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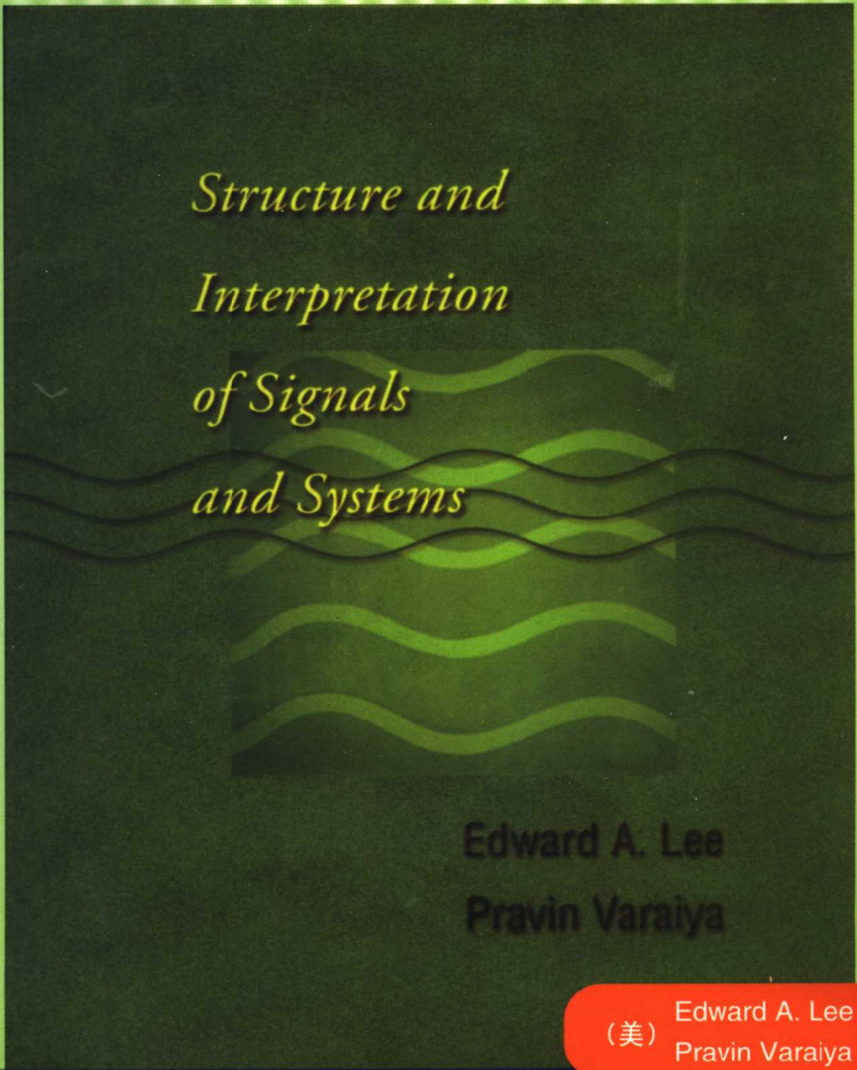

Structure and Interpretation of Signals and Systems

Edward A. Lee
Pravin Varaiya

（美）Edward A. Lee
Pravin Varaiya 著

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Structure and Interpretation of Signals and Systems

“这部著作的确展现了信号与系统在当前研究和应用范围内的核心地位。”

—— Ravi Mazumdar，普度大学

“Lee和Varaiya在富有建设性的重大课程改革中迈出了大胆的一步。他们采用了革命性的方法，而不是逐步改动，这也正是我们所需要的。”

—— Theodore Djaferis，马萨诸塞大学

“这部著作是相关主题中最好的，它在内容和表述风格上都是革命性的。”

—— Ratnesh Kumar，肯塔基大学

本书结合加州大学伯克利分校多年成功授课的经验而编写，对信号与系统进行了深刻与清晰的剖析，力求反映当今数字化世界的成果。所用实例包含声音和图像处理，取代以前的枯燥电路，从而激发读者的兴趣去了解应用背后的理论知识。

本书的配套Web站点（www.aw.com/lee_varaiya）包括扩充的实验材料，可帮助读者跨越理论与实践之间的障碍。另外，还提供了更多内容，包括声音和图像交互式操作的Java小程序，帮助读者更加直观地理解书中内容。

本书适合作为电子工程、计算机工程、计算机科学等专业的教材。

作者简介

Edward A. Lee1986年于加州大学伯克利分校获得博士学位，现为该校电子工程与计算机科学系教授。他因在工程教育领域的成就和扩展性的研究而闻名。其主要研究方向为设计、建模、嵌入式仿真和实时计算系统等。他曾获得多项殊荣，其中包括工程教育界的Frederick Emmons Terman奖。

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TO *RHONDA* AND *HELEN*,
AND TO *RUTH* AS ALWAYS

Preface

This textbook is about signals and systems, a discipline rooted in the intellectual tradition of electrical engineering (EE). This tradition, however, has evolved in unexpected ways. EE has lost its tight coupling with the "electrical." Electricity provides the impetus, the potential, but not the body of the subject. How else could microelectromechanical systems (MEMS) become so important in EE? Is this not mechanical engineering? Or signal processing? Is this not mathematics? Or digital networking? Is this not computer science? How is it that control system techniques are profitably applied to aeronautical systems, structural mechanics, electrical systems, and options pricing?

This book approaches signals and systems from a computational point of view. It is intended for students interested in the modern, highly digital problems of electrical engineering, computer science, and computer engineering. In particular, the approach is applicable to problems in computer networking, wireless communication systems, embedded control, audio and video signal processing, and, of course, circuits.

A more traditional introduction to signals and systems would be biased toward the latter application, circuits. It would focus almost exclusively on linear time-invariant systems, and would develop continuous-time models first, with discrete-time models then treated as an advanced topic. The discipline, after all, grew out of the context of circuit analysis. But it has changed. Even pure EE graduates are more likely to write software than to push electrons, and yet we still recognize them as electrical engineers.

The approach in this book benefits students by showing from the start that the methods of signals and systems are applicable to software systems, and most interestingly, to systems that mix computers with physical devices such as circuits, mechanical control systems, and physical media. Such systems have become pervasive, and profoundly affect our daily lives.

The shift away from circuits implies some changes in the way the methodology of signals and systems is presented. While it is still true that a voltage that varies over time is a signal, so is a packet sequence on a network. This text defines *signals* to cover both. While it is still true that an RLC circuit is a system, so is a computer program for decoding Internet audio. This text defines *systems* to cover both. While for some systems the state is still captured adequately by variables in a differential equation, for many it is now the values in registers and memory of a computer. This text defines *state* to cover both.

The fundamental limits also change. Although we still face thermal noise and the speed of light, we are likely to encounter other limits—such as complexity, computability, chaos, and, most commonly, limits imposed by other human constructions—before we get to these. A voiceband data modem, for example, uses the telephone network, which was designed to carry voice, and offers as immutable limits such nonphysical constraints as its 3 kHz bandwidth. This has no intrinsic origin in the physics of the network; it is put there by engineers. Similarly, computer-based audio systems face latency and jitter imposed by the operating system. This text focuses on composition of systems so that the limits imposed by one system on another can be understood.

The mathematical basis for the discipline also changes. Although we still use calculus and differential equations, we frequently need discrete math, set theory, and mathematical logic. Whereas the mathematics of calculus and differential equations evolved to describe the physical world, the world we face as system designers often has nonphysical properties that are not such a good match for this mathematics. This text bases the entire study on a highly adaptable formalism rooted in elementary set theory.

Despite these fundamental changes in the medium with which we operate, the methodology of signals and systems remains robust and powerful. It is the methodology, not the medium, that defines the field.

The book is based on a course at Berkeley taught over the past four years to more than 2,000 students in electrical engineering and computer sciences. That experience is reflected in certain distinguished features of this book. First, no background in electrical engineering or computer science is assumed. Readers should have some exposure to calculus, elementary set theory, series, first-order linear differential equations, trigonometry, and elementary complex numbers. The appendices review set theory and complex numbers, so this background is less essential.

Approach

This book is about mathematical modeling and analysis of signals and systems, applications of these methods, and the connection between mathematical models and computational realizations. We develop three themes. The first theme is the use of sets and functions as a universal language to describe diverse signals and systems. Signals—voice, images, bit sequences—are represented as functions with an appropriate domain and range. Systems are represented as functions whose domain and range are themselves sets of signals. Thus, for example, a modem is represented as a function that maps bit sequences into voice-like signals.

The second theme is that complex systems are constructed by connecting simpler subsystems in standard ways—cascade, parallel, and feedback. The connections detennine the behavior of the interconnected system from the behaviors of component subsystems. The connections place consistency requirements on the input and output signals of the systems being connected.

Our third theme is to relate the declarative view (mathematical, "what is") with the imperative view (procedural, "how to"). That is, we associate mathematical analysis of systems with realizations of these systems. This is the heart of engineering. When EE was entirely about circuits, this was relatively easy, because it was the physics of the circuits that was being described by the mathematics. Today we have to somehow associate the mathematical analysis with very different realizations of the systems, most especially software. We make this association through the study of state machines, and through the consideration of many real-world signals, which, unlike their mathematical abstractions, have little discernable declarative structure. Speech signals, for instance, are far more interesting than sinusoids, and yet many signals and systems textbooks talk only about sinusoids.

Content

We begin in chapter 1 by describing signals as functions, focusing on characterizing the domain and the range for familiar signals that humans perceive, such as sound, images, video, trajectories of vehicles, as well as signals typically used by machines to store or manipulate information, such as sequences of words or bits.

In chapter 2, systems are described as functions, but now the domain and the range are themselves sets of signals. The telephone handset converts voice into an analog electrical signal, and the line card in the telephone central office converts the latter into a stream of bits. Systems can be connected to form a more complex system, and the function describing these more complex systems is a composition of functions describing the component systems.

Characterizing concretely the functions that describe signals and systems is the content of the book. We begin to characterize systems in chapter 3 using the notion of state, the state transition function, and the output function, all in the context of finite-state machines. In chapter 4, state machines are composed in various ways (cascade, parallel, and feedback) to make more interesting systems. Applications to feedback control illustrate the power of the state machine model.

In chapter 5, time-based systems are studied in more depth, first with discrete-time systems (which have simpler mathematics), and then with continuous-time systems. We define linear time-invariant (LTI) systems as infinite state machines with linear state transition and output functions and zero initial state. The input–output behavior of these systems is now fully characterized by their impulse response.

Chapter 6 bridges the finite-state machines of chapters 3 and 4 with the time-based systems of chapter 5, showing that they can be combined in useful ways to get hybrid systems. This greatly extends the applicability of LTI systems, because, although most systems are not LTI, many have modes of operation that are approximately LTI. The concept of modal models is illustrated with supervisory control systems. This chapter alone would justify the unified modeling approach in this text, because it offers a glimpse of a far more powerful conceptual framework than either state machines or LTI methods can offer alone.

Chapter 7 introduces frequency decomposition of signals; chapter 8 introduces frequency response of LTI systems; and chapter 9 brings the two together by discussing filtering. The approach is to present frequency domain concepts as a complementary toolset, different from that of state machines, and much more powerful when applicable. Frequency decomposition of signals is motivated first using psychoacoustics, and gradually developed until all four Fourier transforms (the Fourier series, the Fourier transform, the discrete-time Fourier transform, and the discrete Fourier transform) have been described. We linger on the first of these, the Fourier series, since it is conceptually the easiest, and then more quickly present the others as generalizations of the Fourier series. LTI systems yield best to frequency-domain analysis because of the property that complex exponentials are eigenfunctions. Consequently, they are fully characterized by their frequency response—the main reason that frequency domain methods are important in the analysis of filters and feedback control.

Chapter 10 covers classical Fourier transform material such as properties of the four Fourier transforms and transforms of basic signals. Chapter 11 applies frequency domain methods to a study of sampling and aliasing.

Chapters 12, 13, and 14 extend frequency-domain techniques to include the Z transform and the Laplace transform. Applications in signal processing and feedback control illustrate the concepts and the utility of the techniques. Mathematically, the Z transform and the Laplace transform are introduced as extensions of the discrete-time and continuous-time Fourier *transforms to signals* that are not absolutely summable or integrable.

The unified modeling approach in this text is rich enough to describe a wide range of signals and systems, including those based on discrete events and those based on signals in time, both continuous and discrete. The complementary tools of state machines and frequency-domain methods permit analysis and implementation of concrete signals and systems. Hybrid systems and modal models offer systematic ways to combine these complementary toolsets. The framework and the tools of this text provide a foundation on which to build later courses on digital systems, embedded software, communications, signal processing, hybrid systems, and control.

The Web site

The book has an extensive companion Web site, **http://www.aw.com/lee_varaiya**. It includes:

- **The laboratory component.** A suite of exercises based on MATLAB and Simulink®* help reconcile the declarative and imperative points of view. MATLAB is an imperative programming language. Simulink is a block diagram language, in which one connects blocks implementing simpler subsystems to construct more interesting systems. It is much easier to quickly construct interesting signals and systems using the extensive built-in libraries of MATLAB and Simulink than using a conventional programming language like C++, Java, or Scheme. These laboratory exercises involve audio, video, and images, which are much more interesting signals than sinusoids.
- **The applets.** An extensive set of interactive applets brings out the imperative view and illustrates concepts of frequency analysis. These include speech, music, and image examples, interactive applets showing finite Fourier series approximations, and illustrations of complex exponentials and phasors.
- **Instructor and student aids.** A large set of Web pages, arranged by topic, can be used by the instructor in class and by students to review the material. These pages integrate many of the applets, and thus offer more interactive and dynamic presentation material than what is possible with more conventional presentation material. At Berkeley, we use them in the classroom, as a supplement to the blackboard. Qualified instructors can download a snapshot of the Web pages, including the applets, so a network connection is not required in the classroom.
- **Additional sidebars.** The Web site includes additional topics in sidebar form, beyond those in the text. For example, there is a discussion of image encoding methods that are commonly used on the Web.
- **Solutions.** Solutions to exercises are available from the publisher to qualified instructors.

*MATLAB and Simulink are registered trademarks of The MathWorks, Inc.

Pedagogical features

This book has a number of highlights that make it well suited as a textbook for an introductory course.

1. "Probing Further" sidebars briefly introduce the reader to interesting extensions of the subject, to applications, and to more advanced material. They serve to indicate directions in which the subject can be explored.
2. "Basics" sidebars offer readers with less mathematical background some basic tools and methods.
3. Appendix A reviews basic set theory and helps establish the notation used throughout the book.
4. Appendix B reviews complex variables, making it unnecessary for students to have much background in this area.
5. Key equations are boxed to emphasize their importance. They can serve as the places to pause in a quick reading. In the index, the page numbers where key terms are defined are shown in bold.
6. The exercises at the end of each chapter are annotated with the letters E, T, or C to distinguish those exercises that are mechanical (E for excercise) from those requiring a plan of attack (T for thought) and from those that generally have more than one reasonable answer (C for conceptualization).

Notation

The notation in this text is unusual when compared to standard texts on signals and systems. We explain our reasons for this as follows:

Domains and ranges. It is common in signals and systems texts to use the form of the argument of a function to define its domain. For example, $x(n)$ is a discrete-time signal, while $x(t)$ is a continuous-time signal; $X(j\omega)$ is the continuous-time Fourier transform and $X(e^{j\omega})$ is the discrete-time Fourier transform. This leads to apparent nonsense like $x(n) = x(nT)$ to define sampling, or to confusion like $X(j\omega) \neq X(e^{j\omega})$ even when $j\omega = e^{j\omega}$.

We treat the domain of a function as part of its definition. Thus, a discrete-time, real-valued signal is a function $x : Integers \to Reals$, and its discrete-time Fourier transform is a function $x : Reals \to Complex$. The DTFT itself is a function whose domain and range are sets of functions,

$$DTFT\colon [Integers \to Reals] \to [Reals \to Complex].$$

Then we can unambiguously write $X = DTFT(x)$.

Functions as values. Most texts call the expression $x(t)$ a function. A better interpretation is that $x(t)$ is an element in the range of the function x. The difficulty with the former interpretation becomes obvious when talking about systems. Many texts pay lip service to the notion that a system is a function by introducing a notation like $y(t) = T(x(t))$. This makes it seem that T acts on the value $x(t)$ rather than on the entire function x.

Our notation includes set of functions, allowing systems to be defined as functions with such sets as the domain and range. Continuous-time convolution, for example, becomes

$$Convolution\colon [Reals \to Reals] \times [Reals \to Reals] \to [Reals \to Reals].$$

We then introduce the notation $*$ as a shorthand,

$$y = x * h = Convolution(x, h),$$

and define the convolution function by

$$\forall\, t \in Reals, \quad y(t) = (x * h)(t) = \int_{-\infty}^{\infty} X(\tau)y(t - \tau)\, d\tau.$$

Note the careful parenthesization. The more traditional notation, $y(t) = x(t) * h(t)$, would seem to imply that $y(t - T) = x(t - T) * h(t - T)$. But it is not so!

A major advantage of our notation is that it easily extends beyond LTI systems to the sorts of systems that inevitably arise in any real world application, such as mixtures of discrete event and continuous-time systems.

Names of functions. We use long names for functions and variables when they have a concrete interpretation. Thus, instead of x we might use *Sound*. This follows a long-standing tradition in software, where readability is considerably improved by long names. By giving us a much richer set of names to use, this helps us avoid some of the preceding pitfalls. For example, to define sampling of an audio signal, we might write

$$SampledSound = Sampler_T(Sound).$$

It also helps bridge the gap between realizations of systems (which are often software) and their mathematical models. How to manage and understand this gap is a major theme of our approach.

How to use this book

At Berkeley, the first 11 chapters of this book are covered in a 15-week, one-semester course. Even though it leaves Laplace transforms, Z transforms, and feedback control systems to a follow-up course, it remains a fairly intense experience. Each week consists of three 50-minute lectures, a one-hour problem session, and one three-hour laboratory. The lectures and problem sessions are conducted by a faculty member while the laboratory is led by teaching assistants, who are usually graduate students, but are also often talented juniors or seniors.

The laboratory component is based on MATLAB and Simulink, and is closely coordinated with the lectures. The text does not offer a tutorial on MATLAB, although the labs include enough material so that, combined with on-line help, they are sufficient. Some examples in the text and some exercises at the ends of the chapters depend on MATLAB.

At Berkeley, this course is taken by all electrical engineering and computer science students, and is followed by a more traditional signals and systems course. That course covers the material in the last three chapters plus applications of frequency-domain methods to communications systems. The follow- up course is not taken by most computer science students. In a program that is more purely electrical and computer engineering than ours, a better approach might be to spend two quarters or two semesters on the material in this text, since the unity of notation and approach would be better than having two disjoint courses, the introductory one using a modern approach, and the follow-up course using a traditional one.

Acknowledgments

Many people have contributed to the content of this book. Dave Messerschmitt conceptualized the first version of the course on which the book is based, and later committed considerable departmental resources to the development of the course while he was chair of the EECS department at Berkeley. Randy Katz, Richard Newton, and Shankar Sastry continued to invest considerable resources in the course when they each took over as chair, and backed our efforts to establish the course as a cornerstone of our undergraduate curriculum. This took considerable courage, since the conceptual approach of the course was largely unproven.

Tom Henzinger probably had more intellectual influence over the approach than any other individual, and to this day we still argue in the halls about details of the approach. The view of state machines, of composition of systems, and of hybrid systems owe much to Tom. Gerard Berry also contributed a great deal to our way of presenting synchronous composition.

We were impressed by the approach of Harold Abelson and and Gerald Jay Sussman, in *Structure and Interpretation of Computer Programs* (MIT Press, 1996), who confronted a similar transition in their discipline. The title of our book shows their influence. Jim McLellan, Ron Shafer, and Mark Yoder influenced this book through their pioneering departure from tradition in signals and systems, *DSP First—A Multimedia Approach* (Prentice-Hall, 1998). Ken Steiglitz greatly influenced the labs with his inspirational book, *A DSP Primer: With Applications to Digital Audio and Computer Music* (Addison-Wesley, 1996).

A number of people have been involved in the media applications, examples, the laboratory development, and the Web content associated with the book.

These include Brian Evans and Ferenc Kovac. We also owe gratitude for the superb technical support from Christopher Hylands. Jie Liu contributed sticky masses example to the hybrid systems chapter, and Yuhong Xiong contributed the technical stock trading example. Other examples and ideas were contributed by Steve Neuendorffer, Cory Sharp, and Tunc Simsek.

For each of the past four years, about 500 students at Berkeley have taken the course that provided the impetus for this book. They used successive versions of the book and the Web content. Their varied response to the course helped us define the structure of the book and the level of discussion. The course is taught with the help of undergraduate teaching assistants. Their comments helped shape the laboratory material.

Several colleagues kindly consented to be interviewed: Panos Antsaklis, University of Notre Dame; Gerard Berry, Esterel Technologies; P. R. Kumar, University of Illinois, Urbana–Champaign; Dawn Tilbury, University of Michigan, Ann Arbor; Jeff Bier, BDTI; and Xavier Rodet, IRCAM, France. We thank them for sharing the experience that encouraged them toward a career in electrical and computer engineering.

Parts of this book were reviewed by more than 30 faculty members around the country. Their criticisms helped us correct defects and inconsistencies in earlier versions. Of course, we alone are responsible for the opinions expressed in the book, and the errors that remain. We especially thank: Jack Kurzweil, San Jose State University; Lee Swindlehurst, Brigham Young University; Malur K. Sundareshan, University of Arizona; Stéphane Lafortune, University of Michigan; Ronald E. Nelson, Arkansas Tech University; Ravi Mazumdar, Purdue University; Ratnesh Kumar, University of Kentucky; Rahul Singh, San Diego State University; Paul Neudorfer, Seattle University; R. Mark Nélms, Auburn University; Chen-Ching Liu, University of Washington; John H. Painter, Texas A&M University; T. Kirubarajan, University of Connecticut; James Harris, California Polytechnic State University in San Luis Obispo; Frank B. Gross, Florida A&M University; Donald L. Snyder, Washington University in St. Louis; Theodore E. Djaferis, University of Massachusetts in Amherst; Soura Dasgupta, University of Iowa; Maurice Felix Aburdene, Bucknell University; and Don H. Johnson, Rice University.

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It has taken much longer to write this book than we expected when we embarked on this project five years ago. It has been a worthwhile effort nonetheless. Our friendship has deepened, and our mutual respect has grown as we learned from each other. Rhonda Lee Righter and Ruth Varaiya have been remarkably sympathetic and encouraging through the many hours at nights and on weekends that this project has demanded. To them we owe our immense gratitude.

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