Engineering Circuit Analysis

Ninth Edition

McGraw Hill Education

William H. Hayt, Jr. • Jack E. Kemmerly
Jamie D. Phillips • Steven M. Durbin

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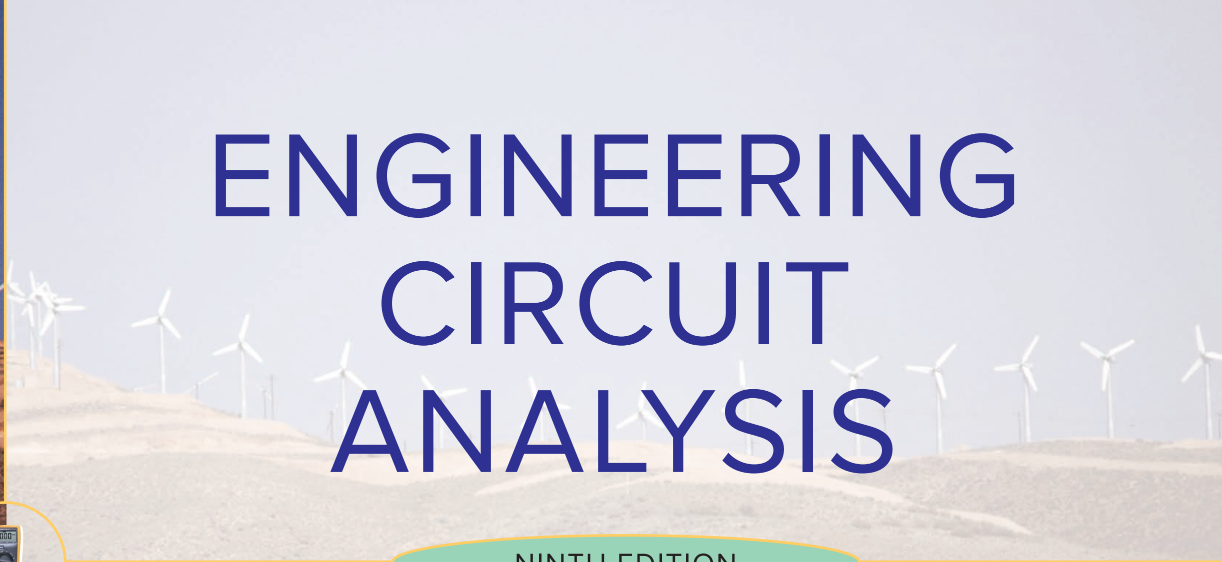

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To Brooke and Jamie.
My short circuit to happiness. —J.D. Phillips

To Sean and Kristi.
The best part of every day. —S.M. Durbin

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ABOUT THE AUTHORS

WILLIAM H. HAYT, JR., received his B.S. and M.S. at Purdue University and his Ph.D. from the University of Illinois. After spending four years in industry, Professor Hayt joined the faculty of Purdue University, where he served as Professor and Head of the School of Electrical Engineering, and as Professor Emeritus after retiring in 1986. Besides *Engineering Circuit Analysis*, Professor Hayt authored three other texts, including *Engineering Electromagnetics*, now in its eighth edition with McGraw-Hill. Professor Hayt's professional society memberships included Eta Kappa Nu, Tau Beta Pi, Sigma Xi, Sigma Delta Chi, Fellow of IEEE, ASEE, and NAEB. While at Purdue, he received numerous teaching awards, including the university's Best Teacher Award. He is also listed in Purdue's Book of Great Teachers, a permanent wall display in the Purdue Memorial Union, dedicated on April 23, 1999. The book bears the names of the inaugural group of 225 faculty members, past and present, who have devoted their lives to excellence in teaching and scholarship. They were chosen by their students and their peers as Purdue's finest educators.

JACK E. KEMMERLY received his B.S. magna cum laude from The Catholic University of America, M.S. from University of Denver, and Ph.D. from Purdue University. Professor Kemmerly first taught at Purdue University and later worked as principal engineer at the Aeronutronic Division of Ford Motor Company. He then joined California State University, Fullerton, where he served as Professor, Chairman of the Faculty of Electrical Engineering, Chairman of the Engineering Division, and Professor Emeritus. Professor Kemmerly's professional society memberships included Eta Kappa Nu, Tau Beta Pi, Sigma Xi, ASEE, and IEEE (Senior Member). His pursuits outside of academe included being an officer in the Little League and a scoutmaster in the Boy Scouts.

JAMIE PHILLIPS received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from the University of Michigan, Ann Arbor, Michigan. He was a postdoctoral researcher at Sandia National Laboratories in Albuquerque, New Mexico, and a research scientist at the Rockwell Science Center in Thousand Oaks, California, before returning to the University of Michigan as a faculty member in the EECS Department in 2002. Prof. Phillips has taught and developed numerous courses in circuits and semiconductor devices spanning from first-year undergraduate courses to advanced graduate courses. He has received several teaching honors including the University Undergraduate Teaching Award and an Arthur F. Thurnau Professorship recognizing faculty for outstanding contributions to undergraduate education. His research interests are on semiconductor optoelectronic devices with particular emphasis on infrared detectors and photovoltaics and engineering education. His professional memberships include IEEE (Senior Member), Eta Kappa Nu, Materials Research Society, Tau Beta Pi, and ASEE.

STEVEN M. DURBIN received the B.S., M.S. and Ph.D. degrees in Electrical Engineering from Purdue University, West Lafayette, Indiana. Subsequently, he was with the Department of Electrical Engineering at Florida State University and Florida A&M University before joining the University of Canterbury, New Zealand, in 2000. In 2010, he joined the University at Buffalo, The State University of New York, where he held a joint tenured appointment between the Departments of Electrical Engineering. Since 2013, he has been with the Department of Electrical and Computer Engineering at Western Michigan University. His teaching interests include circuits, electronics, electromagnetics, solid-state electronics and nanotechnology. His research interests are primarily concerned with the development of new semiconductor materials—in particular those based on oxide and nitride compounds—as well as novel optoelectronic device structures. He is a founding principal investigator of the MacDiarmid Institute for Advanced Materials and Nanotechnology, a New Zealand National Centre of Research Excellence, and coauthor of over 100 technical publications. He is a senior member of the IEEE, and a member of Eta Kappa Nu, the Materials Research Society, the AVS (formerly the American Vacuum Society), the American Physical Society, and the Royal Society of New Zealand.

BRIEF CONTENTS

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CONTENTS

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The target audience colors everything about a book, being a major factor in decisions big and small, particularly both the pace and the overall writing style. Consequently it is important to note that the authors have made the conscious decision to write this book to the **student**, and not to the instructor. Our underlying philosophy is that reading the book should be enjoyable, despite the level of technical detail that it must incorporate. When we look back to the very first edition of *Engineering Circuit Analysis*, it's clear that it was developed specifically to be more of a conversation than a dry, dull discourse on a prescribed set of fundamental topics. To keep it conversational, we've had to work hard at updating the book so that it continues to speak to the increasingly diverse group of students using it all over the world.

Although in many engineering programs the introductory circuits course is preceded or accompanied by an introductory physics course in which electricity and magnetism are introduced (typically from a fields perspective), this is not required to use this book. After finishing the course, many students find themselves truly amazed that such a broad set of analytical tools have been derived from **only three simple scientific laws**—Ohm's law and Kirchhoff's voltage and current laws. The first six chapters assume only a familiarity with algebra and simultaneous equations; subsequent chapters assume a first course in calculus (derivatives and integrals) is being taken in tandem. Beyond that, we have tried to incorporate sufficient details to allow the book to be read on its own.

So, what key features have been designed into this book with the student in mind? First, individual chapters are organized into relatively short subsections, each having a single primary topic. The language has been updated to remain informal and to flow smoothly. Color is used to highlight important information as opposed to merely improve the aesthetics of the page layout, and white space is provided for jotting down short notes and questions. New terms are defined as they are introduced, and examples are placed strategically to demonstrate not only basic concepts, but problem-solving approaches as well. Practice problems relevant to the examples are placed in proximity so that students can try out the techniques for themselves before attempting the end-of-chapter exercises. The exercises represent a broad range of difficulties, generally ordered from simpler to more complex, and grouped according to the relevant section of each chapter. Answers to selected odd-numbered, end-of-chapter exercises are posted on the book's website at www.mhhe.com/haytdurbin9e.

Engineering is an intensive subject to study, and students often find themselves faced with deadlines and serious workloads. This does not mean that textbooks have to be dry and pompous, however, or that coursework should never contain any element of fun. In fact, successfully solving a problem often *is* fun, and learning how to do that can be fun as well. Determining how to best accomplish this within the context of a textbook is an ongoing process.

The authors have always relied on the often very candid feedback received from our own students at Purdue University; the California State University, Fullerton; Fort Lewis College in Durango; the joint engineering program at Florida A&M University and Florida State University; the University of Canterbury (New Zealand); and the University at Buffalo, Western Michigan University, and the University of Michigan. We also rely on comments, corrections, and suggestions from instructors and students worldwide, and for this edition, consideration has been given to a new source of comments, namely, semianonymous postings on various websites.

The first edition of *Engineering Circuit Analysis* was written by Bill Hayt and Jack Kemmerly, two engineering professors who very much enjoyed teaching, interacting with their students, and training generations of future engineers. It was well received due to its compact structure, "to the point" informal writing style, and logical organization. There is no timidity when it comes to presenting the theory underlying a specific topic, or pulling punches when developing mathematical expressions. Everything, however, was carefully designed to assist students in their learning, present things in a straightforward fashion, and leave theory for theory's sake to other books. They clearly put a great deal of thought into writing the book, and their enthusiasm for the subject comes across to the reader.

KEY FEATURES OF THE NINTH EDITION

We have taken great care to retain key features from the eighth edition which were clearly working well. These include the general layout and sequence of chapters, the basic style of both the text and line drawings, the use of four-color printing where appropriate, numerous worked examples and related practice problems, and grouping of end-of-chapter exercises according to section. Transformers continue to merit their own chapter, and complex frequency is briefly introduced through a student-friendly extension of the phasor technique, instead of indirectly by merely stating the Laplace transform integral. We also have retained the use of icons, an idea first introduced in the sixth edition:


Provides a heads-up to common mistakes;


Indicates a point that's worth noting;

Denotes a design problem to which there is no unique answer;


Indicates a problem which requires computer-aided analysis.


Indicates an Example that reinforces the flow chart illustrating a typical problem-solving methodology that is presented in Chapter 1.

Circuit analysis is a robust method for training engineering students to think analytically, step-by-step, and returning to check their answers. A flow chart illustrating a typical problem-solving methodology is presented in

Chapter 1; these steps are explicitly included in one example in each of the subsequent chapters to reinforce the concept.

The introduction of engineering-oriented analysis and design software in the book has been done with the mind-set that it should assist, not replace, the learning process. Consequently, the computer icon denotes problems that are typically phrased such that the software is used to *verify* answers, and not simply provide them. Both MATLAB® and LTspice® are used in this context.

SPECIFIC CHANGES FOR THE NINTH EDITION INCLUDE:

- Hundreds of new and revised end-of-chapter exercises
- Dedicated coverage of the concept of energy, and calculations related to circuit power consumption and energy storage in batteries
- Expanded coverage of positive feedback op amp circuits including comparators and Schmitt triggers
- Updated transient analysis coverage, including an intuitive explanation of energy transfer in *RLC* circuits
- Consolidation of the Laplace transform material and **s**-domain circuit analysis into a single chapter
- Revised coverage of frequency response to follow a more natural progression beginning with singular poles/zeros and then progressing to resonant behavior
- New figures and photos
- Updated screen captures and text descriptions of computer-aided analysis software, and transition to use of LTspice as freeware software that is available natively on both Windows and Mac OS platforms
- New worked examples and practice problems
- Updates to the Practical Application feature, introduced to help students connect material in each chapter to broader concepts in engineering. Topics include distortion in amplifiers, circuits to measure an electrocardiogram, automated external defibrillators, practical aspects of grounding, resistivity, and the memristor, sometimes called "the missing element"
- Streamlining of text, especially in the worked examples, to get to the point faster
- Answers to selected odd-numbered end-of-chapter exercises posted on the book's website at www.mhhe.com/haytdurbin9e

Steve Durbin joined the book as a co-author in 1999, and sadly never had the opportunity to speak to either Bill or Jack about the revision process. He counts himself lucky to have taken a circuits course from Bill Hayt while he was a student at Purdue.

For the ninth edition, it is a distinct pleasure to welcome a new co-author, Jamie Phillips, whose energy and enthusiasm made the entire revision process a great experience. Both Steve and Jamie are grateful for the constant support of Raghu Srinivasan, the Global Publisher responsible

for kicking off the project, Thomas Scaife, Senior Portfolio Manager, Tina Bower, Product Developer, and Jane Mohr, Content Project Manager, who helped track down endless details as we developed the revision on a purely electronic platform for the first time. Steve would also like to thank the following people for providing technical suggestions and/or photographs: Prof. Damon Miller of Western Michigan University, Prof. Masakazu Kobayashi of Waseda University, Dr. Wade Enright, Prof. Pat Bodger, Prof. Rick Millane, and Mr. Gary Turner of the University of Canterbury, Prof. Richard Blaikie of the University of Otago, and Profs. Reginald Perry and Jim Zheng of Florida A&M University and the Florida State University. Jamie would like to thank Prof. David Blaauw and the Michigan Integrated Circuits Laboratory at the University of Michigan for photographs of their microprocessor circuits.

Finally, Steve would like to briefly thank several other people who have contributed both directly and indirectly to the ninth edition: First and foremost, my wife, Kristi, and our son, Sean, for their patience, understanding, support, welcome distractions, and helpful advice. Throughout the day, it has always been a pleasure to talk to friends and colleagues about what should be taught, how it should be taught, and how to measure learning. In particular, Martin Allen, Richard Blaikie, Steve Carr, Peter Cottrell, Wade Enright, Jeff Gray, Mike Hayes, Bill Kennedy, Susan Lord, Philippa Martin, Chris McConville, Damon Miller, Reginald Perry, Joan Redwing, Roger Reeves, Dick Schwartz, Leonard Tung, Jim Zheng, and many others have provided me with many useful insights, as did my father, Jesse Durbin, an electrical engineering graduate of the Indiana Institute of Technology.

Similarly, Jamie would like to thank a number of people for their direct or indirect help with the ninth edition: Firstly, I would like thank my wife, Jamie, and our daughter, Brooke, for their unwavering support and understanding over the course of this project. I would also like to thank the many students at the University of Michigan that I have had the pleasure of sharing the classroom with over the years, who have both shaped my understanding of circuit analysis and served as my inspiration for this endeavor. I am grateful to my colleagues at the University of Michigan for countless discussions on teaching circuits and pedagogical approaches, and in particular Cynthia Finelli, Alexander Ganago, Leo McAfee, Fred Terry, and Fawwaz Ulaby.

Steven M. Durbin, Kalamazoo, Michigan
Jamie D. Phillips, Ann Arbor, Michigan

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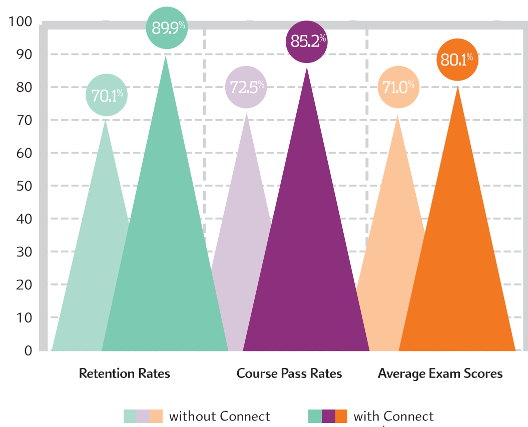

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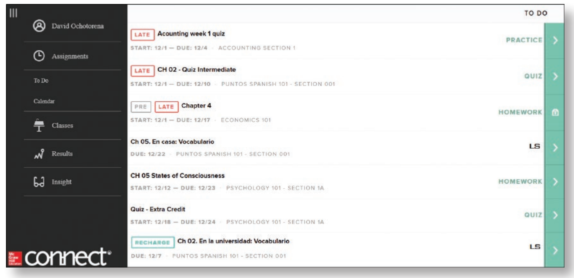

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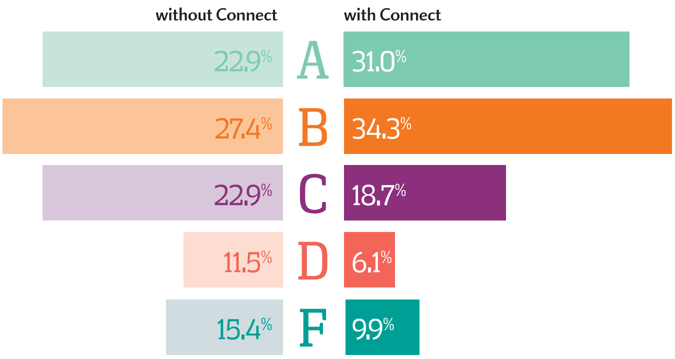

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CHAPTER 1

Introduction

KEY CONCEPTS

Linear versus Nonlinear Circuits

Four Main Categories of Circuit Analysis:

- DC
- Transient
- Sinusoidal
- Frequency Domain

Circuit Analysis Beyond Circuits

Analysis and Design

Use of Engineering Software

A Problem-Solving Strategy

PREAMBLE

Although there are clear specialties within the field of engineering, all engineers share a considerable amount of common ground, particularly when it comes to problem solving. In fact, many practicing engineers find it is possible to work in a large variety of settings and even outside their traditional specialty, as their skill set is often transferable to other environments. Today's engineering graduates find themselves employed in a broad range of jobs, from design of individual components and systems, to leadership in solving socioeconomic problems such as air and water pollution, urban planning, communication, medical treatments, mass transportation, power generation and distribution, and efficient use and conservation of natural resources.

Circuit analysis has long been a traditional introduction to the **art of problem solving** from an engineering perspective, even for those whose interests lie outside electrical engineering. There are many reasons for this, but one of the best is that in today's world it's extremely unlikely for any engineer to encounter a system that does not in some way include electrical circuitry. As circuits become smaller and require less power, and power sources become smaller and cheaper, embedded circuits are seemingly everywhere. Since most engineering situations require a team effort at some stage, having a working knowledge of circuit analysis therefore helps to provide everyone on a project with the background needed for effective communication.

Consequently, this book is not just about "circuit analysis" from an engineering perspective, but it is also about developing

Not all electrical engineers routinely make use of circuit analysis, but they often bring to bear analytical and problem-solving skills learned early on in their careers. A circuit analysis course is one of the first exposures to such concepts.
(Solar Mirrors: ©Darren Baker/Shutterstock; Skyline: ©Eugene Lu/Shutterstock; Oil Rig: ©Photodisc/Getty Images RF; Dish: ©Jonathan Larsen/iStock/Getty Images)

basic problem-solving skills as they apply to situations an engineer is likely to encounter. Along the way, we also find that we're developing an intuitive understanding at a general level, and often we can understand a complex system by its analogy to an electrical circuit. Before launching into all this, however, we should begin with a quick preview of the topics found in the remainder of the book, pausing briefly to ponder the difference between analysis and design, and the evolving role computer tools play in modern engineering.

Flat panel displays include many nonlinear circuits. Many of them, however, can be understood and analyzed with the assistance of linear models.
(©Scanrail1/Shutterstock)

1.1 OVERVIEW OF TEXT

The fundamental subject of this text is ***linear circuit analysis***, which sometimes prompts a few readers to ask,

> "Is there ever any *nonlinear* circuit analysis?"

Sure! We encounter nonlinear circuits every day: they capture and decode signals for our TVs and radios, perform calculations hundreds of millions (even billions) of times a second inside microprocessors, convert speech into electrical signals for transmission over fiber-optic cables as well as cellular networks, and execute many other functions outside our field of view. In designing, testing, and implementing such nonlinear circuits, detailed analysis is unavoidable.

"Then why study *linear* circuit analysis?"

you might ask. An excellent question. The simple fact of the matter is that no physical system (including electrical circuits) is ever perfectly linear. Fortunately for us, however, a great many systems behave in a reasonably linear fashion over a limited range—allowing us to model them as linear systems if we keep the range limitations in mind.

For example, consider the common function

$$f(x) = e^x$$

A linear approximation to this function is

$$f(x) \approx 1 + x$$

Let's test this out. Table 1.1 shows both the exact value and the approximate value of $f(x)$ for a range of x. Interestingly, the linear approximation is exceptionally accurate up to about $x = 0.1$, when the relative error is still less than 1%. Although many engineers are rather quick on a calculator, it's hard to argue that any approach is faster than just adding 1.

TABLE **1.1** Comparison of a Linear Model for e^x to Exact Value

x	$f(x)$*	$1 + x$	Relative Error**
0.0001	1.0001	1.0001	0.0000005%
0.001	1.0010	1.001	0.00005%
0.01	1.0101	1.01	0.005%
0.1	1.1052	1.1	0.5%
1.0	2.7183	2.0	26%

*Quoted to four significant figures.

**Relative error $\triangleq \left| 100 \times \frac{e^x - (1 + x)}{e^x} \right|$

Linear problems are inherently more easily solved than their nonlinear counterparts. For this reason, we often seek reasonably accurate linear approximations (or *models*) to physical situations. Furthermore, the linear models are more easily manipulated and understood—making the design process more straightforward.

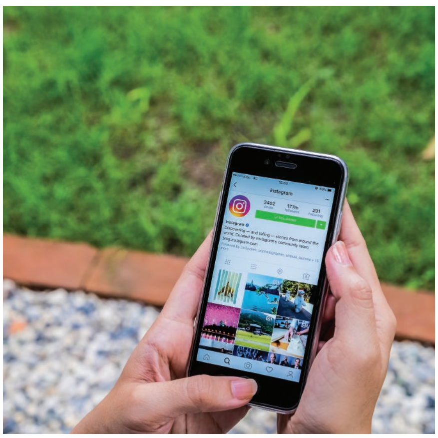
The circuits we will encounter in subsequent chapters all represent linear approximations to physical electric circuits. Where appropriate, brief discussions of potential inaccuracies or limitations to these models are provided, but generally speaking we find them to be suitably accurate for most applications. When greater accuracy is required in practice, nonlinear models are employed, but with a considerable increase in solution complexity. A detailed discussion of what constitutes a *linear electric circuit* can be found in Chap. 2.

Linear circuit analysis can be separated into four broad categories: (1) *dc analysis,* where the energy sources do not change with time; (2) *transient analysis,* where things often change quickly; (3) *sinusoidal analysis,* which applies to both ac power and signals; and (4) *frequency response,* which is the most general of the four categories, but typically assumes something is changing with time. We begin our journey with the topic of resistive circuits, which may include simple examples such as a flashlight or a toaster. This provides us with a perfect opportunity to learn a number of very powerful engineering circuit analysis techniques, such as *nodal analysis, mesh analysis, superposition, source transformation, Thévenin's theorem, Norton's theorem,* and several methods for simplifying networks of components connected in series or parallel. The single most redeeming feature of resistive circuits is that the time dependence of any quantity of interest does not affect our analysis procedure. In other words, if asked for an electrical quantity of a resistive circuit at several specific instants in time, we do not need to analyze the circuit more than once. As a result, we will spend most of our effort early on considering only dc circuits—those circuits whose electrical parameters do not vary with time.

Modern trains are powered by electric motors. Their electrical systems are best analyzed using ac or phasor analysis techniques.
(©Dr. Masakazu Kobayashi)

Although dc circuits such as flashlights or automotive rear window defoggers are undeniably important in everyday life, things are often much more interesting when something happens suddenly. In circuit analysis parlance, we refer to *transient analysis* as the suite of techniques used to study circuits that are suddenly energized or de-energized. To make such circuits interesting, we need to add elements that respond to the rate of change of electrical quantities, leading to circuit equations that include derivatives and integrals. Fortunately, we can obtain such equations using the simple techniques learned in the first part of our study.

Still, not all time-varying circuits are turned on and off suddenly. Air conditioners, fans, and fluorescent lights are only a few of the many examples we may see daily. In such situations, a calculus-based approach for every analysis can become tedious and time-consuming. Fortunately, there is a better alternative for situations where equipment has been allowed to run long enough for transient effects to die out, and this is commonly referred to as ac or sinusoidal analysis, or sometimes *phasor analysis*.



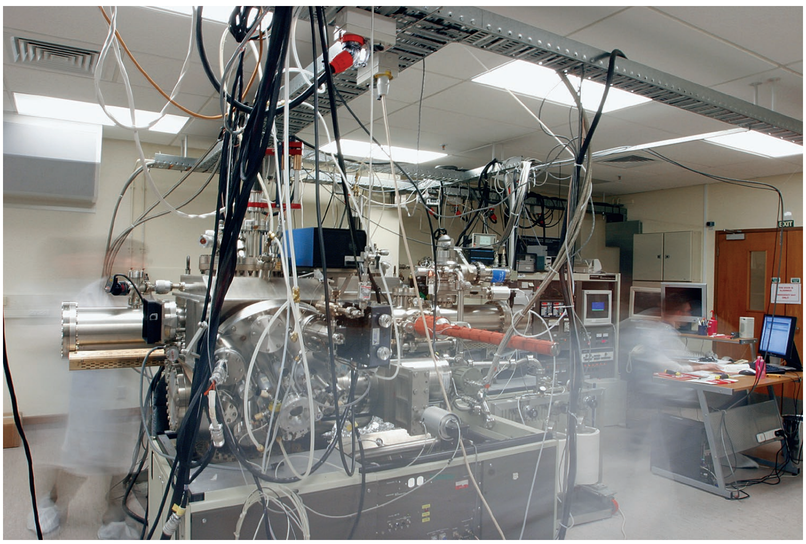
Frequency-dependent circuits lie at the heart of many electronic devices, and they can be a great deal of fun to design.
(©Jirapong Manustrong/Shutterstock)

The final leg of our journey deals with a subject known as *frequency response*. Working directly with the differential equations obtained in time-domain analysis helps us develop an intuitive understanding of the operation of circuits containing energy storage elements (e.g., capacitors and inductors). As we shall see, however, circuits with even a relatively small number of components can be somewhat onerous to analyze, and much more straightforward methods have been developed. These methods, which include Laplace and Fourier analysis, allow us to transform differential equations into algebraic equations. Such methods also enable us to design circuits to respond in specific ways to particular frequencies. We make use of frequency-dependent circuits every day when we use a mobile phone, select our favorite radio station, or connect to the Internet.

1.2 RELATIONSHIP OF CIRCUIT ANALYSIS TO ENGINEERING

It is worth noting that there are several layers to the concepts under study in this text. Beyond the nuts and bolts of circuit analysis techniques lies the opportunity to develop a methodical approach to problem solving, the ability to determine the goal or goals of a particular problem, skill at collecting the information needed to effect a solution, and, perhaps equally importantly, opportunities for practice at verifying solution accuracy.

Students familiar with the study of other engineering topics such as fluid flow, automotive suspension systems, bridge design, supply chain management, or robotics will recognize the general form of many of the equations we develop to describe the behavior of various circuits. We simply need to learn how to "translate" the relevant variables (for example, replacing *voltage* with *force, charge* with *distance, resistance* with *friction coefficient,* etc.) to find that we already know how to work a new type of problem. Very often, if we have previous experience in solving a similar or related problem, our intuition can guide us through the solution of a totally new problem.



A molecular beam epitaxy crystal growth facility. The equations governing its operation closely resemble those used to describe simple linear circuits.
(©Steve Durbin)

An example of a robotic manipulator. The feedback control system can be modeled using linear circuit elements to determine situations in which the operation may become unstable.
(Source: NASA Marshall Space Flight Center)

What we are about to learn regarding linear circuit analysis forms the basis for many subsequent electrical engineering courses. The study of electronics relies on the analysis of circuits with devices known as diodes and transistors, which are used to construct power supplies, amplifiers, and digital circuits. The skills which we will develop are typically applied in a rapid, methodical fashion by electronics engineers, who sometimes can analyze a complicated circuit without even reaching for a pencil. The time-domain and frequency-domain chapters of this text lead directly into discussions of signal processing, power transmission, control theory, and communications. We find that frequency-domain analysis in particular is an extremely powerful technique, easily applied to any physical system subjected to time-varying excitation, and particularly helpful in the design of filters.

1.3 ANALYSIS AND DESIGN

Engineers take a fundamental understanding of scientific principles, combine this with practical knowledge often expressed in mathematical terms, and (frequently with considerable creativity) arrive at a solution to a given problem. ***Analysis*** is the process through which we determine the scope of a problem, obtain the information required to understand it, and compute the parameters of interest. ***Design*** is the process by which we synthesize something new as part of the solution to a problem. Generally speaking, there is an expectation that a problem requiring design will have no unique solution, whereas the analysis phase typically will. Thus, the last step in designing is always analyzing the result to see if it meets specifications.

This text is focused on developing our ability to analyze and solve problems because it is the starting point in every engineering situation. The philosophy of this book is that we need clear explanations, well-placed examples, and plenty of practice to develop such an ability. Therefore, elements of design are integrated into end-of-chapter problems and later chapters so as to be enjoyable rather than distracting.

Two proposed designs for a next-generation space shuttle. Although both contain similar elements, each is unique.
(Source: NASA Dryden Flight Research Center)

1.4 COMPUTER-AIDED ANALYSIS

Solving the types of equations that result from circuit analysis can often become notably cumbersome for even moderately complex circuits. This of course introduces an increased probability that errors will be made, in addition to considerable time in performing the calculations. The desire to find a tool to help with this process actually predates electronic computers, with purely mechanical computers such as the Analytical Engine designed by Charles Babbage in the 1880s proposed as possible solutions. Perhaps the earliest successful electronic computer designed for solution of differential equations was the 1940s-era ENIAC, whose vacuum tubes filled a large room. With the advent of low-cost desktop computers, however, computer-aided circuit analysis has developed into an invaluable everyday tool which has become an integral part of not only analysis but design as well. All of today's computer chips are first designed and analyzed using computer simulations based on a set of known physical rules, which are

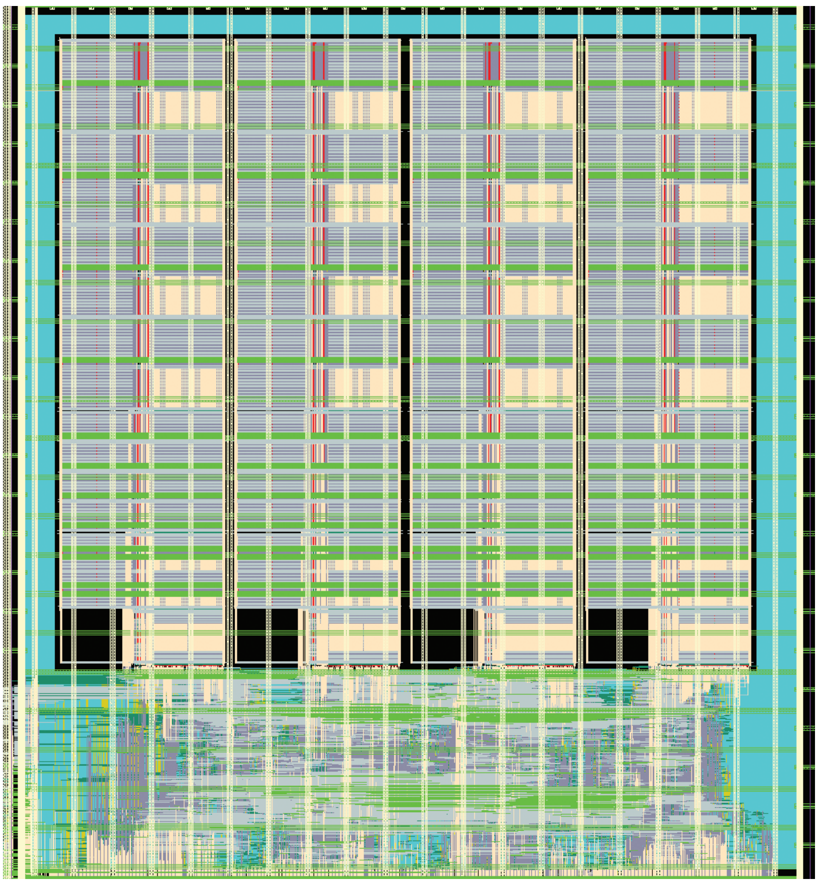
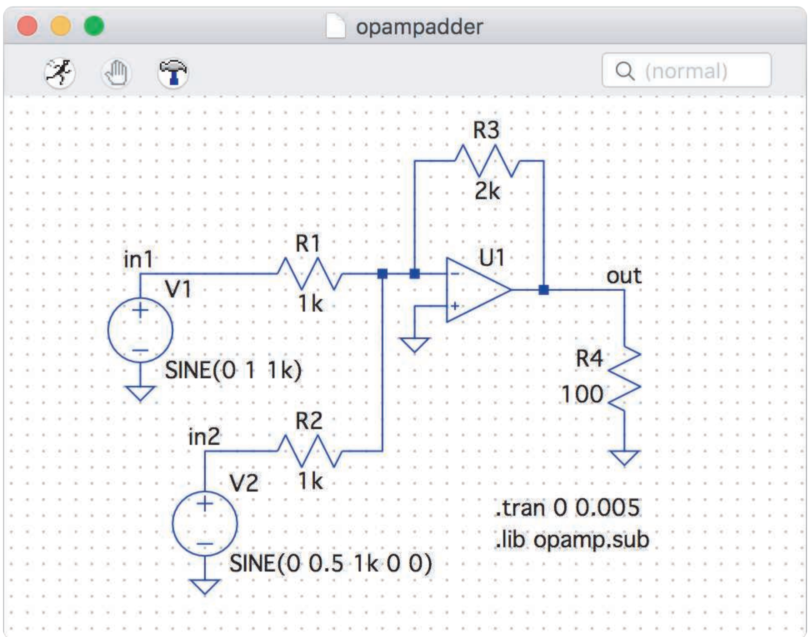


Image of computer-aided design of a Deep Learning Neural Network processor, containing approximately 20 million transistors.
(Source: Jingcheng Wang, Suyoung Bang, David Blaauw and Dennis Sylvester, Michigan Integrated Circuits Laboratory at the University of Michigan)

typically combined with empirical data to account for "real world" performance characteristics. Once the simulations show desired results, the design is then used to provide the information needed to fabricate the real circuit or system. Without computer-aided analysis and design, this process would be nearly impossible, as today's chips contain millions of devices in a single circuit!

One of the most powerful aspects of computer-aided design is the relatively recent integration of multiple programs in a fashion transparent to the user. This allows the circuit to be drawn schematically on the screen, reduced automatically to the format required by an analysis program (such as SPICE, introduced in Chap. 4), and the resulting output smoothly transferred to a third program capable of plotting various electrical quantities of interest that describe the operation of the circuit. Once the engineer is satisfied with the simulated performance of the design, the same software can generate the printed circuit board layout using geometrical parameters in the components library. This level of integration is continually increasing, to the point where soon an engineer will be able to draw a schematic, click a few buttons, and walk to the other side of the table to pick up a manufactured version of the circuit, ready to test!

The reader should be wary, however, of one thing. Circuit analysis software, although fun to use, is by no means a replacement for good old-fashioned paper-and-pencil analysis. We need to have a solid understanding of how circuits work in order to develop an ability to design them. Simply going through the motions of running a particular software package is a little like playing the lottery: with user-generated entry errors, hidden default parameters in the myriad of menu choices, and the occasional shortcoming of human-written code, there is no substitute for having at least an



An amplifier circuit drawn using a commercial schematic capture software package.

approximate idea of the expected behavior of a circuit. Then, if the simulation result does not agree with expectations, we can find the error early, rather than after it's too late.

Still, computer-aided analysis is a powerful tool. It allows us to vary parameter values and evaluate the change in circuit performance, and to consider several variations to a design in a straightforward manner. The result is a reduction of repetitive tasks, and more time to concentrate on engineering details.

1.5 SUCCESSFUL PROBLEM-SOLVING STRATEGIES

As the reader might have picked up, this book is just as much about problem solving as it is about circuit analysis. During your time as an engineering student, the expectation is that you are learning how to solve problems—just at this moment, those skills are not yet fully developed. As you proceed through your course of study, you will pick up techniques that work for you, and likely continue to do so as a practicing engineer.

By far the most common difficulty encountered by engineering students is *not knowing how to start* a problem. This improves with experience, but early on that's of no help. The best advice we can give is to adopt a methodical approach, beginning with reading the problem statement slowly and carefully (and more than once, if needed). Since experience usually gives us some type of insight into how to deal with a specific problem, worked examples appear throughout the book. Rather than just read them, however, it might be helpful to work through them with a pencil and a piece of paper.

Once we've read through the problem, and feel we might have some useful experience, the next step is to identify the goal of the problem—perhaps to calculate a voltage or a power, or to select a component value. Knowing where we're going is a big help. The next step is to collect as much information as we can and to organize it somehow.

At this point *we're still not ready to reach for the calculator.* It's best first to devise a plan, perhaps based on experience, perhaps based simply on our intuition. Sometimes plans work, and sometimes they don't. Starting with our initial plan, it's time to construct an initial set of equations. If they appear complete, we can solve them. If not, we need to either locate more information, modify our plan, or both.

Once we have what appears to be a working solution, we should not stop, even if exhausted and ready for a break. **No engineering problem is solved unless the solution is tested somehow.** We might do this by performing a computer simulation, or solving the problem a different way, or perhaps even just estimating what answer might be reasonable.

Since not everyone likes to read to learn, these steps are summarized in the flowchart that follows. This is just one problem-solving strategy, and the reader of course should feel free to modify it as necessary. The real key, however, is to try and learn in a relaxed, low-stress environment free of distractions. Experience is the best teacher, and learning from our own mistakes will always be part of the process of becoming a skilled engineer.