Hard-to-Teach Biology Concepts: A Framework to Deepen Student Understanding
Hard-to-Teach Biology Concepts

A Framework to Deepen Student Understanding

By Susan Koba with Anne Tweed

Copyright © 2009 NSTA. All rights reserved. For more information, go to www.nsta.org/permissions.
Hard-to-teach biology concepts: a framework to deepen student understanding / by Susan Koba, with Anne Tweed.

Includes bibliographical references and index.

ISBN 978-1-933531-41-0

1. Biology—Study and teaching (Secondary) I. Tweed, Anne. II. Title.

QH315.K58 2009

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
You may photocopy, print, or email 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 only may reproduce a single NSTA book chapter for classroom or noncommercial, professional-development use only. For 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.

SciLinks—Up-to-the minute online content, classroom ideas, and other materials. For more information go to www.scilinks.org/faq/moreinformation.asp.
## Contents

### About the Authors

Introduction

- Science Education Reform and Conceptual Understanding
- Hard-to-Teach Biology Concepts—Why Are They Hard?
- Why Aren’t Students Learning?
- Organization of the Book

### Part I: The Toolbox: A Framework and Strategies

Chapter 1. The Instructional Planning Framework: Addressing Conceptual Change

- Why Are There Hard-to-Teach Biology Concepts?
- Introducing the Instructional Planning Framework
- The Research Behind the Framework
- Endnotes

Chapter 2. Instructional Approaches to Promote Student Understanding

- Overview
- Instructional Strategy Sequencing Tool
- Metacognitive Approach Tools
- Standards-Based Approach Tools
- Sense Making: Linguistic and Nonlinguistic Representational Tools
- A Note on Technology
- Some Thoughts on Assessment
- Instructional Tools 2.1–2.14
- Recommended Resources
- Endnotes

### Part II: Toolbox Implementation: The Framework and Strategies in Practice

Chapter 3. Reproduction: Meiosis and Variation

- Why This Topic?
- Overview
- Case Study: Setting the Stage
- Instructional Planning Framework: Predictive Phase
  - What Is the Conceptual Target?
  - What Is a Logical Learning Sequence?
- Instructional Planning Framework: Responsive Phase
  - What Criteria Should We Use to Determine Understanding?
- Tables 3.1–3.2
- Recommended Resources
- Endnotes

Copyright © 2009 NSTA. All rights reserved. For more information, go to www.nsta.org/permissions.
## Chapter 4. Flow of Energy and Matter: Photosynthesis

- **Why This Topic?**
- **Overview**
- **Instructional Planning Framework: Predictive Phase**
- **Instructional Planning Framework: Responsive Phase**
  - Identifying Preconceptions
  - Learning About Research-Identified Misconceptions
  - Identifying Our Students’ Preconceptions
  - Description of Assessment for Preconceptions
  - Eliciting and Confronting Preconceptions
  - Completing the *Responsive Phase*: Sense Making and Demonstrating Understanding
- **Tables 4.1–4.3**
- **Recommended Resources**
- **Endnotes**

## Chapter 5. Evolution: Natural Selection

- **Why This Topic?**
- **Overview**
- **Instructional Planning Framework: Predictive Phase**
- **Instructional Planning Framework: Responsive Phase**
  - Identifying Preconceptions
  - Eliciting and Confronting Preconceptions and Sense Making
- **Tables 5.1–5.3**
- **Recommended Resources**
- **Endnote**

## Chapter 6. Molecular Genetics: Proteins and Genes

- **Why This Topic?**
- **Overview**
- **Instructional Planning Framework: Predictive Phase**
- **Instructional Planning Framework: Responsive Phase**
  - Identifying, Eliciting, and Confronting Preconceptions
  - Sense Making: Strategies to Address Preconceptions
  - Demonstrating Understanding
  - Sense Making and Demonstrating Understanding for the Learning Targets
- **Table 6.1**
- **Recommended Resources**
- **Endnotes**
# Chapter 7. Interdependence: Environmental Systems and Human Impact

- Why This Topic? ........................................................................................................... 192
- Overview .................................................................................................................. 193
- Instructional Planning Framework: Predictive Phase ................................................. 193
  - What Are the Conceptual Targets? What Are the Essential Understandings? .......... 194
  - What Is a Logical Learning Sequence? ............................................................... 199
  - What Criteria Should We Use to Determine Understanding? ............................ 200
- Instructional Planning Framework: Responsive Phase .............................................. 201
  - Identifying Preconceptions .............................................................................. 202
  - Eliciting and Confronting Preconceptions, Sense Making, and Demonstrating Understanding.................................................. 206
  - Closing .............................................................................................................. 215
- Tables 7.1–7.3 .............................................................................................................. 217
- Recommended Resources .......................................................................................... 226
- Endnotes .................................................................................................................. 228

## References

229

## Appendix A1: Teacher Work Template (Blank)

244

## Appendix A2: Steps of the Planning Process

246


248

## Appendix B2: Concept Map for Evolution of Life: “Natural Selection”

249

## Appendix B3: Concept Map for Cells: “Cell Functions”

250

## Index

251
About the Authors

**Susan Koba**, a science education consultant, works primarily with the National Science Teachers Association (NSTA) on its professional development website, The NSTA Learning Center. She recently retired after 30 years in the Omaha Public Schools (OPS), having taught on the middle and high school levels for 20 years and then having served as a curriculum specialist and district mentor. Koba ended her service to OPS as project director and professional development coordinator for the OPS Urban Systemic Program, serving 60 schools.

Koba has been named Alice Buffett Outstanding Teacher, Outstanding Biology Teacher for Nebraska, Tandy Technology Scholar, and Access Excellence Fellow. She is also a recipient of a Christa McAuliffe Fellowship and of a Presidential Award for Excellence in Mathematics and Science Teaching. She received her BS in biology from Doane College, MA in biology from the University of Nebraska-Omaha, and PhD in science education from the University of Nebraska-Lincoln.

Koba has published and presented on many topics, including school and teacher change, equity in science, inquiry, and action research. She has developed curriculum at the local, state, and national levels and served as curriculum specialist for a U.S. Department of Education Technology Innovation Challenge Grant. A past director of coordination and supervision on the NSTA Board and a past president of her state NSTA chapter, she currently serves NSTA on the Nominations Committee. Other past NSTA work includes serving as the conference chairperson for the 2006 Area Conference in Omaha and on the Budget and Finance Committee. She also serves on the National Science Education Leadership Association (NSELA) Board of Directors as the Region E Director.

**Anne Tweed**, a principal consultant with Mid-continent Research for Education and Learning (McREL) in Aurora, Colorado, also serves as the associate director of the North Central Comprehensive Center in St. Paul, Minnesota. Her work at McREL supports professional development in the areas of formative assessment, high-quality instructional practices, teaching reading in content areas, effective science instruction, analyzing instructional materials, and audits of science curricula and programs.

Tweed is a past president of the National Science Teachers Association (NSTA) (2004–2005). A veteran high school science educator and department coordinator, she spent the majority of her 30-year teaching career with the Cherry Creek School District.
About the Authors

in Colorado. She earned a BA in biology from Colorado College, an MS in botany from the University of Minnesota, and a teaching certificate from the University of Colorado.

Tweed has held several leadership positions with NSTA and with the Colorado Association of Science Teachers and the Colorado Alliance for Science. She also was on the review committee for the National Science Education Standards and was a contributor to the Colorado Model Content Standards for Science. In addition, she served on the program-planning team that revised the 2009 NAEP Framework for Science. She has received the Distinguished High School Science Teaching Award from NSTA and the Outstanding Biology Teacher Award for Colorado and is a state Presidential Award for Excellence in Mathematics and Science Teaching honoree.

* * * * * * *

Contributors

Kelly Gatewood, PhD, assistant professor of graduate studies, Peru State College, Peru, Nebraska.

Frank Tworek, PhD, science teacher, King Science and Technology Magnet Center, Omaha, Nebraska.

Introduction

“Biology has become the most active, the most relevant, and the most personal science, one characterized by extraordinary rigor and predictive power.”
—John A. Moore, 1993

“A pessimist sees the difficulty in every opportunity; an optimist sees the opportunity in every difficulty.”
—Winston Churchill (1874–1965)

Biology is a science in which the curriculum continuously changes. New knowledge and emerging content have an enormous impact on our lives. With each new discovery, biologists develop new questions, which lead to more new knowledge. As biology teachers, we constantly learn new content and develop not only our own understanding of biological concepts but also ways to best teach that content to our students.

This book does not contain a recipe to follow as you plan and deliver lessons. Nor is it a set of predesigned lessons for use in biology classrooms. Instead, it features both an instructional framework you can use as you plan—our Instructional Planning Framework (for a visual representation of the framework, see Figure 1.1, p. 6)—and sets of strategies and resources you can select from to help your students learn. We believe that the framework can be used by both new and veteran teachers alike to develop students’ conceptual understanding of five hard-to-teach biology topics: reproduction, photosynthesis, natural selection, molecular genetics, and interdependence of living things. We do not expect you to completely change what you do already. By using the examples provided in the content chapters (Chapters 3–7) as a guide and tackling one piece at a time, you can make adjustments to your planning and teaching that, we believe, will result in improved conceptual understanding for your students.

We begin by looking at what is known biologically. From there we must determine what and how we should teach to develop our students’ biological literacy (essential biology concepts) and appreciation of the living world. Obviously we all want students to understand ideas such as genetic engineering, stem cell research, and evolutionary biology. But before students can learn about genetic engineering, they have to understand how DNA (deoxyribonucleic acid) and RNA (ribonucleic acid) work and how they provide the genetic information in all living things. To understand stem cells, students have to understand the process of cell division and differentiation. Making sure that students understand the fundamentals of biology is not a simple process and therein lays the dilemma we all face.
Learning biology is clearly a struggle for many of our students, as evidenced by biology achievement scores across the country. In other words, if you have trouble teaching your students the basic principles of biology, you’re not alone! What might be the reasons for these difficulties? With the advent of state standards and high-stakes assessments, biology teachers are finding it difficult to teach in ways that worked for them in the past. A common complaint of both students and teachers is that there is so much content to cover that there is not enough time to do the experiments and inquiry activities that engage students with the ideas. Biology teachers know that laboratory experiences help students learn complex concepts (Singer, Hilton, and Schweinbruger 2007), yet we get caught up in the attempt to cover so many topics and lists of vocabulary that, on average, students are only provided one laboratory experience each week. In the classroom, we often focus on the names and labels for living organisms or steps in processes, and our students get lost in details without learning the important, essential biological principles.

With this book, the authors seek to help all biology teachers to teach the five hard-to-teach biology concepts listed on the previous page. Although this book is not about providing teachers with scripted lessons, it does include much that we have learned from our own experiences and from recent research findings. Science research that focuses on how students learn recommends certain strategies that teachers can use to help develop and implement effective instructional methods. In this book, we do not tackle all the issues in high school biology. Rather we focus on selected research that informs our Instructional Planning Framework.

We realize that teachers’ implementation of selected instructional strategies impacts the effectiveness of a strategy in the classroom. Even with research-based strategies and tools, we need to figure out ways to use them in the best way possible. For example, we know that classroom discourse (discussion) helps students think about their ideas and supports sense making. But if we just ask students to discuss a question or problem without setting a time limit, establishing the groups they will work with, and determining how they will report-out to the class, then classroom discourse won’t help students make sense of the hard-to-teach biology concepts.

We love teaching biology, and we want to provide opportunities for you to meet the challenges posed when teaching hard-to-teach biology concepts. We were prompted to write this book because guidance for teachers is located in so many different places; our hope was to put all of the findings together into a model that made sense to us and would support your work. This book presents a framework for planning, shares appropriate approaches to develop student understanding, and provides opportunities to reflect on and apply those approaches to specific, hard-to-teach concepts and topics. It is more about helping you learn how to improve your practice than it is about providing sample lessons that recommend a “best” way to provide instruction. Clearly, you must decide what works best for you.
Science Education Reform and Conceptual Understanding

At that same time that our students struggle to master biology concepts, many states require students to pass high-stakes tests in order to graduate. Science reform efforts stress science understanding by all citizens; unfortunately, little impact is made on persistent achievement gaps (Chubb and Loveless 2002). However, the current cycle of science education reform that resulted in the Benchmarks for Science Literacy (AAAS 1993) and the National Science Education Standards (NRC 1996) expects, among other things, (1) meaningful science learning for all students at all grade levels, (2) that students are able to discriminate among science ideas, and (3) that they are able to build connections among ideas, moving past recall and into more sophisticated understandings of science. To meet the standards, it is critical that all of us work to implement strategies shown as effective to build these types of student understandings.

We know that serious change takes time, often seven to ten years to move from establishing goals to changing teacher practice and curriculum materials that meet the needs of our students (Bybee 1997). One major obstacle to change is the lack of support for teachers to fully understand ways to teach hard-to-teach concepts (Flick 1997). School structures in the United States do not adequately provide professional support for us to engage in new learning to improve our teaching. We are rarely provided the time to work individually or collaboratively to inquire into our own teaching and our students’ learning (Fisher, Wandersee, and Moody 2000). So what makes current reform efforts any different from those in the past? Perhaps the standards, political influences, and the growing body of research provide an answer.

Hope for change begins with the standards because we now at least have common targets for both teaching and learning. We know the content learning goals for our students (Bybee 1997). One major obstacle to change is the lack of support for teachers to fully understand ways to teach hard-to-teach concepts (Flick 1997). School structures in the United States do not adequately provide professional support for us to engage in new learning to improve our teaching. We are rarely provided the time to work individually or collaboratively to inquire into our own teaching and our students’ learning (Fisher, Wandersee, and Moody 2000). So what makes current reform efforts any different from those in the past? Perhaps the standards, political influences, and the growing body of research provide an answer.

The next ray of hope is that the political focus on science education has grown dramatically over the past few years, as evidenced by the 2007 report by the National Academy of Sciences (NAS), Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future (NAS 2007). The federal government’s growing focus on the needs in mathematics and science has resulted in increased funding for science education efforts in support of science, technology, engineering and mathematics (STEM) education.

What should directly impact us, as educators, is a growing body of research on teaching and learning in general (Bransford, Brown, and Cocking 1999) and science teaching and learning in particular (NRC 2005). Also, we now have access to a considerable body of research on the understandings and skills required for meaningful learning in biology (Fisher, Wandersee, and Moody 2000; Hershey 2004), inquiry (Anderson 2007), and the nature of science (Lederman 2007). Finally, there is an increasing
understanding of conceptual change (Driver 1983; Hewson 1992; Lemke 1990; Mortimer 1995; Scott, Asoko, and Driver 1992, Strike and Posner 1992), as well as research on common misconceptions and strategies to address them (Committee on Undergraduate Science Education 1997; Driver et. al. 1994, Mortimer and Scott 2003; NAS 1997; Tanner and Allen 2005).

But hope, by itself, is not a method. Because biology is the most common entry course for science in secondary schools, it is essential that changes in science teaching and learning begin with us, the biology teachers. It is the goal of this book to support your walk down the path to more effective teaching and learning in biology.

Hard-to-Teach Biology Concepts—Why Are They Hard?

Traditionally students struggle to learn some of the basic ideas taught in high school biology classes. To understand why, we must analyze not only the content itself but also the classroom conditions and learning environment. One concern cited by biology teachers is the “overstuffed” biology curriculum. Because of the sheer amount of information that is taught related to each topic, even good students find it difficult to retain what they learn (NRC 2001b). Because of an emphasis on a fact-based biology curriculum, instruction often relies on direct instruction to cover all of the material. As a result, students have limited experiences with the ideas and rarely retain what they learned past the quiz or unit test.

Certain biology topics are hard for students to learn because students aren’t given the time they need to think and process learning. We must give students multiple opportunities to engage with ideas. Research suggests that students need at least four to six experiences in different contexts with a concept before they can integrate the concept and make sense of what they are learning (Marzano, Pickering, and Pollock 2001).

Another reason that some biology topics are hard to teach (and learn) relates to the prior knowledge of our students. High school students are far from being blank slates; they come to us with their own ideas and explanations about biology principles. After all, everyone knows something about biology and our students have had a variety of experiences both as they have grown up outside school and in previous science classrooms. Student preconceptions can be incomplete and students often hold onto them tenaciously. One classic research study was captured in the video A Private Universe: Minds of Our Own (Harvard-Smithsonian Center for Astrophysics 1995). In one segment, researchers asked Harvard graduates where the mass of a log came from. The response was water and nutrients from the soil. Students and even college graduates hadn’t learned the fundamental concept that photosynthesis requires carbon dioxide from the air to manufacture carbohydrates, which are the basis for the vast majority of a tree’s mass.

This example relates to two additional reasons why some biology topics are hard to teach. One, many biology lessons are highly conceptual and students can’t visualize what is taking place on a microscopic level. And two, some biology teachers are not aware of strategies that engage students with a scientific way of knowing (Banilower
et al. 2008; Lederman 2007). Such strategies include asking questions, inferring from data, challenging each other’s ideas, communicating inquiry results, and synthesizing student explanations with scientific explanations.

When we consider these various impeding factors, it is no wonder that students struggle in our biology classes.

Why Aren’t Students Learning?

Science research helps us answer the question about why students aren’t learning.

- Students may not learn because of their learning environments. The meta-analyses of the research in *How People Learn: Brain, Mind, Experience, and School* (Bransford, Brown, and Cocking 1999) and *How Students Learn: Science in the Classroom* (NRC 2005) report that the instructional environment must be learner-, not teacher-, centered. Students come to school with conceptions of biological phenomena from their everyday experiences and teachers need to take into account such preconceptions. Furthermore, what we teach is often too hard for students because they lack the necessary backgrounds on which the hard-to-teach topics are based.

- Several studies have shown that high school students perceive science knowledge as either right or wrong (NRC 2005). Unfortunately, biology concepts are rarely this clear-cut and the body of knowledge in biology is ever changing. Biological systems are dynamic, and long-term observations are often needed to understand and make sense of the evidence. The norm in many classrooms, however, is to come up with a correct answer, which is not reasonable or possible in biology classrooms, where we look at probabilities, changes over time, and trends. Quantitative and qualitative data can be ambiguous. This can be very uncomfortable for students who ask us, Why don’t you just tell me the answer? While biologists, like other scientists, give priority to evidence to justify explanations, students think that we should have THE answer to biology questions and problems. Students may believe that biology is really a collection of facts because we often use direct instruction to cover the biology facts and vocabulary that may be addressed in state assessments.

- Students learn best when they are able to work collaboratively with other students. With only one investigation per week in the average biology classroom, students may not receive sufficient opportunities to engage in interactive work.

Organization of the Book

*Hard-to-Teach Biology Concepts: A Framework to Deepen Student Understanding* is designed to support biology teachers as they plan and implement lessons that will intellectu-
ally engage students with the biology concepts that most students find challenging. To develop successful learners, teachers must identify prior student conceptions and research-identified misconceptions related to the concept being taught and then select instructional approaches to dispel those misconceptions and promote students’ conceptual understanding.

The book is made up of two parts: Part I, The Toolbox: A Framework and Strategies (Chapters 1 and 2), and Part II, Toolbox Implementation: The Framework and Strategies in Practice (Chapters 3–7).* In Part I, we share a research-based framework to address conceptual change—the Instructional Planning Framework—as well as specific instructional approaches shown to dispel preconceptions. Chapter 1 outlines the Instructional Planning Framework and gives an overview of (1) the identification of conceptual targets and preconceptions, (2) the importance of confronting preconceptions, (3) sense-making strategies to address preconceptions, and (4) best ways in which students can demonstrate understanding. Chapter 2 discusses specific instructional approaches that teachers might use to dispel preconceptions: metacognitive approaches, standards-based approaches, and specific strategies for sense making. Though the framework can be followed in a linear manner, it is not really intended as a stepwise process. Instead, it is important for you to reflect on the framework presented in Chapter 1, adapting it for your use and selecting strategies from Chapter 2 most appropriate for your own classroom.

Part II is organized to model use of this framework through its application in the analysis of five hard-to-teach topics. The topics were carefully chosen to reflect the grade-level-appropriate content common to both the National Science Education Standards (NSES) and the Benchmarks for Science Literacy (NRC 1996; AAAS 1993). Each topic, in its own chapter, is used to model a specific aspect of the framework. Each chapter also provides opportunities for personal reflection. Recommended resources, including technology applications and websites, will be found at the end of each chapter in Part II.

Chapter 3 focuses on meiosis and variation, specifically looking at the first aspect of the framework: conceptual targets, the learning sequence, and criteria for understanding. Chapter 4 looks carefully at ways to identify and confront preconceptions, using the hard-to-teach concepts associated with photosynthesis. Chapter 5 focuses on evolution (specifically, natural selection), and looks carefully at specific sense-making approaches to address research-identified misconceptions. Chapter 6 addresses molecular genetics (specifically, the relationship of genes and proteins) and considers both sense-making strategies and ways to demonstrate understanding. Finally, in Chapter 7, the topic of interdependence of organisms is modeled with a review of the entire framework. The appendices enhance our understanding of the framework and its application.

* The Instructional Tools in Chapter 2 and all tables in Chapters 3–7 are located at the end of each chapter.
Chapter 4

Flow of Energy and Matter: Photosynthesis
“It doesn’t seem intuitive that you could add mass by taking in a gas.”
—Student speaking in the video A Private Universe, Minds of Our Own, 1995

Why This Topic?
Photosynthesis is one of the most difficult topics to teach, partly because it is such a broad and conceptually complex topic. The cycling of matter and flow of energy occur at many levels of biological organization—molecules, cells, organs, organisms, and ecosystems—and crosses many disciplines (AAAS 1993; Russell, Netherwood, and Robinson 2004). It is hard for students to visualize the process because it is abstract and microscopic and plants grow so slowly that learners don’t see immediate results (Russell, Netherwood, and Robinson 2004).

It is especially tricky because photosynthesis is often presented purely as a molecular process (Russell, Netherwood, and Robinson 2004) even though many biology students have a limited understanding of chemistry, specifically of matter and the atomic-molecular levels of interactions (Duschl, Schweingruber, and Shouse 2007; Ross, Tronson, and Ritchie 2006). Furthermore, students are often given only words and descriptions of processes for topics such as photosynthesis. As a result, students tend to develop shallow understandings of the processes and hold on to the preconceptions they brought with them to the class. Many of these preconceptions cross grade levels and even persist in adults who, like our students, find it hard to believe that much of the mass of plants comes from the air around them (Duschl, Schweingruber, and Shouse 2007). What can teachers do to make this concept more accessible? In our experience, the answer is to contextualize the process in the plant, helping students to visualize photosynthesis and providing the framework to add molecular details (Russell, Netherwood, and Robinson 2004). We elaborate on this process later in the chapter.

In the meantime, we ask you to consider a segment from the well-known video A Private Universe: Minds of Our Own (Harvard-Smithsonian Center for Astrophysics 1995). The video begins with interviews of Harvard and MIT graduates. The graduates are shown a seed and a log and are asked to imagine the seed planted in the ground and growing into a tree. They are then asked where they think all the “stuff” that makes up the tree came from. Responses include

- water and minerals in the soil;
- water, light, and soil; and
- minerals in the soil itself—the water and nutrients it absorbs.

Notice that none of the responses refer to carbon dioxide.
The graduates are further asked what they would say if someone told them that most of the weight came from carbon dioxide in the air. In each case they are disbelieving. One graduate says that she would disagree because the same volume of air could not weigh as much unless it were highly compressed. Another states that she would be very confused and wonders how that could happen. A third says it would be hard for him to believe since carbon dioxide is a gas, and it doesn’t seem intuitive to him that mass could be increased by taking in a gas. These graduates, who are among those often considered our best and brightest, have the same basic misconception found among students across grade levels: that a gas cannot possibly provide the mass of a grown plant.

The remainder of the video explores student thinking related to this topic in elementary, middle, and high school classes and considers the type of instruction that leads to common misconceptions about plant growth. We encourage you to watch the video if you haven’t already done so and consider implications for your own teaching.\(^1\)

**Overview**

In this chapter, we explore the misconception that carbon from carbon dioxide is the source of a plant’s mass. We also look at other common, research-identified misconceptions that make it difficult for students to understand photosynthesis and to connect the photosynthetic processes in a plant cell to the plant and its surroundings. We will discuss photosynthesis in the context of the various levels of biological organization, although we won’t address applications to the ecosystem. Of course, we understand the importance of photosynthesis in the food chain and more broadly its relation to topics such as global climate change, but our emphasis is on general cellular processes, actual plants as a contexts for learning, and gas exchange with the surroundings (refer to the left side of Figure 4.1 on p. 122).

We focus on photosynthesis as a mechanism for harnessing energy and generating organic carbon from atmospheric carbon. We also briefly discuss what happens to that carbon in the plant once photosynthesis is complete and we discuss gas exchange in plants during respiration. We will not address food chains or animal respirations.\(^2\)

(\textit{Note:} All tables are grouped together at the end of the chapter, beginning on p. 133. They are followed by Recommended Resources and Endnotes.)

We consider photosynthesis the foundation on which students can build their understandings about flow of energy and cycling of matter in the ecosystem, as well as the interdependence of life, further explored in Chapter 7.
Figure 4.1

Carbon Cycling in Environmental Systems

Atmosphere (Physical System)
Atmospheric carbon dioxide

Photosynthesis
Generating organic carbon and harnessing energy

Respiration and Combustion
Oxidizing carbon and dissipating energy

Movement of organic carbon and passing on energy

Biosphere (Biological System)
(Food chains, growth and weight loss, and carbon sequestration)


Instructional Planning Framework: Predictive Phase

Because the predictive phase of the Instructional Planning Framework was thoroughly covered in Chapter 3, we limit our coverage in this chapter to a brief review of this phase and show its application to a lesson on photosynthesis. First, however, we include here expectations for adult science literacy to remind you of our end target, or anchor, for learning about photosynthesis (Figure 4.2, p. 123).
**Chapter 4: Flow of Energy and Matter: Photosynthesis**

**Figure 4.2**

*Adult Science Literacy Expectations Regarding Photosynthesis*

“However complex the workings of living organisms, they share with all other natural systems the same physical principles of the conservation and transformation of matter and energy. Over long spans of time, matter and energy are transformed among living things, and between them and the physical environment. In these grand-scale cycles, the total amount of matter and energy remains constant, even though their form and location undergo continual change.

“Almost all life on earth is ultimately maintained by transformations of energy from the sun. Plants capture the sun’s energy and use it to synthesize complex, energy-rich molecules (chiefly sugars) from molecules of carbon dioxide and water. These synthesized molecules then serve, directly or indirectly, as the source of energy for the plants themselves and ultimately for all animals and decomposer organisms (such as bacteria and fungi).” (AAAS 1989, p. 66)

We did our initial planning for the *predictive phase* based on the adult-science-learning expectations in Figure 4.2. We used the process outlined in Chapter 3 to determine the conceptual target, the learning sequence required to help students understand photosynthesis, and the criteria that would be used to demonstrate student understanding. Figure 4.3 shows a summary of this process.

**Figure 4.3**

*Planning in the Predictive Phase*

1. Identify the essential understandings for the lesson.
   a. Begin with the descriptions of adult science literacy to determine an anchor goal.
   b. Consider the middle school and high school standards and benchmarks.
   c. Optional: Study existing research on learning progressions. A good resource (www.project2061.org/publications/2061Connections/2007/2007-04a-resources.htm) is found in the 2061 Connections online newsletter (AAAS 2007a).
   d. Dig a bit deeper and think about the concepts included in the standards.
   e. Decide what is essential and what can be pruned.

2. Develop a logical sequence of learning targets for the lesson.
   a. Consider first the middle school experiences students should have had.
   b. Outline the key ideas embedded in the high school standards and benchmarks.
   c. Sequence the key ideas in a way to build student understanding.
   d. Consider connections from one lesson to the next.

3. Identify the criteria for demonstrating understanding. (Note: Steps b and c are completed later, after a review of research).
   a. Identify one criterion for each Learning Target.
   b. Identify one criterion for your selected standards-based strategy (Inquiry, HOS, or NOS).
   c. Identify one criterion for your selected metacognitive strategy.
The result of our planning was the beginning of a Teacher Work Template for this topic, completing the *predictive phase*. Carefully study the completed work shown in Table 4.1 (p. 133). Following the steps outlined in Figure 4.3, we completed the template with the national standards that would be addressed, previous conceptual learning from middle school, prior instruction in the biology course itself, and the essential understandings, knowledge, and skills that are the targets of this lesson. In addition, we developed our learning sequence targets, each of which is included in the Teacher Work Template on page 134 and in Figure 4.4.

### Reflection and Application

This is our second look at the process used (Figure 4.3) to complete the *predictive phase*. The first was Chapter 3. Take a moment to reflect on the application of the *predictive phase* to the topic of photosynthesis:

1. How have you taught this topic in the past?
2. In what ways does your past instruction align with the work in the *predictive phase* for this topic? In what ways is it different?
3. Are there changes you might make in your instruction based on your answers to questions #1 and #2?

#### Figure 4.4

**Photosynthesis Learning Sequence**

<table>
<thead>
<tr>
<th>Target #1: The vast majority of plants are able to convert inorganic carbon in CO₂ into organic carbon through photosynthesis. Carbon dioxide and water are used in the process to create biomass. The surrounding environment is the source of raw materials for photosynthesis.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target #2:</strong> Photosynthesis captures the energy of sunlight that is used to create chemical bonds in the creation of carbohydrates. Chloroplasts in the cells of plant leaves contain compounds able to capture light energy. Photosynthesis utilizes CO₂ and the hydrogen from water to form carbohydrates, releasing oxygen.</td>
</tr>
<tr>
<td><strong>Target #3:</strong> Carbohydrates produced during photosynthesis in leaves can be used immediately for energy in the plant, stored for future use, or converted to other macromolecules that help the plant grow and function.</td>
</tr>
<tr>
<td><strong>Target #4:</strong> A variety of gases move into and out of plant leaves. Leaves use CO₂ and release O₂ during photosynthesis. When they respire, leaves use O₂ and release CO₂. Other gases enter the leaf as well, but are excreted.</td>
</tr>
</tbody>
</table>

**Essential Understandings:** Plants have the ability to capture the energy of sunlight and use it to combine low-energy molecules (carbon dioxide and water) to form higher energy molecules (glucose and starches). This is called *photosynthesis*. They can use the glucose immediately as a source of energy, convert it into other molecules that help their cells function, or store it for later use. Regardless, the total amount of matter and energy in the system stays the same.
**Instructional Planning Framework: Responsive Phase**

You are now ready to consider the *responsive phase* of the Instructional Planning Framework and determine how to help your students reach each target in the learning sequence shown in Table 4.1 on page 134. Remember that the *responsive phase* is not a linear process but rather iterative in nature. Teachers need to use ongoing formative assessment processes to determine what their students do or don’t understand and address these gaps with instruction (Hipkins et al. 2002). Though teachers can flesh out an initial instructional plan, conducting formative assessments along the way might require that they modify instruction. Regardless, the work for the *responsive phase* must be completed, and it is to that work that we turn our attention.

**Identifying Preconceptions**

The primary purpose of this chapter is to model the first portions of the Instructional Planning Framework’s *responsive phase*: identifying, eliciting, and confronting preconceptions and becoming aware of research-identified misconceptions (Figure 4.5, p. 126).

Why do teachers need to be concerned about their students’ preinstructional ideas or about typical misconceptions that have been identified in the research? The answer is that learning occurs when students make connections and construct patterns, and doing so depends on their prior knowledge (Lowery 1990). This means that teachers must gear their lessons to the developmental level of their students and provide multiple pathways to understanding (Weiss et al. 2003). They must provide opportunities for their students to express and confront their own preconceptions and those of their classmates if the students are to develop conceptual understanding.

**Learning About Research-Identified Misconceptions**

You can learn a lot by conducting your own review of your students’ misconceptions about photosynthesis. It can be time consuming, but if you are, for instance, involved in a study group with other biology teachers and want to improve instruction for a specific standard, research on misconceptions and effective strategies to address those misconceptions might be a rich area of study for your group. Or if there is a content area in which you are not as strong as in others, this type of review can help you dig deeper into the content. If you decide that this is something you want to do for another topic, consider the steps and resources shown in Figure 4.6 on page 126. These steps are sequenced, based on how easy it may be for you to obtain the resources. They are also sequenced by simplicity of use.
We understand that many of you do not have time to conduct this type of research review, so we completed a literature review that resulted in an extensive list of misconceptions about photosynthesis in particular and carbon cycling in general. We then sorted the misconceptions by the Learning Targets established in the predictive phase. Finally, we added these misconceptions to the responsive phase portion of the Teacher Work Template for photosynthesis (Table 4.2, p. 135).
**Figure 4.6**

**Steps for a Misconception Literature Review**


2. Complete a web search for misconceptions on the selected topic. Simply run a search for your topic and misconceptions (e.g., “photosynthesis + misconceptions”). If you run your search at Google Scholar (http://scholar.google.com), you will gain access to numerous resources. In some cases you will only access an abstract, but in others you will find entire documents. This process is more time-consuming than step #1 but yields additional resources.

3. An excellent source for a summary of students’ misconceptions is *Making Sense of Secondary Science: Research into Children’s Ideas* (Driver et al. 1994). The book is outlined by science topic and provides a rich summary of research on children’s ideas about these topics.

**Reflection and Application**

Take a moment to reflect on misconceptions on photosynthesis that we found in the research (Table 4.2). Consider also the process that we used (“Identifying Student Perceptions” in the table). Then answer the following questions:

1. The authors of this book identified photosynthesis as a hard-to-teach topic. If you agree, what do you think makes it hard to teach?

2. If you conducted your own review of the research, what aspects of the review were most helpful to you? Why were they helpful?

3. How might the research review conducted by the authors help you in your instruction? What might you do differently in your current lesson on photosynthesis, based on the research we summarized?

**Identifying Our Students’ Preconceptions**

Misconceptions that have been identified by researchers can vary by age, sex, geography, and student motivation or interest (Westcott and Cunningham 2005). There is extensive research on how to elicit students’ prior ideas in science and how, by taking students’ ideas into account, to develop teaching strategies that move them toward science ideas. (The Instructional Tools in Chapter 2 include many of these strategies for use in planning.)

In the ideal situation, teachers would identify their students’ preconceptions just prior to planning a unit or lesson. However, the reality of day-to-day teaching requires that teachers plan well ahead of the actual instructional time. We recommend that teach-
ers start planning for each learning target with the research-identified misconceptions; teachers should also determine their own students’ preconceptions. To do this, we used the process outlined in Figure 4.7, and we suggest that you complete the steps yourself.

Study the Instructional Strategy Sequencing Tool (2.1). It provides an extensive list of strategies that teachers can use to uncover their students’ preconceptions. We selected annotated drawings, concept cartoons, concept mapping, informational text strategies, and questioning. Study that list. Can you see how we determined the strategies on the list?

**Figure 4.7**

*Strategy Selection: Identifying, Eliciting, and Confronting Student Preconceptions*

1. Use the Instructional Strategy Sequencing Tools in Chapter 2 (starting on p. 29) to identify possible strategies that work to identify, elicit, and confront student preconceptions.
2. Review the strategies in the Instructional Tools. See the Metacognitive Strategy Tools (Instructional Tools 2.2–2.4, starting on p. 33), the three Standards-Based Strategy Tools (Instructional Tools 2.5–2.7, starting on p. 43, and the seven Sense-Making Strategy Tools (Instructional Tools 2.8–2.14, starting on p. 55).
3. Carefully review the research and application recommendations for each of the strategies.
4. Determine several strategies that fit well with the particular content you are teaching.
5. Review the resources in each Instructional Tool to more fully understand the strategies and to determine what they might look like in application.
6. Select one metacognitive strategy, one standards-based strategy, and two or three sense-making strategies for use in your lesson. (Recall that these strategies will be used to differentiate instruction and to provide further instruction if formative assessments indicate that some or all students do not demonstrate understanding of the learning targets.)
7. Determine one criterion to demonstrate understanding for each metacognitive and standards-based focus.

As we continue our planning, we reviewed the various Instructional Strategy Tools (Steps #2–4 in Figure 4.7). That helped us to narrow the list of possible strategies; some have been shown to be particularly effective for developing student understandings of abstract topics such as photosynthesis (e.g., annotated drawings, concept cartoons, and concept maps). To narrow our choices further, we covered steps #5 and #6 in Figure 4.7. We then examined the strengths of each sense-making approach (Table 4.3, p. 140).

How did we determine which of the three strategies in Table 4.3 would best suit our needs? First, all three strategies have been shown to be effective for eliciting preconceptions and promoting conceptual change, especially of abstract concepts such as photosynthesis. Second, each strategy engages students in the learning process, motivates them to deal with the concepts, and requires them to grapple with their ideas, thus serving a metacognitive function.
Annotated drawings and concept cartoons might have some advantage over concept mapping, especially in diverse classrooms. Annotated drawings tend to involve more students in the learning process because (1) students who might not express themselves in words are given a different option for expression, and (2) students are free to choose what they draw and to draw from their own experiences. Concept cartoons have several advantages: (1) they create an environment that promotes participation in class discussion and lessens students’ anxiety over the wrong answer, (2) they present cognitive conflict that requires students to consider explanations for the situations in the cartoons, confronting both their own and their peers’ preconceptions, and (3) they lead naturally to decisions about possible investigations (and photosynthesis is an ideal topic for student-designed investigations).

The third strategy—concept mapping—is effective in support of conceptual change and requires students to show relationships among concepts. Annotated drawings and concept cartoons, however, are more effective at eliciting student preconceptions. Furthermore, regarding photosynthesis, annotated drawings help contextualize photosynthesis in the plant, which is important if you want students to be able to visualize the process—thus making it more accessible (Russell, Netherwood, and Robinson 2004).

The strategies fit our lesson and should provide a good entry into this content. We then add these strategies to our Teacher Work Template (see Table 4.2, “Identifying Student Preconceptions”) as our means of determining our students’ general preconceptions about photosynthesis. We began our lesson with one of these activities to specifically elicit and confront misconceptions about Learning Target #1 (Table 4.2).

We next consider the metacognitive and standards-based strategies that best align with this content and the selected sense-making strategies. Remember, we decided to use annotated drawing and concept cartoons to contextualize photosynthesis in the plant. We required that students make a claim, and we prepared them for investigations. We chose to focus on openness to other students’ ideas as students gathered evidence to support claims. We also focused on having students contrast their personal claims with those of historical theories, helping them better understand both the history and nature of science. We then developed criteria for each of these areas of focus and added them to the work template (see “Criteria to Demonstrate Understanding,” Table 4.1).

**Description of Assessment for Preconceptions**

What do these three strategies look like in practice? Let’s start with students’ general understandings about photosynthesis and use some of the strategies we just discussed to determine their preconceptions. Our plan begins with use of annotated drawings and is outlined below.

- Show a time-lapsed video of a seed growing into a plant to provide the context for the preassessment activities. A variety of videos are available online (see Technology Applications and Websites at the end of this chapter, p. 141).
• Ask each student to prepare an annotated drawing in response to the probe, “How did the seed change into a seedling and finally into a ____?” Write an appropriate probe depending on the video you choose. Also ask students to write paragraphs that describe what is happening in their drawings. Circulate around the room, asking open-ended, probing questions of students to further determine their individual understandings. (Note: You can conduct this activity at the close of a class period, collect all student responses, and use them to modify your lesson prior to the next day’s instruction.)

• Ask students to share their drawings in small groups, discuss their drawings, and make a composite drawing on poster paper that reflects the group’s thinking. Again, you should circulate around the room asking probing questions of each group. The resulting posters can be posted, reflected on, and modified during the course of the lesson. You can use this information to inform further lesson development.

• Facilitate a full-class discussion about the posters and generate a list of student questions about the depicted processes. Point out common ideas and areas of disagreement. Let students know that these ideas will be explored during the lesson.

This activity engages students through various learning modes: drawing, writing, small-group and whole-class discussion, and personal and collaborative reflection. It also requires students to stay open to others’ ideas as they generate claims.

Reflection and Application
Let’s take another moment to reflect. Consider the process used and the tools developed to identify your own students’ preconceptions. Ask yourself the following questions:

1. What aspects of this research-review process were most helpful to you in your instruction? Why were they helpful? What was most difficult and why?
2. Does this modify your thinking about beginning a lesson? If so, how?
3. Consider your current lesson on photosynthesis. How might you modify it based on the tools and resources provided?

Eliciting and Confronting Preconceptions
Let’s revisit the Learning Target #1 in our learning sequence (Table 4.2) before moving forward with the lesson. The Learning Target reads as follows: “The vast majority of plants are able to convert inorganic carbon in CO₂ into organic carbon through photosynthesis. Carbon dioxide and water are used in the process to create biomass. The surrounding environment is the source of raw materials for photosynthesis.”
We continue to determine our students’ preconceptions, with the specific purpose of eliciting and confronting preconceptions they have about this Learning Target. Notice that each of the research-identified misconceptions in Table 4.2 revolves around the source of biomass in the plant or what causes the plant to grow. Students attribute mass in the growing plant to almost anything but the carbon in carbon dioxide. We use a concept cartoon because it provides the students with alternative conceptions that include the scientific explanation as well as research-identified misconceptions and sets the stage for student dialogue and determination of possible areas of investigation. The intent is to display the concept cartoon (Figure 4.8) and ask each student which response he or she most agrees with. Students then record their own responses in their journals; the responses should be in the form of explanations that support the stances they have taken.

**Figure 4.8**

**Concept Cartoon: Where Does a Plant’s Mass Come From?**

**Question:** This large tree started as a little seed. What provided most of the mass that made the tree grow so large?

I think most of it came from nutrients in the soil that are taken up by the plant’s roots.

I think most of it came from the Sun’s energy.

I think most of it came from molecules in the air that came in through holes in the plant’s leaves.

I think most of it came from the water taken up directly by the plant’s roots.

Next, groups of students determine the group’s “best answer” to the cartoon, confronting their individual conceptions as well as those of their peers. They consider the stance taken in their answer and respond to the probe, “How would you test your claim?” Although there are many resources the teacher can use to help students test their claims, we suggest using one of two options.

Option #1: Students mass out radish seeds in three batches, each batch weighing 1.5g, and apply to the seeds various experimental treatments (choices might include seeds on moist paper towels in the light, seeds on moist paper towels in the dark, and seeds not moistened in the light). They grow them for one week, dry them overnight in an oven, and measure total biomass in grams. Prior to revealing results, students predict the biomass of the plants receiving various treatments (Ebert-May 2003).
Option #2: Students design experiments using Wisconsin Fast Plants to test their claims. Information about use of Fast Plants as well as developed activities can be found at www.fastplants.org.

Reflection and Application
Let’s take a final moment to reflect now that we have considered a tool—concept cartoons—that elicits and confronts preconceptions.

1. How might the use of concept cartoons help to elicit and confront your own students’ preconceptions about photosynthesis?
2. Consider cartoons you might develop to use with each of the other learning targets. How would you need to change your current instruction to further implement this strategy?

Completing the Responsive Phase: Sense Making and Demonstrating Understanding
Rather than complete a detailed description of the remainder of the lesson on photosynthesis at this time, we briefly summarize it in the Teacher Work Template for the responsive phase (Table 4.2). We include a brief description of how to elicit and confront student conceptions for Learning Targets #2, #3, and #4. We also outline how the lesson addresses sense making and demonstrating understanding. A fully developed lesson would include teacher support materials and student work materials; Table 4.2 provides an outline that you can use as you develop a lesson for use in your own classroom.

Once you study the remaining aspects of the Instructional Planning Framework developed in this book, you can further flesh out this lesson, using the framework as your guide. Further description of “eliciting and confronting preconceptions” is provided in Chapter 5, while “sense making” and “demonstrating understanding” are covered in the remaining chapters.
### Table 4.1

**Teacher Work Template: Predictive Phase**

<table>
<thead>
<tr>
<th>Conceptual Target Development</th>
<th>National Standard(s) Addressed</th>
<th>Previous Conceptual Learning</th>
<th>Previous Conceptual Learning</th>
</tr>
</thead>
<tbody>
<tr>
<td>From 9–12 NSES:</td>
<td>From 9–12 Benchmarks:</td>
<td>From middle grade NSES:</td>
<td>From middle grade Benchmarks:</td>
</tr>
<tr>
<td>- Plant cells contain chloroplasts, the site of photosynthesis. Plants and many microorganisms use solar energy to combine molecules of carbon dioxide and water into complex, energy rich organic compounds and release oxygen to the environment. This process of photosynthesis provides a vital connection between the sun and the energy needs of living systems. (p. 184)</td>
<td>- Plants alter the earth’s atmosphere by removing carbon dioxide from it, using the carbon to make sugars and releasing oxygen. This process is responsible for the oxygen content of air. (p. 74)</td>
<td>- For ecosystems, the major source of energy is sunlight. Energy entering ecosystems as sunlight is transferred by producers into chemical energy through photosynthesis. That energy then passes from organism to organism in food web. (p. 158)</td>
<td>- Food provides the fuel and the building material for all organisms. Plants use the energy from light to make sugars from carbon dioxide and water. This food can be used immediately or stored for later use…. (p. 120)</td>
</tr>
<tr>
<td>- The atoms and molecules on the earth cycle among the living and nonliving components of the biosphere. (p. 186)</td>
<td>- The chemical elements that make up the molecules of living things pass through food webs and are combined and recombined in different ways. At each link in a food web, some energy is stored in newly made structures but much is dissipated into the environment. Continual input of energy from sunlight keeps the process going. (p.121)</td>
<td>- Energy flows through ecosystems in one direction, from photosynthetic organisms to herbivores to carnivores and decomposers. (p. 186)</td>
<td>- Over a long time, matter is transferred from one organism to another repeatedly and between organisms and their physical environment. As in all material systems, the total amount of matter remains constant, even though its form and location change. (p. 120)</td>
</tr>
<tr>
<td>- Energy flows through ecosystems in one direction, from photosynthetic organisms to herbivores to carnivores and decomposers. (p. 186)</td>
<td>- The energy for life primarily derives from the sun. Plants capture energy by absorbing light and using it to form strong (covalent) chemical bonds between the atoms of carbon-containing organic molecules. These molecules can be used to assemble larger molecules with biological activity (including proteins, DNA, sugars, and fats). In addition, the energy stored in bonds between the atoms (chemical energy) can be used as sources of energy for life processes. (p. 186)</td>
<td>- The energy for life primarily derives from the sun. Plants capture energy by absorbing light and using it to form strong (covalent) chemical bonds between the atoms of carbon-containing organic molecules. These molecules can be used to assemble larger molecules with biological activity (including proteins, DNA, sugars, and fats). In addition, the energy stored in bonds between the atoms (chemical energy) can be used as sources of energy for life processes. (p. 186)</td>
<td>- Energy can change from one form to another in living things…. Almost all food energy comes originally from sunlight. (p. 120)</td>
</tr>
<tr>
<td>- The energy for life primarily derives from the sun. Plants capture energy by absorbing light and using it to form strong (covalent) chemical bonds between the atoms of carbon-containing organic molecules. These molecules can be used to assemble larger molecules with biological activity (including proteins, DNA, sugars, and fats). In addition, the energy stored in bonds between the atoms (chemical energy) can be used as sources of energy for life processes. (p. 186)</td>
<td>- The energy for life primarily derives from the sun. Plants capture energy by absorbing light and using it to form strong (covalent) chemical bonds between the atoms of carbon-containing organic molecules. These molecules can be used to assemble larger molecules with biological activity (including proteins, DNA, sugars, and fats). In addition, the energy stored in bonds between the atoms (chemical energy) can be used as sources of energy for life processes. (p. 186)</td>
<td>- Energy can change from one form to another in living things…. Almost all food energy comes originally from sunlight. (p. 120)</td>
<td>- Energy can change from one form to another in living things…. Almost all food energy comes originally from sunlight. (p. 120)</td>
</tr>
</tbody>
</table>

From prior instruction in the biology course: Basic cell structure and function, types of organic molecules, both monomers and polymers that comprise biomolecules, cellular respiration...
### Table 4.1 (continued)

<table>
<thead>
<tr>
<th>Conceptual Target Development (continued)</th>
<th>Knowledge and Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Essential knowledge:</strong> See Learning Targets #1–#2 and unpack for embedded knowledge.</td>
<td>See Learning Targets #1–#2 and unpack for embedded knowledge.</td>
</tr>
<tr>
<td><strong>Subtopics that may be pruned:</strong> Details about the steps of photosynthesis, including photosystems, electron transport, ATP formation, dark reactions, and the Calvin cycle.</td>
<td>Details about the steps of photosynthesis, including photosystems, electron transport, ATP formation, dark reactions, and the Calvin cycle.</td>
</tr>
<tr>
<td><strong>Essential vocabulary:</strong> photosynthesis, biomass, cellular respiration, glucose versus sugar</td>
<td>photosynthesis, biomass, cellular respiration, glucose versus sugar</td>
</tr>
<tr>
<td><strong>Vocabulary that may be pruned:</strong> electron transport chain, polysaccharide</td>
<td>electron transport chain, polysaccharide</td>
</tr>
</tbody>
</table>

### Essential Understandings

Plants have the ability to capture the energy of sunlight and use it to combine low-energy molecules (carbon dioxide and water) to form higher energy molecules (glucose and starches). This process is called photosynthesis. Plants can use the glucose immediately as a source of energy, convert it into other molecules that help their cells function, or store it for later use. Regardless, the total amount of matter and energy in the system stays the same.

### Learning Sequence Targets

| Learning Target #1 | The vast majority of plants are able to convert inorganic carbon in CO₂ into organic carbon through photosynthesis. Carbon dioxide and water are used in the process to create biomass. The surrounding environment is the source of raw materials for photosynthesis. |
| Learning Target #2 | Photosynthesis captures the energy of sunlight that is used to create chemical bonds in the creation carbohydrates. Chloroplasts in the cells of plant leaves contain compounds able to capture light energy. Photosynthesis uses CO₂ and the hydrogen from water to form carbohydrates, releasing oxygen. |
| Learning Target #3 | Carbohydrates produced during photosynthesis in leaves can be used immediately for energy in the plant, stored for future use, or converted to other macromolecules that help the plant grow and function. |
| Learning Target #4 | A variety of gases move into and out of plant leaves. Leaves use CO₂ and release O₂ during photosynthesis. When they respire, leaves use O₂ and release CO₂. Other gases enter the leaf as well, but are excreted. |

### Criteria to Demonstrate Understanding

- Predict the source of biomass in plants and thoroughly justify claims based on experimental results.
- Find patterns in data to determine the possible role of light in photosynthesis and design an experiment to test claims that are made based on these data.
- Carefully perform analyses to determine the various plant products that make up a plant’s biomass.
- Propose and support a well-crafted explanation for the variations in levels of oxygen and carbon dioxide during daytime and nighttime.
Table 4.2

Teacher Work Template: Responsive Phase

<table>
<thead>
<tr>
<th>Lesson Topic—Flow of Energy and Matter: Photosynthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Identifying Student Preconceptions</strong></td>
</tr>
<tr>
<td>Two major activities are used to determine students’ preconceptions in this lesson. The first targets the “big ideas” for the lesson and the second is used with Learning Target #1, which addresses a major misconception related to photosynthesis and plant growth.</td>
</tr>
<tr>
<td>1. Use a concept cartoon to probe students’ understandings about carbon as the source of plant biomass.</td>
</tr>
<tr>
<td>2. Use student-developed, annotated drawings to determine students’ ideas about the processes and resources a plant uses to grow from seed to mature plant. The intent is to determine students’ current understandings about flow of matter and cycling of energy in a plant system.</td>
</tr>
</tbody>
</table>

Learning Sequence Targets

| Learning Target #1 | The vast majority of plants are able to convert inorganic carbon in CO₂ into organic carbon through photosynthesis. Carbon dioxide and water are used in the process to create biomass. The surrounding environment is the source of raw materials for photosynthesis. |

Research-Identified Misconceptions Addressed

- When asked to describe a plant’s needs, some students attribute anthropomorphic characteristics to plants, such as breathing, drinking, and eating (Barman et al. 2006; Ebert-May 2006).
- Some students of all ages are unaware that plants make their food internally, thinking instead that they take it in from the outside. They struggle to comprehend that plants make their food from water and air, and that this is their only source of food (AAAS 1993).
- Students think photosynthesis provides energy for uptake of nutrients through roots and building biomass and that no biomass is built through photosynthesis alone (Ebert-May 2006).
- Some students at all ages think plants get most of their food from the soil, through their roots. This is why some students will say that plants need fertilizer (Barker 1995; Barman et al. 2006; Driver et al. 1994; Köse 2008; Russell, Netherwood, and Robinson 2004).
- Many students know that water is absorbed through a plant’s roots, but they assume that water is the primary growth material for the plant. Other studies show that students often think minerals are food for plants or that they directly contribute to photosynthesis (Driver et al. 1994).
- There is disbelief that weight increase in plants is due to a gas (CO₂), even if students know that the gas is absorbed by plants (Driver et al. 1994; Ebert-May 2006).
- Only a third of 15-year-olds understand gas exchange in plants or that green plants take in carbon dioxide. Forty-six percent of 16-year-olds do not understand that increased photosynthesis decreases the level of carbon dioxide in a closed system (Driver et al. 1994).
CHAPTER 4: Flow of Energy and Matter: Photosynthesis

Table 4.2 (continued)

<table>
<thead>
<tr>
<th>Initial Instructional Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eliciting Preconceptions:</strong> Notice that each of the research-identified misconceptions revolves around the source of biomass in the plant or around what causes the plant to grow. Students attribute mass in the growing plant to almost anything but the carbon in CO$_2$, and the concept cartoon elicits our own students’ preconceptions by choosing each student’s individual “best answer” to the cartoon.</td>
</tr>
<tr>
<td><strong>Confronting Preconceptions:</strong> Groups of students now determine the group’s “best answer” to the cartoon, confronting their individual conceptions as well as those of their peers. At the same time, teachers should support the metacognitive focus by using a strategy Claim/Support/Question, found at the Visible Thinking website (<a href="http://www.pz.harvard.edu/vt">www.pz.harvard.edu/vt</a>). It requires students to clarify claims of truth by making claims, identifying support for their claims, and further questioning their own claims. Have student groups consider the stance taken in their answers and ask them, “How would you test your claim?” There are many resources we can use to help students test their claims. We suggest these two options:</td>
</tr>
<tr>
<td><strong>Option #1:</strong> Students mass out three batches of radish seeds, each batch weighing 1.5g. Apply various experimental treatments to the seeds (e.g., seeds on moist paper towels in the light, seeds on moist paper towels in the dark, and seeds not moistened in the light). Grow the seeds for one week. Then dry them overnight in an oven and measure biomass in grams. Prior to revealing results, have students predict the biomass of the various treatments (Ebert-May 2003).</td>
</tr>
<tr>
<td><strong>Option #2:</strong> Students design experiments using Wisconsin Fast Plants (floating leaf discs) to test their claims. Information about use of Fast Plants as well as developed activities can be found at <a href="http://www.fastplants.org">www.fastplants.org</a>.</td>
</tr>
<tr>
<td><strong>Sense Making:</strong> Students write an explanation about the results once results are revealed. If there is not enough time to conduct the Option #1 experiment, the author’s (Ebert-May 2003) results can be used (light no water, 1.46g; light, water, 1.63g; and no light, water, 1.20g). Conclude with a discussion comparing student results to the Van Helmont experiment and his conclusions. Have students discuss in small groups and then record their explanations in their science notebooks. Additional discussion can help students explore common research-identified misconceptions, including why no soil is required in hydroponics and why soil does not disappear from pots in which plants are growing.</td>
</tr>
<tr>
<td><strong>Formative Assessment Plan (Demonstrating Understanding)</strong></td>
</tr>
<tr>
<td>1. Student discussions and explanations in their science notebooks serve as formative assessments.</td>
</tr>
<tr>
<td>2. Revisit the concept cartoon and ask students to record their current responses in their science notebooks and justify their explanations.</td>
</tr>
<tr>
<td>3. Finally, ask students to propose equations for photosynthesis based on their current understanding, record these equations in their science notebooks, and write explanations of their thinking.</td>
</tr>
</tbody>
</table>
Table 4.2 (continued)

| Learning Target #2 | Photosynthesis captures the energy of sunlight that is used to create chemical bonds in the creation of carbohydrates. Chloroplasts in the cells of plant leaves contain compounds able to capture light energy. Photosynthesis uses CO₂ and the hydrogen from water to form carbohydrates, releasing oxygen. |

Research-Identified Misconceptions Addressed

- Some students of all ages confuse energy with other concepts—including food, force and temperature—making it difficult to understand the importance of energy conversions in photosynthesis (AAAS 1993).
- There is confusion about what chlorophyll is and what its role is in plants. Few students understand its role in converting light to chemical energy (Driver et al. 1994).
- Many students believe that plants are green because they absorb green light (Russell, Netherwood, and Robinson 2004).
- Chlorophyll alone is insufficient for plant photosynthesis. Many other enzymes and organic compounds are required. “Chloroplasts” is a better requirement (Hershey 2004).

Initial Instructional Plan

Eliciting and Confronting Preconceptions: Students continue experiments begun in Learning Target #1 and compare the results with other activities that address this target. Provide students with secondary sources that show oxygen concentration around leaves over a 24-hour period. Ask them to find patterns in the data and make a claim, using the data as evidence.

Sense Making: Establish that the evidence supports photosynthesis occurring in the presence of daylight, and ask students to propose investigations that would further test their claims. Students then devise a way to measure photosynthesis under varying conditions, stressing light intensity. Have them make predictions, time the collection of fixed amount of oxygen or use an oxygen probe, graph results, and identify/explain anomalous results. One approach is to use floating leaf discs, an example of which is “Exploring Photosynthesis with Fast Plants,” an activity in which students measure rates of photosynthesis by measuring oxygen produced (www.fastplants.org/pdf/activities/exploring_photosynthesis.pdf). An optional activity is to read and discuss historical experiments with radioactively tagged water to identify water as the source of oxygen. Note: There are difficulties with approaches using the freshwater plant Elodea that tend to produce erroneous data. Photosynthesis does not always cause the bubbles formed on submerged leaves. If you use cold water, bubbles form as the water warms and gases become less soluble. The gas is not always pure oxygen since, as photosynthetic oxygen dissolves, some nitrogen comes out of solution (Hershey 2004).

Close with an activity that requires students to compare their results with those of Joseph Priestley.

Formative Assessment Plan (Demonstrating Understanding)

Students expand or modify their equations for photosynthesis. Require that they explain their reasoning for changes they make to their equations.
Table 4.2 (continued)

| Learning Target #3 | Carbohydrates produced during photosynthesis in leaves can be used immediately for energy in the plant, stored for future use, or converted to other macromolecules that help the plant grow and function. |

Research-Identified Misconceptions Addressed

- Students have little understanding of energy transfers in plant metabolism, thinking that food accumulates in a plant as it grows and having little understanding that food provides energy for a plant’s life processes (Driver et al. 1994).
- Glucose is not the major photosynthetic product. There is virtually no free glucose produced in photosynthesis. The most common product is starch or sucrose, and students often test leaves for starch (Hershey 2004).

Initial Instructional Plan

**Eliciting Preconceptions:** Have student groups brainstorm what they know about plant parts and their use as food sources, using one of the brainstorming webs (Instructional Tool 2.10, on page 72. Encourage them to think of all plant parts that might eventually lead them to plant products that include molecules other than glucose.

**Confronting Preconceptions:** Show students some variegated plants. Ask them to consider why only some parts of the leaves are green and what that might mean about photosynthesis. You can use traditional activities—with green leaves that have parts covered or with variegated leaves—to demonstrate that only green parts of plants make glucose and store it as starch. Have student groups conduct experiments and make sketches of their results. Summarize the results of all groups and discuss consistencies and inconsistencies. Revisit the idea that chlorophyll is necessary to absorb light.

Present students with a wide range of plant products (e.g., cellulose, fats, proteins, starches, sugars) and have them test some for a variety of moles (e.g., fats, proteins, starches, sugars).

**Sense Making:** Have students research the composition and role of the various plant products in the plant. Establish that these determine the plant’s biomass, together with the glucose. A possible extension is to have students find out about the molecular structures of glucose, sucrose, and starch and the relationship among them. At this point, they have not been exposed to respiration in the plant, but this sense-making activity serves as a transition to Learning Target #4.

Formative Assessment Plan (Demonstrating Understanding)

Again have student revisit their equations for photosynthesis, having them modify their equations and write explanations for any modifications.
Table 4.2 (continued)

| Learning Target #4 | A variety of gases move into and out of plant leaves. Leaves use CO$_2$ and release O$_2$ during photosynthesis. When they respire, leaves use O$_2$ and release CO$_2$. Other gases enter the leaf as well, but are excreted. |

Research-Identified Misconceptions Addressed

- Photosynthesis is often seen as something that plants do for the benefit of animals and people (especially with gas exchange) and that it is not as important to the plant itself (Driver et al. 2004).
- Some students at various ages think that the main job of leaves is to give off carbon dioxide or give off oxygen (Köse 2008).
- Students often think that air is used in opposite ways in plants and animals or they think that plants don’t use air (Driver et al. 1994).
- Plants carry on photosynthesis; animals respire (Cottrell 2004; Köse 2008).
- Photosynthesis and respiration function in an opposite and contrasting manner (Köse 2008).
- Plants carry on photosynthesis during the day and respiration during the night (Hershey 2008; Russell, Netherwood, and Robinson 2004). While photosynthesis in plants takes in CO$_2$ and gives off O$_2$ during the day, it takes in O$_2$ and gives off CO$_2$ at night (Köse 2008).
- Many students think plants require light to grow, including for the germination of seeds (Driver et al. 2004).

Initial Instructional Plan

**Eliciting Preconceptions:** Raise the question, “If plants produce oxygen, why don’t oxygen levels continually rise in the atmosphere?” Students’ likely response will be that respiration occurs in animals (since that topic has already been studied).

**Confronting Preconceptions:**

- Provide students with secondary data sources that indicate O$_2$ and CO$_2$ levels around leaves during daytime and nighttime. Ask students what happens at night and how this might be tested. You can again use floating leaf discs (Wisconsin Fast Plants) to have students design and conduct experiments that test their thinking. A wonderful resource explaining use of leaf discs is found at www.elbiology.com/labtools/Leafdisk.html (Williamson, n.d.). It will be helpful with Learning Targets #1 and #4 because it not only explains use of the leaf discs to test oxygen generation in the light, but also includes an extension with discs in the dark.
- You can also consider germinating pea seedlings in the dark over a period of about four weeks. Indeed, you might initiate germination at the beginning of this lesson/unit. O’Connell (2008) provides the steps of the process: (1) obtain uniform lots of peas and begin germination; (2) remove some seedlings from each lot on days 8, 15, and 22, leaving them to air dry; and (3) on days 25 and 26, when the seedlings should be completely dry (the author provides details on how to ensure this), mass out all peas and examine and explain data. Refer to O’Connell (2008) for more detailed information.

**Sense Making:** Student groups share experimental results. Consistencies and inconsistencies are discussed. Individual students record findings and explanations in their science notebooks.

**Formative Assessment Plan (Demonstrating Understanding)**

Students finalize their photosynthesis equations, once again justifying any changes.
Table 4.3

Strategies for Teaching Photosynthesis

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Strengths of the Strategies</th>
</tr>
</thead>
</table>
| Drawings and Annotated Drawings | • They may be best used when teaching nonobservable science concepts (i.e., photosynthesis).  
• Student-created descriptive drawings are more effective at promoting conceptual change than just writing (without drawing).  
• They are even more effective when coupled with verbal information (questioning/interviews).  
• Some students who might find it difficult to express themselves in words may be able to express themselves through drawing.  
• Annotated illustrations require the student to select, organize, and integrate ideas. These are cognitive processes necessary for meaningful learning.  
• Annotated drawings make students’ knowledge-construction visible and let them grapple with their own ideas and adjust their thinking. Thus, annotated drawings serve a metacognitive function.  
• Drawings provide information about specific misconceptions, which is helpful to both students and teachers.  
• They provide information to the teacher that helps determine what strategies to use.  
• They are less biased than some strategies or assessments because students choose what they draw and draw from their own experiences. This also allows the teacher to respond to the interests, background knowledge, and skills of individual students. |
| Concept Cartoons        | • They have been shown effective in eliciting and addressing student misconceptions about photosynthesis.  
• They present cognitive conflict, which both provides motivation and challenges a student’s misconceptions.  
• They engage students in the learning process because students are required to focus on construction of explanations for the situations in the cartoons.  
• They make the flow of learning more continuous because elicitation of student ideas and restructuring of their thinking occur simultaneously.  
• Students choose between alternative explanations, making the need for investigation evident. They are then responsible for choosing the appropriate investigation, which gives the teacher time to respond to students’ individual needs.  
• They create an environment that promotes participation of all students in class discussion, activates students to support their ideas, and remedies misconceptions.  
• They may lessen student anxiety over offering a wrong answer. |
| Concept Maps            | • They are effective when working with concept-rich units such as photosynthesis.  
• They motivate and engage students in the content.  
• They show relationships among concepts.  
• They challenge students to analyze their thinking, thereby enhancing metacognition.  
• Group concept mapping is especially powerful.  
• Effective use of concept maps requires training for the teacher so that he or she can then train the student. It takes students about eight weeks of school to become proficient at concept mapping. |
Recommended Resources

Technology Applications and Websites

Each of the following websites provide video of germination of seeds and continuing plant growth that can be used to elicit student preconceptions:

- Minds of Our Own video (www.learner.org/resources/series26.html)
- From Seed to Flower at the Teacher’s Domain website (www.teachersdomain.org/resources/tdc02/sci/life/colt/plantsgrow/index.html)
- The Giant Sequoia seed germination at the ARKive Images of Life on Earth website (www.arkive.org/species/GES/plants_and_algae/Sequoiadendron_giganteum/Sequoiadendron_gigant_09c.html)
- Several time-lapse seed germination videos at the Teacher Tube website, including Wisconsin Fast Plants Life Cycle Time Lapse and Time Lapse Radish (www.teachertube.com/search_result.php?search_id=seed)

Two helpful sites for use during investigations include the following:

- Wisconsin Fast Plants website (www.fastplants.org)
- “The Floating Leaf Disk Assay for Investigating Photosynthesis” is found at the Exploring Life Community website (www.elbiology.com/labtools/Leafdisk.html)

Finally, a summary of misconceptions related to photosynthesis is found at the AIBS website (www.actionbioscience.org/education/hershey.html).

Additional resources to support the framework process are found in endnote #3.

Build Your Library


Endnotes

1. Annenberg has made video segments available online at www.learner.org/resources/series26.html.

2. This diagram is modified from the work of Mohan, Chen, and Anderson (2007). Theirs is a loop diagram for carbon cycling in socio-ecological systems and includes human and economic systems as well as environmental systems. Their diagram was designed to model how humans impact carbon cycling in an ecosystem.
3. Several sources were used to determine the best learning sequence for this lesson. They are rich resources for your further study of carbon cycling broadly and photosynthesis in particular. These sources are

- Multiple papers at the Environmental Literacy website at Michigan State University ([http://edr1.educ.msu.edu/EnvironmentalLit/index.htm](http://edr1.educ.msu.edu/EnvironmentalLit/index.htm)) (5/15/08)

4. Students build new knowledge based on what they already know. Although their ideas seem reasonable and appropriate to them, the ideas may not be consistent with scientific explanations or the ideas may be limited in application (Driver et al. 1994). If they are going to change their perceptions, students must become dissatisfied with their existing views by being presented with a new conception that seems reasonable and more attractive than their previous ideas. The new conception must help them explain scientific phenomena and make predictions as they make sense of their world (Strike and Posner 1985). Conceptual change research is grounded in the idea that students’ ideas must be restructured rather than replaced (Duit and Treagust 1998). This means that teachers must value their students’ ideas and teach them to reflect on the ideas. Then, teachers can help students reach the conceptual targets that the teachers have set (Hipkins et al. 2002). Weiss et al. (2003) summarize four areas in which teachers have the most impact on students’ scientific learning. Teachers must (1) engage students in grappling with important science content, (2) motivate students to engage in the content, (3) portray science as a dynamic body of knowledge, and (4) take students where they are and move them forward. “Instruction must begin with close attention to students’ ideas, knowledge, skills, and attitudes, which provide the foundation on which new learning builds” (NRC 2005, p. 14).

5. A review of related research (Scott, Asoko, and Driver 1992) categorized two main types of conceptual change teaching strategies. The first is sometimes called the cognitive conflict model and uses strategies that elicit student ideas at the beginning of a lesson and immediately has students contrast the ideas with scientists’ ideas. The second is called the conceptual development model and begins with students’ ideas, leading them gradually toward scientific ideas. The strategies in Chapter 2 use both of these models.
Index

Note: **Boldface** pages numbers indicate figures.

Analogies, 68–69  
Annotated drawings, 83–84  
Assessment, 27–28

Brainstorming webs, 25–26, 36, 72–74

Carbon cycling in environmental systems, 122  
Case studies, 95, 95  
Categorical organizers, 76–77  
Cause-effect organizers, 76  
Circle maps, 73–74  
Classroom inquiry, essential features, 20  
Clustering, 72  
Comparison organizers, 77–78  
Completing responsive phase, 132–140  
brainstorming webs, 25–26  
linguistic representations, 24  
nonlinguistic representations, 24–27  
drawing, 26  
kinesesthetic activities, 26–27  
maps, 25–26  
models, 25  
task-specific organizers, 26  
thinking-process maps, 26  
Concept cartoons, 85  
Concept mapping, 79–80  
Conceptual change, instructional planning framework, 3–14  
criteria demonstrating understanding, 6–7  
criteria for developing understanding, 7  
learning sequence, 6–7  
overview, 5–7  
preconceptions  
comprehension strategies  
addressing, 7  
confronting, 7  
eliciting, 7  
identification of, 7  
research, 8–12  
predictive phase, 8–9  
responsive phase, 9–12  
target, 6–7  
understanding, criteria demonstrating, 6–7  
Creative thinking, 18, 29, 36–37  
strategies supporting, 36–37  
Creativity routines, 36  
Critical thinking, 18, 29  
Debriefing thinking process, 42  
Demonstration experiments, 49  
Description of assessment for preconceptions, 129–130  
Descriptive organizers, 75  
Diagrams, 70  
Digging further into standards, 195–196  
Drawing, 26, 83–84  
Drawing out thinking, 83–85  
Dynamic models, 25, 70–71  
Ecosystems. See Socio-ecological systems  
Energy, matter, flow of, 119–142  
carbon cycling in environmental systems, 122
completing responsive phase, 132–140
comprehension, 132–140
confronting preconceptions, 128
description of assessment for
preconceptions, 129–130
eliciting preconceptions, 128, 130–132
formative assessment plan, 136–139
identifying our students’
preconceptions, 127–129
identifying preconceptions, 125, 128
initial instructional plan, 136–139
instructional planning framework,
122–130
identifying preconceptions, 128
predictive phase, 122–124, 133–134
reflection, 124, 127, 130, 132
research-identified misconceptions,
137–139
resources, 141
responsive phase, 125–130, 135–139
selection of topic, 120–121
steps for misconception literature
review, 127
strategies, 140
strategy selection, 128
teacher work template, 133–139
technology applications, 141
websites, 141
Environmental systems, 191–228, 197
education, 199, 201
build on middle school experiences, 199
comprehension strategies, 209
conceptual targets, 194–198
confronting preconceptions, 206–215,
224–226
criteria determining understanding, 200
digging further into standards, 195–196
ecosystems, 199–200
eliciting preconceptions, 206–215,
224–226
finalizing process to promote
understanding, 207
formative assessment plan, 219–222
high school standards, 194–195
components of, 199–200
identifying preconceptions, 202, 202–205
initial instructional plan, 219–222
instructional planning framework
predictive phase, 193–201
responsive phase, 201–215
learning sequence targets, 219
library suggestions, 227–228
logical learning sequence, 199–200
loop diagram, 197
map for living environment, 196
metacognitive approach strategies, 208
middle school standards, 194–195
planning in predictive phase, 193
planning instruction for learning
targets, 209
preconceptions, 206–215
identifying, 223
predictive phase, 193–201, 217–218
pruning content, 198
reflection, 200–201, 205, 215
research-identified misconceptions,
202–204, 219–222
research on learning progressions,
197–198
resources, 226–228
responsive phase, 201–215, 218
selection of topic, 192
standards-based approach strategies,
208–209
strategy selection, 206–208
teacher work predictive phase template,
217–222
technology applications, 226–227
understanding, 224–226
websites, 226–227
Evidence, formulating explanations from,
46–47
Evolution, 143–168
comprehension, 156–158
confronting preconceptions, 149, 151–158
differential mortality, 154–156
eliciting preconceptions, 149, 151–158
formative assessment plan, 162–163
identifying preconceptions, 148–149
initial instructional plan, 161–163
instructional planning framework
   predictive phase, 146–148
   responsive phase, 145, 148–166
learning sequence targets, 160–161
library suggestions, 167
natural selection learning sequence, 148
planning in predictive phase, 147
planning in responsive phase, 149
population growth, 153
preconceptions, 149
reflection, 147–148, 150, 158–166
research-identified misconceptions, 149, 161–163
resources, 166–167
selection of topic, 144
teacher work template
   predictive phase, 159–160
   responsive phase, 161–163
teaching strategies, 164–166
technology applications, 166–167
websites, 166–167

Fairness routines, 34
Finalizing process to promote understanding, 207
Focusing labs, 53–54

Genes, 169–190. See also Genetic variation
comprehension, strategies addressing preconceptions, 175–176
confronting preconceptions, 173–175
demonstrating understanding, 176–178
demonstrating understanding for learning targets, 178–180
eliciting preconceptions, 173–175
finalizing process to promote understanding, 180
formative assessment plan, 186–188
identifying preconceptions, 173–175
initial instructional plan, 185–188

instructional planning framework
   predictive phase, 171–173
   responsive phase, 173–188
learning sequence, 173
learning sequence targets, 185
learning targets, 178–182
library suggestions, 189
planned learning sequence, 177
planning in predictive phase, 172
planning in responsive phase, 174
preconceptions, 173–175
   strategies addressing, 175–176
   predictive phase, 171–173
protein synthesis instruction, case study, 171
reflection, 173, 175, 180–188
research-identified misconceptions, 185–188
resources, 188–189
responsive phase, 173–188
selection of topic, 170
teacher work template, 183–188
technology applications, 188–189
websites, 188–189

Genetic variation, 93–118
adult science literacy, 96–97
case study, 95, 95
conceptual target, 96–102
criteria, 104–107
   variation, 107
criteria for demonstrating understanding, 107
expectations of adult science learning, 97
experienced biology teacher with new assignment, 95
formative assessment plan, 113–115
heredity map, 99
high school science standards, 97–100
   components of, 103–104
initial instructional plan, 114–115
instructional planning framework
   predictive phase, 96, 96–108
   responsive phase, 108–115, 109
learning progressions research, 100–101
learning sequence, 104
learning sequence targets, 111
library suggestions, 115–116
logical learning sequence, 102–104
map for heredity, 99
middle school experiences, building on, 103
middle school science standards, 97–100
planning in predictive phase, 102, 107
predictive phase, 96
planning, 102, 107
reflection, 107–108
research-identified misconceptions, 113–114
resources, 115–116
responsive phase, 109
selection of topic, 94
teacher work template, 110–111
responsive phase, 112–115
technology applications, 115
websites, 115
Graphs, 70
Group discussions, 62–64
Hands-on experiments, 86–87
Heredity map, 99
High school standards, 97–100, 194–195
components of, 103–104, 199–200
History of science, 21, 29, 49–50
History of science tools, 21–23
Human impact on environment, 191–228.
See also Socio-ecological systems
Identification of knowledge bases, 38
Informational text strategies, 59–60
Initial instructional plan, 114–115, 136–139, 219–222
Inquiry, standards-based approaches, 43–48
Inquiry tools, 19–21
Instructional approaches
classroom inquiry, essential features of, 20
student understanding, 15–90
assessment, 27–28
comprehension, 23–27
brainstorming webs, 25–26
linguistic representations, 24
nonlinguistic representations, 24–27
drawing, 26
kinesthetic activities, 26–27
maps, 25–26
models, 25
task-specific organizers, 26
thinking-process maps, 26
instructional strategy sequencing, 16–17
linguistic representational tools, 23–27
brainstorming webs, 25–26
dynamic models, 25
mental models, 25
nonlinguistic representations, 24–27
drawing, 26
graphic organizers, 25–26
kinesthetic activities, 26–27
mental models, 25
physical models, 25
task-specific organizers, 26
thinking-process maps, 26
verbal models, 25
visual models, 25
metacognitive approach tools, 17–18
creative thinking, 18
critical thinking, 18
self-regulated thinking, 18
nonlinguistic representational tools, 23–27
resources, 87–88
library suggestions, 88
technology applications, 87
websites, 87
standards-based approach tools, 19–23
history of science, 21–23
inquiry tools, 19–21
nature of science, 21–23
technology, 27
Instructional planning framework, 6, 122–130
conceptual change, 3–14
  criteria for developing understanding, 7
  instructional planning framework, overview, 5–7
  learning sequence, 6–7
  preconceptions
  comprehension strategies, 7
  confronting, 7
  eliciting, 7
  identification of, 7
  research, 8–12
  predictive phase, 8–9
  responsive phase, 9–12
  target, 6–7
  understanding, criteria demonstrating, 6–7
  predictive phase, 96, 96–108, 193–201
  responsive phase, 108–115, 109, 201–215
Instructional strategy sequencing, 16–17
Instructional strategy sequencing tool, 29–32
Interdependence of organisms, 191–228, 197, 199, 201
  build on middle school experiences, 199
  comprehension strategies, 209
  conceptual targets, 194–198
  confronting preconceptions, 206–215, 224–226
  criteria determining understanding, 200
  digging further into standards, 195–196
  ecosystems, 199–200
  eliciting preconceptions, 206–215, 224–226
  finalizing process to promote understanding, 207
  formative assessment plan, 219–222
  high school standards, 194–195
  components of, 199–200
  identifying preconceptions, 202, 202–205
  initial instructional plan, 219–222
  instructional planning framework
  predictive phase, 193–201
  responsive phase, 201–215
  learning sequence targets, 219
  library suggestions, 227–228
  logical learning sequence, 199–200
  loop diagram, 197
  map for living environment, 196
  metacognitive approach strategies, 208
  middle school standards, 194–195
  planning in predictive phase, 193
  planning instruction for learning targets, 209
  preconceptions, 206–215
  identifying, 223
  predictive phase, 193–201, 217–218
  pruning content, 198
  reflection, 200–201, 205, 215
  research-identified misconceptions, 202–204, 219–222
  research on learning progressions, 197–198
  resources, 226–228
  responsive phase, 201–215, 218
  selection of topic, 192
  standards-based approach strategies, 208–209
  strategy selection, 206–208
  teacher work predictive phase template, 217–222
  technology applications, 226–227
  understanding, 224–226
  websites, 226–227

Journals, 39–40
  Kinesthetics, 26–27, 32, 86–87
  Knowledge bases, identification of, 38
  Language, importance of, 52
  Large-group discourse, 62–64
  Learning about research-identified misconceptions, 125–127
  Learning logs, 39–40, 55
  Learning progressions research, 100–101
  Learning sequence, 6–7, 104
  Learning sequence targets, 111, 134, 219
  Library suggestions, 115–116, 141, 227–228
  Linguistic representational tools, 23–27
  brainstorming webs, 25–26
  dynamic models, 25
  mental models, 25
nonlinguistic representations, 24–27
drawing, 26
graphic organizers, 25–26
kinesthetic activities, 26–27
mental models, 25
physical models, 25
task-specific organizers, 26
thinking-process maps, 26
verbal models, 25
visual models, 25
Linguistic representations, 24, 31, 55–65
Logical learning sequence, 102–104, 199–200
Loop diagram, 197
Map for cells, 250
Map for evolution of life, 249
Map for flow of matter, energy, 248
Map for living environment, 196
Meiosis, 93–118
adult science literacy, 96–97
case study, 95, 95
case study, 95, 95
case study, 95, 95
case study, 95, 95
conceptual target, 96–102
criteria, 104–107
variation, 107
criteria for demonstrating understanding, 107
expectations of adult science learning, 97
experienced biology teacher with new assignment, 95
formative assessment plan, 113–115
heredity map, 99
high school science standards, 97–100
components of, 103–104
initial instructional plan, 114–115
instructional planning framework
predictive phase, 96, 96–108
responsive phase, 108–115, 109
learning sequence, 104
learning sequence targets, 111
library suggestions, 115–116
logical learning sequence, 102–104
map for heredity, 99
middle school experiences, building on, 103
middle school science standards,
97–100
planning in predictive phase, 102, 107
predictive phase, 96
planning, 102, 107
reflection, 107–108
research-identified misconceptions, 113–114
resources, 115–116
responsive phase, 109
selection of topic, 94
teacher work template, 110–111
responsive phase, 112–115
technology applications, 115
websites, 115
Mental models, 25, 66–67
Metacognitive approach tools, 17–18
creative thinking, 18
critical thinking, 18
self-regulated thinking, 18
Metacognitive approaches, 29, 33–42, 208
Metaphors, 69
Middle school experiences, building on, 103
Middle school standards, 97–100, 194–195
Mind mapping, 72–73
Misconception literature review, 127
Models, 25, 66–71
Molecular genetics, 169–190
comprehension, strategies addressing preconceptions, 175–176
confronting preconceptions, 173–175
demonstrating understanding, 176–178
demonstrating understanding for learning targets, 178–180
eliciting preconceptions, 173–175
finalizing process to promote understanding, 180
formative assessment plan, 186–188
identifying preconceptions, 173–175
initial instructional plan, 185–188
instructional planning framework
predictive phase, 171–173
responsive phase, 173–188
learning sequence, 173
learning sequence targets, 185
learning targets, 178–182
library suggestions, 189
planned learning sequence, 177
planning in predictive phase, 172
planning in responsive phase, 174
preconceptions, 173–175
  strategies addressing, 175–176
predictive phase, 171–173
protein synthesis instruction, case study, 171
reflection, 173, 175, 180–188
research-identified misconceptions, 185–188
resources, 188–189
responsive phase, 173–188
selection of topic, 170
teacher work template, 183–188
technology applications, 188–189
websites, 188–189

Narratives, 49–50
Natural selection, 143–168
  comprehension, 156–158
  confronting preconceptions, 149, 151–158
differential mortality, 154–156
eliciting preconceptions, 149, 151–158
formative assessment plan, 162–163
identifying preconceptions, 148–149
initial instructional plan, 161–163
instructional planning framework
  predictive phase, 146–148
  responsive phase, 145, 148–166
learning sequence targets, 160–161
library suggestions, 167
natural selection learning sequence, 148
planning in predictive phase, 147
planning in responsive phase, 149
population growth, 153
preconceptions, 149
reflection, 147–148, 150, 158–166
research-identified misconceptions, 149, 161–163
resources, 166–167
selection of topic, 144
teacher work template
  predictive phase, 159–160
  responsive phase, 161–163
teaching strategies, 164–166
technology applications, 166–167
websites, 166–167
Nature of science, 22–23, 51–54
Nature of science tools, 21–23
Nonlinguistic representations, 23–27, 32, 66–85
drawing, 26
graphic organizers, 25–26
kinesthetic activities, 26–27
maps, 25–26
mental models, 25
models, 25

Photosynthesis, 119–142
carbon cycling in environmental systems, 122
completing responsive phase, 132–140
comprehension, 132–140
confronting preconceptions, 128
description of assessment for
  preconceptions, 129–130
eliciting preconceptions, 128, 130–132
formative assessment plan, 136–139
identifying our students’ preconceptions, 127–129
identifying preconceptions, 125, 128
initial instructional plan, 136–139
instructional planning framework, 122–130
learning about research-identified misconceptions, 125–127
learning sequence targets, 134
library suggestions, 141
photosynthesis learning sequence, 124
planning in predictive phase, 123
preconceptions, 128
predictive phase, 122–124, 133–134
reflection, 124, 127, 130, 132
research-identified misconceptions, 137–139
resources, 141
responsive phase, 125–130, 135–139
selection of topic, 120–121
steps for misconception literature review, 127
strategies, 140
strategy selection, 128
teacher work template, 133–139
technology applications, 141
websites, 141
Physical gestures, 86–87
Physical models, 25
Pictures, 70
Planning in predictive phase, 123, 193
Planning instruction for learning targets, 209
Preconceptions, 29–32, 128, 206–215
comprehension strategies, 7
comprehension strategies addressing, 7
confronting, 7
eliciting, 7
identification of, 7
identifying, 223
planning, 102
planning in, 107
Problem-solution organizers, 78
Proteins, 169–190
comprehension, strategies addressing preconceptions, 175–176
confronting preconceptions, 173–175
demonstrating understanding, 176–178
demonstrating understanding for learning targets, 178–180
eliciting preconceptions, 173–175
finalizing process to promote understanding, 180
formative assessment plan, 186–188
identifying preconceptions, 173–175
initial instructional plan, 185–188
instructional planning framework predictive phase, 171–173
responsive phase, 173–188
learning sequence, 173
learning sequence targets, 185
learning targets, 178–182
library suggestions, 189
planned learning sequence, 177
planning in predictive phase, 172
planning in responsive phase, 174
preconceptions, 173–175
strategies addressing, 175–176
predictive phase, 171–173
protein synthesis instruction, case study, 171
reflection, 173, 175, 180–188
research-identified misconceptions, 185–188
resources, 188–189
responsive phase, 173–188
selection of topic, 170
teacher work template, 183–188
technology applications, 188–189
websites, 188–189
Pruning content, 198
Reading-to-learn tools, 31, 59–61
Relational organizers, 77–78
Reproduction, 93–118
adult science literacy, 96–97
case studies, 95, 95
conceptual target, 96–102
criteria, 104–107
variation, 107
criteria for demonstrating understanding, 107
expectations of adult science learning, 97
experienced biology teacher with new assignment, 95
formative assessment plan, 113–115
heredity map, 99
high school science standards, 97–100
components of, 103–104
initial instructional plan, 114–115
instructional planning framework predictive phase, 96, 96–108
responsive phase, 108–115, 109
learning progressions research, 100–101
learning sequence, 104
learning sequence targets, 111
library suggestions, 115–116
logical learning sequence, 102–104
map for heredity, 99
middle school experiences, building on, 103
middle school science standards, 97–100
planning in predictive phase, 102, 107
predictive phase, 96
planning, 102, 107
reflection, 107–108
research-identified misconceptions, 113–114
resources, 115–116
responsive phase, 109
selection of topic, 94
teacher work template, 110–111
responsive phase, 112–115
technology applications, 115
websites, 115
Research
predictive phase, 8–9
responsive phase, 9–12
Research-identified misconceptions, 113–114, 137–139, 202–204, 219–222
Research on learning progressions, 197–198
Resources, 87–88, 115–116, 141, 226–228
library suggestions, 88
technology applications, 87
websites, 87
Responsive phase, 125–130, 135–139, 201–215, 218
Science notebooks, 55–56
Science writing heuristic, 57
Scientific explanations, writing of, 56–57
Selection of topic, 94, 120–121, 192
Self-regulated thinking, 18, 29, 38–42
strategies supporting, 38–42
Self-regulation, 41
Sense-making approaches. See
Comprehension approaches
Sequential organizers, 75–76
Small-group discourse, 62–64
Socio-ecological systems, 191–228, 197, 199, 201
build on middle school experiences, 199
comprehension strategies, 209
conceptual targets, 194–198
confronting preconceptions, 206–215, 224–226
criteria determining understanding, 200
digging further into standards, 195–196
ecosystems, 199–200
eliciting preconceptions, 206–215, 224–226
finalizing process to promote understanding, 207
formative assessment plan, 219–222
high school standards, 194–195
components of, 199–200
identifying preconceptions, 202, 202–205
initial instructional plan, 219–222
instructional planning framework
predictive phase, 193–201
responsive phase, 201–215
learning sequence targets, 219
library suggestions, 227–228
logical learning sequence, 199–200
loop diagram, 197
map for living environment, 196
metacognitive approach strategies, 208
middle school standards, 194–195
planning in predictive phase, 193
planning instruction for learning targets, 209
preconceptions, 206–215
identifying, 223
predictive phase, 193–201, 217–218
pruning content, 198
reflection, 200–201, 205, 215
research-identified misconceptions, 202–204, 219–222
research on learning progressions, 197–198
resources, 226–228
responsive phase, 201–215, 218
selection of topic, 192
standards-based approach strategies, 208–209
strategy selection, 206–208
teacher work predictive phase template, 217–222
technology applications, 226–227
understanding, 224–226
websites, 226–227
Socratic dialogue, 35, 37, 65
Speaking-to-learn tools, 31, 62–65
Standards-based approach strategies, 208–209
Standards-based approach tools, 19–23
  - history of science, 21
  - history of science tools, 21–23
  - inquiry tools, 19–21
  - nature of science, 22–23
  - nature of science tools, 21–23
Steps of planning process, 246–247
Strategy selection, 128, 206–208
Student questioning, 64–65
Student understanding, instructional approaches, 15–90
  - assessment, 27–28
  - comprehension, 23–27
    - brainstorming webs, 25–26
    - linguistic representations, 24
    - nonlinguistic representations, 24–27
      - drawing, 26
      - kinesthetic activities, 26–27
      - maps, 25–26
      - models, 25
      - task-specific organizers, 26
      - thinking-process maps, 26
  - features of classroom inquiry, 20
  - instructional strategy sequencing, 16–17
  - linguistic representational tools, 23–27
    - brainstorming webs, 25–26
    - dynamic models, 25
    - mental models, 25
    - nonlinguistic representations, 24–27
      - drawing, 26
      - graphic organizers, 25–26
      - kinesthetic activities, 26–27
      - mental models, 25
    - physical models, 25
    - task-specific organizers, 26
    - thinking-process maps, 26
    - verbal models, 25
    - visual models, 25
  - metacognitive approach tools, 17–18
  - creative thinking, 18
  - critical thinking, 18
  - self-regulated thinking, 18
  - nonlinguistic representational tools, 23–27
  - resources, 87–88
    - library suggestions, 88
    - technology applications, 87
    - websites, 87
  - standards-based approach tools, 19–23
    - history of science, 21
    - history of science tools, 21–23
    - inquiry tools, 19–21
    - nature of science, 22–23
    - nature of science tools, 21–23
  - technology, 27
  - Systems diagrams, 80–81
  - Task-specific organizers, 26, 75–78
  - Teacher work template, 110–111, 133–139, 244–245
    - responsive phase, 112–115
  - Teacher work predictive phase template, 217–222
  - Technology, 27, 115, 141, 226–227
  - Thinking maps, 26, 61, 79–82
  - Truth routines, 33
  - Understanding, 224–226
    - criteria demonstrating, 6–7
  - Variation, genetic. See Genetic variation
  - Verbal models, 25, 68–69
  - Visible thinking, 33–34
  - Visual models, 25, 70
  - Vocabulary development, 58–59
  - Webs of brainstorming, 25–26
  - Websites, 115, 141, 226–227
  - Writing of scientific explanations, 56–57
  - Writing-to-learn tools, 31, 55–57