

INTRODUCTION TO PROFESSIONAL ENGINEERING IN CANADA

FIFTH
EDITION

GORDON C. ANDREWS
J. DWIGHT APLEVICH
ROYDON A. FRASER
CAROLYN G. MACGREGOR



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Preface to the Fifth Edition

This book is intended to explain the elements of what every beginning engineering student should know about the engineering profession in Canada. The authors feel strongly that such an introduction should not be left to the final year of an undergraduate education. Therefore, the content is directed at students in their first or second year of study.

There is no universal canon of material taught everywhere in introductory engineering courses. Consequently, the number of topics introduced in this book is relatively large, and we expect instructors to choose a subset of them to cover, supplementing the material with discipline-specific and province-specific assignments, readings, or multimedia. The choice of material has been influenced by the needs of undergraduates on their first internship or work-term and by the criteria employed by the Canadian Engineering Accreditation Board (CEAB), which requires that every engineering student be introduced to the profession and various technical topics.

The fifth edition includes updates and revisions, particularly to the chapter on environmental sustainability to reflect recent developments, a revised design chapter, and numerous minor revisions to references to the profession and to electronic communication. Ethical theories have been introduced in the material on professional engineering ethics, and, so that students will be aware of developments at the foundation of engineering measurements, proposed changes to the SI system of units have been included.

Part I
The engineering
profession,
Chapters 1 to 5

Chapters 1, 2, and 3 emphasize that the word *engineering* means more than a set of required courses; it refers to an organized profession, with strict requirements for admission, a code of ethics, professional regulations, and requirements for maintaining competency. Chapter 4 explains how engineering societies focus on activities outside the main mandate of the provincial regulatory organizations. Chapter 5 gives advice for studying and writing examinations to help students, both in their immediate task of acquiring an engineering education and for lifelong learning.

Part II
Engineering
communications,
Chapters 6 to 9

In emphasizing the value of communicating effectively in print and electronically, Chapter 6 reviews technical document types, including some that are not typically discussed in English courses, and Chapter 7 reviews basic writing techniques. Chapter 8 contains a thorough discussion of the purpose and structure of engineering reports and the mechanics of writing them. Many students need this knowledge immediately because they may be required to write formal reports in their courses or during their first work-term or internship. Our philosophy has also been to attempt to show how to write a report that will stand up to challenge, such as might happen in a court of law. Chapter 9

describes elementary principles for the use and design of graphics and the essential rules for including graphics in engineering documents.

Part III
Engineering
measurements,
Chapters 10 to 14

Measurement is at the core of the applied physical sciences, and its correct interpretation is crucial to many engineering decisions. Part III introduces techniques for interpreting, manipulating, and presenting measured quantities. Chapter 10 contains a careful treatment of unit systems, with emphasis on SI units and rules for including them in written documents. Systematic and random measurement errors are treated in Chapter 11, together with correct use of significant digits. Chapter 12 introduces methods for estimating propagated error and provides motivation for the elementary application of statistics and probability to measurements in Chapters 13 and 14. The CEAB requires that every engineering program contain material on statistics, and these chapters have been used successfully to satisfy this accreditation requirement.

Part IV
Engineering practice,
Chapters 15 to 21

Part IV introduces several distinctive topics that make engineering a profession of practice, rather than the subject of purely academic study. Chapter 15 describes the design process, emphasizing the iterative nature of design. Chapter 16 briefly introduces project management and illustrates several common planning techniques using examples. Chapter 17 discusses safety in engineering design and practice and lists guidelines for eliminating workplace and other hazards. Chapter 18 introduces the complex problem of calculating and managing risks associated with large systems. Chapter 19 discusses environmental issues and sustainability, with an emphasis on global warming, climate change, and the responsibilities of engineers. Chapter 20 is a brief introduction to résumés, interviews, presentations, and the relationship of engineers to businesses. The rapidly changing domain of intellectual property is described in Chapter 21 in order to show how the results of the creative process are protected and exploited.

**How to use this
book**

The authors and others have used this book in several introductory engineering courses, supplemented with videos, exercises, assignments, and an introduction to software tools to suit the engineering discipline and course goals. The assignments usually include a formal engineering report on a topic requiring basic analysis or design. Conceptual knowledge is tested by several short examinations during the term. Portions of the material—particularly the report-writing and design chapters—are also used in higher-level courses.

The Quick Quiz questions at the end of each chapter are intended for students to answer in a few minutes in order to solidify their knowledge of each chapter immediately after reading it. Other questions are also included to reinforce and expand the chapter contents.

The order in which material is presented can be varied considerably. We advise introducing the professional matters in Part I early, together with an introduction to Part II if student assignments include writing engineering reports. The chapters in Part III on measurements and errors can then be covered, ending the course with chapters on design, intellectual property, and safety from Part IV. However, a different order may suit other courses. Some programs include error propagation and statistics in later courses, so only Chapters 10 and 11 are required for report writing. The basic material in Chapters 12 to 14 is designed for programs that do not contain this material in higher courses.

Acknowledgments The authors would like to thank all those who assisted, directly or indirectly, in this and previous editions of this book. The contents and the intended use of the material have evolved over time and are the result of the efforts of a large number of people over more than two decades. We are in their debt.

The first edition of this publication was a rewriting of material that had been distributed to students in various forms. We acknowledge the ideas and careful writing of H. C. Ratz, a co-author with Gordon Andrews of early material and co-author of the first two editions of this book. Gordon Andrews (1937–2014) was a driving force, both in recognizing the need for careful presentation of an introduction to the engineering profession and in preparing the details, especially of Part I. He participated fully in the evolution of the material, and his passing during the preparation of the fourth edition continues to be felt with regret by his fellow authors.

We gratefully acknowledge the students, teaching assistants, and many colleagues who provided suggestions, comments, and criticism. We thank the two award-winning graduates, who wished anonymity, pictured in Figure 1.1. Surin Kalra, Bob Pearce, and Alan Hale assisted immensely with early material and are gratefully remembered. Comments and suggestions from Ewart Brundrett, Rob Gorbet, June Lowe, Roy Pick, John Shortreed, Carl Thompson, Neil Thomson, Barry Wills, and others were very much appreciated. The various directors of first-year studies at the University of Waterloo created a positive environment for the development of this book, and we would like to thank all who have held this position in the last two decades.

We are grateful to several anonymous instructors who provided reviews for this and previous editions. Their thoughtful comments brought home to us both the diversity of engineering education in Canada and the enthusiasm of engineering instructors. The reviews helped us arrive at a compromise among teaching objectives, breadth of coverage, and size of a book intended to be affordable for undergraduate students.

We are indebted to people who helped us to get permission to use copyrighted material and to the copyright holders. In particular, we would like to thank Connie Mucklestone and Johnny Zuccone of PEO, Melissa Mertz of APEGNB, Lynne Vanin of MD Robotics, Paul Deslauriers of Waterloo FSAE, and Nick Farinaccio of Chipworks.

We thank Connie Mucklestone of PEO for her thorough reading and detailed comments on Part I of the first edition of the book.

We also thank Anne Sharkey and co-workers at the Standards Council of Canada, who provided useful comments about our discussion of engineering standards.

Samantha Colasante and Lynn Villeneuve provided the most up-to-date data from Engineers Canada for several editions.

Dennis Burningham, MSc, chemical engineer and UK industry consultant, provided his personal insight into sustainability, and many of his notes and comments are woven into Chapter 19. The authors would like to acknowledge this assistance and express thanks.

From the beginning, one of our objectives has been to keep the price of this book to a reasonable level. This objective affects the size, the soft-cover production, and the use of copyright material in the book. We thank the various acquisitions editors at Pearson who understood this objective and who allowed us to persist with an unconventional production process in which the authors were responsible for formatting and artwork.

We owe thanks to the people at or associated with Pearson Education Canada who helped us: Cathleen Sullivan, Madhu Ranadive, Christine Langone, Susan Johnson, Kathleen Reed, Joanne Tang, and those who worked on earlier editions. Paul McInnis deserves special thanks for his perspicacious suggestions about the first edition.

Every effort has been made to avoid errors and to credit sources. The authors would be grateful for advice concerning any errors or omissions. In particular, we would like to know, from students, what you particularly liked or disliked in this book and, from instructors, what changes you would like to see in later editions.

J. Dwight Aplevich
Roydon A. Fraser
Carolyn G. MacGregor

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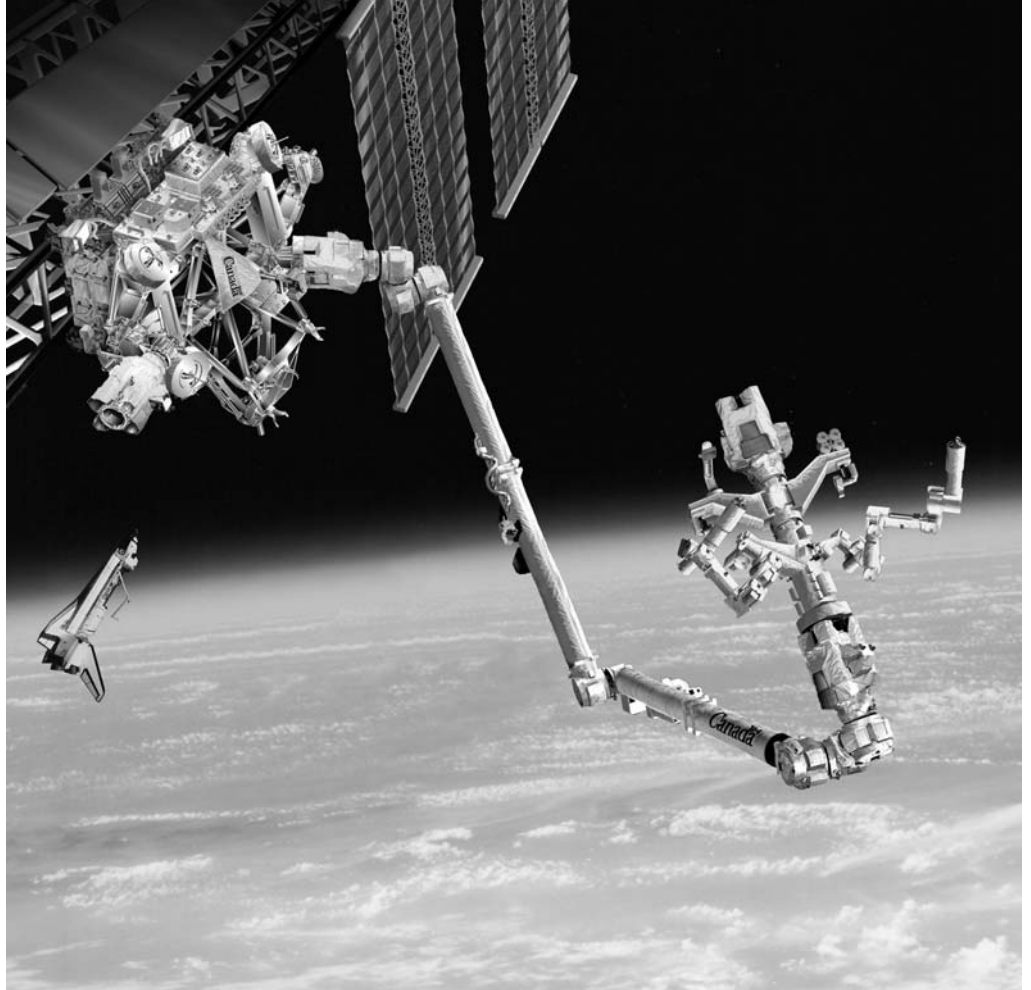


Figure I.1 Design of the Canadarm and Canadarm2 required expertise in several engineering disciplines: materials, structures, robotics, electronics, control systems, computers, and software. The Canadarm is listed among the five most significant Canadian engineering achievements of the 20th century. A key part of the American space shuttle program for almost 30 years, the original Canadarm was retired in 2011, with the Canadarm2 continuing on the International Space Station. (Courtesy of MDA)

By choosing engineering, you have taken the first step toward a challenging and rewarding profession. In future years you will share the great sense of personal achievement that is typical of engineering, as your ideas move from the design office or computer lab to the production line or construction site. This book is intended to acquaint future engineers with many basic engineering concepts. However, in passing along this basic information, we hope that the excitement and creativity of engineering also show through.

Part I introduces the engineering profession.

- Chapter 1 An Introduction to Engineering:** Most people know that Canadian engineers wear iron rings, but what does the word *engineering* mean? This chapter gives you a working definition of engineering, an overview of engineering in Canada, and a description of some differences between the work of engineers and other technical specialists such as research scientists, technicians, and technologists.
- Chapter 2 The Licensed Professional Engineer:** An engineering education is not merely a group of related university courses; it is an entry point into a legally recognized profession with strict requirements for admission, a code of ethics, and professional regulations. This chapter tells you how the engineering profession is organized and how to enter it.
- Chapter 3 Professional Engineering Ethics:** The public expects all professionals to be honest, reliable, and ethical. How does the public expectation apply to engineering? This chapter includes engineering codes of ethics, how they apply to typical engineering practice, the proper use of the engineer's seal, and the significance of the iron ring.
- Chapter 4 Engineering Societies:** Engineering societies help you by publishing technical papers, organizing conferences and engineering contests, and presenting short courses. Such assistance can be very useful while you are a student, but it will be even more important after you graduate. This chapter explains the role of engineering societies and mentions several societies that may be of interest to you.
- Chapter 5 Learning Strategies:** You are investing much effort, time, and money in your engineering education. Would you like to protect this investment? If you can master the fundamental advice in this chapter, you should be able to achieve academic success and still have enough free time to enjoy other fulfilling parts of university life.

An Introduction to Engineering

An engineering degree opens the door to a highly respected and structured profession, so graduation is a major achievement. Engineering students look forward to the happy day when they receive their engineering degrees, as shown in Figure 1.1, and their iron rings, described in Section 3.7. Chapter 1 of this book introduces the engineering profession by exploring the following topics:

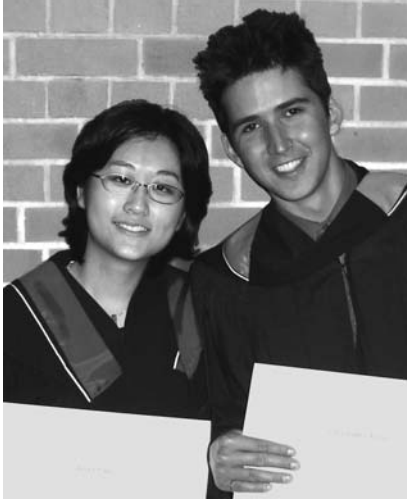


Figure 1.1 Two engineering graduates, diploma in hand and Ritual of the Calling of an Engineer in memory (as described in Section 3.7), celebrate their achievements. Graduation is the first important step to becoming a professional engineer. (Photo: D. Aplevich)

- a definition of *engineer*, to begin the discussion of *engineering*,
- the role of engineers in relation to other technical specialists,
- characteristics of some important engineering disciplines,
- engineering in Canada and the distribution of engineers by province,
- Canadian engineering achievements that have been judged to be of particular significance,
- some of the engineering challenges faced by society.

The Further Study questions at the end of this chapter (Section 1.7) may help you to master the main ideas in the chapter and also to confirm your decision to choose engineering as a career.

1.1

What is an engineer?

The term *engineer* comes to English from the Latin word *ingenium*, meaning talent, genius, cleverness, or native ability. Its first use was to describe those who had an ability to invent and operate weapons of war. Later, the word came to be associated with the design and construction of works, such as ships, roads, canals, and bridges, and the people skilled in these fields were non-military, or *civil*, engineers. The modern meaning of the term *engineering* depends, to some degree, on context. In the United Kingdom, people with practical skills have been called engineers since the Industrial Revolution. In North America, more emphasis is placed on formal training, as a result of a recognized need for trained engineers during the wars of the 1700s and 1800s and the modelling of early American engineering programs on French engineering schools [1].

In Canada, the title *Professional Engineer* is restricted by law for use by persons who have demonstrated their competence and have been licensed by a provincial licensing body, referred to in this book as a provincial *Association* (with a capital letter, to distinguish the meaning from that of a generic association). In addition, the designations *engineer*, *engineering*, *professional engineer*, *P.Eng.*, *consulting engineer*, and their French equivalents are official marks held by Engineers Canada, and only licensed engineers may use these titles. A few exceptions are permitted by law, such as for stationary, operating, and military engineers, who are subject to other regulations. Engineers Canada coordinates policy and acts on behalf of the provincial Associations. The legal definition of engineering and the licensing of engineers are discussed in Chapter 2.

Although early civilizations produced significant engineering achievements, tools and techniques evolved especially rapidly in the 18th and 19th centuries during the Industrial Revolution. Advances in mathematics and science during this period permitted the prediction of strength, motion, flow, power, and other quantities with increasing accuracy. More recently, the development of computers, inexpensive electronic communication, and the Internet have placed huge amounts of information within easy reach, and the role of the engineer continues to evolve together with the rest of modern society. Therefore, modern definitions related to engineering must be broad enough to allow for change. The following definition of an engineer is adequate for most informal discussions, and a more specific definition of engineering is given in the next chapter:

An engineer is a person who uses science, mathematics, experience, and judgment to create, operate, manage, control, or maintain devices, mechanisms, processes, structures, or complex systems, and who does this in a rational and economic way subject to human, societal, and environmental constraints.

This definition emphasizes the rational nature and technological base of engineering, but it does not fully express the human context of the profession. An engineering career involves problem solving, designing, and building, which can give great pleasure to the engineer and others. There are many opportunities for friendship with team members, and engineering projects exercise communication, management, and leadership skills. Engineering decisions may involve societal or ethical questions. Personal experience and judgment are needed for many decisions because projects may involve technical complexity as well as social effects that are not easily reducible to scientific principles or mathematical theorems.

Engineer and writer Henry Petroski emphasized the human side of engineering in *To Engineer Is Human* [2]. He contends that, in response to constantly changing requirements imposed by clients and society, it is human nature to extend design methods to their limits, where unpredicted failures sometimes occur, and to create new design methods as a result of those failures. Samuel Florman, also an engineer and prolific writer, suggests in *The Existential Pleasures of Engineering* [3] that since humankind first began to use tools, the impulse to change the world around us has been part of our nature. Thus, he argues, to be human is to engineer.

1.2

The role of the engineer

Engineering is usually a team activity. Because of the great complexity of many projects, engineering teams often include persons with widely different abilities, interests, and education, who cooperate by contributing their particular expertise to advance the project. Although engineers are only one component of this diverse group, they contribute a vital link between theory and practical application. A team working on a project might include scientists, engineers, technologists, technicians, and skilled workers, whose activities and skills may appear to overlap. The following paragraphs describe the tasks and responsibilities of members of such a team. These are broad categorizations, so exceptions are common.

- Research scientist** The *raison d'être* of pure science is the understanding of natural phenomena, and in a project team, the main responsibility of the scientist is to provide scientific knowledge and analysis. The typical research scientist works in a laboratory together with research assistants on problems that expand the frontiers of knowledge but may not have immediate practical application. A doctorate is usually the basic educational requirement. Scientists are often members of learned societies in their particular field of interest. Although many scientists apply their knowledge to practical tasks, scientific practice does not have the same legal structure or responsibilities as engineering, and scientists are not normally licensed by a professional body with responsibilities defined by law.
- Engineer** The engineer typically provides a key link between theory and practical applications. An engineer must have a combination of extensive theoretical knowledge, the ability to think creatively, a knack for obtaining practical results, and the ability to lead a team toward a common goal. A bachelor's degree is the minimum educational requirement, although many engineers have additional qualifications, including master's and doctoral degrees. In Canada, all work that is legally defined as engineering must be performed or supervised by a licensed professional engineer, who is required, by provincial law, to be a member or licensee of the provincial Association of Professional Engineers (or in Québec, the Ordre des ingénieurs). Membership confers the right to use the title *Professional Engineer*, abbreviated P.Eng. or, in Québec, ing.
- Technologist** The technologist typically works under the direction of engineers in applying engineering principles and methods to complex technical problems. The basic educational requirement is graduation from a three-year technology program at a community college or equivalent, although many technologists have earned university credits as well. Technologists are encouraged to have their qualifications certified by a provincial association such as, for example, the Ontario Association of Certified Engineering Technicians and Technologists (OACETT) or the Association of Science and Engineering Technology Professionals of Alberta (ASET). Credentials issued by provincial associations carry the titles C.E.T. (Certified Engineering Technologist), P.Tech (Professional Technologist), R.E.T. (Registered Engineering Technologist), T.P. (in Québec, Technologue professionnel), or similar titles in related fields. Such credentials are recognized by law in most provinces but are typically not legally essential for working as a technologist. The Canadian Council of Technicians and Technologists (CCTT) is a national body that

coordinates activities of its constituent and related provincial associations, and in 2013 it launched a new designation, International Engineering Technologist, abbreviated as IntET(Canada), which will aid in international recognition of qualifications.

- Technician** The technician typically works under the supervision of an engineer or technologist in the practical aspects of engineering, such as making tests and maintaining equipment. The basic educational requirement is graduation from a two-year technician program at a community college or its equivalent. Associations of technologists and technicians such as those mentioned previously may confer the title C.Tech. (Certified Engineering Technician), although the title is not essential to obtain work as a technician.
- Skilled worker** The skilled worker typically carries out the designs and plans of others. Such a person may have great expertise acquired through formal apprenticeship, years of experience, or both. Most trades (electrician, plumber, carpenter, welder, pattern maker, machinist, and others) have a trade organization and certification procedures.
- Accountability** The categories described above are not rigid. Movement from one group to another is possible, but is not always easy. Each of the above groups has a different task, and there are considerable differences in the skills, knowledge, and responsibilities expected of each. In particular, a much higher level of accountability is expected from the professional engineer than from other members of the engineering team. The engineer is responsible for competent performance of the work that he or she supervises. In fact, engineers may be held legally accountable not only for their own acts but also for advice given to others. Judgment and experience are often as important as mathematics, science, and technical knowledge. Liability insurance is also becoming essential in the public practice of engineering. These professional aspects are discussed further in Chapter 2.

1.3

Engineering disciplines

Most people can name a few branches of engineering: civil, electrical, mechanical, and chemical engineering, perhaps. However, the number of engineering disciplines is much larger than is commonly known. The Canadian Engineering Accreditation Board publishes an annual list of accredited Canadian engineering degree programs [4]. The list changes slightly from year to year as new programs are created or old ones are dropped, but the trend is of a gradually increasing number of programs. Equating equivalent French and English names, counting joint programs as one, and then removing all duplicates reduces the full list of accredited programs to a smaller set of distinct specializations, illustrated in Figure 1.2. The figure shows the names and number of occurrences of programs with names occurring more than once, and at the bottom, the large number of programs with unique names. The five most common branches make up more than half of the total number of accredited programs in Canada.

In the United States there are approximately eight times as many accredited engineering degree programs comparable to those in Canada, with twice as many program names, but the most common names are typically identical and in the same order as in Canada.

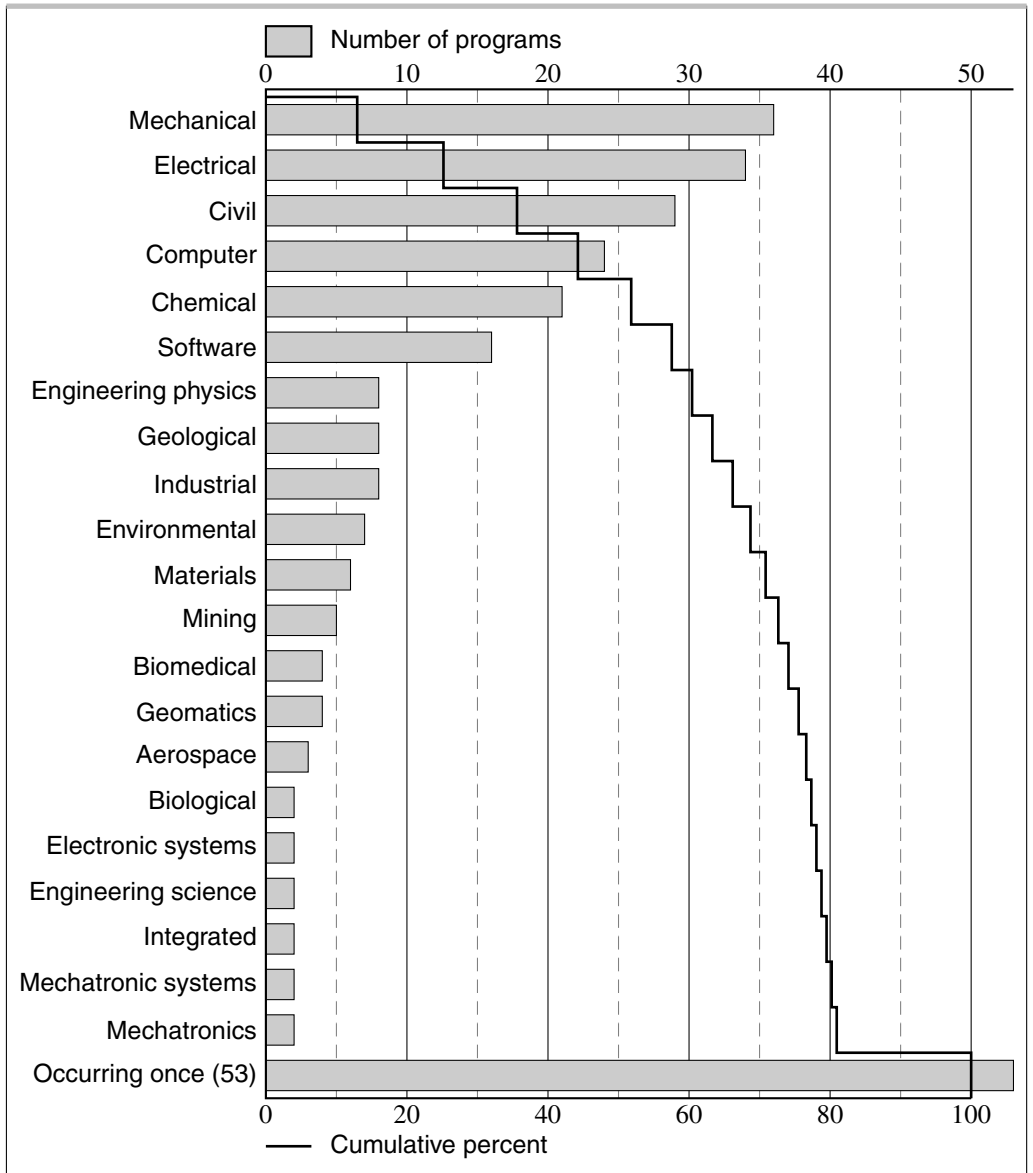


Figure 1.2 Names of accredited Canadian engineering programs in 2017. Of the 278 program names published in reference [4], those occurring more than once are listed on the left, with the bottom row showing that each of 53 others occurs only once. Mechanical engineering, found at 36 institutions, has the largest count. There are 74 distinct names, but the cumulative percent line shows that the most common three make up more than a third of the total and the most common five more than 50%.

1.3.1 Choosing your program

Your choice of university program (that is, your engineering discipline) should be a conscious decision, because it will likely shape the rest of your life. Many students choose before they apply for university, but others are less certain. If you have not made

a choice or have doubts, do not hesitate to seek advice from your professors, guidance counsellors, or perhaps best of all, a friend who is a practising engineer. Typical factors to consider are the program topics that strongly motivate you, the industry in which you wish to work, where you want to work after graduation, or even professors who inspire you. Write a list of the advantages and disadvantages for each program, based on the factors that are most important to you. You may find that you need to gather information by looking at university calendars or websites. You can then make a subjective, but informed, decision.

You might also like to try the computational decision-making method described in Section 15.5.2: create a chart with a column for each program choice and a row for each criterion that is important in your decision. Assign a weight to each criterion, depending on its importance to you. The total benefit for each program is calculated as a weighted sum of values representing how well the program satisfies each of the criteria, as described in detail in Section 15.5.2. The “best” program is one that receives the largest weighted sum. This computational method sometimes yields surprising results! Creating a spreadsheet would be useful because you might want to recalculate with different criteria and weights until you are confident that you have the right result. Employing this detailed process ensures that the stated criteria are systematically considered before a final decision is made.

To help you confirm your knowledge of engineering disciplines, the following paragraphs describe a few well-known specializations. The basic courses are similar in many disciplines, especially in the first year or two. Consequently, switching from one discipline to another is usually easiest then.

- Chemical** Chemical engineers use knowledge of chemistry, physics, biology, and mathematics to design equipment and processes for the manufacture of chemicals and chemical products. The chemical process industries are skill- and capital-intensive, and require highly specialized designers to achieve competitive manufacturing. Some chemical engineers design equipment and processes for the extraction of minerals, petroleum, and other natural resources. Others design new processes for sustaining and reclaiming the natural environment.
- Civil** Civil engineers design and supervise the construction of roads, highways, bridges, dams, airports, railways, harbours, buildings, water supply systems, and sewage systems. Many civil engineers specialize in one phase of their discipline, such as highway, sanitary, soil, structural, transportation, hydraulic, or environmental engineering. The largest fraction of licensed engineers in private practice is in civil engineering.
- Computer** Computer engineers use a combination of electrical engineering and computer science subjects to design, develop, and apply computer systems. They must understand electronic circuits, computer hardware, computer interfacing and interconnection, software development, and algorithms. Most importantly, they must be able to select the optimal combination of hardware and software components required to satisfy specified performance criteria.

- Electrical** Electrical engineers design and manage systems to generate, transmit, and control electrical signals and energy. Electrical engineering overlaps with other disciplines because of the widespread use of electronics. Specialists in electronics use microscopic devices, medium-scale circuitry, and large systems for data sensing, transmission, and computation. Specialists in the power field design and manage electrical equipment and distribution systems, including equipment and software for control of electric machines and the complex networks that transmit and stabilize energy flowing from localized sources as well as large generating stations.
- Environmental** Environmental engineers respond to needs for improved air and water quality and efficient waste management. Environmental engineering is a rapidly growing discipline, concerned with site assessment and approval, air quality in buildings, monitoring and control devices, and a host of investigative, instrumentation, and other support activities. These environmental applications require a broad engineering knowledge, including topics from chemistry, physics, soils engineering, mechanical design, fluid mechanics, and meteorology.
- Geological** Geological engineers use knowledge of the origin and behaviour of geological materials to design structures, such as foundations, roads, or tunnels built on or through these materials, and to develop exploration or extraction methods for petroleum and minerals. They may also work with civil engineers in the geotechnical design or construction of roads, airports, harbours, waste disposal systems, and other civil works. Geological engineers are in increasing demand for groundwater and environmental impact studies and for new petroleum recovery projects.
- Industrial** Industrial engineers use probability, statistics, and other mathematical subjects for the design of efficient manufacturing processes. They assume responsibility for quality control, plant design, and the allocation of material, financial, and human resources for efficient production. Automation, materials handling, environmental protection, robotics, human factors, and data processing are some of the specialized subjects required.
- Mechanical** Mechanical engineers enjoy a wide scope of activity, including the design, development, manufacture, and maintenance of machinery, ranging from small appliances to aircraft. They may be involved with engines, turbines, boilers, pressure vessels, heat exchangers, or machine tools. They may specialize in fields such as machine design, heating, ventilating and refrigeration, thermal and nuclear power generation, manufacturing, quality control, or production scheduling. There are many mechanical engineers employed in related fields, such as mining, metallurgy, transportation, oil refining, and chemical processing.
- Software** Software engineering combines classical engineering project-management skills with the specialized tools and knowledge that are required to design, build, analyze, and maintain complex computer software. In addition to intimate knowledge of the program-design aspects of computer science, the software engineer requires an understanding of the natural sciences in sufficient breadth to allow working with specialists in other disciplines and designing correct software to be embedded in machines.