MUNSON, YOUNG AND OKIISHI'S

FUNDAMENTALS OF FLUID MECHANICS

Eighth Edition

Philip M. Gerhart • Andrew L. Gerhart • John I. Hochstein

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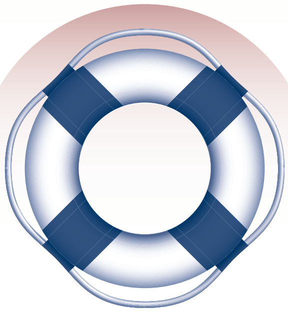

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Munson, Young, and Okiishi's

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Fundamentals of Fluid Mechanics

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About the Authors

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Dr. Gerhart has taught a variety of courses in fluid mechanics and other thermo-fluid sciences. He has consulted widely in the power generation and process industries and has authored or coauthored two previous books on fluid mechanics and fluid machinery.

Since 1975, he has been deeply involved in the development of the American Society of Mechanical Engineers Performance Test Codes. He served as ASME Vice President for Performance Test Codes from 1998 to 2001, and is currently a member and vice-chair of the Committee on Fans, chair of the Committee on Fired Steam Generators, and a member of the Standing Committee on Performance Test Codes.

Dr. Gerhart is a member of the American Society for Engineering Education and is a Life Fellow of the American Society of Mechanical Engineers. His honors and awards include the Outstanding Teacher Award from the Faculty Senate of the United Methodist Church, and the Performance Test Codes Medal from ASME.

Andrew L. Gerhart, Associate Professor of Mechanical Engineering at Lawrence Technological University, received his BSME degree from the University of Evansville in 1996, his MSME from the University of Wyoming, and his Ph.D. in Mechanical Engineering from the University of New Mexico.

At Lawrence Tech, Dr. Gerhart has developed both undergraduate and graduate courses in viscous flow, turbulence, creative problem solving, and first-year introductory engineering. He has co-developed college-wide curriculum in engineering design and university-wide curriculum in leadership. He is the supervisor of the Thermal Science and Aerodynamics Laboratories, Coordinator of the Aeronautical Engineering Minor/Certificate, chair of the First Year Engineering curriculum committee, and faculty advisor for the student branch of the American Institute of Aeronautics and Astronautics and the SAE Aero Design team.

Dr. Gerhart facilitates workshops worldwide, having trained hundreds of faculty members in active, collaborative, and problem-based learning, as well as training professional engineers and students in creative problem solving and innovation. He is a member of the American Society for Engineering Education and has received four best paper awards from their Annual Conferences.

Dr. Gerhart was awarded the 2010 Michigan Professor of the Year by the Carnegie Foundation for the Advancement of Teaching and the Council for Advancement and Support of Education, Lawrence Tech's Henry and Barbara Horldt Excellence in Teaching Award, the Engineering Society of Detroit's (ESD) Outstanding Young Engineer, and ESD's Council Leadership Award. He was elected to ESD's College of Fellows, and is actively involved with The American Society of Mechanical Engineers, serving on the Performance Test Code Committee for Air-Cooled Condensers.

John I. Hochstein, Professor of Mechanical Engineering at the University of Memphis, received a BE from Stevens Institute of Technology in 1973, an M.S. in Mechanical Engineering from the Pennsylvania State University in 1979, and his Ph.D. in Mechanical Engineering from the University of Akron in 1984. He has been on the faculty of the mechanical engineering department at the University of Memphis since 1991 and served as department chair from 1996 to 2014.

Working as an engineer in nonacademic positions, Dr. Hochstein contributed to the design of the Ohio-Class submarines at the Electric Boat Division of General Dynamics and to the design of the Clinch River Breeder Reactor while an engineer at the Babcock & Wilcox Company. The focus of his doctoral studies was computational modeling of spacecraft cryogenic propellant management systems, and he has remained involved with NASA research on this topic since that time.

Dr. Hochstein has twice been a NASA Summer Faculty Fellow for two consecutive summers: once at the NASA Lewis (now Glenn) Research Center, and once at the NASA Marshall Space Flight Center. Dr. Hochstein's current primary research focus is on the capture of hydrokinetic energy to produce electricity.

Dr. Hochstein is an Associate Fellow of AIAA and has served on the Microgravity Space Processes Technical Committee since 1986. He joined ASME as an undergraduate student and served for 4 years on the K20 Computational Heat Transfer Committee. He is a member of ASEE and has served the profession as an ABET Program Evaluator since 2002.

A Quarter-Century of Excellence

Bruce R. Munson, Professor Emeritus of Engineering Mechanics at Iowa State University, received his B.S. and M.S. degrees from Purdue University and his Ph.D. degree from the Aerospace Engineering and Mechanics Department of the University of Minnesota in 1970.

Prior to joining the Iowa State University faculty in 1974, Dr. Munson was on the mechanical engineering faculty of Duke University from 1970 to 1974. From 1964 to 1966, he worked as an engineer in the jet engine fuel control department of Bendix Aerospace Corporation, South Bend, Indiana.

Dr. Munson's main professional activity has been in the area of fluid mechanics education and research. He has been responsible for the development of many fluid mechanics courses for studies in civil engineering, mechanical engineering, engineering science, and agricultural engineering and is the recipient of an Iowa State University Superior Engineering Teacher Award and the Iowa State University Alumni Association Faculty Citation.

He has authored and coauthored many theoretical and experimental technical papers on hydrodynamic stability, low Reynolds number flow, secondary flow, and the applications of viscous incompressible flow. He is a member of The American Society of Mechanical Engineers.

Donald F. Young, Anson Marston Distinguished Professor Emeritus in Engineering, received his B.S. degree in mechanical engineering, his M.S. and Ph.D. degrees in theoretical and applied mechanics from Iowa State University, and has taught both undergraduate and graduate courses in fluid mechanics at Iowa State for many years. In addition to being named a Distinguished Professor in the College of Engineering, Dr. Young has also received the Standard Oil Foundation Outstanding Teacher Award and the Iowa State University Alumni Association Faculty Citation. He has been engaged in fluid mechanics research for more than 35 years, with special interests in similitude and modeling and the interdisciplinary field of biomedical fluid mechanics. Dr. Young has contributed to many technical publications and is the author or coauthor of two textbooks on applied mechanics. He is a Fellow of The American Society of Mechanical Engineers.

Ted H. Okiishi, Professor Emeritus of Mechanical Engineering at Iowa State University, joined the faculty there in 1967 after receiving his undergraduate and graduate degrees from that institution.

From 1965 to 1967, Dr. Okiishi served as a U.S. Army officer with duty assignments at the National Aeronautics and Space Administration Lewis Research Center, Cleveland, Ohio, where he participated in rocket nozzle heat transfer research, and at the Combined Intelligence Center, Saigon, Republic of South Vietnam, where he studied seasonal river flooding problems.

Professor Okiishi and his students have been active in research on turbomachinery fluid dynamics. Some of these projects have involved significant collaboration with government and industrial laboratory researchers, with two of their papers winning the ASME Melville Medal (in 1989 and 1998).

Dr. Okiishi has received several awards for teaching. He has developed undergraduate and graduate courses in classical fluid dynamics as well as the fluid dynamics of turbomachines.

He is a licensed professional engineer. His professional society activities include having been a vice president of The American Society of Mechanical Engineers (ASME) and of the American Society for Engineering Education. He is a Life Fellow of The American Society of Mechanical Engineers and past editor of its *Journal of Turbomachinery*. He was recently honored with the ASME R. Tom Sawyer Award.

Wade W. Huebsch, Associate Professor in the Department of Mechanical and Aerospace Engineering at West Virginia University, received his B.S. degree in aerospace engineering from San Jose State University where he played college baseball. He received his M.S. degree in mechanical engineering and his Ph.D. in aerospace engineering from Iowa State University in 2000.

Dr. Huebsch specializes in computational fluid dynamics research and has authored multiple journal articles in the areas of aircraft icing, roughness-induced flow phenomena, and boundary layer flow control. He has taught both undergraduate and graduate courses in fluid mechanics and has developed a new undergraduate course in computational fluid dynamics. He has received multiple teaching awards such as Outstanding Teacher and Teacher of the Year from the College of Engineering and Mineral Resources at WVU as well as the Ralph R. Teetor Educational Award from SAE. He was also named as the Young Researcher of the Year from WVU. He is a member of the American Institute of Aeronautics and Astronautics, the Sigma Xi research society, the Society of Automotive Engineers, and the American Society of Engineering Education.

Alric P. Rothmayer, Professor of Aerospace Engineering at Iowa State University, received his undergraduate and graduate degrees from the Aerospace Engineering Department at the University of Cincinnati, during which time he also worked at NASA Langley Research Center and was a visiting graduate research student at the Imperial College of Science and Technology in London. He joined the faculty at Iowa State University (ISU) in 1985 after a research fellowship sponsored by the Office of Naval Research at University College in London.

Dr. Rothmayer has taught a wide variety of undergraduate fluid mechanics and propulsion courses for over 25 years, ranging from classical low and high speed flows to propulsion cycle analysis.

Dr. Rothmayer was awarded an ISU Engineering Student Council Leadership Award, an ISU Foundation Award for Early Achievement in Research, an ISU Young Engineering Faculty Research Award, and a National Science Foundation Presidential Young Investigator Award. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA), and was chair of the 3rd AIAA Theoretical Fluid Mechanics Conference.

Dr. Rothmayer specializes in the integration of Computational Fluid Dynamics with asymptotic methods and low order modeling for viscous flows. His research has been applied to diverse areas ranging from internal flows through compliant tubes to flow control and aircraft icing. In 2001, Dr. Rothmayer won a NASA Turning Goals into Reality (TGIR) Award as a member of the Aircraft Icing Project Team, and also won a NASA Group Achievement Award in 2009 as a member of the LEWICE Ice Accretion Software Development Team. He was also a member of the SAE AC-9C Aircraft Icing Technology Subcommittee of the Aircraft Environmental Systems Committee of SAE and the Fluid Dynamics Technical Committee of AIAA.

Preface

This book is intended to help undergraduate engineering students learn the fundamentals of fluid mechanics. It was developed for use in a first course on fluid mechanics, either one or two semesters/terms. While the principles of this course have been well-established for many years, fluid mechanics education has evolved and improved.

With this eighth edition, a new team of authors is working to continue the distinguished tradition of this text. As it has throughout the past seven editions, the original core prepared by Munson, Young, and Okiishi remains. We have sought to augment this fine text, drawing on our many years of teaching experience. Based on our experience and suggestions from colleagues and students, we have made a number of changes to this edition. The changes (listed below, and indicated by the word ***New*** in descriptions in this preface) are made to clarify, update, and expand certain ideas and concepts.

New to This Edition

In addition to the continual effort of updating the scope of the material presented and improving the presentation of all of the material, the following items are new to this edition.

Self-Contained: Material that had been removed from the text and provided only on-line has been brought back into the text. Most notable are Section 5.4 on the second law of thermodynamics and useful energy loss and Appendix E containing units conversion factors.

Compressible Flow: Chapter 11 on compressible flow has been extensively reorganized and a limited amount of ***new*** material added. There are ten ***new*** example problems; some of them replace previous examples. All have special emphasis on engineering applications of the material. Example solutions employ tabulated compressible flow functions as well as graphs.

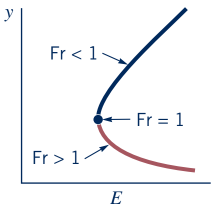
Appendices: Appendix A has been expanded. Compressible flow function tables have been added to Appendix D. A ***new*** extensive set of units conversion factors in a useful and compact format appears in Appendix E.

Computational Fluid Dynamics (CFD): A still unsettled issue in introductory fluid mechanics texts is what to do about computational fluid dynamics. A complete development of the subject is well beyond the scope of an introductory text; nevertheless, highly complex, highly capable CFD codes are being employed for engineering design and analysis in a continually expanding number of industries. We have chosen to provide a description of many of the challenges and practices that characterize widely used CFD codes. Our aim is twofold: to show how reasonably complex flows can be computed and to foster a healthy skepticism in the nonspecialist. This material is presented in an expanded Appendix A.

Problems and Examples: Many ***new*** examples and problems emphasize engineering applications. Approximately 30% ***new*** homework problems have been added for this edition, and there are additional problems in *WileyPLUS*.

Value: Nearly everyone is concerned about the upward spiral of textbook prices (yes, even authors and publishers!). We have taken a few modest steps to keep the price of this book reasonable. Most of these steps involve the removal of "bells and whistles." For example, the thumbnail photos that accompanied the video icons in the 7th edition have been dropped. Wiley has also developed a number of different products to meet differing student needs and budgets.

Key Features

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Illustrations, Photographs, and Videos

Fluid mechanics has always been a "visual" subject—much can be learned by viewing various characteristics of fluid flow. Fortunately this visual component is becoming easier to incorporate into the learning environment, for both access and delivery, and is an important help in learning fluid mechanics. Thus, many photographs and illustrations have been included in the book. Some of these are within the text material; some are used to enhance the example problems; and some are included as margin figures of the type shown in the left margin to more clearly illustrate various points discussed in the text. Numerous video segments illustrate many interesting and practical applications of real-world fluid phenomena. Each video segment is identified at the appropriate location in the text material by a video icon of the type shown in the left margin. Each video segment has a separate associated text description of what is shown in the video. There are many homework problems that are directly related to the topics in the videos.

Examples

VIDEO *V1.9 Floating razor blade*

One of our aims is to represent fluid mechanics as it really is—an exciting and useful discipline. To this end, we include analyses of numerous everyday examples of fluid-flow phenomena to which students and faculty can easily relate. In this edition there are numerous examples that provide detailed solutions to a variety of problems. Many of the examples illustrate engineering applications of fluid mechanics, as is appropriate in an engineering textbook. Several illustrate what happens if one or more of the parameters is changed. This gives the student a better feel for some of the basic principles involved. In addition, many of the examples contain photographs of the actual device or item involved in the example. Also, all of the examples are outlined and carried out with the problem solving methodology of "Given, Find, Solution, and Comment" as discussed in the "Note to User" before Example 1.1.

The Wide World of Fluids

The set of approximately 60 short "The Wide World of Fluids" stories reflect some important, and novel, ways that fluid mechanics affects our lives. Many of these stories have homework problems associated with them. The title of this feature has been changed from the 7th edition's "Fluids in the News" because the stories cover more than just the latest developments in fluid mechanics.

Homework Problems

A wide variety of homework problems (approximately 30% ***new*** to this edition) stresses the practical application of principles. The problems are grouped and identified according to topic. The following types of problems are included:

1) "standard" problems,
2) computer problems,
3) discussion problems,
4) supply-your-own-data problems,
5) problems based on "The Wide World of Fluids" topics,
6) problems based on the videos,
7) "Lifelong learning" problems,
8) problems that require the user to obtain a photograph/image of a given flow situation and write a brief paragraph to describe it,

Computer Problems—Several problems are designated as computer problems. Depending on the preference of the instructor or student, *any* of the problems with numerical data may be solved with the aid of a personal computer, a programmable calculator, or even a smartphone.

Lifelong Learning Problems—Each chapter has lifelong learning problems that involve obtaining additional information about various fluid mechanics topics and writing a brief report about this material.

Well-Paced Concept and Problem-Solving Development

Since this is an introductory text, we have designed the presentation of material to allow for the gradual development of student confidence in fluid mechanics problem solving. Each important concept or notion is considered in terms of simple and easy-to-understand circumstances before more complicated features are introduced. Many pages contain a brief summary (a highlight) sentence in the margin that serves to prepare or remind the reader about an important concept discussed on that page.

Several brief elements have been included in each chapter to help the student see the "big picture" and recognize the central points developed in the chapter. A brief Learning Objectives section is provided at the beginning of each chapter. It is helpful to read through this list prior to reading the chapter to gain a preview of the main concepts presented. Upon completion of the chapter, it is beneficial to look back at the original learning objectives. Additional reinforcement of these learning objectives is provided in the form of a Chapter Summary and Study Guide at the end of each chapter. In this section a brief summary of the key concepts and principles introduced in the chapter is included along with a listing of important terms with which the student should be familiar. These terms are highlighted in the text. All items in the Learning Objectives and the Study Guide are "action items" stating something that the student should be able to *do*. A list of the main equations in the chapter is included in the chapter summary.

System of Units

Three systems of units are used throughout the text: the International System of Units (newtons, kilograms, meters, and seconds), the British Gravitational System (pounds, slugs, feet, and seconds), and the English Engineering System, sometimes called the U.S. Customary System (pounds (or pounds force), pounds mass, feet, and seconds). Distribution of the examples and homework problems between the three sets of units is about 50%, 40%, 10%.

Prerequisites and Topical Organization

A first course in Fluid Mechanics typically appears in the junior year of a traditional engineering curriculum. Students should have studied statics and dynamics, and mechanics of materials should be at least a co-requisite. Prior mathematics should include calculus, with at least the rudiments of vector calculus, and differential equations.

In the first four chapters of this text the student is made aware of some fundamental aspects of fluid mechanics, including important fluid properties, flow regimes, pressure variation in fluids at rest and in motion, fluid kinematics, and methods of flow description and analysis. The Bernoulli equation is introduced in Chapter 3 to draw attention, early on, to some of the interesting effects and applications of the relationship between fluid motion and pressure in a flow field. We believe that this early consideration of elementary fluid dynamics increases student enthusiasm for the more complicated material that follows. In Chapter 4 we convey the essential elements of flow kinematics, including Eulerian and Lagrangian descriptions of flow fields, and indicate the vital relationship between the two views. For instructors who wish to consider kinematics in detail before the material on elementary fluid dynamics, Chapters 3 and 4 can be interchanged without loss of continuity.

Chapters 5, 6, and 7 expand on the basic methods generally used to solve or to begin solving fluid mechanics problems. Emphasis is placed on understanding how flow phenomena are described mathematically and on when and how to use infinitesimal or finite control volumes. The effects of fluid friction on pressure and velocity are also considered in some detail. Although Chapter 5 considers fluid energy and energy dissipation, a formal course in thermodynamics is not a necessary prerequisite. Chapter 7 features the advantages of using dimensional analysis and similitude for organizing data and for planning experiments and the basic techniques involved.

Owing to the growing importance of computational fluid dynamics (CFD) in engineering design and analysis, material on this subject is included in Appendix A. This material may be omitted without any loss of continuity to the rest of the text.

Chapters 8 through 12 offer students opportunities for the further application of the principles learned earlier in the text. Also, where appropriate, additional important notions such as boundary layers, transition from laminar to turbulent flow, turbulence modeling, and flow separation are introduced. Practical concerns such as pipe flow, open-channel flow, flow measurement, drag and lift, the effects of compressibility, and the fundamental fluid mechanics of turbomachinery are included.

Students who study this text and solve a representative set of the problems will have acquired a useful knowledge of the fundamentals of fluid mechanics. Faculty who use this text are provided with numerous topics to select from in order to meet the objectives of their own courses. More material is included than can be reasonably covered in one term. There is sufficient material for a second course, most likely titled "Applied Fluid Mechanics." All are reminded of the fine collection of supplementary material. We have cited throughout the text various articles and books that are available for enrichment.

Instructor Resources

WileyPLUS provides instructor resources, such as the Instructor Solutions Manual, containing complete, detailed solutions to all of the problems in the text, and figures from the text appropriate for use in lecture slides. Sign up for access at www.wileyplus.com.

Student Resources:

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- Integrated, multimedia resources—including fluids phenomena videos, problem-solving videos, What An Engineer Sees animations, practice reading questions, and much more—that provide multiple study paths and encourage more active learning.

What do instructors receive with *WileyPLUS*?

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Acknowledgments

First, we wish to express our gratitude to Bruce Munson, Donald Young, Ted Okiishi, Wade Huebsch, and Alric Rothmayer for their part in producing seven editions of this excellent book. Also we thank the people at Wiley, especially Don Fowley, Linda Ratts, and Jenny Welter, for trusting us to assume responsibility for this text. Finally, we thank our families for their continued encouragement during the writing of this edition.

Working with students and colleagues over the years has taught us much about fluid mechanics education. We have drawn from this experience for the benefit of users of this book. Obviously we are still learning, and we welcome any suggestions and comments from you.

Philip M. Gerhart
Andrew L. Gerhart
John I. Hochstein

Contents

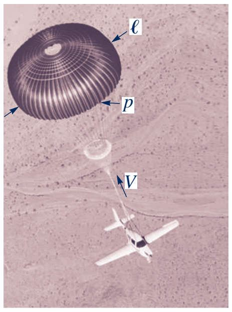
1 Introduction

Learning Objectives

After completing this chapter, you should be able to:

- list the dimensions and units of physical quantities.
- identify the key fluid properties used in the analysis of fluid behavior.
- calculate values for common fluid properties given appropriate information.
- explain effects of fluid compressibility.
- use the concepts of viscosity, vapor pressure, and surface tension.

Fluid mechanics is the discipline within the broad field of applied mechanics that is concerned with the behavior of liquids and gases at rest or in motion. It covers a vast array of phenomena that occur in nature (with or without human intervention), in biology, and in numerous engineered, invented, or manufactured situations. There are few aspects of our lives that do not involve fluids, either directly or indirectly.



(Photograph courtesy of CIRRUS Design Corporation.)

The immense range of different flow conditions is mind-boggling and strongly dependent on the value of the numerous parameters that describe fluid flow. Among the long list of parameters involved are (1) the physical size of the flow, ℓ; (2) the speed of the flow, V; and (3) the pressure, p, as indicated in the figure in the margin for a light aircraft parachute recovery system. These are just three of the important parameters that, along with many others, are discussed in detail in various sections of this book. To get an inkling of the range of some of the parameter values involved and the flow situations generated, consider the following.

- Size, ℓ

  Every flow has a characteristic (or typical) length associated with it. For example, for flow of fluid within pipes, the pipe diameter is a characteristic length. Pipe flows include the flow of water in the pipes in our homes, the blood flow in our arteries and veins, and the airflow in our bronchial tree. They also involve pipe sizes that are not within our everyday experiences. Such examples include the flow of oil across Alaska through a 4-foot-diameter, 799-mile-long pipe and, at the other end of the size scale, the new area of interest involving flow in nano scale pipes whose diameters are on the order of 10^{-8} m. Each of these pipe flows has important characteristics that are not found in the others.

  Characteristic lengths of some other flows are shown in Fig. 1.1*a*.

- Speed, V

  As we note from The Weather Channel, on a given day the wind speed may cover what we think of as a wide range, from a gentle 5-mph breeze to a 100-mph hurricane or a 250-mph

VIDEO *V1.1 Mt. St. Helens eruption*

tornado. However, this speed range is small compared to that of the almost imperceptible flow of the fluid-like magma below the Earth's surface that drives the continental drift motion of the tectonic plates at a speed of about 2×10^{-8} m/s or the hypersonic airflow around a meteor as it streaks through the atmosphere at 3×10^4 m/s.

Characteristic speeds of some other flows are shown in Fig. 1.1*b*.

■ Pressure, p

The pressure within fluids covers an extremely wide range of values. We are accustomed to the 35 psi (lb/in.^{2}) pressure within our car's tires, the "120 over 70" typical blood pressure reading, or the standard 14.7 psi atmospheric pressure. However, the large 10,000 psi pressure in the hydraulic ram of an earth mover or the tiny 2×10^{-6} psi pressure of a sound wave generated at ordinary talking levels are not easy to comprehend.

Characteristic pressures of some other flows are shown in Fig. 1.1*c*.

The list of fluid mechanics applications goes on and on. But you get the point. Fluid mechanics is a very important, practical subject that encompasses a wide variety of situations. It is very likely that during your career as an engineer you will be involved in the analysis and design of systems that require a good understanding of fluid mechanics. Although it is not possible to adequately cover all of the important areas of fluid mechanics within one book, it is hoped that this introductory text will provide a sound foundation of the fundamental aspects of fluid mechanics.

VIDEO *V1.2 E. coli swimming*

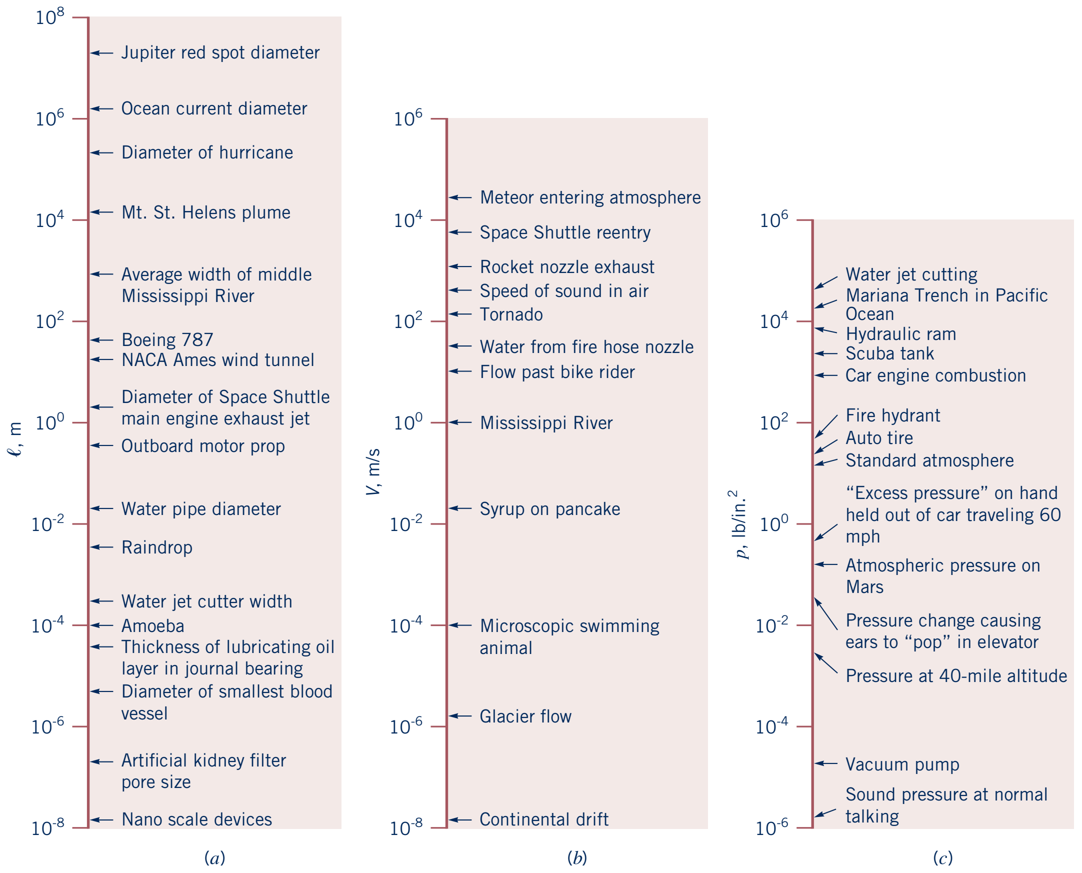


Figure 1.1 **Characteristic values of some fluid flow parameters for a variety of flows: (*a*) object size, (*b*) fluid speed, (*c*) fluid pressure.**

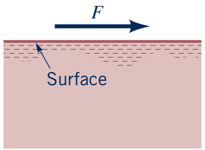
1.1 Some Characteristics of Fluids

One of the first questions we need to explore is—what is a fluid? Or we might ask–what is the difference between a solid and a fluid? We have a general, vague idea of the difference. A solid is "hard" and not easily deformed, whereas a fluid is "soft" and is easily deformed (we can readily move through air). Although quite descriptive, these casual observations of the differences between solids and fluids are not very satisfactory from a scientific or engineering point of view. A closer look at the molecular structure of materials reveals that matter that we commonly think of as a solid (steel, concrete, etc.) has densely spaced molecules with large intermolecular cohesive forces that allow the solid to maintain its shape, and to not be easily deformed. However, for matter that we normally think of as a liquid (water, oil, etc.), the molecules are spaced farther apart, the intermolecular forces are smaller than for solids, and the molecules have more freedom of movement. Thus, liquids can be easily deformed (but not easily compressed) and can be poured into containers or forced through a tube. Gases (air, oxygen, etc.) have even greater molecular spacing and freedom of motion with negligible cohesive intermolecular forces, and as a consequence are easily deformed (and compressed) and will completely fill the volume of any container in which they are placed. Both liquids and gases are fluids.

Both liquids and gases are fluids.

THE WIDE WORLD OF FLUIDS

Will what works in air work in water? For the past few years a San Francisco company has been working on small, maneuverable submarines designed to travel through water using wings, controls, and thrusters that are similar to those on jet airplanes. After all, water (for submarines) and air (for airplanes) are both fluids, so it is expected that many of the principles governing the flight of airplanes should carry over to the "flight" of winged submarines. Of course, there are differences. For example, the submarine must be designed to withstand external pressures of nearly 700 pounds per square inch greater than that inside the vehicle. On the other hand, at high altitude where commercial jets fly, the exterior pressure is 3.5 psi rather than standard sea-level pressure of 14.7 psi, so the vehicle must be pressurized internally for passenger comfort. In both cases, however, the design of the craft for minimal drag, maximum lift, and efficient thrust is governed by the same fluid dynamic concepts.



Although the differences between solids and fluids can be explained qualitatively on the basis of molecular structure, a more specific distinction is based on how they deform under the action of an external load. Specifically, *a **fluid** is defined as a substance that deforms continuously when acted on by a shearing stress of any magnitude.* A shearing stress (force per unit area) is created whenever a tangential force acts on a surface as shown by the figure in the margin. When common solids such as steel or other metals are acted on by a shearing stress, they will initially deform (usually a very small deformation), but they will not continuously deform (flow). However, common fluids such as water, oil, and air satisfy the definition of a fluid—that is, they will flow when acted on by a shearing stress. Some materials, such as slurries, tar, putty, toothpaste, and so on, are not easily classified since they will behave as a solid if the applied shearing stress is small, but if the stress exceeds some critical value, the substance will flow. The study of such materials is called *rheology* and does not fall within the province of classical fluid mechanics. Thus, all the fluids we will be concerned with in this text will conform to the definition of a fluid.

Although the molecular structure of fluids is important in distinguishing one fluid from another, it is not yet practical to study the behavior of individual molecules when trying to describe the behavior of fluids at rest or in motion. Rather, we characterize the behavior by considering the average, or macroscopic, value of the quantity of interest, where the average is evaluated over a small volume containing a large number of molecules. Thus, when we say that the velocity at a certain point in a fluid is so much, we are really indicating the average velocity of the molecules in a small volume surrounding the point. The volume is small compared with the physical dimensions of the system of interest, but large compared with the average distance between molecules. Is this a reasonable way to describe the behavior of a fluid? The answer is generally yes, since the spacing between molecules is typically very small. For gases at normal pressures and temperatures, the spacing is on the order of 10^{-6} mm, and for liquids it is on the order of 10^{-7} mm. The number of molecules per cubic millimeter is on the order of 10^{18} for gases and 10^{21} for liquids. It is thus clear that the number of molecules in a very tiny volume is huge and the idea of using average values taken over this volume is certainly reasonable. We thus assume that all the fluid characteristics we are interested in (pressure, velocity, etc.) vary continuously throughout the fluid—that is, we treat the fluid as a *continuum* and we refer to the very small volume as a point in the flow. This concept will certainly be valid for all the circumstances considered in this text. One area of fluid mechanics for which the continuum concept breaks down is in the study of rarefied gases such as would be encountered at very high altitudes. In this case the spacing between air molecules can become large and the continuum concept is no longer acceptable.

1.2 Dimensions, Dimensional Homogeneity, and Units

Fluid characteristics can be described qualitatively in terms of certain basic quantities such as length, time, and mass.

Since in our study of fluid mechanics we will be dealing with a variety of fluid characteristics, it is necessary to develop a system for describing these characteristics both *qualitatively* and *quantitatively.* The qualitative aspect serves to identify the nature, or type, of the characteristics (such as length, time, stress, and velocity), whereas the quantitative aspect provides a numerical measure of the characteristics. The quantitative description requires both a number and a standard by which various quantities can be compared. A standard for length might be a meter or foot, for time an hour or second, and for mass a slug or kilogram. Such standards are called ***units,*** and several systems of units are in common use as described in the following section. The qualitative description is conveniently given in terms of certain *primary quantities,* such as length, L, time, T, mass, M, and temperature, Θ. These primary quantities can then be used to provide a qualitative description of any other *secondary quantity*: for example, area $\doteq L^2$, velocity $\doteq LT^{-1}$, density $\doteq ML^{-3}$, and so on, where the symbol $\doteq$ is used to indicate the *dimensions* of the secondary quantity in terms of the primary quantities. Thus, to describe qualitatively a velocity, V, we would write

$$V \doteq LT^{-1}$$

and say that "the dimensions of a velocity equal length divided by time." The primary quantities are also referred to as ***basic dimensions.***

For a wide variety of problems involving fluid mechanics, only the three basic dimensions, L, T, and M are required. Alternatively, L, T, and F could be used, where F is the basic dimensions of force. Since Newton's law states that force is equal to mass times acceleration, it follows that $F \doteq MLT^{-2}$ or $M \doteq FL^{-1}T^2$. Thus, secondary quantities expressed in terms of M can be expressed in terms of F through the relationship above. For example, stress, σ, is a force per unit area, so that $\sigma \doteq FL^{-2}$, but an equivalent dimensional equation is $\sigma \doteq ML^{-1}T^{-2}$. Table 1.1 provides a list of dimensions for a number of common physical quantities.

All theoretically derived equations are ***dimensionally homogeneous***—that is, the dimensions of the left side of the equation must be the same as those on the right side, and all additive separate terms must have the same dimensions. We accept as a fundamental premise that all equations describing physical phenomena must be dimensionally homogeneous. If this were not true, we would be attempting to equate or add unlike physical quantities, which would not make sense. For example, the equation for the velocity, V, of a uniformly accelerated body is

$$V = V_0 + at \tag{1.1}$$

where V_0 is the initial velocity, a the acceleration, and t the time interval. In terms of dimensions the equation is

$$LT^{-1} \doteq LT^{-1} + LT^{-2}T$$

and thus Eq. 1.1 is dimensionally homogeneous.

Some equations that are known to be valid contain constants having dimensions. The equation for the distance, d, traveled by a freely falling body can be written as

$$d = 16.1t^2 \tag{1.2}$$

Table 1.1

Dimensions Associated with Common Physical Quantities

	FLT System	*MLT* System
Acceleration	LT^{-2}	LT^{-2}
Angle	$F^0L^0T^0$	$M^0L^0T^0$
Angular acceleration	T^{-2}	T^{-2}
Angular velocity	T^{-1}	T^{-1}
Area	L^2	L^2
Density	$FL^{-4}T^2$	ML^{-3}
Energy	FL	ML^2T^{-2}
Force	F	MLT^{-2}
Frequency	T^{-1}	T^{-1}
Heat	FL	ML^2T^{-2}
Length	L	L
Mass	$FL^{-1}T^2$	M
Modulus of elasticity	FL^{-2}	$ML^{-1}T^{-2}$
Moment of a force	FL	ML^2T^{-2}
Moment of inertia (area)	L^4	L^4
Moment of inertia (mass)	FLT^2	ML^2
Momentum	FT	MLT^{-1}
Power	FLT^{-1}	ML^2T^{-3}
Pressure	FL^{-2}	$ML^{-1}T^{-2}$
Specific heat	$L^2T^{-2}\Theta^{-1}$	$L^2T^{-2}\Theta^{-1}$
Specific weight	FL^{-3}	$ML^{-2}T^{-2}$
Strain	$F^0L^0T^0$	$M^0L^0T^0$
Stress	FL^{-2}	$ML^{-1}T^{-2}$
Surface tension	FL^{-1}	MT^{-2}
Temperature	Θ	Θ
Time	T	T
Torque	FL	ML^2T^{-2}
Velocity	LT^{-1}	LT^{-1}
Viscosity (dynamic)	$FL^{-2}T$	$ML^{-1}T^{-1}$
Viscosity (kinematic)	L^2T^{-1}	L^2T^{-1}
Volume	L^3	L^3
Work	FL	ML^2T^{-2}

and a check of the dimensions reveals that the constant must have the dimensions of LT^{-2} if the equation is to be dimensionally homogeneous. Actually, Eq. 1.2 is a special form of the well-known equation from physics for freely falling bodies,

$$d = \frac{gt^2}{2} \tag{1.3}$$

in which g is the acceleration of gravity. Equation 1.3 is dimensionally homogeneous and valid in any system of units. For $g = 32.2 \text{ ft/s}^2$ the equation reduces to Eq. 1.2 and thus Eq. 1.2 is valid only for the system of units using feet and seconds. Equations that are restricted to a particular system of units can be denoted as *restricted homogeneous equations,* as opposed to equations valid in any system of units, which are *general homogeneous equations.* The preceding discussion indicates one rather elementary, but important, use of the concept of dimensions: the determination of one aspect of the generality of a given equation simply based on a consideration of the dimensions of the various terms in the equation. The concept of dimensions also forms the basis for the powerful tool of *dimensional analysis,* which is considered in detail in Chapter 7.

General homogeneous equations are valid in any system of units.

Note to the users of this text. All of the examples in the text use a consistent problem-solving methodology, which is similar to that in other engineering courses such as statics. Each example highlights the key elements of analysis: ***Given, Find, Solution,*** and ***Comment.***

The ***Given*** and ***Find*** are steps that ensure the user understands what is being asked in the problem and explicitly list the items provided to help solve the problem.

The ***Solution*** step is where the equations needed to solve the problem are formulated and the problem is actually solved. In this step, there are typically several other tasks that help to set up the solution and are required to solve the problem. The first is a drawing of the problem; where appropriate, it is always helpful to draw a sketch of the problem. Here the relevant geometry and coordinate system to be used as well as features such as control volumes, forces and pressures, velocities, and mass flow rates are included. This helps in gaining an understanding of the problem. Making appropriate assumptions to solve the problem is the second task. In a realistic engineering problem-solving environment, the necessary assumptions are developed as an integral part of the solution process. Assumptions can provide appropriate simplifications or offer useful constraints, both of which can help in solving the problem. Throughout the examples in this text, the necessary assumptions are embedded within the ***Solution*** step, as they are in solving a real-world problem. This provides a realistic problem-solving experience.

The final element in the methodology is the ***Comment.*** For the examples in the text, this section is used to provide further insight into the problem or the solution. It can also be a point in the analysis at which certain questions are posed. For example: Is the answer reasonable, and does it make physical sense? Are the final units correct? If a certain parameter were changed, how would the answer change? Adopting this type of methodology will aid in the development of problem-solving skills for fluid mechanics, as well as other engineering disciplines.

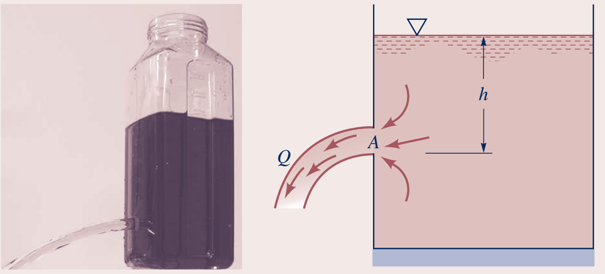
EXAMPLE 1.1 Restricted and General Homogeneous Equations

GIVEN A liquid flows through an orifice located in the side of a tank as shown in Fig. E1.1. A commonly used equation for determining the volume rate of flow, Q, through the orifice is

$$Q = 0.61\, A\sqrt{2gh}$$

where A is the area of the orifice, g is the acceleration of gravity, and h is the height of the liquid above the orifice.

FIND Investigate the dimensional homogeneity of this formula.



(*a*) (*b*)

■ **Figure E1.1**

SOLUTION

The dimensions of the various terms in the equation are $Q =$ volume/time $\doteq L^3T^{-1}$, $A =$ area $\doteq L^2$, $g =$ acceleration of gravity $\doteq LT^{-2}$, and $h =$ height $\doteq L$.

These terms, when substituted into the equation, yield the dimensional form:

$$(L^3T^{-1}) \doteq (0.61)(L^2)(\sqrt{2})(LT^{-2})^{1/2}(L)^{1/2}$$

or

$$(L^3T^{-1}) \doteq [0.61\sqrt{2}](L^3T^{-1})$$

It is clear from this result that the equation is dimensionally homogeneous (both sides of the formula have the same dimensions of L^3T^{-1}), and the number $0.61\sqrt{2}$ is dimensionless.

If we were going to use this relationship repeatedly, we might be tempted to simplify it by replacing g with its standard value of 32.2 ft/s^2 and rewriting the formula as

$$Q = 4.90\, A\sqrt{h} \qquad \textbf{(1)}$$

A quick check of the dimensions reveals that

$$L^3T^{-1} \doteq (4.90)(L^{5/2})$$

and, therefore, the equation expressed as Eq. 1 can only be dimensionally correct if the number 4.90 has the dimensions of $L^{1/2}T^{-1}$. Whenever a number appearing in an equation or formula has dimensions, it means that the specific value of the number will depend on the system of units used. Thus, for the case being considered with feet and seconds used as units, the number 4.90 has units of ft$^{1/2}$/s. Equation 1 will only give the correct value for Q (in ft^3/s) when A is expressed in square feet and h in feet. Thus, Eq. 1 is a *restricted* homogeneous equation, whereas the original equation is a *general* homogeneous equation that would be valid for any consistent system of units.

COMMENT A quick check of the dimensions of the various terms in an equation is a useful practice and will often be helpful in eliminating errors—that is, as noted previously, all physically meaningful equations must be dimensionally homogeneous. We have briefly alluded to units in this example, and this important topic will be considered in more detail in the next section.

1.2.1 Systems of Units

In addition to the qualitative description of the various quantities of interest, it is generally necessary to have a quantitative measure of any given quantity. For example, if we measure the width of this page in the book and say that it is 10 units wide, the statement has no meaning until the unit of length is defined. If we indicate that the unit of length is a meter, and define the meter as some standard length, a unit system for length has been established (and a numerical value can be given to the page width). In addition to length, a unit must be established for each of the remaining basic quantities (force, mass, time, and temperature). There are several systems of units in use, and we shall consider three systems that are commonly used in engineering.

International System (SI). In 1960 the Eleventh General Conference on Weights and Measures, the international organization responsible for maintaining precise uniform standards of measurements, formally adopted the *International System of Units* as the international standard. This system, commonly termed SI, has been widely adopted worldwide and is widely used (although certainly not exclusively) in the United States. It is expected that the long-term trend will be for all countries to accept SI as the accepted standard and it is imperative that engineering students become familiar with this system. In SI the unit of length is the meter (m), the time unit is the second (s), the mass unit is the kilogram (kg), and the temperature unit is the kelvin (K). Note that there is no degree symbol used when expressing a temperature in kelvin units. The kelvin temperature scale is an absolute scale and is related to the Celsius (centigrade) scale (°C) through the relationship

$$\mathrm{K} = {}^\circ\mathrm{C} + 273.15$$

Although the Celsius scale is not in itself part of SI, it is common practice to specify temperatures in degrees Celsius when using SI units.

The force unit, called the newton (N), is defined from Newton's second law as

$$1\ \mathrm{N} = (1\ \mathrm{kg})(1\ \mathrm{m/s^2})$$

In mechanics it is very important to distinguish between weight and mass.

Thus, a 1-N force acting on a 1-kg mass will give the mass an acceleration of 1 $\mathrm{m/s^2}$. Standard gravity in SI is 9.807 $\mathrm{m/s^2}$ (commonly approximated as 9.81 $\mathrm{m/s^2}$) so that a 1-kg mass weighs 9.81 N under standard gravity. Note that weight and mass are different, both qualitatively and quantitatively! The unit of *work* in SI is the joule (J), which is the work done when the point of application of a 1-N force is displaced through a 1-m distance in the direction of a force. Thus,

$$1\ \mathrm{J} = 1\ \mathrm{N \cdot m}$$

The unit of *power* is the watt (W) defined as a joule per second. Thus,

$$1\ \mathrm{W} = 1\ \mathrm{J/s} = 1\ \mathrm{N \cdot m/s}$$

Prefixes for forming multiples and fractions of SI units are given in Table 1.2. For example, the notation kN would be read as "kilonewtons" and stands for 10^3 N. Similarly, mm would be read as "millimeters" and stands for 10^{-3} m. The centimeter is not an accepted unit of length in the SI system, so for most problems in fluid mechanics in which SI units are used, lengths will be expressed in millimeters or meters.

British Gravitational (BG) System. In the BG system the unit of length is the foot (ft), the time unit is the second (s), the force unit is the pound (lb), and the temperature unit is the degree Fahrenheit (°F) or the absolute temperature unit is the degree Rankine (°R), where

$${}^\circ\mathrm{R} = {}^\circ\mathrm{F} + 459.67$$

Table 1.2
Prefixes for SI Units

Factor by Which Unit Is Multiplied	Prefix	Symbol	Factor by Which Unit Is Multiplied	Prefix	Symbol
10^{15}	peta	P	10^{-2}	centi	c
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10	deka	da	10^{-18}	atto	a
10^{-1}	deci	d			

The mass unit, called the *slug,* is defined from Newton's second law (force $=$ mass $\times$ acceleration) as

$$1 \text{ lb} = (1 \text{ slug})(1 \text{ ft/s}^2)$$

This relationship indicates that a 1-lb force acting on a mass of 1 slug will give the mass an acceleration of 1 ft/s^2.

Two systems of units that are widely used in engineering are the British Gravitational (BG) System and the International System (SI).

The weight, $\mathcal{W}$ (which is the force due to gravity, g), of a mass, m, is given by the equation

$$\mathcal{W} = mg$$

and in BG units

$$\mathcal{W}(\text{lb}) = m(\text{slugs})\ g(\text{ft/s}^2)$$

Since Earth's standard gravity is taken as $g = 32.174$ ft/s^2 (commonly approximated as 32.2 ft/s^2), it follows that a mass of 1 slug weighs 32.2 lb under standard gravity.

THE WIDE WORLD OF FLUIDS

How long is a foot? Today, in the United States, the common length *unit* is the *foot,* but throughout antiquity the unit used to measure length has quite a history. The first length units were based on the lengths of various body parts. One of the earliest units was the Egyptian cubit, first used around 3000 B.C. and defined as the length of the arm from elbow to extended fingertips. Other measures followed, with the foot simply taken as the length of a man's foot. Since this length obviously varies from person to person it was often "standardized" by using the length of the current reigning royalty's foot. In 1791 a special French commission proposed that a new universal length unit called a meter (metre) be defined as the distance of one-quarter of the Earth's meridian (north pole to the equator) divided by 10 million. Although controversial, the meter was accepted in 1799 as the standard. With the development of advanced technology, the length of a meter was redefined in 1983 as the distance traveled by light in a vacuum during the time interval of 1/299,792,458 s. The foot is now defined as 0.3048 meter. Our simple rulers and yardsticks indeed have an intriguing history.

English Engineering (EE) System. In the EE system, units for force *and* mass are defined independently; thus special care must be exercised when using this system in conjunction with Newton's second law. The basic unit of mass is the pound mass (lbm), and the unit of force is the pound (lb).[1] The unit of length is the foot (ft), the unit of time is the second (s), and the absolute temperature scale is the degree Rankine (°R). To make the equation expressing Newton's second law dimensionally homogeneous we write it as

$$\mathbf{F} = \frac{m\mathbf{a}}{g_c} \tag{1.4}$$

where g_c is a constant of proportionality, which allows us to define units for both force and mass. For the BG system, only the force unit was prescribed and the mass unit defined in a consistent manner such that $g_c = 1$. Similarly, for SI the mass unit was prescribed and the force unit defined in a consistent manner such that $g_c = 1$. For the EE system, a 1-lb force is defined as that force which gives a 1 lbm a standard acceleration of gravity, which is taken as 32.174 ft/s^2. Thus, for Eq. 1.4 to be both numerically and dimensionally correct

$$1 \text{ lb} = \frac{(1 \text{ lbm})(32.174 \text{ ft/s}^2)}{g_c}$$

so that

$$g_c = \frac{(1 \text{ lbm})(32.174 \text{ ft/s}^2)}{(1 \text{ lb})}$$

[1]It is also common practice to use the notation, lbf, to indicate pound force.

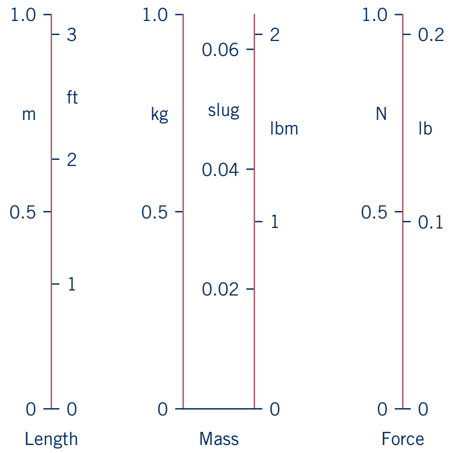


Figure 1.2 **Comparison of SI, BG, and EE units.**

With the EE system, weight and mass are related through the equation

$$\mathcal{W} = \frac{mg}{g_c}$$

where g is the local acceleration of gravity. Under conditions of standard gravity ($g = g_c$) the weight in pounds and the mass in pound mass are numerically equal. Also, since a 1-lb force gives a mass of 1 lbm an acceleration of 32.174 ft/s^2 and a mass of 1 slug an acceleration of 1 ft/s^2, it follows that

$$1 \text{ slug} = 32.174 \text{ lbm}$$

When solving problems it is important to use a consistent system of units, e.g., don't mix BG and SI units.

We cannot overemphasize the importance of paying close attention to units when solving problems. It is very easy to introduce huge errors into problem solutions through the use of incorrect units. Get in the habit of using a *consistent* system of units throughout a given solution. It really makes no difference which system you use as long as you are consistent; for example, don't mix slugs and newtons. If problem data are specified in SI units, then use SI units throughout the solution. If the data are specified in BG units, then use BG units throughout the solution. The relative sizes of the SI, BG, and EE units of length, mass, and force are shown in Fig. 1.2.

Extensive tables of conversion factors between unit systems, and within unit systems, are provided in Appendix E. For your convenience, abbreviated tables of conversion factors for some quantities commonly encountered in fluid mechanics are presented in Tables 1.3 and 1.4 on the inside back cover (using a slightly different format than Appendix E). Note that numbers in these tables are presented in computer exponential notation. For example, the number 5.154 E+2 is the number 5.154×10^2 in scientific notation. You should note that each conversion factor can be thought of as a fraction in which the numerator and denominator are equivalent. For example, an entry for "Length" from Table 1.4 instructs the user "To convert from … m … to … ft … Multiply by 3.281." Therefore 1 m is the same length as 3.281 ft. Therefore a fraction formed with a numerator of 1 m and a denominator of 3.281 ft is the very definition of a fraction with a value of one, as is its reciprocal. This may seem obvious when the units of the denominator and numerator are of the same dimension. It is equally true for the more complicated conversion factors that include multiple dimensions and therefore a greater number of units. You already know that you can multiply any quantity by one without changing its value. Likewise, you can multiply (or divide) any quantity by any conversion factor in the tables, provided you use both the number and the units. The result will not be incorrect, even if it does not yield the result you hoped for.