PREFACE

Microelectronic Circuits, sixth edition, is intended as a text for the core courses in electronic circuits taught to majors in electrical and computer engineering. It should also prove useful to engineers and other professionals wishing to update their knowledge through self-study.

As was the case with the first five editions, the objective of this book is to develop in the reader the ability to analyze and design electronic circuits, both analog and digital, discrete and integrated. While the application of integrated circuits is covered, emphasis is placed on transistor circuit design. This is done because of our belief that even if the majority of those studying this book were not to pursue a career in IC design, knowledge of what is inside the IC package would enable intelligent and innovative application of such chips. Furthermore, with the advances in VLSI technology and design methodology, IC design itself is becoming accessible to an increasing number of engineers.

Prerequisites

The prerequisite for studying the material in this book is a first course in circuit analysis. As a review, some linear circuits material is included here in the appendices: specifically, two-port network parameters in Appendix C; some useful network theorems in Appendix D; single-time-constant circuits in Appendix E; and *s*-domain analysis in Appendix F. No prior knowledge of physical electronics is assumed. All required semiconductor device physics is included, and Appendix A provides a brief description of IC fabrication. All these appendices can be found on the DVD that accompanies this book.

Emphasis on Design

It has been our philosophy that circuit design is best taught by pointing out the various trade-offs available in selecting a circuit configuration and in selecting component values for a given configuration. The emphasis on design has been increased in this edition by including more design examples, simulation examples, exercise problems, and end-of-chapter problems. Those exercises and end-of-chapter problems that are considered "design-oriented" are indicated with a D. Also, considerable material is provided on the most valuable design aid, SPICE, including Appendix B, which is available on the DVD so that it can be offered in searchable format, and in the full detail it deserves while not crowding other topics out of the text.

New to This Edition

Although the philosophy and pedagogical approach of the first five editions have been retained, several changes have been made to both organization and coverage.

1. **Four-Part Organization.** The book has been reorganized into four Parts. Part I: *Devices and Basic Circuits* (Chapters 1-6) provides a coherent and comprehensive single-semester introductory course in electronics. Similarly, Part II: *Integrated-Circuit Amplifiers* (Chapters 7-12) presents a rich package of material suitable for a second course. Part III: *Digital Integrated Circuits* (Chapters 13-15) represents a nearly self-contained coverage of digital electronics that can be studied after Chapters 5 (MOSFETs) and 6 (BJTs), or even only 5 if the emphasis is on MOS digital circuits—extremely helpful for teaching Computer Engineering students. Finally, Part IV: *Filters and Oscillators* (Chapters 16-17), deals with more specific application-oriented material that can be used to supplement a second course on analog circuits, be part of a third course, or used as reading and reference material to support student design projects. More on course design is given below.
2. **Flexible organization.** The most important feature of this edition is its flexible organization. Some manifestations of this flexibility are:
   - **MOSFETs and BJTs**. Chapter 5 (MOSFETs) and Chapter 6 (BJTs) are written to be completely independent of each other and thus can be taught in whatever order the instructor desires. Because the two chapters have identical structures, the chapter taught second can be covered much faster.
   - **Robust Digital Coverage**. The digital material has been grouped together in the new Part III, updated, and expanded. It can be covered at various points in the first or second course. All that is needed by way of background is the material on the two transistor types (Chapters 5 and 6) or even just Chapter 5 since most digital electronics today is MOS-based.
   - **Semiconductors as Needed**. The required material on semiconductor physics has been grouped together in a short chapter (Chapter 3) that can be taught, skipped, or assigned as reading material, depending on the background of the students and the instructor's teaching philosophy. This chapter serves as a primer on the basics, or as a refresher, depending on whether students have had a prior course in semiconductors.
   - **Op-amps Anywhere**. The op-amp chapter (Chapter 2) can be taught at any point in the first or second course, or skipped altogether if this material is taught in other courses.
   - **Frequency Response**. The material on amplifier frequency response has been grouped together into a single chapter (Chapter 9). The chapter is organized in a way that allows coverage of as few sections as the instructor deems necessary. Also, some of the basic material (Sections 9.1 to 9.3) can be covered earlier (after Chapters 5 or 6) as part of the first course.
   - **"Must-Cover" Topics First.** Each chapter is organized so that the essential "must-cover" topics are placed first, and the more specialized material appears last. More specialized material that can be skipped on a first reading, while the student is first learning the basics, is marked with a ⊕. Once the students understand the core concepts, they can return to these important but specialized topics.

3. **Streamlined MOSFETs and BJTs**. Chapters 5 (MOSFETs) and 6 (BJTs) have been rewritten to increase the clarity of presentation and emphasize essential topics. Also, these chapters are now shorter and can be covered faster.
4. **Cascode Configuration**. A novel and intuitively appealing approach is used to introduce the cascode configuration in Chapter 7.
5. **Comparison of MOSFETs and BJTs**. The insightful comparison of the MOSFET and the BJT has been moved to an appendix attached to Chapter 7. The appendix also includes an update of the device parameter values corresponding to various generations of fabrication process technologies. This appendix provides a good review and a reference that can be consulted at various points in a second course.
6. **Feedback**. The feedback chapter (Chapter 10) has been rewritten to increase clarity. Also, a large number of new examples, mostly MOS-based, are included.
7. **Class AB Amplifiers**. New material on MOSFET class AB amplifiers is included in Chapter 11.
8. **Low-Voltage Bipolar Design**. While the classical 741 op-amp circuit is retained, a new section on modern techniques for the design of low-voltage bipolar op amps has been added to Chapter 12.
9. **Deep-Submicron Design**. In addition to augmenting and consolidating the material on digital electronics in Part III, a new section on technology scaling (Moore's Law) and deep-submicron design issues has been added (Chapter 13).
10. **MOS Emphasis**. Throughout the book, greater emphasis is placed on MOS circuits to reflect the current dominance of the MOSFET in electronics.
11. **Bonus Reading on DVD**. Supplementary material on a wide variety of topics that were included in previous editions is made available on the DVD accompanying the book (see a listing below).
12. **Examples, Exercises, and Problems**. The number of Examples has been increased. Also, the in-chapter Exercises and end-of-chapter Problems have been updated with parameter values of current technologies so students work with a real-world perspective on technology. More Exercises and Problems, of a greater variety, have been added.
13. **Summary Tables**. As a study aid and for easy reference, many summary tables are included. See the complete List of Summary Tables after the Table of Contents.
14. **Learning Objectives**. A new section (In This Chapter You Will Learn…) has been added at the beginning of each chapter to focus attention on the major learning objectives of the chapter.
15. **SPICE**. A significant number of new simulation examples using National Instruments™ Multisim™ are added to the Cadence PSpice® simulation examples. Together with a section describing the SPICE device models, these design and simulation examples are grouped together in Appendix B. They can also be found together with other simulation files in the Lab-on-a-Disc on the DVD.
16. **Simulation**. A number of end-of-chapter Problems in each chapter are marked with the SIM icon SIM as simulation problems. Students attempting these problems will find considerable additional guidance on the DVD.
17. **Key Equations**. All equations that will be cross-referenced and used again are numbered. Particularly important equations are marked with a special icon.

As well as the structural differences described above, new coverage is included on all of the following technical topics.

- Entirely rewritten coverage of semiconductors (Chapter 3)
- MOSFET and BJT chapters extensively rewritten and restructured, with new figures and examples (Chapter 5 and 6)
- The basic gain cell (Chapter 7)
- The cascode amplifier (Chapter 7)
- CC-CE, CD-CS, and CD-CE transistor configurations (Chapter 7)
- CMRR (Chapter 8)
- The differential amplifier with active load (Chapter 8)
- Determining the output resistance R_o (Chapter 8)
- All new sections on frequency response (Chapter 9)
- Many, many new MOS examples of feedback (Chapter 10)
- CMOS class AB output stages (Chapter 11)
- Rejection ratios (CMRR and PSRR) (Chapter 12)
- Modern techniques for the design of BJT op amps (Section 12.7)
- Digital logic inverters (Chapter 13)
- The CMOS inverter (Chapter 13)
- Deep submicron design and technology scaling (Moore's Law) (Section 13.5)

The DVD and the Website

A DVD accompanies this book. It contains much useful supplementary information and material intended to enrich the student's learning experience. These include

1. Student versions of both Cadence PSpice® and National Instruments™ Multisim™.
2. The input files for all the PSpice® and Multisim™ examples in this book.
3. Step-by-step guidance to help with the simulation Examples and end-of-chapter Problems identified with a SIM icon.
4. A link to the book's website, offering PowerPoint slides of every figure in this book that students can print and carry to class to facilitate taking notes.
5. Bonus text material of specialized topics not covered in the current edition of the textbook. These include:
   - Junction Field-Effect Transistors (JFETs)
   - Gallium Arsenide (GaAs) devices and circuits
   - Transistor-Transistor Logic (TTL) circuits
   - Analog-to-Digital and Digital-to-Analog converter circuits
6. Appendices for the book:
   - Appendix A: VLSI Fabrication Technology
   - Appendix B: SPICE Device Models and Design and Simulation Examples Using PSpice® and Multisim™
   - Appendix C: Two-Port Network Parameters
   - Appendix D: Some Useful Network Theorems
   - Appendix E: Single-Time-Constant Circuits
   - Appendix F: *s*-domain Analysis: Poles, Zeroes, and Bode Plots
   - Appendix G: Bibliography

A website for the book has been set up (www.oup.com/us/sedrasmith, or www.sedrasmith.org). Its content will change frequently to reflect new developments in the field. On the site, PowerPoint-based slides of all the figures in the text are available for easy note-taking. The website also features datasheets for hundreds of useful devices to help in laboratory experiments, links to industrial and academic websites of interest, and a message center to communicate with the authors and with Oxford University Press.

Exercises and End-of-Chapter Problems

Over 475 Exercises are integrated throughout the text. The answer to each exercise is given below the exercise so students can check their understanding of the material as they read. Solving these exercises should enable the reader to gauge his or her grasp of the preceding material. In addition, more than 1450 end-of-chapter Problems, 55% of which are new or revised in this edition, are provided. The problems are keyed to the individual chapter sections and their degree of difficulty is indicated by a rating system: difficult problems are marked with an asterisk (*); more difficult problems with two asterisks (**); and very difficult (and/or time consuming) problems with three asterisks (***). We must admit, however, that this classification is by no means exact. Our rating no doubt depended to some degree on our thinking (and mood!) at the time a particular problem was created. Answers to sample problems are given in Appendix I, so students have a checkpoint to tell if they are working out the problems correctly. Complete solutions for all exercises and problems are included in the *Instructor's Solutions Manual*, which is available from the publisher to those instructors who adopt the book.

As in the previous five editions, many examples are included. The examples, and indeed most of the problems and exercises, are based on real circuits and anticipate the applications encountered in designing real-life circuits. This edition continues the use of numbered solution steps in the figures for many examples, as an attempt to recreate the dynamics of the classroom.

Course Organization

The book contains sufficient material for a sequence of two single-semester courses (each of 40-50 lecture hours). The organization of the book provides considerable flexibility for course design. In the following, we suggest various possibilities for the two courses. This is also laid out in an easy-to-follow visual form at the beginning of the Instructor's Edition of the book.

The First Course

At the core of the first course are Chapters 4 (Diodes), 5 (MOSFETs), and 6 (BJTs). Of these three, the MOSFET chapter is the one that has to be covered most thoroughly. If it is covered before the BJT, and we recommend that it should be, then the BJT chapter can be covered much faster. If time does not permit, some of the later sections in Chapter 4 can be skipped. Chapter 1 (Signals and Amplifiers) deserves some treatment in class. Although the signal concepts can be assigned as out-of-class reading, the amplifier material should be discussed. However, if frequency response is not emphasized in the first course, Section 1.6 can be skipped.

Around this core, one can build three possible curricula for the first course:

1. *Standard*: Chapters 1–6. Here, some or all of Chapter 2 (Op Amps) can be delayed. Also, the decision as to how much to cover of Chapter 3 (Semiconductors) will

depend on the students' background and the instructor's philosophy. If desired, this course can be supplemented by the material on amplifier frequency response in Sections 9.1–9.3.

2. *Digital Orientation*: Chapters 1 (without Section 1.6), 4 (without the later applications sections), all of 5, 6 (perhaps focusing only on the early sections), Section 9.2, and Chapters 13, 14, and 15. If time constraints are a concern, coverage of 6 can be shortened; Section 13.5 on Moore's Law and deep-submicron design can be skipped, and Sections 14.4 and 14.5 that depend on BJTs can be omitted. This course is ideal for Computer Engineering students.
3. *Analog Orientation*. Chapters 1, 4 (perhaps without all of the later, more application-oriented sections), 5, 6, 7 (without the advanced material in 7.6), 8, 9 (including at least 9.1–9.3, and the instructor's selection of other topics), and 10 (a selection of topics). This is a heavy course, and assumes that the students have previously covered op amps and maybe diodes, as well as device physics. This course is ideal where the first electrical engineering course is a hybrid of circuits and basic electronics, and where students have taken a semiconductor device physics course.

The Second Course

There are three possibilities for the second course:

1. *Standard*: Chapters 7–12. If time does not permit, some of the later sections in Chapter 9 can be skipped. Also, some of the more advanced topics in Chapters 11 and 12 can be skipped. If desired, some material from Chapter 16 (Filters) and Chapters 17 (Oscillators) can be included. This course ideally follows the "Standard First Course" outlined above.
2. *Analog and Digital Combination*: Chapters 7, 8, 9 (selection of topics); 10 (selection of topics), 13 (perhaps without Section 13.5 on technology scaling), 14 (omitting 14.4 and 14.5 if time is short), and 15 (selection of topics).
3. *Electrical Follow-up*: Chapters 6, 7, 8, 9, 10, and a choice of topics as time allows, selected from Chapters 11 and 12. This course is ideal for Electrical Engineering students who took a first semester with a "Digital Orientation" outlined above to accommodate Computer Engineering students.

Supplementary Material/Third Course

Chapters 16 (Filters) and 17 (Oscillators) contain material that can be used to supplement a third course on analog circuits. As well, this material is highly design-oriented and can be used to aid students who are pursuing design projects.

Chapters 13, 14, and 15 can be used as about half (15 hours of lecture) of a senior level course on digital IC design.

An Outline for the Reader

Part I, *Devices and Basic Circuits*, includes the most fundamental and essential topics for the study of electronic circuits. At the same time, it constitutes a complete package for a first course on the subject.

Chapter 1. The book starts with an introduction to the basic concepts of electronics in Chapter 1. Signals, their frequency spectra, and their analog and digital forms are presented.

Amplifiers are introduced as circuit building blocks and their various types and models are studied. This chapter also establishes some of the terminology and conventions used throughout the text.

Chapter 2. Chapter 2 deals with operational amplifiers, their terminal characteristics, simple applications, and practical limitations. We chose to discuss the op amp as a circuit building block at this early stage simply because it is easy to deal with and because the student can experiment with op-amp circuits that perform nontrivial tasks with relative ease and with a sense of accomplishment. We have found this approach to be highly motivating to the student. We should point out, however, that part or all of this chapter can be skipped and studied at a later stage (for instance, in conjunction with Chapter 8, Chapter 10, and/or Chapter 12) with no loss of continuity.

Chapter 3. Chapter 3 provides an overview of semiconductor concepts at a level sufficient for understanding the operation of diodes and transistors in later chapters. Coverage of this material is useful in particular for students who have had no prior exposure to device physics. Even those with such a background would find a review of Chapter 3 beneficial as a refresher. The instructor can choose to cover this material in class or assign it for outside reading.

Chapter 4. The first electronic device, the diode, is studied in Chapter 4. The diode terminal characteristics, the circuit models that are used to represent it, and its circuit applications are presented. Depending on the time available in the course, some of the diode applications (e.g., Section 4.6) can be skipped. Also, the brief description of special diode types (Section 4.7) can be left for the student to read.

Chapters 5 and 6. The foundation of electronic circuits is established by the study of the two transistor types in use today: the MOS transistor in Chapter 5 and the bipolar transistor in Chapter 6. These are the two most important chapters of the book. ***These two chapters have been written to be completely independent of one another and thus can be studied in either order, as desired.*** Furthermore, the two chapters have the same structure, making it easier and faster to study the second device, as well as to draw comparisons between the two device types.

Each of Chapters 5 and 6 begins with a study of the device structure and its physical operation, leading to a description of its terminal characteristics. Then, to allow the student to become very familiar with the operation of the transistor as a circuit element, a large number of examples are presented of dc circuits utilizing the device. We then ask: How can the transistor be used as an amplifier? To answer the question we consider the large-signal operation of the basic common-source (common-emitter) circuit and use it to delineate the regions over which the device can be used as a linear amplifier, from those regions where it can be used as a switch. We then pursue the small-signal operation of the transistor and develop circuit models for its representation. The various configurations in which the transistor can be used as an amplifier are then studied and contrasted. This is followed by a study of methods to bias the transistor to operate as an amplifier in discrete-circuit applications. We then put everything together by presenting complete practical discrete-circuit transistor amplifiers. The last section of each of Chapters 5 and 6 deals with second-order effects that are included for completeness, but that can be skipped if time does not permit detailed coverage.

After the study of Part I, the reader will be fully prepared to study either integrated-circuit amplifiers in Part II, or digital integrated circuits in Part III.

Part II, *Integrated-Circuit Amplifiers*, is devoted to the study of practical amplifier circuits that can be fabricated in the integrated-circuit (IC) form. Its six chapters constitute a coherent treatment of IC amplifier design and can thus serve as a second course in electronic circuits.

Chapter 7. Beginning with a brief introduction to the philosophy of IC design, Chapter 7 presents the basic circuit building blocks that are used in the design of IC amplifiers. We start with the basic gain cell comprising a common-source (common-emitter) transistor loaded with a current source, and ask: How can we increase its voltage gain? This leads naturally to the concept of cascoding and its use in the cascode amplifier and the cascode current source. We then consider the methods used for biasing IC amplifiers. The chapter concludes, as do most chapters in the book, with advanced topics (Sections 7.5 and 7.6) that can be skipped if the instructor is pressed for time.

Chapter Appendix 7.A. Chapter 7 includes an appendix that provides a comprehensive compilation and comparison of the properties of the MOSFET and the BJT. The comparison is aided by the inclusion of typical parameter values of devices fabricated with modern process technologies. This appendix can be consulted at any point from Chapter 7 on, and should serve as a concise review of the important characteristics of both transistor types.

MOS and Bipolar. Throughout Part II, both MOS and bipolar circuits are presented side-by-side. Because the MOSFET is by far the dominant device, its circuits are presented first. Bipolar circuits are discussed to the same depth but occasionally more briefly.

Chapter 8. The most important IC building block, the differential pair, is the main topic of Chapter 8. The last section of Chapter 8 is devoted to the study of multistage amplifiers.

Chapter 9. Chapter 9 presents a comprehensive treatment of the important subject of amplifier frequency response. Here, Sections 9.1, 9.2, and 9.3 contain essential material; Sections 9.4 and 9.5 provide an in-depth treatment of very useful new tools; and Sections 9.6 to 9.10 present the frequency response analysis of a variety of amplifier configurations that can be studied as and when needed. A selection of the latter sections can be made depending on the time available and the instructor's preference.

Chapter 10. The fourth of the essential topics of Part II, feedback, is the subject of Chapter 10. Both the theory of negative feedback and its application in the design of practical feedback amplifiers are presented. We also discuss the stability problem in feedback amplifiers and treat frequency compensation in some detail.

Chapter 11. In Chapter 11 we switch gears from dealing with small-signal amplifiers to those that are required to handle large signals and large amounts of power. Here we study the different amplifier classes—A, B, and AB—and their realization in bipolar and CMOS technologies. We also consider power BJTs and power MOSFETs, and study representative IC power amplifiers. Depending on the availability of time, some of the later sections (e.g., 11.8–11.10 on special applications) can be skipped in a first reading.

Chapter 12. Finally, Chapter 12 brings together all the topics of Part II in an important application; namely, the design of operational amplifier circuits. We study both CMOS and bipolar op amps. In the latter category, besides the classical and still timely 741 circuit, we present modern techniques for the design of low-voltage op amps (Section 12.7).

Part III, *Digital Integrated Circuits*, provides a brief but nonetheless comprehensive and sufficiently detailed study of digital IC design. Our treatment is almost self-contained, requiring for the most part only a thorough understanding of the MOSFET material presented in Chapter 5. Thus, Part III can be studied right after Chapter 5. The only exceptions to this are the last two sections in Chapter 14 which require knowledge of the BJT (Chapter 6). Also, knowledge of the MOSFET internal capacitances (Section 9.2.2) will be needed.

Chapter 13. Chapter 13 is the foundation of Part III. It begins with digital logic inverters (Section 13.1), and then concentrates on the bread-and-butter topics of digital IC design: the CMOS inverter (Sections 13.2 and 13.3) and CMOS logic gates (Section 13.4). The last section (13.5) deals with the implications of technology scaling (Moore's law) and discusses important issues in deep-submicron technologies. With the possible exception of Section 13.5, the material in Chapter 13 is the minimum needed to learn something meaningful about

digital circuits.

Chapter 14. Chapter 14 builds on the foundation established in Chapter 13 and presents three important types of MOS logic circuits. As well, a significant family of bipolar logic circuits, emitter-coupled logic, is studied. The chapter concludes with an interesting digital circuit technology that attempts to combine the best attributes of bipolar and CMOS: BiCMOS.

Chapter 15. Digital circuits can be broadly divided into logic and memory circuits. The latter is the subject of Chapter 15.

Part IV, *Filters and Oscillators*, is intentionally oriented toward applications and systems. The two topics illustrate powerfully and dramatically the application of both negative and positive feedback.

Chapter 16. Chapter 16 deals with the design of filters, which are important building blocks of communication and instrumentation systems. A comprehensive, design-oriented treatment of the subject is presented. The material provided should allow the reader to perform a complete filter design, starting from specification and ending with a complete circuit realization. A wealth of design tables is included.

Chapter 17. Chapter 17 deals with circuits for the generation of signals with a variety of waveforms: sinusoidal, square, and triangular. We also present circuits for the nonlinear shaping of waveforms.

Appendices. The eight appendices contain much useful background and supplementary material. We wish to draw the reader's attention in particular to the first two: Appendix A provides a concise introduction to the important topic of IC fabrication technology including IC layout. Appendix B provides SPICE device models as well as a large number of design and simulation examples in PSpice® and Multisim™. The examples are keyed to the book chapters. These Appendices and a great deal more material on these simulation examples can be found on the DVD accompanying the book.

Ancillaries

A complete set of ancillary materials is available with this text to support your course.

For the Instructor

The *Instructor's Solutions Manual* provides complete worked solutions to all the exercises in each chapter and all the end-of-chapter problems in the text.

The *Instructor's Resource CD* is bound into the *Instructor's Solutions Manual* so instructors can find all their support materials in one place. The *Resource CD* contains PowerPoint-based slides of every figure in the book and each corresponding caption. The slides can be projected in class, added to a course management system, printed as overhead transparencies, or used as handouts. The CD also contains complete solutions and instructor's support for the Lab-on-a-Disc simulation problems. (ISBN 9780195340303)

For the Student and Instructor

The *DVD* included with every new copy of the textbook contains Lab-on-a-Disc simulation activities in Multisim™ and PSpice® for many of the simulation Examples and Problems in the text. It also contains a Student Edition of Cadence PSpice® v. 16.2 Demo software, and a Student Edition of National Instruments™ Multisim™ version 10.1.1, both of which can be

run by students on their own computers so they can practice their coursework wherever they happen to study. Bonus text topics, the Appendices, and a link to the book's website featuring manufacturer datasheets and PowerPoint-based slides of all of the book's illustrations, complete the DVD.

Acknowledgments

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Adel S. Sedra
Kenneth C. (KC) Smith

Problem Solvers and Accuracy Checkers, Solutions Manual

Mandana Amiri, University of British Columbia, BC
Alok Berry, George Mason University, VA
Marc Cahay, University of Cincinnati, OH
Yun Chiu, University of Illinois–Urbana-Champaign, IL
Norman Cox, Missouri University of Science and Technology, MO
John Davis, University of Texas–Austin, TX
Michael Green, University of California–Irvine, CA
Roger King, University of Toledo, OH
Clark Kinnaird, Southern Methodist University, TX
Robert Krueger, University of Wisconsin–Milwaukee, WI
Shahriar Mirabbasi, University of British Columbia, BC
Daniel Moore, Rose-Hulman Institute of Technology, IN
Kathleen Muhonen, The Pennsylvania State University, PA
Angela Rasmussen, University of Utah, UT
Roberto Rosales, University of British Columbia, BC
John Wilson, Royal Military College, ON

Reviewers of the Sixth Edition

Elizabeth Brauer, Northern Arizona University, AZ
Martin Brooke, Duke University, NC
Yun Chiu, University of Illinois–Urbana-Champaign, IL
Norman Cox, Missouri University of Science and Technology, MO
Robert Bruce Darling, University of Washington, WA
John Davis, University of Texas–Austin, TX
Christopher DeMarco, University of Wisconsin–Madison, WI
Robert Engelken, Arkansas State University, AR
Ethan Farquhar, University of Tennessee, TN
Patrick Fay, University of Notre Dame, IN
George Giakos, University of Akron, OH
John Gilmer, Wilkes University, PA
Tayeb Giuma, University of North Florida, FL
Michael Green, University of California–Irvine, CA
Steven de Haas, California State University–Sacramento, CA
Anas Hamoui, McGill University, QC
William Harrell, Clemson University, SC
Reid Harrison, University of Utah, UT
Timothy Horiuchi, University of Maryland–College Park, MD
Mohammed Ismail, The Ohio State University, OH
Paul Israelson, Utah State University, UT
Zhenhua Jiang, University of Miami, FL
Seongsin M. Kim, University of Alabama, AL
Roger King, University of Toledo, OH
Clark Kinnaird, Southern Methodist University, TX
Tsu-Jae King Liu, University of California–Berkeley, CA
Yicheng Lu, Rutgers University, NJ
David Nairn, University of Waterloo, ON
Thomas Matthews, California State University–Sacramento, CA
Ken Noren, University of Idaho, ID
Brita Olson, California Polytechnic University–Pomona, CA
Martin Peckerar, University of Maryland–College Park, MD
Khoman Phang, University of Toronto, ON
Mahmudur Rahman, Santa Clara University, CA
John Ringo, Washington State University, WA
Norman Scheinberg, City College, NY

Kuang Sheng, Rutgers University, NJ
Andrew Szeto, San Diego State University, CA
Joel Therrien, University of Massachusetts–Lowell, MA
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