APPENDIX D

PAGES FROM THE INTRODUCTION TO THE TEACHER

Starting with the Students:
Students' Ideas about Plants and Ways of Thinking

A. Learning About Plants and Their Food: Memorizing or Making Sense?

•Have you ever heard of the word photosynthesis?
If yes, tell what it means as best you can.
•How does that tree outside our window get its food?

If these questions were posed to your middle school students after they had studied photosynthesis in your class, how would you hope your students would respond? What are the most basic, critical concepts that you want them to remember and understand? Is it sufficient that a student correctly supplies the formula for photosynthesis or states that "photosynthesis is when plants use carbon dioxide, water, and sunlight to make their own food"? Would you hope that your students would connect the question, "How does that tree outside our window get its food?," to the idea of photosynthesis?

In our research we have found that students can often define photosynthesis in satisfactory ways, but when they are asked questions that test their understanding of photosynthesis, their answers reveal that they have merely memorized a definition of photosynthesis without really making sense of and internalizing the concept. For example, we asked students who had just studied about photosynthesis to describe what food is for plants. Despite having learned about photosynthesis in class, the students' answers to this question rarely made reference to photosynthesis. In the following student responses, notice the contrast between the students' accurate descriptions of photosynthesis and their failure to use that concept to explain how plants get their food:

Question:	**Tell what photosynthesis means as best you can.**	**Describe what food is for plants.**
Dick	When a plant makes its own food.	Minerals, etc.
Denise	The process by which plants make food.	Minerals, water help the plants grow tall and healthy.
Lauren	How a plant makes food for itself.	Plants need sun and minerals and water for energy and to grow.
Heidi	When a plant uses water, sunlight, and air to make food.	Water and minerals and protein.

These students have "learned" a definition of photosynthesis, but they contradict themselves when they are asked to describe food for plants! This is a pattern of thinking that we have seen over and over again in our research. Students can parrot back memorized terms, but they cannot answer questions that require application of those memorized terms. Why do students have such difficulty making sense of central concepts like photosynthesis?

The teaching materials in this unit are based on one answer to this question. The answer arises from extensive research comparing students' ways of thinking about natural phenomena with scientific experts' ways of thinking about the same phenomena. In general, this research shows that the students' think and act in ways that are perfectly sensible given their everyday experiences. But their ideas are incompatible with accepted scientific thought. And their ways of thinking differ from those valued by scientists.

For example, many students have trouble learning about photosynthesis because they assume that plants, like people, must take in food from the environment. Scientists, on the other hand, emphasize the critical *differences* between the ways plants and people get their food. In the scientific view, plants are unique in their ability to take low energy-containing matter (water and carbon dioxide) and use energy from the sun to change that matter into high energy-containing matter (food). Thus, the food that plants make during photosynthesis is very different in nature from the materials that plants take in (water, minerals, carbon dioxide).

The presence of students' alternate ways of thinking makes the learning of science a far more complicated process than scientists and teachers normally imagine. For these students, learning about photosynthesis is not simply a matter of absorbing or memorizing scientific content. Instead, they must change their commonsense, everyday understandings of the world. Furthermore, they must abandon misconceptions or habits of thought that have served them well all their lives in favor of new and unfamiliar new ideas.

And we all know how difficult change is! These old habits of thought often persist even after students have apparently learned the scientific alternatives. Many students become quite good at learning what is expected of them to pass science tests while continuing to use their old ideas in "real world" situations. They separate "school knowledge" from what they really know and believe ("real world knowledge"). The students quoted above, for example, memorized a definition of photosynthesis without realizing its implications for their understanding of how real-world plants get their food. Richard and Daniel, quoted below, show another common pattern of incomplete learning.

Question:	**Describe what is food for plants.**
Richard	Sun, good soil, water, and the food made during photosynthesis.
Daniel	Glucose, sunlight, and minerals from the ground.

Learning about photosynthesis did change their explanations of how plants get food, but not enough! They still do not appreciate the crucial difference between the low-energy materials that plants take in (minerals from the ground, water) and the high-energy products of photosynthesis.

We have adopted a phrase from David Hawkins and describe students' alternative ways of thinking that interfere with their understanding of scientific thinking as "critical barriers" to the learning of science. In our research, we have tried to understand the critical barriers to student learning about central topics in the science curriculum and to use those understandings to define teaching strategies that will help students overcome those barriers and develop richer, fuller, and more personally meaningful understandings of the world around them.

B. Critical Barriers to Understandings Plants and Their Food

Four general issues are particularly difficult for most students when learning about how plants make their own food. These issues and the reasons for their importance from the students' points of view are as follows:

1. Food.

    This word is rarely used with precision by either students or biologists. When talking about the food made by plants during photosynthesis, however, biologists are more consistent. In this context, biologists use the word "food" to refer to organic compounds with high-energy molecular bonds that organisms can use for growth and metabolism. Other substances that organisms need, such as water, oxygen, and minerals are inorganic and do not contain high-energy bonds in their molecules. These substances are NOT considered *food* by this scientific definition. It is this distinction that makes the statement "plants make their own food" meaningful. The process of photosynthesis provides the only bridge by which inorganic matter can be transformed into organic matter.

The biological distinction between energy-supplying substances (food) and nonenergy-supplying substances (not food) is critical to understanding the significance of photosynthesis. Plants and other organisms convert glucose into the millions of other organic compounds (proteins, fats, hormones, enzymes, etc.) that make up the bodies of living things. However, all of those compounds (in other words, all food) are ultimately derived from a single source: glucose make during photosynthesis.

The distinction between plants as producers and animals as consumers in ecosystems cannot be meaningful to students who do not understand that the food made during photosynthesis is different in a very important way from other nutrients such as water and minerals. After all, what is it that plants produce and animals consume?

Students do not think about food in these ways, however. To them, food is whatever plants or animals take in to keep them alive and growing. From this perspective, it is easy to see how they could misunderstand or distort instruction about photosynthesis. Their definition of food is sensible, but it misses the essential distinction between energy-containing and non-energy-containing matter.

2. Energy.

The significance of the distinction between energy-containing and nonenergy-containing substances lies primarily in energy relationships. Photosynthesis captures energy from sunlight and converts it to chemical potential energy stored in organic compounds (food).

Energy, however, is an abstract and difficult concept for most students. They tend to think about energy in vague terms, as part of everything that plants or people need. In order to appreciate the significance of energy in photosynthesis, they must learn to follow the path that energy takes and the changes it undergoes. Energy can change form. For example, light energy can be transformed into heat energy (notice the heat near a light bulb or the sun's light energy being changed into heat energy which warms the earth). Students must appreciate the critical importance photosynthesis plays in changing energy from light energy into another form -- chemically stored energy -- that is usable by living things.

3. Matter.

Biologists' conceptions of photosynthesis also depend on a chemical understanding of the nature of matter. Biologists make a distinction between energy (light, heat, chemically stored energy, sound, etc.) and matter. Photosynthesis is seen as a process by which light energy is used to change matter chemically -- a chemical change or chemical reaction. The substances involved are characterized as chemical compounds. In these chemical reactions, matter is changed but conserved. Scientists think of these chemical reactions as involving rearrangements of molecules which result in the formation of new compounds. Water molecules and carbon dioxide molecules are rearranged to form sugar molecules and oxygen molecules.

Most students, however, are not used to thinking about molecules, chemical formulas, or chemical reactions. In fact, they do not typically think about things they cannot see -- such as the idea that things are happening inside of plants other than water being sucked into the plant by the roots.

These invisible things and processes seem very mysterious to them and only vaguely understandable.

4. The Functional Nature of Scientific Explanations.

Consider these answers that students gave to another question about food for plants:

Question:	**Do plants need food? Why or why not?**
Susan:	Yes. They need sun, fertilizer, water, and soil.
Brooks:	Yes. It's like people, they can't live without food.
Ryan:	Yes. Because plants have to eat or they would die.

It is notable that the students' explanations of "why" don't really explain anything. Susan and Ryan's explanations are essentially circular; they restate in different words that plants need food. Brooks appeals to an analogy between plants and humans.

Scientists, on the other hand, strive for **functional** explanations (for example, "Plants need food because their cells use food as a source of energy.") Biologists think about the function that each substance plays in the internal workings of the plant. They seek to understand not just whether or not a plant needs a particular substance to stay alive; they want to know what happens to that substance inside a plant. How does the plant use it? Thus, an essential part of learning about photosynthesis is learning to develop appropriate functional explanations and definitions.

We have chosen to emphasize these four issues because the concepts they involve are absolutely essential for students to make real sense of photosynthesis. Unfortunately, most textbooks and courses fail to treat these concepts adequately, forcing students to memorize more technical vocabulary and advanced concepts before they have struggled with these fundamental ideas.

To help students understand the central ideas, we have carefully limited the amount of scientific terminology introduced, we have not discussed photosynthesis at a molecular level, and we have omitted discussions of the light and dark phases of photosynthesis. The production of oxygen in photosynthesis is de-emphasized in order to emphasize food production. In earlier research, we found that emphasis on these ideas often served only to distract students from the central issues.

C. Why does this unit provide a central question -- Shouldn't we use *students'* questions instead?: Teaching about Scientific Inquiry and the Nature of Science

Constructivist teachers often worry about the teacher selecting the central question for a unit: Shouldn't the question come from the students? In this unit, the teacher poses the central question to the students, and the class together wrestles with coming up with a satisfying answer based on empirical evidence as much as possible. Why did we organize instruction this way?

Through our research we have found that students need <u>explicit instruction about how to think in scientific ways.</u> We studied students in hands-on, inquiry-oriented classrooms who were actively engaged in generating hypotheses, doing experiments and collecting data, organizing data into graphs, and drawing conclusions. Unfortunately, many students spent 6 weeks in such a unit which was designed to teach them about plants' role as food producers and ended the unit with views of science such as Rachel's:

> I don't know <u>why</u> we kept measuring those plants. I mean it was fun for awhile.
> But I already knew that plants need light and now I know it again.
> --Rachel, 5th grade student

Students like Rachel not only failed to change their concepts about how plants get their food after six weeks of experimenting, graphing, and discussing. They also failed to develop important understandings about the nature of science.

What did Rachel learn about scientific inquiry and thinking? She learned that science involves a lot of activity that does not help you make any better sense of things. She learned that it is important to make careful observations and to record them accurately not because such care helps you develop better understandings, but because "that's what you do in science." Because Rachel did not develop better conceptual understandings about plants, the processes of science seemed meaningless and not worth the effort.

Thus, it is critical for the scientific processes to help students make important changes in their thinking for students to believe that scientific thinking is worthwhile. BUT it is not enough just to engage students in using scientific processes to develop good understandings. Students like Darla, a fifth grader who received instruction from this *Food for Plants* unit in its first version, were engaged in using scientific thinking processes and used these processes to develop rather deep understandings about how plants make their food. These students felt really good about how much their ideas had changed and grown. But they did not recognize the process of scientific thinking that helped them get there. They asked questions at the end of the year like Darla's:

> Ms. Roth, do you like arguing or something?

Darla knew that their teacher liked them to debate ideas using evidence from their experiments. But she thought this was just a personal quirk of her teacher. She did not connect this process with the nature of scientific work.

In later implementations of this unit, we have made explicit to the students the ways in which their work in the classroom represents scientific ways of knowing. Our research indicates that this enabled students not only to undergo significant conceptual change about plants, it also enabled them to develop deeper understandings of scientific ways of thinking and knowing.

So why does this unit provide the focus question instead of allowing the students to pursue their own interests? We are certainly in favor of valuing students' questions and providing opportunities for them to pursue their own questions. But there is also a very important role that work on a shared problem of significance can enhance student learning about plants AND about the nature of science. We point to two important reasons.

First, having students work together as a group toward consensus about a shared question of scientific significance provides a context in which the teacher can provide essential modeling and coaching about scientific ways of thinking. Conceptual change is not easy! Students need a teacher to help them figure out what it means to really understand something by using evidence and scientific ways of thinking. It is impossible for a teacher to provide enough of this kind of scaffolding if students are pursuing different questions.

Second, the group working towards consensus provides an excellent context in which to make explicit scientific ways of thinking, talking, and working. The class community can become a scientific inquiry community, and the teacher can make explicit ways in which this community is a scientific community. The emphasis on using evidence to debate and change ideas is a natural lesson that can be modeled in this group context.

D. Why should students care about how plants get their food?:
E. "Why do I have to learn this?"

WHY is this content important for students and literate adults to understand? Why is this content worth teaching? How would we respond to students who ask, "Why do we have to learn this?" Of course, we can easily respond that this content is in the *National Science Education Standards* and in the *Benchmarks for Science Literacy*. But how can we help our students see that it matters?

Students need to understand the concept, the idea of photosynthesis, so that they can develop a deep appreciation for and understanding of the importance of plants in our world, in ecosystems. Their lives to be enriched by a fascination with the inner workings of "everyday" things around them, like trees and grass and plants. Becoming <u>knowledgeable</u> about plants and their food important groundwork to help them become activists in support of ecologically sound practices -- people who will make good personal and political decisions about how to live within our biosphere. I also think a basic understanding of photosynthesis will enable students to be more socially smart about food shortage problems in the world.

So these are the big, long-term reasons for wanting students to understand these concepts. But what about in the here and now? In the here and now, students encounter plants around them, no matter where they live. Taking a closer look at plants and getting engaged with them in first-hand ways will awaken students to seeing their world around them in new ways. Plants provides a great context for "looking beneath the surface" of everyday things around us. And middle school students are fascinated by issues of growth and change. While that interest often focuses primarily on themselves, that interest can be tapped in the context of a study of plants.

E. Student Conceptions and Scientific Conceptions

The chart on the following two pages is one way of stating the main ideas for this unit. Our research indicates that most middle school students begin instruction with beliefs like those in the column labeled, "Naive Conceptions." These materials are designed to help students change to ways of thinking more consistent with scientific thinking as represented in the column labeled "Goal Conceptions."

COMPARING STUDENT CONCEPTIONS AND WAYS OF THINKING WITH SCIENTISTS' CONCEPTIONS AND WAYS OF THINKING...ABOUT PLANTS AND THEIR FOOD

ISSUE	GOAL CONCEPTIONS	NAIVE CONCEPTIONS
Plants' source of food	Plants make their own food internally using carbon dioxide, water, and sun in a process called photosynthesis. This is plants' only source of food.	Plants take in their food from the outside environment. Plants have multiple sources of food.
Nature of food	Food made by green plants is matter that organisms can use as a source of energy. It is an energy-containing material.	Food is the stuff that organisms eat, chew, take into their bodies.
Function of food in plants	Food supplies the energy that each cell of a plant needs for internal life processes (functional explanation).	Food is need to keep plants alive, to grow (nonfunctional explanation).
Matter transformation (chemical change)	Water and carbon dioxide taken into plants is changed into new matter as a result of a chemical reaction. In this chemical change, nonenergy-containing matter (carbon dioxide and water) is rearranged and recombined to make energy-containing food (glucose).	Water and carbon dioxide taken into plants are not changed. They are used unchanged to support two separate life processes -- drinking/eating the water and breathing the carbon dioxide.
Movement of matter	Water and carbon dioxide travel to cells in the leaf where they are involved in one process -- photosynthesis.	Water and carbon dioxide travel throughout the plant where they are used for two separate processes -- eating/drinking the water and breathing the carbon dioxide.
Energy transformation	During photosynthesis, light energy from the sun is changed into chemical energy stored in the food that plants make.	Plants need sun to live, grow, to be green. (No notion of energy being absorbed, needed, or changed) OR Plants get their energy directly from the sun -- this is their food. (No notion of light energy being transformed into food energy)

Importance of food-making process for plants	Most important product is food. This food is the plant cells' only source of energy.	The food-making process in plants is something they do for the benefit of people/animals. Plants are important because they give us oxygen and food.
Importance of food-making process for people/animals	Animals depend on plants for food as well as oxygen. Only green plants can change light energy from sun into chemical energy stored in food. Thus, only green plants can make energy-containing food that all living things need.	Plants are important because they make oxygen for people and animals to breathe. (Focus on oxygen production, not food production) Plants are also an important source of food for animals, but they are not the only source.