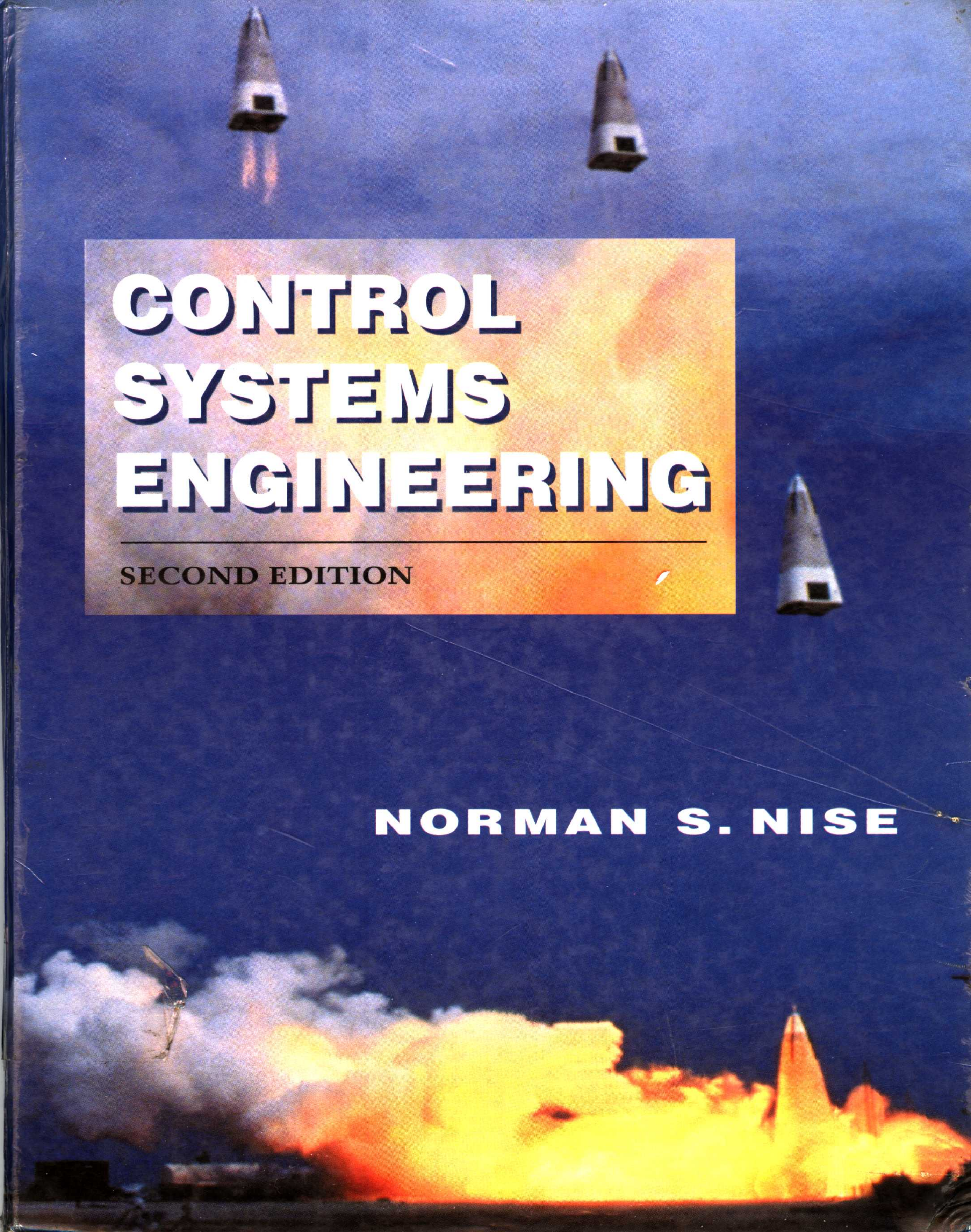
CONTROL
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ENGINEERING
SECOND EDITION
NORMAN S. NISE

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California State Polytechnic University,
Pomona

Control Systems Engineering

Second Edition

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About the cover: A DC-X experimental rocket enveloped in orange flame ascends approximately 90 meters above the desert floor during a test flight at the U.S. Army's missile range at White Sands, New Mexico (front cover, far right). The rocket then progresses sideways for over 100 meters and lands on four deployable legs (rear cover, far left). The photograph is a digital composite of a sequence of 10 images taken during various phases of the flight by a succession of remotely triggered Nikon cameras. The single-stage-to-orbit rocket, a one-third scale model prototype built by McDonnell-Douglas, uses four Pratt & Whitney engines capable of producing required thrusts between 19,400 to 64,800 newtons each. Using modern control systems, only three operators are required to issue commands to the DC-X from a mobile site near the launch pad. NASA is investigating the application of DC-X technology to future launch vehicles.

Credits appear following the glossary.

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To my wife, Ellen; sons, Benjamin and Alan; and daughter, Sharon.

Preface

This book introduces students to the theory and practice of control systems engineering. The text emphasizes the practical application of the subject to the analysis and design of feedback systems.

The study of control systems engineering is essential for students pursuing degrees in electrical, mechanical, aerospace, or chemical engineering. Control systems are found in a broad range of applications within these disciplines, from aircraft and spacecraft to robots and process control systems.

Control Systems Engineering is suitable for upper-division college and university engineering students and for those who wish to master the subject matter through self-study. The student using this text should have completed typical lower-division courses in physics and mathematics, through differential equations. Other required background material, including Laplace transforms and linear algebra, is incorporated in the text, either within chapter discussions or separately in appendixes. This review material can be omitted without loss of continuity if students do not require it.

Key Features

Following are the key features of this second edition, each of which is discussed below:

- Standardized chapter organization
- Qualitative and quantitative explanations
- Examples and Case Studies throughout the text
- Abundant illustrations
- Numerous end-of-chapter problems
- Emphasis on design
- Flexible coverage
- Emphasis on computer-aided analysis and design

Standardized Chapter Organization

Each chapter begins with a summary of objectives. Topics are then divided into clearly numbered and labeled sections. These numbered sections are followed by one or more Case Studies, as outlined below. Each chapter ends with a brief summary, several review questions requiring short answers, and a set of homework problems.

Qualitative and Quantitative Explanations

Explanations are clear and complete and, where appropriate, include a brief review of required background material. Topics build upon and support one another in a logical fashion. Groundwork for new concepts and terminology is carefully laid to avoid overwhelming the student and to facilitate self-study.

Although quantitative solutions are obviously important, a qualitative or intuitive understanding of problems and methods of solution is vital to producing the insight required to develop sound designs. Therefore, whenever possible, new concepts are discussed from a qualitative perspective before quantitative analysis and design are addressed. For example, in Chapter 8, the student can simply look at the root locus and describe qualitatively the changes in transient response that will occur as a system parameter, such as gain, is varied. This ability is developed with the help of a few simple equations from Chapter 4.

Examples and Case Studies

Explanations are clearly illustrated by means of numerous numbered and labeled examples throughout the text. Broader examples in the form of Case Studies can be found after the last numbered section of every chapter, with the exception of Chapter 1. These Case Studies are practical application problems that demonstrate the concepts introduced in the chapter. Each Case Study concludes with a Challenge problem that students can work in order to test their understanding of the material.

One of the Case Studies, an antenna azimuth position control system, is carried throughout the book. The purpose is to illustrate the application of new material in each chapter to the same physical system, thus highlighting the continuity of the design process. Another, more challenging Case Study, an Unmanned Free-Swimming Submersible vehicle, is developed over the course of five chapters.

Abundant Illustrations

The ability to visualize concepts and processes is critical to the student's understanding. For this reason, approximately 750 photos, diagrams, graphs, and tables appear throughout the book to illustrate the topics under discussion.

Numerous End-of-Chapter Problems

Each chapter ends with a variety of homework problems that allow students to test their understanding of the material presented in the chapter. Problems vary in degree of difficulty and complexity, and most chapters include several practical, "real life" problems to help maintain students' motivation.

Emphasis on Design

This textbook places a heavy emphasis on design. Chapters 8, 9, 11, 12, and 13 focus primarily on design. But even in chapters that emphasize analysis, simple design examples are included wherever possible.

Throughout the book, design examples involving physical systems are identified by a D icon. End-of-chapter problems that involve the design of physical systems are included under the separate heading, Design Problems. In these examples and problems, a desired response is specified and the student must evaluate certain system parameters, such as gain, or specify a system configuration along with parameter values. In addition, the text includes numerous design examples and problems (not identified by an icon) that involve purely mathematical systems.

Because visualization is so vital to understanding design, this text carefully relates indirect design specifications to more familiar ones. For example, the less familiar and indirect phase margin is carefully related to the more direct and familiar percent overshoot before being used as a design specification.

For each general type of design problem introduced in the text, a methodology for solving the problem is presented—in many cases in the form of a step-by-step procedure, beginning with a statement of design objectives. Example problems serve to demonstrate the methodology by following the procedure, making simplifying assumptions, and presenting the results of the design in tables or plots that compare the performance of the original system with that of the improved system. This comparison also serves as a check on the simplifying assumptions.

Transient response design topics are covered comprehensively in the text. They include:

- Design via gain adjustment using the root locus
- Design of compensation and controllers via the root locus
- Design via gain adjustment using sinusoidal frequency response methods
- Design of compensation via sinusoidal frequency response methods
- Design of controllers in state space using pole-placement techniques
- Design of observers in state space using pole-placement techniques
- Design of digital control systems via gain adjustment on the root locus

Steady-state error design is also covered comprehensively in the textbook. Topics include:

- Gain adjustment
- Design of compensation via the root locus
- Design of compensation via sinusoidal frequency response methods
- Design of integral control in state space

Finally, the design of gain to yield stability is examined from the following perspectives:

- Routh-Hurwitz criterion
- Root locus
- Nyquist criterion
- Bode plots

Flexible Coverage

The material in this book can be adapted for a one-quarter or a one-semester course. The organization is flexible, allowing the instructor to select the material that best suits the requirements and time constraints of the class.

Throughout the book, state-space methods are presented along with the classical approach. Chapters and sections (as well as Examples, Review Questions, and Problems) that cover state space are marked by an S icon and can be omitted without loss of continuity. Those wishing to study only the classical approach can omit all chapters and sections marked with the S icon. Those wishing to add a basic introduction to state-space modeling can include Chapter 3 in the syllabus.

In a one-semester course, the discussions of state-space analysis in Chapters 4, 5, and 6, as well as state-space design in Chapter 12, can be covered along with the classical approach. Another option is to teach state space separately by gathering the appropriate chapters and sections marked with the S icon into a single unit that follows the classical approach. In a one-quarter course, Chapter 13, Digital Control Systems, could be eliminated.

Emphasis on Computer-Aided Analysis and Design

Control systems problems, particularly analysis and design problems using the root locus, can be tedious, since their solution involves trial and error. To solve these problems, students should be given access to computers or programmable calculators configured with appropriate software.

Many problems presented in this text can be solved without a computer. Most problems requiring a computer can also be solved using a hand-held, programmable calculator. For example, students can use the programmable calculator to (1) determine whether a point on the s-plane is also on the root locus, (2) find magnitude and phase frequency response data for Nyquist and Bode diagrams, and (3) convert between the following representations of a second-order system:

- Pole location in polar coordinates
- Pole location in Cartesian coordinates
- Characteristic polynomial
- Natural frequency and damping ratio
- Settling time and percent overshoot
- Peak time and percent overshoot
- Settling time and peak time

Hand-held calculators have the advantage of easy accessibility for homework and exams. Programs in Appendix D, written in Microsoft QuickBASIC, can be adapted to hand-held calculators programmable in BASIC. Some modification of these programs may be required, depending on the form of BASIC and the machine used.

Mainframe or personal computers are better suited for more computation-intensive applications, such as plotting time responses, root loci, and frequency response curves, as well as finding state-transition matrices. These computers also give the student a real-world environment in which to analyze and design control systems. In this second edition MATLAB is integrated into the text as an optional feature. Those not using MATLAB can write their own programs or use other programs such as Program CC. The QuickBASIC programs in Appendix D can also be used on personal computers.

Without access to computers or programmable calculators, students cannot obtain meaningful analysis and design results and the learning experience can be limited.

New to this Edition

In this second edition, we have revised and added material in response to suggestions from students and professors who adopted the first edition of the text. Following are the key changes in the second edition:

End-of-chapter problems The number of end-of-chapter problems has been increased from 382 in the first edition to 478 in the second.

MATLAB® The use of MATLAB for computer-aided analysis and design is integrated into discussions and problems as an optional feature. The MATLAB material, in a special typeface marked by an M icon, describes an example or problem to be solved using MATLAB. The MATLAB material also contains references to Appendix C, a self-study tutorial that includes MATLAB code and explanations. Because MATLAB code is not used in the text itself, the study of control systems and discussions of its applications is not interrupted. MATLAB material can be omitted if the instructor so desires, without loss of continuity.

Objectives Each chapter opens with a statement of objectives that describes what students will learn and how they will be able to apply the knowledge to Case Studies at the end of the chapter.

Case Studies As already noted, each chapter, with the exception of Chapter 1, has a clearly marked section that includes one or more Case Studies emphasizing chapter objectives. Each Case Study ends with a Challenge problem that enables students to test their understanding of the chapter material.

Icons The three icons shown in the left margin are used throughout the textbook as follows:

The M icon identifies MATLAB discussions, examples, and problems. MATLAB coverage is provided as an enhancement and is not required to use the text.

The S icon highlights state-space discussions, examples, and problems. Like MATLAB, state-space material is optional and can be omitted without loss of continuity.

The D icon clearly identifies design problems involving physical systems.

Chapter 1 The history of control systems has been significantly expanded and divided into six categories: liquid level control; steam pressure and temperature controls; speed control; stability, stabilization, and steering; twentieth-century developments; and contemporary applications.

Chapter 2 The discussion of electrical and mechanical systems has been modified so that those without a background in Laplace transform methods of representing, analyzing, and designing systems can be brought up to speed quickly. A section on electrical analogs has been added.

Chapter 4 This second edition includes a discussion of how to obtain transfer functions through step response testing.

Chapter 6 A discussion of the reverse coefficients method, an alternative to the ϵ method for Routh tables that have a zero only in the first column, has been added. Chapter 6 also includes a new discussion of the bounded-input, bounded-output (BIBO) definition of stability.

Chapter 8 To improve clarity, the derivation of the root locus asymptotes has been moved to an appendix and root locus rules have been clearly partitioned into two categories: those used to provide a quick sketch and those used to refine the sketch. The root locus rules have been expanded to include calculation of the angles of departure from and arrival to complex poles and zeros, respectively. A discussion of the transition method for finding breakaway and break-in points has been added.

Chapter 10 The chapter now includes a section that describes and demonstrates the experimental determination of transfer functions via frequency response testing.

Appendix C This new appendix is a self-study MATLAB tutorial focused on control systems and coordinated with the text.

Appendix E For students without a background in electrical machinery, this new appendix derives the schematic and parameter relationships for an armature-controlled dc motor.

Appendix F A new appendix that derives the state-equation solution for $t_0 \neq 0$ was added to provide enrichment and additional insight.

Appendix G This appendix shows the derivation of two root locus rules. One is the derivation of the asymptotes for the root locus (this material was formerly in Chapter 8). The other (new) derivation develops the transition method for finding breakaway and break-in points.

Chapter Organization

Many times it is helpful to understand an author's reasoning behind the organization of the course material. The following paragraphs may shed light on this topic.

The primary goal of Chapter 1 is to motivate students. In this chapter students learn about the many applications of control systems in everyday life and about the advantages of study and a career in this field. Control systems engineering design objectives, such as transient response, steady-state error, and stability are introduced, as is the path to obtaining these objectives.

Many students have trouble with an early step in the analysis and design sequence: transforming a physical system into a schematic. This step requires many simplifying assumptions based on experience the typical college student does not yet possess. Identifying some of these assumptions in Chapter 1 helps to fill the experience gap.

Chapters 2, 3, and 5 address the representation of physical systems. Chapters 2 and 3 cover modeling of open-loop systems, using frequency response and state-space techniques, respectively. Chapter 5 discusses the representation and reduction of systems formed of interconnected open-loop subsystems. Only a representative sample of physical systems can be covered in a textbook of this length. Electrical, mechanical (both translational and rotational), and electromechanical systems are used as examples of physical systems that are modeled, analyzed, and designed. Linearization of a nonlinear system—one technique used by the engineer to simplify a system in order to represent it mathematically—is also introduced.

Chapter 4 provides an introduction to system analysis, that is, finding and describing the output response of a system. It may seem more logical to reverse the order of Chapters 4 and 5, to present the material in Chapter 4 along with other chapters covering analysis. However, many years of teaching control systems have taught me that the sooner students see an application of the study of system representation, the higher their motivation levels remain.

Chapters 6, 7, and 8 return to control systems analysis and design with the study of stability (Chapter 6), steady-state errors (Chapter 7), and transient response of higher-order systems, using root locus techniques (Chapter 8). Chapter 9 covers the design of compensators and controllers, using the root locus.

Chapters 10 and 11 focus on sinusoidal frequency analysis and design. Chapter 10, like Chapter 8, covers basic concepts of stability, transient response, and steady-state error analysis. However, Nyquist and Bode methods are used in place of root locus. Chapter 11, like Chapter 9, covers the design of compensators, but from the point of view of sinusoidal frequency techniques rather than root locus techniques.

An introduction to state-space design and digital control systems analysis and design completes the text in Chapters 12 and 13, respectively. Although these chapters can be used as an introduction for students who will be continuing the study of control systems engineering, they are useful by themselves and as a supplement to the discussion of analysis and design in the previous chapters. The subject matter cannot be given a comprehensive treatment in two chapters, but the emphasis is clearly outlined and logically linked to the rest of the book.

The Teaching Package

The following materials comprise the teaching package for *Control Systems Engineering*, second edition.

***Using MATLAB to Analyze and Design Control Systems,* second edition** By Naomi Ehrich Leonard (Princeton University) and William S. Levine (University of Maryland), this easy-to-use manual teaches students to use MATLAB 4.1 and 4.2 through interactive examples and exercises. Coverage of SIMULINK is incorporated throughout this second edition. The manual follows the organization of *Control Systems Engineering* and is an ideal supplement to the text. (32193-4)

***Solutions Manual for Control Systems Engineering,* second edition** By Norman S. Nise, this manual contains detailed solutions to most of the problems in the text. (35426-3) The *Solutions Manual* is available only to qualifying faculty.

PowerPoint Lecture Transparencies Approximately two hundred key figures from the text are available as full color electronic transparencies in Microsoft's PowerPoint 3.0 format, Adobe Acrobat format, and in PostScript files.

The transparencies are fully customizable with PowerPoint and Acrobat software. Available only via anonymous ftp from bc.aw.com.

Control System Design Software A free companion disk with MATLAB M-files for *Control Systems Engineering, second edition* is available at no cost from The MathWorks. Use the card bound in this text to order the disk, or download the functions via anonymous FTP at ftp.mathworks.com in pub/books or via bc.aw.com. MATLAB and the Control System Toolbox, available from The MathWorks, are required to run the *Control Systems Engineering* M-files (see page 761). Companion software is also available for *Using MATLAB to Analyze and Design Control Systems, second edition* via FTP or by returning the card included in that text. Consult the text or README file for requirements to run the software.

Please contact your Addison-Wesley•Benjamin/Cummings sales representative at 1-800-950-BOOK for more information about *Control Systems Engineering* and its teaching package.

Acknowledgments

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This second edition was completely error-checked by my colleague Samy M. El-Sawah, and for that I and the students reading it are grateful.

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The manuscript for this second edition was scrutinized by numerous reviewers. Their mastery of the subject matter and attention to detail led to many suggestions and improvements. In particular, Charles P. Neuman, Carnegie Mellon University, made numerous suggestions throughout the entire project and encouraged me to include MATLAB in the second edition. Other reviewers, in addition to the focus group, whose invaluable contributions are acknowledged here are Anthony J. Calise, Georgia Institute of Technology; Stephen R. McNeill, University of South Carolina; Robert L. Mertz, University of San Diego; Medhat M. Morcos, Kansas State University; Satish S. Nair, University of Missouri, Columbia; and Bruce Wilson, Northeastern University.

I would especially like to thank my students who used the previous edition over the last three years. Their suggestions provided the required insight to improve this new edition.

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Norman S. Nise

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