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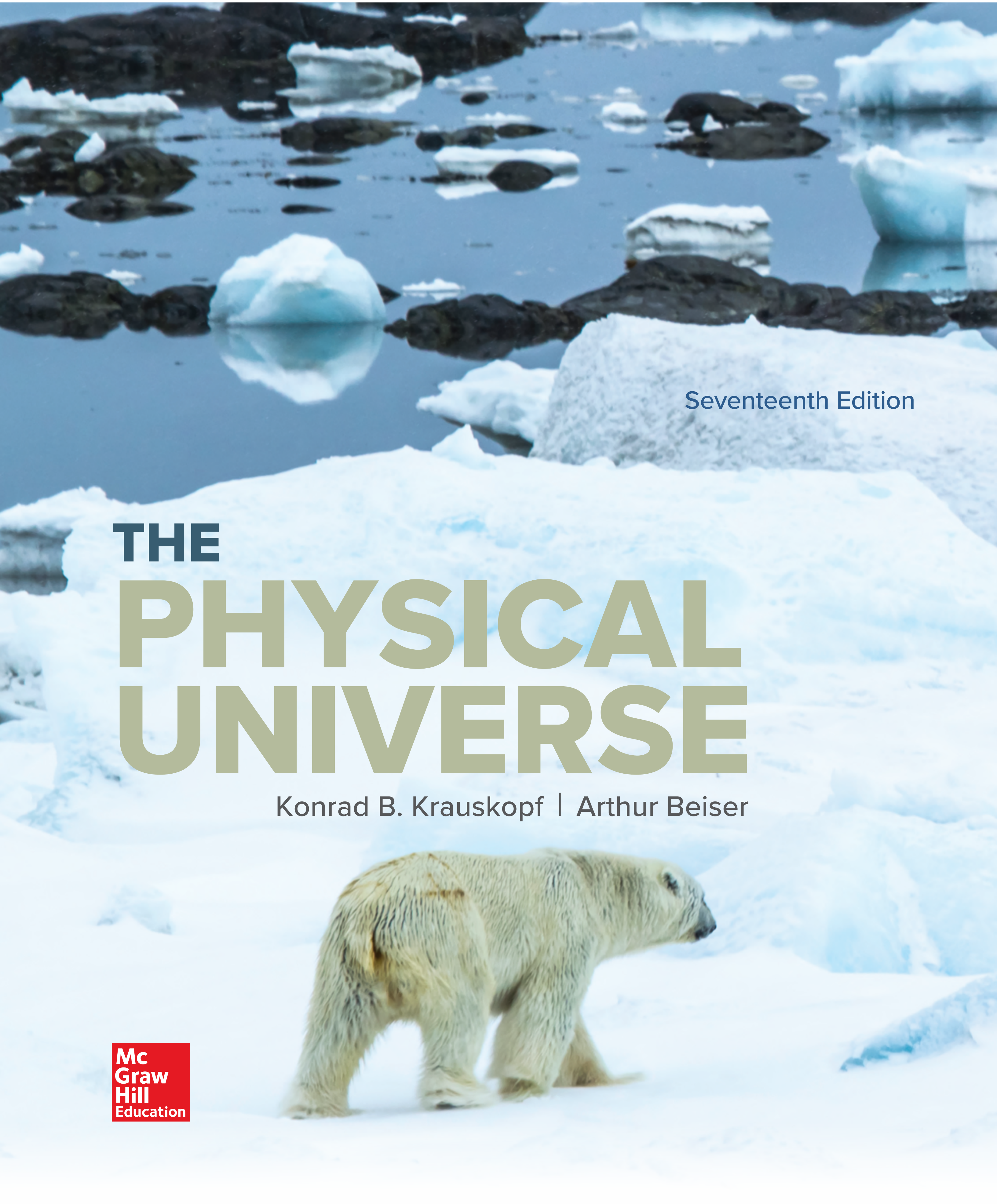
Seventeenth Edition

THE PHYSICAL UNIVERSE

Konrad B. Krauskopf | Arthur Beiser



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Conversion Factors

1 meter (m) = 100 cm = 39.4 in. = 3.28 ft

1 centimeter (cm) = 10 millimeters (mm) = 0.394 in.

1 kilometer (km) = 1000 m = 0.621 mi

1 foot (ft) = 12 in. = 0.305 m

1 inch (in.) = 0.0833 ft = 2.54 cm

1 mile (mi) = 5280 ft = 1.61 km

1 liter = 1000 cm^3 = 10^{-3} m^3 = 1.056 quart

1 day = 86,400 s = 2.74×10^{-3} year

1 year = 3.16×10^7 s = 365 days

1 m/s = 3.28 ft/s = 2.24 mi/h = 3.60 km/h

1 ft/s = 0.305 m/s = 0.682 mi/h = 1.10 km/h

1 mi/h = 1.47 ft/s = 0.447 m/s = 1.61 km/h

1 kilogram (kg) = 1000 grams (g)

(Note: 1 kg corresponds to 2.21 lb in the sense that the weight of 1 kg is 2.21 lb.)

1 atomic mass unit (u) = 1.66×10^{-27} kg
= 1.49×10^{-10} J
= 931 MeV

1 newton (N) = 0.225 lb

1 pound (lb) = 4.45 N

1 joule (J) = 2.39×10^{-4} kcal
= 6.24×10^{18} eV

1 kWh = 3.6 MJ

1 kilocalorie = 4.185 kJ

1 electron volt (eV) = 10^{-6} MeV = 10^{-9} GeV
= 1.60×10^{-19} J
= 1.18×10^{-19} ft·lb = 3.83×10^{-23} kcal

1 watt (W) = 1 J/s

1 kilowatt (kW) = 1000 W = 1.34 hp

1 horsepower (hp) = 746 W

1 pascal (Pa) = 1 N/m^2

1 atmosphere of pressure (atm) = 1.013×10^5 Pa
= 14.7 lb/in.^{2}

1 bar = 10^5 Pa

$$°C = \frac{5}{9}(°F - 32°)$$

$$°F = \frac{9}{5}°C + 32°$$

K = °C + 273

Powers of Ten

10^{-10}	= 0.000,000,000,1	10^0	= 1
10^{-9}	= 0.000,000,001	10^1	= 10
10^{-8}	= 0.000,000,01	10^2	= 100
10^{-7}	= 0.000,000,1	10^3	= 1000
10^{-6}	= 0.000,001	10^4	= 10,000
10^{-5}	= 0.000,01	10^5	= 100,000
10^{-4}	= 0.000,1	10^6	= 1,000,000
10^{-3}	= 0.001	10^7	= 10,000,000
10^{-2}	= 0.01	10^8	= 100,000,000
10^{-1}	= 0.1	10^9	= 1,000,000,000
10^0	= 1	10^{10}	= 10,000,000,000

Multipliers for SI Units

a	atto-	10^{-18}	da	deka-	10^1
f	femto-	10^{-15}	h	hecto-	10^2
p	pico-	10^{-12}	k	kilo-	10^3
n	nano-	10^{-9}	M	mega-	10^6
μ	micro-	10^{-6}	G	giga-	10^9
m	milli-	10^{-3}	T	tera-	10^{12}
c	centi-	10^{-2}	P	peta-	10^{15}
d	deci-	10^{-1}	E	exa-	10^{18}

Physical and Chemical Constants

Speed of light in vacuum	c	3.00×10^8 m/s
Charge on electron	e	1.60×10^{-19} C
Gravitational constant	G	6.67×10^{-11} N·m^2/kg^2
Acceleration of gravity at earth's surface	g	9.81 m/s^2
Planck's constant	h	6.63×10^{-34} J·s
Coulomb constant	K	8.99×10^9 N·m^2/C^2
Electron rest mass	m_e	9.11×10^{-31} kg
Neutron rest mass	m_n	1.675×10^{-27} kg
Proton rest mass	m_p	1.673×10^{-27} kg
Avogadro's number	N_0	6.02×10^{23} formula units/mole

The Physical Universse

Seventeenth Edition

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Arthur Beiser

Mc Graw Hill Education

THE PHYSICAL UNIVERSE

Published by McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LWI 21 20 19

ISBN 978-1-260-56590-4
MHID 1-260-56590-4

Cover Image: ©*Kris Grablec/Shutterstock*

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Brief Contents

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Contents

Preface

Creating Informed Citizens

The aim of *The Physical Universe* is to present, as simply and clearly as possible, the essentials of physics, chemistry, earth science, and astronomy to students whose main interests lie elsewhere.

Because of the scope of these sciences and because we assume minimal preparation on the part of the reader, our choice of topics and how far to develop them had to be limited. The emphasis throughout is on the basic concepts of each discipline. We also try to show how scientists approach problems and why science is a never-ending quest rather than a fixed set of facts.

The book concentrates on those aspects of the physical sciences most relevant to a nonscientist who wants to understand how the universe works and to know something about the connections between science and everyday life. We hope to equip readers to appreciate major developments in science as they arrive and to be able to act as informed citizens on matters that involve science and public policy. In particular, there are serious questions today concerning energy supply and use and the contribution of carbon dioxide emissions to the climate changes that are under way. Debates on these questions require a certain amount of scientific literacy, which this book is intended to provide, in order that sensible choices be made that will determine the welfare of generations to come. Recent choices have not always benefited our planet and its inhabitants: it is up to us to see that future choices do. There is little time left to make some of these choices, as Chapter 4 makes clear, and there is no Planet B to fall back on if we make the wrong ones. As President Theodore Roosevelt said in 1910, "Of all the questions which can come before this nation there isn't one which compares in importance with the central task of leaving this land even a better land for our descendants than it is for us."

Scope and Organization

There are many possible ways to organize a book of this kind. We chose the one that provides the most logical progression of ideas, so that each new subject builds on the ones that came before.

Our first concern in *The Physical Universe* is the scientific method, using as illustration the steps that led to today's picture of the universe and the earth's place in it. Next we consider motion and the influences that affect moving bodies. Gravity, energy, and momentum are examined, and the theory of relativity is introduced. Then we examine the many issues associated with the energy that today's world consumes in ever-increasing amounts and the accompanying environmental consequences. Matter in its three states next draws our attention, and we pursue this theme from the kinetic-molecular model to the laws of thermodynamics and the significance of entropy. A grounding in electricity and magnetism follows, and then an exploration of wave phenomena that includes the electromagnetic theory of light. We go on from there to the atomic nucleus and elementary particles, followed by a discussion of the quantum theories of light and of matter that lead to the modern view of atomic structure.

The transition from physics to chemistry is made via the periodic table. A look at chemical bonds and how they act to hold together molecules, solids, and liquids is followed by a survey of chemical reactions, organic chemistry, and the chemistry of life.

Our concern next shifts to the planet on which we live, and we begin by inquiring into the oceans of air and water that cover it. From there we proceed to the materials of the earth, to its ever-evolving crust, and to its no-longer-mysterious interior. After a survey of the main events in the earth's geological history (with a look at those of its biological history) we go on to what we know about our nearest neighbors in space—planets and satellites, asteroids, meteoroids, and comets.

Now the sun, the monarch of the solar system and the provider of nearly all our energy, claims our notice. We go on to broaden our astronomical sights to include the other stars, both individually and as members of the immense assemblies called galaxies. The evolution of the universe starting from the big bang is the last major subject, and we end with the origin of the earth and the likelihood that other inhabited planets exist in the universe and how we might communicate with them.

Website

A website (www.mhhe.com/Krauskopf) has been established that contains additional material of various kinds such as an instructor's manual, PowerPoint lectures, test bank, more worked examples, sidebars, and biographies.

Mathematical Level

The physical sciences are quantitative, which has both advantages and disadvantages. On the plus side, the use of mathematics allows many concepts to be put in the form of clear, definite statements that can be carried further by reasoning and whose predictions can be tested objectively. Less welcome is the discomfort many of us feel when faced with mathematical discussions.

The mathematical level of *The Physical Universe* follows Albert Einstein's prescription for physical theories: "Everything should be as simple as possible, but not simpler." A modest amount of mathematics enables the book to show how science makes sense of the natural world and how its findings led to the technological world of today. In general, the more complicated material supplements rather than dominates the presentation, and full mastery is not needed to understand the rest of the book. The basic algebra needed is reviewed in the Math Refresher. Powers-of-ten notation for small and large numbers is carefully explained there. This section is self-contained and can provide all the math background needed.

How much mathematics is appropriate for a given classroom is for each instructor to decide. To this end, a section is included in the Instructor's Manual that lists the slightly more difficult computational material in the text. This material can be covered as wished or omitted without affecting the continuity or conceptual coverage of a course.

A Student-Focused Revision

For the seventeenth edition, real student data points and input, derived from thousands of our LearnSmart users, were used to guide the revision. LearnSmart Heat Maps provided clear visual snapshots of usage of portions of the text and the relative difficulty students experienced in mastering the content. With these data, the text content was honed:

- If the data indicated that the subject covered was more difficult than other parts of the book, as evidenced by a high proportion of students responding incorrectly to LearnSmart probes, the text content was substantively revised or reorganized to be as clear and illustrative as possible.
- When the data showed that a smaller percentage of the students had difficulty learning the material, the text was revised to provide a clearer presentation by rewriting the section or providing additional sample problems to strengthen student problem-solving skills.

This process was used to direct many of the revisions for this new edition. Of course, many updates have also been made according to changing scientific data, based on current events and so forth. The following "Changes in This Edition" summary lists the more major additions and refinements.

Changes in This Edition

The entire book was brought up to date and new material was added where appropriate. More than 700 changes were made, of which the principal ones are the following:

- There are 78 new photographs, and new or revised drawings throughout the text.
- Section 1.1 on the scientific method was revised and Sec. 1.12 on the SI system was updated.
- Section 2.14 on artificial satellites was updated.
- Sections 3.5, 3.8, and 3.10 respectively on energy conservation, linear momentum, and angular momentum were all revised.
- Chapter 4, whose 14 sections consider every aspect of the energy problem (including population pressures, energy supply, climate change, pros and cons of energy sources, and strategies to protect the environment), was almost entirely rewritten with about 200 changes that provide updates and greater coverage.
- Sections 6.11 and 6.19 on electricity transmission were revised and updated.
- Chapter 8 on the atomic nucleus and nuclear energy was completely updated.
- Sections 10.3, 10.10, and 10.11 respectively have new sidebars on molecules, atomic sizes, and salt.
- Section 11.1 has a new sidebar on liquids, the sidebar on forms of carbon was revised, and Sec. 11.13 now considers ocean acidification.
- Section 12.6 was revised for greater clarity and Sec. 12.13 on electrochemical cells was updated and has a new sidebar on lithium-ion batteries.
- Section 13.10 on plastic waste and Sec. 13.17 on the origin of life were both updated.
- Section 14.1 on air pollution was revised and updated.
- Section 15.15 on volcanoes was revised.
- Chapter 16 on the evolving earth was revised and updated and has a new sidebar on whales.
- Chapter 17 on the solar system was entirely revised and updated with more material on the possibility of life elsewhere on other planets and their satellites.
- Section 18.1 on telescopes was updated and Sec. 18.16 has a new sidebar on gravitational waves.
- Chapter 19 on the universe was revised and updated with more attention on exoplanets and the possibility of life on them.

The Learning System

A variety of aids are provided in *The Physical Universe* to help the reader master the text.

Chapter Opener An outline provides a preview of major topics, showing at a glance what the chapter covers. Notable findings and ideas the chapter introduces are listed in order by section.

Illustrations Almost 800 illustrations, both line drawings and photographs, are full partners to the text and provide a visual pathway to understanding scientific observations and principles for students unaccustomed to abstract argument.

Worked Examples A full grasp of physical and chemical ideas includes an ability to solve problems based on these ideas. Some students, although able to follow the discussions in the book, nevertheless may have trouble putting their knowledge to use in this way. To help them, detailed solutions of typical problems are provided that show how to apply formulas and equations to real-world situations. Besides the worked examples, answers and outline solutions for half the end-of-chapter exercises are given at the end of the text. Thinking through the model solutions should bring the unsolved even-numbered problems within reach. In addition to its role in reinforcing the understanding of physical and chemical ideas, solving problems can provide great pleasure, and it would be a shame to miss out on this pleasure. The worked examples in the text are not limited to problems—nearly half of them show how basic ideas can be used to answer serious questions that do not involve calculations.

Bringing Science to Life

Biographies Brief biographies of major figures in the development of the physical sciences appear where appropriate throughout the text. The biographies provide human and historical perspectives by attaching faces and stories to milestones in these sciences.

Sidebars These are brief accounts of topics related to the main text. A sidebar may provide additional information on a particular subject, comment on its significance, describe its applications, consider its historical background, or present recent findings. Twenty new ones have been added for this edition.

End-of-Chapter Features

Important Terms and Ideas Important terms introduced in the chapter are listed together with their meanings, which serves as a chapter summary. A list of the **Important Formulas** needed to solve problems based on the chapter material is also given where appropriate.

Exercises An average of over a hundred exercises on all levels of difficulty follow each chapter. They are of three kinds, multiple choice, questions, and problems:

- **Multiple Choice** An average chapter has 41 Multiple-Choice exercises (with answers at the back of the book) that act as a quick, painless check on understanding. Correct answers provide reinforcement and encouragement; incorrect ones identify areas of weakness.
- **Exercises** Exercises consist of both questions and problems arranged according to the corresponding text section. Each group begins with questions and goes on to problems. Some of the questions are meant to find out how well the reader has understood the chapter material. Others ask the reader to apply what he or she has learned to new situations. Answers to the odd-numbered questions are given at the back of the book. The physics and chemistry chapters include problems that range from quite easy to moderately challenging. The ability to work out such problems signifies a real understanding of these subjects. Outline solutions (not just answers) for the odd-numbered problems are given at the back of the book.

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For Students

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>
> -Jordan Cunningham,
> Eastern Washington University

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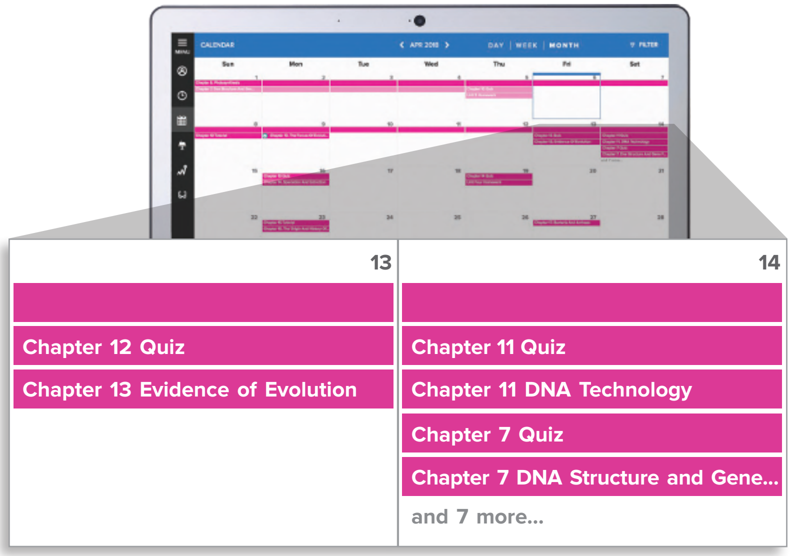

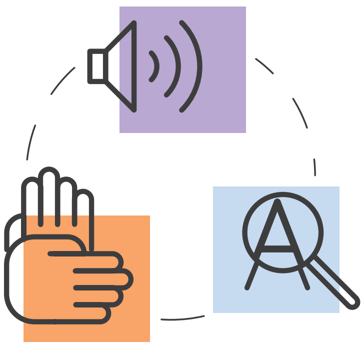

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- **Photos** The photo collection contains digital files of photographs from the text, which can be reproduced for multiple classroom uses.
- **Tables and Worked Examples** Tables and Worked Examples that appear in the text have been saved in electronic form for use in classroom presentations and/or quizzes.
- **Animations** Numerous full-color animations illustrating important processes are also provided. Harness the visual impact of concepts in motion by incorporating these animated examples in classroom presentations or online course materials.

Also residing on your textbook's Instructor Resource site are:

- **Accessible PowerPoint Lecture Outlines** Ready-made presentations that combine art (with alternative text tagging) and lecture notes are provided for each chapter of the text.
- **PowerPoint Slides** For instructors who prefer to create their lectures from scratch, illustrations, photos, tables, and worked examples from the text are pre-inserted by chapter into PowerPoint slides.

Student Study Guide

Another helpful resource can be found in *The Physical Universe* Student Study Guide. With this study guide, students will maximize their use of *The Physical Universe* text package. It supplements the text with additional, self-directed activities and complements the text by focusing on the important concepts, theories, facts, and processes presented by the authors. The Student Study Guide ISBN 125968346X can be customized to your course and is available through McGraw-Hill Create™. Questions and Interactive Problems from the Student Study Guide are also assignable in Connect in an auto-gradable format.

Acknowledgments

Comments from users have always been of much help in revising *The Physical Universe.* Detailed reviews of its previous editions by the following teachers were especially valuable and are much appreciated:

Maryanne Angliongto, *Jefferson College*
Jason Barbour, *Anne Arundel Community College*
Charles Blatchley, *Pittsburg State University*
Paul Bruinsma, *North Central Missouri College*
Carol Chin, *Northestern State University*
Diondra DeMolle, *Delgado Community College*
Padmaja Guggilla, *Alabama A&M University*

Michael Kazarinov, *Kennedy-King College*
Terrence Lee, *Middle Tennessee State University*
Lori Mayberry, *Tulsa Community College*
Rahul Mehta, *University of Central Arkansas*
Basil Miller, *Henderson State University*
Marquerite Moloney, *Nicholls State University*
Tchao Podona, *Miami Dade College*
Troy Sampere, *McNeese State University*
Jason Self, *Ozarka College*
Eugene Steinruck, *Bloomsburg University of Pennsylvania*
Stephon Void, *Claflin University*
Azida Walker, *University of Central Arkansas*
Patricia Warner, *Northwest Missouri State University*
Latoya Whitley Cosme, *Claflin University*
Binyam Woldemichael, *Anne Arundel Community College*

Nancy Woods of Des Moines Area Community College compiled the Videolists in the Instructor's Manual for *The Physical Universe.* Linda Kondrick of Arkansas Tech University was of great help in checking the exercises and their answers while preparing the online homework versions of the exercises. I am grateful to all of them.

Thanks are due to the various ancillary authors. Steven Carey of the University of Mobile wrote the Student Study Guide to accompany the text. Jessica Miles, Laurie Riley, and Sean Ryan helped write and review learning goal-oriented content for LearnSmart for *The Physical Universe.*

Finally, I want to thank my friends at McGraw-Hill, especially Mary Hurley and Jeni McAtee, for their skilled and dedicated help in producing this edition. Thanks are also due to Kevin Campbell, the copy editor, and to Jane Hoover, who with her eagle eyes checked the proofs where she found many ways to improve the clarity of the text.

Arthur Beiser

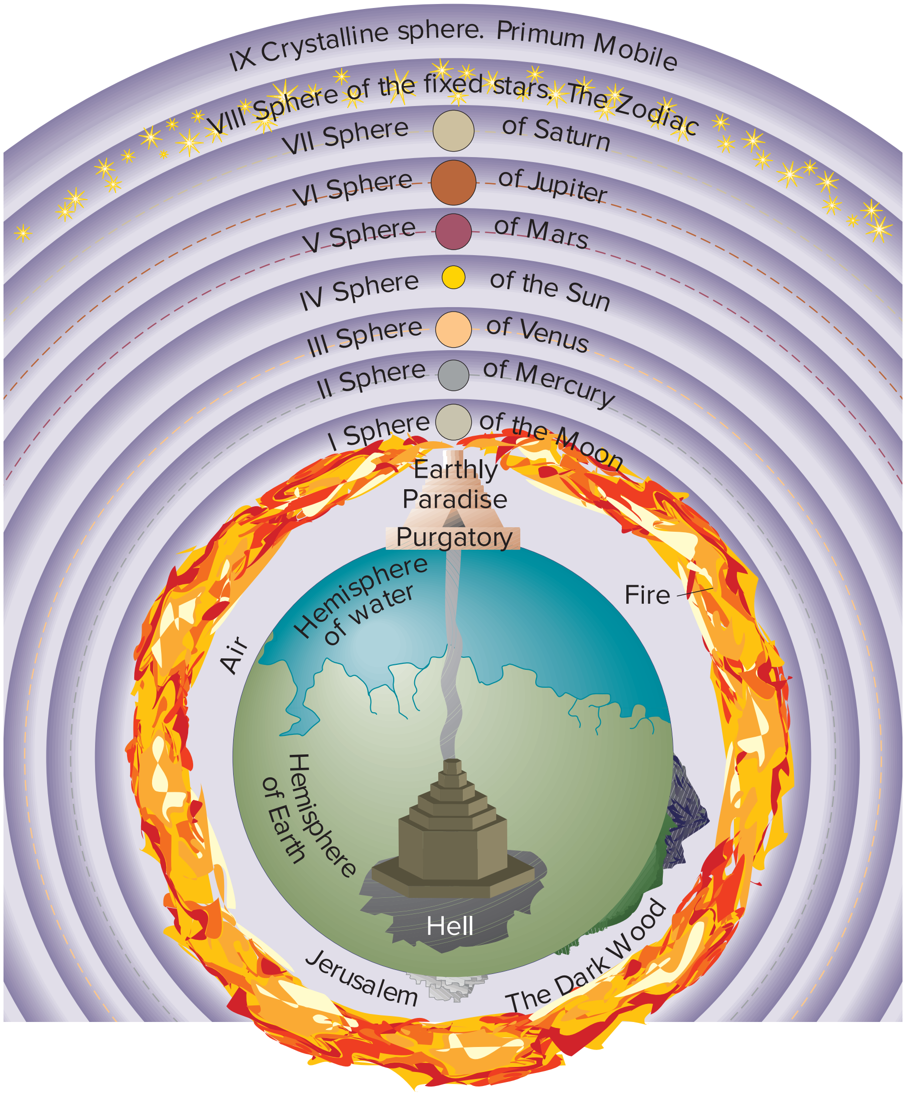
Meet the Authors

Konrad B. Krauskopf was born and raised in Madison, Wisconsin, and earned a B.S. in chemistry from the University of Wisconsin in 1931. He then earned a Ph.D. in chemistry at the University of California in Berkeley. When the Great Depression made jobs in chemistry scarce, Professor Krauskopf decided to study geology, which had long fascinated him. Through additional graduate work at Stanford University, he earned a second Ph.D. and eventually a position on the Stanford faculty. He remained at Stanford until his retirement in 1976. During his tenure, Professor Krauskopf also worked at various times with the U.S. Geological Survey, served with the U.S. Army in occupied Japan, and traveled to Norway, France, and Germany on sabbatical leaves. His research interests included field work on granites and metamorphic rocks and laboratory study on applications of chemistry to geologic problems, especially the formation of ore deposits. In later years, Professor Krauskopf spent time working with various government agencies on the problem of radioactive waste disposal. Professor Krauskopf passed away on May 8, 2003.

Arthur Beiser, a native of New York City, received B.S., M.S., and Ph.D. degrees in physics from New York University, where he later served as Associate Professor of Physics. He then was a Senior Research Scientist at the Lamont Geological Observatory of Columbia University. His research interests were chiefly in cosmic rays and in magnetohydrodynamics as applied to geophysics and astrophysics. In addition to theoretical work, he participated in a cosmic-ray expedition to an Alaskan peak and directed a search for magnetohydrodynamic waves from space in various Pacific locations. A Fellow of The Explorers Club, Dr. Beiser was the first chairman of its Committee on Space Exploration. He is the author or coauthor of 36 books, mostly college texts on physics and mathematics, 14 of which have been translated into a total of 27 languages. Two of his books are on sailing, *The Proper Yacht* and *The Sailor's World.* Figure 13-21 is a photograph of Dr. Beiser at the helm of his 58-ft sloop; he and his wife Germaine have sailed over 150,000 miles, including two Atlantic crossings and a rounding of Cape Horn. Germaine Beiser, who has degrees in physics from the Massachusetts Institute of Technology and New York University, is the author or coauthor of seven books on various aspects of physics and has contributed to *The Physical Universe.* For a number of years she was the editor of a cruising guide to the Adriatic Sea.

CHAPTER 1

The Scientific Method



Medieval picture of the universe.
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CHAPTER OUTLINE AND GOALS

Your chief goal in reading each section should be to understand the important findings and ideas indicated (•) below.

How Scientists Study Nature

1.1 ***The Scientific Method***
Four Steps
- What the scientific method is.
- The difference between a law and a theory.
- The role of models in science.

1.2 ***Why Science Is Successful***
Science Is a Living Body of Knowledge, Not a Set of Frozen Ideas
- Why the scientific method is so successful in understanding the natural world.

The Solar System

1.3 ***A Survey of the Sky***
Everything Seems to Circle the North Star
- Why Polaris seems almost stationary in the sky.
- How to distinguish planets from stars without a telescope.

1.4 ***The Ptolemaic System***
The Earth as the Center of the Universe
- How the ptolemaic system explains the astronomical universe.

1.5 ***The Copernican System***
A Spinning Earth That Circles the Sun
- How the copernican system explains the astronomical system.

1.6 ***Kepler's Laws***
How the Planets Actually Move
- The significance of Kepler's laws.

1.7 ***Why Copernicus Was Right***
Evidence Was Needed That Supported His Model While Contradicting Ptolemy's Model
- How parallax showed which system provides the best explanation for what we see.

Universal Gravitation

1.8 ***What Is Gravity?***
A Fundamental Force
- Why gravity is a fundamental force.

1.9 ***Why the Earth Is Round***
The Big Squeeze
- What keeps the earth from being a perfect sphere.

1.10 ***The Tides***
Up and Down Twice a Day
- The origin of the tides.
- The difference between spring and neap tides and how it comes about.

1.11 ***The Discovery of Neptune***
Another Triumph for the Law of Gravity
- The role of the scientific method in finding a hitherto unknown planet.

How Many of What

1.12 ***The SI System***
All Scientists Use These Units
- How to go from one system of units to another.
- The use of metric prefixes for small and large quantities.
- What significant figures are and how to calculate with them.

All of us belong to two worlds, the world of people and the world of nature. As members of the world of people, we take an interest in human events of the past and present and find such matters as politics and economics worth knowing about. As members of the world of nature, we also owe ourselves some knowledge of the sciences that seek to understand this world. It is not idle curiosity to ask why the sun shines, why the sky is blue, how old the earth is, why things fall down. These are serious questions, and to know their answers adds an important dimension to our personal lives.

We are made of atoms linked together into molecules, and we live on a planet circling a star—the sun—that is a member of one of the many galaxies of stars in the universe. It is the purpose of this book to survey what physics, chemistry, geology, and astronomy have to tell us about atoms and molecules, stars and galaxies, and everything in between. No single volume can cover all that is significant in this vast span, but the basic ideas of each science can be summarized along with the raw material of observation and reasoning that led to them.

Like any other voyage into the unknown, the exploration of nature is an adventure. This book records that adventure and contains many tales of wonder and discovery. The search for knowledge is far from over, with no end of exciting things still to be found. What some of these things might be and where they are being looked for are part of the story in the chapters to come.

HOW SCIENTISTS STUDY NATURE

Every scientist dreams of lighting up some dark corner of the natural world—or, almost as good, of finding a dark corner where none had been suspected. The most careful observations, the most elaborate calculations will not be fruitful unless the right questions are asked. Here is where creative imagination enters science, which is why many of the greatest scientific advances have been made by young, nimble minds.

Scientists study nature in a variety of ways. Some approaches are quite direct: a geologist takes a rock sample to a laboratory and, by inspection and analysis, finds out what it is made of and how and when it was probably formed. Other approaches are indirect: nobody has ever visited the center of the earth or ever will, but by combining a lot of thought with clues from different sources, a geologist can say with near certainty that the earth has a core of molten iron.

No matter what the approaches to particular problems may be, however, the work scientists do always fits into a certain pattern of steps. This pattern, a general scheme for gaining reliable information about the universe, has become known as the **scientific method.** The scientific method is the most powerful lens we have with which to examine the natural world.

1.1 The Scientific Method

Four Steps

We can think of the scientific method in terms of four steps: (1) formulating a problem, (2) observation and experiment, (3) interpreting the data, and (4) testing the interpretation by further observation and experiment to check its predictions. These steps are often carried out by different scientists, sometimes many years apart and not always in this order. Whatever way it is carried out, though, the scientific method is not a mechanical process but a human activity that needs creative thinking in all its steps. Looking at the natural world is at the heart of the scientific method, because the results of observation and experiment serve not only as the foundations on which scientists build their ideas but also as the means by which these ideas are checked (Fig. 1-1).

1. **Formulating a problem** may mean no more than choosing a certain field to work in, but more often a scientist has in mind some specific idea he or she wishes to investigate. In many cases formulating a problem and interpreting the data overlap. The scientist has a speculation, perhaps only a hunch, perhaps a fully developed **hypothesis,** about some aspect of nature but cannot come to a definite conclusion without further study.
2. **Observation and experiment** are carried out with great care. Facts about nature are the building blocks of science and the ultimate test of its results. This insistence on accurate, objective data is what sets science apart from other modes of intellectual endeavor.
3. **Interpretation** may lead to a general rule or **law** to which the data seem to conform. Or it may lead to a **theory,** which is a more ambitious attempt to account for what has been found in terms of how nature works. In any case, the interpretation

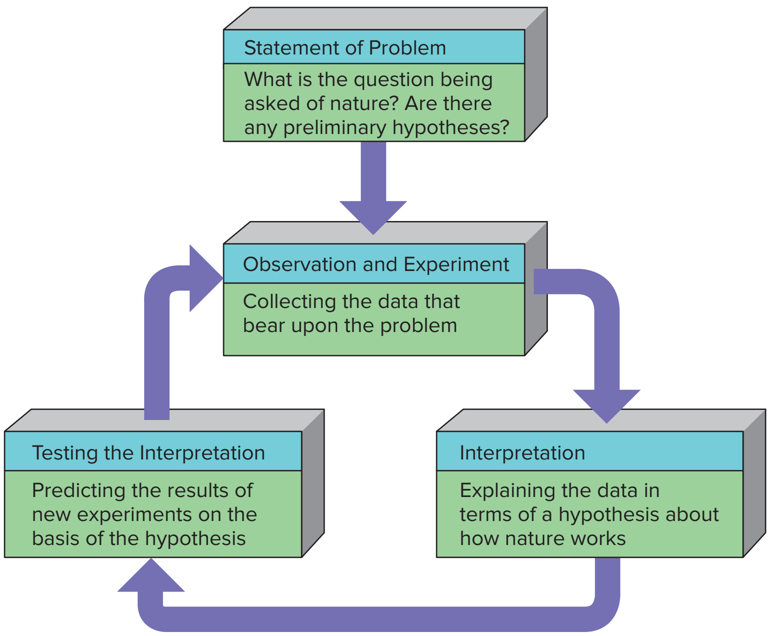

Figure 1-1 The scientific method. No hypothesis is ever final because future data may show that it is incorrect or incomplete. Unless it turns out to be wrong, a hypothesis never leaves the loop of experiment, interpretation, testing. Of course, the more times the hypothesis goes around the loop successfully, the more likely it is to be a valid interpretation of nature and become a law or theory. Experiment and hypothesis thus evolve together, with experiment having the final word. Although a hypothesis may occur to a scientist as he or she studies experimental results, often the hypothesis comes first and relevant data are sought afterward to test it.

must be able to cover new data obtained under different circumstances. As put forward orginally, a scientific interpretation is usually called a hypothesis.

4. **Testing the interpretation** involves making new observations or performing new experiments to see whether the interpretation correctly predicts the results. If the results agree with the predictions, the scientist is clearly on the right track. The new data may well lead to refinements of the original idea, which in turn must be checked, and so on indefinitely. As Edwin Hubble, the astronomer who discovered the expansion of the universe, said, "The scientist explains the world by successive approximations."

The Laws of Nature The laws of a country tell its citizens how they are supposed to behave. Different countries have different laws, and even in one country laws are changed from time to time. Furthermore, though he or she may be caught and punished for doing so, anybody can break any law at any time.

The laws of nature are different. Everything in the universe, from atoms to galaxies of stars, behaves in certain regular ways, and these regularities are the laws of nature. To be considered a law of nature, a given regularity must hold everywhere at all times within its range of applicability.

The laws of nature are worth knowing for two reasons apart from satisfying our curiosity about how the universe works. First, we can use them to predict phenomena not yet discovered. Thus Isaac Newton's law of gravity was applied over a century ago to apparent irregularities in the motion of the planet Uranus, then the farthest known planet from the sun. Calculations not only showed that another, more distant planet should exist but also indicated where in the sky to look for it. Astronomers who looked there found a new planet, which was named Neptune.

Second, the laws of nature can give us an idea of what goes on in places we cannot examine directly. We will never visit the sun's interior (much too hot) or the interior of an atom (much too small), but we know a lot about both regions. The evidence is indirect but persuasive.

Theories A **law** tells us *what;* a **theory** tells us *why.* A theory explains why certain events take place and, if they obey a particular law, how that law originates in terms of broader considerations. For example, Albert Einstein's general theory of relativity interprets gravity as a distortion in the properties of space and time around a body of matter. This theory not only accounts for Newton's law of gravity but goes further, including the prediction—later confirmed—that light should be affected by gravity.

As the French mathematician Henri Poincaré once remarked, "Science is built with facts just as a house is built with bricks, but a collection of facts is not a science any more than a pile of bricks is a house."

Models It may not be easy to get a firm intellectual grip on some aspect of nature. Therefore a **model**—a simplified version of reality—is often part of a hypothesis or theory. In developing the law of gravity, Newton considered the earth to be perfectly round, even though it is actually more like a grapefruit than like a billiard ball. Newton regarded the path of the earth around the sun as an oval called an **ellipse,** but the actual orbit has wiggles no ellipse ever had. By choosing a sphere as a model for the earth and an ellipse as a model for its orbit, Newton isolated the most important features of the earth and its path and used them to arrive at the law of gravity.

If Newton had started with a more realistic model—a somewhat squashed earth moving somewhat irregularly around the sun—he probably would have made little progress. Once he had formulated the law of gravity, Newton was then able to explain how the spinning of the earth causes it to become distorted into the shape of a grapefruit and how the attractions of the other planets cause the earth's orbit to differ from a perfect ellipse.

Another kind of model arises when we try to understand the microscopic world of atoms and molecules. Thus a useful model of a gas pictures it as a collection of tiny particles like miniature billiard balls that fly about in all directions. This model

Finding the Royal Road

Hermann von Helmholtz, a nineteenth-century German physicist and biologist, summed up his experience of scientific research in these words: "I would compare myself to a mountain climber who, not knowing the way, ascends slowly and toilsomely and is often compelled to retrace his steps because his progress is blocked; who, sometimes by reasoning and sometimes by accident, hits upon signs of a fresh path, which leads him a little farther; and who, finally, when he has reached his goal, discovers to his annoyance a royal road which he might have followed if he had been clever enough to find the right starting point at the beginning."

Experiment Is the Test

A master of several sciences, Michael Faraday is best remembered for his discoveries in electricity and magnetism (see his biography in Sec. 6.18). This statement appears in the entry for March 19, 1849 in his laboratory notebook: "Nothing is too wonderful to be true if it be consistent with the laws of nature, and . . . experiment is the best test of such consistency."

Faraday was a Fellow of Britain's Royal Society, which was founded in 1660 to promote the use of observation and experiment to study the natural world. The oldest scientific organization in the world, the Royal Society has as its motto *Nullus in Verba*—Latin for "Take nobody's word for it." On its 350th anniversary, the Royal Society held a celebration of "the joy and vitality of science, its importance to society and culture, and its role in shaping who we are and who we will become."

Theory

In science a *theory* is a fully developed logical structure based on general principles that ties together a variety of observations and experimental findings and permits as-yet-unknown phenomena and connections to be predicted. A theory may be more or less speculative when proposed, but the point is that it is a large-scale framework of ideas and relationships.

To people ignorant of science, a theory is a suggestion, a proposal, what in science is called a hypothesis. For instance, believers in creationism, the unsupported notion that all living things simultaneously appeared on earth a few thousand years ago, scorn Darwin's theory of evolution (see Sec. 16.8) as "just a theory" despite the wealth of evidence in its favor and its bedrock position in modern biology. In fact, few aspects of our knowledge of the natural world are as solidly established as the theory of evolution.

is quite successful in accounting for many aspects of the behavior of gases. But it is still a model and not the whole story, since when we examine the particles themselves they turn out not to be like billiard balls at all and in certain respects do not even act like particles in the usual sense.

1.2 Why Science Is Successful

Science Is a Living Body of Knowledge, Not a Set of Frozen Ideas

What has made science such a powerful tool for investigating nature is the constant testing and retesting of its findings. As a result, science is a living body of information and not a collection of dogmas. The laws and theories of science are not necessarily the final word on a subject: they are valid only as long as no contrary evidence comes to light. If such contrary evidence does turn up, the law or theory must be modified or even discarded. To rock the boat is part of the game; to overturn it is one way to win. Thus science is a self-correcting search for better understanding of the natural world, a search with no end in sight.

Scientists are open about the details of their work, so that others can follow their thinking and repeat their experiments and observations. Nothing is accepted on anybody's word alone, or because it is part of a religious or political doctrine. "Common sense" is not a valid argument, either; if common sense were a reliable guide, we would not need science. What counts are definite measurements and clear reasoning, not vague notions that vary from person to person.

The power of the scientific approach is shown not only by its success in understanding the natural world but also by the success of the technology based on science. It is hard to think of any aspect of life today untouched in some way by science. The synthetic clothing we wear, the medicines that lengthen our lives, the cars and airplanes we travel in, the telephone, Internet, radio, and television by which we communicate—all are ultimately the products of a certain way of thinking. Curiosity and imagination are part of that way of thinking, but the most important part is that nothing is ever taken for granted but is always subject to test and change.

Evolution

In the past, scientists were sometimes punished for daring to make their own interpretations of what they saw. Galileo, the first modern scientist (see his biography in Sec. 2.5), was forced by the Roman Catholic Church in 1633 under threat of torture to deny that the earth moves about the sun. Even today, attempts are being made to compel the teaching of religious beliefs—for instance, the story of the Creation as given in the Bible—under the name of science. But "creation science" is a contradiction in terms. Science follows where evidence leads, whereas the essence of creationism is that it is a fixed doctrine with no basis in observation. The scientific method has been the means of liberating the world from ignorance and superstition. To discard this method in favor of taking at face value every word in the Bible is to replace the inquiring mind with a closed mind.

Degrees of Doubt

Although in principle everything in science is open to question, in practice many ideas are not really in doubt. The earth is certainly round, for instance, and the planets certainly revolve around the sun. Even though the earth is not a perfect sphere and the planetary orbits are not perfect ellipses, the basic models will always be valid.

Other beliefs are less firm. An example is the current picture of the future of the universe. Quite convincing data suggest that the universe has been expanding since its start in a "big bang" about 13.8 billion years ago. What about the future? It seems likely from the latest measurements that the expansion will continue forever, but this conclusion is still tentative and is under active study by astronomers today.

What the Constitution Says

The founders of the United States of America insisted on the separation of church and state, a separation that is part of the Constitution. What happens in countries with no such separation, in the past and in the present, testifies to the wisdom of the founders.

In 1987 the U.S. Supreme Court ruled that teaching creationism in the public schools is illegal because it is a purely religious doctrine. In response, the believers in creationism changed its name to "intelligent design" without specifying who the designer was or how the design was put into effect. Their sole argument is that life is too complex and diverse to be explained by evolution, when in fact this is precisely what evolution does with overwhelming success. Nevertheless, attempts have continued to be made to include intelligent design in science classes in public schools. All such attempts have been ruled illegal by the courts.

Those who wish to believe that the entire universe came into being in 6 days a few thousand years ago are free to do so. What is not proper is for certain politicians (whom Galileo would recognize if he were alive today) to try to turn back the intellectual clock and compel such matters of faith to be taught in schools alongside or even in place of scientific concepts, such as evolution (see Sec. 16.8), that have abundant support in the world around us. To anyone with an open mind, the evidence that the universe and its inhabitants have developed over time and continue to do so is overwhelming, as we shall see in later chapters. Nothing stands still. The ongoing evolution of living things is central to biology; the ongoing evolution of the earth is central to geology; the ongoing evolution of the universe is central to astronomy.

Advocates of creationism (or "intelligent design") assert that evolution is an atheistic concept. Yet religious leaders of almost all faiths see no conflict between evolution and religious belief. According to Cardinal Paul Poupard, head of the Roman Catholic Church's Pontifical Council for Culture, "we . . . know the dangers of a religion that severs its links with reason and becomes prey to fundamentalism. The faithful have the obligation to listen to that which secular modern science has to offer."

THE SOLAR SYSTEM

Each day the sun rises in the east, sweeps across the sky, and sets in the west. The moon, planets, and most stars do the same. These heavenly bodies also move relative to one another, though more slowly.

There are two ways to explain the general east-to-west motion. The most obvious is that the earth is stationary and all that we see in the sky revolves around it. The other possibility is that the earth itself turns once a day, so that the heavenly bodies only appear to circle it. How the second alternative came to be seen as correct and how this finding led to the discovery of the law of gravity are important chapters in the history of the scientific method.

1.3 A Survey of the Sky

Everything Seems to Circle the North Star

One star in the northern sky seems barely to move at all. This is the North Star, or **Polaris,** long used as a guide by travelers because of its nearly unchanging position. Stars near Polaris do not rise or set but instead move around it in circles (Fig. 1-2). These circles carry the stars under Polaris from west to east and over it from east to west. Farther from Polaris the circles get larger and larger, until eventually they dip below the horizon. Sun, moon, and stars rise and set because their circles lie partly below the horizon. Thus, to an observer north of the equator, the whole sky appears to revolve once a day about this otherwise ordinary star.

Why does Polaris occupy such a central position? The earth rotates once a day on its axis, and Polaris happens by chance to lie almost directly over the North Pole.

Figure 1-2 Time exposure of stars in the northern sky. The trail of Polaris is the bright arc slightly to the left of the center of the circles.
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As the earth turns, everything else around it seems to be moving. Except for their circular motion around Polaris, the stars appear fixed in their positions with respect to one another. Stars of the Big Dipper move halfway around Polaris between every sunset and sunrise, but the shape of the Dipper itself remains unaltered. (Actually, as discussed later, the stars *do* change their relative positions, but the stars are so far away that these changes are not easy to detect.)

Constellations Easily recognized groups of stars, like those that form the Big Dipper, are called **constellations** (Fig. 1-3). Near the Big Dipper is the less conspicuous Little Dipper with Polaris at the end of its handle. On the other side of

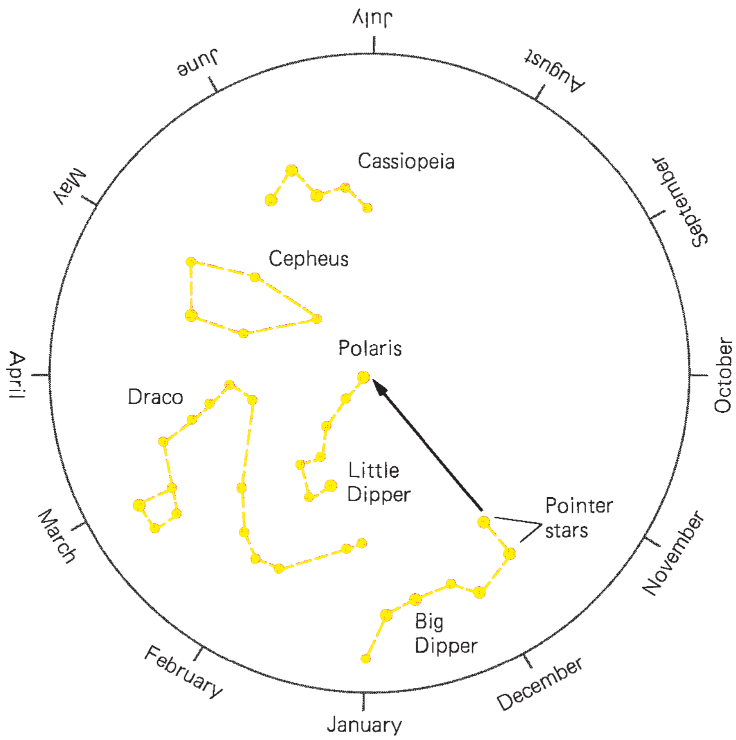

Figure 1-3 Constellations near Polaris as they appear in the early evening to an observer who faces north with the figure turned so that the current month is at the bottom. Polaris is located on an imaginary line drawn through the two "pointer" stars at the end of the bowl of the Big Dipper. The brighter stars are shown larger in size.

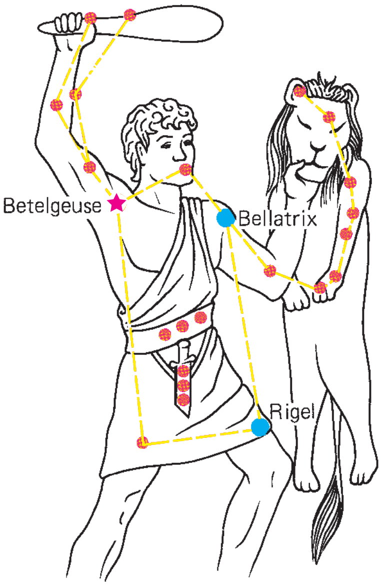

Figure 1-4 Orion, the mighty hunter. Betelgeuse is a bright red star, and Bellatrix and Rigel are bright blue stars. Stars that seem near one another in the sky may actually be far apart in space. The three stars in Orion's belt, for instance, are in reality at very different distances from us.

Polaris from the Big Dipper are Cepheus and the W-shaped Cassiopeia, named, respectively, for an ancient king and queen of Ethiopia. Next to Cepheus is Draco, which means dragon.

Elsewhere in the sky are dozens of other constellations that represent animals, heroes, and beautiful women. An especially easy one to recognize on winter evenings in the northern hemisphere is Orion, the mighty hunter of legend. Orion has four stars, three of them quite bright, at the corners of a warped rectangle with a belt of three stars in line across its middle (Fig. 1-4). Except for the Dippers, a lot of imagination is needed to connect a given star pattern with its corresponding figure, but the constellations nevertheless are useful as convenient labels for regions of the sky.

Sun and Moon In their daily east-west crossing of the sky, the sun and moon move more slowly than the stars and so appear to drift eastward relative to the constellations. In the same way, a person on a train traveling west who walks toward the rear car is moving east relative to the train although still moving west relative to the ground. In the sky, the apparent eastward motion is most easily observed for the moon. If the moon is seen near a bright star on one evening, by the next evening it will be some distance east of that star, and on later nights it will be farther and farther to the east. In about 4 weeks the moon drifts eastward completely around the sky and returns to its starting point.

The sun's relative motion is less easy to follow because we cannot observe directly which stars it is near. But if we note which constellations appear where the sun has just set, we can estimate the sun's location among the stars and follow it from day to day. We find that the sun drifts eastward more slowly than the moon, so slowly that the day-to-day change is scarcely noticeable. Because of the sun's motion each constellation appears to rise about 4 min earlier each night, and so, after a few weeks or months, the appearance of the night sky becomes quite different from what it was when we started our observations.

By the time the sun has migrated eastward completely around the sky, a year has gone by. In fact, the **year** is defined as the time needed for the sun to make such an apparent circuit of the stars.

Planets Five other celestial objects visible to the naked eye also shift their positions with respect to the stars. These objects, which themselves resemble stars, are **planets** (Greek for "wanderer") and are named for the Roman gods Mercury, Venus, Mars, Jupiter, and Saturn. Like the sun and moon, the planets shift their positions so slowly that their day-to-day motion is hard to detect. Unlike the sun, they move in complex paths. In general, each planet drifts eastward among the stars, but its relative speed varies and at times the planet even reverses its relative direction to head westward briefly. Thus the path of a planet appears to consist of loops that recur regularly, as in Fig. 1-5.

1.4 The Ptolemaic System

The Earth as the Center of the Universe

Although the philosophers of ancient Greece knew that the apparent daily rotation of the sky could be explained by a rotation of the earth, most of them preferred to regard

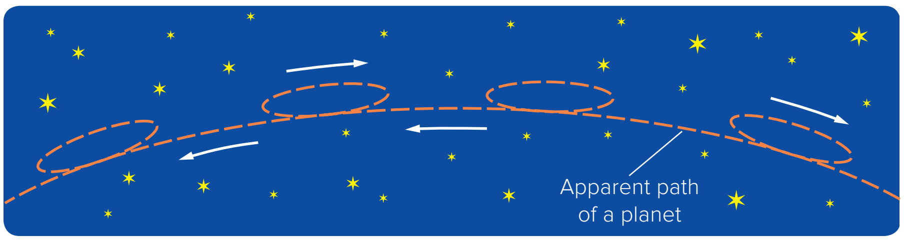

Figure 1-5 Apparent path of a planet in the sky looking south from the northern hemisphere of the earth. The planets seem to move eastward relative to the stars most of the time, but at intervals they reverse their motion and briefly move westward.

the earth as stationary. The scheme most widely accepted was originally the work of Hipparchus. Ptolemy of Alexandria (Fig. 1-6) later included Hipparchus's ideas into his *Almagest,* a survey of astronomy that was to be the standard reference on the subject for over a thousand years. This model of the universe became known as the **ptolemaic system.**

The model was intricate and ingenious (Fig. 1-7). Our earth stands at the center, motionless, with everything else in the universe moving about it either in circles or in combinations of circles. (To the Greeks, the circle was the only "perfect" curve, hence the only possible path for a celestial object.) The fixed stars are embedded in a huge crystal sphere that makes a little more than a complete turn around the earth each day. Inside the crystal sphere is the sun, which moves around the earth exactly once a day. The difference in speed between sun and stars is just enough so that the sun appears to move eastward past the stars, returning to a given point among them once a year. Near the earth in a small orbit is the moon, revolving more slowly than the sun. The planets Venus and Mercury come between moon and sun, the other planets between sun and stars.

To account for irregularities in the motions of the planets, Ptolemy imagined that each planet moves in a small circle about a point that in turn follows a large circle about the earth. By a combination of these circular motions a planet travels in a series of loops. Since we observe these loops edgewise, it appears to us as if the planets move with variable speeds and sometimes even reverse their directions of motion in the sky.

From observations made by himself and by others, Ptolemy calculated the speed of each celestial object in its assumed orbit. Using these speeds he could then figure out the location in the sky of any object at any time, past or future. These calculated positions checked fairly well, though not perfectly, with positions that had been recorded centuries earlier, and the predictions also agreed at first with observations

Figure 1-6 Ptolemy (A.D. 100–170).

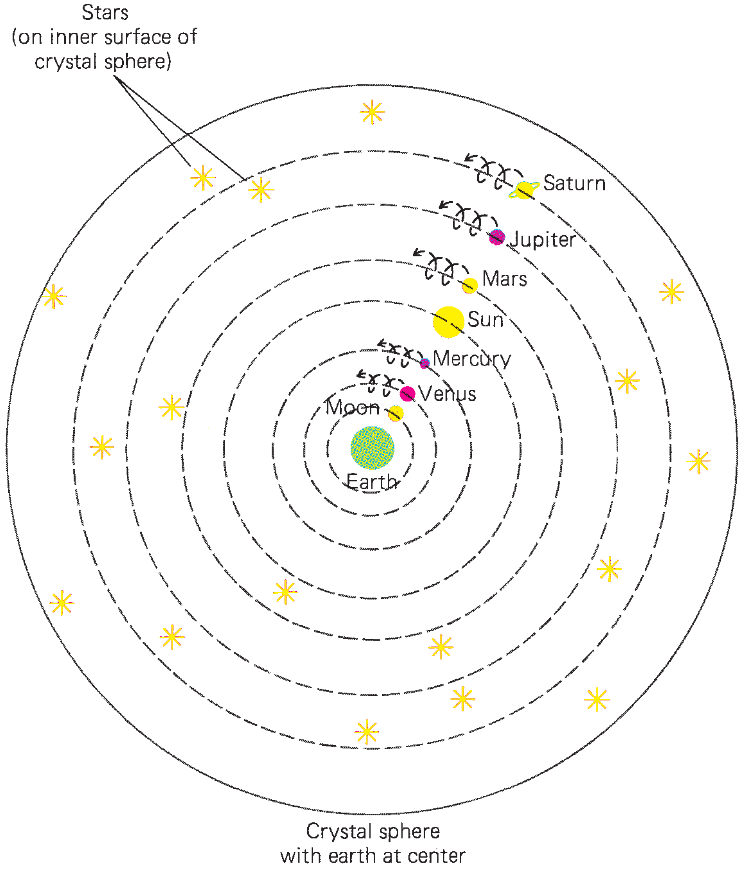

Figure 1-7 The ptolemaic system, showing the assumed arrangement of the members of the solar system within the celestial sphere. Each planet is supposed to travel around the earth in a series of loops, while the orbits of the sun and moon are circular. Only the planets known in Ptolemy's time are shown. The stars are all supposed to be at the same distance from the earth.