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Learning about Seasons: A Guide for Teachers and Curriculum Developers

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Abstract

The video *A Private Universe* evokes surprise and dismay among educators and scientists by demonstrating that even the brightest students fail to grasp a seemingly simple and fundamental concept—the reason for seasons. This literature review describes the findings of 41 studies that collectively illustrate why the concept proves difficult to learn, what is lacking in the standard sequence of astronomy education, and what promising methods might be brought to bear. Helping students understand the seasons at a deep level can provide a storyline that cuts across different domains of science, touching on global climate zones, the behavior of light, and connecting the model of Earth as a planet in space with observations that students can make on their own. We include a learning progression, intended to guide the development of instructional materials and assessments as well as questions for further research.

1. INTRODUCTION

1.1. Perceptions of the Problem

A series of research reviews in this journal have shown that students hold a great many misconceptions about fundamental concepts in astronomy; and although increasing age and education tend to reduce these misconceptions, even some highly educated graduate students and teachers express erroneous ideas similar to those of middle-school students (Agan and Sneider 2003; Kavanagh, Agan, and Sneider 2005; Kavanagh and Sneider 2006a, 2006b). In our experience, many college professors who read about these studies, or whose own students enter their classes with a poor understanding of fundamental concepts in astronomy, tend to attribute their students' misconceptions to a deficit in K–12 teachers' understanding, resulting in poor teaching and learning.

Perhaps the single most powerful piece of evidence to dispel this simplistic explanation is the remarkable video *A Private Universe* (Schnepps and Sadler 1989). This documentary presents Harvard graduates and even a professor, who all give the same wrong explanation for the seasons—that Earth is closer to the Sun in summer and further away in winter—which is typical of explanations given by much younger naïve students. The video then pans to a local high school where we meet a bright student who clearly paid attention in school, but nonetheless developed several unusual misconceptions, which survive despite individualized teaching by the creators of the video.

In our experience, showing this video to a mixed group of scientists and teachers invariably leads to a rich and productive discussion about possible explanations for why students have such difficulty understanding such an

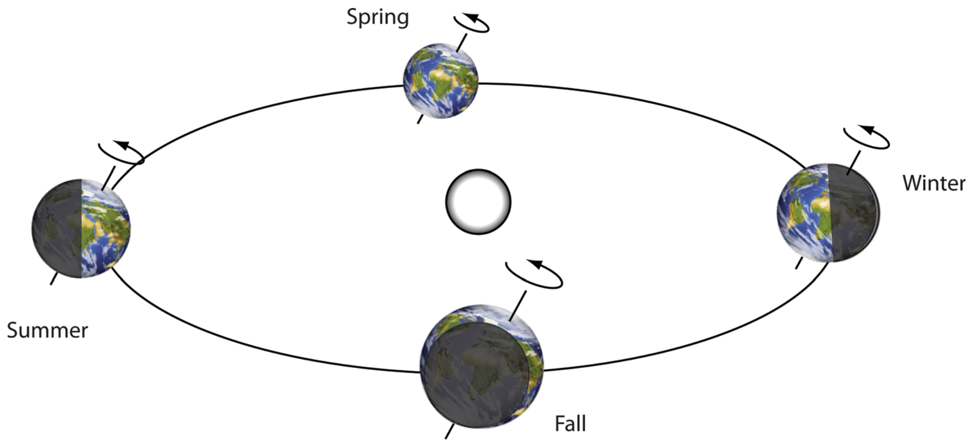

Figure 1. Typical diagram illustrating the cause of seasons in the northern hemisphere.

"elementary" concept as the cause of the seasons. For example, as suggested in the video, members of the audience commonly recall illustrations that they have seen in textbooks that give the wrong impression of Earth's orbit around the Sun by drawing it as an elongated ellipse in an effort to depict three dimensions (see Figure 1). Instead of paying attention to the tilt of Earth's axis, many students see the apparently elliptical orbit as confirmation of their prior belief that seasons are caused by the changing distance between the Earth and Sun.

In the years since the release of A Private Universe, a great deal of progress has been made by educational researchers to understand the nature and extent of misconceptions about the seasons. Spurred by the findings revealed in the video, educational researchers have developed and tested a variety of instructional strategies to teach the concept more effectively. This paper reviews the methods and findings of 41 studies that provide data relevant to the question of when and how children should be introduced to the concept.

In particular, we were struck with the large number of subconcepts that function as prerequisite understandings that students must have before they can fully understand the reasons for seasons. On the one hand this may discourage some readers because it illustrates the difficulty of helping students fully understand this concept. On the other hand, it is tremendously exciting to see how learning about seasons can provide a unifying thread, or storyline that brings together a number of important ideas in science, about light, energy, climate zones, and Earth's place in the solar system. We will lay out this set of connected concepts in Part 3. A Learning Progression for Seasons, which is designed to help teachers and curriculum developers build meaningful relationships between seemingly disparate concepts, in order to cultivate a richer understanding of seasonal variation on the globe.

In order to ground the subsequent review and discussion of recent research on this topic, we will expand upon the relevance of this topic for students and note in some detail how understanding of the seasons has changed through history by referring to earlier cultural explanations for the seasonal variation of climate.

1.2. Why Is It Important for Students to Learn about the Seasons?

If even the best students have difficulty understanding the causes of the seasons, why is it important that everyone be able to explain this phenomenon? We do not claim that failure to understand seasons will doom our children to a life of conceptual poverty. The Harvard students in the video of A Private Universe have probably done well, despite their inability to explain the real reason for the seasons. However, we propose four reasons why the concept of seasons should be part of every child's science education.

(1) The ability to connect observations, evidence, and explanation is the essence of science. Several of the learning studies reported in this paper demonstrate that seasons can provide an excellent means for teaching the essence of science. These methods include having students observe the changing path of the Sun in the sky during the year, gathering evidence to understand why the local climate changes as it does, and later formulating and testing alternative hypotheses about the changing interaction between the Earth and Sun during the year. In other words, if taught well, the topic of seasons can be a powerful

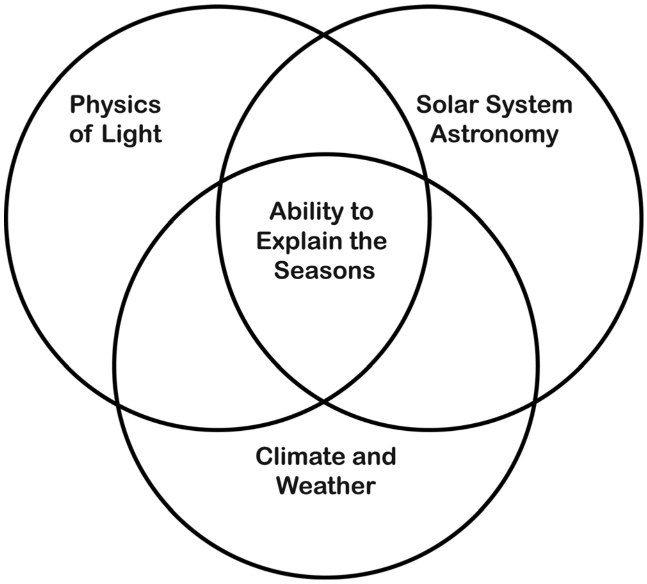

Figure 2. Understanding seasons weaves together threads from different parts of the curriculum.

means for enabling students to understand the nature of science, and its relevance to their everyday lives, by connecting small scale observations with large scale theoretical models and scaffolding students' emergent ability to transpose one view upon the other flexibly and interchangeably. To study seasons is a lesson in perspective-taking, as we have seen with the shape of the Earth and gravity concepts (Agan and Sneider 2003) as well as Moon phases and eclipses (Kavanagh, Agan, and Sneider 2005).

(2) Understanding climate is an essential step in understanding long-term climate change. One of the major international concerns is the relationship of human activities, such as burning of fossil fuels, to long-term climate change. In order for students to understand the scientific arguments surrounding this issue they must first understand how and why climate and seasonal changes differ in various regions around the globe. If we are serious about expecting our students to graduate from high school able to understand and connect the science underlying important environmental challenges, then understanding the natural reasons for seasonal change should be an essential goal. Being able to distinguish the causes of seasonal variation and the atmospheric science of global climate change is another important episode in expanding upon children's ability to develop and differentiate perspectives among or between theoretical models and provides an excellent foundation for future citizen scientists who will likely be called upon to develop and/or ratify political responses to the prospect of global warming in their generation.

(3) The concept of the seasons can serve to unite several science disciplines. Like many other topics in Earth and space science, understanding seasons means weaving together threads from different parts of the curriculum, including the physics of light, astronomy of the solar system, and weather and climate (see Figure 2). If one of our goals for science education is for students to understand the unity of the sciences, then teaching about seasons provides an excellent nexus.

(4) Understanding Earth as a planet is an essential element of modern culture. Explanations for the seasons have been a part of human culture for as long as we have oral traditions and written records. As illustrated in the next section, those explanations were rooted in a broader mental model of the universe as a whole and of our place within it. Teaching students about the seasons is one way of sharing our modern cultural heritage.

1.3. Historical Evolution of the Modern Concept of the Seasons

Initially mythological explanations were invented to explain the seasons such as the following story told by the Nez Perce Indians (Heady 1969). It is a story of conflict between the five sons of Youn (the cold) and the five sons of Lo-ki-ye-wah (the heat). The sons of Youn won a major battle, and the surviving daughter of Lo-ki-ye-wah retreated to the south, where she gave birth to a son. When the son grew up and went north to continue the feud, Ki-yote (the boss of all) intervened and declared that from now on it would not always be cold, nor always warm.

Perhaps the best-known story of the seasons in the western world is the story of Persephone, who was kidnapped by Hades and taken to live in the underworld as his wife. Her mother, the Earth goddess Demeter, went into mourning for her lost daughter and all green things died. Zeus could not leave the Earth to die, so he forced Hades to return Persephone. However, Hades tricked Persephone into eating four pomegranate seeds and because of this she was condemned to spend four months in the Underworld every year. During these four months, her mother Demeter mourns and no longer gives fertility to the earth.

The ancient Greek philosophers of a later period are credited with developing the first scientific explanation of the seasons without recourse to the supernatural. According to the model of the world described by Aristotle (384–322 BC) and later refined by Ptolemy (90–168 AD), the universe consists of a huge sphere of stars, containing nested crystal spheres. Each sphere carries one of the seven known planets (Sun, Moon, Mercury, Venus, Mars, Saturn, and Jupiter). In the center was the sphere of the Earth itself. The sphere of the stars was observed to rotate around the Earth once a day.

As observed from Greece, some of the constellations rose far to the South, never rose high in the sky, and spent a very short time above the horizon. Other constellations followed a much longer path in the sky, rose far higher, and spent a much longer time above the horizon. The planets were seen to "wander" among the constellations, and to share the motion of the stars where they happened to be at any given time. The Sun (considered to be a planet) was seen to wander among twelve constellations (of the Zodiac) making a complete circuit of the sky once a year (see Note 1). In the winter the Sun was located near constellations that rose very low in the sky and stayed up only a few hours, so the weather was cold. In the summer the Sun was located near constellations that rose much higher in the sky and stayed up for a longer period, so it could warm the Earth more. For more than 2000 years the Sun's annual motion among the stars remained the scientific explanation (as opposed to the mythological explanation) for the seasons.

Copernicus was the first to provide a nearly modern explanation for seasons. Chapter 11 of his book, *De Revolutionibus Orbium Coelestium* (*On the Revolutions of the Heavenly Spheres*) (Copernicus 1543), describes two motions of the Earth and their consequences. The daily rotation of the Earth on its axis makes the Sun, Moon, and stars *appear* to move around the Earth once a day, and the Earth's annual motion around the Sun, coupled with the tilt of its axis with respect to the plane of its orbit around the Sun,

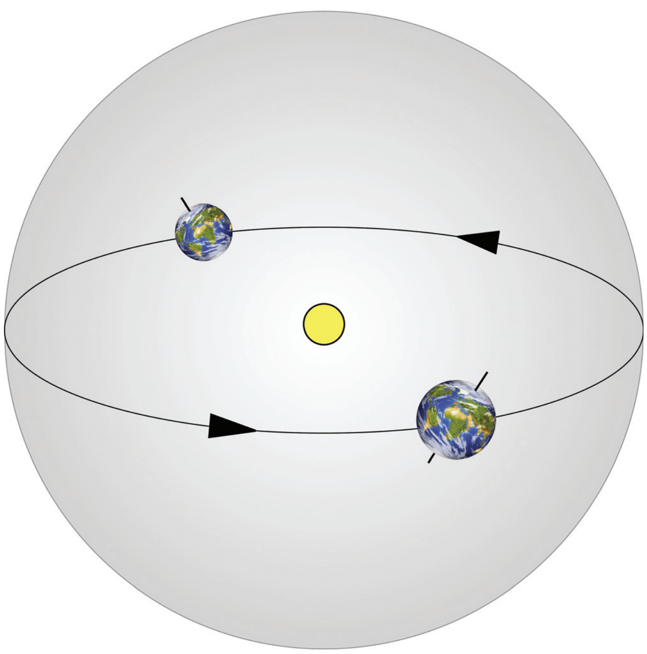

Figure 3. Copernicus thought that Earth was embedded in the surface of a crystal sphere, so that the orientation of its axis would change as it circled the Sun. The crystal sphere is illustrated by the large sphere in this image. As the large sphere rotates once a year, Earth's axis will slowly change its orientation. Not shown is a counter motion that Copernicus proposed to keep the axis pointed in the same direction so as to explain the seasons.

causes the *observed* differences in the path of the Sun through the sky, and changes in the number of hours of daylight.

As Thomas Kuhn points out in *The Copernican Revolution* (Kuhn 1957), despite this modern explanation of the seasons, Copernicus still operated within the tradition of Aristotle and Ptolemy, and assumed that the planets were all embedded in crystal spheres. As shown in Figure 3, he imagined that as Earth's sphere revolved around the Sun; the axis would gradually change its orientation in space. As we will see later in this paper, many students who have learned about Earth's tilt share this misconception, albeit for a different reason. They think that the Earth's axis changes its orientation so that first one hemisphere and then the other points toward the Sun. Copernicus realized that, if this were so, Earth's seasons would *never* change, as one hemisphere would always be pointed toward the Sun. He proposed a third motion that would counter this shift, keeping Earth's axis in precisely the same orientation—always pointed toward the north and south celestial poles—as it circles the Sun.

1.4. Theoretical Perspective

In order to be explicit about the perspective of this review, this section briefly describes a framework developed by Stella Vosniadou and William Brewer as a way of understanding and classifying children's changing ideas about astronomical concepts. The framework is consistent with broader constructivist conceptions of how people acquire knowledge. As described in their seminal paper (Vosniadou and Brewer 1994) and recently refined (Brewer 2008), children enter the classroom with certain presuppositions as a result of daily interactions with the world. As they are exposed to scientific ideas in their classroom settings they synthesize this new information with their extant presuppositions to formulate novel mental models or theories. As they continue to learn, they modify their synthetic models so that they gradually approximate the scientific concepts held by knowledgeable adults.

The body of research reviewed in the next section reveals that students hold a great many alternative conceptions, and it is difficult to predict the path that any individual's thinking will take. The teacher's job is to move students from their naïve and initial theories and models toward a more scientific understanding. That involves not only providing compelling experiences aimed at teaching a scientific explanation of seasonal phenomena, but also the ability to listen to students' discussions so as to understand their current mental models.

Finally, as the studies reviewed in this paper illustrate, it is important for teachers to recognize that, despite their best efforts, some students will not fully understand the reasons for seasons as a result of any one lesson, but instead will acquire new synthetic and alternative theories and models. It is best to celebrate such cognitive gains as stepping stones toward a more adequate understanding, rather than be disappointed if all students do not master challenging concepts immediately.

2. RESEARCH REVIEW

As we reviewed the 41 studies, patterns began to emerge. Status studies found the same initial, synthetic, and alternative theories in a wide variety of different countries with students of different ages and educational levels. Learning studies established the age at which students could attain a given level of understanding, and identified instructional methods that overcame the misconceptions of most students. This research also provided criteria for determining whether or not a student "understands" why we experience seasons.

We realize that these are not the only studies that provide useful information about children's and adult's understanding of seasonal change. The search engines that we employed (ERIC and Google Scholar) would have missed papers that did not include our list of key words, and in fact the peer review process revealed several additional studies. However, our finding of similar patterns among several studies suggests that we have uncovered sufficient information to draw valid conclusions.

It is also important to point out that this paper does not describe all 41 studies in detail. Rather, we selected studies that we judged to provide the most useful information to curriculum developers, teachers, and other educational researchers. In cases where three or four studies provided the same essential information, we chose to report the study that we judged to be most persuasive. The list of studies that we consulted appears in the References.

2.1. Initial Exploration of Children's Ideas about the Seasons

Piaget (1929) documented changes in children's conceptions of the world over time in his seminal book, *The Child's Conception of the World*. Asking children ages 5–9 why it is cold in winter produced a number of associations with things that are cold. In the following examples the children's ideas are in *italics*.

> Roc (6): Why is it cold in winter? *Because there is snow*. What is it that makes the cold? *The snow*. If there were no snow would it be cold? *No*.
>
> Hend (9): Why is it cold in winter*? Because there is wind*. And what about those days when there is no wind? *Then it's because of the clouds, which break up that makes snow and that makes it cold.*
>
> Older children, ages 8–13, revealed a later phase, in which students associate winter and cold with the absence of the Sun.
>
> Baud (13): Where does the cold come from in winter*? Because of the wind*. Isn't there a wind as well in summer? *It's because the air is cold*. Why is the air cold in winter*? Because there's no Sun.*
>
> Schaw (10): Where does the cold come from? *Because there's no Sun*. Isn't there any Sun in winter? *No.* Where is it? *Behind the clouds.*

Piaget's pioneering studies not only identified an important topic for research—children's explanations of natural phenomena—he also developed structured interviews as a very powerful means for understanding how children view the world, which would later be used to understand how children's ideas change—or failed to change—as a result of instruction.

2.2. A Broader Picture Emerges

Although there were a few studies that touched on children's understanding of seasons in the 1970s and 1980s, many more studies were conducted in the late 1980s and 1990s, primarily to document students' understanding of seasons after typical textbook lessons in school. We classify these as "status" studies since they do not compare students' understanding before and after a given treatment or in comparison with alternative methods—they only reveal the state of understanding of students' current knowledge as a result of normal schooling.

Baxter (1989) interviewed 20 British students and collected questionnaire data from 100 students, ages 9–16, to determine the variety and prevalence of students' ideas about seasons, among other topics in astronomy. The researcher identified six misconceptions: (1) Cold planets take heat from the Sun; (2) heavy winter clouds stop heat from the Sun; (3) the Sun is further away from the Earth in winter; (4) the Sun moves to the other side of the Earth to give them summer; (5) changes in plants cause the seasons; and (6) seasons are due to Earth's axis being set at an angle to the Sun's axis. For the most part young children's ideas involved near and familiar objects. Older children gave explanations involving astral bodies changing their positions. However, among all age levels, the most common explanation was that Earth is closer to the Sun in summer and further away in winter.

Schoon (1992) administered a questionnaire to 1213 elementary, secondary, and adult students in the United States, and found that the most common misconception about the seasons was that Earth is closer to the Sun in summer, which was given by 77.6% of the respondents. Also, 82.4% of the total sample believed that the Sun is overhead at noon every day. The percentage increased at older ages suggesting this idea is learned.

Kikas (1998) investigated the impact of astronomy education on 20 10–11 year-old students in Estonia, where fifth graders are taught about seasons. The lessons were formal and traditional in that the children were expected to memorize information. During interviews conducted two months after instruction 10 of the children (50%) explained the seasons using the same wording as in the book: "The sun warms the Southern and Northern Hemispheres differently because the Earth's axis is tilted and the Earth revolves around the Sun." Seven of the children confused the explanation of the day/night cycle with the explanation of the seasons, while the other three gave various responses. The same students were interviewed as 9th graders. After a 4 year interval, just four of the students remembered the explanation of seasons learned in the fifth grade. The authors concluded, “The impact of teaching where the stress is on memorizing may seem great shortly after learning. But such teaching is not effective in a longer perspective.”

In order to understand how students reason about the seasons, Kikas (2005) conducted an in-depth study of sixth-grade students (ages 11–13) in Estonia, who had learned about the seasons the year before, and who had studied light in physics and climate zones in geography class. A total of 104 students were selected to participate in small group discussions, with four same-gender students per group. The researcher recorded the students’ class discussions, such as the following in which students are talking about their choice of a highly elliptical orbit:

> Anu: Here it is winter.
>
> Riin: Here it is definitely Spring.
>
> Kai: No, this is not how it was in the physics book.
>
> Irja: But there’s really no difference.
>
> Anu: Here it is summer.
>
> Kai: In the physics textbook it was here.
>
> Anu: Let’s do it as it’s on the compass.
>
> Kai: What do you mean?
>
> Anu: Well, on the compass winter is up—the North Pole is above and the South Pole is below.

Kikas concludes by noting that, like adults, children strive for consistency among many different ideas to make sense of the world. They integrate the ideas drawn from what they learn in books, from their teachers, and their everyday experience in building mental models to explain phenomena.

The same researcher (Kikas 2003) also conducted a study of 132 first-year university students in Estonia, and found that only 16% of the students gave a scientifically acceptable answer to questions about seasons. In a status study of teachers in Estonia, Kikas (2004) found that although most teachers understood that the tilt of Earth’s axis was an important factor in seasonal change, many of the teachers believed that the tilt brought Estonia closer to the equator. Others thought Earth’s orbit (and therefore proximity to the Sun) to be a causative factor. These findings confirm the constructivist view that neither children nor adults are likely to fully understand a concept simply by being asked to memorize an explanation.

Danaia and McKinnon (2007) administered the Astronomy Diagnostic Test to 1920 7th, 8th, and 9th graders from 30 schools in Australia. The test was modified for use in the Southern Hemisphere, and also included additional items asking students to draw their ideas about phenomena, including the cause of seasons. Even though seasons is taught in grades 3 and 4 and again in grade 7 in Australia’s mandatory science curriculum, the most common conception was that seasons are caused by Earth’s changing distance from the Sun, expressed by 85% of 7th graders, 89% of 8th graders, and 92% of 9th graders.

Roald and Mikalsen (2001) interviewed 26 deaf students between the ages of 7 and 17, and 13 hearing students between the ages 9 and 10, using sign language to interview the deaf children. Only two of the students gave scientifically correct but incomplete explanations for the seasons. There were no significant differences in percentage of correct responses by the deaf and hearing students.

Trumper (2000, 2001a, 2001b, 2001c, 2003, 2006) conducted a series of studies in Israel on students’ and teachers’ understanding of astronomy concepts, including seasons, using a multiple-choice test. Subjects included students at the junior high, senior high, and college level; future primary school teachers; and future high-school teachers. Although many students correctly answered that seasonal change is due to the tilt of Earth’s axis as it revolves around the Sun, when asked why it is warmer in summer than in winter, most reverted to nonscientific explanations, the most common being that Earth is closer to the Sun in summer than in winter, and that Earth’s axis flips back and forth as Earth revolves around the Sun. Another important finding was that a large percentage of students at all levels believed that the Sun can be seen overhead at noon every day, suggesting that learning about seasons is primarily through books and lectures rather than observing the Sun in the sky.

Trumper's findings highlight a common misconception among educators: That if children attribute the cause of the seasons to the tilt of Earth's axis, then they understand the explanation for why it is warmer in summer than in winter. In fact, children may be confused in a number of ways concerning *how* Earth's tilt causes the seasons. We will learn more about these alternative explanations in subsequent sections.

Together, these findings demonstrate that the widespread misconceptions about the seasons vividly illustrated in A Private Universe are not confined to the United States. Students from diverse countries and cultures encounter the same learning difficulties, and even develop some of the same alternative conceptions about the seasons.

2.3. Learning Studies with Children

A number of learning studies have shown that seasons is a very difficult concept for students at the upper-elementary and middle-school level. For example, a study in England, reported in several publications (Sharp and Grace 2004; Sharp and Kuerbis 2006; Sharp and Sharp 2007), described the results of a constructivist astronomy unit in which seasons was one of the topics. The unit was taught to 31 students between the ages of 9 and 11, who were compared with 31 control subjects of the same age in the same school. All 62 students were interviewed immediately before and after the unit, and the experimental subjects were interviewed again three months later. 94% improved their mental models of the solar system, but only 48% were able to explain the seasons right after the class, and only 29% retained their knowledge four months later.

Salierno, Edelson, and Sherin (2005) conducted an in-depth qualitative study of three fifth-grade students who had studied an Earth science unit that included instruction on the seasons. The treatment was a middle-school curriculum unit that combined computer-supported investigations of geospatial data with hands-on laboratory activities. Results were as follows:

> Alice began with an unusual misconception that different areas of Earth are warmed by different parts of the sun. After the unit she correctly understood that the equator is the warmest part of Earth because the surface is almost 90° to incoming sunlight. However, she was confused on other points, and when asked why it is cooler in areas like Alaska, she explained that light would have to curve to get there.
>
> Matthew shifted his thinking during the unit from the misconception that the side facing the Sun has summer, to another misconception, that because of its orbit, Earth is closer to the Sun in summer and further away in winter.
>
> Alex changed his initial ideas about "heat-trapping gases" causing differences in temperature to the idea that the equator "gets more sunlight" which is "more direct." However, he was unable to explain what he meant by "direct" and did not mention the angle at which sunlight struck the Earth or refer to area or intensity of light. His final understanding was that different sides of the Earth face the Sun in different seasons.

The authors speculated that the fifth-grade students were not developmentally ready to learn about seasons. They also noted that the curriculum did not address prerequisite understandings (such as the Earth's daily and annual motions and the effect of angle of incoming sunlight on temperature), and that common misconceptions were not addressed by the instructional program.

Dunlop (2000) gave a written pre- and post-test to 67 children, ages 7–14, who attended a planetarium program in Auckland, New Zealand that provided explanations for the day/night cycle, moon phases, and seasons, using an Earth-Moon-Sun model. The children whose responses included references to Earth's tilt or a combination of tilt and orbit increased from 25% on the pretest to 45% on the post-test. However, as described in several studies below, reference to "tilt" does not necessarily mean that students understand how the tilt of Earth's axis results in seasonal climate change.

Tsai and Chang (2005) compared a traditional approach with a constructivist approach that consisted of a 2-day unit in which 9th grade students first expressed their current understanding of seasons and were then confronted with a discrepant event—that Earth is slightly further away from the Sun in June and July, and closer to the Sun in December and January. The teacher then challenged the students' misconceptions by explaining that if the

Earth were closer to the Sun in summer, and further away in winter, then seasons in the northern and southern hemispheres would occur at the same time; and they do not. Interviews conducted 1 week after instruction showed that more students in the experimental group understood the scientific causes of seasons (76% vs. 68%) and more retained their understanding when interviewed again after 2 months (65% vs. 41%) and once again after 8 months (56% vs. 23%). Further analysis showed that students who learned with the traditional method were able to recall the essential facts, but were less able than students in the experimental group to understand the concept at a deeper level.

Wild and Trundle (2010) used a quasiexperimental study to compare the effectiveness of an inquiry-based instructional program with a traditional unit. The study involved seven visually impaired students in 7th grade, including three control subjects, who learned about the seasons from text and lecture, and four who learned about the seasons from the LHS GEMS unit, the *Real Reasons for Seasons*. Interviews conducted prior to instruction found that none of the students expressed a scientific understanding of the seasons. After instruction there was no change in the control group, while all four experimental subjects gave scientific explanations, including two who met the criteria for full understanding, that: (1) The Earth moves in an orbit around the Sun; (2) Earth's axis is tilted; (3) the tilt in relation to the orbit results in different places on Earth receiving various amounts of sunlight throughout the year; and (4) the varying amount of sunlight results in changes in temperature and hours of daylight. Although the number of subjects was small, this research is of special note because it is one of the few learning studies that succeeded with students at the middle-school level, and one of the few that tested students' abilities to explain how the tilt of Earth's axis causes seasons.

Lynch *et al*. (2006) conducted a quasiexperimental study with more than 2000 middle-school students who used the same instructional unit as Wild and Trundle—the *Real Reasons for Seasons*. While students in both control and experimental conditions improved their understanding of seasons, those in the comparison group improved their understanding more. Observations indicated that the comparison unit was not a "traditional" unit, since the teachers used videos, hands-on activities, observations of phenomena, and discussion among small groups of students. The study was repeated the following year with the same result. The researchers speculated that the GEMS unit may have focused too strongly on helping students overcome misconceptions, and be too teacher-directed, without allowing sufficient time for the students to "talk science with one another."

Overall, the results of learning studies with upper-elementary and middle-school students have had mixed and generally discouraging results. While some students seem to improve in their understanding, studies with delayed posttests show that many of those who seem to understand the concept immediately after instruction regress to earlier ideas after a few months. Nonetheless, qualitative studies demonstrate that students do change their thinking as a result of instruction. This is an important finding that was explored in considerable depth by Sadler (1998). We emphasize the importance of this study by discussing it in some depth in the next section.

2.4. Stepping Stones to Seasons

Sadler and his colleagues developed an astronomy course for high-school students called *Project STAR*. The final exam included multiple-choice questions in which the distracters were drawn from research on common misconceptions. In analyzing the results of the test taken by 1250 students who had completed the course, Sadler (1998) used the method of item-response modeling to investigate which distracters were chosen by students of different ability levels. The results are shown in Figure 4.The vertical axis of the graph is the percentage of students who selected a given response, and the horizontal axis represents performance in standard deviations above and below the population-mean score on the test.

Notice that the question does not require students to explain the seasons in terms of Earth's tilt, but only to recall that the Sun is higher in the sky during the summer. In other words, students in Project STAR are expected to at least explain the seasons from the Earth-bound perspective (i.e., that the Sun is higher in the sky during summer).

In the graph, notice that at the lowest ability levels about half of the students fail to answer the question, while the other half are divided among all the answers, suggesting random choice. Among students with average scores, the most common answer is A that the distance between the Earth and Sun changes, indicating the

Question: The main reason for its being hotter in summer than in winter is:

A. The Earth's distance from the Sun changes.
B. The Sun is higher in the sky. (Correct response)
C. The distance between the northern hemisphere and the Sun changes.
D. Ocean currents carry warm water north.
E. An increase occurs in "greenhouse" gases.

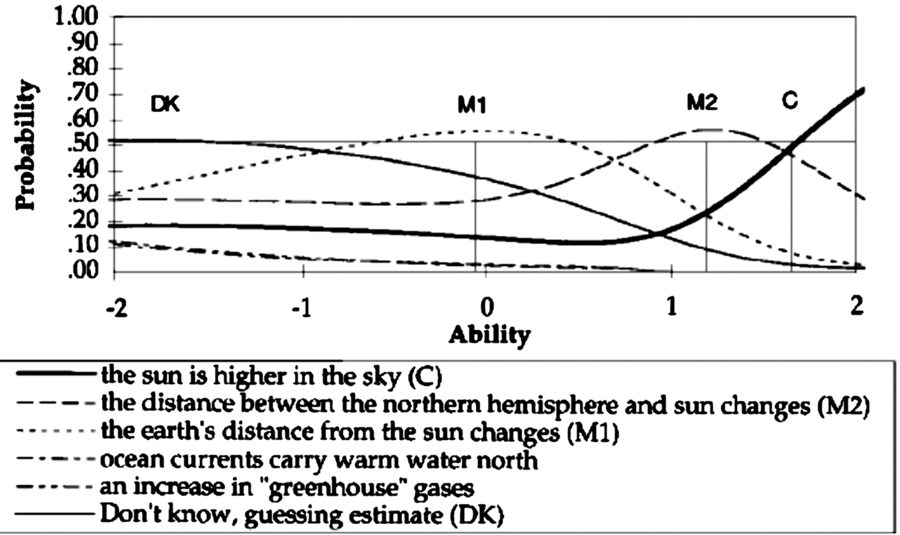

Figure 4. Distracters chosen by students in response to a question about the seasons, as a function of ability level.

misconception that Earth's orbit is highly eccentric. This is also the most common misconception reported by nearly all other researchers.

Among students with higher-than-average scores, around one standard deviation above the mean, the most common response is that the distance between the northern hemisphere and the Sun changes, suggesting that students with high ability know that the tilt of Earth's axis is involved in explaining the seasons, but think the tilt brings the northern hemisphere closer to the Sun in summer. It is only the students with the highest performance, near two standard deviations above the mean, who correctly respond that it is warmer in summer because the Sun is higher in the sky.

Sadler interprets this finding in a positive light, noting that most students require a long time to acquire certain concepts, such as seasons, and that "Moving from thinking that the seasons are caused by an elliptical orbit to that of a hemisphere distance differential is a positive step." He concludes that alternative conceptions should not be treated as errors, but rather as "stepping stones to scientific thinking."

2.5. Interpreting Orbit Diagrams

Several researchers have speculated that when students see diagrams in a textbook of what appears to be Earth's elliptical orbit around the Sun, they assume it is summertime when Earth is close to the Sun, and winter when further away (e.g., Schnepps and Sadler 1989; Ojala, 1992, 1997; Kikas 1998). Lee (2010) investigated this hypothesis in a carefully designed quasiexperiment. A total of 652 9th grade students in the United States were given a short written assessment. First they answered two questions by completing the sentences: (1) "It is warmer in summer because…" and (2) "It is colder in winter because…." They were then shown a diagram illustrating the cause of the seasons, and then asked to answer the same two questions again. Each student received one of six diagrams. Diagram 1 showed Earth's orbit around the Sun as a circle. Four Earth's were shown, each labeled with one of the seasons. Diagram 2 showed Earth's orbit as an elongated ellipse. Earth was shown in four position, with an indication of its tilted axis, and with the same four season labels. Diagram 3 was similar to Diagram 2 except the orbit was further elongated with overlapping images to emphasize perspective in the drawing. Diagrams 4, 5, and 6 were the same as 1, 2, and 3, except that the images of Earth were shaded to show which sides were in daylight and which were in darkness.

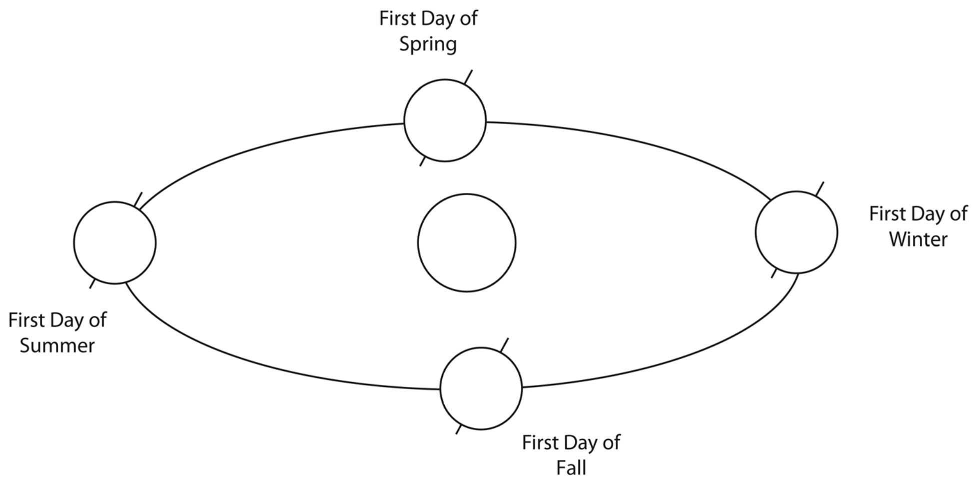

Figure 5. Diagram that Lee (2010) found most likely to attract students to the tilt explanation of seasons.

By comparing the students' responses before and after they saw the diagram, the researcher was able to infer changes in the students' explanation of the seasons as a result of the very short intervention—simply looking at the diagram. The findings failed to support the hypothesis that an elongated orbit diagram encourages the misconception that Earth is closer to the Sun in summer. Instead Diagram 2 (shown below as Figure 5) tended to attract more students to the explanation that Earth's tilt was important in explaining the seasons.

The study also showed that the diagrams that used shading to indicate which parts of the Earth are in daylight, and which are in shadow, had the counterproductive effect of encouraging the misconception that seasons are caused by the spinning of Earth on its axis (which explains the day-night cycle, but not seasons).

Lee concluded that the interaction between students' prior conceptions and various cues in a diagram is not simple or easy to predict. However, the finding that many students' ideas changed after looking at a single diagram suggested that diagrams can be a useful intervention that teachers can use with appropriate scaffolding, such as pointing out relevant cues, and thinking out loud about how to make sense of the diagram.

2.6. Light and Energy As Essential Prerequisites

The tilt of Earth's axis as it circles the Sun has two effects—length of daylight hours and intensity of sunlight. Length of daylight can be physically modeled using globes in a darkened room. However, the intensity of sunlight as a function of the angle at which sunlight strikes the Earth is more difficult to illustrate. Textbooks that address this issue generally use some sort of diagram showing how sunlight spreads out over a larger area as the angle becomes shallower (see Note 2).

Galili and Lavrik (1998) studied students' understanding of the effects of changing the angle of sunlight by presenting 72 10th-grade physics students with two open-ended questions: To explain the cause of the seasons, and to comment on a sketch showing two light bulbs illuminating a book—one from overhead and one from the side. The researchers classified the students' responses to both questions as due to differences in distance, angle of illumination, or a hybrid of the two. The distance scheme was most frequently applied to the season's task, while the orientation scheme was most frequently applied to the illumination task. The authors interpreted their findings by noting that few students understood light to be a form of energy, a misunderstanding that may result from the common depiction of light in textbooks as insubstantial rays.

A related problem is use of the term "direct" vs. "indirect" rays of the Sun, as in the following quote from *Science for All Americans*:

> The Earth's one-year revolution around the Sun, because of the tilt of Earth's axis, changes how directly sunlight falls on one part or another of Earth. This difference in heating different parts of the Earth's surface produces seasonal variations in climate (Rutherford and Ahlgren 1989, p. 43).

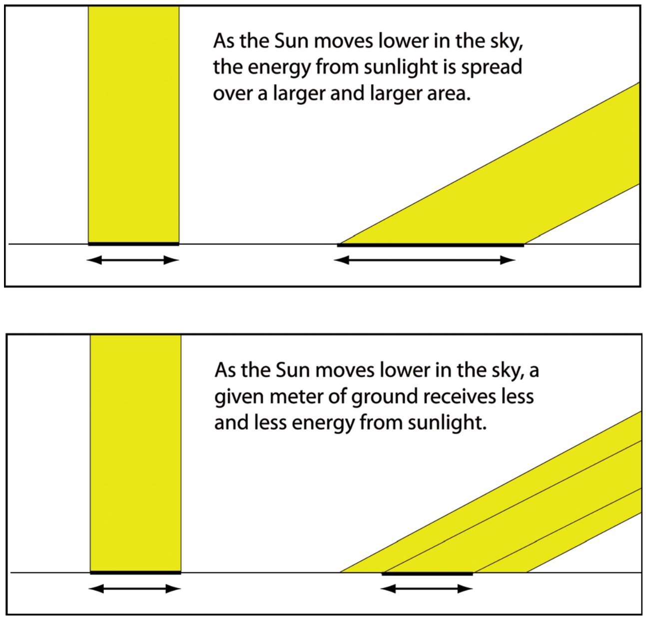

Figure 6. Alternative diagrams for illustrating how the intensity of sunlight is reduced as the Sun moves lower in the sky.

Use of the term direct or indirect rays, now widely used in textbooks to explain seasons, seemed to present a major obstacle to the bright student who had persistent difficulties in the A Private Universe video. Many students are simply unable to translate these terms into observed phenomena. Some researchers have used the terms “shallow angle” or “steep angle” or simply refer to the Sun as “higher” or “lower” in the sky.

The usual approach to demonstrating this idea, shown in some textbooks, is to show how a beam of sunlight spreads out further as the Sun approaches the horizon. An alternative approach that may be more helpful is to focus on a square meter of ground, heated by a beam of sunlight, and show how more and more of the beam falls outside the square as the sun moves lower in the sky. Diagrams illustrating these two approaches are shown in Figure 6.

A common textbook illustration comparing the Sun’s path in the sky during summer and winter as viewed from the temperate zone is shown in Figure 7. This illustration correctly shows that the rising and setting

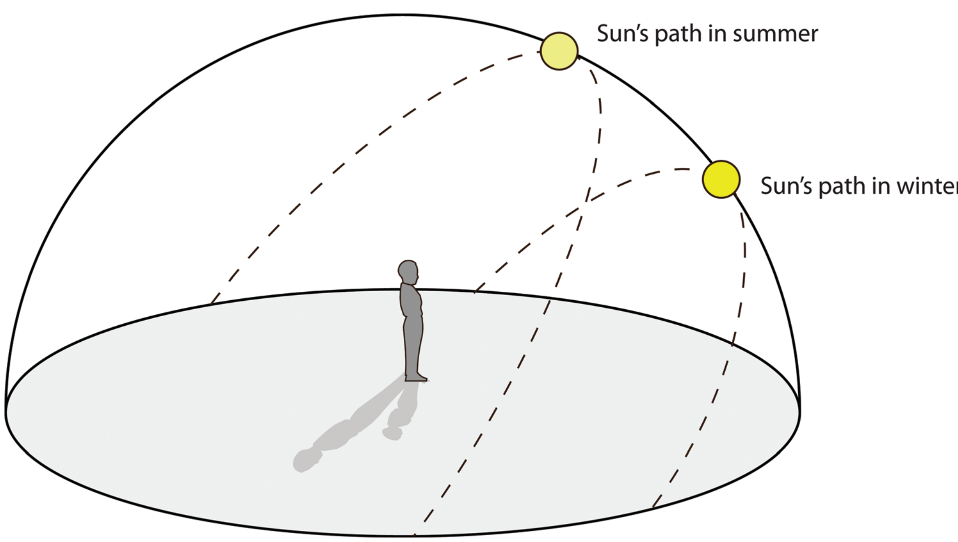

Figure 7. Illustration of Sun’s path in summer and winter.

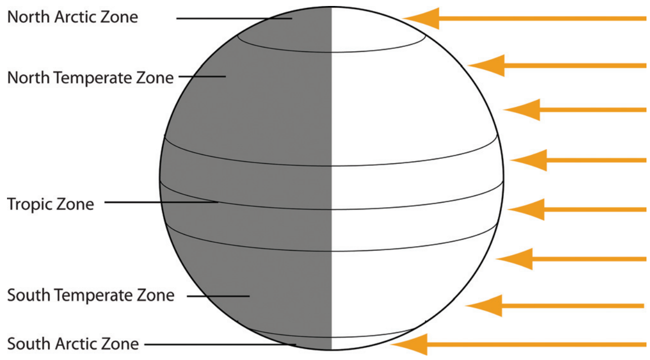

Figure 8. Diagram showing how sunlight varies within climate zones.

points of the Sun change through the year, and the Sun reaches a higher altitude at noon in the summer than during winter. It also correctly shows that noontime shadows in summer are shorter than noontime shadows in winter.

While this illustration can be useful, it can also be easily misinterpreted. At the elementary level it reinforces a common misconception that people live on a flat platform in the middle of the spherical Earth (Agan and Sneider 2003). Even for students who understand that the disk represents a small region on Earth's spherical surface the diagram distorts the distance between the Earth and Sun. So it can easily be misinterpreted to indicate that sunlight strikes different parts of the local landscape at different angles. Consequently, such diagrams should primarily be used in conjunction with students' actual observations of the Sun's changing path in the sky during the year.

One more diagram that is used to illustrate the effects of different angles of illumination is shown in Figure 8. This can be a very useful diagram to illustrate why there would still be climate zones if Earth's orbit were not tilted at all. As a consequence of the Sun's great distance, Sunbeams are parallel. These parallel beams strike the surface at a very shallow angle in the arctic zones, at a steeper angle in the temperate zones, and nearly perpendicular within the tropics.

Diagrams like this could help students such as those encountered by Salierno, Edelson, and Sherin (2005), who thought light had to "curve" to reach the arctic regions. However, this diagram also can be misinterpreted, as many students have difficulty imagining themselves on the Earth in the diagram, and envisioning how a person in each climate zone would see the Sun move through the sky on the same day. Given the complex spatial reasoning that is required to interpret such diagrams, we turn next to a series of studies that have used computers to help students make these connections for themselves.

2.7. Using Digital 3D Modeling to As an Aid to Learning

In recent years powerful new technologies have been invented to help students learn concepts that involve complex spatial visualization. This section reviews three such efforts.

Bakas and Mikropoulos (2003) developed a virtual interactive simulation of the Earth-Sun-Moon system, which models the sizes and distances of celestial bodies and enables students to "fly" through the solar system in a virtual spacecraft. The students are able to control various aspects of the virtual world, including rotation and revolution rates, and can change certain parameters, such as the inclination of Earth's spin axis, and see what will happen. The effectiveness of the educational experience was measured through structured interviews with 27 students aged 12–13 in Greece. The students were very enthusiastic about the experience. All of the students gave correct answers to questions about the motions of the Earth, and all but four of the students had a good grasp of the causes of the seasons.

Kücükozer, Kücükozer, and Yürümezoglu (2009) investigated the use of three-dimensional (3D) computer modeling and a predict-observe-explain teaching strategy as a means for helping students understand the causes of astronomical phenomena, including seasons. Subjects were 131 students, ages 11–13, from two different schools in Turkey. Instruction began by asking the students to make predictions. They then used 3D modeling software to find out if their prediction was correct. Finally, the students were asked to explain how well their predictions fit their observations using the simulation. A conceptual astronomy test measured students' understanding before and after treatment, and interviews were conducted with eight students after instruction. The percentage of students who gave correct answers to questions about the cause of the seasons increased from 5% on the pretest to 47% on the posttest.

Barnett *et al*. (2000) assessed growth of university students' conceptual understanding of seasons as a result of an experimental astronomy course in which the students used software that enabled students to construct a 3D model of the Earth-Moon-Sun system and observe it on the computer screen from different viewpoints. Participants were eight undergraduates who were interviewed before and after the course on the causes of seasons and other astronomical concepts. Six of the eight students began the course with a range of alternative mental models of the seasons. After the course, every student identified the tilt of the Earth's axis as the primary cause of the seasons and had a fairly accurate explanation. However, only three students included the importance of the angle of incidence of sunlight on the Earth's surface as an important factor in why it is warmer in summer than winter.

In summary, use of 3D computer simulations does indeed appear to help students understand the reasons for seasons. However, as with any other form of treatment, it is essential that the curriculum designers determine each of the subconcepts they want to address, to design the experience so that students will learn those concepts, and that they assess learning on each subconcept.

2.8. Learning Studies with Teachers

Given that students are unlikely to learn the correct reason for the seasons if their teachers do not already possess a clear understanding of the concepts, a number of researchers have conducted studies with teachers. Status studies of teachers found the same misconceptions as in prior studies of middle-school, high-school, and college students (Ojala 1992, 1997; Mant and Summers 1993; Summers and Mant 1995; Atwood and Atwood 1996; Kikas 2004). Here we highlight learning studies that used especially effective teaching methods.

Parker and Heywood (1998) studied a total of 89 teachers in England learning astronomy in three different programs and found that after concluding their programs, only 11 participants were able to provide a scientific explanation of seasons. On the other hand, Atwood and Atwood (1997) interviewed 51 college seniors bound for a teaching career before and after they engaged in a short workshop on the day/night cycle and seasons, using physical models, and found that the number who expressed a scientific understanding increased from 2% to 82%.

Sebastià and Torregrosa (2005) conducted a professional development program for 132 future elementary teachers in Spain. Rather than emphasizing the tilt model the instructors emphasized phenomena that can be observed, such as the Sun's changing path in the sky and the annual pattern of day length. Instruction involved a "data-to-model" approach in which students made observations and then developed a theoretical model consistent with their observations. Students were guided in making the most useful observations and in "reinventing" the heliocentric model. The program was evaluated using a pre-post questionnaire, which included both multiple-choice items and short essay questions. Prior to instruction few participants knew how the Sun's path in the sky changed through the year, and 80% used the changing distance between the Earth and Sun to explain annual changes in day length. After the course most students understood the scientific explanations for night and day and seasons, and were able to make complex predictions, such as the path of the Sun on the same date but at a different latitude, or which months would have approximately the same number of daylight hours.

Trumper (2006) compared 119 university students studying to be teachers, enrolled in a traditional astronomy course, with 19 junior-high-school technology teachers who were being retrained as science teachers, enrolled in a constructivist program. The experimental treatment engaged students in systematic observations of the Sun's rising and setting points and path in the sky, hands-on activities with flashlights to observe the effect of different angles of incidence, confronting the teachers with evidence contrary to their beliefs, presenting a clear scientific explanation using models and/or analogies, and demonstrating how the scientific model provides a better account of observations than prior beliefs. The only group that improved significantly from pretest to post-test was the experimental group of teachers who improved their performance on questions about the seasons from 28% correct on the pretest to 85% correct on the post-test.

Frede (2008) conducted a professional development program for 20 preservice elementary teachers in France. The teachers were presented with three hypotheses, based on common conceptions about the seasons: (1) The Earth is closer to the Sun in summer and further away in winter; (2) the rotation axis changes direction during the year; and (3) the rotation axis is tilted but keeps a fixed direction in space (the scientifically accepted hypothesis). The participants were given relevant documents, time to look up information on the Internet, and also a globe, light source, and piece of string to test each of the three hypotheses. A moderator was present to assist the teachers in testing the three hypotheses. However, the participants needed very little assistance since the task was clearly presented and resources were available. The participants were able to reject the first hypothesis when they found that Earth is slightly closer to the Sun during the northern-hemisphere winter. The globe, light source, and string (used for measurement) made it possible to test the other two hypotheses by comparing the hours of daylight in Toulouse, France with Sydney, Australia when Earth was on different sides of the Sun. They found that if Earth's axis tilted back and forth during the year, France would experience summer twice each year. Only the third hypothesis was consistent with the evidence gathered from the model. The participants were asked three questions about the seasons before and after the activities and after 30 days. Average test scores increased from 44% correct on the pretest to 97% on the post-test, and 85% on a delayed post-test.

2.9. Educational Research Summary

Status studies indicate that young children tend to associate winter with ice and snow, and do not begin to consider causal mechanisms for seasonal changes until at least the upper-elementary school years. As students are introduced to the seasons at the middle-school level through lectures and textbooks, they are likely to develop misconceptions. The most common misconception is that it is warmer in summer than in winter because Earth's orbit is highly elliptical, causing Earth to be closer to the Sun in summer than in winter. As children learn about the relevance of the tilt of Earth's axis, they attempt to integrate this new information with what they already believe by assuming that the tilt brings one hemisphere or the other closer to the Sun. Some students also think that the Earth's axis changes its orientation in space during the year, and that this change in tilt causes the seasons. Although Sadler points out that each of these alternative conceptions may be a step forward, students rarely if ever have a chance to revisit this topic in later years. Consequently they may graduate from a university and possibly become teachers with no more sophisticated understanding of the Earth-Sun system than a typical middle-school student.

Learning studies are encouraging in that several techniques have been found to be helpful, provided the students are sufficiently mature to carry out the complex spatial visualization skills that are needed. Some of the successful approaches include having students observe changes in the path of the Sun during the year, learning about seasonal changes at different latitudes, including the southern hemisphere, testing common misconceptions against actual data using physical models, and using 3D modeling software. Several instructional methods were shown to be highly effective with teachers. However, even when the most successful approaches are used with students at the middle-school level, only about one-half to three-quarters of the students fully understand the lesson, and even fewer demonstrate understanding on delayed post-tests.

Taken together the learning studies also revealed a number of subconcepts or prerequisite ideas that are necessary for full understanding of the seasons. These include: (1) Observations of how changes in the length of day and average temperature are correlated with changes in the Sun's path in the sky during the year; (2) awareness of Earth's motion on its axis and its orbit around the Sun; (3) use of models to see how maintaining the orientation of Earth's axis in space as it circles the Sun brings about changes in the length of daylight, and the angle at which sunlight strikes the surface at different latitudes and different times of year at the same hour of the day; and (4) understanding of how light travels in straight lines, and how the angle of incidence of sunlight affects the extent of warming. Putting these ideas together into a coherent learning progression is the work of the next section.

3. LEARNING PROGRESSION FOR THE SEASONS CONCEPT

3.1. A Learning Progression Approach

The development of learning progressions is a relatively new approach to applying the findings of educational research to the development of instructional standards and objectives, teaching methods and materials, and assessments. Following is a description of the approach from a recent monograph that pulls together a number of current efforts to create learning progressions in science.

> Learning progressions in science are empirically-grounded and testable hypotheses about how students' understanding of, and ability to use, core scientific concepts and explanations and related scientific practices grow and become more sophisticated over time, with appropriate instruction (National Research Council (NRC) 2007). These hypotheses describe the pathways students are likely to follow to the mastery of core concepts. They are based on research about how students' learning actually progresses—as opposed to selecting sequences of topics and learning experiences based only on logical analysis of current disciplinary knowledge and on personal experience in teaching. (Corcoran, Mosher, and Rogat 2009, p. 15).

The first researchers to develop a learning progression for the seasons were Ted Willard and Jo Ellen Roseman of Project 2061, the team that developed *Benchmarks for Science Literacy* (AAAS 1993, 2009) and the *Atlas of Science Literacy* (AAAS 2001, 2007). Their reason for examining research on seasons was to decide if the following benchmark should be moved from the middle-school to the high-school level.

> Because the Earth turns daily on an axis that is tilted relative to the plane of the Earth's yearly orbit around the Sun, sunlight falls more intensely on different parts of the Earth during the year. The difference in heating of the Earth's surface produces the planet's seasons and weather patterns. (AAAS 1993, 2009, p. 69).

Willard and Roseman (2007) went further in "unpacking" prerequisite knowledge that students would need to have in order to understand this benchmark and proposed a tentative learning progression. They concluded that components of the seasons concept should be taught in elementary and middle school and then brought together in high school "when students are expected to understand how the motions of the Earth with respect to the Sun are the cause of variations in the amount of sunlight different locations receive [hours of daylight and intensity] over the course of a year." The authors conclude that, in order to test this proposed learning progression, it will be necessary to develop assessment items and a set of instructional interventions that plausibly could move students stepwise through the learning progression.

A learning progression for the concept of seasons was also developed by Plummer (2008) concerning phenomena that can be observed from Earth. Her study began by interviewing 20 students in each of grades 1, 3, and 8 ($N = 60$) to determine their knowledge of apparent motions of the Sun, Moon, and stars. While she found a general trend toward higher levels of understanding among the older students, students at each grade level held naïve beliefs about the Sun's apparent motion. Further, there was no significant difference between third-grade students' and eighth-grade students' understanding of the Sun's highest altitude, the Sun's path through the sky, or change in the Sun's path across seasons.

Next, Plummer conducted a learning study with a sample of the students that she had previously interviewed, using a small (4-ft-diameter) planetarium. The instructional method engaged the students in predicting the movements of the Sun, Moon, and stars; observing the motions simulated by the planetarium; and then contrasting the predictions with the simulation. More than one-half of the students showed improved understanding of seasons after the planetarium program.

Plummer proposed a tentative learning progression concerning the Sun's apparent motion based on these findings. Given instruction using a kinesthetic learning technique, students in grades K–1 should be able to learn that the Sun is in the sky during the day, but not at night; and the Sun rises and sets during the day. In grades 2–3 students should be able to learn that the Sun's motion across the sky is continuous and that it rises and sets on opposite sides of the sky. In grades 4–5 students should first be able to learn that the Sun is highest at noon, but it does not pass directly overhead daily. Finally, they should be able to learn that the length of the Sun's path in the sky changes across seasons, and the Sun's altitude changes across the seasons.

In our view, neither of these two pioneering efforts at constructing a learning progression for seasons captures the richness of the available data. The Willard and Roseman study was constrained by using previously

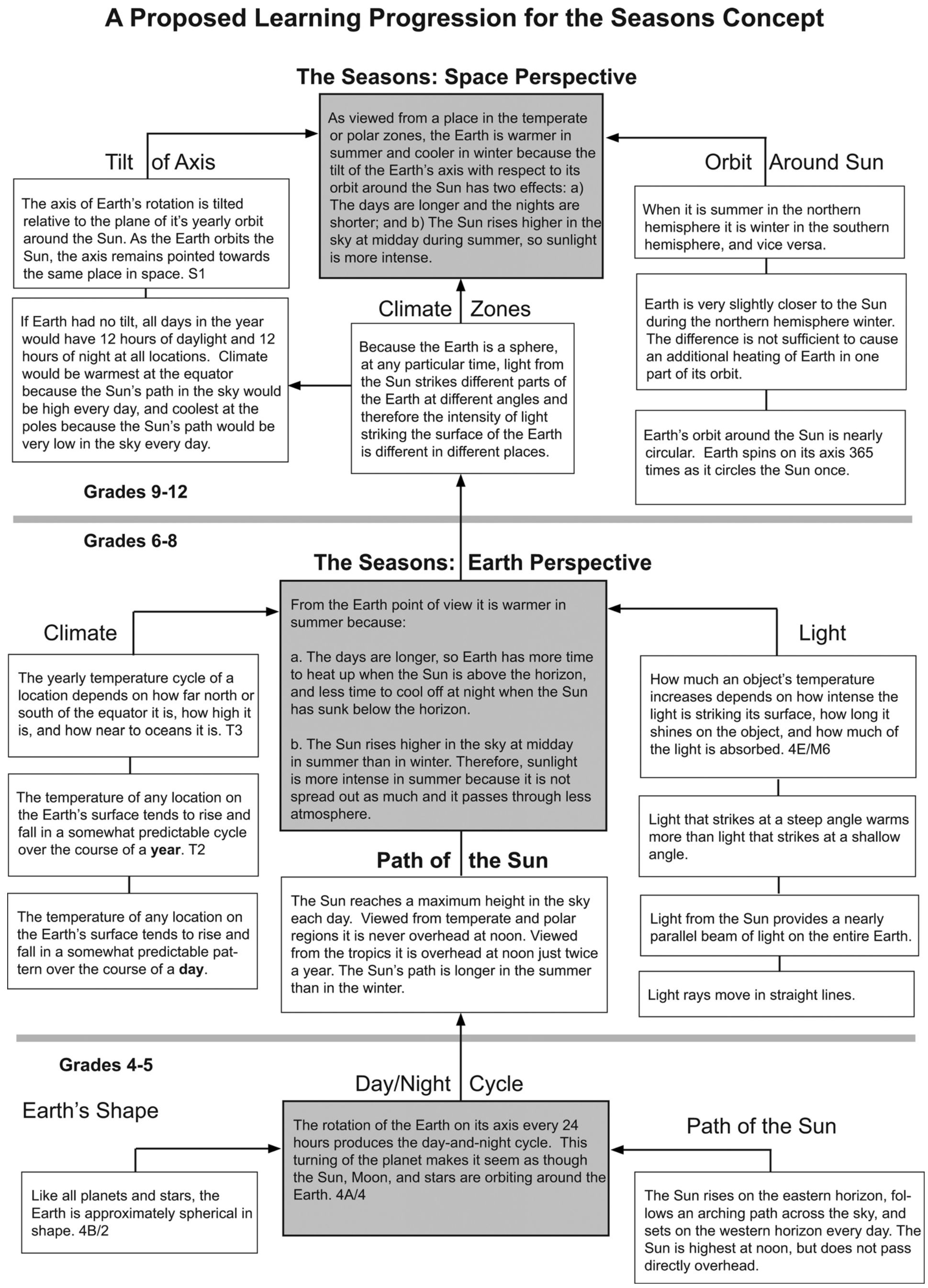

Figure 9. Proposed learning progression for the seasons concept. Codes at the end of some of the statements indicate their use in *Benchmarks* and *Atlas for Science Literacy*.

published benchmarks from the Project 2061 materials. Plummer's work provided further detail about what students can and should observe about the Sun's changing path in the sky, but it was limited to the Earthbound observer's perspective.

A proposed learning progression, which builds on the work of Willard and Roseman (2007) and Plummer (2008) and reflects the findings of the studies considered in this review, is shown in Figure 9. The proposed progression is organized in sets of related concepts to facilitate development of instructional units. The progression spans three grade ranges, 4–5, 6–8, and 9–12. While there are roots in learning at the K–2 level, concepts at that level are of a more general nature, so we choose not to mention them here. Following is a brief summary of the diagram (Figure 9).

Grades 4–5: At this level students are expected to learn about: (1) Earth's spherical shape; (2) the Sun's path though the sky on a daily (not yearly) basis; and (3) the day/night cycle in terms of Earth's shape and daily spin. Although students of this age are capable of understanding the Earth's spherical shape and the explanation for the day/night cycle, this concept should be revisited each time astronomy is taught up through the high-school level.

Grades 6–8: We recommend that students engage in four major units of study at the middle-school level to prepare them to explain the seasons from the Earth perspective. These include: (1) Daily and seasonal climate change, and how climate varies with latitude; (2) the Sun's changing path in the sky during the year; (3) the behavior of light; and (4) the reasons why it is warmer in summer and cooler in winter due to the change in daylight hours and the angle at which sunlight strikes the Earth.

Grades 9–12: This is the level at which students can be expected to bring together their understanding of seasons from the Earth perspective with a vision of the Earth in space. It also involves four units, beginning with how climate depends on Earth's spherical shape. (1) Even if Earth's axis were not tilted, climate zones would result from Earth's spherical shape, as light from the Sun strikes different parts of the sphere at different angles. (2) Earth's orbit around the Sun is nearly circular, and we are slightly closer to the Sun during the northern hemisphere winter; so changing distance from the Sun cannot explain the seasons. Also, when it is summer in the northern hemisphere it is winter in the southern hemisphere and vice versa. (3) Starting with a simplified model in which Earth's axis is *not* tilted, students consider how people in different climate zones would view the Sun, and the consequences for the length of day (which would not change as Earth orbited the Sun, and would be the same for all locations along the same latitude line) and intensity of sunlight (cold at the poles and warm at the equator). Then students explore how observations of the Sun would change if Earth's axis were tilted. (4) Students synthesize their knowledge of Earth's climate zones, their understanding of Earth's orbit around the Sun and the tilt of the Earth's axis to understand why the length of daylight changes during the seasons, and why the Sun's path in the sky and maximum height of the sun above the horizon changes with the seasons.

4. CONCLUSIONS

For more than 20 years educators and scientists have expressed surprise and dismay when viewing the video A Private Universe (Schnepps and Sadler 1989). Surprise comes from observing obviously bright people who failed to learn seemingly simple science concepts that have traditionally been taught at the upper-elementary and middle-school level. Dismay comes from the realization that people who impress us with their abilities to solve complex mathematical problems may not have even a rudimentary understanding of the concepts that underlie the problems they are solving.

Thanks to the collective results of a large body of research it is now possible to understand why learning the causes of seasons is so challenging. First, there are large numbers of subconcepts, or prerequisite understandings that students must have in order to fully understand the change of seasons. Second, few instructional materials have students make the important observations of the Sun's changing path in the sky. Third, understanding the behavior of light is critically important to understanding climate zones (e.g., tropics, temperate, and arctic zones); and without understanding why there are climate zones, it is difficult to understand why there are seasonal changes within each zone. And fourth, combining the space perspective with the Earth perspective requires substantial spatial reasoning skills.

These challenges are made all the more difficult because some of the more advanced concepts, especially involving the physics of light and the interaction of light and matter, need to be understood before students are able to synthesize the Earth and space perspectives of the seasons. Notice, however, that reconciling the Earth and space views can begin in the upper-elementary level with respect to the day/night cycle, since it is less complex to visualize than the reasons for the seasons.

Despite these difficult challenges—and in some ways because of them—teaching the concept of seasons should remain on the list of what all students should learn in order to be considered scientifically literate. That is because the mental effort involved in understanding the full scientific explanation for seasonal changes can help students merge their view from planet Earth with the modern conception of the Earth in space, among other planets, stars, and galaxies. And once students understand the concept, it can serve as a unifying construct for synthesizing other important ideas in the physical and Earth and space sciences.

A constructivist approach does not necessarily rule out the use of textbooks, as clear writing and good diagrams can help many students revise their thinking. However, most modern textbooks do a poor job of explaining the seasons. Lucas and Cohen (1999) reviewed methods used to teach the seasons over the past 200 years. They found that the same diagrams have been used in textbooks since the early 1800s, and that some of the earlier descriptions of seasons were clearer and more complete than contemporary textbooks. For example, a textbook on physical science published by Edward Jackson in 1894 began with clear and detailed explanations of phenomena that are precursors to understanding the seasons, including gradual changes in the intensity of sunlight during the day and year, and Earth's daily and annual motions. As an introduction to seasons, Jackson's text invites students to consider what climates around the globe would be like if Earth's axis were not inclined to its orbit around the Sun. Following a thorough description of seasons using a series of diagrams, from both the geocentric and heliocentric perspective, the text goes on to explain why the hottest and coldest times of the year do not correspond to the solstices. The authors analyzed ten contemporary science textbooks and found that, although all included the idea that the tilt of Earth's axis caused the seasons, some of the textbooks ignored seasonal phenomena that students could directly observe. Only eight of the ten textbooks mentioned a difference in the length of daylight hours, only seven mentioned that the Sun appears higher in the sky in summer than in winter, and only five of the ten mentioned that the Sun rises and sets at different locations through the year. The authors lament that few students have opportunities to learn about seasons through their own observations.

We join with Lucas and Cohen in calling for a more thoughtful and thorough approach to introducing seasonal change, using a framework such as the learning progression depicted in Figure 9 and some of the teaching methods found to be successful as reported in this review. Keeping in mind, of course, that although our proposed learning progression is based on 41 research studies, it must be subjected to further tests to be certain that it really does represent the trajectories of actual student learning, given certain teaching methods. Even then we can expect that many of our students will not be able to make the leap all at once from naïve ideas to full scientific understanding. We need to celebrate their success, one steppingstone at a time.

Notes

Note 1: The Greek astronomers understood that even though the stars were not visible during the day because of the glare of the Sun, they were there nonetheless. This could be confirmed when the rising or setting Sun was observed near a bright star.

Note 2: A second reason for the reduction in light intensity as the Sun nears the horizon is that the light is attenuated as it travels through more of the atmosphere. This effect is obvious at sunset when it is possible to look directly at the Sun without injury. However, this effect is usually overlooked since the explanation of seasons is already so complex.

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