RICHARD M. FELDER

REBECCA BRENT

TEACHING AND LEARNING STEM

SECOND EDITION

A PRACTICAL GUIDE

JOSSEY-BASS™
A Wiley Brand

TEACHING AND LEARNING STEM

Second Edition

TEACHING AND LEARNING STEM

A PRACTICAL GUIDE

Second Edition

Richard M. Felder and Rebecca Brent

JOSSEY-BASS™
A Wiley Brand

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data Is Available:

ISBN 9781394196340 (Cloth)
ISBN 9781394196357 (ePDF)
ISBN 9781394196364 (ePub)

Cover Design: Wiley
Cover Image: © AniGraphics/Getty Images

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

CONTENTS

THE AUTHORS

Richard M. 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* (4th edition, Wiley, 2016), 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 over 300 papers on chemical 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 most of his education-related columns and articles can be found at <https://www.engr.ncsu.edu/stem-resources/>.

Rebecca Brent, EdD, is president of Education Designs, LLC, a consulting firm in Chapel Hill, North Carolina. She has more than 40 years of experience in education and specializes in STEM faculty development, precollege teacher preparation, and evaluation of educational programs at both 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 130 papers on effective teaching and faculty development, and coordinated faculty development in the National Science Foundation–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 over 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 codirected the American Society for Engineering Education National Effective Teaching Institute from 1991 to 2015.

LIST OF TABLES, FIGURES, AND EXHIBITS

Chapter 11

Chapter 12

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. AI is opening whole new careers for students, with large language models upending everything we thought we knew about how to teach. Rich and Rebecca have you covered there, with intriguing new insights that will help you look at your teaching in fresh ways. 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 allows 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 high school and college 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. In a world where the advances of AI are underpinning a revolution in the workplace, nothing could be more important than laying a good foundation for students in STEM.

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 teacher 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 recently have 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, the pedagogical framework of this book. That workshop changed the whole focus of my teaching and allowed 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
Distinguished Professor of Engineering, Oakland University,
Rochester, Michigan
Winner, McGraw Prize in Lifelong Learning
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.

PREFACE TO THE FIRST EDITION

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 N.C. 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 15 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 the students left the lectures thinking they understood everything. The result was that I got high ratings and won some awards. There was just one minor hitch. After the lectures the students struggled for hours to complete assignments that involved problems like 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. I subsequently met some pedagogical experts who helped me sharpen my understanding, one of whom became my professional colleague and the coauthor of this book—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 educational 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 nonacademic professions who wanted to change careers and become teachers, and it was then that I realized that passing along a few well-chosen techniques could go a long way toward helping people 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, communication, 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 several of the "Random Thoughts" columns that appeared in the quarterly journal *Chemical Engineering Education* between 1988 and 2017. 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 reviewed chapter drafts, shared course materials, and provided invaluable encouragement and constructive criticism. 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 Lisa Bullard, Jo-Ann Cohen, Jackie Dietz, John Falconer, Elena Felder, Gary Felder, Kenny Felder, Mary Felder, Stephanie Farrell, Cindy Furse, Jeff Joines, Milo Koretsky, Susan Lord, Nikki Monahan, Michael Moys, Mike Prince, Julie Sharp, Kimberly Tanner, John Tolle, 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 assuring us that the world desperately needed this book when we doubted ourselves, red-inking our occasionally pedantic or hyperbolic prose, and gently prodding us back into action when not much work was showing up in her inbox. 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 13 of you are reading this, we will have started to keep that resolution.

Richard M. Felder
Rebecca Brent

PREFACE TO THE SECOND EDITION

We finished writing the first edition of this book in 2015, and since then the core beliefs of teaching and learning experts about teaching and learning haven't changed much. Clear learning objectives should still guide the design of courses and instruction; actively engaged students still learn more and deeper than passive recipients of information; communication, creative and critical thinking, teamwork, and self-directed learning skills are still as important to students' career and personal development as technical skills, and so on. So, the second edition is not dramatically different from the first.

But there have been a few dramatic developments in teaching and learning since 2015 that are reflected in the second edition. Arguably the most dramatic ones have resulted from the COVID-19 pandemic that started in 2020 and its sudden plunging of most teachers at all levels into online instruction, whether or not they wanted to be there. The second edition's chapter on teaching with technology now covers and compares the strengths and weaknesses of face-to-face, synchronous and asynchronous online, and blended instruction, and strategies for making those teaching modes as effective as possible.

A more recent and even more dramatic development since 2015 was the appearance and widespread availability of ChatGPT in late 2022, followed by a rapid proliferation of other large language models. Every chapter of the second edition refers to current and potential future applications of artificial intelligence, but here in 2023 the eventual impact of AI on education is still as unpredictable as the eventual impacts of computers in the 1950s and the internet in the 1970s. Since speculation about it is most of what we've got to work with, it's much of what we'll do.

Yet another significant change in the second edition is its targeted readership. The first edition focused exclusively on higher education. The Foreword to that edition discussed the difficulties encountered by new professors in their first teaching positions, Chapter 1 was entitled "Introduction to College Teaching," and its first section was entitled "Welcome to the University, There's Your Office, Good Luck." In an early posted comment on the book, a high school mathematics teacher observed:

> *While designed for university faculty,* Teaching and Learning STEM *serves equally well for high school teachers of STEM courses, particularly those of us working with advanced level students. The chapters on active learning, effective use of technology, and developing problem solving and creative thinking skills should be studied by teachers of all subjects working with students of any age.*

Catalyzed by that comment, we broadened the scope of the second edition to explicitly include high school education, noting cases where the norms and practices of high school and college differ. (There are surprisingly few such cases that impact pedagogy—good teaching is good teaching!)

As with the first edition, we received invaluable help from family members and friends at every stage of this edition's creation. Our grateful thanks go to Kenny Felder and Barb Oakley, who read virtually every word of our draft manuscript and provided lovingly detailed factual and stylistic corrections and suggestions. Countless improvements also resulted from contributions by Cindy Atman, Lisa Bullard, Matt Cooper, and Joyce, Elena, and Gary Felder,

We were gratified by the reviews the first edition received in STEM education journals and comments we received from STEM educators. One comment from a prominent biology professor particularly stands out: "*Imagine a book that is like having a welcoming and seasoned faculty colleague just down the hall, with engaging stories and sage advice. That is this book*." More than anything else anyone has written, that comment captures what we want the book to be. We hope it reflects your experience with this edition.

Richard M. Felder
Rebecca Brent

1

INTRODUCTION TO TEACHING

1.0 Welcome, There's Your Desk, 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, physicists, physicians, and psychologists spend years earning degrees in their fields, and the physicians spend still more years in internships and residencies. It would be unthinkable to allow people to practice a skilled profession without first being well trained for it, especially if their mistakes could cause harm to others . . . unless they are college instructors or certain K–12 teachers.

The standard preparation for a college STEM (Science, Technology, Engineering, and Mathematics) faculty career is taking undergraduate and graduate courses in a STEM 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 on such things as health and retirement benefits and the importance of laboratory safety and an hour or two on how to teach. The unstated assumption is that if you have a degree in a STEM subject, you must know how to teach that subject.

The situation is somewhat better at the high school level. Most high schools require their teachers to get and maintain teaching licenses from their state governments, which means they must have degrees in education or at least receive some teacher training. However, many other schools hire STEM degree holders with no pedagogical training, especially if the schools are in regions with inadequate numbers of licensed teachers.

Again, the assumption is that if you have a degree in chemistry or mathematics you must be able to teach those subjects.

Anyone who has ever taken STEM courses in high school or college knows how bad that assumption can be. What student has never had a teacher who taught at a level ridiculously above anything the students had a chance of understanding, or flashed PowerPoint slides at a rate few normal human brains could keep up with, 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? If you teach like those teachers, 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 teaching evaluations from administrators, colleagues, or students.

Being a competent STEM teacher requires knowing many things calculus and chemistry courses and short teaching workshops don't teach, such as how to design courses and deliver them effectively; how to write assignments and exams that are both rigorous and fair; and how to deal with classroom management, advising problems, cheating, and a slew of other headaches teachers routinely encounter. Figuring out all those things on your own is not trivial.

Although there's 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 teachers take years to learn how to teach well, and others never learn. Getting a degree in education and/or getting training in teaching of course doesn't guarantee that the recipient will be a good teacher—a lot depends on the recipient's aptitude for teaching and the quality of the training program—but it considerably improves the chances of it.

Things don't have to be this way. Proven methods for teaching effectively—that is, enhancing students' motivation to learn and helping them acquire the knowledge, skills, and values they will need to succeed in high school, 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 is and always will be a challenging and time-consuming task, especially the first time you teach it. The point is that teaching well doesn't have to be harder than teaching poorly. The purpose of this book is to help you learn how to teach well.

1.1 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'll find variations of two completely different definitions:

Teach: To show or explain something.
Teach: To cause someone 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 taught the course, whether or not anyone learned it. By the second definition, if students don't learn something, the instructor didn't teach it.

Many STEM instructors subscribe to the first definition. "My job is to cover the syllabus/curriculum," 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 taking notes and 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 education as it has been practiced for centuries throughout the world, and it's entirely 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 *learner-centered teaching (LCT)*. The teacher of an LCT-based 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 but more as a coach or guide, whose task is to help the students 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 make students more responsible for their own learning than they're accustomed to being, they won't all leap to their feet and embrace you with gratitude! Weimer (2013) 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.* (p. 199)

If you haven't used learner-centered teaching yet, the resistance you may encounter from some students the first time you try it may come as a shock. You may envision your teaching evaluations plummeting and your chances for career advancement shrinking, and it can be easy for you to say, "Who needs this?" and go back to traditional lecturing.

If that occurs, fight the temptation to retreat. Several references on learner-centered teaching methods discuss student resistance: why it's there, what forms it might take, and how instructors can deal with it (Andrews et al., 2022; Felder, 2007, 2011; Felder & Brent, 1996; Seidel & Tanner, 2013; Weimer, 2013, Ch. 8). We'll explore this issue 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 if it appears it isn't likely to last very long