American Geosciences Institute ▪ National Association of Geoscience Teachers

EDITED BY
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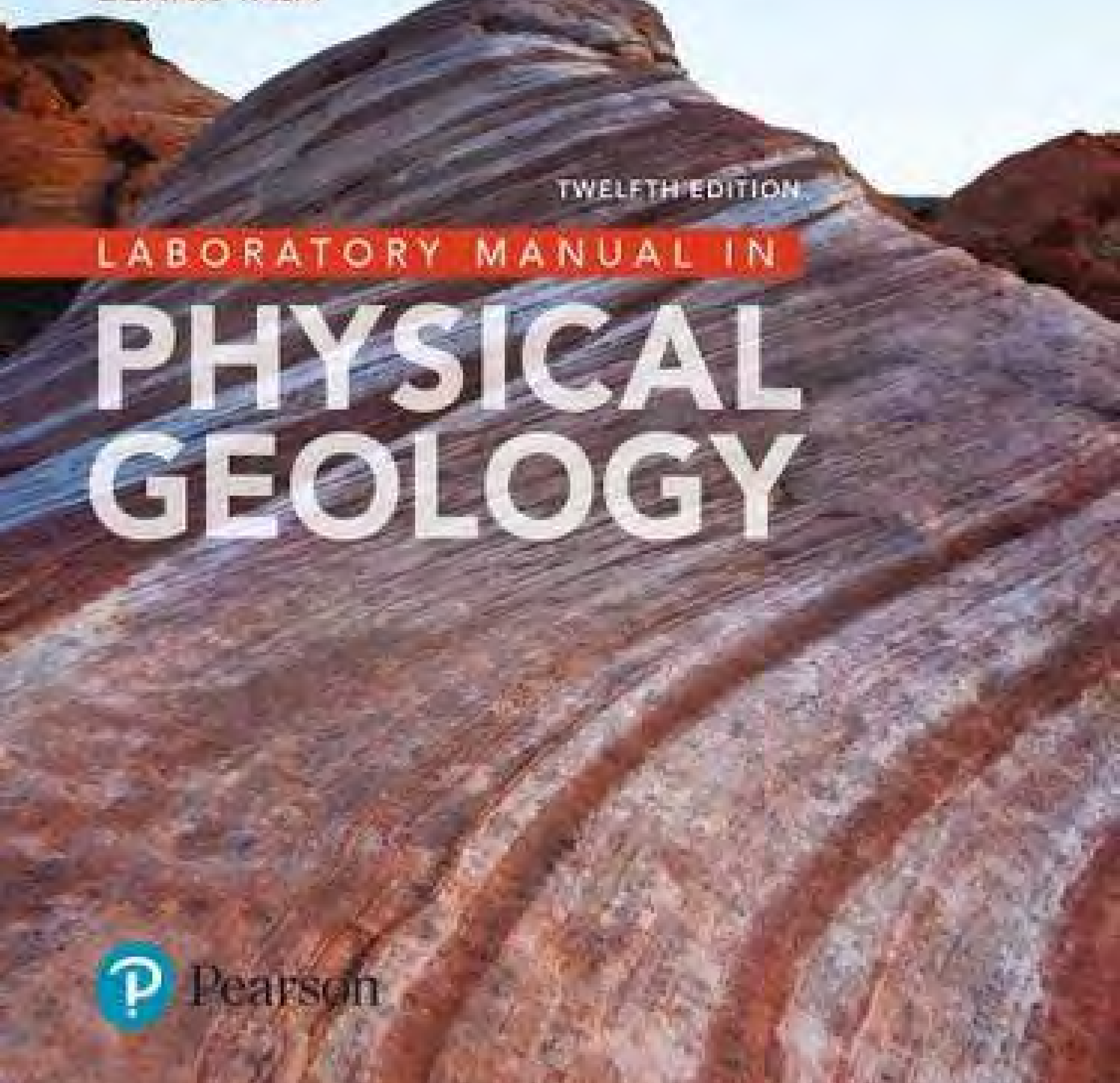
TWELFTH EDITION

LABORATORY MANUAL IN PHYSICAL GEOLOGY



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Preface

Laboratory Manual in Physical Geology has been developed by the geoscience education community for the benefit of our students and is produced under the auspices of the American Geosciences Institute (AGI) and the National Association of Geoscience Teachers (NAGT). For decades and continuing through the present day, it has been the most widely adopted manual available for teaching laboratories in introductory geology and geoscience.

The idea for this jointly sponsored laboratory manual originated with Robert W. Ridky (past president of NAGT and member of the AGI Education Advisory Committee), who envisioned a manual made up of the "best laboratory investigations written by geology teachers." To that end, this edition represents the cumulative ideas of more than 225 contributing authors, 35 years of evolution in geoscience and geoscience education, the comments of faculty peer reviewers and geoscience professionals, instructors and their students who have used past editions since the laboratory manual was first published in 1986.

Proceeds from the sale of the *Laboratory Manual in Physical Geology* provide substantial financial support for the work of AGI and NAGT, benefiting the entire geoscience community.

New and Different in the 12th Edition

New editions of the *Laboratory Manual in Physical Geology* are developed because our science is continually evolving. New technologies, new data, and new hypotheses are being applied to the geosciences, as geoscientists strive to apply new knowledge and expertise to a society trying to cope with challenges related to water, energy, mineral resources, natural and human-induced environmental hazards, and global change. An ever-changing *Laboratory Manual in Physical Geology* is essential for AGI and NAGT to fulfill their missions in helping to educate and inform the public and to facilitate the development of the next generation of geoscientists.

The team that developed the new edition of this classic laboratory manual sought to preserve features that are familiar and valued by the geoscience education community while making revisions that were requested by users or deemed necessary to better reflect current developments in the geosciences.

Major Changes

- **New Laboratory.** The 12th edition includes a new laboratory (Lab 17) that focuses on a few important geological aspects of climate change. Six activities are provided to help guide student exploration of data and concepts related to climate change and the lab bring into focus some of the implications of a warming climate.
- **Earth System Science.** The idea of Earth as a system is now a more explicit thread throughout the lab manual. By describing students to Earth as a network of interacting systems, we hope they will better to understand the interconnectedness and interdependencies of our Earth environment. An introduction to systems thinking in geoscience is provided in Lab 1, and key words related to Earth system science are highlighted with in-text callouts in all chapters.
- **Rock and Mineral Identification.** New text and graphics have been added to the labs concerned with minerals and rocks to clarify the process of specimen identification. Specifically, new determinative tables for the field identification of igneous, sedimentary, and metamorphic rocks have been included that are broadly similar to tables in earlier editions. A new flow chart for the identification of unknown minerals has also been included. New photographs and photomicrographs add to already extensive explanations of form, texture, and composition to help students understand how to identify specimens.
- **Learning Goals.** Each lab activity now begins with a statement of learning goals for students as they work through the assignment. Typically, the learning goal is a statement of what a student will gain in working on that activity, such as experience working with data, increased understanding of materials or processes, or a chance to synthesize information and place it into a meaningful context.
- **"Digging Deeper" Content and Activities.** Content that might be considered somewhat advanced or suitable for enrichment beyond the basic educational needs of a student are identified with a "Digging Deeper" callout.

Incremental Changes

- **Text.** Portions of the supporting text in the 12th edition are new or have been revised, generally based on suggestions and reviews by faculty and students. Some material that was considered extraneous has not been included in the new edition. Great care has been taken to compose supporting text that is scientifically correct, uses the appropriate geoscience terms correctly, is comprehensible by undergraduate college students, and is well supported with illustrations.
- **Activities.** There are 11 new or significantly revised activities in the 12th edition in addition to the activities in the new climate-change lab, for a total of 17 new or

revised activities. The revisions were primarily intended to improve clarity or update content.

- **Photographs.** There are just over one hundred new photographs in the 12th edition. All of the new photographs of rock and mineral specimens are the result of very high-resolution macro photography enhanced by focus-stacking technology.
- **Maps.** Map scales throughout the lab book have been adjusted to make it easier for students to determine distances on maps using simple proportions. New topographic maps are based on the most current U.S. topographic map product published digitally by the USGS. Many of the maps have been simplified to reduce irrelevant elements and improve clarity.
- **Illustrations.** There are nearly 150 new or revised graphics, and countless minor revisions in the art components of the lab manual thanks to the remarkable contributions of Dennis Tasa.
- **Reordering of Lab Chapters.** The laboratory devoted to studying earthquakes is now located after the lab on Earth structures, because of the obvious connection between faults, folds, and earthquakes.
- **Reordering of Lab Activities.** Some of the lab activities featured in the previous edition are reordered within the respective labs in order to better follow the flow of information in the introductory text. In a few cases, the content of previous lab activities has been redistributed for clarity or to adjust the time needed to complete an activity. A full accounting of these types of changes is provided in the *Instructor Resource Manual* that is available to teachers from Pearson.

Familiar Features in the 12th Edition

This edition contains the tried-and-tested strengths of eleven past editions of the *Laboratory Manual in Physical Geology* that have benefited students and teachers over more than three decades, along with updates that are consistent with current understanding in geoscience. The outstanding features listed below remain a core part of this manual.

Pedagogy for Diverse Styles/Preferences of Learning

Hands-on multisensory-oriented activities with samples, cardboard models, and GeoTools appeal to *concrete/kinesthetic learners*. High-quality images, maps, charts, diagrams, PowerPoints™, cardboard models, and visualizations appeal to *visual/spatial learners*. Activity sheets, charts, lists, supporting text, and opportunities for discourse appeal to *linguistic/verbal/read-write learners*. Presentation graphics (PowerPoint) and video clips appeal to *auditory/aural learners*. This content will be available on Mastering Geology. Numerical data, mathematics, models, graphs, systems, and opportunities for discourse appeal to *logical/abstract learners*.

Format and Pedagogical Framework

- **Big Ideas and Engaging Chapter Openers.** Every laboratory opens with an engaging image and a statement of *Big Ideas*, which establish the overall conceptual themes upon which the laboratory is based. *Big Ideas* are concise statements that help students understand and focus on the lab topic.
- **Supporting Text as a Persistent Reference.** The text that appears before the Activity section of each chapter serves two goals. One is the practical goal of providing essential information to students so that they can succeed in working through the Activities. The second is to provide students with a coherent body of information that will remain after the Activities are completed, and after the Activity pages are removed from the book.
- **Activities.** Laboratory geoscience courses should be environments where students engage directly with specimens, maps, photographs, data, and the processes of measurement and analysis. The 105 activities in the 12th edition are based on common samples and equipment that are available in typical geoscience teaching laboratories. Having access to such a large number of activities allows an instructor to select and adapt activities according to course content and level of difficulty. Because most activities do not require sophisticated equipment, they can also be assigned for students to complete as pre-laboratory assignments, lecture supplements, homework, or recitation topics.
- **Learning Goals.** As noted above, a new feature in the 12th edition is a statement of learning goals at the top of every activity worksheet.
- **Reflect & Discuss Questions.** Most activities conclude with a *Reflect & Discuss* question designed to foster greater accommodation of knowledge by having students apply what they learned to a new situation or to state broader conceptual understanding.
- **Continuous Assessment Options.** The pedagogical framework and organization provide many options for continuous assessment. Grading of students' work is easier because all students submit their own work in a similar format. Instructors save time, energy, and resources because they no longer need to photocopy and distribute worksheets to supplement the manual.

Other Key Features

- **Outstanding Art.** Dennis Tasa's brilliant artwork reinforces the visual aspect of geology and enhances student learning. We are continuing a process begun with the previous edition that will ultimately make all of our illustrations more accessible to people with color blindness or other vision-related issues. We are committed to a geoscience community that is diverse, inclusive, and welcoming to all.
- **Language and Geoscience Terminology.** We have continued the tradition of using vocabulary appropriate to undergraduate students in the 12th edition and have sought to keep geoscience jargon to a necessary

minimum. Rock and mineral terms are used in a way that is consistent with the published standards of the International Mineralogical Association and the International Union of Geological Sciences, as well as with the latest edition of the American Geoscience Institute (AGI) *Glossary of Geology*. The complete AGI *Glossary of Geology* is available in print, as an e-book for Kindle and Nook, as an app for mobile devices (available at the Apple Store and at Google Play), and online for universities and companies (but not for individuals; www.americangeosciences.org/pubs/glossary).
- **Math.** Geoscience is based largely on quantitative observations, measurements, and descriptions. Students are assumed to have an average understanding of basic high-school mathematics, although most of the mathematics needed to complete activities in this lab book is at a middle-school level. Through laboratory activities, we help students to refresh or develop useful math skills as they are needed to understand the material.
- **GeoTools, GPS and UTM.** Rulers, protractors, a sediment grain size scale, UTM grids, and other laboratory tools are available to cut from transparent sheets at the back of the manual. No other manual provides such abundant supporting tools! Students are introduced to GPS and UTM and their application in mapping. UTM grids are provided for most scales of U.S. and Canadian maps.

Pre-Lab Videos

Links to Pre-Lab videos are found on the chapter-opening pages of each lab and are accessed via a Quick Response (QR) code or URL. These videos allow students to come to lab better prepared and ready to immediately benefit from their engagement with lab exercise. The videos can be viewed during the students' own preparatory time and review key concepts relevant to the lab activities. The videos, created by Callan Bentley (*Northern Virginia Community College*), are personable and friendly, and assure students that they will be able to successfully complete the lab activities by following a clear series of steps. Students can download free QR reader apps from the Apple App Store or Google Play.

Enhanced Learning Options

- **Transferable Skill Development and Real-World Connections.** Many activities have been designed or revised for students to develop transferrable skills and make connections that are relevant to their lives and the world in which they live. For example, they learn how to obtain and use data and maps that will enable them to make wiser choices about where they live and work. They evaluate their use of Earth resources in relation to questions about resource management and sustainability. They learn to use resources provided by the U.S. Geological Survey, JPL-NASA, NOAA, Google Earth™, and other online sources of reliable data and analysis about Earth's resources, hazards, changes, and management.
- **The Math You Need (TMYN) Options.** Throughout the laboratories, students are referred to online options for them to review or learn mathematical skills using *The Math You Need, When You Need It* (TMYN). TMYN consists of modular math tutorials that have been designed for students in any introductory geoscience course by Jennifer Wenner (University of Wisconsin–Oshkosh) and Eric Baer (Highline Community College).
- **Mobile-Enabled Media and Web Resources.** Quick Response (QR) codes give students with smartphones or other mobile devices instant access to supporting online media content and websites.

Instructor Support

An *Instructor Resource Manual for Laboratory Manual in Physical Geology,* 12th edition, is available online to verified teachers via their Mastering account (www.masteringgeology.com). The Instructor Manual has been designed to help seasoned and new professors alike, offering a detailed listing of changes between the 11th and 12th editions, teaching tips, information to help teachers prepare for each lab, answers and explanations for each activity, a list of web resources, and the source references for the laboratory topic. Also available for each chapter are JPEG images of each of the figures as well as a PowerPoint document with all the figures. Contact your Pearson representative for access information and instructions (www.pearson.com/us/contact-us/find-your-rep.html).

Educational Technology from Pearson

Mastering Geology

The Mastering Geology platform delivers engaging, dynamic learning opportunities—focused on course objectives and responsive to each student's progress—that are proven to help make course material accessible and to help them develop their understanding of difficult concepts. Robust diagnostics and unrivalled gradebook reporting allow instructors to pinpoint the weaknesses and misconceptions of a student or class to provide timely intervention.

- **Pre-lab video quizzes** help students come to lab better prepared and ready to immediately get started with the lab exercise.
- **Post-lab quizzes** assess students' understanding and analysis of the lab content.

Learn more at www.masteringgeology.com.

Learning Catalytics

Learning Catalytics™ is a "bring your own device" student engagement, assessment, and classroom intelligence system. With Learning Catalytics you can:

- assess students in real time, using open-ended tasks to probe student understanding.
- understand immediately areas in which adjustments to instruction will be helpful to students.
- improve your students' critical-thinking skills.

- access rich analytics to understand student performance.
- add your own questions to make Learning Catalytics fit your course exactly.
- manage student interactions with intelligent grouping and timing.

Learning Catalytics is a technology that has grown out of twenty years of cutting edge research, innovation, and implementation of interactive teaching and peer instruction. Available integrated with Mastering Geology. To learn more, go to www.learningcatalytics.com.

About the Editor

Vince Cronin is an award-winning geoscience educator who has served as a teaching assistant, teacher, or laboratory coordinator for introductory physical geology courses taught at several private and public colleges and universities since 1978. Dr. Cronin is currently Professor of Geosciences at Baylor University and is a licensed and certified professional geologist whose experience in applied and academic geology is quite broad. His research has included plate kinematics, crustal deformation, active faulting, clastic stratigraphy, topics in engineering geoscience, and geoethics.

Contribute Your Ideas

The continued enhancement and success of the *Laboratory Manual in Physical Geology* depends on constructive criticisms, suggestions, and new contributions from the students and teachers who use it. We welcome all constructive input that will contribute to the positive evolution of this resource. With your help, this lab manual will continue to develop in a beneficial way for students and for the geoscience community served by AGI and NAGT. Please continue to submit your ideas, suggestions, and constructive criticisms directly to the editor: Vince Cronin (Vince_LM_Editor@CroninProjects.org).

Acknowledgments

Development and production of this revised 12th edition of *Laboratory Manual in Physical Geology* required the expertise, dedication, and cooperation of many people and organizations, to which we want to express our sincere appreciation. This edition is an evolutionary outgrowth of work done by countless geoscientists, educators, editors, and publishing experts on previous editions, nine of which were edited by Richard Busch. We are indebted to all of these contributors to earlier editions for the strong foundation they provided for this, the 12th edition.

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Sharon Tahirkheli, *Executive Director, AGI*
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Measurement Units

Residents of the United States have historically used the British imperial system of measurement that includes units such as inches, feet, miles, acres, pounds, gallons, and degrees Fahrenheit. However, over the course of the last century, most other nations of the world chosen to adopt a different, simpler system called the International System or SI. In 1975, the U.S. Congress recognized that global communication, science, technology, and commerce were aided by use of a common system of measurement, and they made SI the official measurement system of the United States. Most Americans currently use both English and SI systems of measurement.

The International System (SI)

The International System of Units (SI) is the decimal system of measurement adopted by most nations of the world, including the United States (http://www.bipm.org/en/publications/si-brochure/). Each SI unit can be divided or multiplied by 10 and its powers to form the smaller or larger units. Therefore, SI is a "base-10" or "decimal" system.

SYMBOL	NUMBER	NUMERAL	POWER OF 10	PREFIX
T	one trillion	1,000,000,000,000	10^{12}	tera-
G	one billion	1,000,000,000	10^{9}	giga-
M	one million	1,000,000	10^{6}	mega-
k	one thousand	1000	10^{3}	kilo-
h	one hundred	100	10^{2}	hecto-
da	ten	10	10^{1}	deka-
	one	1	10^{0}	
d	one-tenth	0.1	10^{-1}	deci-
c	one-hundredth	0.01	10^{-2}	centi-
m	one-thousandth	0.001	10^{-3}	milli-
μ	one-millionth	0.000001	10^{-6}	micro-
n	one-billionth	0.000000001	10^{-9}	nano-
p	one-trillionth	0.000000000001	10^{-12}	pico-

Examples

1 meter (1 m) = 0.001 kilometers (0.001 km), 10 decimeters (10 dm), 100 centimeters (100 cm), or 1000 millimeters (1000 mm)
1 kilometer (1 km) = 1000 meters (1000 m)
1 micrometer (1 μm) = 0.000,001 meter (.000001 m) or 0.001 millimeters (0.001 mm)
1 kilogram (kg) = 1000 grams (1000 g)
1 gram (1 g) = 0.001 kilograms (0.001 kg)
1 metric ton (1 t) = 1000 kilograms (1000 kg)
1 liter (1 L) = 1000 milliliters (1000 mL)
1 milliliter (1 mL or 1 ml) = 0.001 liter (0.001 L)

Abbreviations for Measures of Time

A number of abbreviations are used in the geological literature to refer to time. In this edition, we use the abbreviation "yr" for years, preceded as necessary with the letters "k" (kyr) for thousand years, "M" (Myr) for million years, or G (Gyr) for billion years.

Mathematical Conversions

To convert:	To:	Multiply by:	
kilometers (km)	meters (m)	1000 m/km	LENGTHS AND DISTANCES
	centimeters (cm)	100,000 cm/km	
	miles (mi)	0.6214 mi/km	
	feet (ft)	3280.83 ft/km	
meters (m)	centimeters (cm)	100 cm/m	
	millimeters (mm)	1000 mm/m	
	feet (ft)	3.2808 ft/m	
	yards (yd)	1.0936 yd/m	
	inches (in)	39.37 in/m	
	kilometers (km)	0.001 km/m	
	miles (mi)	0.0006214 mi/m	
centimeters (cm)	meters (m)	0.01 m/cm	
	millimeters (mm)	10 mm/cm	
	feet (ft)	0.0328 ft/cm	
	inches (in)	0.3937 in/cm	
	micrometers (μm)	10,000 μm/cm	
millimeters (mm)	meters (m)	0.001 m/mm	
	centimeters (cm)	0.1 cm/mm	
	inches (in)	0.03937 in/mm	
	micrometers (μm)	1000 μm/mm	
	nanometers (nm)	1,000,000 nm/mm	
micrometers* (μm)	millimeters (mm)	0.001 mm/μm	
nanometers (nm)	millimeters (mm)	0.000001 mm/nm	
miles (mi)	kilometers (km)	1.609 km/mi	
	feet (ft)	5280 ft/mi	
	meters (m)	1609.34 m/mi	
feet (ft)	centimeters (cm)	30.48 cm/ft	
	meters (m)	0.3048 m/ft	
	inches (in)	12 in/ft	
	miles (mi)	0.000189 mi/ft	
inches (in)	centimeters (cm)	2.54 cm/in	
	millimeters (mm)	25.4 mm/in	
	micrometers* (μm)	25,400 μm/in	
square miles (mi^2)	acres (a)	640 acres/mi^2	AREAS
	square km (km^2)	2.589988 km^2/mi^2	
square km (km^2)	square miles (mi^2)	0.3861 mi^2/km^2	
acres	square miles (mi^2)	0.001563 mi^2/acr	
	square km (km^2)	0.00405 km^2/acr	
gallons (gal)	liters (L)	3.78 L/gal	VOLUMES
fluid ounces (oz)	milliliters (mL)	30 mL/fluid oz	
milliliters (mL)	liters (L)	0.001 L/mL	
	cubic centimeters (cm^3)	1 cm^3/mL	
liters (L)	milliliters (mL)	1000 mL/L	
	cubic centimeters (cm^3)	1000 cm^3/L	
	gallons (gal)	0.2646 gal/L	
	quarts (qt)	1.0582 qt/L	
	pints (pt)	2.1164 pt/L	
grams (g)	kilograms (kg)	0.001 kg/g	WEIGHTS AND MASSES
	pounds avdp (lb)	0.002205 lb/g	
ounces avdp (oz)	grams (g)	28.35 g/oz	
ounces troy (ozt)	grams (g)	31.10 g/ozt	
pounds avdp (lb)	kilograms (kg)	0.4536 kg/lb	
kilograms (kg)	pounds avdp (lb)	2.2046 lb/kg	

To convert from degrees Fahrenheit (°F) to degrees Celsius (°C), subtract 32 degrees and then divide by 1.8. To convert from degrees Celsius (°C) to degrees Fahrenheit (°F), multiply by 1.8 and then add 32 degrees.

*Sometimes called microns (μ).

LABORATORY EQUIPMENT

Also refer to the GeoTools provided at the back of this laboratory manual.

NORTH AMERICA
Political & Physical Map
Metropolitan areas more than 20 million
Metropolitan areas 10–20 million
Metropolitan areas 5–9.9 million
Metropolitan areas 1–4.9 million
Selected smaller metropolitan areas
Plate boundaries
ELEVATION IN METERS
4000+
2000–4000
500–1,999
200–499
0–199
Below sea level
Sea Level
0 300 Miles
0 300 Kilometers
Anchorage
Bering Sea
Aleutian Islands
ARCTIC OCEAN
Bering Strait
Prudhoe Bay
Brooks Range
Alaska Range
Anchorage
NORTH AMERICAN PLATE
Gulf of Alaska
PACIFIC PLATE
PACIFIC OCEAN
YUKON TERRITORY
Whitehorse
NORTHWEST TERRITORIES
Mackenzie R.
Great Slave Lake
NUNAVUT
Greenland
EURASIAN PLATE
Baffin Bay
Baffin Island
Arctic Circle
Hudson Bay
NEWFOUNDLAND AND LABRADOR
Newfoundland
Prince Edward Island
P.E.I.
NEW BRUNSWICK
Saint John
Halifax
NOVA SCOTIA
QUÉBEC
Quebec City
Montréal
Ottawa
St. Lawrence R.
ONTARIO
MANITOBA
SASKATCHEWAN
ALBERTA
BRITISH COLUMBIA
C A N A D A
Coast Mountains
Edmonton
Calgary
Saskatoon
Regina
Winnipeg
Lake Winnipeg
Vancouver Island
Vancouver
Puget Sound
Seattle
Columbia R.
ROCKY MOUNTAINS
GREAT PLAINS
JUAN DE FUCA PLATE
PACIFIC PLATE
Portland
Cascade Range
Coast Ranges
Boise
Teton Range
Great Basin
Great Salt Lake
Salt Lake City
Central Valley
Sierra Nevada
Sacramento
San Francisco
San Jose
Colorado R.
Denver
Missouri R.
Platte R.
Minneapolis-St. Paul
L. Superior
L. Michigan
L. Huron
L. Ontario
L. Erie
Toronto
Hamilton
Buffalo
Detroit
Cleveland
Milwaukee
Chicago
Pittsburgh
Columbus
Indianapolis
Cincinnati
Ohio R.
Louisville
St. Louis
Kansas City
Arkansas R.
UNITED STATES
Adirondack Mtns.
Boston
Providence
Bridgeport
New York City
Philadelphia
Baltimore
Washington, D.C.
Chesapeake Bay
Virginia Beach
APPALACHIAN HIGHLANDS
Piedmont
Charlotte
Nashville
Atlanta
Ozark Mtns.
Ouachita Plateau
Memphis
Mississippi R.
ATLANTIC OCEAN
Las Vegas
Grand Canyon
Colorado Plateau
Los Angeles
Riverside
Salton Sea
San Diego
Phoenix
Tucson
Albuquerque
Oklahoma City
Red R.
Dallas-Fort Worth
El Paso
Austin
Houston
San Antonio
New Orleans
Rio Grande
Jacksonville
Orlando
Tampa-St. Petersburg
Miami
Florida Keys
Gulf of Mexico
MEXICO
NORTH AMERICAN PLATE
PACIFIC PLATE
0 250 500 Miles
0 250 500 Kilometers
PACIFIC OCEAN
Kauai
Oahu
Honolulu
Maui
HAWAII
Hawaii
0 100 Miles
0 100 Kilometers

Laboratory 1

Filling Your Geoscience Toolbox

Contributing Authors

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▲ Svartifoss (Black Falls) flowing over columnar basalt at Skaftafell in Vatnajökull National Park, Iceland (64.0275°N, 16.9753°W).

Big IDEAS

Geoscience is the science of Earth. Society needs reliable information about Earth as it confronts challenges related to resources, natural hazards, environmental health, and sustainable development. Geoscientists think of Earth as a system of interacting subsystems. We seek to understand Earth's history and the processes controlling its future evolution. Geoscientists observe Earth using many technologies, from sophisticated airborne or orbital sensors to laboratory instruments and basic fieldwork. We map Earth's surface and describe locations using several coordinate systems. Mapping Earth helps us document change over time and identify where useful resources occur. Mathematics is an important language we use to communicate ideas in geoscience.

Lab ACTIVITIES

Pre-Lab Video 1

https://goo.gl/c3zAzr

Introduction

On December 7, 1972, three astronauts in Apollo 17 looked back on Earth from a distance of ~29,000 km as they glided toward their rendezvous with the Moon. Either Jack Schmitt—an astronaut who is also a geologist—or Ron Evans took a photograph of our home in full sunlight (**Fig. 1.1**). Earth is a breathtakingly beautiful sight, cloaked in a swirling atmosphere that reveals the South Atlantic and Indian Oceans, Africa, Arabia, Antarctica, and the island of Madagascar near the center of the image. It is a portrait of a dynamic planet—a global system with many interacting subsystems.

Below those slowly moving clouds are oceans of liquid water circulating much more slowly than the atmosphere. There are also plates of solid lithosphere in which the continents are embedded and that extend below the ocean basins. The plates are also in motion, gliding over the top of a solid mantle that flows even more slowly. Below the rocky mantle and almost 3000 kilometers (km) below Earth's surface is a liquid iron core whose circulation is responsible for the magnetic field that protects Earth from many of the most dangerous effects of solar radiation. Even the solid inner core is thought to be in motion, rotating slightly faster than the outer part of the planet.

This dynamic Earth is the stage on which all of the acts of life are played. It is the source of all the resources we need to survive. As vast as Earth is from our perspective as individuals living out our lives on its surface, it is just a pale blue speck in the vastness of space.

Figure 1.1 **The blue marble.** Photograph of Earth taken by the crew of Apollo 17 on their way to the Moon in December 1972. Earth's restless, dynamic nature is well expressed in this image of our home.

We are intimately connected to the planet. Since Earth was photographed from Apollo 17, the human population of Earth has more than doubled—each new person with the same fundamental human rights as you. Also since that time, the atmospheric concentration of the greenhouse gas carbon dioxide (CO_2) has also increased, from about 328 parts per million (ppm) to about 412 ppm as of April 1, 2019—a concentration higher than at any time in the past 3 million years. Much of this increase is due to human activities.

In developing this laboratory manual, we provide you with the opportunity

- To see good examples of the materials that make up the surface of Earth
- To work with maps and imagery and other forms of data used in the geosciences
- To experience using some simple mathematics to help us understand relationships within the physical world
- To learn more about this planet as a system that we share and are a part of.

The labs in this course are for actively *doing* things. We want you to experience science and, in particular, to engage in geoscience. In working through these labs, you will tap into online sources of research-quality data collected by field-based geoscientists as well as by automated networks of seismographs and GPS receivers, Earth-observing satellites, and stream gages. Moderate to high-resolution images of Earth are now available online for free as are new digital topographic maps and archival maps for most of the United States. You won't just hear the stale factoid that Los Angeles and San Francisco are moving toward each other because they are located on different plates, but you will learn how to access the GPS velocity data and will acquire the knowledge needed to explore motion along that remarkable plate boundary yourself.

Earth is an oasis for life in space. It is worth your time to gain a basic understanding of our home. This lab book is a gateway to your exploration of Earth.

Science as a Process for Learning Reliable Information

An essential goal of any introductory geoscience course is to help you deepen your understanding of science and of its importance to our lives. The geoscientists who have collaborated in developing this laboratory manual would like you to understand at least some of the essential characteristics of science:

- Science is a way of learning reliable information about the world.
- Reliable information is derived from reproducible observations.
- All scientific observations involve some degree of uncertainty, and the proper assessment and reporting of

that uncertainty are a fundamental responsibility of scientists.

- We refer to reproducible observations with their associated uncertainties as **scientific facts**. Scientific facts are always subject to refinement.
- Scientific explanations of the relationships between scientific facts—**hypotheses**—must be testable.
- Many or most preliminary hypotheses are eventually found to be incomplete or simply wrong. Hypotheses in science generally have a short life span because they are replaced by better, more complete hypotheses. Science is a winnowing process that helps us identify the false leads and dead ends so that we can focus on potentially fruitful areas of inquiry.
- Scientific reports are critically reviewed by appropriate scientific experts prior to publication in the peer-reviewed journals that form the communication backbone of science.
- Science involves the work of individual scientists and teams of scientists in the context of a worldwide community involved in reproducing data, assessing uncertainty, testing hypotheses, reviewing scientific reports made by other scientists, and adding reliable information to our models of how the world works.
- Mathematics is a fundamental language in science because of the clarity and efficiency with which it describes the relationships among scientific facts.

In the lab, experience science as scientists do. Conduct investigations and use your senses and tools to make observations. As you do, record the data you develop. Engage in critical thinking—apply, analyze, interpret, and evaluate the evidence to form tentative ideas or conclusions. Engage in discourse or collaborative inquiry with others (exchange, organization, evaluation, and debate of data and ideas). Communicate inferences—write down or otherwise share your conclusions and justify them with your data and critical thinking process.

These components of geoscience work are often not a linear "scientific method" to be followed in steps. You might find yourself doing them all simultaneously or in odd order. For example, when you observe an object or event, you may form an initial interpretation about it. Those initial impressions need to be expanded and formalized into testable hypotheses, and that process of developing hypotheses often inspires the collection of new data. Your tentative ideas are likely to change as you acquire additional information.

When making observations, observe and record **qualitative data** by describing how things look, feel, smell, sound, taste, or behave. You should also collect and record **quantitative data** by counting, measuring, or otherwise expressing in numbers what you observe. Carefully and precisely record your data in a way that others could understand and use it.

Your instructor will not accept simple *yes* or *no* answers to questions. He or she will expect your answers to be complete statements justified with data, sometimes accompanied by an explanation of your critical thinking. Show your work whenever you use mathematics to solve a problem so your method of thinking is clear.

Geoscience and Geoethics

Geoscience is the branch of science that is primarily concerned with the natural history, materials, and processes of Earth and, by extension, of other planetary and subplanetary bodies within our observational reach. Geoscientists study Earth through many different types of inquiry. A geoscientist's work must be reproducible or else it is not scientifically valid or useful.

Some envision science as a search for truth, although that begs the classic philosophical question "What is truth?" Scientific knowledge can be very reliable, but it never fully escapes its provisional nature. We are always improving our knowledge by testing our hypotheses with new data. Albert Einstein wrote, "Truth is what stands the test of experience" in an essay on ethics. Ethics is foundational to all that we do in science. Virtually all of the major professional organizations in science and in geoscience have developed codes of ethics (**http://www.americangeosciences.org/community/agi-guidelines-ethical-professional-conduct**). The international effort to further develop and spread the fundamental ideas of **geoethics**—ethics as applied to geoscience and the stewardship of Earth—is quite vigorous (**http://www.geoethics.org**).

Geoscientists have important responsibilities toward society because of our unique knowledge of Earth (**Fig. 1.2**). Geoscientists must act ethically to provide society with the reliable information needed to make good choices related to energy, mineral resources, water management, environmental health, natural hazards, climate change, and many other issues of public policy. Only reliable information is useful as we confront our many challenges. In addition to our responsibilities toward society, geoscientists are also responsible for acting as caretakers of the only habitable planet that we have useful access to—our home, Earth.

The fact that you are privileged to have access to a college course in physical geology imparts ethical responsibilities to you. Take full advantage of your opportunity to think, to question, and to learn about Earth. To paraphrase James Blaisdell of Pomona College, you bear your added riches in trust for all of humanity.

Learning to Think Like a Geoscientist

As you complete exercises in this laboratory manual, think and act like a geoscientist. Begin to develop a curiosity about Earth materials and history, natural resources, processes and rates of environmental change, where and how people live in relation to the environment, and how geology contributes to sustaining the human population. As your understanding deepens, you will begin to recognize some of the important connections between different parts of the Earth system.

Figure 1.2 Society needs the input of geoscientists. A landslide destroyed this important access road in southern California that cost many millions of dollars to repair. Geoscientists provide society with the expertise needed to effectively address challenges related to energy, supply of industrial minerals, fresh water, climate change, and natural hazards ranging from landslides and floods to earthquakes and volcanic eruptions.

Earth System Science

Geoscientists think about Earth as a system. Earth system science is the study of the connections and interactions between the major parts of the planet, also known as Earth's *spheres*: the **geosphere**, **atmosphere**, **hydrosphere**, **cryosphere**, and **biosphere**. Studies of these components over the past few decades have revealed that we live in a far more dynamic and complex world than we previously imagined. The goal of Earth system science is to understand how the planet works and answer questions about global change—past, present, and future. Clearly, any attempt to construct a model of something as large, old, and complex as Earth faces some serious challenges. To achieve this goal, we must narrow our field of view, carefully sample often-widespread phenomena, and make generalizations about how the Earth system functions. Despite limitations, such studies have provided deeper insights into the interconnected nature of Earth's major systems.

Building Better Models

Geoscientists are now able to model major global **interactions**, from the effects of atmospheric winds on the circulation of the oceans, the role of thermal convection on worldwide volcanism, and the effects of mountain building and uplift on climate to the transfer of carbon through Earth's biosphere and other systems. Such integrated studies increasingly reveal that humankind is not an independent variable in the Earth system. We play an increasingly significant role, and our quest for natural resources affects systems as diverse as the rock cycle and global ecology. Humans are also affected by global change, from short-term natural hazards such as earthquakes, volcanoes, and tsunamis to processes like El Niño and changes in global climate. Looking ahead, the exponential growth in data gathering networks and computer processing power has set the stage for us to improve upon our predictions of what Earth's future and ours might hold.

Global Connections

By looking at Earth as a system you will discover numerous connections between topics in this lab manual. Our approach will be to begin with small steps and focus on organization or **structure** in systems. The structure of the geosphere, or rocky part of the planet, is probably already familiar. Earth's core, mantle, and crust form concentric layers differentiated by their physical properties. To go a step further and seek understanding about how Earth systems work, we must find out about key **processes**. Processes cause systems to change in some way. More specifically, we want to consider the flow or **transfer of energy and matter** into, within, and out of systems. To return to our geosphere example, Earth's largest reservoir of heat is found at great depth in the core and mantle rocks.

The transfer of energy to Earth's surface drives plate tectonics and has far-reaching effects on the rock cycle as well as on Earth's spheres.

If we shift our focus to the surface of the crust, other transfers of energy become important. Part of Earth's incoming solar radiation is reflected from the surface to indirectly heat the atmosphere. The redistribution of heat along a thermal gradient from equatorial to polar regions drives global atmospheric circulation, affecting weather and climate. The crust interacts with the atmosphere whose physical and chemical properties influence the breakdown of rocks and landforms. By asking questions about systems we can explore connections across great scales in space and develop an understanding of how the crust is affected by the flow of energy from both internal and external sources. In effect, thinking about the flows of energy helps us to recognize relationships between distant parts of the Earth system that might otherwise seem disconnected.

When geoscientists think about the sizes of systems, they use the term **scale**. In **spatial** terms, a lithospheric plate is a very large-scale system. Larger systems often contain smaller systems or **subsystems**, like the volcanoes along a plate margin, and even smaller ones such as a body of magma. We can consider time in a similar way and examine very long-term processes such as mantle convection, plate tectonics, and mountain building to those operating over shorter **time scales**, like earthquakes (**Fig. 1.3**). Thinking about systems over time raises interesting questions about the timing, rate, duration, and possible recurrence of Earth's processes, from plate tectonics, to cycles of climatic warming and cooling, to speciation and extinction in the biosphere, among many others. Fortunately for scientists, evidence of global change is partially preserved in the geologic record, which holds the long-term record of climate, oceanographic history, and the evolution of the biosphere. Today, much of the news is focused on the rate of global change over relatively short time scales, reflecting just a few generations in human terms.

Ultimately, we want to be able to provide sound scientific descriptions and explanations about how the Earth system works. At larger scales, Earth's systems tend toward greater complexity and involve more components. Their behavior is often dynamic, typically fluctuating around an average level or state. Think about the location of a shoreline along the coast where distinctive cycles occur due to patterns of waves and tides. At any given time, the shoreline is not static but a zone in which daily, monthly, and seasonal fluctuations of waves and tides are superimposed on long-term patterns of sea level. When describing the state of a system, we can say that if the forces affecting change are balanced by those resisting it, then a system is in **equilibrium**. With a *static equilibrium*, there is no impetus to change. But because Earth's systems, like shoreline, are constantly responding to varying amounts of energy and matter, they typically exhibit a *dynamic equilibrium*. Here, the sum of many processes results in a stable or average state.

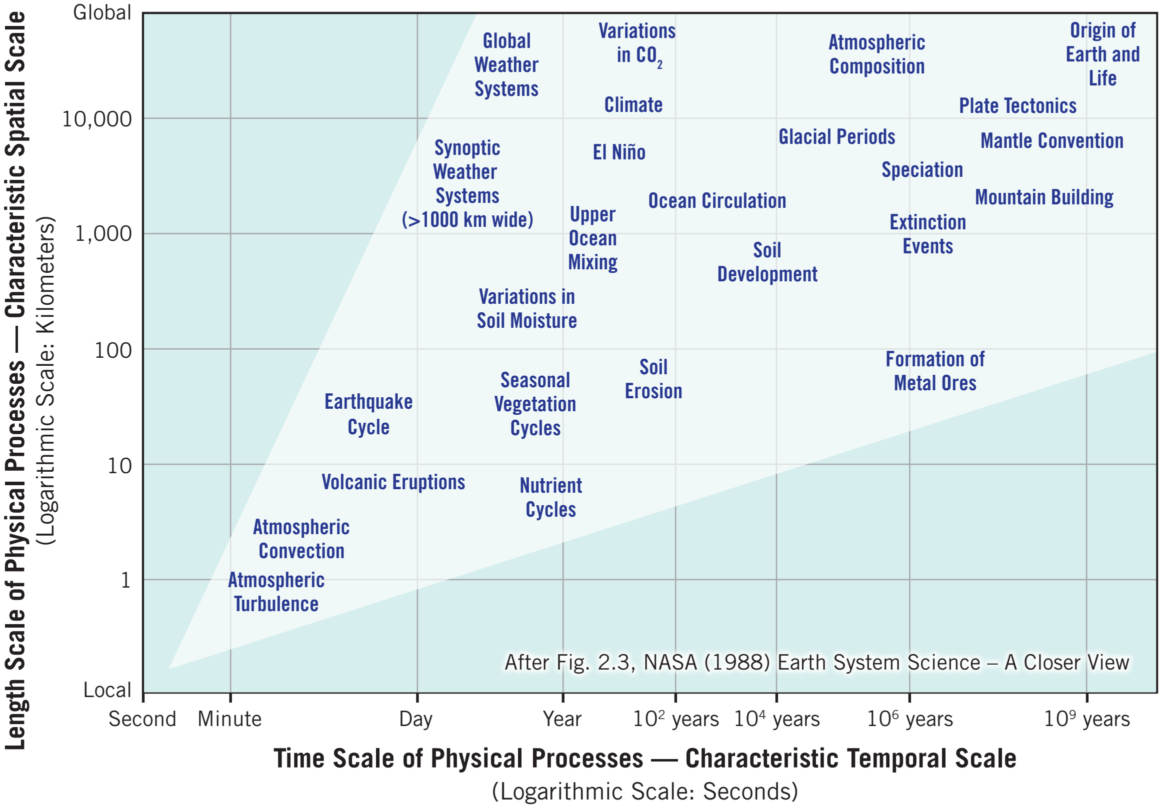

Figure 1.3 **Major Earth system processes: space and time scales.** Important interactions connect many of the processes shown here to other parts of the Earth that operate over different time and space scales. This highlights the complex nature of the Earth system.

Internal mechanisms that create stability are known as **negative feedback** loops. They act to reduce or dampen the impact of an initial change to a system and generally have a stabilizing effect. Mechanisms that amplify the effects of an initial change are called **positive feedback** loops and promote instability. Such feedback causes the state of a system to shift and function in a different way than before. Natural systems can contain both kinds of feedback mechanism, often operating over different time scales. Humans can also introduce positive and negative feedback mechanisms into Earth's systems, sometimes deliberately and sometimes inadvertently.

Looking at Earth as a system will provide you with a framework for thinking about many of the scientific concepts in this book. It should also provide a tool for developing questions about parts of the Earth system (and their behaviors) that are not covered here. Sometimes you will focus on how one part of the Earth system operates. Sometimes you will examine major interactions between Earth's spheres.

The following list of some key themes in systems thinking provides a brief definition of each theme. These terms have been highlighted within the chapters to guide you toward thinking about the Earth as a system.

- **Earth system:** The interactions of Earth's subsystems—the geosphere, atmosphere, hydrosphere, cryosphere, and biosphere—through physical, chemical, and biological processes. Major interactions between these integrated parts of the Earth system affect global change.
- **Subsystem:** Any system within its own right contained within a larger system.
- **Open system:** A system in which both matter and energy can cross the boundary and be exchanged with the surrounding environment.
- **Process:** Any phenomena governed by physical, chemical, or biological laws that effect change.
- **Transfer of energy and matter:** Any form of energy and matter that flows into or out of an open system. These are also known as inputs and outputs. Transfers occur between **reservoirs** or stores in the Earth systems.
- **Cycle:** An interval of time during which a sequence of processes or events repeats itself.
- **Equilibrium:** A state of stability or physical balance. Stability occurs when opposing forces affecting change cancel each other out. A system moving toward equilibrium is in a state of disequilibrium.
- **Feedback mechanisms:** Mechanisms in systems that operate to either reduce or increase changes in that system. **Negative feedback** refers to self-regulatory processes that operate to reduce the effect of a change and return the system to its initial state. Such processes move the system toward a stable condition. **Positive feedback** mechanisms act in the opposite direction; they reinforce the original direction of change and move the system away from its initial state.
- **Thresholds:** Specific conditions within a system that when exceeded can trigger a dramatic change in the state of a system.
- **Spatial scale:** The extent or size of a system given by a precise length, area, or volume. Sometimes descriptive terms such as *local*, *regional*, *continental*, or *global* are used.
- **Time scale:** The duration over which a system or a particular process operates, from seconds to billions of years.

How Is Each Laboratory Chapter Organized?

There are important features in this lab manual you might miss if they were not pointed out to you. Square black-and-white QR codes are printed throughout the lab manual that can be scanned with a smartphone that has an app for reading QR codes. Many such apps are available on the web for little or no cost. Scanning the QR code links you to a web resource that will likely be helpful.

Each chapter begins with some general information followed by an *Activity Box* that introduces you to the first of the lab activities. Each Activity Box alerts you to an upcoming activity. **The text that follows an Activity Box is closely related to the activity, so you should read the relevant section of text before you begin the activity.** As you are working on an activity at the back of the chapter and need to find relevant information in the text, the corresponding Activity Box functions like a bookmark. Just find the corresponding Activity Box and start reading down from there.

Terms that are particularly important for you to know are printed in a **bold** typeface. Those terms are usually defined in the text, but additional information is available online and from glossaries of geologic terms produced by the American Geosciences Institute (**https://www.americangeosciences.org/pubs/glossary**).

ACTIVITY 1.1

A View of Earth from Above (p. 17)

ACTIVITY 1.2

Finding Latitude and Longitude or UTM Coordinates of a Point (p. 19)

Study the section *Getting to Know Your Planet* to complete Activities 1.1 and 1.2.

Getting to Know Your Planet

As anyone who has had a window seat on an aircraft on a clear day can tell you, Earth's surface is endlessly fascinating (**Fig. 1.4**). We are fortunate to live during a time when many technologies are available to help us study Earth's surface from above. Throughout this course, you will encounter opportunities to look at Earth's surface using

Figure 1.4 Grand Prismatic Spring. This beautiful pool at Yellowstone National Park is one of the largest hot springs on Earth and is home to bacteria capable of living under extremely harsh conditions. The solid Earth, liquid water, water vapor, a hint of Earth's hot interior, and evidence of life are all visible in this image, illustrating the interconnectedness of Earth's systems. (Photo by Jim Peaco of the National Park Service)

Google Earth, which is a free application that you can access through **earth.google.com**. The first task you will need to be able to perform using Google Earth is to find a particular place on Earth's surface given the coordinates of that point. That involves entering the map coordinates of the point into the Search box in Google Earth and clicking the "Search" button. You will also need to learn how to activate different features (e.g., Places, Borders, Photos), to zoom in and out of the image, to determine the height above Earth that is depicted in the image, and generally to move from place to place across the surface. Different versions of Google Earth operate differently. The Help resource on your particular version of Google Earth will guide you in learning how to use its various functions to study the surface of Earth.

First, you need to learn about two ways that have been developed to specify the location of a given point on Earth, using map coordinates: geographic coordinates of latitude and longitude and UTM coordinates.

Geographic Coordinates (Latitude and Longitude)

The location of a point on Earth can be specified using its latitude and longitude (Fig. 1.5). **Latitude** is measured relative to the **equator**, which is the circle around Earth located in the tropics exactly halfway between the north and south poles. The latitude is 0° at the equator, 90° at the north pole,

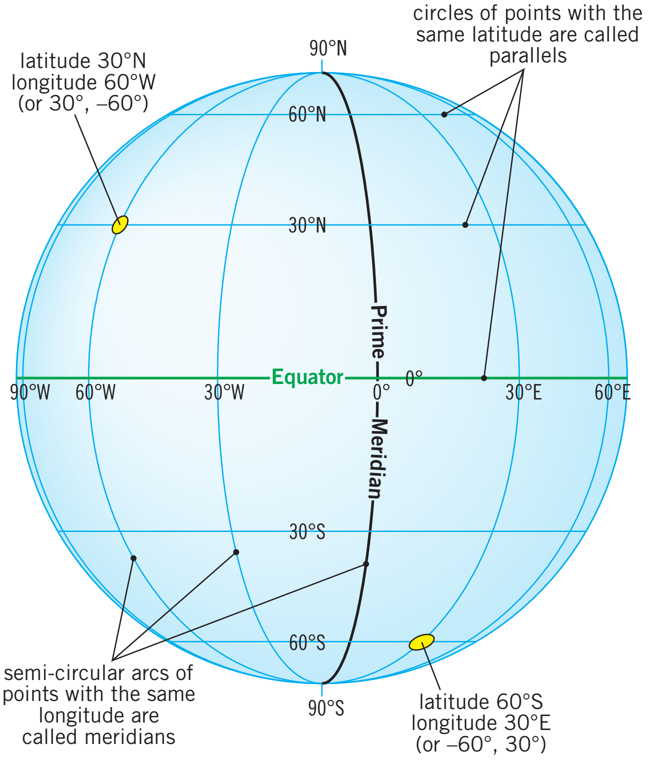

Figure 1.5 Geographic coordinate system of latitude and longitude. Explanation of the major elements of the geographic coordinate system.

and $-90°$ at the south pole. The poles are the places where Earth's spin axis intersects the ground surface to the north (**north pole**) and south (**south pole**). Semicircles that wrap around Earth from the north pole to the south pole are called **meridians**. We measure the latitude of a given point along the meridian that passes through that point. The latitude is the angle from the point where that particular meridian crosses the equator to the center of Earth and back out to the given point.

Longitude is measured relative to a particular meridian that passes through a specific point on the grounds of the Royal Observatory at Greenwich, England. A group called the *Earth Rotation and Reference Systems Service* keeps track of the practical definition of the international reference meridian (the **prime meridian**) for us so we don't have to worry about it. The angle between the prime meridian and the meridian that passes through a given point is that point's longitude. Longitudes measured to the east of the prime meridian (east longitudes) are considered *positive* longitudes, and longitudes measured to the west of the prime meridian (west longitudes) are considered *negative* longitudes. So longitudes range from 180° (180°E) to 0° along the prime meridian to $-180°$ (180°W). With the exception of several of the western Aleutian Islands in Alaska, all of the states in the United States have west, or negative, longitudes.

If you are moving either due north or due south, a change of one degree in latitude (at the same longitude) is a difference of ~111.2 km across Earth's surface. (The symbol "~" is used here to indicate an approximate number.) One degree of latitude is 1/360th of the distance around Earth whose average radius is ~6,371 km and whose circumference is ~40,030 km. The meridians that mark different longitudes all converge at the north and south poles and are spaced their maximum distance of ~111.2 km per degree of longitude where they cross the equator. So it would take a commercial jetliner over 7 minutes to fly across 1 degree of longitude at the equator (~111.2 km), but it would take a motivated sugar ant about a quarter of a second to walk 1 degree of longitude (~1.7 centimeters [cm]) if the ant were just a meter away from the north or south pole.

Geoscientists frequently use **decimal degrees** to indicate position when we use the geographic coordinate system of latitudes and longitudes. For example, the great obelisk of the Washington Monument in Washington, D.C., is located at latitude 38.8894695°N, longitude 77.0352585°W. When it is made clear that the number pair refers to latitude and longitude, we can simply write 38.889469, −77.035258 without the degree symbol or the letters N and W because positive-signed latitude is understood to be north latitude and negative-signed longitude is understood to be west longitude. You can find the Washington Monument in Google Earth by entering 38.889469, −77.035258 in the Search box. You can also find it by entering 38.889469°, −77.035258° or 38.889469°N, 77.035258°W, but then you would need to remember how to insert the degree (°) symbol using your web-enabled device.

An alternative to decimal degrees that has persisted for a very long time is the **degrees-minutes-seconds** system that subdivides each degree into 60 minutes of arc and then each minute of arc into 60 seconds of arc. Most maps produced by the U.S. Geological Survey (USGS) are based on the degree-minute-second way of expressing latitude and longitude.

It is useful to know how to convert from the degrees-minutes-seconds system to decimal degrees. Let's say we have an angle of *a* degrees, *b* minutes, and *c* seconds, which is commonly written as $a°\,b'\,c''$. The decimal-degree equivalent is $[a + (b/60) + (c/3600)]$ degrees, noting that $60 \times 60 = 3600$. Here's an example.

$$14°38'52'' \text{ is the same as } [14 + (38/60) + (52/3600)]° \cong 14.647778°$$

Google Earth can locate points expressed in the degree-minute-second, degree-decimal minute, and decimal degree systems of expressing longitude and latitude.

ACTIVITY 1.3

Plotting a Point on a Map Using UTM Coordinates (p. 21)

Study the section *Universal Transverse Mercator (UTM) Coordinates* to complete Activity 1.3.

Universal Transverse Mercator (UTM) Coordinates

Most handheld GPS receivers can provide us with locations in either a latitude–longitude format or a UTM format. Latitude–longitude is a bit easier to explain, but UTM has some practical advantages. UTM coordinates are based on a projection of Earth's surface onto a plane that has a coordinate grid in meters that is aligned (approximately) north–south, east–west. It is more useful to people trying to navigate from point A to point B to know how many meters they need to go in a given direction than to know how many degrees of longitude or latitude.

As of mid-2019, only Google Earth Pro for desktop (GE Pro) can interpret UTM coordinates. The UTM coordinates of a point are listed in the following order: **zone number**, **latitude band**, **easting**, and **northing** (**Fig. 1.6**). Type the following coordinates in the Search box of GE Pro and see where it leads you: 12T 370730 4608526.

UTM Zones. Earth is divided into 60 zones starting at longitude 180°—the **international dateline** halfway around Earth from the prime meridian—and proceeding to the east. Each zone is 6° of longitude wide and extends from 80°S to 84°N latitudes. Zone 1 is from 180° to 174°W followed by zone 2 from 174°W to 168°W. The continental United States extends from UTM zone 10 in the west to 19 in the east. Each zone has a **central meridian**, which is halfway between the two zone boundaries (**Fig. 1.6**). For example, the central meridian of zone 2 is longitude 171°W.

UTM Bands. Each zone is divided into 20 latitude bands that are 8° of latitude tall. The bands are lettered from C (between 80°S and 72°S latitude) to X (between 72°N and

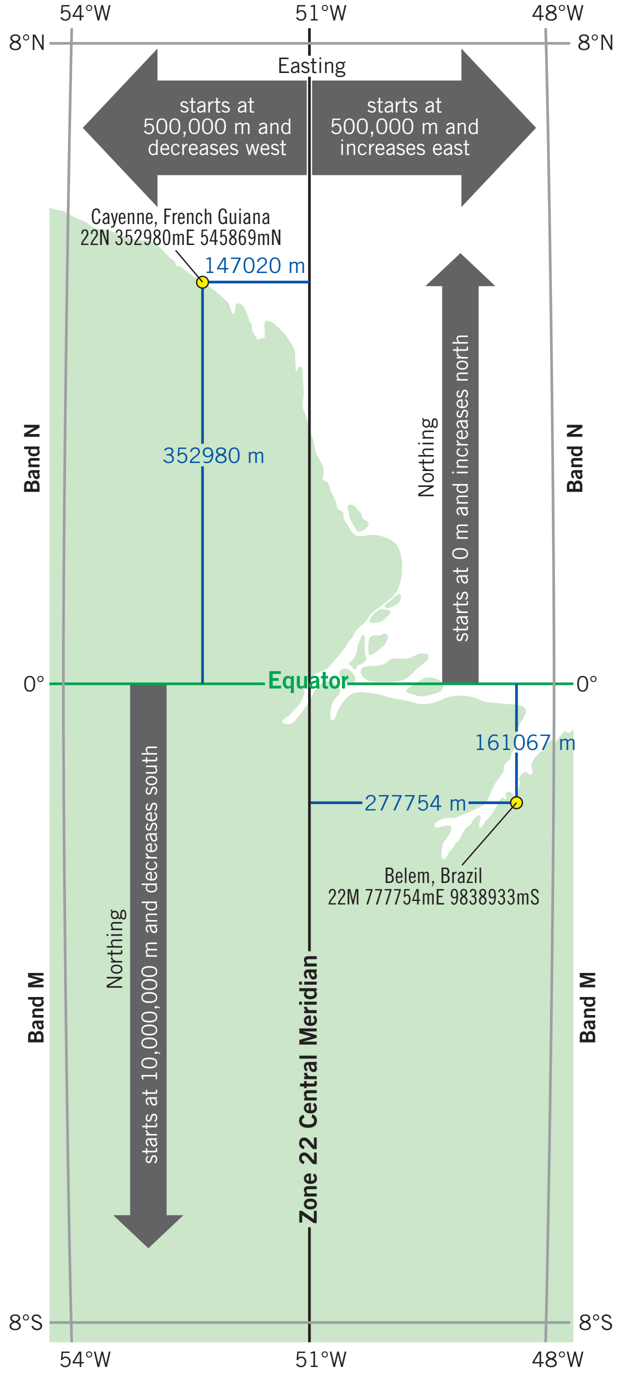

Figure 1.6 Universal Transverse Mercator (UTM) coordinate system. UTM zone 22, latitude bands M and N along the equator near the mouth of the Amazon River, northeastern South America. UTM coordinates of two cities are shown as examples.

84°N latitude). Zone X is the only zone that is larger than 8° high; it was extended to 12° high to cover all of the major continental areas above sea level. The bands from N to X are in the northern hemisphere (**Fig. 1.6**). The continental United States is in bands R, S, T, and U.

UTM Easting. The easting within a given zone is measured in meters perpendicular to the zone's central meridian whose easting is defined as 500,000 meters east, or 500,000 mE (**Fig. 1.6**). (The abbreviation *mE* is expressed in words as "meters east" or "easting.") It seems odd to express position in this way because we normally define position relative to some point whose coordinate is defined as 0, but the originators of UTM coordinates did not want to have any negative numbers in their system. Zones are a maximum of ~668,000 meters (m) wide, so giving all points along a central meridian the same easting of 500,000 mE ensures that no east–west coordinate in the zone has a negative value. A point that is 1500 m to the *west* of the central meridian has an easting of 500,000 − 1500 = 498,500 mE, whereas a point that is 24,000 m east of the central meridian has an easting of 500,000 + 24,000 = 524,000 mE.

UTM Northing. The northing of a given point in the northern hemisphere is its distance in meters from the equator measured along the meridian—the north–south line—that passes through the point. UTM northings in the northern hemisphere start at the equator (0 mN) and increase northward to ~9,300,000 mN at the top of the UTM projection at 84°N latitude (**Fig. 1.6**). In contrast, UTM northings in the southern hemisphere start at the equator (10,000,000 mS) and decrease southward to ~1,100,000 mS at the bottom of the UTM projection at 80°S latitude.

Expressing UTM Coordinates. Google Earth Pro is able to interpret UTM coordinates (zone, band, easting, northing) typed into its Search box. For example, typing 18S 323482 4306480 and pressing the "Search" button will send you to the Washington Monument in Washington, D.C. Typing 13T 623803.10 4859551.20 and pressing the "Search" button will get you to George Washington's sculpted nose at Mount Rushmore, South Dakota. Fully written out in a conventional way, as you would in a geoscientific report, the UTM coordinates of his nose would be 13T 623803.10 mE 4859551.20 mN.

Scaling, Proportion, and Using Maps

The ability to work with proportions is an essential skill when working with maps, which are an important tool used by geoscientists. Imagine a map of your hand at 1/2 scale, so the image of your hand is just 50% the size of your actual hand. With that scale, a finger that is 2 cm wide on your hand would be 1 cm wide on the map image. Your thumb, at 2.5 cm wide, would be 1.25 cm wide on the map. Your little finger is 7 cm long but just 3.5 cm long on the map. Your middle finger is 9 cm long, but the image of that finger is 4.5 cm long on the map. The ratio of the length of the feature on the map to the length of the corresponding feature on your hand is always 1 to 2.

$$\frac{1}{2} = \frac{1.25}{2.5} = \frac{3.5}{7} = \frac{4.5}{9}$$

Fractional Scale. Printed on some maps is a **fractional scale** (more formally known as a representative fraction scale) that is fundamentally a ratio. Examples of the two

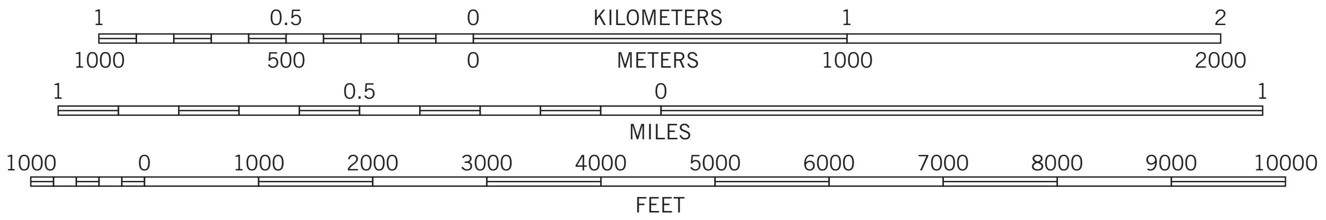

Figure 1.7 Typical bar scale used by the USGS. This bar scale was copied from a USGS topographic map published in 2015. It shows a metric bar scale in kilometers and two types of scales that use the Imperial units miles and feet.

most common styles of fractional scales are 1/24,000 and 1:24,000. These scales are identical to each other—they represent two styles of presenting the same information. The meaning of "1:24,000" is that one unit of some sort (centimeters, for example) on the map is equal to 24,000 of that same unit (cm) on the ground in the mapped area. The problem with representative fractional scales is that they are of no use if the map is enlarged or reduced in size during reproduction. The "1:24,000" will still be printed on the map even if the map is reproduced to the size of a postage stamp or billboard.

Bar Scale. Many maps contain some form of a thin rectangle called a **bar scale** that represents a specific length on the map. An example of the style of bar scale used by the USGS is shown in **Fig. 1.7**. Bar scales are used extensively in this book and throughout the geosciences in part because the printed bar expands and contracts along with the map, so the map scale can always be interpreted.

Let's work an example. Imagine that you have a map with a bar scale that represents a length of 2000 m (2 km) on the ground in the mapped area. You measure the bar with a ruler and find that 2 km on the ground is the same as 4 cm on the map because the distance from 0 to 2 km on the map's bar scale is 4 cm. Now, imagine that you want to take a 5-km stroll: 2.5 km down the road and 2.5 km back. What is the length of a line on the map that represents 2.5 km along the road?

We can frame this problem as a proportion or ratio problem: 4 cm is to 2 km as c (the unknown map distance) is to 2.5 km. This is a type of problem we would like to be able to solve every time we encounter it regardless of the specific numbers involved. So rather than use numbers, let's use a unique letter to represent each of the numbers in our problem, rather than just the unknown map distance (c), and restate the problem: a is to b as c is to d. In other words, the ratio of a to b is the same as the ratio of c to d, or

$$\left(\frac{a}{b}\right) = \left(\frac{c}{d}\right)$$

This equation can be rearranged as $(a \times d) = (b \times c)$. In our original problem, the value of variable c was unknown. We can rearrange the equation again so that variable c is isolated by itself on one side of the equation.

$$c = \frac{(a \times d)}{b}$$

Now, let's insert the numbers from our problem.

$$c = \frac{(a \times d)}{b} = \frac{(4 \times 2.5)}{2}, \text{ so } c = 5$$

You would look on your map, mark a point 5 cm down the road on your map, find a recognizable landmark like a street corner near your mark, and start walking there and back for your stroll.

What if you saw something interesting on the same map (like an all-night ice cream store) and measured a map distance of 7 cm from your current location to that point. How far would you have to walk to get there? This is just another form of the same problem except that this time variable c is known but d is unknown. Recall that $(a \times d) = (b \times c)$, so we can rearrange this equation to isolate d on one side of the equation and then replace the variables with the actual numbers from our problem.

$$d = \frac{(b \times c)}{a} = \frac{(2 \times 7)}{4}, \text{ so } d = 3.5$$

You would need to walk 3.5 km there and another 3.5 km back. The ability to manipulate these simple equations and solve proportion problems is a very useful skill.

Rearranging Equations—The Math You Need

You can learn more about how to rearrange equations to solve for a given variable (including practice problems) at **http://serc.carleton.edu/mathyouneed/equations/index.html** featuring The Math You Need, When You Need It tutorials for students in introductory geoscience courses.

https://goo.gl/eaVJq7

ACTIVITY 1.4

Scaling, Density, and Earth's Deep Interior (p. 22)

Study the section *Measuring Earth Materials* to complete Activity 1.4.

Measuring Earth Materials

Observation and measurement are fundamental parts of the scientific process. Here, we review a few basics of measurement that will be needed throughout this laboratory course.

SI Units of Length Measurement

The International System of Units (SI) is based on seven basic units of measure from which other units are derived. The SI system is used throughout science with few exceptions. The standard of length measurement is the **meter** (m), and useful units derived from that base unit include the **kilometer** (km; 1 km = 1000 m), **centimeter** (cm; 100 cm = 1 m), **millimeter** (mm; 1000 mm = 1 m), and **micrometer** or **micron** (μm; 1,000,000 μm = 1 m). Since 1983, the official SI definition of a meter is "the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second." Practically speaking, we use a manufactured secondary standard such as a ruler or a tape measure to determine length most of the time, although very accurate measurements of length are now made using lasers, radar, and other technologies.

People who grew up in the United States are probably more familiar with units of measurement that we inherited from England, and a vestige of that remains in the topographic maps of the USGS where topographic contours are defined in feet (ft) and bar scales sometimes include miles (mi). Because of this, you will need to know that 1 mile is 5280 ft, each foot has 12 inches (in), and the international definition of 1 inch is a length equal to 2.54 cm *exactly* (**Fig. 1.8A**). From that one conversion factor we can

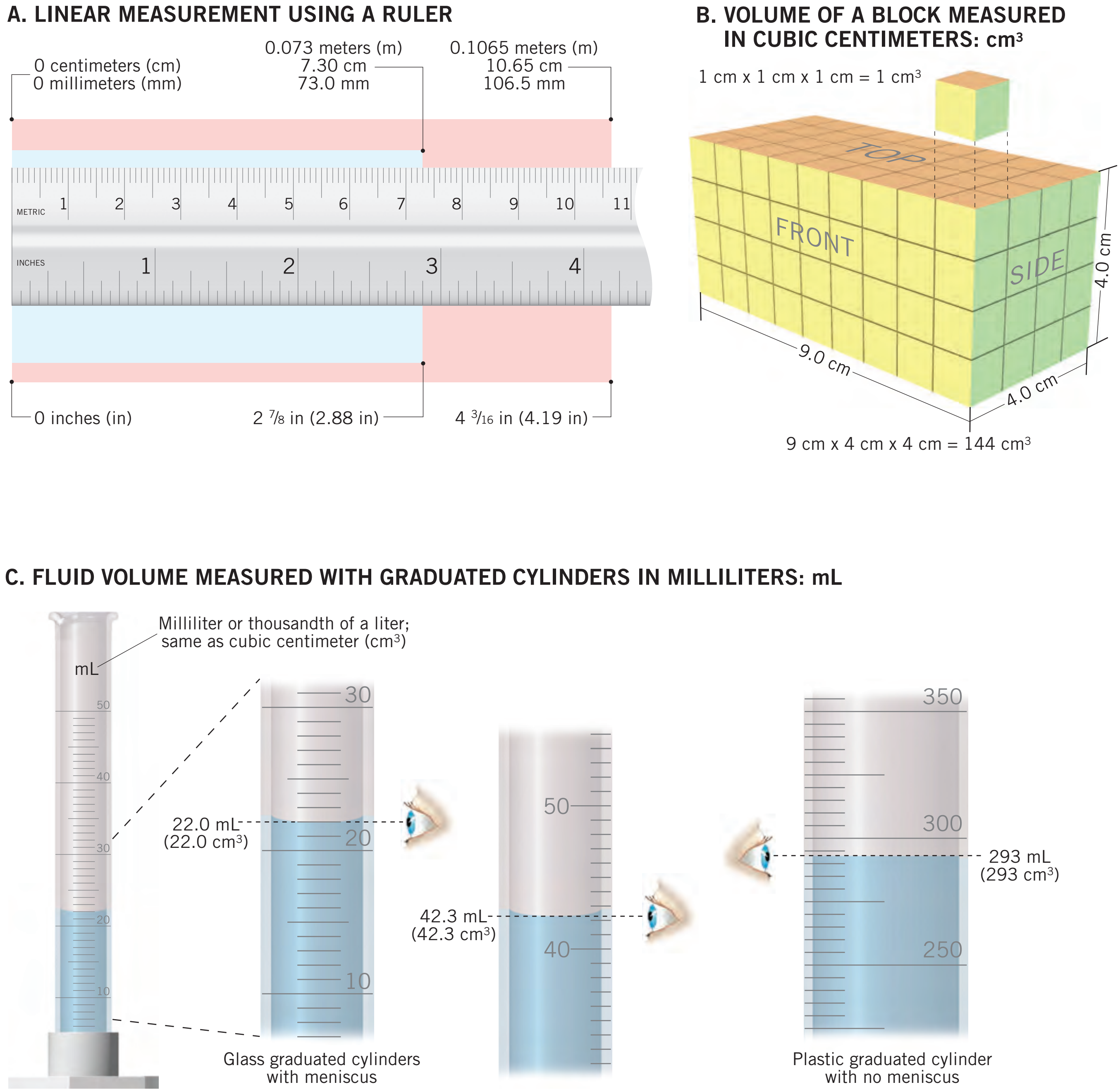

Figure 1.8 Tools and scales of measurement. **A.** Measurement of length using a ruler. **B.** Volume of a rectangular prism measured in cubic centimeters. **C.** Liquid volume measured with a graduated cylinder.

obtain all other conversions in lengths from metric to the old English or Imperial system.

Review the measurement examples in **Fig. 1.8A** to be sure that you understand how to make *reliable* or *reproducible* metric measurements. Note that the length of an object may not coincide with a specific centimeter or millimeter mark on the ruler, so you may have to estimate the fraction of a unit *as exactly as you can*. The length of the red rectangle in **Fig. 1.8A** is between graduation marks for 106 and 107 mm, so the most reasonable measurement of this length is 106.5 mm. Also be sure that you measure lengths starting from the zero point on the ruler, *not necessarily from the end of the ruler*.

Sometimes you will need to convert a measurement from one unit of measure to another. This can be done with the aid of the mathematical conversion charts like the one printed in the Preface of this laboratory manual. For example, to convert mm to m, divide the measurement in mm by 1000 (because there are 1000 mm per m):

$$\frac{106.5\ \text{mm}}{1000\ \text{mm/m}} = 0.1065\ \text{m}$$

Thus, 106.5 mm is the same as 0.1065 m.

Unit Conversion—The Math You Need

You can learn more about unit conversion (including practice problems) at **http://serc.carleton.edu/mathyouneed/units/index.html** featuring The Math You Need, When You Need It tutorials for students in introductory geoscience courses.

https://goo.gl/Tiy3ft

Area and Volume

The SI base unit used in the measurement of area and volume is the meter. Area is described using square meters (m^2) and volume is described in cubic meters (m^3) or **liters** (L) where 1 liter is equal to 1000 cm^3 or 0.001 m^3 (**Figs. 1.8B** and **1.8C**). It is convenient to remember that 1 mL ($1\ \text{mL} = 1/1000\ \text{L}$) is the same volume as 1 cm^3. The graduated cylinders used in many geoscience labs are marked in mL.

Most natural materials have an irregular shape, so their volumes cannot be calculated accurately from measurements made with rulers. However, the volumes of these odd-shaped materials can be determined by measuring the volume of water they displace. This is often done in the laboratory with a *graduated cylinder* (**Fig. 1.8C**), a vessel used to measure liquid volume. Most graduated cylinders are marked in mL. When you pour water into a graduated cylinder made of glass, the surface of the liquid is usually a curved *meniscus*, and the volume is read at the bottom of the curve (**Figs. 1.8C**, middle and left-hand examples). In some plastic graduated cylinders, however, there is no meniscus and the water level is flat (**Figs. 1.8C**, right-hand example).

If you place a rock in a graduated cylinder full of water, the rock takes up space previously occupied by water at the bottom of the graduated cylinder. This displaced water has nowhere to go except higher into the graduated cylinder. Therefore, the volume of an object such as a rock is exactly the same as the volume of water that it displaces.

Mass

The SI base unit for mass is the **kilogram** (kg), which is the same as 1000 **grams** (g). One kg is the mass of 1 L of pure water at 4°C at which temperature liquid water has a density of exactly $1\ \text{kg/L} = 1\ \text{g/mL} = 1\text{g/cm}^3$. So the common 1-L bottle of water or soda has a mass of about 1 kg. Mass is measured using a laboratory balance. Research balances are calibrated so that they accurately measure the mass of a standard object of known mass called a *reference mass*.

Density

The amount of mass in a known volume of material is the **density**. In the SI system, density is expressed typically in either kg/m^3 or g/cm^3, depending on the context. It is easy enough to demonstrate that $1\ \text{kg/m}^3 = 1000\ \text{g} \div 1{,}000{,}000\ \text{cm}^3 = 0.001\ \text{g/cm}^3$. For example, a typical crystal of the mineral *quartz* has a density of $2650\ \text{kg/m}^3$ or $2.65\ \text{g/cm}^3$. Scientists and engineers use the Greek character rho (ρ) to represent density.

Determining Density—The Math You Need

You can learn more about calculating density (including practice problems) at **http://serc.carleton.edu/mathyouneed/density/index.html** featuring The Math You Need, When You Need It tutorials for students in introductory geoscience courses.

https://goo.gl/utMHYF

ACTIVITY 1.5

Investigating Earth's Highs and Lows (p. 24)

Study the section *Isostasy and Earth's Global Topography* to complete Activity 1.5.

Isostasy and Earth's Global Topography

Earth's outermost solid layer is called the **crust**. There are two main types of crust—continental and oceanic—that differ from one another in several important respects. **Continental crust** has a granitic average composition (**Fig. 1.9**) with a density of around 2.7 to 2.8 grams per cubic centimeter (g/cm^3) and an average thickness of around 40 km. Continental crust underlies about 40% of Earth's surface. **Oceanic crust** has a basaltic-gabbroic composition, is denser at around 2.9 to 3.0 g/cm^3, and averages only about 5 to 8 km in thickness. Continental and oceanic crust lie atop Earth's **mantle**, the uppermost part of which has a density of around 3.3 g/cm^3. The mantle is solid rock, but it is also hot enough so it can flow slowly, like solid Silly Putty™ can flow. The mantle extends from below the crust to a depth of ~2891 km. So continental crust is less dense than oceanic crust, the crust is less dense than the mantle below, and the mantle can be thought of as a viscous fluid because it can flow if a stress is applied to it.

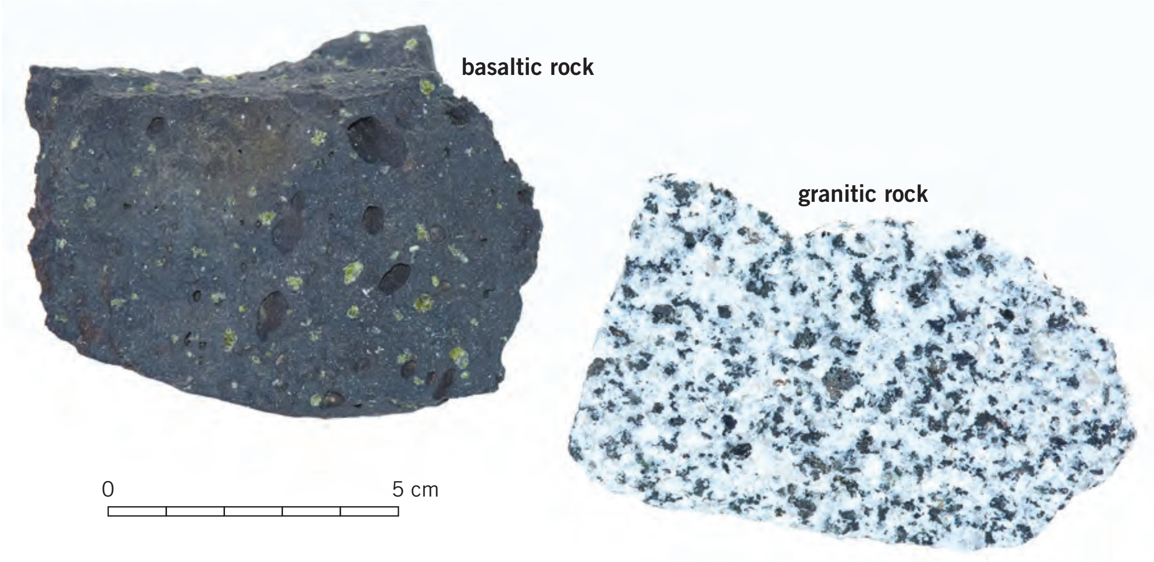

Figure 1.9 Average composition of oceanic and continental crust. **A.** Below a covering of sediment and sedimentary rock, the oceanic crust is composed of rock with a composition like this dark basalt. **B.** Continental crust has an overall composition similar to this light-toned granitic rock, although the crust is composed of many different rock types.

Buoyancy and Isostasy

In the late 1880s, American geologist Clarence Dutton suggested that the crust "floats" on the mantle, in accordance with **Archimedes' Principle**: a solid object immersed in a denser fluid displaces a volume of the fluid that is equal in weight to the weight of the object. The object is subject to the downward force of gravity, and it is supported by an upward **buoyant force** equal to the weight of the fluid displaced by the object. Dutton envisioned Earth's crust as consisting of buoyant blocks of rock that float in gravitational balance at the top of the mantle. Dutton called this floating condition **isostasy**—a term derived from Greek for "equal standing." Isostatic equilibrium occurs when the downward force of gravity is balanced by the upward buoyant force for a given block. Isostasy has broad application for understanding global-scale topography, on Earth and on other planets and their major satellites.

Equations—The Math You Need

You can learn more about equations (including practice isostasy problems) at **http://serc.carleton.edu/mathyouneed/equations/ManEqSP.html** featuring The Math You Need, When You Need It tutorials for students in introductory geoscience courses.

https://goo.gl/bt7D0Q

Global Topography: The Hypsometric Curve

Digging Deeper

A variety of technologies carried aboard aircraft and orbital satellites now measure the shape of Earth's outer surface very exactly. We can even use satellite data to provide general bathymetric maps of the seafloor, although the seafloor maps that have the highest resolution are made using data collected using ship-borne sensors. These improved digital elevation models of Earth allow us to produce relief maps like the image of the solid outer surface of Earth in **Fig. 1.10A**.

Color is used to indicate elevation in **Fig. 1.10A**, and the explanation for the different colors is contained within the bar chart (histogram) in **Fig. 1.10B**. For example, all of the points on Earth's solid surface between sea level and 1 km above sea level are shown in green, composing about 21.6% of Earth's total surface. Notice that the histogram has two bars that are longer than the rest, so we say that the distribution of elevations is *bimodal*. One of the elevation modes corresponds to elevations between sea level and 1 km above sea level and corresponds to most areas on continents and islands. The other elevation mode occurs between 4 and 5 km below sea level and corresponds to most of the ocean floor.

A **hypsometric curve** (or *hypsographic curve*) of Earth's surface elevations, based on the ETOPO1 elevation model, is provided in **Fig. 1.10C**. This shows the cumulative percentage of Earth's surface that occurs at specific elevations or depths relative to sea level. (The word *hypsometric* is based on the Greek *húpsos* or *hypsos* for "height.") This curve is not a topographic profile of any particular part of Earth's surface but rather is a summary of the elevations across Earth's entire surface.

Although the elevation difference between Earth's highest and lowest points spans almost 20 km, very little of Earth's surface is either greater than 2 km (6,562 ft) above sea level or greater than 6 km (19,685 ft) below sea level. The hypsometric curve shows that less than one third of Earth's surface is above sea level, and the rest is covered by ocean. Half of the surface area that is above sea level has an elevation of ~420 meters or less. Half of the surface area below sea level has a depth of 4,094 meters or less. The difference between the average

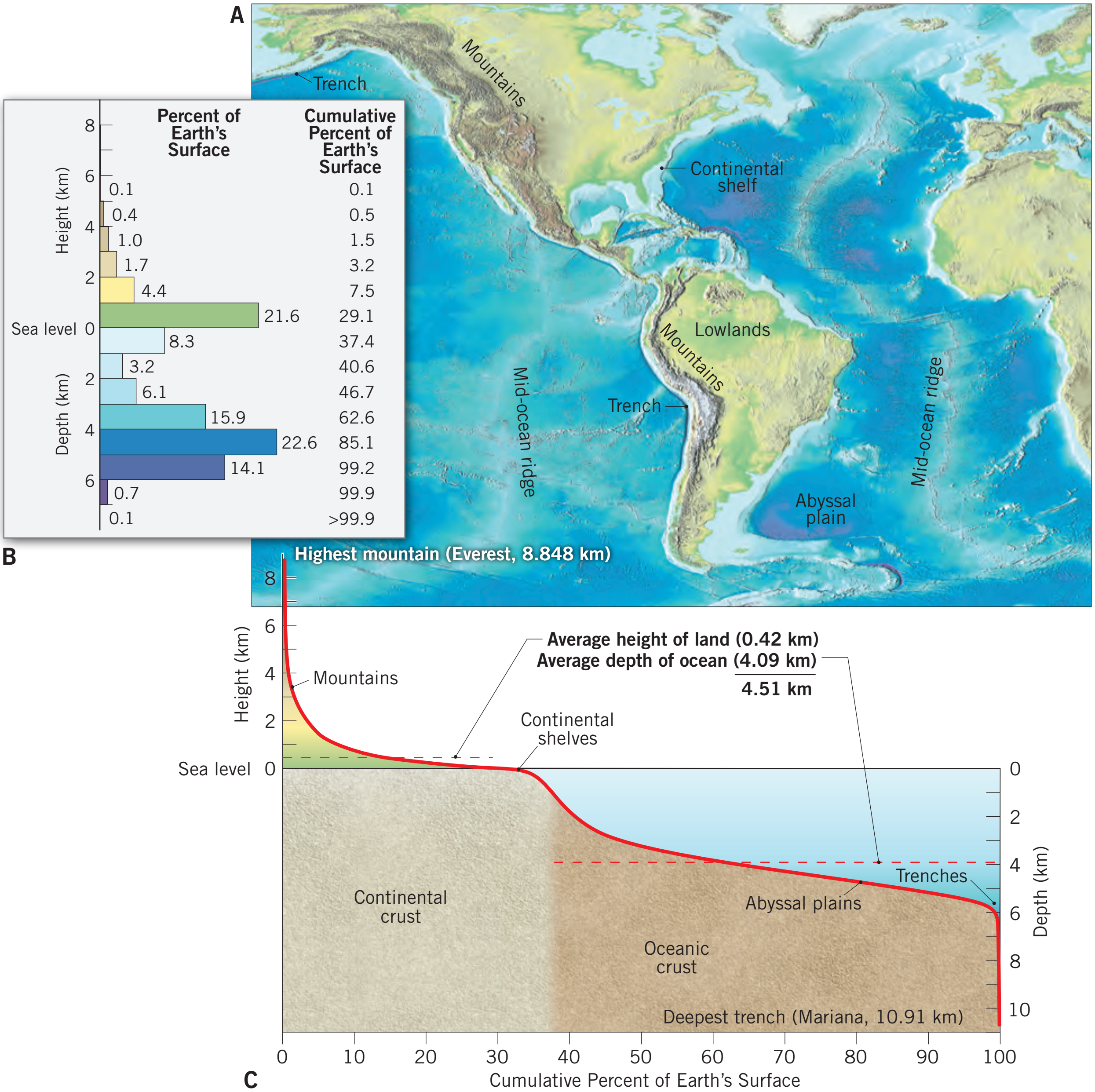

Figure 1.10 Global topography of Earth. **A.** Relief map of the solid upper surface of Earth with different elevations marked by different colors. **B.** Histogram of global topography. **C.** Hypsometric curve (or hypsographic curve) of Earth's global topography.

continental and ocean basin elevations is 4.51 km, or about 2.8 miles! If the continents were not so much higher than the seafloor, then Earth would have no dry land and we would not exist. What could account for this large elevation difference?

Higher-density rock forms the oceanic crust beneath a thin veneer of sediment, and the lower-density rock of continental crust is also covered by a thin veneer of sediment in most places. At first glance, you might think of the continents (green and brown in **Fig. 1.10A**) as granitic islands surrounded by a lowland "sea" of basaltic ocean crust (blue). All of these rocky bodies rest on a solid upper mantle that can flow. Could compositional or density differences between the two types of crust help us to understand Earth's bimodal global topography?

Graphing—The Math You Need

You can learn more about graphing and how to use graphs in the geosciences at **http://serc.carleton.edu/mathyouneed/graphing/index.html** featuring The Math You Need, When You Need It tutorials for students in introductory geoscience courses.

https://goo.gl/6CENFY

Hypsometric Curve—The Math You Need

You can learn more about the hypsometric curve and how to read and use it at **http://serc.carleton.edu/mathyouneed/hypsometric/index.html** featuring The Math You Need, When You Need It tutorials for students in introductory geoscience courses.

https://goo.gl/9QMxsc

ACTIVITY 1.6

Unit Conversions, Scientific Notation, and Rates (p. 25)

ACTIVITY 1.7

Graphing and Interpreting Data (p. 27)

Study the section *Basic Number Management* to complete Activities 1.6 and 1.7.

Basic Number Management

Many scientists spend a lot of their time working with numbers, so some fundamental math skills are worth learning about. If our goal and responsibility as scientists is to acquire reliable information about our world, we must always be concerned with the question of how reliable our information is likely to be. What is its uncertainty? Also, we must be careful about not representing quantitative information in a way that misleads others into thinking that we know something much better than we actually know it.

Significant Figures

All measurements have some uncertainty. Our ability to make accurate measurements is always limited by the maximum resolution of the method we use to measure, and perhaps by other factors related to measurement procedure.

Imagine that a person's length is measured independently by five careful observers using a mm scale, and their results are 1778 mm, 1779 mm, 1778 mm, 1777.5 mm, and 1778.5 mm. Most observers reported results to the nearest mm, but two reported to the 10ths of a mm. The observer who reported a length of 1777.5 probably meant "somewhere between 1777 and 1778" rather than "between 1777.4 and 1777.6." If we use a calculator to compute the average of these lengths, the result it returns is 1778.2. If we report only significant figures, what number should be reported as the average? The resolution of the result is only as good as the input data with the least resolution, so the average should be reported as 1778. All of the observers would agree on the first three digits—177—but there is an uncertainty of about ± 1 in the last digit.

When a scientist does not explicitly state the uncertainty of a number, the convention—an agreed-upon practice—is to assume that there is an uncertainty of about ± 1 unit in the last decimal place reported. For example, a measurement of 5.23 that is reported to the proper number of significant figures can be interpreted to mean 5.23 ± 0.01. We infer that the most accurate value would lie somewhere between 5.22 and 5.24.

Some numbers are known exactly with no uncertainty. A number can be known exactly because of the way it is defined. For example, 1 inch is equal to 2.54 cm *exactly*. We could add an infinite number of zeros to the right of the "4" and all would be significant digits. Simple counting can yield exact numbers as well. For example, three baby birds are observed in a nest. There are exactly 3 birds, not 3 ± 1.

Rounding Numbers

Scientists generally follow a convention for rounding numbers to an appropriate number of significant figures. We round the results of calculations prior to reporting them but do not round values obtained within a series of calculations that lead to the results.

Imagine that we have a set of numbers that we need to round to the nearest integer—the nearest whole number without any digits to the right of the decimal point. We won't even need the decimal point for the rounded number.

1. If the first digit to the right of the decimal point is *smaller than 5*, then drop all digits right of the decimal point and leave the first digit to the left of the decimal point unchanged. For example, each number in the following set is rounded to 137: {137.0, 137.1, 137.2, 137.3, 137.4}.
2. If the first digit to the right of the decimal point is *larger than 5*, drop all digits to the right of the decimal point and add 1 to the first digit to the left of the decimal point (i.e., round up). For example, each number in the following set is rounded to 138: {137.6, 137.7, 137.8, 137.9}.
3. If the first digit to the right of the decimal point *is 5* and there are nonzero numbers to the right of the 5, then drop all digits to the right of the decimal point and add 1 to the first digit to the left of the decimal point (i.e., round up). For example, 134.51 rounds to 135.
4. If the first digit to the right of the decimal point *is 5*, there are no nonzero numbers to the right of the 5, and the digit to its left is an *even* number, then drop all digits to the right of the decimal point and leave the first digit to the left of the decimal point unchanged. For example, 130.5 rounds to 130.
5. If the first digit to the right of the decimal point *is 5*, there are no nonzero numbers to the right of the 5, and the digit to its left is an *odd* number, then drop all digits to the right of the decimal point and add 1 to the first digit to the left of the decimal point (i.e., round up). For example, 131.5 rounds to 132.

This convention minimizes the effect of rounding errors.

Exponential Notation (Base^{Exponent})

One consequence of living in the modern world is the need to be able to work with numbers that are very big and very small. The annual budget of the United States is reported to be on the order of 3.7 trillion dollars ($3,700,000,000,000). The size of a disease-causing bacterium is measured in micrometers (one millionth of a meter), and our upcoming discussions of atoms and molecules involve lengths on the scale of one picometer (one trillionth of a meter).

Scientists use exponential notation to express very large and very small numbers. The number 10^5 is said to be in exponential form because it uses an exponent (5) to indicate that 5 copies of the base number (10) are multiplied together: $10 \times 10 \times 10 \times 10 \times 10$. Hence, the exponential number 10^5 is equal to 100,000.