Complete Preface-Introduction

The man who has ceased to learn ought not to be allowed to wander around loose in these dangerous days.

—M. M. Coady

A. Who Is The Intended Audience?

This Web site and the text break new ground as their interaction is unique and provides one of the highest level active learning resources ever available. With the advent of sliders in both Wolfram and Python, students can explore the reactions and reactor by carrying out simulation experiments and then writing a set of conclusions describing what they found. This book was written with today's students in mind. It provides instantaneous access to information; does not waste time on extraneous details; cuts right to the point; uses more bullets to make information easier to access; and includes new, novel problems on chemical reaction engineering (e.g., solar water splitting).

The book and interactive Web site are intended for use as both an undergraduate-level and a graduate-level text in chemical reaction engineering. The undergraduate level typically covers Chapters 1 though 13, while some schools include a lecture or two on diffusion effects and effectiveness factors from Chapters 14 and 15. The graduate level, after a brief review of Chapters 1-13, course focuses on Chapters 14 through 18 on mass transfer limitations, non-ideal reactors, residence time distribution (RTD) and dispersion and reaction. The graduate course also includes material from the Web sites Professional Reference Shelf (PRS) such as collision theory, transition state theory, multiphase reactors and reactor stability. The level will depend on the choice of chapters, the Professional Reference Shelf (PRS) material from the companion Web site to be covered, and the type and degree of difficulty of problems assigned.

This edition gives an enhanced emphasis on chemical reactor safety by ending each chapter with a safety lesson called *And Now A Word from Our Sponsor-Safety* (AWFOS) taken from the Web site http://umich.edu/~safeche/.

B. What Are The Goals Of This Book?

B.1 To Have Fun Learning Chemical Reaction Engineering (CRE)

Chemical reaction engineering (CRE) and separations are the two core courses unique to chemical engineering. CRE is a great subject that is fun to learn and is the heart of chemical engineering. In this edition, as with other editions, I have tried to provide a little Michigan humor (e.g., the tidbits about the country of Jofostan) as we go. Take a look at the humorous YouTube videos (e.g., "Black Widow" or

"Chemical Engineering Gone Wrong") that illustrate certain principles in the text. These videos were made by chemical engineering students at the universities of Alabama and Michigan. In addition, I have found that students very much enjoy the Interactive Computer Games (ICGs) that, along with the videos, are linked from the CRE homepage.

B.2 To Develop a Fundamental Understanding of Reaction Engineering

The second goal of the book is to help the reader clearly understand the fundamentals of CRE. This goal is achieved by presenting a structure that allows the reader to solve reaction engineering problems through reasoning rather than through memorization and recall of numerous equations and the restrictions and conditions under which each equation applies. The algorithms presented in the text for reactor design provide this framework, and the homework problems give the reader practice using the algorithms described in Figures P-1 and P-2, shown in Preface Section C. The conventional homework problems at the end of each chapter are designed to reinforce the principles in the chapter. These problems are divided between those that can be solved with a calculator (1/3) and those that require a personal computer with a numerical software package (2/3), such as Polymath, Wolfram, Python, MATLAB, AspenTech, or COMSOL.

To give a reference point as to the level of understanding of CRE required in the profession, a number of reaction engineering problems from the California Board of Registration for Civil and Professional Engineers—Chemical Engineering Examinations (PECEE) are included in the text.[1] Typically, these problems should each require approximately 30 minutes to solve. *However*, you should try to shoot to solve the CRE problems in 20 minutes so you will have extra time to work on the more difficult thermo problems.

Finally, the companion Web site has been extensively revised and expanded. The updated site includes interactive *Computer Simulations and Experiments* with Living Example Problems that facilitate Inquiry Based Learning (**IBL**),[2] discussed in Section D.2. The companion Web site includes Interactive Summary Notes of the material in each chapter, PowerPoint slides of class lecture notes, YouTube Videos, Web Modules, i>Clicker Questions, expanded derivations, and Self-Tests in the *Summary Notes*. A complete description of these learning resources is in Web Appendix I (*http://www.umich.edu/~elements/6e/appendix/Web-Appendix-I.pdf*).

B.3. To Enhance Thinking Skills

A third goal of the text is to enhance *critical thinking skills and creative thinking skills*. How does the book help enhance your critical and creative thinking skills? We discuss ways to achieve this enhancement in Sections G.1 Critical Thinking and G.2 Creative Thinking. For example, see *Thoughts on Problem Solving* (*http://www.umich.edu/~elements/6e/probsolv/index.htm*).

C. What Is The Structure of CRE?

C.1 What Are The Concepts that Form the Foundation of CRE?

The strategy behind the presentation of material is to build continually on a few basic ideas in CRE to solve a wide variety of problems. These ideas, referred to as the Pillars of Chemical Reaction

[1]The permission for use of these problems—which, incidentally, may be obtained from the Documents Section, California Board of Registration for Civil and Professional Engineers—Chemical Engineering, 1004 6th Street, Sacramento, CA 95814, is gratefully acknowledged. (Note: These problems have been copyrighted by the California Board of Registration and may not be reproduced without its permission.)

[2]Adbi, A. "The Effect of Inquiry-based Learning Methods on Students' Academic Achievement in Science Course," *Universal Journal of Educational Research*, 2(1), 37–41 (2014). Also see Freeman, S., S. L. Eddy, M. McDonough, M. K. Smith, N. Okoroafor, H. Jordt, and M. P. Wenderoth, "Active Learning Increases Student Performance in Science, Engineering, and Mathematics," Proceedings of the National Academy of Sciences, Vol. 111 No. 23, p. 8410 (2014).

Engineering (Figure P-1), are the foundation on which different applications rest. They represent not only components of chemical reaction analysis, but also the physical phenomena of diffusion and contacting that affect chemical reactor performance.

Figure P-2 shows the first *Building Blocks of CRE* and the primary algorithm that allows us to solve isothermal CRE problems through logic rather than memorization. We start with the Mole Balance Building Block (Chapter 1) and then place the other blocks one at a time on top of the others until we reach the Evaluate Block (Chapter 5), by which time we can solve a multitude of isothermal CRE problems. As we study each block we need to make sure we understand everything in that block and don't cut corners by leaving anything out so we don't wind up with a pile of cylindrical blocks. A tower containing cylindrical blocks would be unstable and would fall apart as we study later chapters. Look at the **Plain PowerPoint** slides for Lecture 1 Notes (*http://www.umich.edu/~elements/6e/lectures/umich.html*), starting at slide 43 to see the CRE tower fall if one has an unstable tower with cylindrical blocks.

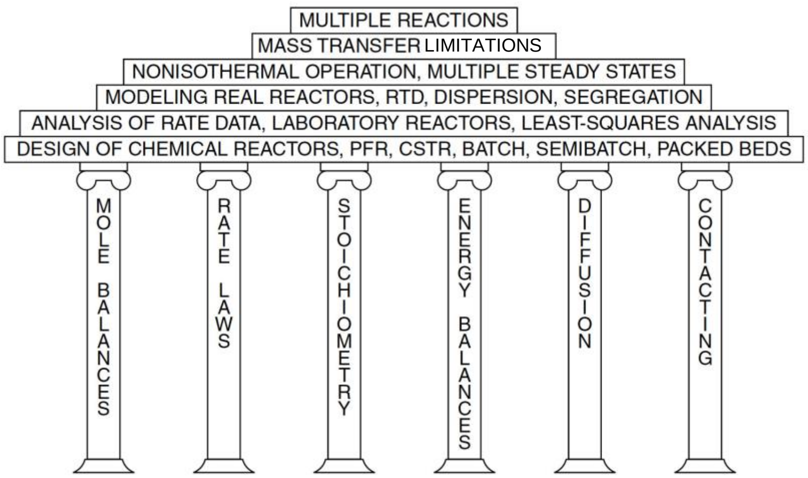

Figure P-1 Pillars of Chemical Reaction Engineering

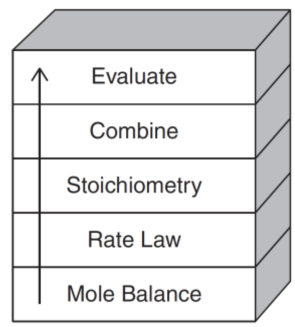

Figure P-2 Building Blocks

For nonisothermal reactions we replace the "Combine" building block in Figure P-2 with the "Energy Balance" building block because nonisothermal reactions almost always require a computer-generated solution. Consequently, we don't need the "Combine" block because the computer combines everything for us. From these pillars and building blocks, we construct our CRE algorithm:

Mole Balance + **Rate Laws** + **Stoichiometry** + **Energy Balance** + **Combine** → **Solution**

C.2 In What Order Can We Study the Chapters?

With a few restrictions, the contents of this book can be studied in virtually any order after students have mastered the first six chapters. A flow diagram showing the possible paths is shown in Figure P-3.

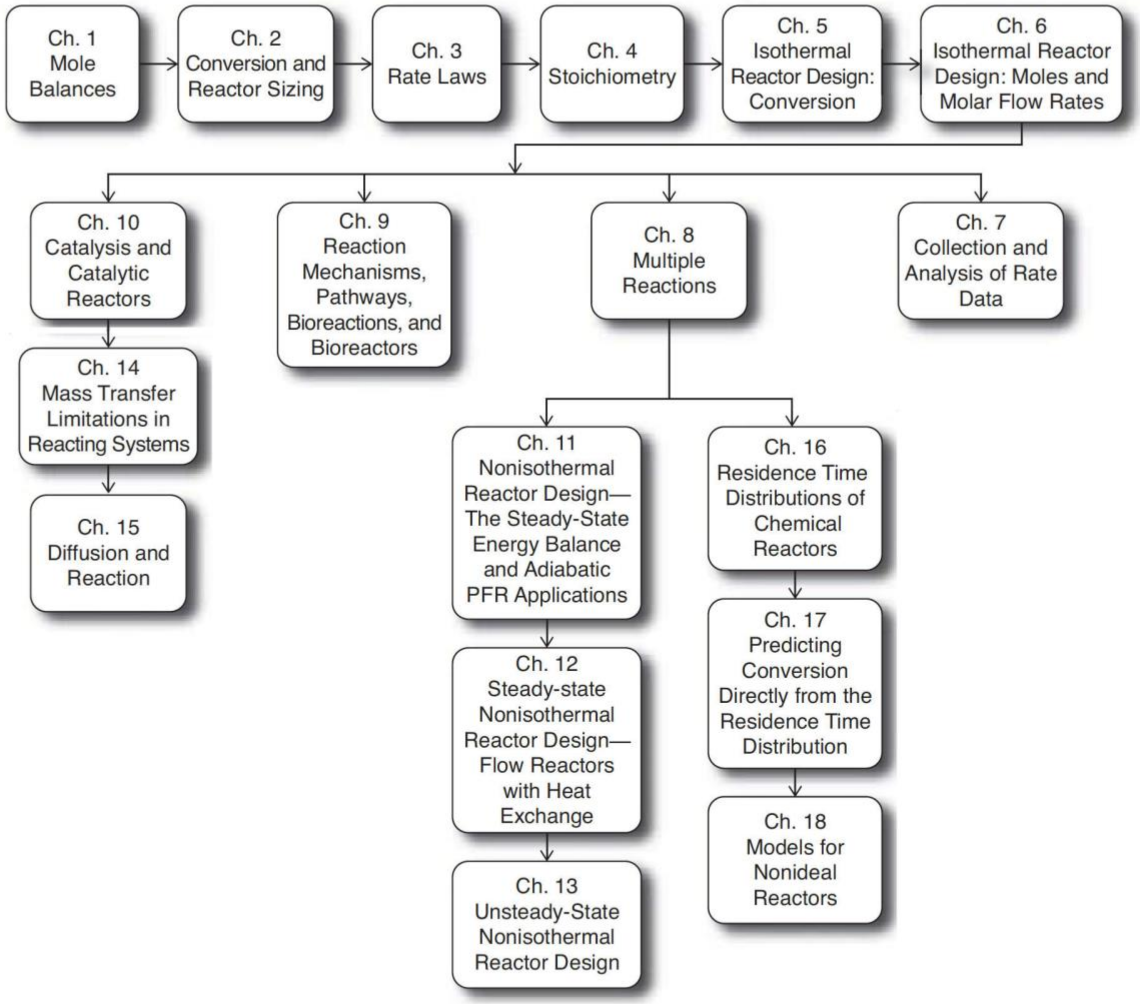

Figure P-3 Sequences for study using the text.

The reader will observe that although metric units are used primarily in the text (e.g., kmol/m3, J/mol), English units are also employed (e.g., lbm/ft3, Btu) in a few problems and examples. This choice is intentional! We believe that whereas most papers published today use the metric system, a significant amount of reaction engineering data exists in the older literature in English units. Because engineers will be faced with extracting information and reaction rate data from older literature as well as from the current literature, they should be equally at ease with both English and metric units.

C.3 What Is the Sequence of Topics in which This Book Can be Used?

Table P-1 shows examples of topics that can be converged in a graduate course and an undergraduate course. In a four-hour undergraduate course at the University of Michigan, approximately thirteen chapters are covered in the following order: Chapters 1 through 6 (Exam 1); Chapters 7, 8, 11, and 12 (Exam 2); and Chapter 13 and parts of Chapters 9 and 10 (Exam 3). While some sections related to mass transfer limitations, effectiveness factors and residence times in Chapters 14, 15 and 16 are briefly covered in the undergraduate course at some universities, these chapters along with Chapters 17-18 are primarily used in the graduate course. The graduate course also uses significant material from the PRS on this Web site such as collision and transition state theory, the complete Advanced Reaction System Screening Tool (ARSST), multiphase reactors, linearized reaction stability and comparing X_{seg} with X_{mm}.

TABLE P-1 UNDERGRADUATE/GRADUATE COVERAGE OF CRE

Undergraduate Material/Course	*Graduate Material/Course*
Mole Balances (Ch. 1)	Short Review (Ch. 1–8, 11–12)
Smog in Los Angeles Basin (PRS Ch. 1)	Collision Theory (PRS Ch. 3)
Reactor Staging (Ch. 2)	Transition State Theory (PRS Ch. 3)
Hippopotamus Stomach (PRS Ch. 2)	Molecular Dynamics (PRS Ch. 3)
Rate Laws (Ch. 3)	Aerosol Reactors (PRS Ch. 4)
Stoichiometry (Ch. 4)	Multiple Reactions (Ch. 8): Side-Fed Membrane Reactors
Reactors (Ch. 5): Batch, PFR, CSTR, PBR	Bioreactions and Reactors (Ch. 9, PRS 9.3–9.5)
Reactors (Ch. 6): Semibatch, Membrane	Polymerization (PRS Ch. 9)
Data Analysis: Regression (Ch. 7)	Co- and Countercurrent Heat Exchange (Ch. 12)
Multiple Reactions (Ch. 8)	Radial and Axial Gradients in a Tubular Reactor COMSOL (Ch. 18)
Bioreaction Engineering (Ch. 9)	Reactor Stability and Safety (Ch. 13 PRS)
Adiabatic Reactor (Ch. 11)	Runaway Reactions (PRS, Ch. 13)
Steady-State Heat Effects (Ch. 12): PFR and CSTR with and without a Heat Exchanger Multiple Steady States	Catalyst Deactivation (Ch. 10)
Unsteady-State Heat Effects (Ch. 13) Reactor Safety	Residence Time Distribution (Ch. 16, 17)
Catalysis (Ch. 10)	Models of Real Reactors (Ch. 18)
	Applications (PRS): Multiphase Reactors, CVD Reactors, Bioreactors

There are notes in the margins, which are meant to serve two purposes. First, they act as guides or commentary as one reads through the material. Second, they identify key equations and relationships that are used to solve CRE problems.

Margin Notes

D. What Are The Components on the CRE Web Site?

This interactive companion Web site material has been significantly updated to a level that it's interaction with the textbook can be considered as a ***minor paradigm shift***. The computer simulation experiments allow the student to take ownership of understanding the chemical reactions and reactor in which they take place. The home page for the CRE Web site (*http://www.umich.edu/~elements/6e/index.html*) is shown in Figure P-4. For discussion of how to use the Web site and text interactively, see Web Appendix I.

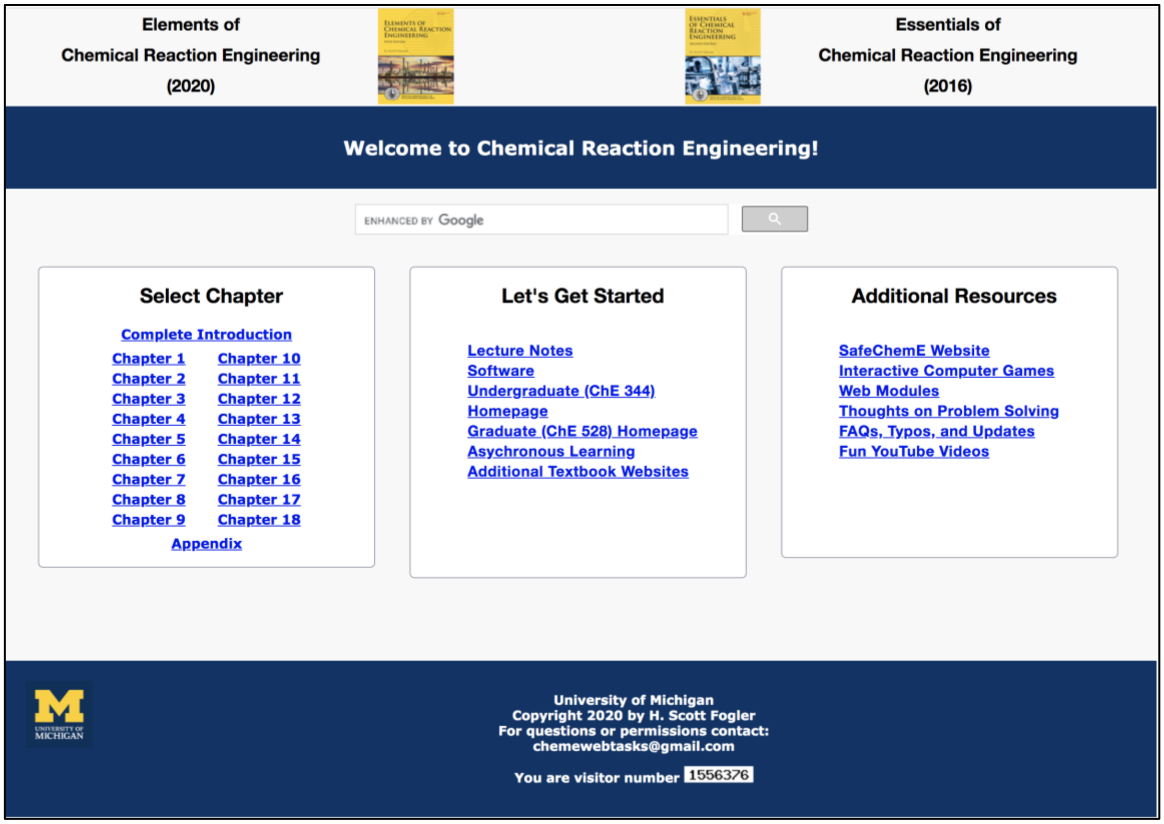

Figure P-4 Screen shot of the book's companion Web site
(*http://www.umich.edu/~elements/6e/index.html*)

The objectives of the Web site are fivefold:

(1) To use the Wolfram and Python LEP simulations interactively to explore the reactions and the reactor in which they occur and then to write a set of conclusions.

(2) To facilitate the interactive learning of CRE by using the companion Web site and actively address the Felder/Solomon Inventory of Learning Styles (*https://www.engr.ncsu.edu/stem-resources/legacy-site/learning-styles/*) discussed in Web Appendix I.

(3) To provide additional technical material in the extended material and in the Professional Reference Shelf.

(4) To provide tutorial information and self-assessment exercises such as the i>Clicker and the Self-Test questions.

(5) To make the learning of CRE fun through the use of interactive games, LEP simulations, and computer experiments, which allow one to use *Inquiry-Based Learning (IBL)* to explore the concepts of CRE.

I would like to expand a bit on a couple of things that we use extensively, namely the Chapter Resources and the Living Example Problems. These items can be accessed by clicking on the chapters table of contents (TOC) bar across the top of the page. The TOC contains all the major topics. As an example, let's consider Chapter 12, for which the following screen shot shows the TOC page for Chapter 12.

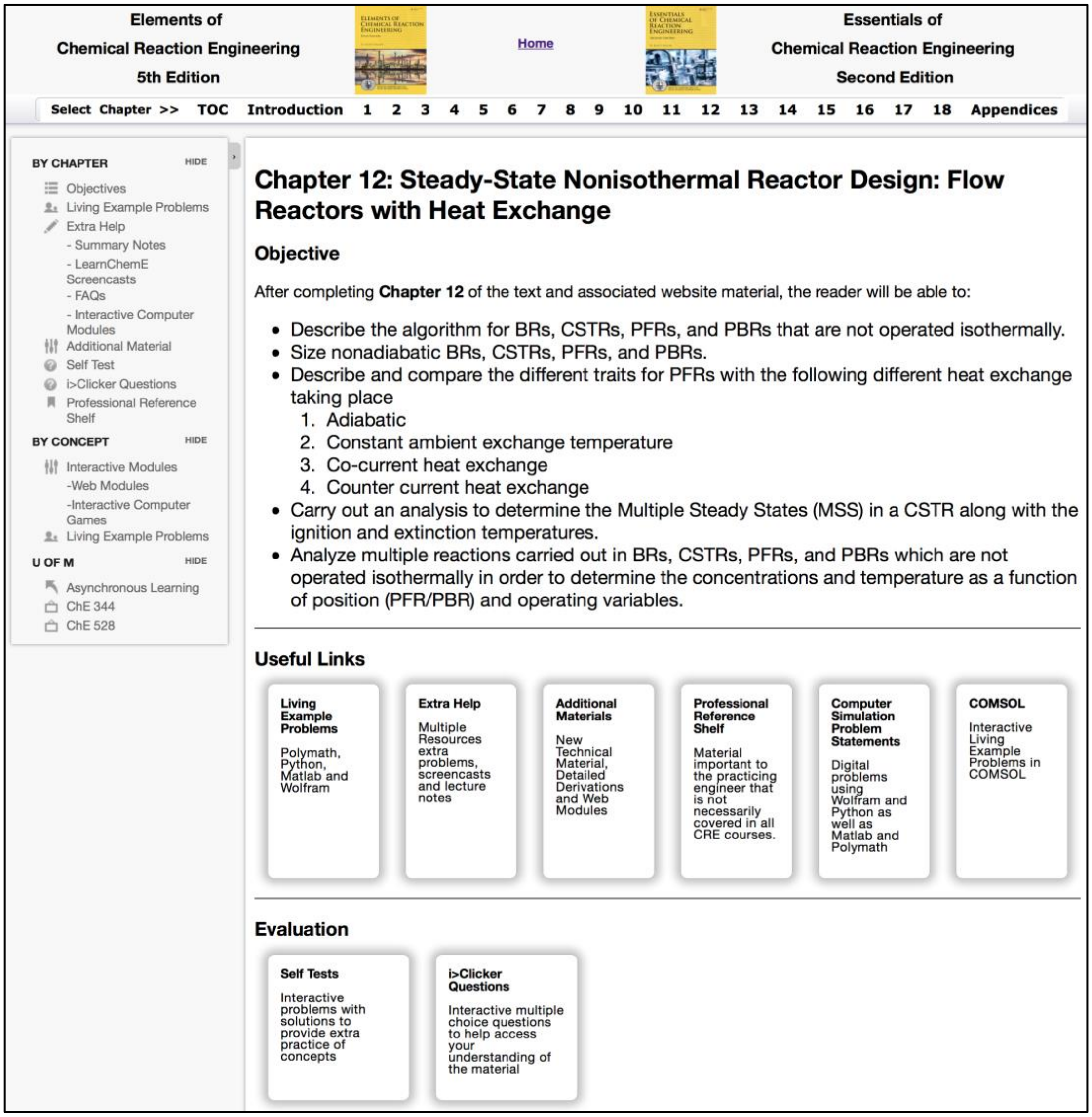

Figure P-5 Screen shot of Chapter 12 TOC page
(*http://www.umich.edu/~elements/6e/12chap/obj.html#/*)

In addition to listing the objectives for this chapter, you will find all the Useful Links for the chapter that include, Living Example Problems, Extra Help, Additional Materials, Professional Reference Shelf, Computer Simulation Problem Statements and in some cases, COMSOL. To learn how well you are doing in understanding the material use the **Evaluation** Links, Self-Tests and i>Clicker Questions. We will now discuss each of these Useful Links and Evaluation Links in detail.

D.1 Learning Resources

The Learning Resources give an overview of the material in each chapter through the Interactive Summary Notes. These notes include on-demand derivations of key equations, audio explanations, additional resources which include Interaction Computer Games (ICG), computer simulations and experiments, Web modules of novel applications of CRE, solved problems, study aids, Frequently Asked Questions (FAQs), PowerPoint lecture slides, and links to LearnChemE videos.

D.2 Living Example Problems (LEPs)

What are LEPs? LEPs are Example Problems that have solutions on the Web that allow you to change the value of a parameter and see its effect on the answer. LEPs have been unique to this book since their invention and inclusion in the third edition of Elements of Chemical Reaction Engineering in 1999. The LEPs use simulation software (e.g., Polymath's Ordinary Differential Equation (ODE) solvers, Wolfram, Python and MATLAB), which one can load directly onto one's own computers in order to "play with" the key variables and assumptions. We treat each example problem like a **piece of equipment** on which we can perform simulations, i.e., experiments. For Example, with Wolfram one moves the sliders as shown in Figure P-6 to learn how the various parameters affect the reactor and the reaction. The output for one set of slider conditions is shown in Figure P-7. After exploring the LEP the student then writes a number of conclusions on what was found in their investigation.

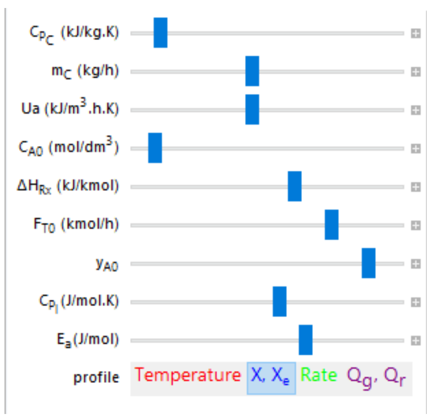

Figure P-6 Wolfram sliders

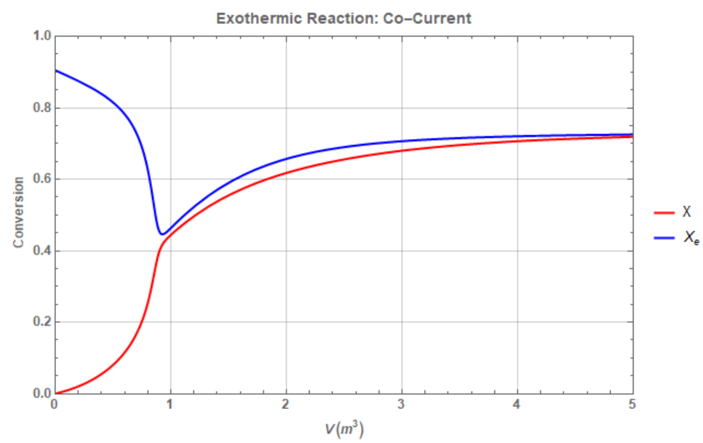

Figure P-7 Wolfram profiles.

Wolfram and Python can be downloaded for free while most of the universities in the U.S. have licenses for Polymath and MATLAB and therefore provide free access to these software packages for students as well.

Using the LEPs to explore the problem and asking "What if…?" questions provide students with the opportunity to practice critical and creative thinking skills. To guide students in using these simulations, questions for each chapter (e.g., *http://www.umich.edu/~elements/6e/12chap/live.html*) are given on the Web site. In addition, the students using this edition are asked to comment on the reasonableness of their answers to the assigned home problem.

The simulations labeled "**Stop and Smell the Roses**" are comprehensive-interactive simulations that will provide significant insight and an intuitive feel of the reactor and reaction when you take the time to explore the parameters using the Wolfram or Python sliders. #wellworthyourtime.

It has been shown that students using *Inquiry Based Learning (IBL)* have a much greater understanding of information than students educated by traditional methods (Universal Journal of Education Research, 2(1), 37–41 (2014)).[3,4] In fact with the advent of Python, Wolfram and MATLAB sliders, there has been a minor paradigm shift in the way homework problems are phrased.

You will note that software tutorials are listed at the bottom of the Living Example Problems page. There are 11 Polymath Tutorials showing the different applications of Polymath (*http://www.umich.edu/~elements/6e/software/polymath.html*), and one LEP tutorial for each Polymath, Wolfram, Python, and MATLAB Example Problems. There are also six COMSOL tutorials. To access

[3]Ibid, Adbi, A.
[4]See *Studies in Higher Education*, 2013, Vol. 38, No. 9, 1239–1258, *https://www.tandfonline.com/doi/abs/10.1080/03075079.2011.616584*

the LEP software you want to use, i.e., Polymath, Wolfram, Python or MATLAB, just click on the appropriate hot button, and then load and run the LEPs in the software you have chosen. Homework problems using the LEPs have been added to each chapter that require the use of Wolfram and Polymath. The use of Wolfram will allow students to get a thorough understanding of the *Computer Simulation Experiments* problems.

While we will still use the old paradigm problems "Find the reactor volume to achieve 50% conversion," the new paradigm, i.e., *Inquiry Based Learning*, treats each example problem as a piece of equipment that allows one to do experiments on it. After varying a number of the parameters by moving the sliders, the students then write a set of conclusions. The learning was most definitely enhanced when it came to questions that required interpretation such as, "Why did the temperature profile go through a minimum?" Each chapter has a section on Computer Simulations and Experiments that will guide students in practicing IBL. Students have commented that the Wolfram slider LEPs are a very efficient way to study the operation of a chemical reactor. For example, one can carry out a simulation experiment on the reactor (e.g., LEP 13-2) to investigate what conditions would lead to unsafe operation.

D.3 Additional Material

The additional material includes derivations, examples, new and novel applications of CRE principles that build on the CRE algorithm.

D.4 YouTube Videos

Here, you will find links to humorous YouTube videos made by students in Professor Alan Lane's 2008 chemical reaction engineering class at the University of Alabama, as well as videos from the University of Michigan's 2011 CRE class, which includes the ever-popular chemical engineering classic, "Reaction Engineering Gone Wrong." If you have a humorous YouTube video on CRE, please send it to me as I would be happy to consider linking to it.

D.5 Professional Reference Shelf (PRS)

The PRS is important to the practicing engineer, such as details of the industrial reactor design for the oxidation of SO2 and design of spherical and multiphase reactors and other material that is typically not included in the majority of chemical reaction engineering courses. It also contains significant amount of material for graduate courses such as slurry reactors, reactor stability along with collision and transition state theories.

D.6 Computer Simulations Problems

As previously mentioned, these problems represent a **minor paradigm shift** on how to study CRE. They uniquely help guide students to understand how the parameters and operating conditions affect the reaction and the reactors. These problems are in the printed version of the second edition of *Essentials of Chemical Reaction Engineering*, and the sixth edition of *Elements of Chemical Reaction Engineering*, but not in the printed version of the fifth edition of *Elements of Chemical Reaction Engineering*. Consequently, they are reproduced on the CRE Web site. We will use Wolfram and Python in the Living Example Problems on the CRE Web site extensively to carry out simulations so that students can

- Get a more intuitive feel of reactor system.
- Gain insight about the most sensitive parameters (e.g., the equilibrium constant, K_C) and how they affect outlet conditions.
- Learn how reactors are affected by different operating conditions, e.g., temperature rates above.
- Simulate dangerous situations such as potential runaway reactions.
- Compare the model and parameters with experimental data.
- Optimize the reaction system.

D.7 Web Modules

The *Web Modules* are a number of examples that apply key CRE concepts to both standard and nonstandard reaction engineering problems (e.g., glow sticks, the use of wetlands to degrade toxic chemicals, and pharmacokinetics of death from a cobra bite). The Web Modules can be loaded directly from the CRE Web site (*http://www.umich.edu/~elements/6e/web_mod/index.html*).

D.8 COMSOL

The COMSOL Multiphysics software is a partial differential equation solver that is used with Chapters 13 and 18 to view both axial and radial temperature and concentration profiles. For users of the text, Dr. Ed Fontes of COMSOL has provided a special Web site that includes a step-by-step tutorial, along with examples. See *https://www.comsol.com/books/elements-of-chemical-reaction-engineering-5th/models.* Further details are given in the Living Example Problems on the Web site.

D.9 i>Clicker Questions

i>Clicker questions have been added for every chapter. Students can use these to test their understanding by viewing and responding to multiple-choice questions and then seeing the answer. The i>Clicker questions help students access how well they are understanding the CRE material.

D.10 Self Tests

This section includes additional problems with interactive solutions that can be used for studying for exams. The Self-Test problems can be found in the *Summary Notes* on the Web site.

D.11 Extra Help

Now let's click on the Extra Help link for Chapter 12 shown in Figure P-5 to display Figure P-8.

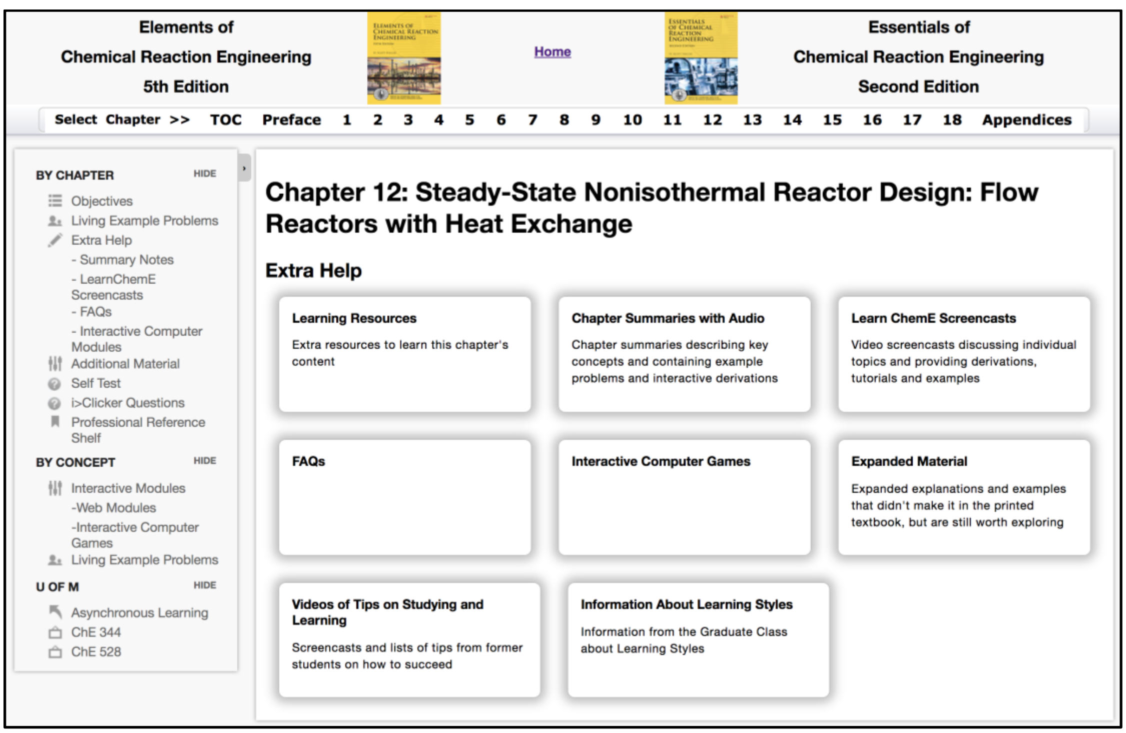

Figure P-8 Screen shot of Chapter 12 Extra Help (*http://www.umich.edu/~elements/6e/12chap/obj.html#/extra-help/*)

The **Summary Notes** which include the *On Demand Derivations* and *Self-Tests* can be accessed under "By Chapter" on the left hand side as shown in Figure P-8. It is my belief that the Extra Help videos on tips on studying and learning will be useful in other courses as well as CRE. There are also links to relevant LearnChemE screencasts, FAQs, and Expanded Material. One should go to the link on information About Learning Styles and take the Solomon/Felder test (*https://www.engr.ncsu.edu/stem-resources/legacy-site/learning-styles/*) to find out their learning style and then go to Web Appendix I to learn how to best use all the resources associated with the text.

E. Why Do We Assign Home Problems?

The working of homework problems facilitates a true understanding of CRE. After reading a chapter a student may "feel" they have an understanding of the material. However, when attempting a new or slightly different application of CRE in a homework problem, students often get stuck and sometimes need to go back and re-read different parts of the chapter to get the level of understanding needed to eventually solve the homework problem.

Two new additions have been added to this edition, **Questions Before Reading (QBR)** and identification of **Old Exam Questions (OEQ)**. As noted in Question Q-1, Chapter 1, research has shown that if the students asks or reads a Question Before Reading the material they will have a greater retention of the material. The same is true when using old exam problems in studying for exams.

It is recommended that students first work through *Computer Simulation and Experiments Problems* before going on to other problems. These simulations of the LEPs are a key resource. Approximately 1/3 of the problems only required a calculator while the other 2/3 require a software package such as Polymath. The subscript letter (A, B, C, or D) after each problem number (e.g., $12\text{-}2_B$) denotes the difficulty of the problem (i.e., A = easy; D = difficult). Most problems are B level.

When studying for an exam many students find additional reinforcement and insight by using the *Self-Tests* and *i>Clicker Questions*.

F. Are There Other Web Site Resources?

CRE Web Site (*http://www.umich.edu/~elements/6e/index.html*). A complete description of all the educational resources and ways to use them can be found in Web Appendix I on this CRE Web site. One of the first things you might want to do is to take the Felder-Solomon learning style test (*https://www.webtools.ncsu.edu/learningstyles/*) to learn your learning style. Once you have done this exercise, read through the tips in this section to see "how to best use the web-book interaction to facilitate your learning."

Safety Website (*http://umich.edu/~safeche/*). During the past two years, a safety website has been developed for all core chemical engineering courses A section at the end of each chapter called *And Now A Word From Our Sponsor-Safety (AWFOS-S)* has taken the tutorials and distributed them in chapters throughout the text. A safety module for both the T2 Laboratory incident (*http://umich.edu/~safeche/assets/pdf/courses/Problems/CRE/344ReactionEngrModule(1)PS-T2.pdf*) and the Monsanto incident (*http://umich.edu/~safeche/assets/pdf/courses/Problems/CRE/344ReactionEngrModule(2)PS-Monsanto.pdf*) can be found on the safety website. A safety algorithm is included in both of these modules.

What Entertainment Is on the Web Site?
Yes Indeed!!
A. YouTube Videos. The humorous videos are discussed in section D, What are the Components of the CRE Web Site, above.
B. Interactive Computer Games (ICGs). Students have found the Interactive Computer Games to be both fun and extremely useful for reviewing the important chapter concepts and then applying them to real problems in a unique and entertaining fashion. The following ICGs are available on the Web site:

- Quiz Show I (Ch. 1)
- Reactor Staging (Ch. 2)
- Quiz Show II (Ch. 4)
- Murder Mystery (Ch. 5)
- Tic Tac (Ch. 5)
- Ecology (Ch. 7)
- The Great Race (Ch. 8)
- Enzyme Man (Ch. 9)
- Catalysis (Ch. 10)
- Heat Effects I (Ch. 12)
- Heat Effects II (Ch. 12)

As you play these interactive games, you will be asked a number of questions related to the corresponding material in the textbook. The ICG keeps track of all the correct answers and at the end of the game displays a coded performance number that reflects how well you mastered the material in the text. Instructors have a manual to decode the performance number.

F.1 Interactive Computer Games (ICGs)

Interactive Computer Games (ICGs) provide not only a review of the material of the chapter being studied, but also an interactive self-assessment when you play the game. The Jeopardy games for Chapters 1 and 3 will help students prepare for the student chapter competition at the Annual AIChE meeting. The Chapter 5 game, *Murder Mystery* is world famous and the murder and victim are assigned randomly at each sign-on. The derivation for *Heat Effects I* and *II* are particularly fun as the symbols talk to each other as they move around the page to arrive at the final equation (*http://www.umich.edu/~elements/6e/icm/index.html*).

G. How Can One's Critical Thinking and Creative Thinking Skills be Enhanced? (*http://umich.edu/~scps/html/probsolv/strategy/crit-n-creat.htm*)

G.1 Enhance Critical Thinking Skills

A third goal of this book is to enhance critical thinking skills. How does one enhance their critical thinking skills? Answer: By learning how to ask the critical thinking questions of the type shown in Table P-2 and to carry out the actions shown in Table P-3. A number of homework problems have been included that are designed for this purpose. Socratic questioning is at the heart of critical thinking, and a number of homework problems draw from R. W. Paul's six types of Socratic questions,[5] shown in Table P-2 and given in the expanded material on the Web site (*http://www.umich.edu/~scps/html/03chap/frames.htm*).

It is important to know these six types and be able to apply them when investigating a problem such as "Is there a chance the reactor will run away and explode?" or "Why did the reactor explode?"

Another important skill is to be able to examine and challenge someone's hypothesis or statement. An algorithm to make this challenge is Structured Critical Reasoning (SCR), developed by Professors Marco Angelini and Scott Fogler while on sabbatical at University College London (*http://www.umich.edu/~elements/6e/toc/SCPS,3rdEdBookCh03.pdf*).

Critical thinking skills are like any skill, they must be practiced. Scheffer and Rubenfeld[6,7] describe how to practice critical thinking skills using the activities, statements, and questions shown in Table P-3. The reader should try to practice using some or all of these actions every day, as well as asking the critical thinking questions in Table P-1 and on the Web site.

[5] R. W. Paul, *Critical Thinking* (Santa Rosa, CA: Foundation for Critical Thinking, 1992).

[6] Courtesy of B. K. Scheffer and M. G. Rubenfeld, "A Consensus Statement on Critical Thinking in Nursing," *Journal of Nursing Education*, 39, 352–359 (2000).

[7] Courtesy of B. K. Scheffer and M. G. Rubenfeld, "Critical Thinking: What Is It and How Do We Teach It?" *Current Issues in Nursing* (2001).

I have found that the best way to develop and practice critical thinking skills is to use Tables P-2 and P-3 to help students write a question on any assigned homework problem and then to explain why the question involves critical thinking.

More information on critical thinking can be found on the Website in the section on Problem Solving (*http://www.umich.edu/~elements/6e/probsolv/index.htm*).

TABLE P-2 SIX TYPES OF SOCRATIC QUESTIONS USED IN CRITICAL THINKING

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(1) ***Questions for clarification:*** Why do you say that? How does this relate to our discussion?
"Are you going to include diffusion in your mole balance equations?"

(2) ***Questions that probe assumptions:*** What could we assume instead? How can you verify or disprove that assumption?
"Why are you neglecting radial diffusion and including only axial diffusion?"

(3) ***Questions that probe reasons and evidence:*** What would be an example?
"Do you think that diffusion is responsible for the lower conversion?"

(4) ***Questions about viewpoints and perspectives:*** What would be an alternative?
"With all the bends in the pipe, from an industrial/practical perspective, do you think diffusion and dispersion will be large enough to affect the conversion?"

(5) ***Questions that probe implications and consequences:*** What generalizations can you make? What are the consequences of that assumption?
"How would the results be affected if you neglected diffusion?"

(6) ***Questions about the question:*** What was the point of this question? Why do you think I asked this question?
"Why do you think diffusion is important?"

TABLE P-3 CRITICAL THINKING ACTIONS[8]

Analyzing: separating or breaking a whole into parts to discover their nature, function, and relationships
"I studied it piece by piece."
"I sorted things out."
Applying Standards: judging according to established personal, professional, or social rules or criteria
"I judged it according to…."
Discriminating: recognizing differences and similarities among things or situations and distinguishing carefully as to category or rank
"I rank ordered the various…."
"I grouped things together."
Information Seeking: searching for evidence, facts, or knowledge by identifying relevant sources and gathering objective, subjective, historical, and current data from those sources
"I knew I needed to look up/study…."
"I kept searching for data."
Logical Reasoning: drawing inferences or conclusions that are supported in or justified by evidence
"I deduced from the information that…."
"My rationale for the conclusion was…."
Predicting: envisioning a plan and its consequences
"I envisioned the outcome would be…."
"I was prepared for…."

[8]R. W. Paul, *Critical Thinking* (Santa Rosa, CA: Foundation for Critical Thinking, 1992); B. K. Scheffer and M. G. Rubenfeld, "A Consensus Statement on Critical Thinking in Nursing," *Journal of Nursing Education*, 39, 352–359 (2000).

TABLE P-3 CRITICAL THINKING ACTIONS (CONTINUED)

Transforming Knowledge: changing or converting the condition, nature, form, or function of concepts among contexts

"I improved on the basics by…."

"I wondered if that would fit the situation of …."

G.2 Enhance Creative Thinking Skills

The fourth goal of this book is to help enhance creative thinking skills. This goal is achieved by using a number of problems that are open-ended to various degrees. With these, students can practice their *creative skills* by exploring the example problems, as outlined at the beginning of the home problems of each chapter, and by making up and solving an original problem. Question **Q5-3** on page 217 in the text gives some guidelines for developing original problems. A number of techniques that can aid students in practicing and enhancing their creativity[9] can be found in Fogler, LeBlanc, and Rizzo[10] (and its companion Web site), *Strategies for Creative Problem Solving*, Third Edition (*http://umich.edu/~scps/index.htm*). The Web site for that book can be accessed from the CRE Web site home page. We use these techniques, such as Osborn's checklist and de Bono's lateral thinking (which involves considering other people's views and responding to random stimulation) to answer add-on questions such as those in Table P-4. Mental blocks to idea generation can be found in *http://umich.edu/~scps/html/06chap/frames.htm*, while 12 Things You Can Do To Improve Your Creativity can be found at *http://www.umich.edu/~elements/6e/probsolv/strategy/creative.htm*. Osborn and deBono's brain-storming techniques, along with futuring, analogy, cross-fertilization, and TRIZ techniques TRIZ, can be found at *http://www.umich.edu/~scps/html/07chap/frames.htm* and the book link *http://www.umich.edu/~elements/6e/toc/SCPS,3rdEdBook(Ch07).pdf*.

One of my favorite techniques is DeBono's Random Stimulation where one points a finger that lands on a word on a printed page. One then uses that word to generate other words in a paper trail until they uncover a new idea related to the problem.

TABLE P-4 PRACTICING CREATIVE THINKING

---

(1) Brainstorm ideas to ask another question or suggest another calculation that can be made for this homework problem.

(2) Brainstorm ways you could work this homework problem incorrectly.

(3) Brainstorm ways to make this problem easier or more difficult or more exciting.

(4) Brainstorm a list of things you learned from working this homework problem and what you think the point of the problem is.

(5) Brainstorm the reasons why your calculations overpredicted the conversion that was measured when the reactor was put on stream. Assume you made no numerical errors in your calculations.

(6) "What if…" questions: The "What if…" questions are particularly effective when used with the *Living Example Problems*, where one varies the parameters to explore the problem and to carry out a sensitivity analysis. For example, *what if someone suggested that you should double the catalyst particle diameter, what would you say?*

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[9] Creativity: *http://www.umich.edu/~scps/html/06chap/frames.htm*.

[10] H. S. Fogler, S. E. LeBlanc, with B. Rizzo, *Strategies for Creative Problem Solving*, 3rd ed. (Upper Saddle River, N.J.: Prentice Hall, 2014), *http://www.umich.edu/~scps/*.

A major Goal of the CRE Book

One of the major goals at the undergraduate level is to bring students to the point where they can solve complex reaction problems, such as multiple reactions with heat effects, and then ask "What if . . . ?" questions and look for optimum operating conditions or unsafe operating conditions. The solution to one problem exemplifies this goal: the Manufacture of Styrene (Chapter 12, Problem P12-26C). This problem is particularly interesting because two reactions are endothermic and one is exothermic.

(1) Ethylbenzene → Styrene + Hydrogen: Endothermic
(2) Ethylbenzene → Benzene + Ethylene: Endothermic
(3) Ethylbenzene + Hydrogen → Toluene + Methane: Exothermic

The student could get further practice in critical and creative thinking skills by adding any of the following exercises (x), (y), and (z) to any of the end-of-chapter homework problems.

(x) How could you make this problem easier? More difficult?
(y) Critique your answer by writing a critical thinking question.
(z) Describe two ways you could work this problem incorrectly.

To summarize, it is this author's experience that both critical and creative thinking skills can be enhanced by using Tables P-2, P-3, and P-4 to extend any of the homework problems at the end of each chapter.

H. What's New in This Edition?

H.1 Pedagogy

This Web site and textbook interaction is a mini paradigm shift in active learning. There is a symbiotic relationship between the textbook and the Web site that allows the student to get an intuitive feel of the reactions and reactors. Here the students can use the software packages of Wolfram, Python, MATLAB and Polymath to explore the reactions and the reactors. In addition, this edition maintains all the strengths of the previous editions of *Elements of Chemical Reaction Engineering* by using algorithms that allow students to learn chemical reaction engineering through logic rather than memorization.

At the same time, this edition provides new resources that allow students to go beyond solving equations in order to get an intuitive feel and understanding of how reactors behave under different situations. Taken together the text and the associated Web site represent a mini-paradigm shift in the learning of chemical reaction engineering. This shift is achieved using Inquiry-Based Learning[11] (IBL) and the interaction between the text and the Web site's Living Example Problems (LEPs), as discussed in Preface Section D.2. The advent of Wolfram in CRE is one of the things that facilitated this paradigm shift.

Creative thinking skills can be enhanced by exploring the example problems and asking "What if . . . ?" questions, by using one or more of the brainstorming exercises in Table P-4 to extend any of the homework problems, and by solving the open-ended problems. For example, in the case study on safety, students can use the LEP on the CRE Web site to carry out a postmortem analysis on the nitroaniline explosion in Example 13-2 to learn what would have happened if the cooling had failed for five minutes instead of ten minutes. To this end, a new feature in the text is an Analysis paragraph at the end of each and every example problem.

In this edition there are more than 80 interactive simulations (LEPs) provided on the Web site. The Web site has been greatly expanded to address the Felder/Solomon Inventory of Different Learning

[11]ibid, Adhi, A

Styles[12] through interactive Summary Notes, i>Clicker questions and Interactive Computer Games (ICGs). For example, as discussed in Web Appendix I (*http://www.umich.edu/~elements/6e/appendix/Web-Appendix-I.pdf*) the Global Learner can get an overview of the chapter material from the *Summary Notes*; the Sequential Learner can use all the i>Clicker questions and Self Test hot buttons; and the active learner can interact with the ICGs and use the Derive hot buttons in the Summary Notes.

To develop critical thinking skills, instructors can assign one of the new homework problems on troubleshooting, as well as ask the students to expand homework problems by asking a related question that involves critical thinking using Tables P-2 and P-3 on the Web site.

The following areas have an increased emphasis on the Web site for this new edition thorough interactive example problems using Polymath, Wolfram, Python and MATLAB:

1. Safety:[13] Three industrial explosions are discussed and modeled.
   a. Ammonium Nitrate CSTR Explosion (Chapters 12 and 13)
   b. *http://umich.edu/~safeche/* Nitroaniline Batch Reactor Runaway (Chapter 13)
   c. T2 Laboratories Batch Reactor Runaway (Chapter 13)
   d. Resources from SAChE and CCPS (Chapter 12)
2. AspenTech: An AspenTech tutorial for chemical reaction engineering and four example problems are provided on the CRE Web site. The example problems are
   a. Production of Ethylene from Ethane
   b. The Pyrolysis of Benzene
   c. Adiabatic Liquid Phase Isomerization of Normal Butane
   d. Adiabatic Production of Acetic Anhydride

And most importantly we have to always remember that:
Hopefully, all intensive laws tend often to have exceptions. Very important concepts take orderly, responsible statements. Virtually all laws intrinsically are natural thoughts. General observations become laws under experimentation.

I. How Do I Say Thank You?

There are so many colleagues and students who contributed to this book that it would require another chapter to thank them all in an appropriate manner. I again acknowledge all my friends, students, and colleagues for their contributions to the sixth edition of *Elements of Chemical Reaction Engineering*. I would like to give special recognition as follows.

First of all, I am indebted to Ame and Catherine Vennema, whose gift of an endowed chair greatly facilitated the completion of this project. My colleague Dr. Nihat Gürmen coauthored the original Web site during the writing of the fourth edition of *Elements of Chemical Reaction Engineering (CRE)*. He has been a wonderful colleague to work with. I also would like to thank University of Michigan undergraduate ChE students who served early on as webmasters for the CRE Web site namely Arthur Shih, Maria Quigley, Brendan Kirchner and Ben Griessmann. More recently CSE students, Jun Kyungjun Kim, Elsa Wang, Wen He, Kiran Thwardas, Tony Hanchi Zhang, Arav Agarwal and Lisa Ju Young Kim worked on both the CRE Web site and the Safety Web site.

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12 *http://www.ncsu.edu/felder-public/ILSdir/styles.htm*

13 *http://umich.edu/~safeche/*

compositor in time. He provided all of the Wolfram coding for the LEP examples; when necessary, checked and corrected all the Polymath, Wolfram, Python and MATLAB tutorials on the CRE Web site; and also helped proofread all the chapters. A number of summer interns have helped with preparation of the additional material for the book, especially the Safety Web site, as well as related material. Kaushik Nagaraj developed and provided the MATLAB coding in Section 3.5 while Ayush Agarwal (KTH Royal Institute of Technology, Sweden) worked on the Sythron Explosion and Jakub Wlodarczyk (Warsaw University of Technology, Poland) checked all of the i>Clicker questions and solutions. Students from Indian Institute of Technology, Bombay, who contributed to AWFOS-S at the end of each chapter include Kaushik Nagaraj, Triesha Singh, Reshma Kalyan Sundaram, Kshitiz Parihar, Manan Agarwal, Kushal Mittal and Sahil Kulkarni. Vaibav Jain from IIT Delhi and Devosmita Sen, Manjeet Singh and Jnana Sai Jagana (from IIT Bombay) worked on the Solutions Manual. From the University of Michigan, Kara Steshetz, Alec Driesenga, Maeve Gillis, Lydia Peters and Zach Gdowski worked on the Safety material.

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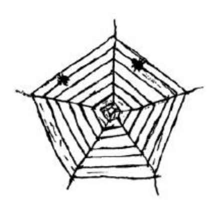
For typographical errors, updates and new and exciting applications, see the Web site home page:

http://umich.edu/~elements/6e/index.html



About the Author

H. Scott Fogler is the Ame and Catherine Vennema professor of chemical engineering and the Arthur F. Thurnau professor at the University of Michigan in Ann Arbor. He was recognized as a 2020 Michigan Distinguished Professor of the year, and was the 2009 National President of the American Institute of Chemical Engineers (AIChE), a 50,000-member organization. He received his B.S. from the University of Illinois and his M.S. and Ph.D. from the University of Colorado. He is also the author of the *Essentials of Chemical Reaction Engineering*, Second Edition, and coauthor, with Steven LeBlanc and Benjamin Rizzo, of *Strategies for Creative Problem Solving*, Third Edition.

Professor Fogler's research interests include flow and reaction in porous media, wax and asphaltene deposition, asphaltene flocculation kinetics, gelation kinetics, colloidal phenomena, and catalyzed dissolution. He has been research advisor to 47 Ph.D. students and has more than 240 refereed publications in these areas. Fogler has chaired ASEE's Chemical Engineering Division, served as director of the AIChE, and earned the Warren K. Lewis Award from AIChE for contributions to chemical engineering education. He also received the Chemical Manufacturers Association's National Catalyst Award, and the 2010 Malcom E. Pruitt Award from the Council for Chemical Research (CCR), and the 2019 Van Antwerpen Award from AIChE. He is the recipient of 12 named lectureships and is associate editor of *Energy & Fuels*. On April 15, 2016, Scott received a *doctor honoris causa* degree from the Universitat Rovira i Virgili,
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