Fifth edition

the Good Earth

Introduction to Earth Science

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THE GOOD EARTH: INTRODUCTION TO EARTH SCIENCE, FIFTH EDITION

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Preface

Teaching earth science can be viewed as content instruction, covering the principles of science and earth systems. But can it also be considered as an opportunity to *engage* students in the nature of scientific inquiry?

A traditional science instructor concentrates on teaching factual knowledge, with the implicit assumption that expert-like ways of thinking about the subject come along for free or are already present. But that is not what cognitive science tells us. It tells us instead that students need to develop these different ways of thinking by means of extended, focused, mental effort.

Carl Wieman
Nobel Prize winner

For many, the wonder of Earth and its features is enough to drive learning. For these happy few, a readable book with lots of attractive photographs is almost all that is required. *But for many—in fact most—learning takes more than pretty words and pictures.* Providing high-quality teaching is the most cost-effective, tangible, and timely effort that geoscience instructors can make to improve student engagement, increase attendance, and add majors.

But how do we do that? There is extensive literature describing what effective teaching looks like, but most science instructors have not had access to these articles and books. Further, few of us were ever explicitly taught the components of good teaching. Instead, we were left to figure it out for ourselves on the basis of our classroom experiences as students.

The Good Earth was published to support both the traditional earth science class ***and*** to serve as an accessible resource for instructors seeking to apply effective teaching strategies to enhance learning.

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The Good Earth *Difference*

We wrote *The Good Earth* to support an active learning approach to teaching and to provide the necessary resources for instructors moving through the transition from passive to active learning. Like you, we want our students to walk away from this course with an appreciation for science and the ability to make life decisions based on scientific reasoning.

Our goal was to write a book that was engaging for students but that also included resources that illustrated for instructors how to use teaching practices that have been shown to support student learning. The materials and methods discussed in the text and the accompanying *Instructor's Manual* have been tried and tested in our own classes. Our research shows that the integration of the materials and pedagogy provided in this book not only improved students' understanding of earth science as measured

I like the fact that the authors are mindful and well versed in science education research and pedagogy. This aspect of the author's background is evident in the design of the Checkpoint questions.

The use of Concept Maps and Venn Diagrams is fairly cutting edge for introductory Earth Science textbooks that I am familiar with. This is probably the most innovative aspect of this book and distinguishes it from similar texts, even though the content is presented very similarly to other texts.

Jeffrey Templeton
Western Oregon University

by standardized national tests, but it can also improve students' logical thinking skills by twice as much as a typical "traditional" lecture class. Such methods are overwhelmingly preferred by students and increase student attendance and satisfaction with the course. Finally, a significant point for us is that these methods make teaching class more fun for the instructor.

> *I love the voice the authors use. Reading the text is like listening to a very intelligent but down-to-earth friend explain a difficult topic. The authors are excellent at organizing and presenting the material. . . . The illustrations are superior to other texts in all ways.*
>
> *Patricia Hartshorn*
> *University of Michigan–Dearborn*

Student-Centered Research

The Good Earth can be used as a text for a traditional, teacher-centered lecture-based course. In fact, we have taken great care to write a book that students would find more engaging than a typical text. But the greatest benefit will come when the book is used as part of an active-learning, student-centered course. For some instructors, it may simply be a matter of adding some of our exercises to an existing active-learning class environment. For others, the book and accompanying materials will give them an opportunity to add components as they gradually change their pedagogy. If you want a more interactive class, try one or all of the following three recommendations based on research findings:

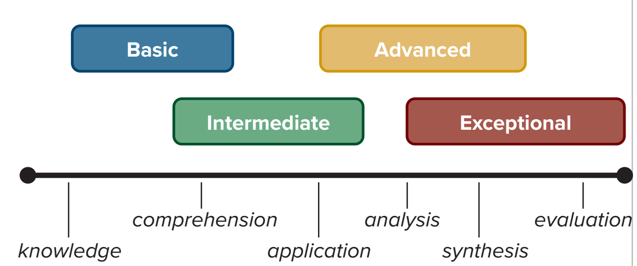
1. Students learn key concepts better when they have opportunities to actively monitor their understanding during class. Rather than just standing up and talking, the instructor can break lectures into segments separated by brief exercises to make sure that students understand concepts before moving on. Students' understanding must be frequently challenged to provide an opportunity to identify misconceptions and replace them with improved, more realistic models.

> *I truly love the practice concept questions, which align with the lecture tutorials I use in class*
>
> *David Ludwikoski*

   The Good Earth includes hundreds of Checkpoint exercises that can also be used as handout-ready PDF files (located on the text website along with answer keys). Practice makes perfect: the more opportunities students have to assess their learning and to practice the application of new skills, the better their performance. If you are concerned about reduced time for lecture, we have found that an emphasis on fostering deeper understanding and less content coverage in lecture, combined with greater student responsibility for reading, produced no decrease in content knowledge attainment and improved student comprehension of key concepts. Some exercises can be assigned as homework, and the answer key in the back of the book can help students to assess their self-directed-learning.

2. Students become better learners when we challenge them to answer questions that require the use of higher-order thinking skills (for example, analysis, synthesis, evaluation). Brain research shows that people become smarter when they experience cognitive challenges. However, it is important not to throw students into the deep end without any help. Instead, instructors need to step through a series of problems of increasing difficulty (scaffolding) so that they can train students to correctly apply their newly acquired thinking skills.

   Therefore, we have carefully created a series of color-coded **Checkpoint** exercises for each section of every chapter. The exercises are pitched at four skill levels: basic, intermediate, advanced, and exceptional, to give students and instructors an opportunity to scaffold student understanding of key concepts. The questions represent four levels of Bloom's taxonomy. Blue and green questions typically are comprehension and application-level questions. Yellow and red checkpoints typically require analysis, synthesis, or evaluation skills. It is not necessary to complete all the exercises; instructors can select the exercises that are most appropriate for their learning goals.



> *This was kind of a neat idea, and the questions [Checkpoints] do get quite challenging at higher orders. I feel these are good things for students to do while studying, with the idea that if they understand the higher order questions they will understand concepts better for exams. I thought these checkpoints have some very well-formulated questions in the chapters I reviewed.*
>
> *Swarndeep Gill*
> *California University of Pennsylvania*

Sort ...

Checkpoint 11.1: Basic

Sort the following 12 terms into six pairs of terms that most closely relate to one another. Explain your choices.

groundwater	plants	transpiration
stream	ice	infiltration
rainfall	precipitation	water vapor
gas	meltwater	runoff

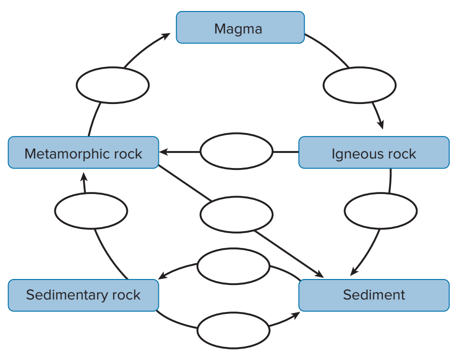
Match the lettered responses ...

Checkpoint 7.22: Intermediate

Rock Cycle Diagram

The following diagram illustrates some of the interactions of the rock cycle. Match the lettered responses to the blank ovals on the diagram. (*Note:* Some letters are used more than once.) Example: If you believe that metamorphic rock is converted to magma by cementation and compaction, enter "a" in the top left oval.

a. Cementation and compaction (lithification)
b. Heat and pressure
c. Weathering, transportation, deposition
d. Cooling and solidification
e. Melting



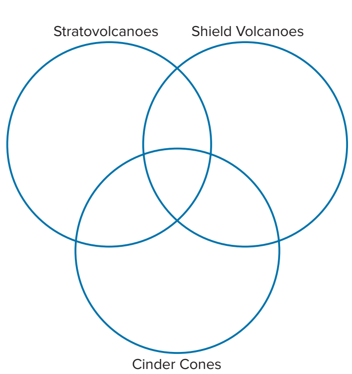
Checkpoint 6.19: Advanced

Venn Diagram: Shield Volcanoes, Stratovolcanoes, and Cinder Cones

Compare and contrast ...

Use the Venn diagram provided here to compare and contrast the three principal types of volcanoes. Place the number corresponding to features unique to each type in the larger areas of the circles; note features they share in the overlap area in the center of the image. Five items are provided; identify at least 12 more.

1. Associated with subduction zones
2. Have a triangular shape in profile
3. Example: Mount Hood, Oregon
4. Mild eruptions
5. Intermediate-silica magma



Evaluate the five most important factors ...

Checkpoint 12.12: Exceptional

Groundwater Evaluation Rubric

You are asked to help locate a new aquifer that will supply your town with water. In examining the potential sites, you recognize that several different factors will influence groundwater availability and at no single site are all of the factors optimal. You decide to create a scoring scheme to evaluate the most important factors that will influence the availability of groundwater. The location that scores the highest according to the rubric will be selected for the well field. One factor is included as an example in the table below; identify five more.

Factors	Poor (1 point)	Moderate (2 points)	Good (3 points)
Depth to water table	Deep	Intermediate	Shallow

I have to compliment you on putting together Checkpoint 3.3. This was probably the best evaluation tool I have seen for determining whether a student really understands the meaning of the words we use to describe the scientific methods (hypothesis, prediction, etc.).

Neil Lundberg
Florida State University

3. Knowledge is socially constructed and people learn best in supportive social settings. Students do not enter our classrooms as empty vessels to be filled with knowledge. Instead, they actively construct mental models that assimilate new information with previous experiences. This construction of knowledge happens most readily when students work in small collaborative groups (three to four students), where they can talk and listen to peers as they build their understanding of new concepts. Students must be provided with opportunities to be self-reflective about their learning and to help them learn how to learn. Our research confirmed that students in classes where small groups worked to solve challenging problems outperformed students in classes where they worked on the same problems independently.

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It is set up very user friendly and will make it easy for instructors to create an interactive learning environment. Also, the way the chapters and questions are laid out, students will know exactly what they should be getting from the chapter and how to test their knowledge and skills.

Jessica Kapp
University of Arizona

Whether you choose to use informal groups ("turn and talk to your neighbors") or formal groups determined by experiences (for example, number of science classes, scores on pretests, academic rank), collaborative learning is a powerful mechanism for maintaining attendance, increasing student-instructor dialogue, and enhancing learning. The Checkpoint exercises (especially advanced and superior level) and conceptests (conceptual multiple choice questions) provided with the book will give you many assignments that you can use as the basis for group work.

For detailed information regarding concept maps, Venn diagrams, Bloom's taxonomy, assessment, and so forth, please consult the *Instructor's Manual*.

Tools for Teaching and Learning Science Literacy

Science can be thought of in three ways: as a body of knowledge, as the processes that people employ to explain the universe, and as a set of attitudes and values possessed by those who "do science." This latter aspect is often overlooked in college science textbooks. For each chapter of *The Good Earth,* the *Instructor's Manual* gives suggestions for incorporating into class discussion science attitudes and values such as open-mindedness, skepticism, persistence, and curiosity.

Additionally, the discussion of the **scientific method** is woven throughout the text. We emphasize three scientific themes throughout the text: 1) scientific literacy, 2) earth science and human experience, and 3) the science of global change. Numerous examples of human interaction with Earth serve as introductions to each chapter. Each chapter includes examples of the connection between science and technology, and builds on a context or event familiar to the student. We believe that links to students' past knowledge and experience are essential foundations upon which to build deeper understanding.

In addition to the theme of global change permeating the text, we devote a full chapter to the topic and do not duck the tough issues related to it. We use data and evidence to help students build their own understanding and assist them to realize that *"Much of what lies ahead for the good Earth is up to us. Know, care, act."*

I am pleased to see the final chapter on global change; most students assume that climate change is a political debate, so it is nice to see a textbook that discusses the science behind the news.

Bryan C. Wilbur
Pasadena City College

Ways to Direct Learning

We begin each chapter with a handful of learning outcomes. Think of these as the main things that students should be able to when they finish the chapter. To get to these larger goals, we need to build a solid foundation of smaller facts and concepts. We help do this by providing additional sets of learning objectives at the beginning of each section in the chapter. By making the learning objectives explicit, we are encouraging students to frequently reflect on their reading to make sure that they understand the principal concepts for each section. Further, it gives the instructor the opportunity to readily emphasize key aspects of their lessons, rather than have the students struggle to figure out what they are supposed to be learning.

Rather than put key vocabulary terms in bold, we put **key concepts** in bold font. Our rationale is that conceptual understanding is the goal; vocabulary terms alone may not lead to the understanding that we desire. Research suggests that listing key terms encourages the memorization of those terms, rather than the understanding of the associated concepts—rather like learning words in a foreign language but being unable to put together a sentence. To make students fluent in science, we chose to focus on

National Committee on Science Education Standards and Assessment

National Research Council

LEARNING SCIENCE IS AN ACTIVE PROCESS. Learning science is something students do, not something that is done to them. In learning science, students describe objects and events, ask questions, acquire knowledge, construct explanations of natural phenomena, test those explanations in many different ways, and communicate their ideas to others. Science teaching must involve students in inquiry-oriented investigations in which they interact with their teachers and peers.

FOCUS AND SUPPORT INQUIRIES. Student inquiry in the science classroom encompasses a range of activities. Some activities provide a basis for observation, data collection, reflection, and analysis of firsthand events and phenomena. Other activities encourage the critical analysis of secondary sources—including media, books, and journals in a library.

ENCOURAGE AND MODEL THE SKILLS OF SCIENTIFIC INQUIRY, AS WELL AS THE CURIOSITY, OPENNESS TO NEW IDEAS, AND SKEPTICISM THAT CHARACTERIZE SCIENCE.

USE MULTIPLE METHODS AND SYSTEMATICALLY GATHER DATA ON STUDENT UNDERSTANDING AND ABILITY. Because assessment information is a powerful tool for monitoring the development of student understanding, modifying activities, and promoting student self-reflection, the effective teacher of science carefully selects and uses assessment tasks that are also good learning experiences.

a vocabulary that builds students' conceptual understanding of major ideas in earth science. These ideas were recommended by standards-setting groups, such as the American Association for the Advancement of Science (AAAS).

Students can use the Checkpoint surveys to self-evaluate their comprehension of the major concepts in the section. Self-evaluation is a life skill that persists far longer than the evaluation imposed by an outside party (that is, the instructor). We believe in ongoing assessment tied to each key concept while ideas are still fresh. In contrast, other texts may provide tools for assessment only at the end of the chapter, after all of the content has been covered.

Often students have some fundamental knowledge of earth science and, when reminded, are able to apply this information to the introduction of new concepts. Each chapter includes a **Self-Reflection Survey** to promote awareness of personal experiences. These are presented at the beginning of each chapter to encourage students to recognize that they already may know something about the chapter topic or may have had a relevant experience.

Self-Reflection Survey

Respond to the following questions as a means of uncovering what you already know about Earth and earth science.

1. Which of the following earth science phenomena have you experienced? Which would you most like to experience? Can you think of three more things to add to the list?
   - A volcanic eruption
   - A glacier
   - A river in flood
   - A cave system
   - An underground mine
   - A canyon
   - An earthquake
   - An erosional coastline (rocky cliffs)
   - A depositional coastline (beaches)
   - A hot desert
   - A continental divide
   - Rock layers with fossils
   - A big, assembled dinosaur skeleton
   - A meteor shower or comet
   - The aurora borealis (the northern lights)
   - A meteorite crater
   - A mountain range over 3,000 meters (over 10,000 feet) in elevation
   - The top of a cloud
2. What three questions about Earth would you like to be able to answer by the end of this course?

Self-Reflection Survey

Answer the following questions as a means of uncovering what you already know about global change.

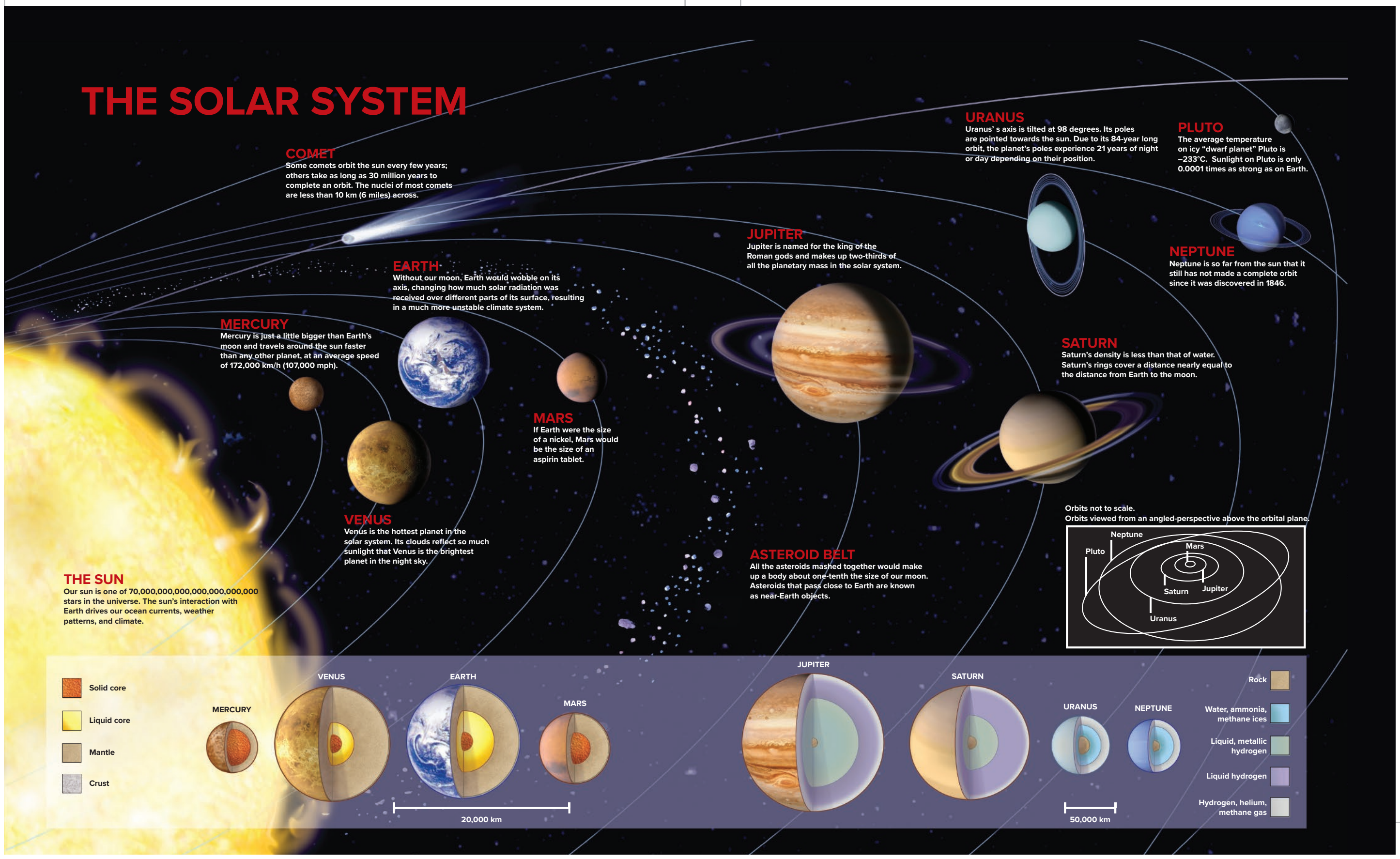
1. Respond to the following questions taken from a recent Gallup poll, and compare your selections to those of other respondents. (See footnotes to compare responses.)

   I. Thinking about the issue of global warming, how well do you feel you understand this issue? Would you say very well, fairly well, not very well, or not at all?
      a. Very well.
      b. Fairly well.
      c. Not very well.
      d. Not at all.
      e. No opinion.

   II. Which of the following statements reflects your view of when the effects of global warming will begin to happen?
      a. Already begun.
      b. Within a few years.
      c. Within my lifetime.
      d. Not within my lifetime, but it will affect the future.
      e. Will never happen.
      f. No opinion.

   III. Thinking about what is said in the news, in your view is the seriousness of global warming generally exaggerated, generally correct, or generally underestimated?
      a. Generally exaggerated.
      b. Generally correct.

Visuals are of great importance for understanding earth science concepts. *The Good Earth* features two-page **Snapshots** to emphasize an important concept in every chapter.



We frequently hear complaints that students don't get the **Big Picture** and become lost in the vocabulary or in trying to memorize facts. We responded to this concern by connecting a chapter- opening "Big Picture" question and photo to the end-of-chapter summary, titled **The Big Picture,** to help students link the key concepts before moving to a new chapter.

the big picture

© Jupiterimages/ Getty Images

When Mount St. Helens began rumbling in 1980, teams of scientists rushed to the mountain with truckloads of instruments to monitor the activity. Still, the May 18 eruption came as a surprise. Despite the experience of the scientists and the sophistication of the devices they deployed, little detailed information on the eruptive history of the volcano had been gathered beforehand and few monitoring instruments had been collecting data. That is no longer the case. In the past quarter-century, scientists have made a concerted effort to place a variety of instruments around the volcano, and even in space, to monitor every rumble and movement. Even with what they know today, it is unlikely that volcanologists would have predicted the precise time of the May 18 eruption. But they would have known enough to have more vigorously encouraged the authorities to move people farther from the volcano itself, dramatically reducing the loss of life.

Educating the public is an important factor in reducing the effects of hazards such as volcanoes. Education should provide a scientifically literate population with the necessary skills to critically respond to scientists' assertions. Deciding what evidence to dismiss and what to pay attention to might mean the difference between life and death for those who live in the shadow of an active volcano. The people living near Mount St. Helens in 1980 weighed the evidence and the accompanying call to action. Some heeded the call to evacuate, while others ignored the evidence provided by the volcanologists, chose to hold their ground, and paid for their decision with their lives.

Mount St. Helens is one of only a few US volcanoes with such a high degree of monitoring. However, the US Geological Survey plans to create a National Volcano Early Warning System that would identify the most threatening volcanic hazards, including the number of people and the extent of property endangered. A preliminary assessment of volcanic threat identified more than 50 volcanoes as high-threat or very-high-threat sites and recommended that each volcano have an extensive network of monitoring equipment to identify the first signs of unrest. Few such networks are currently deployed, and some of these volcanoes have no monitoring systems at all.

One of the volcanoes in the very-high-threat group is Mount Rainier, pictured looming over Tacoma, Washington, at the beginning of this chapter. At 4,392 meters (14,410 feet), Mount Rainier is the tallest and most imposing volcano in Washington. It is located about 70 kilometers (43 miles) southeast of Tacoma. What questions would you ask if you lived in Tacoma?

Historical records indicate that Mount Rainier does not erupt with the frequency of Mount St. Helens. The distance of the peak and the prevailing westerly winds make it unlikely that tephra would ever reach Tacoma. In addition, lava flows and pyroclastic debris would not extend beyond the foot of the mountain, staying tens of kilometers short of Tacoma. Still, large lahars have the potential to reach the northern suburbs of the city and enter neighboring Puget Sound. Even if Tacoma is safe, many smaller towns lie in stream valleys just a 10-minute trip from the volcano by lahar. It is the residents of towns such as Ashford, Packwood, and Orting (Figure 6.33) who need an early warning system for volcanoes.

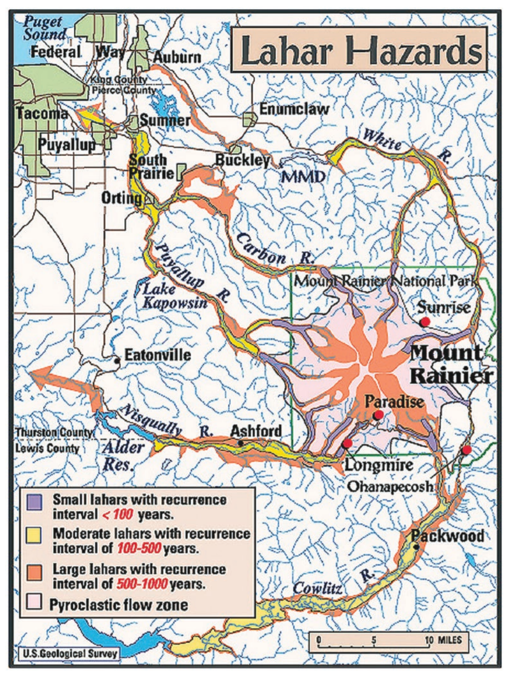


Figure 6.33 Lahar hazards map. Lahar hazards associated with Mount Rainier, Washington.
Source: USGS

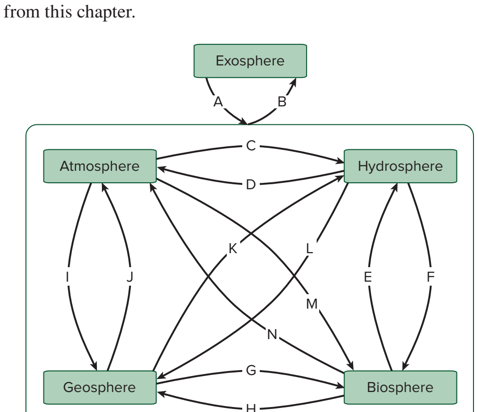
they are formed by movements on faults, movements that generate damaging earthquakes. Building a mountain range like the Himalayas involves thousands of faults that generate millions of earthquakes. Unfortunately, major earthquakes are still common

Interaction	Letter
Eruption melted ice on Nevado del Ruiz to cause fatal lahars.	
Sulfur dioxide blocks incoming sunlight.	
Added water causes partial melting of mantle.	
Volcanoes add CO_2 and sulfur dioxide to atmosphere.	
Commercial airlines are at risk from tephra clouds.	
Solar radiation heats Tibetan plateau.	
Rain strips CO_2 from atmosphere.	
Krakatau eruption generated massive tsunami.	
Tephra is carried downwind over cities.	
Some 500 million people are in risk zones for volcanoes; trees are knocked down.	
Industrial materials are swept into rivers and lakes from mudflows.	
Monsoon rains result from air rising over Himalayas.	
Weathering processes break down rocks in mountains.	
Instrumentation of volcanoes.	

...other young mountain belts. ...uth-central China, at the east- ...hed whole towns, killed more ...5 million homeless. The unrest continues; Earth at this very moment is shifting, rumbling, building, and decaying. We must carefully observe and prepare.

Volcanoes and Mountains: Concept Map

Volcanoes and mountains are part of the larger complex system related to plate tectonics. Complete the following concept map that illustrates the components, interactions, mass and energy flow, and feedback mechanisms associated with plate tectonics and the formation of volcanoes and mountains. Match the following interactions with the lettered labels on the figure, using the information from this chapter.



Numerous diagrams, photos, and tables support visual processes and concepts.

a.

b.

Figure 6.15 Hawaiian lava. **a.** Flow of hot, fluid, low-viscosity basalt lava from Kilauea in June of 2018 forms a braided channel on its way to the ocean. The lava is flowing 24 km/hr (15 mi/hr) near the vent and about 1/10th that fast as it nears the ocean. **b.** Many homes were destroyed in the Hawaiian subdivision of Leilani Estates in May of 2018 when a fissure opened and lava from Kilauea volcano invaded the neighborhood. These flows can be many meters thick. Note the width of the road. How thick is the lava at this location?
Source: 6.15a: USGS; 6.15b1-3: USGS

a.

b.

Figure 8.14 Recently discovered Tiktaalik fossil. **a.** This is a transitional fossil between fish and amphibians. The fossil was discovered on Ellesmere Island, Canada, in 375 million-year-old rocks. Several individuals were found, some up to nearly 3 meters (9 feet) long. **b.** A re-creation of what Tiktaalik may have looked like in life.
Source: 8.14a: Corbin17/Alamy Stock Photo; 8.14b: Zina Deretsky, National Science Foundation

To further aid in the understanding of earth processes, many figures include a simple drawing to portray a **Geologist's View.**

a.

b.

Geologist's View

Figure 5.6 Signs of movement on a fault. Movement on a 44-kilometer-long (27-mile-long) fault caused the Hebgen earthquake in Montana in 1959. **a.** The fault broke the surface near a ranch (background). **b.** The fault can be followed for several kilometers along the south flank of Kirkwood Ridge in the center of the image.
Source: 5.6a: USGS; 5.6b: USGS

How Is This Text Organized?

The Good Earth covers the primary topics included in other earth science texts. However, there are a few notable differences in its content compared to other textbooks.

The Good Earth begins with an introduction (Chapter 1), then takes up the topic of astronomy (Chapters 2, 3), and moves on to solid earth (Chapters 4, 5, 6, 7, 8) and the processes that occur on Earth's surface (Chapters 9, 10, 11, 12), which overlap with the hydrosphere (Chapters 11, 12, 13), before dealing with the atmosphere (Chapters 14, 15, 16) and finishing with a wrap-up chapter on global change (Chapter 17) that incorporates elements of all the previous chapters.

Astronomy is dealt with early in the text (Chapters 2 and 3) from the context of Earth's position in space. By beginning with Earth's place in the universe, we give students a "big picture," set the context for looking at the uniqueness of this planet in contrast to our neighbors in space, and hopefully, inspire a bit of wonder in the reader. In both chapters, we grab the reader's attention by emphasizing space from a human perspective. We believe this provides a more appealing beginning to an earth science class than the traditional several weeks spent discussing minerals, rocks, and weathering. Chapter 2, in particular, guides students to see methods that scientists employ as they build our knowledge of the planet and its place in the universe.

Plate tectonics appears early (Chapter 4). We introduce this important unifying concept at the beginning of the text and then use it as a foundation to introduce other solid earth topics (for example, earthquakes, volcanoes). Because an understanding of plate tectonics is pivotal to all the content that follows in subsequent chapters, we revisit this concept several times, thereby showing students the interrelationships among the other solid earth topics, such as rock formation, earthquakes, and volcanoes.

Driven by recent research findings, we have chosen to emphasize some topics that are discussed briefly or not at all in other earth science texts. We have included chapters on the threat of a collision with near-Earth objects (Chapter 3), Earth's climate system (Chapter 16), and global change (Chapter 17). In addition, the continuing debate about the teaching of creationism in the public schools has lead us to address this topic head-on in our treatment of geologic time (Chapter 8).

New in This Edition

A major change in this edition is the addition of eight new chapter introductions, six written by guest authors. Chapters 1, 2, 5, 8, 10, 12, 13, and 15 all feature new introductions. Our guest authors discuss human explorations of space, the controversy over a new interval of geologic time, the study of dangerous landslides, one state's challenge with managing its groundwater, the potential human consequences of sea level rise, and the explanation of why our hottest and coldest temperatures are not recorded in the middle of the day and night.

There are many structural changes evident in this edition. The e-text is now easily used on mobile devices as well as tablets and PCs.

Additional updates to this edition include:

- Many photos have been updated and changed to be more current and better illustrate concepts
- Revisions to selected checkpoint questions throughout the chapters
- New tables featuring more recent data
- References and discussions have been updated to include:
  - More complete descriptions of geo-scientific ways of thinking and habits of mind, dwarf planets, and the expansion of the universe
  - Additional concepts related to the characteristics of complex systems and the Earth as a system
  - More data and discussion related to extra-solar planets, dwarf planets, and the expansion of the universe
  - Updated statistics related to energy use in the US
  - Updates on changes to sea ice extent in the Arctic and the impacts on local and global ecosystems
  - Expanded discussion of global sea level changes and temperature changes
  - Additional information relate to global carbon emissions and how they compare to the past
  - Discussion of projections from recent climate models and implications for future climates
- Figures have been updated and/or replaced throughout the text to better illustrate key concepts and to provide updated data.

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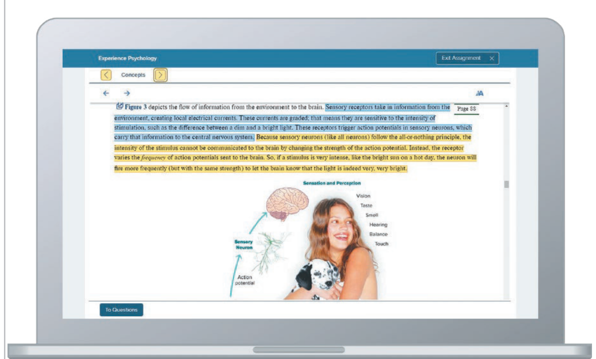

Laptop: McGraw-Hill; Woman/dog: George Doyle/Getty Images

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about the authors

The original version of The Good Earth was a product of a team of educators from the geosciences, science education, and cognitive psychology whose combined expertise created this text to teach essential earth science content in an engaging and cognitively supportive way. We wish to thank our colleagues Kathie Owens, Cathy Knight, and Lisa Park for their contributions to the textbook through the first two editions. The writing team was reduced to the two principal authors starting with the third edition of the book.

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David McConnell grew up in Londonderry, Northern Ireland, and was hooked on geology when he took his first course in high school with an inspirational teacher. His earliest geological exercises involved examining rocks along the rugged coastlines of Ireland. He graduated with a degree in geology from Queen's University, Belfast, before moving to the US to obtain graduate degrees from Oklahoma State and Texas A&M Universities. David spent much of his career at the University of Akron, Ohio, where he met David Steer, beginning a research partnership that eventually resulted in the book you are now holding. David relocated to North Carolina State University to build a geoscience education research group that continues to examine how to improve the student learning experience in large general education science classes.

David has taught a dozen different courses from introductory geoscience classes to advanced graduate courses. He has received several teaching awards, and he and his collaborators and graduate students have made many presentations and published articles on their educational research. When pressed for some personal information, David will tell you that he loves collecting vinyl records, is way too attached to Tottenham Hotspur football club, and enjoys spending weeks each summer hiking trails through a mountain range somewhere.

Courtesy of David Steer

David Steer was fascinated with rocks as a child in Ohio. That interest was nurtured by his participation in a National Science Foundation–sponsored geology field camp for high school students that took him to the Black Hills of South Dakota. David's plan to become a geologist had to wait when he accepted an appointment to West Point and then served for a decade as an Army Corps of Engineers officer. While in the military, David attended Cornell University, earning a Master's of Engineering degree. He was then assigned to West Point Military Academy, where he taught physics. After leaving the service, David returned to Cornell University to pursue his early geological interests at the Ph.D. level, albeit in the field of geophysics. He began his appointment at the University of Akron in 1999.

Several years ago, David began employing student-centered learning techniques in his large introductory earth science classes. He has extensive experience in using conceptual questions, physical models, and other active learning techniques. His education research, allowing him to identify at-risk students very early in the course so that effective intervention can occur, has produced scholarly publications in the *Journal of Geoscience Education* and numerous national and regional conference presentations. David has been recognized for his extensive research and teaching scholarship at the institutional and national levels. He and David McConnell were recognized together as National Association of Geoscience Teachers Distinguished Speakers and travel the country making presentations about their educational research.

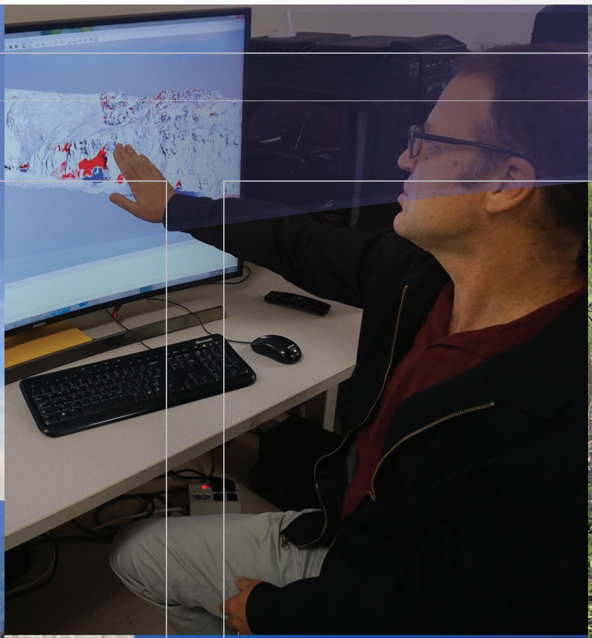
On a more personal note, David frequently experiments with using golf clubs as seismic energy sources and travels the country with his family with a goal of visiting every national park in the continental United States. David brings military discipline to the team and is one of the principal geo-science content writers. David made this comment about his participation: “Writing this text has been both rewarding and humbling. That endeavor constantly reminded me how much I still have to learn about our planet.”

The Good Earth

Although we have long understood Earth’s position in space, the unique nature of our planet was not fully appreciated until we were able to look at our home from some distance. The astronauts aboard the *Apollo 8* spacecraft were the first people to travel to the moon and were the first to glimpse our home planet from distant space. This view of Earth, commonly known as “Earthrise,” was one of the most well-known images of the twentieth century. The photograph was taken by astronaut William Anders during *Apollo 8’s* fourth orbit of the moon on Christmas Eve 1968. (The original image was actually rotated so that the moon’s surface was near-vertical and to the right of Earth.) A few hours after snapping the photograph, the Apollo crew read the first 10 verses of the book of Genesis during a broadcast to Earth. At the end of the reading, Commander Frank Borman closed communications with “. . . Merry Christmas, and God bless all of you, all of you on the good Earth.” For many at home, those early views of the planet from the inky darkness of space illustrated the unique wonders of the fragile environment we share on spaceship Earth.

—Frank Borman

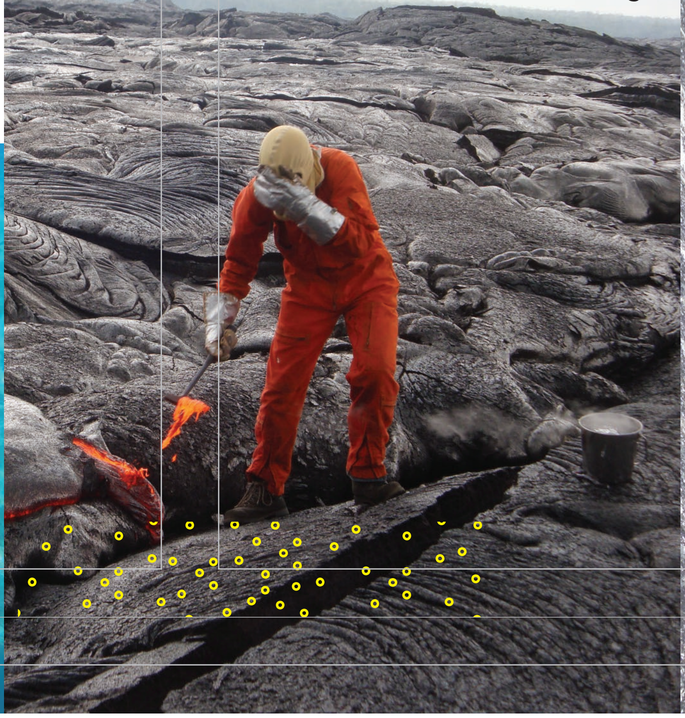
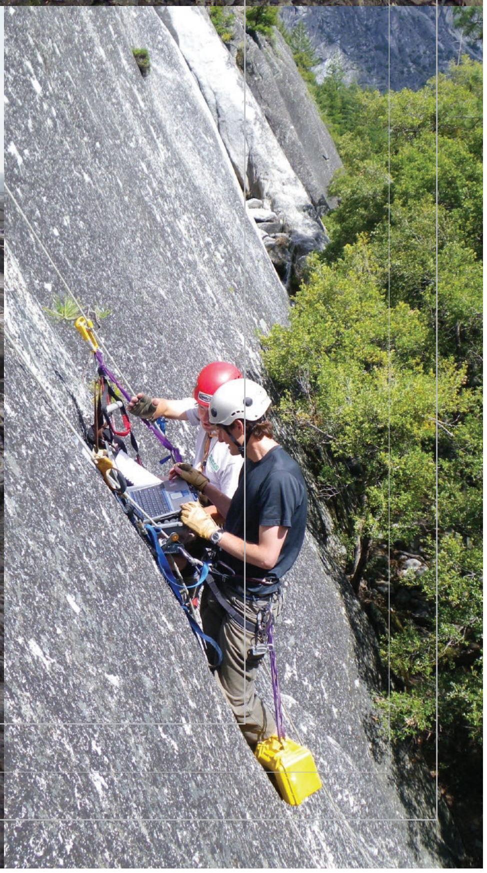
Source: National Aeronautics and Space Administration (NASA)



Science is part of the reality of living; it is the what, the how, and the why of everything in our experience.

—Rachel Carson, marine biologist

Chapter 1

Introduction to Earth Science

Chapter Outline

the big picture

Earth scientists work with a variety of tools across many different environments to collect, analyze and communicate their science to the world.

See The Big Picture box at the end of this chapter to learn more about how earth scientists are investigating how Earth will change in the near future.

(Mount hood) Source: Liz Westby, USGS Cascades Volcano Observatory; (interview) Source: Dann Blackwood, Woods Hole Coastal and Marine Science Center/USGS; (free-diving) Source: Amy West, USGS Science Communications Contractor; (lava-flow heat) Source: Hawaiian Volcano Observatory/USGS; (groundwater well maintenance) Source: National Park Service; (Yosemite rock erosion) Source: Valerie Zimmer, National Park Service/USGS; (hydrothermal vent) Source: Thomas Reiss, USGS Pacific Coastal and Marine Science Center/USGS; (Las Vegas valley wetland deposits) Source: Eric Scott, John D. Cooper Center/USGS and (photo analysis) Source: Amy West, U.S. Geological Survey

Self-Reflection Survey

Respond to the following questions as a means of uncovering what you already know about Earth and earth science.

1. Which of the following earth science phenomena have you experienced? Which would you most like to experience? Can you think of three more things to add to the list?
   - A volcanic eruption
   - A glacier
   - A river in flood
   - A cave system
   - An underground mine
   - A canyon
   - An earthquake
   - An erosional coastline (rocky cliffs)
   - A depositional coastline (beaches)
   - A hot desert
   - A continental divide
   - Rock layers with fossils
   - A big, assembled dinosaur skeleton
   - A meteor shower or comet
   - The aurora borealis (the northern lights)
   - A meteorite crater
   - A mountain range over 3,000 meters (over 10,000 feet) in elevation
   - The top of a cloud
2. What three questions about Earth would you like to be able to answer by the end of this course?

1.1 Earth Science and the Earth System

Chapter Learning Outcomes

- Evaluate claims in a science-based argument.
- Describe the relationships among science, society, and government.
- Recognize that Earth is a complex system of interacting rock, water, air, and life.

Why should you care about science—and earth science in particular? Most of us are not that involved with science in our daily lives. (How many scientists do you know?) Past experiences have convinced some people that they will never understand science, whereas others may view the study of earth science as irrelevant to our comfortable twenty-first-century lifestyle. But, increasingly, the natural processes that sustain the earth system as we know it — and that support our global community—are changing before our eyes. During the lifetime of most people reading this book, we will have to confront a number of challenges related to how we interact with Earth. The news presents us with daily reports of localities that are ill-equipped to deal with natural phenomena that turn into dangerous hazards. We can empathize with the people affected by destructive events such as the wildfires, flooding, hurricanes, and earthquakes, but how will we respond to slower moving, even more significant global-scale challenges? Things like sea level rising to engulf small island nations, municipal water supplies diminishing as a warming climate shrinks glaciers and intensifies droughts, limited access to critical minerals essential to support economic development, and shifting agricultural land use due to climate change. Many of these issues are deeply rooted in the earth sciences and we hope that this book will help you to gain the knowledge necessary to make informed decisions as you confront these future challenges. We seek to help students build a foundational understanding of how the earth system works while also enhancing your ability to apply this understanding to complex and profound issues that link earth science and society (Figure 1.1).

In the remainder of this chapter, we will define science and describe how it is done by trained people doing basic and applied research using an array of skills and tools. Acting as representatives for society, **scientists seek to:**

- Identify and measure natural processes and phenomena.
- Understand the natural processes involved.
- Monitor these variables over time and predict future trends or events.
- Engage citizens and their representatives in using this information to make effective decisions to meet society's needs.

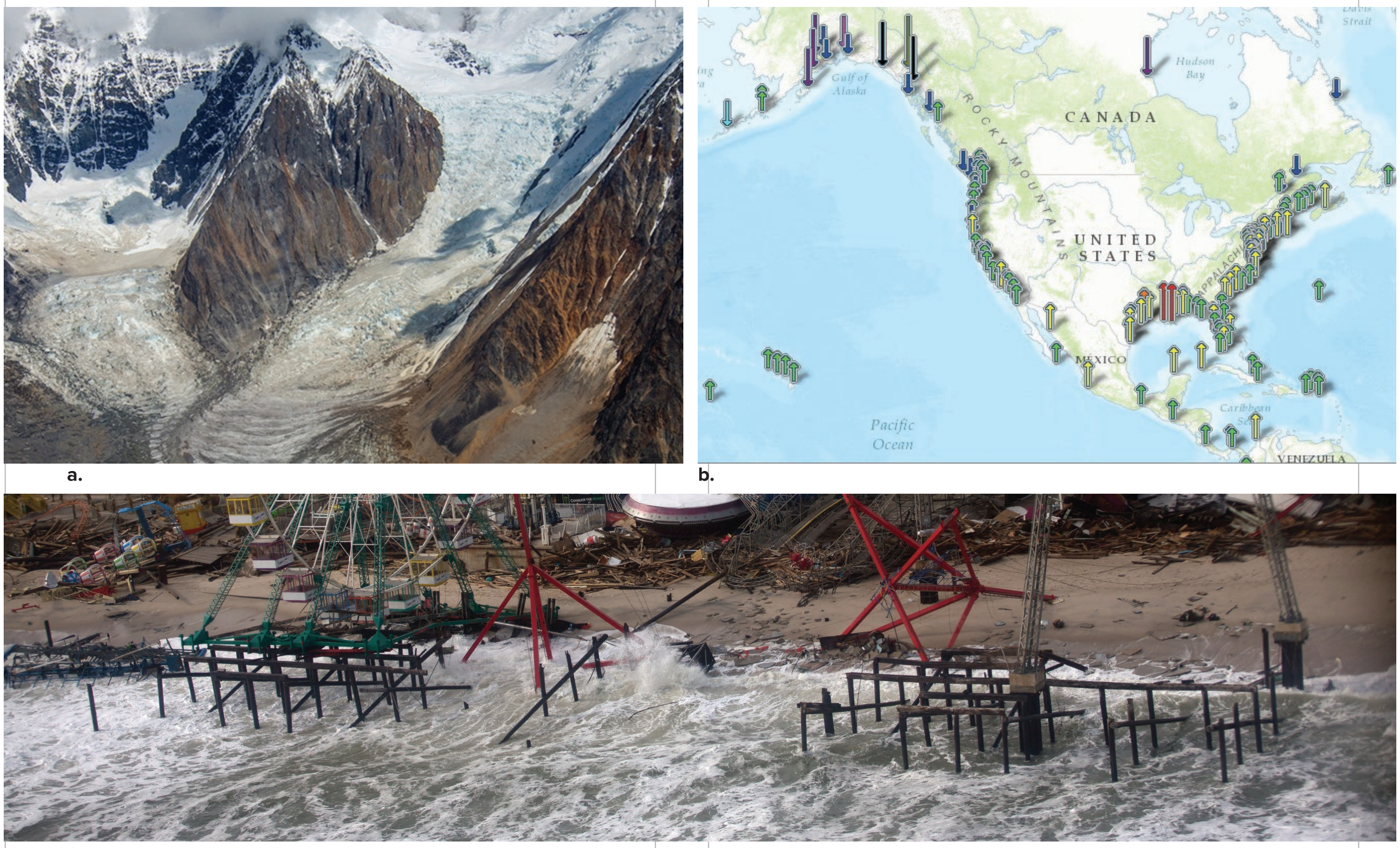


Figure 1.1 Changes to the global water system. **a.** Many glaciers are melting at faster rates than in the past; **b.** Sea level measurements around North America show that sea level is rising in most locations except those that were buried under thick ice sheets during the last ice age; **c.** Rising sea levels will imperil coastal structures.

1.1a: Source: National Oceanic and Atmospheric Administration; 1.1b: Source: National Oceanic and Atmospheric Administration; 1.1c: Source: Official White House Photo by Sonya N. Hebert

These scientists ask questions and analyze data; some create maps or collect fossils, while others use sophisticated technologies to search for oil and gas, track ocean currents, or measure changes in the chemistry of Earth's atmosphere. We will explain the principles that scientists use to conduct investigations that weave together data collected from experiments and observations of the natural world. We will discuss the principal roles of the earth sciences in our lives, from finding ways to protect us from natural hazards to investigating the implications of climate changes for the future of humanity.

We finish the chapter by introducing the concept of global change and humans' impact on Earth. Global change is an idea that is generating research in a wide variety of disciplines relating to all components of the earth system, including geology, ecology, oceanography, and climatology. This work involves thousands of scientists across the globe and is likely to require challenging social decisions within your lifetime. Future economic, cultural, and political choices in the world's nations will depend on the rate and degree of change. We will follow the theme of global change through many of the chapters of *The Good Earth* and use it to show the links among the components of the earth system. As you will see, there is little that happens on Earth that doesn't involve multiple earth system components.

✓ Checkpoint 1.1: Basic

Good questions often produce answers that lead to yet more questions. Review the following statement and suggest some related questions that could clarify or expand the topic.

> *Students who work together in groups often learn more than students in the same class who work alone.*

1.2 The Scope of (Earth) Science

Learning Objectives

- Describe the principal earth system components.
- Write a one-sentence definition of the term *science*.
- Identify examples of the tools that scientists use to learn about Earth.

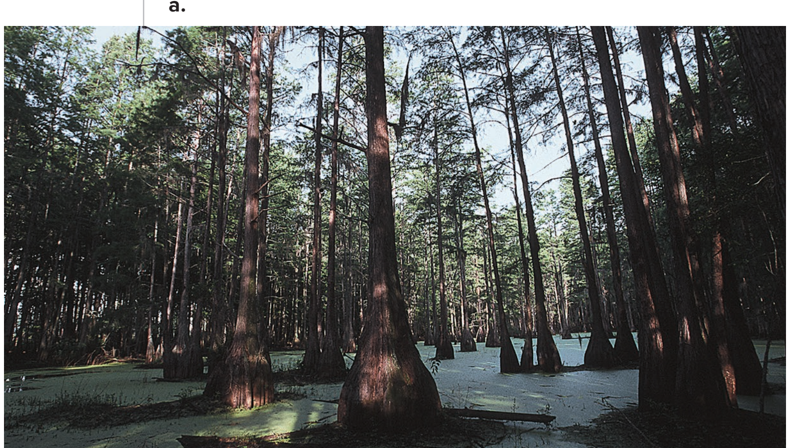
Earth is a Complex System

In *The Good Earth,* we introduce you to the study of earth science. Earth is a complex system of interacting rock, water, air,

a.

b.

Figure 1.2 The four components of the earth system: atmosphere, hydrosphere, biosphere, and geosphere. All components interact with the solar radiation and other elements from space. How many components are featured in each image?



c.

d.

1.2a: Source: Image courtesy NASA's Goddard Space Flight Center; 1.2b: Source: Ralph F. Kresge #1200, NOAA/Department of Commerce; 1.2c: Source: United States Department of Agriculture; 1.2d: ©Dr. Parvinder Sethi and life where the components and interactions cycle energy and mass throughout the system at a variety of timescales. Changes in one part of this complex system can cause ripples that influence multiple related variables and processes. The system can also have balancing or reinforcing feedback mechanisms that can serve to moderate or amplify outcomes or processes. Sometimes complex systems have tipping points that cause the entire system to become unstable when a threshold is broken.

Earth science can be broadly defined as the investigation of interactions among the **four parts of the earth system—the atmosphere (air, weather), hydrosphere (water, ice), biosphere (plants, animals), and geosphere (land, rocks)** (Figure 1.2). Together, these components form an elegant support system for life. In addition, the sun and assorted features from space, collectively termed the **exosphere**, interact with the earth system and are sometimes considered a fifth earth system component. Throughout this book, we will examine the characteristics of each of the components through the lens of human experience. We will look at how the earth system affects us over a wide range of timescales and how we, in turn, affect different earth system components. We will also be interested in how these components interact with one another and how changes in one component influence processes in the others. Representatives of the earth science community spent some time considering the essential principles or big ideas that everyone should appreciate about the earth system. They ended up with nine "big ideas" that can be divided into a series of secondary concepts. The big ideas were as follows:

- Earth is a complex system of interacting rock, water, air, and life.
- Earth scientists use repeatable observations and testable ideas to understand and explain our planet.
- Earth is 4.6 billion years old.
- Earth is continuously changing.
- Earth is the water planet.
- Life evolves on a dynamic Earth and continuously modifies Earth.
- Humans depend on Earth for resources.
- Natural hazards pose risks to humans.
- Humans significantly alter Earth.

We have just introduced you to the first idea and we discuss the second item on the list in the rest of this chapter. The remainder of the points will be discussed in several chapters throughout the book. Take a few moments after you read each chapter to reflect on how many of these big ideas were represented in the material you just read.

✓ Checkpoint 1.2: Intermediate

Make a list of actions or processes illustrating how you interact with the four primary components of the earth system and processes whereby the earth system components act on you.

Science and Discovery

The second word in the term *earth science* is just as important to us as the first. Much of what you learn in college about science will happen in this and perhaps one other course. Therefore, we want you to have a firm understanding of what science is—and what it is not. Science is not a list of facts to be memorized that have no relevance to your life. The only way to understand how to think like a scientist is to learn to use the skills of scientific reasoning. So in this chapter, and throughout the book, we will give you lots of examples to show that science is a process, a way of thinking about the natural world.

Why do we care what you think about science? The United States is a world leader in scientific research and development. Government and corporate science programs flourish because of substantial investment in innovation and the discovery of new ideas. Even though survey results show that Americans are supportive of scientific research, most people have only a shaky grasp of underlying scientific principles. The National Science Foundation has conducted surveys that reveal that less than one-third of the adult population can define what it means to study something scientifically. Even if you do not make a career in science, it is important that you understand how to use scientific reasoning skills to make wise decisions as an informed citizen to help solve daily problems.

Science is a process of discovery that increases our body of knowledge. Earth science is like all sciences; some of it is known and can be learned, and much of it is still waiting to be discovered. But science has another less tangible but equally important element—the innate curiosity of the scientists as they search for answers. Increasingly, individual citizens have the opportunity to become involved in a variety of scientific research projects that are too large to complete without the participation of a large number of talented amateur scientists. These projects can involve thousands of observations made by citizens over a limited time interval. They may involve volunteers with little or no training in collecting data or citizen researchers working with scientists in an online community. Examples of some of these projects follow. Which would you most like to be involved with?

- *GLOBE Observer*: Participants download a smartphone application that allows them to photograph clouds, record atmospheric data, and compare the data with NASA satellite images. The app also provides a mechanism for reporting potential mosquito breeding sites, as well as to identify and count larvae.
- IceWatchUSA: This project by the Nature Abounds organization seeks to compile local climate records by making seasonal observations of ice conditions on water bodies.
- World Water Monitoring Day: Over 1 million people in more than 100 nations used simple sample kits to collect information on the characteristics of local streams and lakes. Data are then entered into an online database to be compared with results from subsequent years.
- Project Budburst: This project seeks to track the timing of the leafing and flowering of native vegetation around North America. Participants can also become data

collectors seeking to help scientists and gardeners determine the effect of non-native plants on the behavior of local bees, butterflies, and other pollinators.

- FeederWatch: This data set yields information on the changes in native and alien species of birds using backyard bird feeders and can serve as a proxy indicator of environmental change.
- Community Collaborative Rain, Hail & Snow Network: Over 20,000 back yard weather observers measure rain, hail, and snow using low-cost measurement tools. The data are uploaded to a website where they are mapped in near real time.
- Did You Feel It?: This US Geological Survey (USGS) online program uses reports from people who feel earthquakes and graphs the data to create Community Internet Intensity Maps. For example, a 5.8 magnitude earthquake in Virginia generated more than 150,000 citizen reports from people in states up and down the east coast.

Earth scientists combine their basic knowledge of facts and concepts with technical skills to explore Earth and solve its mysteries. It is tempting to view science as a list of facts to be memorized and repeated. But the real essence of science is a detective story in which teams of investigators piece together evidence to generate well-founded explanations of the workings of our planet. Scientists constantly refine or challenge these explanations, causing some to be discarded while others gain wide acceptance. Our imaginations and the physical laws of nature present the only limits to science. Throughout this book, we will strive to give you an inside look at how science is done and to initiate you in the process of discovery. Whenever possible, we will feature real-life situations and pose questions that place you in the role of the scientist.

Tools Used by Earth Scientists

Earth scientists use direct measurements, indirect information, and models to better understand Earth. Direct measurements are collected at field locations by scientists or trained technicians (Figure 1.3). For example, they might determine the type of rocks present (see Chapter 7) to create a geologic map, collect water samples from drinking water wells (see Chapter 12), or gather samples of gases erupting from volcanoes (see Chapter 6). Samples are carefully analyzed and cataloged with information about their original location, the conditions under which they were obtained, and any other data that could affect understanding of the importance of that sample. In these cases, the scientist is directly measuring exactly what she is interested in measuring. The actual measurements may be obtained in the field or in a laboratory.

✓ Checkpoint 1.3: Advanced

Three of the big ideas listed near the start of this section detail the interaction of humans and the earth system: (1) Humans depend on Earth for resources; (2) natural hazards pose risks to humans; and (3) humans significantly alter Earth. Take a few minutes and write what you can in support of each of these statements. Consider revising your responses as you progress through the semester to see if you can add more items and/or more information.

Figure 1.3 This instrument consists of numerous bottles that are submerged to collect water samples from the ocean.
Source: National Oceanic and Atmospheric Administration

However, it is often not practical to measure some phenomena directly. In these cases, scientists use indirect measurements. Essentially, they measure something that they can then interpret to get a value for something else. For example, scientists cannot readily examine the features below the world's oceans, but they have been able to use a variety of methods to identify different properties of the rocks of the ocean floor. Measurements of the magnetic patterns of the ocean floor were used to determine that the age of the oceanic crust varied from place to place (see Chapter 4). Satellites measure variations in the height of the ocean surface which is related to the distribution of ridges and trenches on the ocean floor (see Chapter 13). Satellites can also make direct measurements of large regions that would be impossible to map on the surface. For example, scientists have used satellite measurements of Arctic sea ice coverage to show a steady decline over the last few decades (see Chapter 16).

In other cases, scientists use models to better understand Earth. Those models can be physical devices such as wave tanks (Figure 1.4), or they may be theoretical models. The latter are often computer models that simulate complex physical processes to allow investigators to examine the relationships between variables. For example, it has become commonplace for us to see the results of meteorological modeling on our evening news weather forecasts (see Chapter 15). Elsewhere atmospheric scientists use an array of models to predict the track of hurricanes, and ever more sophisticated models are being developed to predict future climate trends (see Chapter 17).

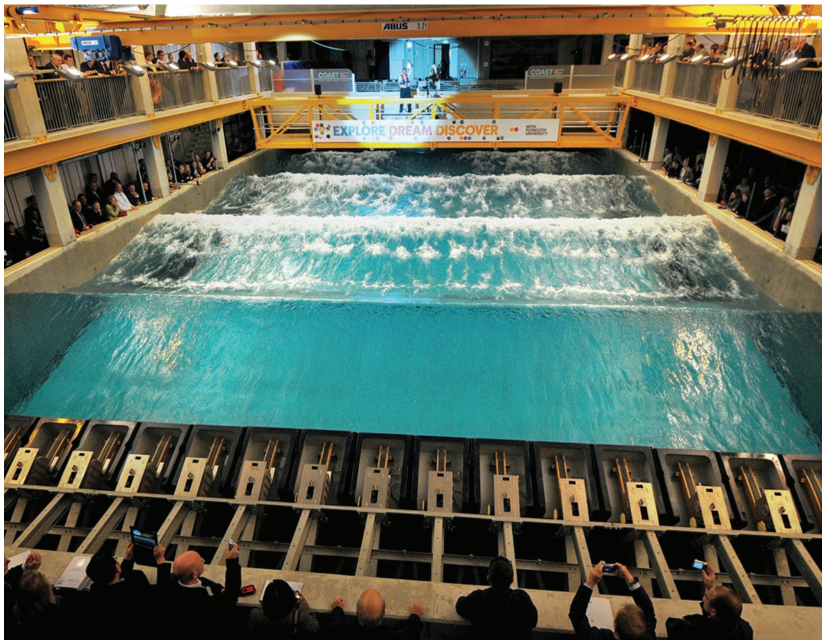


Figure 1.4 Wave tank used to understand processes occurring in coastal environments.
Tim Ireland/AP Images

1.3 Doing Science

Learning Objectives

- Explain how scientists use observations and predictions to test hypotheses.
- Provide examples of inductive and deductive reasoning.
- Analyze the four basic principles of good science as applied to a real-world scientific investigation.
- Describe examples of poor scientific reasoning.

This information-rich world gives us ready access to all the facts we could ever want. In *The Good Earth*, we have cut down the volume of terms and the amount of new information in favor of addressing the skills needed to process that information—to separate the good from the bad, the significant from the trivial. Most people rate the ability to think critically—to analyze and evaluate information so as to make wise decisions—as more important than knowledge of facts or technical skills that can be easily memorized. Critical thinking is also something science does wonderfully well. The benefits of critical thinking extend beyond science to help us interpret information in a variety of forms, weigh the validity of competing claims, and make judgments on which course of action to pursue. Effective critical-thinking and decision-making skills can be applied to many aspects of life, including buying a house, planning a diet, or successfully managing your time in college.

Science advances by the application of the **scientific method, a systematic approach to answering questions** about the natural world. The scientific method implies that sufficient observation will reveal patterns that provide clues to the origin and history of Earth. We assume that the components of the universe interact in consistent, predictable ways. Scientists use their observations as an aid in predicting future events in the earth system and, in some cases, the universe.

Checkpoint 1.4: Exceptional Scientific Analysis

Go to the US Geologic Survey site (www.usgs.gov) and find an example of an earth science topic that USGS scientists have or are investigating.

1. Briefly describe the research, using no more than six sentences.
2. Identify:
   - The question(s) or issue(s) they investigated.
   - The types of instruments or tools they used.
   - An example of the data they collected.
   - The earth system component(s) and interactions most directly related to the study.

From Observation to Hypothesis

All of us make observations that we use to mold our personal views of the cultural and physical worlds we inhabit. Scientists also use observations to shape ideas. Their ideas are known as hypotheses. **A hypothesis is a testable explanation of facts or observations.** For example, if we owned a Ford Mustang that broke down frequently, we might form a hypothesis that Mustangs or even all Fords were poorly built cars. Through experience, we test the limits of our personal world, allowing those limits to expand to accommodate a positive stimulus or shrink from a negative interaction. Suppose a friend is pleased with the performance of her Mustang. That might require us to modify our original interpretation. Personal observations may vary with the individual, but **valid scientific observations are empirical—that is, they can be measured and confirmed by others.** In that regard, we could collect data on a large number of Ford Mustangs and determine the average number of repairs per car over a specific period of time. We could then compare these data with repair rates for comparable vehicles to support or refute our original hypothesis. Further, others might be prompted to test a similarly large set of Mustangs to confirm our interpretation.

Inductive and Deductive Reasoning

The scientific method is not a single set of steps like a recipe. It can take a variety of forms but includes some or all of the following—making observations, forming and testing hypotheses, developing predictions, planning and conducting experiments, analyzing data, and evaluating results. **A scientific hypothesis is developed to provide a potential explanation of observations.** Hypotheses can be generated and tested using two basic procedures: inductive reasoning and deductive reasoning (Figure 1.5). **Inductive reasoning occurs when scientists draw general conclusions from specific observations.** The success of this method comes from recognizing patterns and identifying similarities between comparable systems.

Consider the following situation. Anne, an earth science professor, has students discuss the characteristics of different types

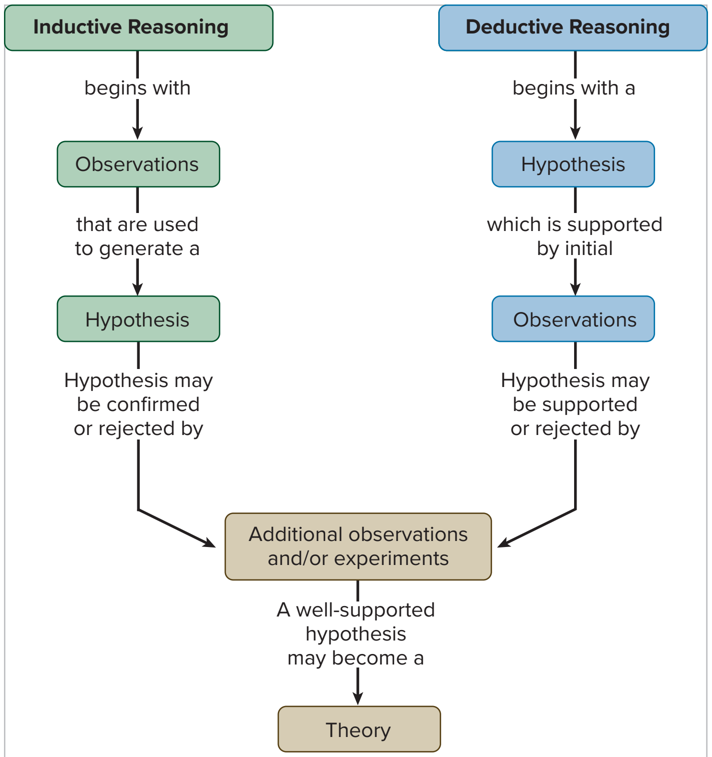


Figure 1.5 Concept map depicting two types of reasoning. Inductive reasoning results when scientists draw general conclusions from specific observations. Deductive reasoning occurs when scientists draw specific conclusions based on general principles.

of volcanoes with their neighbors during one of her classes. Later, she notices that the students do better on the exam questions about volcanoes than on other questions. She forms a hypothesis that students learn concepts better if they work together. She begins to assign daily exercises for the students to complete in small groups during class. Her average exam scores jump by 4.7 percent over previous classes. Anne is pleased that her students appear to be learning the material more thoroughly, and the students are pleased when she tells them that their grades are higher than expected. Anne has used **inductive reasoning, drawing a general conclusion from specific observations.**

Anne describes her teaching experiment to Don, an instructor in the physics department. He tells her that he too started using group assignments in class. Don tells Anne that he read an article in a physics journal by a colleague at another university that described how the use of groups resulted in improved student learning. Don had done some additional reading about the use of these methods in other science classes and determined that several instructors achieved similar improvements. Consequently, he concluded that if groups could improve learning in other science classes, they would probably also help his students. Don used **deductive reasoning** because he **used a general principle to reach a specific conclusion.**

Students frequently confuse inductive and deductive reasoning, so consider two other examples. What type of reasoning (inductive or deductive) is used in the following pair of statements and why?

1. All hurricanes form as low-atmospheric-pressure systems over oceans. Hurricane Harry is forming in the Atlantic. Hurricane Harry is a low-pressure system.
2. Three massive hurricanes caused large amounts of damage to the United States during the 2005 hurricane season. Hurricane Katrina had a pressure of 902 millibars (mbar); Hurricane Rita, 898 mbar; and Hurricane Wilma, 882 mbar. Therefore, massive hurricanes with air pressures of around 900 mbar or less will cause large amounts of damage if they make landfall.

The first scenario starts with a general statement about hurricanes and concludes with a specific statement about a single hurricane. Therefore, the reasoning is deductive—general to specific. The second scenario starts with specific data (air pressures) and ends with a general conclusion. This is inductive reasoning—specific to general. Most science involves components of both inductive and deductive reasoning.

From Hypothesis to Theory

The best hypotheses are logical and can be readily tested by experiment or by more observations. Continued observations over time will either confirm that a hypothesis is accurate or reveal that it is not quite right and needs to be either further refined or rejected. New information sometimes becomes available with the development of increasingly sophisticated technology and may lead to minor or major changes in existing hypotheses.

An initial hypothesis is a reasonable explanation on the basis of current science and needs further examination. After rigorous testing, bulked up with supporting facts and observations, a hypothesis may become a theory. The US National Academy of Sciences defines a **scientific theory as "a well-substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypotheses."** Note that in science, a theory is not just an opinion or a guess; it is a well-supported explanation of a natural phenomenon. (For example, in Chapter 4 we will discuss the theory of plate tectonics.) An even higher standard of scientific scrutiny is reserved for laws. Scientific laws are statements that are so strongly supported by theory and observations that they are considered unchanging in nature. The law of gravity is an example.

In our constantly changing world, hypotheses or even theories will be modified, and none can ever be completely proved.

✓ Checkpoint 1.5: Basic

Scientists suggested the dinosaurs became extinct when an asteroid collided with Earth. They noted that ***the rare element iridium was present in 65-million-year-old rock layers around the world.*** The text in italic is an example of:

a. A hypothesis.
b. A prediction.
c. An observation.
d. A theory.

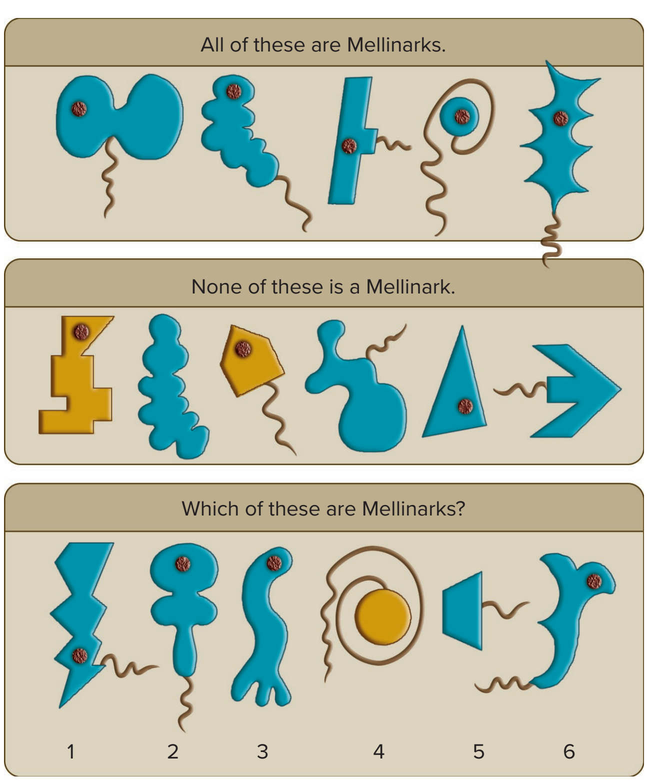
Widely accepted ideas will be confirmed and strengthened by the work of many scientists, but it is always possible that the next person to test the idea will discover a slightly different result and challenge part, or all, of the original hypothesis. **The willingness to continually question prevailing ideas and to modify or discard them as new information becomes available is the strength of science.** Science is an open book, a perpetual lie detector, limited only by the imagination and abilities of its practitioners. Given the complex nature of Earth, no scientist makes an observation, suggests a hypothesis, or develops a theory alone. The work of every scientist relies on the work of others who have gone before. Even Isaac Newton, whose law of gravity has withstood the test of time, noted, "If I have seen further, it is by standing on the shoulders of giants."

Checkpoint 1.6: Intermediate

Observations, Hypotheses, and Mellinarks

Examine the images below. Based on your observations, form a hypothesis as to how many of the images in the bottom row represent Mellinarks.

What was the thought process you went through to arrive at an answer? Try to separate out the "thinking steps" that you took, identifying observations, predictions, and hypotheses. On a separate sheet of paper, briefly describe the steps.



Source: Question adapted from an article by Anton E. Lawson, *Journal of College Science Teaching*, May 1999, pp. 401–11

The Characteristics of Good Science

Good scientific explanations follow four basic principles:

1. **Principle: Scientific explanations are provisional (tentative) and can and do change.** These changes are not always popular. A few years ago, new data on bodies orbiting at the fringe of the solar system resulted in the reclassification of Pluto as a dwarf planet. While science can change, we would emphasize that many of the key concepts discussed in this and other science books have been stable for a long time, some of them well established for centuries. Many of the changes occur in the details of the scientific explanations, rather than the major concepts themselves.
2. **Principle: Scientific explanations should be predictable and testable.** The daily weather forecast is a result of meteorologists using their knowledge of how air and moisture circulate through the atmosphere to predict short-term changes in weather patterns. The idea that hypotheses must be testable brings up a very important point about science. In science, one must be able to test a hypothesis or theory to determine if it could be false. That seems odd, does it not? Scientists construct a hypotheses or a theory to explain nature and then argue that the work is not science unless their idea has the potential to be found to be false. The central idea is this: science deals with the physical world. When we propose a hypothesis, we think it is true. Any additional experiments or observations should either support the hypothesis or show it to be false. Science progresses as hypotheses and theories are tested and shown to be supported (or not). If you cannot test a hypothesis, you are not doing science. Can you think of an idea that cannot be shown to be false (or true for that matter)?
3. **Principle: Scientific explanations are based on observations or experiments and are reproducible.** For example, scientists studying glaciers on different continents have noted that most are decreasing in size (see Chapter 16). These observations can be made routinely by photographing and measuring the dimensions of individual glaciers over several years or decades and are readily confirmed by others willing to visit the same locations. The important characteristic of science lies with the empirical, reproducible data used to support or refute a hypothesis. Scientific results are discussed openly at conferences and published in journals so that all ideas are exposed to review by other scientists (peers). This peer review process ensures that published research is original and adds to the body of valid scientific information. Rogue scientists who publish false data to advance their careers are often discredited by other scientists who are unable to reproduce the original results.
4. **Principle: A valid scientific hypothesis offers a well-defined natural cause or mechanism to explain a natural event.** Science looks for a cause for every effect. A tsunami is caused by an underwater earthquake; an earthquake is caused by movement of tectonic plates; tectonic plates move because Earth is releasing internal heat energy (more on all this in Chapter 4). Sometimes these cause-and-effect relationships are complicated, with multiple causes

Checkpoint 1.7: Advanced

Identify the application of the four characteristics of good science in the passage that follows.

Science in Full View: The Hutchinson Gas Explosions

Jerry Clark heard the explosion and ran outside in time to see debris fall to the ground. Everyone in the city of Hutchinson, Kansas, heard or felt the blast at 10:45 A.M. on Wednesday, January 17, 2001. Glass covered downtown streets, and two stores were soon in flames. City emergency workers initially assumed that the blast was the result of a gas leak and so shut off gas supplies to the area. But the fire burned on. That evening, jets of gas erupted from the ground on the edge of the city east of the explosion site. A second fiery explosion on Thursday killed two people at a mobile home park near the gas jet site. By this time, no one knew what to expect next. The local police and National Guard quickly evacuated residents living near the second blast site, and the governor's office declared a state of emergency.

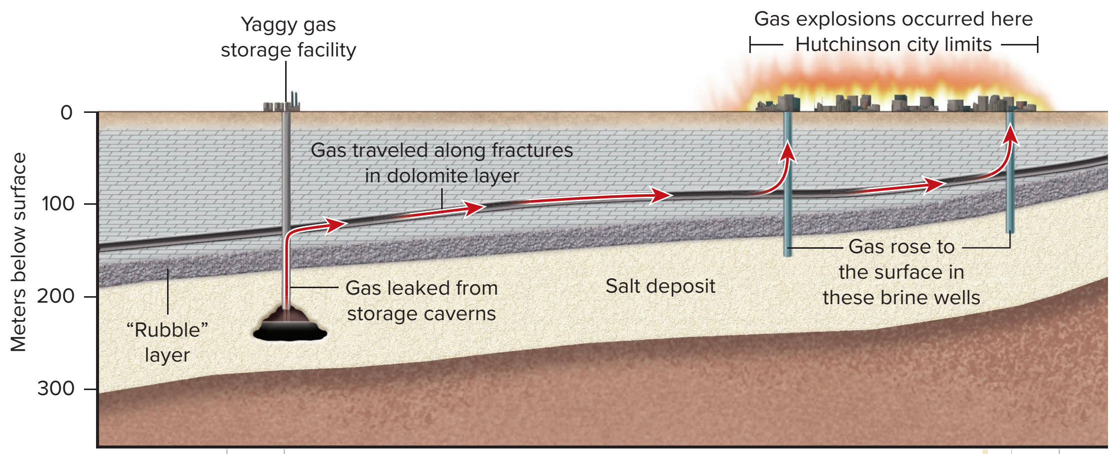
Both explosions and the gas jets were linked to abandoned wells, some drilled perhaps as much as a century earlier. It soon became clear that the gas was escaping through the wells from a source far below the city. Large underground caverns in the nearby Yaggy Corporation gas storage facility (see the figure) experienced a significant pressure drop on Wednesday morning as natural gas was being pumped into the storage caverns. Later investigations revealed that the source of the leak was a fist-sized hole in the casing of one of the wells used to pump gas into and out of the caverns. Kansas Gas Service (KGS) operated the Yaggy facility, one of a network of natural gas storage centers across the nation.

The Kansas Geological Survey immediately volunteered to help investigate the explosions. Survey geologists had previously produced a geologic map of the county around Hutchinson. This survey had provided sufficient information about local rocks to determine that it would be possible for gas to rapidly migrate the 10 kilometers (6 miles) from the Yaggy facility to Hutchinson. The scientists could do little more until they were able to analyze the situation more closely. At this early stage in the study, most investigators thought the gas had escaped from a leaking gas well, migrated upward, and then traveled toward Hutchinson in a rubblelike rock layer that capped the salt deposit containing the storage caverns (see the figure). KGS employees drilled numerous wells in an effort to allow any remaining gas to escape safely to the surface. The drilling revealed that the gas was not traveling along the rubblelike layer but was closer to the surface in a thin band of rocks about 100 meters (330 feet) below the city.

On January 30, the governor of Kansas sent a team of geologists, geophysicists, and engineers from the state Geological Survey to Hutchinson to find any remaining gas buildups. Survey representatives coordinated their work with local officials, KGS employees, and other state agencies and soon launched a website to keep residents and interested observers updated with the latest findings. The search for answers was made transparent as information was shared through the website or in public meetings where Geological Survey personnel answered questions and addressed concerns of local residents, officials, and reporters—even when sometimes the answer was "We don't know."

The scientists used ground imaging technology to examine the characteristics of the rock layers underlying Hutchinson and to search for possible locations where gas had collected. KGS drilled wells in two of those locations and vented large volumes of gas. Rock samples recovered from the gas-bearing zone contained a rock type known as dolomite. Geologists hypothesized that a series of connected fractures in the dolomite had served as a pathway for the gas to travel from the Yaggy facility to Hutchinson. Although they never recovered rock samples showing the presence of fractures, these scientists concluded that fractures in the dolomite layer represented the only reasonable passageway through which the gas could move quickly over that distance. Continued investigation revealed no remaining gas deposits, and on March 29, the Geological Survey's representatives told Hutchinson residents: "From a geological viewpoint, the city is safe."

The example of the Hutchinson gas explosions shows that scientific investigations are driven forward by the curiosity and persistence of scientists who systematically rule out potential solutions to arrive at an explanation. This example also illustrates that science doesn't have unlimited resources, personnel, or time. In some cases, it may be necessary to walk away and settle for the best answer available under the circumstances.



influencing the end result. For example, changes in Earth's climate are caused by effects from every component of the earth system, including the composition of the atmosphere, oceanic circulation patterns, the combustion of fossil fuels, plant respiration, and our position relative to the sun. Ongoing research is attempting to determine just how much each of these factors influences climate change.

Geoscience is a discipline based on making observations of the Earth and testing hypotheses about Earth's history. The methods used by geoscientists include comparing features preserved in the rocks of the geologic record with modern processes to interpret how those ancient features formed; finding commonalities and differences; developing converging lines of evidence and testing through prediction. Geoscientists also think about the Earth using a framework that recognizes that the Earth is very old and has a dynamic history that is shaped by a continuum of many long-lived, low-impact processes and fewer short-duration, high-impact processes. These scientists also value collaboration as a strategy for effectively moving forward our understanding of the Earth. Let's see how these principles were applied in one of the most widely publicized scientific discoveries of recent years.

An Example of Good Science: The Alvarez Hypothesis

More than 30 years ago, a team of scientists led by the father-son pair Luis and Walter Alvarez suggested that the extinction of the dinosaurs was caused by a collision between Earth and an asteroid or comet. Walter Alvarez was a young paleontologist, a geologist specializing in using fossils to decipher the history of Earth. He was investigating the geologic history of the Mediterranean region, and his research took him to a large outcrop of rocks near the town of Gubbio in the Apennine Mountains of central Italy. There, he examined layers of rocks that represented the time in Earth's past that spanned the extinction of the dinosaurs. Dinosaurs (and many other species) died out 65 million years ago (over a period that may have lasted somewhere between 100,000 and 3 million years). Rocks formed before the extinction are classified as Cretaceous in age; those formed after are classified as Tertiary (more on these names in Chapter 8). Most species living on Earth during the Cretaceous became extinct prior to the start of the Tertiary time period. At Gubbio, a thin clay layer marked the Cretaceous-Tertiary boundary (abbreviated as the K-T boundary) between the different ages of rocks. The K-T boundary has subsequently been identified elsewhere (Figure 1.6). You may wonder why it wasn't known as the C-T boundary. Some other periods of geologic time also begin with a C, so, to avoid confusion, it was decided to use the letter K, taken from the German word for chalk 'kreide', which is characteristic of rocks from that time.

Figure 1.6 Badlands near Drumheller, Alberta, Canada, where erosion has exposed the K-T boundary. The boundary is located approximately where the light- and dark-colored rocks meet in the upper part of the outcrop.
Ronnie Chua/Shutterstock

At the time Alvarez was doing his field work, earth scientists had published a variety of different hypotheses seeking to explain the demise of the dinosaurs and other species. For example, some scientists believed the climate got too hot or cold for the dinosaurs, others thought that they were harmed by radiation from a supernova explosion, still others suggested that the evolution of flowering plants affected dinosaur eating habits, while yet others hypothesized that smaller organisms ate their eggs, causing a rapid population decline (provisional hypotheses; principle 1). However, some of these hypotheses could not be readily tested (violated principle 2), and none of the others had been widely accepted, so research continued. Walter Alvarez sought to estimate the rate at which species changed on either side of the K-T boundary by measuring the rate at which space dust had been deposited in the clay layer at the boundary (he used principle 3). Space dust falls to Earth daily and contains rare elements that can be readily measured in the lab, although in low concentrations of parts per billion.

Alvarez returned to the University of California, Berkeley, with samples of the clay layer. His physicist father, Luis Alvarez, suggested that his colleagues Helen Michel and Frank Asaro perform a chemical analysis of the clay material. The analysis revealed the rare metallic element iridium in the clay. Iridium is normally present in concentrations of 0.3 part per billion in rocks of Earth's crust, but Michel and Asaro found concentrations of 9 parts per billion, 30 times the expected amount. They found similar concentrations at other K-T boundary sites in Denmark and New Zealand (supporting data; principle 3). In seeking an explanation for the increase in iridium concentration over such a wide area, the Alvarez team recognized that objects such as asteroids and comets contained elevated levels of iridium and other rare metals. They hypothesized that a relatively large amount of iridium was deposited when an asteroid or comet collided with Earth (natural cause; principle 4; Figure 1.7). They published their hypothesis in 1980 in the journal *Science,* as a paper titled "Extraterrestrial cause for the Cretaceous-Tertiary extinction." The Alvarez hypothesis interpreted the data to suggest that a collision with an approximately 10-kilometer-wide (6-mile-wide) asteroid would have generated so much debris that it blocked incoming sunlight for several years. Vegetation would have died in the absence of light, leading to the deaths of plant-eating dinosaurs and the collapse of the global food chain. The decade following publication of the *Science* article saw a surge in research interest in the extinction event as scientists sought to find data that would support or refute the Alvarez hypothesis (continued study using principles 1–3 above). Within a dozen years, over 2,000 articles and books had been written on the topic.

Soon, several researchers had confirmed the presence of high concentrations of iridium in rocks at the Cretaceous-Tertiary boundary at multiple sites around the world (more data; principle 3). Scientists Alan Hildebrand and William Boynton discovered tsunami deposits in K-T boundary rocks in southern Texas, as well as thick layers of debris in deposits of the same age in Mexico and Haiti; and they predicted that an asteroid impact site should exist somewhere around the Gulf of Mexico (a prediction; principle 2). Soon it was discovered that two petroleum geologists had previously published the results of geophysical exploration in the Yucatan Peninsula, Mexico. They described a buried, near-circular feature (Chicxulub Crater) over 200 kilometers (125 miles) wide that Hildenbrand and Boynton now thought could be the possible impact site (another hypothesis; principle 4). The crater was linked to the K-T collision event as it lies in rocks that are older than the impact event and is covered by rocks that are less than 65 million years old. (For more on impacts, see Chapter 3.)

However, this story is not yet over. The provisional (tentative) nature of science makes it possible that other hypotheses may yet better explain some aspects of the extinction event. In the dinosaur extinction debate, some scientists suggest the source of the iridium was actually a massive series of volcanic eruptions that took place over an interval of half a million years around the same time as the impact event. More-recent research has discovered that iridium can be produced in relatively large quantities by some volcanic eruptions (another observation; principle 3). The span of the volcanic eruptions also better matches the more gradual die-off of some of the extinct species. Of course, it is possible that both events combined to kill the dinosaurs. Stay tuned: it is likely that the public's fascination with dinosaurs means that we haven't heard the last of this scientific debate.

Limitations of Science

We must keep in mind that scientific explanations may be limited by available technology or other factors. For example, prior to the invention of the telescope, knowledge about Earth's position in space was based on observations made with the naked eye. Astronomers such as Galileo used some of the first telescopes to make observations of planetary orbits that would support the hypothesis that the sun, not Earth, was the center of our solar system.

Although science is a powerful method for examining unresolved questions, *science cannot answer all questions*. Questions that center on ethics or theology often have more to do with cultural or social norms than with scientific concepts. For example, recent concerns about the potential for cloning humans can be separated into two distinct questions; one is scientific, the other ethical. Can we successfully clone humans? is a scientific question, and the current answer is no, although research suggests that a future response could be yes. Should we clone humans? is an ethical question. If the answer is no, we may never clone a person even if the scientific knowledge exists to do so.

Figure 1.7 Asteroid impact with Earth. Luis and Walter Alvarez hypothesized that an event like this occurred 65 million years ago and contributed to the extinction of the dinosaurs.
Mark Garlick/Science Photo Library/Getty Images

The Characteristics of Bad Science

Poor scientific reasoning rarely reaches a public forum because of the checks and balances inherent in the scientific process. However, sometimes hypotheses are unveiled in the media before they can be rigorously tested. Unfortunately, on further analysis, some of these ideas may be proved wrong, prompting increased skepticism toward the scientific process and scientists in general. Some telltale signs indicate when an argument is not based on sound scientific thinking. Here are some things to look out for when people claim to disagree with a scientific hypothesis or offer unsupported explanations for natural phenomena:

- **An attack on the scientist, not the science.** Science does not advance based on the personalities of the scientists but on verification of facts and observations. (However, it can move backward when a scientist fabricates data to support a hypothesis. This happens only rarely.)
- **People who argue from authority.** Just because a person is important or powerful does not make him or her right. The extremely powerful Roman Catholic Church disagreed with Copernicus when he pointed out that Earth rotated around the sun, but it turned out that he was correct.
- **Confusion over cause and effect.** This type of thinking is often summarized by the Latin phrase *post hoc, ergo propter hoc:* "it happened after, so it was caused by." For example, a student may claim that he did well on an exam because he wore his "lucky" shirt.
- **The use of bad statistics.** Even the weakest scientific arguments may look appealing if supported by statistics that are based on a biased sample or on a sample size that is too small to be representative.

Scientists who do not engage in peer review to evaluate their research will not have their work published and may be discredited if their results cannot be reproduced by others. Alternatively, some hypotheses receive publicity before they have had an opportunity to be critically reviewed by experts, while other claims are deliberately intended to deceive. In today's information age, we are constantly bombarded with pronouncements related to various products or lifestyle-related programs or activities that will supposedly make us better, stronger, help us live longer, or satisfy some other aspect of our lives. Some of those claims are simply based on poor science; others fall under the realm of something less ethical called pseudoscience. According to Webster's dictionary, **pseudoscience is "a system of theories, assumptions and methods erroneously regarded as science."** The key word in that definition is "erroneously." Pseudoscience is not really bad science; it is intentionally false science designed to deceive. Like good and bad science, pseudoscience can be spotted through one or more of the following signs (from Schmaltz and Lilienfeld, 2014):

1. The use of psychobabble—words that sound scientific, but are used incorrectly, or in a misleading manner.
2. A substantial reliance on anecdotal evidence.
3. Extraordinary claims in the absence of extraordinary evidence.
4. Unfalsifiable claims.
5. An absence of connectivity to other research.
6. The absence of adequate peer review.
7. Lack of self-correction.

The next section describes an example of pseudoscience.

✓ Checkpoint 1.8: Exceptional

Employees at the Ripley's Believe It or Not! Museum in Myrtle Beach, South Carolina, declare that female visitors who come in contact with a pair of African fertility statues are more likely to become pregnant some time later. The statues, from the Boule tribe of the Ivory Coast, stand near the museum's entrance. Some visitors have volunteered the information that they gave birth 9 months after touching the statues and credit the statues. The statues are so popular that the museum now takes them on tour!

1. What hypothesis is presented in this story?
2. Is the hypothesis supported by sufficient observations? Explain.
3. What prediction could be made to verify or falsify the hypothesis?

Source: Summarized from an article by Isaac J. Bailey, *Houston Chronicle*, October 15, 2000

An Example of Pseudoscience: Prediction of a Midcontinent Earthquake

Self-proclaimed climatologist and businessman Iben Browning proposed that an earthquake would occur on the New Madrid fault zone in southeastern Missouri on or around December 3, 1990. He based this prediction on the fact that New Madrid had been the site of an extraordinary series of major earthquakes (sometimes called the Mississippi Valley earthquakes) over a 3-month span from December 1811 to February 1812. Browning hypothesized that tidal forces due to the gravitational pull of the sun and moon could trigger another big earthquake on the New Madrid fault zone . . . or maybe one in Japan . . . or in California . . . well, somewhere in the Northern Hemisphere.

The hypothesis generated widespread media interest in the region and raised public anxiety sufficiently that many local schools closed in anticipation of an impending quake. Browning's claims were widely denounced by earthquake specialists, who were also frequently quoted in local newspapers. By the time the fateful day arrived, the hype had taken over, and the area was besieged with reporters who, as it turned out, were able to report that nothing happened.

This was pseudoscience because Browning did not offer an accepted mechanism to explain the occurrence of the potential earthquake. Although tidal forces do exist, they had not been linked to earthquake activity. But this story also illustrates that even a clear, unambiguous message from experts (there's *not* going to be an earthquake!) can get lost in the shuffle. Scientists analyze situations; they do not write the newspaper stories or determine how schools and other public services should respond.

1.4 Science and Society

Learning Objectives

- Identify physical or chemical and social or cultural aspects of the earth system.
- Compare and contrast protection and adjustment procedures related to natural hazards.
- Explain the four principal roles that earth scientists play in society.
- Describe examples of how citizens interact with the natural environment at local, national, and global scales.

Many citizens are understandably bewildered by media reports that portray battling teams of scientists presenting opposing explanations for complex scientific problems. If the experts cannot agree, they reason, how can we be expected to make a decision? Besides, even if we understand environmental problems, we are often frustrated by the apparent inability of those responsible to do anything about them. This can range from simple individual actions (Why doesn't my neighbor recycle?) to issues of corporate responsibility (Why do companies pollute the air?).

How can we become enlightened citizens capable of identifying problems that will affect us all and participate in their solutions? We have to combine the critical thinking we described in Section 1.3 with civic thinking that involves the analysis, planning, and evaluation of actions that may help society to arrive at solutions to these problems. In this context, *society* may refer to anything from a small town up to the global community. Here we suggest a simple three-step process: know, care, act.

- **Know.** We must take responsibility for our world by knowing how it works.
- **Care.** Our society works best when we care about how our actions affect others. But we should also be aware of how we are affected by the actions of others.
- **Act.** Do something. Make your opinion known. Go to a town meeting, blog about it, write a letter to your local paper, contact your congressperson or senator, vote. To quote anthropologist Margaret Mead: "Never doubt that a small group of thoughtful, committed citizens can change the world. Indeed, it is the only thing that ever has."

✓ Checkpoint 1.9: Basic

Read the following summary of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, 1980). Write a short paragraph describing how this law is an example of the relationship between science, society, and government in solving complex earth system problems.

> *CERCLA established prohibitions and requirements concerning closed and abandoned hazardous waste sites, provided for liability of persons responsible for releases of hazardous waste at these sites, and established a trust fund to provide for cleanup when no responsible party could be identified. The law authorized two kinds of response actions: short-term removals, where actions may be taken to address releases or threatened releases requiring prompt response; and long-term remedial response actions that permanently and significantly reduce the dangers associated with releases or threats of releases of hazardous substances that are serious, but not immediately life threatening.*

The Role of Earth Science

Our demands on the planet have been magnified as technology developed and Earth's population increased. It has become increasingly necessary to monitor fundamental features of the environment around us. The principal elements of the environment (air, water, soil) have specific chemical and physical characteristics that can be readily measured. Scientists can determine the volume of dust in the air or the abundance of a chemical in a stream to figure out if the air or water quality falls below community standards. Social or cultural influences on decisions affecting the environment are more difficult to quantify than physical and chemical conditions. Consequently, environmental decisions are complex to evaluate and are often the subject of vigorous debate. Furthermore, the influence of these social and cultural factors changes with time as perceptions change. For example, our view of the role of wilderness has evolved in the 400 years since the earliest European settlers arrived on the North American continent. The early colonists considered the virgin forests home to unfriendly natives and mythical beasts, so they regarded wilderness with hostility. However, as the population expanded and the number of wilderness areas dwindled, the remaining natural lands began to be considered important cultural assets and were consequently protected by legislation such as the Wilderness Act (1964).

Given the complexities of people's relationships with our planet, earth scientists have several roles to play in modern society. These roles have become more crucial as our global population climbs past 7.7 billion people, with about 80 million more added each year. We are concerned about protecting life and property from the dangers of natural hazards, obtaining sufficient natural resources to maintain or improve our standard of living, and protecting the health of the natural environment. A final, more comprehensive goal, ensuring the future of our own species, is receiving increasing attention as we view a future in which human actions modify the composition of the atmosphere and we recognize the global-scale devastation that may result from catastrophic events such as the impact of an asteroid.

Protecting Against Natural Hazards

Scientists play a vital role in understanding and determining the potential risks from natural phenomena that may harm people and damage property. Natural processes such as earthquakes, landslides, floods, volcanic eruptions, tornadoes, and hurricanes are considered hazards when they occur in populated areas (Figure 1.8). The detailed study of hazards in one area can help predict the potential risks elsewhere. For example, scientists used the information they learned from investigations of a 1980 volcanic eruption of Mount St. Helens in Washington state (see Chapter 6) to accurately predict the size and timing of the larger 1991 eruption of Mount Pinatubo in the Philippines. (Was this an example of inductive or deductive reasoning?)

Each decade the cost of property damage from natural hazards more than doubles (when adjusted for the rate of inflation).

Figure 1.8 Examples of potential hazards associated with earth processes. a. Hurricane Sandy approaches US east coast, 2012; b. Building damage from 1989 Loma Prieta earthquake, CA; c. Slope failure above La Conchita, CA, 2005; d. Flooding on Rio Puerco River, AZ, 2013; e. Tornado touches down near Manitou, OK, 2011.
1.8a: Source: Goddard Space Flight Center/NASA; 1.8b: Source: USGS; 1.8c, d: Source: U.S. Geological Survey; 1.8e: Source: National Oceanic and Atmospheric Administration

In some cases, the risks from natural hazards depend more on development decisions made before these events occur than on the natural phenomena themselves. Human beings are unlikely to be able to stop volcanoes from erupting or to banish earthquakes. However, the application of scientific knowledge and appropriate technology can help save lives and protect property. The principal advantage of technology is to provide accurate information to maximize the safety of people living in areas at risk for natural hazards (Figure 1.9). The effects of some potentially destructive phenomena are partially offset by applied research that uses a variety of tools to collect data so that scientists can monitor potential hazards:

- Weather satellites track hurricanes and predict landfall sites, allowing timely evacuation of residents (Figure 1.8a).
- Engineering structures and strict building codes are deployed in earthquake-prone regions to reduce damage from failed buildings and infrastructure (Figure 1.8b).
- Geologists can investigate landforms associated with steep slopes to estimate the time between dangerous landslide events (Figure 1.8c)
- Networks of streamflow gauges linked by satellites reveal the magnitude and timing of floods, allowing emergency construction of levees and evacuation of residents (Figure 1.8d).
- Doppler radar installations have more than doubled the amount of advance warning time for tornadoes (Figure 1.8e).

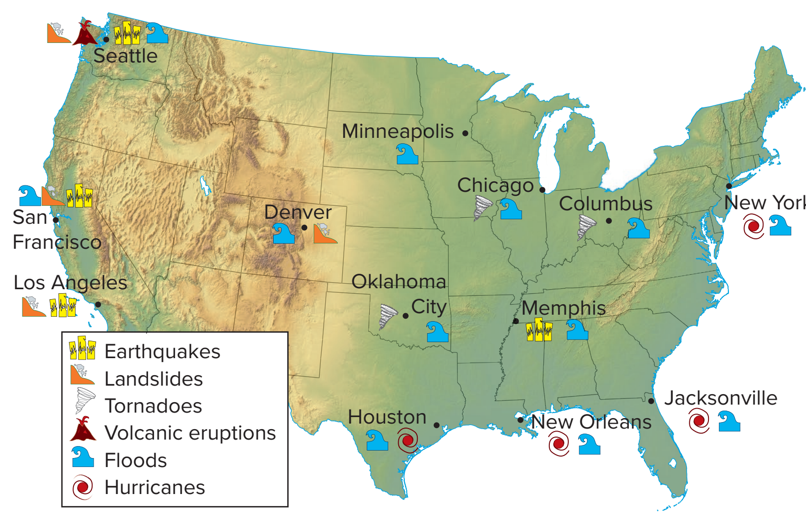


Figure 1.9 Principal natural hazards for some US cities. How does the type of hazard vary by region?

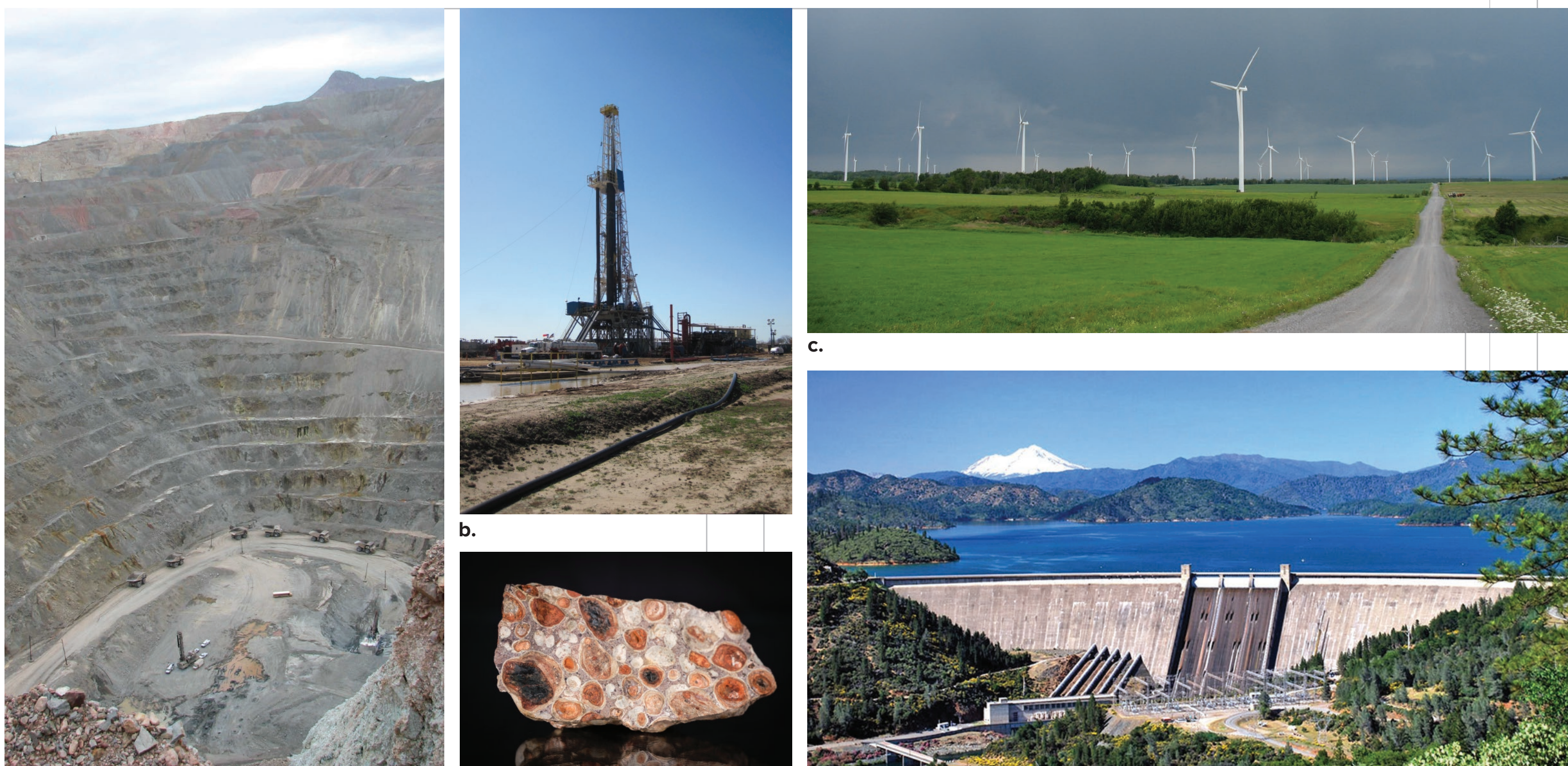


Figure 1.10 Examples of nonrenewable and renewable resources. a. Ray Copper mine, AZ; b. Drill rig, Karnes County, TX; c. Wind turbines, US; d. Bauxite ore sample, France; e. Shasta dam and reservoir, CA.
1.10a: Source: Mark Cocker/USGS; 1.10b: Source: Stephen Opsahl/USGS; 1.10c: Source: Paul Cryan, U.S. Geological Survey; 1.10d: Source: Scott Horvath, USGS; 1.10e: Source: Bureau of Reclamation

Mitigation represents actions that prevent or reduce the probability of a natural disaster or lessen the effects of the event by improving community resilience. Although we cannot prevent most natural hazards from occurring, we can make adjustments that will minimize their impact through careful land use planning, the enforcement of building codes, and the purchase of insurance policies. Floods and landslides are clearly linked to streams and slopes, allowing scientists to make local alterations to the environment or encourage adjustment strategies in efforts to mitigate future hazards. For example, building levees to contain rising streams or reservoirs to store floodwaters and limiting construction in floodplains can locally diminish or eliminate the risk of structural damage resulting from flooding. However, we should be aware that any alteration of a natural system has the potential to cause unanticipated changes. For example, building a levee may reduce flooding locally, but actually increase the flood risk downstream, where the stream is in its natural state.

In assessing the risks associated with natural hazards, earth scientists must try to answer several questions: How often do such hazards occur? How large an area will be affected? How grave is the risk to people and property? What actions can be taken in both the short and long term to prevent some of these events or lessen their impact? How will potential climate changes affect the scale and frequency of future events? Determining the correct answers to these questions requires knowledge of earth processes, the characteristics of the landscape, the distribution and physical and chemical properties of rocks underlying a region, and the factors that influence oceanic and atmospheric circulation. These scientific questions are more than academic—they focus on the very safety and security of human lives. We will explore the science behind natural hazards in Chapters 5, 6, 10, 11, 13, and 15.

Finding and Sustaining Earth's Resources

Life on Earth requires the use of resources. The term *resources* covers everything we use, including such basic assets as air, soil, timber, and water; fuel resources such as coal, oil, and gas; and mineral resources, such as sand and gravel (Figure 1.10). These natural resources may be renewable or nonrenewable. Renewable resources are replenished constantly (wind, soil, water), on short-term timescales measured in months (crops) or over longer intervals of several years (timber). The ready availability of clean water is something we can often take for granted, but in several locations, water supplies are vulnerable to overuse, pollution, and changing climates. Large regions of the world that support agricultural irrigation and cities with water from melting glaciers will inevitably experience a decline in water resources in the next few decades as many glaciers steadily shrink in size. Many geologists work to monitor the availability of freshwater and determine how changing connections between components of the hydrologic cycle will influenced future supplies.

Nonrenewable resources are either lost following consumption (fossil fuels) or may be recycled to be used again in other products (metals). In 1900, renewable resources (agriculture, food, forest materials) accounted for 41 percent of the consumption of US raw materials. Today, they represent less than

10 percent of total materials consumed (by weight). The US is among the world's leaders in the consumption of mineral and energy resources, and our economic growth depends on continued access to these materials. There are 1,700 billion barrels of oil available in global oil reserves. Each day, the world uses approximately 96 million barrels (35 billion barrels per year). How long before oil reserves are depleted, according to those numbers? Energy is essential to every aspect of our daily lives. Currently, the US imports approximately 25% of its oil; in comparison, just over a decade ago, that number would have been around 50%. The big difference has been the development of new technologies that made it possible to increase oil production from US sources and thus reduce the volume of oil we import each year. However, even though we have a secure energy supply, we must also acknowledge that the fossil fuels that account for most of that energy also generate excess greenhouse gases that have contributed to changes in the global climate.

Every day our national economy relies on an abundant supply of minerals, some of which we might know, others that we barely register. For example, we use aluminum, extracted from the mineral bauxite (Figure 1.10d), in almost all sectors of the economy. In contrast, minerals such as gallium, indium, and tantalum are all critical to the manufacture of electronics; and the US is completely reliant on imports for all three, along with a host of other minerals. These minerals are on a list of 35 critical mineral commodities that are considered essential to the economic and national security of the nation. One-third of the world's people live in the rapidly expanding economies of China and India, placing even greater demands on global mineral and energy supplies. **In an ideal world, the human race would develop into a sustainable society, a society that satisfies its desire for resources without completely consuming resources essential for future generations.** However, given the pace of global economic development, it is unlikely that we will achieve sustainability in the near future.

Earth scientists work to find new mineral and energy resources, to understand their distribution and abundance, and manage efficient, environmentally responsible resource extraction. Will there be sufficient resources to support the growing global population 50 years from now? What steps can we take to preserve and protect the most heavily exploited resources? What alternative sources can be utilized to make the nation less dependent on foreign suppliers? Successfully answering these questions requires earth scientists to explore ever more remote parts of Earth's surface, including rain forests, rugged mountain ranges, and the deep ocean floor. It is theoretically possible that Earth could support many times its current population, but such speculation takes no account of the quality of lives people would be required to lead to ensure sufficient food (and other resources) for all. Individual actions, such as turning on a light or pouring a glass of water, involve relatively modest resource use and require little thought except in the most extreme conditions. However, multiply those actions several billion-fold and divide some resources across international borders, and we can readily imagine situations where resource exploitation can have wide-ranging consequences (Figure 1.11). The distribution and exploitation of natural resources are examined in Chapters 2, 7, 9, 11, 12, 14, 16, and 17.

✓ Checkpoint 1.10: Intermediate

Is evacuation of a city before a hurricane an example of the prevention of a hazard or adjustment to a hazard?

a. Prevention

b. Adjustment

What other examples of prevention or adjustment have been described in the chapter so far?

Protecting the Health of the Environment

The biosphere (plants, animals) has exhibited dramatic changes throughout Earth's history, but recent population growth has contributed to environmental change, albeit over a much shorter timescale. Global population more than quadrupled since 1900, and we will add several billion more people this century. As population has expanded, so has industrialization and consequently pollution of land, air, and water. Pollution is still readily visible in developing countries, but in the US, its effects are muted and much more subtle, as indicated by reports of respiratory ailments and contaminated drinking water supplies. We can consider these threats as examples of slow-motion hazards. While they don't have the sudden impact of an earthquake or tornado, their long-term consequences have the potential to be much more devastating.

Human activities have the potential to endanger human life and natural ecosystems. For example, we have found a variety of ways to contaminate the hydrosphere. One of the most spectacular was the April 2010 explosion of the *Deepwater Horizon* oil rig, which resulted in the spill of 4.9 million barrels (206 million gallons) of oil into the Gulf of Mexico. The disaster continued for three months as crews struggled to cap the gushing well on the floor of the Gulf, 1,600 meters (5,100 feet) below the sea surface. Eleven rig workers lost their lives in the initial explosion, and the spill eventually contaminated 1,064 kilometers (665 miles) of coastline in multiple states (Figure 1.12a). The oil spill itself, and the chemicals used to disperse the oil, combined to decimate marine species in much of the northeastern Gulf. Much of the oil remained in the water column at about 1,000 meters depth. The oil that made it to the surface affected over 2,100 km (1,300 miles) of the coast, much of it saltwater marsh. Initially, many coastal birds were affected. In the years since the disaster, coastal ecosystems have displayed remarkable resilience and there appears to be little seafood contamination attributed to the massive spill. British Petroleum, the company that leased the well, has spent approximately $65 billion cleaning up the region (Figure 1.12b), and legal challenges remain. To this day, scientists continue to study the longer-term effects on deep water and coastal ecosystems. We will explore aspects of how the health of the environment is affected by both human and natural causes in Chapters 2, 6, 8, 9, 12, 13, 14, 15, 16, and 17.

Ensuring the Future of Human Life

The issues discussed so far occur at the local, regional, or national scale and involve events that are significant on timescales measured in hours to years. However, if we take a more global view, we can identify processes that have the potential to affect everyone,

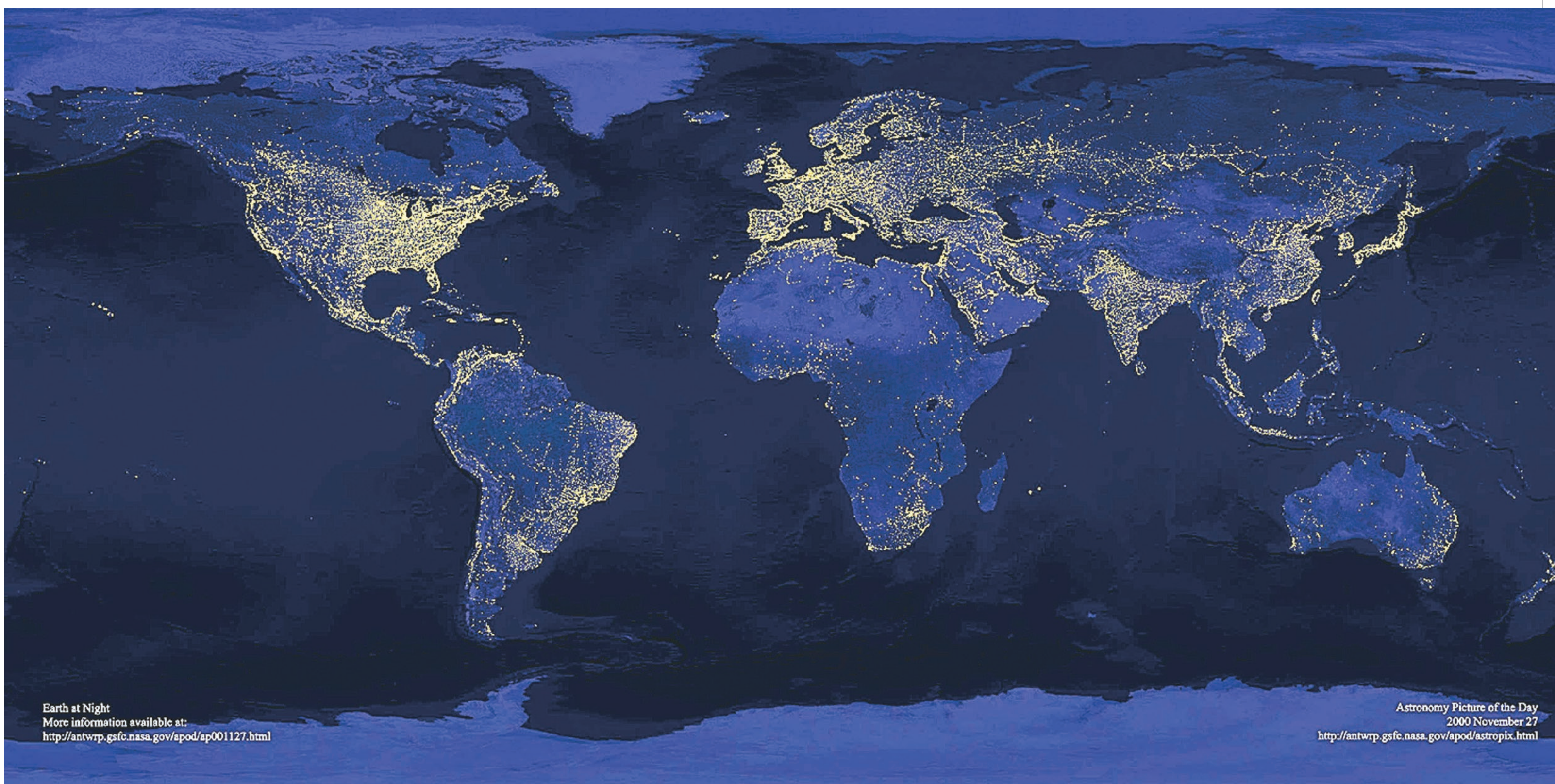
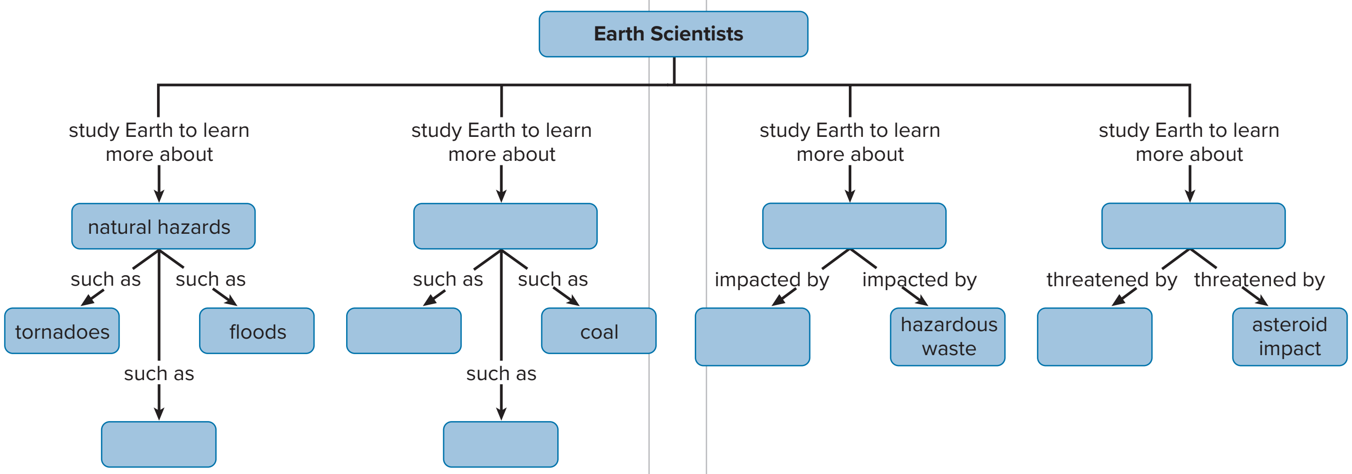


Figure 1.11 Human-generated lights on Earth. These patterns indicate the distribution of population and serve as a proxy (substitute) indicator of energy consumption for different nations. Densely populated, developed regions (United States, Europe) show brighter lights than heavily populated, developing nations (India, China). Sparsely populated regions are dark (South American rain forest, central Australian desert).
Source: NASA

Figure 1.12 Deepwater Horizon oil spill and its consequences. **a.** The extent of the oil spill in the Gulf of Mexico. Oil washed ashore along coastlines of Louisiana, Mississippi, Alabama, and Florida. **b.** Workers clean up spill debris along the Alabama coast.
1.12a: Source: Adapted from http://www.nytimes.com/interactive/2010/05/27/us/20100527-oil-landfall.html 1.12b: ©Zhang Jun/ZUMApress/Newscom

Checkpoint 1.11: Advanced

Complete the following concept map to summarize the characteristics of the four principal roles that earth scientists play in society.



everywhere, for decades and perhaps centuries to come: the impact of a large object from outer space and the effects of global climate change. Any program that attempts to address either impact events or global change would be both complex and expensive, requiring cooperation among many nations and potentially taking decades to complete. Nevertheless, these threats cannot be ignored, and science has the potential to show the way to effective solutions. We examine the science behind these issues in Chapters 2, 3, 4, 6, 8, 13, 14, 16, and 17.

The **impact of a large asteroid or comet with Earth represents a global-scale natural hazard** (Figure 1.7) that has the potential to end all life as we know it or to devastate a continent-sized area of the planet. Concerns about such an impact increased in recent years as we became aware that such events were more commonplace in the geological past than was previously thought. Although scientists have many ideas about how to stop an object on a collision course with Earth, no mechanism yet exists for dealing with such an event. We will address issues related to impact events in Chapter 3.

An international panel of scientists has concluded that **global warming represents an alteration of global climate patterns resulting from human activity.** There is broad consensus among an overwhelming majority of scientists that carbon dioxide and other gases of human origin have altered global climates over the last century. Higher concentrations of carbon dioxide are associated with warmer temperatures. Warmer conditions have the potential to cause wholesale changes in natural systems around the world.

Scientific research on global change is an example of "big science," because it involves researchers around the world working on thousands of different projects, each contributing a small piece to a much larger puzzle. The 1990 Global Change Research Act required the federal government to implement a climate change research program. The US government budgets more than $2 billion for climate change research each year through the US Global Change Research Program, which involves workers from more than a dozen government agencies. The investigations of the program involve hundreds of scientists working in research teams and examining many different topics that will contribute to our understanding of global change. Each team of scientists must make a research plan, collect data, make observations, draw conclusions, present their work at professional meetings, and write technical articles during the term of their research. Researchers seek to piece together a story about past and future global change by reading literally thousands of publications and synthesizing hundreds of ideas to build sophisticated computer models. This process represents a lot of hard work, and the process moves forward slowly in careful increments. This is the nature of science.

Checkpoint 1.12: Exceptional

Read the following quote. Discuss why you agree or disagree with the statement.

> *This is the first generation in the history of the world that finds that what people do to their natural environment may be more important than what the natural environment does to and for them.*
>
> *Harlan Cleveland, former US Assistant Secretary of State.*

the big picture

Earlier in this chapter, the discussion of the Alvarez hypothesis for the extinction of the dinosaurs illustrated how scientists made predictions, tested (and rejected) hypotheses, and arrived at the conclusions that were most reasonable under the circumstances. We finished the chapter with an indication of how humans are affecting the earth, atmosphere, and oceans. More than 100 years ago, the English mathematician and philosopher William Whewell noted that:

> *The hypotheses we accept ought to explain phenomena which we have observed. But they ought to do more than this: our hypotheses ought to foretell phenomena which have not yet been observed.*

The Global Change Research Program involves thousands of researchers seeking to explain the processes that control our current climate and to foretell Earth's future climate. Think of it as a global weather forecast for the next 100 years. We hope you will pardon us for revisiting this story throughout the book, but it will be one constant theme of science that you will hear, see, and read about in the years ahead, so we figured we would get you ready for action.

Making accurate predictions is essential if we are going to ensure a livable environment for the future of our global community. The recognition of ongoing changes to our planet allows us to consider exactly what we might expect in the decades ahead. Nobel Prize–winning scientist Paul Crutzen suggested that human activity has produced such sweeping changes to the planet that we have entered a new phase of Earth history, informally termed the Anthropocene. Crutzen and others point out that global temperature, sea level, and atmospheric chemistry were relatively stable for the last 8,000 years or more, but that social changes have disrupted this apparent stability. Rapid increases in human population were accompanied by economic growth and industrialization in the last few centuries, resulting in widespread resource exploitation and environmental change. Geologists differentiate distinct time intervals in Earth history when they are able to identify some characteristic features in the rock layers formed at that time. Some researchers suggest that thousands of years from now, future scientists will be able to recognize several key markers preserved in various parts of the earth system that will be readily interpreted as the result of changes during the Anthropocene. Key changes include:

- Faster erosion rates: More than one-third of Earth's land surface is exploited by humans. Layers of sediment on the seafloor will record activities such as agriculture and construction that remove more earth materials than natural processes.
- Changes in atmospheric chemistry: Gas bubbles trapped in thick ice sheets will show higher concentrations of such gases as carbon dioxide, methane, and sulfur dioxide.
- Less biotic diversity: Fewer species will be represented in fossil sites as many become extinct or less adaptable as single-variety forms used in agriculture replace the variability of natural species.
- More acidic ocean chemistry: Surface ocean waters are becoming more acidic as they absorb higher concentrations of carbon dioxide. This hinders the growth of some species (for example, corals) and dissolves the shells of others, removing them from the rock record.
- Higher sea levels: Short-term changes will be less than a meter over the next century but may be measured in tens of meters by the end of the millennium.

Source: Eric Scott, John D. Cooper Center/USGS

The concept of the Anthropocene represents significant global changes linked to all parts of the earth system. We will come back and talk about it a little more in Chapter 8, but we will examine different aspects of global change research in many chapters as we move through *The Good Earth*. By introducing the topic of global change here, we hope to give you an opportunity to look over the shoulders of the researchers to see how our understanding unfolds as scientists try to figure out how our home planet works.

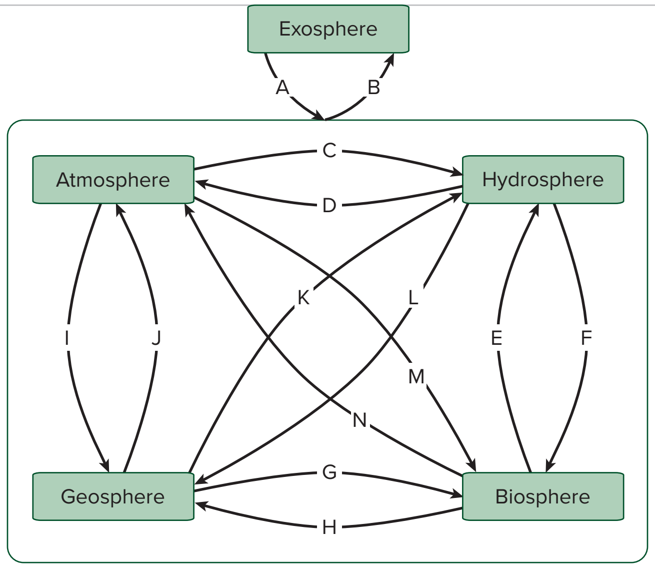
The Climate Change Science Program involves thousands of researchers seeking to explain the processes that control our current climate and to foretell Earth's future climate. Think of it as a global weather forecast for the next 100 years. We hope you will pardon us for revisiting this story throughout the book, but it will be one constant theme of science that you will hear, see, and read about in the years ahead so we figured we would get you ready for action.

Introduction to Earth Science: Concept Map

To evaluate your understanding of the interactions between the components of the earth system discussed in this chapter, complete the following concept map exercise.

Concepts maps are graphical learning tools used to help illustrate your understanding of the relationships between components of a system such as the earth system. When drawing a concept map, you show the interactions and/or relationships between the various components by drawing arrows from one component to another. The direction of the arrowhead indicates the starting component is acting on or somehow related to the other component (the end of the line with the arrowhead). You then label that arrow with the interaction or a short description of the relationship. As you learn more system-related concepts and relationships, you can add more arrows and labels. For example, in the concept map below, one could label arrow A with "sunlight" since sunlight comes from the exosphere and affects all other aspects of the earth system. It is important to realize that one concept map cannot describe the entire system in detail. As we move through the course, you will have opportunities to draw and label concept maps that pertain to the many subsystems of the earth system.

Interaction	Letter
Plants absorb carbon dioxide.	
Earthquake destruction causes deaths.	
Wind blows sand.	
Spacecraft explore deep space.	
Continents deflect ocean currents.	
Plants release oxygen.	
Fish live in oceans.	
Asteroid impacts Earth.	
Volcano emits toxic gases.	
Animals drink water.	
Water evaporates from the oceans.	
Humans mine coal.	
Winds generate waves.	
A stream carves a canyon.	



"We travel together, passengers on a little space ship, dependent on its vulnerable reserves of air and soil; all committed for our safety to its security and peace; preserved from annihilation only by the care, the work, and, I will say, the love we give our fragile craft."

Source: Adlai Stevenson, former governor of Illinois

"We have only one planet. If we screw it up, we have no place to go."

—J. Bennett Johnston, US Senator

Source: NASA GSFC image by Robert Simmon and Reto Stöckli

Chapter 2

Earth in Space

the big picture

A planet you should know. How many more of these are there out there?

See The Big Picture box at the end of this chapter for the full story on this image.

Chapter Outline

Self-Reflection Survey

Answer the questions below as a means of uncovering what you already know about Earth's position in space.

1. Explain how we are influenced by Earth's position in space on a daily basis.
2. If you could make one trip into space, where would you most like to visit and why?
3. Think about some situation in your life where you changed how you thought about something. What circumstances were required for you to change your mind or point of view?

©Paul Byrne

Chapter introduction written by Paul K. Byrne, Ph.D.

Paul is an Assistant Professor of Planetary Science at North Carolina State University. His research focuses on the links between surface and interior processes on rocky and icy solar system bodies using a combination of remotely sensed data, physical and numerical modeling, and fieldwork at analog sites on Earth.

2.1 Old Ideas, New Ideas

Chapter Learning Outcomes

- Explain the major processes and significant events that shaped formation of the solar system over billions of years.
- Describe the cause of the seasons and predict changes to future climate.
- Explain how and why there are various geologic boundaries within Earth.
- Describe the conditions necessary to support life on Earth.

The discovery of the major moons about Jupiter in the seventeenth century by Galileo Galilei marked the beginning of humankind's scientific understanding of our place in the universe. Over the following 400 years, we have come to see Earth as one planet among many others in a staggering array of bodies in our celestial neighborhood. After several decades of planetary exploration by both astronauts and increasingly capable robotic spacecraft, we are able to apply our knowledge of how geology shaped Earth to understand why other planets and moons look the way they do. In return, we have gained a new awareness of our planet, including a glimpse into its very ancient past, as well as a look forward to the prospects for a future Earth.

The first artificial satellite to orbit Earth was the half-meter-sized *Sputnik* probe, launched by the former Soviet Union in 1957. Although *Sputnik* was a relatively simple probe, its launch and successful operation in low Earth orbit for several weeks represented the beginning of what came to be known as the Space Age. Only four years later, cosmonaut Yuri Gagarin became the first person in space, and a little more than a decade after *Sputnik*, Neil Armstrong became the first human to set foot on the moon. Although no one has ventured further than the moon, humankind has extended its reach far beyond by dispatching a great number of spacecraft to other planetary bodies.

The first spacecraft to visit another planet was the NASA *Mariner 2* probe, which flew past Venus in 1962. The exploration milestones came quickly thereafter. The NASA *Mariner 4* mission returned the first high-resolution photographs of another planet during its successful flyby of Mars in 1965. The following year, the Soviet *Luna 9* mission become the first human object to successfully land on the surface of another celestial body when it touched down on the moon. The Soviet *Venera 7* lander broadcast the first images from the surface of another planet, Venus, in 1970. The first flybys of Jupiter, Mercury, and Saturn followed, in order, in 1973, 1974, and 1979; and the distant giant planets Uranus and Neptune were visited by the NASA *Voyager 2* probe in 1986 and 1989, respectively. As a testament to the enormity of the solar system, the preliminary exploration of the nine "classical" planets was completed only in 2015, when the NASA *New Horizons* spacecraft made a three-hour-long close flyby of Pluto (Figure 2.1), following a nine-and-a-half year journey to this distant world.

The robotic reconnaissance of the solar system has revealed that Earth is unique among its planetary kin, because it is the only world with plate tectonics (see Chapter 4). Plate tectonics probably requires liquid water to operate, an ingredient that also seems key to life (as we know it). Some scientists have inferred that plate tectonics may be necessary for life to emerge and survive. Several other Earthly features are present on other planets and their satellites. Most other planets have substantial atmospheres (with only Mercury and the moon possessing tenuous collections of atmospheric gases); familiar phenomena, including storms, lightning, and precipitation, have been observed or inferred for bodies as diverse as Mars, Jupiter, and Saturn's icy moon Titan; and even diminutive Mercury shares with Earth the trait of an internally generated magnetic field. But nowhere else does a mosaic of tectonic plates exist (at least today), liquid water is not stable on any other planetary surface, and there is certainly no evidence for life on any other planetary body in the solar system.

Yet our exploration of other worlds suggests that water is in no way restricted to Earth. In fact, our visits to the outer solar system have revealed that huge volumes of liquid water exist beneath the cold, icy shells of some of the enigmatic moons that circle Jupiter and Saturn. Tantalizingly, Mars boasts evidence of having once hosted liquid water seas and perhaps even an ocean, raising the question of whether the cold and dry Red Planet was once habitable and even inhabited by primitive lifeforms. Intriguing chemical measurements of the Venus atmosphere hint at the presence of

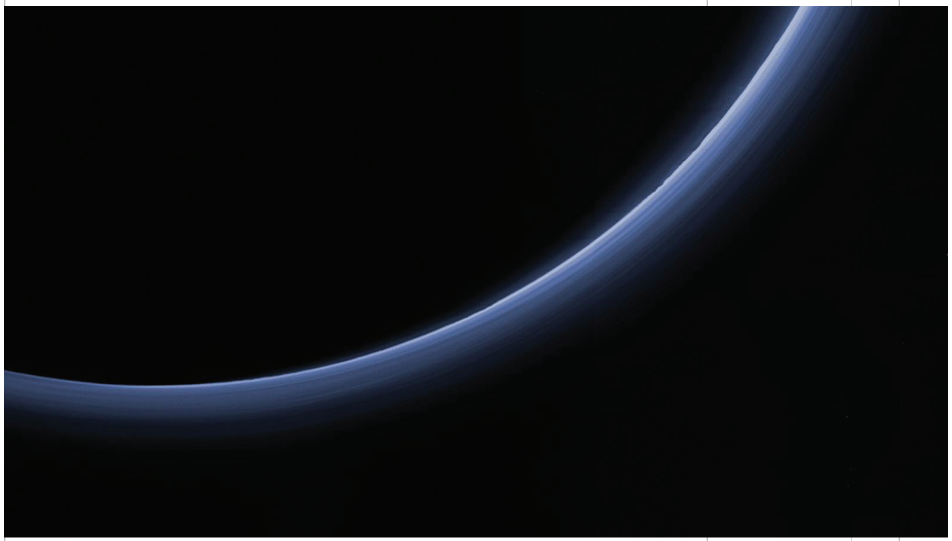


Figure 2.1 The nitrogen-rich atmosphere of Pluto, backlit by the sun, as glimpsed by the NASA New Horizons probe in 2015. This image is in approximately true color. The small bumps along the horizon (upper right) are water-ice mountains, some of which stand several kilometers tall.
Source: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

oceans on that planet's surface billions of years ago. It seems, then, that the present-day conditions in the solar system have changed over time, a realization that helps us to better understand what things were like during the earliest days of Earth, and even what possible fate awaits our planet.

For example, plate tectonics and erosion have effectively removed 95 percent of the rock record of Earth's history. However, even a cursory examination of the surfaces of Mercury, the moon, and Mars reveals the presence of truly gigantic impact basins, some of which were formed by colliding asteroids and comets more than 4 billion years ago. Such massive impacts must surely have also wounded Earth, but no evidence of their formation survives for us to examine first hand. Our exploration of the solar system has therefore shown us the face of Earth in its infancy. We can look elsewhere to see a potential analogy for Earth's fate in the distant future. Our neighbor Venus is a similar size as Earth but lies closer to the sun, a star that grows ever brighter and hotter as it ages. Venus might once have had oceans, but today its surface lies below a thick, carbon dioxide atmosphere with hellish surface temperatures approaching those of a self-cleaning oven. Increasing sunlight would have evaporated water from any early Venusian oceans and driven the planet into a runaway greenhouse effect. The sun will continue to brighten and heat Earth before it reaches a future red giant phase—and so we can to ask, "Will Earth lose its oceans as Venus might once have?"

For all of the insight gained over the past 60 years of space exploration, however, perhaps none has been more important than our discovery of exoplanets, planets in orbit about other stars. The first confirmed detection of an exoplanet occurred only in 1992, despite depictions of alien solar systems in fiction for hundreds of years. Improved detection methods (including by telescopes orbiting Earth) have revealed thousands of exoplanets, and very many more candidates await confirmation. Most certified examples are giant planets, simply because they are easier to find. Nonetheless, we are starting to recognize an increasing number of Earth-sized worlds, including examples situated at a distance from their host star where water could exist as liquid on the surface. These distant counterparts to Earth are therefore playing an ever more important role in planetary science, particularly the determination of how common planets like our own might be. The past half-century has seen enormous advances in our understanding of our world as a planet among many; with our investigations into exoplanets, we may be growing ever closer to an answer to that most fundamental question of planetary exploration: "Are we alone in the universe?"

In this chapter, we will step back in time to describe the birth of the planet and travel even farther back to review the origin of the universe. We will describe our planet's safety features for this flight and explore the hostile space environment beyond our atmosphere. We will learn why energy from our sun makes life possible and that the inevitable demise of our nearest star will eventually result in the destruction of Earth. We will describe how internal and external energy sources may one day help reduce our dependence on fossil fuels and diminish the impact of global warming. Finally, we will consider why our home planet is the only one in our solar system capable of supporting widespread life and why many people cannot correctly answer the question, *Why is it warmer in summer and colder in winter?* All of this should provide us with clues about where to look for life elsewhere in the universe.

2.2 Origin of the Universe

Learning Objectives

- Explain the inflationary model of the origin of the universe known as the *Big Bang.*
- Predict the motion of distant stars, using the concept of Doppler shift.
- Compare and contrast examples of good and poor scientific process as it relates to understanding the origin of the Universe.

Earth is a small, rocky planet that circles the sun, one of the hundreds of billions of stars making up the Milky Way galaxy. A galaxy is a collection of stars, gases, and other matter bound together by the force of gravity. The Milky Way galaxy is one of billions of galaxies embedded in the much larger universe. Astronomers using the orbiting Hubble Space Telescope were able to catalog thousands of other galaxies in a relatively small section of deep space. Based on this small measurement, **scientists project there are hundreds of billions of galaxies in the universe, each galaxy having billions of stars.**

The universe itself comprises all of the energy and matter that physically exists. Estimates of the age, scale, and origin of the universe are based on our understanding of the relative motions of distant galaxies. Current models suggest an age for the universe of 13.8 billion years (with an uncertainty of +/- 50 million years). Age estimates may change as technology improves and we learn more about the characteristics of the most distant galaxies and stars.

Determining the Age and Size of the Universe

Brightness and Luminosity. For many decades, astronomers have used telescopes to study space. The first indication of the enormity of the universe came from measurements of the brightness of distant stars. The brightness of a star depends on the distance to the star and the amount of light energy it radiates (called luminosity).

From earlier discoveries, astronomers have identified a specific class of stars called *cepheid variables.* These stars pulsate (like the flashing of a road construction caution sign). Scientists can use modern telescopes to measure the time required for one of these pulsations, called the *period* of the pulsation. The pulsation period provides a good estimate of the cepheid luminosity. Scientists then use the brightness and luminosity to calculate our distance from the star. Edwin Hubble, for whom the Hubble Space Telescope is named, used data from these stars and distances to other galaxies to show that the universe extends far beyond the Milky Way. Hubble worked with Milton Humason to discover that galaxies are moving away from us; in other words, they discovered that **our universe is expanding.** (Humason had an interesting entry into science: he was a former janitor at California's Mount Wilson observatory with no formal education past the age of 14. He volunteered at the observatory, and his careful technique resulted in his being hired as a full-time staff member.)

The Doppler Effect. As technology improved, even more distant objects could be identified by using increasingly sophisticated telescopes. Unfortunately, technology was (and is) not advanced enough to measure pulsating stars in the most distant galaxies. Nevertheless, as is often the case in science, work in one area can

in Further Depth

Although Earth's position in the solar system may seem obvious, it took us a few thousand years to arrive at this knowledge. The activities of the sun were crucial to the daily routines of ancient civilizations who lacked access to today's sophisticated lighting and heating technology. People observed the sun rising in the east and setting in the west and inferred (wrongly!) that the sun revolved around Earth in a daily orbit. This interpretation received further support when observations of the stars revealed a similar pattern. **This early perception—that Earth lies at the center of our planetary system—is known as the geocentric orbit hypothesis.** Through research and observation, we now know that Earth rotates once each day so that we turn to face the sun in the morning and rotate away from its light as night descends.

Like almost everyone else living 2,300 years ago, the Greek philosopher Aristotle believed Earth was at the center of the universe and that the visible planets (Mercury, Venus, Mars, Jupiter, Saturn) and stars, including the sun, revolved around Earth (made a complete path around Earth) in a geocentric orbit (Figure 1). Aristotle's geocentric view of Earth's position in space dominated astronomy for almost two millennia, but not without being challenged. Another Greek philosopher, Aristarchus, made some rudimentary calculations of the relative size of Earth, the moon, and the sun, and concluded that it was more probable that **Earth revolved around the larger sun in a heliocentric (sun-centered) orbit.** Furthermore, Aristarchus suggested that Earth rotated (turned around a central axis of rotation) and that the Earth-sun system was part of a much larger cosmos. Aristarchus was generally correct; however, as is often the case, his peers disregarded his novel ideas because they contradicted the widely held views of his time and there was no way to confirm his hypotheses. That would take another 1,800 years.

The sixteenth-century scientist Nicolas Copernicus was the first person to expand on the heliocentric model sufficiently that it became a well-reasoned alternative to the geocentric view. But, as with many new scientific hypotheses, the technology did not yet exist to either confirm or reject Copernicus's ideas. It was not until 1609, when the Italian mathematician Galileo Galilei introduced the telescope into cosmic exploration, that observations could be made to test Copernicus's prediction and confirm the heliocentric hypothesis once and for all. As predicted by the heliocentric model, Galileo observed that the appearance and relative size of Venus varied as its position changed relative to the sun and Earth (Figure 2a). In the geocentric model, the sun was interpreted to revolve around Earth beyond Venus. Consequently, if Venus was located between Earth and the sun, an observer from Earth should only be able to see a small crescent of Venus lit by the more distant sun. In the heliocentric model, Venus constantly changes position relative to the sun, and an observer on Earth would see the full face of the planet lit when Venus was beyond the sun and progressively less of the planet as it moved between the sun and Earth (Figure 2b). At about the same time, a vocal supporter of Galileo, Johannes Kepler, was able to show that planetary orbits followed elliptical paths and the speed of a planet varied as it orbited the sun.

Galileo's evidence was followed less than a century later by Isaac Newton's explanation of the force that held the planets in their orbits around the sun—gravity. As technology evolved, scientists discovered additional planets and moons, and they were able to make increasingly detailed observations about the characteristics of our neighborhood in space. Eventually, scientists were able to use their understanding of planetary motions to send spacecraft throughout our solar system to collect more data on these ancient worlds.

Figure 1 Ancient representation of the geocentric Earth. Note the position of the sun in orbit in the right center of the image.
Science Source

Checkpoint 2.1: Basic

Which of these lists of cosmic features is in the correct order of size, beginning with the largest?

a. Universe, galaxy, star, planet
b. Star, galaxy, universe, planet
c. Universe, planet, star, galaxy
d. Galaxy, universe, star, planet

unexpectedly contribute to the solution of some other problem. For example, Hubble's work with cepheid variables provided him with data needed to develop a new technique for measuring vast interstellar (between stars) distances on the basis of an everyday effect that we have all experienced.

You have probably noticed the changing frequency (pitch) of the siren on a passing emergency vehicle as you stand on the sidewalk or sit stationary in a car. In fact, the tone changes dramatically just as the vehicle passes your car. You hear a higher pitch (higher frequency) when the vehicle approaches and a lower pitch

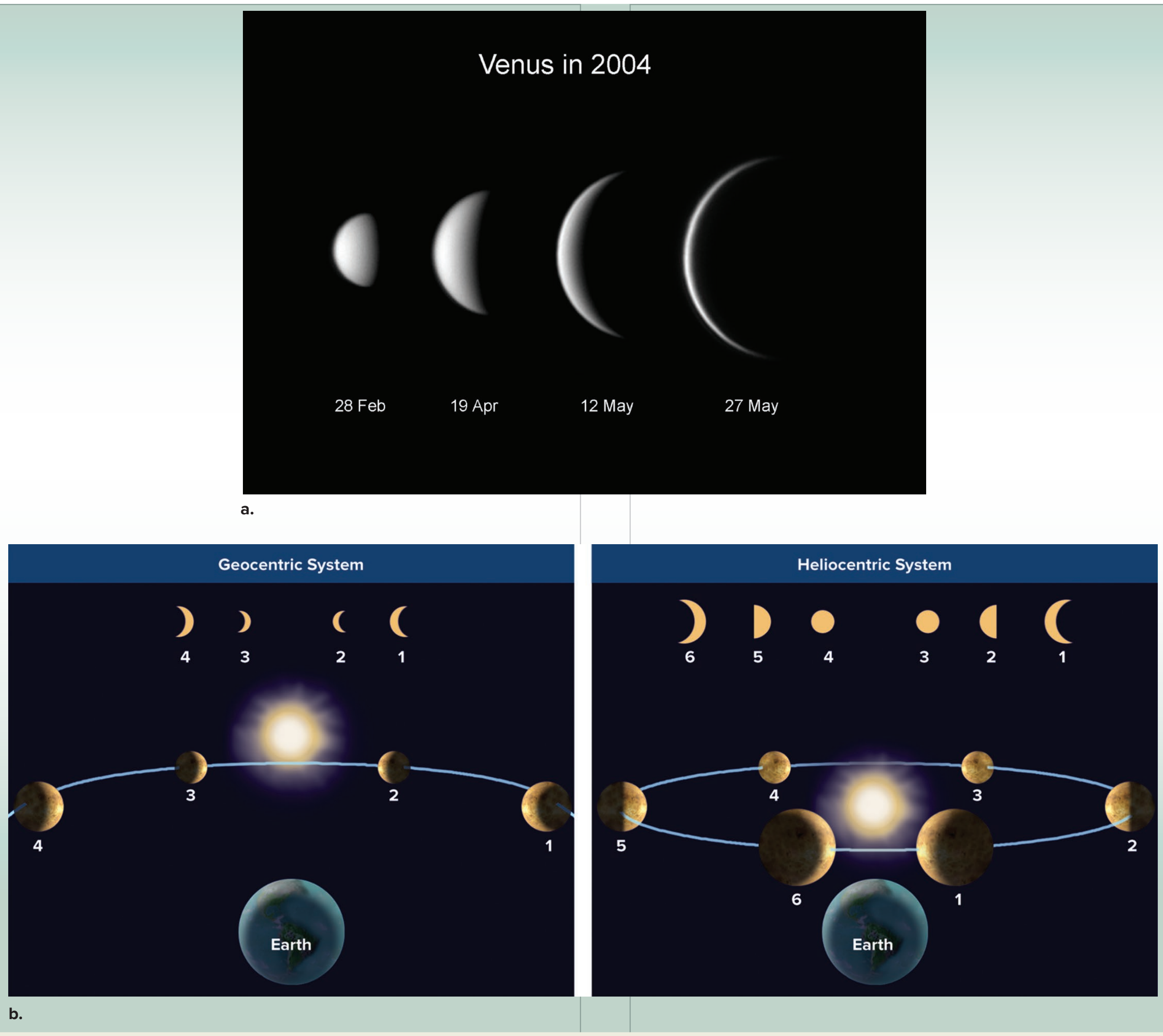
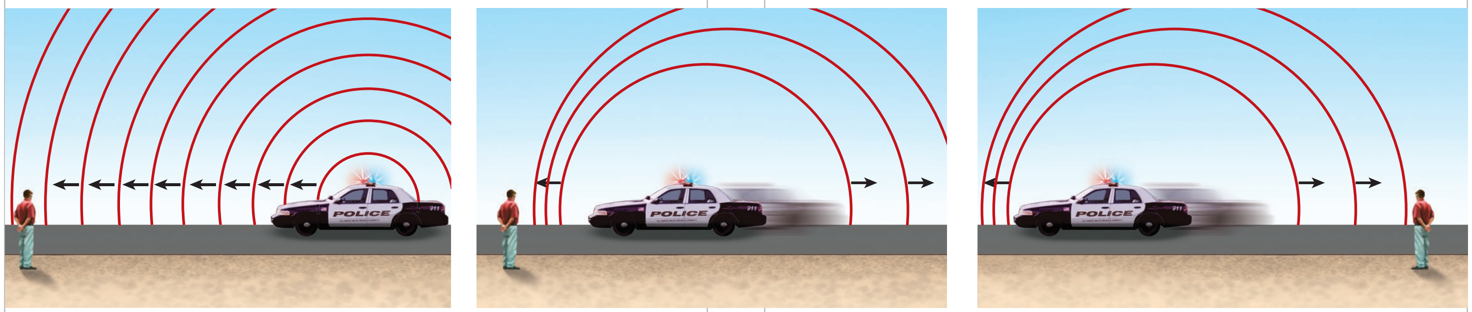


Figure 2 Phases of Venus in the heliocentric and geocentric systems. **a.** The phases of Venus from January 24 to May 14, 2004. Note how the size and appearance of the planet change. **b.** These changes cannot be explained by the geocentric model, where Venus lies between Earth and the sun. Consequently, the geocentric hypothesis is falsified by the phases of Venus. In the heliocentric model, Venus is either in front of the sun or behind the sun, relative to Earth. This is the pattern that Galileo observed and that we can see today.
SSPL/Getty Images



a. Observer hears normal frequency for the siren of stationary police car.

b. Observer hears higher frequency (shorter wavelength) siren for an approaching police car.

c. Lower frequency (longer wavelength) siren is heard for a police car moving away from observer.

Figure 2.2 The Doppler effect. **a.** When a police car is not moving, the frequency of its siren is normal. **b.** An approaching siren has a higher frequency. **c.** A receding siren has a lower frequency.

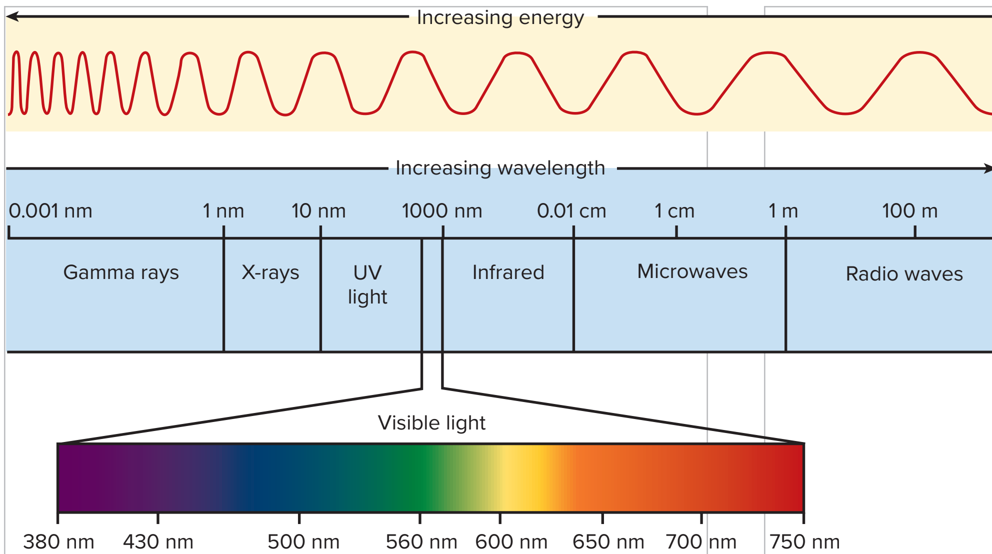


Figure 2.3 The electromagnetic spectrum. Radio waves can have wavelengths measured in hundreds of meters. In contrast, wavelengths for visible light are less than 1,000 nanometers [abbreviated as nm; 1,000 nm = 0.0001 centimeter (cm)] across but are 1 million times longer than the wavelength of gamma rays.

(lower frequency) as the vehicle moves away. The siren on the vehicle always creates the same frequency sound—that is, if you were driving an ambulance or standing beside a stationary ambulance, the sound of the siren would always be the same (Figure 2.2a). The change in pitch experienced by an observer occurs when the source of sound is moving relative to the observer (Figure 2.2b and 2.2c). **This apparently changing frequency due to the relative motion of a sound source is called the Doppler effect** (after the mathematician who discovered it). If you knew the frequency of the vehicle siren and measured the frequency of an approaching siren, you could calculate the speed of the emergency vehicle. The same effect occurs with light, and Hubble used the Doppler effect on light to estimate Earth's distance from faraway stars. This principle is routinely applied by meteorologists who use radar measurements to determine if storms and other weather phenomena are moving toward or away from their location.

In space, the velocity of light is always 3×10^8 meters per second (or 300,000 kilometers per second; 186,000 miles per second). In addition, the white light that we are so familiar with is actually a combination of the different colors of light that form a spectrum from violet to red. Each color has a different wavelength ranging between 380 and 750 nanometers (1 nanometer = 0.000000001 meter; Figure 2.3). Violet and blue have the shortest wavelengths, and red has the longest wavelength. Hubble analyzed the wavelengths of light from distant pulsating stars and noted that

✓ Checkpoint 2.2: Intermediate

Suppose the light spectrum from a distant star shifted toward the blue end of the light spectrum. What would this imply?

a. The star is moving away from us.
b. The star is moving toward us.
c. The star is not moving relative to us.

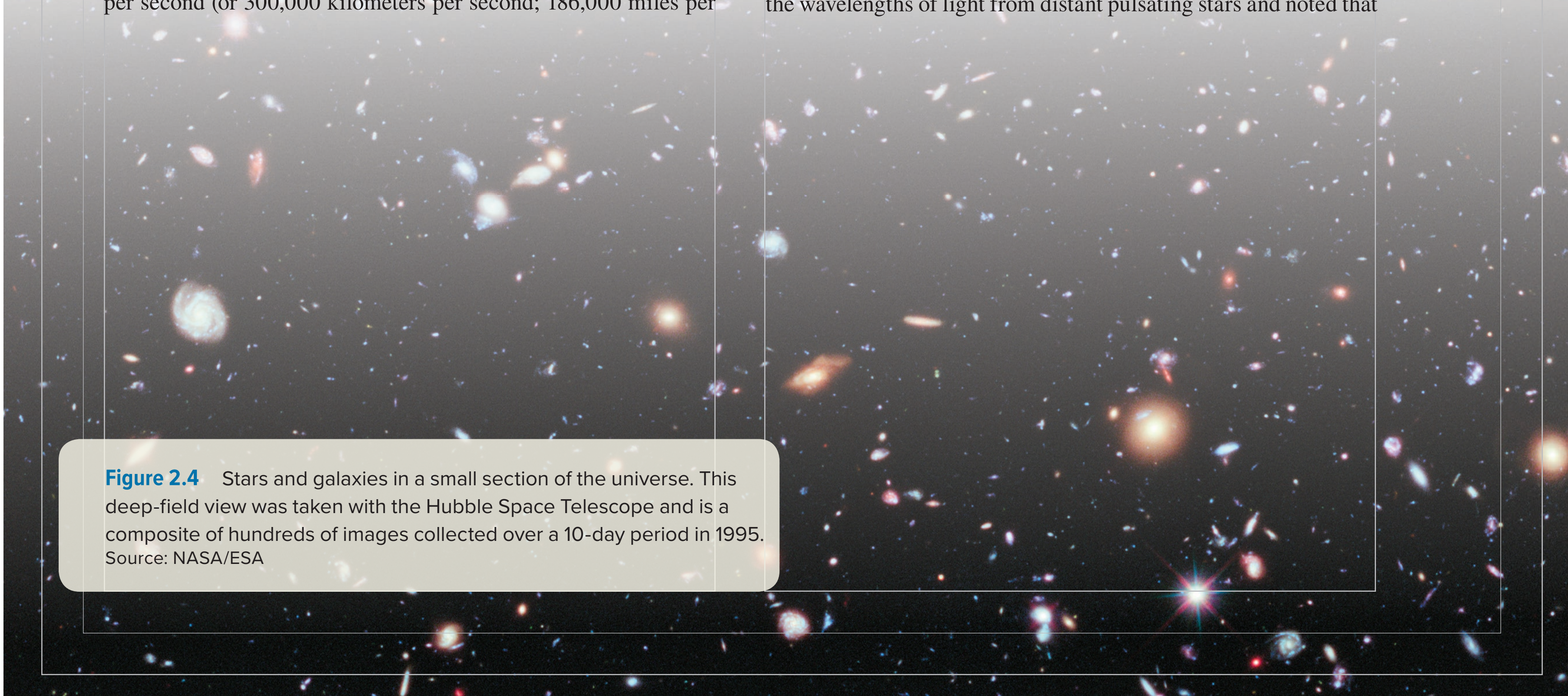


Figure 2.4 Stars and galaxies in a small section of the universe. This deep-field view was taken with the Hubble Space Telescope and is a composite of hundreds of images collected over a 10-day period in 1995.
Source: NASA/ESA

the wavelengths were typically longer—closer to the red end of the spectrum—when compared to light from closer stars.

This phenomenon, the shifting of the color of light from distant galaxies toward longer wavelengths, became known as *red shift*. Just as the frequency of the siren appears to change as an ambulance moves away from us, the wavelength of light appears to increase (undergo red shift) as stars in distant galaxies move away from us in the expanding universe. By calibrating the red shift data with information on the brightness of cepheid variables, scientists were able to use the size of the red shift to estimate the speed that individual galaxies were traveling away from us. Hubble also noted that **most (though not all) galaxies are moving away from us, and the farther away the galaxy, the greater the red shift (the faster they are moving away).** Astronomers used the amount of red shift to calculate the distance to the farthest galaxies. Taking this observation to its logical conclusion, we can anticipate that ever more distant objects would have even longer wavelengths of electromagnetic radiation that would stretch beyond the visible light spectrum to infrared and microwave radiation (Figure 2.3).

Measuring Distances in Light-Years. The most distant objects so far observed in the universe are more than 13 billion light-years from Earth (Figure 2.4). **One light-year is the distance that light can travel in one year and is equivalent to 9,500 billion kilometers (5,940 billion miles).** So, even though it is called a light-*year,* it is actually a measure of distance, not time. In comparison, our galaxy is approximately 150,000 light-years across; the nearest star to our sun, *Proxima Centauri,* is 4.3 light-years away; and our modest little solar system is just a fraction of a light-year from one side to the other. Using light-years to measure distance has the added benefit of having a time component that allows us to identify the age of objects. For example, if we could look at Proxima Centauri through a telescope, we would actually be observing how it looked 4.3 years ago. Think about it—when we observe the most distant stars we are actually looking back in time at light generated more than 13 billion years ago. These images (Figure 2.4) provide us with a glimpse of the earliest components of the young universe, created just a few hundred million years after it formed!

The Big Bang Theory

The discovery that distant galaxies are moving away from us yields clues about the origins of the universe. Because the universe is still expanding, the young universe clearly had to be much smaller than the one we see today. Initially, astronomers simply reversed the expansion of the universe to step back in time. By running the movie backward, it seemed clear that the universe must have been much smaller and more compact during its earliest stages. Astrophysicists are currently testing the theory that **the universe began with a massive and rapid expansion called the *Big Bang.*** Prior to this expansion, there was no space or time.

The Big Bang sent energy in all directions. Mathematical models indicate that the universe began as a rapid expansion of space and time (rather than an explosion) and the mass of the universe is being carried with the expansion. The models explain conditions back to a fraction of a second after initiation of the expansion (to the shortest meaningful measure of time, 10^{-43} second). At 10^{-34} second, the universe had expanded faster than the speed of light to the size of a golf ball. Within one second, the universe inflated from the size of a golf ball to being about 20 light years across. At this stage, the universe consisted of subatomic particles (protons, electrons) and free energy. Within a matter of minutes, these particles would have combined to form simple nuclei such as hydrogen and helium. Most complex elements would not form for several hundreds of thousands of years and would require the high temperatures and pressures found in the cores of stars (see Section 2.3).

The Big Bang theory predicted that cosmic radiation would have been released in all directions everywhere around us. So where was it? The answer to that question came from two scientists in New Jersey who were working on an entirely different problem. In 1964, Arno Penzias and Robert Wilson were trying to reduce static noise in a radio experiment that involved using a big, dishlike radio antenna. Despite their best efforts, they could not eliminate a steady hissing background noise from their results. It was there at every hour of the day and appeared to come from everywhere. They determined that this static was made up of certain frequencies of microwave radiation, but they could not figure out its source. It even reached the point where they climbed into the dish and gave it a good cleaning. In desperation, they

✓ Checkpoint 2.3: Advanced

Scientists often suggest that the expansion of the universe is similar to the expansion of raisin bread as it bakes in an oven. The raisins can be thought of as galaxy clusters embedded in the dough that represents space. Think about the motion of the raisins (galaxy clusters) as the dough (space) expands. Imagine you are an observer in one of those raisins looking at the other raisins and the expanding dough. Which of the following statements are true and which are false?

1. All of the raisins (galaxy clusters) are moving away from me no matter which direction I look.
2. The farther away the raisin (galaxy cluster), the slower it is moving away from me.
3. The dough (space) closer to me is expanding slower than the dough (space) far away.
4. The expanding dough (space) forces some raisins (galaxy clusters) to collide.

✓ Checkpoint 2.4: Exceptional

Scientific Analysis

Explain how the development of concepts presented in this section exhibited the key characteristics of scientific explanations:

1. Provisional (tentative)
2. Based on observations
3. Predictable and testable
4. Offer natural causes for natural events

contacted Robert Dicke, a scientist just down the road at Princeton University who, coincidentally, was looking for the missing radiation predicted by the Big Bang theory. Dicke recognized that Penzias and Wilson's troublesome signal was the missing cosmic background radiation. The missing background radiation originated in the much smaller early universe. It has been spreading out and "red shifting" ever since. As the universe expands, that radiation has become less energetic since the same amount of energy now occupies a much larger volume of space (see Figure 2.5a). In 1978, Penzias and Wilson were awarded the Nobel Prize in Physics for their unexpected discovery.

The Existence of Galaxies. The discovery of cosmic background radiation still did not answer questions related to the existence of "clumps" of matter (galaxies) in the universe. Again, the process of science kicked into gear. The original Big Bang model had to be refined to explain the existence of galaxies. Current versions of the theory suggest that at the time of the initial expansion, the mass-energy that now makes up the universe was not uniformly distributed. There were "gaps" and "bumps" that later formed regions where gravitational attraction pulled together clumps of gas and dust to form galaxies. Processes within these giant clouds of debris would result in material being pulled together to form massive stars and smaller planets (Figure 2.5a).

But the story does not end there. In the late 1990s, data from the Hubble Space Telescope showed that the universe expanded slower in the past than it appears to be expanding today. That observation did not fit the existing models for the formation and evolution of the universe. Those models suggested the expansion should be slowing, not speeding up. Theorists went to work to explain the Hubble data; perhaps Einstein's theory of gravity was wrong or maybe there was a yet unknown energy, particle, or force involved. While scientists still don't agree on the precise cause of the speeding expansion, they theorize that there is matter and energy throughout the universe that we simply cannot observe; and lots of it. Strangely, it turns out the missing matter and energy needs to make up about 95 percent of the universe to explain the observations. Think about it—that means all the galaxies and stars and other matter we can observe makes up less than 5 percent of the matter in the universe (Figure 2.5b). Astrophysicists call this material dark energy and dark matter. So, what is dark energy and dark matter? Well, at the moment, we know very little about the nature of dark matter and dark energy; we simply know how much

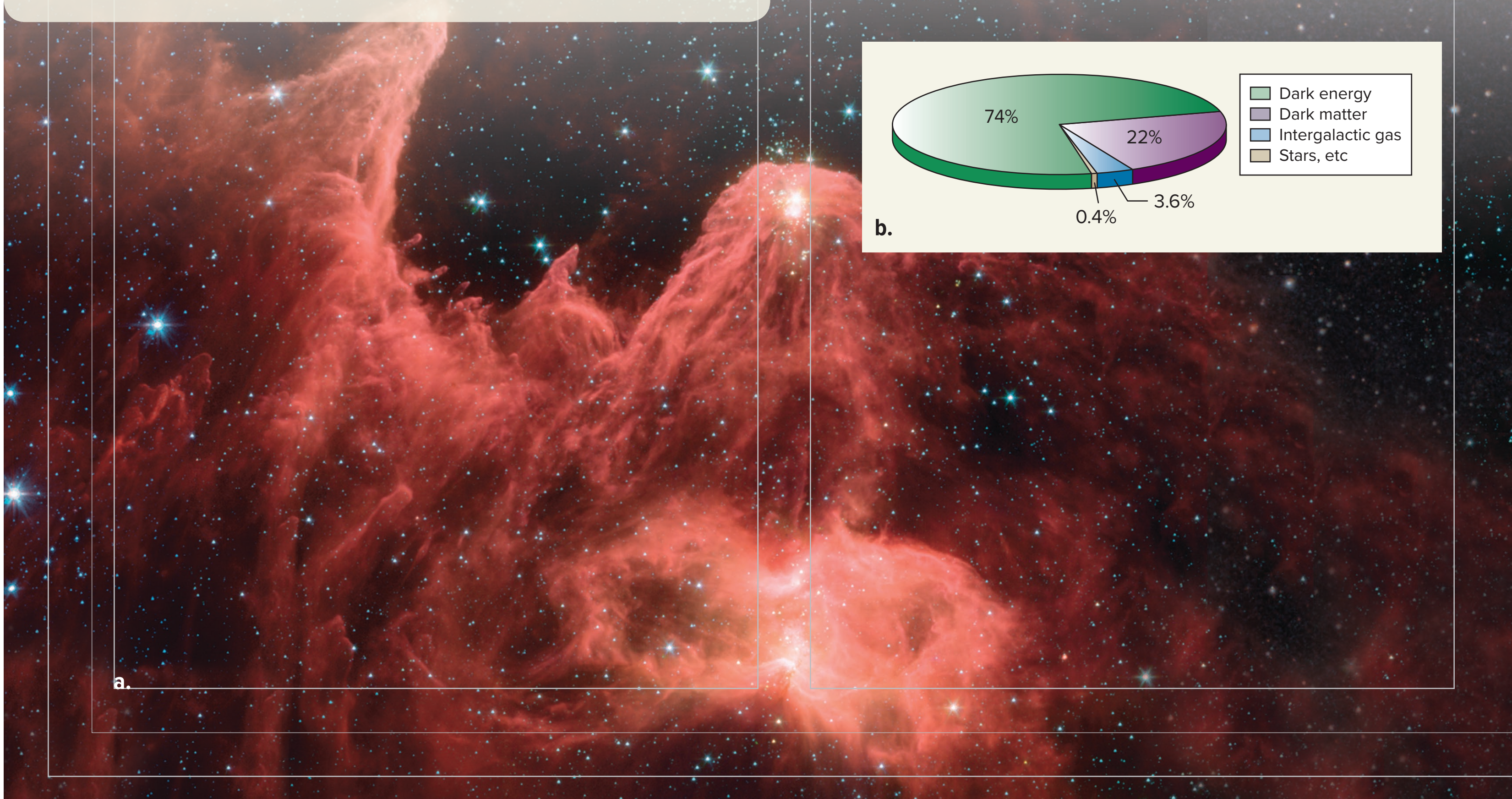


Figure 2.5 **a.** This false-color image from the National Aeronautics and Space Administration (NASA) Spitzer Space Telescope shows towering pillars of cool gas and dust that are incubators for the formation of new stars. Dozens of young stars can be seen inside the gas pillars. **b.** Pie chart showing the distribution of observable matter (such as shown in the NASA image) and unobserved, theoretically required dark matter and energy in the universe.
2.5a: Courtesy NASA/JPL-Caltech; 2.5b: Source: https://www.nasa.gov/vision/universe/starsgalaxies/Collision_Feature.html

is needed to explain the Hubble observations. This mystery is far from solved. Stay tuned to your favorite authoritative source for contemporary updates to this scientific debate.

2.3 Stars and Planets

Learning Objectives

- Describe the sequence of events in the life cycle of a star such as the sun.
- Summarize the characteristics of the universe, stars, and planets and their principal relationships.
- Discuss how scientists search for extra-solar planets and how they might determine if these planets could support life.

Techno musician Moby had a hit record several years ago that was titled "We Are All Made of Stars." It turns out that the title is true. We *are* all made of stars; well, technically we are made of things that are made *in* stars. The cells in a human body are composed of a variety of different elements, but just eight of those elements account for more than 99 percent of each of us by weight. Living cells are composed mostly of water (hydrogen and oxygen) and basic organic compounds built around carbon. These three elements—hydrogen, oxygen, and carbon—account for more than 90 percent of your body by weight. Another five elements (nitrogen, calcium, phosphorus, potassium, and sulfur) get us over the 99 percent mark. Hydrogen was created during the original formation of the universe, and all of these other elements are produced during the life cycle of stars. Many more elements are present in our bodies in just trace amounts and are essential for good health. The life cycle of big stars represents a manufacturing process that churns out elements that combine to generate the complex compounds necessary for the formation of our planet and everything on it, including us. Instruments aboard spacecraft have detected over 70 different chemical compounds in clouds of cosmic debris, including molecules of common substances such as water, methane, and carbon dioxide. Scientists use observations from other stars and our own solar system coupled with simulations to deduce how the sun and planets formed.

How Stars Formed

If you look up at the night sky, you can see about 2,000 stars from any location on Earth. If you were to spend a few hundred dollars you could get yourself a nice telescope that would allow you to see several hundred thousand stars. If you were willing to invest several thousand dollars in a really nice telescope you could see tens of thousands of galaxies, including hundreds of billions of stars (Figure 2.6). And those are just the stars that are close by. So how did all those stars form?

Checkpoint 2.5: Basic

Construct a time line diagram that illustrates the life cycle of the sun.

Figure 2.6 The spiral galaxy NGC 4414. This is one of three main categories of galaxies (elliptical and irregular are the others). The galaxy's disk is about 56,000 light-years across. The system lies about 62 million light-years from Earth. As-yet undiscovered planets may orbit some sun-sized stars within the galaxy.
Source: NASA

Variations in the distribution of matter after the Big Bang led to gravity pulling matter together in clumps to form galaxies. Within these galaxies, clouds of dust and gas coalesced, increasing the mass of the cloud and pulling in adjoining material. Eventually, the gravitational pull of these masses produced giant hot balls of glowing gas. After several million years, the temperatures and pressures at the centers of these objects became so intense they fused together the nuclei of hydrogen atoms. This process, called *nuclear fusion,* occurs when hydrogen nuclei are mashed together under high temperatures and pressures to form helium. The result: stars were born.

Stars have several characteristics including luminosity, color, surface temperature, size, and mass. When plotted based on their temperature and luminosity (Figure 2.7), stars can be grouped into categories. Main sequence stars include the sun and other stars up to 3 times the size of our sun. Those stars all undergo fusion of hydrogen into helium in their cores. If the star is less than about 1.5 times the size of our sun (which is 1 solar mass), **heat energy comes from the nuclear fusion of four hydrogen atoms to form a single helium atom.** Larger main sequence stars also undergo hydrogen fusion but through a more complex sequence involving carbon, nitrogen, and oxygen.

In general, the more massive the star, the shorter its life span. Intermediate-sized stars, such as our sun, last about 10 billion years. More massive stars, such as supergiants (like Deneb and Rigel in Figure 2.7), are 70 to 100 times larger than our sun but will last for just 10 to 100 million years. The nearest star to the sun is a red dwarf, Proxima Centauri. It is smaller but more dense than the sun and its life cycle is measured in trillions of years.

The sun is composed exclusively of gases, with hydrogen and helium making up almost all of its mass. The fusion reactions are steadily consuming the sun's supply of hydrogen. According to our current understanding of the life cycle of stars, we are approximately halfway through the sun's life. As it burns through its hydrogen, the sun is slowly getting hotter. In the far distant future, about 2 billion years from now, this increasing heat will have caused Earth's oceans to evaporate and our planet will become more like Venus. In about 5 billion years, the outward pressure generated by