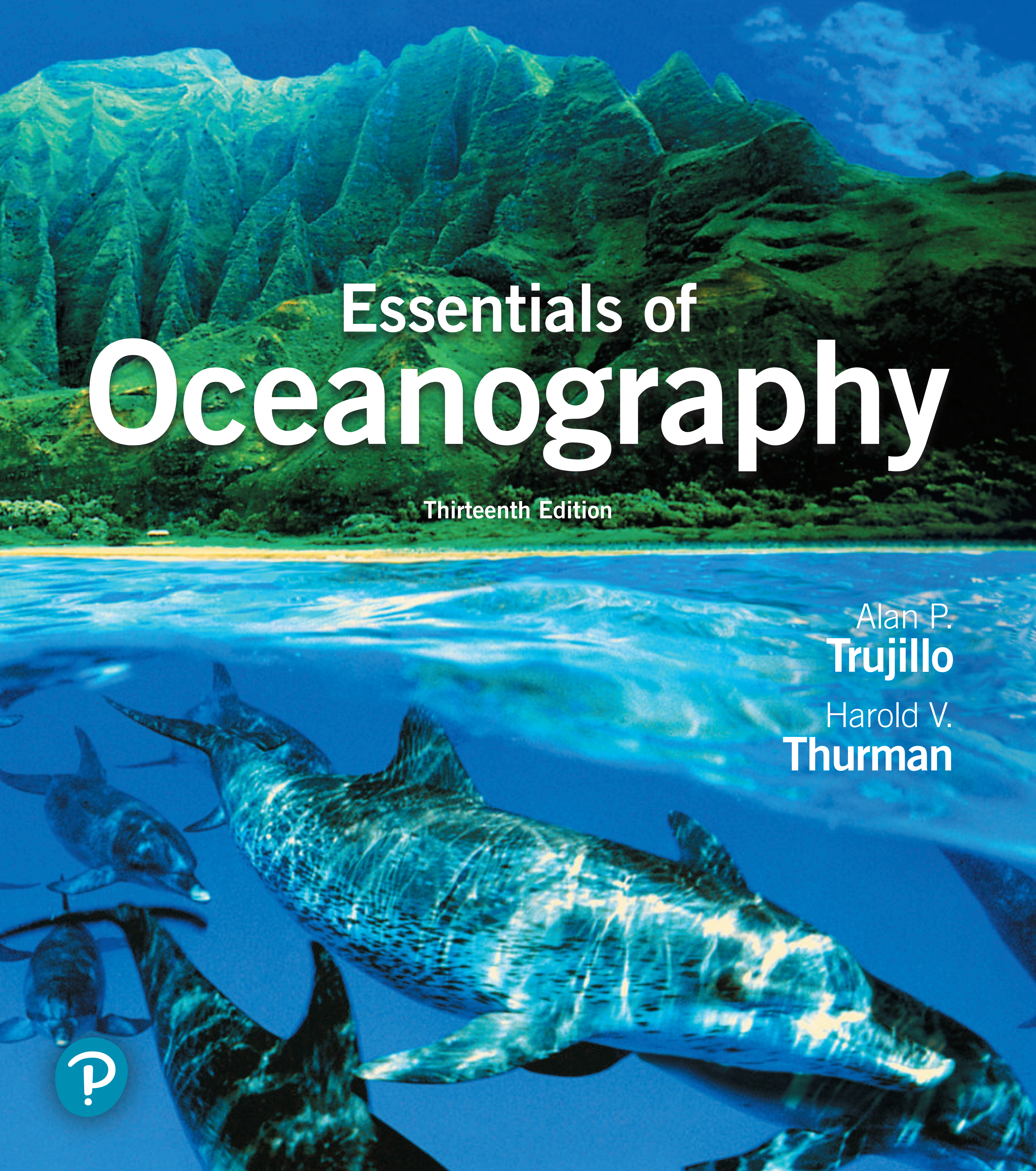


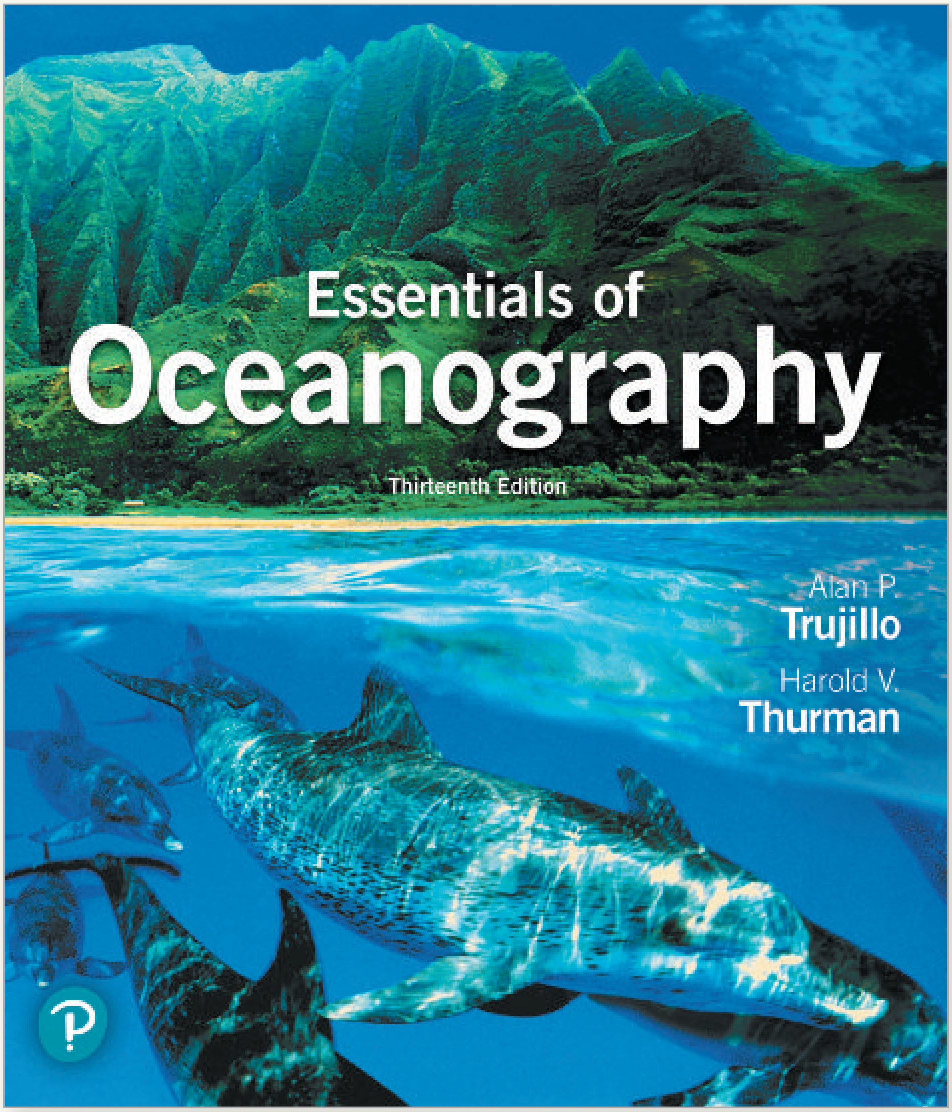
Essentials of Oceanography

Thirteenth Edition

Alan P. Trujillo
Harold V. Thurman

BRIEF CONTENTS

Dive into Oceanography with Trusted Content and Innovative Media



The best-selling brief book in the oceanography market combines dynamic visuals and a student-friendly narrative to bring oceanography to life and inspire students to engage and learn more about the oceans and environments around them. The 13th edition creates an interactive learning experience, providing tightly integrated text and digital offerings that make oceanography approachable and digestible for students. An emphasis on the **process of science** throughout the text provides students with an understanding of how scientists think and work. It also helps students develop the scientific skills of devising experiments and interpreting data.

Pearson

Dive into the Process of Science

GraphIt! Activities are a great way to help your students develop their understanding of graphs and data. These activities use real data to help students build science literacy skills and their understanding of how to analyze and interpret graphs.

NEW Process of Science features develop student understanding of how scientists think and work. Each one highlights an area of oceanographic inquiry and explicitly points out the associated background, method, and conclusion of the inquiry.

NEW Process of Science in Mastering. Each of the new Process of Science features includes an assignable Mastering coaching activity to enable students to be active participants and develop 21st Century Skills.

PROCESS OF SCIENCE 4.1: When The Dinosaurs Died: The Cretaceous–Tertiary (K–T) Event

BACKGROUND

The extinction of the dinosaurs—and about 75% of all plant and animal species on Earth, including many marine species—occurred about 66 million years ago. This extinction marks the boundary between the Cretaceous (K) and Tertiary (T) Periods of geologic time and is known as the **K–T event** or, because of recent changes in the geologic time scale, the *Cretaceous–Paleogene (K–Pg) event*. Did slow climate change lead to the extinction of these organisms, or was it a catastrophic event? Was their demise related to disease, diet, predation, or volcanic activity? Earth scientists have long sought clues to this mystery.

FORMING A HYPOTHESIS

In 1980, geologist Walter Alvarez, his father, Nobel Physics Laureate Luis Alvarez, and two nuclear chemists, Frank Asaro and Helen Michel, reported that marine deposits collected in northern Italy from the K–T boundary contained an unusual clay layer with high proportions of the metallic element iridium (Ir), an element rare in Earth rocks but much more abundant in meteorites. The high concentrations of iridium suggested minerals in the clay had an extraterrestrial origin. In addition, the clay layer contained shocked quartz grains, indicating an event had occurred with enough force to fracture and partially melt pieces of quartz. Other deposits from the K–T boundary revealed similar features, supporting the hypothesis that Earth experienced an extraterrestrial impact at the same time that the dinosaurs died.

One problem with the impact hypothesis, however, is that dust spewing from volcanic eruptions on Earth could create similar clay deposits enriched in iridium and containing shocked quartz. In fact, at about the same time as the dinosaur extinction, large outpourings of basaltic volcanic rock in India (called the Deccan Traps) and other locations had occurred. Also, if there was a catastrophic meteor impact, where was the crater?

In the early 1990s, the 190-kilometer (120-mile)-wide *Chicxulub* (pronounced "SCHICK-sue-lube") *Crater* off the Yucatán coast in the Gulf of Mexico was identified as a likely candidate because of its structure, age, and size. To create a crater this large, a 10-kilometer (6-mile)-wide object composed of rock and/or ice traveling at speeds up to 72,000 kilometers (45,000 miles) per hour must have slammed into Earth (Figure 4B). Such an impact would have created huge waves—estimated to be more than 900 meters (3000 feet) high—that traveled throughout the oceans. In addition, the dust and debris lifted into the atmosphere most likely limited photosynthesis, chilled Earth's surface, and brought about the extinction of the dinosaurs and many other species. Finally, acid rains and global fires may have added to the environmental disaster.

DEVISING AN EXPERIMENT

Supporting evidence for the meteor impact hypothesis was provided in 1997 by recovering cores of sediment from the sea floor. Previous drilling close to the impact site did not reveal any K–T deposits. Evidently, the impact and resulting huge waves had stripped the ocean floor of its sediment. However, at 1600 kilometers (1000 miles) from the impact site, the telltale sediments from the catastrophe, such as the iridium-rich clay layer, were preserved in sea floor sediments.

INTERPRETING THE RESULTS

Convincing evidence of the K–T impact from this and other cores collected in 2016 suggests that Earth has experienced many such extraterrestrial impacts over geologic time. Statistics show that an impact the size of the K–T event should occur on Earth about once every 100 million years, severely affecting life on Earth as it did the dinosaurs. This frequency is consistent with the fossil record, which indicates that in the last 500 million years, Earth has experienced five major extinction events.

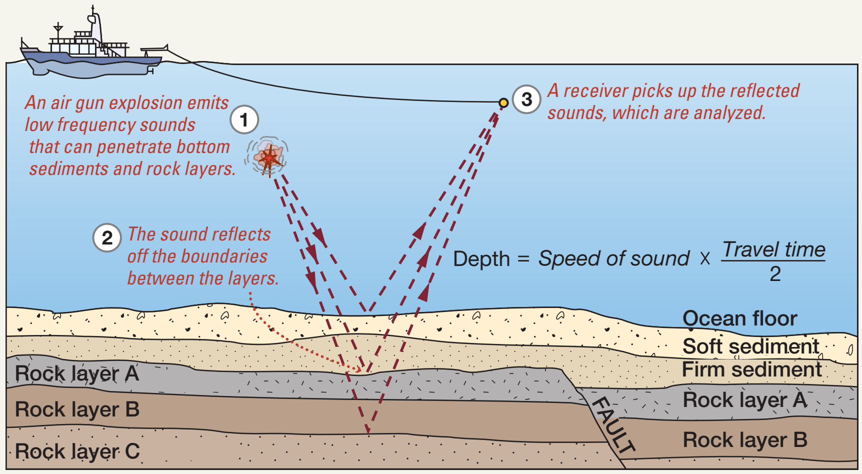
THINKING LIKE A SCIENTIST: WHAT'S NEXT?

What kind of evidence would you expect to find in coastal rock sequences that were deposited during the time of the huge waves that were created by the meteor impact?

Figure 4B **The K–T meteorite impact event.**

with Trusted Content and Dynamic Media

EXPLORING DATA ▶ **Using the equation shown in Figure 3.7a, determine the time it takes sound to reach the deepest part of the ocean, the Challenger Deep in the Mariana Trench, which is 11,022 meters (36,161 feet) below sea level. Use the average speed of sound in seawater of 1507 meters (4945 feet) per second.**



(a) A ship conducting seismic profiling. Note that depth can be determined by knowing the speed of sound in seawater and the travel time of the sound.

NEW Exploring Data Activities help students engage with graphs and other data-driven features to enable them to practice their data interpretation skills.

NEW MapMaster 2.0 is GIS inspired, allowing students to layer various thematic maps to analyze spatial patterns and data at regional and global scales. Now, fully mobile, this tool includes zoom and annotation functionality with hundreds of map layers leveraging recent data from sources such as NOAA, NASA, USGS, United Nations, and CIA. Students can also upload their own data. Students are able to access MapMaster 2.0 in the Study Area on their own and instructors can assign auto-graded activities.

Dive into Student Engagement

STUDENTS SOMETIMES ASK . . .

How can I accept a scientific idea if it's just a theory?

When most people use the word "theory" in everyday life, it usually means an idea or a guess (such as the all-too-common "conspiracy theory"), but the word has a much different meaning in science. In science, a theory is not a guess or a hunch. It's a well-substantiated, well-supported, well-documented explanation for observations about the natural world. It's a powerful tool that ties together all the facts about something, providing an explanation that fits all the observations and is used to make predictions (for example, what will happen given a certain set of circumstances). In science, a theory is a well-established explanation of how the natural world works. For a scientific theory to exist, scientists have to be *very* sure about it. So, don't discount a scientific idea because it's "just a theory." As famed astrophysicist Neil deGrasse Tyson has stated about the validity of science, *"The good thing about science is that it's true whether or not you believe in it."*

Students Sometimes Ask features display common and often entertaining questions posed by real students, like "Why do my fingers get wrinkly when they are in the water for a long time?" and pose scientific explanations.

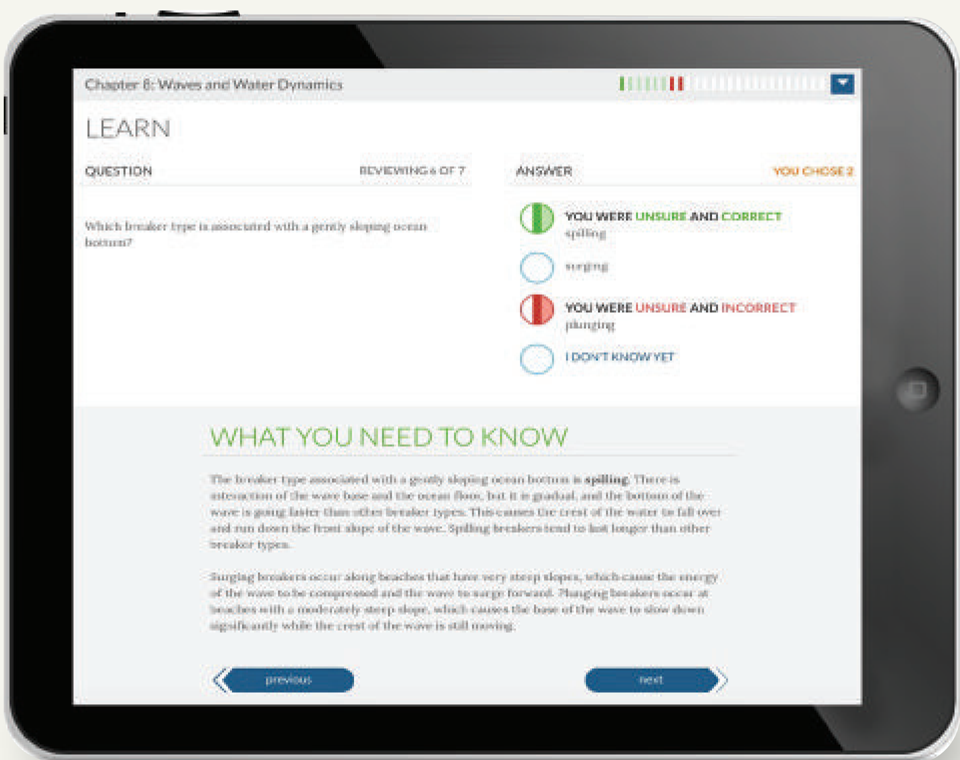
CREATURE FEATURE 2.1

Can you help me find my way home?

The **green sea turtle** (*Chelonia mydas*) is not named for its external color, but for the greenish color of its body fat.

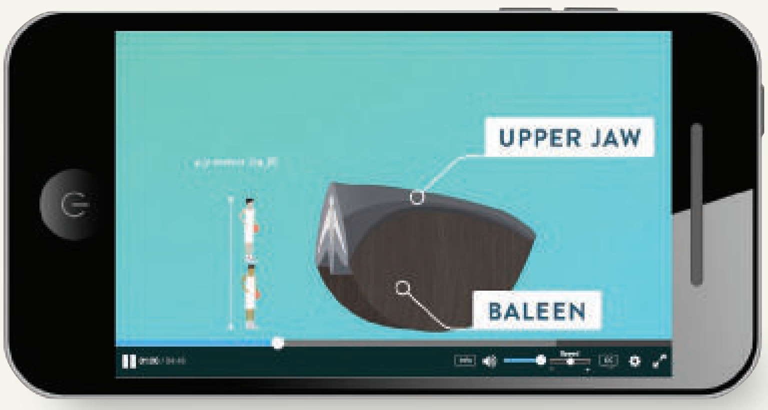
Green sea turtles spend many years living at sea in tropical and subtropical oceans but unerringly return to their place of birth to lay eggs on sandy beaches. How do they navigate so precisely? See **Process of Science 2.1**.

NEW Creature Features draw student interest by introducing compelling facts about marine organisms in an engaging "Who am I?" format.



NEW! Dynamic Study Modules help students study effectively—and at their own pace—by keeping them motivated and engaged. The assignable modules rely on the latest research in cognitive science, using methods—such as adaptivity, gamification, and intermittent rewards—to stimulate learning and improve retention.

with Tools that Enhance Learning



Oceanography Animations captivate students with animations that illustrate key concepts in a visually dynamic and engaging way.

SmartFigures are 3- to 4-minute mini video lessons containing explanations of difficult-to-understand oceanographic concepts and numerical data directed by an oceanography teaching expert and NASA Science Communicator.

The **Student-Centric Approach** enables students to form a path to successful learning. There is a **Recap** feature throughout each chapter, summarizing essential concepts. **Critical Thinking Questions** and **Active Learning Exercises** encourage students to think deeply about and engage with chapter topics.

ESSENTIAL LEARNING CONCEPTS

At the end of this chapter, you should be able to:

- ☐ **3.1** Discuss the techniques that are used to determine ocean bathymetry.
- ☐ **3.2** Describe the sea floor features that exist on continental margins.
- ☐ **3.3** Describe the sea floor features that exist in the deep-ocean basins.
- ☐ **3.4** Describe the sea floor features that exist along the mid-ocean ridge.

RECAP Sending pings of sound into the ocean (echo sounding) is a commonly used technique for determining ocean bathymetry. More recently, satellites are being used to map sea floor features.

CONCEPT CHECK 3.1 ▸ **Discuss the techniques that are used to determine ocean bathymetry.**

1 What is bathymetry? How is it different from topography?

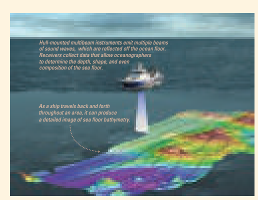
2 Describe how an echo sounder works.

3 Discuss the development of bathymetric techniques, indicating significant advancements in technology.

ESSENTIAL CONCEPTS REVIEW

3.1 ▶ What techniques are used to determine ocean bathymetry?

- *Bathymetry is the measurement of ocean depths and the charting of ocean floor topography*. The varied bathymetry of the ocean floor was first determined using *soundings* to measure water depth. Later, the development of the *echo sounder* gave ocean scientists a more detailed representation of the sea floor.
- Today, much of our knowledge of the ocean floor has been obtained using various *multibeam echo sounders* or *side-scan sonar instruments* (to make detailed bathymetric maps of a small area of the ocean floor), *satellite measurement* of the ocean surface (to produce maps of the world ocean floor), and *seismic reflection profiles* (to examine Earth structure beneath the sea floor).



Selected Key Terms

Use the **glossary** at the end of this book to discover the meanings of these Selected Key Terms: **bathymetry, sounding, echo sounder, sonar, seismic reflection profile.**

Critical Thinking Question

Describe how satellite measurements of the ocean *surface* allow oceanographers to create a map of the sea *floor*.

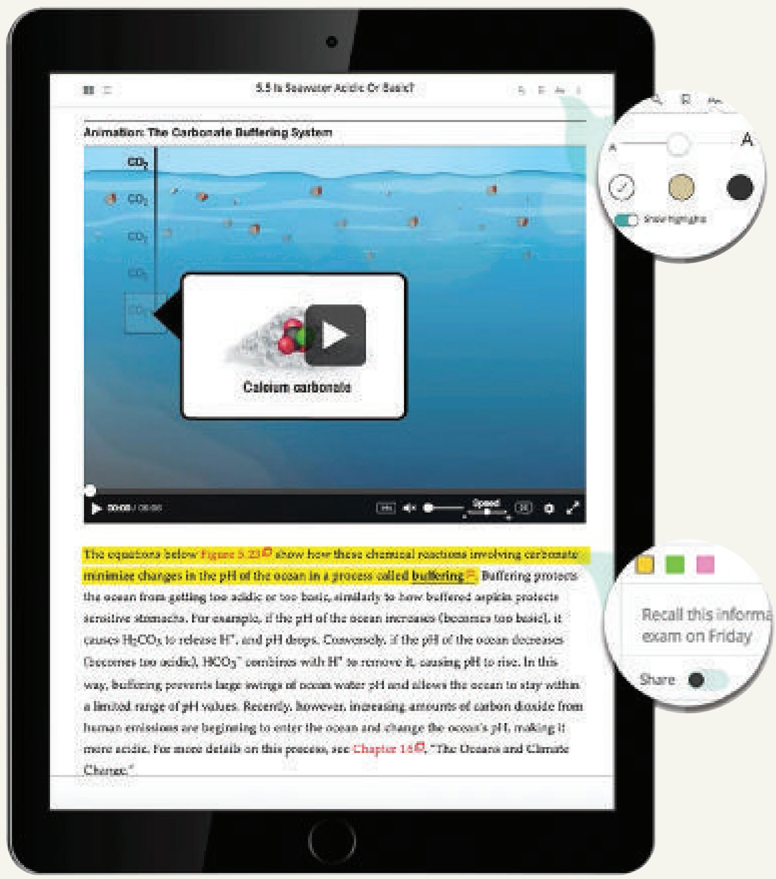
Active Learning Exercise

Use the Internet to research how a "fish finder" works on modern sport-fishing boats. How do these techniques compare to the sonar techniques described in this textchapter?

Dive into a Whole New Learning Experience with Pearson eText

Give students anytime, anywhere access with **Pearson eText**, the simple-to-use, mobile-optimized, and personalized reading experience available within Mastering. It allows students to easily highlight, take notes, and review key vocabulary all in one place—even when offline. Seamlessly integrated videos and other rich media engage students and give them access to the help they need, when they need it.

"I absolutely love the digital book that came with my main paper book, all the audio and video materials made my course so entertaining, and as a result A+ for the semester!"



Pearson eText for Oceanography has hundreds of videos and animations that bring concepts to life. Instructors are able to highlight key concepts within the eText and share with their students to guide them through the reading and help them grasp key concepts.

Essentials of
Oceanography

THIRTEENTH EDITION

Alan P. Trujillo

DISTINGUISHED TEACHING PROFESSOR
PALOMAR COLLEGE

Harold V. Thurman

FORMER PROFESSOR EMERITUS
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Cover Photo Description

A pod of dolphins swims off the Hawaiian coast. A pod of pantropical spotted dolphin (*Stenella attenuata*) swims in shallow water off the northern coast of the Hawaiian island of Kauai. This species of dolphin is often found in deeper water throughout the world's temperate and tropical oceans swimming above schools of tuna and as a result were often caught in purse seine nets as bycatch by the tuna fishing industry, which is discussed in Chapter 13, "Biological Productivity and Energy Transfer." In the 1980s, the rise of "dolphin-friendly" tuna capture methods saved millions of these marine mammals in the eastern Pacific Ocean and it is now one of the most abundant dolphin species in the world.

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ABOUT THE AUTHORS

ALAN P. TRUJILLO Al Trujillo is a Distinguished Teaching Professor in the Earth, Space, and Environmental Sciences Department at Palomar College in San Marcos, California. He received his bachelor's degree in geology from the University of California at Davis and his master's degree in geology from Northern Arizona University, afterward working for several years in industry. Al began teaching at Palomar in 1990. In 1997, he was awarded Palomar's Distinguished Faculty Award for Excellence in Teaching, and in 2005 he received Palomar's Faculty Research Award. He has coauthored *Introductory Oceanography* with Hal Thurman and is a contributing author for the textbooks *Earth* and *Earth Science*. In addition to writing and teaching, Al works as a naturalist and lecturer aboard Holland America Line and natural history expedition vessels for Lindblad Expeditions/National Geographic in Alaska, Iceland, the Sea of Cortez/Baja California, Central/South America, and across the South Pacific Ocean. His research interests include beach processes, sea cliff erosion, and active teaching techniques. He enjoys photography, and he collects sand as a hobby. Al and his wife, Sandy, have two children, Karl and Eva.

HAROLD V. THURMAN Hal Thurman's interest in geology led to a bachelor's degree from Oklahoma A&M University, followed by seven years working as a petroleum geologist, mainly in the Gulf of Mexico, where his interest in the oceans developed. He earned a master's degree from California State University at Los Angeles. Hal began teaching at Mt. San Antonio College in Walnut, California, in 1968 as a temporary teacher and taught Physics 1 (a surveying class) and three Physical Geology labs. In 1970, he taught his first class of General Oceanography. It was from this experience that he decided to write a textbook on oceanography and received a contract with Charles E. Merrill Publishing Company in 1973. The first edition of his book *Introductory Oceanography* was released in 1975. Harold authored or coauthored over 20 editions of textbooks that include *Introductory Oceanography*, *Essentials of Oceanography*, *Physical Geology*, *Marine Biology*, and *Oceanography Laboratory Manual*, many of which are still being used today throughout the world. In addition, he contributed to the *World Book Encyclopedia* on the topics of "Arctic Ocean," "Atlantic Ocean," "Indian Ocean," and "Pacific Ocean." Hal Thurman retired in May 1994, after 24 years of teaching, and moved to be closer to family in Oklahoma, then to Florida. Hal passed away at the age of 78 on December 29, 2012. His writing expertise, knowledge about the oceans, and easygoing demeanor are dearly missed.

Dedicated to my wife Sandy, who has taken care of me through thick and thin

—AL TRUJILLO

In memory of Dr. Anthony Trujillo (1926–2017)

CONTENTS

BONUS ONLINE CONTENT

PREFACE

"The sea, once it casts its spell, holds one in its net of wonder forever."

—Jacques-Yves Cousteau, oceanographer, underwater videographer, and explorer (circa 1963)

To the Student

Welcome! You're about to embark on a journey that is far from ordinary. Over the course of this term, you will discover the central role the oceans play in the vast global system, of which you are a part.

This book's content was carefully developed to provide a foundation in science by examining the vast body of oceanic knowledge. This knowledge includes information from a variety of scientific disciplines—geology, chemistry, physics, and biology—as they relate to the oceans. However, no formal background in any of these disciplines is required to successfully master the subject matter contained within this book. Our desire is to have you take away from your oceanography course much more than just a collection of facts. Instead, we want you to develop a fundamental understanding of how the oceans work and why the oceans behave the way that they do.

This book is intended to help you in your quest to know more about the oceans. Taken as a whole, the components of the ocean—its sea floor, chemical constituents, physical components, and life-forms—comprise one of Earth's largest interacting, interrelated, and interdependent systems. Because human activities impact Earth systems, it is important to understand not only how the oceans operate but also how the oceans interact with Earth's other systems (such as its atmosphere, biosphere, and hydrosphere) as part of a larger picture. Thus, this book uses a systems approach to highlight the interdisciplinary relationships among oceanographic phenomena and how those phenomena affect other Earth systems.

DIVING DEEPER PREFACE.1

A USER'S GUIDE FOR STUDENTS: HOW TO READ A SCIENCE TEXTBOOK

Have you known someone who could scan a reading assignment or sleep with it under their pillow and somehow absorb all the information? Studies have shown that those people haven't really committed anything to long-term memory. For most of us, it takes a focused, concentrated effort to gain knowledge through reading. Interestingly, if you have the proper motivation and reading techniques, you can develop excellent reading comprehension. What is the best way to read a science textbook such as this one that contains many new and unfamiliar terms?

One common mistake is to approach reading a science textbook as one would read a newspaper, magazine, or novel. Instead, many reading instructors suggest using the SQ4R reading technique, which is based on research about how the brain learns. The SQ4R technique includes these steps:

1. **Survey:** Read the title, introduction, major headings, first sentences, concept statements, review questions, summary, and study aids to become familiar with the content in advance.
2. **Question:** Have questions in mind when you read. If you can't think of any good questions, use the chapter questions as a guide.
3. **Read:** Read flexibly through the chapter, using short time periods to accomplish the task one section at a time (not all in one sitting).
4. **Recite:** Answer the chapter questions. Take notes after each section and review your notes before you move on.
5. **(w)Rite:** Write summaries and/or reflections on what you've read. Write answers to the questions in Step 2.
6. **Review:** Review the text using the strategy in the survey step. Take the time to review your end-of-section notes as well as your summaries.

To help you study most effectively, this textbook includes many study aids that are designed to be used with the SQ4R technique. For example, each chapter includes a list of learning objectives that are tied to the Essential Concepts throughout the chapter; review Concept Check questions embedded at the end of each section; and an Essential Concepts Review that includes a chapter summary, study resources, and critical thinking questions.

Here are some additional reading tips that may seem like common sense and are based on brain-based research, but are often overlooked:

- Don't attempt to do your reading when you are tired, distracted, or agitated.
- Break up your reading into manageable sections. Don't save it all until the last minute.
- Take a short break if your concentration begins to fade. Listen to music, call a friend, have a snack, or drink some water. Then return to your reading.

Remember that every person is different, so experiment with new study techniques to discover what works best for you. In addition, being a successful student is hard work; it is not something one does in his/her spare time. With a little effort in applying the SQ4R reading technique, you will begin to see a difference in what you remember from your reading.

To that end—and to help you make the most of your study time—we focused the presentation in this book by organizing the material around three essential components:

1. **CONCEPTS:** General ideas derived or inferred from specific instances or occurrences (for instance, the concept of density can be used to explain why the oceans are layered)
2. **PROCESSES:** Actions or occurrences that bring about a result (for instance, the process of waves breaking at an angle to the shore results in the movement of sediment along the shoreline)
3. **PRINCIPLES:** Rules or laws concerning the functioning of natural phenomena or mechanical processes (for instance, the principle of sea floor spreading suggests that the geographic positions of the continents have changed through time)

Interwoven within these concepts, processes, and principles are hundreds of photographs, illustrations, real-world examples, and applications that make the material relevant and accessible (and maybe sometimes even entertaining) by bringing science to life.

Ultimately, it is our hope that by understanding how the oceans work, you will develop a new awareness and appreciation of all aspects of the marine environment and its role in Earth systems. To this end, the book has been written for you, a student of the oceans. So enjoy and immerse yourself! You're in for an exciting ride.

—**Al Trujillo**

To the Instructor

This thirteenth edition of *Essentials of Oceanography* is designed to accompany an introductory college-level course in oceanography taught to students who have no formal background in mathematics or science. As in previous editions, the goal of this edition of the textbook is to clearly present the relationships of scientific principles to ocean phenomena in an engaging and meaningful way. In addition, the content of this book is carefully designed to help students engage with and learn oceanographic material.

This edition has greatly benefited from being thoroughly reviewed by hundreds of students who made numerous suggestions for improvement. Comments by former students about the book include, *"I have really enjoyed the oceanography book we've used this semester. It had just the right mix of graphics, text, and user-friendliness that really held my interest;" "I really liked the videos embedded in the daily chapter quizzes, particularly the SmartFigures done by Laura Faye Tenenbaum. I loved her delivery. Her style helped me understand some complex topics and just made it really digestible. She's so bright and her humor came through just in the right way, kept it lively;"* and *"What I really liked about the book is that it's a welcoming textbook—open and airy. You could almost read it at bedtime like a story because of all the interesting pictures."*

This edition has been reviewed in detail by a host of instructors from leading institutions across the country. Reviewers of the twelfth edition described the text as follows: *"Essentials of Oceanography is a great textbook to introduce oceanography to non-science majors, and it has a lot of great supplemental materials for you and your students;" "Students find it easily understandable. The writing and graphics are excellent; easy to comprehend and remember;" "Your book is truly wonderful. Your writing voice is so excellent, and the fact that you have included so many etymological roots of terms is a real memory aid for students. I'm always stressing to them how, among other things, science is a language, and your book is right in groove with that;"* and *"An excellent introductory oceanography textbook that can be used for courses from two to four credit hours. Easily read, flows well through the chapters and from chapter-to-chapter. Many helpful aids for students as well as ancillaries for instructors. It makes our job easier, and students are happy because they can understand the topics well, leading to higher average grades."*

In 2012, the tenth edition of *Essentials of Oceanography* received a Textbook Excellence Award, called a "Texty," from the Text and Academic Authors Association (TAA). The Texty award recognizes written works for their excellence in the areas of content, presentation, appeal, and teachability. The publisher, Pearson Education, nominated the book for the award, and the textbook was critically reviewed by a panel of expert judges. In 2017, the twelfth edition of *Essentials of Oceanography* received TAA's McGuffey Longevity Award for its long-standing history of publication.

The 16-chapter format of this textbook is designed for easy coverage of the material in a 15- or 16-week semester. For courses taught on a 10-week quarter system, instructors may need to select those chapters that cover the topics and concepts of primary relevance to their course. Chapters are self-contained and can thus be covered in any order. Following the introductory chapter (Chapter 1, which covers the general geography of the oceans; a historical perspective of oceanography; the method behind the process of science; and a discussion of the origin of Earth, the atmosphere, the oceans, and life itself), the four major academic disciplines of oceanography are represented in the following chapters:

- Geological oceanography (Chapters 2–4 and Chapter 10)
- Chemical oceanography (Chapter 5 and Chapter 11)
- Physical oceanography (Chapters 6–9)
- Biological oceanography (Chapters 12–15)
- Interdisciplinary oceanography: Climate change (Chapter 16)

We strongly believe that oceanography is at its best when it links together several scientific disciplines and shows how they are interrelated in the oceans. Therefore, this interdisciplinary approach is a key element of every chapter, particularly Chapter 16, "The Oceans and Climate Change."

What's New in This Edition?

Changes in this edition are designed to increase the readability, relevance, and appeal of this book. Major changes include the following:

- An emphasis on the process of science, including a new "Process of Science" boxed feature in most chapters that illustrates the scientific method by highlighting an area of oceanographic inquiry and explicitly pointing out how the process of science was used in that particular case; each feature also includes a critical thinking assessment question "Thinking Like a Scientist: What's Next?" so that students gain practice approaching problems scientifically and analytically
- New "Exploring Data" questions added to every chapter; this new feature directs students to engage with data and checks their

DIVING DEEPER PREFACE.2

OCEAN LITERACY: WHAT SHOULD PEOPLE KNOW ABOUT THE OCEAN?

The ocean is the defining feature of our planet. Accordingly, there is great interest in developing *ocean literacy*, which means understanding the ocean's influence on humans as well as humans' influence on the ocean. For example, scientists and educators agree that an ocean-literate person:

- Understands the essential principles and fundamental concepts about the functioning of the ocean.
- Can communicate about the ocean in a meaningful way.
- Is able to make informed and responsible decisions regarding the ocean and its resources.

To achieve this goal, ocean educators and experts have developed the **Seven Principles of Ocean Literacy**. The following ideas are what everyone—especially those who successfully pass a college course in oceanography or marine science—should understand about the ocean:

1. Earth has one big ocean with many features.
2. The ocean and life in the ocean shape the features of Earth.
3. The ocean is a major influence on weather and climate.
4. The ocean makes Earth habitable.
5. The ocean supports a great diversity of life and ecosystems.
6. The ocean and humans are inextricably interconnected.
7. The ocean is largely unexplored.

This book is intended to help all people achieve ocean literacy. For more information about the Seven Principles of Ocean Literacy, see **http://oceanliteracy.wp2.coexploration.org/**

understanding by asking data interpretation questions related to data-rich figures, graphs, tables, and maps
- The addition in all chapters of a new "Creature Feature," which uses compelling facts about a marine organism to reinforce the theme of the chapter. Each "Creature Feature's" title is written in an engaging "Who Am I?" format to draw student interest
- Expansion of the discussion of carbon and oxygen in the ocean in Chapter 5, "Water and Seawater," which includes explanation of how the distribution of dissolved gases and pH changes with depth, and their significance
- A thoroughly updated Chapter 16 "The Oceans and Climate Change," introducing a new discussion about the carbon cycle, and describing the most recent findings of the IPCC; the rewrite includes highlights of the 2017 *Climate Science Special Report: Fourth National Climate Assessment*, which was produced at the behest of the U.S. Congress to provide an assessment of the state of science relating to climate change and its physical impacts in the United States; also included in this chapter is a new review of solutions to human-caused greenhouse gas emissions in the atmosphere, and four new or revised "Students Sometimes Ask . . . " questions that address student misconceptions and concerns regarding climate change
- Greater emphasis on the ocean's role in Earth systems
- A stronger learning path that directly links the learning objectives listed at the beginning of each chapter to the end-of-section "Concept Checks," which allow and encourage students to pause and test their knowledge as they proceed through the chapter
- A new active learning pedagogy that divides chapter material into easily digestible chunks, which makes studying easier and assists student learning (cognitive science research shows that the ability to "chunk" information is essential to enhancing learning and memory)
- The inclusion of an array of new SmartFigures and SmartTables, which provide a video explanation of difficult-to-understand oceanographic concepts and numerical data by an oceanography teaching expert
- The addition of one or more "What Did You Learn?" assessment questions to each "Diving Deeper" boxed feature
- Removal of all footnotes; pertinent information from previous footnotes is now contained within the body of the text
- Migration of each chapter's Squidtoons call-out to Mastering Oceanography Study Area as Bonus Web Content
- In all Essential Concept Review (end-of-chapter) materials, the revision of existing "Critical Thinking Questions" and "Active Learning Exercise" questions that can be used for in-class group activities
- The addition of a new "Selected Key Terms" feature in each section's end-of-chapter box that simplifies and replaces the word cloud formerly at the beginning of each chapter and directs students to the glossary at the end of the book to discover the meanings of the most important vocabulary terms that are boldfaced in each section of the text
- Updating of information throughout the text to include technological advances that have resulted in the modernization of oceanographic research and continue to shape the discipline today; for example, space-based oceanographic and atmospheric observations from NASA Earth-observing satellite missions
- Addition of an array of new "Students Sometimes Ask . . . " questions throughout the book
- An enhanced illustration package showcasing new photos, satellite images, and figures to make oceanographic topics more accessible, current, and engaging
- The revision or updating of over half of existing figures and incorporating annotations and labels within key figures that direct student attention and help explain information in storyboard form; this research-proven technique helps students focus on the most relevant information, interpret complex art, and integrate written and visual information

- Standardization of the color scheme and labeling of all figures to make them more appealing and consistent throughout
- Inclusion of more than 70 Web Animations from Pearson's Geoscience Animations Library, which include state-of-the-art computer animations that have been created by Al Trujillo and a panel of geoscience educators
- An enhanced eText, which allows students to review previously learned material with a single click that will place this content side-by-side the page they are currently studying
- Selected Diving Deeper feature boxes have been migrated online to Mastering Oceanography as Bonus Web Content in an effort to reduce the length of the text
- The remaining Diving Deeper features appearing in the book are organized around the following four themes:
  - **HISTORICAL FEATURES**, which focus on historical developments in oceanography that tie into chapter topics
  - **RESEARCH METHODS IN OCEANOGRAPHY**, which highlight how oceanographic knowledge is obtained
  - **OCEANS AND PEOPLE**, which illustrate the interaction of humans and the ocean environment
  - **FOCUS ON THE ENVIRONMENT**, which emphasizes environmental issues that are an increasingly important component of ocean studies
- The former Afterword has been shortened to one page; information about Marine Protected Areas (MPAs) has been moved to Chapter 13 and information about what individuals can do to minimize human impact on the oceans (including former Diving Deeper Aft.1) has been moved to Chapter 16
- All text in the chapters has been thoroughly reviewed and edited by students and oceanography instructors in a continued effort to refine the style and clarity of the writing

Note that a detailed list of specific chapter-by-chapter changes is available at **https://www2.palomar.edu/pages/atrujillo/**

In addition, this edition continues to offer some of the previous edition's most popular features, including the following:

- Scientifically accurate and thorough coverage of oceanography topics
- A series of SmartFigures and SmartTables, which maximize instructional value of the media and help students learn important content
- "Students Sometimes Ask . . . " questions, which present actual student questions along with the authors' answers
- A "Recap" feature that summarizes key points throughout the text, making studying easier
- The continuation of existing "Critical Thinking Questions" and "Active Learning Exercise" questions that can be used for group activities in class in all Essential Concept Review (end-of-chapter) materials
- QR codes embedded in the text that allow students to use their mobile devices to link directly to Mastering Oceanography Animations, SmartFigures and SmartTables, and Web Videos
- QR codes and links to more than 50 hand-picked Web videos that show important oceanographic processes in action
- Use of the international metric system (Système International [SI] units), with comparable English system units in parentheses
- Explanation of word etymons (*etumon* = sense of a word) as new terms are introduced, in an effort to demystify scientific terms by showing what the terms actually mean
- A "Climate Change Connection" icon that alerts students to topics that are related to the overarching theme of global climate change
- Use of **bold print** on key terms, which are defined when they are introduced and are described in the glossary
- A reorganized "Essential Concepts Review" summary at the end of each chapter
- **Mastering Oceanography**, which features chapter-specific Self Study Quizzes, SmartFigures and SmartTables, Oceanography Videos and Animations, Squidtoons, Dynamic Study Modules, and an optional Pearson eText with embedded videos.

For the Student

- **MASTERING OCEANOGRAPHY** delivers engaging, dynamic learning opportunities—focused on course objectives and responsive to each student's progress—that are proven to help students absorb course material and understand difficult concepts. Mastering Oceanography is a customized learning resource that includes:
  - **Student Study Area**, which is designed to be a one-stop resource for students to acquire study help and serve as a launching pad for further exploration. Content for the site was written by author Al Trujillo and is tied, chapter-by-chapter, to the text. The Student Study Area is organized around a four-step learning pathway:
    1. *Review*, which contains **Essential Concepts** as learning objectives
    2. *Read*, which contains the **eText** and **Bonus Web Content**
    3. *Visualize*, which contains Oceanography Animations, Oceanography Videos, and Smart Figures.
    4. *Test Yourself*, which contains a **Chapter Quiz** that is automatically graded for instant feedback.
  - **Study Tools** such as flashcards and a searchable online glossary to help make the most of students' study time
- **THE PEARSON eTEXT** gives students complete access to a digital version of the text whenever and wherever they have access to the Internet.

For the Instructor

- **MASTERING OCEANOGRAPHY: CONTINUOUS LEARNING BEFORE, DURING, AND AFTER CLASS** Mastering Oceanography is an online homework, tutorials, and assessments program designed to improve results by helping students quickly master oceanography concepts. Students will benefit from self-paced tutorials that feature immediate wrong-answer feedback and hints that emulate the office-hour experience to help keep them on track. With a wide range of interactive, engaging, and assignable activities, students will be encouraged to actively learn and retain tough course concepts:

  - **New Process of Science Coaching Activities** support the text feature that highlights an area of oceanographic inquiry and explicitly point out the associated background, method, and conclusion.
  - **New Exploring Data activities** help students actively engage with graphs and other data-driven features and their data interpretation skills.
  - **SmartFigures/SmartTables**, which are three- to four-minute mini-lessons that examine and explain the concepts illustrated by a figure or table. Over 90 SmartFigures/SmartTables are assignable in **Mastering**.
  - **Oceanography Animations,** which illuminate the most difficult-to-understand topics in oceanography and were created by an expert team of geoscience educators. The animation activities include audio narration, a text transcript, and assignable multiple-choice questions with specific wrong-answer feedback.
  - **Video Field Trips** give students fascinating behind-the-scenes experiences at prescribed fire burns, solar energy, and coal-fired power plants, wastewater treatment facilities, landfills, farms, and more. Each Video Field Trip includes assessment questions for easily assignable homework.
  - **Visualizing Oceanography Activities** ask students to label art from the text to ensure they are interpreting and understanding figures.
  - **Dynamic Study Modules**, which help students study effectively on their own by continuously assessing their activity and performance in real time. Here's how it works: Students complete a set of questions with a unique answer format that also asks them to indicate their confidence level. Questions repeat until the student can answer them all correctly and confidently. Once completed, Dynamic Study Modules explain the concept using materials from the text. These are available as graded assignments prior to class, and accessible on smartphones, tablets, and computers.
  - **Learning Catalytics™**, which are an interactive student response tool that uses students' smartphones, tablets, or laptops to engage them in more sophisticated tasks and thinking. Now included with MyLab & Mastering and eText, Learning Catalytics™ enables you to generate classroom discussion, guide your lecture, and promote peer-to-peer learning with real-time analytics.

- **STUDENT PERFORMANCE ANALYTICS** Mastering Oceanography allows an instructor to gain easy access to information about student performance and their ability to meet student learning outcomes. Instructors can quickly add their own learning outcomes, or use publisher-provided ones, to track student performance.
- **INSTRUCTOR MANUAL (DOWNLOAD ONLY)** This resource contains learning objectives, chapter outlines, answers to embedded end-of-section questions, and suggested teaching tips to spice up your lectures.
- **TESTGEN® COMPUTERIZED TEST BANK (DOWNLOAD ONLY)** This resource is a computerized test generator that lets instructors view and edit *Test Bank* questions, transfer questions to tests, and print the test in a variety of customized formats. The *Test Bank* includes over 1200 multiple-choice, matching, and short-answer/essay questions. All questions are tied to the chapter's learning outcomes, include a rating based on Bloom's taxonomy of learning domains (Bloom's 1–6) and contain the section number in which each question's answer can be found.
- **INSTRUCTOR POWERPOINT® PRESENTATIONS (DOWNLOAD ONLY)** Instructor Resource Materials include the following three PowerPoint® files for each chapter so that you can cut down on your preparation time, no matter what your lecture needs:

  1. **EXCLUSIVELY ART:** This file provides all the photos, art, and tables from the text, in order, loaded into PowerPoint® slides.
  2. **LECTURE OUTLINE:** This file averages 50 PowerPoint® slides per chapter and includes customizable lecture outlines with supporting art.
  3. **CLASSROOM RESPONSE SYSTEM (CRS) QUESTIONS:** Authored for use in conjunction with classroom response systems, this PowerPoint® file allows you to electronically poll your class for responses to questions, pop quizzes, attendance, and more.

For more information about these instructor resources, contact your Pearson textbook representative.

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Although this book has benefited from careful review by many individuals, the accuracy of the information rests with the authors. If you find errors or have comments about the text, please contact me.

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"If there is magic on this planet, it is contained in water."
—Loren Eiseley, American educator
and natural science writer (1907–1977)

SmartFigures

SmartTables

Introduction To Planet "Earth"

1

ESSENTIAL LEARNING CONCEPTS

At the end of this chapter, you should be able to:

- ☐ **1.1** Compare the characteristics of Earth's oceans.
- ☐ **1.2** Discuss how early exploration of the oceans was achieved.
- ☐ **1.3** Explain why oceanography is considered an interdisciplinary science.
- ☐ **1.4** Describe the process of science and the nature of scientific inquiry.
- ☐ **1.5** Explain how Earth and the solar system formed.
- ☐ **1.6** Explain how Earth's atmosphere and oceans formed.
- ☐ **1.7** Discuss why life is thought to have originated in the oceans.
- ☐ **1.8** Demonstrate an understanding of how old Earth is.

↑ *Check when completed*

The **oceans**[1] are the largest and most prominent feature on Earth. In fact, they are the single most defining feature of our planet. As viewed from space, our planet is a beautiful blue, white, and brown globe (see this chapter's opening photo). The abundance of liquid water on Earth's surface is a distinguishing characteristic of our home planet, and hidden under the ocean's surface is a submarine landscape that rivals anything on dry land.

So it seems perplexing that our planet is called "Earth" when 70.8% of its surface is covered by oceans. Many early human cultures that lived near the Mediterranean (*medi* = middle, *terra* = land) Sea envisioned the world as being composed of large landmasses surrounded by marginal bodies of water. From their viewpoint, landmasses—not oceans—dominated the surface of Earth. How surprised they must have been when they ventured into the larger oceans of the world. Our planet is misnamed "Earth" because we live on the land portion of the planet. If we were marine animals, our planet would probably be called "Ocean," "Water," "Hydro," "Aqua," or even "Oceanus" to indicate the prominence of Earth's oceans. Let's begin our study of the oceans by examining some of the unique geographic characteristics of our watery world.

1.1 ▶ How Are Earth's Oceans Unique?

In all of the planets and moons in our solar system, Earth is the only one that has oceans of liquid water on its surface. No other body in the solar system has a confirmed ocean, but recent satellite missions to other planets have revealed some tantalizing possibilities. For example, the spidery network of dark cracks on Jupiter's moon Europa (**Figure 1.1**) almost certainly betrays the presence of an ocean of liquid water beneath its icy surface. In fact, a recent analysis of the icy blocks that cover Europa's surface indicates that the blocks are actively being reshaped in a process analogous to plate tectonics on Earth. Two other moons of Jupiter, Ganymede and Callisto, may also have liquid oceans of water beneath their cold, icy crust. Yet another possibility for a nearby world with an ocean beneath its icy surface is Saturn's tiny moon Enceladus, which displays geysers of water vapor and ice that have recently been analyzed and, remarkably, contain salt. Recent analysis of the gravity field of Enceladus suggests the presence of a 10-kilometer (6.2-mile) deep saltwater ocean beneath a thick layer of surface ice. Also contained in the geysers' icy spray are tiny mineral grains; in 2015, analysis of these particles by a spacecraft flyby indicated that

"When you're circling the Earth every 90 minutes, what becomes clearest is that it's mostly water; the continents look like they're floating objects."

—Loren Shriver, NASA astronaut (2008)

[1]Throughout this book, all **bolded** words are key vocabulary terms that are defined in the glossary at the end of this book.

◀ **The blue marble, next generation.** This composite image of satellite data shows Earth's interrelated atmosphere, oceans, and land—including human presence. Its various layers include the land surface, sea ice, ocean, cloud cover, city lights, and the hazy edge of Earth's atmosphere.

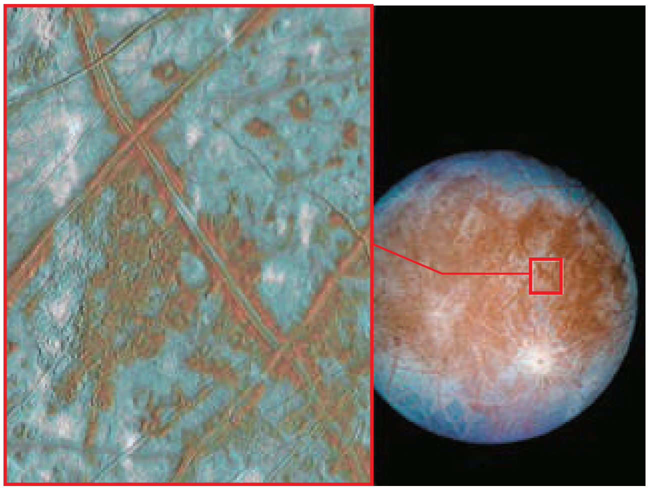


Figure 1.1 Jupiter's moon Europa. Scientists speculate that Europa's network of dark cracks is the result of tidal forces on an ocean beneath its icy surface. It's possible that, when Europa's orbit takes it close to Jupiter, the tide of the sea beneath the ice rises higher than normal. If this is so, the constant raising and lowering of the sea may have caused many of the cracks observed on the surface of the moon.

STUDENTS SOMETIMES ASK . . .

How can a spacecraft flyby determine if a planetary body has an ocean below its surface?

Modern spacecraft like NASA's Cassini carry an impressive array of scientific instruments for studying planetary bodies but perhaps the most important of these for detecting subsurface oceans are cameras. Images of geysers of water vapor and ice spurting into space obtained by the Cassini spacecraft give away the presence of liquid subsurface water on Saturn's icy moon Enceladus. Cameras also reveal the presence of fissures and cracks in the icy crust of Jupiter's moon Europa, which may be caused by tidal forces that raise and lower a liquid ocean beneath the surface. The possibility of a liquid underground ocean on Europa was first suggested after a flyby by the Galileo spacecraft detected fluctuations in Europa's magnetic field, indicating the presence of a subsurface conducting fluid—likely a salty ocean.

the dust-sized grains likely form when hot, mineral-laden water from the moon's rocky interior travels upward, coming into contact with cooler water. This evidence of subsurface hydrothermal activity is reminiscent of underwater hot springs in the deep oceans on Earth, a place that may have been key to the development of life on Earth. In 2016, another of Saturn's moons, Dione, was reported to have the telltale sign of a liquid ocean deep beneath its icy surface. And evidence continues to mount that Saturn's giant moon Titan hosts small seas of liquid hydrocarbons, suggesting that Titan may be the only other body in the solar system besides Earth known to have liquid at its surface. Even the dwarf planet Pluto has surface features that imply it too may harbor an ocean beneath its surface. Because these planetary bodies almost certainly have oceans of one sort or another, they are all enticing targets for space missions to search for signs of extraterrestrial life. Still, the fact that our planet has so much water on its surface, *and in the liquid form*, is unique in the solar system.

Earth's Amazing Oceans

Earth's oceans have had a profound effect on our planet and continue to shape our planet in critical ways. The oceans are essential to all life-forms and are in large part responsible for the development of life on Earth, providing a stable environment in which life could evolve over billions of years. Today, the oceans contain the greatest number of living things on the planet, from microscopic bacteria and algae to the largest life-form alive today (the blue whale). Interestingly, water is the major component of nearly every life-form on Earth, and our own body fluid chemistry is remarkably similar to the chemistry of seawater.

Another unique characteristic of Earth's oceans is that *the volume of the oceans is immense*. The oceans comprise the planet's largest habitat and contain 97.2% of all the water on or near Earth's surface (**Figure 1.2**). The oceans influence climate and weather all over the globe—even in continental areas far from any ocean—through an intricate pattern of currents and heating/cooling mechanisms, some of which scientists are only now beginning to understand. The oceans are also the "lungs" of the planet, taking carbon dioxide gas out of the atmosphere and replacing it with oxygen gas. Scientists have estimated that the oceans supply as much as 70% of the oxygen that humans breathe.

The oceans determine where our continents end and have thus shaped political boundaries and human history. The oceans conceal many features; in fact, the majority of Earth's geographic features are on the ocean floor. Remarkably, there was once more known about the surface of the Moon than about the floor of the oceans! Fortunately, our knowledge of both has increased dramatically over the past several decades.

The oceans also hold many secrets waiting to be discovered, and new scientific discoveries about the oceans are made nearly every day. The oceans are a source of food, minerals, and energy that remains largely untapped. More than half of the world's population lives in coastal areas near the oceans, taking advantage of the mild climate, an inexpensive form of transportation, proximity to food resources, and vast recreational opportunities. Unfortunately, the oceans are also the dumping ground for many of society's wastes. In fact, the oceans are currently showing alarming changes caused by pollution, overfishing, invasive species, and climate change, among other things. All of these and many other topics are contained within this book.

How Many Oceans Exist on Earth?

The oceans are a common metaphor for vastness. When one examines a world map (**Figure 1.3**), it's easy to appreciate the impressive extent of Earth's oceans. Notice that *the oceans dominate the surface area of the globe*. For those people who have traveled by boat across an ocean (or even flown across one in an airplane), the one thing that immediately strikes them is that the oceans are enormous. Notice, also, that *the oceans are interconnected* and form a single continuous body of seawater, which is why the oceans are commonly referred to as a "world ocean" (singular, not plural). For instance, a vessel at sea can travel from one ocean to another, whereas it is impossible to travel on land from one continent to most others without crossing an ocean.

The Four Principal Oceans, Plus One

Our world ocean can be divided into four principal oceans plus an additional ocean, based on the shape of the ocean basins and the positions of the continents (Figure 1.3).

PACIFIC OCEAN The **Pacific Ocean** is the world's largest ocean, covering more than half of the ocean surface area on Earth (**Figure 1.4b**). The Pacific Ocean is the single largest geographic feature on the planet, spanning more than one-third of Earth's entire surface. The Pacific Ocean is so large that *all* of the continents could fit into the space occupied by it—with room left over! Although the Pacific Ocean is also the deepest ocean in the world (**Figure 1.4c**), it contains many small tropical islands. It was named in 1520 by explorer Ferdinand Magellan's party in honor of the fine weather they encountered while crossing into the Pacific (*paci* = peace) Ocean.

ATLANTIC OCEAN The **Atlantic Ocean** is about half the size of the Pacific Ocean and is not quite as deep (Figure 1.4c). It separates the Old World (Europe, Asia, and Africa) from the New World (North and South America). The Atlantic Ocean was named after Atlas, who was one of the Titans in Greek mythology.

INDIAN OCEAN The **Indian Ocean** is slightly smaller than the Atlantic Ocean and has about the same average depth (Figure 1.4c). It is mostly in the Southern Hemisphere (south of the equator, or below 0 degrees latitude in Figure 1.3). The Indian Ocean was named for its proximity to the subcontinent of India.

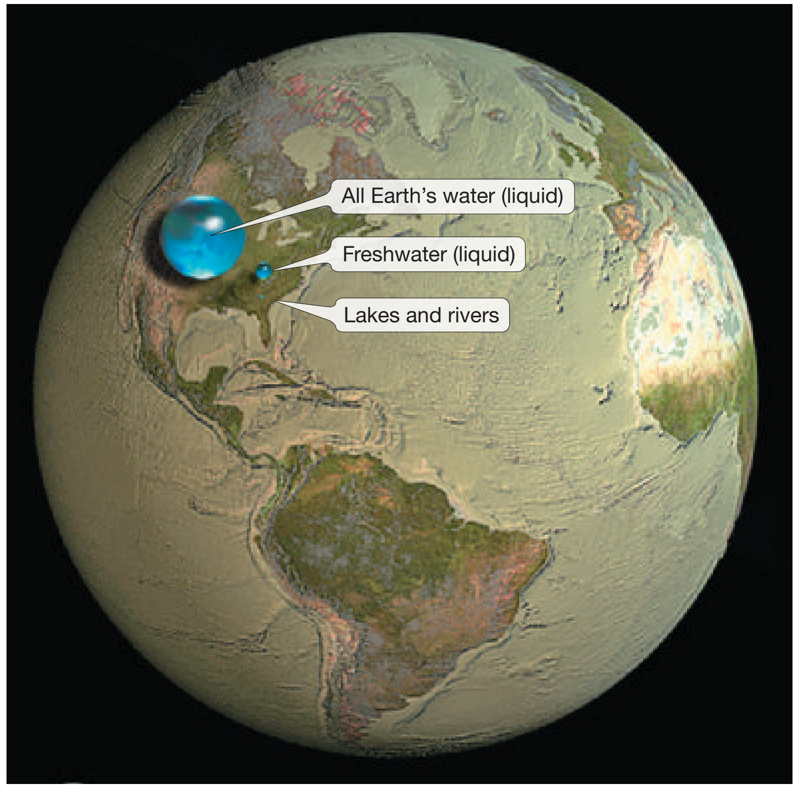
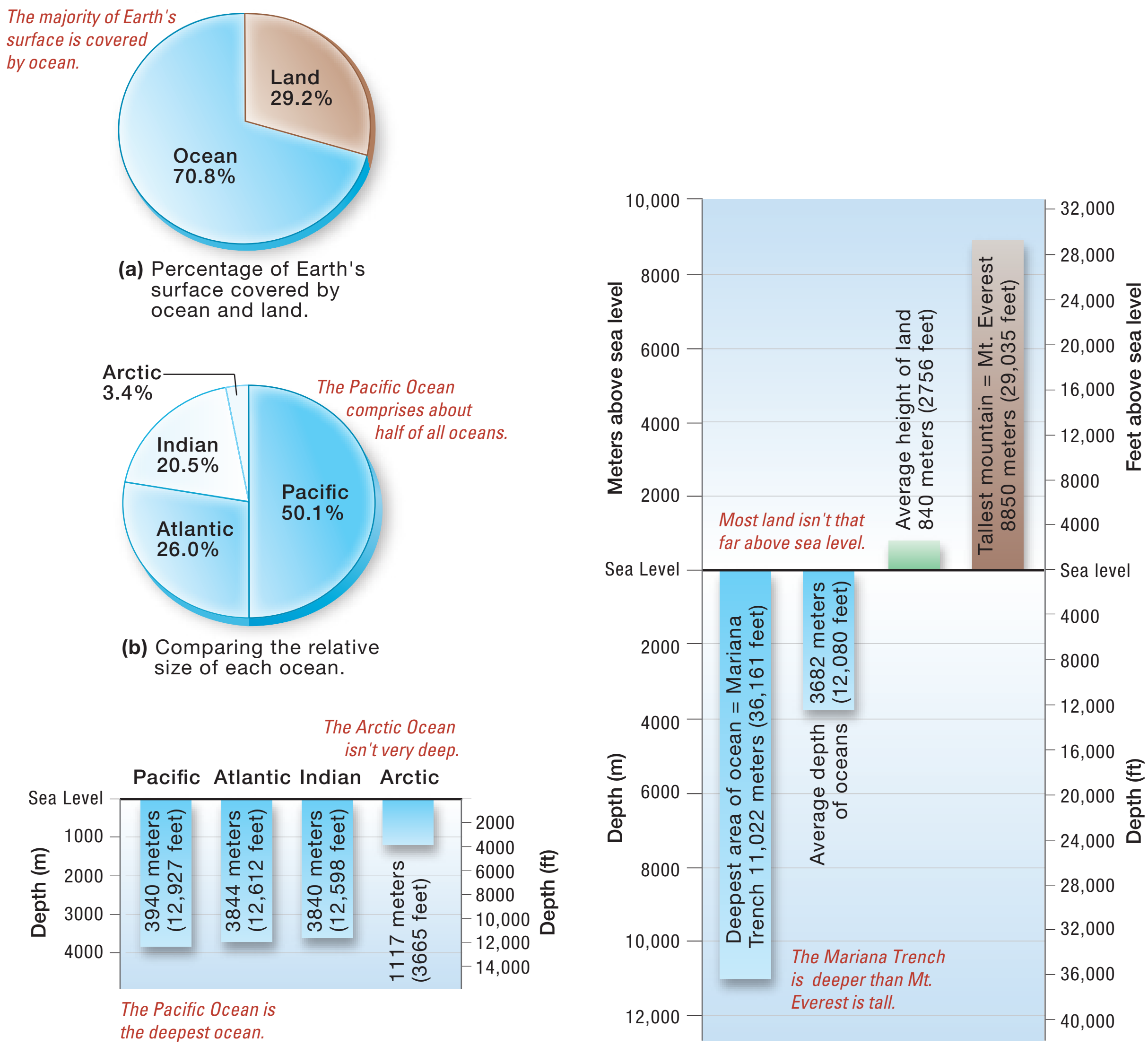


Figure 1.2 Relative sizes of the spheres of water on Earth. This image shows all of Earth's liquid water using three blue spheres of proportional sizes. The big sphere is all liquid water in the world, 97% of which is seawater. The next smallest sphere represents a subset of the larger sphere, showing freshwater in the ground, lakes, swamps, and rivers. The tiny speck below it represents an even smaller subset of all the water—just the freshwater in lakes and rivers.

SmartFigure 1.3 Earth's oceans. Map showing the four principal oceans plus the Southern Ocean, or Antarctic Ocean. https://goo.gl/BJXqyt

Figure 1.4 Ocean size and depth. **(a)** Relative proportions of land and ocean on Earth's surface. **(b)** Relative size of the four principal oceans. **(c)** Average ocean depth. **(d)** Comparing average and maximum depth of the oceans to average and maximum height of land.



(a) Percentage of Earth's surface covered by ocean and land.

(b) Comparing the relative size of each ocean.

(c) Comparing the average depth of each ocean.

(d) Comparing the depth of the oceans to the height of land.

EXPLORING DATA ▶

1. Rank the four main world's oceans from largest to smallest, and also from deepest to shallowest.

2. Using data, support the argument that the Arctic Ocean technically should be classified as a sea. If you are not sure about the difference between an ocean and a sea, please read on . . . .

Animation
Earth's Water and the Hydrologic Cycle
http://goo.gl/kAo8FC

ARCTIC OCEAN The **Arctic Ocean** is about 7% the size of the Pacific Ocean and is only a little more than one-quarter as deep as the rest of the oceans (Figure 1.4c). Although it has a permanent layer of sea ice at the surface, the ice is only a few meters thick. The Arctic Ocean was named after its location in the Arctic region, which exists beneath the northern constellation Ursa Major, otherwise known as the Big Dipper, or the Bear (*arktos* = bear).

SOUTHERN OCEAN, OR ANTARCTIC OCEAN Oceanographers recognize an additional ocean near the continent of Antarctica in the Southern Hemisphere (Figure 1.3). Defined by the meeting of currents near Antarctica called the Antarctic Convergence, the **Southern Ocean**, or **Antarctic Ocean**, is really the portions of the Pacific, Atlantic, and Indian Oceans south of about 50 degrees south latitude. This ocean was named for its location in the Southern Hemisphere.

RECAP **The four principal oceans are the Pacific, Atlantic, Indian, and Arctic Oceans. An additional ocean, the Southern Ocean, or Antarctic Ocean, is also recognized.**

Oceans versus Seas

What is the difference between an ocean and a sea? In common use, the terms *sea* and *ocean* are often used interchangeably. For instance, a *sea* star lives in the *ocean*, the *ocean* is full of *sea* water, *sea* ice forms in the *ocean*, and one might stroll

Figure 1.5 Map of the ancient seven seas. This map represents the extent of the known world to Europeans before the 15th century.

the *sea* shore while living on *ocean*-front property. Technically, however, a *sea* is defined as follows:

- Smaller and shallower than an ocean (this is why the Arctic Ocean might be more appropriately considered a sea)
- Composed of salt water (although some inland "seas," such as the Caspian Sea in Asia, are actually large lakes with relatively high salinity)
- Somewhat enclosed by land (although some seas, such as the Sargasso Sea in the Atlantic Ocean, are defined by strong ocean currents rather than by land)
- Directly connected to the world ocean

COMPARING THE OCEANS TO THE CONTINENTS Figure 1.4d shows that the average depth of the world's oceans is 3682 meters[2] (12,080 feet). This means that there must be some extremely deep areas in the ocean to offset the shallow areas close to shore. Figure 1.4d also shows that the deepest depth in the oceans (the Challenger Deep region of the Mariana Trench, which is near Guam) is a staggering 11,022 meters (36,161 feet) below sea level.

How do the continents compare to the oceans? Figure 1.4d shows that the average height of the continents is only 840 meters (2756 feet), illustrating that the average height of the land is not very far above sea level. The highest mountain in the world (the mountain with the greatest height above sea level) is Mount Everest in the Himalaya Mountains of Asia, at 8850 meters (29,035 feet). Even so, Mount Everest is a full 2172 meters (7126 feet) shorter than the Mariana Trench is deep. The mountain with the *greatest total height* from base to top is Mauna Kea on the island of Hawaii in the United States. It measures 4206 meters (13,800 feet) above

[2]Throughout this book, metric measurements are used and the corresponding English measurements follow in parentheses. See Mastering Oceanography Appendix I, "Metric and English Units Compared," for conversion factors between the two systems of units.

STUDENTS SOMETIMES ASK . . .

Where are the seven seas?

"Sailing the seven seas" is a familiar phrase in literature and song, but the origin of the saying is shaded in antiquity. To the ancients, the term "seven" often meant "many," and before the 15th century, Europeans considered these the main seas of the world (Figure 1.5):

1. The Red Sea
2. The Mediterranean Sea
3. The Persian Gulf
4. The Black Sea
5. The Adriatic Sea
6. The Caspian Sea
7. The Indian Ocean (notice how "ocean" and "sea" are used interchangeably)

Today, however, more than 100 seas, bays, and gulfs are recognized worldwide, nearly all of them smaller portions of the huge interconnected world ocean.

STUDENTS SOMETIMES ASK . . .

Have humans ever explored the deepest ocean trenches? Could anything live there?

Humans have indeed visited the deepest part of the oceans—where there is crushing high pressure, complete darkness, and near-freezing water temperatures—and they first did so over half a century ago! In January 1960, U.S. Navy Lt. Don Walsh and explorer Jacques Piccard descended to the bottom of the Challenger Deep region of the Mariana Trench in the *Trieste*, a deep-diving bathyscaphe (*bathos* = depth, *scaphe* = a small ship) (**Figure 1.6**). At 9906 meters (32,500 feet), the men heard a loud cracking sound that shook the cabin. They were unable to see that a 7.6-centimeter (3-inch) Plexiglas viewing port had cracked (miraculously, it held for the rest of the dive). More than five hours after leaving the surface, they reached the bottom, at 10,912 meters (35,800 feet)—a record depth for human descent. They did observe some small organisms that are adapted to life in the deep: a flatfish, a shrimp, and some jellies.

In 2012, film icon James Cameron made a historic solo dive to the Mariana Trench in his submersible *DEEPSEA CHALLENGER* (**Figure 1.7**). On the seven-hour round-trip voyage, Cameron spent about three hours at the deepest spot on the planet to take photographs and collect samples for scientific research. Other notable voyages to the deep ocean in submersibles are discussed in Mastering Oceanography **Web Diving Deeper 1.3**.

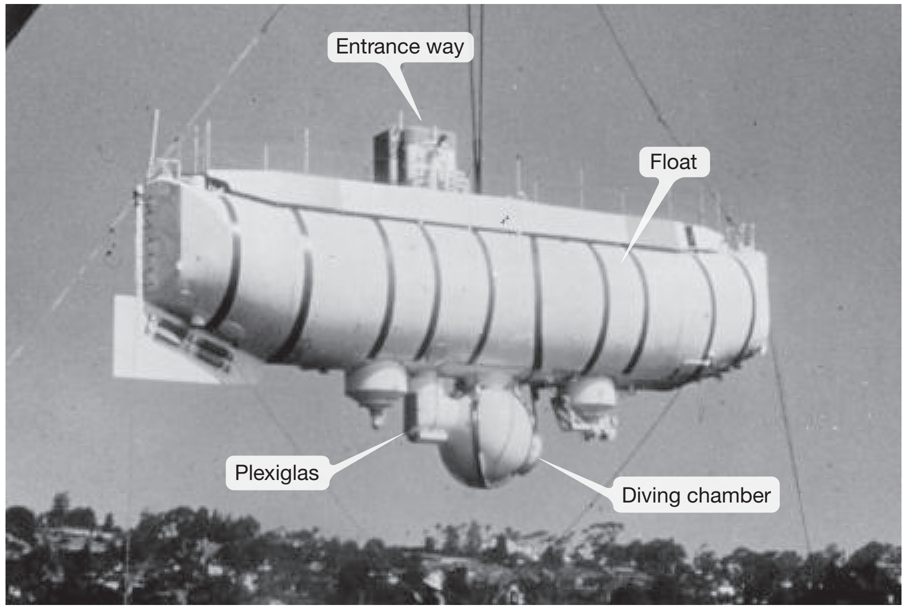


Figure 1.6 The U.S. Navy's bathyscaphe *Trieste*. The *Trieste* suspended on a crane before its record-setting deep dive in 1960. The 1.8-meter (6-foot) diameter diving chamber (the round ball below the float) accommodated two people and had steel walls 7.6 centimeters (3 inches) thick.

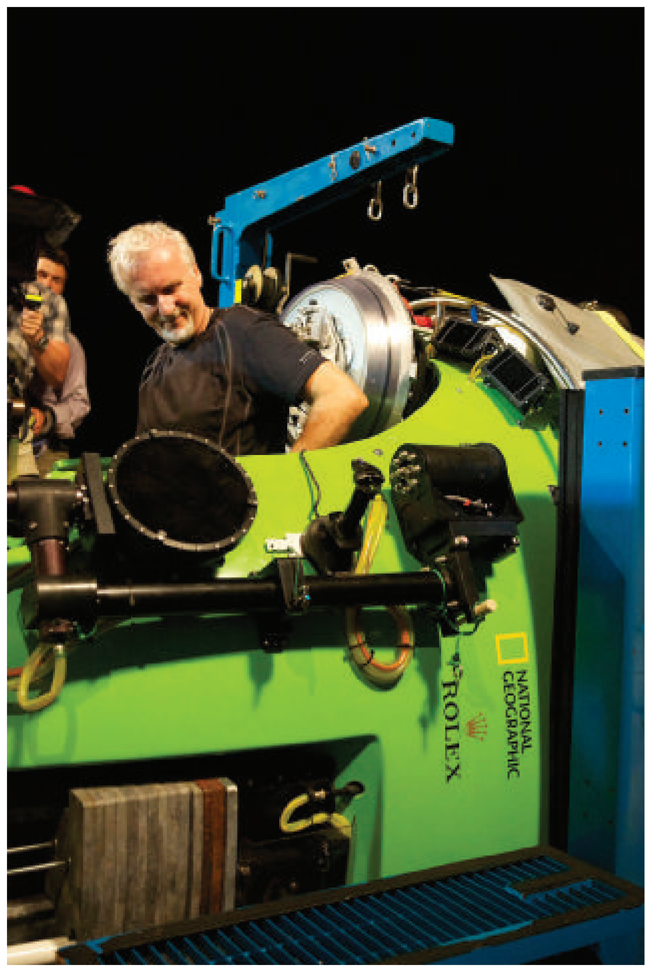


Figure 1.7 James Cameron emerges from the submersible *DEEPSEA CHALLENGER* after his solo dive to the Mariana Trench. In 2012, famous moviemaker James Cameron completed a record-breaking solo dive to the bottom of the Mariana Trench, becoming only the third human to visit the deepest spot on Earth.

CREATURE FEATURE 1.1

I light up the deep sea!

Jellies (often incorrectly called *jellyfish*) are gelatinous marine organisms that live throughout the oceans.

Jellies are primitive, free-drifting marine organisms that use stinging cells to capture food. About half of all jellies are capable of bioluminescence, which is the ability to produce light; jellies thus are bright spots in the vast darkness of the deep sea.

sea level and 5426 meters (17,800 feet) from sea level down to its base, for a total height of 9632 meters (31,601 feet). The total height of Mauna Kea is 782 meters (2566 feet) higher than Mount Everest, but it is still 1390 meters (4560 feet) shorter than the Mariana Trench is deep. Therefore, no mountain on Earth is taller than the Mariana Trench is deep.

RECAP **The deepest part of the ocean is the Mariana Trench in the Pacific Ocean. It is 11,022 meters (36,161 feet) deep and has been visited only twice by humans: once in 1960 and more recently in 2012.**

CONCEPT CHECK 1.1 ▸ Compare the characteristics of Earth's oceans.

1 How did the view of the ocean by early Mediterranean cultures influence the naming of planet Earth?

2 Although the terms *ocean* and *sea* are sometimes used interchangeably, what is the technical difference between an ocean and a sea?

3 Where is the deepest part of the ocean? How deep is it, and how does it compare to the height of the tallest mountain on Earth?

1.2 ▸ How Was Early Exploration of the Oceans Achieved?

As a testimony to the human spirit, early cultures explored the ocean's furthest reaches in spite of the risks caused by crossing vast expanses of open ocean. Over time, humans developed technology that allowed entire civilizations to safely travel across even the largest oceans. For example, today we can cross even the Pacific Ocean in less than a day by airplane. Even so, much of the deep ocean remains out of reach and woefully unexplored. In fact, the surface of the Moon has been mapped more accurately than most parts of the sea floor. Nonetheless, new technologies employed on land and sea, and Earth-observing satellites orbiting at great distances, are being used to gain knowledge about our watery home at an unprecedented rate.

Early History

Humankind probably first viewed the oceans as a source of food. Archeological evidence suggests that when boat technology was developed about 40,000 years ago, people probably traveled the oceans. Most likely, their vessels were built to move upon the ocean's surface and transport oceangoing people to new fishing grounds. The oceans also provided an inexpensive and efficient way to move large and heavy objects, facilitating trade and interaction between cultures.

PACIFIC NAVIGATORS The peopling of the Pacific Islands (Oceania) is somewhat perplexing because there is no anthropological evidence that people actually evolved on these islands—in other words, they had to come from elsewhere. Their presence required travel over hundreds or even thousands of kilometers of open ocean from the continents (probably in small vessels of that time—double canoes, outrigger canoes, or balsa rafts), as well as remarkable navigation skills (see Mastering Oceanography **Web Diving Deeper 1.4**). The islands in the Pacific Ocean are widely scattered, so it is likely that only a fortunate few of the voyagers made landfall and that many others perished during voyages. **Figure 1.8** shows the three major inhabited island regions in the Pacific Ocean: Micronesia

Figure 1.8 **The peopling of the Pacific islands.** The major island groups of the Pacific Ocean are Micronesia (brown shading), Melanesia (*peach shading*), and Polynesia (*green shading*). The "Lapita people" present in New Ireland 5000–4000 B.C.E. can be traced to Fiji, Tonga, and Samoa by 1100 B.C.E. (*yellow arrow*). Green arrows show the peopling of distant islands throughout Polynesia. The 1947 route of Thor Heyerdahl's balsa raft *Kon Tiki* is also shown (*red arrow*).

(*micro* = small, *nesia* = islands); Melanesia (*mela* = black, *nesia* = islands); and Polynesia (*poly* = many, *nesia* = islands), which covers the largest area.

No written records of Pacific human history have been found prior to the arrival of Europeans in the 16th century. Nevertheless, the movement of Asian peoples into Micronesia and Melanesia is easy to imagine, because distances between islands are relatively short. In Polynesia, however, large distances separate island groups, which must have presented great challenges to ocean voyagers. Easter Island, for example, at the southeastern corner of the triangular-shaped Polynesian Islands region, is more than 1600 kilometers (1000 miles) from Pitcairn Island, the next nearest island. Clearly, a voyage to the Hawaiian Islands must have been one of the most difficult because Hawaii is more than 3000 kilometers (2000 miles) from the nearest inhabited islands, the Marquesas Islands (Figure 1.8).

Archeological evidence suggests that humans from New Guinea may have occupied New Ireland as early as 4000 or 5000 B.C.E. However, there is little evidence of human travel farther into the Pacific Ocean before 1100 B.C.E. By then, the *Lapita people,* a group of early settlers who produced a distinctive type of pottery, had traveled on to Fiji, Tonga, and Samoa (Figure 1.8, *yellow arrow*). From there, Polynesians sailed on to the Marquesas (about 30 B.C.E.), which appear to have been the starting point for voyages to other islands in the far reaches of the Pacific (Figure 1.8, *green arrows*), including the Hawaiian Islands (about 300 C.E.) and New Zealand (about 800 C.E.). (Recently, a combination of genetic, linguistic, and archaeological evidence has suggested that the forebears of the Lapita people—and thus Polynesians—originated in Taiwan, just off the coast of China.) Surprisingly, new genetic research suggests that Polynesians populated Easter Island relatively recently, about 1200 C.E.

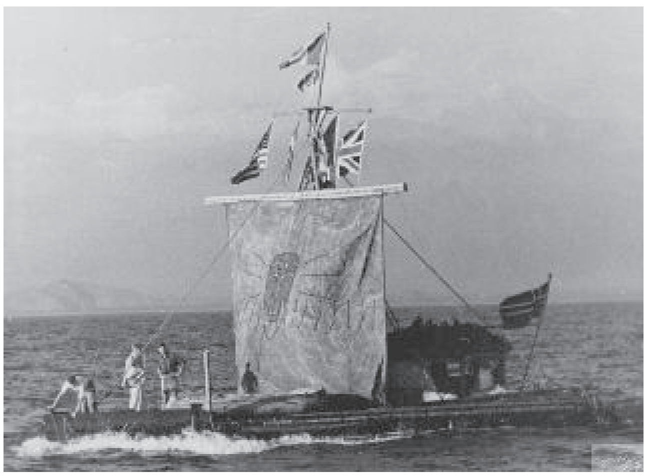


Figure 1.9 The balsa raft *Kon Tiki*. In 1947, Thor Heyerdahl sailed this authentic wooden balsa raft named *Kon Tiki* from South America to Polynesia to show that ancient South American cultures may have completed similar voyages.

Despite the obvious Polynesian backgrounds of the Hawaiians, the Maori of New Zealand, and the Easter Islanders, an adventurous biologist/anthropologist named **Thor Heyerdahl** proposed that voyagers from South America may have reached islands of the South Pacific before the coming of the Polynesians. To prove his point, in 1947 he sailed the ***Kon Tiki***—a balsa raft designed like those that were used by South American navigators at the time of European discovery (Figure 1.9)—from South America to the Tuamotu Islands, a journey of more than 11,300 kilometers (7000 miles) (Figure 1.8, *red arrow*). Although the remarkable voyage of the *Kon Tiki* demonstrates that early South Americans could have traveled to Polynesia just as easily as early Asian cultures, anthropologists can find no evidence of such a migration. Further, comparative DNA studies show a strong genetic relationship between the peoples of Easter Island and Polynesia but none between these groups and natives in coastal North or South America.

EUROPEAN NAVIGATORS The first Mediterranean people known to have developed the art of navigation were the **Phoenicians**, who lived at the eastern end of the Mediterranean Sea, in the present-day area of Egypt, Syria, Lebanon, and Israel. As early as 2000 B.C.E., they investigated the Mediterranean Sea, the Red Sea, and the Indian Ocean. The first recorded circumnavigation of Africa, in 590 B.C.E., was made by the Phoenicians, who also sailed as far north as the British Isles.

The Greek astronomer-geographer **Pytheas** sailed northward in 325 B.C.E. using a simple yet elegant method for determining latitude (one's position north or south) in the Northern Hemisphere. His method involved measuring the angle between an observer's line of sight to the North Star and line of sight to the northern horizon. (Note that Pytheas's method of determining latitude is featured in Appendix III, "Latitude and Longitude on Earth.") Despite Pytheas's method for determining latitude, it was still impossible to accurately determine longitude (one's position east or west).

One of the key repositories of scientific knowledge at the time was the **Library of Alexandria** in Alexandria, Egypt, which was founded in the 3rd century B.C.E. by *Alexander the Great*. It housed an impressive collection of written knowledge that attracted scientists, poets, philosophers, artists, and writers who studied and researched there. The Library of Alexandria soon became the intellectual capital of the world, featuring history's greatest accumulation of ancient writings.

As long ago as 450 B.C.E., Greek scholars became convinced that Earth was round, using lines of evidence such as the way ships disappeared beyond the horizon and the shadows of Earth that appeared during eclipses of the Moon. This inspired the Greek **Eratosthenes** (pronounced "AIR-uh-TOS-thuh-neez") (276–192 B.C.E.), the second librarian at the Library of Alexandria, to cleverly use the shadow of a stick in a hole in the ground and elementary geometry to determine Earth's circumference. His value of 40,000 kilometers (24,840 miles) compares remarkably well with the true value of 40,032 kilometers (24,875 miles) known today.

An Egyptian-Greek geographer named **Claudius Ptolemy** (c. 85 C.E.–c. 165 C.E.) produced a map of the world in about 150 C.E. that represented the extent of Roman knowledge at that time (Figure 1.10). The map not only included the continents of Europe, Asia, and Africa, as did earlier Greek maps, but it also included vertical lines of longitude and horizontal lines of latitude, which had been developed by Alexandrian scholars. Moreover, Ptolemy showed the known seas to be surrounded by land, much of which was as yet unknown and proved to be a great enticement to explorers.

Figure 1.10 Ptolemy's map of the world. In about 150 C.E., an Egyptian-Greek geographer named Claudius Ptolemy produced this map of the world that showed the extent of Roman geographic knowledge. Note the use of a coordinate system on land, similar to latitude and longitude used today.

Ptolemy also introduced an (erroneous) update to Eratosthenes's surprisingly accurate estimate of Earth's circumference. Ptolemy wrongly depended on flawed calculations and an overestimation of the size of Asia, and as a result, he determined Earth's circumference to be 29,000 kilometers (18,000 miles), which is about 28% too small. Nearly 1500 years later, Ptolemy's error caused explorer Christopher Columbus to believe he had encountered parts of Asia rather than a new world.

The Middle Ages

After the destruction of the Library of Alexandria in 415 C.E. (in which all of its contents were burned) and the fall of the Roman Empire in 476 C.E., the achievements of the Phoenicians, Greeks, and Romans were mostly lost. Some of the knowledge, however, was retained by the *Arabs,* who controlled northern Africa and Spain. The Arabs used this knowledge to become the dominant navigators in the Mediterranean Sea area and to trade extensively with East Africa, India, and Southeast Asia. The Arabs were able to trade across the Indian Ocean because they had learned how to take advantage of the seasonal patterns of monsoon winds. During the summer, when monsoon winds blow from the southwest, ships laden with goods would leave the Arabian ports and sail eastward across the Indian Ocean. During the winter, when the trade winds blow from the northeast, ships would return west. (More details about Indian Ocean monsoons can be found in Chapter 7, "Ocean Circulation.")

Meanwhile, in the rest of southern and eastern Europe, Christianity was on the rise. Scientific inquiry counter to religious teachings was actively suppressed, and the knowledge gained by previous civilizations was either lost or ignored. As a result, the Western concept of world geography degenerated considerably during these so-called *Dark Ages*. For example, one notion envisioned the world as a disk with Jerusalem at the center.

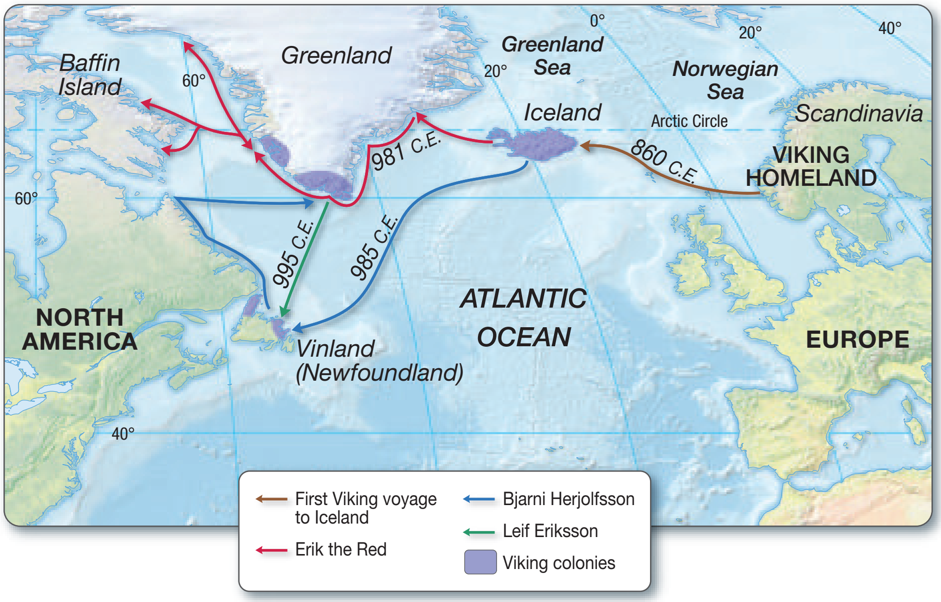


Figure 1.11 Viking colonies in the North Atlantic. Map showing the routes and dates of Viking explorations and the locations of the colonies that were established in Iceland, Greenland, and parts of North America.

In northern Europe, the **Vikings** of Scandinavia, who had excellent ships and good navigation skills, actively explored the Atlantic Ocean (Figure 1.11). Late in the 10th century, aided by a period of worldwide climatic warming, the Vikings colonized Iceland. In about 981 C.E., **Erik "the Red" Thorvaldson** sailed westward from Iceland and discovered Greenland. He may also have traveled further westward to Baffin Island. He returned to Iceland and led the first wave of Viking colonists to Greenland in 985 C.E. **Bjarni Herjólfsson** sailed from Iceland to join the colonists, but he sailed too far southwest and is thought to be the first Viking to have seen what is now called Newfoundland. Bjarni did not land but instead returned to the new colony at Greenland. **Leif Eriksson**, son of Erik the Red, became intrigued by Bjarni's stories about the new land Bjarni had seen. In 995 C.E., Leif bought Bjarni's ship and set out from Greenland for the land that Bjarni had seen to the southwest. Leif spent the winter in that portion of North America and named the land *Vinland* (now Newfoundland, Canada) after the grapes that were found there. Climatic cooling and inappropriate farming practices for the region caused these Viking colonies in Greenland and Vinland to struggle and die out by about 1450.

The Age of Discovery in Europe

The 30-year period from 1492 to 1522 is known as Europe's **Age of Discovery**. During this time, Europeans explored the continents of North and South America, and the globe was circumnavigated for the first time. As a result, Europeans learned the true extent of the world's oceans and that human populations existed elsewhere on newly "discovered" continents and islands with cultures vastly different from those familiar to European voyagers.

Why was there such an increase in ocean exploration during Europe's Age of Discovery? One reason was that Sultan Mohammed II had captured Constantinople (the capital of eastern Christendom) in 1453, a conquest that isolated Mediterranean port cities from the riches of India, Asia, and the East Indies (modern-day Indonesia). As a result, the Western world had to search for new eastern trade routes by sea.

The Portuguese, under the leadership of **Prince Henry the Navigator** (1392–1460), led a renewed effort to explore outside Europe. The prince established a marine institution at Sagres to improve Portuguese sailing skills. The treacherous journey around the tip of Africa was a great obstacle to an alternative trade route. Cape Agulhas (at the southern tip of Africa) was first rounded by **Bartholomeu Diaz** in 1486. He was followed in 1498 by **Vasco da Gama**, who continued around the tip of Africa to India, thus establishing a new eastern trade route to Asia.

Meanwhile, the Italian navigator and explorer **Christopher Columbus** was financed by Spanish monarchs to find a new route to the East Indies across the Atlantic Ocean. During Columbus's first voyage in 1492, he sailed west from Spain and made landfall after a two-month journey (Figure 1.12). Columbus believed that he had arrived in the East Indies somewhere near India, but Earth's circumference had been substantially underestimated, so he was unaware that he had actually arrived in uncharted territory in the Caribbean. Upon his return to Spain and the announcement of his discovery, additional voyages were planned. During the next 10 years, Columbus made three more trips across the Atlantic.

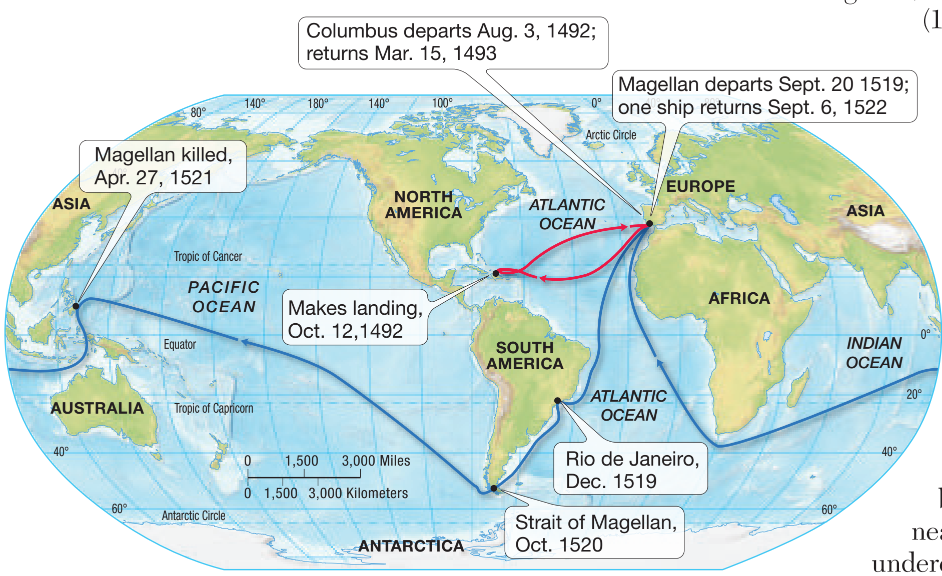


Figure 1.12 Voyages of Columbus and Magellan. Map showing the dates and routes of Columbus's first voyage and the first circumnavigation of the globe by Magellan's party.

Even though Christopher Columbus is widely credited with discovering North America, he never actually set foot on the continent. (For more information about the voyages of Columbus, see Diving Deeper 6.1 in Chapter 6, "Air–Sea Interaction.") Still, his journeys inspired other navigators to explore the "New World." For example, in 1497, only five years after Columbus's first voyage, the Italian navigator and explorer **Giovanni Caboto**, who was also known as **John Cabot**, landed somewhere on the northeastern coast of North America. Later, Europeans first saw the Pacific Ocean in 1513, when **Vasco Núñez de Balboa** attempted a land crossing of the Isthmus of Panama and sighted a large ocean to the west from atop a mountain.

The culmination of the Age of Discovery was a remarkable circumnavigation of the globe initiated by **Ferdinand Magellan** (Figure 1.12). Magellan left Spain in September 1519, with five ships and 280 sailors. He crossed the Atlantic Ocean, sailed down the eastern coast of South America, and traveled through a passage to the Pacific Ocean at 52 degrees south latitude, now named the Strait of Magellan in his honor. About a month after landing in the Philippines in March 1521, Magellan was killed in a fight with the inhabitants of these islands. **Juan Sebastian del Caño** completed the circumnavigation by taking the last of the ships, the *Victoria*, across the Indian Ocean, around Africa, and back to Spain in 1522. After three years, just one ship and 18 men completed the voyage.

Following these expeditions, the Spanish initiated many other voyages to take gold from the Aztec and Inca cultures in Mexico and South America. The English and Dutch, meanwhile, used smaller, more maneuverable ships to rob the gold from bulky Spanish galleons, which resulted in many confrontations at sea. The maritime dominance of Spain ended when the English defeated the Spanish Armada in 1588. With control of the seas, the English thus became the dominant world power—a status they retained until early in the 20th century.

The Beginning of Voyaging for Science

The English realized that increasing their scientific knowledge of the oceans would help maintain their maritime superiority. For this reason, Captain **James Cook** (1728–1779), an English navigator and prolific explorer (**Figure 1.13**), undertook three voyages of scientific discovery with the ships *Endeavour*, *Resolution*, and *Adventure* between 1768 and 1779. He searched for the continent Terra Australis ("Southern Land," or Antarctica) and concluded that it lay beneath or beyond the extensive ice fields of the southern oceans if it existed at all. Cook also mapped many islands previously unknown to Europeans, including the South Georgia, South Sandwich, and Hawaiian Islands. During his last voyage, Cook searched for the fabled "Northwest Passage" from the Pacific Ocean to the Atlantic Ocean and stopped in Hawaii, where he was killed in a skirmish with native Hawaiians.

Cook's expeditions added greatly to the scientific knowledge of the oceans. He determined the outline of the Pacific Ocean and was the first person known to cross the Antarctic Circle in his search for Antarctica. Cook initiated systematic sampling of subsurface water temperatures, measuring winds and currents, taking *soundings* (which are depth measurements that, at the time, were taken by lowering a long rope with a weight on the end to the sea floor), and collecting data on coral reefs. Cook also discovered that a shipboard diet containing the German staple sauerkraut prevented his crew from contracting scurvy, a disease that incapacitated sailors. Scurvy is caused by a vitamin C deficiency, and the cabbage used to make sauerkraut contains large quantities of vitamin C. Prior to Cook's discovery about preventing scurvy, the malady claimed more lives than all other types of deaths at sea, including contagious disease,

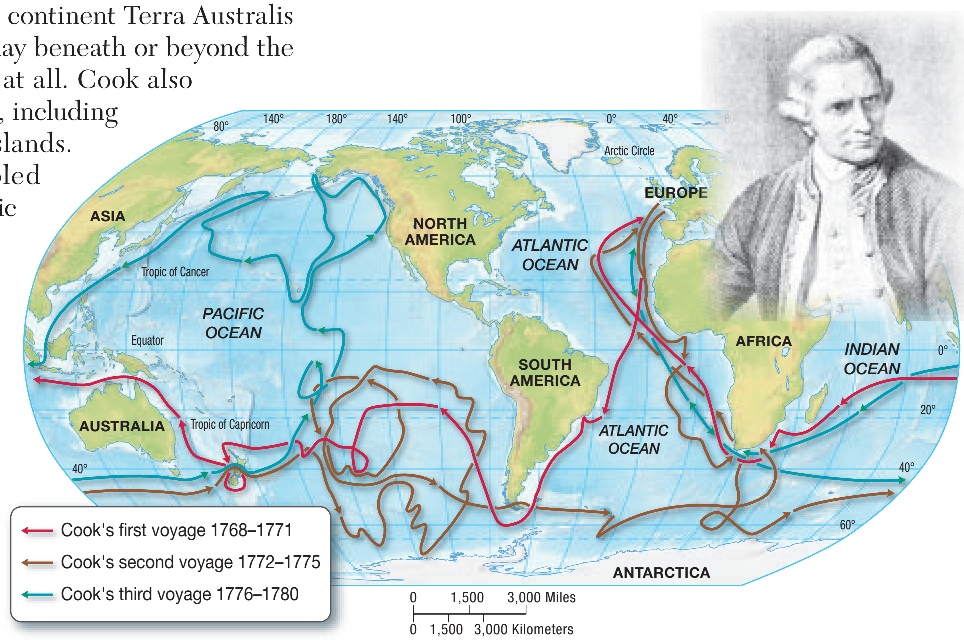


Figure 1.13 Captain James Cook (1728–1779) and his voyages of exploration. Routes taken by Captain James Cook (*inset*) on his three scientific voyages, which initiated scientific exploration of the oceans. Cook was killed in 1779 in Hawaii during his third voyage.

gunfire, and shipwreck. In addition, Cook made possible the first accurate maps of Earth's surface by proving the value of a new—and controversial— scientific device for determining longitude, which was a precision timepiece invented by English cabinetmaker John Harrison (see Mastering Oceanography **Web Diving Deeper 1.4**).

History of Oceanography . . . To Be Continued

Much has changed since the early days of studying the oceans, when scientists used buckets, nets, and lines deployed from ships. And yet, some things remain the same. For example, going to sea aboard ships continues to be a mainstay of ocean science. Also, even though efforts to monitor the ocean are getting bigger and more sophisticated, vast swaths of the marine world remain unknown.

Today, oceanographers employ many high-technology tools, such as state-of-the-art research vessels that routinely use sonar to map the sea floor, remotely operated data collection devices, drifting buoys, robotics, sea floor observation networks, sophisticated computer models, and Earth-orbiting satellites. Many of these tools are featured throughout this book. Further, additional events in the history of oceanography can be found as Diving Deeper features in subsequent chapters. These boxed features are identified by the "Historical Feature" theme, and each introduces an important historical event that is related to the subject of that particular chapter.

RECAP **The ocean's large size did not prohibit early explorers from venturing into all parts of the ocean for discovery, trade, or conquest. Voyaging for science began relatively recently, and many parts of the ocean remain unknown.**

CONCEPT CHECK 1.2 ▸ Discuss how early exploration of the oceans was achieved.

1 While the Arabs dominated the Mediterranean region during the Middle Ages, what were the most significant ocean-related events taking place in northern Europe?

2 Describe the important events in oceanography that occurred during the Age of Discovery in Europe.

3 List some of the major achievements of Captain James Cook.

STUDENTS SOMETIMES ASK . . .

What is NOAA? What is its role in oceanographic research?

NOAA (pronounced "NO-ah") stands for National Oceanic and Atmospheric Administration and is the branch of the U.S. Department of Commerce that oversees oceanographic research. Scientists at NOAA work to ensure wise use of ocean resources through the National Ocean Service, the National Oceanographic Data Center, the National Marine Fisheries Service, and the National Sea Grant Office. Other U.S. government agencies that work with oceanographic data include the U.S. Naval Oceanographic Office, the Office of Naval Research, the U.S. Coast Guard, and the U.S. Geological Survey (coastal processes and marine geology). The NOAA Website is at **www.noaa.gov**. In 2013, federal officials developed the National Ocean Policy Implementation Plan, which proposes moving NOAA to the Department of the Interior so that agencies dealing with natural resources would all be grouped within the same department.

1.3 ▸ What Fields of Science Does Oceanography Include?

Oceanography (*ocean* = the marine environment, *graphy* = description of) is literally the description of the marine environment. Although the term was first coined in the 1870s, at the beginning of scientific exploration of the oceans, this definition does not fully portray the extent of what oceanography encompasses: Oceanography does much more than just *describe* marine phenomena. Oceanography could be more accurately called the scientific study of all aspects of the marine environment. Hence, the field of study called oceanography could (and maybe *should*) be called oceanology (*ocean* = the marine environment, *ology* = the study of). However, the science of studying the oceans has traditionally been called *oceanography*. It is also called *marine science* and includes the study of the water of the ocean, the life within it, and the (not so) solid Earth beneath it.

Since prehistoric time, people have used the oceans as a means of transportation and as a source of food. Ocean processes, on the other hand, have been studied using technology only since the 1930s, beginning with the search for offshore petroleum and then expanding greatly during World War II with seafaring nations' interest in ocean warfare. The recognition of the importance of marine problems by governments, their readiness to make money available for research, the growth in the number of ocean scientists at work, and the increasing sophistication of scientific equipment have all made it feasible to study the ocean on a scale and to a degree of complexity never before attempted nor even possible.

Consider, for example, the logical assumption that those who make their living fishing in the ocean will go where the physical processes of the oceans offer good fishing (for more details about this topic, see Chapter 13, "Biological Productivity and Energy Transfer"). How ocean geology, chemistry, and physics work together with biology to create good fishing grounds has been more or less a mystery until only recently, when scientists from those disciplines began to investigate the oceans with new technology. One insight from these studies was the realization of how much of an impact humans are beginning to have on the ocean. As a result, much recent research has been concerned with documenting human impacts on the ocean.

Oceanography is traditionally divided into different academic disciplines (or subfields) of study. The four main disciplines of oceanography that are covered in this book are as follows:

- *Geological oceanography*, which is the study of the structure of the sea floor and how the sea floor has changed through time; the creation of sea floor features; and the history of sediments deposited on it
- *Chemical oceanography*, which is the study of the chemical composition and properties of seawater, how to extract certain chemicals from seawater, and the effects of pollutants
- *Physical oceanography*, which is the study of waves, tides, and currents; the ocean–atmosphere relationship that influences weather and climate; and the transmission of light and sound in the oceans
- *Biological oceanography*, which is the study of the various oceanic life-forms and their relationships to one another, their adaptations to the marine environment, and developing sustainable methods of harvesting seafood

Other disciplines include ocean engineering, marine archaeology, and marine policy. Because the study of oceanography often examines in detail all the different disciplines of oceanography, it is frequently described as being an **interdisciplinary science**, or one covering all the disciplines of science as they apply to the oceans (Figure 1.14). In essence, this is a book about *all* aspects of the oceans.

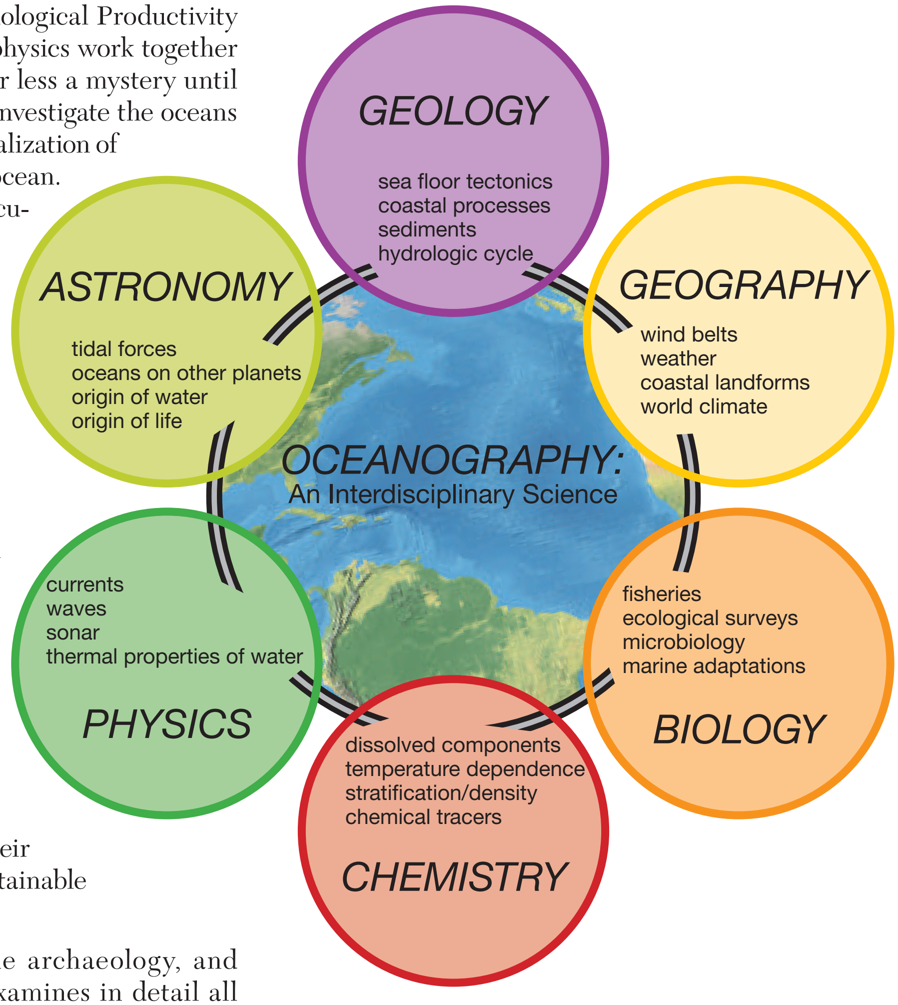


Figure 1.14 A Venn diagram showing the interdisciplinary nature of oceanography. Oceanography is an interdisciplinary science that overlaps into many scientific disciplines.

CONCEPT CHECK 1.3 ▸ Explain why oceanography is considered an interdisciplinary science.

1 What was the impetus for studying ocean processes that led to the great expansion of the science of oceanography?

2 What are the four main disciplines or subfields of study in oceanography? What other marine-related disciplines exist?

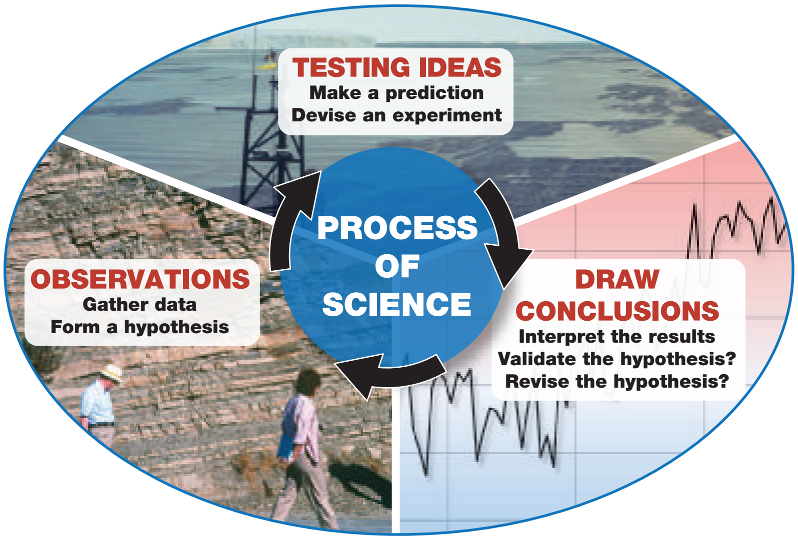
3 What does it mean when oceanography is called an interdisciplinary science?

RECAP A broad range of interdisciplinary science topics from the diverse fields of geology, chemistry, physics, and biology are included in the study of oceanography.

1.4 ▸ What Is the Process of Science and the Nature of Scientific Inquiry?

In modern society, scientific studies are increasingly used to substantiate the need for political, community, or personal action. However, there is often little understanding of how science operates. For instance, how certain are we about a particular scientific theory? How are facts different from theories?

The overall goal of science is to discover underlying patterns in the natural world and then to use this knowledge to make predictions about what should or should not be expected to happen given a certain set of circumstances. Scientists develop explanations about the causes and effects of various natural



SmartFigure 1.15 **The process of science.** As shown in this figure, the process of science is iterative. After analyzing the results of an experiment, a scientist will often revise a hypothesis, decide more observations are necessary, talk to colleagues, and test alternative explanations. A hallmark of a good study is not that it provides a pat answer to a problem but that it opens the door to new questions and a deeper understanding of the natural world.
https://goo.gl/cNH567

phenomena (such as why Earth has seasons or what the structure of matter is). This work is based on an assumption that all natural phenomena are controlled by understandable physical processes, and that the same physical processes operating today have been operating throughout time. Consequently, science has demonstrated remarkable power in allowing scientists to describe the natural world accurately, to identify the underlying causes of natural phenomena, and to better predict future events that rely on natural processes.

Science supports the explanation of the natural world that best explains all available observations. The investigation of natural phenomena using scientific principles is formalized into what is called the **process of science**, which is the way scientists ask questions, collect and evaluate evidence, and draw conclusions. As Figure 1.15 shows, *testing ideas* is central to the process of science: only with evidence that meets the high standards of scientific scrutiny can you separate science from pseudoscience, fact from fiction.

Observations

Although the process of science is actually cyclic or *iterative* (meaning that, based on the results of one test you go back to the start and run another test) you could say that the process of science begins with **observations**. Observations are events or phenomena we can detect with our senses. They are things we can manipulate, measure, see, touch, hear, taste, or smell, often by experimenting with them directly or by using sophisticated tools (such as a microscope or telescope) to sense them. Observations can occur in the controlled environment of a scientific experiment, or they can happen by chance, such as when a diver on vacation notices an unusual die-off of coral on a reef. When observations are repeated and documented, they become *data*—information about our natural world that then leads scientists to form hypotheses.

Hypotheses

As observations are being made, the human mind attempts to sort out the observations in a way that reveals some underlying order or pattern in the observations or phenomena. This sorting process—which involves a lot of trial and error—seems to be driven by a fundamental human urge to make sense of our world. This is how **hypotheses** (*hypo* = under, *thesis* = an arranging) are made. A hypothesis is more than an informed or educated guess. A hypothesis is a tentative, testable statement about the general nature of the phenomena being observed. In other words, a hypothesis is an initial idea of how or why things happen in nature. For example, there were several hypotheses about why whales *breach* (that is, why whales sometimes leap entirely out of water) until a group of scientists made headway by systematically studying it (see Process of Science 1.1).

Scientists often use the *multiple working hypotheses* to guide them as they collect data. Only through testing of hypotheses and collection of data does a single hypothesis begin to make sense. That's why testing is an iterative process. Further, a defining property of a hypothesis is its ability to make *predictions*. For example, when testing a hypothesis, a scientist might note that if a certain hypothesis is true, then another thing should be happening. Note that if a hypothesis cannot be tested, it is not scientifically useful, no matter how interesting it might seem.

Testing

Hypotheses are used to understand certain occurrences that lead to further research and the refinement of those hypotheses. For instance, if we are trying to

PROCESS OF SCIENCE 1.1: Why Do Whales Leap?

BACKGROUND

Most species of whales have been observed at times to leap out of the water, a spectacular display called "breaching" (Figure 1D). But why do whales breach? It has long been known that whales communicate with each other over long distances using underwater vocalizations, such as clicks, whistles, and even elaborate songs. Whales have also been observed to use pectoral (side) fin and tail (fluke) slaps on the water surface, presumably to communicate with other whales nearby.

FORMING A HYPOTHESIS

Scientists suspected that breaching was an additional form of surface communication, but how breaching fit in with whales' other ways to communicate has been a mystery until recently. Indeed, many have wondered why such large, bulky creatures would expend so much energy to leap out of the water at all.

DEVISING AN EXPERIMENT

If breaching is a form of whale communication, then whales should breach in predictable situations and with a defined purpose. In 2010 and 2011, a scientific team examined this idea by observing 94 different groups of humpback whales (*Megaptera novaeangliae*) migrating along the coast of Australia. The migratory route is close to land, so scientists were able to view the whales from shore to ensure that the team did not disturb the normal behavior of the whales. The scientists meticulously observed and recorded the whales' behavior and listened to their sounds using underwater microphones. After several weeks of monitoring the social and environmental contexts of how whales interacted within their group—and with other groups in the vicinity—the scientists began to notice some patterns.

Figure 1D A breaching humpback whale (*Megaptera novaeangliae*).

INTERPRETING THE RESULTS

The study showed that distance between groups was the main variable in predicting breaching behavior. The researchers found that groups of whales traveling close to each other engaged in fin- and fluke-slaps more often than breaching. As the groups moved farther away from each other or split, or if ocean conditions were louder, they tended to breach more often. This makes sense if breaching is a form of communication—the noise from a whale's body striking the water during a breach creates a percussion sound that, like a loud hammer, can be heard over longer distances or louder conditions than the quieter fin-and fluke-slaps. The scientists in this study concluded that breaching is indeed related to whale communication, with whale groups using breaching to communicate when they are farther apart.

THINKING LIKE A SCIENTIST: WHAT'S NEXT?

Other than communication, several alternative explanations for whale breaching have included dislodging of external parasites, mating rituals, territorial displays, or even just for play. Can you think of others? Choose one of these possible explanations and design an experiment to test your hypothesis for whale breaching.

understand why some large sharks attack people, one hypothesis could be that people floating at the surface are mistaken for their food source—which is normally seals and sea lions. Another hypothesis is that sharks are territorial and so they are defending their space. A careful study would have to examine the types and occurrences of shark attacks on people to compile data, which would either support one or the other of the hypotheses, or cause them to be reconsidered and modified. If observations clearly suggest that a hypothesis is incorrect (that is, the hypothesis is *falsified*), then it must be dropped, and other alternative explanations of the facts must be considered. Only after much testing and experimentation—usually done by many experimenters using a wide variety of repeatable tests—does a hypothesis gain validity.

STUDENTS SOMETIMES ASK . . .

How can I accept a scientific idea if it's just a theory?

When most people use the word "theory" in everyday life, it usually means an idea or a guess (such as the all-too-common "conspiracy theory"), but the word has a much different meaning in science. In science, a theory is not a guess or a hunch. It's a well-substantiated, well-supported, well-documented explanation for observations about the natural world. It's a powerful tool that ties together all the facts about something, providing an explanation that fits all the observations and is used to make predictions (for example, what will happen given a certain set of circumstances). In science, a theory is a well-established explanation of how the natural world works. For a scientific theory to exist, scientists have to be *very* sure about it. So, don't discount a scientific idea because it's "just a theory." As famed astrophysicist Neil deGrasse Tyson has stated about the validity of science, *"The good thing about science is that it's true whether or not you believe in it."*

STUDENTS SOMETIMES ASK . . .

If a theory is proven again and again, does it become a law?

No, but that's a common misconception. In science, we collect facts, or observations, we use natural laws to describe them (often using mathematics), and we use a theory to explain them. Natural laws are typically conclusions based on repeated scientific experiments and observations over many years and which have become accepted universally within the scientific community. For example, the *law of gravity* is a description of the force; then there is the *theory of gravitational attraction,* which explains why the force occurs. Theories don't get "promoted" to a law by an abundance of proof, and so a theory never becomes a law. They're really two separate things.

RECAP Science supports the explanation of the natural world that best explains all available observations. Because new observations can modify existing theories, scientific ideas are constantly being refined and updated.

Theory

A **theory** (*theoria* = a looking at) is different from a hypothesis in that it provides a much broader explanation of some aspect of the natural world that incorporates facts, scientific laws (which are quantifiable generalizations about the physical universe, such as Newton's law of gravity), and logical inferences, as well as tested hypotheses. A theory is not a guess or a hunch. Rather, it is a well-substantiated understanding of the natural world that develops from extensive observation, experimentation, and creative reflection. Successful theories do not include numerous special cases or exceptions. Examples of prominent, well-accepted theories that are held with a very high degree of confidence include biology's theory of evolution (which is discussed later in this chapter) and geology's theory of plate tectonics (which is covered in the next chapter).

In science, theories are formalized only after many years of testing and verification. Thus, scientific theories have been rigorously scrutinized to the point where most scientists agree that they are the best explanation of certain observable facts. Nonetheless, scientists recognize that a theory is never really "proven." The search for new observations and new questions—as well as the development of new technology ensures the continuation of the cycle that is the process of science.

Theories and the Truth

We've seen how the process of science is used to develop theories, but does science ever arrive at the undisputed "truth"? Science never reaches an absolute truth because we can never be certain that we have all the observations, especially considering that new technology will be available in the future to examine phenomena in different ways. Notice that there is no end point to the process depicted here. New observations are always possible, so the nature of scientific truth is subject to change. Therefore, it is more accurate to say that science arrives at a conclusion that is *most likely* true, based on the available observations.

It is not a downfall or weakness of science that scientific ideas are modified as more observations are collected. In fact, the opposite is true. Science is a process that depends on reexamining ideas as new observations are made. Thus, science progresses when new observations yield new hypotheses and modification of theories. As a result, science is littered with hypotheses that have been abandoned in favor of later explanations that fit new observations. One of the best known is the idea that Earth was at the center of the universe, a proposal that was supported by the apparent daily motion of the Sun, Moon, and stars around Earth. At the time, this was a very reasonable idea—an obvious "truth"— to anyone who looked up at the sky.

The statements of science should never be accepted as the "final truth." Over time, however, they generally form a sequence of increasingly more accurate statements. Theories are the endpoints in science and do not turn into facts through accumulation of evidence. Nevertheless, the data can become so convincing that the accuracy of a theory is no longer questioned. For instance, the *heliocentric* (*helios* = sun, *centric* = center) *theory* of our solar system states that Earth revolves around the Sun rather than vice versa. Such concepts are supported by such abundant observational and experimental evidence that they are no longer questioned in science and are considered to be scientific facts.

Is the process of science as formal as Figure 1.15 suggests? Actually, the work of scientists is much less formal and is not always done in a clearly logical and systematic manner. In reality, the process of science is a rich and complex process that is not always so methodical. (For a more detailed look at how the process of science works, see https://undsci.berkeley.edu/article/howscienceworks_01.) Like detectives analyzing a crime scene, scientists use ingenuity and serendipity, visualization of models, synthesizing ideas, and sometimes even follow hunches in order to unravel the mysteries of nature.

A final word about theories and scientific truth must take into account the essential role of peer review in verifying scientific ideas. Once scientists make a discovery, their goal is to get word of their results out to the scientific community. This is typically done via a published paper, but a draft of the manuscript is first checked by other experts to see if the work has been conducted according to proper scientific protocols and if the conclusions are valid. Normally, changes or corrections are suggested, and the paper is revised before it is published. This process helps weed out inaccurate or poorly formed ideas. Peer review is the final test of a scientific idea: if the evidence and conclusions of a study meet the strict standards of the scientific community, then it is ready to be shared.

CONCEPT CHECK 1.4 ▶ Describe the process of science and the nature of scientific inquiry.

1 Describe the steps involved in the process of science, starting with an observation about the natural world.

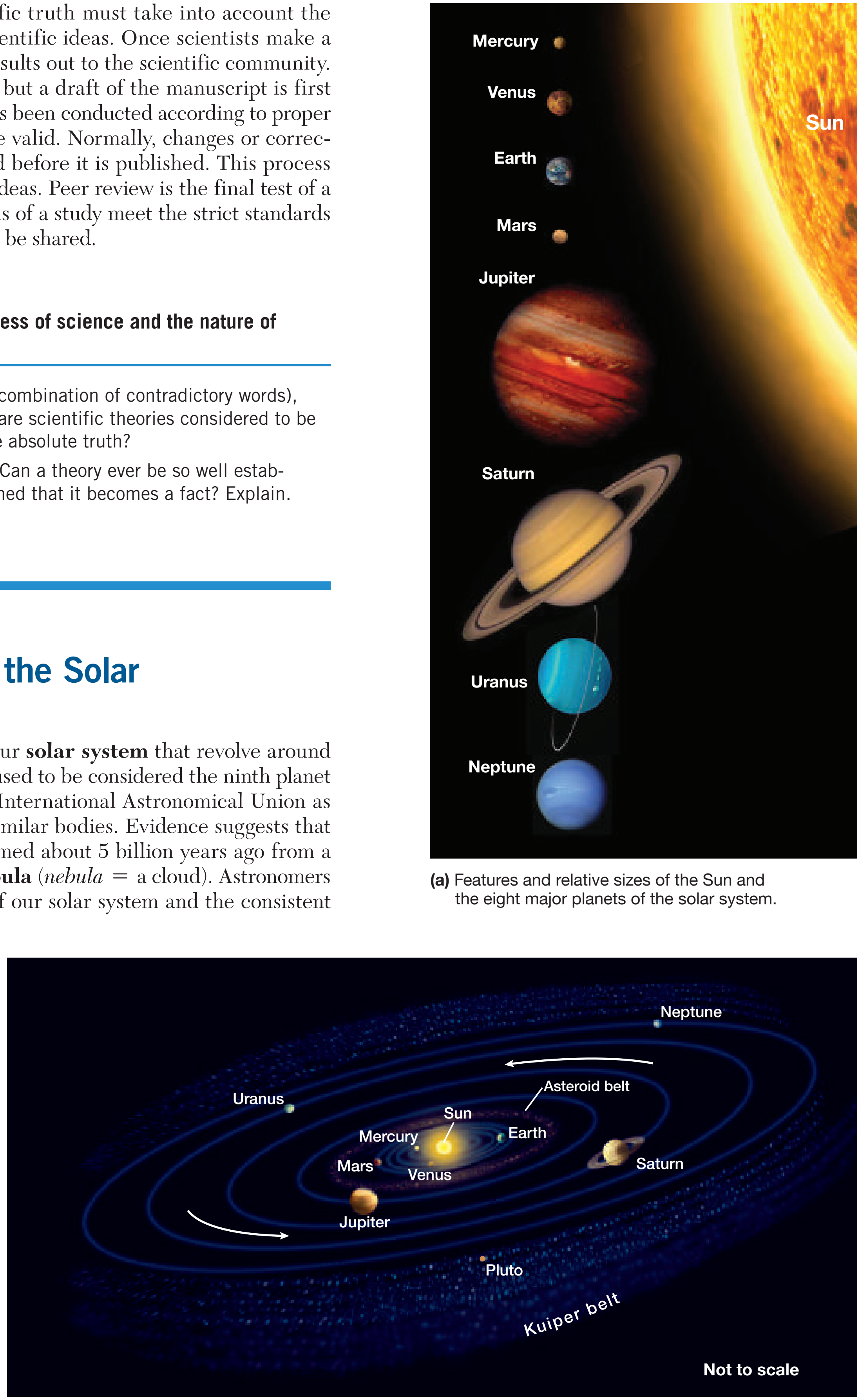
2 What is the difference between a hypothesis and a theory?

3 Briefly comment on the phrase "scientific certainty." Is it an oxymoron (a combination of contradictory words), or are scientific theories considered to be the absolute truth?

4 Can a theory ever be so well established that it becomes a fact? Explain.

1.5 ▶ How Were Earth and the Solar System Formed?

Earth is the third of eight major planets in our **solar system** that revolve around the Sun (**Figure 1.16**). Note that Pluto, which used to be considered the ninth planet in our solar system, was reclassified by the International Astronomical Union as a "dwarf planet" in 2006, along with other similar bodies. Evidence suggests that the Sun and the rest of the solar system formed about 5 billion years ago from a huge cloud of gas and space dust called a **nebula** (*nebula* = a cloud). Astronomers base this hypothesis on the orderly nature of our solar system and the consistent age of meteorites (pieces of the early solar system). Using sophisticated telescopes, astronomers have also been able to observe distant nebula and planetary systems in various stages of formation elsewhere in our galaxy (**Figure 1.17**). In addition, nearly 4000 planets have been discovered outside our solar system—including several that are about the size of Earth—by detecting the telltale wobble of distant stars or slight changes in the emitted light of remote stars, such as the decrease in brightness as planets pass in front of them.



(a) Features and relative sizes of the Sun and the eight major planets of the solar system.

(b) Orbits and relative positions of various features of the solar system.

Figure 1.16 The solar system. Schematic views of the solar system, which includes the Sun and eight major planets.

Figure 1.17 The Ghost Head Nebula. NASA's Hubble Space Telescope image of the Ghost Head Nebula (NGC 2080), which is a site of active star formation.

The Nebular Hypothesis

According to the **nebular hypothesis** (Figure 1.18), all bodies in the solar system formed from an enormous cloud composed mostly of hydrogen and helium, with only a small percentage of heavy elements. As this huge accumulation of gas and dust revolved around its center, it began to contract under its own gravity, becoming hotter and denser, eventually forming the Sun.

As the nebular matter that formed the Sun contracted, small amounts of it were left behind in swirling eddies, which are similar to small whirlpools in a stream. The material in these eddies was the beginning of the **protoplanets** (*proto* = original, *planetes* = wanderers) and their orbiting satellites, which later consolidated into the present planets and their moons.

Proto-Earth

Proto-Earth looked very different from Earth today. Its size was larger than today's Earth, and there were neither oceans nor any life on the planet. In addition, the structure of the deep proto-Earth is thought to have been *homogenous* (*homo* = alike, *genous* = producing), which means that it had a uniform composition throughout. The structure of proto-Earth changed, however, as its heavier constituents sank toward the center to form a heavy core.

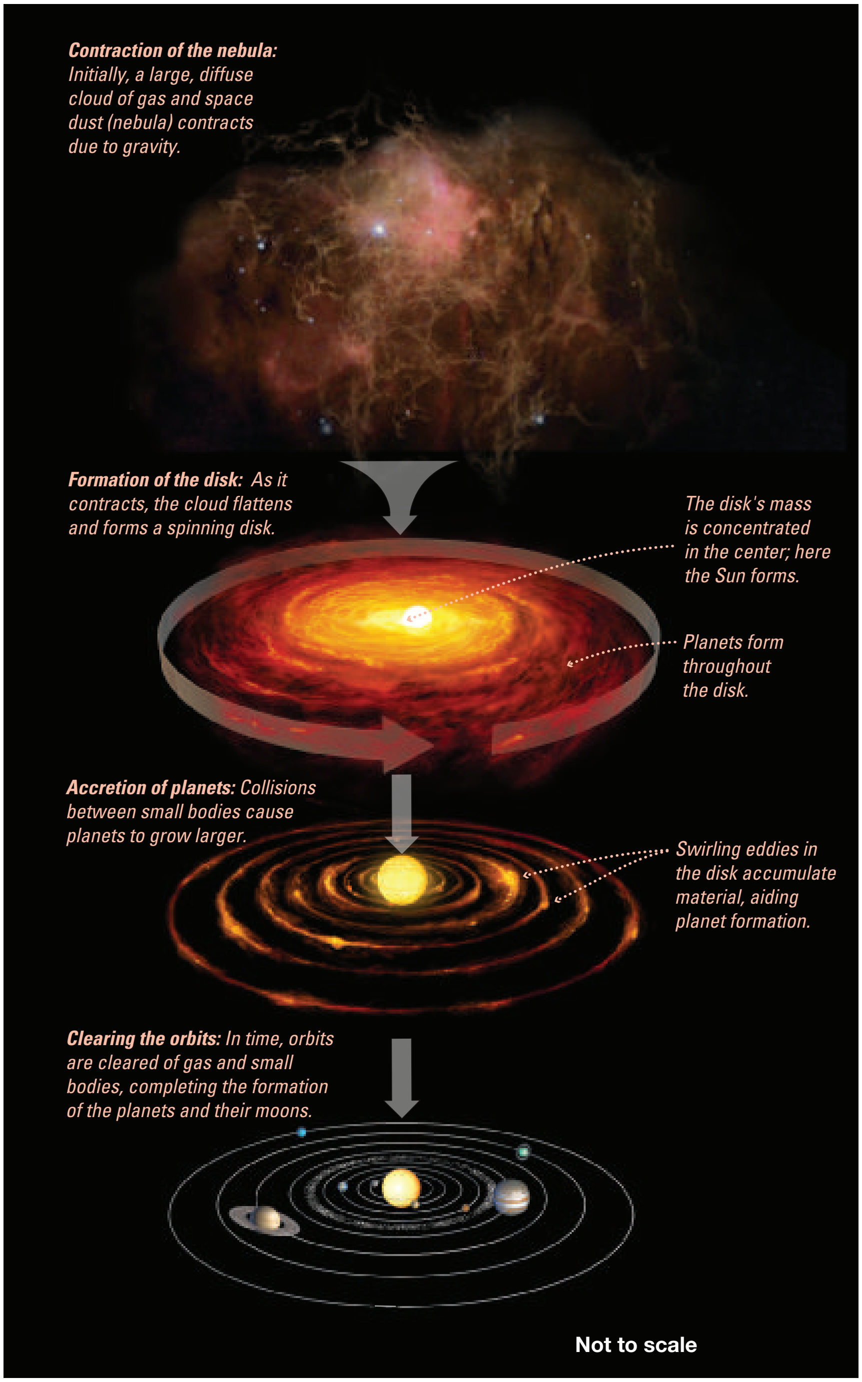
During this early stage of formation, many meteorites and comets from space bombarded proto-Earth (Figure 1.19). In fact, a leading theory states that the Moon was born in the aftermath of a titanic collision between a Mars-sized planet named *Theia* and proto-Earth. While most of Theia was swallowed up and incorporated into the magma ocean it created on impact, the collision also flung a small world's worth of vaporized and molten rock into orbit. Over time, this debris coalesced into a sphere and created Earth's orbiting companion, the Moon.

During this early formation of the protoplanets and their satellites, the Sun condensed into a body so massive and hot that pressure within its core initiated the process of **thermonuclear fusion** (*thermo* = hot, *nucleos* = a little nut; *fusus* = melted). Thermonuclear fusion occurs when temperatures reach tens of millions of degrees and hydrogen **atoms** (*a* = not, *tomos* = cut) combine to form helium atoms, releasing enormous amounts of energy. (Thermonuclear fusion in stars also creates larger and more complex elements, such as carbon. It is interesting to note that as a result, all matter—even the matter that comprises our bodies—originated as stardust long ago.) Not only does the Sun emit light, it also emits *ionized* (electrically charged) particles that make up the *solar wind*. During the early stages of formation of the solar system, this solar wind blew away the nebular gas that remained from the formation of the planets and their satellites.

The protoplanets closest to the Sun (including Earth) also lost their initial atmospheres (mostly hydrogen and helium), blown away by the bombardment by ionized solar radiation. At the same time, these rocky protoplanets were gradually cooling, causing them to contract and drastically shrink in size. As the protoplanets continued to contract, another source of heat was produced deep within their cores from the spontaneous disintegration of atoms, called *radioactivity* (*radio* = ray, *acti* = to cause).

Density and Density Stratification

Density, which is an extremely important physical property of matter, is defined as mass per unit volume. In common terms, an easy way to think about density is that it is a measure of *how heavy something is for its size*. For instance, an object that has a low density is light for its size (like a dry sponge, foam packing, or a surfboard). Conversely, an object that has a high density is heavy for its size (like cement, most metals, or a large container full of water). Note that density has nothing to do with the *thickness* of an object; some objects (like a



SmartFigure 1.18 **The nebular hypothesis of solar system formation.** According to the nebular hypothesis, our solar system formed from the gravitational contraction of an interstellar cloud of gas and space dust called a *nebula*. https://goo.gl/FoY7Yt

Animation
The Nebular Hypothesis of Solar System Formation
http://goo.gl/KObsRK

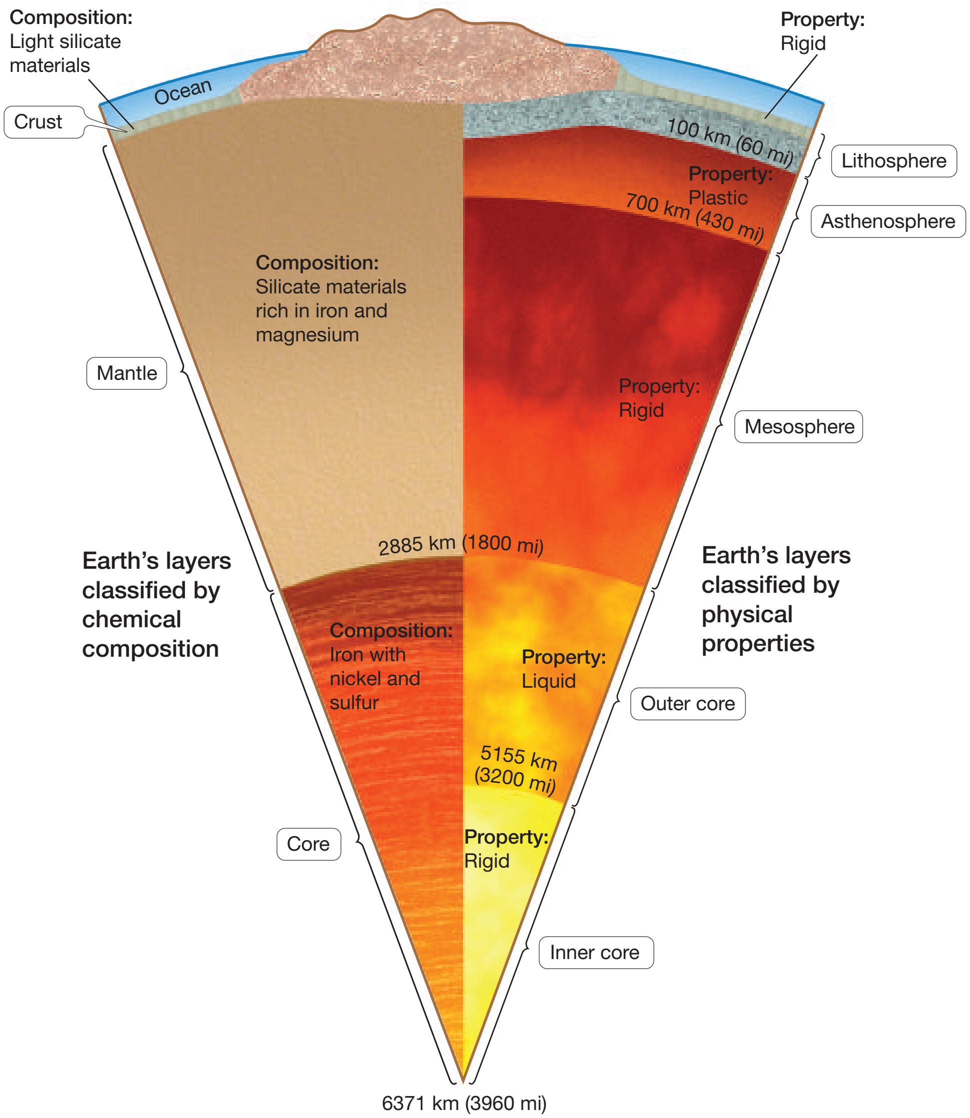
Figure 1.19 **Proto-Earth.** An artist's conception of what Earth may have looked like early in its development.

stack of foam packing) can be thick but have low density. In reality, density is related to molecular packing, with higher packing of molecules into a certain space resulting in higher density. Density is an extremely important concept that will be discussed in many other chapters in this book. For example, the density of Earth's layers dramatically affects their locations within Earth (Chapter 2), the density of air masses affects their positions in the atmosphere and other properties (Chapter 6), and the density of water masses determines how deep in the ocean they are found and how they move (Chapter 7).

On the early Earth, heat generated at the surface by the bombardment of space debris and heat released internally by the decay of radioactive elements was so intense that Earth's surface became molten. Once Earth became a ball of hot liquid rock, the elements were able to segregate according to their densities in a process called **density stratification** (*strati* = a layer, *fication* = making), which occurs because of *gravitational separation*. The highest-density materials (primarily iron and nickel) concentrated in the core, whereas progressively lower-density components (primarily rocky material) formed concentric spheres around the core. If you've ever noticed how oil-and-vinegar salad dressing settles out into a lower-density top layer (the oil) and a higher-density bottom layer (the vinegar), then you've seen how density stratification causes separate layers to form.

EXPLORING DATA

1. Comparing the two halves of this figure, explain why the boundaries on the two sides don't always align.
2. Other than the center of Earth and Earth's surface, what is the one boundary that actually does match up?



SmartFigure 1.20 Comparison of Earth's chemical composition and physical properties. A cross-sectional view of Earth, showing Earth's layers classified by chemical composition along the left side of the diagram. For comparison, Earth's layers classified by physical properties are shown along the right side of the diagram. Layers near the surface are enlarged for clarity.
https://goo.gl/JjglcZ

Earth's Internal Structure

As a result of density stratification, Earth became a layered sphere based on density, with the highest-density material found near the center of Earth and the lowest-density material located near the surface. Let's examine Earth's internal structure and the characteristics of its layers.

CHEMICAL COMPOSITION VERSUS PHYSICAL PROPERTIES The cross-sectional view of Earth in Figure 1.20 shows that Earth's inner structure can be subdivided according to its chemical composition (the chemical makeup of Earth materials) or its physical properties (how the rocks respond to increased temperature and pressure at depth).

CHEMICAL COMPOSITION Based on chemical composition, Earth consists of three layers: the **crust**, the **mantle**, and the **core** (Figure 1.20). If Earth were reduced to the size of an apple, then the crust would be its thin skin. It extends from the surface to an average depth of about 30 kilometers (20 miles). The crust is composed of relatively low-density rock, consisting mostly of various *silicate minerals* (common rock-forming minerals with silicon and oxygen). There are two types of crust—oceanic and continental—that will be discussed in the next section.

Immediately below the crust is the mantle. It occupies the largest volume of the three layers and extends to a depth of about 2885 kilometers (1800 miles). The mantle is composed of relatively high-density iron and magnesium silicate rock.

Beneath the mantle is the core. It forms a large mass from 2885 kilometers (1800 miles) to the center of Earth at 6371 kilometers (3960 miles). The core is composed of even higher-density metal (mostly iron and nickel).

PHYSICAL PROPERTIES Based on physical properties, Earth is composed of five layers (Figure 1.20): the **inner core**, the **outer core**, the **mesosphere** (*mesos* = middle, *sphere* = ball), the **asthenosphere** (*asthenos* = weak, *sphere* = ball), and the **lithosphere** (*lithos* = rock, *sphere* = ball).

The lithosphere is Earth's cool, rigid, outermost layer. It extends from the surface to an average depth of about 100 kilometers (62 miles) and includes the crust plus the topmost portion of the mantle. The lithosphere is *brittle* (*brytten* = to shatter), meaning that it will fracture when force is applied to it. As will be discussed in Chapter 2, "Plate Tectonics and the Ocean Floor," the plates involved in plate tectonic motion are the plates of the lithosphere.

Beneath the lithosphere is the asthenosphere. The asthenosphere is *plastic* (*plasticus* = molded), meaning that it will flow when a gradual force is applied to it. It extends from about 100 kilometers (62 miles) to 700 kilometers (430 miles) below the surface, which is the base of the upper mantle. At these depths, it is hot enough to partially melt portions of most rocks.

Beneath the asthenosphere is the mesosphere. The mesosphere extends to a depth of about 2885 kilometers (1800 miles), which corresponds to the middle and lower mantle. Although the asthenosphere deforms plastically, the mesosphere is rigid because of the increased pressure at these depths.

Beneath the mesosphere is the core. The core consists of the outer core, which is liquid and capable of flowing, and the inner core, which is rigid and does not flow. Again, the increased pressure at the center of Earth keeps the inner core from flowing.

STUDENTS SOMETIMES ASK . . .

How do we know about the internal structure of Earth?

You might suspect that the internal structure of Earth has been sampled directly. Although attempts are currently underway, the truth is humans have never penetrated beneath Earth's crust! Instead, the internal structure of Earth is determined by analyzing earthquakes that send vibrations through the deep interior of our planet. These vibrations are called *seismic waves*, which change their speed and are bent and reflected as they move through zones having different properties. For example, seismic waves travel more slowly through areas of hotter rock and speed up thorough colder rock. An extensive network of monitoring stations around the world detects and records these vibrations. The data are analyzed and used to determine the structure and properties of the deep Earth and how they change over time. In fact, repeated analysis of seismic waves that pass through Earth has allowed researchers to construct a detailed three-dimensional model of Earth's interior—similar to an MRI in medical technology—which reveals the inner workings of our planet (**Figure 1.21**).

Animation
How Seismic Waves Reveal Earth's Internal Layers
http://goo.gl/76mJf8

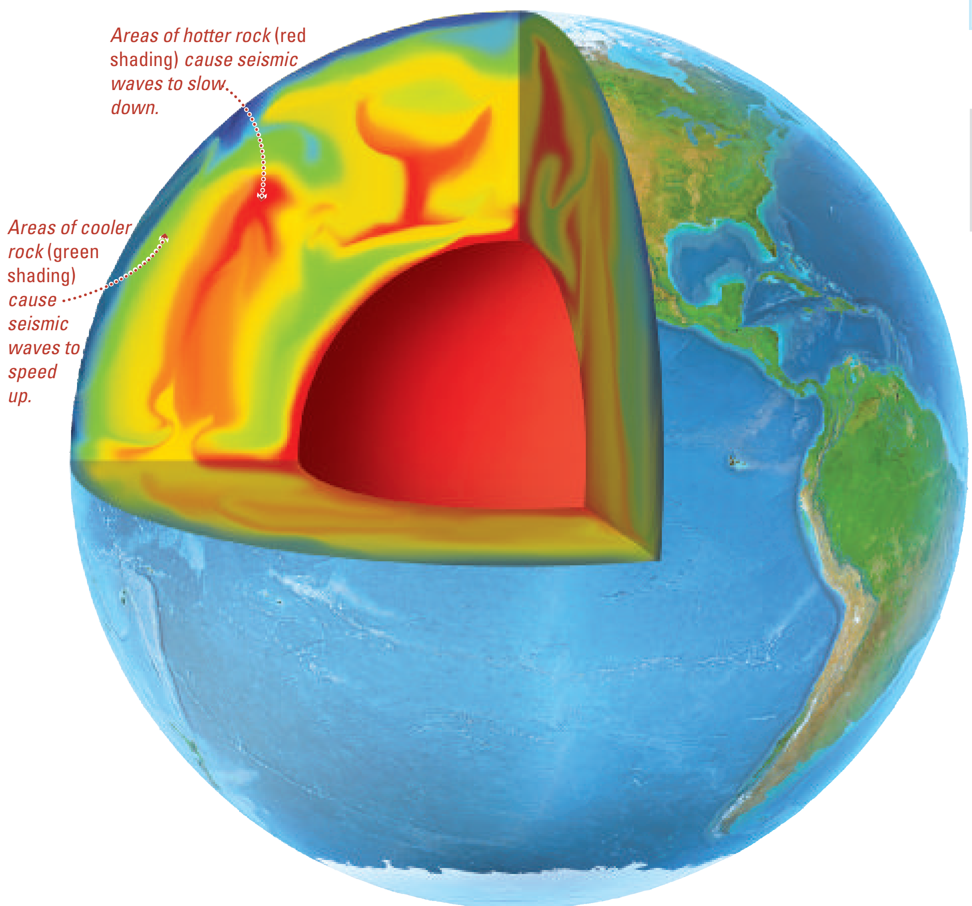


Figure 1.21 Determining the internal structure of Earth. By analyzing how various seismic waves travel through Earth, scientists are able to map Earth's complex inner structure.

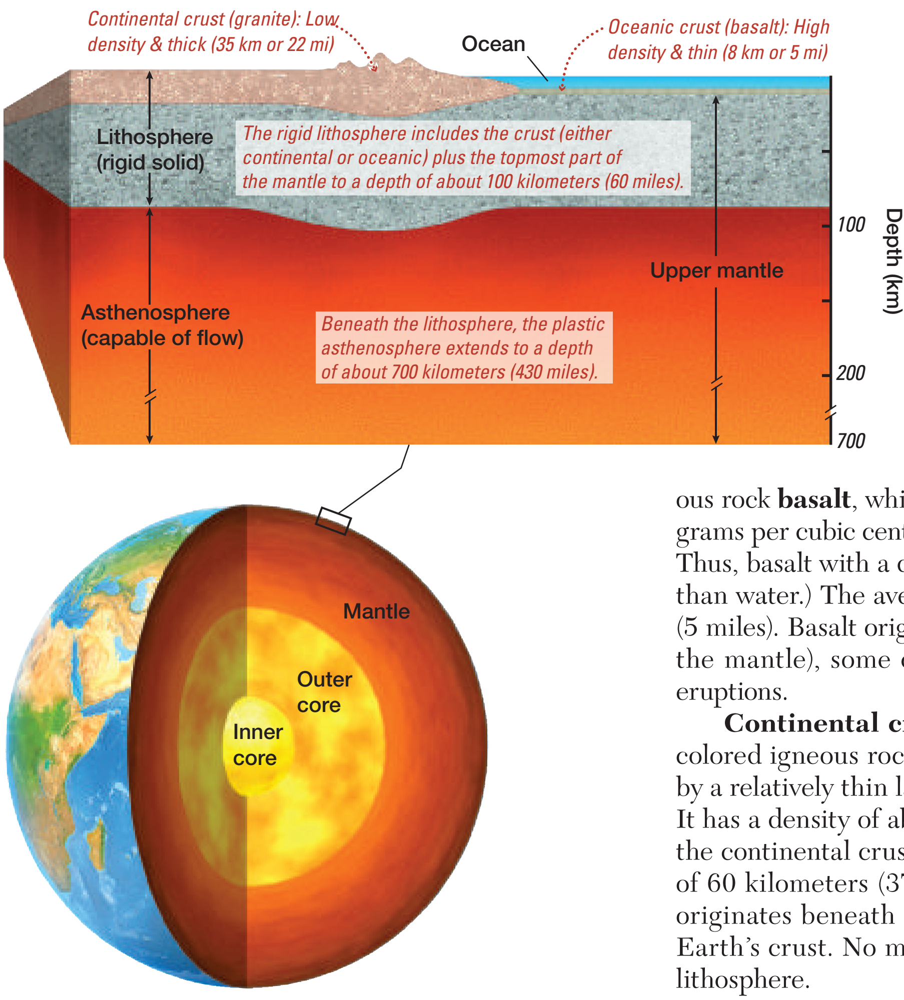


Figure 1.22 Internal structure of Earth showing an enlargement of layers close to the surface.

SmartTable 1.1 Comparing oceanic and continental crust.
https://goo.gl/EneJOl

NEAR THE SURFACE The top portion of Figure 1.22 shows an enlargement of Earth's layers closest to the surface.

Lithosphere The lithosphere is a relatively cool, rigid shell that includes all the crust and the topmost part of the mantle. In essence, the topmost part of the mantle is attached to the crust, and the two act as a single unit, approximately 100 kilometers (62 miles) thick. The expanded view in Figure 1.22 shows that the crust portion of the lithosphere is further subdivided into oceanic crust and continental crust, which are compared in Table 1.1.

Oceanic versus Continental Crust **Oceanic crust** underlies the ocean basins and is composed of the igneous rock **basalt**, which is dark colored and has a relatively high density of about 3.0 grams per cubic centimeter. (Water has a density of 1.0 grams per cubic centimeter. Thus, basalt with a density of 3.0 grams per cubic centimeter is three times denser than water.) The average thickness of the oceanic crust is only about 8 kilometers (5 miles). Basalt originates as molten magma beneath Earth's crust (typically from the mantle), some of which comes to the surface during underwater sea floor eruptions.

Continental crust is composed primarily of the lower-density and lighter-colored igneous rock **granite**. (At the surface, continental crust is often covered by a relatively thin layer of surface sediments. Below these, granite can be found.) It has a density of about 2.7 grams per cubic centimeter. The average thickness of the continental crust is about 35 kilometers (22 miles) but may reach a maximum of 60 kilometers (37 miles) beneath the highest mountain ranges. Most granite originates beneath the surface as molten magma that cools and hardens within Earth's crust. No matter which type of crust is at the surface, it is all part of the lithosphere.

Asthenosphere The asthenosphere is a relatively hot, plastic region beneath the lithosphere. It extends from the base of the lithosphere to a depth of about 700 kilometers (430 miles) and is entirely contained within the upper mantle. The asthenosphere can deform without fracturing if a force is applied slowly. This means that it has the ability to flow but has high **viscosity** (*viscosus* = sticky). Viscosity is a measure of a substance's resistance to flow. (Substances that have high viscosity—a high resistance to flow—include toothpaste, honey, tar, and Silly Putty; a common substance that has low viscosity is water. Note that a substance's viscosity often changes with temperature. For instance, as honey is heated, it flows more easily.) Studies indicate that the high-viscosity asthenosphere is flowing slowly through time; this has important implications for the movement of lithospheric plates.

ISOSTATIC ADJUSTMENT **Isostatic adjustment** (*iso* = equal, *stasis* = standing)—the vertical movement of crust—is the result of the buoyancy of Earth's lithosphere as it floats on the denser, plastic-like asthenosphere below. Figure 1.23, which shows a container ship floating in water, provides an example of isostatic adjustment. It shows that an empty ship floats high in the water. Once the ship is loaded with cargo, though, the ship undergoes isostatic adjustment and floats lower in the water (but hopefully won't sink!). When the cargo is unloaded, the ship isostatically adjusts itself and floats higher again.

SmartTable 1.1 Comparing oceanic and continental crust

	Oceanic crust	Continental crust
Main rock type	Basalt (dark-colored igneous rock)	Granite (light-colored igneous rock)
Density (grams per cubic centimeter)	3.0	2.7
Average thickness	8 kilometers (5 miles)	35 kilometers (22 miles)

EXPLORING DATA ▲

Although the density difference between granite and basalt seems small, the units reported in Table 1.1 are for a very small volume, so let's examine a larger volume. Imagine a typical swimming pool, which has a volume of about 400 cubic meters. If that swimming pool was filled with liquid granite, how much would it weigh? Imagine a second identical pool that was filled with liquid basalt. How much would that pool weigh? And, what is the difference in weight (metric tons) between the two pools?

Similarly, both continental and oceanic crust float on the denser mantle beneath. Oceanic crust is denser than continental crust, however, so oceanic crust floats lower in the mantle because of isostatic adjustment. Oceanic crust is also thin, which creates low areas for the oceans to occupy. Areas where the continental crust is thickest (such as large mountain ranges on the continents) float higher than continental crust of normal thickness, also because of isostatic adjustment. These mountains are similar to the top of a floating iceberg—they float high because there is a very thick mass of crustal material beneath them, plunged deeper into the asthenosphere. Thus, tall mountain ranges on Earth are composed of a great thickness of crustal material sometimes referred to as a root, which in essence keeps them buoyed up.

Areas that are exposed to an increased or decreased load experience isostatic adjustment. For instance, during the most recent ice age (which occurred during the Pleistocene Epoch between about 1.8 million and 10,000 years ago), massive ice sheets alternately covered and exposed northern regions such as Scandinavia and northern Canada. The additional weight of ice several kilometers thick caused these areas to isostatically adjust themselves lower in the mantle. Since the end of the most recent ice age, the reduced load on these areas caused by the melting of ice caused these areas to rise and experience **isostatic rebound**, which continues today. The rate at which isostatic rebound occurs gives scientists important information about the properties of the upper mantle.

Further, isostatic adjustment provides additional evidence for the movement of Earth's tectonic plates. Because continents isostatically adjust themselves by moving *vertically* they must not be firmly fixed in one position on Earth. As a result, the plates that contain these continents should certainly be able to move *horizontally* across Earth's surface. This remarkable idea will be explored in more detail in the next chapter.

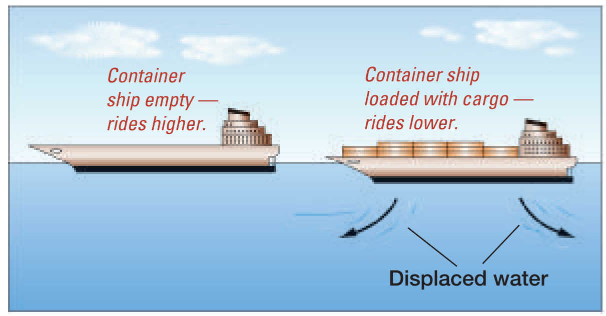


Figure 1.23 A container ship experiences isostatic adjustment. A ship will ride higher in water when it is empty and will ride lower in water when it is loaded with cargo, illustrating the principle of isostatic adjustment.

Animation
Isostatic Adjustment
https://goo.gl/esrK8U

RECAP Earth has differences in composition and physical properties that create layers such as the brittle lithosphere and the plastic asthenosphere, which is capable of flowing slowly over time.

CONCEPT CHECK 1.5 ▸ Explain how Earth and the solar system formed.

1 Discuss the origin of the solar system using the nebular hypothesis.

2 How was proto-Earth different from Earth today?

3 What is density stratification, and how did it change proto-Earth?

4 What are some differences between the lithosphere and the asthenosphere?

1.6 ▶ How Were Earth's Atmosphere and Oceans Formed?

The formation of Earth's atmosphere is related to the formation of the oceans; both are a direct result of density stratification.

Origin of Earth's Atmosphere

Where did the atmosphere come from? As previously mentioned, Earth's initial atmosphere consisted of leftover gases from the nebula, but those particles were blown out to space by the Sun's solar wind. After that, a second atmosphere was most likely expelled from inside Earth by a process called **outgassing**. During the period of density stratification, the lowest-density material contained within Earth was composed of various gases. These gases rose to the surface and were expelled to form Earth's early atmosphere.

What was the composition of these atmospheric gases? They are believed to have been similar to the gases emitted from volcanoes, geysers, and hot springs today: mostly water vapor (steam), with small amounts of carbon dioxide, hydrogen, and other gases. The composition of this early atmosphere was not, however, the same composition as today's atmosphere. The composition of the atmosphere changed over time because of the influence of life (as will be discussed shortly) and possibly because of changes in the mixing of material in the mantle.

Origin of Earth's Oceans

Where did the oceans come from? Similarly, their origin is linked directly to the origin of the atmosphere. Because outgassing releases mostly water vapor, this was the primary source of water on Earth, including supplying the oceans with water. Figure 1.24 shows that as Earth cooled, the water vapor released to the atmosphere during outgassing condensed, fell to Earth, and accumulated in low areas. Evidence suggests that by at least 4 billion years ago, most of the water vapor from outgassing had accumulated to form the first permanent oceans on Earth.

Recent research, however, suggests that not all water came from inside Earth. Comets, which are composed of about half water, were once widely held to be the source of Earth's oceans. During Earth's early development, space debris left over from the origin of the solar system bombarded the young planet, and there could have been plenty of water supplied to Earth in this way. However, spectral analyses of the chemical composition of three comets—Halley, Hyakutake, and Hale-Bopp—during near-Earth passes they made in 1986, 1996, and 1997, respectively, revealed a crucial chemical difference between the hydrogen in comet ice and that in Earth's water. In 2014, the European Space Agency's Rosetta spacecraft reached the orbit of a comet to gather data on its ice. Although the lander sent to the comet's surface failed to send back data, the orbiter was able to analyze the comet's ice and determined that it, too, did not chemically match the water in Earth's oceans. If similar comets supplied large quantities of water to Earth, much of Earth's water would still exhibit the telltale type of hydrogen identified in these comets.

Even though comet ice doesn't match the chemical signature of Earth's water, there are a variety of small bodies in the solar system that could have supplied water to Earth. For example, recent analysis of a comet from the Kuiper Belt (an icy debris disk in the outer solar system that includes Pluto) indicates it *does* contain water with nearly the correct type of hydrogen that is found in Earth's water. In addition to Kuiper Belt objects, asteroids—rocky bodies that contain ice and orbit the Sun between Mars and Jupiter—also have a similar type of hydrogen and thus could have contributed water to an early Earth. These findings point to an emerging picture of a complex and dynamic evolution of the early solar system. Although it seems likely that most of Earth's water was derived from outgassing, other sources of water may have contributed to Earth's oceans as well.

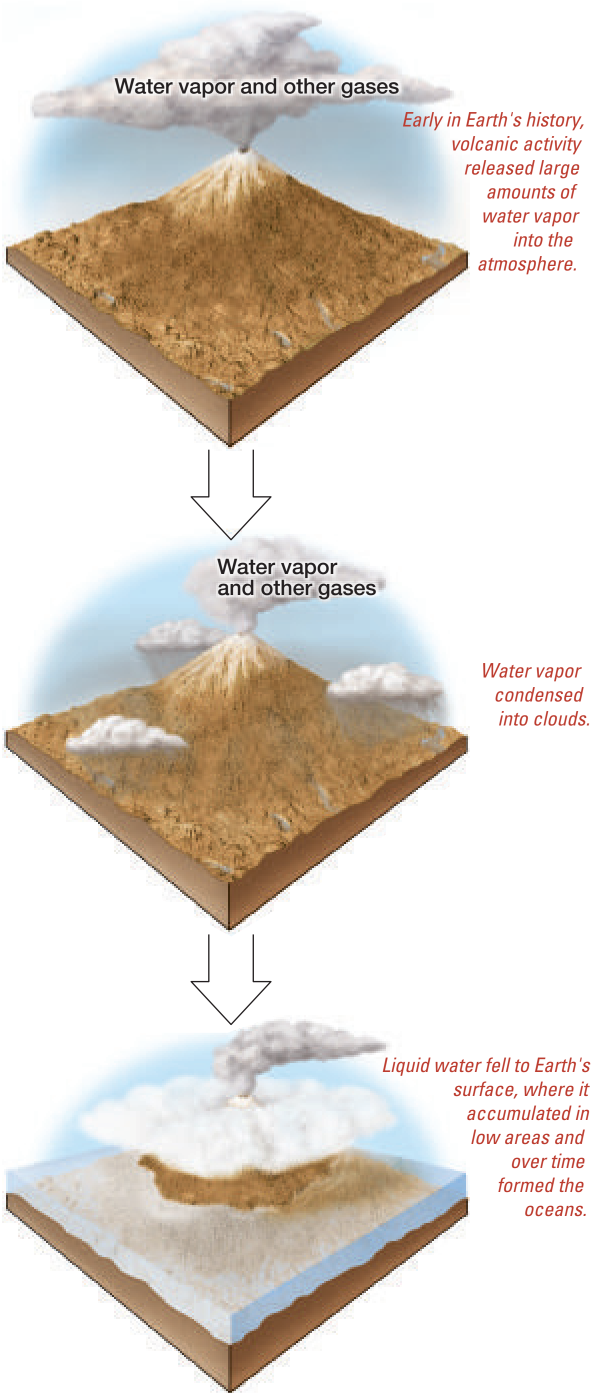


Figure 1.24 Formation of Earth's oceans.

Animation
Formation of Earth's Oceans
https://goo.gl/gCXrDg

THE DEVELOPMENT OF OCEAN SALINITY The relentless rainfall that landed on Earth's rocky surface dissolved many elements and compounds and carried them into the newly forming oceans. Even though Earth's oceans have existed since early in the formation of the planet, their chemical composition must have changed. This is because the high carbon dioxide and sulfur dioxide content in the early atmosphere would have created a very acidic rain, capable of dissolving greater amounts of minerals in the crust than occurs today. In addition, volcanic gases such as chlorine became dissolved in the atmosphere. As rain fell and washed to the ocean, it carried some of these dissolved compounds, which accumulated in the newly forming oceans. (Note that some of these dissolved components were removed or modified by chemical reactions between ocean water and rocks on the sea floor.) Eventually, a balance between inputs and outputs was reached, producing an ocean with a chemical composition similar to today's oceans. Further aspects of the oceans' salinity are explored in Chapter 5, "Water and Seawater."

RECAP **Originally, Earth had no oceans. The oceans (and atmosphere) came from inside Earth as a result of outgassing and were present by at least 4 billion years ago.**

CONCEPT CHECK 1.6 ▸ Explain how Earth's atmosphere and oceans formed.

1 Describe the origin of Earth's oceans.

2 Describe the origin of Earth's atmosphere. How is its origin related to the origin of Earth's oceans?

3 Have the oceans always been salty? Why or why not?

1.7 ▸ Did Life Begin in the Oceans?

The fundamental question of how life began on Earth has puzzled humankind since ancient times, and has recently received a great amount of scientific study. The evidence required to understand our planet's prebiotic environment and the events that led to first living systems is scant and difficult to decipher. Still, the inventory of current views on life's origin reveals a broad assortment of opposing positions. One recent hypothesis is that the organic building blocks of life may have arrived embedded in meteors, comets, or cosmic dust. Alternatively, life may have originated around hydrothermal vents—hot springs—on the deep-ocean floor. Yet another idea is that life originated in certain minerals that acted as chemical catalysts within rocks deep below Earth's surface.

According to the fossil record on Earth, the earliest-known life-forms were primitive bacteria that lived in sea floor rocks about 3.5 billion years ago. Unfortunately, Earth's geologic record for these early times is so sparse and the rocks are so deformed by Earth processes that the rocks no longer reveal life's precursor molecules. In addition, there is no direct evidence of Earth's environmental conditions (such as its temperature, ocean acidity, or the exact composition of the atmosphere) at the time of life's origin. Still, it is clear that the basic building blocks for the development of life were available from materials already present on the early Earth. And the presence of oceans on Earth was critical because this is the most likely place for these basic materials to interact and produce life.

The Importance of Oxygen to Life

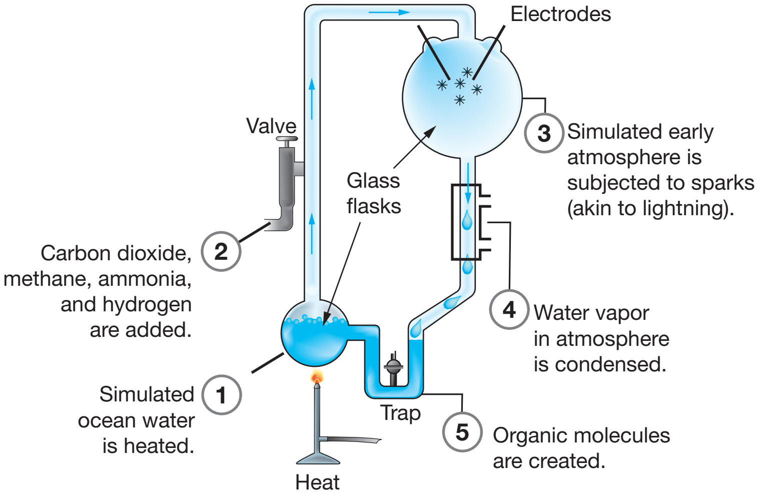
Oxygen, which comprises almost 21% of Earth's present atmosphere, is essential to human life for two reasons. First, our bodies need oxygen to "burn" (*oxidize*) food, releasing energy to our cells. Second, oxygen in the upper atmosphere in the form of *ozone* (*ozone* = to smell; ozone gets its name because of its pungent, irritating odor) protects the surface of Earth from most of the Sun's harmful ultraviolet radiation (which is why the atmospheric ozone hole over Antarctica has generated such concern).

STUDENTS SOMETIMES ASK . . .

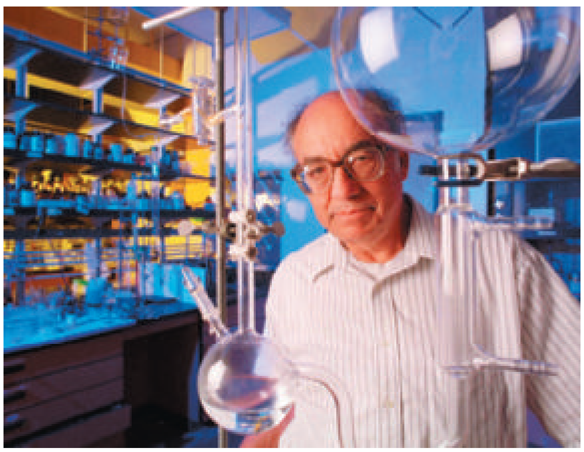
Have the oceans always been salty? Are the oceans growing more or less salty through time?

It is likely that the oceans have always been salty because wherever water comes in contact with the rocks of Earth's crust, some of the minerals dissolve. This is the source of salts in the oceans, whether from stream runoff or dissolving directly from the sea floor. Today, new minerals are forming on the sea floor at the same rate as dissolved materials are added. Thus, the salt content of the ocean is in a "steady state," meaning that it is not increasing or decreasing.

Interestingly, these questions can also be answered by studying the proportion of water vapor to chloride ion, Cl^-, in ancient marine rocks. Chloride ion is important because it forms part of the most common salts in the ocean (for example, sodium chloride, potassium chloride, and magnesium chloride). Also, chloride ion is produced by outgassing, like the water vapor that formed the oceans. Currently, there is no indication that the ratio of water vapor to chloride ion has fluctuated throughout geologic time, so it can be reasonably concluded that the oceans' salinity has been relatively constant through time.



(a) Laboratory apparatus used by Stanley Miller to simulate the conditions of the early atmosphere and the oceans. The experiment produced various organic molecules and suggests that the basic components of life were created in a "prebiotic soup" in the oceans.



(b) Stanley Miller in 1999, with his famous apparatus in the foreground.

SmartFigure 1.25 Creation of organic molecules.
https://goo.gl/qLpjYn

RECAP Organic molecules were produced in a simulation of Earth's early atmosphere and ocean, suggesting that life most likely originated in the oceans.

Evidence suggests that Earth's early atmosphere (the product of outgassing) was different from Earth's initial hydrogen–helium atmosphere and different from the mostly nitrogen–oxygen atmosphere of today. The early atmosphere probably contained large percentages of water vapor and carbon dioxide and smaller percentages of hydrogen, methane, and ammonia, but very little free oxygen (oxygen that is not chemically bound to other atoms). Why was there so little free oxygen in the early atmosphere? Oxygen may well have been outgassed, but oxygen and iron have a strong affinity for each other. (As an example of the strong affinity of iron and oxygen, consider how common rust—a compound of iron and oxygen—is on Earth's surface.) As a result, iron in Earth's early crust would have reacted with the outgassed oxygen immediately, removing it from the atmosphere.

Without oxygen in Earth's early atmosphere, moreover, there would have been no ozone layer to block most of the Sun's ultraviolet radiation. The lack of a protective ozone layer may, in fact, have played a crucial role in several of life's most important developmental milestones.

Stanley Miller's Experiment

In 1952, **Stanley Miller** (**Figure 1.25b**)—then a 22-year-old graduate student of chemist Harold Urey at the University of Chicago—conducted a laboratory experiment that had profound implications about the development of life on Earth. In Miller's experiment, he exposed a mixture of carbon dioxide, methane, ammonia, hydrogen, and water (the components of the early atmosphere and ocean) to ultraviolet light (from the Sun) and an electrical spark (to imitate lightning) (**Figure 1.25a**). By the end of the first day, the mixture turned pink, and after a week it was a deep, muddy brown, indicating the formation of a large assortment of organic molecules, including amino acids—which are the basic components of life—and other biologically significant compounds.

Miller's now-famous laboratory experiment of a simulated primitive Earth in a bottle—which has been duplicated and confirmed numerous times since—demonstrated that vast amounts of organic molecules could have been produced in Earth's early oceans, often called a "prebiotic soup." This prebiotic soup, perhaps spiced by extraterrestrial molecules aboard comets, meteorites, or interplanetary dust, was fueled by raw materials from volcanoes, certain minerals in sea floor rocks, and undersea hydrothermal vents. On early Earth, the mixture was energized by lightning, cosmic rays, and the planet's own internal heat, and it is thought to have created life's precursor molecules about 4 billion years ago.

Exactly how these simple organic compounds in the prebiotic soup assembled themselves into more complex molecules—such as proteins and DNA—and then into the first living entities remains one of the most tantalizing questions in science. Research suggests that with the vast array of organic compounds available in the prebiotic soup, several kinds of chemical reactions led to increasingly elaborate molecular structures. In fact, research suggests that small, simple molecules could have acted as templates, or "molecular midwives," in helping the building blocks of life's genetic material form long chains and thus may have assisted in the formation of longer, more elaborate molecular complexes. Among these complexes, some began to carry out functions associated with the basic molecules of life. As the products of one generation became the building blocks for another, even more complex molecules, or polymers, emerged over many generations that could store and transfer information. Such genetic polymers ultimately became encapsulated within cell-like membranes that were also present in Earth's primitive broth. The resulting cell-like complexes thereby housed self-replicating molecules capable of multiplying—and hence evolving—genetic information. Many specialists consider this emergence of genetic replication to be the true origin of life. Moreover, Miller's experiment demonstrates that simple chemicals under the right conditions could give rise to more complex chemical compounds that may lead to life-like behavior on other worlds.

THE VOYAGE OF HMS *BEAGLE*: HOW IT SHAPED CHARLES DARWIN'S THINKING ABOUT THE THEORY OF EVOLUTION

"Nothing in biology makes sense except in the light of evolution."
—Geneticist Theodosius Dobzhansky (1973)

To help explain how biologic processes operating in nature were responsible for producing the many diverse and remarkable species on Earth, the English naturalist **Charles Darwin** (1809–1882) proposed the *theory of evolution* by natural selection, which he referred to as "common descent with modification." Many of the observations upon which he based the theory were made aboard the vessel HMS *Beagle* during its famous expedition from 1831 to 1836 that circumnavigated the globe (**Figure 1E**).

Darwin became interested in natural history during his student days at Cambridge University, where he was studying to become a minister. Because of the influence of John Henslow, a professor of botany, he was selected to serve as an unpaid naturalist on HMS *Beagle*. The *Beagle* sailed from Devonport, England, on December 27, 1831, under the command of Captain Robert Fitzroy. The major objective of the voyage was to complete a survey of the coast of Patagonia (Argentina) and Tierra del Fuego and to make chronometric measurements. The voyage allowed the 22-year-old Darwin—who was often seasick—to disembark at various locations and study local plants and animals. What particularly influenced his thinking about evolution were the discovery of fossils in South America, the different tortoises throughout the Galápagos Islands, and the identification of 15 closely related species of Galápagos finches. These finches differ greatly in the configuration of their beaks (Figure 1E, *left inset*), which are suited to their diverse feeding habitats. After his return to England, Darwin noted the adaptations of finches and other organisms living in different habitats and concluded that all organisms change slowly over time as products of their environment.

Darwin recognized the similarities between birds and mammals and reasoned that they must have evolved from reptiles. Patiently making observations over many years, he also noted the similar skeletal framework of species such as bats, horses, giraffes, elephants, porpoises, and humans, which led him to establish relationships between various groups. Darwin suggested that the differences between species were the result of adaptation over time to different environments and modes of existence.

In 1858, Darwin hastily published a summary of his ideas about natural selection because fellow naturalist *Alfred Russel Wallace*, working half a world away cataloguing species in what is now Indonesia, had independently discovered the same idea.

A year later, Darwin published his remarkable masterwork *On the Origin of Species by Means of Natural Selection* (Figure 1E, *right inset*), in which he provided extensive and compelling evidence that all living beings—including humans—have evolved from a common ancestor. At the time, Darwin's ideas were highly controversial because they stood in stark conflict with what most people believed about the origin of humans. Darwin also produced important publications on subjects as diverse as barnacle biology, carnivorous plants, and the formation of coral reefs.

Over 150 years later, Darwin's theory of evolution is so well established by evidence and reproducible experiment that it is considered a landmark influence in the scientific understanding of the underlying biologic processes operating in nature. Discoveries made since Darwin's time—including genetics and the structure of DNA—confirm how the process of evolution works. For example, the sequencing of the genomes of all 15 species of Darwin's finches was published in 2015, confirming Darwin's ideas about their evolutionary history.

It is interesting to note that most of Darwin's ideas have been so thoroughly accepted by scientists that they are now the underpinnings of the modern study of biology. That's why the name *Darwin* is synonymous with evolution. In 2009, to commemorate Darwin's birth and his accomplishments, the Church of England even issued this formal apology to Darwin: *"The Church of England owes you an apology for misunderstanding you and, by getting our first reaction wrong, encouraging others to misunderstand you still."*

What Did You Learn?

Describe the three different types of organisms that Charles Darwin observed during his voyage on the *Beagle* that influenced his thinking about the theory of evolution.

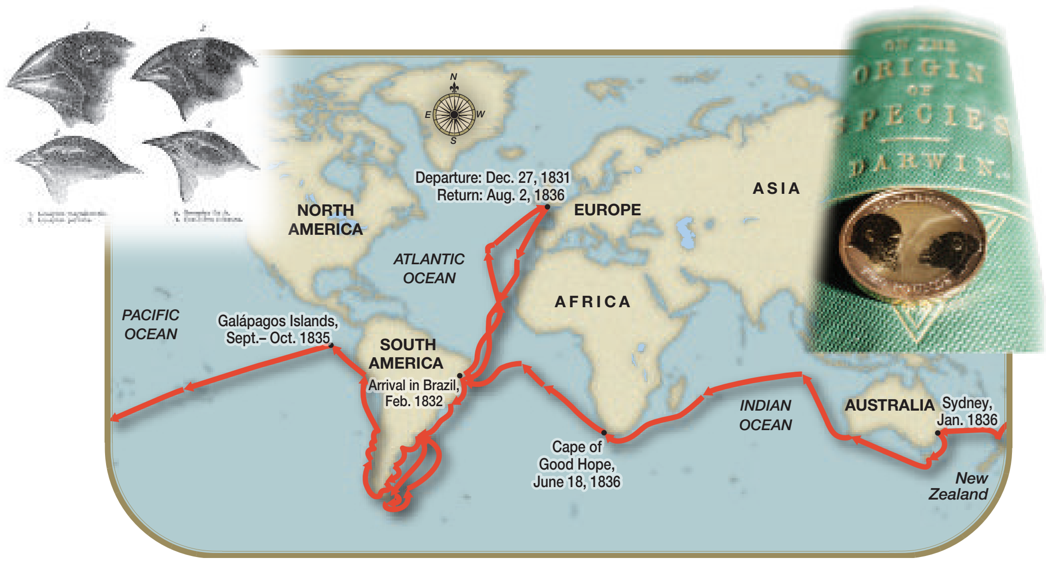


Figure 1E **Charles Darwin's legacy: Galápagos finches, route of the HMS *Beagle*, and *On the Origin of Species*.** Map showing the route of the HMS *Beagle*, beak differences in Galápagos finches (*left inset*) that greatly influenced Charles Darwin, and the British two-pound coin commemorating Darwin and his masterwork *On the Origin of Species* (*right inset*).

STUDENTS SOMETIMES ASK . . .

I've heard of the discovery of other planets outside of our solar system. Could any of them contain life?

Outside our solar system, about 4000 exoplanets have been discovered orbiting other star systems, including a few rocky exoplanets that are Earth-sized and may be orbiting their Sun-like stars at just the right distance for water to remain liquid, potentially sustaining life. Astronomers are able to detect if these exoplanets have water or not by analyzing specific frequencies of light. New discoveries of exoplanets are a frequent occurrence, suggesting that there could be hundreds to billions of Earth-like worlds in the vastness of the galaxy. And if our own solar system is any example, salty oceans with the ingredients for life—whether liquid on the surface or deep beneath a world's icy exterior—may be common. However, most of these exoplanets are many light-years away, so we may never know if any of them contain life.

Evolution and Natural Selection

Every living organism that inhabits Earth today is the result of **evolution** by the process of **natural selection**, which has been occurring since life first existed on Earth. Evolution in organisms is observed when the appearance and characteristics of individuals within populations change, or *evolve*, over time. This happens because naturally-occurring *mutations* in an organism's DNA can sometimes give an individual a survival advantage, and if the helpful mutation is passed down to the next generation, eventually the mutation may become common. This change in the genetic makeup of a population over time is driven by natural selection—the idea that organisms with traits best-suited to a certain environment survive and reproduce at higher rates than individuals lacking those traits. New traits in organisms that arise in response to environmental changes are called *adaptations*. New **species** (*species* = a kind) emerge when the accumulated genetic changes in a population reach a certain threshold (see Diving Deeper 1.1 on page 29). Evolution by the process of natural selection has been the driving force that allows organisms to inhabit increasingly numerous environments on Earth.

For most organisms, evolution occurs very slowly over long periods of time. As we shall see, when species adapt to Earth's various environments, they can also modify the environments in which they live. This modification can be localized or nearly global in scale. For example, when plants emerged from the oceans and inhabited the land, they changed Earth from a harsh and bleak landscape as barren as that of the Moon to one that is green and lush.

Plants and Animals Evolve

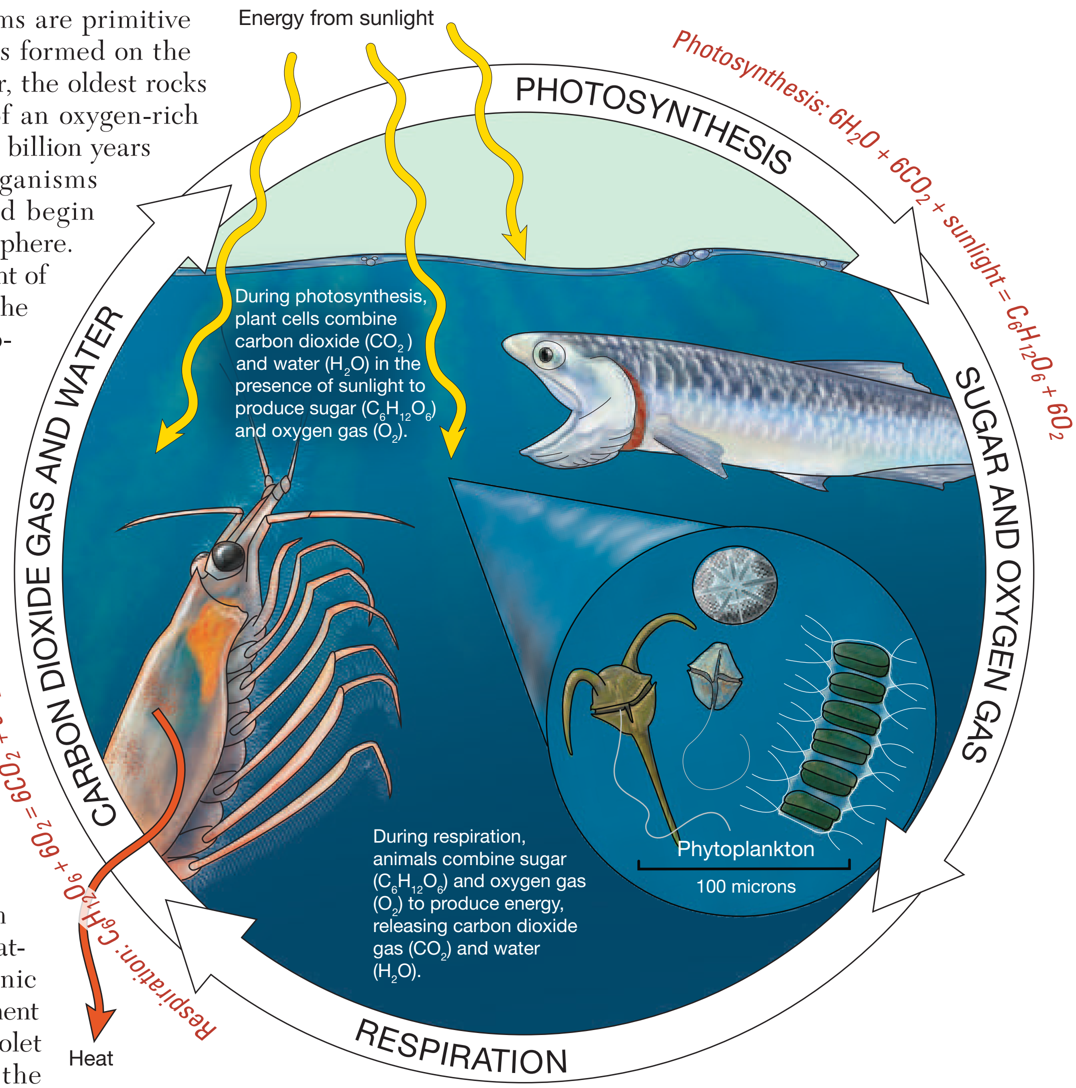
The very earliest forms of life were probably **heterotrophs** (*hetero* = different, *tropho* = nourishment). Heterotrophs require an external food supply, which was abundantly available in the form of nonliving organic matter in the ocean around them. **Autotrophs** (*auto* = self, *tropho* = nourishment), which can manufacture their own food supply, evolved later. The first autotrophs were probably similar to present-day **anaerobic** (*an* = without, *aero* = air) bacteria, which live without atmospheric oxygen. They may have been able to derive energy from inorganic compounds at deep-water hydrothermal vents using a process called **chemosynthesis** (*chemo* = chemistry, *syn* = with, *thesis* = an arranging). (More details about chemosynthesis are discussed in Chapter 15, "Animals of the Benthic Environment.") In fact, the detection of microbes deep within the ocean crust as well as the discovery of 3.2-billion-year-old microfossils of bacteria from deep-water marine rocks support the idea of life's origin on the deep-ocean floor in the absence of sunlight.

PHOTOSYNTHESIS AND RESPIRATION Eventually, more complex single-celled autotrophs evolved. They developed a green pigment called **chlorophyll** (*chloro* = green, *phyll* = leaf), which captures the Sun's energy through cellular **photosynthesis** (*photo* = light, *syn* = with, *thesis* = an arranging). In photosynthesis (Figure 1.26), plant and algae cells capture energy from sunlight and store it as sugars, releasing oxygen gas as a by-product. Alternatively, in cellular **respiration** (*respirare* = to breathe) (Figure 1.26), animals who consume the sugars produced by photosynthesis combine them with oxygen, releasing the stored energy of the sugars to carry on cellular tasks important for various life processes.

Figure 1.26 shows that photosynthesis and respiration are complementary processes, with photosynthesis producing what is needed for respiration (sugar and oxygen gas), and respiration producing what is needed for photosynthesis (carbon dioxide gas and water). In fact, the cyclic nature of Figure 1.26 shows that autotrophs (algae and plants) and heterotrophs (most bacteria and animals) began to develop a mutual need for each other.

The oldest fossilized remains of organisms are primitive photosynthetic bacteria recovered from rocks formed on the sea floor about 3.5 billion years ago. However, the oldest rocks containing iron oxide (rust)—an indicator of an oxygen-rich atmosphere—did not appear until about 2.45 billion years ago. This indicates that photosynthetic organisms needed about a billion years to develop and begin producing abundant free oxygen in the atmosphere. Another possible scenario is that a large amount of oxygen-rich (ferric) iron sank to the base of the mantle, where it was heated by the core and subsequently rose as a plume to the ocean floor, releasing large amounts of oxygen through outgassing about 2.5 billion years ago.

THE GREAT OXIDATION EVENT/OXYGEN CRISIS Based on the chemical makeup of certain rocks, Earth's atmosphere became oxygen-rich about 2.45 billion years ago—called the *great oxidation event*—and fundamentally changed Earth's ability to support life. Particularly for anaerobic bacteria, which had grown successfully in an oxygen-free world, all this oxygen was nothing short of a catastrophe! This is because the increased atmospheric oxygen caused the ozone concentration in the upper atmosphere to build up, thereby shielding Earth's surface from ultraviolet radiation—and effectively eliminating anaerobic bacteria's food supply of organic molecules. (Recall that Stanley Miller's experiment created organic molecules but needed ultraviolet light.) In addition, oxygen (particularly in the presence of light) is highly reactive with organic matter. When anaerobic bacteria are exposed to oxygen and light, they are killed instantaneously. By 1.8 billion years ago, the atmosphere's oxygen content had increased to such a high level that it began causing the extinction of many anaerobic organisms. Nonetheless, descendants of such bacteria survive on Earth today in isolated microenvironments that are dark and free of oxygen, such as deep in soil or rocks, in landfills, and inside other organisms.



SmartFigure 1.26 Photosynthesis and respiration are cyclic and complimentary processes that are fundamental to life on Earth. https://goo.gl/SsyVda

Although oxygen is very reactive with organic matter and can even be toxic, it also yields nearly 20 times more energy than anaerobic respiration—a fact that some organisms exploited. For example, blue-green algae, which are also known as *cyanobacteria* (*kuanos* = dark blue), adapted to and thrived in this new oxygen-rich environment. In doing so, they altered the composition of the atmosphere.

CHANGES TO EARTH'S ATMOSPHERE The development and successful evolution of photosynthetic organisms are greatly responsible for the world as we know it today (**Figure 1.27**). By the trillions upon trillions, these microscopic organisms transformed the planet by capturing the energy of the Sun to make food and releasing oxygen as a waste product. By this process, these organisms reduced the high amount of carbon dioxide in the early atmosphere and gradually replaced it with free oxygen. This created a third and final atmosphere on Earth: one that is oxygen rich (about 21% today). Little by little, these tiny organisms turned the atmosphere into

Climate Connection