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Rethinking Engineering Education

The CDIO Approach

With Foreword by Charles M. Vest

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Educating Engineers for 2020 and Beyond

Charles M. Vest
President Emeritus
MIT

Most of my career was played out in the 20^{th} 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 21^{st} 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 the nano-, meso-, 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, understand 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 can 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 codes. The new engineering science required a new panoply of textbooks 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, 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 fundamentals, 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.

CHAPTER ONE
INTRODUCTION

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. It is from this emphasis on the product, process, or system lifecycle that the initiative derives its name–CDIO.

Within these pages, we demonstrate how conceiving, designing, implementing, and operating products, processes, and systems is the appropriate context for engineering education. The CDIO approach builds on stakeholder input to identify the learning needs of the students in a program, and construct a sequence of integrated learning experiences to meet those needs. We incorporate a comprehensive and broadly applicable approach to improving curriculum, teaching and learning, and 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.

BACKGROUND

In the 1980s and 1990s, 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.

The challenge that remains is that of introducing change to relieve this tension, to respond to the needs of our external stakeholders, to reform our programs and educational approaches, and in fact, to transform the culture of education.

THE CDIO INITIATIVE

The CDIO Initiative 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 moderny, team-based environment. The Initiative has 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.

This context of 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 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. We use modern pedagogical approaches, innovative teaching methods, and new learning environments to provide real-world 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.

THE SYLLABUS AND THE STANDARDS

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 to construct a sequence of learning experiences to meet those needs. These two elements are captured in a best-practice framework, consisting of the CDIO Syllabus and the CDIO Standards.

Specific learning outcomes are codified in the CDIO Syllabus. The Syllabus is a rational, relevant, and consistent set of skills for an engineer. The Syllabus was derived from needs assessment 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 program design and assessment.

A CDIO program creates a curriculum organized around mutually supporting technical disciplines with personal and interpersonal skills, and product, process, and system building skills highly interwoven. These programs are rich with student design-implement experiences conducted in modern workspaces. They feature active and experiential learning and are continuously improved through a robust, quality assessment process. These characteristics are formalized in twelve CDIO Standards, which 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.

IMPLEMENTATION AND EVOLUTION

Development and implementation of the CDIO approach was initiated at four universities: Chalmers University of Technology (Chalmers) in Göteborg, the Royal Institute of Technology (KTH) in Stockholm, Linköping University (LiU) in Linköping, and the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts. The number of programs collaborating in the Initiative has expanded to more than 20 universities worldwide.

Little in our approach has been invented 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. The CDIO Initiative 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 use the shared open-source resources and parallel-coordinated efforts to facilitate rapid transition to a steady state that largely retasks existing personnel, time, and space resources.

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. We recognize this. We invite you to share your results, and contribute to our collective effort.

THE BOOK

We have written this book to serve as an introduction to the approaches and resources created by the CDIO Initiative. It is a practical guide with enough information to acquaint you with the high-level rationale, philosophy, and key approaches, 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 in-depth overview of the CDIO Initiative. This chapter will leave the reader with an understanding of the need for change, the goals, vision, and pedagogical foundation of the CDIO 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 program evaluation, student assessment, and implementation and change processes. 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.

CHAPTER TWO
OVERVIEW

INTRODUCTION

The objective of engineering education is to educate students who are "ready to engineer," that is, broadly prepared with the pre-professional skills of engineering, and deeply knowledgeable of the technical fundamentals. It is the task of engineering educators to continuously improve the quality and nature of undergraduate engineering education in order to meet this objective. Over the past 25 years, many in industry, government, and university programs have addressed the need for reform of engineering education, often by stating the 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 reforms engineering education to meet this underlying need. The value of this approach to students 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 be *dual-impact*, facilitating student learning of critical personal and interpersonal skills, and product, process, and system building skills, and simultaneously enhancing the learning of the fundamentals.

The CDIO approach incorporates comprehensive and broadly applicable processes for improving curriculum, teaching and learning, and workspaces, and is supported by robust assessment, and change processes.

This overview chapter outlines the key premises and features of the CDIO Initiative. It begins with a discussion of the motivation for improvement in engineering education, including a discussion of the needs of our students, the historical environment of our education, and the requirements for an effective program of reform. The second section describes the Initiative in some detail: its goals, vision, and pedagogical foundation. The structure of this second section serves as the framework for many of the remaining chapters of the book, which go into more detail on the topics of setting goals for learning, improving curriculum and workspaces, teaching and learning, and conducting student assessment and program evaluation. The final part of the chapter describes approaches to development, including the available resources and collaboration approach, and underscores the need to recognize educational reform as a process for organizational and cultural change at the university.

CHAPTER OBJECTIVES

This chapter is designed so that you can

- recognize the contemporary motivation for engineering education reform
- explain the underlying goals, vision, and pedagogical foundation
- describe the key characteristics of a CDIO program
- explain the approach to the development of the CDIO Initiative

MOTIVATION FOR CHANGE

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 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." Creation of new products and direction of natural resources remain the tasks of engineers today.

What modern engineers do

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 of society. Good engineers observe and listen carefully to determine the needs of the member of society for whom the benefit is intended. 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. That is the stuff of startups and breakthrough innovations. However, much of engineering design is performed by applying and adapting existing technology to meet society's changing needs. In most of the world, society is uplifted by broad-based applications of existing technology. Good engineers apply appropriate technology to design.

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. Some engineers, such as those who develop software, are actually involved in both the design and implementation of the code. In other industries, engineers specialize in implementation, such as manufacturing engineers.

Modern engineers work in teams when they conceive, design and implement the product, process, or system. Teams are often geographically distributed and international. Engineers exchange thoughts, ideas, data and drawings, elements and devices with others around the work site and around the world. They capture the tacit knowledge of a system's design and implementation so that it can be revised and upgraded in the future. Good engineers work in teams and communicate effectively, while always exercising personal creativity and responsibility.

In order to deliver a benefit to a member of society, engineering devices and systems must be operated. Simpler devices, 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. Good engineers consider and plan for the operation of the product, process, or system as an integral part of design. They are sometimes involved in the operation of the system as well.

Conceive-Design-Implement-Operate

Modern engineers lead or are involved in all phases of a product, process, or system lifecycle. That is, they Conceive, Design, Implement, and Operate. The *Conceive* stage includes defining customer needs; considering technology, enterprise strategy, and regulations; and developing conceptual, technical, and business plans. The second stage, *Design*, focuses on creating the design, that is, 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 product, including hardware manufacturing, software coding, testing, and validation. The final stage, *Operate*, uses the implemented product, process, or system to deliver the intended value, including maintaining, evolving, recycling, and retiring the system.

These four terms, and the activities and outcomes of the four phases, have been chosen because they are applicable to a wide range of engineering disciplines. Details of the tasks that fall into these four main phases—conceiving, designing, implementing, and operating—are found in Figure 2.1. 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