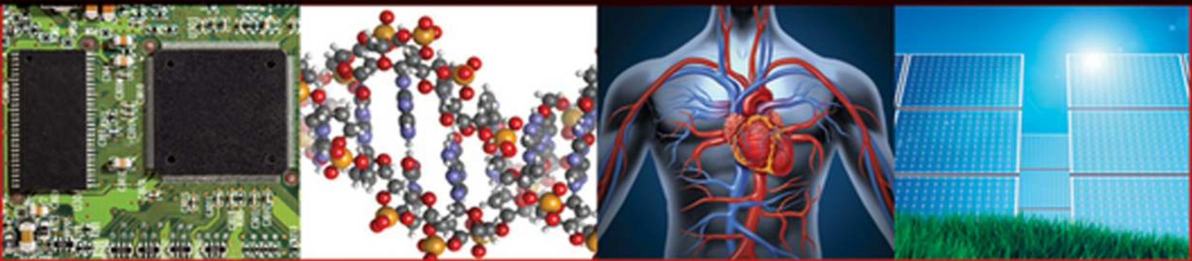
4TH EDITION

ELEMENTARY PRINCIPLES OF CHEMICAL PROCESSES



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WILEY

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EDITION

Elementary Principles of Chemical Processes

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WILEY

We dedicate this book to our first and most important teachers, our parents: Shirley and Robert Felder, Dorothy and Ivy John Rousseau, and Faye and Bobby Gardner.

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About the Authors

Richard M. Felder is Hoechst Celanese Professor Emeritus of Chemical Engineering at North Carolina State University. He received his B.Ch.E. degree from the City College of New York in 1962 and his Ph.D. in chemical engineering from Princeton University in 1966. He worked for the Atomic Energy Research Establishment (Harwell, England) and Brookhaven National Laboratory before joining the North Carolina State faculty in 1969. He is coauthor of *Teaching and Learning STEM: A Practical Guide* (Jossey-Bass, 2016), and he has authored or coauthored over 300 papers on chemical process engineering and engineering education and presented hundreds of invited talks, workshops, and short courses in both categories at conferences and to industrial and research institutions and universities throughout the United States and abroad. His honors include the International Federation of Engineering Education Societies Global Award for Excellence in Engineering Education (2010, first recipient), the ASEE Lifetime Achievement Award in Engineering Education (2012, first recipient), the ASEE Chester F. Carlson Award for innovation in engineering education, and the AIChE Warren K. Lewis Award for contributions to Chemical Engineering Education. He is a Fellow of the American Society for Engineering Education, and holds honorary doctorates from the State University of New York and the University of Illinois. Many of his education-related publications can be found at <*www.ncsu.edu/effective_teaching*>.

Ronald W. Rousseau holds the Cecil J. "Pete" Silas Chair in Chemical Engineering at the Georgia Institute of Technology, where he chaired the School of Chemical & Biomolecular Engineering from 1987 to 2014. He has B.S. and Ph.D. degrees in Chemical Engineering from Louisiana State University and a *Docteur Honoris Causa* from L'Institut National Polytechnique de Toulouse. An elected member of the LSU Engineering Hall of Distinction, he has served as executive editor of *Chemical Engineering Science*, topic editor for *Crystal Growth and Design*, consulting editor for the *AIChE Journal*, and associate editor of the *Journal of Crystal Growth* and editor of the *Handbook of Separation Process Technology*. His research in the field of separations has focused on crystal nucleation and growth, and applications of crystallization science and technology. From the American Institute of Chemical Engineers he received the AIChE Founders Award for outstanding contributions to the field of chemical engineering, the Warren K. Lewis Award for contributions to chemical engineering education, and the Clarence G. Gerhold Award for contributions to the field of chemical separations. The Chemical Engineering Division of ASEE presented him with a Lifetime Achievement Award, and the Council for Chemical Search selected him for the Mac Pruitt Award. He is a Fellow of both AIChE and the American Association for the Advancement of Science and has been a member of the AIChE Board of Directors and chair of the Council for Chemical Research.

Lisa G. Bullard is an Alumni Distinguished Undergraduate Professor and Director of Undergraduate Studies in the Department of Chemical and Biomolecular Engineering at North Carolina State University. After obtaining her BS in Chemical Engineering at NC State in 1986 and her Ph.D. in Chemical Engineering from Carnegie Mellon University in 1991, she served in engineering and management positions within Eastman Chemical Company in Kingsport, TN from 1991–2000. A faculty member at NC State since 2000, Dr. Bullard has won numerous awards for both teaching and advising, including the ASEE Raymond W. Fahien Award, the John Wiley Premier Award for Engineering Education Courseware, NC State Faculty Advising Award, National Effective Teaching Institute Fellow, NC State Alumni Outstanding Teacher Award, George H. Blessis Outstanding Undergraduate Advisor Award, the ASEE Martin Award, and the ASEE Southeastern Section Mid-Career Teacher Award. She is a past Chair of the Chemical Engineering Division of ASEE, editor of the "Lifelong Learning" column for *Chemical Engineering Education*, and a member of the 2017 ASEE Chemical Engineering Summer School planning team. Her research interests lie in the area of educational scholarship, including teaching and advising effectiveness, academic integrity, process design instruction, organizational culture, and the integration of writing, speaking, and computing within the curriculum.

Preface to the Fourth Edition

An introductory material and energy balance course traditionally plays several important roles in the chemical engineering curriculum. On the most obvious level, it prepares the student to formulate and solve material and energy balances on chemical process systems and lays the foundation for subsequent courses in thermodynamics, transport phenomena, separation processes, kinetics and reactor design, and process dynamics and control. More fundamentally, it introduces the engineering approach to solving process-related problems: breaking a process into its components, establishing the relations between known and unknown process variables, assembling the information needed to solve for the unknowns using a combination of experimentation, empiricism, and the application of natural laws, and, finally, putting the pieces together to obtain the desired problem solution.

We have tried in this book to fulfill each of these functions. Moreover, recognizing that the material and energy balance course is often the students' first real encounter with what they think may be their chosen profession, we have attempted to provide in the text a realistic, informative, and positive introduction to the practice of chemical engineering. In the first chapter we survey fields that recent chemical engineering graduates have entered and describe the variety of research, design, and production problems they might confront. In the rest of the book we systematically develop the structure of elementary process analysis: definitions, measurement and calculation of process variables, conservation laws and thermodynamic relations that govern the performance of processes, and physical properties of process materials that must be determined in order to design a new process or analyze and improve an existing one.

The chemical process constitutes the framework for the presentation of all of the text material. When we bring in concepts from physical chemistry such as vapor pressure, solubility, and heat capacity, we introduce them as quantities whose values are required to determine process variables or to perform material and energy balance calculations on a process. When we discuss spreadsheets and computational techniques, we present them on the same need-to-know basis in the context of process analysis.

Not much has happened to the laws of conservation of mass and energy or the basic principles of physical chemistry since the most recent edition of *Elementary Principles* appeared a decade ago, so instructors who used the third edition of the book will see some changes in the chapter texts, but they won't be dramatic. The biggest difference is in the problems, which reflect the broadening of the scope of chemical engineering during the lifetime of this book from almost exclusively industrial chemistry and petrochemicals to biomedical, biochemical, biomolecular, environmental, energy, materials, and safety applications. There are around 350 new and revised chapter-end problems in this edition, many of which address those diverse areas. In addition, an entirely new suite of resources for students and instructors has been assembled, including a spreadsheet-based tool that eliminates much of the drudgery of routine calculations that require large expenditures of time and have little instructional value.

The two authors of the first three editions acknowledge with gratitude the contributions of colleagues and students from the time work began on the book. Our thanks go to Dick Seagrave and the late Professors John Stevens and David Marsland, who read the first draft of the first edition and offered many suggestions for its improvement; our department head, the late Jim Ferrell, who gave us invaluable encouragement when we brashly (some might say, foolishly) launched into the book in our third year as faculty members; and our colleagues around the world who helped us prepare problems and case studies and suggested improvements to each successive edition. We raise our glasses to the students in the Fall 1973 offering of CHE 205 at N.C. State, who had the bad luck to get the first draft as a course text. We also thank the N.C. State graduate and undergraduate students who helped prepare the solution manuals, and the many N.C. State and Georgia Tech students who took the trouble to point out errors in the text. We know they did it out of a sense of professional responsibility and not just to collect the dollars.

The three authors of this edition thank our colleagues who contributed ideas for end-of-chapter problems in areas of expertise far removed from ours, whose names are acknowledged in footnotes. We are particularly grateful to Stephanie Farrell, Mariano Savelski, and Stewart Slater of Rowan University for contributing several excellent problems from a library of pharmaceutical engineering problems (see <*www.PharmaHUB.org*>). Support for the development of the library was provided by a grant from the National Science Foundation through the Engineering Research Center for Structured Organic Particulate Systems, ECC0540855.

Support for the development of the problems on climbing Kilimanjaro was provided by grants from the National Science Foundation through the Division of Undergraduate Education grants # 0088437 and 1140631. These problems were contributed by Stephanie Farrell of Rowan University.

Our heartfelt thanks also go to Emma Barber, Michael Burroughs, Andrew Drake, David Hurrelbrink, Samuel Jasper, Michael Jones, William Kappler, Katie Kirkley, Manami Kudoh, George Marshall, Jonathan Mihu, Adam Mullis, Kaitlyn Nilsen, Cailean Pritchard, Jordan Shack, Gitanjali Talreja, and Kristen

Twidt, who contributed to the development and testing of the fourth edition on-line content and solution manual, and especially to Karen Uffalussy, who meticulously read every sentence and equation in the manuscript and caught a frightening number of mistakes, some of which dated back to the first edition.

Finally, we thank our Wiley colleagues Dan Sayre and Jenny Welter for their help in bringing this and previous editions into existence; Rebecca, Sandra, and Michael for many years of unfailing encouragement and support; and the late Magnificent Mary Wade, who uncomplainingly and with great good humor typed revision after revision of the first edition, until the authors, unable to stand any more, declared the book done.

RMF
RWR
LGB

Notes to Instructors

Topical coverage

The organization of this text has been planned to provide enough flexibility to accommodate classes with diverse backgrounds within the scope of a one-semester or two-quarter course. We anticipate that semester-long courses in which most students have traditional first-year engineering backgrounds will cover most of the first nine chapters, and a one-quarter course should cover Chapters 1 through 6. Students who have been exposed to dimensional analysis and elementary data correlation can skip or skim Chapter 2, and students whose freshman chemistry courses provided a detailed coverage of process variable definitions and the systematic use of units to describe and analyze chemical processes may omit Chapter 3. The time gained as a result of these omissions may be used to cover additional sections in Chapters 4 through 9 or to add Chapter 10 on transient balances.

Teaching and promoting a systematic approach to process analysis

We have consistently found that the key to student success in this course is approaching problems systematically: drawing and labeling flow charts, counting degrees of freedom to make sure that problems are solvable, and formulating solution plans before doing any calculations. We have also found that students are remarkably resistant to this process, preferring to launch directly into writing equations in the hope that sooner or later a solution will emerge. The students who make the transition to the systematic approach generally do well, while those who continue to resist it frequently fail.

In our experience, the only way students learn to use this approach is by repeatedly practicing it. Hundreds of chapter-end problems in the text are structured to provide this practice. Representative assignment schedules are given in the instructor's resources, and there is enough duplication of problem types for the schedules to be varied considerably from one course offering to another.

Support for a wide range of course learning outcomes

Most of the problems in the book focus on setting up and solving basic material and energy balance problems, which is as it should be. Not all of them, however: many exercises focus on learning objectives beyond analytical problem-solving skills, including developing critical and creative thinking skills and understanding the industrial and social contexts of many of the processes treated in the chapter-end problems. (All of those learning outcomes, we might add, map onto required learning outcomes of the ABET Engineering Criteria.) Some of the exercises are included in the problems, and others are separate "*creativity exercises*" and "*explore and discover exercises*."

We encourage instructors to use these exercises as focal points for in-class activities, include them in homework assignments, and put similar exercises on tests after ample practice has been provided in assignments. The exercises can convey to the students a sense of the challenging and intellectually stimulating possibilities in a chemical engineering career, which may be the most important task that the introductory course can accomplish.

Digital Resources and *WileyPLUS*

WileyPLUS *WileyPLUS* is an online environment that provides educational resources to teachers and students. When instructors choose to adopt *WileyPLUS* for their course, their students obtain access via a registration code that may be added to a print edition or purchased for online-only access. In this section, we first describe resources available to all users of *Elementary Principles of Chemical Processes*, and then we provide more information about the resources provided to instructors and students in classes in which *WileyPLUS* has been adopted.

Resources for all instructors

Two websites provide resources for instructors using the textbook.

- **Instructor Companion Website: www.wiley.com/college/felder**

  This publisher-maintained site contains a section-problem concordance, sample assignment schedules, sample responses to creativity exercises, reproductions of selected figures from the text, solutions to chapter-end problems, a *Visual Encyclopedia of Chemical Engineering Equipment*, and *Notes with Gaps*, a resource new to the fourth edition. The password-protected site is accessible only to certified course instructors.

  The ***Visual Encyclopedia of Chemical Engineering Equipment*** is an online tool developed by Susan Montgomery of the University of Michigan that provides photos, cutaway diagrams, videos, animations, and explanations of many common chemical processing equipment items. Icons referencing the Visual Encyclopedia are found throughout the text.

  Notes with Gaps is an extensively class-tested set of lecture notes for Chapters 2–9 of the text. There are two versions of the set. One is for students and includes blank spaces (gaps) in which to fill in answers to imbedded questions, curves on plots for which only the axes are shown, stream labels on flowcharts, numbers in degrees-of-freedom analyses, and critical steps in derivations and problem solutions. On the second set of notes, which is for instructors, the gaps are filled in.

  The student version of the notes can be loaded on a tablet computer and projected in class, or it can be printed, duplicated, and bound into a coursepack that students bring to every class session. The instructor can direct the students to read through completely straightforward parts of the notes (short simple paragraphs, definitions of terms and system variables, and routine algebraic calculations), which students can do in much less time than it would take to present the same information in a traditional lecture. When instructors reach gaps, they may either lecture on them traditionally or (better) direct the students to fill in the gaps in active learning exercises. The students don't have to spend a lot of time taking notes on straightforward content but can focus almost entirely on the key methods and concepts in the lecture, and they get practice and immediate feedback on hard or tricky parts of the methods. Research has shown that handing out partial notes of this type leads to deeper learning than either requiring students to take all their own notes or giving them complete sets of notes either before or after class.

- **Author-maintained website: http://epcp.wordpress.ncsu.edu**

  This site contains frequently updated errata lists for the text, a website for the material and energy balance course with a sample syllabus and representative study guides and tests, and links to several publications describing how to teach the course effectively.

Resources for adopters of *WileyPLUS*

- **Introductory videos for all chapters.** The authors introduce each chapter, highlight important chapter content, and explain how the chapter fits in with the rest of the text, and the two original authors describe the history of the text. Award-winning professor Michael Dickey of North Carolina State University carries out demonstration experiments that illustrate key course concepts.
- **Algorithmic problems.** Individualized machine-gradable on-line homework problems (in which each student has unique values for key variables) can provide students with feedback, hints, and scaffolded tutorials to assist their learning. Instructors can determine the level of feedback (no feedback, final answer, full solution, or fully guided solution with feedback on each step) that students receive and the number of submissions that are allowed. Students can use on-line reading questions as a qualitative self-check to ensure that they have mastered the learning objectives for each section (similar to the more quantitative *Test Yourself* questions in the text), while instructor-assigned reading questions can be used to quiz students prior to class (in a flipped classroom environment) or after class.
- **APEx (Analyzing Processes with Excel)**, an Excel add-in developed by David Silverstein of the University of Kentucky, enables users to easily perform time-consuming tasks required to solve the text's chapter-end problems. APEx automates the processes of looking up physical properties of chemical species at specified phases, temperatures, and pressures; calculating vapor pressures and boiling points of species at specified temperatures or pressures; integrating tabulated heat capacity formulas to determine enthalpy changes for heating and cooling species between specified temperatures; inserting tabulated and calculated values into system equations; and solving the equations using Excel's Solver.
- **Library of case studies.** Nine case studies demonstrate the role of the calculations illustrated in Chapters 2–9 in the analysis of authentic industrial processes. The case studies are designed to be worked on as term projects by individuals or small teams of students.

Postscript: Introduction to an Author

Many instructors and students who have used this book can't tell you its title without looking at the cover. Since the first edition appeared in 1978, the text has generally been referred to as "Felder and Rousseau." The practice of using authors' last names to refer to textbooks is common, and it has become so universal for this one that one of us has occasionally begun talks by informing the audience that his first name is Ronald, not Felderand. So whether or not you know the title, if you've used the book before you probably noticed that the list of authors has metamorphosed in this edition to FelderandRousseauandBullard.

Who is Bullard, you might be asking. Before we formally introduce Lisa, let us give you a little history. We began work on this book when we were young untenured assistant professors. That was in 1972. By the time we started work on the fourth edition, we were neither untenured nor assistant professors, and you can do the math on "young" for yourself. We agreed that our careers and interests had moved in different directions, and if there were to be more editions after this one, someone else would have to play a major role in writing them. It made sense to bring in that individual to work with us and help assure a smooth transition in the future.

We quickly assembled a shopping list of desirable attributes for our future coauthor. We wanted to find an outstanding teacher with an extensive background in teaching material and energy balances; an experienced engineer with first-hand knowledge of both the science and the art of the practice of chemical engineering; and a good writer, who could carry on the work long after the original authors had begun to fully devote themselves to their children, grandchildren, good books, plays, operas, excellent food and wine, and occasional stays in five-star inns in the beautiful places in the world. (Look, you have your fantasies, we have ours.)

We found some excellent candidates, and then we got to Lisa Bullard and our search was over. Lisa was all of those things, as well as the finest academic advisor her N.C. State coauthor had ever seen or heard of and an author of papers and presenter of national and international seminars and workshops on effective teaching and advising. And so we invited her to join us, and she accepted. Our good fortune. And yours.

Felder & Rousseau

Nomenclature

The variables to be listed will be expressed in SI units for illustrative purposes, but they could be expressed equally well in any dimensionally consistent units.

a, b, c, d	Arbitrary constants, or parameters in an equation of state, or coefficients of a polynomial expression for heat capacity, such as those listed in Appendix B.2.
C_p[kJ/(mol·K)], C_v[kJ/(mol·K)]	Heat capacities at constant pressure and constant volume, respectively.
E_k(kJ), $\dot{E}_\mathrm{k}$(kJ/s)	Kinetic energy, rate of kinetic energy transport by a flowing stream.
E_p(kJ), $\dot{E}_\mathrm{p}$(kJ/s)	Potential energy, rate of potential energy transport by a flowing stream.
f	Fractional conversion.
$\hat{F}$(kJ/mol)	Friction loss.
g(m/s^2)	Gravitational acceleration constant, equal to 9.8066 m/s^2 or 32.174 ft/s^2 at sea level.
H(kJ), $\dot{H}$(kJ/s), $\hat{H}$(kJ/mol)	Enthalpy of a system (H), rate of transport of enthalpy by a process stream ($\dot{H}$), specific enthalpy ($\hat{H}$). $\hat{H} = \hat{U} + P\hat{V}$, all determined relative to a specified reference state.
m(kg), $\dot{m}$(kg/s)	Mass (m) or mass flow rate ($\dot{m}$) of a process stream or stream component.
M(g/mol)	Molecular weight of a species.
n(mol), $\dot{n}$(mol/s)	Number of moles (n) or molar flow rate ($\dot{n}$) of a process stream or stream component.
p_A(atm)	Partial pressure of species A in a mixture of gaseous species, $= y_\mathrm{A}P$.
$p_\mathrm{A}^*(T)$ (atm)	Vapor pressure of species A at temperature T.
P(atm)	Total pressure of a system. Unless specifically told otherwise, assume that P is absolute pressure and not gauge pressure.
P_c(atm)	Critical pressure. Values of this property are listed in Table B.1.
P_r	Reduced pressure. Ratio of system pressure to the critical pressure, P/P_c.
Q(kJ), $\dot{Q}$(kJ/s)	Total heat transferred to or from a system (Q), rate of heat transfer to or from a system ($\dot{Q}$). Q is defined to be positive if heat is transferred to the system.
R[kJ/(mol·K)]	Gas constant, given in different units on the inside back cover of the text.
SCMH, SCLH, SCFH.	Abbreviations for standard cubic meters per hour [m^3(STP)/h], standard liters per hour [L(STP/h)], and standard cubic feet per hour [ft^3(STP)/h], respectively: the volumetric flow rate of a gas stream if the stream were brought from its actual temperature and pressure to standard temperature and pressure (0°C and 1 atm).
SG	Specific gravity, or ratio of the density of a species to the density of a reference species. The abbreviation is always used for liquids and solids in this text and usually refers to species for which specific gravities are listed in Table B.1.
t(s)	Time.
T(K)	Temperature.
T_m, T_b, T_c(K)	Melting point temperature, boiling point temperature, and critical temperature, respectively. The *normal* melting and boiling points are the values of those properties at a pressure of one atmosphere. Values of these properties are listed in Table B.1.
T_r	Reduced temperature. Ratio of system temperature to the critical temperature, T/T_c.
u(m/s)	Velocity.
U(kJ), $\dot{U}$(kJ/s), $\hat{U}$(kJ/mol)	Internal energy of a system (U), rate of transport of internal energy by a process stream ($\dot{U}$), specific internal energy ($\hat{U}$).

v_A (m^3)	Pure component volume of species A in a mixture of gaseous species, $= y_A V$.
V(m^3), $\dot{V}$(m^3/s), $\hat{V}$(m^3/mol)	Volume (V), volumetric flow rate ($\dot{V}$) of a process stream, specific volume ($\hat{V}$) of a process material.
W(kJ), $\dot{W}_s$ (kJ/s)	Work transferred to or from a system (W), rate of transfer of shaft work to or from a continuous process system ($\dot{W}_s$). Work is defined to be positive (in this text) if it is transferred to a system from its surroundings.
x, y, z	Mass fraction or mole fraction of a species in a mixture. (Subscripts are usually used to identify the species.) In liquid-vapor systems, x usually denotes fraction in the liquid and y denotes fraction in the vapor. z may also denote the compressibility factor of a gas.

GREEK LETTERS

Δ	In batch (closed) systems, ΔX denotes the difference $X_{\text{final}} - X_{\text{initial}}$, where X is any system property. In continuous (open) systems, $\Delta \dot{X}$ denotes the difference $\dot{X}_{\text{output}} - \dot{X}_{\text{input}}$.
$\Delta \hat{H}_c^\circ$(kJ/mol)	Standard heat of combustion, the enthalpy change when one g-mole of a species at 25°C and 1 atm undergoes complete combustion and the products are at the same temperature and pressure. Standard heats of combustion are listed in Table B.1.
$\Delta \hat{H}_f^\circ$(kJ/mol)	Standard heat of formation, the enthalpy change when one g-mole of a species at 25°C and 1 atm is formed from its elements in their naturally occurring states (e.g., H_2, O_2). Standard heats of formation are listed in Table B.1.
$\Delta \hat{H}_m(T, P)$ (kJ/mol)	Heat of melting (fusion) at temperature T and pressure P, the enthalpy change when one g-mole of a species goes from solid to liquid at a constant temperature and pressure. Heats of melting at 1 atm and the normal melting point are listed in Table B.1.
$\Delta \hat{H}_v(T, P)$ (kJ/mol)	Heat of vaporization at temperature T and pressure P, the enthalpy change when one g-mole of a species goes from liquid to vapor at a constant temperature and pressure. Heats of vaporization at 1 atm and the normal boiling point are listed in Table B.1.
$\Delta H_r(T)$ (kJ)	Heat of reaction, the enthalpy change when stoichiometric quantities of reactants at temperature T react completely at constant temperature.
ν_A(mol), $\dot{\nu}_A$(mol/s)	Stoichiometric coefficient of species A in a chemical reaction, defined to be positive for products, negative for reactants. For $N_2 + 3H_2 \rightarrow 2NH_3$, $\nu_{N_2} = -1$ mol, $\nu_{H_2} = -3$ mol, $\nu_{NH_3} = 2$ mol.
ξ	Extent of reaction. If n_{A0} (mol) of reactive species A is initially present in a reactor and n_A (mol) is present some time later, then the extent of reaction at that time is $\xi = (n_{A0} - n_A)/\nu_A$, where ν_A (mol A) is the stoichiometric number of moles of A. If A is a product whose stoichiometric coefficient is 2, then ν_A in the equation for ξ would be 2 mol A; if A is a reactant, then ν_A would be −2 mol A. In a continuous system, n_A and ν_A would be replaced by $\dot{n}_A$(mol A/s) and $\dot{\nu}_A$ (mol A/s). The value of ξ is the same regardless of which reactant or product is chosen as species A.
ρ (kg/m^3)	Density.

OTHER SYMBOLS

$\dot{}$ (e.g., $\dot{m}$)	A dot over a term designates that it is a rate (e.g. mass flow rate).
$\hat{}$ (e.g., $\hat{U}$)	A caret over a term designates that it is a specific property, e.g. specific internal energy.
( )	Parentheses are used to express functional dependence, as in $p^*(T)$ to denote a vapor pressure that depends on temperature, and also to enclose units of variables, as in m(g) to denote a mass expressed in grams.

Glossary of Chemical Process Terms

Glossary terms indicated with @ can be found in the Equipment Encyclopedia at www.wiley.com/college/felder.

@ **Absorption** A process in which a gas mixture contacts a liquid solvent and a component (or several components) of the gas dissolves in the liquid. In an *absorption column* or *absorption tower* (or simply *absorber*), the solvent enters the top of a column, flows down, and emerges at the bottom, and the gas enters at the bottom, flows up (contacting the liquid), and leaves at the top.

Adiabatic A term applied to a process in which no heat is transferred between the process system and its surroundings.

@ **Adsorption** A process in which a gas or liquid mixture contacts a solid (the *adsorbent*) and a mixture component (the *adsorbate*) adheres to the surface of the solid.

Barometer A device that measures atmospheric pressure.

@ **Boiler** A process unit in which tubes pass through a combustion furnace. *Boiler feedwater* is fed into the tubes, and heat transferred from the hot combustion products through the tube walls converts the feedwater to steam.

Boiling point (at a given pressure) For a pure species, the temperature at which the liquid and vapor can coexist in equilibrium at the given pressure. When applied to the heating of a mixture of liquids exposed to a gas at the given pressure, the temperature at which the mixture begins to boil.

Bottoms product The product that leaves the bottom of a distillation column. The bottoms product is relatively rich in the less volatile components of the feed to the column.

Bubble point (of a mixture of liquids at a given pressure) The temperature at which the first vapor bubble appears when the mixture is heated.

Calibration (of a process variable measurement instrument) A procedure in which an instrument is used to measure several independently known process variable values, and a *calibration curve* of known variable values versus the corresponding instrument readings is plotted. Once the instrument has been calibrated, readings obtained with it can be converted to equivalent process variable values directly from the calibration curve.

@ **Catalyst** A substance that significantly increases the rate of a chemical reaction although it is neither a reactant nor a product.

Compressibility factor, z $z = PV/nRT$ for a gas. If $z = 1$, then $PV = nRT$ (the ideal-gas equation of state) and the gas is said to behave ideally.

@ **Compressor** A device that raises the pressure of a gas.

Condensation A process in which an entering gas is cooled and/or compressed, causing one or more of the gas components to liquefy. Uncondensed gases and liquid *condensate* leave the condenser as separate streams.

Critical pressure, P_c The highest pressure at which distinct vapor and liquid phases can coexist for a species.

Critical temperature, T_c The highest temperature at which distinct vapor and liquid phases can coexist for a species. The critical temperature and pressure, collectively referred to as the *critical constants*, are listed for various species in Table B.1.

@ **Crystallization** A process in which a liquid is cooled or solvent is evaporated to an extent that solid crystals form. The crystals in a *slurry* (suspension of solids in a liquid) leaving the crystallizer may subsequently be separated from the liquid in a filter or centrifuge.

Decanter A device in which two liquid phases or liquid and solid phases separate by gravity.

Degrees of freedom When applied to a general process, the difference between the number of unknown process variables and the number of equations relating those variables; the number of unknown variables for which values must be specified before the remaining values can be calculated. When applied to a system at equilibrium, the number of intensive system variables for which values must be specified before the remaining values can be calculated. The degrees of freedom in the second sense is determined using the Gibbs Phase Rule.

Dew point (of a gas mixture at a given pressure) The temperature at which the first liquid droplet appears when the mixture is cooled at constant pressure.

Distillation A process in which a mixture of two or more species is fed to a vertical column that contains either a series of vertically spaced horizontal plates or solid packing through which fluid can flow. Liquid mixtures of the feed components flow down the column and vapor mixtures flow up. Interphase contact, partial condensation of the vapor, and partial vaporization of the liquid all take place throughout the column. The vapor flowing up the column becomes progressively richer in the more volatile components of the feed, and the liquid flowing down becomes richer in the less volatile components. The vapor leaving the top of the column is condensed: part of the condensate is taken off as the *overhead product* and the rest is recycled to the reactor as *reflux*, becoming the liquid stream that flows down the column. The liquid leaving the bottom of the column is partially vaporized: the vapor is recycled to the reactor as *boilup*, becoming the vapor stream that flows up the column, and the residual liquid is taken off as the *bottoms product*.

Drying A process in which a wet solid is heated or contacted with a hot gas stream, causing some or all of the entering liquid to evaporate. The vapor and the gas it evaporates into emerge as one outlet stream, and the solid and remaining residual liquid emerge as a second outlet stream.

Enthalpy (kJ) Property of a system defined as $H = U + PV$, where U = internal energy, P = absolute pressure, and V = volume of the system.

Evaporation (vaporization) A process in which a pure liquid, liquid mixture, or solvent in a solution is vaporized.

Extraction (liquid extraction) A process in which a liquid mixture of two species (the *solute* and the *feed carrier*) is contacted in a mixer with another liquid (the *solvent*) that is immiscible or nearly immiscible with the feed carrier. When the liquids are contacted, solute transfers from the feed carrier to the solvent. The combined mixture is then allowed to settle into two phases that are then separated by gravity.

Filtration A process in which a slurry of solid particles (often crystals) suspended in a liquid, most of which passes through the filter to form the *filtrate*; the solids and some entrained liquid are retained on the filter to form the *filter cake*. Filtration may also be used to separate solids or liquids from gases.

Flash vaporization A process in which a liquid feed at a high pressure is suddenly exposed to a lower pressure, causing some vaporization to occur. The vapor product is rich in the more volatile components of the feed and the residual liquid is rich in the less volatile components.

Flue gas See stack gas.

Heat Energy transferred between a system and its surroundings as a consequence of a temperature difference. Heat always flows from a higher temperature to a lower one. It is conventionally defined as positive when it flows to a system from its surroundings.

Heat exchanger A process unit through which two fluid streams at different temperatures flow on opposite sides of a metal barrier (e.g., a bundle of metal tubes). Heat is transferred from the stream at the higher temperature through the barrier to the other stream.

Internal energy (*U*) The total energy possessed by the individual molecules in a system (as opposed to the kinetic and potential energies of the system as a whole). U is a strong function of temperature, phase, and molecular structure and a weak function of pressure (it is independent of pressure for ideal gases). Its absolute value cannot be determined, so it is always expressed relative to a reference state at which it is defined to be zero.

Membrane A thin solid or liquid film through which one or more species in a process stream can permeate.

Overhead product The product that leaves the top of a distillation column. The overhead product is relatively rich in the most volatile components of the feed to the column.

Pump A device used to propel a liquid or slurry from one location to another, usually through a pipe or tube.

Scrubber An absorption column designed to remove an undesirable component from a gas stream.

Settler See decanter.

Shaft work All work transferred between a continuous system and its surroundings other than that done by or on the process fluid at the system entrance and exit.

Stack gas The gaseous products exiting from a combustion furnace.

Stripping A process in which a liquid containing a dissolved gas flows down a column and a gas (stripping gas) flows up the column at conditions such that the dissolved gas comes out of solution and is carried off with the stripping gas.

Vapor pressure The pressure at which pure liquid A can coexist with its vapor at a given temperature. In this text, vapor pressures can be determined from tabulated data (e.g., Tables B.3 and B5–B7 for water) or the Antoine equation (Table B.4).

Volume percent (% v/v) For liquid mixtures, the percentage of the total volume occupied by a particular component; for ideal gases, the same as mole percent. For nonideal gases the volume percent has no meaningful physical significance.

Work Energy transferred between a system and its surroundings as a consequence of motion against a restraining force, electricity or radiation, or any other driving force except a temperature difference. In this book, work is defined as positive if it flows to a system from its surroundings.

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Front cover photos: Some environments and products chemical engineers work on and with.

Top: Chemical plant (chemical, petrochemical, polymer, pharmaceutical, materials science and engineering, specialty chemical development and manufacturing)

Below, left: Printed circuit boards (microelectronic materials development and manufacturing, nanotechnology)

Below, center left and center right: Nucleic acid and the human body (biotechnology, biochemical engineering, biomedical engineering)

Below, right: Solar panels (clean fuel production and combustion, alternative energy sources)

FACTORS FOR UNIT CONVERSIONS

Quantity	Equivalent Values
Mass	$1\ \text{kg} = 1000\ \text{g} = 0.001$ metric ton (tonne) $= 2.20462\ \text{lb}_\text{m} = 35.27392\ \text{oz}$ $1\ \text{lb}_\text{m} = 16\ \text{oz} = 5 \times 10^{-4}\ \text{ton} = 453.593\ \text{g} = 0.453593\ \text{kg}$
Length	$1\ \text{m} = 100\ \text{cm} = 1000\ \text{mm} = 10^{6}$ microns (μm) $= 10^{10}$ angstroms (Å) $= 39.37\ \text{in} = 3.2808\ \text{ft} = 1.0936\ \text{yd} = 0.0006214$ mile $1\ \text{ft} = 12\ \text{in} = 1/3\ \text{yd} = 0.3048\ \text{m} = 30.48\ \text{cm}$
Volume	$1\ \text{m}^3 = 1000\ \text{L} = 10^6\ \text{cm}^3 = 10^6\ \text{mL} = 35.3145\ \text{ft}^3$ $= 219.97$ imperial gallons $= 264.17\ \text{gal} = 1056.68\ \text{qt}$ $1\ \text{ft}^3 = 1728\ \text{in}^3 = 7.4805\ \text{gal} = 29.922\ \text{qt} = 0.028317\ \text{m}^3 = 28.317\ \text{L}$
Density	$1\ \text{g/cm}^3 = 1000\ \text{kg/m}^3 = 62.43\ \text{lb}_\text{m}/\text{ft}^3$ = density of liquid water at 4°C (reference for specific gravities)
Force	$1\ \text{N} = 1\ \text{kg}\cdot\text{m/s}^2 = 10^5\ \text{dynes} = 10^5\ \text{g}\cdot\text{cm/s}^2 = 0.22481\ \text{lb}_\text{f}$ $1\ \text{lb}_\text{f} = 32.174\ \text{lb}_\text{m}\cdot\text{ft/s}^2 = 4.4482\ \text{N} = 4.4482 \times 10^5\ \text{dynes}$
Pressure	$1\ \text{atm} = 1.01325 \times 10^5\ \text{N/m}^2\ (\text{Pa}) = 101.325\ \text{kPa} = 1.01325\ \text{bar}$ $= 1.01325 \times 10^6\ \text{dynes/cm}^2 = 14.696\ \text{lb}_\text{f}/\text{in}^2$ (psi) $= 760$ mm Hg at 0°C (torr) $= 10.333$ m $H_2O(l)$ at 4°C $= 29.921$ inches Hg at 0°C $= 406.8$ inches $H_2O(l)$ at 4°C
Energy	$1\ \text{J} = 1\ \text{N}\cdot\text{m} = 10^7\ \text{ergs} = 10^7\ \text{dyne}\cdot\text{cm} = 1\ \text{kg}\cdot\text{m}^2/\text{s}^2$ $= 2.778 \times 10^{-7}\ \text{kW}\cdot\text{h} = 0.23901\ \text{cal} = 0.23901 \times 10^{-3}$ kcal (food calorie) $= 0.7376\ \text{ft}\cdot\text{lb}_\text{f} = 9.486 \times 10^{-4}\ \text{Btu}$
Power	$1\ \text{W} = 1\ \text{J/s} = 1\ \text{N}\cdot\text{m/s} = 0.23901\ \text{cal/s} = 0.7376\ \text{ft}\cdot\text{lb}_\text{f}/\text{s}$ $= 9.486 \times 10^{-4}\ \text{Btu/s} = 1.341 \times 10^{-3}\ \text{hp}$

Example: The factor to convert grams to lb_m is $\left(\dfrac{2.20462\ \text{lb}_\text{m}}{1000\ \text{g}}\right)$ or $\left(\dfrac{1\ \text{lb}_\text{m}}{453.593\ \text{g}}\right)$.

ATOMIC WEIGHTS AND NUMBERS

Atomic weights apply to naturally occurring isotopic compositions and are based on an atomic mass of $^{12}C = 12$

Element	Symbol	Atomic Number	Atomic Weight	Element	Symbol	Atomic Number	Atomic Weight
Actinium	Ac	89	—	Iridium	Ir	77	192.2
Aluminum	Al	13	26.9815	Iron	Fe	26	55.847
Americium	Am	95	—	Krypton	Kr	36	83.80
Antimony	Sb	51	121.75	Lanthanum	La	57	138.91
Argon	Ar	18	39.948	Lawrencium	Lr	103	—
Arsenic	As	33	74.9216	Lead	Pb	82	207.19
Astatine	At	85	—	Lithium	Li	3	6.939
Barium	Ba	56	137.34	Lutetium	Lu	71	174.97
Berkelium	Bk	97	—	Magnesium	Mg	12	24.312
Beryllium	Be	4	9.0122	Manganese	Mn	25	54.9380
Bismuth	Bi	83	208.980	Mendelevium	Md	101	—
Boron	B	5	10.811	Mercury	Hg	80	200.59
Bromine	Br	35	79.904	Molybdenum	Mo	42	95.94
Cadmium	Cd	48	112.40	Neodymium	Nd	60	144.24
Calcium	Ca	20	40.08	Neon	Ne	10	20.183
Californium	Cf	98	—	Neptunium	Np	93	—
Carbon	C	6	12.01115	Nickel	Ni	28	58.71
Cerium	Ce	58	140.12	Niobium	Nb	41	92.906
Cesium	Cs	55	132.905	Nitrogen	N	7	14.0067
Chlorine	Cl	17	35.453	Nobelium	No	102	—
Chromium	Cr	24	51.996	Osmium	Os	75	190.2
Cobalt	Co	27	58.9332	Oxygen	O	8	15.9994
Copper	Cu	29	63.546	Palladium	Pd	46	106.4
Curium	Cm	96	—	Phosphorus	P	15	30.9738
Dysprosium	Dy	66	162.50	Platinum	Pt	78	195.09
Einsteinium	Es	99	—	Plutonium	Pu	94	—
Erbium	Er	68	167.26	Polonium	Po	84	—
Europium	Eu	63	151.96	Potassium	K	19	39.102
Fermium	Fm	100	—	Praseodymium	Pr	59	140.907
Fluorine	F	9	18.9984	Promethium	Pm	61	—
Francium	Fr	87	—	Protactinium	Pa	91	—
Gadolinium	Gd	64	157.25	Radium	Ra	88	—
Gallium	Ga	31	69.72	Radon	Rn	86	—
Germanium	Ge	32	72.59	Rhenium	Re	75	186.2
Gold	Au	79	196.967	Rhodium	Rh	45	102.905
Hafnium	Hf	72	178.49	Rubidium	Rb	37	84.57
Helium	He	2	4.0026	Ruthenium	Ru	44	101.07
Holmium	Ho	67	164.930	Samarium	Sm	62	150.35
Hydrogen	H	1	1.00797	Scandium	Sc	21	44.956
Indium	In	49	114.82	Selenium	Se	34	78.96
Iodine	I	53	126.9044	Silicon	Si	14	28.086

Atomic weights apply to naturally occurring isotopic compositions and are based on an atomic mass of $^{12}\mathrm{C} = 12$

Element	Symbol	Atomic Number	Atomic Weight	Element	Symbol	Atomic Number	Atomic Weight
Silver	Ag	47	107.868	Tin	Sn	50	118.69
Sodium	Na	11	22.9898	Titanium	Ti	22	47.90
Strontium	Sr	38	87.62	Tungsten	W	74	183.85
Sulfur	S	16	32.064	Uranium	U	92	238.03
Tantalum	Ta	73	180.948	Vanadium	V	23	50.942
Technetium	Tc	43	—	Xenon	Xe	54	131.30
Tellurium	Te	52	127.60	Ytterbium	Yb	70	173.04
Terbium	Tb	65	158.924	Yttrium	Y	39	88.905
Thallium	Tl	81	204.37	Zinc	Zn	30	65.37
Thorium	Th	90	232.038	Zirconium	Zr	40	91.22
Thulium	Tm	69	168.934				

THE GAS CONSTANT (*R*)

8.314 m^3·Pa/(mol·K)
0.08314 L·bar/(mol·K)
0.08206 L·atm/(mol·K)
62.36 L·mm Hg/(mol·K)
0.7302 ft^3·atm/(lb-mole·°R)
10.73 ft^3·psia/(lb-mole·°R)

8.314 J/(mol·K)
1.987 cal/(mol·K)
1.987 Btu/(lb-mole·°R)

PART 1

Engineering Problem Analysis

CHAPTER 1

What Some Chemical Engineers Do for a Living

Last May, thousands of chemical engineering seniors took their last final examination, attended their graduation ceremonies, flipped their tassels and threw their mortarboards in the air, enjoyed their farewell parties, said goodbye to one another and promised faithfully to stay in touch, and headed off in an impressive variety of geographical and career directions.

Since you bought this book, you are probably thinking about following in the footsteps of those graduates—spending the next few years learning to be a chemical engineer and possibly the next 40 applying what you learn in a career. Even so, it is a fairly safe bet that, like most people in your position, you have only a limited idea of what chemical engineering is or what chemical engineers do. A logical way for us to begin this book might therefore be with a definition of chemical engineering.

Unfortunately, no universally accepted definition of chemical engineering exists, and almost every type of skilled work you can think of is done somewhere by people educated as chemical engineers. Providing a definition has recently become even more difficult as university chemical engineering departments have morphed into departments of chemical and biomolecular engineering or chemical and materials engineering or chemical and environmental engineering. We will therefore abandon the idea of formulating a simple definition, and instead take a closer look at what those recent graduates did either immediately after graduation or following a well-earned vacation. We will also do some speculating about what they might do several years after graduating, based on our experiences with graduates from previous classes. Consider these examples and see if any of them sound like the sort of career you can see yourself pursuing and enjoying.

- About 45% of the class went to work for chemical, petrochemical, pulp and paper, and polymer (plastics) manufacturing firms.
- Another 35% went to work for government agencies and design and consulting firms (many specializing in environmental regulation and pollution control), companies in fields such as microelectronics and information technology that have not been traditionally associated with chemical engineering, and firms specializing in emerging areas such as biotechnology and sustainable development (development that addresses economic, ecological, cultural, and political considerations).
- About 10% of the class went directly into graduate school in chemical engineering. The master's degree candidates will get advanced training in traditional chemical engineering areas (thermodynamics, chemical reactor analysis and design, fluid dynamics, mass and heat transfer, and chemical process design and control) and emerging areas such as biotechnology, biomedicine, materials science and engineering, nanotechnology, and sustainable development. They will have access to most of the jobs available to the bachelor's degree holders plus jobs in those emerging areas that require additional training. The doctoral degree candidates will get more advanced training and work on major research projects, and in four to five years most will graduate and either go into industrial research and development or join university faculties.
- A small number were drawn to entrepreneurship, and within a few years after graduation will start their own companies in areas that might or might not have anything to do with their college backgrounds.

- The remaining 10% of the class went into graduate school in areas other than engineering, discovering that their chemical engineering backgrounds made them strongly competitive for admission to top universities. Several who took biology electives in their undergraduate programs went to medical school. Others went to law school, planning to go into patent or corporate law, and still others enrolled in Master of Business Administration programs with the goal of moving into management in industry.
- One graduate joined the Peace Corps for a two-year stint in East Africa helping local communities develop sanitary waste disposal systems and also teaching science and English in a rural school. When she returns, she will complete a Ph.D. program in environmental engineering, join a chemical engineering faculty, write a definitive book on environmental applications of chemical engineering principles, quickly rise through the ranks to become a full professor, resign after 10 years to run for the United States Senate, win two terms, and eventually become head of a large and highly successful private foundation dedicated to improving education in economically deprived communities. She will attribute her career successes in part to the problem-solving skills she acquired in her undergraduate training in chemical engineering.
- At various points in their careers, some of the graduates will work in chemical or biochemical or biomedical or material science laboratories doing research and development or quality engineering, at computer terminals designing processes and products and control systems, at field locations managing the construction and startup of manufacturing plants, on production floors supervising and troubleshooting and improving operations, on the road doing technical sales and service, in executive offices performing administrative functions, in government agencies responsible for environmental and occupational health and safety, in hospitals and clinics practicing medicine or biomedical engineering, in law offices specializing in chemical process-related patent work, and in classrooms teaching the next generation of students.

The careers just described are clearly too diverse to fall into a single category. They involve disciplines including physics, chemistry, biology, environmental science, medicine, law, applied mathematics, statistics, information technology, economics, research, design, construction, sales and service, production supervision, and business administration. The single feature they have in common is that chemical engineers can be found doing them. Some of the specific knowledge needed to carry out the tasks will be presented later in the chemical engineering curriculum, and most of it must be learned after graduation. There are, however, basic techniques that have been developed for setting up and attacking technical problems that apply across a broad range of disciplines. What some of these techniques are and how and when to use them are the subjects of this book.

CHAPTER

2

Introduction to Engineering Calculations

Chapter 1 suggests the range of problems encompassed by chemical engineering,[1] both in traditional areas of chemical processing and in relatively new fields such as environmental science and engineering, bioengineering, and semiconductor manufacturing. Differences between the areas mentioned in the chapter—chemical manufacturing, genetic engineering, and pollution control—are obvious. In this book, we examine the similarities.

One similarity is that all of the systems described involve **processes** designed to transform raw materials into desired products. Many of the problems that arise in connection with the design of a new process or the analysis of an existing one are of a certain type: given amounts and properties of the raw materials, calculate amounts and properties of the products, or vice versa.

The object of this text is to present a systematic approach to the solution of problems of this type. This chapter presents basic techniques for expressing the values of system variables and for setting up and solving equations that relate these variables. In Chapter 3 we discuss the variables of specific concern in process analysis—temperatures, pressures, chemical compositions, and amounts or flow rates of process streams—describing how they are defined, calculated, and, in some cases, measured. Parts Two and Three of the book deal with the laws of conservation of mass and energy, which relate the inputs and outputs of manufacturing systems, power plants, and the human body. The laws of nature constitute the underlying structure of all process design and analysis, including the techniques we present in the book.

2.0 LEARNING OBJECTIVES

After completing this chapter, you should be able to do the following:

- Convert a quantity expressed in one set of units into its equivalent in any other dimensionally consistent units using appropriate conversion factors. [For example, convert a heat flux of 235 $\text{kJ/(m}^2\cdot\text{s)}$ into its equivalent in $\text{Btu/(ft}^2\cdot\text{h)}$.]
- Identify the units commonly used to express both mass and weight in SI, CGS, and U.S. customary units. Calculate weights from given masses in either natural units (e.g., $\text{kg}\cdot\text{m/s}^2$ or $\text{lb}_\text{m}\cdot\text{ft/s}^2$) or defined units (N, lb_f).
- Identify the number of significant figures in a given value expressed in either decimal or scientific notation and state the precision with which the value is known based on its significant figures. Determine the correct number of significant figures in the result of a series of arithmetic operations (adding, subtracting, multiplying, and dividing).
- Validate a quantitative problem solution by applying back-substitution, order-of-magnitude estimation, and the test of reasonableness.
- Given a set of measured values, calculate the sample mean, range, sample variance, and sample standard deviation. Explain in your own words what each of the calculated quantities means and why it is important.

---

[1] When we refer to chemical engineering, we intend to encompass all aspects of a discipline that includes applications in biology as well as a number of other fields.

- Explain the concept of dimensional homogeneity of equations. Given the units of some terms in an equation, use this concept to assign units to other terms.
- Given tabulated data for two variables (x and y), use linear interpolation between two data points to estimate the value of one variable for a given value of the other. Sketch a plot of y versus x and use it to illustrate how and when linear interpolation can lead to significant errors in estimated values.
- Given two points on a straight-line plot of y versus x, derive the expression for $y(x)$. Given tabulated data for x and y, fit a straight line by visual inspection.
- Given a two-parameter expression relating two variables [such as $y = a\sin(2x) + b$ or $P = 1/(aQ^3 + b)$ and two adjustable parameters (a and b), state what you would plot to generate a straight line. Given data for x and y, generate the plot and estimate the parameters a and b.
- Given a power-law or exponential expression involving two variables (such as $y = ax^b$ or $k = ae^{b/T}$), state what you would plot on rectangular, semilog, or logarithmic axes that would generate a straight line. Given a linear plot involving two variables on any of the three types of axes and two points on the line, determine the expression relating the two variables and the values of the two parameters.

2.1 UNITS AND DIMENSIONS

A measured or counted quantity has a numerical **value** (2.47) and a **unit** (whatever there are 2.47 of). It is useful in most engineering calculations—and essential in many—to write both the value and the unit of each quantity appearing in an equation:

$$2 \text{ meters}, \quad \tfrac{1}{3} \text{ second}, \quad 4.29 \text{ kilograms}, \quad 5 \text{ gold rings}$$

A **dimension** is a property that can be measured, such as length, time, mass, or temperature, or calculated by multiplying or dividing other dimensions, such as length/time (velocity), length^3 (volume), or mass/length^3 (density). Measurable units (as opposed to countable units) are specific values of dimensions that have been defined by convention, custom, or law, such as grams for mass, seconds for time, and centimeters or feet for length.

Units can be treated like algebraic variables when quantities are added, subtracted, multiplied, or divided. *Two quantities may be added or subtracted only if their units are the same.*

$$3 \text{ cm} - 1 \text{ cm} = 2 \text{ cm} \qquad (3x - x = 2x)$$

but

$$3 \text{ cm} - 1 \text{ mm (or 1 s)} = ? \qquad (3x - y = ?)$$

On the other hand, *numerical values and their corresponding units may always be combined by multiplication or division.*

$$\begin{aligned}
3 \text{ N} \times 4 \text{ m} &= 12 \text{ N}\cdot\text{m} \\
\frac{5.0 \text{ km}}{2.0 \text{ h}} &= 2.5 \text{ km/h} \\
7.0 \frac{\text{km}}{\text{h}} \times 4 \text{ h} &= 28 \text{ km} \\
3 \text{ m} \times 4 \text{ m} &= 12 \text{ m}^2 \\
6 \text{ cm} \times 5 \frac{\text{cm}}{\text{s}} &= 30 \text{ cm}^2/\text{s} \\
\frac{6 \text{ g}}{2 \text{ g}} &= 3 \qquad \text{(3 is a \textit{dimensionless} quantity)} \\
\left(5.0 \frac{\text{kg}}{\text{s}}\right) \bigg/ \left(0.20 \frac{\text{kg}}{\text{m}^3}\right) &= 25 \text{ m}^3/\text{s} \qquad \text{(Convince yourself)}
\end{aligned}$$

2.2 CONVERSION OF UNITS

A measured quantity can be expressed in terms of any units having the appropriate dimension. A particular velocity, for instance, may be expressed in ft/s, miles/h, cm/yr, or any other ratio of a length unit to a time unit. The numerical value of the velocity naturally depends on the units chosen.

The equivalence between two expressions of the same quantity may be defined in terms of a ratio:

$$\frac{1\text{ cm}}{10\text{ mm}} \quad \text{(1 centimeter per 10 millimeters)} \tag{2.2-1}$$

$$\frac{10\text{ mm}}{1\text{ cm}} \quad \text{(10 millimeters per centimeter)} \tag{2.2-2}$$

$$\left[\frac{10\text{ mm}}{1\text{ cm}}\right]^2 = \frac{100\text{ mm}^2}{1\text{ cm}^2} \tag{2.2-3}$$

Ratios of the form of Equations 2.2-1, 2.2-2, and 2.2-3 are known as **conversion factors**.

To convert a quantity expressed in terms of one unit to its equivalent in terms of another unit, multiply the given quantity by the conversion factor (new unit/old unit). For example, to convert 36 mg to its equivalent in grams, write

$$36\text{ mg} \times \frac{1\text{ g}}{1000\text{ mg}} = 0.036\text{ g} \tag{2.2-4}$$

(Note how the old units cancel, leaving the desired unit.) An alternative way to write this equation is to use a vertical line instead of the multiplication symbol:

$$\begin{array}{c|c} 36\text{ mg} & 1\text{ g} \\ \hline & 1000\text{ mg} \end{array} = 0.036\text{ g}$$

Carrying along units in calculations of this type is the best way of avoiding the common mistake of multiplying when you mean to divide and vice versa. In the given example, the result is known to be correct because milligrams cancel leaving only grams on the left side, whereas

$$\begin{array}{c|c} 36\text{ mg} & 1000\text{ mg} \\ \hline & 1\text{ g} \end{array} = 36{,}000\text{ mg}^2/\text{g}$$

is clearly wrong. (More precisely, it is not what you intended to calculate.)

The practice of carrying units along with calculations will require discipline, but it is sure to save you from making countless errors. To illustrate, simply insert the phrase "unit conversion errors" in your favorite search engine, and a list of famous ones will be displayed. Our experience is that once you start carrying units, two things will happen: (1) you will make fewer mistakes in calculations, and (2) you often will gain understanding of otherwise incomprehensible mathematical expressions.

If you are given a quantity having a compound unit [e.g., miles/h, cal/(g·°C)], and you wish to convert it to its equivalent in terms of another set of units, set up a **dimensional equation**: write the given quantity and its units on the left, write the units of conversion factors that cancel the old units and replace them with the desired ones, fill in the values of the conversion factors, and carry out the indicated arithmetic to find the desired value. (See Example 2.2-1.)

Test Yourself

(Answers, p. 654)

1. What is a conversion factor?
2. What is the conversion factor for s/min (s = second)?
3. What is the conversion factor for min^2/s^2? (See Equation 2.2-3.)
4. What is the conversion factor for m^3/cm^3?

Example 2.2-1 Conversion of Units

Convert an acceleration of $1\ \text{cm/s}^2$ to its equivalent in km/yr^2.

Solution

$$\begin{array}{c|r|r|r|c|c} 1\ \text{cm} & 3600^2\ \text{s}^2 & 24^2\ \text{h}^2 & 365^2\ \text{day}^2 & 1\ \text{m} & 1\ \text{km} \\ \hline \text{s}^2 & 1^2\ \text{h}^2 & 1^2\ \text{day}^2 & 1^2\ \text{yr}^2 & 10^2\ \text{cm} & 10^3\ \text{m} \end{array}$$

$$= \frac{(3600 \times 24 \times 365)^2}{10^2 \times 10^3} \frac{\text{km}}{\text{yr}^2} = \boxed{9.95 \times 10^9\ \text{km/yr}^2}$$

A principle illustrated in this example is that raising a quantity (in particular, a conversion factor) to a power raises its units to the same power. The conversion factor for h^2/day^2 is therefore the square of the factor for h/day:

$$\left(\frac{24\ \text{h}}{1\ \text{day}}\right)^2 = 24^2\ \frac{\text{h}^2}{\text{day}^2}$$

2.3 SYSTEMS OF UNITS

A system of units has the following components:

1. ***Base units*** for mass, length, time, temperature, electrical current, and light intensity.
2. ***Multiple units,*** which are defined as multiples or fractions of base units such as minutes, hours, and milliseconds, all of which are defined in terms of the base unit of a second. Multiple units are defined for convenience rather than necessity; it is simply more convenient to refer to 3 yr than to 94,608,000 s.
3. ***Derived units,*** obtained in one of two ways:
   (a) By multiplying and dividing base or multiple units (cm^2, ft/min, $\text{kg}\cdot\text{m/s}^2$, etc.). Derived units of this type are referred to as **compound units**.
   (b) As defined equivalents of compound units (e.g., $1\ \text{erg} \equiv 1\ \text{g}\cdot\text{cm/s}^2$, $1\ \text{lb}_\text{f} \equiv 32.174\ \text{lb}_\text{m}\cdot\text{ft/s}^2$).

The "Système Internationale d'Unités," or **SI** for short, has gained widespread acceptance in the scientific and engineering community.[2] Two of the base SI units—the ampere for electrical current and the candela for luminous intensity—will not concern us in this book. A third, the kelvin for temperature, will be discussed later. The others are the meter (m) for length, the kilogram (kg) for mass, and the second (s) for time.

Prefixes are used in SI to indicate powers of ten. The most common of these prefixes and their abbreviations are mega (M) for 10^6 (1 megawatt = 1 MW = 10^6 watts), kilo (k) for 10^3, centi (c) for 10^{-2}, milli (m) for 10^{-3}, micro (μ) for 10^{-6}, and nano (n) for 10^{-9}. The conversion factors between, say, centimeters and meters are therefore 10^{-2} m/cm and 10^2 cm/m. The principal SI units and prefixes are summarized in Table 2.3-1.

The **CGS system** is almost identical to SI, the principal difference being that grams (g) and centimeters (cm) are used instead of kilograms and meters as the base units of mass and length. The principal units of the CGS system are shown in Table 2.3-1.

The base units of the **U.S. customary system** are the foot (ft) for length, the pound-mass (lb_m) for mass, and the second (s) for time. This system has two principal difficulties. The first is the occurrence of conversion factors (such as 1 ft/12 in), which, unlike those in the metric systems, are not multiples of 10; the second, which has to do with the unit of force, is discussed in the next section.

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[2] For additional information about the SI system, including its history, see http://physics.nist.gov/cuu/Units/.

Factors for converting from one system of units to another may be determined by taking ratios of quantities listed in the table on the inside front cover of this book. A larger table of conversion factors is given on pp. 1-2 through 1-18 of *Perry's Chemical Engineers' Handbook*.[3]

TABLE 2.3-1 SI and CGS Units

Base Units

Quantity	Unit	Symbol
Length	meter (SI) centimeter (CGS)	m cm
Mass	kilogram (SI) gram (CGS)	kg g
Moles	gram-mole	mol or g-mole
Time	second	s
Temperature	kelvin	K
Electric current	ampere	A
Light intensity	candela	cd

Multiple Unit Preferences

tera (T) = 10^{12}	centi (c) = 10^{-2}
giga (G) = 10^{9}	milli (m) = 10^{-3}
mega (M) = 10^{6}	micro (μ) = 10^{-6}
kilo (k) = 10^{3}	nano (n) = 10^{-9}

Derived Units

Quantity	Unit	Symbol	Equivalent in Terms of Base Units
Volume	liter	L	$0.001\ \text{m}^3$ $1000\ \text{cm}^3$
Force	newton (SI) dyne (CGS)	N	$1\ \text{kg}\cdot\text{m/s}^2$ $1\ \text{g}\cdot\text{cm/s}^2$
Pressure	pascal (SI)	Pa	$1\ \text{N/m}^2$
Energy, work	joule (SI) erg (CGS) gram-calorie	J cal	$1\ \text{N}\cdot\text{m} = 1\ \text{kg}\cdot\text{m}^2/\text{s}^2$ $1\ \text{dyne}\cdot\text{cm} = 1\ \text{g}\cdot\text{cm}^2/\text{s}^2$ $4.184\ \text{J} = 4.184\ \text{kg}\cdot\text{m}^2/\text{s}^2$
Power	watt	W	$1\ \text{J/s} = 1\ \text{kg}\cdot\text{m}^2/\text{s}^3$

Test Yourself

(Answers, p. 654)

1. What are the factors (numerical values and units) needed to convert

(a) meters to millimeters?

(b) nanoseconds to seconds?

(c) square centimeters to square meters?

(d) cubic feet to cubic meters (use the conversion factor table on the inside front cover)?

(e) horsepower to British thermal units per second?

2. What is the derived SI unit for velocity? The velocity unit in the CGS system? In U.S. customary units?

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[3] R. H. Perry and D. W. Green, Eds., *Perry's Chemical Engineers' Handbook*, 8th Edition, McGraw-Hill, New York, 2008.