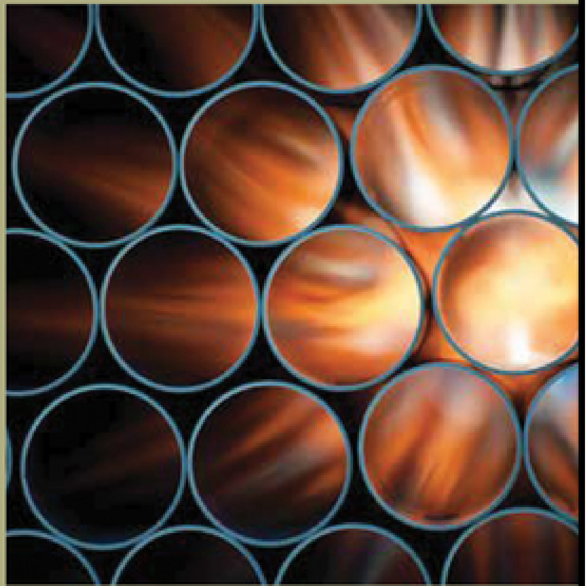
ENGINEERING FLUID MECHANICS


eleventh edition

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Wiley Binder Version

WILEY

ELEVENTH EDITION

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This 11th Edition is dedicated to Dr. Clayton Crowe (1933–2012) and to our wonderful colleagues, students, friends, and families. We especially acknowledge our spouses Linda and Jim and Barbara's grandson Moses Pakootas for their patience and support.

CONTENTS

PREFACE

Audience

This book is written for engineering students of all majors who are taking a first or second course in fluid mechanics. Students should have background knowledge in physics (mechanics), chemistry, statics, and calculus.

Why We Wrote This Book

Our mission is to equip people to do engineering skillfully. Thus, we wrote this book to explain the main ideas of fluid mechanics at a level appropriate for a first or second college course. In addition, we have included selected engineering skills (e.g., critical thinking, problem solving, and estimation) because we believe that practicing these skills will help all students learn fluid mechanics better.

Approach

Knowledge. Each chapter begins with statements of what is important to learn. These learning outcomes are formulated in terms of what *students will be able to do.* Then, the chapter sections present the knowledge. Finally, the knowledge is summarized at the end of each chapter.

Practice with Feedback. The research of Dr. Anders Ericsson suggests that learning is brought about through *deliberate practice*. Deliberate practice involves doing something and then getting feedback. To provide opportunities for deliberate practice, we have provided two sets of resources:

1. This text contains more than 1100 end-of-chapter problems. The answers to selected, even-numbered problems are provided in the back of the book. Professors can gain access to the solution manual by contacting their Wiley representative.
2. *WileyPlus* provides a way for professors to assign end-of-chapter problems and to have the grading and the record keeping done by a computer system. This may be useful to professors with large classes or to professors who do not have a budget to pay a grader.

Features of this Book

Learning Outcomes. Each chapter begins with learning outcomes so that students can identify what knowledge they should gain by studying the chapter.

Rationale. Each section describes what content is presented and why this content is relevant.

Visual Approach. This text uses sketches and photographs to help students learn more effectively by connecting images to words and equations.

Foundational Concepts. This text presents major concepts in a clear and concise format. These concepts form building blocks for higher levels of learning.

Seminal Equations. This text emphasizes technical derivations so that students can learn to do the derivations on their own, increasing their level of knowledge. Features include the following:

- Derivations of main equations are presented in a step-by-step fashion.
- The holistic meaning of main equations is explained using words.
- Main equations are named and listed in Table F.2.
- Main equations are summarized in tables in the chapters.
- A process for applying each main equation is presented in the relevant chapter.

Chapter Summaries. Each chapter concludes with a summary so that students can review the key knowledge in the chapter.

Online Problems. We have created many online problems that provide immediate feedback to students while also ensuring that students complete the assigned work on time. These problems are available in *WileyPLUS* at instructor's discretion.

Process Approach. A process is a method for getting results. A process approach involves figuring out how experts do things and adapting this same approach. This textbook presents multiple processes.

Wales-Woods Model. The Wales-Woods Model represents how experts solve problems. This model is presented in Chapter 1 and used in example problems throughout the text.

Grid Method. This text presents a systematic process, called the grid method, for carrying and canceling units. Unit practice is emphasized because it helps engineers spot and fix mistakes and because it helps engineers put meaning on concepts and equations.

Traditional and SI Units. Examples and homework problems are presented using both SI and traditional unit systems. This presentation helps students gain familiarity with units that are used in professional practice.

Example Problems. Each chapter has examples to show how the knowledge is used in context and to present essential details needed for application.

Solutions Manual. The text includes a detailed solutions manual for instructors. Many solutions are presented with the Wales-Woods Model.

Image Gallery. The figures from the text are available in PowerPoint format, for easy inclusion in lecture presentations. This resource is available only to instructors. To request access to this and all instructor resources, please contact your local Wiley sale representative.

Interdisciplinary Approach. Historically, this text was written for the civil engineer. We are retaining this approach while adding material so that the text is also appropriate for other engineering disciplines. For example, the text presents the Bernoulli equation using both head terms (civil engineering approach) and terms with units of pressure (the approach used by chemical and mechanical engineers). We include problems that are relevant to product development as practiced by mechanical and electrical engineers. Some problems feature other disciplines, such as exercise physiology. The reason for this interdisciplinary approach is that the world of today's engineer is becoming more and more interdisciplinary.

What is New in the 11th Edition

1. Critical Thinking (CT) is introduced in Chapter 1. **Rationale**: When students apply CT, they learn fluid mechanics better. Also, they become better engineers.
2. Learn outcomes are organized into categories. **Rationale**: The grouping of outcomes increases the clarity about what is important.
3. New material was added in Chapter 1 describing force, mass, weight, Newton's law of universal gravitation, density, and specific weight. **Rationale**: We have seen many instances of student work indicating that these basic concepts are sometimes not in place. Also, introducing these topics in Chapter 1 provides a way to introduce engineering calculations earlier in the book.
4. We introduced the **Voice of the Engineer** in Chapter 1 as a way to present wisdom. **Rationale**: The **Voice of the Engineer** provides a structure for presenting an attitude that is widely shared in the professional engineering community.

5. In Chapter 1, new material was added about the ideal gas law (IGL). **Rationale**: The IGL section now has the right level of technical detail for engineering problems.
6. In Chapter 1, the material on problem solving was rewritten. Also, the Wales-Woods Model is now summarized on one page. **Rationale**: Solving problems and building math models are fundamental skills for the engineer. The ideas in Chapter 1 represent the best ideas that we have seen in the literature.
7. Chapter 2 has a new section on finding fluid properties. This new section, §2.2, contains the summary table that previously was situated at the end of the chapter. **Rationale**: Finding fluid properties is an important learning outcome for Chapter 2. The new section puts an emphasis on this outcome and organizes the ideas in one place. Previously, the knowledge needed to find fluid properties was scattered throughout Chapter 2.
8. Chapter 2 has a new section on stress, how to relate stress to force, and on common forces. **Rationale**: Stress and force are seminal ideas in mechanics. This section defines the relevant terms and shows how they are related.
9. The Chapter 2 discussions on the shear stress equation were edited to increase clarity and concision. **Rationale**: The shear stress equation is one of the seminal fluid mechanics equations.
10. The end-of-chapter problems include over 300 new or revised problems. **Rationale**: Both learning and assessment of learning are made easier by having problems available.
11. Chapter 9 was rewritten to make the chapter more suitable for students taking a first course in fluid mechanics.

Author Team

The book was originally written by Professor John Roberson, with Professor Clayton Crowe adding the material on compressible flow. Professor Roberson retired from active authorship after the 6th edition, Professor Donald Elger joined on the 7th edition, and Professor Barbara LeBret joined on the 9th edition. Professor Crowe retired from active authorship after the 9th edition. Professor Crowe passed away on February 5, 2012.

Donald Elger, Barbara LeBret, and Clayton Crowe (Photo by Archer Photography: www.archerstudio.com)

Acknowledgments

We acknowledge our colleagues and mentors. Donald Elger acknowledges his Ph.D. mentor, Ronald Adams, who always asked why and how. He also acknowledges Ralph Budwig, fluid mechanics researcher and colleague, who has provided many hours of delightful inquiry about fluid mechanics. Barbara LeBret acknowledges Wilfried Brutsuert at Cornell University and George Bloomsburg at the University of Idaho, who inspired her passion for fluid mechanics. Last but not least, we thank technical reviewer Daniel Flick for his excellent work.

Contact Us

We welcome feedback and ideas for interesting end-of-chapter problems. Please contact us at the following email addresses:

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TABLE F.1 Formulas for Unit Conversions*

Name, Symbol, Dimensions			Conversion Formula
Length	L	L	**1 m** = 3.281 ft = 1.094 yd = 39.37 in = km/1000 = 10^6 μm **1 ft** = 0.3048 m = 12 in = mile/5280 = km/3281 **1 mm** = m/1000 = in/25.4 = 39.37 mil = 1000 μm = 10^7 Å
Speed	V	L/T	**1 m/s** = 3.600 km/hr = 3.281 ft/s = 2.237 mph = 1.944 knots **1 ft/s** = 0.3048 m/s = 0.6818 mph = 1.097 km/hr = 0.5925 knots
Mass	m	M	**1 kg** = 2.205 lbm = 1000 g = slug/14.59 = (metric ton or tonne or Mg)/1000 **1 lbm** = lbf·s^2/(32.17 ft) = kg/2.205 = slug/32.17 = 453.6 g = 16 oz = 7000 grains = short ton/2000 = metric ton (tonne)/2205
Density	ρ	M/L^3	**1000 kg/m^3** = 62.43 lbm/ft^3 = 1.940 slug/ft^3 = 8.345 lbm/gal (US)
Force	F	ML/T^2	**1 lbf** = 4.448 N = 32.17 lbm·ft/s^2 **1 N** = kg·m/s^2 = 0.2248 lbf = 10^5 dyne
Pressure, shear stress	p, τ	M/LT^2	**1 Pa** = N/m^2 = kg/m·s^2 = 10^{-5} bar = 1.450×10^{-4} lbf/in^2 = inch H_2O/249.1 = 0.007501 torr = 10.00 dyne/cm^2 **1 atm** = 101.3 kPa = 2116 psf = 1.013 bar = 14.70 lbf/in^2 = 33.90 ft of water = 29.92 in of mercury = 10.33 m of water = 760 mm of mercury = 760 torr **1 psi** = atm/14.70 = 6.895 kPa = 27.68 in H_2O = 51.71 torr
Volume	$\forall$	L^3	**1 m^3** = 35.31 ft^3 = 1000 L = 264.2 U.S. gal **1 ft^3** = 0.02832 m^3 = 28.32 L = 7.481 U.S. gal = acre-ft/43,560 **1 U.S. gal** = 231 in^3 = barrel (petroleum)/42 = 4 U.S. quarts = 8 U.S. pints = 3.785 L = 0.003785 m^3
Volume flow rate (discharge)	Q	L^3/T	**1 m^3/s** = 35.31 ft^3/s = 2119 cfm = 264.2 gal (US)/s = 15850 gal (US)/m **1 cfs** = 1 ft^3/s = 28.32 L/s = 7.481 gal (US)/s = 448.8 gal (US)/m
Mass flow rate	$\dot{m}$	M/T	**1 kg/s** = 2.205 lbm/s = 0.06852 slug/s
Energy and work	E, W	ML^2/T^2	**1 J** = kg·m^2/s^2 = N·m = W·s = volt·coulomb = 0.7376 ft·lbf = 9.478×10^{-4} Btu = 0.2388 cal = 0.0002388 Cal = 10^7 erg = kWh/3.600×10^6
Power	P, $\dot{E}$, $\dot{W}$	ML^2/T^3	**1 W** = J/s = N·m/s = kg·m^2/s^3 = 1.341×10^{-3} hp = 0.7376 ft·lbf/s = 1.0 volt-ampere = 0.2388 cal/s = 9.478×10^{-4} Btu/s **1 hp** = 0.7457 kW = 550 ft·lbf/s = 33,000 ft·lbf/min = 2544 Btu/h
Angular speed	ω	T^{-1}	**1.0 rad/s** = 9.549 rpm = 0.1591 rev/s
Viscosity	μ	M/LT	**1 Pa·s** = kg/m·s = N·s/m^2 = 10 poise = 0.02089 lbf·s/ft^2 = 0.6720 lbm/ft·s
Kinematic viscosity	ν	L^2/T	**1 m^2/s** = 10.76 ft^2/s = 10^6 cSt
Temperature	T	Θ	**K** = °C + 273.15 = °R/1.8 **°C** = (°F − 32)/1.8 **°R** = °F + 459.67 = 1.8 K **°F** = 1.8°C + 32

*Visit www.onlineconversion.com for a useful online reference.

TABLE F.2 Commonly Used Equations

Ideal gas law equations

$p = \rho RT$

$p\forall = mRT$

$p\forall = nR_uT$

$M = m/n;\ R = R_u/M$ (§1.6)

Specific weight

$\gamma = \rho g$ (Eq. 1.21)

Kinematic viscosity

$\nu = \mu/\rho$ (Eq. 2.1)

Specific gravity

$$S = \frac{\rho}{\rho_{\mathrm{H_2O\ at\ 4°C}}} = \frac{\gamma}{\gamma_{\mathrm{H_2O\ at\ 4°C}}} \quad \text{(Eq. 2.3)}$$

Definition of viscosity

$$\tau = \mu\frac{dV}{dy} \quad \text{(Eq. 2.15)}$$

Pressure equations

$p_{\mathrm{gage}} = p_{\mathrm{abs}} - p_{\mathrm{atm}}$ (Eq. 3.3a)

$p_{\mathrm{vacuum}} = p_{\mathrm{atm}} - p_{\mathrm{abs}}$ (Eq. 3.3b)

Hydrostatic equation

$$\frac{p_1}{\gamma} + z_1 = \frac{p_2}{\gamma} + z_2 = \text{constant} \quad \text{(Eq. 3.10a)}$$

$$p_z = p_1 + \gamma z_1 = p_2 + \gamma z_2 = \text{constant} \quad \text{(Eq. 3.10b)}$$

$$\Delta p = -\gamma \Delta z \quad \text{(Eq. 3.10c)}$$

Manometer equations

$$p_2 = p_1 + \sum_{\text{down}} \gamma_i h_i - \sum_{\text{up}} \gamma_i h_i \quad \text{(Eq. 3.21)}$$

$$h_1 - h_2 = \Delta h(\gamma_B/\gamma_A - 1) \quad \text{(Eq. 3.22)}$$

Hydrostatic force equations (flat panels)

$$F_P = \bar{p}A \quad \text{(Eq. 3.28)}$$

$$y_{\mathrm{cp}} - \bar{y} = \frac{\bar{I}}{\bar{y}A} \quad \text{(Eq. 3.33)}$$

Buoyant force (Archimedes equation)

$$F_B = \gamma \forall_D \quad \text{(Eq. 3.41a)}$$

The Bernoulli equation

$$\left(\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1\right) = \left(\frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2\right) \quad \text{(Eq. 4.21b)}$$

$$\left(p_1 + \frac{\rho V_1^2}{2} + \rho g z_1\right) = \left(p_2 + \frac{\rho V_2^2}{2} + \rho g z_2\right) \quad \text{(Eq. 4.21a)}$$

Volume flow rate equation

$$Q = \bar{V}A = \frac{\dot{m}}{\rho} = \int_A V\,dA = \int_A \mathbf{V}\cdot d\mathbf{A} \quad \text{(Eq. 5.10)}$$

Mass flow rate equation

$$\dot{m} = \rho A\bar{V} = \rho Q = \int_A \rho V\,dA = \int_A \rho\mathbf{V}\cdot d\mathbf{A} \quad \text{(Eq. 5.11)}$$

Continuity equation

$$\frac{d}{dt}\int_{\mathrm{cv}} \rho\, d\forall + \int_{\mathrm{cs}} \rho\mathbf{V}\cdot d\mathbf{A} = 0 \quad \text{(Eq. 5.28)}$$

$$\frac{d}{dt}M_{\mathrm{cv}} + \sum_{\mathrm{cs}} \dot{m}_o - \sum_{\mathrm{cs}} \dot{m}_i = 0 \quad \text{(Eq. 5.29)}$$

$$\rho_2 A_2 V_2 = \rho_1 A_1 V_1 \quad \text{(Eq. 5.33)}$$

Momentum equation

$$\sum \mathbf{F} = \frac{d}{dt}\int_{\mathrm{cv}} \mathbf{v}\rho\, d\forall + \int_{\mathrm{cs}} \mathbf{v}\rho\mathbf{V}\cdot d\mathbf{A} \quad \text{(Eq. 6.7)}$$

$$\sum \mathbf{F} = \frac{d(m_{\mathrm{cv}}\mathbf{v}_{\mathrm{cv}})}{dt} + \sum_{\mathrm{cs}} \dot{m}_o\mathbf{v}_o - \sum_{\mathrm{cs}} \dot{m}_i\mathbf{v}_i \quad \text{(Eq. 6.10)}$$

Energy equation

$$\left(\frac{p_1}{\gamma} + \alpha_1\frac{\bar{V}_1^2}{2g} + z_1\right) + h_p = \left(\frac{p_2}{\gamma} + \alpha_2\frac{\bar{V}_2^2}{2g} + z_2\right) + h_t + h_L \quad \text{(Eq. 7.29)}$$

The power equation

$P = FV = T\omega$ (Eq. 7.3)

$P = \dot{m}gh = \gamma Qh$ (Eq. 7.31)

Efficiency of a machine

$$\eta = \frac{P_{\mathrm{output}}}{P_{\mathrm{input}}} \quad \text{(Eq. 7.32)}$$

Reynolds number (pipe)

$$\mathrm{Re}_D = \frac{VD}{\nu} = \frac{\rho VD}{\mu} = \frac{4Q}{\pi D\nu} = \frac{4\dot{m}}{\pi D\mu} \quad \text{(Eq. 10.1)}$$

Combined head loss equation

$$h_L = \sum_{\text{pipes}} f\frac{L}{D}\frac{V^2}{2g} + \sum_{\text{components}} K\frac{V^2}{2g} \quad \text{(Eq. 10.45)}$$

Friction factor *f* (Resistance coefficient)

$$f = \frac{64}{\mathrm{Re}_D} \quad \mathrm{Re}_D \le 2000 \quad \text{(Eq. 10.34)}$$

$$f = \frac{0.25}{\left[\log_{10}\left(\frac{k_s}{3.7D} + \frac{5.74}{\mathrm{Re}_D^{0.9}}\right)\right]^2} \quad (\mathrm{Re}_D \ge 3000) \quad \text{(Eq. 10.39)}$$

Drag force equation

$$F_D = C_D A\left(\frac{\rho V_0^2}{2}\right) \quad \text{(Eq. 11.5)}$$

Lift force equation

$$F_L = C_L A\left(\frac{\rho V_0^2}{2}\right) \quad \text{(Eq. 11.17)}$$

TABLE F.3 Useful Constants

Name of Constant	Value
Acceleration of gravity	$g = 9.81 \text{ m/s}^2 = 32.2 \text{ ft/s}^2$
Universal gas constant	$R_u = 8.314 \text{ kJ/kmol·K} = 1545 \text{ ft·lbf/lbmol·°R}$
Standard atmospheric pressure	$p_{atm} = 1.0 \text{ atm} = 101.3 \text{ kPa} = 14.70 \text{ psi} = 2116 \text{ psf} = 33.90 \text{ ft of water}$ $p_{atm} = 10.33 \text{ m of water} = 760 \text{ mm of Hg} = 29.92 \text{ in of Hg} = 760 \text{ torr} = 1.013 \text{ bar}$

TABLE F.4 Properties of Air [$T = 20°\text{C}$ (68°F), $p = 1$ atm]

Property	SI Units	Traditional Units
Specific gas constant	$R_{air} = 287.0 \text{ J/kg·K}$	$R_{air} = 1716 \text{ ft·lbf/slug·°R}$
Density	$\rho = 1.20 \text{ kg/m}^3$	$\rho = 0.0752 \text{ lbm/ft}^3 = 0.00234 \text{ slug/ft}^3$
Specific weight	$\gamma = 11.8 \text{ N/m}^3$	$\gamma = 0.0752 \text{ lbf/ft}^3$
Viscosity	$\mu = 1.81 \times 10^{-5} \text{ N·s/m}^2$	$\mu = 3.81 \times 10^{-7} \text{ lbf·s/ft}^2$
Kinematic viscosity	$\nu = 1.51 \times 10^{-5} \text{ m}^2\text{/s}$	$\nu = 1.63 \times 10^{-4} \text{ ft}^2\text{/s}$
Specific heat ratio	$k = c_p/c_v = 1.40$	$k = c_p/c_v = 1.40$
Specific heat	$c_p = 1004 \text{ J/kg·K}$	$c_p = 0.241 \text{ Btu/lbm·°R}$
Speed of sound	$c = 343 \text{ m/s}$	$c = 1130 \text{ ft/s}$

TABLE F.5 Properties of Water [$T = 15°\text{C}$ (59°F), $p = 1$ atm]

Property	SI Units	Traditional Units
Density	$\rho = 999 \text{ kg/m}^3$	$\rho = 62.4 \text{ lbm/ft}^3 = 1.94 \text{ slug/ft}^3$
Specific weight	$\gamma = 9800 \text{ N/m}^3$	$\gamma = 62.4 \text{ lbf/ft}^3$
Viscosity	$\mu = 1.14 \times 10^{-3} \text{ N·s/m}^2$	$\mu = 2.38 \times 10^{-5} \text{ lbf·s/ft}^2$
Kinematic viscosity	$\nu = 1.14 \times 10^{-6} \text{ m}^2\text{/s}$	$\nu = 1.23 \times 10^{-5} \text{ ft}^2\text{/s}$
Surface tension (water–air)	$\sigma = 0.073 \text{ N/m}$	$\sigma = 0.0050 \text{ lbf/ft}$
Bulk modulus of elasticity	$E_v = 2.14 \times 10^9 \text{ Pa}$	$E_v = 3.10 \times 10^5 \text{ psi}$

TABLE F.6 Properties of Water [$T = 4°\text{C}$ (39°F), $p = 1$ atm]

Property	SI Units	Traditional Units
Density	$\rho = 1000 \text{ kg/m}^3$	$\rho = 62.4 \text{ lbm/ft}^3 = 1.94 \text{ slug/ft}^3$
Specific weight	$\gamma = 9810 \text{ N/m}^3$	$\gamma = 62.4 \text{ lbf/ft}^3$

CHAPTER**ONE**

Introduction

CHAPTER ROAD MAP Our purpose is to equip you for success. Success means that you can do engineering skillfully. This chapter presents (a) fluid mechanics topics and (b) engineering skills. The engineering skills are optional. We included these skills because we believe that applying these skills while you are learning fluid mechanics will strengthen your fluid mechanics knowledge while also making you a better engineer.

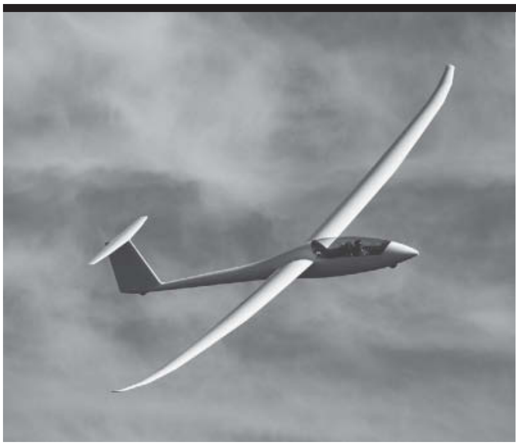


FIGURE 1.1
As engineers, we get to design fascinating systems like this glider. This is exciting! (© Ben Blankenburg/Corbis RF/Age Fotostock America, Inc.)

LEARNING OUTCOMES

ENGINEERING FLUID MECHANICS (§1.1*).

- Define engineering.
- Define fluid mechanics.

MATERIAL SCIENCE TOPICS (§1.2).

- Explain material behaviors using either a microscopic or a macroscopic approach or both.
- Know the main characteristics of liquids, gases, and fluids.
- Understand the concepts of body, material particle, body-as-a-particle, and the continuum assumption.

DENSITY AND SPECIFIC WEIGHT (§1.5).

- Know the main ideas about $W = mg$
- Know the main ideas about density and specific weight.

THE IDEAL GAS LAW (IGL) (§1.6).

- Describe an ideal gas and a real gas.
- Convert temperature, pressure, and mole/mass units.
- Apply the IGL equations.

OPTIONAL ENGINEERING SKILLS (§1.1, §1.3, §1.4, §1.7, §1.8).

- Apply critical thinking to fluid mechanics problems.
- Make estimates when solving fluid mechanics problems.
- Apply ideas from calculus to fluid mechanics.
- Carry and cancel units when doing calculations.
- Check that an equation is DH (dimensionally homogeneous).
- Apply problem solving methods to fluid mechanics problems.

*The symbol § means "section"; e.g., the notation "§1.1" means Section 1.1.

1.1 Engineering Fluid Mechanics

In this section, we explain what engineering fluid mechanics means, and then we introduce *critical thinking* (CT), a method that is at the heart of doing engineering well.

About Engineering Fluid Mechanics

Why study engineering fluid mechanics? To answer this question, we'll start with some examples:

- When people started living in cities, they faced problems involving water. Those people who solved these problems were the engineers. For example, engineers designed aqueducts to bring water to the people. Engineers innovated technologies to remove waste water from the cities, thereby keeping the towns clean and free from effluent. Engineers developed technologies for treating water to remove waterborne diseases and to remove hazards such as arsenic.
- At one time, people had no flying machines. So, the Wright Brothers applied the engineering method to develop the world's first airplane. In the 1940s, engineers developed practical jet engines. More recently, the engineers at The Boeing Company developed the 787 Dreamliner.
- People have access to electrical power because engineers have developed technologies such as the water turbine, the wind turbine, the electric generator, the motor, and the electric grid system.

The preceding examples reveal that engineers solve problems and innovate in ways that lead to the development or improvement of technology. *How are engineers able to accomplish these difficult feats*? Why were the Wright brothers able to succeed? What was the secret sauce that Edison had? The answer is that engineers have developed a method for success that is called the **engineering method**, which is actually a collection of submethods such as building math models, designing and conducting experiments, and designing and building physical systems.

Based on the ideas just presented, **engineering** is the body of knowledge that is concerned with solving problems by creating, designing, applying, and improving technology. **Engineering fluid mechanics** is engineering when a project involves substantial knowledge from the discipline of fluid mechanics.

Defining Mechanics

Mechanics is the branch of science that deals with motion and the forces that produce this motion. Mechanics is organized into two main categories: **solid mechanics** (materials in the solid state) and **fluid mechanics** (materials in the gas or liquid state). Note that many of the concepts of mechanics apply to both fluid mechanics and solid mechanics.

Critical Thinking (CT)

This section introduces critical thinking. Rationale. (1) The heart of the engineering method is critical thinking (CT); thus, skill with CT will give you the ability to do engineering well. (2) Applying CT while you are learning fluid mechanics will result in better learning.

Examples of CT are common. One example is seen when a police detective uses physical evidence and deductive reasoning to reach a conclusion about who committed a crime. A second example occurs when a medical doctor uses diagnostic test data and evidence from a physical examination to reach a conclusion about why a patient is ill. A third example exists when an engineering researcher gathers experimental data about groundwater flow, then reaches some conclusions and publishes these conclusions in a scientific journal. A fourth

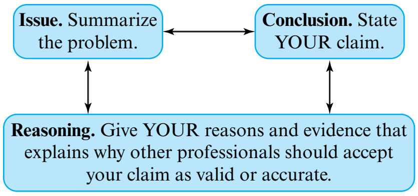


FIGURE 1.2
The Standard Structure of Critical Thinking (SSCT).

example arises when a practicing engineer uses experimental data and engineering calculations to conclude that Site ABC is a good choice for a wind turbine. These examples reveal some facts about critical thinking:

- CT is used by professionals in most fields (e.g., detectives, medical doctors, scientists, and engineers).
- Professionals apply CT to avoid major mistakes. No competent detective wants an innocent person convicted of a crime. No competent physician wants to make an incorrect diagnosis. No competent engineer wants a bridge to fail.
- CT involves methods that are agreed upon by a professional community. For example, the method of fingerprinting is accepted within the law enforcement community. Similarly, engineering has many agreed-upon methods (you can learn some of these methods in this book).

In summary, **critical thinking** is a collection of beliefs and methods that are accepted by a professional community for reaching a sound or strong conclusion. Some examples of the beliefs associated with CT are as follows.

- I want to find out the best idea or what is most correct (I have no interest in *being right*; I want to find out *what is right*).
- I want to make sure that my technical work is valid or correct (I don't want major mistakes or flaws; I bend over backwards to validate my findings).
- I am open to new beliefs and ideas, especially when these ideas are aligned with the knowledge and the beliefs of the professional community (I don't get stuck thinking that I am always right, my ideas are best, or that I know everything; by being open to new ideas, I open myself up to learning).

Regarding "how to do critical thinking," we teach and we apply the **Standard Structure of CT** (Fig. 1.2), which involves three methods:

1. **Issue**. Define the problem you are trying to solve so that is clear and unambiguous. Note that you will often need to rewrite or paraphrase the issue or question.
2. **Reasoning**. List the reasons that explain why professionals should accept your claim (i.e., your answer, your explanation, your conclusion, or your recommendation). To create your reasoning, take actions such as stating facts, citing references, defining terms, applying deductive logic, applying inductive logic, and building subconclusions.
3. **Conclusions**. State your claim. Make sure your claim addresses the issue. Recognize that a claim can be presented in multiple ways, such as an answer, a recommendation, or your stance on a controversial issue.

1.2 How Materials are Idealized

To understand the behavior of materials, engineers apply a few simple ideas. This section presents some of these ideas.

The Microscopic and Macroscopic Descriptions

Engineers strive to understand things. For example, an engineer might ask, why does Steel Alloy #1 fail given that Steel Alloy #2 does not fail in the same application? Or, an engineer might ask, why does water boil? Why does this boiling sometimes damage materials, as in cavitation*? To address questions about materials, engineers often apply the following ideas:

- **Microscopic Description**. Explain something about a material by describing what is happening at the atomic level (i.e., describing the atoms, molecules, electrons, etc.).
- **Macroscopic Description**. Explain something about a material without resorting to descriptions at the atomic level.

Forces between Molecules

One of the best ways to understand materials is to apply the idea that molecules attract one another if they are close together and repel if they are too close[†] (Fig. 1.3).

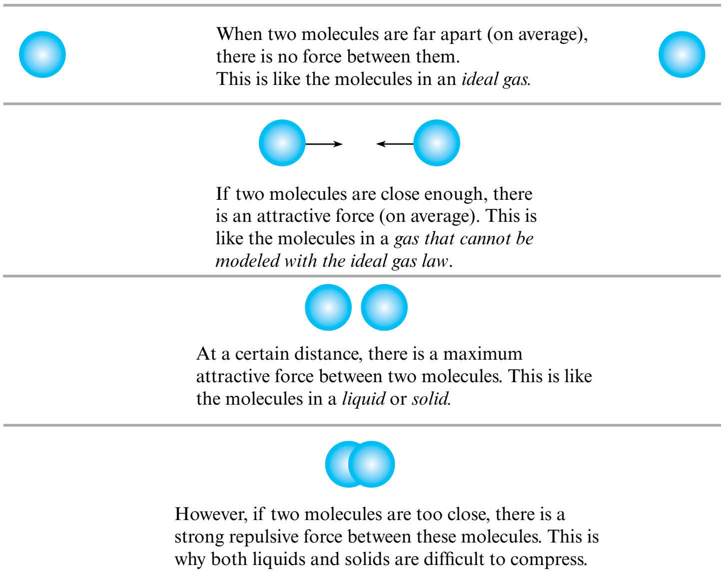
Defining the Liquid, Gas, and Fluid

In science, there are four states of matter: gas, liquid, solid, and plasma. A **gas** is a state of matter in which the molecules are on average far apart so that the forces between molecules (or atoms) is typically very small or zero. Consequently, a gas lacks a fixed shape, and it also lacks a fixed volume, because a gas will expand to fill its container.

A **liquid** is a state of matter in which the molecules are on average close together so that the forces between molecules (or atoms) are strong. In addition, the molecules are relatively

FIGURE 1.3

A description[‡] of the forces between molecules.

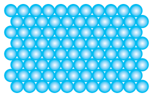
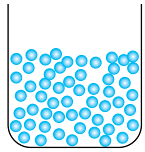
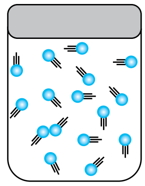


**Cavitation* is explained in §5.5.

[†]Dr. Richard Feynman, who won the Nobel Prize in Physics, calls this the *single most important idea in science*. See the *Feynman Lectures on Physics*, Vol. 1, p. 2.

[‡]For additional details about forces between molecules, consult an expert source, such as a chemistry text or a professor who teaches material science.

TABLE 1.1 Comparison of Solids, Liquids, and Gases

Attribute	Solid	Liquid	Gas
Typical Visualization			
Description	Solids hold their shape; no need for a container	Liquids take the shape of the container and will stay in an open container	Gases expand to fill a closed container
Mobility of Molecules	Molecules have low mobility because they are bound in a structure by strong intermolecular forces	Molecules move around freely even though there are strong intermolecular forces between the molecules	Molecules move around freely with little interaction except during collisions; this is why gases expand to fill their container
Typical Density	Often high; e.g., the density of steel is 7700 kg/m^3	Medium; e.g., the density of water is 1000 kg/m^3	Small; e.g., the density of air at sea level is 1.2 kg/m^3
Molecular Spacing	Small—molecules are close together	Small—molecules are held close together by intermolecular forces	Large—on average, molecules are far apart
Effect of Shear Stress	Produces deformation	Produces flow	Produces flow
Effect of Normal Stress	Produces deformation that may associate with volume change; can cause failure	Produces deformation associated with volume change	Produces deformation associated with volume change
Viscosity	NA	High; decreases as temperature increases	Low; increases as temperature increases
Compressibility	Difficult to compress; bulk modulus of steel is 160×10^9 Pa	Difficult to compress; bulk modulus of liquid water is 2.2×10^9 Pa	Easy to compress; bulk modulus of a gas at room conditions is about 1.0×10^5 Pa

free to move around. In comparison, when a material is in the solid state, atoms tend to be fixed in place—for example, in a crystalline lattice. Thus, a liquid flows easily as compared to a solid. Due to the strong forces between molecules, a liquid has a fixed volume but not a fixed shape.

The term **fluid** refers to both a liquid and a gas and is generally defined as a state of matter in which the material flows freely under the action of a shear stress*.

Table 1.1 provides additional facts about solids, liquids, and gases. Notice that many features in this table can be explained by applying the ideas in Fig. 1.3. **Example.** The density of a liquid or a solid is much higher than the density of a gas because the strong attractive forces in a liquid or solid act to bring the molecules closer together. **Example.** A liquid is difficult to compress because the molecules will have strong repulsive forces if they are brought close together. In contrast, a gas is easy to compress because there are no forces (on average) between the molecules.

*Shear stress is explained in §2.4.

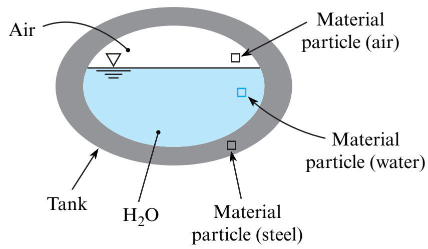


FIGURE 1.4

To find examples of material particles: (1) Select any body; for example, we selected a steel tank filled with water and air. (2) Select a small amount of matter and define this small chunk of matter as a material particle. This figure shows a material particle comprised of air, a material particle comprised of water, and a material particle comprised of steel.

The Body, the Material Particle, the Body-as-a-Particle

Engineers have invented terms that can be used to describe *any material*. Learning this vocabulary will help you learn engineering.

In engineering, the term "body" or "material body" has a special meaning Examples. A coffee cup can be a *body*. The air inside a basketball can be a *body*. A jet airplane can be a *body*. **Body** or **material body** is a label to identify objects or matter that exists in the real world, without specifying any specific object. It is like applying the term "sports" to identify many activities (e.g., soccer, tennis, golf, or swimming) without specifying a particular sport.

A **material particle** is a small region of matter within a *material body* (Fig. 1.4). Some useful facts about material particles are as follows:

- A material particle is often imagined to be *infinitesimal* in the calculus sense.
- A material particle can be selected or visualized so that it has any shape (e.g., spherical, cubical, cylindrical, or amorphous*).
- The term "fluid particle" refers to a material particle that is comprised of a liquid or a gas.

There is another way that engineers use the term "particle." For example, to model the motion of an airplane, an engineer can idealize the airplane as a *particle*. A physics book might state that Newton's second law of motion only applies to a *particle*. In this context, the term has a different meaning than *material particle.* This alternative concept is that the **particle (the body-as-a-particle)** is a way to idealize a material body as if all the mass of the body is concentrated at a point and the dimensions of the body are negligible.

Summary. There are two distinct concepts used in engineering: the *material particle* and the *body-as-a-particle*. However, it is common for the label "particle" to be used for both of these ideas. Engineers typically figure out which idea is meant by the context in which the term is being used.

The Continuum Assumption

Because a body of fluid is comprised of molecules, properties are due to average molecular behavior. That is, a fluid usually behaves as if it were comprised of continuous matter that is infinitely divisible into smaller and smaller parts. This idea is called the **continuum assumption**.

When the continuum assumption is valid, engineers can apply limit concepts from differential calculus. A limit concept typically involves letting a length, an area, or a volume approach zero. Because of the continuum assumption, fluid properties such as density and velocity can be considered continuous functions of position with a value at each point in space.

To gain insight into the validity of the continuum assumption, consider a hypothetical experiment to find density. Fig. 1.5a shows a container of gas in which a volume $\Delta V\!\!\!\!-$ has been

*"Amorphous" means without a clearly defined shape or form.

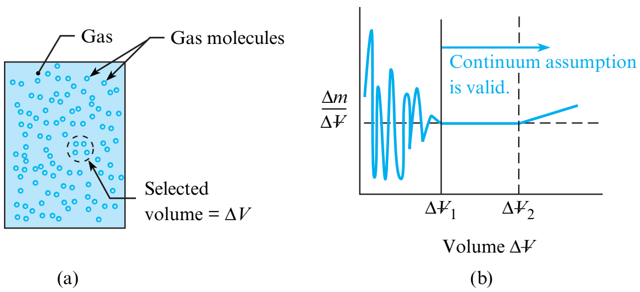


FIGURE 1.5
When a measuring volume ΔV is large enough for random molecular effects to average out, the continuum assumption is valid.

identified. The idea is to find the mass of the molecules Δm inside the volume and then to calculate density by

$$\rho = \frac{\Delta m}{\Delta V}$$

The calculated density is plotted in Fig. 1.5b. When the measuring volume ΔV is very small (approaching zero), the number of molecules in the volume will vary with time because of the random nature of molecular motion. Thus, the density will vary as shown by the wiggles in the blue line. As volume increases, the variations in calculated density will decrease until the calculated density is independent of the measuring volume. This condition corresponds to the vertical line at ΔV_1. If the volume is too large, as shown by ΔV_2, then the value of density may change due to spatial variations.

In most applications, the continuum assumption is valid, as shown by the next example.

EXAMPLE. Probability theory shows that including 10^6 molecules in a volume will allow the determination of density to within 1%. Thus, a cube that contains 10^6 molecules should be large enough to accurately estimate macroscopic properties such as density and velocity. Find the length of a cube that contains 10^6 molecules. Assume room conditions. Do calculations for (a) water and (b) air.

Solution. (a) The number of moles of water is $10^6/6.02 \times 10^{23} = 1.66 \times 10^{-18}$ mol. The mass of the water is $(1.66 \times 10^{-18}\text{ mol})(0.0180\text{ kg/mol}) = 2.99 \times 10^{-20}$ kg. The volume of the cube is $(2.99 \times 10^{-20}\text{ kg})/(999\text{ kg/m}^3) = 2.99 \times 10^{-23}\text{ m}^3$. Thus, the length of the side of a cube is 3.1×10^{-8} m. (b) Repeating this calculation with air gives a length of 3.5×10^{-7} m.

Review. For the continuum assumption to apply, the object being analyzed would need to be larger than the lengths calculated in the solution. If we select 100 times larger as our criteria, then the *continuum assumption applies* to objects with:

- Length $(L) > 3.1 \times 10^{-6}$ m (for liquid water at room conditions)
- Length $(L) > 3.5 \times 10^{-5}$ m (for air at room conditions)

Given the two length scales just calculated, it is apparent that the *continuum assumption applies to most problems of engineering importance*. However, there are a few situations where the problem length scales are too small.

EXAMPLE. When air is in motion at a very low density, such as when a spacecraft enters the earth's atmosphere, then the spacing between molecules is significant in comparison to the size of the spacecraft.

EXAMPLE. When a fluid flows through the tiny passages in nanotechnology devices, then the spacing between molecules is significant compared to the size of these passageways.

1.3 Weight, Mass, and Newton's Law of Gravitation

This section reviews weight and mass and also introduce ideas (called the "voice of the engineer") that will help you learn fluid mechanics better.

Voice of the Engineer. *Build working knowledge in every subject that you learn*. Working knowledge is defined as knowledge that you have firmly locked into your brain (no need to look up anything) that is useful for engineering tasks. **Rationale**. Working knowledge is essential for estimation and validation, and these two skills are essential for doing engineering well. Examples of working knowledge are as follows:

- 1.0 pound of force (i.e., 1.0 lbf) is about 4.5 newtons.
- 1.0 horsepower is about 750 watts.
- The weight of water at typical room conditions is about 10,000 newtons for each cubic meter.

Voice of the Engineer. Learn the meaning of main concepts such as mass and force. **Rationale**. Understanding concepts and the relationships between these concepts is needed if you want to apply your knowledge.

Defining Mass

The *mass* of 1.0 liters of liquid water at room conditions is 1.0 kilograms. A body with a *mass* of 2.0 slugs has a *mass* of 29 kilograms. In Newton's second law, the sum-of-forces-vector is exactly balanced by the product of the *mass* and the acceleration. **Mass** is a property of a *body* that provides a measure of the amount of matter in the body. For example, Body *A*, which has a mass of 20 grams, has more matter than Body *B*, which has a mass of 5 grams.

Recommended working knowledge. Know four mass units (kilograms, grams, slugs, and pounds mass) and be able to convert between these units without the need of a calculator*. Regarding conversion formulas, see Table F.1, which is located on the inside cover of this text.

Defining Force

When water falls in a waterfall, we can say that the earth is pulling on the water with a force that is called the *gravity force*. When wind blows on a stop sign, we can say that the air is exerting a *drag force* on the sign. When water behind a dam pushes on the dam, we can say that the water is exerting a *hydrostatic force* on the face of the dam.

Some facts about force are as follows:

- Every force can be thought of a push or as a pull of one body on another.
- Force is a vector. In this text, we use a bold face roman font (e.g., **F**) to represent a vector. To represent the magnitude of a vector we use a italic font (e.g., *F*).
- *Recommended working knowledge.* Know two force units: pounds-force (lbf) and newtons (N). Be able to convert units (i.e., make estimates) without the need of a calculator.
- Forces classify into two categories:
  - A **surface force** is any force that requires the two bodies to be touching. Most forces are surface forces. Some books use the term *contact force*.

*Your accuracy should be typical of an engineering estimate—for example, within 10% of the number you would get if you used a calculator.

- A **body force** is any force that does not require the two bodies to be touching. There are only a few types of body forces (e.g., the *gravity force*, the *electrostatic force*, and the *magnetic force*).
- Another way to describe forces is to talk about *action forces* (a force that acts to cause a body to accelerate) and *reaction forces* (a force that acts to prevent a body from accelerating; typically a force from a support). We do not use the concepts of action and reaction forces in this textbook.

In summary, a **force** is a push or pull between two bodies. A push or pull is an action that will cause a body to accelerate if the sum-of-forces vector in Newton's Second Law of Motion is nonzero.

Equation Literacy

Voice of the Engineer. Build equation literacy in all your engineering subjects. **Rationale**. Equation literacy is essential for building math models, and building math models is arguably the most important skill of the engineering method.

You have **equation literacy** for equation XYZ if you can do the following tasks: (1) You can explain how the equation was derived or where the equation came from. (2) You can explain the main ideas—that is, the physical interpretation—of the equation. (3) You can list the common equational forms, define each variable, and state the units and dimensions. (4) You can describe the assumptions and limitations of the equation and make correct choices about when to apply this equation or when to avoid applying this equation. (5) You have a systematic method for applying the equation correctly.

Newton's Law of Universal Gravitation (NLUG)

Newton's Law of Universal Gravitation (NLUG) reveals that any two bodies will attract each other with a force **F**, which is called the gravitational force (Fig. 1.6). Because this idea applies to any two bodies located anywhere in the universe, the equation is *universal* (hence the name).

The magnitude of the gravitational force F is given by

$$F = G\frac{m_1 m_2}{R^2} \tag{1.1}$$

where the term $G = 6.674 \times 10^{-11}\ \mathrm{N{\cdot}m^2/kg^2}$ is called the *gravitational constant*, m_1 is the mass of Body #1, m_2 is the mass of Body #2, and R is the distance between the center of mass of each body.

The law of gravity, like nearly all scientific laws, was developed by *inductive reasoning*. In particular, Newton examined data on planetary motion and found that the data were fit by Eq. (1.1). Newton concluded that the equation must be true in general.

To apply Eq. (1.1) on earth, start with Fig. 1.6 and let Body #1 represent the earth and Body #2 represent a body that is on or near the surface of the earth. Now, G and m_1 are constant and R is very nearly constant. Thus, define a new constant g that is given by $g \equiv Gm_E/R_E^2$, in

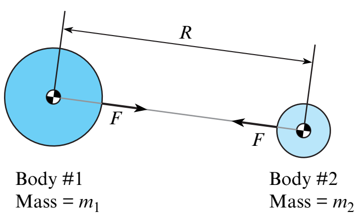


FIGURE 1.6

Any two bodies will attract one another. The corresponding force is called the **gravitational force**. Note that the magnitude of the gravitational force on Body #1 equals the magnitude of the gravitational force on Body #2.

which the subscript E denotes "earth." Also, rename the gravitational force F to be the weight of the body W. Then, Eq. (1.1) simplifies to

$$W = mg \tag{1.2}$$

where W is the weight of a body on a planet (typically Earth), m is the mass of the body, and g is a constant.

Useful Facts and Information

- The constant g is called **gravitational acceleration**. On earth, this parameter varies slightly with altitude; however, engineers commonly use the standard value, which is $g = 9.80665\ \text{m/s}^2 = 32.1740\ \text{ft/s}^2$.
- Gravitational acceleration (g) has a useful physical interpretation; g is the vertical component of acceleration that results when the vertical component of the sum-of-forces-vector in Newton's Second Law of Motion is exactly equal to the weight vector.
- In general, a falling body will not accelerate at a rate g because of the presence of additional forces, such as the lift force, the drag force, or the buoyant force.
- It is common for people to state that $W = mg$ is derived from $\Sigma \mathbf{F} = m\mathbf{a}$. However, it is more correct to say that $W = mg$ is derived from NLUG.
- **Weight** is the gravitational force acting on a body from a planet (typically Earth).
- Weight and mass are different concepts. For example, the mass of a body is the same at any location whereas the weight can change with location. For example, if a body weighs 60 newtons on Earth, the same body will weigh about 10 newtons on the moon. Also, recognize that it is common (but incorrect) to report a weight using mass units. For example, to say that a body weighs 10 grams or that a body weighs 60 kg is incorrect.

Relating Force and Mass Units

We wrote this section because we have seen many mistakes involving force and mass units. Three useful ideas about units are (1) units were invented by people, (2) units are related to each other by equations, and (3) the definition of a given unit can be looked up.

The definition of a newton is "one newton of force is the quantity of force that will give one kilogram of mass an acceleration of one meter per second squared."

To relate force and mass units, engineers start with Newton's second law of motion ($\Sigma \mathbf{F} = m\mathbf{a}$). Next, apply the definition of the newton to conclude that it must be true that

$$(1.0\ \text{N}) \equiv (1.0\ \text{kg})(1.0\ \text{m/s}^2) \tag{1.3}$$

Since Eq. (1.3) is true, it must also be true (by algebra) that

$$1.0 = \left(\frac{\text{kg} \cdot \text{m}}{\text{N} \cdot \text{s}^2}\right) \tag{1.4}$$

Thus, the weight of a 2.0 kilogram body must be 19.6 N because of the analysis shown in Eq. (1.5).

$$W = mg = \frac{2.0\ \cancel{\text{kg}}}{} \left| \frac{9.81\ \cancel{\text{m}}}{\cancel{\text{s}^2}} \right| \frac{\text{N} \cdot \cancel{\text{s}^2}}{\cancel{\text{kg}} \cdot \cancel{\text{m}}} = \boxed{19.6\ \text{N}} \tag{1.5}$$

Do you see the logic? Eq. (1.5) must be true because it is based on correct facts that are applied in a correct way. The main issue that we want to address is that many people become confused with English units. However, with English units you can apply the same logic. In particular, start with the definition of the pound-force (lbf). One pound of force is the amount of force that will accelerate one pound of mass (lbm) at a rate of 32.2 feet per second squared. Thus, it is true that

$$(1.0 \text{ lbf}) \equiv (1.0 \text{ lbm})(32.2 \text{ ft/s}^2) \tag{1.6}$$

Since Eq. (1.6) is true, it must also be true (by algebra) that

$$1.0 = \left(\frac{\text{lbf} \cdot \text{s}^2}{32.2 \text{ lbm} \cdot \text{ft}}\right) \tag{1.7}$$

Thus, the weight of a 2.0 lbm body must be 2.0 lbf because of the analysis shown in Eq. (1.8).

$$W = mg = \frac{2.0 \cancel{\text{lbm}}}{} \left| \frac{\cancel{32.2} \cancel{\text{ft}}}{\cancel{\text{s}^2}} \right| \frac{\text{lbf} \cdot \cancel{\text{s}^2}}{\cancel{32.2} \cancel{\text{lbm}} \cdot \cancel{\text{ft}}} = \boxed{2.0 \text{ lbf}} \tag{1.8}$$

Eq. (1.8) shows that the magnitude of the weight (2.0) is the same as the magnitude of the mass (2.0). This occurs because of the way that English units are defined. It is correct to say that a body that has a mass of 2.0 lbm will have a weight of 2.0 lbf on earth. However, avoid generalizing this. For example, a body with a mass of 2.0 lbm will have a weight about 0.33 lbf on the moon. Also, avoid saying that 2.0 lbm equals 2.0 lbf, because mass and weight are different concepts.

The General Equation

A **general equation** is an equation that applies to many or to all problems. A **special-case equation** is an equation that is derived from a general equation but is more limited in scope because there are assumptions that must to be met in order to apply the special-case equation.

Voice of the Engineer. *Learn the general equations and then derive each special-case equation on an as needed basis*. **Rationale**. (1) Given that there are only a few general equations, this approach will make your learning simpler. (2) You are less likely to make mistakes because general equations, by definition, apply more often than special-case equations. Examples of general and special case equations follow.

- NLUG is a general equation, and $W = mg$ is a special-case equation that is derived from NLUG.
- Newton's second law of motion, $\Sigma \mathbf{F} = m\mathbf{a}$, is general equation; note that this is a vector equation. Some special-case equations that can be derived from this equation are $\Sigma F_x = ma_x$ (a scalar equation) and $\Sigma F_z = 0$ (also a scalar equation).
- The general equation that defines mechanical work W is the line integral of the force vector dotted with the displacement vector $W = \oint_{x_1}^{x_2} \mathbf{F} \cdot \mathbf{dx}$. One associated special-case equation is $W = Fd$, where W is work, F is force, and d is displacement.

1.4 Essential Math Topics

Estimates

Voice of the Engineer. *Become skilled with pencil/paper estimates.* A **pencil/paper estimate** is defined as an estimate that you can do using only your brain, a pencil, and a sheet of paper (i.e., no books, calculators, or computers needed). **Rationale**: (1) All engineering calculations are estimates anyway; learning pencil/paper estimation skills will give you great insight into the nature of engineering estimates. (2) In the process of learning how to do pencil/paper estimates, you will acquire a great deal of practical knowledge. (3) You will save yourself huge amounts of time because you will do calculations much faster. (4) You will have strong methods for validating your technical work. (5) It is fun to figure out clever ways to estimate things.

Four Tips for Representing Numbers

To represent your numerical results in simple and effective ways, we have four recommendations:

1. Represent your result so that the digit term is between 0.1 and 1000; this makes your result easier to understand and remember. For example, 645798 can be represented as 646E3 or as 64.6E4 or as 6.46E5.
2. Use scientific or engineering notation to represent large and small numbers.
3. Use metric prefixes to represent numbers; for example, 142,711 pascals can be represented as 143 kPa.
4. Use a maximum of three significant figures to represent your final answers (unless you can justify more significant figures).

Scientific notation is method of writing a number as a product of two numbers: a digit term and an exponential term. For example, the number 7600 is written as the product of 7.6 (the digit term) and 10^3 (the exponential term) to give 7.6×10^3. **Fact.** There are three common forms of scientific notation, which are as follows: 7.6×10^3 = 7.6E3 (upper case "E") = 7.6e3 (lower case "e"). Avoid mixing up the "e" that is used in scientific notation with Euler's number, which is $e = 2.718$.

Engineering notation is a version of scientific notation in which the powers of 10 are written as multiples of three. **Example.** 0.000475 = 4.75E-4 (scientific notation) = 0.475E-3 (engineering notation) = 475E-6 (engineering notation). **Example.** 692000 = 6.92E5 (scientific notation) = 0.692e6 (engineering notation).

Unit Prefixes (Metric System). In the SI system, it is common to use prefixes on units to multiply or divide by powers of ten. **Example.** 0.001 newtons = 1.0 mN. **Example.** 0.000475 m = 0.475 mm = 475 μm. **Example.** 1000 pascals = 1.0 kPa.

Significant Figures. When a number is reported with three significant figures (e.g., 1.97), this means that two of the digits are known with precision (i.e., the 1 and the 9), and one of the digits (i.e., the 7) is an approximation. The rationale for significant figures is that values in engineering (e.g., the density of water is about 998 kg/m^3) ultimately come from measurements, and measurements can only provide certain levels of precision. In this text, we report answers with three significant figures. Of course, during intermediate calculations, you should carry more than three significant digits to prevent rounding errors.

Thinking with the Derivative

We have seen many mistakes because the main idea of the derivative was not in place. Thus, we wrote this subsection to explain this idea in detail.

To describe a common mistake, we'll give an example of this mistake. Suppose you were asked to answer the following true/false question. (**T/F**). If a car has traveled in a straight line for Δx = 10.0 meters during a time interval of Δt = 2.5 seconds, then its speed at the end of the time interval is (10.0 m)/(2.5 s) = 4.0 m/s.

It seems like one could answer this question as true, because $V = (\Delta x)/(\Delta t)$ = (10.0 m)/(2.5 s) = 4.0 m/s. However, this answer is only valid if the speed of the car was constant with time. A better answer is to say false, because there is not enough information to reach the conclusion that the car is traveling at 4 m/s at the end of the time interval. The problem we are illustrating is the difference between *average speed* and *instantaneous speed*. The best way to think about speed is to apply the definition of the derivative. In words, speed is the ratio of distance traveled to the amount of time in the limit as the amount of time goes to zero. In equation form (more compact), speed V is defined by

$$V = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} \quad (1.9)$$

If speed is constant, then Eq. (1.9) will automatically simplify to give the equation for average speed. If speed is varying with time, then Eq. (1.9) will give a correct value of speed. Of course, Eq. (1.9) is based on the definition of the derivative. Regarding this definition, calculus books give the definition in three ways:

$$\frac{dy}{dx} = \lim_{h\to 0}\frac{y(x+h) - y(x)}{h} \tag{1.10}$$

$$= \lim_{\Delta x\to 0}\frac{y(x+\Delta x) - y(x)}{\Delta x} \tag{1.11}$$

$$= \lim_{\Delta x\to 0}\frac{\Delta y}{\Delta x} \tag{1.12}$$

We apply the last definition, Eq. (1.12), in multiple places in this text. This definition shows that the derivative means the ratio of Δy to Δx in the limit as Δx goes to zero. Note that the delta symbol (i.e., the triangle) preceding the variable y denotes an amount or quantity of the variable y.

Thinking with the Integral

The integral was invented to solve problems in which rates change with time. To build up the definition of the integral, we note that it is tempting to state that the distance a car travels (Δx) is given by $\Delta x = V\Delta t$, where V is the speed and Δt is the time that the car has been traveling. The problem with this formula is that it does not apply in general, because speed can be changing. To modify the formula so that it is more general, one can do the following:

$$\Delta x = \sum_{i=1}^{N} V_i\,\Delta t_i \tag{1.13}$$

where the motion has been divided into time intervals. Here, Δt_i is a small time interval, V_i is the speed during this time interval, and N is the number of time intervals. To make this formula more accurate, we can let $N \to \infty$, and we arrive at a general formula for distance traveled:

$$\Delta x = \lim_{N\to\infty}\sum_{i=1}^{N} V_i\,\Delta t_i \tag{1.14}$$

Now, the summation on the right hand side of Eq. (1.14) can be modified by applying the definition of the integral to give

$$\Delta x = \int_0^{t_f} V\,dt \tag{1.15}$$

In calculus texts, you will find the following definition of the integral:

$$\int_a^b f(x)\,dx = \lim_{N\to\infty}\sum_{i=1}^{N} f(x_i)\,\Delta x_i \tag{1.16}$$

Thus, the integral is an infinite sum of small terms that is applied when a dependent variable f is changing in response to changes in the independent variable x.

1.5 Density and Specific Weight

Solving most problems in fluids requires calculation of mass or weight. These calculations involve the properties of density and specific weight, which are presented in this section.

Defining Density

For a simple problem, density (ρ) can be found by taking the ratio of mass (Δm) to volume ($\Delta \forall$) as in

$$\rho = \frac{\Delta m}{\Delta \forall} \tag{1.17}$$

For example, if you took 1.0 liter of water at room conditions and measured the mass, the amount of mass would be (Δm) ≈ 1000 grams, and so the density would be

$$\rho = \Delta m/\Delta \forall = (1000 \text{ grams})/(1.0 \text{ liter}) = 1.0 \text{ kg/L}$$

EXAMPLE. What is the mass of 2.5 liters of water? **Reasoning.** (1) The mass is given by $\Delta m = \rho(\Delta \forall)$. (2) The density of water at room conditions is about 1.0 kg/L. (3) Thus, the mass is $\Delta m = (1.0 \text{ kg/L})(2.5 \text{ L}) = 2.5$ kg.

Eq. (1.17) defines average density, not the density at a point. To build a more general definition of density, apply the concept of the derivative (see §1.4). In general, density is defined using the derivative as shown in Eq. (1.18).

$$\rho \equiv \lim_{\Delta \forall \to 0} \frac{\Delta m}{\Delta \forall} \tag{1.18}$$

where $\Delta \forall$ denotes the volume of a tiny region of material surrounding a point (e.g., an *x,y,z* location) and Δm is the corresponding amount of mass that is contained within this region. Thus, density can be defined as the ratio of mass to volume at a point.

Some useful facts about density are as follows:

- You can look up density values in the front of the book (Tables F.4 to F.6) and in the appendices (Tables A.2 to A.5).
- In general, the value of the density will vary with the pressure and temperature of the material. For a liquid, the variation with pressure is usually negligible.
- The density of a gas is often calculated by applying the *density form* of the ideal gas law: $p = \rho RT$.
- To calculate the amount of mass in a given volume, it is tempting to apply: $\Delta m = \rho \Delta \forall$. However, this equation is a special-case equation, not a general equation. The general equation which accounts for the fact that density can vary with position is

$$m = \int_{\forall} \rho \, d\forall \tag{1.19}$$

- *Recommended working knowledge*. Know the density of liquid water at typical room conditions in common units: $\rho = 1000 \text{ kg/m}^3 = 1.0 \text{ gram/mL} = 1.0 \text{ kg/L} = 62.4 \text{ lbm/ft}^3 = 1.94 \text{ slug/ft}^3$. Know the density of air at atmospheric pressure and 20°C: $\rho = 1.2 \text{ kg/m}^3 = 1.2 \text{ g/L}$.

Defining Specific Weight

Specific weight is the ratio of weight to volume at a point:

$$\gamma \equiv \lim_{\Delta \forall \to 0} \frac{\Delta W}{\Delta \forall} \tag{1.20}$$

where $\Delta V\!\!\!\!-$ denotes the volume of a tiny region of material surrounding a point (e.g., an x,y,z location) and ΔW is the corresponding weight of the mass that is contained within this region. Specific weight and density are related by this equation:

$$\gamma = \rho g \tag{1.21}$$

Thus, if you know one property, you can easily calculate the other. **Example**. The specific weight corresponding to a density of 800 kg/m^3 is $\gamma = (800\ \text{kg/m}^3)(9.81\ \text{m/s}^2) = 7.85\ \text{kN/m}^3$.

The reasoning to show that Eq. (1.21) is true involves the following steps. (1) On Earth, NLUG simplifies to $W = mg$. (2) Divide $W = mg$ by volume to give $(\Delta W/\Delta V\!\!\!\!-) = (\Delta m/\Delta V\!\!\!\!-)g$. (3) Take the limit as volume goes to zero. (4) Apply the definitions of γ and ρ to give $\gamma = \rho g$.

Some useful facts about specific weight are as follows:

- You can look values of γ in the front of the book (Tables F.4 to F.6) and in the back of the book (Tables A.3 to A.5).
- Since ρ and γ are related via Eq. (1.21), γ varies with temperature and pressure in a similar fashion to density.
- Specific weight is commonly used for liquids, but not commonly used for gases.
- *Recommended working knowledge*. Know the specific weight of liquid water at typical room conditions: $\gamma = 9800\ \text{N/m}^3 = 9.80\ \text{N/L} = 62.4\ \text{lbf/ft}^3$.

1.6 The Ideal Gas Law (IGL)

The IGL is commonly applied in fluid mechanics. For example, you will likely apply the IGL when you are designing products such as air bags, shock absorbers, combustion systems, and aircraft.

The IGL, the Ideal Gas, and the Real Gas

The IGL was developed by the logical method called induction. *Induction* involves making many experimental observations and then concluding that something is always true because every experiment indicates this truth. For example, if a person concludes that the sun will rise tomorrow because it has risen every day in the past, this is an example of inductive reasoning.

The IGL was developed by combining three empirical equations that had been discovered previously. The first of these equations, called Boyle's law, states that when temperature T is held constant, the pressure p and volume $V\!\!\!\!-$ of a fixed quantity of gas are related by

$$pV\!\!\!\!- = \text{constant} \qquad \text{(Boyle's law)} \tag{1.22}$$

The second equation, Charles's law, states that when pressure is held constant, the temperature and volume $V\!\!\!\!-$ of a fixed quantity of gas are related by

$$\frac{V\!\!\!\!-}{T} = \text{constant} \qquad \text{(Charles's law)} \tag{1.23}$$

The third equation was derived by a hypothesis formulated by Avogadro: *Equal volumes of gases at the same temperature and pressure contain equal number of molecules.* When Boyle's law, Charles's law, and Avogadro's law are combined, the result is the ideal gas equation in this form:

$$pV\!\!\!\!- = nR_uT \tag{1.24}$$

where n is the amount of gas measured in units of moles.

Eq. (1.24) is called the *$pV\!\!\!\!-T$ form* or the *mole form* of the IGL. **Tip**. There is no need to remember Charles' law, or Boyle's law, because they are both special cases of the IGL.

The ideal gas and the real gas can be defined as follows:

- An **ideal gas** refers to a gas which can be modeled using the ideal gas equation, Eq. (1.24), with an acceptable degree of accuracy; for example, calculations have less than a 5% deviation from the true values. Another way to define an ideal gas is to state that an ideal gas is any gas in which the molecules do not interact except during collisions.
- A **real gas** refers to a gas which cannot be modeled using the ideal gas equation, Eq. (1.24), with an acceptable degree of accuracy because the molecules are close enough together (on average) that there are forces between the molecules. Although real gas behavior can be modeled, the equations are more complex than the IGL. Thus, the IGL is the preferred model if it provides an acceptable level of accuracy.

For every problem that we (the authors) have solved, the IGL has provided a valid model for gas behavior; that is, we have never needed to apply the equations used to model real gas behavior. However, there are a few instances in which you should be careful about applying the IGL:

- When a gas is very cold or under very high pressure, then the molecules can move close enough together to invalidate the IGL.
- When both the liquid phase and the gas phase are present (e.g., propane in a tank used for a barbecue), you might want to be careful about applying the IGL to the gas phase.
- When a gas is very hot, such as the exhaust stream of a rocket, then the gas can ionize or disassociate. Both of these effects can invalidate the ideal gas law.

Also, the IGL works well for modeling a mixture of gases. The classic example is air, which is a mixture of nitrogen, oxygen, and other gases.

Units in the IGL

Because we have seen many mistakes with units, we wrote this subsection to give you the essential facts so that you can avoid most of these mistakes and also save time.

Temperature in the IGL must be expressed using *absolute temperature*. Absolute temperature is measured relative to a temperature of absolute zero, which is the temperature at which (theoretically) all molecular motion ceases. The SI unit of absolute temperature is Kelvin (K with no degree symbol, as in 300 K). A temperature given in Celsius (°C) can be converted to Kelvin using this equation: $T(\text{K}) = T(°\text{C}) + 273.15$. For example, a temperature of 15°C will convert to 15°C + 273 = 288 K. The English unit of absolute temperature is Rankine; for example, a temperature of 70°F is the same as a temperature of 530°R. A temperature given in Fahrenheit (°F) may be converted to Rankine using this equation: $T(°\text{R}) = T(°\text{F}) + 459.67$ For example, a temperature of 65°F will convert to 65°F + 460 = 525°R.

Pressure in the IGL must be expressed using *absolute pressure*. Absolute pressure is measured relative to a perfect vacuum, such as outer space. Now, it is common in engineering to give a value of pressure that is measured relative to local atmospheric pressure; this is called *gage pressure*. To convert a gage pressure to absolute pressure, add the value of local atmospheric pressure. For example, if the gage pressure is 20 kPa and the local atmospheric pressure is 100 kPa, then the absolute pressure will be 100 kPa + 20 kPa = 120 kPa. If the local atmospheric pressure is unavailable, then use the standard value of atmospheric pressure, which is 101.325 kPa (14.696 psi or 2116.2 psf). More details about pressure are presented in §3.1.

The IGL also uses the **mole**, defined as the amount of material that has the same number of "entities" (atoms, molecules, ions, etc.) as there are atoms in 12 grams of carbon 12 (C^{12}). Think of the mole as a way to count *how many*. By analogy, the dozen is also a unit for counting how many; for example, three dozen donuts is a way of specifying 36 donuts. The number of