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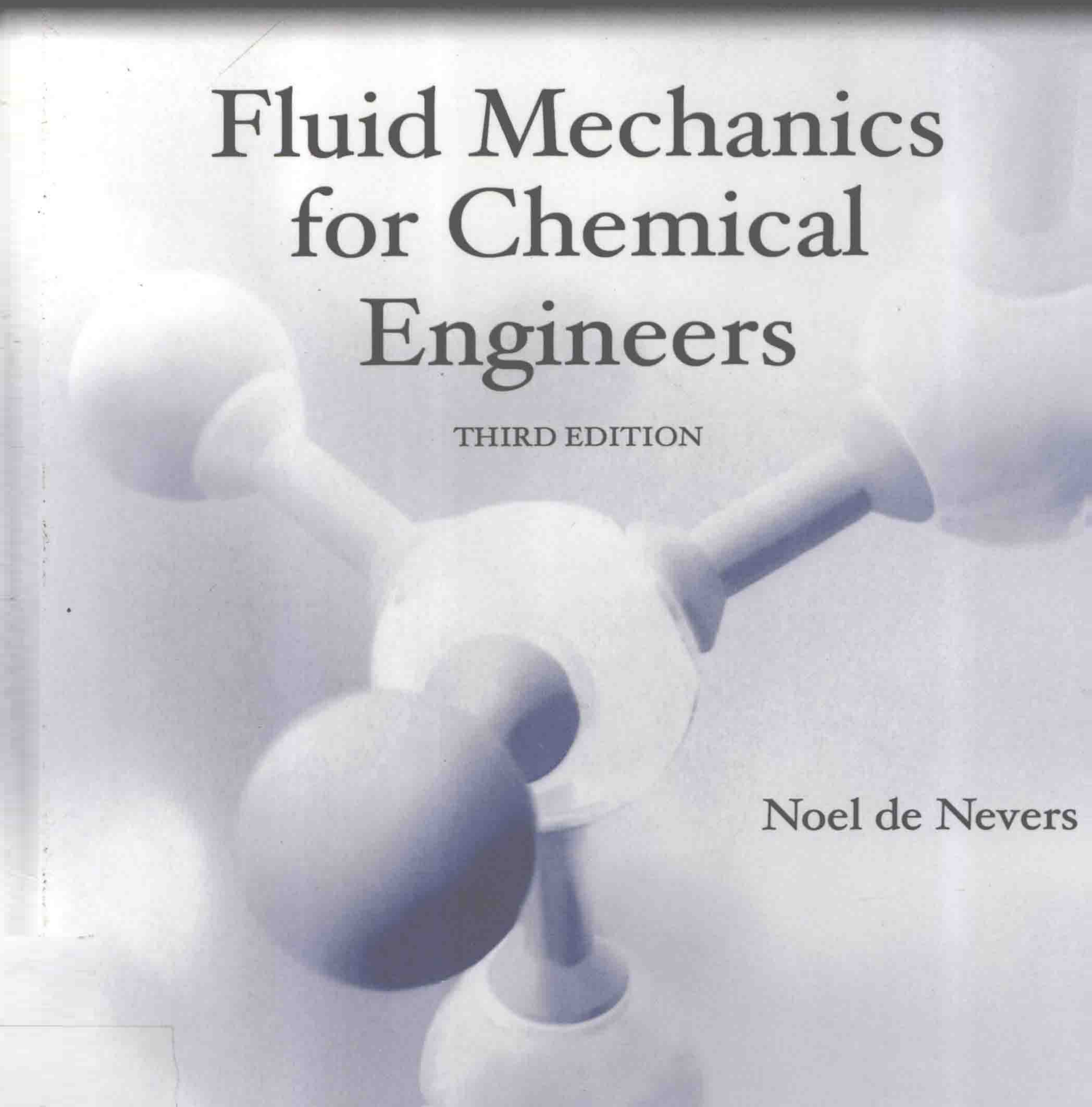
Fluid Mechanics for Chemical Engineers

THIRD EDITION



Noel de Nevers

FLUID MECHANICS FOR CHEMICAL ENGINEERS

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Noel de Nevers

Department of Chemical and Fuels Engineering
University of Utah

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ABOUT THE AUTHOR

Noel de Nevers received a B.S. from Stanford in 1954, and M.S. and Ph.D. degrees from the University of Michigan in 1956 and 1959, all in chemical engineering.

He worked for the research arms of the Chevron Oil Company from 1958 to 1963 in the areas of chemical process development, chemical and refinery process design, and secondary recovery of petroleum. He has been on the faculty of the University of Utah from 1963 to the present in the Department of Chemical and Fuels Engineering, becoming emeritus in 2002.

He has worked for the National Reactor Testing Site, Idaho Falls, Idaho, on nuclear problems, for the U.S. Army Harry Diamond Laboratory, Washington DC, on weapons, and for the Office of Air Programs of the U.S. EPA in Durham, NC, on air pollution.

He was a Fulbright student of Chemical Engineering at the Technical University of Karlsruhe, Germany, in 1954–1955, a Fulbright lecturer on Air Pollution at the Universidad del Valle, in Cali, Colombia, in the summer of 1974, and at the Universidad de la República, Montevideo Uruguay and the Universidad Naciónal Mar del Plata, Argentina in the Autumn of 1996.

His areas of research and publication are in fluid mechanics, thermodynamics, air pollution, technology and society, energy and energy policy, and explosions and fires. He regularly consults on air pollution problems, explosions, fires and toxic exposures.

In 1993 he received the Corcoran Award from the Chemical Engineering Division of the American Society for Engineering Education for the best paper ("'Product in the Way' Processes") that year in *Chemical Engineering Education.*

In 2000 his textbook, *Air Pollution Control Engineering,* Second Edition, was issued by McGraw-Hill.

In 2002 his textbook, *Physical and Chemical Equilibrium for Chemical Engineers* was issued by John Wiley.

In addition to his serious work he has three "de Nevers's Laws" in the latest "Murphy's Laws" compilation, and won the title "Poet Laureate of Jell-O Salad" at the Last Annual Jell-O Salad Festival in Salt Lake City in 1983. He is the official discoverer of Private Arch in Arches National Park.

NOTATION

a	acceleration	ft / s^2	m / s^2
a	some arbitrary direction or length (Sec. 2.1)	ft	m
a	resistance of filter medium (Sec. 11.4)	1 / ft	1 / m
a_x, a_y, a_z	x, y, and z components of acceleration	ft / s^2	m / s^2
a_c	centrifugal acceleration	ft / s^2	m / s^2
a, b, c, d	exponents in algebraic procedure (Sec. 9.3)	—	—
A	area or cross-sectional area perpendicular to flow	ft^2	m^2
A	independent variable (Sec. 9.3)	various	various
A, B, C, D	arbitrary constants	various	various
b	background concentration (Sec. 3.6)	lbm / ft^3	kg / m^3
B	dependent variable (Sec. 9.3)	various	various
c	volume fraction in hindered settling	—	—
c	speed of light (Chap. 4 only)	ft / s	m / s
c	speed of sound	ft / s	m / s
c	concentration	lbm / ft^3	kg / m^3
C	heat capacity	Btu / lbm · °F or Btu / lbmol · °F	J / kg · K or J / mol · K
C_d	drag coefficient (Sec. 6.13)	—	—
C_i	constants of integration	various	various
C_l	lift coefficient (Sec. 6.13)	—	—
C_f	integrated drag coefficient (Sec. 17.2)	—	—
C'_f	local drag coefficient (Sec. 17.2)	—	—
C_P	heat capacity at constant pressure	Btu / lbm · °F or Btu / lbmol · °F	J / kg · K or J / mol · K
C_v	orifice or venturi coefficient (Sec. 5.8)	—	—
C_V	heat capacity at constant volume	Btu / lbm · °F or Btu / lbmol · °F	J / kg · K or J / mol · K
CC	capital cost factor (Sec. 6.12)	1 / yr	1 / yr
D	diameter	ft	m
D_p	particle diameter	ft	m
D / Dt	Stokes or substantive or convective derivative	1 / s	1 / s
$\mathcal{D}$	diffusivity, molecular or turbulent	ft^2 / s	m^2 / s
erf	gauss error function (see Fig. 19.5)	—	—
E	energy	Btu or equivalent	J
E	voltage	volt	volt
E_s	surface energy	ft · lbf / ft^2	J / m^2
f	Fanning friction factor (Sec. 6.4)	—	—
$f_{\mathrm{P.M.}}$	friction factor for porous medium (Sec. 11.1)	—	—
$f(n)$	spectrum function (Sec. 18.4)	1 / hertz	1 / hertz

°F	temperature or temperature interval, degrees Fahrenheit	°F	
F	force	lbf	N
$\mathscr{F}$	friction heating per lbm	ft · lbf / lbm or equivalent	J / kg
F_x, F_y, F_z	*x*, *y*, and *z* components of force	lbf	N
F_θ	tangential component of force	lbf	N
$F_I, F_V, F_G, F_S, F_E, F_P$	inertia, viscous, gravity, surface, elastic, and pressure forces (Sec. 9.3)	lbf	N
$F(n)$	spectrum function (Sec. 18.4)	—	—
$\mathscr{F}r$	Froude number	—	—
g	acceleration of gravity	ft / s^2	m / s^2
g_c	conversion factor $= 1 = 32.2$ lbm · ft / lbf · s^2	—	—
h	height or depth	ft	m
h	enthalpy per unit mass or mole $(u + Pv)$	Btu / lbm or Btu / lbmol	J / kg or J / mol
h_c	centroid depth measured from free surface (Prob. 2.26)	ft	m
H	enthalpy $(U + PV)$	Btu	J
H	height	ft	m
H	effective stack height (Chap. 19)	ft	m
H	mixing height (Chap. 3)	ft	m
hp	horsepower	ft · lbf / s	
$\mathscr{H}e$	Hedstrom number (Chap. 13)	—	—
HR	hydraulic radius	ft	m
i, j, k	unit vectors in the *x*, *y*, and *z* directions	—	—
I	electric current (dQ / dt)	amp	amp
I	angular moment of inertia (Chap. 7)	lbm · ft^2	kg · m^2
I_{sp}	specific impulse	lbf · s / lbm	N · s / kg
J_x, J_y, J_z	*x*, *y*, and *z* components of the electric current density (Sec. 16.3)	amp / m^2	amp / m^2
k	number of independent dimensions (Sec. 9.3)	—	—
k	ratio of specific heats, C_P / C_V (Sec. 8.1)	—	—
k	thermal conductivity (Sec. 16.3)	Btu / hr · °F · ft	W / m · K
k	permeability (Sec. 16.3 and Chap. 11)	ft^2	m^2
k	ratio of radii in a Couette viscometer	—	—
k	turbulent k.e. per unit mass	Btu / lbm	J / kg
ke	kinetic energy per unit mass	Btu / lbm	J / kg
K	arbitrary constant in "power law" (Chap. 13)	lbf · s^n / ft^2	N · s^n / m^2
K	bulk modulus (Sec. 8.1)	lbf / in^2	Pa
K	resistance coefficient (Sec. 6.9)	—	—
K	arbitrary constant in jet equation (Chap. 19)	—	—
KE	kinetic energy	Btu	J
l	length	ft	m
L	length or lever arm	ft	m
L	angular momentum (Chap. 7)	lbm · ft^2 / s	kg · m^2 / s
m	mass	lbm	kg
$\dot{m}$	mass flow rate	lbm / s	kg / s
M	molecular weight	lbm / lbmol	g / mol
$\mathscr{M}$	Mach number	—	—
n	number of independent variables	—	—
n	number of moles	lbmol	mol
n	arbitrary power in "power law" (Chap. 13)	—	—
n	frequency	cyc / s	hertz
n	constant in Chézy Eq. (Chap. 6)	—	—

N	$4f\,\Delta x / D$ (Sec. 8.4)	—	—
N	rotation rate (rpm or rps)	1 / min; 1 / s	1 / min; 1 / s
pe	potential energy per unit mass	Btu / lbm	J / kg
P	pressure	lbf / in^2	Pa
Po	power	ft · lbf / s	W
PE	potential energy	Btu	J
PC	pumping cost (Sec. 6.12)	\$ / yr · hp	
PP	purchased price factor for a pipe (Sec. 6.12)	\$ / in · ft	
q	emission rate per unit area (Sec. 3.6)	lbm / s · ft^2	kg / s · m^2
q_x, q_y, q_z	x, y, and z components of heat flux (Sec. 16.3)	Btu / h · ft^2	W / m^2
Q	volumetric flow rate	ft^3 / s	m^3 / s
Q	heat	Btu	J
$\mathscr{Q}$	charge	coul	coul
r	radius	ft	m
R	universal gas constant	See inside back cover	See inside back cover
R	correlation coefficient (Sec. 18.5)	—	—
R	radius of curvature (Chap. 14)	ft	m
$\mathscr{R}$	Reynolds number	—	—
$\mathscr{R}_p$	particle Reynolds number	—	—
$\mathscr{R}_{\text{P.M.}}$	Reynolds number for porous media	—	—
$\mathscr{R}_x$	Reynolds number based on distance from leading edge	—	—
$\mathscr{R}_{\text{power law}}$	Reynolds number for power law fluids	—	—
$\mathscr{R}_{\text{Bingham}}$	Reynolds number for Bingham plastics	—	—
$\mathscr{R}_{\text{impeller}}$	Reynolds number for a mixer impeller	—	—
s	entropy per unit mass or per mole	Btu / lbm · °R or Btu / lbmol · °R	J / kg · K or J / mol · K
s	cake compressibility coefficient (Sec. 11.4)	—	—
SG	specific gravity	—	—
t	time	s	s
t	wall thickness (Sec. 2.4)	ft	m
T	absolute temperature	°R or K	K
T	relative intensity of turbulence (Sec. 18.4)	—	—
u	internal energy per unit mass or per mole	Btu / lbm or Btu / lbmol	J / kg or J / mol
u^*	friction velocity (Sec. 17.4)	ft / s	m / s
u^+	V_x / u^* (Sec. 17.4)	—	—
U	internal energy	Btu	J
υ	volume per unit mass	ft^3 / lbm	m^3 / kg
υ	fluctuating component of velocity (Chaps. 17 and 18)	ft / s	m / s
V	velocity	ft / s	m / s
V	volume	ft^3	m^3
V_x, V_y, V_z	x, y, and z components of velocity	ft / s	m / s
V_θ	tangential component of velocity	ft / s	m / s
V_r	radial velocity	ft / s	m / s
V_{avg}	average velocity	ft / s	m / s
$V_{\text{centerline}}$	centerline velocity in a pipe	ft / s	m / s
V_∞	free-stream velocity	ft / s	m / s
V_s	superficial velocity (Sec. 11.1)	ft / s	m / s
V_I	interstitial velocity (Sec. 11.1)	ft / s	m / s
V_{mf}	minimum fluidizing velocity (Sec. 11.5)	ft / s	m / s
W	work	ft · lbf	J
W	weight	lbf	N
W	width	ft	m

$W_{n.f.}$	non-flow work (excluding injection work)	ft · lbf	J
W	volumetric solids content of slurry (Sec. 11.4)	—	—
x, y, z	directions of coordinate axes, or lengths	ft	m
x	distance	ft	m
y	distance perpendicular to the flow direction	ft	m
y^+	$(r_{wall} - r)u^* / \nu$ (Sec. 17.4)	—	—
z	elevation	ft	m
α	coefficient of thermal expansion	1 / °F	1 / K
α	specific resistance of filter cake (Sec. 11.4)	1 / lbf	1 / N
α	small angle, jet angle (Chap. 19)	rad	rad
α	thermal diffusivity	ft^2 / s	m^2 / s
α	constant in Chézy Eq. (Chap. 6)	—	—
β	isothermal compressibility $= 1 /$ (bulk modulus)	1 / (lbf / in^2)	1 / Pa
γ	specific weight $= \rho g$	lbf / ft^3	N / m^3
Γ	torque	ft · lbf	N · m
δ	boundary-layer thickness (Chap. 17)	ft	m
δ^*	displacement thickness (Sec. 17.2)	ft	m
ε	absolute roughness	ft	m
ε	porosity or void fraction or volume fraction of gas	—	—
ε	eddy (kinematic) viscosity	ft^2 / s	m^2 / s
ε	turbulent dissipation rate	ft^2 / s^3	m^2 / s^3
ζ	vorticity $= 2\omega$	1 / s	1 / s
η	efficiency	—	—
η	$y(V_x / \nu_x)^{1/2}$ (Sec. 17.2)	—	—
η	viscosity (non-Newtonian fluids)	lbm / ft · s or cP	Pa · s
θ	angle	rad	rad
θ	momentum thickness (Sec. 17.2)	ft	m
θ	contact angle (Sec. 17.3)	rad	rad
μ	viscosity	lbm / ft · s or cP	Pa · s
ν	kinematic viscosity (μ / ρ)	ft^2 / s or cSt	m^2 / s
π	number of dimensionless groups (Chap. 9)	—	—
ρ	density	lbm / ft^3	kg / m^3
ρ	resistivity (Sec. 16.3)	—	ohm · m
σ	surface tension	lbf / ft	N / m
σ	stress	lbf / in^2	Pa
σ	shear rate	1 / s	1 / s
$\sigma_x, \sigma_y, \sigma_z$	turbulent dispersion coefficients (Chap. 19)	ft	m
σ_{xx}	normal stress in x direction	lbf / in^2	Pa
τ	shear stress	lbf / in^2	Pa
τ_{xy}	shear stress in the x direction on a face perpendicular to the y axis	lbf / in^2	Pa
τ_{wall}	shear stress at a solid wall	lbf / in^2	Pa
τ_0	shear stress at a solid surface	lbf / in^2	Pa
τ_{yield}	yield stress for a Bingham fluid	lbf / in^2	Pa
ϕ	potential	ft^2 / s for fluid flow	m^2 / s for fluid flow
$\phi(t)$	arbitrary function of time (Sec. 16.2)	—	—
ψ	stream function	ft^2 / s	m^2 / s
ω	angular velocity	rad / s	rad / s

Superscripts

*	sonic condition (Chap. 8)		
$\overline{X}$	time average of X	various	various

Subscripts			
R	reservoir state in Chap. 8		
S	isentropic condition (speed of sound)		
1, 2	arbitrary states		
x, y	conditions before and after a normal shock in Chap. 8		
Vector			
boldface	indicates a vector	various	various
$\mathbf{\nabla}$	$\mathbf{\nabla} = \mathbf{i}\dfrac{\partial}{\partial x} + \mathbf{j}\dfrac{\partial}{\partial y} + \mathbf{k}\dfrac{\partial}{\partial z}$	1 / ft	1 / m

PREFACE

This book presents an introduction to fluid mechanics for undergraduate chemical engineering students.

Throughout the text, emphasis is placed on the connection between physical reality and the mathematical models of reality, which we manipulate. The ultimate test of a mathematical solution is its ability to predict the results of future experiments. Because a mathematically correct consequence of inapplicable assumptions is often simply wrong, the text occasionally offers intentionally wrong solutions to caution the student.

The simplest mathematical approaches are used, consistent with technical vigor.

Considerable attention is paid to the units of quantities in the equations because students usually have trouble with them, and because this reminds them that each symbol in our equations stands for a real physical quantity.

The book is divided into four sections. Section I, preliminaries, provides background for the study of flowing fluids. It includes a separate chapter on the balance equation. One might think that this is such a simple topic that it deserves only a few lines. However, it is a continual source of trouble to students. Furthermore, it is the most all-pervasive concept of chemical engineering, forming the basic mathematical framework for the application of the laws of thermodynamics, Newtonian mechanics, stoichiometry, and for the study of chemically reacting systems. There is also a chapter on the first law of thermodynamics. In the undergraduate program at the University of Utah, the students study basic engineering thermodynamics before they are introduced to fluid mechanics; thus, Chapter 4 is merely a review for them.

Section II discusses flows that are practically one-dimensional or can be treated as such. This organization of the book is radically different from the organization of fluids books written by mechanical and civil engineers, who begin with three-dimensional fluid mechanics and work their way down to one-dimensional fluid mechanics. The reasons for this organization, which fits better with the background of chemical engineers, are spelled out in Section 1.11. Sections I and II are the core of the book, covering all the basic ideas in fluid mechanics, and many of the problems of greatest interest to chemical engineers.

Section III discusses some other topics that can be viewed by the methods of one-dimensional fluid mechanics. These six chapters introduce other areas of fluid mechanics that are of great practical interest to some chemical engineers but that are not covered in an introductory course for want of time. They can be assigned, in any order, as supplementary reading, or covered briefly in class, introducing students to the terminology and basic ideas of these fields and helping them to read related matters in the current literature.

Section IV introduces the student to two- and three-dimensional fluid mechanics. It shows the relations between the methods used for these flows and the simpler approaches used in Sections II and III. It shows what two- and three-dimensional problems can be solved by hand (a small number) and shows the basis on which most such problems are currently solved by Computational Fluid Mechanics programs. A separate chapter introduces the student to mixing, which is basic chemical engineering, but not routinely covered in fluid mechanics texts.

Computers do not make hand calculations unnecessary. No new or unfamiliar computer solution should be believed until manual plausibility checks have shown that the computer is indeed solving the problem we think it is solving and that its solution is physically reasonable. Simply plugging values into available computer packages does not build physical insight, which is one of the most important tools of the successful engineer. Good pedagogy begins with hand solutions of simplified versions of the real problem, which build physical insight and some understanding of physical magnitudes, followed by computer solutions, which can relax the simplifications and cover a wider variety of conditions, followed by manual plausibility checks of the computer solutions.

After an initial rush of enthusiasm for SI, engineering educators seem to be deciding that the English system of units is not likely to vanish overnight. For this reason our students must become like educated Europeans, who speak more than one language fluently and can read and understand one or two additional languages. Our students must be fluent in SI and in the English system of units and must understand traditional metric and cgs, and be able to read and understand texts using the slug and the poundal. This book has a long discussion of these various systems of units. Examples are presented in both SI and English units. This is unlikely to please purists of any persuasion, but it probably serves our students as well as any other approach and better than some.

My goal is to present a text that average chemical engineering undergraduates can read and understand and from which they can attack a variety of meaningful problems. I have tried to help the student develop a physical insight into the processes of fluid mechanics and develop the understanding that the equations on these pages truly describe what nature does. I have tried to choose examples from the student's own experiences, or that relate to things they can observe in their everyday lives. The home is a wonderful place to observe the principles of chemical engineering; good teachers help students interpret what they see in the home in terms of chemical engineering principles.

The true test of the quality of a textbook is whether it becomes the most worn and tattered book on a practicing engineer's bookshelf. Former students tell me that the first two editions of this book pass that test. I hope copies of this edition will become even more worn and tattered.

For instructor resources visit the text's Web site at http://www.mcgraw-hill.engineeringcs.com.

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