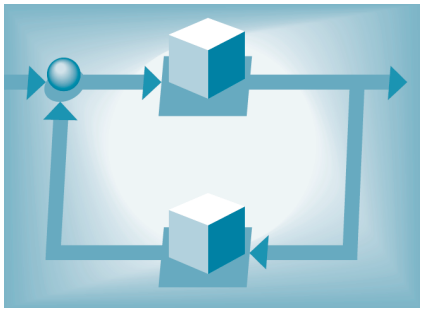


CONTROL SYSTEMS ENGINEERING

Fourth Edition

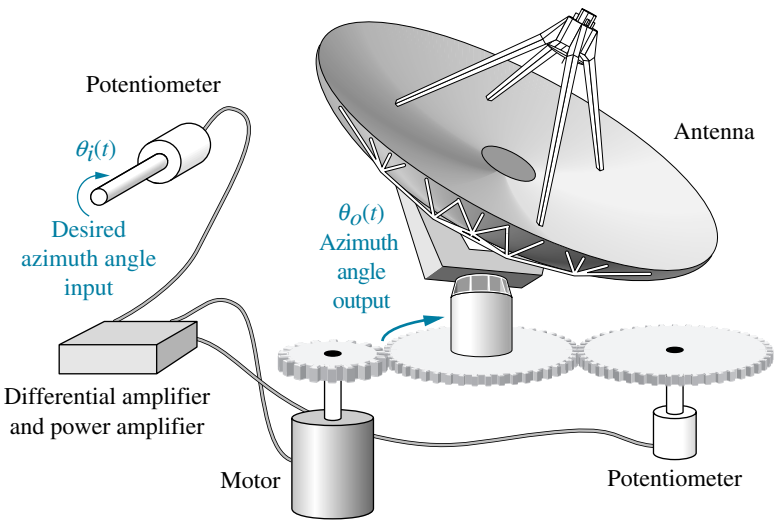
Norman S. Nise

California State Polytechnic University, Pomona

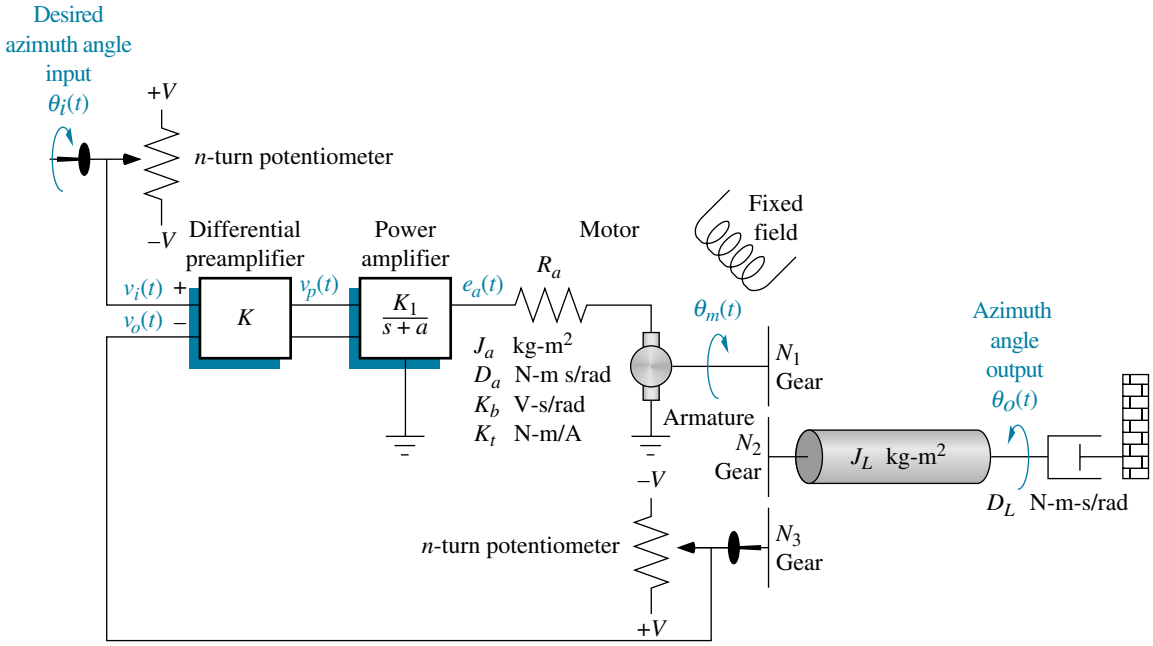
JOHN WILEY & SONS, INC.

Antenna Azimuth Position Control System

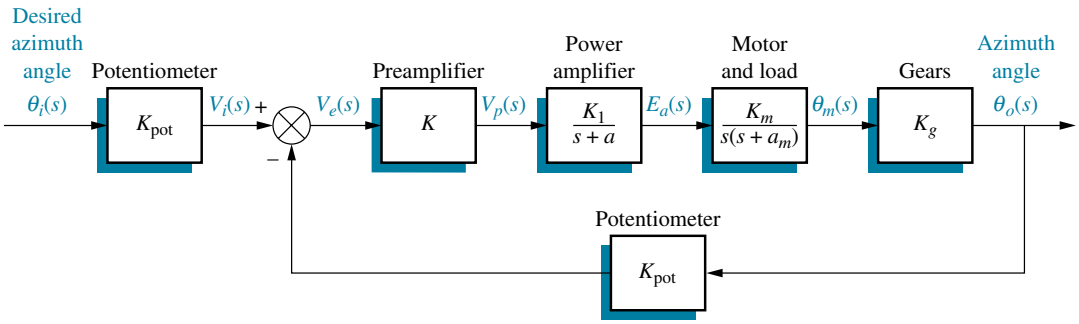
Layout



Schematic



Block Diagram



Schematic Parameters

Parameter	Configuration 1	Configuration 2	Configuration 3
V	10	10	10
n	10	1	1
K	—	—	—
K_1	100	150	100
a	100	150	100
R_a	8	5	5
J_a	0.02	0.05	0.05
D_a	0.01	0.01	0.01
K_b	0.5	1	1
K_t	0.5	1	1
N_1	25	50	50
N_2	250	250	250
N_3	250	250	250
J_L	1	5	5
D_L	1	3	3

Block Diagram Parameters

Parameter	Configuration 1	Configuration 2	Configuration 3
K_{pot}	0.318		
K	—		
K_1	100		
a	100		
K_m	2.083		
a_m	1.71		
K_g	0.1		

Note: reader may fill in Configuration 2 and Configuration 3 columns after completing the antenna control Case Study challenge proglems in Chapters 2 and 10, respectively.

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Manny, a robot mannequin, was built at the Department of Energy's Pacific Northwest Laboratory. The robot was designed to simulate human movements, sweating, and breathing in order to test protective clothing worn by firefighters and handlers of hazardous material. Protective clothing is stressed by Manny's 40 joints, which move with the help of hydraulic actuators. Water is conducted through tubes to simulate perspiration, while breathing is imitated by introducing moist air through the nose and mouth to produce human-like chest motion.

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To my wife, Ellen;
sons, Benjamin and Alan;
daughter, Sharon;
and to the memory of
my mother-in-love,
Bobby Manashil,
whose love of reading has
been an inspiration.

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 the appendixes or on an accompanying CD-ROM. This review material can be omitted without loss of continuity if the student does not require it.

Key Features

The key features of this fourth edition are

- Standardized chapter organization
- Qualitative and quantitative explanations
- **Examples, Skill-Assessment Exercises,** and **Case Studies** throughout the text
- Control Solutions Powered by JustAsk!©
- **Cyber Exploration Laboratory** experiments
- Abundant illustrations
- Numerous end-of-chapter problems
- Emphasis on design
- Flexible coverage

- Emphasis on computer-aided analysis and design
- Icons identifying major topics
- CD-ROM containing additional material

Let us look at each feature in more detail.

Standardized Chapter Organization

Each chapter begins with a list of chapter objectives, followed by a list of case study objectives that relate the chapter objectives to specific student performance in solving a practical case study problem, such as an antenna azimuth position control system.

Topics are then divided into clearly numbered and labeled sections containing explanations, examples, and, where appropriate, skill-assessment exercises with answers. These numbered sections are followed by one or more case studies, as will be outlined in a few paragraphs. 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, Skill-Assessment Exercises, and Case Studies

Explanations are clearly illustrated by means of numerous numbered and labeled **Examples** throughout the text. Where appropriate, a section concludes with **Skill-Assessment Exercises**. These are computation drills, most with answers, that test comprehension and provide immediate feedback. Complete solutions can be found on the accompanying CD-ROM.

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 may work in order to test their understanding of the material.

One of the case studies, concerning 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, involving an Unmanned Free-Swimming Submersible Vehicle, is developed over the course of five chapters.

Control Solutions Powered by JustAsk!

Control Solutions is a Web site that is essentially a tutor serving the needs of both the student and the professor. A total of over 150 end-of-chapter problems and Skill-Assessment Exercises from the book will have step-by-step solutions. These problems are worked in detail and explanations of every facet of the solutions are provided. As such, this Web site is a valuable tool in the use of this book. This site is password protected and can be accessed by purchasing ***The Control Solutions Companion***, ISBN 0471483885. This companion supplies you with an access code to the Control Solutions Web site as well as instructions on how to use the Web site. ***The Control Solutions Companion*** can be purchased on the book companion Web site, www.wiley.com/college/nise.

Cyber Exploration Laboratory Experiments

Computer experiments using MATLAB, Simulink, and the Control System Toolbox are found at the end of the Problems section of Chapters 4 through 13 under the subheading **Cyber Exploration Laboratory**. The experiments allow the reader to verify the concepts covered in the chapter via simulation. The reader also can change parameters and perform "what if" exploration to gain insight into the effect of parameter and configuration changes. The experiments are written with stated Objectives, Minimum required software packages, as well as Prelab, Lab, and Postlab tasks and questions. Thus, the experiments may be used for a laboratory course that accompanies the class.

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. Also, the homework problems contain a progressive analysis and design problem that uses the same practical system to demonstrate the concepts of each chapter.

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

icon. End-of-chapter problems that involve the design of physical systems are included under the separate heading **Design Problems** and also, in chapters covering design, under the heading **Progressive Analysis and**

Design Problem. 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 to 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
- Design of digital control system compensation via *s*-plane design and the Tustin transformation

Steady-state error design is covered comprehensively in this textbook and includes

- 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 covered 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, exercises, review questions, and problems) that cover state space are marked by a State Space icon and can be omitted without any loss of continuity. 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, 6, and 7, 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 State Space 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. In this fourth edition, MATLAB®[1] continues to be integrated into the text as an optional feature.

Many problems in this text can be solved with either a computer or a handheld, 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

Handheld calculators have the advantage of easy accessibility for homework and exams. Please consult Appendix G, located on the enclosed CD-ROM, for a discussion of computational aids that can be adapted to handheld calculators.

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

[1]MATLAB is a registered trademark of The MathWorks, Inc.

a real-world environment in which to analyze and design control systems. Those not using MATLAB can write their own programs or use other programs, such as Program CC. Please consult Appendix G, on the accompanying CD-ROM, for a discussion of computational aids that can be adapted for use on computers that do not have MATLAB installed.

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

Icons Identifying Major Topics

Several icons identify coverage and optional material. The icons are summarized as follows:

The Control Solutions icon identifies problems included on the Control Solutions Web site powered by JustAsk! These problems are worked in detail and explanations of every facet of the solution are provided.

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

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

The GUI Tool icon identifies MATLAB GUI Tools discussions, examples, exercises, and problems. The discussion of the tools, which includes the LTI Viewer, the Simulink LTI Viewer, and the SISO Design Tool, is provided as an enhancement and is not required to use the text.

The Symbolic Math icon identifies Symbolic Math Toolbox discussions, examples, exercises, and problems. Symbolic Math Toolbox coverage is provided as an enhancement and is not required to use the text.

The State Space icon highlights state-space discussions, examples, exercises, and problems. State-space material is optional and can be omitted without loss of continuity.

Design

The Design icon clearly identifies design problems involving physical systems.

Control Solutions Control Solutions powered by JustAsk! is a Web site that contains step-by-step solutions to over 150 end-of-chapter problems. Details are described under Key Features earlier in this Preface.

CD-ROM Containing Additional Material

A CD-ROM disk accompanies the textbook. The disk contains the following:

- PowerPoint®[1] and Acrobat®[2] files containing most figures from the textbook. The files may be used as a convenient method to project graphics on a screen to enhance lectures.
- Solutions to skill-assessment exercises
- All M-files used in the MATLAB, Simulink, GUI Tools, and Symbolic Math Toolbox tutorials
- Additional computer programs that can be used by readers without access to MATLAB
- Copies of Cyber Exploration Laboratory experiments for convenience in printing, for the purpose of including the experiment questions and tasks as a cover sheet for the lab reports
- Additional appendixes; topics in Table of Contents
- A link to the JustAsk! Website

New to this Edition

The following list describes the key changes in this fourth edition.

End-of-chapter problems There is at least a 10% change in the problems at the end of the chapters.

Control Solutions Control Solutions powered by JustAsk! is a Web site that contains step-by-step solutions to over 150 end-of-chapter problems. Details are described under Key Features earlier in this Preface.

MATLAB The use of MATLAB for computer-aided analysis and design continues to be integrated into discussions and problems as an optional feature in the fourth edition. The MATLAB tutorial has been updated to MATLAB Version 6.5 the Control System Toolbox Version 5.2, and the Symbolic Math Toolbox Version 3.0.

MATLAB's Simulink?[3] The use of Simulink to show the effects of nonlinearities upon the time response of open-loop and closed-loop systems appears again in

[1]PowerPoint is a registered trademark of Microsoft Corporation.

[2]Acrobat is a registered trademark of Adobe Systems Incorporated.

[3]Simulink is a registered trademark of The MathWorks, Inc

this fourth edition. We also continue to use Simulink to demonstrate how to simulate digital systems. In addition, Simulink has been added to the new subsection described below—the Cyber Exploration Laboratory. Finally, the Simulink tutorial has been updated to Simulink 5.

MATLAB's GUI Tools The MATLAB's GUI Tools tutorial has been updated to include new and revised versions of the LTI Viewer, the Simulink LTI Viewer, and the SISO Design Tool, which replaces the Root Locus Design GUI.

Cyber Exploration Laboratory New to this edition are computer experiments using MATLAB, Simulink, and the Control System Toolbox. These experiments are found at the end of the Problems section of Chapters 4 through 13 under the subheading, "Cyber Exploration Laboratory." The experiments may be used for a laboratory course that accompanies the class. Copies of these experiments can be found on the accompanying CD-ROM and can be printed for convenience.

Topics moved to CD-ROM Derivations in Chapters 4 and 5 were moved to the accompanying CD-ROM. In particular, the derivation of the time domain solution of state equations, in Section 4.11, in the third edition, now occupies Appendix I on the accompanying CD-ROM. Also, the derivation of similarity transformations, previously in Section 5.8, is now in Appendix K on the accompanying CD-ROM. Sections 4.11 and 5.8 still contain the results of the derivations as well as examples. Finally, the derivation of a schematic for a dc motor, previously in Appendix F in the third edition, has been moved to Appendix H on the accompanying CD-ROM.

Book Organization by Chapter

Many times it is helpful to understand an author's reasoning behind the organization of the course material. The following paragraphs hopefully 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. New and unfamiliar terms also are included in the Glossary.

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 techniques 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, 8, and 9 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 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 for 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.

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 their 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, fourth edition. Be sure to periodically check www.wiley.com/college/nise for up-to-date information on this publication.

Control Solutions powered by JUSTASK! is a website that is essentially a tutor serving the needs of both the student and the professor. A total of over 150 end-of-chapter problems and Skill Assessment Exercises covering numerous topics within the chapter will have step-by-step solutions. These problems are worked in detail, and explanations of every facet of the solution are provided. As such, this website is a valuable tool in the use of this book. This site is password-protected site but can be accessed by purchasing the ***The Control Solutions Companion,*** ISBN 0471483885. This companion supplies you with access code to the Control Solutions website as well as instructions on how to use the website. ***The Control Solutions Companion*** can be purchased on the book's companion website, www.wiley.com/college/nise.

PowerPoint Lecture Graphics Key figures from the text are available as full-color electronic graphics in Microsoft's PowerPoint. These files can be found on the accompanying CD-ROM and at www.wiley.com/college/nise.

Control Systems Engineering Toolbox All MATLAB M-files and Simulink files used in the appendixes of this textbook can be found on the accompanying CD-ROM and at www.wiley.com/college/nise.

***Solutions Manual for Control Systems Engineering*, fourth edition** by Norman S. Nise, this manual contains detailed solutions to most of the problems in the text. The Solutions Manual is available online only to qualifying faculty.

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Norman S. Nise

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