, follow-on research proposals. Their figures support a conclusion that there was a 6:1 cost-benefit ratio from this combined linkage of academic and research goals [5]. Others testify that their student projects have been so successful in attracting sponsors that they have made a profit rather than spent their allocated budgets for the course. Furthermore, the workload on the instructors

can be kept reasonable by letting students perform more of the assessment and feedback work. Such activities could also be turned into powerful learning activities.

Engineering Workspaces

We shape our buildings; thereafter they shape us. (Winston Churchill)

Providing students with successful design-implement experiences requires a learning environment with adequate spaces, equipment, and tools. We call these facilities *workspaces* to suggest their linkage to creative engineering development, and distinguish them from laboratories that are traditionally the site of scientific inquiry. Workspaces may be newly built spaces, or laboratories and rooms retasked from other existing uses. In fact, they may even be set up as part of field studies, manifested by enabling appropriate devices and equipment on site without ordinary devoted premises. Their prime distinguishing feature is that they provide multimodal learning environments that support the conceive-design-implement-operate process for simple and complex problems, for individual or groups of students. They create the infrastructure that visibly signals and supports active and hands-on learning strategies.

Role and Benefit of CDIO Workspaces

If students are to experience that conceiving—designing—implementing—operating is the context of their education, they need to be immersed in workspaces that are organized around C, D, I, and O. We can use the organization of the space to signal the importance of the context to the students and to strengthen their education. Consequently, workspaces comprise a key element of the CDIO program strategy. Workspaces that support hands-on learning are important resources for developing skills in designing, building, and testing products, processes, and systems. Workspaces are the focus of Standard 6.

STANDARD 6—**ENGINEERING WORKSPACES**
Engineering workspaces and laboratories that support and encourage hands-on learning of product, process, and system building, disciplinary knowledge, and social learning

The physical learning environment for a CDIO program includes traditional teaching and learning spaces, such as classrooms, lecture halls, and seminar rooms, as well as engineering workspaces. These workspaces aim to support the learning of product, process, and system building skills, while at the same time developing and strengthening both disciplinary and multidisciplinary knowledge. They are designed to promote hands-on learning in which students are directly engaged in their own development, and to provide opportunities for social interaction and training. CDIO workspaces are settings in which students can learn from each other and interact in groups. Students who have access to modern engineering tools, software, equipment, and laboratories have opportunities to develop the knowledge, skills, and attitudes that support product, process, and system building competencies. These competencies are best developed in workspaces that are student centered, user friendly, accessible, and interactive.

In addition to these direct educational benefits, inviting workspaces that attract students and allow them to work together in stimulating environments strengthen the motivation of students. As the students establish a pattern of working in these spaces, faculty soon start to visit, improving student-faculty interaction. Purely social functions also occur. Thus, workspaces also play a role that goes beyond their initial intended purposes—as community-building spaces for students and faculty.

Designing Engineering Workspaces

Engineering workspaces are designed to engage students actively in creative and experiential learning and are designed to support the entire curriculum. This is in contrast to conventional student laboratories that, as a rule, are allocated for specific disciplines. Traditional student workspaces tend to enable the learning of specific skills, for example, *LabView*-supported environments [6], project studios [7, 8], CAD/CAM/CAE labs connected to workshops [9], and multimedia environments [10], rather than provide an integrated resource for an entire program. Conventional student laboratories also tend to be heavily oriented towards demonstrations, and typically do not support conceiving, designing, or community building.

A CDIO program generally requires new types of workspaces that allow students to work through the entire product, process, or system lifecycle. In this context, the term *engineering workspaces* denotes facilities that cover a wide span, ranging from traditional student work areas to team-based project areas, concurrent engineering computer-driven design rooms, and facilities designed for extracurricular engineering activities. The concept of engineering workspaces includes environments that enable students to interact, develop and exchange ideas, experiment, tinker, manufacture and assemble things, code and load software, and conduct similar work as needed. It is generally desirable for all engineering workspaces to be student-focused and, at least partly, student-controlled and student-managed, since student involvement helps keep the premises serving their purposes.

Workspaces vary significantly between programs and institutions. Therefore, the guidelines given for engineering workspaces identify common criteria, independent of engineering discipline. The guidelines concentrate on the essential attributes and usage modes of engineering workspaces and are not intended to provide strict

Table 5.2 Essential and desirable attributes of engineering workspaces

Essential attributes	It is essential that engineering workspaces • Encourage hands-on learning of product, process, and system design and implementation • Support reinforcement of disciplinary and interdisciplinary knowledge • Facilitate student learning of personal and interpersonal skills • Facilitate group activities, social interaction, and communication leading to social learning • Comply with local health and safety regulations • Be sustainable
Desirable attributes	It is desirable that engineering workspaces • Be at least partly organized and managed by students • Provide flexible equipment, furniture, and facilities • Facilitate access by students beyond normal class hours • Provide access to modern and relevant tools, equipment, and software

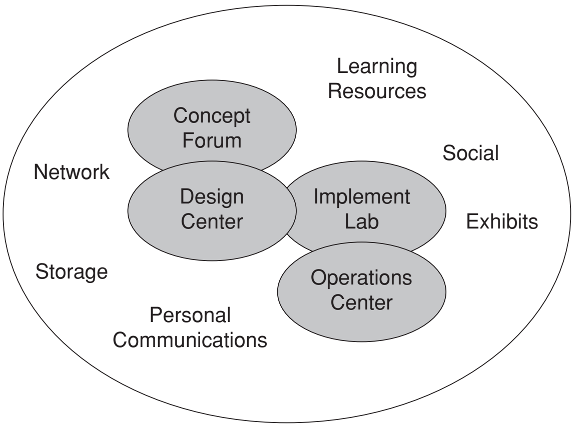

Fig. 5.3 Conceptual model of CDIO workspaces

blueprints for learning environments. Workspace configuration, size, equipment, and instrumentation depend on available resources. Furnishing and fittings need not necessarily be fancy and expensive to serve their purpose. Table 5.2 summarizes the essential and desirable attributes for engineering workspaces in CDIO programs.

If we are to emphasize that conceiving, designing, implementing, and operating is the context of engineering, it is desirable to make the spaces in which students work explicitly reflect these phases. Facilities need to be flexible and multifunctional, supporting information-based, as well as hardware-based, projects. Workspaces typically support learning about the four phases of CDIO in four different kinds of spaces, as illustrated in Fig. 5.3 [11].

- *Conceive* workspaces enable students to envision new systems, reach understanding of user needs, and develop concepts. They may include both team and personal spaces in order to encourage conceptual development and reflection.

Typical equipment and resources include whiteboards, access to online and library resources, and data projectors. Conceive workspaces are largely technology-free zones. Their primary purpose is to support reflection and human interaction by means of talking, illustrating, and listening.

- *Design* workspaces support the new paradigm of collaborative, digitally supported design. They enable students to design, simulate designs, share designs, and explore interactions. Typical equipment includes computers with software for computer-aided design, computer-aided manufacturing, software development and simulation. Additional equipment, for example, videoconferencing and shared databases, may support collaboration with other remote student groups. Design workspaces should also be accessible after normal class hours as students often conduct design work during available off-schedule time.
- *Implementation* workspaces enable students to build or develop small, medium, and large systems including, for example, mechanical or electronic software components, or new chemical processes. Typical equipment includes hand tools and instruments, measurement and manufacturing equipment, and computers for integration of software. The range of student projects calls for a great deal of flexibility. Safety and accessibility are other critical issues.
- *Operate* workspaces provide arenas where students can test the performance of their creations, verify their meeting of requirement specifications, and demonstrate the results of their efforts. The students receive very clear and direct feedback on their work and also on their assumptions and how successful their approaches to solve different problems were. Operation is difficult to teach in an academic setting, but students can learn how to run and evaluate both experiments and the final result of their work. Simulations of real operations and electronic links to real operations environments could also supplement direct student experiences [11].

These physical workspaces should preferably be co-located in order to reinforce their ideological linkages. In addition, they should be connected to other common student facilities, such as the library, social spaces, storage facilities, and through networks to the online community. A workspace could also include exhibits that reflect engineering research and development achievements, or a sequence of projects within a department or academic program that are relevant for the ongoing activities in the workspace.

Examples of CDIO Workspaces

CDIO workspaces do not have to be new, but can use existing spaces. Many universities have student laboratories of the conventional kind that are underutilized. Re-tasking some of this space as engineering workspaces often results in much higher utilization. Our experience is that as the students engage in active work in the new workspaces, both the attractiveness and need for conventional passive student laboratories diminishes. It may also be possible to re-task classrooms and meeting rooms for projects that do not require much manufacturing equipment.

Implementation of engineering workspaces at collaborating universities has ranged from design and construction of new space to adaptation and redesign of existing physical layouts. At Chalmers University of Technology in Gothenburg, existing spaces were re-tasked to create a Prototype Laboratory. In this facility, students from programs in mechanical, automation and mechatronics, and industrial design engineering create computer-assisted design models to manufacture prototypes and test functional models of various mechanical and mechatronic products. Prototypes can be made of wood, metal, plastic, cardboard, electronics, and/or software as best suits individual project needs.

Another example of an engineering workspace is *The Pool* at the Royal Institute of Technology (KTH) in Stockholm. Converted from previously underutilized classrooms, this facility measures approximately 60 m^2 and is highly reconfigurable serving both as design space, meeting room, manufacturing, assembly and test room for students enrolled in the vehicle engineering program. With relatively moderate resources, students have produced a broad range of air, land, and water vehicles over the years, each being new to both students and faculty to accentuate the novelty of the work to everyone involved [12].

A third example of more significant re-tasking of space, combined with some new construction, is the MIT Complex Systems Laboratory. The Department of Aeronautics and Astronautics established a full suite of workspace facilities to address each specific Conceive, Design, Implement, and Operate element of the CDIO lifecycle model. Two floors of the department building were renovated, creating a new learning laboratory complex. Specific CDIO functions were designated for each work area: conceiving in the Seamans Concept and Management Forum, designing in the Design Center, implementing in the Gelb Laboratory (containing machine and electronics shops, and a rapid prototyping facility), and operating in the Neumann Laboratory and the hangar and flight operations center. In the Seamans Laboratory, there is an additional open area of approximately 1,500 m^2 designated for study and for community building. Students study in groups, interact informally with faculty and teaching assistants, and have access to computers to assist them with their assignments. Several key architectural themes are incorporated into these workspace facilities. Movable furniture allows convenient space reconfiguration to meet changing demands of class size, teaching style, and project needs. Electronic door controls give students access to the facilities (other than machine shops) at night and on weekends [11].

Using the lessons learned from these and other world-class student workspaces, including the Integrated Teaching and Learning Laboratory at the University of Colorado and the Integrated Learning Center at Queen's University in Kingston, Canada, other collaborating institutions have succeeded in developing their own workspaces that support their educational goals. The breadth and scope of each university's workspace facilities vary according to available space, funding, program needs, and other factors, but the common theme is the awareness that Conceive, Design, Implement, and Operate workspaces are effective facilitators of improved engineering education.

Teaching and Learning Modes in Engineering Workspaces

Teaching and learning modes in CDIO workspaces fall into three major categories: product, process, and system design and implementation; reinforcement of disciplinary knowledge; and, knowledge discovery. In addition, workspaces play a major role in building community among students. For each category, a number of more detailed teaching and learning modes can be described. These modes are not meant to be exhaustive and may be overlapping. They are intended to serve as a guide in thinking through the requirements for workspace design at a specific university. Figure 5.4 illustrates the teaching and learning modes facilitated by these workspaces.

Product, process, and system design and implementation. This category represents the most obvious major mode of teaching and learning that takes place in an engineering workspace. However, it should also be recognized that there are many variations of this mode with different requirements for the design of the workspace.

- *Basic design-implement projects* are course-based design projects carried out over a period of a semester by student teams from a given course. Design work includes computer simulation and visualization and the outcome is typically both a "paper" design and a simple prototype. The work is conducted in smaller teams of maybe three to five students. Support for this mode includes design tools, management tools, visualization tools, and basic prototyping facilities.
- *Advanced design-implement projects* are design intensive and team oriented, requiring dedicated space for periods of time ranging from a full semester to a year. Advanced design-implement projects involve several disciplines and result in a product or prototype consisting of varying amounts of hardware and software. These projects typically take place in the later part of the curriculum and are usually conducted by teams of 10–15 students.
- *Collaborative design projects* are those conducted in collaboration with other universities, government, or industry. Projects may be a response to a collaborator's needs, or a partnership in which team members are all working on various segments of the same system. This mode is communication intensive and requires real-time data, voice, and video communication.
- *Extracurricular design project*s are typically aimed at building something for competition, such as human-powered aircraft, robotic helicopters, or solar cars. Teams come from several engineering disciplines and require office space, design space, building and testing space, storage space, and after-hour access to the facilities. These one-year to multi-year projects typically involve teams of 5–20 people and result in operational prototypes of significant size and complexity.
- *Test and operate* modes are intended to teach students about the operational concepts of engineering systems by giving them hands-on experience in testing and operation. This mode requires personnel dedicated to the maintenance and

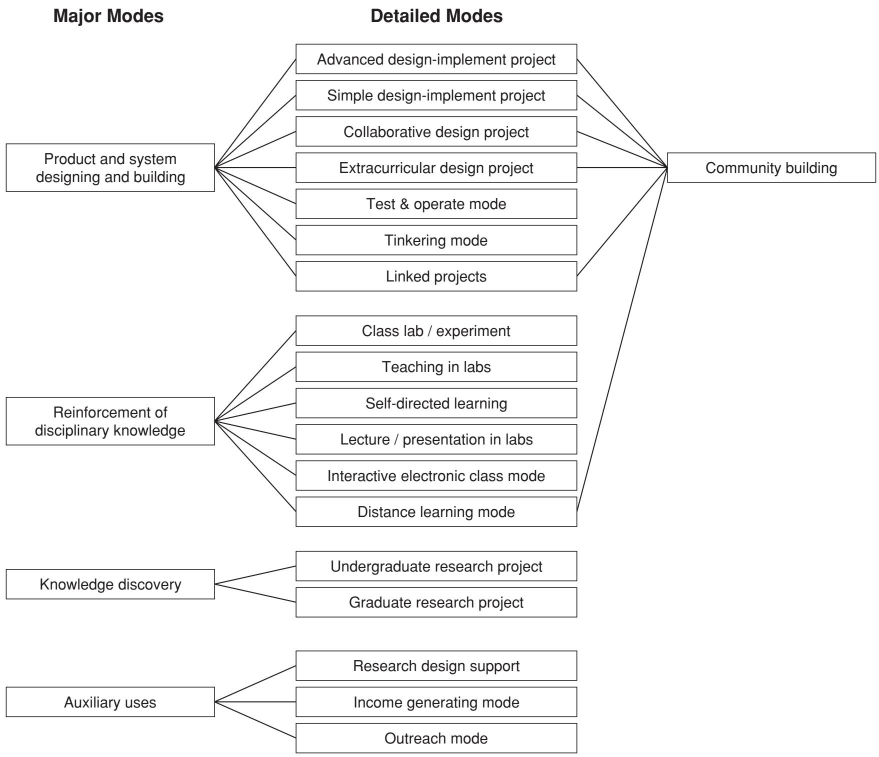

Fig. 5.4 Teaching and learning modes in engineering workspaces

operation of the systems, long-term dedicated space for equipment, and often real-time communications with other departments or sites.

- The *tinkering* mode is for individuals working on projects in their spare time. These projects typically require the use of shop equipment, tools and work surfaces, and happen any time workspaces are open.
- *Linked projects* are longer-term interdisciplinary projects between several sections of the department and/or the university. The projects can connect several courses within a program. For example, an autonomous ground vehicle project may require mechanical prototyping and fabrication using metalworking machines, computer-aided design software for mechanical layouts, computer tools for software generation, and hardware testing. Linked projects can also connect different programs, involving teams of students in different specializations working together and contributing their expertise from their respective disciplines. The interdisciplinary nature of this mode requires spaces for meetings, work, storage, and formal presentations.

The variety of modes strongly suggests the need for careful consideration of the links between the curriculum and workspace design and the need for both short-term and long-term flexibility.

Reinforcement of disciplinary knowledge. Engineering workspaces are designed to strengthen students' disciplinary knowledge by providing support for hands-on active learning strategies that engage students directly in thinking and problem solving activities. (Active and experiential learning are described in more detail in Chap. 6.) There are a number of teaching and learning modes in these workspaces that lead to the reinforcement of disciplinary knowledge.

- The *class lab experiment* is the traditional lab assigned by faculty in which students collect and reduce data. They then write reports on the procedure. These labs are usually conducted in teams of two to four students and require bench set-ups or larger fixed installations.
- The *teaching-in-labs* mode is a demonstration of principles and phenomena with equipment that is specific to the lab. Instructors usually give the demonstration. An extension of this mode is the use of electronic classrooms to maximize space and use equipment dedicated to the room, such as networked projection units.
- In the *self-directed learning* mode, students learn engineering concepts and principles on their own. Traditionally, this has meant reading textbooks and doing research in the library. Self-learning now includes educational videos, online interactive tutorials, and other computer-based instructions and guidance.
- *Lecture or presentation* is the standard classroom-teaching mode. Faculty use electronic presentation hardware and software in the classroom for showing course material and simulations that demonstrate theories and principles.
- *Interactive electronic class* is a fully electronic classroom where students are able to do computer-based work in real time with faculty supervision and assistance. Interactive software is used to comment on work, and projection equipment is used to demonstrate examples. Interactive design classes are an extension of this mode.
- *Distance learning* includes videoconference classrooms and broadcast studios in which instruction is delivered to multiple remote sites in real time.

Knowledge discovery. Engineering workspaces can also support student research projects. They do so by making accessible to students a range of equipment usually found only in research labs.

- *Undergraduate research projects* focus on 3rd- and 4th-year student research projects that involve students designing, building, operating, and reporting on experiments with the guidance of faculty advisors. This mode is typically conducted over several semesters, where the first semester is dedicated to background research, and the second to building the apparatus, running the experiment, and reporting results in a formal presentation and document.
- *Graduate research* mode is intended to support a graduate student who needs to establish an experimental set-up for some period of time. The time scale ranges from one semester to several years, requiring that the space be dedicated for that amount of time.

Community building. Engineering workspaces also play a central role in building community among students. In addition to working on their design-implement projects, students use the workspaces to study for disciplinary courses and for informal social functions. These workspaces also provide facilities for student clubs devoted to tinkering, model building, and other extracurricular projects. This is more of an emergent mode that occurs when the previous three modes of use have drawn the students to the workspace, engaged them, and allowed them to interact.

Auxiliary uses. In addition to the teaching and learning modes directly linked to program learning outcomes, there are a number of other auxiliary uses for engineering workspaces.

- *Research design support* mode. Research teams use the design center capabilities of the workspaces for a short time, that is, hours or days, to work through a segment of the research design. This short-term dedication of space supports the research team's design efforts with analytical tools, design tools, communications, and presentation equipment. This mode may be directly supported by the distance-learning mode, where communications equipment is used for meetings with research sponsors.
- The *income-generating external* mode supports external companies who lease the use of specialized experimental facilities. This mode typically lasts for several weeks and requires the dedicated use of the equipment, support staff to operate the equipment, and space. Security of information may be an issue with some companies.
- The *outreach* mode supports public awareness of the engineering programs and workspaces. Tours of the university include workspaces and explanations of programs that use these facilities. Students might host tours of these workspaces for industry representatives and other guests, explaining ways in which the learning environment supports the program. This mode allows students to present their work, reinforces their learning, and facilitates interactions with industry.

Challenges of Engineering Workspaces

Integrated learning spaces can provide significant resources and innovative mechanisms to support engineering education. However they can pose challenges in development and operation. Workspaces can vary significantly with regard to costs, formats, the number of students, and available financial resources [13]. However, four design and operational challenges stand out regardless of scope. Those challenges are summarized below.

1. *The need for a workspace design driven by curriculum and usage modes*
   Young et al. [13] discuss the various usage modes of the workspaces, as presented above. They indicate the multipurpose nature of engineering workspaces and the central role that they can play in the curriculum. The workspaces can also enable initiatives to emerge from among the students in the domains of design, implementation, and experimentation. These students can be involved in the operation of the workspaces, as tutors and as "lead users" to inspire workspace development.

2. *Planning for flexibility in usage modes and for enabling workspaces to evolve over time*
   Workspaces need to be flexible and adaptable to suit the needs of different student groups and projects, and to facilitate upgrading of equipment based on operational experiences. Experience shows that perceived limitations of the workspaces typically concern available floor or storage space rather than missing equipment.
3. *Safety concerns and expanded access for students*
   It is highly desirable to allow access by students 24/7 with entry controlled by internal security measures, such as ID card controls and keys. While usage of clearly hazardous equipment would be kept to normal academic working hours under staff supervision, engineering workspaces can be deliberately designed to provide an environment for group study, socialization, and mixing of students and faculty in both curricular and extra-curricular settings.
4. *Operational scheduling and staffing of the workspace*
   Challenging issues have been identified in the operation of engineering workspaces. As the attractiveness of the workspace becomes understood and the demand grows, scheduling during the academic semesters becomes a challenge, particularly during highly congested periods of work that emerge at midterm and end-of-term periods. Acquiring technical staff proficient in a wide number of professional areas who are willing to work closely with numerous students throughout the year is a key enabler for successful acceptance by the students. Close coordination with academic instructors to plan upcoming workspace projects, as well as to manage ongoing projects, requires diligent effort from all parties.

Student surveys show that students respond positively to workshop environments where they have opportunities to conceive, design, implement, and operate engineering products, processes, and systems as part of the curriculum and in extracurricular activities. Students' responses to these workspace initiatives has been uniformly positive at all participating universities. As an example, surveys at MIT show that graduating students in the aerospace program feel that the redesigned workspaces have not only increased their ability to learn disciplinary material, but also increased their positive feelings towards their classmates and their chosen profession.

Summary

A design-implement experience is a learning event in which learning takes place through the creation of a product, process, or system. These learning experiences play a central role in a CDIO approach. In addition to teaching students how to design, build, and test products, processes, and systems, they add realism to engineering education. Students find that design-implement experiences are fun and motivating. They foster students' creative abilities and strengthen their self-confidence. From a learning perspective, design-implement experiences stimulate learning of technical knowledge, link theory to practice, illustrate connections between subjects, and enhance the understanding of engineering science. Design-implement projects also serve as means for teaching personal and interpersonal skills, as outlined in the CDIO syllabus. These educational experiences are highly rated by students, faculty, and industry stakeholders. However, design-implement tasks need to be carefully planned as designated learning events in themselves and also as parts of a planned sequence of design-implement experiences in an integrated curriculum.

Adequate CDIO workspaces significantly add value to the education of engineering students. Students respond positively to workshop environments where they experience the four stages of the product or process lifecycle—conceiving, designing, implementing, and operating. These spaces facilitate activities that encourage the learning of design and implementation skills, reinforce disciplinary knowledge, and lead to discovery and experimentation. These spaces can vary significantly with regard to costs and format, depending on goals, number of students and available financial resources. However, some design issues stand out regardless of scope: the need for a workspace design driven by curriculum and usage modes, planning for flexibility in usage modes and evolution over time, safety concerns and extended access, and operational issues. The benefits include enabling new approaches to engineering education, strengthening of student motivation, and improved student-faculty interaction. CDIO workspaces have been shown to play an important role in building social and learning communities that go far beyond their intended purposes. Design-implement experiences, supported by engineering workspaces, constitute a key part of the integrated curriculum that was presented in Chap. 4. They also support both active and experiential learning, the subject of the next chapter.

Discussion Questions

1. What design-implement experiences do you offer in your current programs?
2. In what ways would you modify current design-implement experiences or create new ones in light of the ideas expressed in this chapter?
3. How would you address the key challenges to creating and implementing effective design-implement experiences?
4. How can your existing learning facilities and workspaces be modified to support a CDIO approach to design-implement experiences?
5. What specific functions would new workspaces serve?
6. How would you maximize workspace utilization and accessibility for the students while managing safety regulations and security issues?

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Chapter 6
Teaching and Learning

Introduction

This chapter broadens and concludes the discussion of the second question central to the reform of engineering education: *How can we do better at ensuring that students learn these skills?* In this chapter, we emphasize the alignment of teaching and learning approaches with the intended learning outcomes. In the curriculum design process, presented in Chap. 4, the program learning outcomes are defined, and courses are assigned responsibility for their contributions to the overall objectives. The next step is to implement this program design at the course level. As mentioned in Chap. 2, the CDIO approach has its roots in experiential learning linked to constructivism and cognitive development theory. We believe that learning activities that are designed to support pre-professional behavior facilitate the integration of necessary professional skills with disciplinary knowledge. Hence, the goal is to create integrated learning experiences that address the learning outcomes related both to professional skills and to the understanding of disciplinary knowledge. Design-implement projects, discussed in Chap. 5, are good examples of integrated learning, but integrated learning is not limited to project-based courses. Integrated learning can be achieved in a wide variety of disciplinary settings. We explore selected examples of teaching and learning methods that are effective in integrating skills development with disciplinary knowledge. Integrated learning experiences and active and experiential learning are fundamental to reaching the educational goals of a CDIO program. Studies indicate that students are more likely to achieve intended outcomes and are more satisfied with their education when they are engaged in such learning methods. The key attributes of these approaches are that

- Planning for integrated learning requires clear specification of intended outcomes related to professional skills (personal and interpersonal skills, and product, process, and system building skills), as well as disciplinary knowledge and understanding.

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- Integrated learning places the engineering instructor at the center of student learning of both the technical discipline and the professional skills, and emphasizes the value and linkages of both parts of the education.
- Active learning, which engages students in manipulating, applying, and evaluating ideas, can be applied also in traditional disciplinary courses and larger class settings.
- Experiential learning engages students in situations that resemble what engineers will encounter in their profession, and includes design-implement projects, case studies, simulations, role playing, and many other methods.

When implementing the CDIO approach to teaching and learning, it is important to take the student experiences and student perspectives into account. This chapter begins by reviewing the results of studies conducted in CDIO programs that describe engineering students' learning experiences, as seen from their own perspectives. It then outlines an approach to course development that builds on the curriculum design process. Then we describe how the integrated learning outcomes can be realized through teaching and learning activities. Examples of active and experiential learning illustrate how skills can be integrated into lecture-based courses, as well as project-based courses. Finally, some key challenges to effective teaching and learning are addressed, including the need for support to enhance faculty competence in teaching and learning. This challenge is addressed again in Chap. 8.

Chapter Objectives

This chapter is designed so that you will be able to

- appreciate the importance of student perspectives on learning and student motivation for learning.
- explain the process of integrating skills with engineering disciplinary knowledge outcomes.
- design courses that are aligned with a CDIO approach.
- give examples of active and experiential learning methods that foster deep understanding of disciplinary knowledge and acquisition of professional engineering skills.
- recognize the benefits and address the challenges of integrated learning and active and experiential learning methods.

Student Perspectives and Motivation

Implementing a CDIO approach in a university engineering program often requires the development of new approaches to teaching, learning, and assessment. It is helpful to examine the learning process from the perspective of learners.

Student Perspectives on Teaching and Learning

To inform the development process, it is often helpful to get input from students on their experiences with existing learning methods. For example, student representatives at Chalmers University of Technology, the Royal Institute of Technology, and Linköping University conducted interviews with 56 of their fellow students. Their aim was to contribute student perspectives on teaching and learning during the planning phases that preceded implementation of a CDIO approach. Such interviews have the potential to identify common concerns in the student learning experience. All interview transcripts were interpreted by the student representatives together with experts on teaching and learning, drawing on research literature on student learning. The study provided valuable insight into students' perceptions of teaching and learning [1]. Moreover, it validated the appropriateness and necessity of reforming the programs. Table 6.1 summarizes recommendations for more effective teaching and learning that were drawn from the interviews.

Not surprisingly, many of the students' recommendations are related to learning assessment and the expectations placed on them. Learning and assessment are, in fact, intertwined. The alignment of assessment with active and experiential learning is addressed more fully in Chap. 7. The survey found that many students expressed concerns about the usefulness and practical applications of theoretical knowledge. Students frequently felt that engineering theory needed to be memorized for exams, and they did not associate theory with problem solving and engineering practice. This view is in stark contrast to the way that instructors see theory as the basis for solving problems and understanding the world.

In the same survey, students pointed out that in response to the perceived demands of the course, their studying led to superficial understanding, poor long-term retention, and low motivation. This indicates that many students adopted a surface approach to learning [2–4], meaning that they studied merely to be able to reproduce the material in order to pass the course. In Chap. 2, factors associated with a surface approach are compared to factors that encourage students to adopt a deep approach to learning. (See Table 2.1) As the students themselves observed, any knowledge resulting from a surface approach is poorly structured and quickly forgotten. The opposite is a deep approach to learning, one in which the student's intention is to understand the material. Here, the resulting knowledge is well structured and tends to be retained in the long term.

The concepts of surface and deep approach to learning are important to bear in mind when designing learning activities. The study showed that for a majority of students, the road to understanding theory is through applications and connections to real-world problems. When students learn theory in relation to practical applications, they are more motivated and they see their education as useful and relevant. This increase in motivation leads to an increase in confidence in their knowledge and skills. As a result, they feel more competent and better prepared for their future roles as engineers.

Table 6.1 Students' recommendations for more effective teaching and learning

1	*Set clear intended learning outcomes relevant to engineering practice*
	Clear intended learning outcomes increase motivation and guide studies. Seeing how the course contributes to professional competence is motivating
2	*Develop teaching activities and assessment tasks that help students reach the intended learning outcomes*
	Motivation is increased when students know why they are asked to engage in learning and assessment activities
3	*Focus on deep working knowledge of basic concepts and provide connections to engineering practice*
	This focus promotes a deep approach to learning, increases motivation, and fosters long-term retention
4	*Prioritize course content*
	"Covering" a topic is not the same as understanding. Reorganizing and reducing content coverage promotes a deep approach to learning and makes for clearer connections among related concepts
5	*Set an assessment task early in the course*
	This helps students get started and gives them an opportunity for an early success. Timely and effective feedback promotes learning and knowing what is expected motivates students
6	*Set assessment tasks regularly during the course*
	Regular feedback is necessary for student learning. Regular monitoring of progress helps students allocate time and keep up with the pace of the course
7	*Establish explicit criteria for assessment*
	Explicit criteria help students focus on the critical aspects of a learning activity or assessment task
8	*Design learning activities with built-in interaction*
	Interaction is a form of active learning, a factor that encourages a deep approach to learning
9	*Make a realistic plan for time requirements in the course and get regular feedback from students on actual time spent. Coordinate deadlines and workload with parallel courses*
	Management of time requirements helps reduce stress levels students experience related to time management issues
10	*Show enthusiasm for the course and its associated learning tasks*
	Faculty enthusiasm enhances the value of the course and encourages students to appreciate its relevance and worth

Student Motivation

CDIO programs integrate the learning of professional engineering skills with disciplinary knowledge through active and experiential learning methods. Through the implementation of the CDIO approach to learning, engineering programs can become more attractive to students. Students find meaning, motivation, and personal development in learning experiences that result in conceptual understanding, in developing engineering skills and attributes, in working with real problems in context, in aligning education with professional practice, and in a purposeful approach to engineering in society [5].

In many western countries, engineering education faces serious problems in attracting prospective students, in particular, female students. Engineering as a career is perceived not to accommodate personal development and passion in work. The ROSE study [6] shows that while secondary school students rate it highly important to work with "*something I find important and meaningful*" (females more than males) and agree that science and technology are "*important for society*", they give low ratings to "*I would like to get a job in technology*" (females less than males). In developing countries, the picture seems to be better because engineering is still associated with growth and progress in the economy and society.

The attractiveness of the educational experience in itself is of particular importance for students who have not traditionally chosen engineering as a field of study or as a career, and who may not be perceived by their environment as "typical" engineering students. Although improving, engineering education has a long tradition of being a predominantly male environment with underrepresentation of women and ethnic minorities. In selecting active and experiential learning methods, we need to be sensitive to the ways in which we can help all students to thrive and succeed. Making engineering education attractive is not so much a matter of correcting student perceptions as it is about developing learning experiences in engineering programs and leading change processes in our institutions [7]. Changes brought about by CDIO programs can be positive steps toward an engineering education where all students can flourish.

Integrated Learning

As mentioned earlier, integrated learning is a key feature of CDIO programs in that students learn professional engineering skills together with disciplinary knowledge. With integrated learning experiences, faculty can be more effective in helping students apply disciplinary knowledge to engineering practice and can better prepare students to meet the demands of the engineering profession. While Standard 3—Integrated Curriculum emphasizes a systematic plan to integrate skills learning outcomes into a program, Standard 7—Integrated Learning focuses on the implementation of that plan in each of the program's courses. Standards 3 and 7 can be seen as two sides of the same coin.

CDIO STANDARD 7—INTEGRATED LEARNING EXPERIENCES

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

Benefits of Integrated Learning

Dual-purpose activities serve as vehicles for developing students' engineering skills while at the same time deepening their understanding of technical knowledge. The rationale for integration is that technical knowledge and professional engineering skills are interdependent and must therefore be developed and assessed together. For example, students' ability to communicate in engineering contexts is deeply embedded in their technical understanding. Engineers should be able to describe and present technical ideas, argue for or against conceptual ideas and solutions, and develop solutions through collaborative engineering reasoning and sketching. It is obvious that such communication skills are inseparable from the expression and application of technical knowledge. In fact, they are as much an indicator of technical understanding as an indicator of communication skills. Learning activities and assessment should therefore be modified to address learning outcomes related to skills simultaneously with those related to disciplinary knowledge.

Development of Skills

To make dual use of learning time, learning activities and assessment methods must adopt new approaches. The CDIO Syllabus is not a table of contents for a body of theoretical knowledge from sociology, psychology, philosophy, or economics, to be learned through lectures and assessed through exams. Students cannot develop skills by listening to lectures. Skills are acquired through repeated practice in cycles of application, feedback, and reflection. Integrated learning requires learning experiences where students are active and develop skills through practical exercises. Later in this chapter, we introduce Standard 8—Active Learning, and provide several examples of learning activities that are conducive to skills development. Many of those activities can be implemented as activities in lecture-based courses. Learning and assessing the most complex engineering skills, such as product, process, and system building skills, is most effective in authentic contexts, that is, in situations that are aligned with the working modes of engineering practice. The design of such learning activities is discussed in Chap. 5.

Integrated Learning Across Multiple Experiences

Many skills need to be taught and assessed in several courses throughout the program because it takes repeated cycles of practice to reach the required level of proficiency. Learning activities should then be sequenced to build upon students' previous experiences rather than starting over in each course or learning experience. In Chap. 4, the curriculum design process addresses the placement of skills in sequenced courses. (See Fig. 4.7) This same sequence forms a framework for planning integrated learning activities. For example, methods of teaching can be coordinated across several courses. Box 6.1 gives an example of the integration of communication skills into the teaching and learning of the disciplinary content in a mechanical engineering program at Chalmers University of Technology.

Box 6.1 Integrated Learning of Communication Skills

In the Mechanical Engineering program at Chalmers University of Technology, oral and written communication skills are integrated into three courses in the first three years of the curriculum: the introductory course in the first year, a design-implement project course in the second year, and as an integral part of the bachelor thesis project at the end of the third year. During the first three years, the development of communication skills is focused mainly on academic writing even though there are strong elements of reflective writing, that is, writing in order to learn. On the Master's level (4th and 5th years of the program), communication skills are further developed with emphasis on improving the learning of the technical content.

The intended learning outcomes are that students should be able to write both technical design reports and scientific reports, to give oral presentations using presentation tools, and to be able to review scientific literature. From the table, we can see that assessment is carried out through feedback on the different activities, where language and communication teachers work together with engineering faculty to assess content, form, and language. On the Master's level (4th and 5th years), communication skills are integrated mainly into project-based courses. However, even in some lecture-based courses, we highlight the importance of effective communication. For example, in a course on Internal Combustion Engines, students give oral reports of their assignments. Feedback is given on the presentation, both on the delivery and on the quality and relevance of slides.

	Introductory Course (1st year)
Integrated task	A technical report and an oral presentation of the group's proposal
Lectures	Technical reports, oral presentations, multimedia, and electronic communication
Discussion	Communication, critical thinking, writing as a method for reflection, form and content of written presentations
Practice	Graphic communication skills (sketching), oral presentation, report writing
Feedback	Feedback on written final report and oral presentations

(*Continued*)

Box 6.1 Integrated Learning of Communication Skills—Cont'd

	Design-Implement Project Course (2nd year)
Integrated task	Same as in year one
Lectures	Communication strategy, multimedia, written communication, oral presentation
Discussion	Workshop on oral presentation, workshop on report writing
Practice	Oral presentation, report writing
Feedback	Feedback on report drafts, reports, and oral presentations
	Bachelor Thesis Project (3rd year)
Integrated task	Combined research and writing process
Lectures	Research methodology, critical evaluation of scientific information, information literacy, writing scientific papers
Practice	Planning reports, final reports, oral presentations
Feedback	Troubleshooting and feedback sessions, feedback on planning reports and final reports, feedback on oral presentations, peer feedback on final reports and oral presentations

—S. Andersson, M. Enelund, Chalmers University of Technology

Course Design Aligned with a CDIO Approach

Planning for integrated learning begins by deciding on the purpose of the course, expressed as the intended learning outcomes. These may already be partly specified in the curriculum design process, as described in Chap. 4, when the contribution of the course in relation to the program goals was negotiated in a process involving faculty, students, and other stakeholders. However, refinement and detailing of the outcomes is the responsibility of each course. The process of explicitly defining and agreeing on the intended learning outcomes is a way to reach agreement on the purpose of the course—an important preamble to course development. Making learning outcomes explicit helps to ensure that they will be taught and assessed. For example, asking students to work in teams does not automatically mean that they will learn effective teamwork skills. Productive learning occurs when activities give students specific opportunities for practice, feedback, and reflection on their experiences and the applications of theoretical concepts. In contrast, when students work in groups to reach disciplinary learning outcomes only, the development of teamwork skills is not part of the intended learning outcomes of that course. The development of teamwork skills is seen as a secondary side effect that may or may not happen. However, when teamwork skills *are* part of the intended outcomes of the course, these skills must be carefully addressed in the course design.

Constructive Alignment: A Model for Course Design

The purposeful relationship between intended learning outcomes, teaching and learning activities, and assessment is known as *constructive alignment* [4], as

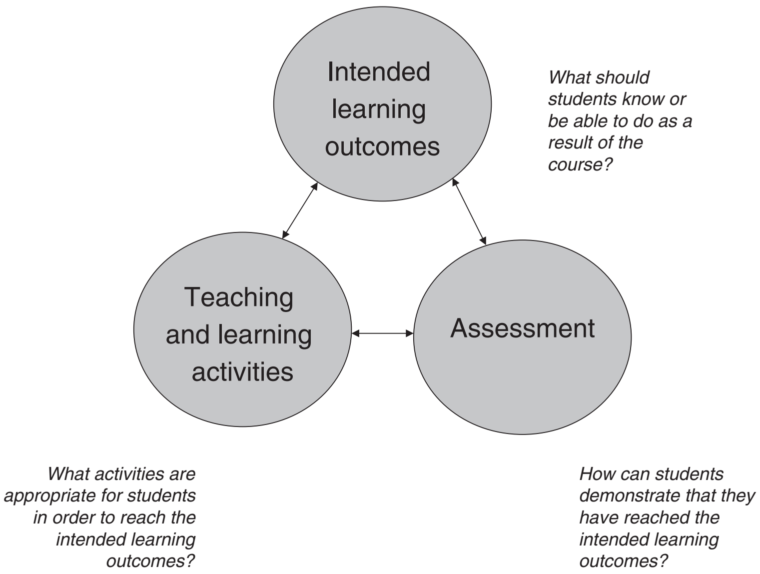

Fig. 6.1 Constructive alignment

illustrated in Fig. 6.1. The constructive alignment concept represents a systems view on courses. The model helps us design the course so it will bring about appropriate learning activity, meaning that the course as a whole should encourage students to take on their studies with a deep approach to learning. This approach is supported by the design of intended learning outcomes, learning activities, and assessment, and the relationship between these course components.

Integrating professional engineering skills into a course means that they are explicitly addressed in the learning outcomes of the course, in the teaching and learning activities, and in the assessment of student learning. In this chapter, we focus on the alignment of teaching and learning activities with the intended learning outcomes of a course. Chapter 7 examines the alignment of assessment methods with intended learning outcomes and with teaching and learning activities.

Specification of Intended Learning Outcomes

Intended learning outcomes describe what the student will be able to do as a result of the course. These outcomes should be observable, that is, it must be possible for students to demonstrate, and faculty to determine, whether and how well the learning outcomes have been met. Therefore, statements of student performance use active verbs and phrases, such as *describe, give examples of, choose, explain in your own words, estimate, calculate, solve, apply, design, interpret, plan, evaluate, modify, decide, sketch, critique.* Examples of such assessable learning outcomes include *"Discuss and determine the statistical validity of data"* and *"Elicit and*

Table 6.2 Feisel-Schmitz taxonomy

Level	Description
Judge	Evaluate multiple solutions, select an optimum solution, evaluate supporting evidence
Solve	Analyze or synthesize to model a system, modify a model of a system, provide assumptions
Explain	State the concept in one's own words, explain the procedure used, discuss the outcome
Compute	Follow rules and procedures, substitute quantities in equations, "plug and chug"
Define	State the definition of the concept or describe in a qualitative or quantitative manner

interpret customer needs." Collecting evidence of demonstrated performance of the intended learning outcomes is the focus of student learning assessment and is discussed in Chap. 7.

Levels of Intended Learning Outcomes

Intended learning outcomes should also hint at the desired level of understanding that students must reach. This is the basis for choosing appropriate teaching, learning, and assessment methods. Classifications of learning outcomes, or taxonomies, are tools for specifying learning outcomes aimed at different levels of understanding. An implication of constructive alignment is that learning activities must be aligned to the intended level of understanding, that is, they must support students in reaching the same desired level of understanding that is reflected in the learning outcomes. As described in Chap. 3, Bloom's *Taxonomy of Educational Objectives* [8] lists six levels of understanding: Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation. Bloom and his colleagues suggested a hierarchical framework from knowledge to evaluation, with each level subsuming the previous ones. (See Table 3.7 for examples of learning outcomes aligned with Bloom's Taxonomy.)

For technical disciplinary courses that focus on problem solving, the Feisel-Schmitz *technical taxonomy* [9], may be particularly useful. (See Table 6.2.) Its five levels of understanding include Define, Compute, Explain, Solve, and Judge. This taxonomy makes a highly useful distinction between two levels of problem solving, *Compute* and *Solve*. *Compute* means to follow a known procedure to solve a known type of problem. *Solve* refers to a higher level of problem solving in which an element of modeling, or synthesis of knowledge, is required, and thus a higher level of conceptual understanding is implied. The hierarchical nature of the taxonomy means for instance that students can reach the level of *Compute* without being able to *Explain*, while *Solve* includes all the underlying levels *Explain, Compute,* and *Define*.

Examples of Intended Learning Outcomes

To summarize, intended learning outcomes should be stated in terms of observable performances and should indicate the level of understanding students are meant

Table 6.3 Examples of intended learning outcomes related to specific topics in the CDIO Syllabus

As a result of this learning experience, you should be able to …	Relates to CDIO Syllabus:
Explain, at a level understandable by a non-technical person, how jet propulsion works	1.3 Advanced engineering fundamental knowledge, methods, and tools
Compare experimental data to available models	2.2.3 Experimental inquiry
Formulate solutions to problems using creativity and effective decision making skills	2.4.3 Creative thinking
Analyze the strengths and weaknesses of the team	3.1.2 Team operation
Emphasize main points and clarify the relationship between ideas	3.2.6 Oral presentation
Appraise the operation system for your team's product and recommend improvements	4.6.4 System improvement and evolution

to demonstrate. Further, the learning outcomes for a course should be realistic with regard to student time and resources. Table 6.3 gives examples of intended learning outcomes that are used in CDIO programs, and their relationship to corresponding topics in the CDIO Syllabus, that might be assigned to a course.

Active and Experiential Learning Methods

Active learning methods engage students directly in thinking and problem-solving activities. There is less emphasis on passive transmission of information and more emphasis on engaging students in manipulating, applying, analyzing, and evaluating ideas. By engaging students in thinking about concepts, particularly new ideas, and requiring some kind of overt response, students not only learn more, but they also recognize for themselves what and how they learn. Such metacognitive awareness supports students' motivation for the learning task at hand, and can also contribute to fostering habits of lifelong learning. Active learning is further considered *experiential* when students take on roles that simulate professional engineering practice, such as, design-implement projects, simulations, and case studies. CDIO Standard 8 addresses the need for active and experiential learning.

CDIO Standard 8—Active Learning

Teaching and learning based on active and experiential learning methods.

Active learning is known to support a deep approach to learning [2–4]. As explained earlier in this chapter, a deep approach to learning means that students intend to seek meaning, as opposed to simply reproducing the information on an exam. Active and experiential learning methods influence the approach that students are likely to adopt. When students are given an active role in their own learning, they learn more, and this is precisely because they are more likely to take a deep approach to learning. Students who are actively involved in their own learning make better connections, both with past learning and also between new concepts [4].

Inherent in any active learning method is the fact that students actually *do* something. However, as Gibbs [3] puts it, “doing is not sufficient for learning.” The whole point of activity is to give students opportunities to explore new concepts, take on new problems, or try new ways of working, and then to reflect on these experiences, in order to improve their performance in an iterative cycle. Thus, a learning activity is appropriate if it supports students in reflective practice, and the key component for evoking productive reflection is feedback. Feedback can, of course, be given to each individual student by the instructor, but from a teaching perspective it may be more cost-effective to use group-, peer- and self-feedback methods. It may even be more conducive to learning to apply well-implemented peer feedback methods, since students learn from both giving and also receiving feedback. Feedback directed at the student as a person, e.g., praise, contains little useful information, and is therefore unlikely to be effective in supporting learning [10]. Feedback is most effective in supporting deep mastery of tasks when it is directed at the *process* used to complete a task rather than on how well the task is performed, and when it is directed at the student’s self-regulation.

Active Learning Methods

Active learning methods help students make connections among key concepts and facilitate the application of this knowledge to new settings. These methods can be incorporated into all types of courses, including traditional large-group lecture-based courses. Methods that are suitable for improving learning in lectures include muddy cards [11] and peer instruction [12]. Student-led recitations [13] also improve students’ preparations in problem solving outside scheduled hours.

Muddy cards. Muddy cards, also known as Muddiest-Point-of-the-Lecture cards, help to gather in-class feedback to determine gaps in student comprehension [11]. Near the end of a lecture or other learning experience, students are asked to reflect on what they have learned. They write down the concepts or ideas—the point—they found the muddiest, that is, the most unclear. The instructor collects the cards for later review. Muddy points can be addressed in a number of ways: posting questions and answers on the course website, answering questions at the start of next class meeting, distributing printed copies of answers to the most common muddy points, or sending email responses to the class. Instructors who use muddy cards have experienced many benefits from using them. Muddy cards provide time for student reflection, with a consequent increase in learning retention. Writing their questions and comments helps students to organize their thoughts and study more effectively. Moreover, the cards provide information to the instructor in time to correct misconceptions by the next class meeting and to assist in improving the course for the next offering. Despite the fact that muddy cards can require a large commitment of time—particularly the first time they are used—many instructors have found them very useful both as an active learning method and as an assessment method.

Peer instruction. Peer instruction is promoted by Harvard Professor Eric Mazur [12] to improve students' understanding of the underlying concepts of the subject. In lectures, students are asked to respond to multiple-choice questions. Some of the inaccurate answers map to known common misconceptions, which often exist due to conflicting naïve preexisting conceptions. Peer instruction allows students to actively put their mental models to the test and obliges them to confront any discrepancies.

The peer instruction cycle is implemented in five steps:

1. A problem with multiple-choice answers is displayed, and students are given time to think it over.
2. Students record their answers, using for instance show of hands, flash cards, or an electronic response system.
3. When there is disagreement within the group, students are given a few minutes to convince their neighbors (peer instruction) of their answer choice. The intent is that students think for themselves and practice ways to express their understanding in words.
4. Students record their revised answers.
5. The instructor leads a discussion on ways of reasoning and arguing in relation to the problem.

Asking the students to respond to these questions represents a method for actively probing students' conceptual understanding in order to generate feedback for himself or herself and for the instructor. The active mental provocation inherent in the method lies in stark contrast to the situation where students are passively listening to lectures. There, misconceptions are seldom exposed, either to the instructor or the students themselves. With peer instruction, this monitoring is done in real-time, instead of waiting until the exam to discover any problems. Peer instruction is a way to use a social situation that exposes variations in thinking and reasoning.

Results show that peer instruction is a very effective way of improving students' conceptual understanding by confronting misconceptions and by practicing their ability to reason conceptually. Further, students' increased conceptual understanding leads to improved performance also in conventional problem solving. The effectiveness of peer instruction lies in its pedagogical approach, which does not necessarily require an electronic response system.

Quizzes for reflection. Quizzes can be used in the beginning of a lecture to help students recapitulate a previous lecture. This method was developed at Chalmers University of Technology in an attempt to enhance active reflection, using fewer resources than muddy cards [14]. It is related to peer instruction in that it uses five or six multiple-choice questions that students discuss with their peers. However, there are several differences. Students spend about seven minutes at the beginning of the lecture discussing the questions. They may collaborate with others and use their study notes. The instructor concludes by explaining why each choice is either correct or incorrect. This approach has been shown to be successful. Students take different approaches to the quizzes: some engage in discussions, some prefer to review their notes privately, while others enjoy the competition of getting the correct answers. "*The best part was the moment we understood why a wrong answer was wrong*" was one of quotes from students that indicated that they were taking a deep approach to learning. One student said that the quizzes made it possible for her to relax and understand without getting into a state of extreme anxiety. Exam results have been affected positively by these quizzes.

Student-led recitations. Student-led recitations are appropriate in many basic engineering courses where the focus is on problem solving. They are used at the Royal Institute of Technology (KTH) in Stockholm to enhance tutoring sessions in groups of up to 20 students [13]. For each weekly recitation session, all students are asked to work through a set of problems. At the session, the students tick on a list which problems they are willing and prepared to present. The instructor starts by randomly selecting a student from the list to present the solution to the first problem on the board; thereafter, a second student solves the next problem, and so on. As the purpose of this activity is a purely formative one, the quality of the presentation does not affect the grade, but students are required to tick 75 % of the problems in order to pass the course. The rule is that the selected student must demonstrate that he or she has made an honest effort in preparing the problem, so even if the solution is wrong, the student must be able to lead a classroom discussion to a satisfactory solution. Otherwise, this student's ticks for that recitation session are erased. At KTH, students react positively to this active learning method, and they often comment in course evaluations that the method really helps them to learn.

Student-led recitations promote effective learning for several reasons:

- Preparing the weekly problems makes students spend time on the task. For every problem presented by one student, up 20 students have worked on solving the problem. Interviews show that students spend six to seven hours in preparing for each student-led recitation, often in groups where they can rehearse the problem-solving presentations. Another positive effect is that the study time is spread out regularly during the whole course.
- This method generates appropriate learner activity. It is not sufficient to solve the problems only in order to arrive at the right answer. Since students must also be prepared to present their solutions in class, they are obliged to reflect on how to explain their methods and argue for their problem-solving strategies. Using the terminology of the Feisel-Schmitz taxonomy (Table 6.2), this learning activity raises what the students do from the *Compute* level to *Explain*. They are, therefore, more likely to reach learning outcomes at a deeper level of understanding.
- This active learning method provides immediate feedback for all students, and often leads to good discussions on alternative solutions. The role of the

instructor is to encourage a good discussion, by providing triggers such as "Did anyone solve the problem in a different way?", "In what way is this problem different from a similar one we had last week?", or "I see that not so many have ticked this one, where did you get stuck?" Because students have worked on the same problems that others present, they are able to follow the problem-solving approaches, even when a presentation is less than perfect.

- Student-led recitations take advantage of a social dimension that creates strong student motivation. Since these social forces are very strong, it is important to create a safe and friendly emotional climate.

Experiential Learning Methods

As defined earlier, experiential learning engages students by setting teaching and learning in contexts that simulate engineering roles and practice. Experiential learning methods include project-based learning. In a CDIO approach, this entails the design-implement experiences that are the focus of Chap. 5. These methods are based on pedagogical theories of how students, especially engineering students, learn and develop cognitive skills. The CDIO approach to engineering education is based on experiential learning theory. The learning cycle, proposed by Kolb [15], provides helpful insights for planning teaching and learning activities. One such planning application is illustrated in Fig. 6.2.

In the CDIO approach, the experiential learning cycle is entered at different points. Lecture-based courses that incorporate active learning begin with reflective observation to stimulate learning because students have a common base of experience. Lectures may also begin with abstract generalization and conclude with active experimentation, for example, problem sets or exercises. The introductory engineering course provides the first concrete experience in engineering, creating the cognitive framework for subsequent learning of theory. In design-implement experiences, concrete experiences are the entry point to the experiential learning cycle. Students engage in tasks similar to real engineering practice, reflect on what they have learned from these experiences, generalize their learning to develop abstract ideas and principles, and test these new ideas with active experimentation and application to other problems. Embedded experiential learning throughout the curriculum provides opportunities for reinforcement. The capstone experience provides opportunities to apply theory and to build students' confidence in engineering.

Project-based learning. Project-based learning is built on authentic, or real world, situations or problems for which a solution is sought or created. For the most part, a CDIO approach does not follow a fully problem-based project-organized curriculum, as does for example Aalborg University in Denmark [16]. However, it is common to use several project-based learning activities in an existing, mainly discipline-based, curriculum framework. Faculty identify problems that encompass the concepts and principles relevant to the content domain, and they design authentic tasks in which the thinking required is consistent with the thinking in an engineering

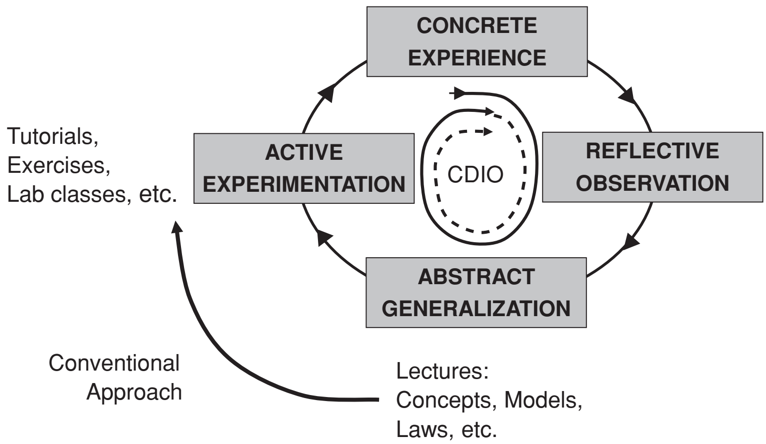

Fig. 6.2 Experiential learning model (adapted from Kolb [15])

environment. The design-implement experience, described in Chap. 5, is a specific type of advanced problem-based and project-organized learning activity. The task and environment reflect the complexity of engineering environments and encourage students to test their ideas against alternative views and contexts. Projects provide opportunities for reflection on both the content and the learning process itself.

Insructors have found that project-based learning increases student motivation and improves students' ability to apply engineering knowledge and skills to real-world problems. However, for the inexperienced instructor the transition to project-based courses is often perceived as demanding. Many departments have a deeply rooted culture of conventionally taught lecture courses, and may quickly discover that it takes a great deal of effort to increase the use of, and competence in, new teaching and assessment methods. The competence required from faculty often transcends a purely disciplinary science background, simply because engineering problems rarely respect disciplinary boundaries. Most of all, this approach requires a change in expectations of faculty, from lecturing a body of relatively static knowledge to facilitating student development of skills and application of knowledge in much more dynamic contexts. A different teaching and learning format may also make it necessary to reallocate some the resources required to design and monitor learning experiences—people, time, equipment, and space. Some early experiences with project-based learning, including recommendations for addressing perceived barriers for implementation, are outlined in a report that is available on the CDIO website [17].

Simulations. Similar to project-based learning, simulations are activities in which students take on engineer-like roles in the application of engineering laws or principles. Simulations often have specific rules, guiding principles, and structured roles and relationships [18]. The instructor's role in a simulation is (1) to explain the rules, the situation, and the roles students are to take on; (2) to monitor the simulation as it is played out; (3) to help students reflect on the experience; and, (4) to lead a debriefing session. Most simulations are based on computer hardware and software. For example, the aeronautics and astronautics program at the Massachusetts Institute of Technology (MIT) uses a flight simulator to give students practice in piloting in preparation for the design-implement-fly contest of a radio-controlled plane. Instructors who use simulations have found that these learning activities provide students with opportunities to experience engineering tasks in a safer environment than the real situation would require. In addition, students have access to what would otherwise be scarce or inaccessible equipment and facilities.

Case studies. Although case studies have been used primarily in law, business, and medical education, they are equally appropriate for engineering education. A good case tells the story of a real engineering experience, usually from the point of view of the participants. In addition to the narrative, a typical case provides detailed background, such as original calculations and drawings, budget and schedule limitations, the availability of material resources and technical facilities, and the people and organizations involved in accomplishing the task [19]. Through a case discussion, students vicariously experience the activity in the case and are involved in the resolution of problems and issues. The goal is to help students develop independent thinking and decision-making skills through practice. Instructors who use case studies have found that this teaching and learning technique helps students to develop analytic and problem-solving skills, and enables them to explore solutions to complex issues. Moreover, the glimpse at what engineers do provides background information on the history and traditions of the engineering profession. One difficulty that instructors face with the case study approach is finding cases relevant to specific disciplinary content.

Using Multiple Active and Experiential Methods

Many instructors combine two or more active and experiential learning methods in a single course. For example, an advanced course in aerodynamics at MIT combines: peer instruction, readings and problems assigned prior to lecture, and team-based project-based learning. In addition, the course includes oral examinations as a method of student learning assessment. Box 6.2 describes this example.

Box 6.2 Active and Experiential Learning in an Aerodynamics Course

Active and experiential learning methods have transformed an advanced course in aerodynamics at the Massachusetts Institute of Technology. *Aerodynamics* is a 3rd-year undergraduate course with a typical enrollment of 40 students. Prior to 1999, the course was a traditional engineering course with lectures, recitations, weekly homework assignments, a small end-of-semester design project, and written exams. The current course includes several active and experiential learning activities:

(*Continued*)

Box 6.2 Active and Experiential Learning in an Aerodynamics Course—Cont'd

- *Concept-based lectures with real-time feedback*
  In this approach, two or three multiple-choice concept questions are part of each lecture. These questions are designed to include the important concepts of the subject and their common misconceptions. After a few minutes of independent reflection, students use an electronic response system to select an answer. Responses are charted and projected in real-time. Depending on the responses, students discuss their answers with each other or the instructor clarifies misconceptions.
- *Weekly (graded) homework given prior to class lecture and discussion*
  In *Aerodynamics*, students complete homework assignments and related readings prior to in-class discussion. With this preparation, the classroom becomes an interactive environment where students bring a common language to discuss the conceptual difficulties they have encountered.
- *Semester-long, team-based project involving analysis and design of an aircraft*
  In this project-based approach, theoretical knowledge is immediately applied to the complex design of modern aircraft. In addition, the use of a semester-long project provides a context for learning the technical fundamentals. In recent years, two design projects have been developed, one based on a military fighter aircraft, and another on a blended-wing body commercial transport aircraft.
- *Oral examinations*
  Oral examinations take an active approach to assessment of student learning. They provide insight into how students understand and relate concepts. Furthermore, practicing engineers are faced daily with the real-time need to apply rational arguments based on fundamental concepts. By using oral exams, it is possible to assess a student's ability to construct sound conceptual arguments.

End-of-semester student evaluations of the changes in pedagogy and assessment reveal these findings:

- The new pedagogy is consistently rated as highly effective.
- Challenging pre-class homework increases the effectiveness of lecture.
- An increase in learning occurs over the length of the semester as students transition to the new approaches.
- Effective implementation of the team project is difficult.
- Oral examinations are effective in helping the instructor to determine if students have achieved the course learning outcomes.
- Many students find oral exams to be a more accurate representation of their understanding than traditional written exams. In fact, several students have said that the oral exams were the best parts of the course.

— **D. Darmofal, Massachusetts Institute of Technology**

Benefits and Challenges

We have been studying the results of the changes in teaching and learning methods. As a result of integrating skills with disciplinary content and using active and experiential learning, we find that

- Introducing the CDIO approach has deepened, not diminished, students' understanding of engineering disciplines.
- Annual surveys of graduating students indicate that they have developed the intended engineering knowledge, skills, and attitudes.
- Course evaluation results indicate that instructors are using a wider variety of teaching and assessment methods than they were before the university applied the CDIO approach.
- Student self-report data indicate high student satisfaction with the learning experiences.
- Longitudinal studies of students in CDIO programs show increases in program enrollment, decreasing failure rates, particularly among female students, and increased student satisfaction with learning.

Integration of professional engineering skills with disciplinary content, and active and experiential learning methods are not, however, without challenges. Despite evidence to the contrary, instructors sometimes perceive a conflict between disciplinary content and the learning of professional engineering skills. They are sometimes reluctant to reduce the amount of material covered in their courses because subsequent courses depend on a full coverage of topics. Instructors and students alike often resist changes to the ways they are accustomed to teaching and learning. Finally, instructors may lack the expertise to implement active and experiential learning methods. The issue of enhancing faculty teaching, learning, and assessment methods is addressed in Chap. 8.

Summary

Integrated learning makes it possible for students to develop professional engineering skills, while simultaneously deepening their conceptual understanding of disciplinary knowledge. Students who practice and learn engineering in authentic contexts are more satisfied with their learning experiences. In 1st- and 2nd-year courses, they are also introduced to and motivated to learn disciplinary abstractions. In subsequent years, this disciplinary knowledge is reinforced by application and students are empowered by their accomplishments.

Active learning methods, for example, muddy cards, peer instruction, and student-led recitations, engage students in their learning by requiring deliberate mental effort and evoking overt responses. Instructors can adapt a variety of active learning methods to lecture-based and project-based courses and seminars. With experiential learning, such as project-based learning, simulations, and case studies, students have opportunities to take on a variety of engineering roles in increasingly complex learning situations.

A CDIO approach integrates the learning of professional skills with disciplinary knowledge through active and experiential learning methods. Because of this approach to learning, engineering is more attractive to students, especially those students who traditionally have not chosen engineering as a field of study or career.

Together with Chaps. 4 and 5, this chapter provides an answer to the second central question for engineering education: *How can we do better at ensuring that students learn these skills?* We focused on learning outcomes that integrate skills with disciplinary knowledge, and the alignment of teaching and learning methods with these outcomes. Chapter 7 continues this approach with the alignment of student learning assessment methods with the learning outcomes and teaching and learning methods.

Discussion Questions

1. In what ways can you begin to integrate professional engineering skills into your courses?
2. What active and experiential learning methods are used effectively in your courses?
3. How can you find out more about your students' perceptions of their learning?
4. How would you begin to address the key challenges to integrated learning and active and experiential learning posed in this chapter?

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Chapter 7
Student Learning Assessment

Introduction

The last three chapters have discussed answers to the second of the two questions central to the reform of engineering education: *How can we do better at ensuring that students learn these skills?* Integrated curriculum, design-implement experiences, integrated learning, and active and experiential learning are the main components of a reformed engineering education that better ensures that students reach the intended outcomes required of all engineering graduates. Implicit in the question *"How can we do better…"* is an additional question: *How do we know that we are doing better?*

- How do we know that students are achieving the intended learning outcomes?
- How do we know that our engineering programs are effective?

We answer the first part of the question in this chapter on student learning assessment, and then return to address the second part of the question later in Chap. 9 on program evaluation. Student learning assessment measures the extent to which each student achieves specified learning outcomes. Faculty members plan and implement student learning assessment with respect to the outcomes within their courses. In contrast, program evaluation examines the key success factors of CDIO programs in terms of both the overarching student learning outcomes and the adoption of the CDIO Standards.

Learning is assessed before, during, and after instructional activities. Formative assessment collects evidence of student achievement while students are in the process of learning. Results of formative assessment inform students about their progress, help monitor the pace of instruction, and indicate areas of instruction that may need to be changed. Summative assessment gathers evidence at the end of an instructional event, such as a major project, a course, or an entire program. Results of summative assessment indicate the extent to which students have achieved the intended

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learning outcomes of the project, course, or program. If the instructional event will be repeated with other students, summative assessment is used to improve curriculum, teaching and learning methods, and the design and use of learning spaces.

Assessment of student learning in personal and interpersonal skills, in process, product, and system building skills, and in disciplinary knowledge has four main phases:

- Specification of learning outcomes.
- Alignment of assessment methods with curriculum, learning outcomes, and teaching methods.
- Use of a variety of assessment methods to gather evidence of student achievement.
- Use of assessment results to improve teaching and learning.

The importance of specifying learning outcomes and aligning them with teaching and learning has been highlighted in previous chapters. The focus now is on assessment methods appropriately matched to curriculum and teaching methods. Effective learning assessment is aligned with intended learning outcomes, that is, the knowledge, skills, and attitudes that students are expected to master as a result of their educational experiences.

We use a variety of methods for collecting evidence that students are achieving intended learning outcomes, such as, written and oral questions, observations, product reviews, journals, portfolios, and other self-report measures. These methods can collect evidence of student progress and achievement in a variety of teaching and learning environments. Gathering data and evaluating information from multiple and diverse sources make it possible to know with confidence what students have learned. However, the learning assessment process is not complete until assessment results are used to improve students' educational experiences.

In this chapter, we emphasize the idea that in a culture that is cooperative, collaborative, and supportive, learning assessment is used to diagnose and promote learning. Teaching and learning are intertwined, and students and instructors learn together. We look, in detail, at the learning assessment process, describe selected assessment methods, and give examples of student learning assessment in representative programs. Finally, we identify key challenges to effective learning assessment and point the way to addressing these challenges.

Chapter Objectives

This chapter is designed so that you can

- explain what is meant by a learning assessment process.
- align assessment methods with intended learning outcomes and teaching and learning methods.

Table 7.1 Teaching-centered versus learner-centered assessment

• Teaching and assessing are separate	• Teaching and assessing are intertwined
• Assessment is used to monitor learning	• Assessment is used to promote and diagnose learning
• Emphasis is on right answers	• Emphasis is on students' generating better questions and learning from their errors
• Desired learning is assessed indirectly through the use of objectively scored tests	• Desired learning is assessed directly through papers, projects, performances, etc
• Culture is competitive and individualistic	• Culture is cooperative, collaborative, and supportive
• Only students are viewed as learners	• Professors and students learn together

- describe a variety of assessment methods that provide evidence of student learning.
- use assessment results for the continuous improvement of learning experiences.
- describe the key benefits and challenges to sound learning assessment.

The Learning Assessment Process

In a traditional view, assessment is regarded as separate from teaching. Many instructors believe that time devoted to assessment takes away from "teaching" time; students often regard assessment with dread and intimidation. In contrast, a CDIO approach views assessment as learner-centered, promoting better learning in a culture where students and instructors learn together. Table 7.1 is a comparison of teaching-centered assessment and learner-centered assessment, based on the work of Huba and Freed [1].

Assessment is learner-centered in that it is aligned with 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. This student learning assessment is the focus of Standard 11.

STANDARD 11—LEARNING ASSESSMENT
Assessment of student learning in personal and interpersonal skills, and product, process, and system building skills, as well as in disciplinary knowledge.

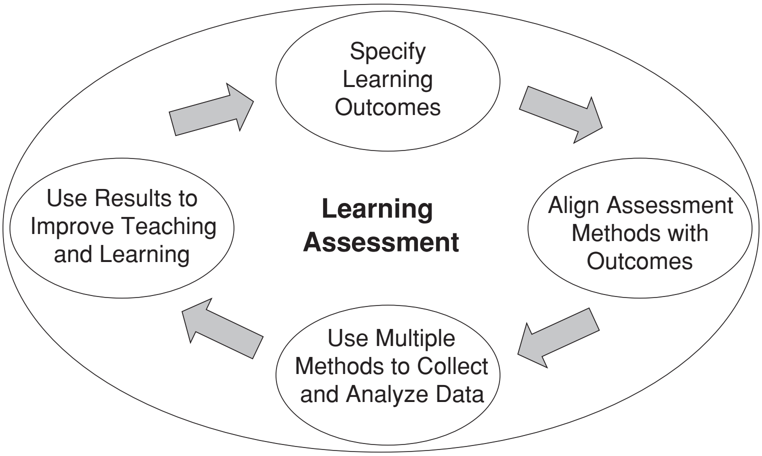

Fig. 7.1 Student learning assessment process

The process of assessing student learning has four key phases: the specification of learning outcomes, the alignment of assessment methods with learning outcomes and teaching methods, the use of a variety of assessment methods to gather evidence of student learning, and the use of assessment results to improve teaching and learning. Figure 7.1 illustrates a process of learning assessment that can be implemented in any educational program. The unique characteristics of student learning assessment in CDIO programs are related to the nature of the learning outcomes and their integration into the curriculum.

In most engineering programs, learning assessment focuses on disciplinary content. While this focus continues to be important in a CDIO approach, an equal emphasis needs to be placed on assessing the personal and interpersonal skills, and the product, process, and system building skills that are integrated into the curriculum. A single assessment method will not suffice to gather evidence of the broad range of learning outcomes.

Assessment of student learning begins with the specification of learning outcomes that students will achieve as a result of instruction and related learning experiences. Personal and interpersonal skills, product, process, and system building skills, and the disciplinary knowledge upon which they are based, comprise the overarching learning outcomes. In Chap. 3, we described the process of deriving learning outcomes from the CDIO Syllabus. (See Table 3.8) Once the learning outcomes are clearly stated, they are integrated into the curriculum, and sequenced for appropriate learning experiences. Chapters 4, 5, 6 describe this integration and sequencing in more detail. Just as different categories of learning outcomes require different teaching methods that produce different learning experiences—notably active and experiential learning approaches—they also require different assessment methods to ensure the reliability and validity of the assessment data. The next sections of this chapter address the second, third, and fourth phases of the learning assessment process.

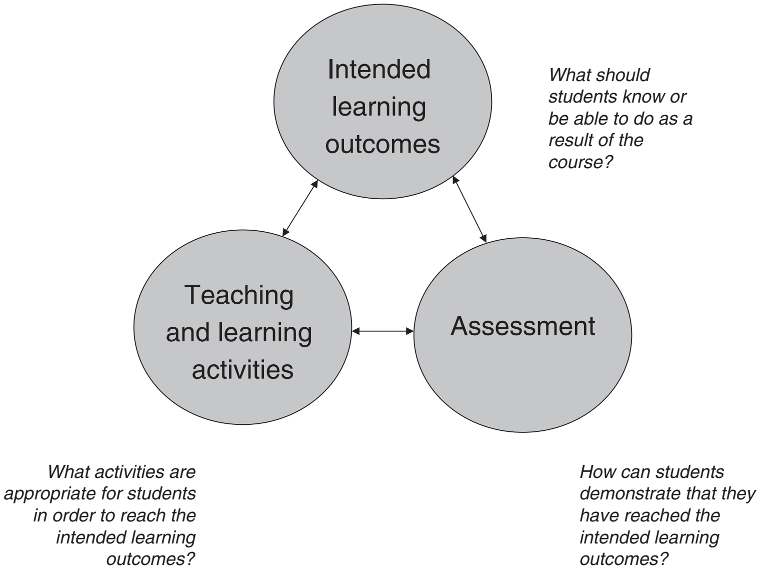

Fig. 7.2 Constructive alignment

Aligning Assessment Methods with Learning Outcomes

In the previous chapter on teaching and learning methods, we described the concept of *constructive alignment* [2]. There, we looked at ways in which teaching and learning methods are aligned with intended learning outcomes. Here, we highlight the importance of aligning learning assessment methods with the intended learning outcomes (Fig. 7.2).

In some cases, the teaching methods and the assessment methods may be the same for a specific learning outcome. For example, students learn how to give effective oral presentations by practicing them. To assess whether or not they have achieved the intended learning outcome, we observe them as they give oral presentations. This is an example of performance assessment.

Methods for Assessing Student Learning

The third phase of the student learning assessment process, as illustrated in Fig. 7.1, is the use of multiple methods to collect and analyze data. Traditionally, assessment in engineering courses takes the form of written examinations, occurring usually at the end of the term. In contrast, student learning assessment in a CDIO approach uses a variety of methods to collect evidence of learning before, during, and after learning experiences to give both formative and summative views of the changes that have occurred in students' achievements and attitudes.

Some assessment methods, when used during learning experiences, are effective as *teaching* methods, as well. For example, concept questions are effective both for learning new concepts and for giving instructors feedback on student learning. Evidence of student learning is gathered with written and oral questions, performance ratings, product reviews, journals, portfolios, and other self-report instruments. Criteria and standards of performance, incorporated into rating scales and rubrics, are used to assess the quality of student learning and achievement. We now look at a few of these assessment methods and give examples from our programs.

Written and Oral Questions

Most engineering instructors are familiar with written examinations that include multiple-choice and other closed items, calculations, and open-ended questions. Instructors are encouraged to map their written examination questions to course learning outcomes and to examine students' achievement in light of these outcomes. Written examinations continue to be effective and efficient means to assess students' conceptual understanding. A large number of students can be assessed in the same time period and there is documentation of student achievement. However, good questions are difficult to construct, and students' answers do not always reveal the causes of their errors or the sources of their misconceptions. Oral questions, on the other hand, enable faculty to uncover students' misconceptions. Oral examinations require that students think on their feet and speak coherently. The use of oral exams, in conjunction with in-class concept questions, was described in Chap. 6 in the example of an aerodynamics course at MIT (See Box 6.1).

In both written and oral exams, instructors can use concept questions to determine students' deeper level of understanding of disciplinary content. The use of concept questions is an example of a method that can be appropriate both for teaching and for assessment (See the work of Eric Mazur of Harvard University for examples of how to use concept questions for learning and assessment.) [3]. Box 7.1 describes the use of concept questions to measure conceptual understanding in mechanics and mathematics at Chalmers University of Technology. The concept questions formed the second part of a longitudinal study that followed students over a three-year period.

Box 7.1 Excerpt of a Longitudinal Study of Students in Mechanical Engineering at Chalmers

The mechanical engineering program at Chalmers University of Technology conducted a study using the *Force Concept Inventory*, a well-known survey for testing students' understanding of basic physics concepts. [a] The FCI is more specifically designed to assess students' understanding of basic concepts in Newtonian physics, although it can be used for a variety of purposes and in many different contexts. The study compared the FCI survey completed in January 2002, with a second one completed in the Fall of 2002, when students were in their second year of the mechanical engineering program. Students were also asked conceptual questions about their understanding of physical concepts.

The following year, another study focused on mathematical modeling, that is, students' ability to use mathematics in applied situations. Students were given a well-known and frequently used mathematical modeling test, constructed by researchers in Australia, England, and Ireland, to collect evidence of growth in mathematical modeling competencies. [b] The modeling test was given twice, first in September 2003, when students had just started their third year of studies in the mechanical engineering program. The second survey was completed in February 2004, with the students in the second half of their third year.

Results of these longitudinal studies indicated that students in mechanical engineering showed increases in conceptual understanding of physics, mathematics, and mechanics from pre-test to post-test. Furthermore, the *Force Concept Inventory* and the mathematical modeling tool proved useful in assessing students' achievement of learning outcomes related to disciplinary knowledge. The study showed differences in results by gender, but these differences could not be adequately explained in the context of the study. Further investigations are planned to determine which contextual factors affected the results.

[a] Hestenes, D., Wells, M., and Swackhammer, G., "Force Concept Inventory," *The Physics Teacher*, vol. *30*, 1992, pp. 141-151.

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Observations and Ratings of Student Performance

Many intended learning outcomes can be assessed by observing students in the performance of specific tasks, for example, oral communication and teamwork. Instructors, lab supervisors, industry experts, project sponsors, evaluation specialists, and the students themselves can all take part in observing and rating student

Table 7.2 Sample rubric to assess technical briefings and oral presentations

	Poor	Fair	Good	Very Good	Comments
Presentation quality					
Main objective of presentation is clearly stated					
Presenter maintains good eye contact with the audience					
Presenter uses voice effectively (volume, clarity, inflection)					
Presenter is poised and professional (appearance, posture, gestures)					
Transitions to the next presenter are smooth and effective					
Technical content					
Technical content is accurate and significant					
Technical content shows sufficient development					
Main points are emphasized and the relationship between ideas is clear					
Ideas are supported with sufficient details and clear drawings					
Graphics and demonstrations are effectively designed and used					
Alternatives are presented with a rationale for those selected					
Key issues are addressed					
Questions are answered accurately and concisely					

Overall comments:

performance. Increasing the number of observations and the number of observers leads to assessment that is more reliable and valid. Rating scales and rubrics can facilitate the observations and the recording and analysis of assessment data.

A rubric is a list of criteria that define the quality of a performance, process, or product, with a scale that reflects degrees of quality. In addition to their value to faculty, they convey expected performance to students. Since the same criteria are applied across the entire class, students often feel that assessment is fair and more objective [4]. Rubrics are efficient means of recording observations and judgments, but their construction is time consuming and challenging.

Fortunately, examples of existing rubrics can be found in journal articles and conference proceedings of engineering education organizations. Table 7.2 is an example of a rubric that is used in some CDIO programs to rate the quality of students' technical briefings and oral presentations. Note that observers are asked to rate students' understanding of technical information, as well as their ability to present their ideas clearly and professionally. The sample rubric shown in Table 7.2 is an example of an analytic rubric. Here, the criteria are specified in some detail in the left-hand column. The evaluator makes a judgment about the quality of each criterion separately. In contrast, a holistic rubric starts with the gradations of quality, and describes in detail what, for example, a very good presentation would look like, with additional descriptions for each level of quality.

Product, Process, and Project Reviews

Similar rubrics can be used to assess student products and projects. One of the key differentiating factors of a CDIO program is its emphasis on design-implement experiences. Students need to demonstrate their ability to conceive, design, implement, and operate products, processes, and systems. The assessment can be conducted by judging the demonstration of the process or reviewing the physical product, for example, an artifact, report, or computer drawing. Box 7.2 gives an example of a rubric that was designed and implemented at Queen's University Belfast to assess learning in a design project module. The emphasis of this assessment is on process.

BOX 7.2 PROJECT DESIGN REVIEW AT QUEEN'S UNIVERSITY BELFAST

The rating form embodies criteria designed to assess students' learning related to the project module outcomes. Project supervisors observe students and complete these forms.

The performance of the student during the course of the project will be assessed on the skills outlined in the table below. The supervisor is expected to rate the student's performance using the following scale:

Project Learning Outcomes	Unsatisfactory	Satisfactory	Good	Excellent
Communicated effectively in writing, verbally, and through graphic media				
Managed time, resources, and priorities, and worked to given deadlines				
Used computers and information technology effectively				
Located and assembled information using various external resources				
Demonstrated generic problem-solving skills acquired during project				
Worked and learned independently				
Worked safely				
Communicated effectively with technicians and other support staff				

—R. KENNY, QUEEN'S UNIVERSITY BELFAST

If the emphasis of the assessment is on engineering products, criteria related to project design, implementation, and operation can be added to the rating scale. Examples of these criteria include:

- Problem solution (or the product) demonstrates advanced technical understanding.
- Problem solution demonstrates technical originality.
- Problem solution fulfills the customer requirements.
- Digital models are relevant and sufficiently complex.
- Digital models are used to improve the product.
- Physical models communicate and improve the product.

A brief mention should be made here about *peer assessment*, that is, students assessing each other. Peer assessment most often occurs in the context of performance ratings and product reviews. For example, in the rubric in Table 7.2, students are given the rubric and asked to rate the oral presentations of members of their team or other class members. Of course, peer assessment does not have to be recorded with rubrics. In some programs, each student team is assigned the task of critiquing, both orally and in writing, the performance and products of at least one other team in the class.

Journals and Portfolios

Journals and portfolios provide records of students' individual and collaborative efforts in design-implement projects, and experimental research. They reveal students' critical thinking and reasoning skills, and record the steps students followed in an engineering process. These documents provide evidence of student achievement in situations where there may be no final tangible product. Moreover, journals help to distinguish individual contributions to group projects and activities. Although journals and portfolios take time to read and evaluate, they are most effective when students receive regular feedback. Table 7.3 is an example of a holistic rubric that can be used to assess journals or reflective portfolios.

Other Self-Report Measures

Other self-report measures, such as inventories and questionnaires, help students to develop a sense of themselves as learners and future engineers. Asking students to reflect on their learning experiences helps them to see more clearly the connections among the concepts they have learned, as well as the applications of these concepts to new situations. When reflections are combined with portfolios that include samples of students' work, they serve as useful tools for assessing individual student achievement and evaluating programs overall.

Table 7.3 Sample rubric to assess a reflective journal

Very good	Required entries are included Entries are dated and identified Observations are descriptive and detailed Interpretations are reasonable and based on evidence Shows an understanding of the engineering process Attention to format, grammar, and spelling
Good	Most required entries are included Entries are dated or identified Observations are descriptive Some reflection is evident Interpretations are reasonable Shows a basic awareness of the engineering process Attention to format, grammar, and spelling
Minimally satisfactory	More than one required entry is missing Entries are dated or identified Observations are included Reflection is insufficient or superficial Inadequate attention to format, grammar, and spelling
Must be rewritten	Little basis for judgment

Table 7.4 Selection guide to align assessment methods with intended learning outcomes

	Written and Oral Questions	Performance Ratings	Project Reviews	Journals and Portfolios	Self-Report Instruments
Conceptual understanding	X				
Problem solving	X			X	
Knowledge creation and synthesis		X	X	X	
Skills and processes		X	X	X	X
Attitudes			X	X	X

Guide to Selecting Appropriate Assessment Methods

The constructive alignment of assessment methods with the intended learning outcomes can provide a useful guide for selecting appropriate assessment methods. The intended learning outcomes for a course, module, or other learning experience can be sorted into categories to facilitate the selection of appropriate assessment methods. For example, Table 7.4 is a general guide for selecting appropriate assessment methods aligned with specific categories of learning outcomes. It is based on the work of R. J. Stiggins, an educational assessment specialist who works with classroom teachers [5]. The first column identifies categories related to knowledge (3 levels), skills, and attitudes. Column headings are categories of assessment methods that were highlighted in this section. The table emphasizes the importance of selecting assessment methods that are appropriate for collecting evidence that students have achieved the specified learning outcomes. However, it is simply a guide.

The table suggests that conceptual understanding can be effectively assessed with written and oral questions. These questions might be included in examinations, interviews, or information interactions with students. Examples of learning outcomes in this category include:

- *Distinguish emissions from combustion characteristics* (discipline-specific entry in CDIO Syllabus 1.3).
- *Define a system, its behavior, and its elements* (CDIO Syllabus 2.3).

Problem solving and procedural knowledge can be assessed by asking students to find solutions to simple and complex situations with the use of oral questioning, written formats, or in reports and journals (See the work of D. H. Jonassen for examples of teaching and assessing problem solving.) [6]. Examples of learning outcomes addressing problem solving include

- *Formulate solutions to problems using creativity and good decision making skills* (CDIO Syllabus 2.1).
- *Apply probabilistic and statistical models of events and sequences.* (CDIO Syllabus 2.1).

Knowledge creation and synthesis learning outcomes, while more difficult to measure, can be assessed with some of the same methods as skills and processes. Examples include

- *Conceive and design an engineering product to meet customer requirements* (CDIO Syllabus 4.3 and 4.4).
- *Appraise operations systems and recommend improvements* (CDIO Syllabus 4.6).

Learning outcomes that can be categorized as skills and processes are appropriately assessed with performance ratings, product reviews, journals, portfolios, and other self-report instruments. Examples of these outcomes include

- *Determine the stress and deformation states of structures using the appropriate simulation tools* (discipline-specific entry in CDIO Syllabus 1.3).
- *Use appropriate nonverbal communications, for example, gestures, eye contact, poise* (CDIO Syllabus 3.2).

Finally, attitudes can be assessed with most self-report instruments, including journals and portfolios. The CDIO Syllabus specifies affective learning outcomes (attitudes) meant to be integrated into the curriculum. Examples include

- *Recognize the ethical issues involved in using people in scientific experiments* (CDIO Syllabus 2.2).
- *Commit to a personal program of lifelong learning and professional development.* (CDIO Syllabus 2.4).

The table is a guide for matching assessment methods to learning outcomes; it does not prescribe exact matches. The choice of assessment methods often depends on a faculty member's experience with a method and available resources for data collection and analysis.

Using Results to Improve Teaching and Learning

The fourth perhaps most important step in the student learning assessment process, shown in Fig. 7.1, is the use of assessment results to improve teaching and learning and help improve the program as a whole. This final step closes the assessment loop.

Feedback to Students

When both formative and summative learning assessment results are shared with students, learning is reinforced and improved. This feedback to students is most helpful when it is consistent and regular throughout the term. To be effective, feedback should be as specific as possible so that students know what learning outcomes they have achieved and how best to improve their knowledge, skills, and attitudes. Feedback also needs to follow closely the completion of exams, assignments, and projects. If students are to benefit, feedback from instructors, supervisors, and peers should be positive, correcting errors but avoiding any sarcasm or condescending comments.

A Culture of Quality

The elements of the learning assessment process are intended to help develop and demonstrate a *culture of quality*, as described by Massy [7]. He identifies a series of core quality principles that define the quality process for higher education.

- Define education quality in terms of student outcomes.
- Focus on the process of teaching, learning, and student assessment.
- Strive for coherence in curriculum, educational processes, and assessment.
- Work collaboratively to achieve mutual involvement and support.
- Base decisions on facts wherever possible.
- Identify and learn from best practice.
- Make continuous academic improvement a top priority.

Programs that regularly apply these principles in a process of continuous improvement demonstrate a culture of quality.

In the example of the project module assessment at Queen's University Belfast, described in Box 7.2, a number of instruments are used to identify the achievement of learning outcomes. The instruments are used to rate students' performance against the learning outcomes, thereby gathering direct evidence of student learning. The assessment instruments also provide a ready means of identifying where and how well the program's intended learning outcomes are being achieved. For example, if students are rated "unsatisfactory" by different examiners on any criteria on the rubric shown in the case study, then improvement efforts are targeted to remedy these deficiencies.

In addition to improving teaching and learning, assessment information may be gathered to satisfy institutional or external reviewers. For example, the criteria used in accreditation reviews of the Accreditation Board of Engineering and Technology state that a program should have in place:

- A curriculum that provides students opportunities to learn, practice and demonstrate student learning outcomes.
- An assessment process that produces documented results that students have achieved the specified learning outcomes.
- Documented assessment processes with measurable student outcomes and feedback loops showing continuous program improvement [8].

Regardless of the requirements of external reviewing bodies, the most important use of assessment information is for the purpose of a program's own continuous improvement. The use of student learning assessment data for program evaluation is addressed in more detail in Chap. 9.

Key Benefits and Challenges

Sound learning assessment methods contribute to student and program success in several ways: (1) gathering and evaluating information from multiple and diverse sources makes it possible to know with confidence what students have learned; (2) teaching and assessment are intertwined, so that improving assessment methods also improves teaching and learning; and (3) there are appropriate assessment methods to measure student progress and achievement in a variety of teaching-learning environments.

In implementing sound learning assessment, several challenges remain:

- Shifting the traditional view of assessment to a more learner-centered approach is a challenge because engineering faculty tend to rely on the same assessment methods that were used in their own engineering studies, for example, problem sets and written exams. Support for enhancing faculty competence in assessment methods is described in Chap. 8.
- Finding or creating reliable, valid, and appropriate learning assessment methods and tools matched to all learning outcomes can seem daunting, at first. The CDIO Initiative supports collaborations that encourage the sharing of assessment tools and results.

- Creating or adapting learning assessment methods that support deeper understanding of engineering concepts requires a serious commitment of faculty time. Formative assessment methods that take place within instructional units can give faculty and students opportunities to monitor the development of knowledge, skills, and attitudes and reveal misconceptions. Summative assessment methods that take place at the end of instructional units can give faculty and students opportunities to gain a broader and more cumulative perspective on the achievement of learning outcomes.
- The results of learning assessment, both formative and summative, are not always fully used. Results, if shared with faculty, students, and other instructional leaders can help to determine the extent to which learning outcomes have been achieved. The quality of these achievements can then become the motivation for continued excellence, or improvement, of future teaching and learning experiences.

Summary

A program has implemented sound learning assessment when there is an explicit student learning assessment plan and a variety of assessment methods matched appropriately to learning outcomes. Implementation is considered successful if a majority of the faculty are using a variety of appropriate assessment methods, and using assessment results to determine student achievement to improve teaching and learning experiences in their courses. In short, a program has successfully implemented student learning assessment when there is evidence that all four phases of the learning assessment process described in this chapter are in place.

Finding or creating reliable, valid, and appropriate assessment methods and tools matched to learning outcomes remains a challenge. Collaborators in the CDIO Initiative are building an inventory of assessment approaches, for example, oral exams, performance rubrics, portfolios, and self-report instruments. This chapter examined alternatives for planning sound learning assessment and suggested ways to overcome key challenges to its implementation. Establishing a culture in which assessment promotes learning requires a shift in perspective from a teaching-centered to a learner-centered approach and a commitment to use assessment results to improve curriculum, teaching methods, and the overall learning environment. Issues related to expanding faculty competence in the use of student learning assessment methods, as well as teaching and learning methods, are addressed in the next chapter.

Discussion Questions

1. What types of data or evidence do you rely on most often in your decisions about engineering courses and programs?
2. What assessment methods can you introduce or improve in your courses?

3. How do you use learning assessment results to improve curriculum, teaching and learning, student and instructor satisfaction, and learning spaces in your programs?
4. How would you begin to address the key challenges to assessment posed in this chapter?

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Chapter 8
Adapting and Implementing a CDIO Approach

Introduction

Adapting and implementing a CDIO approach can be of great value to educational programs and the students they serve. However, that means change—an inherently challenging endeavor, especially at a university. Program leaders are more likely to succeed in this change process if faculty are equipped with an understanding of how to bring about change and provided with relevant guidance and resources. This chapter discusses the implementation of a CDIO approach in terms of three change processes: (1) cultural and organizational change, (2) faculty development and support, and (3) program change.

The transformation to a CDIO program will affect all faculty members in the program, and it will influence the context and the organization of the education program. To succeed, faculty need to view the transformation as an instance of cultural and organizational change and to make use of the best practices that facilitate such change processes. The first section of the chapter reviews these practices and applies them to a university context.

Implementation places new demands on the entire instructional staff. We cannot expect them to acquire new skills without the resources to enhance their own competence. In the second section of the chapter, CDIO Standards 9 and 10 will be introduced. Standards 9 and 10 deal with the issue of faculty competence in professional engineering skills and in teaching and assessment. This section also discusses approaches that enhance the competence of current faculty in order to build a stronger faculty in the future. The chapter concludes with a roadmap for program change that represents adaptation and implementation as an engineering design process. This final section outlines examples of supporting resources that are currently available.

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Chapter Objectives

This chapter is designed so that you can

- Recognize key success factors that influence change in an organization.
- View the development of a CDIO program as an example of organizational and cultural change.
- Plan activities that enhance faculty competence in personal and interpersonal skills, and product, process, and system building skills.
- Plan activities that enhance faculty competence in teaching, learning, and assessment methods.
- Describe approaches and locate resources that facilitate the adoption. and implementation of a CDIO approach in engineering programs.

Development of a CDIO Program as an Example of Organizational and Cultural Change

As described in Chap. 2, the dominant paradigm for engineering education today is one in which the *content* is disciplinary and based on engineering science. The unintended consequence of the transformation in the last century to this paradigm is that the *context* of the education also became based on engineering science and research. Some degree of cultural change is required to transform a program to the desired vision, one which better integrates the engineering science disciplines and sets them in the context of conceiving-designing-implementing-operating products, processes, and systems.

Fortunately, there is broad understanding of the factors that support successful cultural change in organizations. Adapting these change factors to the university environment facilitates the transition to a CDIO approach. We begin our discussion of change by re-examining the two central questions that were posed in Chap. 2:

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

The approach to answering the first question was answered in Chap. 3 with the discussion of the CDIO Syllabus. Chapters 4–7 presented approaches to answering the second question. But how can we convince our colleagues of the need to "do better at ensuring that students learn these skills?"

The second question is deliberately posed in the language of continuous process improvement. We can benchmark our peers and learn from best practice. We can better acquaint ourselves with learning theory and apply it appropriately. We can listen to our internal and external stakeholders. We can learn to apply technology in improved ways. We can do better. Our students ask us to do better, our industry stakeholders prod us to do better, our government and professional regulators encourage us to do better. It is not a matter of fixing something that is broken, but of improving something that is vital to our future, namely, technological education.

However, adapting and implementing a CDIO approach may be a challenge at some universities, and for good reason—it requires change. The words *change* and *university* do not easily sit in the same sentence. There are two perspectives that must be understood before beginning the process of change at a university:

Perspective 1: Universities as organizations are by design resistant to change.
Perspective 2: Notwithstanding Perspective 1, universities *can* be changed by appropriate application of best practice in leading organizational change.

Universities are resistant to change as a matter of organizational design and tradition. In Europe, universities emerged in the Middle Ages from cathedrals and monastic organizations designed for stability and contemplation in an era of societal chaos. Universities adopted the concept of tenure. At best a license to be bold and innovative, tenure makes difficult the concept of organizational alignment. Despite the fact that universities appear hierarchic (departments, deans, provost, others), they are actually flat organizations in which lines of authority are fuzzy, weak, or nonexistent. Historically, universities tended to be introspective, relying on self-reflection and debate to drive change. As a result, universities are stable, long-enduring institutions. In Europe, of the more than 25 institutions that have operated continuously since the Reformation, all but four are universities. In the United States, there were already nine universities as early as 1770 [1]. More than one university in Europe and the United States shared the outlook that "a little change is good, no change is better."

Yet change can be effected at universities. In the 1880s, Eliot changed Harvard from a colonial college to a modern university [1]. Bush [2] created a new frontier in *Science The Endless Frontier*, fundamentally altering the view of research at universities in the United States. As we pointed out in Chap. 2, the engineering science revolution of the latter half of the 20th century fundamentally changed the approach to engineering education worldwide. This evidence suggests that change, even major transformational change, is possible in universities. However, leaders are more likely to be effective in bringing about change if they are equipped with an understanding of how to lead organizational transformations.

Change at a University as an Instance of Organizational Change

The key factors that facilitate change at a university are not dissimilar from frameworks that have been developed to help other types of organizations succeed in change. For example, there is general consensus that the start of the process is critical and that the force of urgency and understanding of need, vision, and first

Table 8.1 Kotter's eight stages of the change process

1	**Establishing a sense of urgency**
	Examining market and competitive realities
	Identifying and discussing crises, potential crises, or major opportunities
2	**Forming a powerful guiding coalition**
	Assembling a group with enough power to lead the change effort
	Encouraging the group to work together as a team
3	**Creating a vision**
	Creating a vision to help direct the change effort
	Developing strategies for achieving that vision
4	**Communicating the vision**
	Using every vehicle possible to communicate the new vision and strategies
	Teaching new behaviors by the example of the guiding coalition
5	**Empowering others to act on the vision**
	Getting rid of obstacles to change
	Changing systems or structures that seriously undermine the vision
	Encouraging risk-taking and nontraditional ideas, activities, and actions
6	**Planning for and creating short-term wins**
	Planning for visible performance improvements
	Creating those improvements
	Recognizing and rewarding employees involved in the improvements
7	**Consolidating improvements and producing still more change**
	Using increased credibility to change systems, structures, and policies that do not fit the vision
	Hiring, promoting, and developing employees who can implement the vision
	Reinvigorating the process with new projects, themes, and change agents
8	**Institutionalizing new approaches**
	Articulating the connections between the new behaviors and corporate success
	Developing the means to ensure leadership development and succession

steps must be coordinated to overcome resistance to change. In fact, there is even a formula based on this observation, credited to Gleicher et al. [3].

$$D \times V \times F > R$$

The formula is read as: dissatisfaction, D (a measure of the understanding of the true need and the opportunity to improve) times vision, V, times first steps, F, must be greater than the resistance to change, R. Other frameworks, such as the one developed by Kotter [4] outline steps generally applicable to organizational change, as shown in Table 8.1.

In alignment with these steps, other researchers have extended Kotter's work for application to engineering schools in particular and universities in general. Arguing that success in change management is the result of the effectiveness of a team in driving the politics of change, Eijkman et al. have proposed to use a soft or human systems thinking as a method to address the politics of change, which these researchers termed the "generally ignored elephant in the room" [5]. The politics in this context refers to the structure of power that defines the relationship between stakeholders and the ability to influence decision-making and resource allocation. By modeling an engineering education program as an interconnected human activity system made up of stakeholders who have different or conflicting viewpoints and interests, these researchers reason that achieving curriculum innovation is mostly about managing a contentious and socio-political process. To this end, they developed a Soft Systems Methodology (SSM) to help change leaders manage such a process. The term *soft* here refers to the fact that human activities are the core of the change process, and the *systems thinking approach* refers to the necessity that change agents understand "the emergent systems of meaning and dilemmas that surface in the process" [5]. Using the SSM, workshops led by facilitators are used as the means for participants to engage in structured, group discussion activities.

The problem of managing change in engineering institutions in different countries has also been a subject of recent studies in the form of transitioning from traditional learning approaches to project-based and problem-based learning approaches. For example, Kolmos and Graaf [6] examined transformation patterns across institutions and countries, and synthesized a number of frameworks for depicting relevant elements that should be considered in the change process and strategies for managing change. The researchers propose an approach that would employ both bottom-up and top-down strategies. This approach ensures that if the change starts from the top, (for example, with a department head or dean), change agents will be found among faculty and staff members at the bottom. And conversely, if the change starts from the bottom with faculty members, change agents would be found at the top [6].

Key Success Factors that Promote Organizational and Cultural Change

Based on our experiences and observations of change implementation at member CDIO universities worldwide, we have distilled the best practices into twelve key success factors that can be used to guide change at a university. These factors fall broadly into three categories: (1) getting started, (2) building momentum, and (3) institutionalizing change.

Getting off to the right start

- Understanding the need for change.
- Leadership from the top.
- Creating a vision.
- Support of early adopters.
- Early successes.

Building the momentum in the core activities of change

- Moving off assumptions.
- Including students as agents of change.
- Involvement and ownership.
- Adequate resources.

Institutionalizing change

- Faculty recognition and incentives.
- Faculty learning culture.
- Student expectations and academic requirements.

Each of these success factors is discussed with a view toward the general issue and its application to adapting and implementing a CDIO approach in a university program.

The First Phase of Change: Getting Off to the Right Start

There are five key success factors that help the change process in its initial stages: (1) understanding the need for change, (2) leadership from the top, (3) creating a vision, (4) support of early adopters, and (5) early successes.

Understanding the need for change. There must be a stimulus and motivation for change. The stronger and more clearly understood this need is, and the more urgent, the more willing the organization will be to change. Crises and external threats are classically strong motivators, but universities are usually somewhat insulated from such influences. However, it is vital in this change process that the team understand the need and be committed to addressing it. Since a university acts as a collective of faculty and staff, it is important to articulate this need for change in such a way that groups as well as individuals understand it.

As this is an educational change, it is best to focus on the needs of the students, those who benefit directly from the education. What are their needs? According to whom? This issue is sometimes cast as dissatisfaction with the current situation. Alternatively, it can be cast in the terminology of continuous process improvement—*can we do better at meeting the needs of the students?*

The stimuli we have found successful at precipitating an examination of needs rely in large part on external references. Input from industry, discussed in Chaps. 2 and 3, are examples. Guidance from alumni of the program is valuable, as are the inputs from external review committees and external members of program boards. It is also useful to cite the opinions of thought leaders and "authorities." If approached constructively, a national accreditation process can also be an external stimulus for change, as it was at the United States Naval Academy (See Box 8.1).

Box 8.1 **The Adoption and Assessment of a CDIO Approach at the U. S. Naval Academy**

The Department of Aerospace Engineering at the United States Naval Academy adopted a CDIO approach in July 2003, providing us with the framework and tools necessary to make and assess changes in our program.

The Naval Academy produces officers who serve in the United States Navy and Marine Corps. Therefore, the goals and outcomes of all the academic programs, including the Aerospace Engineering program, support the Naval Academy mission under the leadership of the Academic Dean and Provost. The institution has developed a set of strategic educational outcomes that describe the results it wishes to produce in the graduates. The mission of the Aerospace Engineering Department must follow from the mission of the Naval Academy, and at the same time emphasize the role of the aerospace engineering major. Our mission is to:

> *Provide the Navy and Marine Corps with engineering graduates capable of growing to fill engineering, management, and leadership roles in the Navy, government, and industry, maturing their fascination with Air and Space systems.*

Our departmental vision follows our mission:

> *Mission fulfillment requires a program wherein Midshipmen Conceive-Design-Implement-Operate complex mission-effective aerospace systems in a modern team-based environment.*

Both our departmental mission and our vision are a direct result of our participation in the collaboration of universities who have adopted the CDIO approach.

Initially, our primary interest was the approach to program assessment that is tied to the CDIO Syllabus. We believed that this approach would be of great assistance in meeting ABET's new accreditation standards. However, as we learned more about the CDIO approach, we were convinced that it was right for us for many reasons beyond our initial interest in the assessment process. The primary reasons for adopting a CDIO approach in the Aerospace Engineering program at the Naval Academy were:

- Our desire to go beyond "paper designs" in capstone design courses.
- The strong focus at the Naval Academy on operations—our graduates become operators of systems.
- To have a structure to make necessary changes in our program.
- To benefit from lessons learned from the four founding universities of the CDIO Initiative that would help guide our design and implementation of a renewed Aerospace Engineering program.

Once we decided to adopt the CDIO Syllabus, our next question was, *how do we gain support from the administration, the program leaders, and the faculty?* Once we completed the CDIO Syllabus and looked at our existing program, it was clear that we valued topics in the Syllabus, but we were not addressing the topics. This discrepancy provided the motivation for change and made the job of convincing our faculty to adopt a CDIO approach. The survey of our key stakeholders further solidified the need for change and the advantages of the CDIO Syllabus and approach.

—D. G. Boden, United States Naval Academy

Another valuable means of external reference is benchmarking. In some systems, universities share data while in others the government publishes data on performance. Top universities are constantly benchmarking themselves against peers through both formal and informal means. Pressure from above is another way to stimulate commitment. When a university president or school dean mandates examination, strategic planning, or program re-assessment, it can be a good opportunity to catalyze action at a department or program level.

Barring external stimuli, it is possible to create an internal urgency by framing the issue in the terminology of continuous process improvement. It is important to avoid the formulation that something needs to be fixed, and ask instead how we can improve. New resources can be a catalyst for change. New faculty positions, new building funds, new equipment funds, new calls for proposals from government agencies can all be used to bring focus to change, especially if the resources are to be awarded competitively. Finally, large-scale social shifts can provide the context in which change is possible. In the United States, the competition with the Soviets, made clear by the launch of Sputnik, was a catalyst for massive educational change. In Europe, the Bologna Accord has created greater fluidity in higher education thinking [7].

Leadership from the top. Leaders are in the best position to change a culture. The commitment and active participation of the leader are vital. In a university department or program, the department chair or program head must lead the change process. Delegation to a committee or a junior member of the team will almost certainly produce weak results. The formal leader must be supported by a strong inner team of recognized individuals in the program. In order to change an organization, thought leaders must visibly demonstrate their interest and participation. This inner team can be made up of senior and junior faculty members who are effective as innovators. In addition to providing visible support, the team can serve as a sounding board, brainstorming, and planning group. It is not advisable to make this group exclusive, for that might create an "us versus them" sense with the extended population. Rather, the inner group needs to be porous and inclusive.

It is also desirable to have the visible support of people in the organization who are at one or two levels above the change leaders. Deans, provosts, rectors, and vice-chancellors provide resources and organizational authority. They often seek change in the organization, but are too remote from the faculty to lead effectively at individual department or program levels. Therefore, they are often supportive of proposals for change from departments, programs, or schools.

Creating a vision. In promoting change, it is most helpful if the leader, sometimes aided by a small group, quickly communicates a vision of how the urgent needs will be addressed. This vision should be easy to communicate, and become the organizing theme of the work. It may evolve into a full-blown strategy for change. In consensus organizations, such as university departments or programs, tension often arises on this point. On one hand, if the inner group arrives at the vision too quickly, there will be a sense that it was imposed, losing the values of broad-based ownership that are important for long-term acceptance. On the other hand, delaying too long before reaching consensus on a vision leads to organizational confusion and loss of any potential acceptance. The leader must strike this balance appropriately.

We have adopted an explicit vision, conveyed in Chap. 2—that engineering education should be set in the context of conceiving-designing-implementing-operating products, processes, and systems, and that the education is best executed by organizing around the engineering disciplines with design-implement experiences interwoven. We have formally incorporated this vision into Standard One. In adapting a CDIO approach to a particular program, it may be useful to start with this premise and build a vision. Alternatively, it is also possible to start with an organization-specific version, for example, *the whole engineer*, and then build on the similarity with the CDIO vision.

Support of early adopters. In any population, on any issue, there are those who are more inclined to try new approaches, those who will wait a bit, and those who will tend to resist change. The first group is generally referred to as *early adopters*. These individuals can be very important agents of change. Early adopters should be included in the change process as quickly as possible. To the extent possible, they should be given resources to develop pilots or experiments. When successful, these efforts should be celebrated. In this way, momentum will build and not-so-early adopters among their peers may become curious and engaged.

The program leader should identify early adopters at the beginning of the change process and encourage them to join the effort. Academic departments and programs are often small enough that known attitudes and performance make it easy to identify the early adopters. Students are also a good source of information because they recognize dedicated educators. Inviting an outside speaker on education or calling an optional meeting and seeing who shows up can often identify these individuals. In brief, it pays to identify early adopters, engage them, support them, and celebrate their successes. Most universities have organizations dedicated to educational research, development, and support, staffed by professionals in education and pedagogy. Another form of support that can be given to early adopters is collaboration with staff from such an educational support service organization. These groups are often enthusiastic about the prospect of participating in large-scale reform and are often themselves among the early adopters.

Early successes. It is important to achieve some visible successes early in order to attract interest and stimulate the effort for change. Often in the reform of academic programs, there is a long planning process spanning multiple years. Educational reform is more likely to succeed if there is a spiral process in which early goals are identified, early pilots run, the results reflected upon, and new goals set. Positive outcomes of these early pilots often attract the support and interest of others. These early successes are often the results of the early adopters.

In starting the change process, the leader should explicitly plan on developing some successes as soon as possible. Ideally, these early successes would have high visibility and wide impact. They should be recognizable as making the education better or the job of the teaching staff more productive. Examples that we have developed include modifications of:

- A first-year course to include a basic design-implement experience.
- An upper-level course to include more comprehensive, yet low-cost, design-implement experiences.
- An appropriate meeting room or flexible classroom to create a design-implement workspaces that supports hands-on and social learning.

As a program transitions from this first phase of "getting off to the right start," it is important to reflect on its progress and accomplishments. Box 8.2 summarizes observations of a former program leader of the Mechanical and Materials Engineering Department at Queen's University in Kingston, Ontario (Canada) about this transitional point in the adaptation and implementation of a CDIO approach.

Box 8.2 **The Adoption of a CDIO Approach at Queen's University (Canada)**

The Department of Mechanical and Materials Engineering in the Faculty of Applied Science at Queen's University is one of the larger departments of its kind in Canada. Its program includes many technical electives from which students can choose, making it attractive to students because they can find employment in many different areas. The departmental research strengths are in energy systems, biomechanical engineering, manufacturing, and materials.

In late 2002, Ed Crawley from MIT introduced the CDIO approach at Queen's University to faculty and others interested in engineering education. A few members of the department then participated in the collaborator meetings at the Massachusetts Institute of Technology and the Technical University of Denmark to learn more about the CDIO Initiative. Their reports were convincing enough to get unanimous departmental support for joining with universities who had adopted a CDIO approach in December 2003. Courses and ideas similar to those advocated by a CDIO approach already existed to a limited extent in the departmental program. Furthermore, the recent completion of the *Integrated Learning Centre* (ILC) provided an ideal facility to support a CDIO curriculum.

Feedback from an annual industrial review board, student evaluations, and faculty initiatives all pointed in the same direction. More emphasis was placed on *conceive, design, implement* and *operate* exercises, communication, teamwork, and other professional skills, without sacrificing the teaching and learning of basic engineering knowledge and skills. It was clear that the collaboration of CDIO programs had gone further by gathering feedback on the engineering curriculum from students, faculty, alumni, and industry in the United States and Sweden. It had also developed a syllabus containing the necessary elements of an engineering curriculum. At the same time it was felt that Queen's University could also contribute.

The following are some of the activities that have been undertaken at Queen's since adopting the CDIO approach. Without the impetus provided by the collaboration, these activities would not have been done at all or would have been undertaken only to a very limited extent.

- An alumni survey with over 400 respondents.
- Benchmarking of the program against the CDIO Standards.
- Adding "C-D" in one capstone course and "I-O" in another
- Improving the way we provide technical communication training.

There is still more work that can be done to improve the curriculum of Mechanical and Materials Engineering. It is clear to us that continued collaboration with other CDIO programs will allow us to learn from their experiences as we continue to improve our program.

—**U. Wyss, Queen's University (Canada)**

The Second Phase of Change: Building Momentum in the Core Activities of Change

There are four key success factors of cultural change that build momentum: (1) moving off assumptions, (2) including students as agents of change, (3) involvement and ownership, and (4) adequate resources.

Moving off assumptions. Once the change process is underway, the leader needs to get the team to move off their traditional assumptions of what and how things should be done. A successful change process requires willingness to think outside the box and to try new things. Despite academic commitment to research, scholarship, and innovation, organizational willingness to change is not a strength of most universities. There are several approaches that can be used to stimulate flexibility. An appeal to professionalism is a powerful one. Faculty members are often dedicated and distinguished professionals in their respective fields of engineering. If we can appeal to their professionalism as engineers and transfer that sense of professionalism to education reform, we can harness an important force. This appeal can be accomplished by posing the change process as an engineering design problem. This immediately raises questions such as: What are the requirements? What technology is available? How can we create prototypes? Such questions engage faculty in a new way. An expanded discussion of this point is found in the chapter section that describes the third phase of the change process.

Evidence is another important way to move people's opinions. We tend to underutilize evidence-based approaches in universities. Just exactly what are thought leaders outside your institution saying? What is the status of other initiatives at peer universities? What are other departments or programs in your university doing? What resources are available? Compiling briefing books of such evidence provides an opportunity for evidence-based policy change. One way to engage the faculty in reviewing this evidence is to conduct an Oxford- or Cambridge-style formal debate. In this format, the faculty member does not necessarily argue his or her own personal opinion, but a pre-assigned position, either for or against the issue, based on the evidence or other accumulated facts that are presented. Clever positioning of the individuals involved will often cause a person to be arguing a position counter to his or her personal opinion. If faculty members know they are playing roles, most will try hard to be persuasive, and perhaps even persuade themselves. Another common technique to make a group feel comfortable with change is called "stretch and relax." This requires first *stretching*—considering change that is credible but slightly extreme; then, allowing the team to *relax* back to a position that is less extreme but still forward of the status quo. This is the essence of the art of political compromise.

Including students as agents of change. Another force that can either promote or delay change is student opinion. We have found that it is important to include students in a substantive way in the educational change process. On the positive side, students can be powerful agents for change in their own right. They tend to know what works well and what does not, who teaches well and who does not. They can be a valuable source of information in planning for change and in providing feedback after changes have been piloted. This role is enhanced if we explain to students the motivation behind the change and the direction in which it is going. Once students experience program change, they often put pressure on the not-so-early adopters to improve as well.

On the negative side, students can be uncomfortable with change in the same way that the faculty might be. Students are particularly threatened by change in their personal futures. An approach to overcoming this fear is to create rolling change starting in the early years of the program. In this way, the more senior students can advise students in subsequent years about change that will occur in the program. It is important to include students, in varying degrees, in the decision making process at the university. Students can act as important agents of change. Engage formal student groups and invite individual thoughtful students to participate in discussions. Appeal to students' professionalism as well. Consider giving them a major role in the change process.

Involvement and ownership. It will eventually be necessary to involve all of the members of the team in the change process. Our experience is that it is better to do this early. Academic programs are *owned* and implemented by a wide variety of faculty members, some of whom may not be formal members of the department or program. For the reforms to take hold and be executed in individual courses, all of the participating faculty must be at least satisfied with, if not enthusiastic about, the change.

The initial inclination in launching a change effort in a department or program is to form a committee of early adopters to plan the change. While this has its advantages, it may appear exclusive. It requires a two-step process of first working with this group, and then having this group influence the larger group. Although more awkward, it may be preferable to engage the entire group as a committee of the whole or at least invite all to participate. If the leader must work with a smaller group, it should be representative of the various interests of the larger group, so that you have allies from all interest groups in the broader selling process. It is sometimes helpful to give an important task to a known skeptic. If that person becomes convinced, he or she will often persuade many others. In gaining involvement and ownership, it is important to allow participants time away to reflect and debate. Traditional approaches to this are off-site meetings or retreats. It is important to plan these times carefully, laying out agendas that actively engage the group and selecting effective discussion facilitators.

Adequate resources. Sustainable change must be accompanied by adequate resources. While it is unlikely that there will be significant new resources available to the program in the long-term steady state, it is also true that educational change cannot be achieved in the margin. The transformation will require time and interim support for the participating instructors and staff members. These transitional resources can be released time from teaching, extra teaching assistants, or teaching technology and materials. In some universities, it is possible to obtain support for academic projects beyond the academic year. In a culture that values engineering science and research, it is important to make the statement that time dedicated to reforming education should be part of the educational pool of resources and not drawn from the time allotted to research.

We have had two main goals with regard to resources. First, we have tried to create a collaborative effort that has produced the open-source resources described in a later section of this chapter. This combination of approach and shared resources minimizes the additional time and energy that must be expended by a program in the transition. Second, our objective is that in the steady state a program would need no new resources; instead, existing resources would be re-allotted.

The Third Phase of Change: Institutionalizing Change

Three key success factors facilitate the institutionalization of change: (1) faculty recognition and incentives, (2) a culture of faculty learning, and (3) student expectations and academic requirements.

Faculty recognition and incentives. A maxim of sustainable change is that incentives must be aligned with change. In any organization, you get the behavior that is rewarded. If education is important, the leader of the program or department must create both the perception and the reality of incentives and recognition that reward educational reform. The leader must be supported by those at higher levels in the university in this effort to reward sustainable change. Many universities have recognition programs for faculty in the form of teaching awards. These awards can be combined with the presentation of special status to those who are known for particularly good teaching, such as chairs for teaching or other university-wide recognition. This group of honored faculty can convene and discuss educational innovation throughout the university and act as an academy for education within the university. Occasionally, recognition for faculty contributions to education comes from national academies of engineering or other honorific bodies.

It is vital that the formal review process recognize and reward educational contributions. This means that in annual review cycles, submissions of educational contributions should be reviewed. More importantly, in hiring, promotion, and tenure decisions, these efforts need to be recognized. In particular, scholarly publications in education should be valued as highly as those in other scholarly research publications.

Faculty learning culture. All universities place great emphasis on learning, particularly on the broad learning of students and of the faculty in their professional disciplines. Ironically, many university faculties do not also embrace a culture that broad lifelong learning by the faculty is important beyond their disciplines. Leaders of change must create the expectation and set the standard that lifelong learning of instructors is important, not only in their professions, but also in education and the teaching of professional skills. Movement in this dimension often begins with simply making this observation and setting this expectation.

Actions can include granting faculty leaves and sabbaticals for professional engineering activities or educationally related activities, in addition to research sabbaticals. A department or program can begin to circulate important writings on these topics for discussion at faculty meetings, much like a research group reads the current literature. Faculty members can be asked to develop their own professional development plan as a part of their annual review. They might be challenged to define what and how they are going to learn in the next year. If the leader sees a pattern in the learning needs of the faculty, he or she can create learning opportunities at the university by bringing in outside experts, providing short courses for the faculty, or making connections to other university groups, including the university teaching and learning center.

Student expectations and academic requirements. Students are the immediate customers and beneficiaries of the educational services we provide. As in any change process in a customer service organization, their expectations must be carefully considered. This can take two forms: their informal expectations and the formal academic requirements. We have observed that, like all first impressions, a program has one chance to set expectations for learning and behavior in its students. At a university, this is the first day of the first year or the first day students enter a program. At this first opportunity, the goals of the education should be made explicit. More importantly, the expected norm of student involvement in learning must be immediately established. If we are to expect more active learning with more student responsibility for their own learning, we should establish this pattern on the first day of instruction and consistently throughout all of the classes or modules the student encounters. It is also desirable to institutionalize the learning outcomes in formal descriptions of the academic program. This can be done at the course or module level by including the learning outcomes and objectives in the descriptions, and, at a higher level, in the overview or description of the course of studies or program.

In summary, with intentionality, thoughtfulness, commitment, attention to process, and sensitivity to the unique characteristics of the university environment, we can effect the changes necessary to implement a CDIO approach. Box 8.3 describes two applications of the above-discussed change process: one at the level of a college at the Technical University of Denmark (Danmarks Tekniske Universitet), and the second at the level of a system of universities at the Vietnam National University-Ho Chi Minh City.

Box 8.3 Implementing a CDIO Approach: Two Case Studies

The story of implementing the CDIO approach at the Technical University of Denmark (DTU) spans more than 7½ years from the first executive decision to the graduation of the first group of engineers. DTU has four kinds of education programs: Bachelor of Engineering (with 10 different engineering majors), Bachelor of Science and Technology, Master of Science and Technology, and PhD programs. The CDIO approach was systematically introduced in the 3½- year Bachelor of Engineering program in order to distinguish it as a program of applied science directing candidates toward jobs in industry. Another reason for implementing CDIO was that it presented a framework of quality improvement and assessment of educational activities giving educators a common language and a goal of higher standards. In the beginning, implementation was prepared in committee work that involved students and faculty members. This was generally a top-down initiative. However, in some departments, it sparked a grass-roots drive for reform. Top-down or grass-root, a platform was needed for faculty members to meet, discuss, and inspire each other, and for early adopters of CDIO principles to lead the way. It was helpful to us that the CDIO Standards indicated those standards that are essential. This gave direction to the discussions on education reform and focused the early preparations.

Our first step was to work on a DTU version of the CDIO Syllabus, translate it into Danish, and discuss it in a DTU context. The faculty took ownership and related the CDIO Syllabus to the daily teaching and learning activities for which they were responsible. With ownership, constructive and sincere engagement in the reform activities followed. Faculty members started to participate in regional and international CDIO meetings, and a road map for the implementation process was created. The road map contained a number of deliverables and deadlines. It also included an introduction to CDIO plus important tools such as instructions on how to design learning outcomes, a course-competence matrix, and design-implement projects. After approximately 2 years, the road map developed into a formal *DTU Handbook on CDIO* that became a document that introduced new faculty members to CDIO. During this phase, CDIO was made part of the mandatory teacher-training program at DTU (See Box 8.5).

Two years into the successful implementation of the CDIO approach, many courses were linked and interdependent, as intended. For the longer term, faculty members needed a stable source of curriculum information and a clear overview of how students progressed through the program.

(*Continued*)

Box 8.3 Implementing a CDIO Approach: Two Case Studies—Cont'd

A Wiki-based document with a blueprint of the curriculum design and continuous updates on learning outcomes for each of the ten majors was created so that faculty could coordinate teaching activities and optimize student learning. Implementation of the CDIO approach was solidified by including wording about CDIO as the context for education (Standard 1) in the DTU strategic documents on education. In addition, a special career-track system of professor promotion was adopted on the basis of leadership and innovation within education. Such manifestations by university government were important to sustain continuous educational improvements as a part of the core culture of university faculty.

—M. E. Vigild, Danmarks Tekniske Universitet (Denmark)

The Vietnam National University-Ho Chi Minh City (VNU-HCM) System has spearheaded the adoption of CDIO principles since 2008 to accelerate national efforts in curriculum reform through widespread implementation of the CDIO approach in Vietnam. In adopting the CDIO approach and leveraging the strength of VNU-HCM's system of universities, we developed: (1) a framework for curriculum reform that has the potential to be generalizable to other institutions in Vietnam, and (2) a seven-year plan to implement the framework in a few strategic departments and to accelerate its implementation throughout all of our universities.

The framework that we developed seeks to achieve the following goals: (1) adapt CDIO principles to reform systematically the curriculum of strategic university departments by providing students with the knowledge, skills, and attitudes desired by relevant stakeholders; and (2) use the pilot implementation of the CDIO approach as a means to develop generalizable approaches that can be replicated at universities within the VNU-HCM System and at other universities in Vietnam.

We committed substantial resources and made important strides in our initial implementation of the framework. We invited international experts in the CDIO approach to serve as our advisors and to conduct workshops for high-level managers and faculty members. We translated and published *Rethinking Engineering Education: A CDIO Approach* (2007) into Vietnamese, working with the Ministry of Education and Training to distribute the book free of charge to universities throughout Vietnam. In 2010, we initiated the pilot implementation of the CDIO approach in the Department of Mechanical Engineering of the University of Technology and in the Department of Information Technology of the University of Sciences. These two strategic university departments have adopted the CDIO principles and have committed to implementing the CDIO approach. They have also agreed to serve as model departments that will help disseminate the CDIO approach within the VNU-HCM system and throughout Vietnam.

—N. T. Ho and T. Doan,
Vietnam National University-Ho chi Minh City (Vietnam)

Faculty Development and Support

As is evident in the discussion of the key success factors, faculty involvement and enthusiasm greatly facilitate the implementation of a CDIO approach in engineering programs. Faculty members are asked to be innovators, that is, they are asked to adapt their teaching styles to ones that are more student-centered and to teach the professional engineering skills and attitudes specified in the CDIO Syllabus. There must be a process for supporting faculty as they enhance their competence in teaching, in new forms of evaluation, and in engineering practice and related skills. Enhancement of faculty competence must be accomplished while protecting the academic careers of faculty. Professional development activities should enhance their opportunities for promotion and tenure, not put future academic promotion at risk. Consistent with the key factors above, the recognition and incentives for faculty ideally should be in support of this approach to professional development.

Enhancement of Faculty Competence in Skills

CDIO programs should provide support for faculty members to improve their own competence in personal and interpersonal skills, and product, process, and system building skills as described in the Syllabus. The nature and scope of faculty development varies with the resources and intentions of each program and institution. Examples of actions that enhance faculty competence include: professional leave to work in industry, partnerships with industry colleagues in research and education projects, inclusion of engineering practice as a criterion for hiring and promotion, and appropriate professional development experiences at the university. Enhancement of faculty competence in professional skills related to the CDIO Syllabus is the focus of Standard 9.

> STANDARD 9—ENHANCEMENT OF FACULTY SKILLS COMPETENCE
>
> **Actions that enhance faculty competence in personal and interpersonal skills, and product, process, and system building skills.**

If faculty members are expected to teach a curriculum of personal and interpersonal skills, and product, process, and system building skills integrated with disciplinary knowledge, they need to be competent in those skills themselves. Most engineering professors tend to be experts in the research and knowledge base of their respective disciplines with only limited experience in the practice of engineering in business and industrial settings. Faculty members may need to enhance their engineering knowledge and skills so that they can provide relevant examples to students and also serve as role models of contemporary engineers. Faculty development and support can have three basic approaches.

- Hire new faculty who have industrial experience or give newly hired faculty a year in industry to gain the experience before they begin teaching.
- Provide educational programs, such as seminars, workshops, and short courses for the current faculty or allow current faculty sabbatical leaves to work in industry.
- Recruit senior faculty with significant industry experience to teach and mentor other faculty or attract practicing engineers from industry to spend time teaching at the university.

Each of these three approaches is described below.

In hiring new faculty, one can consider whether they have had any actual engineering experience. If so, this should be valued as a positive aspect of their background. If not, the department or program could offer released time to fill in this professional experience. As an example, some programs send newly hired faculty to work with industry for one year prior to the start of their formal teaching responsibilities. This program is aimed at professionals beginning their faculty careers immediately after their advanced degrees. The goal of the year with industry is to develop product, process, and system building skills, as well as to broaden their perspectives on engineering research. This time does not count toward the time required to gain promotion. As an added benefit, faculty return with a deeper understanding of the research needs of industry. Programs must have institutional support to resource this effort.

Programs also face the challenge of encouraging existing faculty to teach professional engineering skills and attitudes in their courses. A variety of approaches can lead to enhanced skills of the existing faculty. One approach is to sponsor short courses or training programs within the university on professional engineering skills and attitudes. Commercially available short courses can be used as well. Larger industrial enterprises often have extensive internal training programs and may invite faculty participation. Encouraging such programs also sends the message to faculty that program leaders consider these skills important and are willing to expend resources to help the faculty acquire them. Faculty leaves and sabbaticals that are often taken at other universities or in government agencies can be taken in industry. Again, program leaders must ensure this time is used to expand the faculty member's competence in teaching the CDIO Syllabus skills and attitudes (Sections 2, 3, and 4). Otherwise, faculty might be inclined to pursue only their research interests.

Finally, programs can attract distinguished engineers with significant experience in product development and system building. Programs will need institutional support for this effort as career engineers often do not satisfy traditional hiring criteria. An excellent example of a nationally sponsored effort of this type is the *Visiting Professors' Scheme*, sponsored by the Royal Academy of Engineering in the United Kingdom [8]. This program brings experienced engineering professionals to the university to share their experiences with both students and faculty.

At MIT, a position called *Professor of the Practice* was created to allow the appointment of similar distinguished practitioners. Another approach is to attract senior engineers to short-term placements as visitors or adjunct instructors. These senior practitioners bring personal and interpersonal skills, and product, process, and system building skills not only to the classroom, but also to their interactions with other program faculty. Consequently, the proficiency level of the entire faculty increases as a result of hiring practiced engineers.

Enhancement of Faculty Competence in Teaching and Assessment

Programs should support the faculty as they improve their competence in integrated learning experiences, active and experiential learning, and assessment of student learning. Teaching approaches and assessment methods are described in Chaps. 6 and 7, respectively. Examples of actions that enhance faculty competence include: support for faculty participation in university and external faculty development programs, forums for sharing ideas and best practices, and emphasis on effective teaching skills at performance reviews and hiring. Enhancement of faculty competence in teaching and assessment is the focus of Standard 10.

STANDARD 10—ENHANCEMENT OF FACULTY TEACHING COMPETENCE

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

If faculty members are expected to teach and assess in new ways, they need opportunities to develop and improve their competence in these domains. There are two common approaches to this development task. Many universities have faculty development programs and groups that support improvement in faculty teaching and are often eager to collaborate. In addition, programs seeking to emphasize the importance of teaching, learning, and assessment, should be prepared to commit adequate resources for faculty development in these areas.

Transforming the faculty requires changes not only to curriculum but also to teaching and assessment methods. Changing teaching methods is often more threatening to faculty than changing the curriculum. It is important to recognize these fears and reduce or remove barriers to implementing active and experiential learning in the classroom. Bonwell and Sutherland identify five major barriers as (1) lack of coverage, (2) increased faculty preparation time, (3) large class sizes, (4) lack of resources, and (5) risk to the faculty member [9]. Lack of coverage is the concern that “all of the material won’t be covered.” This concern is partially overcome by emphasizing student learning rather than faculty teaching. Recent changes in accreditation criteria focusing on program outcomes rather than on program content support this effort. When possible, program leaders might provide faculty with compensatory time in order to plan and implement changes to their teaching. Giving faculty time and resources to enhance their teaching competence accomplishes two objectives: (1) faculty have the necessary time to plan and pilot changes; and (2) it sends the message to the entire faculty that these changes are important and valued. Program leaders, working with senior leaders of the university, need to convince the institution as a whole that faculty efforts to improve teaching and assessment are worthy of inclusion in promotion credentials.

Program leaders can also influence change in the teaching culture during the hiring process. Candidates for faculty positions are usually questioned about their education, research, and job experience, but rarely about their understanding of, and interest in, teaching. Including questions about teaching philosophy, teaching experience, and willingness to experiment with new teaching methods helps to identify candidates who can contribute to implementing a CDIO approach. Prospective faculty can even be asked to give a seminar on education in addition to their traditional seminar on research. At Queen's University in Canada, prospective faculty members are asked to teach a mock class to a group of instructors who take on the role of students.

Program leaders can also enlist the support of external education experts through seminars, workshops, and guest lectures. Most universities have teaching and learning centers staffed by education experts who are excellent sources of information and support. In some countries, there are national trends toward requiring training and educational certification for new university instructors. A good example of a university-wide system to enhance faculty competence in teaching and assessment, found at the Technical University of Denmark, engages every new faculty member in his or her first year at the university (See Box 8.4).

Box 8.4 **Enhancing Faculty Teaching Skills at the Technical University Of Denmark**

Effective teaching and assessment skills are essential in the implementation of a CDIO approach. The Technical University of Denmark (DTU) offers a variety of activities aimed at enhancing faculty members' teaching and assessment skills. These activities include courses, seminars, and development projects. To become a member of the faculty and be able to take on long-term teaching responsibility, there is a mandatory teacher-training program. The program is based on the assignment of a relevant teaching task and includes: (1) supervision of classroom teaching by a mentor from the instructor's department, (2) development of a teaching portfolio, and (3) peer coaching on teaching. The core element of the teacher-training program is *Education in University Teaching*, a course that combines learning theory with teaching practice. The course consists of four modules with a total workload of 250 h distributed over 1½ years. This workload is included in the course participants' overall teaching obligations in their home departments.

The first three modules of the course are regular classes, whereas the fourth module is a development project applied to the participants' own teaching practices. The modules address learning objectives, engineering competencies, course planning, assessment, feedback, and evaluation. The content of the modules is based on current research and state-of-the-art principles of teaching and learning in higher education. These principles are also aligned with the underlying principles of the CDIO approach, which is explicitly introduced to course participants and exemplified by case studies of the implementation of CDIO in engineering courses at DTU.

The overall program is structured according to the conceive-design-implement-operate pattern. Participants prepare by finding a relevant teaching assignment to work with during the program. During the first modules, they conceive and design ways to structure their teaching, for example, learning objectives, core elements, course planning. In the fourth module, they implement and operate the teaching assignment, performing in a real-life teaching setting, evaluating the process, and reflecting on the results. In the final written report, the evaluation and reflection parts become central as the main purpose of the fourth module is to investigate student learning outcomes. Overall, the program strives to develop faculty competence in reflecting critically on their own teaching and in evaluating it with respect to student learning and the attainment of intended learning outcomes.

The program is organized as a collaborative effort between the central support unit for teaching and learning development at DTU, *LearningLab* DTU, and the individual departments. Each year, approximately 50 faculty members complete the program and join forces with colleagues who contribute to the community of teaching and learning at DTU, where engineering education is discussed, analyzed, and developed.

—P. H. Andersson, Technical University Of Denmark

By using the resources available to them, programs can go about systematically enhancing the competence of the faculty in engineering skills as well as in active and experiential learning and student assessment.

Resources to Support Program Change

We have created a number of approaches and open-source resources to facilitate adaptation and implementation of the CDIO approach in diverse university engineering programs. Available resources include practical advice, implementation guidelines, instructional materials, and descriptions of transition activities. The universities that have adopted a CDIO approach support collaborative development and sponsor workshops and conferences for the exchange of ideas and best practices.

Engineering Design Paradigm for the Development of a CDIO Approach

An engineering design paradigm has been applied to the development of the CDIO approach. This paradigm also serves as a useful roadmap for adaptation and implementation in existing engineering programs. Education can be viewed as a service that can be engineered using the methods of product and system development and operation. Using the engineering design paradigm to develop a CDIO program has several distinct benefits.

- It appeals to the professionalism of engineering faculty by evoking positive attributes of their profession, that is, addressing needs, solving problems, developing new approaches, and applying quality standards. Casting the change process in an engineering design framework enables faculty to feel more comfortable with change.
- It draws on the established competencies of the faculty. Structuring the change process as an engineering task enables them to apply their expertise, for example, defining requirements, building prototypes, and collecting data.
- It ensures that valid learning outcomes are specified and form the basis for curriculum development, teaching and learning methods, and assessment plans. The engineering design paradigm guides the ways in which the CDIO approach is documented and codified, that is, a comprehensive goal statement, curriculum structuring and mapping techniques, and a quantified model for continuous improvement. The documentation, processes, and examples are the subject of Chap. 3 through Chap. 9.

The process of adapting and implementing the CDIO approach is closely aligned with the phases of the product, process, and system lifecycle, as illustrated in Fig. 8.1. The approach uses the techniques of product, process, and system development to structure an educational program based on the premise that the proper context for engineering education is the product, process, and system lifecycle. The *Conceive* phase analyzes the needs of a graduating engineer, sets clear and consistent learning outcomes, and works out a concept for engineering education that addresses requirements. This concept for engineering education is consistent with university and national goals and standards and reflects scientific and technical advances. The outcomes of the *Conceive* phase are unique for each program but are guided by the CDIO Syllabus and the CDIO Standards. The *Design* phase includes benchmarking the existing curriculum and using open-source tools that help in curriculum development, course development, teaching and learning methods, assessment methods, and student workspaces. In the

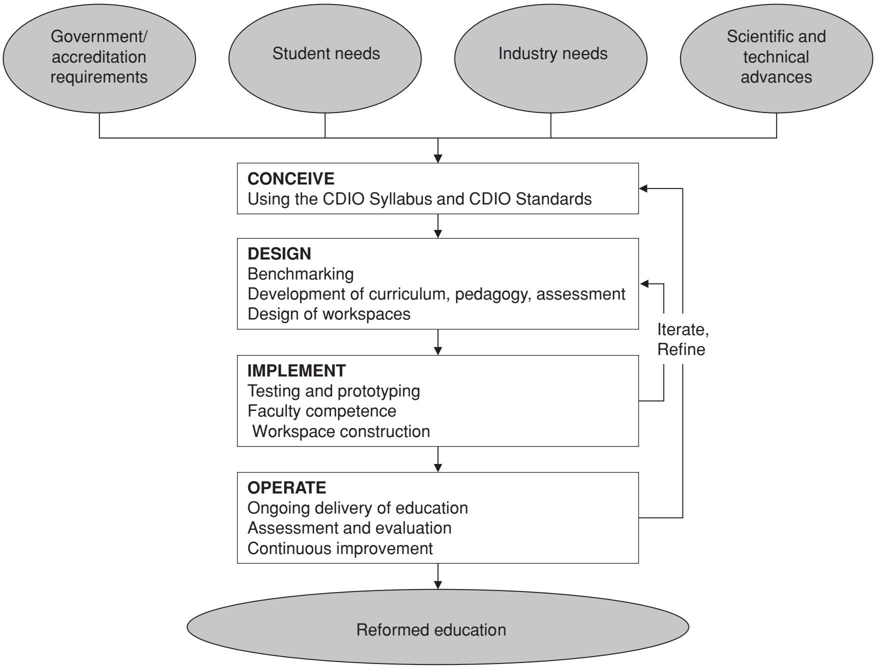

Fig. 8.1 Design and development of a CDIO approach

Implement phase, new educational tools and resources are tested in engineering programs at collaborating universities. This collaboration enables programs to compare results, evaluate, iterate, and improve processes and materials, and adapt the approach to engineering programs in a variety of educational environments. It is in this phase that human and physical resources are developed. Finally, the *Operate* phase occurs when the educational reform initiatives move beyond prototype and test stages to a steady-state phase where major program changes have been implemented. Evaluation and continuous improvement of the program and of the CDIO approach continue in this phase and are supported by assessment and evaluation.

Open-Source Ideas and Resources

The CDIO approach has been implemented in diverse universities, disciplines, and nations. These existing programs also reflect diversity in goals, students, financial resources, existing infrastructure, university context, industry desires, government regulations, and professional societies' accreditation standards. To accommodate this diversity, the approach is codified as an open source. This open accessible architecture for program materials promotes the dissemination and exchange of

Table 8.2 Open-source resources of the CDIO initiative

Resource	Purpose	Description
The CDIO Syllabus	Facilitate the creation of clear and comprehensive goals and learning outcomes for engineering programs	A customizable template of goal statements that include technical knowledge and personal and interpersonal skills, and product, process, and system building skills
The CDIO Standards	Distinguish a CDIO program and its graduates, and guide adoption and implementation	Twelve features that characterize a CDIO program, including description, rationale, and evidence that the feature is in place; includes a rubric for each standard
Start-up guidance	Provide ideas and support to program leaders who are adapting and implementing a CDIO approach	Practical advice on how to initiate educational reform and develop a CDIO approach
Published papers and reports	Document the dissemination and adoption of the CDIO approach	Journal and conference papers and reports written by collaborating universities about the development and adoption of a CDIO approach
CDIO website	Provide information about the CDIO approach and the activities of collaborating universities	Includes tools and resources, CDIO Standards, CDIO Syllabus, papers, information about meetings

ideas and resources. A wide variety of resources is available. The major resources are described in Table 8.2. They can be found at http://www.cdio.org. The CDIO Syllabus and CDIO Standards are discussed in detail in Chaps. 3 and 1, respectively. These resources have been developed to enable engineering programs to adapt the CDIO approach to their specific needs. Engineering programs can implement the entire approach or choose specific components.

The CDIO approach is not prescriptive. We understand that every program, school, university, discipline, and nation has unique needs. We have created a set of resources, approaches, and ideas that can be adapted to improve engineering education for students and other key stakeholders. We acknowledge that almost every quality engineering education program is engaged with some or many aspects of this reform, and are making contributions from which we can all learn. Resources are limited at all universities. Very few universities can engage in a comprehensive reform with the expectation that steady-state resources will increase. We have developed the CDIO approach with the assumption that steady-state resources will not increase and that programs will have to re-task existing human, space, and time resources. Occasionally, universities and national agencies enable programs to argue for additional steady-state resources. Having a well-developed approach often enables a program to compete more effectively for these new resources. In the transition from a conventional engineering program to a CDIO program, some additional time and support will be needed. It will not be possible to design a new curriculum, develop new learning experiences, re-task workspaces, and develop assessment tools without additional time and effort. We have created the resources outlined here in an effort to minimize this transition, but the effort may still be considerable.

Value of Collaboration for Parallel Development

We have observed that engineering educators worldwide face similar issues. Many of the underlying issues are traceable to the tension between the two main goals of deep understanding of the fundamentals and competence in broader professional skills. Other issues are as common as how one divides students into groups on projects and assesses these group projects. Addressing even the common issues in a rigorous way is a challenge for any single program or department. The scope of these issues and their worldwide commonality suggest that it would be desirable to work together to address them in an organized way toward common goals. Collaboration among CDIO programs worldwide enables us to develop and implement a general and adaptable educational model. The value of international collaboration lies in

- Creating more robust and generalized starting positions for the development of CDIO programs. For example, surveys and benchmark studies compare stakeholder expectations and institutional conditions at different universities and countries.
- Sharing approaches and ideas within a structured framework of common goals.

- Creating a set of transferable resources that can be used by other universities to facilitate adaptation and implementation.
- Sharpening the key features of the CDIO Standards.

There is another important benefit of working in a collaborative format. Working together promotes visibility into what others are doing. This raises the level of ambition for educational development at our universities through friendly competition toward a mutual goal. It strengthens the arguments for adopting a CDIO approach at collaborators' respective universities. Evidence of success at competitors' universities can be a very persuasive force for change.

In order to facilitate interaction, the international CDIO collaboration sponsors a number of activities. These include: (1) workshops at which the key ideas are introduced, (2) regional meetings that allow participating universities within a geographic region to come together to exchange ideas and develop new approaches, and (3) annual international conferences that bring together educators from around the world to exchange key learning and successes that have emerged. We invite participation in all these activities, as well as contributions from programs engaged in the improvement of engineering education.

Summary

The transformation to a CDIO program affects all faculty members in a department or program as it resets the context and reorganizes the education process. This chapter examined twelve key success factors that facilitate organizational change and gave examples of how engineering programs incorporated these factors in their transition. The importance of faculty support and development was also highlighted. The discussion showed the ways that programs wishing to implement a CDIO approach to engineering education can take advantage of the experiences of existing programs and use the open-source resources available on the CDIO website. Chapter 9 creates a program evaluation framework based on the twelve CDIO Standards.

Discussion Questions

1. What strategies have you employed to implement change? Are they aligned with those suggested in this chapter?
2. What policies and incentives are in place to enhance faculty competence? How effective have they been?
3. Can you identify people, programs, and resources that support faculty development in teaching and assessment at your university?
4. How do you anticipate using the resources found at the CDIO website?

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Chapter 9
Program Evaluation

Introduction

In previous chapters, we described key characteristics of a CDIO program. First, we addressed *what* we should teach: learning outcomes that address disciplinary content, as well as personal and interpersonal skills, and process, product, and system building skills. We went on to discuss *how* we should teach: an integrated curriculum; a sequence of design-implement experiences in workspaces specifically designed to support the intended learning outcomes; integrated teaching, learning, and student assessment. In Chapter Eight, we presented approaches to enhance faculty competence in engineering skills and in teaching and assessment methods. We now address three key questions dealing with the effectiveness of the CDIO approach:

1. *How do we determine if programs are successfully implementing a CDIO approach?*
2. *How can we improve programs that are not up to standard?*
3. *What is the impact of implementing a CDIO program?*

These general questions of quality assurance are most appropriately answered by a process of program evaluation that is naturally set within the context of the 12 CDIO Standards.

Program evaluation is a process for judging the overall effectiveness of a program based on evidence of progress toward attaining its goals. The specific approach to program evaluation can take a variety of forms, depending on the conceptual framework and rationale for the evaluation. Evaluation of CDIO programs follows primarily a judgment model based on inputs, processes, and outputs. *Inputs* include feedback from personnel, use and usability of facilities and workspaces, and use and availability of resources; *processes* include teaching, assessment, evaluation methods; and, *outputs* are the intended learning outcomes for students and overall program outcomes related to the 12 CDIO Standards.

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One way to judge overall program quality is to focus on a program's progress toward implementation of the CDIO Standards described throughout this book. Because the standards address inputs, processes, outcomes, and to a limited extent, impact, program evaluation based on the CDIO Standards can provide program leaders with data upon which to determine whether programs are achieving their goals, operating effectively, allocating resources appropriately, and making a difference overall.

We use the term *standards-based program evaluation* to describe the approach we use with CDIO programs. This approach is consistent with a judgment model of program evaluation. A standard, in this context, is a criterion or characteristic that defines a program. Evidence of progress toward implementation of a CDIO approach is collected from multiple sources, using a variety of quantitative and qualitative methods. When this evidence is regularly reported back to faculty, students, program administrators, alumni, and other key stakeholders, the feedback forms the basis for making decisions about the program and its continuous improvement.

Standards-based program evaluation, using the 12 CDIO Standards, is consistent with accreditation models and other national evaluation approaches. This consistency is based on similar purposes. Both approaches set criteria, collect evidence of compliance with the criteria, and require plans to improve programs. In this chapter, we discuss the purpose and value of a standards-based approach to program evaluation as a way to determine if programs are successfully implementing a CDIO approach. In doing so, we identify key evaluation questions aligned with the standards and examine a variety of methods to collect data to answer the evaluation questions. We give examples of data collection and analysis in representative programs. We make connections of program evaluation results with the process of continuous improvement and give suggestions for improving programs that are not up to standard. Finally, we summarize results that give evidence of the impact of CDIO programs overall.

Chapter Objectives

This chapter is designed so that you can

- Recognize the characteristics of a standards-based approach to program evaluation.
- Identify key questions that guide program evaluation and align them with the CDIO Standards.
- Describe a variety of methods that provide evidence of program quality.
- Give examples of standards-based program evaluation.
- Emphasize the connections between program evaluation, continuous program improvement, and quality assurance.
- Evaluate the overall impact of programs that have implemented a CDIO approach.

Standards-Based Program Evaluation

The conceptual framework of program evaluation depends on the purpose and rationale for conducting the evaluation. For example, objectives-based models focus on the purpose of the program and the attainment of specified goals, objectives, and outcomes. In contrast, goal-free evaluation focuses on the outcomes without the specification of any pre-determined goals. Naturalistic approaches are broad in scope, focusing on human elements and processes of the program in specific contexts. Judgment models, such as program accreditation, address compliance with standard guidelines and tend to focus on inputs and processes. Management-oriented program evaluation focuses on key questions of decision makers, limiting the range of data collection to specific questions. These questions tend to emphasize the outcomes and overall impact of a program [1].

Evaluation of CDIO programs is primarily a judgment model, with components of objectives-based and management-oriented models. Similar to many accreditation models, judgments are made on the inputs to the program, for example, qualifications of the academic staff, access to modern engineering tools, workspaces, and such program processes as teaching, advising, and enrollment. Program evaluation, then, is a matter of showing compliance with criteria that address these inputs and processes. In recent years, accreditation models have broadened their scope to include outcome measures [2]. Similar to objectives-based models, program evaluation focuses on the attainment of program goals and specific program learning outcomes. Management-oriented models, such as *The Balanced Scorecard* [3] implemented at Linköping University, contribute components of strategic planning, allocation of resources, and measurement of impact, all of which broaden program evaluation beyond judgment and objective-based models.

Standards-based program evaluation describes any approach to evaluation that focuses on the explicit criteria, standards, and other components of the evaluation process [4]. This approach aligns well with the rationale for the three models presented—judgment, objectives-based, and management-oriented—and shares common features with them. Standards that address program objectives and outcomes focus on the end results of the program for the people it is intended to serve. These standards concern the cumulative results of the educational experiences offered to students by the program. Included are student learning outcomes in courses and other activities, as well as the culminating outcomes that are expected as a result of completing a program. Of course, it is hoped that most of these outcomes are the ones intended, but there also may be unintended outcomes.

In addition to outcomes, standards-based program evaluation examines the processes that lead to those outcomes. Process evaluation is the systematic review of what is happening inside the program and involves an evaluation of how the program is operating in order to meet its goals. Program processes may include admissions, advising, registration, student support services, teaching, learning, and internship and job placement. Examination of these processes helps to explain the program outcomes and points to features of the program that are more or less successful [5].

To a limited extent, standards-based program evaluation also measures the overall impact of a program by looking at what happens to participants and others as a result of the program. Such impact is often construed as long-term outcomes and may include the effects of the program on the larger community and society. Impact studies may look at workforce capabilities, ethnic and gender equality, and productivity. Such studies may follow graduates for their entire careers to determine the long-term impact of a program [6].

In evaluating a program within the framework of the CDIO Standards, we examine evidence of processes and outcomes, and to a limited extent, inputs and impact. Taking a broad view, Standards 1 and 6 address inputs; Standard 2 specifies the intended learning outcomes; Standards 3, 4, 5, 7, 8, 9, 10, and 11 focus on processes. While the standards do not specifically address long-term impact, the evaluation of our programs often includes questions related to students' future plans, alumni contributions to their engineering fields, and influences of a program on local, national, and international industries. The remaining standard, Standard 12, is the criterion for program evaluation itself, that is, a CDIO program takes a systematic and comprehensive approach to data collection and analysis and program improvement.

Standard 12—**Program Evaluation**

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

Standards-based evaluation is systematic in that it identifies and addresses a wide range of questions, uses a variety of methods to collect and analyze data, and uses the data to make decisions about program effectiveness and the need for continuous improvement. We now examine this systematic evaluation process as it applies to CDIO programs.

The CDIO Standards and Associated Key Questions

Program evaluation, as described in this chapter, is based on twelve best practices associated with a quality engineering education program. We refer to these best practices as the CDIO Standards. Before proceeding with a detailed discussion of the process of program evaluation, we present the rationale and organization of the standards themselves. The CDIO Standards were introduced in Chapter Two and discussed as the organizing theme of Chapters Three through Eight. They are listed in the appendix with a description, rationale, and rubric for each standard.

Rationale and Organization of the CDIO Standards

We developed and adopted the CDIO Standards in order to help programs as they address the perceived need of educating students who are able to conceive, design, implement and operate complex value added engineering products, processes, and systems in a modern, team-based environment. The standards form a bridge from the program goals to a tangible set of educational inputs, processes, and outcomes. They give guidance to individual university programs regarding how to proceed, and attempt to answer the central questions of engineering education reform that were first presented in Chap. 4.

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

It is important to understand what the standards are, and are not. They are a means of guiding programs toward fulfillment of specific needs and goals. They are a codification of best practice based on research and our collective experience around the world. They are intended to provide support for change in the direction desired by program stakeholders. They are designed to be consistent with national accreditation and evaluation criteria, yet also provide international benchmarks against peer institutions. In addition, the standards form the basis for program evaluation and continuous improvement.

The standards are intended to distinguish those programs which offer a comprehensive CDIO approach to education from those who incorporate only a few of the components. They were originally developed in response to program leaders, alumni, and industrial stakeholders who wanted to know how they would recognize CDIO programs and their graduates. Of the 12 standards, we sometimes distinguish seven that are distinguishing features of the CDIO approach:

- Standard 1—The Context.
- Standard 2—Learning Outcomes.
- Standard 3—Integrated Curriculum.
- Standard 5—Design-Implement Experiences.
- Standard 7—Integrated Learning Experiences.
- Standard 9—Enhancement of Faculty Competence.
- Standard 11—Learning Assessment.

The remaining five standards are indicative of good practice, but not necessarily distinguishing features of a CDIO approach: Standard 4—Introduction to Engineering, Standard 6—Engineering Workspaces, Standard 8—Active Learning, Standard 10—Enhancement of Faculty Teaching Competence, and Standard 12—Program Evaluation.

The standards do not include all components of an engineering program. They omit some of common inputs and processes, for example, faculty qualifications in their engineering disciplines, student advising and counseling, and classrooms and

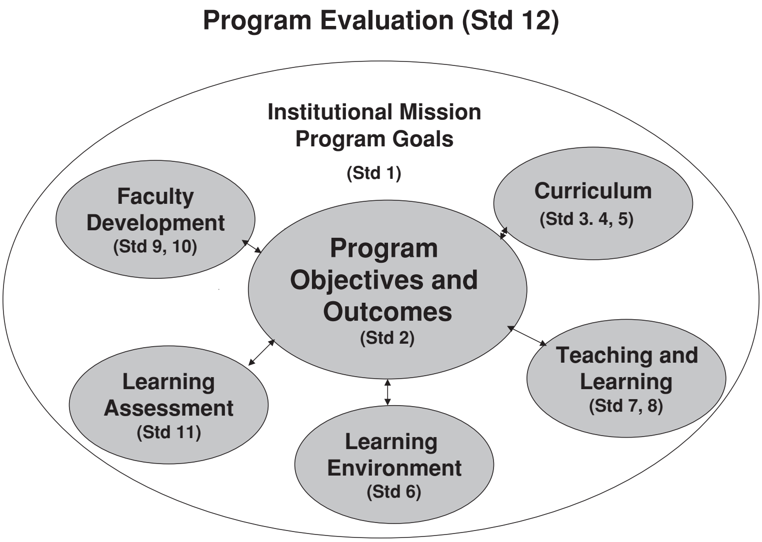

Fig. 9.1 Program evaluation and the CDIO Standards

libraries. This limited scope is deliberate in order to accentuate distinctions and bias toward a program vision that has been found to meet the program goals. Having said this, there is nothing in the standards that is absolutely unique to programs that have applied the CDIO approach. High-quality engineering education programs around the world have some of the inputs, processes, and outcomes discussed in the standards, and programs of the highest quality have many. The standards are offered as a guide for continuous improvement, regardless of a program's initial quality.

The standards can be organized in a way that is consistent with traditional program evaluation. As illustrated in Fig. 9.1, program evaluation focuses on the outcomes of the program and the processes that contribute to students' achieving those outcomes, as embodied in the CDIO Standards. The standards can be grouped into one or more focus areas: program mission and goals, curriculum, teaching and learning methods, the learning environment, learning assessment, and faculty development. Note that program evaluation, itself, is one of the standards.

Key Questions Aligned with the CDIO Standards

In planning an evaluation, key questions are posed for each important focus area. Table 9.1 illustrates the alignment of the key questions of an evaluation plan with the CDIO Standards. These key questions are derived from the descriptions of the CDIO Standards.

Table 9.1 Key questions aligned with the CDIO Standards

Key questions
Institutional mission and program goals
Standard 1—the context
To what extent is the product, process, and system lifecycle (CDIO) considered the context for engineering education in that it is the cultural framework in which technical knowledge and other skills are learned?
Program outcomes
Standard 2—learning outcomes
To what extent are detailed learning outcomes for disciplinary knowledge, personal and interpersonal skills, and product, process, and system building skills, consistent with program goals and validated by program stakeholders?
Curriculum
Standard 3—integrated curriculum
To what extent is the curriculum designed with mutually supporting disciplinary courses, with an explicit plan to integrate personal and interpersonal skills, and product, process, and system building skills?
Standard 4—introduction to engineering
How effectively does the introductory engineering course provide the framework for engineering practice in product, process, and system building skills, and introduce essential personal and interpersonal skills?
To what extent do introductory courses strengthen students' motivation for the field of engineering?
Standard 5—design-implement experiences
Does the curriculum include two or more design-implement experiences, including one at a basic level and one at an advanced level?
Teaching and learning
Standard 7—integrated learning experiences
To what extent do integrated learning experiences lead to the acquisition of disciplinary knowledge, as well as personal and interpersonal skills, and product, process, and system building skills?
Standard 8—active learning
How do active and experiential methods contribute to the attainment of program outcomes in a CDIO context?
To what extent are teaching and learning methods based on approaches that engage students directly in thinking and problem solving activities?
Learning environment
Standard 6—engineering workspaces
To what extent do students have access to modern engineering software and laboratories that provide them with opportunities to develop the knowledge, skills, and attitudes that support product, process, and system building skills?
To what extent are workspaces student-centered, user-friendly, safe, accessible, and interactive?
Learning assessment
Standard 11—learning assessment
How is assessment of student learning in personal and interpersonal skills, product, process, and system building skills, and disciplinary knowledge embedded in the program?
What have students achieved with respect to program outcomes?

(Continued)

Table 9.1 (Continued)

Key questions
Faculty development
Standard 9—enhancement of faculty skills competence
How are actions that enhance faculty competence in personal and interpersonal skills, and product, process, and system building skills supported and encouraged?
Standard 10—enhancement of faculty teaching competence
What actions have been taken to enhance faculty competence in providing integrated learning experiences, using active experiential learning methods, and assessing student learning?
Program evaluation
Standard 12—program evaluation
Is there a systematic process in place to evaluate programs against the 12 CDIO standards?
To what extent are evaluation results provided to students, faculty, and other stakeholders for the purposes of continuous improvement?

Key Program Evaluation Questions for Comparative Purposes

Because more than one hundred universities worldwide have adopted the CDIO approach, it is becoming important to establish processes that assure internal and external stakeholders that engineering programs are adhering to the CDIO Standards. The standards provide a vehicle for realizing the CDIO vision to transform the culture of engineering education. Five key program evaluation questions can be used to enhance quality assurance processes:

- How can institutions and programs evaluate their efforts and guide continuous improvement relative to the CDIO Standards, and determine if the resources that are being put into programs are having the desired impact?
- How can engineering program leaders determine the progress that has been made over time in the adoption of the standards across programs and the worldwide impact of the CDIO approach?
- How can engineering program leaders at regional levels verify a program's level of adoption of the CDIO Standards?
- How can the CDIO Standards be used to meet accreditation expectations intended to assure internal and external stakeholders that institutions and programs are of the highest quality? [7].

In summary, in a program that has adopted the CDIO approach, the criteria of success are the CDIO Standards. A program is considered successful if it can show evidence that the program components described in the standards are in place. Different stakeholder groups will emphasize subsets of the CDIO Standards, but all standards are important measures for at least one stakeholder group. In a later section of this chapter, we give examples of ways to document the extent to which each of the key evaluation questions has been answered in representative CDIO programs. We now examine a variety of methods to collect reliable and valid evaluation data.

Methods to Evaluate Programs

Once the key questions have been articulated, it is important to consider the source of the information and how the data may be collected within resource constraints of the program. Effective program evaluation makes use of multiple data collection methods at multiple points in the program. Some of the methods used in existing programs to determine quality and design plans for continuous improvement are described here. These include document reviews, interviews, surveys, instructor reflections, expert reviews, and longitudinal studies.

Document Reviews

In implementing the CDIO Standards, it is helpful to document plans and actions at each step in the process. For example, program mission statements and learning outcomes, curriculum designs, and course syllabi can be archived in order to document program development. Including the analysis of current facilities, teaching-learning methods, and assessment techniques in the documentation helps to identify best practices and areas of potential innovation. Data collected as the program is being implemented can guide its refinement and continuous improvement. Reports of student learning outcome assessment and evaluations of specific program components can provide the data for judging the success of the program in achieving its goals. A document review process focuses on the importance of establishing and maintaining a program archive. In our programs, these documents are reviewed internally but are not usually shared externally.

Personal and Focus-Group Interviews

Formal documents do not tell the whole story of a program's success. Personal and focus-group interviews can provide information about the effect of programs on students and other stakeholders. They have the advantage of being able to ask open-ended exploratory questions. For example, MIT uses focus-group interviews to gather data from students as they begin their programs and again as they complete them. Personal interviews have been conducted with instructors to gather information about the specific teaching and assessment methods they use in their courses. Focus-group interviews often provide more complete data than personal interviews because the group interaction generates additional questions and responses [8]. Some CDIO programs conduct focus-group interviews to evaluate courses. Panels of students, instructors, and course managers meet to review each course at the end of each term. Focus groups are also used to gather input from key stakeholders to define program outcomes. Examples of these focus groups were described in Chap. 3.

Written Questionnaires

Written questionnaires ask a common structured set of questions. They can be more efficient than interviews since they may be used to collect large amounts of information from diverse groups of respondents in the same time period. Moreover, it is possible to collect statistically valid data from large samples. Responses can be collected in person, by postal mail, by email, or online [9]. Examples of questionnaires used in CDIO programs include stakeholder surveys of the CDIO Syllabus, student ratings of faculty and courses, and exit surveys of graduating students.

Instructor Reflections

In memos or reports or instructor reflections, instructors summarize their experiences with teaching, learning, and assessment in their respective courses. These reflections may address the following:

- Intended learning outcomes and evidence that they have been met.
- Ways in which personal and interpersonal skills, and product, process, and system building skills have been integrated into their courses.
- Evidence that their teaching and assessment methods have been effective.
- Plans to improve the course in subsequent offerings.

These individual reports can be summarized across a program to form another source of information about the success of a program. Instructors can also meet with the program head, or the person responsible for instructional quality, to discuss the reflections and other issues related to curriculum and instruction.

Faculty members at MIT have been writing reflective memos since 1999. They report that the underlying value of these memos is the opportunity to reflect on their teaching and record proposed changes while the experience of the term is still fresh in their memories. This practice has made a significant contribution to the improvement of teaching and learning in the program [10]. Annual summaries of these reflective memos are also valuable sources of information for regional and national accreditation reviews.

Program Reviews by External Experts

It is often helpful to have people who are not directly connected to a program provide an independent evaluation. External evaluators may be provided with questions such as those listed in Table 9.1. In preparation for visiting committees, program personnel often prepare summary materials that include

- A program evaluation plan.
- Information about the program.

- A self-evaluation report identifying program strengths, weaknesses, and issues related to the standards.
- Specific questions that program stakeholders would like to address.

Program reviews by external experts include regional and national accreditations, institutional reviews, and certification or approval ratings from engineering professional associations. For example, in Sweden, programs are reviewed by the Swedish National Agency for Higher Education. A description of a recent review is found in Box 9.3 in a later section of this chapter.

Longitudinal Studies

In longitudinal studies, data are collected from groups of respondents over time. Data may be collected from cohort groups, that is, students who go through the program together, at regular intervals during and after their involvement in the program, or from different groups who are studied at the same point in their programs. Interviews and questionnaires are common methods for collecting longitudinal data. Linköping University provides a good example of a longitudinal study that examines students' expectations and satisfaction from the time they enter the Applied Physics and Electrical Engineering program until the time they complete their degree requirements. This longitudinal study is described in Box 9.1 in a later section of this chapter.

Evaluating A Program Against the CDIO Standards

In collecting data to answer the key program evaluation questions, it is important to bear in mind four factors related to evidence:

- Criteria of success for each important area, that is, what does a good example look like?
- Evidence that will indicate that the program is doing well in each key area.
- Kinds of evidence that will persuade key stakeholders.
- Ways in which the evidence should be summarized for different stakeholder groups.

Once reliable and valid data have been collected and analyzed, the results can be organized in such a way as to answer the key evaluation questions posed earlier in this chapter. Similar to most judgment models of evaluation, determination of a program's progress toward meeting the CDIO Standards may be accomplished through self-evaluation. The CDIO approach proposes a six-level rating scale, or rubric, to indicate progress toward the planning, implementation, and adoption of each standard. A generic rubric for self-evaluation is found in Table 9.2. The rubrics are designed to encourage planning and allow various styles of implementation and adoption.

Table 9.2 Generic rubric for self-evaluation

Rating scale	Description
5	Evidence related to the standard is regularly reviewed and used to make improvements
4	There is documented evidence of the full implementation and impact of the standard across program components and constituents
3	Implementation of the plan to address the standard is underway across the program components and constituents
2	There is a plan in place to address the standard
1	There is an awareness of need to adopt the standard and a process is in place to address it
0	There is no documented plan or activity related to the standard

Table 9.3 Rubric customized for Standard 5—design-implement experiences

Rating scale	Description
5	The design-implement experiences are regularly evaluated and revised, based on feedback from students, instructors, and other stakeholders
4	There is documented evidence that students have achieved the intended learning outcomes of the design-implement experiences
3	At least two design-implement experiences of increasing complexity are being implemented
2	There is a plan to develop a design-implement experience at a basic and advanced level
1	A needs analysis has been conducted to identify opportunities to include design-implement experiences in the curriculum
0	There are no design-implement experiences in the engineering program

Rubrics are customized for each of the 12 CDIO Standards based on the generic rubric. As an example, Table 9.3 illustrates the generic rubric customized for CDIO Standard 5—Design-Implement Experiences. The CDIO Standards v2.0 with customized rubrics is found in the appendix.

In addition to the numerical ratings, each program describes the evidence that is the basis for the rating of each standard. This evidence serves as the foundation for decisions about program improvement and quality assurance. As an example, Table 9.4 shows evidence that programs cited in a survey of self-evaluations, again related to CDIO Standard 5—Design-Implement Experiences. Initially, the programs that were involved in the development of the CDIO approach declined comparisons of ratings across institutions because of the inherent subjectivity of the self-rating process. They believe that the real value of a program self-evaluation is the contribution to its own continuous improvement process. Despite these concerns, a number of CDIO programs from universities around the world agreed to participate in periodic surveys of their self-evaluation results. The surveys' purpose was to help determine the overall impact of the CDIO approach around the world [11].

Table 9.4 Examples of evidence for self-evaluation of CDIO Standard 5—design-implement experiences

Scale	Examples of evidence
5	Feedback provides direction for revision of our cross-curricular, practice-oriented projects in order to improve student performance
4	In addition to evaluating design-build-experience skills in all courses supporting these DBEs, there is a competency module in which students are evaluated with respect to personal, communication, presentation, ethics, law, and project management knowledge and skills
3	We now have a basic design-implement experience in year 1, an intermediate design-implement-test experience in year 2, and several advanced design-implement-test experiences in years 4 and 5
2	There is a plan for all 1st-year students to take an introductory design course
1	We have realized that some design-implement experiences are needed in the first years
0	There are no design-implement experiences in the engineering program

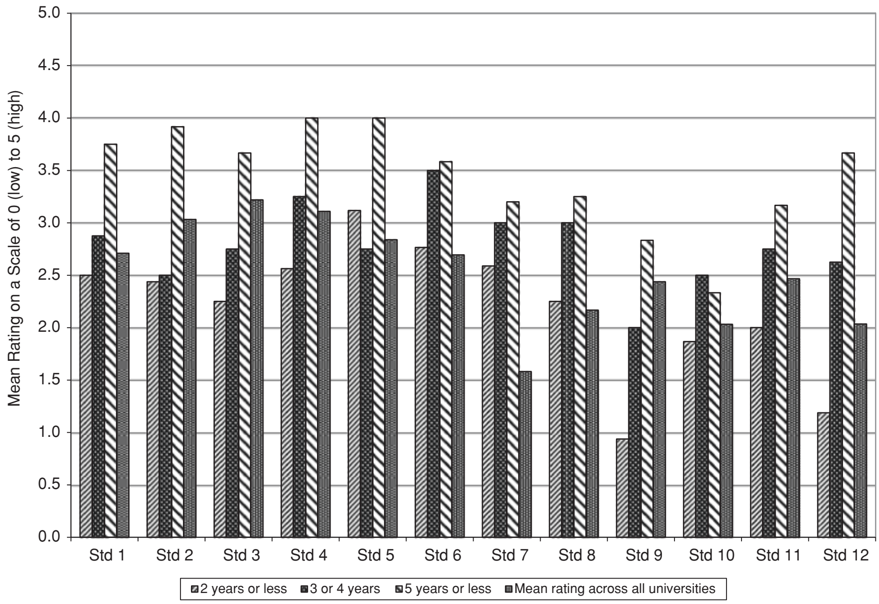

Fig. 9.2 Self-evaluation using the CDIO Standards by number of years using a CDIO approach

Survey results showed that the factor that accounts for most of the wide variation in the self-ratings is the number of years that a program has been engaged engineering education reform. Figure 9.2 shows the average ratings reported by programs that had been using a CDIO approach for 2 years or fewer, 3 or 4 years, and 5 or more years.

A few trends can be seen in the self-evaluations using the CDIO Standards:

- Design-implement experiences (Std 5) and engineering workspaces (Std 6) seem to be the focus at the start of a program's reform initiatives.
- New methods of teaching, learning, and assessment (Std 8 and Std 11) are implemented after the second or third year of program reform.
- While programs begin by specifying program outcomes (Std 2) and re-designing curriculum (Std 3), it is not until about the fifth year that programs rate themselves as having met those two standards.
- Although CDIO programs begin program evaluation at the start, they need a few years to implement comprehensive systematic program evaluation (Std 12).

Summarizing program self-evaluations and analyzing trends of CDIO programs around the world can shed light on areas in which engineering programs might collaborate in the continuous improvement of engineering education.

Continuous Program Improvement Process

In addition to providing information about a program's progress and status, self-evaluation against the CDIO Standards enables a program to plan specific actions for continuous improvement. Standards relating to input, processes, and outcomes are all examined for areas that fall short of full implementation or that lack the quality desired by each respective program. Figure 9.3 illustrates a continuous program improvement process at four stages: input, processes, outcomes, and improvement. At the *input* stage, a program examines data related to its mission, goals, and purpose, the adequacy of its resources, and the qualifications of faculty and staff. At the *processes* stage, a program looks at the effectiveness and efficiency of its processes, including teaching, advising, student assessment, and other activities. The *outcomes* stage focuses on the analysis of results, including short-term learning outcomes of students, as well as long-term impact of the program on stakeholders, the local community, and professional disciplines. The process is not complete, however, until evaluation results from the first three stages are used to improve the program. The cycle is continually repeated, collecting and analyzing data, and using results for program improvement.

To illustrate the way that program evaluation data is used as the basis for continuous improvement and decision-making, Box 9.1 describes a longitudinal study at Linköping University [12]. The purpose of the study was to provide reliable and valid data to the program in *Applied Physics and Electrical Engineering* to support its goal of making its program more attractive to students, focusing on students from underrepresented populations.

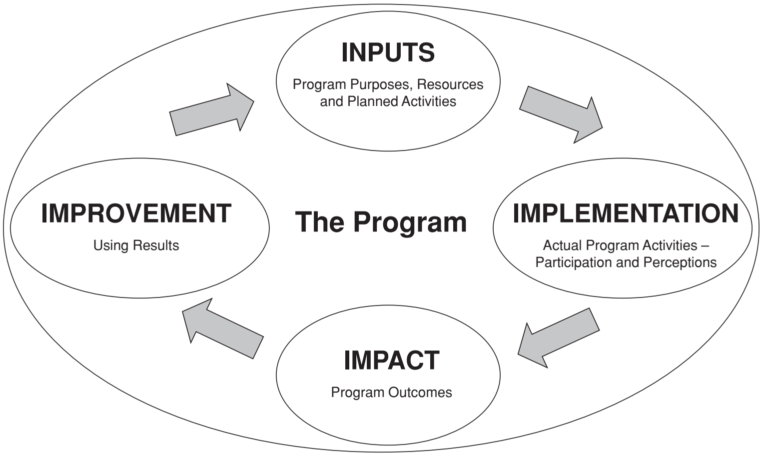

Fig. 9.3 Continuous program improvement process

Box 9.1 Longitudinal Studies for Program Evaluation at Linköping University

The program board of Linköping University's *Applied Physics and Electrical Engineering Program* (Y-Program) initiated a study with the aim of inquiring into students' self-reported experiences related to:

- Their expectations when they started the Y-program.
- The curriculum and study environment in different phases of the program.
- Ways in which the program prepared them for their professional lives.

The result was of great interest and value for further development of the curriculum, as well as for the improvement of the program.
The design of the study is based on:

- Questionnaires distributed to all students in each cohort, twice the first year, once a year during their study years 2 through 5, and a questionnaire one year after graduation.
- Interviews with ten students, five male and five female, in each cohort. The same students are interviewed twice the first year, and once a year during their study years 2 through 5.
- Telephone interviews with the students one year after graduation.
- Interviews with lecturers.

Results from the study have continuously been fed back to the program board, and consequently, the Y-Program has improved in a number of ways, including taking action to attract and retain more students from underrepresented populations. Reports and conference papers have been published on the Y-Program website. When interpreting the results of these studies, it

(*Continued*)

Box 9.1 Longitudinal Studies for Program Evaluation at Linköping University—Cont'd

is important to note that outcomes of a study program cannot be predicted merely from the intentions of the program or the prerequisites and intentions of the students. It is a complex interplay between individual, institutional and political factors. In this longitudinal study, each new cohort enters with different experiences. The intentions of the program are, therefore, experienced differently. Results must be related to a context, in time and situation, as well as to reflections on the interactions between intended and unintended consequences of the actions taken.

– E. Edvardsson-Stiwne, Linköping University

Overall Impact of CDIO Programs

As stated in Chaps. 1 and 2, the overall goals of the CDIO approach are explicitly to improve the education of engineering students, and implicitly to educate more engineers. The explicit statement of the goals is—To educate students who are able to:

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

Implicitly, the approach seeks to develop programs that are educationally effective *and* more exciting to students, attracting them to engineering, retaining them in the program and in the profession.

A standards-based approach to program evaluation provides evidence of a program's overall success in meeting these goals and of the broader impact of engineering education programs. To the extent that the standards measure inputs, processes, outcomes, and impact, program evaluation also measures improvement in these features. Considering the required development and implementation time from specification of mission to inputs, processes, and outcomes related to student learning, it is still relatively early to determine the overall impact of CDIO programs on their respective stakeholders. However, a few preliminary results are available.

Preliminary Results of Inputs, Processes, and Short-term Outcomes

For several years, we have been collecting and analyzing data related to the key program evaluation questions posed earlier in this chapter. The use of multiple methods of data collection has yielded these preliminary evaluation results for inputs and processes:

Self-reports of program evaluation status indicate that many participating programs have engaged in, or completed, the re-design of their respective curricula, the assessment of student skills, and the improvement of faculty competence.

Self-reports and site visits indicate significant development and high degrees of student engagement in design-implement experiences and engineering workspaces.

Course evaluation results and instructor reflection reports indicate that faculty are using a wide variety of teaching and assessment methods.

We are using the evaluation tools to document steady progress toward full implementation of the inputs and processes standards. In addition, early indications show that programs are achieving their goal of improving the education of students, and the goals of attracting and retaining them in the profession.

- Self-reports indicate that participating programs have adopted a mission that includes Conceiving-Designing-Implementing-Operating as the context and most have engaged in stakeholder surveys to set learning outcomes.
- Annual surveys of graduating students have indicated that they are developing intended program knowledge and skills.
- Student self-report data indicate high student satisfaction with the design-implement experiences and workspaces that promote a sense of community among learners.
- There is no evidence of any decrease in student knowledge or skills in technical fundamentals caused by, or as the result of, the integration of personal and interpersonal skills, and product, process, and system building skills.
- Longitudinal studies of students show increases in program enrollment, decreasing failing rates, particularly among students in underrepresented populations, and increased student satisfaction with their learning experiences. The description of a series of longitudinal studies found in Box 9.1 is an example of such an approach.
- Studies of student self-efficacy are being used to determine students' progress toward the achievement of specific personal and interpersonal skills. A description of the development and use of a series of self-efficacy studies is found in Box 9.2.

Box 9.2 Student Self-Efficacy of Selected Personal and Interpersonal Skills

Self-efficacy, the self-belief that one can perform a narrowly defined set of tasks, is a strong predictor of the persistent pursuit of goals in all walks of human life, including the choice and pursuit of careers among adolescents and young adults. For example, self-efficacy for mathematics is a determining factor explaining which 15 year-old students enter university to study science, mathematics, and engineering; and, self-efficacy for engineering is a major factor in retention levels among undergraduates studying engineering. Because self-efficacy is most directly influenced by the successful

(*Continued*)

Box 9.2 Student Self-Efficacy of Selected Personal and Interpersonal Skills—Cont'd

performance of tasks in different domains, it is a valuable tool in the assessment of project-based learning and the CDIO approach that emphasize the use of professional practice.

Examples of using the CDIO syllabus to develop task statements

3.0 Interpersonal skills, teamwork, and communication	
3.1 Teamwork	
3.1.2 Team operation	
Goals and agenda	Organize a process that gets a team to set clear objectives they can all agree on
The planning and facilitation of effective meetings	Encourage team members to follow consistent rules for team meetings
4. Conceiving, designing, implementing and operating systems in the enterprise, societal and environmental context	
4.4 Designing	
4.4.1 The design process	
Appropriate optimization in the presence of constraints	Design a system that fits within its allocated budget
Iteration until convergence	After completing a first design, go back and reduce its complexity and cost to meet project goals

The measurement of self-efficacy is best performed through the use of relatively specific definition of tasks that are in some way established as representing a well-defined domain. The CDIO Syllabus is a useful foundation for selecting tasks because its hierarchical structure identifies levels of capability that lend themselves to writing the relatively specific tasks that are called for in self-efficacy studies. For example, in the CDIO Syllabus area of Interpersonal Skills (3.1), one of the sub-domains is Team Operation, which contains a fourth-level of subject areas that include *Choose goals and agenda*, and *Execute the planning and facilitation of effective meetings*. The items prepared for a survey must select tasks that take into consideration the different levels of undergraduate understanding and provide tasks of appropriate difficulty, and here the tasks were selected for first- and second-year students. Studies of team capabilities have asked that first-year students rate their confidence that they can "Organize a process that gets a team to set clear objectives they can all agree on;" and separately, that they can "Encourage team members to follow consistent rules for team meetings."

The second example provides self-efficacy task items based on the CDIO Syllabus domain of 4.4 Designing. The sub-domain of 4.4.1 The Design Process includes the need for students to be capable of creating designs that optimize a design within the given constraints, and then be capable of continuing to iterate the solution over time until it converges on a successful design. It should be noted that the items provided here are not intended for the study of particular engineering courses, but should instead be seen as measures of undergraduate progress relative to the CDIO Syllabus. This type of measurement also enables the comparison of results across courses.

Studies of a number of first-year project-based learning courses with engineering content have shown that courses with professional practice increase student self-efficacy. One of the studies has specifically shown that students with higher self-efficacy for the performance of engineering tasks are more likely to select an engineering major and persist in engineering over time.

– W. A. Lucas, Massachusetts Institute of Technology

Studies of Long-term Outcomes and Overall Impact

The CDIO Standards focus on inputs, processes, and short-term outcomes. The standards do not specifically address long-term impact, which is difficult to measure, and inherently involves long periods of time before meaningful data can be obtained. The evaluation of CDIO programs may also include questions related to students' future plans and employment after leaving the university. Such data can show attitudinal change and the beginnings of career behaviors that suggest long-term impact. In a much longer time frame, surveys reveal alumni contributions to their engineering fields, and the influence of a program on local, national, and international industries.

A different dimension of impact is seen by the breadth of applicability of the CDIO approach. Program evaluation based on the CDIO Standards has been applied throughout Sweden to evaluate science, technology, and engineering programs at ten different universities. Box 9.3 describes the approach to program evaluation taken in 2005 by the *Högskoleverket*, the Swedish National Agency for Higher Education [13]. The exercise and subsequent survey found the CDIO Standards to be broadly applicable and valuable in identifying pathways to program improvement.

Box 9.3 CDIO Program Evaluation and the Swedish National Agency for Higher Education (HSV)

The *Högskoleverket* (HSV), the Swedish National Agency for Higher Education, is the government agency responsible for the evaluation of university education in Sweden. Courses and professional degree programs are evaluated every six years. HSV also evaluates applications from universities and colleges to start new programs at bachelor, master, and doctoral levels.

In 2005, an evaluation of the *civilingenjör* engineering degree programs took place. These programs were 4.5 yr integrated engineering programs, now 5 years, roughly equivalent to Master of Science or *Diplom-Ingenieur* degrees. There are about 100 such programs in Sweden at about 10 universities. The programs range across all domains of science and engineering, including engineering physics, mechanical engineering, information technology, and industrial engineering. The questions are divided into university-level questions and program-level questions. During this evaluation process, HSV decided to add an overall program evaluation component to

- Complement the responses to the basic questions in order to attain a more comprehensive evaluation of the university and program.
- Give the external review panel an additional instrument for its analysis and evaluation, and
- provide the universities and programs with an instrument that could be applied as a basis for future continuous improvement efforts.

The CDIO Standards were chosen for this purpose, with modifications to adapt the standards to the context. When the self-evaluations were complete, program managers were surveyed to determine the usefulness of the CDIO Standards as a basis for program evaluation.

Survey and interview results indicate that the CDIO Standards are relevant and applicable to a wide range of programs, and that taking steps toward implementing the standards would improve program quality. Survey results also indicated that the standards' most important benefit is that they provide a basis for systematic program development. There were some concerns that the emphasis on personal and interpersonal skills, and product, process, and system building skills in the CDIO Standards might lessen the importance of disciplinary knowledge and engineering research. This concern can be addressed by supplementing the CDIO Standards with other key questions and instruments in an overall program evaluation.

– **J. Malmqvist, K. Edström, S. Östlund, S. Gunnarsson**

As was acknowledged above, program evaluation based on the CDIO Standards may not address all the key questions needed for a complete picture of a program. As was found in the example in Sweden, other data collection activities may be required to supplement those related to the CDIO Standards.

Summary

The CDIO Standards are useful in several ways for evaluating programs and curriculum change. They are based on the needs, goals, and approaches identified by CDIO programs and are founded on scholarship and emerging best practice. They provide a framework for the key questions focused on evaluation of program inputs, processes and outcomes. They can be applied flexibly to a wide range of programs, institutions, and academic cultures. The self-evaluation process results in specific actions for continuous program improvement and can be carried out on a regular basis. Furthermore, the standards can be used to guide new program development. They are not a generic program evaluation tool but emphasize the specific features of an engineering education set in the context of conceiving, designing, implementing and operating. The key questions and associated rubrics allow programs to evaluate current status, identify areas of potential improvement, plan reform, and benchmark their programs against peer programs worldwide.

The application of a standards-based approach to program evaluation is not without limitations, however. The key challenges to effective program evaluation are focused in two areas: (1) implementing a variety of program evaluation methods to gather data from students, faculty, program leaders, alumni, and other key stakeholders that appropriately address the range of program outcomes; and, (2) documenting a continuous improvement process based on program evaluation results. Most engineering programs collect volumes of data about their students, faculty, facilities, and stakeholders. The challenge is to analyze the data and summarize results into information that is useful for decision-making.

Some programs have been using this standards-based program evaluation approach for more than ten years. Others conduct similar program evaluations as they begin their reform process and as they project their desired status in 2 to 5 years. In Sweden, academic groups responsible for the evaluation of higher education programs have piloted the CDIO Standards as a component of their evaluation processes. The standards are also consistent with evaluative criteria of national accreditation groups in the United States, Canada, the United Kingdom, and South Africa. With its emphasis on continuous program improvement, the standards-based approach augments accreditation reviews.

To this point in the book, we have examined, in detail, the key characteristics of CDIO programs, approaches to the design and development of a CDIO approach, and methods to implement and evaluate programs. We have seen examples from representative programs at each stage in their planning, implementation, and evaluation. In the final two chapters, we look back at the historical context of engineering education reform and forward to anticipated changes in future engineering education programs.

Discussion Questions

1. How can you use the CDIO Standards as the framework for evaluating your own programs?
2. What types of data or evidence do you rely on in your decisions about engineering programs?
3. How do you use evaluation results to improve curriculum, teaching and learning, student and instructor satisfaction, and learning spaces in your programs?
4. What would be the major outcomes of implementing a CDIO program in your institution?

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Chapter 10
Historical Accounts of Engineering Education

Introduction

When engaging in the reform of engineering education, it is important to understand its historical context. For more than 150 years, educational institutions have played a major role in shaping the skills and professional identities of engineers. During this period, the appropriate approach to engineering education has been the subject of constant discussions and controversy. Major changes have occurred both in the way engineering education is organized and in its relation to science education. Radical changes have also occurred in the technologies and technical specialties within engineering. Despite this history, and particularly in view of the controversies surrounding the role of engineering education since the late 1960s, engineering schools have been surprisingly stable in their basic philosophy regarding the structure and core content of the engineering curriculum. Only modest reforms have been implemented in the curriculum and pedagogy of engineering education in several decades. Most of these reforms have been focused on increasing the number of technical engineering topics and solving the resulting problems of disciplinary congestion.

By the 1990s, organized efforts in both the United States and Europe raised basic questions about the relevance of engineering education as it had developed since World War II. The problems included a lack of practical skills in modern engineering training, the lack of relevance for industry of the science being taught, and the kind of analytical qualifications being awarded in engineering education compared with visions of engineers as creative designers and innovators of future technologies. With its emphasis on science and knowledge structured around technical disciplines, engineering education developed into an education of technically skilled cooperative workers. However, many felt that the knowledge and broad innovative capacity needed to produce creative design engineers able to cope with contemporary technological change seemed to be lacking in engineering education.

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Several educational initiatives have addressed these issues and attempted to outline plans to reform engineering education. Some focus on engineering curriculum or pedagogy while others develop completely new engineering programs based on new technologies. Other initiatives combine business, management, and organizational understanding with engineering, or alternatively emphasize the creative and design aspects of engineering. Some reform initiatives have been supported by grants from government agencies, such as the National Science Foundation (NSF) in the United States; others have arisen from the Bologna Process that attempts to promote a unified system of education across Europe. While most initiatives focus on local, regional, or national experiments and reform, the CDIO Initiative is multinational, with open-source resources, and a broad, comprehensive methodology.

Contemporary tensions in engineering education may be deeply rooted in the diversity of modern technologies. The applications of these diverse technologies throughout society require increasing differentiation in the education of engineers. This diversity has already presented new challenges to the definition of engineering competence. The diversity of technologies presents new challenges to an engineering institution's sense of unity, identity, and standardization of professional preparation. Despite the complexity and multiplicity of technologies, institutional unity and its manifestation in a common engineering core curriculum have so far been successfully maintained by the engineering profession and by elite engineering universities. Nevertheless, the policies of identity formation and the creation of a homogeneous image of engineering are issues that need to be taken seriously, both in historical accounts and in contemporary reform initiatives. Engineering identity plays a vital part in educational reform and negotiations for change.

Critical accounts by observers close to the situation point to the need for reform in engineering education [1, 2]. Other critics seem more confident in the achievements of engineers in society, and argue for the continuation of a traditional science-based engineering curriculum [3]. From their perspective, technology and the natural sciences are two distinctly separate approaches to knowledge [4]. Their studies contradict the popular misleading notion that engineering science is *applied science*. However, they do not raise critical issues related to the social and institutional dependencies of technology. Even engineering schools and professional institutions have supported the idea of a close relationship between science and technology by asserting that natural sciences are the core foundation of engineering. Contemporary developments in the natural sciences and engineering sciences have blurred the boundaries. New approaches of *techno-science* seem to be gaining ground as the characterization of the ties between modern science and technology, leaving neither one in a subsidiary role [5]. These new approaches recognize the role of technology as a contributor to scientific achievements and change the basic idea of nature and technology.

The basic question is whether the critics are pointing to problems that will require radical reforms and transformations or to a crisis in engineering education that will go away, as has happened so often before when technology and engineering have been criticized. The view that technology drives change and innovation seems to be less criticized today than in the 1970s. At the same time, there is a crisis in engineering practice itself that relates to problems in the conception and use of technology, and in the needs expressed by industry and society pushing for reform.

The objective of this chapter is to set the CDIO approach in a historical context that traces the tensions of engineering practices, institutional changes, identity formation, and technological developments that are the context for modern engineering education. The intent is to highlight the complexities of the historical context, and not necessarily to produce a natural evolutionary history of engineering education that led to the development of the approach. The first section describes the early establishment of civil (non-military) engineering education, and illustrates models of engineering education that reflected diverse national identities and perceptions of the role of engineers in society. The next section delineates the role of engineering in industrial and societal development and how that role created the framework for the classical engineering specialties that led to international standardization of engineering subjects. The third section emphasizes the transformation to a *science* of engineering after World War II when more engineering science subjects were added to traditional natural science subjects. The discussions highlight the move away from practical skills in recent decades due to the diminishing need for skilled technicians and craftsmen who once formed an important recruitment base for engineering education. A description of the contemporary explosion in the number of new engineering disciplines, schools, and programs focusing on technological domains leads to a discussion of the controversy about what should be the engineering core curriculum of the future.

Chapter Objectives

This chapter is designed so that you can

- Recognize historic changes and institutional differences in engineering education.
- Recognize the controversy over how engineering experience and practice should be represented in education.
- Understand the contribution of engineering education to the construction of engineering identity.
- Explain the reasons that reform initiatives have developed in recent years.
- Evaluate the controversy between engineering problem solving approaches and the natural sciences as the foundation for an engineering core curriculum.
- Be inspired to experiment with new ways to provide students with engineering competencies.

The Genesis of Engineering Education

Tensions between theory and practice have permeated engineering education since its formal inception in the 19th century. Scholars in the United States have used the metaphor of a swinging pendulum to describe various waves of practical orientation versus theoretical priorities setting the agenda for engineering education [6]. A closer study reveals a spectrum of positions, ranging from practical, skilled, craft-based technical education to science-based educations that developed in engineering schools and technical universities. The idea of the swinging pendulum is also seen in institutions with polar differences in identities and focus, as was the case for a long time in several European countries.

Engineering professions emerged during the 19th century. Civil engineering developed first, as an offshoot of military engineering, which focused on the construction of armaments, fortifications, and infrastructure [3]. Early industrial work was based on practical skills and crafts and led to the establishment of technical schools. Engineering, on the other hand, was based on a vision of technical development and the use of systematic, analytical approaches, similar to the French idea of *polytechnique* [7]. This idea was developed and promoted through the building of *Ecole Polytechnique* in 1792, marking the beginning of a new era of civil engineering education. The ideas permeated both Europe and the United States in the first half of the 19th century and led to the establishment of a new type of institution of higher education. At the same time, military schools, such as West Point in the United States, were heavily influenced by the analytical approaches that developed from the polytechnic idea. The practical and theoretical approaches led to distinct institutional structures of technical engineering and engineering education in Europe and the U.S. What today may seem to be a homogeneous profession with a well-defined international identity has a hard-won and conflict-ridden history. We now take a brief look at the evolution of engineering education in France, northern Europe, the United Kingdom, and the United States.

Engineering Education in France

In France, engineering institutions developed according to the structure of French government institutions and industry [8]. Inspired by the idea of *polytechnique*, the *grande écoles* have been the core of French state education, setting the ideal standards for the education of engineers. Besides working in government institutions, engineers were involved in creating the new infrastructures demanded by growing cities and industries in need of transportation, energy, and communication. In this context, the technical sciences were seen as applied sciences. This thinking was based on the assumption that mathematical theory and general principles of science would form a foundation on which to improve technology moving it from the level of practice and skill-based experience to a higher form of practical knowledge.

Other engineering schools were established, several of which were focused on emerging sectors of industrial importance, such as the mining and mechanical industries which supplied agriculture and factories with new technology-based equipment. Though practical training was included and the demands of industry influenced the content of the curriculum, the elitist structure of these engineering schools maintained the hierarchy and roles of theoretical training.

Engineering Education in Northern Europe

In northern Europe, the dominant structure of engineering education consists of two models of engineering recruitment and education. One model, the *fachhochshulen,* is based on a practical education that recruits skilled craftsmen from industry and trades. This line of education developed in the late 19th century from technical schools to supplement the skills of workers coming from apprenticeship-based craft training by providing more theoretical subjects ranging from technical drawing to calculus [9]. The second model is a university-like academic engineering education, typically differentiated from the more discipline-oriented university education in natural science. Often named *technische hochshulen* (renamed *technical universities* in the late 20th century), a variety of technical universities developed in Germany and the Scandinavian countries to meet local institutional traditions. The basis for these two models was the strong tradition of skilled workers and the continued differentiation in identity, supported by two different recruitment paths: one offered to the practically skilled engineers, the other to the academically trained engineers coming directly from secondary school.

The second model gained legitimacy from the idea that the technical universities contributed to the production of reason, while the model of the *fachhochshulen* established its legitimacy by emphasizing its contribution to progress through its focus on quality techniques, the usefulness of practical engineering skills in industry, and the application of technology [10]. Engineers with academic educations contributed for more than 50 years to the construction of societal infrastructures and institutions [11]. Some of these theoretically trained engineers contributed to the rise of new industries following inventions in chemistry and electronics. However, in the 19th century, the numbers of practically skilled engineers still dominated industrial development in both the mechanical industries and in mining. Even in Germany where the theoretical training at engineering universities was initiated and supported by the creation of research and development facilities in larger corporations, the contribution of engineers in industrial innovation came from their practical experiences and systematic experiments, and only in small part from theoretical, science-based knowledge [12].

Engineering Education in the United Kingdom

In the United Kingdom, a quite different institutional model developed. Engineering was seen as growing from practical skilled crafts and was therefore kept from the universities and the sciences. Although the idea of a polytechnic education found its way to the U.K. in the form of polytechnic institutions, its implementation resembled the class structure in society where leadership in government and industry was dominated by university graduates, and where engineering was seen as a secondary trade—important but based in practical skills.

This division kept engineering education at a distance from the universities for quite some time.

In addition to the specific character of engineering education and the image of practical work in the U.K., the British system of accreditation formed an important difference between the systems created in Germany and France, which dominated continental Europe. In Europe, government committees defined the qualifications of engineers through their educational programs. The British system of accreditation emphasized practical skills and engineering experience, and it also supported the idea that engineering competencies were of a different nature than the academic qualifications given by universities. The U.K. system of accreditation has been copied to some extent in the United States.

Engineering Education in the United States

In the United States, mechanical engineering and civil engineering were among the first fields of engineering. Mechanical engineering emerged from the rich and diverse machine shop and agricultural machine cultures that sprang up to support industrialization. The earliest institution, Rensselaer Polytechnic Institute in New York, was founded in 1824 and acquired its modern name in 1861. Although its name resembles *polytechnique,* Rensselaer exemplified an American approach to engineering education that emphasized practical, industrial, and agricultural experiences for students, with comparatively less emphasis on mathematics and science. Other schools founded in succeeding decades emulated this essentially advanced apprenticeship model. In the mid-19th century, the establishment of the Agricultural and Mechanics (A&M) schools and land grant schools, including the Massachusetts Institute of Technology in 1861, reinforced this practical approach with close ties to industry, a dominant focus on practical knowledge, machine shop work, with little independent faculty research.

During the late 19th century, American engineering educators, for example, Robert Thurston, recognized the strengths of the European systems and began to advocate for an increased presence of science and mathematics in the curriculum. This view coincided with an increasing desire for professional respect for engineering equal to fields such as medicine and law. Thurston's agenda also included the addition of a research emphasis. Many activities were included under this research umbrella, often through engineering experiment stations modeled on those in agriculture [6].

Although stirrings of new approaches appeared during the 1920s and 1930s, American engineering education remained largely within this practical, industrial orientation until World War II. In contrast, European schools, with such leaders as Felix Klein at Göttingen, excelled at applying scientific and theoretical approaches to engineering problems. During this period, intellectual leaders in the U.S. with European educations, for example, Theodore von Kármán (a student of

Klein), transferred the idea of a more science-based type of engineering training to American institutions [6].

The practical approach of engineering institutions in the U.S. and in the polytechnics and *fachhochshulens* in Europe were of major importance to the development and implementation of technology in industry and society. These institutions influenced the formation of a professional engineering identity. Although this fact is recognized in contemporary discussions, it is overshadowed by the focus on the theoretical science-based training that forms the modern ideal of formalized engineering teaching. The tension originates from the creation of an engineering identity where attempts to distance engineers from skilled technicians and their apprentice-based training resulted in a focus on an academic tradition based on the vision of the polytechnic institutions of higher education.

Engineering and Industrial Development

Many engineering universities and schools originate from civil and mechanical engineering developed during the first part of the 19th century. Their graduates were employed in government institutions or involved in the creation of public and private companies that developed with the building of new infrastructures: transportation systems, roads, bridges, harbors, canals, ships, sewers, water supplies, and eventually, systems producing and distributing gas. Engineers' responsibilities and contributions to progress were based on their roles as constructors of the material pillars of modern society. Later, the view of their roles expanded to include engineers as innovators and system builders because of their contributions to new institutions, new knowledge, and the technical infrastructure [2]. To legitimize large investments in infrastructure, decision makers required hard data, and this need matched the focus on formal, science-based knowledge. The need to legitimize development also supported the creation of hierarchical and bureaucratic technological institutions. The idea of a technocracy that could support and even contribute to government policy was, therefore, consistent with the basic patterns and structures of knowledge created in relation to these large construction and infrastructure projects. For example, the connection in France between the idea of a *polytechnique* and the role of government bureaucracy is illustrated in the ideas of Hans Christian Oerstedt, the Danish founder of the *Polyteknisk Læreanstalt* (now the Technical University of Denmark) in 1829. Oerstedt saw a close relationship between polytechnic education and education in the political sciences in the German and Danish *statswissenschaft* [13].

The role of military organizations and the inspiration from large infrastructure projects employing military engineers also had a great influence on the factory systems established in large corporations [14, 15]. These corporate systems were inspired by the military model of hierarchical organization and the need for unity and standards. The quest for standards also gave rise to the idea of improving productivity and sustaining control over the production process and work force through the use of scientific management principles, which soon became a core element of engineering management.

The tensions between the polytechnic training based on physics and mathematics versus practical skills in technical drawing and laboratory experiments were evident from the beginning. The controversies were fueled by the work of new polytechnic graduates trained in the natural sciences, but primarily engaged in constructing the new technical infrastructures, that is, the water systems, sewers, gas pipes, and electrical power systems. The polytechnic graduates were also involved in establishing transport infrastructures, such as canals and rails, and the new communication infrastructures, such as telegraph, telephone and radio systems connecting cities, regions and nations.

Many of the machine shop developments and early industrial achievements were as much the result of the practically skilled technicians and craftsmen's work. They based their knowledge on the experiences of working with the construction of machines and chemical processes in industry, and they transferred their knowledge through visits to other sites. Traveling, working abroad, and returning with knowledge of technical constructions and innovations, detailed technical drawings and descriptions of new machines were common ways of transferring knowledge and new technologies [16]. The diffusion of the new technical constructs was supported by national journals.

During early industrial development, technical schools supplied many of the inventors of new machines, tools, and production systems. Practically skilled engineers, recruited from these schools, played an important part in industrialization until the late 19th century [11]. These engineers were involved in the new industries because of their experience with rationally organized experiments, documentation processes, and their experience with the achievements of developing technologies [17]. Though engineering disciplines show similar patterns across countries, differences of engineering practice exist across national cultures, especially in the way the theoretical contributions from engineering science are used in engineering practice [18]. In the later part of the 19th century, when research and innovations in petrochemicals gave a boost to the chemical industries and energy distribution systems, academic research and academically trained engineers gained importance. In this way, the developments of petrochemical and electrical technologies led to changes in the role of technical institutions of higher education, particularly in northern Europe.

The structure of many engineering institutions who built their curriculums on the *big four* in engineering—civil, mechanical, chemical, and electrical—originates from this period. Although engineering schools still tended to train their students to solve practical industrial problems, and academic research was often difficult to distinguish from industrial consulting, electrical engineering was the exception. In this engineering discipline, the relationship between theoretical teaching and industrially developed technologies was closer than in other engineering domains. Still, many universities maintained basic engineering skills by requiring electrical engineers to study mechanics, technical drawing, and surveying. These requirements could not be explained in relation to the knowledge and skills needed in the new field of electrical engineering, but were established as part of the early curriculum for engineering education, in which mechanical and civil engineering practices were the standard.

In the course of history, many engineering disciplines developed from what could be called an encyclopedia stage, dominated by descriptive representations of technological exemplars, into a more abstracted and theory-based scientific stage [19, 20]. This latter stage adds the strength of applying model descriptions, including mathematical representations and topic generalizations. However, in the transformation process, concrete experiences and practice-based knowledge, embedded in specific technical solutions, were often lost. Consequently, the transition represents a movement from scattered collections of representational exemplars to more complete representations of the technologies in question, documented by constructed theories and models. At the same time, the transition represents movement away from the engineering practice and experiences that are needed to make technology functional [21].

Science as the Basis for Engineering

In order to understand today's situation, we must consider one of the most important historical changes in engineering education—the construction of a science base for engineering. This development resulted from the increase in public and military funding of engineering research during World War II. The program to establish a science base for engineering created new theoretically oriented universities and technical schools of higher education in both the United States and Europe. At the outset, there was a gap in engineering curricula between science classes based on high degrees of mathematically formalized knowledge and the more descriptive and less codified technical subjects. Earlier controversies resulted in positioning technical sciences as secondary, or applied, in relation to the natural sciences. Technical universities, at least in Europe, were restricted from giving doctoral degrees and addressing scientific matters without the support of university faculty versed in the natural sciences. However, the new era of expanding technical sciences lessened these controversies because of its increased focus on innovation and awareness of the close interactions between specific areas of science and technology.

Developments in the United States

The watershed event in American engineering was World War II. One of the leading institutions in this change was the Massachusetts Institute of Technology. Before the war, MIT had embraced scientific approaches, under the presidency of physicist Karl Compton. Vannevar Bush, a young MIT faculty member, reoriented his research from circuit simulations for electric power networks to general research in calculating machines—a more scientific orientation—successfully attracting private foundation support [22, 23]. In 1940, Bush set up the National Defense Research Council, a major federal wartime research establishment in Washington, DC. Although engineers made significant contributions during the war, the success of the Manhattan Project put physicists in the spotlight, and savvy engineering leaders recognized that the path to prestige lay in engineers' closer emulation of scientists.

Developments in Europe

In Europe, this orientation toward a scientific basis for engineering already had a long tradition in the intellectual environment around elite institutions, especially in France and Germany. The post-war tendency toward formalization of science councils and large government-sponsored research programs, centered on the peaceful utilization of technologies developed during World War II, spurred a dramatic increase in research at technical universities, and a change in the methods of teaching engineering. During the first half of the 19th century, several natural science subjects were taught either in common at the universities and the polytechnic institutions, or only at the latter, so that natural sciences students had to take lectures at the polytechnic institutions. When the natural sciences became established within the traditional universities, they increasingly were perceived as being the foundation for the applied sciences.

During the first half of the 20th century, polytechnic universities struggled for acceptance. They were acknowledged for their foundations in science but were questioned about whether they could conduct independent scientific research. Moreover, they were limited to practical experiments with technical improvements and practical implementation. These controversies manifested themselves in the acceptance of doctoral studies at technical schools of higher education. In Sweden and Germany, as in many other countries, decisions about what should qualify as scientific achievement and who was qualified to judge were very controversial. The controversy ended with an acceptance of technical or engineering science as a distinct area of scientific inquiry, although the image of engineering science as applied natural science continued to dominate many discussions about the character and role of technical sciences [24].

Post-war Developments

The movement toward a science base was concurrent with a massive post-war expansion of government-funded research in the United States. Sponsorship of fundamental studies in a variety of areas supported the trend away from practice-oriented research and education. Successes in fields such as high-speed aerodynamics, semiconductor electronics, and computing confirmed that physics and mathematics conducted in a laboratory-based environment could open new technological frontiers. Military research during these years also tended to focus on performance—increased power, higher altitudes, faster speeds—goals that were conducive to scientific approaches.

Electrical engineering, for example, no longer focused on electric power and rotating machinery, but instead on electronics, communications theory, and computing machines. As historian Bruce Seely wrote:

> Theoretical studies counted for much more than practice-oriented testing projects; published papers and grants replaced patents and industrial experience as measures of good faculty. By the mid-1960s, the transition to an analytical and more scientific style was largely completed at most American engineering colleges [6].

Yet today, many engineering departments still have their core activities defined by technical disciplines, such as mechanics, energy systems, electronics, chemistry, building construction, or sanitary and civil engineering. Many of these disciplines have specific problems and industries that relate to their founding years, but as the demand for science-based research and teaching became prominent, the original roots to practice and industry lost their significance. With the changing demands, more abstract courses defined by scientific fields, were developed.

The post-war decades saw the rise of systems engineering and thinking as broadly applicable engineering tools [22]. Systems sciences that include control theory, systems theory, systems engineering, operations research, systems dynamics, cybernetics and others led engineers to concentrate on building analytical models of small-scale and large-scale systems, often making use of the new tools provided by digital computers and simulations [25]. Techniques range from practical managerial tools, such as systems engineering, to technical formalisms, such as control theory, to more mathematical formulations, such as operations research. A broad-based movement within engineering found that these tools might finally provide the theoretical basis for all engineering that goes beyond the basic principles provided by the natural sciences. Whereas systems engineering of the 1950s could be narrowly analytical and hierarchically organized, new ideas of systems in the 1980s and 1990s focused on the relationship between technology and its social and industrial context. This new relationship and understanding of the natural and technical sciences is reflected in the notion that engineering as techno-science developed in the field of sociological studies of science and technology to reflect the new intimate relationship between these fields of science [26].

The Decrease in Practical Skills and Experience

The creation of the research university as the ideal and elite model for engineering universities also influenced the staffing of engineering education's lecturer positions. The increase in research-based funding of these positions meant that the tradition of hiring practitioners to lecture in engineering was increasingly supplemented or replaced by lecturers hired on the basis of their achievements in engineering science and laboratory work, instead of their achievements in industrial practice. Voices were raised both inside and outside the universities against this change, resulting in the transformation of almost all lecturer and academic research staff at technical universities. However, within the universities, most objections and arguments came from practitioners who were involved in teaching and laboratory work identified as routine and trivial in comparison with frontline research.

The Transformation of Technical Schools

In the European setting, the requirement of a Ph.D. degree narrows the recruitment of engineering faculty, making it difficult for engineers with careers in industry to satisfy entry requirements for university professorships. New Ph.D. recipients have been entering in increasing numbers into research positions funded by government programs, with fewer going to industrial laboratories and engineering practice. Even though the requirement of a Ph.D. degree can be substituted by personal innovative activities in industry, it is difficult to recruit practically skilled engineers to universities. Academic positions today require that applicants document research activities and demonstrate published works from their research in order to be evaluated for appointment. This threshold, in combination with a gap in the wage levels of industry compared with universities, has reduced the number of qualified engineers with skilled engineering practice in universities.

With the expansion of science-based technical disciplines, changes in the foundation of engineering education also led to changes in the curriculum of traditional vocational schools of engineering, as well as in funding for research. Though with different names, the *polytechnics* in the United Kingdom, the *fachhochschulen* in Germany, and the *teknika* in Denmark shared common characteristics in recruiting students from groups of skilled technicians and supplementing their training with a theoretical education, while maintaining a focus on industrial practice. As a result, the schools inherited the experience-based practical knowledge and skills of students who had previously worked as apprentices in construction firms, machine shops, and industry. During the 1960s, the curriculum of these technical schools was expanded and many of their specialized lines of engineering education were extended in length and scope. Typically, these changes included improvements in mathematics and natural sciences by copying the science base from engineering universities, while attempting to maintain their practical orientation. This led to the appointment of government committees to address the profile of practical engineering education [27]. It also raised questions about the balance between the academics and practice, and whether these schools would continue to supply practice-based engineers to industry.

At the same time, the decline in the apprenticeship training of craftsmen and skilled workers began to undermine the recruitment lines of the polytechnics [28]. While this type of engineering education was well supplied by smaller crafts-based industries, the growth in the size of industries led to a change in the ways the workforce was trained, leading to an increasingly specialized machine shop skills in the workforce. Fewer candidates had the necessary broad skills and apprenticeship training required by the engineering schools. The schools were forced to establish other recruitment systems to survive. This process resulted in a complete reversal of the basis for recruiting students during the 1990s. As a result, it is difficult today to distinguish the two different lines of engineering education from one another, both because of the convergence of their student enrollments and also the nature of their educational focus.

The Response from Industry

The response from industry to the tensions in technical education demonstrated the ambiguity of industry's interests in maintaining practically skilled engineers. Industry was not willing to carry the costs of an educational system to maintain the basic skills needed in the workforce. More generally, the problem also demonstrated the ambiguities in understanding which aspects of practice and experience were important for engineering work. Studies of engineering have demonstrated the importance of combining formal theoretical work based on codified knowledge with methods of drawing, experimentation, models, and analogous reasoning [16]. These skills cannot be based solely on the practical experience of shop-floor technicians, but also on the experiences of practicing engineers. Other practical perspectives, such as having experienced the daily routines of industrial organizations can be gained from other practices than working as an engineer. The ability of engineering institutions to recruit students with practical skills may have diminished, but the problem of maintaining the practical aspects of engineering competence continues to exist [29].

The Return to Practice

During the 1970s, a variety of technical and political events began to change the course of technology in its social context, and began to swing the pendulum yet again toward practice. The oil shocks, the beginning of the modern environmental movement, and the cancellation of the supersonic transport (SST) in the United States were indicators that technology might no longer progress along strictly technical lines. During the 1980s, the U.S. found itself in a crisis of competitiveness, which some blamed on the engineering research establishment's excessive focus on performance and military research, as opposed to other more industrial considerations. The *Made in America* study at MIT reported that design and manufacturing had not received the academic resources or the intellectual prestige of the engineering sciences, and hence the U.S. had fallen behind such rivals as Germany and Japan in actually producing consumer goods [30]. At the same time, the end of the cold war meant that large, military-oriented research funds might no longer be forthcoming. During the 1990s, academic institutions increasingly turned toward industrial sources of support. With new sources of money came new research orientations toward product design, product development, and innovation studies, with more emphasis on problems from engineering practice.

From within the technical universities, voices were raised against the consequences of a too-narrow focus on science-based teaching that lacked interest in the practical aspects of engineering work and competence [31]. Educational programs focusing on project work and problem-based learning spread broadly during the 1990s. They attempted to address the problems from a pedagogical and didactic point of view. In both Denmark and Germany, a few radical reform universities made project-oriented study the trademark of their education, stating that the projects could both cater to the interdisciplinary aspects of engineering methods and problem solving and to the integration of the practical and theoretical elements needed in engineering [32].

While shop-floor training and practical aspects of work organization were the focus in the earlier phases of engineering, the new perspectives on engineering practice emphasize the complexity of engineering tasks, including project organization and communication, the role of specialized consultants, the skills needed to handle innovative design tasks, and the need to include the social dimensions of technology [33]. These new emphases may not eliminate the need for practical skills in drawing, visualization, modeling, and crafting of material objects, but the replication of traditional crafts does not satisfy the need for practical training in engineering. New emphases create a need to redefine engineering practice and to leave the apprenticeship model behind.

Disciplinary Congestion and Blurring Boundaries

The growth of the use of technology in the latter half of the 20th century, in combination with the large investments made in engineering research by industry and by research institutes and universities, has resulted in tremendous growth in the body of technological knowledge, the number of new technological domains, and specialized technical science disciplines [34]. Differentiation in engineering specialties put pressure on engineering education to cope with the diversity and to keep up with the frontline of knowledge in diverse fields. At many institutions, this resulted in a number of new specializations. Several of these specializations relate to sectors and industries that require engineers with particular kinds of knowledge. Changes in the demands for specialization created tension between generalized engineering knowledge and the specialized knowledge needed in individual domains of technology and engineering practice, for example, highway engineering, ship building, sanitary engineering, mining engineering, power engineering, offshore engineering, microcircuit engineering, bioengineering, nanotechnology, multimedia engineering, and wind turbine engineering.

Developments in technology have meant also that the boundaries between engineering disciplines are blurring, and indeed the very nature and existence of engineering has come into question in recent years. What used to be fairly distinct areas of engineering—civil, mechanical, chemical, electrical—have now become combinations of two or more fields and their disciplines. For example, there are now programs in civil and environment engineering, aeronautics and astronautics, electrical engineering and computer science, and materials science and engineering. New programs in bioengineering and biomaterials reflect these shifts as well [1]. Today, many of the larger technical universities offer programs in more than a dozen different engineering fields.

The growth and diversity of technological knowledge also leaves universities with continued pressure for renewal and difficulty in determining which engineering domains to maintain and develop. Several domains and branches of industry have passed their growth phase, and the related technologies are no longer the focus of research funding. The given industry may still be employing large numbers of engineers, but its need for new engineers does not justify creating or sustaining programs in research focused engineering schools. For engineering education, it means the potential loss of important domains of technological knowledge.

Alternatives for Addressing Disciplinary Congestion

Since the 1960s, all these specializations have increasingly led to an expansion in the numbers and variety of courses focused on technical sciences. At some technical universities, for example, the Massachusetts Institute of Technology (MIT) and the Technical University of Denmark (DTU), the curriculum was re-organized to fit into modular structures, giving students choices about how to make up their own education. Some universities expanded the number of formalized specializations, while others coped with disciplinary congestion through negotiation of the core content and opted for elective courses in only a limited part of the curriculum. One of the strategies developed from the core content response was to give more space in the curriculum to science-based teaching, reducing the number of laboratory classes, and consequently weakening the ties to the general industry and the technological domains from which engineering originated. This response represents a return to the historic idea of a general knowledge base for engineering as expressed in the idea of a *polytechnique* and at the time reflects the new fields where science and technology become integrated as reflected in the term *techno-science*.

In parallel to these structural responses, a debate about a general pedagogical reform based on project-oriented work argued for giving students a broad understanding of engineering work and problem solving with less emphasis on covering all the specialized fields of theoretical knowledge represented in the courses and disciplines. The concept of *learning to learn* was coined as an illustration for this strategy and the idea of improving engineering problem solving skills instead of preparing a knowledge base for later use was core.

Blurring Boundaries Between Technology and Nature

The increasing role of technology in all aspects of society demands multidisciplinary approaches, and challenges science-based rational models and problem-solving approaches. These demands gave rise to new areas of engineering education. For example, in the field of environmental studies, the need for new approaches in industry based on cleaner technologies and product chain management challenged the established disciplines in sanitary engineering based on end-of-pipe technologies and chemical analysis. From focusing on nature as a recipient of wastes, engineers had to realize that nature itself has been dramatically affected, and that environmental knowledge had to include the design of production processes and chemicals as part of what had become a continued re-design of nature [35].

Challenges also arise from new fields of bioengineering and climate change, raising fundamental questions to the kind of technologies that have been developed in the wake of mass production and consumption and related energy and materials usage. Blurring boundaries between technology and nature introduces serious ethical and political issues into the core of engineering and its role in contemporary developments. This is not just a question of introducing new technologies to solve the problems resulting from earlier technologies, but raising questions about the ways engineers are solving problems, their techno-scientific knowledge base, and their employment.

Engineering in Society

Changes in the role of technologies in a society where consumer usage, complex production, and infrastructures are increasingly more important have led to more focus on the integration of usability and design features. The traditional jobs in processing and production have not vanished, but new jobs in consulting, design, and market creation have surfaced. These new jobs demand new personal and professional competencies and require new disciplines that contribute to the knowledge base [36, 37]. During the 1990s, several engineering schools started new lines of education emphasizing engineering design skills and introduced aspects of social sciences into the curriculum of engineering design. These additions included technology studies, user ethnographies, entrepreneurship and market development. The innovation of new and diverse technologies also reflects the limitations of technical sciences in being able to cover all aspects of engineering [38]. Examples of these reformed engineering programs can be found at Delft University in the Netherlands, Rensselaer Polytechnic Institute in the U.S., the Technical University of Denmark, the Norwegian University of Science and Technology, and Cranfield University in the U.K.

The decade of the 1990s was not the first time that concerns about the role of technology in society had surfaced, but this time the questions raised issues of a more fundamental nature concerning the content of engineering education and the impact on technology exemplified with controversies about highway planning, chemicals in agriculture, nuclear power plants, and the social impact of automation. The concerns questioned the role of knowledge about technology and some critics demanded a humanistic input into the curriculum with such subjects as ethics, history, philosophy, and disciplines from the social sciences [39]. This idea was based on the assumption that through confrontation with alternate positions and opportunities to discuss social and ethical issues, engineering students would be better prepared to meet the challenges of technology. However, in most engineering education programs, these new subjects ended up being add-on disciplines not integrated with engineering and science subjects, contributing further to the disciplinary congestion in engineering [40].

Another example can be found in the field of housing and building construction engineering. The need for integrating both social and aesthetic elements as well as user interaction in both the project and use phases of construction led to several attempts to overcome the traditional division between civil engineering and architecture. Several engineering education departments tried to solve this problem by employing staff from different disciplines—engineers, architects, and sociologists—hoping that solutions would emerge from the multidisciplinary melting pot. In several cases, the integration turned out to be difficult. Housing construction and city planning in engineering crumbled in spite of the attempts. This dilemma left engineering housing construction departments in situations where the focus became theoretical rather than contributing to the design and functionality of building construction. In contrast, functionality, usability, and flexibility, as well as the inclusion of users in the planning of building design, were left to the architects who seemed more interested in aesthetics. This example illustrates the dominance of disciplinary culture in engineering schools and the ways in which related response strategies define and construct new strands of knowledge and scientific research. A recent development is the focus on entrepreneurship that has surfaced in many engineering schools in the U.S. and Europe. Within this area of engagement, engineering schools have responded to a variety of challenges with rather different response strategies. Some have seen this as an additional competence that engineering students should learn in dedicated courses making them able to sustain their predominantly technology-driven perspective on innovation [41]. Others have responded by renewing their existing management and business teaching for engineers based on the idea of markets and economic processes creating the selection mechanisms that determine which technologies will survive [42]. Others have identified the debate on entrepreneurship as one rooted in a deeper critique of the technical disciplines and their ability to provide relevant solutions for a society facing a series of new challenges that range from a restructuring of industrial mass production, globalization of trade and technology, and an increased embedding of technology in social activities [43].

Expansive Disintegration

Technological change has changed the face of engineering in many other ways. Engineering research and design are changing, due, in no small part, to computers and the Internet. Once taught as fundamental skills, algorithms are now built into automated design software. Large projects are managed through digital links between people who may never have met face to face. What had been largely a white male profession is now diverse in race, national origin, and gender. In addition, it is now possible for companies to conduct engineering functions worldwide with the help of automation and new technologies. The idea of well-defined boundaries for engineering education has been challenged by new technological domains and by existing university educations that already address technology as part of the curriculum.

Areas that address technology and have close affiliations with engineering represent a broad variety of subjects and approaches, for example, pharmaceuticals, architecture, computer science, information technology, environmental studies, biotechnology, nanotechnology, and technology management. These professional areas do not necessarily see themselves as part of engineering. In some areas, new perspectives of techno-science can create new relationships between science and technology. New fields of biotechnology and nanotechnology have blurred the boundaries with the natural sciences, as well, leading to the creation of such fields as mathematical engineering and nanotechnology in the natural sciences. Thus, a situation is developing where the new professionals, industrialists, and politicians question whether technology remains the domain solely of engineers, and whether engineering will continue to be the major source and producer of innovation. This development has been called *expansive disintegration*, reflecting the combined expansion of the number of technologies, specialties and disciplines on the one hand, and the continued disintegration of what once was the unity and identity of engineering on the other [1]. These transformations will fundamentally challenge the role of engineering schools in the future.

Contemporary Challenges

The role of engineers in technology and innovation is often taken for granted. Even in future-oriented reports on engineering, there is a tendency to expect problem solving abilities in societal and environmental issues from engineering without challenging contemporary foundations of engineering curricula [23]. New insights coming from innovation theory, demonstrating a broader scope in innovation, coupled with changes in the societal use of technology that imply growing complexity and a need for social skills, point to the need for improvement in engineering education. On the other hand, innovations during the last decade are leading to changes that may make the role of engineering less central in the future. Policy and management attempts to govern innovation processes have also broadened the scope and shifted the focus from technological development and breakthroughs to a broader focus on market demands, strategic issues, and the use of technologies.

A New Identity for Engineering

Early in the 20th century, the idea that engineers have societal responsibility and are the heroic constructors of the material structures of modern society was being supplanted by a less heroic and more mundane image of engineers as the *servants* of industry. This image of engineering reflects a reduction in the influence of engineers on the direction and content of technological innovation, and supports the positioning of engineers in a less influential and subordinate role in their attempts to promote business interests [37].

This view is not all that different from engineers' self-image in contemporary society. The description of an engineer's competencies might include the following: possesses a scientific base of engineering knowledge, problem-solving capabilities, and the ability to adapt one's knowledge and practices to new types of problems. The focus is more often on problem solving and less on problem identification and definition [38]. This focus emphasizes the problem of engineering identity in distinguishing between engineers as creators and designers versus analysts and scientists. Although engineers' identity as creators and designers is supported in historical writing and in strategic reports about the role of engineering in the future, reality seems to place engineers in roles closer to analysts and scientists in laboratories and modern technical industries [23].

The underlying assumption in the discussion about engineering problem solving is that engineers are working with well-defined technical problems and methods from an existing number of engineering disciplines. This assumption does not answer the question as to whether engineers are competent in handling non-standardized social and technical processes where the problems are undefined and involve new ways of combining knowledge. Simply broadening the science base in a more interdisciplinary direction, including the social sciences and humanities, may not have been a satisfactory solution. The mere addition of topics to the curriculum does not change engineering practices or provide a better integration of knowledge [1]. A new engineering identity will be based on the answers to these questions:

- *What competencies are necessary to manage the creative, socio-technical and design skills that need to be improved in engineering education?*

- *What is the meaning of engineering problem identification and problem solving today, and how can they be reflected in engineering education?*

A New Education for Engineers

The reforms in engineering education initiated in the 1970s emphasized the need for problem solving and project work that simulated real engineering practice, but these reforms did not provide the complete answer. The response lies in a new understanding of the role of science in innovation and the use of technology in context. This approach underlines the existing need to bridge the divide between the disciplinary knowledge of the technical sciences and social sciences and the practical domains of engineering with their unique knowledge and routines that integrate the social, practical, and technical aspects of technology at work [24]. It is necessary to rethink disciplinary knowledge as presented in engineering education and to reform the content and structure of that knowledge.

One solution might be to accept that the idea of a single unifying engineering identity has proven to be problematic. Engineering education will unavoidably become more diverse in the future. Integrating engineering into the general university structure could be a tempting solution, removing the rigid focus on core curriculum, while still fighting the battle for the acceptance of engineering science [1]. However, the problems of including professional practical knowledge and maintaining the need for professional skills in engineering are not solved by referring students to an even more diverse science base at universities. Neither do the many new science-based specializations in engineering provide a solution that even may bring engineering further away from the practical knowledge also needed. Most technical disciplines focus on particular technical solutions taught as individual courses and with less emphasis on their application. These courses are supposed to contribute to a coherent set of engineering competencies, although they have little resemblance to an established domain of engineering practical problem solving and solutions [44].

Debates on engineering education tend to replicate a number of discussions over and over again. One example is the balance between practical skills and theoretical knowledge. While the debate may seem the same, the content has changed radically during the more than one century of controversy [45, 46]. The list of relevant practical skills would not be the same, and similarly, theoretical knowledge has evolved as a result of technological developments, advanced tools, computers, and simulation models. Reforms need to produce a new realization of the kind of practical insights relevant to engineering education today.

Another challenge involves the balance between specialist and generalist knowledge in engineering. A process occurs in which current knowledge and skills continuously change. New knowledge and skills that begin as part of a science frontier are considered demanding. As the frontline of technological innovation moves, that knowledge and those skills become part of standard engineering procedures, technical standards, standardized components, and design concepts, supported by computerized tools and simulation models. What is considered core or basic in an engineering curriculum changes in the wake of the expansion of new engineering domains and disciplines, despite the fact that all are dominated by the idea of a common theoretical foundation. A new education for engineers will answer these questions:

- *What content should a core engineering curriculum have in the future?*
- *Which skills should be part of the curriculum, and which can be developed on the job after completing the education?*
- *What is the relevant sequence of knowledge and skills provided by education from a learning perspective?*

Reform in engineering education needs to address the contemporary challenges highlighted here and find new ways of analyzing and understanding technological knowledge and the professional practices of engineering.

Addressing Contemporary Challenges with a CDIO Approach

From the historical accounts presented in this chapter, we find a number of challenges that continue to be important in contemporary debates about the reform of engineering education. Key elements of the CDIO approach reflect critical issues underscored in this historical account. These elements include:

- A curriculum that includes personal and interpersonal skills, and product, process, and system building skills in the realization of technical solutions, while still emphasizing mathematics, the natural sciences, engineering science, and the technical knowledge specific to technological domains.
- A core belief that personal and interpersonal skills, and product, process, and system building skills must be learned in the context of authentic problem solving and engineering practice.
- An integrated approach to the teaching of engineering science and engineering disciplinary knowledge relevant to specific technologies and engineering practice.
- An increased focus on the need for integrating engineering science subjects with contributions from other knowledge fields to meet contemporary challenges.

The CDIO approach renews the focus on several of the important issues in engineering educational reform. While many reform initiatives have focused on the curriculum content and structure of different science and engineering disciplines, the balance between practical education and theory-based learning, or the potentials of project-based learning as a means of learning teamwork skills, the CDIO approach has created a means to coordinate these elements.

Summary

In this chapter, we demonstrated national differences in the role of engineering in society and industry and the ways engineering education has been influenced. The military use of infrastructure and equipment and the ingenuity of practically skilled builders pointed to the roots and inspiration for the creation of formal training of engineers for civil purposes and industrial development. Later developments emphasized the role of science in engineering training. The relationship between scientific theoretical knowledge in the disciplines, and the practical skills and knowledge derived from technological innovation and engineering practice has been controversial in engineering education and is still presenting challenges for contemporary engineering education.

The differences among countries has led to the implementation of different educational structures characterized both by the background students were expected to have before entering the programs and the ways in which lecturing was combined with laboratory and machine shop work. In the United States, with one dominant model of engineering education, the changing balance between practical and theoretical education has been characterized as a swinging pendulum, while in Europe two models of engineering institutions were created with differing weights placed in the two aspects of engineering.

With the rise of engineering science, especially since World War II, the core elements of engineering have been extended beyond the natural sciences. At the same time, the growth in the number of scientific specialties led to a focus on theoretical science-based engineering education, leaving aside some of the creative design aspects of engineering, as well as some of the experiences and routines from the domains of engineering practice.

Engineering education has faced problems of a growing number of specializations with a consequent disciplinary congestion in the curriculum. At the same time, new areas of technology and new professional specializations outside engineering schools have introduced topics that are difficult to distinguish from engineering, blurring the boundaries between the professions. This blurring of boundaries, together with changes in the image of engineers away from *creator* toward *technical industrial worker,* have challenged the identity and content of engineering for the future.

The chapter concludes with questions about the knowledge base for engineering in modern society and its influence on a core curriculum for engineering education. This chapter points to a need to re-assess the composition of engineering education concerning the way practical skills and experiences are combined with theoretical training and what is considered to be the core elements of an engineering curriculum.

Discussion Questions

1. Can you identify traces of the controversies in the history of engineering education at your institution or in your professional society?

2. How would you characterize engineering education in your country? Can you identify one dominant type of engineering program in the way it balances theory and practice? Is there more than one model?
3. Do you see any limitations or barriers to an engineering program based solely on science and engineering disciplines? How are social issues of technology integrated into the curriculum?
4. In what ways can the CDIO approach change the trajectory of engineering education reform? What are the most important questions facing curriculum planners in engineering?

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Chapter 11
Outlook

Introduction

The CDIO approach responds in an integrated and pragmatic way to the historical context in which engineering education finds itself and to the challenges that lie in the future. We call the collaboration of universities with at least one engineering program that has adopted a CDIO approach to engineering education the *CDIO Initiative*. The collaboration began with four universities in two countries and has expanded rapidly in terms of scope and participating universities. The initial programs were typically within the domains of mechanical, vehicular and electronic engineering, but the CDIO approach has now been implemented in programs in chemical engineering, material science and engineering, and bioengineering. The model has been applied to reform initiatives affecting all engineering programs at a university and as a template for national initiatives and evaluation schemes. The number of universities has now expanded to more than one hundred universities around the world. Development is underway at universities characterized as research-intensive or teaching-focused, large or small, private or public, or historically focused on minority and underrepresented populations. Six regional CDIO centers in North America, Latin America, Europe, the United Kingdom and Ireland, Asia, and Australia and New Zealand, have been established to provide opportunities for the exchange of ideas and support for implementation in local regions. A number of vehicles, tools, and forums for disseminating and developing the CDIO approach have been created, including the website and annual international conferences.

The CDIO approach is likely to evolve and be adapted and implemented in an even wider variety of settings—in engineering disciplines not already covered, in graduate education, and in education beyond engineering. It has been designed to be flexible and adaptable, with the ability to respond to the forces driving engineering education in the near future. We look forward to working with others in this evolutionary process. This chapter highlights what we see as future challenges for

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engineering education and outlines ways in which a CDIO approach can address these challenges.

Chapter Objectives

This chapter is designed so that you can

- Recognize the factors that continue to drive change in engineering education and ways in which the CDIO approach relates to them.
- Discuss the potential for development and broader application of the CDIO approach.

Drivers for Change in Engineering Education

The major goal of engineering education is to serve society and engineering students by providing up-to-date high-quality learning opportunities. Maintaining and improving quality requires an awareness of the key environmental factors that drive change in engineering education. The most important drivers for change in engineering education include:

- Scientific breakthroughs and technological developments
- Internationalization and student mobility and flexibility
- Skills and attitudes of beginning engineering students
- Issues of gender and broadening participation
- Governmental and multilateral policies and initiatives.

It is important to have good mechanisms in place for maintaining awareness of the factors that drive change and to have effective methods to plan and implement changes in engineering programs. Chapter 8 suggests methods for implementing program change and Chap. 9 gives examples of tools and techniques for program evaluation and improvement. The CDIO Syllabus itself, discussed in Chap. 3, can also be a useful tool for monitoring some of the drivers.

Scientific Breakthroughs and Technological Developments

Scientific and technological evolution is an obvious driver for the development and improvement of engineering education. Existing subjects in the curriculum have to be updated according to the progress within the discipline, and new fields of study need to be incorporated into the curriculum. There are several ways to keep a curriculum current and relevant. One way is to see to it that faculty have sufficient resources for research within their disciplines. Relevant research results can then be introduced into the educational program. A second way is to assure that adequate mechanisms exist for bringing developments in industry into the engineering education program. We can achieve closer ties with industry by hiring faculty and research staff with industrial experience and by involving people from industry in program implementation and management.

Technological developments also influence engineering programs in the way that design, development, and production are organized and geographically located. For many industrialized countries today, manufacturing and production are moving outside their borders to other countries where production and labor costs are lower. If engineering research, design, and development follow the export of production and manufacturing, the change will substantially influence the need for engineers and their expertise, and consequently, engineering education.

A CDIO approach offers several ways to keep the education up-to-date with changes in science and technology. As described in Chap. 6, CDIO Standard 7—Integrated Learning Experiences emphasizes real-world problems in engineering education through involvement of industrial partners in the formulation of learning experiences. The Syllabus, described in Chap. 2, is another tool for tracking the development and needs of industry. Results of stakeholder surveys, especially answers from people active in industry, are obvious input to the process of educational development. Finally, faculty who are involved in both education and research are better able to influence engineering programs as a result of scientific breakthroughs and technological development. As explained in Chap. 8, Standard 9—Enhancement of Faculty Skills Competence encourages this latter kind of involvement.

Internationalization and Student Mobility and Flexibility

The globalization of current workplaces and companies requires that graduates be prepared for careers characterized by daily international contacts, frequent travel, and extended distance collaboration. It follows that education will become increasingly international and that it must lead to internationally recognized degrees. We can see that already in the tremendous change in the mobility of students that has taken place during the last two decades. In Europe, for example, student mobility increased with the creation of European student exchange networks, such as *Erasmus* and *Socrates*. Mobility and flexibility are also important aspects of the Bologna Process, because a uniform structure of higher education increases students' opportunities to move between universities. Box 11.1 is a description of key points of the Bologna Process [1] as applied to Sweden and the United Kingdom.

Box 11.1 The Bologna Process in Sweden and the United Kingdom

The Bologna Process is a joint European effort, involving 40 countries, to obtain a uniform structure for higher education in European countries. The Bologna Declaration involves six actions relating to higher education:

- A system of academic grades that are easy to read and compare.
- A system essentially based on two cycles.

(*Continued*)

Box 11.1 The Bologna Process in Sweden and the United Kingdom—Cont'd

- A system of accumulation and transfer of credits.
- Mobility of students, teachers, and researchers.
- Cooperation with regard to quality assurance.
- The European dimension of higher education.

The aim of the process is to make the higher education systems in Europe converge toward a more transparent structure whereby different national systems would have a common framework based on three cycles—bachelor, master and doctorate.

The effort to adapt engineering education in a specific country to the Bologna structure depends on the national goals and organization prior the Bologna Process. For example, in Sweden, engineering education consisted of 3-year programs leading to a bachelor degree (*Högskoleingenjör*) and 5-year programs leading to a master degree (*Civilingenjör*). The degree *Civilingenjör* has a long tradition, and represents a strong brand in Sweden. Therefore, the government proposed that this degree continue to exist after the introduction of the three-cycle system. The main challenge for Swedish universities is to find suitable forms of co-existence between the three-cycle system and engineering programs leading to the degree *Civilingenjör*.

—S. Gunnarsson, Linköping University and J. Malmqvist, Chalmers University of Technology

In the United Kingdom, the Master of Engineering (M.Eng.) degree has an equivalently well-established brand image, despite the potential for confusion inherent in its "master" name. The 4-year M. Eng. degree was considered in the United Kingdom to be an undergraduate first-cycle degree, with enhanced content and greater breadth than the conventional 3-year Bachelor of Engineering. Rather than a bachelor degree with an optional add-on year, a 3 + 1, it was seen as 4 + 0. However, there are now suggestions that it should be viewed as an *integrated master* second-cycle degree. The M. Eng. already co-exists with a postgraduate, that is, second-cycle master qualification, the Master of Science, which usually takes 12 months rather than the typical 24 months of a second-cycle qualification elsewhere and for which the entry qualification is usually a 3-year Bachelor of Engineering or Bachelor of Science. A challenge for institutions in the United Kingdom is to reconcile these three degrees (B.Eng., M. Eng. and M.Sc.) with the two-cycle of the Bologna pattern prior to the doctorate. It is often considered an advantage that the system in the U. K. can take a graduate to the end of the second cycle within 4-years, and there is resistance to any move toward a 3 + 2 model.

—P. Goodhew, University of Liverpool

In North America, there is likewise a long and growing tradition of international mobility in education. For example, in Canada, the largest numbers of international students come from China, India, and the Middle East. They usually complete a 4-year Bachelor of Science program, which is typical for all engineering programs in Canada, consistent with the accreditation requirements of the Canadian Engineering Accreditation Board (CEAB) [2]. In the United States, there are increasing numbers of programs for engineering students to study abroad for at least 1 year. Throughout the world, national higher education systems, including those in Chile and Australia, are considering large-scale structural changes to allow greater mobility of their students, as well.

Commonality in accreditation is another mechanism of internationalization. International agreements, such as the Washington Accord on cross-recognition of professional certification cause various accreditation schemes to converge [3]. In the United States, ABET accreditation criteria have influenced thinking in many national systems and attracted many international programs to apply for accreditation [4]. In Europe, there is an initiative, aligned with the Bologna Process that is developing a common system for accreditation of engineering education. The project, *Accreditation of European Engineering Programmes and Graduates* (EUR-ACE), has been officially accepted by the European Commission [5]. The aim of the project is to create an accreditation system that is compatible with the system currently used in certain European countries [6].

The CDIO Initiative supports internationalization and mobility by providing a well-developed international model, a basis of common comparison of student learning outcomes, and potentially the basis for common accreditation. Meeting the Bologna Process and accreditation criteria will be a basic requirement of all educational programs in the future. However, accreditation requirements are high-level and formal in character. The CDIO Initiative takes a further step toward a truly international education by implementing and adapting a pragmatic model, developed in collaboration by leading universities around the world. Within CDIO programs, there is a close connection between accreditation and the learning outcomes of the Syllabus. In Chap. 3, we compared the CDIO Syllabus with ABET's evaluative criteria, specifically EC 2013 Criterion 3. The national evaluation of engineering education carried out in Sweden during 2005 is another example of connections between a CDIO approach and national accreditation and evaluation efforts. The Swedish Agency for Higher Education (HSV) used the CDIO Standards as a core component of the self-evaluation completed by all universities in Sweden offering engineering education (see Box 9.3 in Chap. 9).

Skills and Attitudes of Beginning Engineering Students

The skills and attitudes of students entering engineering programs are important drivers for the ways that education is designed, both in terms of content and organization. Education systems are part of the surrounding society; hence, changes in societal attitudes affect engineering education. Many industrialized countries are experiencing decreased interest in science and technology among younger students. This lack of interest influences engineering education in that fewer, and less motivated, students may pursue engineering. Attitudes toward science and technology in a society also affect the importance placed on these subjects in secondary education.

In addition, universities in many countries face increasing difficulties with the level of knowledge and background experience of entering students. This is a recognized fact in mathematics and physics [7]. It is also vital that engineering education address the development of the practical skills and technical knowledge gained through pre-college curriculum activities and life experiences, such as tinkering with electronics, building things, repairing everyday devices, and developing software. Such pre-college experiences, more common in the past, facilitate the acquisition of theoretical knowledge by connecting it to practice.

Addressing these issues requires changes at all levels in the school systems. Within the university, introductory courses aim to orient students to the role of science and technology in society and provide initial engineering experiences that strengthen students' motivation. Hands-on and design-implement learning activities provide concrete experiences that connect abstract models for mathematics and physics with practical applications. Such experiences also explicitly seek to make engineering more interesting and exciting, recruiting students to engineering and retaining them in the profession. Design-implement experiences are being considered as extensions to the curriculum in primary and secondary schools, further strengthening students' motivation and preparation to study engineering at the university level.

Issues of Gender and Broadening Participation

Throughout the world, there is significant interest on the part of educators and government to increase the participation in engineering of women and populations that have been historically underrepresented or disenfranchised. Engineering is viewed as a profession of upward mobility, which has the potential to positively influence the well being of society. For these reasons, nations have an interest in making engineering education accessible to qualified students, regardless of their backgrounds.

The CDIO Initiative has been supportive of this effort. We have studied, for example, how gender and related issues manifest themselves in our educational programs. This has highlighted the need for better role models. In addition, our experiences show that it is important to choose examples, project tasks, and other learning experiences that appeal to a broad segment of the student population.

In many countries, there are ongoing discussions about how to influence the attitudes of all young people toward engineering. Students' attitudes toward engineering education are influenced by several internal and external factors. The structure, content, and organization of the engineering education itself are important factors. To date, evidence gained at universities with CDIO programs show that women and underrepresented minority students who participate in first-year design-implement courses are more likely to complete their engineering programs.

Governmental and Multilateral Policies and Initiatives

The development of engineering education programs takes place on several levels, from individual faculty levels to national and international levels. Decisions taken at higher levels create boundaries and conditions for development at lower levels. In Europe, the Bologna Process is a good example of a multilateral initiative. Once multilateral agreements are made at the European level, each participating university interprets policies and makes decisions for its own educational system. Principles defined at the national level then become the starting point for each university in developing its programs. When an individual university has formulated its strategic plans, program development reaches specific engineering programs and courses.

The CDIO Initiative supports this coordination and planning in several ways. Program development focuses on the last two levels, namely, the program level and the course level. The flexibility inherent in our non-prescriptive resources allows tailoring to local and disciplinary contexts. The commonality of the CDIO approach facilitates international benchmarking and collaboration.

Future Development of the CDIO Approach

The CDIO Initiative represents a collaborative effort to reform engineering education with a number of universities around the world involved in various partnerships and consortia. Unlike some reform projects, the Initiative is not primarily focused on educational research. Programs apply ideas and adopt methods that have been shown to be a part of the best practices in science and engineering education and the outgrowth of scholarly research on education. We document the design and implementation of curriculum reform efforts and share these with other engineering educators. Our ambition is to continue to develop the CDIO approach by working with other partnerships as well as individual reformers and researchers. In this section, we discuss the potential for applying the CDIO approach in additional engineering disciplines, in graduate programs, and in fields beyond engineering.

Application to Additional Engineering Disciplines

The first collaborators came from the engineering disciplines of mechanical, vehicular, aerospace, and electrical engineering—disciplines distinguished by discrete serial products and systems. The examples, terminology, and thinking are somewhat biased by these origins. However, in order to show the ability to generalize the CDIO approach, it is important that the approach be tried in additional traditional engineering disciplines, such as civil and chemical engineering, as well as emerging engineering fields, such as bioengineering and nanoengineering. This dissemination is now the focus of both existing and new collaborators.

The aim of applying Conceive-Design-Implement-Operate to other engineering areas brings out a need to answer key questions:

- Can Standard 1, the product, process, and system lifecycle context, be generalized? Is it applicable to other disciplines?
- Are there pedagogical and curricular differences in applying a CDIO approach to:
  - Other traditional engineering disciplines, for example, civil, ocean, software engineering.
  - Fundamental science and engineering disciplines, for example, material science, bioengineering, nanoengineering, applied physics.
  - Industrial engineering, manufacturing engineering, and engineering management.
- Can a program adapt the approach in part, and if so, what percentage of the CDIO Standards must be incorporated in order to be considered a CDIO program?

Generalizing the product, process, and system lifecycle context. The adoption of the principle that product, process, and system lifecycle development and deployment—Conceiving, Designing, Implementing, and Operating—are the context for engineering education (Standard 1) may seem very closely tied to the initial disciplines of the CDIO Initiative. The terms, *systems*, *products*, and *implementation*, may not feel comfortable for a program in civil or chemical engineering. While an academic program manager may be able to translate the terminology to that of the domain, other stakeholders may not do so willingly. However, it is perfectly feasible to change the terms used in Standard 1 to fit a particular field of engineering while still keeping the intent of the standard intact, by focusing on what is designed and implemented by the engineer. For example, civil engineers are likely to prefer to speak about buildings rather than products, and an adapted version of Standard 1 could read "The principle is to educate engineers to meet the needs of the construction industry, that is, planning, design, engineering, production, operations and maintenance of buildings" [8].

Other changes in terminology may follow, once the decision is made to adapt the wording of Standard 1 to a particular domain's context. These may include terminology in other standards as well as in Section 4 of the CDIO Syllabus—Conceiving, Designing, Implementing and Operating Systems and Products in an Enterprise and Societal Context.

Pedagogical and curricular differences. More substantive changes than terminology may be necessary when adapting the CDIO approach to disciplines in which the nature of the design-implement sequence is fundamentally different from the development of discrete products or systems. In bioengineering, for example, the design and implement process is not easily described by end goals, but more aptly as reaching the limits allowed by physics, chemistry, and biology. It may not be possible to decompose the overall problems into separately solvable problems that can then be integrated into a system solution. Indeed, the Engineering Biology Program at Linköping University identified the interpretation of the design-implement concept as one of their key challenges. Box 11.2 is a brief description of their Engineering Biology Program.

Box 11.2 Conceiving-Designing-Implementing-Operating in Engineering Biology at Linköping University

The Engineering Biology Program at Linköping University (LiU) started in 1996. The program is 4.5 years, with the first 3 years focused on mathematics, physics, chemistry, biology, and engineering. Engineering courses include programming, electronics, automatic control, and signal processing, among others. The fourth year is devoted mainly to a specialization. Eight specializations are currently available, including bio-informatics, microsystems and biosensors, and protein engineering.

During 2004, the Engineering Biology Program Board formulated a plan to strengthen the engineering aspects of the program. The CDIO model is an essential component in the plan. The first step in the transformation to a CDIO program is an introductory course that was offered for the first time during 2005. Project courses, connected to the different specializations, are included.

One key issue in the introductory course and subsequent project courses is how to address the design-implement concept. The interpretation of *product, process, and system* in the CDIO Syllabus and the CDIO Standards needs careful consideration. In the first version of the introductory course, several projects dealt with the design and implementation of systems for measurement and monitoring of biological processes, applications that are close to the original CDIO programs but still within the scope of the program.

—S. Gunnarsson, Linköping University

There are creative ways to incorporate design-implement experiences in biological engineering. Molecule-level variants of design-implement learning experiences may be developed, for example, by using site-directed mutagenesis to modify the function of a specific protein in a microorganism. Such a learning experience might start with the students designing a modified gene sequence and predicting the consequences on the protein structure. The next step would be to produce a plasmid containing the modified gene and transfect a bacterium with the plasmid. The bacterium is then cultivated to produce the recombinant protein. Finally, the function of the protein, or of

(*Continued*)

Box 11.2 Conceiving-Designing-Implementing-Operating in Engineering Biology at Linköping University

the genetically modified bacterium, is evaluated using biochemical methods. Asking students to keep laboratory notebooks to document all processes can enhance the learning experiences.

—C. J. Franzén, Chalmers University Of Technology

Other programs are adopting a CDIO approach to bioengineering as well. The mechanical and materials engineering program at Queen's University in Canada introduced a second option in biomedical engineering in 2007. At the University of Liverpool, the approach has been adopted in a program that includes material science and engineering, as described in Box 11.3.

Box 11.3 Conceiving-Designing-Implementing-Operating in Materials Programs at the University of Liverpool

Three-year Bachelor of Engineering and 4-year Master of Engineering programs in materials science at Liverpool were re-cast to comply fully with the CDIO Standards. They share 94 % of a common first year with other engineering programs (Mechanical, Aerospace, Civil, Product Design). Each first-year program also has a small differentiating module designed to introduce the flavor of the sub-discipline. For Materials students, this involves teamwork to develop a classification scheme for materials. This scheme has most of the attributes of a product and certainly requires a systems approach.

All first-year students undertake two design-build-test exercises in teams of five or six. Thus, overall compliance with CDIO objectives is very high. In the second, third, and fourth years, there are a number of ways in which Materials students benefit from operating in a broad engineering department. They are ideal team members able to contribute materials selection input to CDIO exercises, and they integrate particularly well with Product Design majors. An example of a problem-based module taken by Materials students is the "car door" exercise. Teams of students are tasked with improving the performance (weight, dent resistance, and cost) of an existing steel car door design. They necessarily have to engage with product design, materials selection, testing (both real and virtual, using specially designed software), and interpersonal skills such as reporting to company personnel and negotiating advice. All of these activities have been well received by the students.

—P. Goodhew, University of Liverpool

Adapting and adopting parts of the CDIO approach. The programs involved in the CDIO Initiative have the stated aim of implementing all twelve CDIO Standards. However, programs may find some parts useful and others less relevant or unrealistic in their circumstances. This raises the question of what percentage of the standards must be incorporated in order to be considered a CDIO program. There is no distinct threshold where a program becomes, or ceases to be, a CDIO program. However, it would be hard to imagine a CDIO program that did not accept some variant of Standard 1, acknowledging that the product, process, or system lifecycle development is the appropriate context for an engineering education. In Chap. 9, six of the other standards were identified as being the distinguishing features of a CDIO program. The remaining five are considered supplementary, supporting the adoption of best practice.

For educational programs that do not embrace the entire approach, relevant parts can be applied. The CDIO approach then becomes a collection of tools for program development and teaching support. For example, programs that do not accept the lifecycle context or the key role of design-implement experiences may see benefits in the systematic approach toward program development. The focus on systematic planning and documentation, stakeholder engagement, peer comparison, and modern workspaces may be perceived as new and useful.

Application to Graduate Programs

The CDIO Initiative began as a program for reform of undergraduate engineering education. There is broad interest in adapting a CDIO approach to master-level programs, especially in Europe and Latin America. Increasingly, doctoral programs that aim to develop project management and communications skills as well as research skills are emerging, in particular with the intention of educating "doctors for industry." To answer the question of how the approach can be applied in a three-tiered educational system, one must keep in mind the essential aspects, not the details of implementation. A CDIO program provides an education within a context of professional engineering. This education is characterized by educational goals, set by stakeholders, met by sequences of experiential learning activities, and embedded in an integrated curriculum of mutually supporting disciplines.

The professional role of engineers as context. It is evident that this is a factor that may vary from bachelor to doctoral degrees. While most bachelor programs aim primarily to educate engineers, most doctoral programs aim primarily to educate researchers. For master degree programs, there is a full range, from research-oriented programs to engineering-oriented. In order to be able to accommodate these variations, the context may be generalized from the "role of professional engineers" to the "role of professionals," the latter enabling programs to make a deliberate decision as to whether the professional context is research or engineering. Variations may lead to context definitions such as, "The X program is strongly research-oriented where students learn how to think, analyze, and solve problems in a research context rather than in the technical production context. The emphasis is more on knowledge production than on "product production" [8]. Such a modification of the context leads to changes with respect to other CDIO Standards, but many are still applicable.

Educational goals set by stakeholders and met by proper sequence of learning activities. This topic prompts the question of what parts of the CDIO Syllabus are applicable for master and doctoral programs and which are not. Beginning with the question of scope, we believe that Sections 2 and 3 of the Syllabus list knowledge and skills that are important for researchers as well as for engineers. It is evident that researchers need personal skills, such as problem solving, experimentation, knowledge discovery, and systems thinking. Interpersonal skills are equally important for research work. Current research is typically conducted in international teams requiring an ability to cooperate. To be successful in acquiring research funding not only requires good ideas, but also communication skills. Learning outcomes for communication skills in a research-oriented program may be specialized toward research-related communication tasks, for example, writing journal articles and research proposals. The headings in Section 4—Conceiving, Designing, Implementing, Operating—may be more or less applicable depending on the master or doctoral program. A program in product development may opt to use all headings in Section 4, while a physics program may opt to use none. Regardless of the selection of appropriate parts of the Syllabus, there are tools for writing program goal statements and course learning outcomes.

The next issue to consider is the difference of skill outcomes at end of the bachelor, master and doctoral degrees. "What increased level of proficiency in skills is expected for the master degree level?" These differences have not yet been quantitatively investigated in the CDIO Initiative. Pending additional studies, some indications are likely to emerge during the Bologna Process, such as internationally accepted guidelines for what characterizes bachelor, master, and doctoral levels, with respect to some high-level goals, including technical knowledge as well as communication skills [1]. It is also likely that such internationally agreed-upon goals will remain abstract, leaving the details to programs in consultation with their respective stakeholders.

Applying a CDIO approach to a master degree program that is closely coupled to a bachelor degree program will also require consideration of the sequence of learning experiences. Specifically, Standard 4—Introduction to Engineering and Standard 5—Design-Implement Experiences explicitly recommend types of learning experiences in the curriculum. It will be a challenge to work with students who have not had these experiences at the undergraduate level. Such students may be well prepared in terms of technical knowledge, but less capable with regard to personal and interpersonal skills, and product, process, and system building skills. Accommodation of these students in the form of additional learning experiences may be necessary.

Application Beyond Engineering Education

The principles and practices of the CDIO approach can be applied to most programs in higher education. At its most abstract level, the approach asserts the following: the education should be in the context of practice; that there is an identifiable list of knowledge, skills, and attitudes in which students should gain proficiency; that by engaging with stakeholders, the desired level of proficiency can be determined; that curriculum and pedagogy should be constructed in an integrated manner to reasonably ensure meeting the desired learning outcomes; and that learner assessment and program evaluation should be aligned with learning outcomes that in turn should be used to inform faculty and students of progress, and serve as the basis of continuous improvement. What curriculum would not benefit from systematically applying this approach?

The CDIO Syllabus, which defines the desired learning outcomes for engineering programs, can be easily adapted to virtually any educational program. Section 1—Technical Knowledge and Reasoning, can be changed to *Disciplinary Knowledge.* Sections 2 and 3—Personal and Interpersonal Knowledge and Skills are largely common to all university education. A modification to the description of the product lifecycle in Section 4—Conceiving, Designing, Implementing, and Operating Systems in the Enterprise and Societal Context to describe appropriate *Pre-Professional Knowledge and Skills* could generalize that section. Similarly, the CDIO Standards can be adapted with a modification to Standard 1 to "education in the context of practice."

It is also possible to consider similar professions that aim to use products, processes, or systems to explicitly shape outcomes. Architecture, medicine, education, and business management fall into this category. The underlying processes in the practice of architecture are much like engineering, with perhaps more emphasis on aesthetics and visual design. The adaptation of a CDIO approach in this domain would be the most direct. In fact, many architectural educators might observe that Conceiving-Designing-Implementing-Operating moves engineering education closer to architectural education with its emphasis on experiential learning.

Standard 1 defines product, process, and system lifecycle development and deployment as the context for engineering education. In engineering, there is usually a clear interpretation of the meaning of a product, process, or a system, but these concepts may not exist in other areas. For example, in medical education or teacher education, the context is one of service to, and improvement of, patients or students. The introduction of the concept of services to the CDIO Syllabus and the CDIO Standards could facilitate adaptation of the approach beyond engineering to these fields. Business management education is another area of potential application. In business and management programs, there is a need for extending or modifying the definitions of products, processes, and systems. However, to the extent that professionals in business management define strategies, organizations, products, and services, much of the CDIO approach is applicable. Universities in Singapore and Guatemala are currently applying a CDIO approach to business management programs.

Adaptation to fields in which professionals do not explicitly use products, processes, and systems to shape outcomes requires consideration at the most abstract level. Application to the social sciences, humanities, arts and sciences would raise questions such as, "What is the context of practice?" and "Who are the appropriate stakeholders?"

Summary

This chapter has reflected on what we see as the future challenges for engineering education and the ways in which the CDIO Initiative can contribute to meeting these challenges. Issues include scientific breakthroughs and technological developments, internationalization, student mobility and flexibility, the skills and attitudes of beginning engineering students, issues of gender and widening participation, and governmental policies and initiatives. We discussed how the CDIO approach can be applied to additional engineering areas, graduate education, and programs beyond engineering.

We began this book with the following statement: "The purpose of engineering education is to provide the learning required by students to become successful engineers—technical expertise, social awareness, and a bias toward innovation. This combined set of knowledge, skills, and attitudes is essential to strengthening productivity, entrepreneurship, and excellence in an environment that is increasingly based on technologically complex and sustainable products, processes, and systems. It is imperative that we improve the quality and nature of undergraduate engineering education."

We believe that the CDIO meets this imperative. It responds to the identified needs of educating students who are "ready to engineer." It has as its goals that learning should be strengthened both in the fundamentals and skills. It is a pragmatic and systematic approach to an integrated curriculum and pedagogy with appropriately aligned assessment tools. We have produced a set of open resources to make this approach available to others, with the understanding that nothing is prescriptive. We offer a set of resources and approaches that can be adapted and implemented in every local program. We hope that these resources will continue to grow as others contribute. We continue to reflect on the outcomes of these efforts to improve the education of our students as we prepare them to build the technologically complex and sustainable products, processes, and systems that are important to our future.

Discussion Questions

1. In what ways do you expect engineering education to change in the next 10 years? In the next 20 years?

2. What developments in science, technology, and business are likely to have the most influence on engineering education in the next 20 years?
3. In what ways do you expect your own program to change in light of the ideas presented in this book?

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Appendix A: The CDIO Syllabus v2.0

1 DISCIPLINARY KNOWLEDGE AND REASONING (UNESCO: LEARNING TO KNOW)

1.1 KNOWLEDGE OF UNDERLYING MATHEMATICS AND SCIENCES [3a]

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

1.2 CORE ENGINEERING FUNDAMENTAL KNOWLEDGE [3a]

1.3 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE, METHODS AND TOOLS [3k]

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES (UNESCO: LEARNING TO BE)

2.1 ANALYTIC REASONING AND PROBLEM SOLVING [3e]

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

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

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

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

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

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

2.2 EXPERIMENTATION, INVESTIGATION AND KNOWLEDGE DISCOVERY [3b]

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

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

2.2.3 Experimental Inquiry
- The experimental concept and strategy
- The precautions when humans are used in experiments
- Investigations based on social science methods
- Experiment construction
- Test protocols and experimental procedures
- Experimental measurements
- Experimental data
- Experimental data versus available models

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

2.3 SYSTEM THINKING

2.3.1 Thinking Holistically

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

2.3.2 Emergence and Interactions in Systems

The abstractions necessary to define and model the entities or elements of the system
The important relationships, interactions and interfaces among elements
The functional and behavioral properties (intended and unintended) that emerge from the system
Evolutionary adaptation over time

2.3.3 Prioritization and Focus

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

2.3.4 Trade-offs, Judgment and Balance in Resolution

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

2.4 ATTITUDES, THOUGHT AND LEARNING

2.4.1 Initiative and Willingness to Make Decisions in the Face of Uncertainty

The needs and opportunities for initiative
Leadership in new endeavors, with a bias for appropriate action
Decisions, based on the information at hand
Development of a course of action
The potential benefits and risks of an action or decision

2.4.2 Perseverance, Urgency and Will to Deliver, Resourcefulness and Flexibility

Sense of responsibility for outcomes
Self-confidence, courage and enthusiasm
Determination to accomplish objectives
The importance of hard work, intensity and attention to detail
Definitive action, delivery of results and reporting on actions

Adaptation to change
Making ingenious use of the resources of the situation or group
A readiness, willingness and ability to work independently
A willingness to work with others, and to consider and embrace various viewpoints
An acceptance of feedback, criticism and willingness to reflect and respond
The balance between personal and professional life

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

2.4.4 Critical Thinking
Purpose and statement of the problem or issue
Assumptions
Logical arguments (and fallacies) and solutions
Supporting evidence, facts and information
Points of view and theories
Conclusions and implications
Reflection on the quality of the thinking

2.4.5 Self-Awareness, Metacognition and Knowledge Integration
One's skills, interests, strengths and weaknesses
The extent of one's abilities, and one's responsibility for self-improvement to overcome important weaknesses
The importance of both depth and breadth of knowledge
Identification of how effectively and in what way one is thinking
Linking knowledge together and identifying the structure of knowledge

2.4.6 Lifelong Learning and Educating [3i]
The motivation for continued self-education
The skills of self-education
One's own learning styles
Relationships with mentors
Enabling learning in others

2.4.7 Time and Resource Management
Task prioritization
The importance and/or urgency of tasks
Efficient execution of tasks

2.5 ETHICS, EQUITY AND OTHER RESPONSIBILITIES [3f]

2.5.1 Ethics, Integrity and Social Responsibility
- One's ethical standards and principles
- The moral courage to act on principle despite adversity
- The possibility of conflict between professionally ethical imperatives
- A commitment to service
- Truthfulness
- A commitment to help others and society more broadly

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

2.5.3 Proactive Vision and Intention in Life
- A personal vision for one's future
- Aspiration to exercise his/her potentials as a leader
- One's portfolio of professional skills
- Considering one's contributions to society
- Inspiring others

2.5.4 Staying Current on the World of Engineering
- The potential impact of new scientific discoveries
- The social and technical impact of new technologies and innovations
- A familiarity with current practices/technology in engineering
- The links between engineering theory and practice

2.5.5 Equity and Diversity
- A commitment to treat others with equity
- Embracing diversity in groups and workforce
- Accommodating diverse backgrounds

2.5.6 Trust and Loyalty
- Loyalty to one's colleagues and team
- Recognizing and emphasizing the contributions of others
- Working to make others successful

3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION (UNESCO: LEARNING TO LIVE TOGETHER)

3.1 TEAMWORK [3d]

3.1.1 Forming Effective Teams
- The stages of team formation and life cycle
- Task and team processes
- Team roles and responsibilities

The goals, needs and characteristics (works styles, cultural differences) of individual team members
The strengths and weaknesses of the team and its members
Ground rules on norms of team confidentiality, accountability and initiative

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

3.1.3 Team Growth and Evolution
Strategies for reflection, assessment and self-assessment
Skills for team maintenance and growth
Skills for individual growth within the team
Strategies for team communication and reporting

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

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

3.2 COMMUNICATIONS [3g]

3.2.1 Communications Strategy
The communication situation
Communications objectives
The needs and character of the audience
The communication context
A communications strategy
The appropriate combination of media

A communication style (proposing, reviewing, collaborating, documenting, teaching)
The content and organization

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

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

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

3.2.5 Graphical Communications
Sketching and drawing
Construction of tables, graphs and charts
Formal technical drawings and renderings
Use of graphical tools

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

3.2.7 Inquiry, Listening and Dialog
Listening carefully to others, with the intention to understand
Asking thoughtful questions of others
Processing diverse points of view
Constructive dialog
Recognizing ideas that may be better than your own

3.2.8 Negotiation, Compromise and Conflict Resolution
Identifying potential disagreements, tensions or conflicts
Negotiation to find acceptable solutions

Reaching agreement without compromising fundamental principles
Diffusing conflicts

3.2.9 Advocacy
Clearly explaining one's point of view
Explaining how one reached an interpretation or conclusion
Assessing how well you are understood
Adjusting approach to advocacy on audience characteristics

3.2.10 Establishing Diverse Connections and Networking
Appreciating those with different skills, cultures or experiences
Engaging and connecting with diverse individuals
Building extended social networks
Activating and using networks to achieve goals

3.3 COMMUNICATIONS IN FOREIGN LANGUAGES

3.3.1 Communications in English
3.3.2 Communications in Languages of Regional Commerce and Industry
3.3.3 Communications in Other Languages

4 CONCEIVING, DESIGNING, IMPLEMENTING AND OPERATING SYSTEMS IN THE ENTERPRISE, SOCIETAL AND ENVIRONMENTAL CONTEXT—THE INNOVATION PROCESS (UNESCO: LEARNING TO DO)

4.1 EXTERNAL, SOCIETAL AND ENVIRONMENTAL CONTEXT [3h]

4.1.1 Roles and Responsibility of Engineers
The goals and roles of the engineering profession
The responsibilities of engineers to society and a sustainable future

4.1.2 The Impact of Engineering on Society and the Environment
The impact of engineering on the environmental, social, knowledge and economic systems in modern culture

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

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

4.1.5 Contemporary Issues and Values **[3j]**

The important contemporary political, social, legal and environmental issues and values

The processes by which contemporary values are set, and one's role in these processes

The mechanisms for expansion and diffusion of knowledge

4.1.6 Developing a Global Perspective

The internationalization of human activity

The similarities and differences in the political, social, economic, business and technical norms of various cultures

International and intergovernmental agreements and alliances

4.1.7 Sustainability and the Need for Sustainable Development

Definition of sustainability

Goals and importance of sustainability

Principles of sustainability

Need to apply sustainability principles in engineering endeavors

4.2 ENTERPRISE AND BUSINESS CONTEXT

4.2.1 Appreciating Different Enterprise Cultures

The differences in process, culture, and metrics of success in various enterprise cultures:

Corporate versus academic versus governmental versus non-profit/NGO

Market versus policy driven

Large versus small

Centralized versus distributed

Research and development versus operations

Mature versus growth phase versus entrepreneurial

Longer versus faster development cycles

With versus without the participation of organized labor

4.2.2 Enterprise Stakeholders, Strategy and Goals

The stakeholders and beneficiaries of an enterprise (owners, employees, customers, etc.)

Obligations to stakeholders

The mission, scope and goals of the enterprise

Enterprise strategy and resource allocation

An enterprise's core competence and markets

Key alliances and supplier relations

4.2.3 Technical Entrepreneurship

Entrepreneurial opportunities that can be addressed by technology

Technologies that can create new products and systems

Entrepreneurial finance and organization

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

4.2.5 Working in International Organizations
- Culture and tradition of enterprise as a reflection of national culture
- Equivalence of qualifications and degrees
- Governmental regulation of international work

4.2.6 New Technology Development and Assessment
- The research and technology development process
- Identifying and assessing technologies
- Technology development roadmaps
- Intellectual property regimes and patents

4.2.7 Engineering Project Finance and Economics
- Financial and managerial goals and metrics
- Project finance—investments, return, timing
- Financial planning and control
- Impact of projects on enterprise finance, income and cash

4.3 CONCEIVING, SYSTEM ENGINEERING AND MANAGEMENT [3c]

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

4.3.2 Defining Function, Concept and Architecture
- Necessary system functions (and behavioral specifications)
- System concepts

Incorporation of the appropriate level of technology
Trade-offs among and recombination of concepts
High-level architectural form and structure
The decomposition of form into elements, assignment of function to elements, and definition of interfaces

4.3.3 System Engineering, Modeling and Interfaces
Appropriate models of technical performance and other attributes
Consideration of implementation and operations
Life cycle value and costs (design, implementation, operations, opportunity, etc.)
Trade-offs among various goals, function, concept and structure and iteration until convergence
Plans for interface management

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

4.4 DESIGNING [3c]

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

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

4.4.3 Utilization of Knowledge in Design
Technical and scientific knowledge
Modes of thought (problem solving, inquiry, system thinking, creative and critical thinking)

Prior work in the field, standardization and reuse of designs (including reverse engineering and refactoring, redesign)
Design knowledge capture

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

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

4.4.6 Design for Sustainability, Safety, Aesthetics, Operability and Other Objectives
Design for:
Performance, quality, robustness, life cycle cost and value
Sustainability
Safety and security
Aesthetics
Human factors, interaction and supervision
Implementation, verification, test and environmental sustainability
Operations
Maintainability, dependability and reliability
Evolution, product improvement
Retirement, reusability and recycling

4.5 IMPLEMENTING [3c]

4.5.1 Designing a Sustainable Implementation Process
The goals and metrics for implementation performance, cost and quality
The implementation system design:
Task allocation and cell/unit layout
Work flow
Considerations for human user/operators
Consideration of sustainability

4.5.2 Hardware Manufacturing Process
The manufacturing of parts
The assembly of parts into larger constructs
Tolerances, variability, key characteristics and statistical process control

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

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

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

4.5.6 Implementation Management
- The organization and structure for implementation
- Sourcing and partnering
- Supply chains and logistics
- Control of implementation cost, performance and schedule
- Quality assurance
- Human health and safety
- Environmental security
- Possible implementation process improvements

4.6 OPERATING [3c]

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

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

Operations processes
Operations process interactions

4.6.3 Supporting the System Life Cycle
Maintenance and logistics
Life cycle performance and reliability
Life cycle value and costs
Feedback to facilitate system improvement

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

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

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

The Extended CDIO Syllabus: Leadership and Entrepreneurship

This extension to the CDIO Syllabus is provided as a resource for programs that seek to respond to stakeholder expressed needs in the areas of Engineering Leadership and Entrepreneurship

4.7 LEADING ENGINEERING ENDEAVORS

Engineering Leadership builds on factors already included above, including:

- **Attitudes of Leadership—Core Personal Values and Character**, including topics in Attitudes, Thought and Learning (2.4), and in Ethics, Equity and Other Responsibilities (2.5)
- **Relating to Others**, including topics in Teamwork (3.1), Communications (3.2) and potentially Communications in Foreign Languages (3.3)

- **Making Sense of Context**, including topics in External, Societal and Environmental Context (4.1), Enterprise and Business Context (4.2) Conceiving, Systems Engineering and Management (4.3) and System Thinking (2.3)

In addition there are several topics that constitute creating a **Purposeful Vision**:

4.7.1 Identifying the Issue, Problem or Paradox (which builds on Understanding Needs and Setting Goals 4.3.1)
- Synthesizing the understanding of needs or opportunities (that technical systems can address)
- Clarifying the central issues
- Framing the problem to be solved
- Identifying the underlying paradox to be examined

4.7.2 Thinking Creatively and Communicating Possibilities (which builds on and expands Creative Thinking 2.4.3)
- How to create new ideas and approaches
- New visions of technical systems that meet the needs of customers and society
- Communicating visions for products and enterprises
- Compelling visions for the future

4.7.3 Defining the Solution (which builds on and expands Understanding Needs and Setting Goals 4.3.1)
- The vision for the engineering solution
- Achievable goals for quality performance, budget and schedule
- Consideration of customer and beneficiary
- Consideration of technology options
- Consideration of regulatory, political and competitive forces

4.7.4 Creating New Solution Concepts (which builds on and expands 4.3.2 and 4.3.3)
- Setting requirements and specifications
- The high-level concept for the solution
- Architecture and interfaces
- Alignment with other projects of the enterprise
- Alignment with enterprise strategy, resources and infrastructure

And several topics that lead to **Delivering on the Vision:**

4.7.5 Building and Leading an Organization and Extended Organization (which builds on 4.2.4 and 4.2.5)
- Recruiting key team members with complementary skills
- Start-up of team processes, and technical interchange

Defining roles, responsibilities and incentives
Leading group decision-making
Assessing group progress and performance
Building the competence of others and succession
Partnering with external competence

4.7.6 Planning and Managing a Project to Completion (which builds on 4.3.4)

Plans of action and alternatives to deliver completed projects on time
Deviation from plan, and re-planning
Managing human, time, financial and technical resources to meet plan
Program risk, configuration and documentation
Program economics and the impact of decisions on them

4.7.7 Exercising Project/Solution Judgment and Critical Reasoning (which builds on 2.3.4 and 2.4.4)

Making complex technical decisions with uncertain and incomplete information
Questioning and critically evaluating the decisions of others
Corroborating inputs from several sources
Evaluating evidence and identifying the validity of key assumptions
Understanding alternatives that are proposed by others
Judging the expected evolution of all solutions in the future

4.7.8 Innovation—the Conception, Design and Introduction of New Goods and Services (which is the leadership of 4.3 and 4.4)

Designing and introducing new goods and services to the marketplace
Designing solutions to meet customer and societal needs
Designing solutions with the appropriate balance of new and existing technology
Robust, flexible and adaptable products
Consideration of current and future competition
Validating the effectiveness of the solution

4.7.9 Invention—the Development of New Devices, Materials or Processes that Enable New Goods and Services (which builds on 4.2.6)

Science and technology basis and options
Imagining possibilities
Inventing a practical device or process that enables a new product or solution
Adherence to intellectual property regimes

4.7.10 Implementation and Operation—the Creation and Operation of the Goods and Services that will Deliver Value (which are the leadership of 4.5 and 4.6)
- Leading implementing and operating
- Importance of quality
- Safe operations
- Operations to deliver value to the customer and society

These last three items are in fact the leadership of the core processes of engineering: conceiving, designing, implementing and operating

4.8 ENGINEERING ENTREPRENEURSHIP

Engineering Entrepreneurship includes by reference all of the aspects of Societal and Enterprise Context (4.1 and 4.2), all of the skills of Conceiving, Designing, Implementing and Operating (4.3–4.6) and all of the elements of Engineering Leadership (4.7). In addition, there are the entrepreneurship specific skills:

4.8.1 Company Founding, Formulation, Leadership and Organization
- Creating the corporate entity and financial infrastructure
- Team of supporting partners (bank, lawyer, accounting, etc.)
- Consideration of local labor law and practices
- The founding leadership team
- The initial organization
- The board of the company
- Advisors to the company

4.8.2 Business Plan Development
- A need in the world that you will fill
- A technology that can become a product
- A team that can develop the product
- Plan for development
- Uses of capital
- Liquidity strategy

4.8.3 Company Capitalization and Finances
- Capital needed, and timing of need (to reach next major milestone)
- Investors as sources of capital
- Alternative sources of capital (government, etc.)
- Structure of investment (terms, price, etc.)
- Financial analysis for investors
- Management of finances
- Expenditures against intermediate milestones of progress

4.8.4 Innovative Product Marketing
- Size of potential market
- Competitive analyses

Penetration of market
Product positioning
Relationships with customers
Product pricing
Sales initiation
Distribution to customers

4.8.5 Conceiving Products and Services around New Technologies
New technologies available
Assessing the readiness of technology
Assessing the ability of your enterprise to innovate based on the technology
Assessing the product impact of the technology
Accessing the technologies though partnerships, licenses, etc.
A team to productize the technology

4.8.6 The Innovation System, Networks, Infrastructure and Services
Relationships for enterprise success
Mentoring of the enterprise leadership
Supporting financial services
Investor networks
Suppliers

4.8.7 Building the Team and Initiating Engineering Processes (conceiving, designing, implementing and operating)
Hiring the right skill mix
Technical process startup
Building an engineering culture
Establishing enterprise processes

4.8.8 Managing Intellectual Property
IP landscape for your product or technology
IP strategy—offensive and defensive
Filing patents and provisional patents
IP legal support
Entrepreneurial opportunities that can be addressed by technology
Technologies that can create new products and systems
Entrepreneurial finance and organization

Appendix B: The CDIO Standards v2.0

THE CDIO STANDARDS v 2.0

(with customized rubrics)

8 December 2010

Background

A major international project to reform undergraduate engineering education was launched in October 2000. This project, called *The CDIO Initiative*, has expanded to include engineering programs worldwide. The vision of the project is to provide students with an education that stresses engineering fundamentals set in the context of Conceiving-Designing-Implementing-Operating real-world systems, processes, and products. The CDIO Initiative has three overall goals—to educate students who are able to:

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

The CDIO Initiative creates a range of resources that can be adapted and implemented by individual programs to meet these goals. These resources support a curriculum organized around mutually supporting disciplines, interwoven with learning experiences related to personal and interpersonal skills, and product, process, and system building skills. Students receive an education rich in design-implement experiences and active and experiential learning, set in both the classroom and modern learning workspaces. One of these resources, the CDIO Standards, is provided in this document. For more information about the CDIO Initiative, visit http://www.cdio.org.

E. F. Crawley et al., *Rethinking Engineering Education*,
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The CDIO Standards

In January 2004, the CDIO Initiative adopted 12 standards to describe CDIO programs. These guiding principles were developed in response to program leaders, alumni, and industrial partners who wanted to know how they would recognize CDIO programs and their graduates. As a result, these CDIO Standards define the distinguishing features of a CDIO program, serve as guidelines for educational program reform and evaluation, create benchmarks and goals with worldwide application, and provide a framework for continuous improvement. The standards may also be used as a framework for certification purposes.

The 12 CDIO Standards address program philosophy (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), and assessment and evaluation (Standards 11 and 12).

Each standard is presented here with a description, a rationale, and a rubric.

Description. The description elaborates the statement of the standard, explaining its meaning. It defines significant terms and provides background information.

Rationale. The rationale highlights reasons for the adoption of the standard. Reasons are based on educational research and best practices in engineering and higher education. The rationale explains ways in which the standard distinguishes the CDIO approach from other educational reform efforts.

Rubric. A rubric is a scoring guide that seeks to evaluate levels of performance. The rubric of the CDIO Standards is a six-point rating scale for assessing levels of compliance with the standard. Criteria for each level are based on the description and rationale of the standard. The rubric highlights the nature of the evidence that indicates compliance at each level. The rubrics in this document are hierarchical, that is, each successive level includes those at lower levels. For example, Level 5 that addresses continuous process improvement presumes that Level 4 has been attained.

Self-Assessment of Compliance

The assessment of compliance with the CDIO Standards is a self-report process. An engineering program gathers its own evidence and uses the rubrics to rate its status with respect to each of the 12 CDIO Standards. While the rubrics are customized to each CDIO Standard, they follow the pattern of this general rubric.

General Rubric:

Scale	Criteria
5	Evidence related to the standard is regularly reviewed and used to make improvements
4	There is documented evidence of the full implementation and impact of the standard across program components and constituents
3	Implementation of the plan to address the standard is underway across the program components and constituents
2	There is a plan in place to address the standard
1	There is an awareness of need to adopt the standard and a process is in place to address it
0	There is no documented plan or activity related to the standard

An accompanying document gives examples of evidence for different levels of compliance for each CDIO Standard, as reported by CDIO programs in 2005 and 2008.

Standard 1—The Context

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

Description: A CDIO program is based on the principle that product, process, and system lifecycle development and deployment are the appropriate context for engineering education. *Conceiving–Designing–Implementing–Operating* is a model of the entire product, process, and system lifecycle. The *Conceive* stage includes defining customer needs; considering technology, enterprise strategy, and regulations; and, developing conceptual, technical, and business plans. The *Design* stage focuses on creating the design, that is, the plans, drawings, and algorithms that describe what will be implemented. The *Implement* stage refers to the transformation of the design into the product, process, or system, including manufacturing, coding, testing and validation. The final stage, *Operate*, uses the implemented product or process to deliver the intended value, including maintaining, evolving and retiring the system.

The product, process, and system lifecycle is considered the context for engineering education in that it is part of the cultural framework, or environment, in which technical knowledge and other skills are taught, practiced and learned. The principle is adopted by a program when there is explicit agreement of faculty to transition to a CDIO program, and support from program leaders to sustain reform initiatives.

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

Rubric:

Scale	Criteria
5	Evaluation groups recognize that CDIO is the context of the engineering program and use this principle as a guide for continuous improvement
4	There is documented evidence that the CDIO principle is the context of the engineering program and is fully implemented
3	CDIO is adopted as the context for the engineering program and is implemented in one or more years of the program
2	There is an explicit plan to transition to a CDIO context for the engineering program
1	The need to adopt the principle that CDIO is the context of engineering education is recognized and a process to address it has been initiated
0	There is no plan to adopt the principle that CDIO is the context of engineering education for the program

Standard 2—Learning Outcomes

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

Description: The knowledge, skills, and attitudes intended as a result of engineering education, that is, the learning outcomes, are codified in the *CDIO Syllabus*. These learning outcomes detail what students should know and be able to do at the conclusion of their engineering programs. In addition to learning outcomes for technical disciplinary knowledge (Section 1), the *CDIO Syllabus* specifies learning outcomes as personal and interpersonal skills, and product, process, and system building. Personal learning outcomes (Section 2) focus on individual students' cognitive and affective development, for example, engineering reasoning and problem solving, experimentation and knowledge discovery, system thinking, creative thinking, critical thinking, and professional ethics. Interpersonal learning outcomes (Section 3) focus on individual and group interactions, such as, teamwork, leadership, communication, and communication in foreign languages. Product, process, and system building skills (Section 4) focus on conceiving, designing, implementing, and operating systems in enterprise, business, and societal contexts.

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

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

Rubric:

Scale	Criteria
5	Evaluation groups regularly review and revise program learning outcomes, based on changes in stakeholder needs
4	Program learning outcomes are aligned with institutional vision and mission, and levels of proficiency are set for each outcome
3	Program learning outcomes are validated with key program stakeholders, including faculty, students, alumni, and industry representatives
2	A plan to incorporate explicit statements of program learning outcomes is established
1	The need to create or modify program learning outcomes is recognized and such a process has been initiated
0	There are no explicit program learning outcomes that cover knowledge, personal and interpersonal skills, and product, process and system building skills

Standard 3—Integrated Curriculum

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

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

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

Rubric:

Scale	Criteria
5	Stakeholders regularly review the integrated curriculum and make recommendations and adjustments as needed
4	There is evidence that personal, interpersonal, product, process, and system building skills are addressed in all courses responsible for their implementation
3	Personal, interpersonal, product, process, and system building skills are integrated into one or more years in the curriculum
2	A curriculum plan that integrates disciplinary learning, personal, interpersonal, product, process, and system building skills is approved by appropriate groups
1	The need to analyze the curriculum is recognized and initial mapping of disciplinary and skills learning outcomes is underway
0	There is no integration of skills or mutually supporting disciplines in the program

Standard 4—Introduction to Engineering

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

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

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

Rubric:

Scale	Criteria
5	The introductory course is regularly evaluated and revised, based on feedback from students, instructors, and other stakeholders
4	There is documented evidence that students have achieved the intended learning outcomes of the introductory engineering course
3	An introductory course that includes engineering learning experiences and introduces essential personal and interpersonal skills has been implemented
2	A plan for an introductory engineering course introducing a framework for practice has been approved
1	The need for an introductory course that provides the framework for engineering practice is recognized and a process to address that need has been initiated
0	There is no introductory engineering course that provides a framework for practice and introduces key skills

STANDARD 5—DESIGN-IMPLEMENT EXPERIENCES

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

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

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

Rubric:

Scale	Criteria
5	The design-implement experiences are regularly evaluated and revised, based on feedback from students, instructors, and other stakeholders
4	There is documented evidence that students have achieved the intended learning outcomes of the design-implement experiences
3	At least two design-implement experiences of increasing complexity are being implemented
2	There is a plan to develop a design-implement experience at a basic and advanced level
1	A needs analysis has been conducted to identify opportunities to include design-implement experiences in the curriculum
0	There are no design-implement experiences in the engineering program

Standard 6—Engineering Workspaces

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

Description: The physical learning environment includes traditional learning spaces, for example, classrooms, lecture halls, and seminar rooms, as well as engineering workspaces and laboratories. Workspaces and laboratories support the learning of product, process, and system building skills concurrently with disciplinary knowledge. They emphasize hands-on learning in which students are directly engaged in their own learning, and provide opportunities for social learning, that is, settings where students can learn from each other and interact with several groups. The creation of new workspaces, or remodeling of existing laboratories, will vary with the size of the program and resources of the institution.

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

Rubric:

Scale	Criteria
5	Evaluation groups regularly review the impact and effectiveness of workspaces on learning and provide recommendations for improving them
4	Engineering workspaces fully support all components of hands-on, knowledge, and skills learning
3	Plans are being implemented and some new or remodeled spaces are in use
2	Plans to remodel or build additional engineering workspaces have been approved by the appropriate bodies
1	The need for engineering workspaces to support hands-on, knowledge, and skills activities is recognized and a process to address the need has been initiated
0	Engineering workspaces are inadequate or inappropriate to support and encourage hands-on skills, knowledge, and social learning

Standard 7—Integrated Learning Experiences

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

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

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

Rubric:

Scale	Criteria
5	Courses are regularly evaluated and revised regarding their integration of learning outcomes and activities
4	There is evidence of the impact of integrated learning experiences across the curriculum
3	Integrated learning experiences are implemented in courses across the curriculum
2	Course plans with learning outcomes and activities that integrate personal and interpersonal skills with disciplinary knowledge has been approved
1	Course plans have been benchmarked with respect to the integrated curriculum plan
0	There is no evidence of integrated learning of disciplines and skills

STANDARD 8—ACTIVE LEARNING

Teaching and learning based on active experiential learning methods

Description: Active learning methods engage students directly in thinking and problem solving activities. There is less emphasis on passive transmission of information, and more on engaging students in manipulating, applying, analyzing, and evaluating ideas. Active learning in lecture-based courses can include such methods as partner and small-group discussions, demonstrations, debates, concept questions, and feedback from students about what they are learning. Active learning is considered experiential when students take on roles that simulate professional engineering practice, for example, design-implement projects, simulations, and case studies.

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

Rubric:

Scale	Criteria
5	Evaluation groups regularly review the impact of active learning methods and make recommendations for continuous improvement
4	There is documented evidence of the impact of active learning methods on student learning
3	Active learning methods are being implemented across the curriculum
2	There is a plan to include active learning methods in courses across the curriculum
1	There is an awareness of the benefits of active learning, and benchmarking of active learning methods in the curriculum is in process
0	There is no evidence of active experiential learning methods

STANDARD 9—ENHANCEMENT OF FACULTY COMPETENCE

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

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

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

Rubric:

Scale	Criteria
5	Faculty competence in personal, interpersonal, product, process, and system building skills is regularly evaluated and updated where appropriate
4	There is evidence that the collective faculty is competent in personal, interpersonal, product, process, and system building skills
3	The collective faculty participates in faculty development in personal, interpersonal, product, process, and system building skills
2	There is a systematic plan of faculty development in personal, interpersonal, product, process, and system building skills
1	A benchmarking study and needs analysis of faculty competence has been conducted
0	There are no programs or practices to enhance faculty competence in personal, interpersonal, product, process, and system building skills

Standard 10—Enhancement of Faculty Teaching Competence

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

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

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

Rubric:

Scale	Criteria
5	Faculty competence in teaching, learning, and assessment methods is regularly evaluated and updated where appropriate
4	There is evidence that the collective faculty is competent in teaching, learning, and assessment methods
3	Faculty members participate in faculty development in teaching, learning, and assessment methods
2	There is a systematic plan of faculty development in teaching, learning, and assessment methods
1	A benchmarking study and needs analysis of faculty teaching competence has been conducted
0	There are no programs or practices to enhance faculty teaching competence

Standard 11—Learning Assessment

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

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

Rationale: If we value personal and interpersonal skills, and product, process, and system building skills, and incorporate them into curriculum and learning experiences, then we must have effective assessment processes for measuring them. Different categories of learning outcomes require different assessment methods.

For example, learning outcomes related to disciplinary knowledge may be assessed with oral and written tests, while those related to design-implement skills may be better measured with recorded observations. Using a variety of assessment methods accommodates a broader range of learning styles, and increases the reliability and validity of the assessment data. As a result, determinations of students' achievement of the intended learning outcomes can be made with greater confidence.

Rubric:

Scale	Criteria
5	Evaluation groups regularly review the use of learning assessment methods and make recommendations for continuous improvement
4	Learning assessment methods are used effectively in courses across the curriculum
3	Learning assessment methods are implemented across the curriculum
2	There is a plan to incorporate learning assessment methods across the curriculum
1	The need for the improvement of learning assessment methods is recognized and benchmarking of their current use is in process
0	Learning assessment methods are inadequate or inappropriate

STANDARD 12—**PROGRAM EVALUATION**

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

Description: Program evaluation is a judgment of the overall value of a program based on evidence of a program's progress toward attaining its goals. A CDIO program should be evaluated relative to these 12 CDIO Standards. Evidence of overall program value can be collected with course evaluations, instructor reflections, entry and exit interviews, reports of external reviewers, and follow-up studies with graduates and employers. The evidence can be regularly reported back to instructors, students, program administrators, alumni, and other key stakeholders. This feedback forms the basis of decisions about the program and its plans for continuous improvement.

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

Rubric:

Scale	Criteria
5	Systematic and continuous improvement is based on program evaluation results from multiple sources and gathered by multiple methods
4	Program evaluation methods are being used effectively with all stakeholder groups
3	Program evaluation methods are being implemented across the program to gather data from students, faculty, program leaders, alumni, and other stakeholders
2	A program evaluation plan exists
1	The need for program evaluation is recognized and benchmarking of evaluation methods is in process
0	Program evaluation is inadequate or inconsistent

About the Authors

(The Late) **Perry J. Armstrong** was Director of Education in the School of Mechanical and Aerospace Engineering at Queen's University Belfast until he died unexpectedly in 2008. He was instrumental in designing and implementing engineering curriculum reform and the CDIO approach at QUB and other universities in the U.K. in his role as co-chair of the U.K. and Ireland CDIO Region. He helped to develop models for CDIO curriculum development that continue to be used today by universities in many countries. The Perry Armstrong Prize is awarded each year to a graduating engineering student at QUB who exhibits an optimal balance between technical knowledge and personal and professional engineering skills.

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