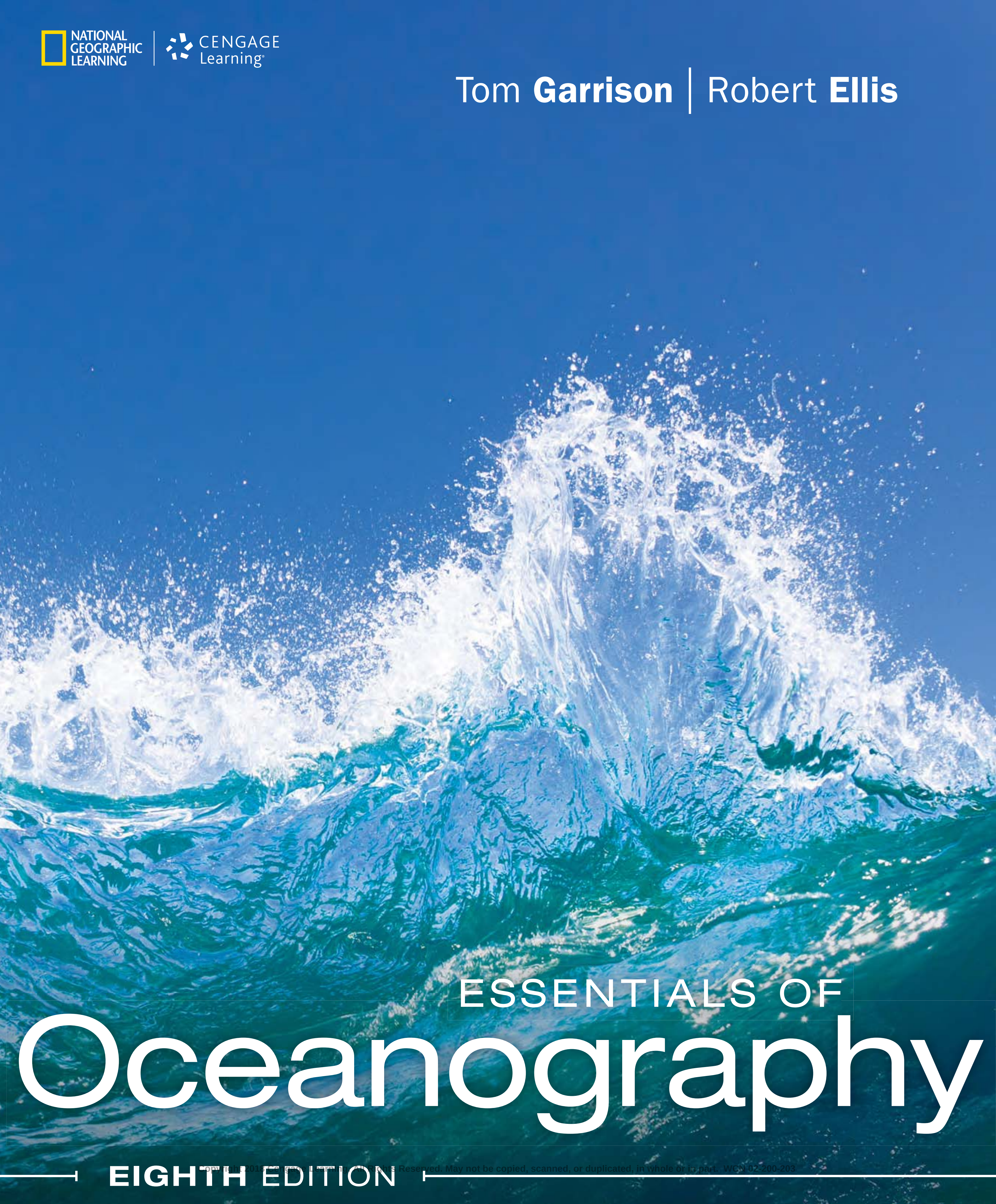

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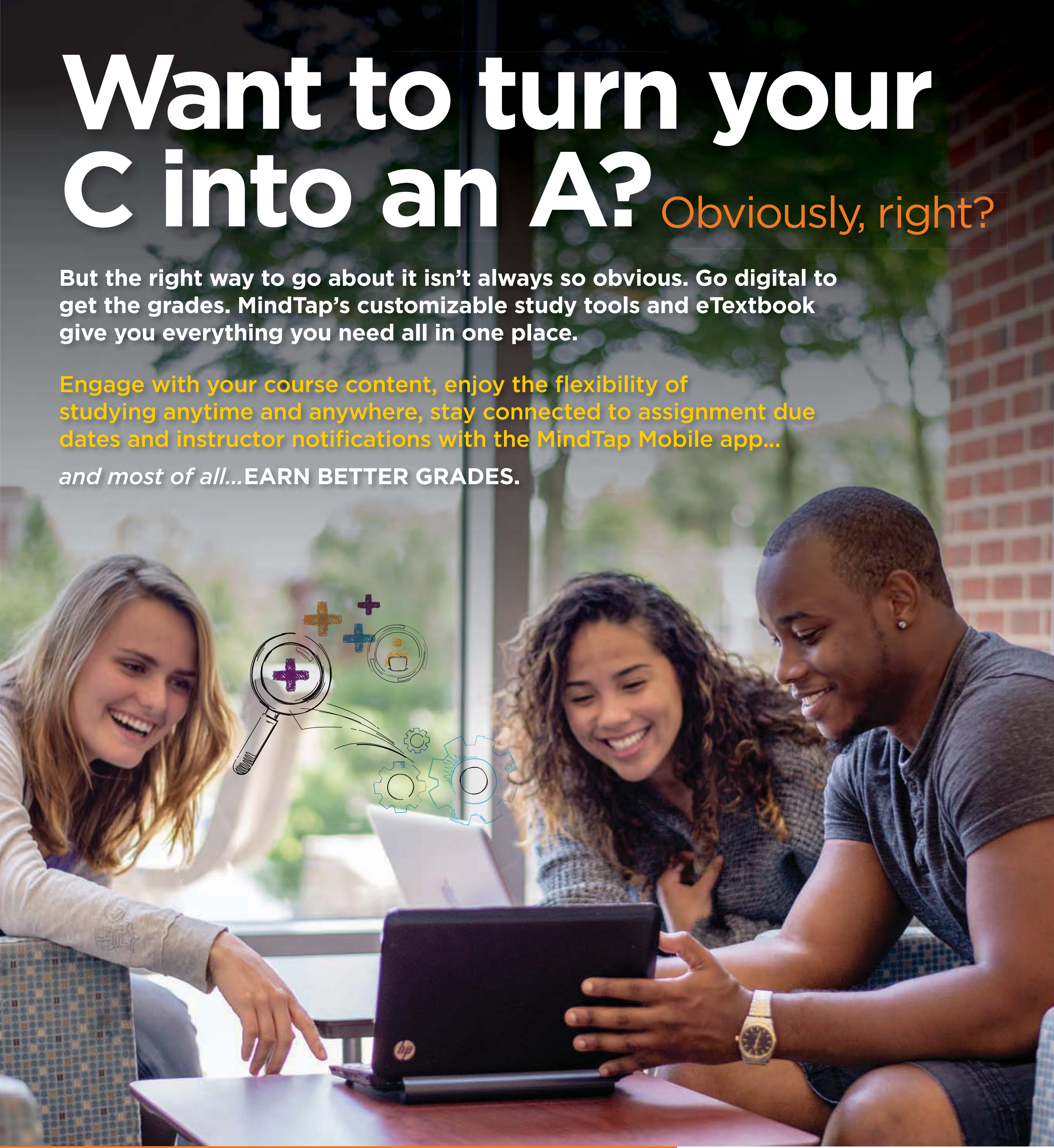
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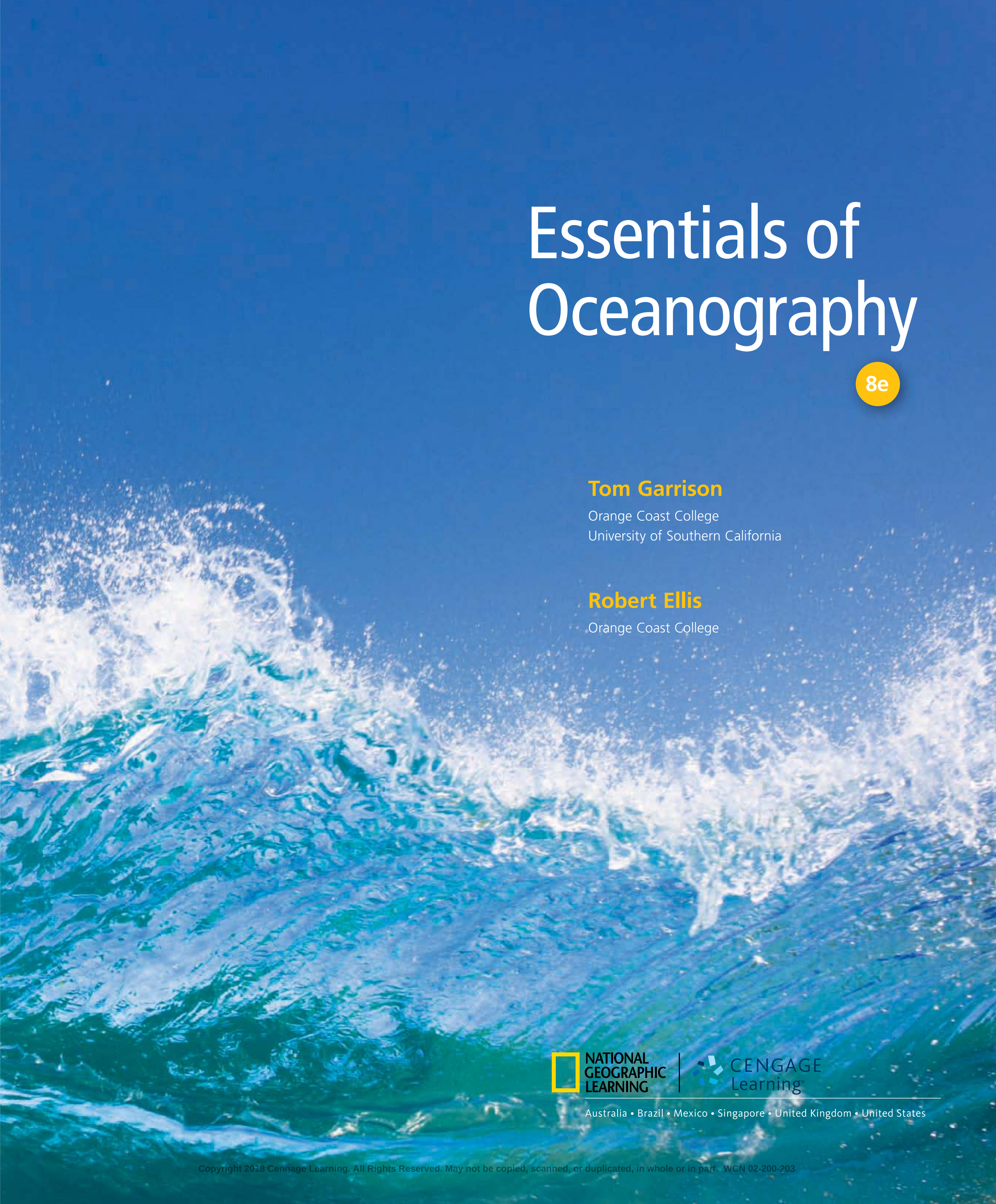

# Essentials of Oceanography

8e

**Tom Garrison**
Orange Coast College
University of Southern California

**Robert Ellis**
Orange Coast College

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To our families and our students,
our hope for the future

# About the Authors

Hank Schellengerhaut, Orange Coast College PR department

**Tom Garrison** (PhD, University of Southern California) was an inspiring professor of Marine Science for over 47 years at Orange Coast College (OCC) in Costa Mesa, California, one of the largest undergraduate marine science departments in the United States. Dr. Garrison also held an adjunct professorship at the University of Southern California. He was named the country's Outstanding Marine Educator by the National Marine Technology Society, was a founding member of COSEE, wrote a regular column for the journal *Oceanography*, and enjoyed writing for *National Geographic* magazine. He was a winner of the prestigious Salgo-Noren Foundation Award for Excellence in College Teaching, and in 1992, 1993, and 1997 was a recipient of the University of Texas NISOD award in recognition of his outstanding contributions in teaching and learning. In 1997, students and faculty at Orange Coast College elected him Faculty Member of the Year. He served as a grants judge for the National Science Foundation in Washington, DC. Dr. Garrison was an Emmy Award team participant as writer and science advisor for the PBS syndicated *Oceanus* television series, and was writer and science advisor for *The Endless Voyage*, a set of television programs in oceanography completed in 2003. His widely used textbooks in oceanography and marine science are the college market's best sellers. In 2009, the faculty of OCC selected Dr. Garrison as the institution's first Distinguished Professor, and in 2010, he was honored by the Association of Community College Trustees as the outstanding community college professor in western North America.

His interest in the ocean dates from his earliest memories. As he grew up with a U.S. Navy admiral as a dad, the subject was hard to avoid! He had the good fortune to meet great teachers who supported and encouraged this interest. Years as a midshipman and commissioned naval officer continued the marine emphasis; graduate school and 42 years of teaching allowed him to pass his oceanic enthusiasm to more than 65,000 students in his career. He retired from full-time professoring in 2011; however, he bothered OCC staff and students on a regular basis right up until his final days.

Dr. Garrison traveled extensively and served as a guest lecturer at the University of Hong Kong, the University of Tasmania (Australia), and the National University of Singapore. He was married to an astonishingly patient lady for nearly 50 years, and had a daughter who teaches in a local public school, a diligent son-in-law, three astonishingly cute granddaughters and a grandson, and a son who, along with his fashionista wife, works in international trade. He and his family lived in and around Newport Beach, California. To most, he was known as Dr. Garrison, the inspiring and enthusiastic professor of marine science, but to a select few he was known as Papa and will forever be remembered as a loving friend, grandpa, dad, and husband.

©Robert Ellis

**Robert Ellis** (M.E.S.M., University of California, Santa Barbara) has been teaching marine, earth, and environmental science courses in both the classroom and the field since 2000. He currently serves as Assistant Professor in the Marine Science Department at Orange Coast College in southern California. When not on campus, Robert often helps to develop and teach international field courses in marine science and management in various parts of the Caribbean, Central America, and South Pacific. His graduate work focused on Marine Resource Management at UC Santa Barbara, and he has participated in and managed research projects and educational programs in many parts of the world. He hopes to have the good fortune to continue to travel and explore the world with his wife, Katie, son, Kalen, and daughter, Abigail.

# Brief Contents



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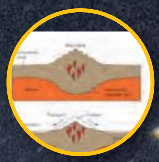
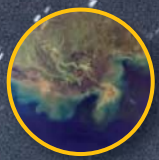
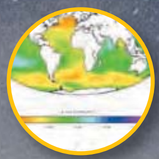
# Contents







# Preface

## The Eighth Edition

Our aim in writing this book was to produce a text that would enhance students' interest in the ocean. Students bring a natural enthusiasm to their study of this subject, an enthusiasm that is greatly enhanced by our partnership with the National Geographic Society. Access to 125 years of archival resources make this National Geographic Learning text uniquely appealing. The most indifferent lecture hall occupant will perk up when presented with stories of encounters with huge waves, photos of giant squid, tales of exploration under the best and worst of circumstances, evidence that vast chunks of Earth's surface slowly move, news of Earth's past battering by asteroids, micrographs of glistening diatoms, and data showing the growing economic importance of seafood and marine materials. If pure spectacle is required to generate an initial interest in the study of science, oceanography wins hands down!

In the end, however, it is subtlety that triumphs. Studying the ocean reinstills in us the sense of wonder we all felt as children when we first encountered the natural world. There is much to tell. The story of the ocean is a story of change and chance—its history is written in the rocks, the water, and the genes of the millions of organisms that have evolved here.

Our students have been involved in this book from the very beginning—indeed, it was their request for a readable, engaging, and thorough text that initiated the project a long time ago. Through the years we have been writing textbooks, our enthusiasm for oceanic knowledge has increased (if that is possible), forcing our patient reviewers and editors to weed out an excessive number of exclamation points. But that enthusiasm does shine through. One student reading the final manuscript of an earlier edition commented, "At last, a textbook that does not read like stereo instructions." Good!

As were its predecessors, this new edition is designed for students who are curious about Earth's largest feature, but who may have little formal background in science. Our goal is to use unintimidating, yet accurate language to create a narrative that showcases many of the wonders of the ocean and use these examples to explain how they relate to important scientific concepts.

## The Plan of This Book

This new edition builds on the established successes of past editions. National Geographic resources have been instrumental in the book's focus on the *processes* of science and exploration. Decades of original art, charts and maps, explorers' diaries, data compilations, artifact collections, and historic photographs have been winnowed and included when appropriate.

Oceanography (also called *marine science*) is broadly interdisciplinary. As always in our books, connections between disciplines are emphasized throughout. Marine science draws on several fields of study, integrating the work of specialists into a unified whole. For example, a geologist studying the composition of marine sediments on the deep seabed must be aware of the biology and life histories of the organisms in the water above, the chemistry that affects the shells and skeletons of the creatures as they fall to the ocean floor, the physics of particle settling and water density and ocean currents, and the age and underlying geology of the study area. This book is organized to make those connections from the first. Readers are invited to see the connections between astronomy, economics, physics, chemistry, history, meteorology, geology, and ecology—areas of study they may once have considered separate.

## Notable Changes to This Edition

This eighth edition of *Essentials of Oceanography* contains a number of substantial changes from the seventh edition. We have significantly streamlined this edition to remove excessive details that can distract students from key concepts. To accomplish this, we have tried to distill complex marine features and processes into a truly "essentials only" textbook that is appropriate for a wide range of students. An underlying goal of this edition was to focus on concise writing. Many of the interesting, but nonessential technical details, past student questions, explorer insights, and the detailed information boxes have been removed so that students can focus on the content without interruptions to the narrative flow.

This edition has a total of 11 chapters compared with the 15 chapters that were in the seventh edition. This allows instructors to cover one chapter a week and still leave time for introductions, exam days, and class activities during the term. We believe these changes result in a student-centered book that illustrates the complexity and beauty of the ocean while making it more economical and therefore accessible to a wider range of students.

Each chapter has been extensively revised to update the content and enhance its presentation with new figures. *Chapter 1: An Ocean World* is a combination of the key components of the seventh edition's first two chapters (Earth and Ocean and A History of Marine Science). The material has been streamlined and unified into a single chapter that describes the Earth's origin and the process by which marine scientists are able to study the ocean. Additional information that reflects our changing understanding of the source of the oceans has also been added. *Chapter 2: Plate Tectonics* has been streamlined and reorganized to put the focus of the chapter on how plate tectonics has shaped ocean features while limiting the historical account of our evolving understanding of Earth's geology. *Chapter 3: The Ocean Floor* is a new chapter that combines material from the previous edition's chapters Ocean Basins and Ocean Sediments. This chapter emphasizes the key features of the seafloor and couples it with the role marine sediments play in our understanding of marine processes.

The next few chapters focus on physical oceanography. *Chapter 4: Water and Ocean Structure* has been revised to improve the flow. It presents a survey of ocean physics and chemistry in preparation for future discussions of atmospheric circulation, classical physical oceanography, and coastal processes. Additional examples have been added and sections that we have found to confuse past students have been rewritten to clarify and emphasize the main points. *Chapter 5: Atmospheric Circulation* has significant changes to the discussion of the Coriolis effect and focuses on more recent storms that students can better relate to. *Chapter 6: Ocean Circulation* incorporates a new example to help understand Ekman spirals and adds a discussion on the 2015–2016 El Niño. *Chapter 7: Waves and Tides* combines two chapters that previously described these topics separately. The previous edition's chapters have been streamlined to focus attention on the similarities and differences among all types of waves and clarify some of the concepts to improve student understanding. *Chapter 8: Coasts* contains new information on sea level rise and a number of new and updated figures to better illustrate the diversity of coasts in different areas of the world.

Our look at marine biology begins with an overview of the problems and benefits of living in seawater, continues with a discussion of the production and consumption of food, and ends with taxonomic and ecological surveys of marine communities. *Chapter 9: Life in the Ocean* begins with a section discussing how life is tied to the ocean. This is a revised section from the previous edition's first chapter that broadens the chapter's discussion and improves the book's overall flow. New figures help to illustrate key concepts. *Chapter 10: Marine Communities* is a new chapter that combines material from the previous edition's chapters Pelagic Communities and Benthic Communities. This information has been significantly reorganized and revised to allow the reader to explore a few of the most interesting and important marine communities and to profile some of their most common organisms. There are a number of new figures and information in this chapter to help students appreciate the diversity and complexity of marine life in the ocean. The last chapter, *Chapter 11: Uses and Abuses of the Ocean*, surveys marine resources and environmental concerns, and illustrates how our present rates of economic growth and environmental degradation are unsustainable. Many of the statistics and figures have been updated to better reflect how humans are impacting the marine environment.

As before, a great many students have participated alongside professional marine scientists in the writing and reviewing process. We have responded to their recommendations, as well as those of instructors who have adopted previous editions of this book. It is our sincere hope that the resulting work accurately reflects the present state of our fast-moving field of science.

## Organization and Pedagogy

A broad view of marine science is presented in 11 chapters, each free-standing (or nearly so) to allow an instructor to assign chapters in any order he or she finds appropriate. Each chapter begins with a list of the **four or five most important concepts** highlighted by a small illustration. An engaging chapter opener photo and caption whets the appetite for the material to come.

The chapters are written in an **engaging style**. Terms are defined and principles are developed in a straightforward manner. Some of the more complex ideas are initially outlined in broad brushstrokes; then the same concepts are discussed again in greater depth after the reader has a clear view of the overall situation. When appropriate to their meanings, the derivations of words are shown. **Measurements** are given in both metric (SI) and American systems. At the request of a great many students, the units are written out (that is, we write *kilometer* rather than *km*) to avoid ambiguity and for ease of reading.

We have modified the **illustration program** to incorporate National Geographic Society assets. The maps, charts,


©Robert Ellis

**A group of students learn navigational techniques before setting sail.**


**Learning about the ocean involves close contact, and often great fun.**

paintings, and photographs drawn from Society archives have greatly enhanced the visual program for increased clarity and accuracy. **Heads and subheads** are written as complete sentences for clarity, with the main heads sequentially numbered.

Each chapter ends with an array of study materials for students, beginning with **Chapter in Perspective**, a narrative review of the chapter just concluded. Important **Terms and Concepts to Remember** are listed next; these are also defined in an extensive **Glossary** in the back of the book. **Study Questions** are also included in each chapter; writing the answers to these questions will cement your understanding of the concepts presented.

**Appendixes** will help you master measurements and conversions, geological time, absolute and relative dating, latitude and longitude, and chart projections. In case you'd like to join us in our life's work, Appendix 6 discusses **jobs in marine science**.

This book has been thoroughly **student tested**. You need not feel intimidated by the concepts—this material has been mastered by students just like you. Read slowly and go step-by-step through any parts that give you trouble. Your predecessors have found the ideas presented in this book to be useful, inspiring, and applicable to their lives. Best of all, they have found the subject to be *interesting*!

## Instructor Resources

### Cognero Test Bank

Cengage Learning Testing Powered by Cognero is a flexible, online system that allows you to:

- Author, edit, and manage test bank content from multiple Cengage Learning solutions


**Father, son, ocean—learning marine science is a joy at any age.**

- Create multiple test versions in an instant
- Deliver tests from your learning management system (LMS), your classroom, or wherever you want

### Instructor's Companion Site

Everything you need for your course in one place! This collection of book-specific lecture and class tools is available online via www.cengage.com/login. Access and download PowerPoint presentations, images, instructor's manual, videos, and more.

## Student Resources

### Earth Science MindTap for *Essentials of Oceanography*

MindTap is well beyond an eBook, a homework solution or digital supplement, a resource center Web site, a course delivery platform, or an LMS. More than 70% of students surveyed said that it was unlike anything they have ever seen before. MindTap is a new personal learning experience that combines

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**A marine science student finds a peaceful place to study on a crisp morning in British Columbia.**

all of your digital assets—readings, multimedia, activities, and assessments—into a singular learning path to improve student outcomes.

### Global Geoscience Watch

Updated several times a day, the Global Geoscience Watch is an ideal one-stop site for current events and research projects for all things geoscience! Broken into the four key areas (geography, geology, meteorology, and oceanography), you can easily find the most relevant information for the course you are taking.

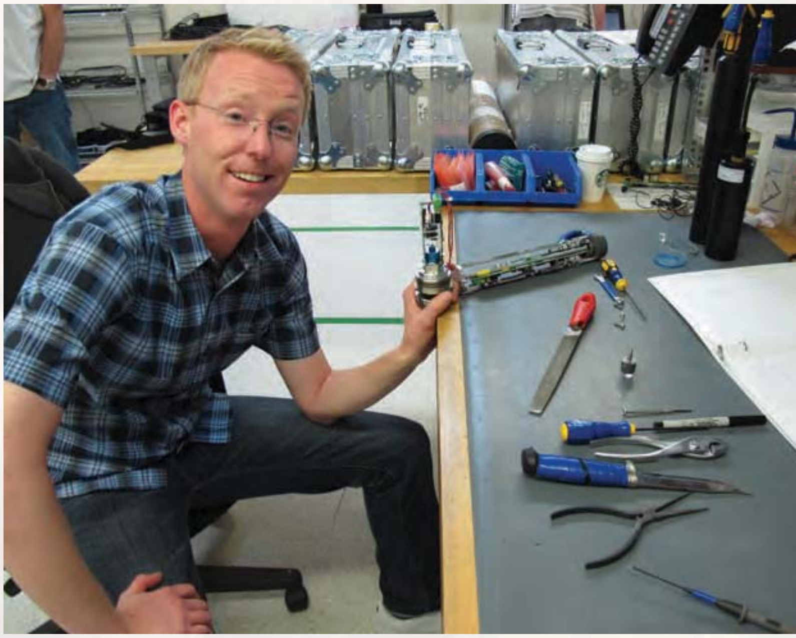
You will have access to the latest information from trusted academic journals, news outlets, and magazines. You will also receive access to statistics, primary sources, case studies, podcasts, and much more!

## Acknowledgments

Many, many years ago, Jack Carey, the grand master of college textbook publishing, willed the first edition of this book into being. His suggestions have been combined with those of more than 1,400 undergraduate students and 175 reviewers to contribute to my continuously growing understanding of marine science. Donald Lovejoy, Stanley Ulanski, Richard Yuretich, Ronald Johnson, John Mylroie, and Steve Lund at the University of Southern California deserve special recognition for many years of patient direction. For this edition, we have especially depended on the expert advice of Wayne Henderson, Kurt Bretsch, Todd Benedict, Anne Gasc, Deborah Friele, Sammy Castonguay, Elizabeth Keddy, Stephen MacAvoy, and Ursula Quillman.

Our long-suffering departmental colleagues Karen Baker, Mary Blasius, Rip Profeta, Dennis Kelly, Don Johnston, Jesus Reyes, Julie Oswald, Lisa Snyder, Joana Tavares-Reager, and our division coordinator, JP Nguyen, again should be awarded medals for putting up with us, answering hundreds of our questions, and being so forbearing through the book's lengthy gestation period. Thanks also to our dean, Tara Giblin, and our college president, Dennis Harkins, for supporting this project and encouraging our faculty to teach, conduct research, and be involved in community service. Our past and present department teaching assistants and student aquarium managers deserve a great deal of praise for helping us develop new educational materials and maintain a positive learning environment for our students, especially Brian Schneiderman, Hannah Rodnunsky, Zane Calendine, Brynne McNabb, Jazmin Eck, Meghan Thompson, Megan Vandewalle, Jillian Demeter, David Krueger, Brittany Rodriguez, Carolynn Rohwer, Tammy Schofield, Casey Moore, Samantha Garcia, Michal Biggerstaff, Leslie Portugal, Jessey Luis, and Jack Bassham.

Yet another round of gold medals should go to our families for being patient (well, *relatively* patient) during those years of days and nights when we were holed up in our respective dark reference-littered caves again working late on "The Book." Thank you, Marsha, Jeanne, Greg, Grace, Sarah, John, Dinara, Alem, Alia, Katie, Kalen, and Abigail for your love and understanding. The many friends and colleagues whom we have bounced ideas off deserve special recognition including Karen Baker, Mary Blasius, Erik Bender, Jim Schneider, Kelli Elliott, Jan Goerrissen, Nick Contopoulos, Jerome Fang, Jenell Schwab, Mary Arbogast, Joana Tavares-Reager, Chris Krajacic, Sarah Sikich, and Andy Balendy.



©Tom Garrison

**A marine technician assembles a sensor. Most oceanographic data are collected by remote sensors like this one.**

©Tom Garrison

**A tourist photographs the steerboard of a restored Viking longship. "Steerboard" became "starboard," the right side of a vessel.**

©Deborah Ellis

**Kayaking in the crystal-clear waters of the tropics can provide relaxation for the entire family.**

The Cengage Learning team performed the customary miracles. The charge was led by Lauren Oliveira, who helped polish the chapters. Sheila Higgins, our copy editor, saved us from many errors. Christine Myaskovsky and Nick Barrows worked tirelessly to assist us in photo research and permissions, and Carol Samet was in charge of production. Kellie Petruzzelli and Lauren Oliveira kept the digital world in line for the book's Web site. The amazing Dawn Giovanniello and Morgan Carney kept us all running in the same direction. What skill!

*My unending thanks to all.*

## A Goal and a Gift

The goal of all this effort: *To allow you to gain an oceanic perspective*. *Perspective* means being able to view things in terms of their relative importance or relationship to one another. An oceanic perspective lets you see this misnamed planet in a new light and helps you plan for its future. You will see that water,

©Tom Garrison

**Despite a severe California drought, these supratidal plants are sustained by heavy morning fogs.**

continents, seafloors, sunlight, storms, seaweeds, and society are connected in subtle and beautiful ways.

The ocean's greatest gift to humanity is intellectual—the constant challenge its restless mass presents. Let yourself be swept into this book and the class it accompanies. Give yourself time to ponder: "Meditation and water are wedded forever," wrote Herman Melville in *Moby Dick*. Ask questions of your instructors and TAs, read some of the references, try your hand at the questions at the end of the chapters.

Be optimistic. Take pleasure in the natural world. Please write to me when you find errors or if you have comments. Above all, *enjoy yourself!*

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University of Southern California

Robert Ellis
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©Zak Noyle/A-Frame

**Trash in the surf in Java, southern Indonesia. Residents dump their waste in rivers that lead to the sea.**

# In Loving Memory of Dr. Tom S. Garrison

*From a daughter to her dad—From a student to her teacher*

On February 24, 2016, Dr. Garrison, my dad, passed away after a long battle with Lymphoma.

To quote my dad's idyllic professor, Earl Pullius, USC, "A teacher is many things...a guide, a model, a modernizer, a searcher, a student, a counselor, and a friend. A teacher is a creator, a doer of routine, a storyteller, and a builder of community. A teacher is a way of being." My dad was the embodiment of this quote. He realized the impact he had on his students, not just in teaching the subject of marine science, but in setting students on the right course by exemplifying the different roles of a teacher, just as Dr. Pullius emphasized.

My dad saw the potential in us all. He called us all "Masters of the Universe." He made all of us want to be better and he made us want to continue growing and pushing forward for the rest of our lives. He celebrated so many victories with *me* and always guided *me* forward when *I* needed it the most, as he did with all his students. As a teacher, my dad was a master at sucking you in to the material through the magic, the mystery, and the astonishing power of his stories and then guiding you on a path that would lead you to exactly where you needed to be. It was then that he would stop and watch you walk ahead, confidently, into your future.

My dad always told me that the most important goal of anyone's life is to be happy. He defined happiness as a state of peace, satisfaction, and friendship. He said it comes from having the education to see the connections between things,

the stability to have meaningful relationships, the ability to get and hold a job, and the desire to make a difference in the world. He always said that Thomas Jefferson was amazingly insightful in basing his vision for a new country on the pursuit of happiness. Not a guarantee, mind you, but the assurance of freedom to pursue whatever you wanted. He also reminded me that there would be hard times and I would need to weather the storms of my own doubts. He encouraged me, as he did with all his students, and was always confident in our abilities to succeed.

He explained to me that teaching is the immortal profession because you have the ability to inspire students long after you're gone. My dad still lives on in me, as I hope he will in all of you. His personality shines through in his textbooks. Growing up, I have fond memories of him sitting at his desk at all hours of the night, listening to classical music and writing. His hope was to pass on his joy, his love of learning, and his knowledge of the ocean to the world. He was a distinguished professor, a world-renowned author, an endearing husband, and a beloved father and friend. He made a difference! I hope he will continue to inspire you to achieve your fullest potential. He told me regularly, "There is much good in this world, go and add to it." This was his motto, along with *citius*, *altius*, *fortius*—faster, higher, stronger. He dedicated his life to his family, his friends, and his students. He wants all of us to know that *we* are his hope for the future. He wants us to find what makes us truly happy and then race, unwaveringly, toward it.

Do as Tennyson suggests in his Ulysses: *To strive*, *to seek*, *to find*, *and not to yield.*

# 1 An Ocean World

## KEY CONCEPTS

The world ocean is Earth's largest surface feature, covering 70.8% of its area. Due to its enormous size, the ocean influences many aspects of life on the planet.

Science is a systematic process of asking questions about the observable world by gathering and then analyzing information.

The materials that formed the Earth and ocean were constructed during the life cycle of stars.

Water vapor from volcanic outgassing and water delivered to Earth during impacts are the most likely sources of the water in Earth's ocean.

Past and current scientific investigations have helped us better understand the ocean's integral role of supporting and influencing life on Earth.

**Nearby stars shine over the ocean as the sun begins to rise in Los Cabos, Mexico.** Earth, its ocean, and all of its inhabitants were formed by unimaginable energies across enormous spans of time. Our story begins here, with the stars.
Kenneth_Wilson/Getty Images

## 1.1 Earth Is an Ocean World

This is a book about the dominant surface feature of a poorly named planet. "Earth" seems a strange name for our home world, 71% of which is covered by an ocean of water.

Traditionally, we have divided this ocean into artificial compartments called *oceans* and *seas*, using the boundaries of continents and relative position on the planet. In fact, the ocean has few dependable natural divisions—only one great mass of water. The Pacific and Atlantic oceans, the Mediterranean and Baltic seas, so named for our convenience, are in reality only temporary features of a single **world ocean**.[1] In this book we refer to the ocean *as a single entity*, with subtly different characteristics at different locations and very few natural partitions. Such a view emphasizes the interdependence of ocean and land, life and water, atmospheric and oceanic circulation, and natural and human-made environments (**Figure 1.1**).

The *ocean* may be defined as the vast body of saline water that occupies the depressions of Earth's surface. On a *human* scale, the ocean is impressively large—it covers 331 million square kilometers (128 million square miles).[2] Its average temperature is a cool 3.9°C (39°F). The average land elevation is only 840 meters (2,756 feet), but the average ocean depth is 4½ times greater! More than 97% of the water on or near Earth's surface is contained in the ocean; only about 2.5% is held in land ice, groundwater, and all the freshwater lakes and rivers. If all Earth's surface water were gathered into a sphere, its diameter would measure only 1,380 kilometers (860 miles) (**Figure 1.2**). The ocean borders most of Earth's largest cities—nearly half of the planet's 7+ billion human inhabitants live within 240 kilometers (150 miles) of a coastline.

On a *planetary* scale, however, the ocean is insignificant. Its average depth is a tiny fraction of Earth's radius—the blue ink representing the ocean on an 8-inch paper globe is proportionally thicker. The ocean accounts for only slightly more than 0.02% of Earth's mass, or 0.13% of its volume. Much more water is trapped within Earth's hot interior than exists in its ocean and atmosphere.

Regardless of the scale in which it is viewed, the ocean's influence on the planet is undeniable. Weather patterns and regional microclimates are significantly affected by the ocean, as is the longer-term global climate. The ocean provides a variety of resources ranging from food and water to energy, construction materials, and life-saving pharmaceuticals. It supports a significant proportion of the biodiversity on the planet and has played a large role in human history and culture through both limiting and promoting trade and providing a means for transportation. The ocean gives us a sense of awe, offers inspiration, and provides many types of recreational opportunities for people all over the world.

## 1.2 Marine Scientists Use the Logic of Science to Study the Ocean

**Oceanography** (or **marine science**) is the scientific study of the ocean, its associated life-forms, and its bordering lands. Marine science draws on many disciplines, integrating the fields of geology, physics, biology, chemistry, astronomy, atmospheric science, anthropology, ecology, computer science, and engineering as they apply to the ocean and its surroundings. Nearly all marine scientists specialize in one area of research, but they also must be familiar with related disciplines and appreciate the linkages between them. **Figure 1.3** shows marine scientists in action.

Marine scientists today are asking some critical questions about the origin of the ocean, the age of its basins, and the nature of the life-forms it has nurtured. We are fortunate to

---

[1] When an important new term is introduced and defined, it is printed in boldface type. These terms are listed at the end of the chapter and are defined in the Glossary.

[2] Throughout this book, SI (metric) measurements precede U.S. measurements. For a quick review of SI units and their abbreviations, please see Appendix 1.

Simon Dannhauer/Shutterstock.com

**Figure 1.1** The ocean influences, and is influenced by, many of the other features on planet Earth. This Costa Rican beach is clearly shaped by a combination of elements including land, ocean, weather, wave energy, living organisms, and nonliving structures.

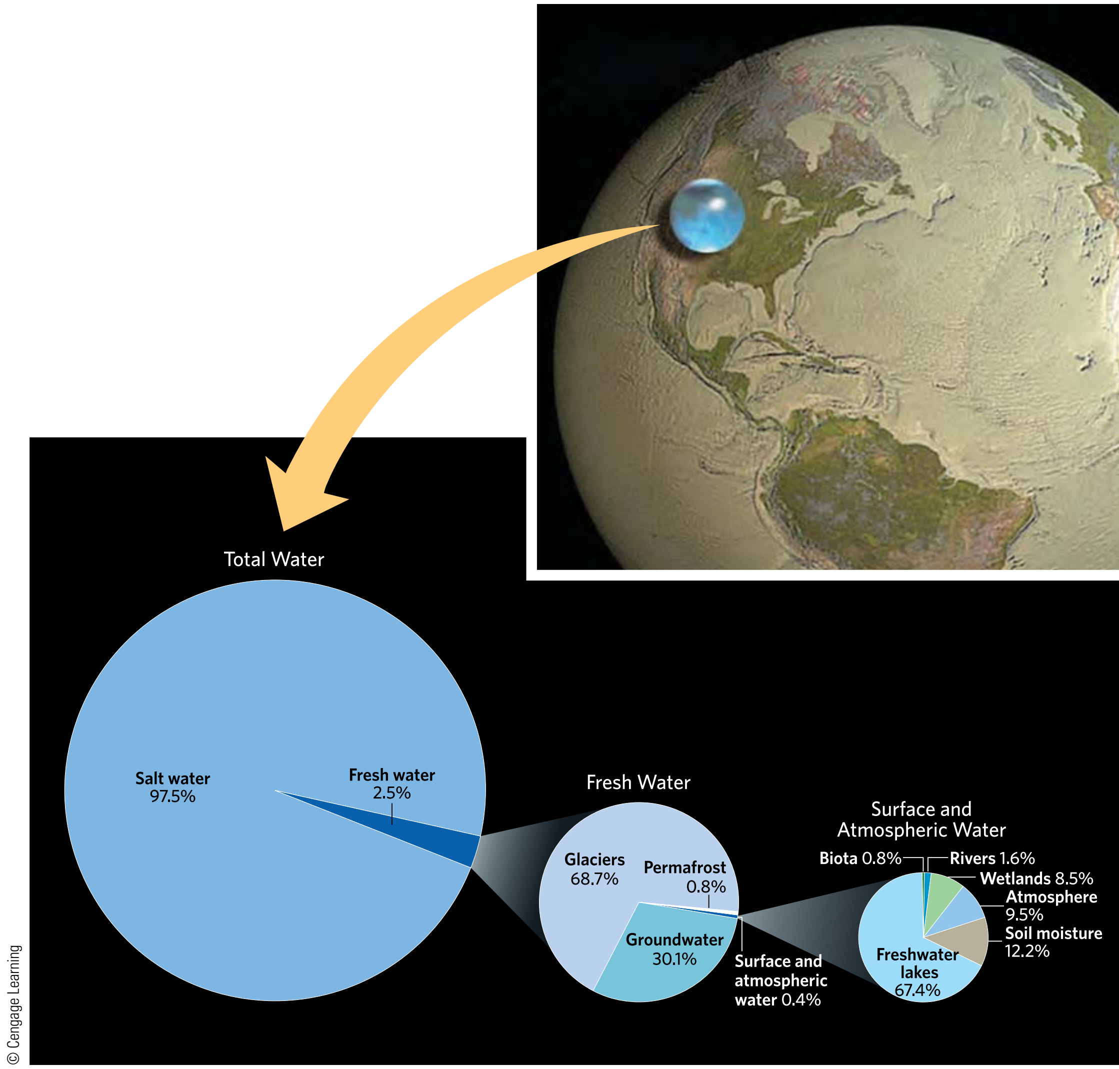



**Figure 1.2** The relative amount of water in various locations on or near Earth's surface. More than 97% of the water lies in the ocean. If all the water at Earth's surface were gathered into a sphere, its diameter would measure only 1,380 kilometers (860 miles).

live at a time when scientific study may be able to answer some of those questions. **Science** is a systematic *process* of asking questions about the observable world by gathering and then studying information (data), but the information by itself is not science. Science *interprets* raw information by constructing a general explanation with which the information is compatible.

Scientists start with a question—a desire to understand something they have observed or measured. They then form a tentative explanation for the observation or measurement. This explanation is often called a working **hypothesis**, a speculation about the natural world that can be tested and verified or disproved by further observations and controlled experiments. (An **experiment** is a test that simplifies observation in nature or in the laboratory by manipulating or controlling the conditions under which the observations are made.) A hypothesis consistently supported by observation, experiment, or historical exploration is advanced to the status of **theory**, a statement that explains the observations. **Laws** are principles explaining events in nature that have been observed to occur with unvarying uniformity under the same conditions. A law *summarizes* observations, usually as a concise mathematical or verbal expression; a theory provides an *explanation* for the observations. *One is not "more true" than the other—both a law and a theory can be statements of facts.*

Theories and laws in science do not arise fully formed or all at once. Scientific thought progresses as a continuous chain of questioning, testing, and matching theories to observations. A theory is strengthened if new facts support it. If not, the theory is modified or a new explanation is sought (science is thus "self-correcting"). The power of science lies in its ability to operate *in reverse;* that is, in the use of a theory or law to predict and anticipate new facts to be observed later.

This procedure, often called the **scientific method**, is an orderly process by which theories are verified or rejected. The scientific method rests upon the assumption that nature "plays fair"—that the rules governing natural phenomena do not change capriciously as our powers of questioning and observing improve. We believe that the answers to our questions about nature are *ultimately knowable.*

There is no one way to conduct science. Some researchers design experiments to investigate their own hypotheses, whereas others observe, describe, and report on a subject and leave it to others to hypothesize. What is called the scientific method is also not a rigid way of looking at an issue. The general method scientists use is a critical attitude

Robert Ellis

**a** A student research team attempts to identify a humpback whale by comparing its unique fluke patterns to previously catalogued individuals.

Ingrid Burke and Stephen Hatosy

**b** Quiet, thoughtful study comes before an experiment is begun and after the data are obtained. A student works with a flashlight on a laboratory report during a power outage at the University of California's Moorea Research Station in the South Pacific.

**Figure 1.3** Doing marine science is sometimes anxious, sometimes patterns, and always interesting.

Philippe Crassous/Science Source

**c** Sometimes marine scientists come up with an unanticipated surprise. Fortunately, this marine worm is very, very small.

about being *shown* rather than being *told*, and taking a logical approach to problem solving. The process is circular and collaborative—new theories and laws always suggest new questions (**Figure 1.4**).

Although clearly powerful in its implications and applications, nothing is ever proven *absolutely true* by the scientific method. Still, the mechanism of science has provided durable, valuable, long-lasting answers to questions about the natural world.

*Science is neither a democratic process nor a popularity contest.* As we can sense from the current acrimonious debates over global climate change or even evolution, conclusions about the natural world that we reach by scientific process may not always be comfortable, easily understood, or immediately embraced. But if those conclusions consistently match observations, they may be considered true.

This textbook shows some of the results of the scientific process as they have been applied to the world ocean. It presents facts, interpretations of facts, examples, stories, and some of the crucial discoveries that have led to our present understanding of the ocean and the world on which it formed. As the results of science change, so will the ideas and interpretations presented in books like this one.

## 1.3 Stars Form Seas

To understand the ocean, we need to understand how it formed and evolved through time. Because the world ocean is the largest feature of Earth's surface, it should not be surprising to find that the origin of the ocean is closely linked to the origin of Earth.

You may be startled to discover that most of the atoms that make up Earth, its ocean, and its inhabitants were formed within stars billions of years ago. The universe's observable mass consists mostly of hydrogen and helium atoms. Stars spend their lives changing this hydrogen and helium to heavier elements such as carbon, oxygen, silicon, and iron through **nuclear fusion**. This process is also responsible for generating the light and heat that influence everything from weather and currents to photosynthesis. As they die, some larger stars can produce even heavier elements and eject these materials into space during cataclysmic explosions known as *supernova* (**Figure 1.5**). The sun and the planets, including Earth, condensed from a cloud of dust and gas enriched by the recycled remnants of exploded stars that disappeared billions of years ago. We are also made of that stardust. Our bones and brains are composed of ancient atoms constructed by stellar fusion long before the solar system existed.

New planets formed in the cloud of dust and debris surrounding the young sun through a process known as **accretion**—the clumping of small particles into large masses. The period of accretion lasted perhaps 30 to 50 million years. Our sun became a star when its internal temperature rose high enough to fuse atoms of hydrogen into helium. The violence of these nuclear reactions sent a solar wind of radiation sweeping past the inner planets, clearing the area of excess particles and ending the period of rapid accretion. Gases like those we now see on the giant outer planets may once have surrounded the inner planets, but this rush of solar energy and particles stripped them away.

## 1.4 Earth, Ocean, and Atmosphere Accumulated in Layers Sorted by Density

The young Earth, formed by the accretion of cold particles within this cloud of dust and gas, was probably chemically homogeneous throughout. Then, in the midst of the accretion phase, Earth's surface was heated by the impact of asteroids, comets, and other falling debris. This heat, combined with gravitational compression and heat from decaying radioactive elements accumulating deep within the newly assembled planet, caused Earth to partially melt. Gravity pulled most of the iron and nickel inward to form the planet's core. The sinking iron released huge amounts of gravitational energy, which, through friction, heated Earth even more. At the same time, a slush of lighter minerals—silicon, magnesium, aluminum, and oxygen-bonded compounds—rose toward the surface, forming Earth's crust (**Figure 1.6**). The lightest of these became the atmosphere. This important process, called **density stratification**, lasted perhaps 100 million years.[3] We can consider the formation of a permanent crust as the "birthday" of Earth, some 4.6 billion years ago.[4]

Earth's surface was so hot that no water could collect there, and no sunlight could penetrate the thick clouds. (A visitor approaching from space 4.4 billion years ago would have seen a vapor-shrouded sphere blanketed by lightning-stroked clouds.) After millions of years the upper clouds cooled enough for some of the outgassed water to form droplets. Hot rains fell toward Earth, only to boil back into the clouds again. As the surface became cooler, water collected in basins and began to dissolve minerals from the rocks. Some of the water evaporated, cooled, and fell again, but the minerals remained behind. The familiar salty world ocean was gradually accumulating.

These heavy rains may have lasted about 20 million years. Large amounts of water vapor and other gases continued to escape through volcanic vents during that time and for millions of years thereafter. The impact of water-containing bodies from space (asteroids and comets) likely delivered additional water.[5] The ocean grew deeper.

The atmosphere was also evolving. Geochemists believe the early atmosphere may have been rich in carbon dioxide, nitrogen, and water vapor, with traces of ammonia and methane. Beginning about 3.5 billion years ago, this mixture began a gradual alteration to its present composition, mostly nitrogen and oxygen. At first this change was brought about by carbon dioxide dissolving in seawater to form carbonic acid, which then combined with crustal rocks. The chemical breakup of water vapor by sunlight high in the atmosphere also played a role. Then about 1.5 billion years later, the ancestors of today's green plants produced—by photosynthesis—enough oxygen to oxidize minerals dissolved in the ocean and surface sediments. Additional oxygen then began to diffuse into the air and accumulate in the atmosphere. (This monumental event in Earth's history is called the *oxygen revolution*.)

## 1.5 Understanding the Ocean: A Short History of Oceanography

Humans are a restless and inquisitive lot, and despite the ocean's great size, we have populated nearly every inhabitable place. This fact was aptly illustrated when European explorers set out to "discover" the world, only to be met by native peoples at nearly every landfall! Clearly the ocean did not prevent the spread of humanity.

Any coastal culture skilled at raft building or small-boat navigation would have economic and nutritional advantages over less skilled competitors (**Figure 1.7**). The first direct evidence we have of **voyaging**, traveling on the ocean for a specific purpose, comes from records of trade in the Mediterranean Sea. The Egyptians organized shipborne commerce on the Nile River, but the first regular ocean traders were probably the Cretans or the Phoenicians.

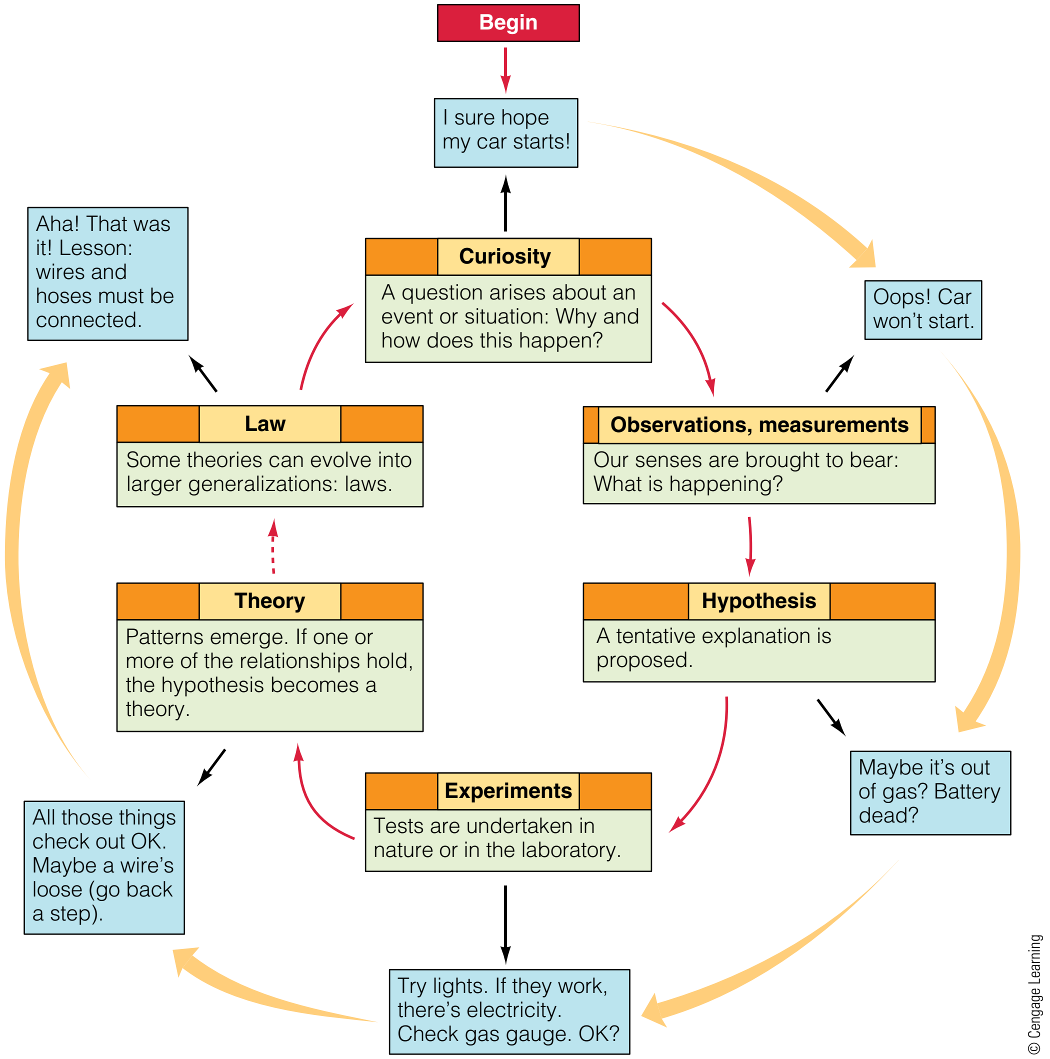
As they went about their business, early mariners began to record information to make their voyages easier and safer—the location of rocks in a harbor, landmarks and the sailing times between them, the direction of currents. The Polynesian peoples learned to interpret more subtle directional clues based off of wind and wave patterns, the sun, moon, and stars, and marine organisms to help them navigate between islands in the Pacific Ocean. Accumulating data for ocean *science*, however, is

[3] Density is an expression of the relative heaviness of a substance; it is defined as the mass per unit volume, usually expressed in grams per cubic centimeter ($g/cm^3$). The density of pure water is 1 $g/cm^3$. Granite rock is about 2.7 times denser, at 2.7 $g/cm^3$.

[4] By the way, regardless of surprisingly persistent opinion, essentially no evidence supports the contention that Earth is between 6,000 and 10,000 years old.

[5] Isotopic ratios suggest that the water found in asteroids is a better match to the water in our ocean than that of comets. Therefore, current evidence points to asteroids as a more likely source of the majority of water that was delivered from impacting bodies.

Figure 1.4 There is no single "scientific method."




**a** In this oversimplistic view, a logical series of steps represents the *procedure* of science. A progression of rational assumptions backed by data (information) leads to a solution to a specific problem. In fact, there is no single way of applying scientific logic applicable to all situations.


Figure 1.5 A dramatic portrait of a star in the early stages of explosive collapse. The bulk of its mass, including the heavy elements constructed during its long life, will be violently ejected into space, perhaps eventually to condense into new stars and solar systems.


**b** The underlying method of science describes an attitude. Scientists like to be shown why an idea is correct, rather than simply being told. All science is a work in progress, never completed. The external world, not internal conviction, must be the testing ground for scientific beliefs. Here, marine scientists are planning an experiment to better understand how small intertidal snails withstand the high temperature of their tropical environment. They have a hypothesis and will design experiments to resolve it.

an activity undertaken by relatively advanced societies with the time and means to satisfy their curiosity. If financial or cultural rewards followed these explorations, so much the better.

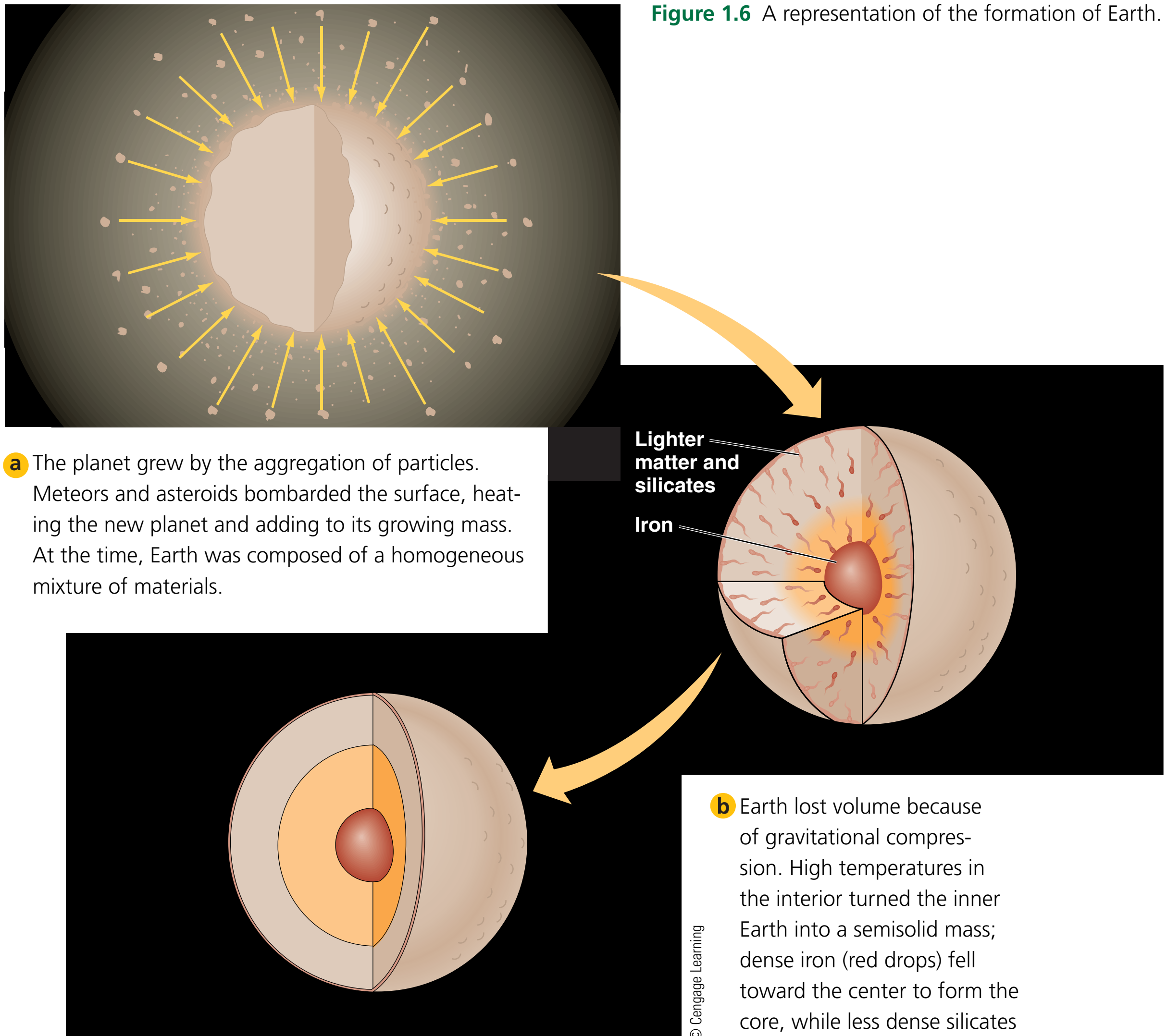
## The Alexandrian Library

Progress in applied marine science began at the **Library of Alexandria**, in Egypt (**Figure 1.8**). Founded in the third century B.C.E. at the behest of Alexander the Great, the library constituted history's greatest accumulation of ancient writings at that time. The library and the adjacent museum could be considered the first university in the world. Written knowledge of all kinds—characteristics of nations, trade, natural wonders, artistic achievements, tourist sights, investment opportunities, and other items of interest to seafarers—was warehoused around its leafy courtyards. When any ship entered the harbor, the books (actually scrolls) it contained were by law removed and copied; the *copies* were returned to the owner and the originals kept for the library. Caravans arriving over land were also searched. Manuscripts describing the Mediterranean coast were of great interest. Traders quickly realized the competitive benefit of this information.

The second librarian at Alexandria was the Greek astronomer, philosopher, and poet **Eratosthenes of Cyrene**. This remarkable man was the first to calculate the circumference of Earth. The Greek Pythagoreans had realized Earth was spherical by the sixth century B.C.E., but Eratosthenes was the first to estimate its true size. Historians estimate that his calculation, made in about 230 B.C.E. and based on the geometric observations of travelers, was accurate to within about 8% of the true value. Within a few hundred years most people in the West who had contact with the library or its scholars knew Earth's approximate size.

**Cartography** (chart making) flourished during this time. The first workable charts that represented a spherical surface on a flat sheet were developed by Alexandrian scholars. Latitude and longitude, systems of imaginary lines dividing the surface of Earth, were invented by Eratosthenes. **Latitude** lines were drawn parallel to the equator, and **longitude** lines ran from pole to pole (see Appendix 5). Eratosthenes placed the lines through prominent landmarks and important places to create a convenient, though irregular grid (**Figure 1.9**). Our present regular grid of latitude and longitude was invented by Hipparchus (c.165–c.127 B.C.E.), a librarian who divided the surface of Earth into 360 degrees. A later Egyptian-Greek, Claudius Ptolemy (90–168 C.E.), *oriented* charts by placing east to the right and north at the top.

Figure 1.6 A representation of the formation of Earth.




a The planet grew by the aggregation of particles. Meteors and asteroids bombarded the surface, heating the new planet and adding to its growing mass. At the time, Earth was composed of a homogeneous mixture of materials.

b Earth lost volume because of gravitational compression. High temperatures in the interior turned the inner Earth into a semisolid mass; dense iron (red drops) fell toward the center to form the core, while less dense silicates moved outward. Friction generated by this movement heated Earth even more.

c The result of *density stratification* is evident in the formation of the inner and outer core, the mantle, and the crust.

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**Figure 1.7** An artist reconstructs the oldest known Greek cargo ship. Used in trade around 390 B.C.E., the lead-sheathed wooden vessel is shown at port on the island of Rhodes. Sailors are loading amphorae of oil for transport to the mainland. A Greek bireme—a warship—is seen in the distance.



**a** The exact site of the Library of Alexandria had been lost to posterity until the early 1980s. By 2004, a theater and 13 classrooms had been unearthed. One of the classrooms is shown here.



**b** A modern Library of Alexandria opened in the spring of 2002. Sponsors of the new *Bibliotheca Alexandrina* hope it will become "a lighthouse of knowledge to the whole world." The goal of this conference center and storehouse is not to restore the past but to revive the ancient library's questing spirit.

**Figure 1.8** The Alexandrian Library.

Ptolemy's division of degrees into minutes and seconds of arc is still used by navigators.

Although it weathered the dissolution of Alexander's empire, the Library of Alexandria did not survive the subsequent period of Roman rule. In 415 C.E., a mob burned the library with all of its contents. The academic loss was incalculable. Trade suffered because shipowners no longer had a clearinghouse for updating the nautical charts and information they had come to depend on. All that remains of the library today is a remnant of an underground storage room and the floors of a few lecture halls.

## Captain James Cook Was the First Marine Scientist

Scientific oceanography as we know it begins with the departure from Plymouth Harbor in 1768 of HMS *Endeavour* under the command of **James Cook** of the British Royal Navy (**Figure 1.10**). An intelligent and patient leader, Cook was also a skillful navigator, cartographer, writer, artist, diplomat, sailor, scientist, and dietitian.

The primary reason for the voyage was to assert the British presence in the South Seas, but the expedition had numerous scientific goals as well. Cook conveyed several members of the Royal Society (a scientific research group) to Tahiti to observe the transit of Venus across the disk of the sun and verified calculations of planetary orbits. He and his men then found and charted New Zealand, mapped Australia's Great Barrier Reef, marked the positions of numerous small islands, made notes on the natural history and human habitation of these distant places, and initiated friendly relations with many chiefs. Cook completed the voyage around the world in 1771. During subsequent voyages in the 1770s Cook went on to discover many other islands and charted the west coast of North America. Because of his insistence on cleanliness and ventilation, and because his provisions included cress, sauerkraut, and citrus extracts, his sailors avoided scurvy—a vitamin C-deficiency disease that for centuries had decimated crews on long voyages.

Cook deserves to be considered a scientist as well as an explorer because of the accuracy, thoroughness, and completeness in his observations and descriptions. He and the scientists aboard took samples of marine life, land plants and animals, the ocean floor, and geological formations; they also reported the characteristics of these samples in their logbooks and journals. Cook's navigation was outstanding, and his charts of the Pacific were accurate enough to be used by the Allies in World War II invasions of the Pacific islands. He drew accurate conclusions, did not exaggerate his findings, and opened friendly diplomatic relations with many native populations. Cook recorded and successfully interpreted events in natural history, anthropology, and oceanography. This first marine scientist peacefully changed the map of the world more than any other explorer or scientist in history.

## Matthew Maury Discovered Worldwide Patterns of Winds and Ocean Currents

Perhaps the first person engaged in full-time oceanographic work was a U.S. naval officer named **Matthew Maury**, who was interested in exploiting winds and currents for commercial and naval purposes. After being crippled in a stagecoach accident, in 1842 Maury was given charge of the navy's Depot of Charts and Instruments. There he studied a huge and neglected treasure trove of ships' logs, with their many regular readings of temperature and wind direction. By 1847 Maury had assembled much of this information into coherent wind and current charts. Maury began to issue these charts free to mariners in exchange for logs of their own new voyages.

Maury was a compiler, not a scientist, and he built on the work of Benjamin Franklin to promote maritime commerce. Nearly a hundred years earlier, Franklin had noticed the peculiar fact that the fastest ships were not always the fastest ships; that is, hull speed did not always correlate with out-and-return time on the European run. Franklin's cousin, a