1 Introduction [2]

It does not matter how slowly you go as long as you do not stop.

Confucius

It is not enough that we do our best; sometimes we must do what is required.

Winston Churchill

I am a slow walker, but I never walk back.

Abraham Lincoln

1.1 What Is an Engineer?

Engineering is defined by the Accreditation Board for Engineering and Technology (ABET) as *the creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behavior under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property*.

Engineering, in some form, has existed as long as humankind has been building devices for specific purposes. Examples of early forms of engineering include the development of the wheel, the use of fire, and the development of tools from bronze and iron. However, the term *engineering* is of more recent origin, and the application of scientific principles had to await the development of science and scientific methods as we know them today.

While science has been vital and important in the development of engineering, it does not account for everything. Engineers often encounter situations where scientific information is unavailable or simply missing. In such situations, human creativity, resourcefulness, and experience can play a key role; this is the "art" of engineering. At the same time, we must emphasize that engineering science provides a critical base of knowledge; without it, we might reinvent the wheel! Today, developments in computer hardware and software have enabled engineers to predict outcomes in situations where measurements are impossible, enabling them to accomplish safe design in "blind" or difficult situations. Consider the situation faced by a pilot who must land a plane in heavy fog with limited visibility. It is here that the genius of design engineers, with their ability to design automatic controls

R. Simpson and S.K. Sastry, *Chemical and Bioprocess Engineering: Fundamental Concepts for First-Year Students*, DOI 10.1007/978-1-4614-9126-2_1,

enabling instrument landings, comes into play. Another situation is the landing of exploration vehicles on Mars: this is happening even as this book goes to press, yet humans have never been on the surface of Mars. How can we engineer devices and systems that respond to our commands from Earth and do our bidding at extreme distances? It is the interplay of art and science under the constraints of economics, safety, and other relevant considerations that makes engineering the amazing and exciting profession that it is. We welcome you to join and enjoy a satisfying career in engineering.

1.2 Is Engineering for Me?

Some tests:

- myfuture.edu.au provides a simple profile test that may help you gain a better understanding of your interests, values, and goals.
- Take the free test at the Career FAQs Web site: www.careerfaqs.com.au.
  Visit http://www.engineeryourcareer.org.au/?page_id=55 for

1.3 What Are Process, Chemical, Bioprocess, and Biochemical Engineers?

We use the term *process* engineers to refer to a broad class of engineers that includes chemical engineers. However, the term *process engineering* is likely less familiar to most laypeople than the better-known *chemical engineering*, and hence we have chosen chemical engineering for this book's title. Process engineers typically are involved in the design, operation, control, and optimization of chemical, physical, and biological processes.

A number of definitional statements exist for chemical engineering. The one adopted by the Institution of Chemical Engineers (UK) in 1924 stated essentially that *a chemical engineer is a professional experienced in the design, construction and operation of plant and works in which matter undergoes a change of state and composition*.

Historically, chemical engineering has been at the heart of major parts of the chemical, petroleum, pharmaceutical, and electronics industries. However, more recently, many chemical engineering and other departments have diversified to encompass biochemical (or biomolecular) engineering.

Biochemical engineering involves the design, construction, and operation of unit processes that involve biological organisms or molecules and is involved in the biotechnology, pharmaceutical, food, environmental, and waste treatment industries. Many similar names (and flavors) exist, including biomolecular (focused on the manipulation of molecules) and biomedical (focused on medical applications) engineering. Nevertheless, a common theme is the central focus on biology as a core discipline. As the world's critical resources will require management and stewardship in the twenty-first century, the discipline of biochemical engineering will take on increasing importance.

While chemical and biochemical engineering are well recognized and represented in department and journal names, we would like to focus specifically on processes, or process engineering, which encompasses a vast class of operations that include chemical and biochemical engineering. Bioprocess engineering, which may be considered a subset of process engineering, deals with the design and development of equipment and processes for the manufacture of products such as food, feed, pharmaceuticals, nutraceuticals, chemicals, and polymers and paper from biological materials.

1.4 History

1.4.1 Why Is History Important?

History is important because by knowing our past we can better understand our present and, thus, better predict the future. It has been said that man is the only animal that trips twice over the same stone[1]; thus knowing history can help us avoid this characteristically human trait.

We shall take a brief look at history to understand how engineering was born within human society and thus facilitate our understanding, especially for young people just starting their studies. Moreover, we will start discussing, briefly, prehistory, because we may well discover that we were born engineers!

1.4.2 Were We Born Engineers?

Prehistory involves the study of the development of human societies before the existence of writing and is based primarily on the analysis of tool artifacts. Thus, we have an opportunity to witness the activities of prehistoric humans through their emerging engineering works; these small works facilitate our understanding of ancient times. As long as humans have existed, they have sought ways to solve problems, and in prehistoric times the basic problems were food, clothing, defense, and habitat. Thus, early engineering works involved manufacturing tools to solve and improve their chances of obtaining food, hides for cover, and weapons for defense and to build appropriate places for shelter (e.g., caves and small huts). In fact, humans are born engineers because we have always sought ways to solve problems, initially to improve our standards of living. Initially ancient engineers solved their problems only through trial and error, and millennia would pass before the development of sciences like mathematics, physics, chemistry, and biology. Over time and to the extent of their understanding of their environment, these ancient engineers slowly incorporated empirical "prescientific" knowledge to solve problems. Around approximately 8,000 years B.C. humans ceased leading a hunter-gatherer (nomadic) lifestyle and created the conditions (first crops and livestock) to live in a fixed location. It is perhaps at this time that ancient engineers merged architecture and engineering. Their main work was the construction of buildings and walls to defend their communities.

From the standpoint of food and food preparation, the development of various cuisines related to practical, engineering-type considerations. For example, Chinese cuisine evolved from the need to conserve fuel during cooking; thus food was cut into small pieces and quickly stir-fried to completion. This represents an early application of heat transfer from energy conservation considerations (Wilson 2012).

Another key operation in chemical engineering involves size reduction. This entailed chopping, grating, and grinding, which were all difficult and labor-intensive tasks historically performed by laborers for the benefit of the rich. Wilson (2012), in a very interesting book, describes the history of this process. When abundant servant labor was available, there was no motivation to improve upon such processes; indeed wealthy people served highly refined food to guests, often in an attempt to show how many servants they could afford. In the present era, we are very concerned with obesity due to highly refined foods, perhaps because of the dietary habits we inherited from our wealthy ancestors!

[1] "El hombre es el único animal que tropieza dos veces en la misma piedra"—Spanish proverb.

1.4.3 Industrial Revolution

Until the seventeenth century, engineering developments were very slow, mainly because scientific advances were also slow. The Industrial Revolution began in the second half of the seventeenth century and continued to the early nineteenth century. Manual labor was gradually replaced by mechanization, mainly in the textile industry. We could say that over the last three centuries, scientific advances have been significant, if not explosive. Improved transportation systems, the invention of the steam engine, and the invention of the railroad facilitated even greater advances, with the steam engine being perhaps the most important invention of the time (http://en.wikipedia.org/wiki/Steam_engine). By this time the production of goods and labor began to organize in factories. Later, engineering started to diversify, a trend that continues to this day and may well continue into the foreseeable future. The first branches of engineering were military engineering, civil and construction engineering, metallurgical engineering, mechanical engineering, electrical engineering, and chemical engineering.

Before going into the descriptive and conceptual issues of engineering as we currently know it, students are encouraged to internalize the information on engineering works in ancient Egypt, Mesopotamia, Greece, Rome, and the East. There is abundant information on the Internet. A good place to start is http://humweb.ucsc.edu/gweltaz/courses/techno/biblio.html.

1.4.4 A Brief History of Chemical and Biochemical Engineering

Many fine descriptions exist for the histories of chemical and biochemical engineering (e.g., Kim 2002; Katzen and Tsao 1999). We will merely present some of the highlights here.

1.4.4.1 Chemical Engineering

Humans have been attempting or performing chemical transformation throughout history. Early efforts included the cooking of food and the production of metals from ores. An early goal of alchemy (the precursor of chemistry) was to convert base metals into gold! The attempt was not successful, but it was not until the advent of our understanding of atomic-level chemistry that we understood why. Various other theories regarding the composition of materials were popular at various times in history—for example, the phlogiston theory, where it was believed that all substances contained phlogiston, a component of all materials that left when the material was burned. It was not until Lavoisier, in the eighteenth century, showed, through careful accounting of mass balances, that the theory was flawed. We could go on indefinitely, but the history of science and its many detours is a fascinating, though separate, subject.

Chemical engineering in its current form probably has its origins in the Industrial Revolution of the nineteenth century. As industrial production accelerated at an ever increasing rate, certain chemicals became necessary to sustain this growth. One critical chemical was sulfuric acid; indeed it was thought that a nation's industrial prowess could be measured by its sulfuric acid output. Both sulfuric acid and alkali were produced on a large scale in Germany and England. However, products were prepared in batch mode, i.e., in individual vats in batches. Batch production was slow and tedious, but rapid production required continuous flow reactors. This in turn greatly increased the complexity of the process since engineering considerations of flow and control became critical. Thus, engineering entered the domain of what had hitherto been industrial chemistry. Among the improvements in this process was the recovery of nitric oxide via a mass transfer tower by John Glover in 1859.

Soap making had also been practiced since the eighteenth century due to demand for washing clothes using sodium carbonate. The LeBlanc process accomplished this from salt using sulfuric acid, limestone, and coal, which produced hydrochloric acid as a byproduct. However, the process had severe environmental consequences and was eventually replaced in 1873 by the Solvay process.

In 1887, George Davis, an alkali inspector, developed a series of 12 lectures on chemical operations for the Manchester Technical School. These eventually came to be known as unit operations, one of the pillars of a chemical engineering education. In 1888, the first 4-year bachelor's program in chemical engineering was created at the Massachusetts Institute of Technology (MIT). The program was largely descriptive at this stage.

Many developments occurred in the chemical industry over the years, including the development of optimization methods, continuously operating reactors, recycling and recovery, and purification technology. These required knowledge of plumbing systems (then unknown to chemists) and physical chemistry (then unknown to mechanical engineers). The study of unit operations, which focused on underlying processes, became the domain of the chemical engineer.

The next major paradigm shift came about with the publication of the textbook *Transport Phenomena* by Bird et al. (1960) and *Mathematical Methods in Chemical Engineering* by Amundson and Aris (1966). These works constituted the scientific pillars of chemical engineering as a discipline and led to a turning away from older, more empirical work. Thus, the core curriculum of chemical engineering consists of unit operations and transport phenomena.

1.4.4.2 Biochemical Engineering

Commercial-scale biomass processing dates back to ancient times. The process of fermentation to produce cheeses, beer, and wine have existed for thousands of years. However, the nature of the process was not understood until Pasteur's development of the science of microbiology. Thereafter, developments in this area proceeded apace, gaining commercial value from the development of valuable medicines such as antibiotics, most notably penicillin.

The term *biochemical engineering* came into use in the 1940s with the development of aerobic submerged culture in response to the need to produce penicillin in large quantities (Katzen and Tsao 1999). This led to the need to improve gas-liquid interfacial mass transfer and the development of engineering science necessary for understanding the technology. Since the energy crises of the 1970s, the need for renewable energy sources has led to work in renewable energy from biomass. Large-scale developments in molecular biology led to an expansion in biochemical engineering to fill the need to produce pharmaceutical and other bioproducts. Developments in this field continue to this day; indeed, many chemical engineering departments have now changed their names to include bioprocess, biological or biomolecular engineering.

1.5 Why Integrate Chemical and Bioprocess Engineering Fundamentals in One Book?

Currently, most available books at the introductory level focus exclusively on the needs of either chemical engineers or biochemical engineers, but not both. With the consolidation of chemical and biochemical engineering programs, it is justified, in our view, to develop a unified textbook that enables the beginning student (whether in chemical or biochemical engineering) to gain the necessary basic skills for further development. In principle, the underlying engineering sciences are the same, although the specifics of the chemistry and process constraints are different in the two cases.

1.6 Chemical and Bioprocess Engineering in the Twenty-First Century

The twentieth century witnessed dramatic growth in the chemical industry, particularly industrial chemicals, petroleum, plastics, and polymers. The twenty-first century promises an increased focus on environmental issues, clean air, water, food security, global warming, and human health and wellness. It is clear that developments in one industry cannot continue unabated without an understanding of the consequences of these developments on humans and biological species on the planet. For this reason, we see the need for an increasingly integrated treatment of chemical and bioprocess engineering.

1.6.1 Required Basic Knowledge: Basic Tools of Mathematics, Chemistry, Physics, and Biology

In developing this book, we were inspired by Robert Frank (Frank 2006), who studied how students learn economy and found that many of them had difficulty with fundamental concepts even after they graduated. Professor Frank attributes that state of affairs to an overemphasis on covering large amounts of material, with the result that many students lack a grasp of basic concepts. It is suggested that a better approach would involve deeper learning, with a less broad coverage of material.

In this connection, we have endeavored to develop and present problems that are interesting, demonstrate most of the applications of chemical and bioprocess engineering, and in turn require a basic knowledge of mathematics, chemistry, physics, and biology.

Our main goal is not to try to teach you too much information but to familiarize and enchant you with chemical and bioprocess engineering and, basically, expose you, in some depth, to one of the most useful tools for a process engineer: material balance. Fortunately, you can learn, and learn well, material balance with the knowledge that you bring with you from high school. As presented and discussed in Chap. 11, we will address some complex mathematical problems that will be solved with the help of a spreadsheet (if you are not accustomed to spreadsheets, several examples will familiarize you with them). In addition, in some specific cases the goal is not necessarily to solve problems and obtain final results but to formulate and understand the problems.

But what is basic knowledge? What do we mean when we say that the knowledge that you bring from high school is enough? More specifically, for example, in mathematics, we can state that you should know algebra at the level of solving systems of equations where normally each equation is a first-order equation. As you will notice, the stress and goal of the majority of, if not all, the problems is to place an emphasis on the formulation and not on your math skills for solving them. We are not saying that math skills are unnecessary; of course they are, but not yet. You will have several math courses to prepare you to solve real problems. The same goes for chemistry, physics, and biology.

Experience has shown us that using this approach students learn more than they expected and acquire a solid understanding of chemical and bioprocess engineering. As one student expressed to us: *The problems are fun, intellectually challenging, and above all they excited and motivated us regarding the career that we were just starting to study."*

1.7 Cognitive Domain: What Will We Comprehend and Learn?

There is not just one mode or way of learning. According to psychologist Benjamin Bloom, there are three intersecting domains of psychology: cognitive, psychomotor, and affective. In this book, the prevailing domain is cognitive, but also important—very important—is the affective domain. The cognitive domain prevails because it relates directly to knowledge and the development of intellectual skills. But why is the affective domain important? Because the affective domain relates to enthusiasm, motivation, and attitude. In our experience, with freshmen, the three most important things for teachers to keep in mind are: motivation, motivation, and motivation.

Our primary goal is to touch you in the affective domain. Then, depending on your interests and motivations, you will start reading and assimilating the topics of this book.

A glimpse at Bloom's taxonomy: Bloom's cognitive domain is related to knowledge and the development of intellectual skills. Bloom's taxonomy is divided into six categories. Each subsequent category implies a higher level of difficulty, and so each one is listed in ascending order. The six categories are as follows:

1. Remembering
2. Understanding
3. Applying
4. Analyzing
5. Evaluating
6. Creating

Each chapter of the book is identified by its own number but also by a number in braquets that relates the chapter to Bloom's cognitive level it is expected to reach. For example, Chaps. 2 and 7 have a Bloom cognitive level of 5, then on the first page of the chapter you will see Chaps. 2[5] and 7[5], respectively, indicating that both chapters are expected to reach the level of evaluation. As you will see, most chapters are expected to reach a level 2 understanding, meaning that most of the book is focused on motivation rather than learning. We would like to motivate you (mainly Chaps. 3[2], 4[2], and 9[2]), to teach you something and illustrate the potential applications of this career (Chaps. 11[3] and 12[3]), and, finally, go into more depth in Chaps. 2[5], 5[4], 7[5], and 8[4].

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A Closer Look at Chemical engineering http://www.youtube.com/watch?v=iAWLMMZlkq4

What is Chemical and Bioprocess Engineering all about http://www.youtube.com/watch?v=Ga2m1TEoDSo ?

Bioprocess Engineering-career guidance http://www.youtube.com/watch?v=mnVe4aF6JZY

Chemical Engineer - Profiles of Scientists and Engineers http://www.youtube.com/watch?v=k-7B_YfHWXQ