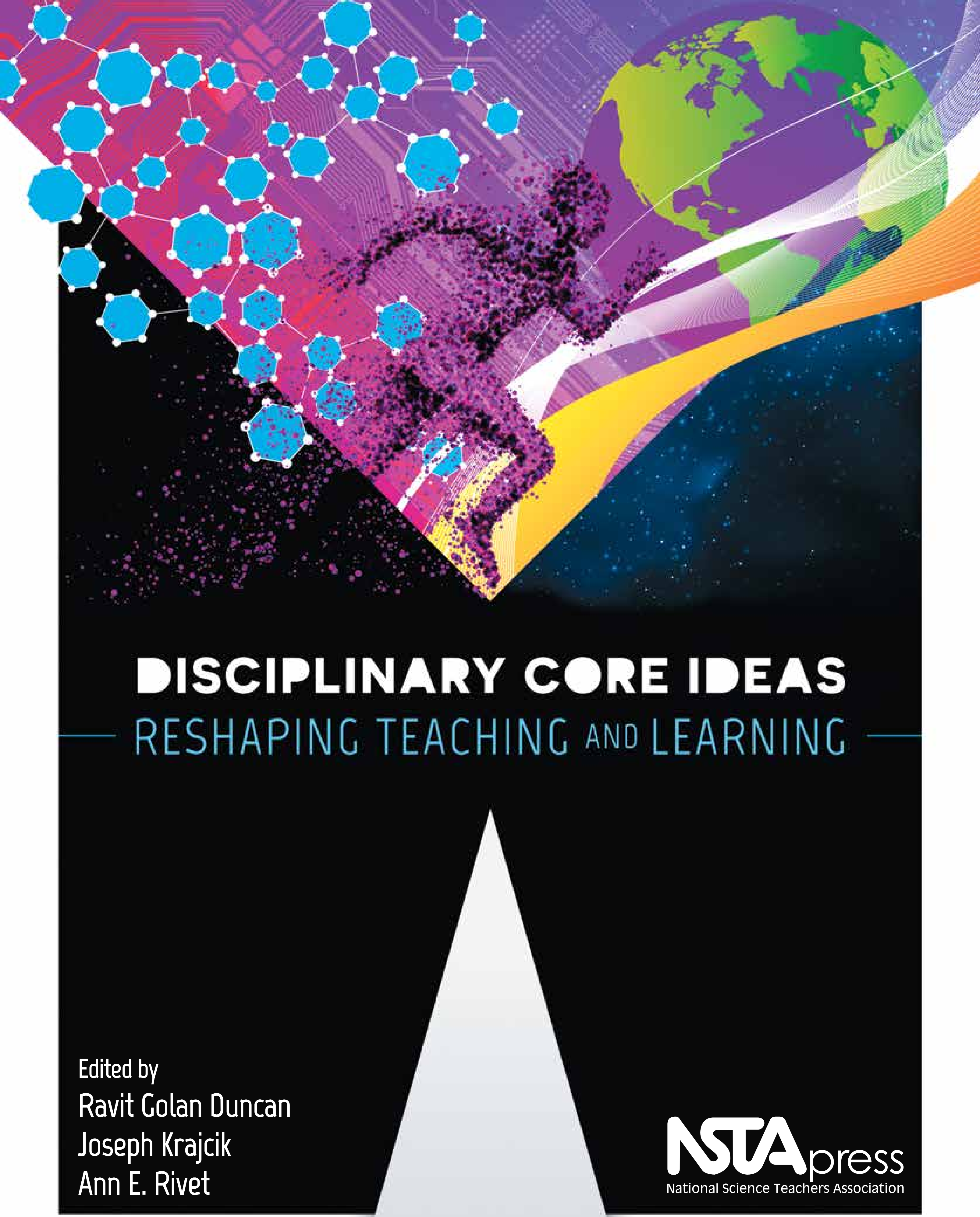


# DISCIPLINARY CORE IDEAS

## RESHAPING TEACHING AND LEARNING

Edited by
Ravit Golan Duncan
Joseph Krajcik
Ann E. Rivet

NSTApress
National Science Teachers Association

# DISCIPLINARY CORE IDEAS

## — RESHAPING TEACHING AND LEARNING —

# DISCIPLINARY CORE IDEAS

## — RESHAPING TEACHING AND LEARNING —

Edited by

Ravit Golan Duncan
Joseph Krajcik
Ann E. Rivet

NSTApress
National Science Teachers Association
Arlington, Virginia

NSTApress®
National Science Teachers Association

Claire Reinburg, Director
Wendy Rubin, Managing Editor
Rachel Ledbetter, Associate Editor
Amanda Van Beuren, Associate Editor
Donna Yudkin, Book Acquisitions Coordinator

Art and Design
Will Thomas Jr., Director
Joe Butera, Senior Graphic Designer, cover and interior design

Printing and Production
Catherine Lorrain, Director

National Science Teachers Association
David L. Evans, Executive Director
David Beacom, Publisher

1840 Wilson Blvd., Arlington, VA 22201
*www.nsta.org/store*
For customer service inquiries, please call 800-277-5300.

Copyright © 2017 by the National Science Teachers Association.
All rights reserved. Printed in the United States of America.
20 19 18 17 4 3 2 1

*NSTA is committed to publishing material that promotes the best in inquiry-based science education. However, conditions of actual use may vary, and the safety procedures and practices described in this book are intended to serve only as a guide. Additional precautionary measures may be required. NSTA and the authors do not warrant or represent that the procedures and practices in this book meet any safety code or standard of federal, state, or local regulations. NSTA and the authors disclaim any liability for personal injury or damage to property arising out of or relating to the use of this book, including any of the recommendations, instructions, or materials contained therein.*

Permissions
Book purchasers may photocopy, print, or e-mail up to five copies of an NSTA book chapter for personal use only; this does not include display or promotional use. Elementary, middle, and high school teachers may reproduce forms, sample documents, and single NSTA book chapters needed for classroom or noncommercial, professional-development use only. E-book buyers may download files to multiple personal devices but are prohibited from posting the files to third-party servers or websites, or from passing files to non-buyers. For additional permission to photocopy or use material electronically from this NSTA Press book, please contact the Copyright Clearance Center (CCC) (*www.copyright.com*; 978-750-8400). Please access *www.nsta.org/permissions* for further information about NSTA's rights and permissions policies.

**Library of Congress Cataloging-in-Publication Data**
Names: Krajcik, Joseph S. | Rivet, Ann E., 1974- | Duncan, Ravit Golan, 1973-
Title: Disciplinary core ideas : reshaping teaching and learning / Joseph Krajcik, Ann E. Rivet, and Ravit Golan Duncan.
Description: Arlington, VA : National Science Teachers Association, [2016] |
Includes bibliographical references and index.
Identifiers: LCCN 2016014730 (print) | LCCN 2016020728 (ebook) | ISBN 9781938946417 (print) | ISBN 9781941316672 (e-book) | ISBN 9781941316672 (epub)
Subjects: LCSH: Science--Study and teaching (Elementary)--United States. |
Science--Study and teaching (Middle school)--United States. |
Science--Study and teaching (Secondary)--United States. |
Interdisciplinary approach in education--United States.
Classification: LCC Q183.3.A1 K73 2016 (print) | LCC Q183.3.A1 (ebook) | DDC 507.1/273--dc23
LC record available at *https://lccn.loc.gov/2016014730*

Copyright © 2017 NSTA. All rights reserved. For more information, go to www.nsta.org/permissions.
TO PURCHASE THIS BOOK, please visit www.nsta.org/store/product_detail.aspx?id=10.2505/9781938946417

# CONTENTS

# FOREWORD

Helen Quinn

This is not a book about disciplinary core ideas (DCIs) in science. This is a book about teaching science organized around DCIs as defined in *A Framework for K–12 Science Education* (*Framework*; NRC 2012) and encapsulated in the performance expectations of the *Next Generation Science Standards* (*NGSS*; NGSS Lead States 2013). As anyone looking at this book knows, the *Framework* and *NGSS* stress three dimensions in science learning: Students are not just learning the DCIs but are also engaging in science and engineering practices and understanding and applying a set of crosscutting concepts. Teachers must meld all three of these dimensions together to build effective science lessons, but before they can do that, they need to understand each dimension and the shifts in emphasis around each that are central to the definition and structure of the *NGSS*.

The *Framework* was developed based on the best available research knowledge on effective science teaching approaches. Central to effectiveness is the recognition that students must build new knowledge by refining and revising prior knowledge (or their preconceptions, if the topic is new to them). Teaching that ignores what has come before and does not capitalize on research into what makes a topic difficult to learn is at best inefficient and at worst ineffective. Hence, it is important not just to have a science curriculum for the current year but to have one that is designed to build knowledge and deepen understanding progressively across multiple years.

This book, then, is about how the *NGSS* are structured with regard to DCIs, how these ideas build across the grade levels, and what aspects are newly emphasized or de-emphasized at each level to achieve continuity and establish a firm base for further learning and use of that knowledge beyond high school. For each DCI, the authors—who are experts in that area of science or engineering learning—discuss how the *NGSS* expectations at each grade band are structured, stressing shifts in emphasis and explaining some of the reasons for these shifts.

Teachers redesigning their instruction to better support the *NGSS* will find that the material in this book provides useful background for that effort, but it will not serve as an instruction manual. As every teacher knows, the art of teaching is the art of making choices, of choosing the right strategy at each moment and combining multiple factors in planning units or lessons to achieve desired outcomes. To make these choices well, a teacher needs both a near view (i.e., what are the goals of today) and a far view (i.e., which goals of today fit into and build toward an overall set of larger and longer-term goals). In the far view, the teacher knows both what came before and what comes after the current lesson, and even the current year. This book helps a teacher engaged in developing or using *NGSS*-oriented curriculum with that view. In combination with other publications that provide a similar overview and perspective on the science and engineering practices and the crosscutting concepts and their development across the K–12 school years, this book provides essential background for those who wish to be effective science teachers in the *NGSS* context.

# ACKNOWLEDGMENTS

The editors would like to thank Kevin J. B. Anderson, a science consultant from the Wisconsin Department of Public Instruction, for his insightful and productive comments on various chapters in this book.

# ABOUT THE EDITORS

The editors have been listed here and on the cover in alphabetical order.

**Ravit Golan Duncan** is an associate professor of science education with a joint appointment in the Graduate School of Education and the School of Environmental and Biological Sciences at Rutgers University. She received her PhD in learning sciences from Northwestern University. She currently has two main research strands: (1) the design and study of inquiry-based learning environments in life sciences that engage students with modeling and argumentation and (2) the study of learning progressions in science education, specifically in genetics. She is the recipient of three early career awards from the National Academy of Education/Spencer Foundation, the National Science Foundation, and the Knowles Science Teaching Foundation. In addition, Duncan also coordinates and teaches in the Certification Program in Life Sciences at Rutgers University and has studied the development of preservice teachers' knowledge and beliefs. Duncan is the recipient of several federal grants that involve the design of instructional materials that support student (and teacher) engagement with scientific inquiry. She has published in both education research journals such as the *Journal of Research in Science Teaching*, *Science Education*, and the National Science Teachers Association (NSTA) practitioner journals *The Science Teacher*, *Science Scope*, and *Science and Children*. Duncan was also one of the reviewers of *A Framework for K–12 Science Education* and has facilitated several NSTA professional development workshops and webinars about the *Next Generation Science Standards* disciplinary core ideas and science practices over the past few years.

## ABOUT THE EDITORS

**Joseph Krajcik**, a Lappan-Phillips Professor of Science Education at Michigan State University (MSU), serves as director of the CREATE for STEM (Collaborative Research for Education, Assessment and Teaching Environments for cience, Technology, Engineering, and Mathematics) Institute, which seeks to improve the teaching and learning of science and mathematics in kindergarten through college through innovation and research. During his career, Krajcik has focused on working with science teachers to reform science teaching practices to promote students' engagement in and learning of science. He served as lead writer for developing physical science standards for the *NGSS* and the lead writer for the physical science design team for *A Framework for K–12 Science Education*. He has authored and coauthored curriculum materials, books, and over 100 manuscripts. Krajcik served as president of the National Association for Research in Science Teaching, from which he received the Distinguished Contributions to Science Education Through Research Award in 2010. In 2014, he received the George G. Mallinson Award for Lifetime Achievement in the Field of Science Education from the Michigan Science Teachers Association for overall excellence of contributions to science education over a significant period of time. The University of Michigan, where Krajcik was a faculty member for 21 years, recognized him for his commitment to graduate education by presenting him with the Faculty Award for Distinguished Graduate Mentoring. Krajcik received his PhD in science education from the University of Iowa. Prior to receiving his PhD, Krajcik taught high school chemistry and physical science in Milwaukee, Wisconsin for eight years.

**Ann E. Rivet** is an associate professor of science education in the Department of Mathematics, Science, and Technology at Teachers College Columbia University. Her research uses learning sciences frameworks to explore the intersections of scientific reasoning, instructional design, and assessment, primarily at the middle and secondary school level. Her current work employs a learning progressions lens to examine students' interpretations and use of representations of large-scale Earth systems and see how their reasoning can be supported and developed through various classroom instructional strategies. She is also actively involved with current efforts to support teachers and instructional leaders with the *Next Generation Science Standards* in collaboration with the National Science Teachers Association. Rivet has extensive experience with the development and evaluation of project-based science curriculum materials, particularly in urban settings. Her prior research looked specifically at the role of contextualizing features of project-based science programs at the middle school level and how the design of those aspects of the curriculum support the activation of students' prior knowledge for learning and lead to more robust understandings of the science content. Her work has been published in several leading journals including *Science*, the *Journal of Research in Science Teaching*, and the *American Education Research Journal*, and she has presented her work in multiple national and international settings. She holds a bachelor's degree in physics from Brown University and a doctoral degree in science education from the University of Michigan.

# CONTRIBUTORS

## Foreword

Helen Quinn, SLAC National Accelerator Laboratory, Menlo Park, California

## Chapter 1

Joseph Krajcik, Michigan State University, East Lansing, Michigan

Ravit Golan Duncan, Rutgers University, New Brunswick, New Jersey

Ann E. Rivet, Teachers College Columbia University, New York, New York

## Chapter 2

Kristin Mayer, Michigan State University, East Lansing, Michigan

Joseph Krajcik, Michigan State University, East Lansing, Michigan

## Chapter 3

David Fortus, Weizmann Institute of Science, Rehovot, Israel

Jeffrey Nordine, Leibniz Institute for Science and Mathematics Education (IPN), Kiel, Germany

## Chapter 4

Jeffrey Nordine, Leibniz Institute for Science and Mathematics Education (IPN), Kiel, Germany

David Fortus, Weizmann Institute of Science, Rehovot, Israel

## Chapter 5

David Fortus, Weizmann Institute of Science, Rehovot, Israel

Joseph Krajcik, Michigan State University, East Lansing, Michigan

## Chapter 6

Aaron Rogat, Purdue University, West Lafayette, Indiana

Barbara Hug, University of Illinois at Urbana-Champaign, Champaign, Illinois

Ravit Golan Duncan, Rutgers University, New Brunswick, New Jersey

## Chapter 7

Charles W. (Andy) Anderson, Michigan State University, East Lansing, Michigan

Jennifer H. Doherty, University of Washington, Seattle, Washington

## Chapter 8

Nicole A. Shea, Bio-Rad Laboratories, Hercules, California

Ravit Golan Duncan, Rutgers University, New Brunswick, New Jersey

## Chapter 9

Cynthia Passmore, University of California, Davis, Davis, California

Julia Svoboda Gouvea, Tufts University, Medford, Massachusetts

Candice Guy, University of California, Davis, Davis, California

Chris Griesemer, University of California, Davis, Davis, California

## Chapter 10

Julia D. Plummer, Pennsylvania State University, University Park, Pennsylvania

## Chapter 11

Ann E. Rivet, Teachers College Columbia University, New York, New York

## Chapter 12

Nancy Brickhouse, Saint Louis University, Saint Louis, Missouri

J. Randy McGinnis, Center for Science and Technology in Education, Department of Teaching and Learning, Policy and Leadership, University of Maryland, College Park, Maryland

Nicole A. Shea, Bio-Rad Laboratories, Hercules, California

Andrea Drewes, School of Education, University of Delaware, Newark, Delaware

Emily Hestness, Center for Science and Technology in Education, Department of Teaching and Learning, Policy and Leadership, University of Maryland, College Park, Maryland

Wayne Breslyn, Center for Science and Technology in Education, Department of Teaching and Learning, Policy and Leadership, University of Maryland, College Park, Maryland

## Chapter 13

David E. Kanter, Kanter Learning Design & Research, New York, New York

David P. Crismond, The City College of New York, New York, New York

## Chapter 14

Cary Sneider, Portland State University, Portland, Oregon

## Chapter 15

Ann E. Rivet, Teachers College Columbia University, New York, New York

Joseph Krajcik, Michigan State University, East Lansing, Michigan

Ravit Golan Duncan, Rutgers University, New Brunswick, New Jersey

# CHAPTER 5

# CORE IDEA PS4

## WAVES AND THEIR APPLICATIONS IN TECHNOLOGIES FOR INFORMATION TRANSFER

David Fortus and Joseph Krajcik

## What Is This Disciplinary Core Idea, and Why Is It Important?

Although you may not realize it, and they cannot always be detected without special instruments, waves are *everywhere*. As you read this chapter, there are radio waves going through your body. Stop reading for a minute, close your eyes, and concentrate on your surroundings, your breathing, and your heartbeat. Can you hear anything, or is it completely silent? Most likely there is something you can hear, evidence that you are immersed in a sea of sound waves. Start reading again. How can you read this text? Light waves are being scattered by the page (if you're reading this on paper) or being generated by a screen (if you're reading this on an electronic device) and reaching your eyes. Are there electric apparatuses near you? Every electric device generates electromagnetic waves. Think about cell phones, GPS devices, heat lamps, x-rays, microwave ovens, police radars, lasers, antennas, stereo systems, computer networks, ultrasound imaging devices, and MRI scanners. Think about contact lenses, sunburns, sunglasses, earthquakes, optical fibers, surfing, telescopes, and microscopes. Are these apparatuses and phenomena relevant to you and your students' lives? Is it important that students have some understanding of how they work? If yes, then waves are important, because waves play a key role in each of these apparatuses and phenomena and in many, many others things as well. In fact, many of the technologies developed in the 20th century and those under development now are dependent on waves. For example, stealth technology is based on waves and uses ideas such as reflection, transmission, absorption, and superposition (which will be described in detail later in this chapter) to render stealth planes nearly invisible to radars. Understanding wave properties and the interactions of electromagnetic radiation with matter is critical to the investigation of nature at all scales, including the invisible world of atoms and molecules and the far away world of stars and galaxies. Wave properties and interactions of electromagnetic radiation with matter explain how information can be transferred over long distances and stored as digital information.

In contrast to the *National Science Education Standards* (NRC 1996) and the AAAS *Benchmarks for Science Literacy* (AAAS 1993), *A Framework for K–12 Science Education* (*Framework*; NRC 2012) emphasizes the dependence of modern technologies, especially communications technologies, on waves. It also highlights the role waves play in transferring energy and information from one location to another. The concepts of wave properties and the interaction of electromagnetic waves with matter explain many important phenomena in our world. We now present the components of the disciplinary core idea (DCI) in the *Framework* that deals with waves.

PS4: Waves and Their Applications in Technologies for Information Transfer provides answers to the question, "How are waves used to transfer energy and information?" This DCI is made up of three component ideas. PS4.A: Wave Properties examines the question, "What are the characteristic properties and behaviors of waves?" PS4.B: Electromagnetic Radiation provides insights into three questions: "What is light?" "How can one explain the varied effects that involve light?" and "What other forms of electromagnetic radiation are there?" Finally, PS4.C: Information Technologies and Instrumentation builds understanding of answers to the question, "How are instruments that transmit and detect waves used to extend human senses?"

## PS4.A Wave Properties

PS4.A: Wave Properties describes the properties of waves. It provides an answer to the question, "What are waves?" Think of a simple example that many of us have experienced: a stone thrown into a pond of water. Before the stone hits the pond, the water's surface is relatively flat and smooth. After the stone hits the water and disappears below the surface, circles centered where the stone hit spread out and away from where they were created (Figure 5.1). These spreading circles and the area between them on the surface of the water are an example of a wave.

**FIGURE 5.1**

Waves in a Pond

The definition of a wave is a disturbance that propagates—that is, moves or spreads—through space. In the case that we just imagined of a stone being thrown into a pond, the disturbance was the deformation of the water's surface caused by the entrance of the stone into the water (the stone applied a force to the water, which caused a change in the water's motion; the water started to move down and away from the stone; see Chapter 3, p. 33, on PS2: Motion and Stability: Forces and Interactions). The spreading out of the circles was the propagation of the disturbance. Because the wave is moving, it has energy (see Chapter 4, p. 55, on PS3: Energy).

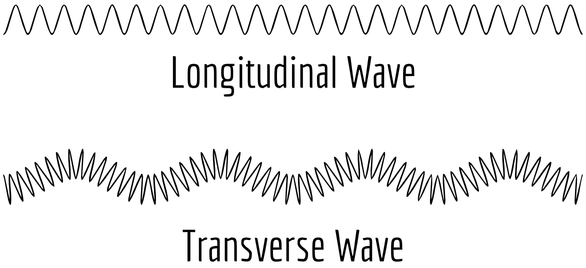
Let's see how this definition works in another case. If you knock on one end of a table with your knuckle, you can feel the knock with your other hand if you place it at the other end of the table, or you can hear the knock if you place your ear on the table. What does this have to do with waves? When your knuckle hits the table, it pushes down on the table, making a small deformation in the table's surface. Although you can't see it, this deformation expands out through the table, which is why you can feel and hear it at a distance. The spreading out of the deformation in the table's surface is a wave.

**FIGURE 5.2**

Stadium Wave

**FIGURE 5.3**

Waves in a Slinky



## LONGITUDINAL AND TRANSVERSE WAVES

When you throw a stone into a pond, the water's surface bobs up and down. (Actually, the movement of any water particle near the surface is a combination of up and down and back and forth motions.) However, the wave generated by this up-down movement of the water's surface moves horizontally. That is, the direction in which the wave moves is perpendicular to the direction in which the disturbance was made. This is called a transverse wave. There are many kinds of transverse waves. All electromagnetic waves are transverse waves. Think about a human wave in a football stadium. People get up and sit down in their seats, but the wave moves horizontally across the stadium (Figure 5.2). This is an example of a transverse wave.

Now imagine a Slinky that is stretched and lying on the floor. One end is held stationary, and the other end is shaken sideways. A wave is generated and propagates through the toy. Try it! Is this a transverse wave? (A demonstration of transverse waves in a Slinky can be found at *www.teachertube.com/viewVideo.php?video_id=75927*.) Now instead of shaking the Slinky's end sideways, move it back and forth in the direction in which the Slinky is stretched. Once again, a wave is generated in the Slinky; however, this time the direction of the disturbance is the same as the direction in which the wave travels (Figure 5.3). This is called a longitudinal wave (for a demonstration of longitudinal waves in a Slinky, visit *www.youtube.com/watch?v=y7qS6SyyrFU*). Sound waves traveling through the air are longitudinal waves, with the air molecules moving back and forth in the direction in which the sound wave is traveling. Sound waves moving through solids (like when you knocked on the table with your knuckle) can be both transverse and longitudinal.

## WHAT MOVES WHEN A WAVE MOVES?

Above we mentioned that a wave is a moving disturbance. In a pond wave, the disturbance is a depression of the surface of the water. When the wave spreads outward, does the water in the pond move outward with it? The answer is no, because otherwise there would be less water left in the area where the wave originated. The water near the top of the pond moves up and down in a coordinated manner so that the water appears to be moving outward when it is actually only moving up and down. So no water really moves away from the wave's source. You may have seen humans create a wave in a football stadium. As the wave moves across the stadium, do the spectators making the wave actually move horizontally with the wave? No. Every spectator moves up and down in a coordinated manner, but each spectator stays in the place where she began—sitting.

This idea that no material moves permanently from its original location is true for all waves. In a sound wave, for example, the air molecules move a bit back and forth around their original location, but they stay on average where they were before the wave was generated and do not move with the wave. Flap your hand at your ear. You can feel the air that is being forced at your ear by your hand. The air molecules are being moved from their original location toward your ear. Now hold your hand near your ear and snap your fingers. You can clearly hear the snapping sound but not feel any wind moving toward your ear. So the sound wave generated by the snapping of your fingers does not cause the air molecules to move toward your ear. This can be seen very nicely in a simulation from Pennsylvania State University's acoustics program at *www.acs.psu.edu/drussell/Demos/waves/Lwave-v8.gif*. The simulation shows the propagation of a sound wave. Follow the red particle. You will see that it moves back and forth but does not propagate with the sound wave. Here, too, you can see why sound waves in the air are longitudinal waves: The air particles move back and forth in the same direction in which the wave travels.

Some students consider sound to be an entity that is carried by individual molecules as they move through a medium (Linder and Erickson 1989). Just as particles can have energy, they think that particles can have sound, that the particle picks up the sound at one place (e.g., a loudspeaker or a tuning fork), carry it from that place to another (e.g., a microphone or an ear), and then release it there. In this view, the more particles that carry the sound, the louder the sound is. This conception of sound is based on the mistaken idea that the particles of the medium actually move along with the wave or that there are special sound particles that differ from the particles that make up the medium. Accordingly, in this scenario, these sound particles are created at the sound's source and destroyed when the sound is heard, which contradicts the law of energy conservation. Another problem with this notion is that there are infinitely different kinds of sound; in what way does the sound carried by the particles in one case differ from the sounds in other cases? Or are there an infinite number of different kinds of sound particles?

A more sophisticated conception than the one above, but still mistaken, is that sound is a physical entity that is transferred from one molecule to another through a medium. In this case, sound is still something carried by the particles of the medium, but instead of moving through the medium, the particles collide with each other and in each collision transfer some sound from one to another.

### WAVE DIMENSIONALITY

Some waves spread out in three dimensions throughout space, others spread out in two dimensions over a surface, and others spread out in one dimension. When you speak, you create sound waves. People in front of you, behind you, to your sides, above you, and below you can all hear you. This is lucky because it means that when you are teaching you needn't repeat yourself 30 times while facing every student in your class. The sound waves you generate spread out in all dimensions, so they are three-dimensional (3-D) waves.

When you knocked on the table, you couldn't hear the sound *in* the table unless you pressed your ear to the table because the sound *in* the table spread out only *in* the table (you could hear the sound of the knocking in the air, but that is because the knocking created a sound wave in the air as well as in the table). The table is relatively thin, so you can say that the sound wave spreads out in the table only horizontally and not vertically, so the sound wave in the table is a two dimensional (2-D) wave.

If you take a pipe or a water hose and speak into it, nobody around you can hear you. However, if somebody holds up the other end of the hose to their ear, they can hear you quite well. In this case, the sound wave traveled in only one direction, along the water hose. Since it propagated in only one direction, we say that it is a one dimensional (1-D) wave.

So a sound wave can be a 1-D, 2-D, or 3-D wave, depending on the structure or configuration of the environment in which it propagates.

Why is the dimensionality of a wave important? It turns out that the dimensionality of a wave determines the rate at which the intensity of the wave decreases. The relation between the rate at which a wave's intensity decreases and its dimensionality is a result of the law of conservation of energy. When 3-D waves spread out, like sound waves disseminating from your mouth, the intensity of the waves decrease as the waves get farther from your mouth. This is why your voice sounds weaker the farther the listener is from you. Close up, it may be loud; far away, it sounds faint. It turns out that all 3-D waves decrease in intensity at the same rate, regardless of whether they are sound waves or electromagnetic waves or tectonic waves or any other kind of wave. The intensity of all 3-D waves depends on $1/r^2$, where $r$ is the distance of the wave from its source. Thus, as the distance of a 3-D wave from its source doubles, its intensity decreases fourfold.

When a 2-D wave spreads out, its intensity also decreases as it gets farther away from its source. However, the rate at which it decreases is different from the rate at which a 3-D wave decreases. The intensity of all 2-D waves, regardless of what kind they are, decreases at a rate of $1/r$ , meaning that when the distance of the wave from its source doubles, the intensity of the wave is halved.

When a wave's dimensionality is 1-D, it does not spread out; it just moves from one place to another. Its intensity does not decrease but remains the same. So the intensity of the sound from your mouth decreases as it gets farther from you unless the sound waves are channeled into a tube where it can travel long distances without getting weaker.

## WAVELENGTH

When a stone is thrown into a pond, not just one ripple is made, but several. We see concentric circles traveling outward from the place where the stone hit the water (see Figure 5.1, p. 76). If we look a bit closer, we will see that the distance between the circles is the same and that this distance is maintained as the ripples move outward. The distance between any two ripples is called the wave's wavelength. The Greek letter $\lambda$ (lambda) is used to represent the wavelength.

Every wave has a wavelength. If you revisit the simulation of a sound wave mentioned on page 78, you will see that there is a constant distance between the areas of high particle density that move to the right. This distance is the wavelength.

### SPEED

Waves also have a speed at which they spread out. Every type of wave has a speed which is dependent on the medium through which the wave is traveling. Thus, the speed of sound is the speed at which sound waves travel through the air. This speed is temperature dependent but is about 300 m/s at room temperature. Look again at the simulation of sound waves—you will see that the air of high density moves to the right at a constant speed. Sound can also travel through other media. The speed of sound in liquids and in most solids is much faster than in air. The speed of sound in helium is different from in air, which is why voices sound funny if one inhales helium and then speaks while exhaling.

### FREQUENCY

Waves have a frequency. When a stone is thrown into a pond, the rings that move outward are generated at a certain frequency, that is, every second a certain number of rings are generated. Look again at the simulation of the sound waves. The areas of high particle density are generated on the left at a constant rate. This rate, the number of areas of high density that are generated every second, is called the wave's frequency. Frequencies can be very low, less than one ripple or one high-density area per second, or very high, thousands or millions or even billions of times per second. Frequencies are measured in hertz (Hz). A sound wave with a frequency of 200 Hz has 200 areas of high density generated per second at the sound's source.

There is a mathematical relation between a wave's wavelength, its frequency, and its speed. The relation is true for *all* waves:

$$v = \lambda \cdot f$$

Here $v$ stands for the wave's speed in [m/s], $\lambda$ stands for the wave's wavelength in meters, and $f$ stands for the wave's frequency in hertz. The relation between the wavelength and frequency of electromagnetic waves is the same as for all other waves.

### AMPLITUDE

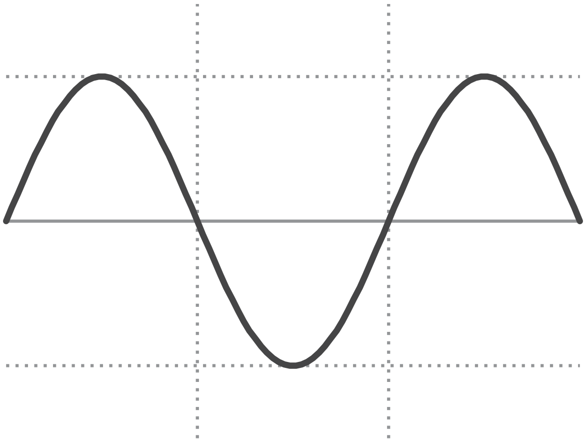
Every wave has an amplitude. The amplitude is the magnitude of the disturbance relative to the situation where there is no disturbance. In the case of the water waves, the amplitude is typically given as the maximum height the water reaches above the height of the water in the pond when there is no wave. In Figure 5.4, the original pond level is the horizontal line through the center of the graph, so the amplitude is the height of the tallest part of the wave where it touches the dotted line above the center line For a sound wave, the amplitude is the maximum change in the density of the particles, so it is the density of the particles at areas of maximum density minus the density of the particles when there is no sound wave. The square of the amplitude ($A^2$) is a measure of the intensity of a wave; the greater the amplitude, the stronger the wave. Thus, a loud sound wave will have a larger amplitude and a soft sound wave will have a smaller amplitude.

### SUPERPOSITION

When waves of the same kind (for example, two water waves) meet each other, they add up,

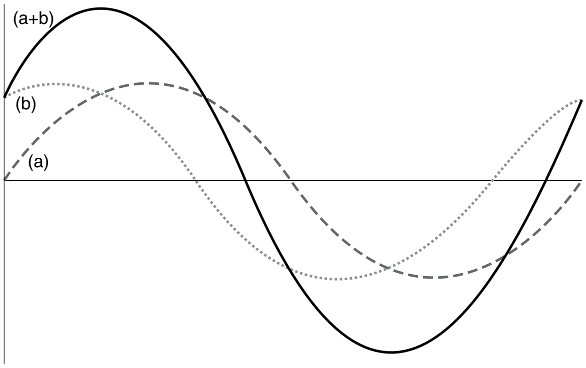
### FIGURE 5.4

Amplitude and Wavelength



### FIGURE 5.5

Superposition of Two Waves



meaning that the height of the surface at any point in the pond will be equal to the height that point would have been if only one of the waves was in the pond *plus* the height of that point if only the second of the waves had been in the pond. Thus, *new height* = *height*(1) + *height*(2). In Figure 5.5, the height of the solid line at the crest of the wave and at the trough of the wave results from the summation of (a) plus (b). This summation of waves is called superposition. Notice, however, that the height of any point on a wave on the surface of the pond goes up and down, so that sometimes it is above the level of the surface of a quiet pond (positive height) and sometimes it is below this level (negative height). So, during the superposition of two waves the height of any point on the pond's surface may be higher or lower than it would have been if there had been only one wave.

Superposition is important because it helps predict what happens when two or more waves meet in various ways. For example, consider two waves with the same height that interact out of phase—that is, when one wave is increasing while the other is decreasing. If these two identical waves are exactly out of phase, their sum will be zero and they will cancel out. An example of this being applied in real life is noise-canceling headphones. Noise-canceling headphones generate sound waves that are identical to those coming from the outside (the ambient noise) but opposite in phase. Because they are opposite in phase, the incoming noise is canceled out. DVD players provide another everyday example of superposition. Light is reflected from the DVD so that it is at the same phase or at the opposite phase as the wave that reached it. These two waves superimpose, making either a stronger wave (= 1) or canceling each other out (= 0). Because digital information is encoded as 1s and 0s, this superposition effect enables the digital storage and transfer of information in DVD and CD players. Superposition also allows us to deconstruct complex waves into the sum of many simple waves.

## AMPLITUDE DECAY

As was described before in the Wave Dimensionality section (p. 78), the intensity of 2-D and 3-D waves declines as the waves get farther away from their source. Since the square of a wave's amplitude is related to the wave's intensity, this mean that the wave's amplitude gets smaller as the wave gets farther away from its source. If you look at a water wave, you can see that it slowly dies out, so that after a certain distance from the spot where the stone entered the pond, the wave is no longer visible. When someone is far away from you, they need to shout to be heard because the amplitude (and the intensity) of the sound waves they create decrease as they get farther from the person, so by the time sound waves reach you, they are already much weaker than they were to begin with and are therefore harder to hear.

## RESONANCE

Every object, or system, has natural frequencies, which are the frequencies at which waves naturally propagate, or spread, through the system. For example, when the stone was thrown into the pond, the waves that were generated had a frequency. Every time you throw another stone, whether it is bigger or smaller, into the same pond, the waves generated will have the same frequency. Thus, this frequency is a natural characteristic of the pond and has little to do with nature of the perturbation, or disturbance, that causes the waves (the stone entering the water). When you strike a tuning fork or pluck a guitar string, regardless of the force used, the sound wave generated always has the same frequency (in music, frequency is also called "pitch"). So, we say that the tuning fork or the guitar string have a natural frequency. However, systems can be forced to oscillate and generate waves at frequencies that are different from the natural frequency of their materials. For example, the membrane of a speaker in a stereo system has a natural frequency, but the amplifier can force it to vibrate at many different frequencies, generating a range of sound waves with different frequencies. When a system is forced to generate waves at a certain frequency, this is called the forced frequency. Sometimes, intentionally or unintentionally, the forced frequency is identical to the system's natural frequency. When this happens, the waves generated can get larger and larger, even though the magnitude of the perturbation remains small. This situation is called resonance. It can be very useful, but it can also be catastrophic. It is the principle by which radios and musical wind instruments work. It can also cause a bridge to collapse, as happened to the Tacoma Narrows Bridge in 1940 as shown at *http://en.wikipedia.org/wiki/Tacoma_Narrows_Bridge_(1940)*.

## INTERACTIONS WITH OBJECTS

All waves, when they reach a boundary between two objects or materials, behave in a combination of ways: They are reflected, transmitted, and absorbed. For example, how do we hear anything? Sound waves are absorbed by the eardrums, which transfers energy to them and makes them vibrate, generating a signal that is transmitted to the brain. How is an echo created? A sound wave is reflected off a large object, such as a cliff, which is far enough away that we hear the reflected echo noticeably later than we hear our original shout. How do we see? Light reflects off materials and onto our retinas, which transmit a message to the brain. Because different materials absorb different frequencies of light, we see light reflected back in different colors. We see a red sweater because the sweater reflects light with red frequencies and absorbs other frequencies. How does an ultrasound imager work? Ultrasound waves generated in a transducer are transmitted through our bodies and reflected at the interfaces between different tissues.

Allow students to experience simple light phenomena and provide them with relevant data. Next, have students construct models to explain the phenomena. Such experiences provide opportunities for students to make sense of phenomena using the important science practice of modeling and building knowledge of the DCI. This simple model can be expanded as students experience more phenomena and collect additional data.

## PS4.B: Electromagnetic (EM) Radiation

PS4.B: Electromagnetic (EM) Radiation explores the question, "What are EM waves?" All electrons create an electromagnetic field in the space around them. When these electrons are forced to move, the electromagnetic field they create changes, first near the electron, then farther away as the change to the electromagnetic field spreads out through space, making an electromagnetic wave. This can occur, for example, when an electric circuit forces electrons to move inside an antenna. If the circuit makes the electrons move at a certain forced frequency, the electromagnetic wave generated can be a radio wave or a microwave, or any other wave in the electromagnetic spectrum. Just as we could see the waves on the surface of a pond or feel or hear the waves in a table, we can detect the electromagnetic waves generated by the electric current. Various instruments such as cell phones or radio receivers can detect and react to certain electromagnetic waves. The water molecules in a piece of food in a microwave can absorb electromagnetic waves created by a microwave. Our eyes, working with our nervous systems, can detect and react to electromagnetic waves in the visible region. Electromagnetic waves have properties like all waves, such as frequency and wavelength.

### THE DIMENSIONALITY OF EM WAVES

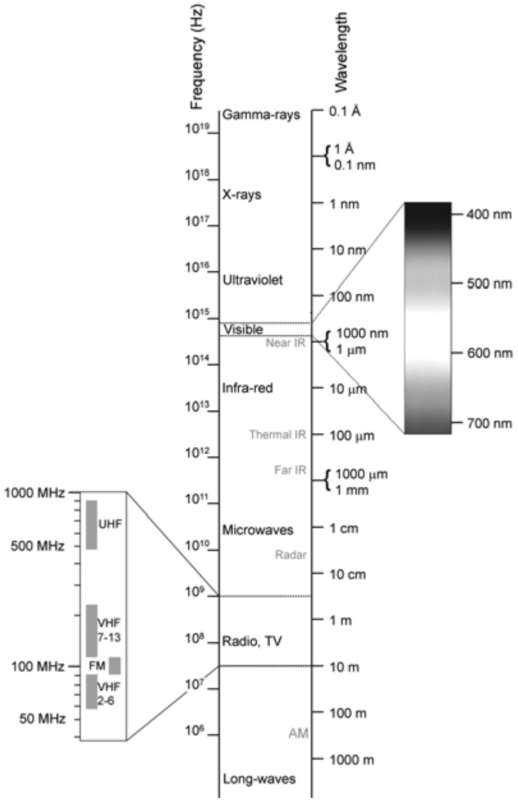
When you turn on a light bulb, it shines in all directions, so the wave that is being generated is a 3-D wave. But what if light is shined into an optical fiber? The light can move through the fiber just as sound can move through a pipe. In this case, light propagates like a 1-D wave. Depending on the circumstances, EM waves can be 1-D, 2-D, or 3-D.

### WAVELENGTH OF EM WAVES

EM waves are propagating perturbations—moving or spreading disturbances—of the EM field. If the EM field were "still" (it never is), the strength and direction of the EM field at any point in space would never change. However, because there are waves, the strength and direction of this field changes with time, getting stronger, then weaker, then stronger, then weaker again, and so on, just as any point on the surface of a pond gets higher and lower repeatedly when there is a water wave. EM waves spread out from sources just like water waves, except they typically expand in 3-D, so they expand as ever-increasing spheres rather than as circles. Just as in water waves, where water doesn't really move from its position but just bobs up and down in a coordinated way, in EM waves, nothing moves; the field just gets stronger and weaker in a coordinated way. Just as in water waves, where there is a constant distance between consecutive circles of the wave (areas where the water surface is high), there is a constant distance between

**FIGURE 5.6**

The Electromagnetic Spectrum



consecutive spheres of the EM wave (areas of maximum EM field strength). Again, this distance is called the wave's wavelength.

### SPEED

EM waves are the only type of wave that does not need a medium to propagate. Their speed in a vacuum, regardless of their wavelength, is the speed of light, which is about 300,000 km/s. When EM waves enter a medium, they move slower than they do in a vacuum, but not by much. Their actual speed in a medium depends on the type of medium.

### FREQUENCY

The Greek letter $\nu$ is used instead of $f$ to represent the frequency, and the letter $c$ is used instead of $v$ to stand for the speed, so the relation between an EM wave's speed, wavelength, and frequency is shown in the following equation:

$$c = \lambda \cdot \nu$$

EM waves are grouped into categories according to their wavelengths and frequencies (Figure 5.6). Radio waves have the longest wavelengths and lowest frequencies; gamma rays have the shortest wavelengths and the highest frequencies.

### AMPLITUDE

The amplitude of an EM wave is the difference between the maximum strength of the EM field due to the wave and the strength of the field if there were no wave, just as the amplitude of a water wave is the difference between the maximum height of the water's surface due to the wave and the height of the water's surface if there had been no wave. The greater the amplitude of an EM wave, the stronger its intensity.

### RESONANCE OF EM WAVES

As described above, every object has natural frequencies, which are the frequencies at which waves naturally propagate through the system. A laser is an example of the resonance of EM waves. The term *laser* is an acronym that stands for "light amplification by stimulated emission of radiation." Lasers basically amplify light. EM waves are generated at a frequency identical to the natural frequency of an apparatus called a laser cavity, in which the waves combine and get stronger and stronger until they are released outside as a strong EM wave with a single frequency, called a laser beam. In "The Laser at 50," Scientific American (2010) provides an overview of the past, present, and potential future of lasers.

### INTERACTION WITH MATTER

As with other waves, when EM waves reach a boundary, they can be reflected, transmitted, or absorbed. Light can be reflected in a single direction by a mirror or in many directions (scattered) by any object, which is how we see objects. Light is transmitted through glass, air, and many other substances. Many EM waves are transmitted through concrete, which is how we can use our cell phones inside buildings. Finally, EM waves are often absorbed by substances, which is why cars get hot in the Sun and food gets warm in a microwave oven. Whenever any type of wave is absorbed, some of its energy is transferred to the object absorbing it, and this energy enables something to happen in that object.

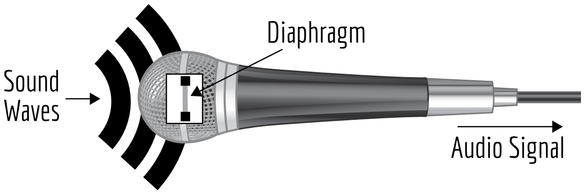
## PS4.C: Information Technologies and Instrumentation

PS4.C: Information Technologies and Instrumentation explores the question, "How are instruments that transmit and detect waves used to extend human senses?"

How do you hear things? Your ears detect sound waves. The waves are absorbed by the eardrum, making it vibrate, which in turn generates a signal which is transmitted to the brain. How does a microphone detect sound waves? By the same principle: A membrane with a coil attached to it absorbs sound waves, causing it to vibrate, which generates an electric signal (Figure 5.7). For any kind of wave to be detected, it must be absorbed. The absorption of the wave transfers energy from the wave to the object absorbing the wave, and this energy enables something to happen (see Chapter 4, p. 55, on PS3: Energy).

**FIGURE 5.7**

How a Microphone Works



Let's look more closely at how a microphone works. Microphones are devices that convert energy from one form to another. A microphone converts sound waves into electric impulses. All microphones have one aspect in common: They all have diaphragms. A diaphragm is a thin piece of material (such as paper or aluminum) that can vibrate when struck by a sound wave. When the diaphragm vibrates, it causes others parts of the microphone to vibrate as well. These vibrations are converted into electric signals that become the audio signal. A speaker converts the electric signal back into a sound wave. The eardrum is also a diaphragm, that is, a piece of tissue that can vibrate. This idea of a wave being absorbed by a material is fundamental to how materials can detect and transfer information. So hearing is really the detection and conversion of sound waves into some other form of vibrations.

## HOW DO YOU SEE THINGS?

How we see works on the same principle as how we hear. It is vibrations of waves—EM waves—being absorbed and then converted into another signal. EM waves (in the form of light) from objects are transmitted to and through your eyes until they reach the retina at the back of the eyes where they are absorbed, generating a signal that is transmitted to the brain. How does a camera detect light waves? Either the light is absorbed by a special chip called a charge-coupled device, which generates an electric signal, or the light is absorbed by a special film, causing a chemical reaction that creates bright and dark areas on the film. Smartphones, like cell phones, detect microwaves (a type of EM wave). An antenna absorbs these waves, making electrons in the antenna vibrate back and forth, thus creating an electric current that can be decoded or converted in audio and visual signals. GPS systems do the same. Similarly, when you put your hand near a heat lamp, your hand absorbs infrared light (a type of EM wave), causing your skin become warm. All information transfer occurs by the absorption and conversion of waves.

## GENERATION OF WAVES

As described earlier, any perturbation or disturbance that propagates is a wave, so almost anything has the capacity to generate waves. My tapping on the keyboard of my laptop generates sound waves that travel throughout the laptop and the air (that's how I hear the tapping).

EM waves are generated by two primary mechanisms: (1) Any accelerating electric charge creates an EM wave. A charge that oscillates back and forth (as in an antenna) will generate an EM wave that has the same frequency as that of the charge's oscillations. Atoms and molecules in all substances are always vibrating randomly. These particles have electric charges, so they emit EM radiation. At room temperature, this EM radiation lies in the infrared range. If it gets hot enough, the radiation will move to the visible range (which is why hot things glow). (2) In the quantum world, every object has possible energy levels. When an object transitions from a high energy level to a lower one, an EM wave is generated. This is how fluorescent lamps work, how solid-state lasers (such as the type in a CD player) work, and how gamma rays are generated; this is the principle underlying the operation of almost all apparatuses that use a single EM frequency.

## TRANSMISSION OF INFORMATION USING WAVES

For information to be transmitted by a wave, it needs to be encoded. Information can be encoded in analog or digital form. In analog encoding, a wave is generated that is similar in "shape" (analogous) to the information being encoded. For example, when I say the word *wave*, my body forces the vocal cords in my throat to vibrate in a certain manner. These vibrations of my vocal cords change the density of the air next to them. This change is a perturbation that then propagates away from my vocal cords as a sound wave until ears or microphones or some other object absorbs part of the wave. This continues until it has insufficient energy to continue the perturbation to any measurable extent, or until other objects absorb the energy. If a graph were made of the change in air density over time due to this sound wave, it would look identical to the displacement of my vocal cords over time: They would have the same frequencies.

If you hold two paper cups with a thread stretched tightly between them and speak into one end, your voice can be heard at the other end. How? The sound waves generated by your vocal cords are absorbed by the base of the paper cup, making it vibrate. The vibrations of the bottom of the paper cup are analogous to those of the sound waves (and therefore analogous to the vibrations of your vocal cords). The vibrations of the paper cup pull and push on the thread, generating a sound wave (again, analogous to the prior vibrations and waves) which propagates along the thread to the other paper cup, and so on. The first paper cup acts like a microphone while the second is similar to a speaker.

Information can also be encoded digitally. In digital encoding, the information is "translated" into a code using on-and-off signals, which are then transmitted analogously. For example, in Morse code, a message is converted into a sequence of short signals, called dots, and long signals, called dashes, separated by short silences. Letters are encoded as unique combinations of dots and dashes. In digital media such as audio CDs, a sound or EM wave can be encoded in a similar way, where bits of information are represented by combinations of zeros and ones.

## How Does Student Understanding of This Disciplinary Core Idea Develop Over Time?

One of the key features of DCIs is that they can be taught and learned over multiple grades at increasing levels of depth and sophistication. Let's see how this progression plays out for waves and what kind of simple experiences that require no special equipment can support them.

In the discussion below, what students should know related to a subcomponent of the core idea is shown in italics. This is followed by various potential learning tasks that could support students as they develop this understanding. Learning tasks are described only until the end of middle school because most of the ideas that are appropriate for high school require the use of special equipment.

## By the End of Grade 2

### PS4.A: WAVE PROPERTIES

- *Waves in water spread out in circles.*

**Possible tasks:** Students should make repeated observations by dropping objects into a tub of water and throwing stones into ponds. Have students look for patterns. Do the sizes of the waves change with the sizes of the rocks? What happens if the same rock is dropped from different heights? Have students make claims based on the patterns they observe. *Safety note:* Make sure students wear eye protection (safety glasses or goggles) for this task. Use caution when dropping objects so as not to injure feet. Immediately wipe up any water spilled or splashed on the floor to prevent a slip or fall hazard.

- *The surface of the water moves up and down while a wave spreads outward.*

**Possible tasks:** Students can observe this idea by first filling a large pot or tub with water, then tapping at the water near the center of the tub, and finally peering at the water waves with their eyes just a bit above the level of the water. Ask students to describe what pattern they see. They will clearly see the water move up and down. If a little boat is placed on the water, they will see it bob up and down but not move away with the wave. Have students make claims about the movement of the boat based on their observations. Students are not expected at this stage to understand that the water does not move away with the wave. *Safety note:* Make sure students wear eye protection (safety glasses or goggles) for this task. Immediately wipe up any water spilled or splashed on the floor to prevent a slip or fall hazard.

- *Vibrating solids can make sounds.*

**Possible tasks:** A plucked guitar string makes a sound. Have students feel the string and describe what they feel. Students will feel it vibrate if they touch it lightly. If they look closely at the string, they will also see it vibrating. What happens if the string is plucked harder? What do they feel then? The same can be done with a tapped tuning fork, music triangle, or cymbal. Students can also use a rubber band (this type of activity does not necessarily require special equipment). Have students stretch the rubber band to different lengths and then pluck it. How does this change the vibrations? What happens if they pluck it hard? Have students describe the patterns they observe.

### PS4.B: ELECTROMAGNETIC (EM) RADIATION

- *Light is needed to see an object.*

**Possible tasks:** Take a shoe box and cut a hole the size of an eye in one end using a utility knife (many shoe boxes already have a round hole in one end). Glue an object inside the box at the far end (away from the hole). With the cover securely fixed on the box, have students peek through the hole and try to see the object inside. Then, open a window on the side of the box near the end where the object is glued so that light can get inside and have the students look into the box again. (You will need to cut this window using a utility knife. Make sure you only cut on the sides and the bottom so that the window is a flap.) Can they see the object now? What is the difference between the two conditions? You can also shine a light through the hole to provide more light. Have students make claims about what is needed to see. Have them support their claims with evidence. *Safety note:* Make sure students wear eye protection (safety glasses or goggles) for this task. Use extreme caution when working with utility knives. Sharps can puncture or cut skin!

- *Mirrors can redirect light.*

**Possible tasks:** Darken a room, then turn on a flashlight and aim it at the wall so that students understand that light is coming from the flashlight and traveling to the wall. Next, place a mirror in the path of the beam and move the mirror around so that it reflects the flashlight's beam in different directions. Have students construct a model to explain their observations. *Safety note:* Make sure to move all fragile or sharp items out of the students' path to prevent injury when working in a dark room.

- *Objects that are very hot give off light.*

**Possible tasks:** Light a burner and hold a wire in the flame until it begins to glow. Take it out of the flame so that the students see that it still glows a bit. Burn a stick of wood under a fume hood and blow out the flame so students can see that the embers still glow. Show the students a video clip of molten metal, molten glass, and lava in a volcano. Have students describe the patterns they see. Have students make claims based on their observations. *Safety note:* Make sure students wear eye protection (safety glasses or goggles) for this task. Use caution when working with active flames or hot objects. They can seriously burn skin!

- *Some materials let light bounce off them, others let light shine through them fully or partially, and others don't let any light get through them, creating shadows behind them.*

**Possible tasks:** Obtain a flashlight, a mirror, a sheet of white paper, a piece of clear glass, a clear CD case, and a key. Darken the room and shine a light on a mirror. Have students describe what they see. Students should observe that the light from the flashlight bounces off the mirror. Hold the piece of paper perpendicular to a wall and shine the flashlight on it at a 45º angle. Have students describe what they see now. An illuminated area on the wall will be seen, even though the flashlight is not pointing there, so the light must be bouncing off the sheet of paper. Now shine the flashlight at the glass and the CD case. Have students describe their observations. Students will see that the light goes through the glass and the CD case. Now shine the flashlight at the key. Have students describe what they see. The flashlight cannot be seen from behind the key, so it must be blocking the light; a key-shaped shadow is made. Have students make claims about the behavior of light and support their claims with evidence from their observations. *Safety note:* Make sure to move all fragile or sharp items out of the students' path to prevent injury when working in a dark room.

## PS4.C: INFORMATION TECHNOLOGIES AND INSTRUMENTATION

- *People can detect light with their eyes, sound with their ears, and vibrations with their fingertips.*

**Possible tasks:** Blindfold students using a good sleep mask that blocks the light, and then turn a flashlight on and off while its beam is aimed at the wall. Ask the students if they can tell when the flashlight is on and when it is off. Have student explain why they can't see anything. Have students cover their ears tightly and turn around so that they're facing the back of the class. Do a few things that make sounds, such as tapping on a table, hitting a tuning fork, and whistling. After the students remove their hands from their ears, have them write down which sounds they heard you make. For feeling vibrations see the former activity on a vibrating string.

- *Many different devices are used to communicate over a distance.*

**Possible tasks:** Have students discuss in groups and build evidence statements showing that devices such as telephones, cell phones, and walkie-talkies communicate over a distance, without delving into how the devices work. Have students build a string telephone by attaching a 10 ft. string to two paper cups. First, cut a small hole in the bottom of one cup and thread the string through it. Then, secure the string by making a small knot. Next, make a small hole in the other paper cup and thread the string through it. Secure it by tying a knot. Now have students stretch the string. Have one student quietly talk into one of the cups and have the other listen by holding the other cup to his or her ear. Have students make models of how they can hear each other talking using this method. Have them explore with different types of strings and cups. Have them also see how long a string can be before they can no longer hear each other. *Safety note:* Make sure students wear eye protection (safety glasses or goggles) for this task.

## By the End of Grade 5

### PS4.A: WAVE PROPERTIES

- *Waves can have different amplitudes or wavelengths and can constructively or destructively interfere with one another.*

**Possible tasks:** To help students understand that waves have these properties, use a stretched Slinky on the floor. Have one student hold one end fixed and another student move the other end of the Slinky back and forth sideways at a constant frequency. Waves will travel along the toy. Have students describe the pattern they see. The wavelength between consecutive peaks will be clearly visible. Next have the student moving the free end of the Slinky continue to do so at the same frequency but with smaller or larger movements. Ask students to describe the changes they see. The change in the amplitude of the waves will be apparent. Then, have the student shaking the Slinky move the free end back and forth at a higher or lower frequency. What pattern do the students observe now? The faster the free end moves back and forth (i.e., the higher the frequency), the smaller the wavelength will be, meaning that the consecutive peaks will be closer to each other, and vice versa, the slower the free end moves back and forth (i.e., the lower the frequency), the larger the wavelength will be. Have students make claims about the types of waves they observe and have them support their claims with evidence.

Next, have both students move their ends of the Slinky, not back and forth, but only once, creating a single peak that travels along the Slinky (actually two peaks, one from each end, traveling in the opposite direction). The students should create the pulse at the same time, moving their hands in the same direction so that both peaks are on the same side of the Slinky. Ask students to describe what they observe now. When the two peaks meet each other, they pass through each other, but when they are one on top of the other, they combine "constructively" so that the peak generated is the sum of both peaks. This is called constructive interference and is an example of wave superposition. Have the students repeat this exercise, but this time have them move their hands in opposite directions so that the peaks are on different sides of the Slinky. What pattern do students observe this time? When the peaks pass through each other, they combine "destructively" so that the new peak generated is smaller than each individual peak. There will be moments when there is no peak. This is called destructive interference and is another example of wave superposition. *Safety note:* Make sure students wear eye protection (safety glasses or goggles) for this task. Make sure there is a cleared path for Slinky movement on the floor or table top to prevent accidental damage.

### PS4.B: ELECTROMAGNETIC (EM) RADIATION

- *Light from an object needs to enter the eye to be seen.*

**Possible tasks:** Glue a small object in a shoe box so that it is at the opposite end from the finger/eye hole that most shoe boxes have (if the shoe box doesn't have a hole, cut one into the box using a utility knife, being sure to keep the knife away from students). Hold the cover tightly on the box so that no light can enter it. Now peer at the object through the hole (see a description of this exercise in the By the End of Grade 2 section for PS4.B, p. 88). Have students describe what they see. Students should not be able to see the object because no light is reaching it, so no light can be scattered by it to their eyes. Now lift the cover of the box just a bit so that a crack of light can enter at the side near the object (or cut a flap in the shoe box near the object). Once again, peer through the hole. This time students should be able to see the object because light is reaching it and being scattered by it to their eyes. Have students construct a model that explains why they can see the object when the flap is open but not when the flap is closed. This model can be extended to explain why we can see through glass and why light reflects off a shiny surface such as that of a mirror. *Safety note:* Make sure students wear eye protection (safety glasses or goggles) for this task. Use caution when using a utility knife. Sharps can puncture or cut skin!

- *The color of an object depends on the color of the light illuminating it and the properties of the object.*

**Possible tasks:** Take a flashlight, a red apple, a green leaf, and two pieces of clear wrapping paper, one blue and one red. Go into a completely dark room. Place the apple and the leaf side by side. Illuminate them with the flashlight, holding the blue transparent paper between the flashlight and the objects so that both objects are illuminated with blue light. What do you see? What colors do the objects appear to be? Now replace the blue transparent paper with the red paper and repeat. What colors do the objects appear to be now? Have students make claims and support their claims with evidence. *Safety note:* Make sure students wear eye protection (safety glasses or goggles) for this task. Make sure there is a cleared path where students are moving in the dark to prevent injury.

- *Lenses bend light and can be used to magnify images of objects.*

**Possible tasks:** In a dark room, using a laser pointer, direct a beam of light at a table at an angle. Now place a lens between the laser pointer and the table so that the beam passes through it. Change the angle of the lens so that the laser reaches it at different inclinations. Have students describe their observations. The spot on the table illuminated by the beam should move around as you tilt the lens, showing that the lens is bending and redirecting the beam. Also, if the lens is thick enough, you should be able to see the beam going through the lens itself and changing directions as it enters and leaves the lens. *Safety note:* Caution students to never look directly at the laser light beam. Never intentionally direct a laser beam toward your eyes or the eyes of others. Direct eye contact can cause serious eye tissue damage! Do not point a laser pointer at a shiny or mirror-like surfaces such as polished metal or glass. The reflected beam can hit you or someone else in the eye. *Some states and school districts do not allow the use of a laser pointer for classroom activities. Check state regulations and school board policies before using a laser pointer.*

## PS4.C: INFORMATION TECHNOLOGIES AND INSTRUMENTATION

- *Information can be digitized and transmitted.*

**Possible tasks:** Show your students Morse code. Have them translate the sentence "Be my friend" into Morse, and then, using a flashlight, flash this message to other students. Have students invent other simple three-word sentences, encode them into Morse, and send them to others with a flashlight for decoding. This is an example of sending information digitally.

- *Technologies can be used to detect digitized signals.*

**Possible tasks:** Have students use their cell phones to make videos of their friends sending them Morse-based messages with a flashlight (as described in the former activity). Or, have students call each other on their cell phones, and then have them tap out a Morse-based message on their cell phones. Discuss how the video and wireless technologies in their cell phones have detected digitized signals.

## By the End of Grade 8

### PS4.A: WAVE PROPERTIES

- *A wave is defined by its amplitude, wavelength, frequency, and medium.*

**Possible tasks:** Repeat the first set of activities described above about wave properties for the end of grade 5 (p. 90) but use two or three different Slinkys, for example, a metal and a plastic one or two metal ones of different diameters. Have students make claims about the behavior of the Slinky and then support their claims. Different Slinkys can serve as different mediums, leading to different wave velocities. Have students measure the wavelength and the frequency of the waves generated at different frequencies, and from them calculate the wave velocity for each Slinky. They should be different but almost independent of the wave frequency. *Safety note:* Make sure students wear eye protection (safety glasses or goggles) for this task. Make sure there is a cleared path for Slinky movement on the floor or table top to prevent accidental damage.

- *Waves can be used to probe the Earth's structure.*

**Possible tasks:** Bring photos of an embryo made with an ultrasound imager and explain how the ultrasound imager uses high-frequency sound waves that are transmitted through the body and reflected at the surfaces of the different organs. The reflected waves are detected and then decoded to generate a picture of organs or an embryo. Likewise, seismic waves (sound waves traveling through the Earth) can be reflected from different parts and layers in the Earth and then detected by us at the surface. Decoding these waves allows us to learn about the structure of the Earth.

If you have a motion detector, you can use it to determine how far above the ground various objects are. A motion detector uses sonar waves and software to detect the distance of an object. You can use this feature to map the profile of a landscape you create in your classroom. Place boxes and other objects on the floor of the classroom and use the motion detector to trace the profile. Have students draw representations of the observations from the data of the motion detector. *Safety note:* Use caution when working around boxes on the floor. They are potential trip or fall hazards.

### PS4.B: ELECTROMAGNETIC (EM) RADIATION

- *When light shines on an object, it is reflected, absorbed, or transmitted through the object,* *depending on the object's material and the frequency (color) of the light.*

**Possible tasks:** Repeat the activities about wave properties and color for the end of grade 5 (pp. 90–92). Explain how the colored plastic wrap “colors” the white light from the flashlight by selectively allowing certain colors (wavelengths) to be transmitted and reflected while others are absorbed. Now explain how the apple and leaf selectively reflect certain colors of light and absorb others, and describe how this makes them appear different colors. Now take an object with a different color and have students explain why it has that color. Look though a prism at the edge of an object that is bright (preferably white) on one side and dark (preferably black) on the other side, such as a sheet of paper that is white on one half and black on the other half. Ask students to describe what they see. The visible spectrum should appear. Explain how all the different colors of light, although they reach the prism in the same direction from the edge of the border, leave the prism in different directions because they are diffracted differently by the prism, which allows us to distinguish among them. *Safety note:* Make sure students wear eye protection (safety glasses or goggles) for this task.

### PS4.C: INFORMATION TECHNOLOGIES AND INSTRUMENTATION

- *Technologies allow us to detect and interpret waves and signals in waves that cannot be detected directly.*

We are immersed in a sea of EM waves but are totally unaware of them. A cell phone can allow us to detect and interpret some of them, as can other appliances that have or act as antennas, such as ultraviolet beads or an ultraviolet intensity meter.

## By the End of Grade 12

As mentioned earlier, learning tasks that can be used to support these understandings are not described here because all the ideas that are appropriate for high school require the use of special equipment. The Acoustics and Vibration Animations website (*www.acs.psu.edu/drussell/demos.html*) from the University of Pennsylvania acoustics program contains a number of appropriate animations illustrating acoustics, vibration, waves, and oscillation phenomena. The PhET simulations (*phet.colorado.edu/en/simulations/category/physics/light-and-radiation*) from the University of Colorado also have a number of interactives to illustrate light phenomena. A number of commercial companies also sell light probes that will allow students to explore various wave properties.

### PS4.A: WAVE PROPERTIES

- *Waves of different frequencies can be combined to encode and transmit information.*
- *During resonance, waves in phase add up, growing in amplitude. Most objects have specific frequencies at which they resonate. This is the basis for the design of all musical instruments.*

### PS4.B: ELECTROMAGNETIC (EM) RADIATION

- *EM radiation can be described as either waves of EM fields or as particles called photons.*
- *We can only identify an object with waves that have a wavelength that is similar to that of the object's size because waves are not much*

*disturbed by objects that are small compared with their wavelengths.*

- *All EM waves travel through a vacuum at the speed of light. The speed of an EM wave in any medium depends on its wavelength and the properties of the medium.*
- *When EM radiation with a wavelength equal to or longer than that of visible light is absorbed by matter, its energy is generally converted into thermal energy within the matter. EM radiation with shorter wavelengths can ionize atoms and cause damage to living cells. Photovoltaic materials emit electrons when they absorb EM radiation of a high enough frequency.*
- *The atoms of each element and the nuclei of each isotope emit and absorb characteristic wavelengths of EM radiation.*

### PS4.C: INFORMATION TECHNOLOGIES AND INSTRUMENTATION

- *Many modern technologies are based on an understanding of waves and their interactions with matter.*
- *Knowledge of quantum physics has enabled the development of semiconductors, computer chips, and lasers, all of which are now essential components of modern imaging, communication, and information technologies.*

## Conclusion

It is important for all students to construct a deep understanding of waves because waves are central to almost all 21st-century technologies and many older technologies. Wave phenomena allow scientists to examine the very small world of atoms or explore galaxies that are very far away. Waves also allow us to communicate large amounts of information quickly and reliably over long distances. Waves are ubiquitous and play a role in many phenomena. Many of the central issues facing society today cannot be fully appreciated without an understanding of waves. For example, a cell phone company wants to place cell phone antennas at the end of the street near your home. Should you be concerned? Do these antennas pose a health hazard? One cannot understand many aspects of this issue without having a deep understanding of waves. Without this understanding, it is difficult to answer important questions such as these: How does the radiation from the antennae travel to my home? How does this radiation get through the walls in my home? How strong is this radiation when it reaches my family and me? What happens to my body when this radiation reaches it? A person cannot be scientifically literate in this century without a basic understanding of waves. Waves are a big idea of science.

## REFERENCES

American Association for the Advancement of Science (AAAS). 1993. *Benchmarks for science literacy.* New York: Oxford University Press.

Linder, C. J., and G. L. Erickson. 1989. A study of tertiary physics students' conceptualizations of sound. *International Journal of Science Education* 11 (5): 491–501.

National Research Council (NRC). 1996. *National science education standards.* Washington, DC: National Academies Press.

National Research Council (NRC). 2012. *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas.* Washington, DC: National Academies Press.

Scientific American. 2010. The laser at 50: Advancing science through beams of coherent light. *www.scientificamerican.com/report/50-years-of-the-laser*.

# INDEX

Page numbers in **boldface** type refer to tables or figures.

# INDEX

# INDEX

# INDEX

# INDEX

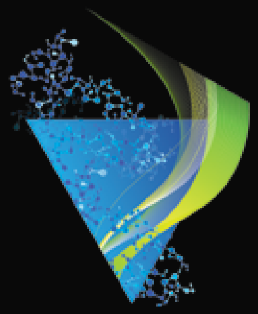
# INDEX

# DISCIPLINARY CORE IDEAS
## RESHAPING TEACHING AND LEARNING

Like all enthusiastic teachers, you want your students to see the connections between important science concepts so they can grasp how the world works now—and maybe even make it work better in the future. But how exactly do you help them learn and apply these core ideas?

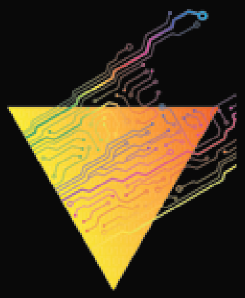
Just as its subtitle says, this book aims to reshape your approach to teaching and your students' way of learning. Building on the foundation provided by *A Framework for K–12 Science Education*, which informed the development of the *Next Generation Science Standards*, the book's four sections cover these broad areas:

**PHYSICAL SCIENCE CORE IDEAS** explain phenomena as diverse as why water freezes and how information can be sent around the world wirelessly.



**LIFE SCIENCE CORE IDEAS** explore phenomena such as why children look similar but not identical to their parents and how human behavior affects global ecosystems.

**EARTH AND SPACE SCIENCE CORE IDEAS** focus on complex interactions in the Earth system and examine phenomena as varied as the big bang and global climate change.



**ENGINEERING, TECHNOLOGY, AND APPLICATIONS OF SCIENCE CORE IDEAS** highlight engineering design and how it can contribute innovative solutions to society's problems.

*Disciplinary Core Ideas* can make your science lessons more coherent and memorable, regardless of what subject matter you cover and what grade you teach. Think of it as a conceptual tool kit you can use to help your students learn important and useful science now—and continue learning throughout their lives.

**Grades K–12**

NSTA press
National Science Teachers Association

PB402X
ISBN: 978-1-938946-41-7