RICHARD M. FELDER
REBECCA BRENT

TEACHING AND LEARNING STEM

A PRACTICAL GUIDE

FOREWORD BY BARBARA OAKLEY

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THE AUTHORS

Richard Felder, PhD, is Hoechst Celanese Professor Emeritus of Chemical Engineering at North Carolina State University, where he has been a faculty member since 1969. He is a coauthor of *Elementary Principles of Chemical Processes* (fourth edition, Wiley, 2015), which has been used as the introductory text by roughly 90% of all chemical engineering departments in the United States and many abroad since it first appeared in 1978, and he has authored or coauthored more than 300 papers on process engineering and STEM education. He has won numerous awards for his teaching, research, and publications, including the International Federation of Engineering Education Societies Global Award for Excellence in Engineering Education (2010, first recipient) and the American Society for Engineering Education Lifetime Achievement Award (2012, first recipient). A bibliography of Dr. Felder's papers and reprints of his columns and articles can be found at www.ncsu.edu/effective_teaching.

Rebecca Brent, EdD, is president of Education Designs, Inc., a consulting firm in Cary, North Carolina. She has more than 35 years of experience in education and specializes in STEM faculty development, precollege teacher preparation, and evaluation of educational programs at precollege and college levels, and she holds a certificate in evaluation practice from the Evaluators' Institute at George Washington University. She has authored or coauthored more than 60 papers on effective teaching and faculty development, and coordinated faculty development in the NSF-sponsored SUCCEED Coalition and new faculty orientation in the Colleges of Engineering and Sciences at North Carolina State University. Prior to entering private consulting, Dr. Brent was an associate professor of education at East Carolina University, where she won an outstanding teacher award. In 2014, she was named a Fellow of the American Society for Engineering Education.

Separately and together, Drs. Felder and Brent have presented more than 450 workshops on effective teaching, course design, mentoring and supporting new faculty members, and STEM faculty development on campuses throughout the United States and abroad. They co-directed the American Society for Engineering Education National Effective Teaching Institute from 1991 to 2015.

We dedicate this book to Charlotte and Wilson Brent, in loving memory of their lives well lived.

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FOREWORD

FOR MANY UNIVERSITY professors, teaching is like being handed the keys to a car without being taught how to drive. The result? Even experienced professors can wind up driving with their pedagogical parking brakes on. They steer forward clumsily, unaware that there's an easier way, and ignoring the smoke emerging from the tailpipe.

This book is hands-down the best instruction manual for professors in science, technology, engineering, and mathematics that you can find. Husband-and-wife team Richard Felder and Rebecca Brent write in an exceptionally clear, non-stuffy voice that makes this a book you can read even at the end of a busy day. A simple glance at the table of contents or index will rapidly take you to what you might need to find at the moment—either before or after you've read the whole book.

The book is packed with special features, which include brief interlude essays that give you a sense of what your students are thinking, succinct summaries of key practical insights from neuroscience, and concrete suggestions based on solid research and decades of experience. Everything is backed with loads of references, so you can easily explore as deeply as you choose.

Books on teaching in the STEM disciplines often center on one discipline—physics, say, or engineering. Few comprehensively encompass teaching in STEM fields ranging from biology and chemistry to theoretical mathematics. This book takes a broad-ranging approach that enables readers to pluck the best insights from a wide variety of STEM disciplines.

And it's a great thing—there's never been a stronger need for a book that lays out the foundations of good teaching at university levels in the STEM disciplines. Worldwide, STEM jobs are like mushrooms—popping up at far higher rates than many other types of jobs, yet not enough candidates for these jobs are graduating from our STEM programs. In fact, often only a small percentage of high school seniors are interested in pursuing STEM careers. Many of those students fall by the wayside as they bump against the challenges of STEM studies.

But as Richard Felder and Rebecca Brent lay out in this remarkably engaging book, there are ways to work smarter as instructors—ways to help improve students' desire and ability to master tough material. This book can help you open important career opportunities for your students, even as you help improve and increase their skills that address profound national and international needs. You will also find that releasing the parking brake of less-than-adequate teaching will make your life as a professor more fulfilling and enjoyable.

Learner-centered approaches go all the way back to the Greeks, the Buddha, and various traditions of the Far East, and have recently been taken up again in the STEM disciplines by expert teachers and researchers such as mathematician Robert Lee Moore and physicists Eric Mazur and Carl Wieman. There is a reason for the continued popularity of learner-centered teaching techniques by the best and most famous teachers—such approaches do much to stimulate student success. This book contains up-to-date practical information about how to apply these techniques in the STEM disciplines.

On a personal note, I first met Rich and Rebecca at the very beginning of my teaching career and was lucky enough to attend a workshop they taught on learner-centered teaching, which is the pedagogical framework of their book. That workshop changed the whole focus of my teaching and enabled me to understand learning in a whole new, deeper way. You'll find that your own understanding of learning will be greatly enriched as you read this extraordinary book.

—Barbara Oakley, PhD, PE
Professor of Engineering, Oakland University, Rochester, Michigan
Visiting Scholar, University of California, San Diego

Author of *New York Times* best-selling book *A Mind for Numbers: How to Excel in Math and Science (Even If You Flunked Algebra),* and co-instructor of *Learning How to Learn: Powerful Mental Tools to Help You Master Tough Subjects*, one of the world's largest massive open online courses, for Coursera-UC San Diego.

PREFACE

WHY ANOTHER "how-to-teach" book, and why us as the authors? Our answers are in our stories.

(Rich's story) *When I started my academic career in chemical engineering at NC State back in prehistoric times, I had the same training in teaching that most college professors get: none. Not knowing that there were alternatives, I fell back on the only teaching model I had, which was how my professors had taught me. Unfortunately, no one ever taught them how to teach either, and so for the first fifteen years of my career I did what all my colleagues did—gave nonstop lectures and tests that were always too long and drastically curved course grades so I wouldn't end up failing most of the class.*

You could take my lecture notes to the bank. The derivations were complete and correct, my delivery was clear and occasionally entertaining, and most students left the lectures thinking they understood everything. The result was that I got high ratings and won some awards. There were just two minor hitches. After the lectures the students struggled for hours to complete assignments that involved problems similar to the ones I worked in class, and many of their exam grades were pitiful. Most who failed blamed themselves, figuring that if they couldn't do well with a teacher as clear as I was, they obviously lacked what it takes to be an engineer.

Most of them were wrong—a lot of the blame for their failure was mine. When I was developing and polishing those lecture notes—finding clear ways to express difficult concepts, coming up with good examples of every method I was teaching—I was really learning that stuff! The problem was that I was then feeding my students predigested food. They didn't have to go through the intellectual labor of working some of it out for themselves, which meant that they never really understood it, no matter how clear it may have seemed in the lectures.

Most STEM professors never read education literature, and I was no exception. It was years before I learned that excellent research has been done on alternative teaching methods, some of which have been found to *promote learning much better than traditional methods do. I started trying some of those alternatives and found that they worked beautifully in my courses, and I subsequently met some pedagogical experts who helped me sharpen my understanding. One of them became my professional colleague and the coauthor of this book and my wife—Rebecca Brent. (Who says educational research doesn't pay off?)*

(Rebecca's story) *I've been a teacher since my earliest preschool days spent "teaching" a neighbor child her letters, and early on I made education the focus of my career. I loved learning about how people learn and creative ways to facilitate learning. I began my professional life as an elementary school teacher, and then got my doctorate and became a teacher educator at East Carolina University. It was fascinating for me to watch my students as they first began to teach and put all the education theory I had taught them into practice on a daily basis. I also worked on a faculty team to develop training programs for people in non-academic professions who wanted to change careers and become teachers. It was then that I realized that passing along a few, well-chosen techniques could go a long way toward helping people to become effective instructors. When Rich and I began to give workshops to university STEM faculty, I found that the approach held up. We could help people understand something about how their students learn, get them to think carefully about what they wanted their students to be able to do and how they could evaluate the students' ability to do it, and offer some simple ways to get students engaged in class, no matter how many of them were in the room. Some workshop attendees tried a few of our suggestions and started to see effects on their students' learning, some made major transformative changes in their courses and saw correspondingly significant impacts, and a few now give excellent teaching workshops themselves, which delights us.*

In our workshops, we review teaching methods that have been proven effective by solid replicated research, most of which are relatively easy to implement. Our goal in this book is to share those methods and some of the supporting research with you.

The first chapter of the book contains a short introduction to some of what educational research has revealed about effective teaching and learning, a preview of the book's contents, and some suggestions for how to use the book. The chapter is a quick read and introduces ideas we will return to periodically in the rest of the book. Following that are chapters that deal with methods for designing and implementing effective courses and helping students acquire and improve their skills at problem solving, communications, creative and critical thinking, high-performance teamwork, and self-directed learning.

There are several things we don't intend the book to be. One is a compendium of everything anyone knows about teaching. Writing something like that would take more time than we have and reading it would take more time than you have. It's also not a scholarly treatise on the theories behind the methods we have chosen to cover. Plenty of books out there review the theories and we will point you to some of them, but our emphasis will be on nuts and bolts of the practice—what the methods are, how to implement them, and pitfalls to avoid when doing so. We'll also share findings from modern cognitive science that provide good clues about why the methods consistently work as well as they do.

The book draws extensively on journal articles we have authored or coauthored. Most notably, the interludes between chapters are almost all based on our "Random Thoughts" columns that have appeared in the quarterly journal *Chemical Engineering Education* since 1988. We are grateful to Managing Editor Lynn Heasley for granting us permission to modify and reprint the columns.

We have not been shy about asking for help, and so we have a long list of colleagues who previewed and critiqued chapter drafts, shared course materials, and provided invaluable encouragement. Rather than elaborating on what most of them did and making this preface longer than some of the chapters, we will simply express our deep thanks to David Brightman, Lisa Bullard, Jo-Ann Cohen, Marc Cubeta, Jackie Dietz, John Falconer, Stephanie Farrell, Elena Felder, Gary Felder, Kenny Felder, Mary Felder, Cindy Furse, Susan Geraghty, Jeff Joines, Milo Koretsky, Susan Lord, Misty Loughry, Nicki Monahan, Michael Moys, Mike Prince, Julie Sharp, Kimberly Tanner, Dan Teague, John Tolle, Thomas Wentworth, and Carl Zorowski.

We will, however, single out two individuals, without whom this book would not exist. From the moment she learned that we were planning a book more years ago than we care to contemplate, the superb author and educator Barbara Oakley functioned as our principal cheerleader, critic, and nudge, repeatedly and good-naturedly assuring us that the world desperately needed this book when we doubted ourselves, red-inking our occasionally pedantic and hyperbolic prose, and gently prodding us back into action when not much from us was showing up in her in-box. Eventually things reached a point where we had to keep pushing on—we couldn't have lived with the guilt we would have felt over disappointing Barb. Words can't begin to convey our gratitude.

And words are equally inadequate to thank our editor, Maryellen Weimer, the long-time guru of *The Teaching Professor* newsletter and author of *Learner-Centered Teaching*. Having a professional icon like Maryellen working with us was somewhat intimidating—it was as if we had set out to compose a symphony and learned that Mozart would be advising us. Fortunately, besides being one of the top authorities on higher education in the world, Maryellen is also one of the finest editors and nicest human beings. She gave us a steady stream of impeccably good advice, without ever trying to impose her views or her voice on our writing, and Rich has even forgiven her for siding with Rebecca every single time the coauthors disagreed about something.

And finally, we want to thank Kenny, Joyce, Elena, Leonicia, Gary, Rosemary, Mary, Ben, Jack, Shannon, Johnny, James, and Cecelia for putting up with our frequent disappearances in the final stages of writing this book. At the top of our very long list headed by "*When we finish this &#^*%& book, we will …*" is "*be more reliable parents and grandparents.*" We hope that by the time the thirteen of you are reading this, we will have started to keep that resolution.

Richard Felder
Rebecca Brent

1

INTRODUCTION TO COLLEGE TEACHING

1.0 Welcome to the University, There's Your Office, Good Luck

As everyone knows, skilled professionals routinely receive training before being certified to practice independently. Electricians, machinists, and chefs get preliminary instruction and then serve for months or years as apprentices. Accountants, psychologists, physicists, and physicians spend years earning degrees in their fields, and the physicians spend additional years in supervised internships and residencies. It would be unthinkable to allow people to practice a skilled profession without first being trained for it, especially if their mistakes could cause harm to others … unless they are college faculty members.

The standard preparation for a faculty career is taking undergraduate and graduate courses in your discipline and completing a research project on a topic someone else has defined. Once you join a faculty, your orientation may consist of nothing but the heading of this section, and perhaps a half-day or a day on such things as health and retirement benefits and the importance of laboratory safety. The unstated assumption is that if you have a degree in a subject, you must know how to teach it at the college level.

Anyone who has ever been a college student knows how bad that assumption can be. What student has never had a professor who taught at a level ridiculously above anything the students had a chance of understanding, or put entire classes to sleep by droning monotonously for 50- or 75-minute stretches with no apparent awareness that there were students in the room, or flashed PowerPoint slides at a rate no human brain could possibly keep up with?

Instructors like these unfortunately abound on college faculties. If you teach like any of them, no matter how much you know and how accurately you present it, you probably won't enjoy looking at your students' test scores or your end-of-class student ratings. Being an excellent or even just a competent teacher requires knowing many things graduate school doesn't teach, such as how to design courses and deliver them effectively; write assignments and exams that are both rigorous and fair; and deal with classroom management, advising problems, cheating, and an uncountable number of other headaches teachers routinely encounter. Figuring out all those things on your own is not trivial. Although there is something to be said for trial-and-error learning, it's not efficient—and in the case of teaching, the ones making the errors are not the ones suffering the consequences. Many new faculty members take years to learn how to teach well, and others never learn.

It doesn't have to be that way. Proven methods for teaching effectively—that is, motivating students to learn and helping them acquire the knowledge, skills, and values they will need to succeed in college and their professions—are well known. Many of those methods are not particularly hard—you can just learn what they are and then start using them. That doesn't mean they make teaching simple: teaching a course—especially for the first time—is and always will be a challenging and time-consuming task. The point is that teaching well does not have to be harder than teaching poorly. The purpose of this book is to help you learn how to teach well.

1.1 Making Learning Happen

Brainwave: What Goes on in Our Brains When We Learn?

Learning is shorthand for encoding and storing information in long-term memory, from which it can later be retrieved and used. According to a widely-used model of this process, new information comes in through the senses, is held for a fraction of a second in a sensory register, and is then either passed on to working memory or lost. Once in working memory, the information is processed, and after a fraction of a minute (or longer if the information is repeated), it is then either stored in long-term memory or lost.

The chances of a new sensory input getting into long-term memory vary dramatically from one input to another. The inputs most likely to make it relate to (1) *threats* to the learner's survival or well-being. In descending order, the next most likely inputs to be stored are those with (2) *strong emotional associations* for the learner; (3) *meaning* (relationship to the learner's interests, goals, prior knowledge, and past experiences); and (4) *sense* (comprehensibility).

It follows that if teachers present information irrelevant to anything students know and care about and it makes little sense to them, there should be no surprise if the students later act as if they never heard it. It never made it into their long-term memory, so for all practical purposes they *didn't* hear it. Moreover, even if information makes it into long-term memory, unless it is reinforced by rehearsal (conscious repetition), the clusters of nerve cells that collectively contain it are weakly connected and the information may not be easily retrieved.

In short, *the more new information has meaning and makes sense to students, the more likely it is to be stored. Once stored, the more often the information is retrieved and rehearsed, the more effective the learning is* (Sousa, 2011, Ch. 3).

Think about something you're really good at. It might be soccer, auto mechanics, chess, piano, physics, Java programming, or anything else. Go on—we'll wait.

Now think about *how* you got good. You might think of courses you took but you probably won't. You're much more likely to think about making your first awkward and unsuccessful efforts, getting feedback from someone else or learning from your mistakes, and trying again. If you persisted, you eventually started to succeed. The more practice and feedback you got, the better you got, until you reached your current level.

That's how people learn. Mastery of a skill comes mainly from doing things, noticing and reflecting on the results, and possibly getting feedback from someone else. If we learn anything by just reading a text or watching and listening to someone lecturing at us, it generally isn't much, and the chances of retaining it for very long are slim. The truth of that message has been recognized for a long time.

> One must learn by doing the thing; for though you think you know it, you have no certainty until you try. (Sophocles)
>
> What we have to learn to do, we learn by doing. (Aristotle)
>
> You cannot teach a man anything: you can only help him to find it within himself. (Galileo)
>
> No thought, no idea, can possibly be conveyed as an idea from one person to another. (John Dewey)

Modern cognitive science and decades of classroom research studies demonstrate that Sophocles and those other sages were right. People learn by doing and reflecting, not by watching and listening. Unfortunately, starting in about the sixth grade and continuing through college, most classes are taught primarily by lecturing. Traditional education is consequently uninspiring and ineffective for most people, and for some it becomes a serious and sometimes permanent deterrent to lifelong learning.

Fortunately, there are excellent alternatives to pure lecture-based instruction. We will describe many of them in this book, starting in the next section of this chapter. They are not traditional in STEM (science, technology, engineering, and mathematics) education, but they have all been validated by extensive research, and many STEM instructors have discovered them and used them successfully. There's even more good news:

To teach effectively you don't have to use every teaching method known to be effective, and you shouldn't even think of trying to implement too many at once.

If you try to change how you teach too drastically, you and your students may be so uncomfortable that the class turns into a disaster, the student pushback can be overwhelming, and you'll never want to do anything new again. Instead, start with one or two relatively simple alternative methods, such as active learning, and introduce new methods gradually, never moving too far out of your comfort zone. If you take that moderate approach, your teaching and your students' learning will steadily improve, which should be your goal.

Becoming a more effective teacher doesn't require throwing out everything traditional.

We won't be telling you, for example, to abandon lecturing and make every class you teach an extravaganza of student activity. We *will* tell you to avoid making lecturing the only thing that happens in your class sessions. Introduce one or two activities in the first few sessions so you and the students can get used to them, and gradually increase their frequency. As you continue to use the method your confidence will rise, and your use of active learning will probably rise with it. The same thing is true for the other teaching methods we will discuss. Again, the key is to take it easy!

You're not going to win them all, and you don't have to.

Even if you use the most effective teaching methods known to education, many of your students will not get top grades and some will fail. That doesn't mean you failed as a teacher. How well students do in a course depends on much more than how their instructor teaches: it also depends on their aptitude for the subject, how interested they are in it, how hard they are willing and able to work on it, how important their course grade is to them, and an uncountable number of other factors. We suggest that your goal as a teacher should not be to have 100% of your students achieve your learning objectives, because that's generally neither possible nor even desirable. Not everyone was born to be a scientist, engineer, or mathematician, and if all of your students fully meet your objectives you may be setting the bar too low. Rather, your goal should be to enable as many as possible of your students with the required aptitude, motivation, and work ethic to succeed in your course and transfer what they learn to other courses and eventually to their careers. *That* you can do.

1.2 Learner-Centered Teaching: Definition, Warning, and Reassurance

The great philosopher and educator John Dewey said, "Teaching and learning are correlative or corresponding processes, as much so as selling and buying. One might as well say he has sold when no one has bought, as to say that he has taught when no one has learned" (Dewey, 1910, p. 29).

That statement may seem obvious but it isn't to everyone. If you look up the word *teach* in a dictionary, you will find variations of two completely different concepts:

1. *Teach:* To show or explain something.
2. *Teach:* To cause to know something.

By the first definition, if everything the students are supposed to learn in a course is covered in lectures and readings, then the instructor has successfully taught the course, whether or not anyone learned it. By the second definition, if students don't learn, the instructor didn't teach.

Many STEM instructors subscribe to the first definition. "My job is to cover the syllabus," they argue. "If the students don't learn it, that's their problem, not mine." They use *teacher-centered instruction,* in which the course instructor defines the course content; designs and delivers lectures; creates, administers, and marks assignments and tests; assigns course grades; and is essentially in control of everything that happens in the course except how the students react and achieve. The students mainly sit through the lectures—some occasionally asking or answering questions and most just passively observing. They absorb whatever they can, and then do their best to reproduce it in the assignments and exams. That model pretty much describes STEM higher education as it has been practiced for centuries throughout the world, despite the fact that it is incompatible with what we now know about how people actually learn.

John Dewey, whose quote began this section, clearly believed in the second definition of teaching—to cause learning to occur. That definition lies at the heart of what is now called *learner-centered teaching (LCT)*. The teacher of a course still sets the broad parameters of instruction, making sure that the learning objectives and lessons cover all the knowledge and skills the course is supposed to address, the assessments match the objectives and are fair, and the course grades are consistent with the assessment data. The difference is that the students are no longer passive recipients and repeaters of information but take much more responsibility for their own learning. The instructor functions not as the sole source of wisdom and knowledge to them but more as a coach or guide, whose task is to help them acquire the desired knowledge and skills for themselves.

Weimer (2013, Ch. 2) surveyed the voluminous research literature on the various forms of learner-centered teaching and observed that properly implemented LCT has been found superior to teacher-centered instruction at achieving almost every conceivable learning outcome. We will use LCT as a framework for the rest of this book. In later chapters we'll discuss specific LCT techniques—what they are, what research says about them, how to implement them, what can go wrong when you use them, and how to make sure it doesn't. Before we preview the book in the next section, though, we'll warn you about something you might find troublesome when you launch into LCT for the first time. When you make students more responsible for their own learning than they have ever been, they will not all leap to their feet and embrace you with gratitude! Weimer (2013, p. 199) offers the following cautionary words:

> Some faculty [members] find the arguments for learner-centered teaching very convincing. With considerable enthusiasm, they start creating new assignments, developing classroom activities, and realigning course policies. By the time they've completed the planning process, they are just plain excited about launching what feels like a whole new course. They introduce these new course features on the first day, sharing with students their conviction that these changes will make the class so much better. And what happens? Students do not respond with corresponding enthusiasm. In fact, they make it very clear that they prefer having things done as they are in most classes. Teachers leave class disheartened. The student response feels like a personal affront.

If you have not used learner-centered teaching yet, the resistance you may encounter from some students the first time you try it may be a shock to your system. You may envision your student ratings plummeting and your chances for advancement on the faculty shrinking, and it can be easy for you to say "Who needs this?" and go back to traditional lecturing.

If you find yourself in that situation, fight the temptation to retreat. Several references on learner-centered teaching methods have discussed the phenomenon of student resistance: why it's there, what forms it might take, and how instructors can deal with it (Felder, 2007, 2011a; Felder & Brent, 1996; Seidel & Tanner, 2013; Weimer, 2013, Ch. 8). We won't go into detail about it now but will explore the issue later when we get into active learning, cooperative learning, and other learner-centered methods. For now, just be aware of the possibility of student resistance to LCT, and be assured that you can minimize or eliminate it if you take the measures we'll tell you about. If your need for immediate reassurance is urgent, check out any of the five references just cited, and then relax.

You may also hear from some of your faculty colleagues that LCT doesn't work. If you do, cheerfully offer to share with them the research that proves it does (we'll provide you with plenty of it). That offer usually ends *that* discussion.

1.3 What's in This Book?

A graphic organizer of the book is shown in Figure 1.3–1.

Here are the main topics covered in the chapters.

Chapter 2.

Writing course learning objectives (statements of how the students will demonstrate their mastery of the knowledge, methods, skills, and attitudes or values the instructor plans to teach) and using them to achieve *constructive alignment,* in which the course lessons, activities, assignments, and assessments of learning all point toward the same goals.

Chapter 3.

Preparing to teach a new or redesigned course for the first time. Writing a syllabus and formulating a course grading policy. Getting the course off to a good start.

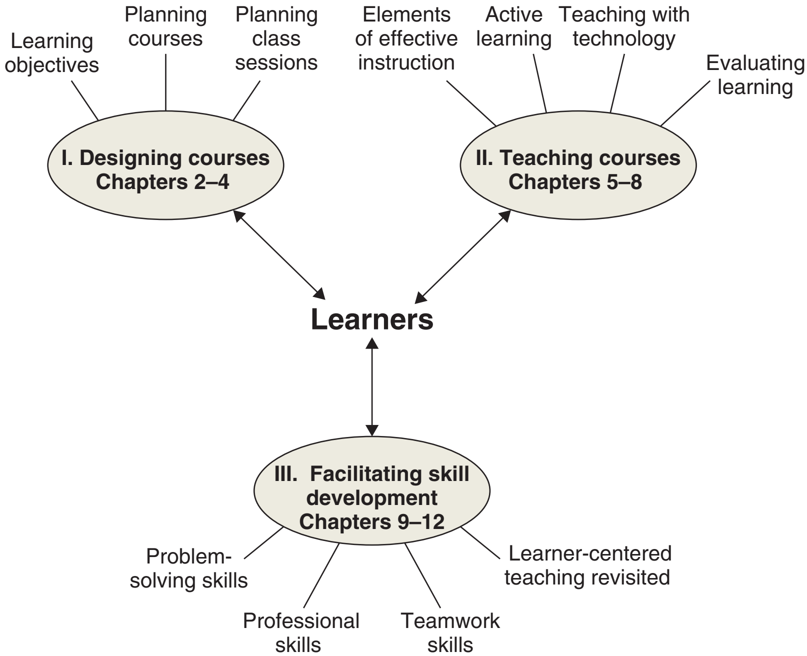

Figure 1.3–1: Elements of Learner-Centered Teaching

Chapter 4.
Planning individual class sessions.

Chapter 5.
Teaching effectively and continuing to improve.

Chapter 6.
Getting students actively engaged in class, no matter how large the class is.

Chapter 7.
Teaching effectively with technology. Blended learning (combining face-to-face and online instruction), flipped (inverted) classrooms, and online courses.

Chapter 8.
Evaluating how well students are acquiring the knowledge, skills, and conceptual understanding specified in the course learning objectives.