Progression of Understanding of the Reasons for Seasons

Ted Willard and Jo Ellen Roseman
AAAS, Project 2061

Paper prepared for the Knowledge Sharing Institute of the
Center for Curriculum Materials in Science
Washington, DC
July 22-25, 2007

Learning Progressions Plenary

Abstract: Maps in *Atlas of Science Literacy* (AAAS, 2001; AAAS, 2007) are based on the premise that science literacy should be approached not as a collection of isolated abilities and bits of information, but as a rich network of mutually supporting ideas and skills that must develop over time. The left side of the Weather and Climate map in *Atlas 2* (AAAS, 2007) presents a progression of understanding of seasons that is based on a rigorous analysis of the logic of the disciplines and a careful examination of relevant research on student learning. This paper describes the progression of understanding of the reasons for seasons and the rationale for the decisions it reflects.

Introduction (Domain and Target)

In its characterization of the knowledge, skills, and habits of mind that constitute adult science literacy, *Science for All Americans* (AAAS, 1989) recommended that all high school graduates would understand the following story about seasons:

> The motion of the earth and its position with regard to the sun and the moon have noticeable effects. The earth's one-year revolution around the sun, because of the tilt of the earth's axis, changes how directly sunlight falls on one part or another of the earth. This difference in heating different parts of the earth's surface produces seasonal variations in climate. (p. 43)

An understanding of the reasons for seasons contributes to science literacy in several important ways. Seasonal variations in temperature have had profound effects upon human society throughout history. As agrarian societies developed, knowledge of the patterns of the seasons became essential knowledge that was passed from generation to generation. Even today, with advanced technologies to aid in forecasting, and the ubiquity of heating and cooling systems in homes and businesses, the seasons still play an important role in the lives of both adults and children. Moreover, an understanding of how and why different locations experience different seasonal variations contributes to understanding climate and the models used to predict climate change.

Benchmarks for Science Literacy (AAAS, 1993) and the *National Science Education Standards* (*NSES*) (NRC, 1996) included the expectation that students would understand the reasons for seasons by the end of grade 8:

> 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. (Benchmarks, p. 69)
>
> The sun is the major source of energy for phenomena on the earth's surface, such as growth of plants, winds, ocean currents, and the water cycle. Seasons result from variations in the amount of the sun's energy hitting the surface, due to the tilt of the earth's rotation on its axis and the length of the day. (NSES, p. 161)

Project 2061's recent efforts to unpack and clarify the meaning of these benchmarks for assessment and curriculum materials design and to map connections among these and other related benchmarks for the second volume of *Atlas of Science Literacy* (AAAS, 2007) have led us to rethink the reasonableness of these expectations for 8^{th} grade students. In the rest of this paper we describe the learning progression that resulted from these efforts and the work still needed to test and refine the progression.

Students' Ideas about Seasons

The Weather and Climate map in *Atlas* 2 summarizes research on student learning about the seasons:

> Students of all ages (including college students and adults) have difficulty understanding what causes the seasons. Students may not be able to understand explanations of the seasons before they reasonably understand the relative size, motion, and distance of the sun and the earth (Sadler, 1987); Vosniadou, 1991). Many students before and after instruction in earth science think that winter is colder than summer because the earth is farther from the sun in winter (Atwood & Atwood, 1996; Dove, 1998; Philips, 1991; Sadler, 1998). This idea is often related to the belief that the earth orbits the sun in an elongated elliptical path (Galili & Lavrik, 1998; Sadler, 1998). Other students, especially after instruction, think that the distance between the northern hemisphere and the sun changes because the earth leans toward the sun in the summer and away from the sun in winter (Galili & Lavrik, 1998; Sadler, 1998). Students' ideas about how light travels and about the earth-sun relationship, including the shape of the earth's orbit, the period of the earth's revolution around the sun, and the period of the earth's rotation around its axis, may interfere with students' understanding of the seasons (Galili & Lavrik, 1998; Salierno, Edelson, & Sherin, 2005). For example, some students believe that the side of the earth not facing the sun experiences winter, indicating a confusion between the daily rotation of the earth and its yearly revolution around the sun (Salierno, Edelson, & Sherin, 2005).

This research suggests at least two lines of understanding that would need to be developed in a learning progression on the reason for seasons: the role of Earth's motions with respect to the sun and the role of sunlight in warming objects.

Research comparing learning of students using the GEMS unit: *The Real Reasons for Seasons* (*Seasons*) to that of students using a comparison unit prompted us to consider whether other lines of student understanding would need to be developed. The study reported that students using the GEMS unit learned less than students using the comparison unit (O'Donnell, Watson, Pyke, & Lynch, 2006). Neither group of students gained a significant understanding of the seasons. Because the unit had been designed to address some of the misconceptions noted above, we decided to take a closer look at the unit. The research team had already noted several weaknesses of the unit, based on their application of the Project 2061 content and instructional criteria (O'Donnell, Watson, Pyke, & Lynch, 2006) and their study of the unit's use indicated that teachers using it were focusing on their teaching rather than on their students' learning (O'Donnell, Watson, Pyke, & Lynch, 2006).

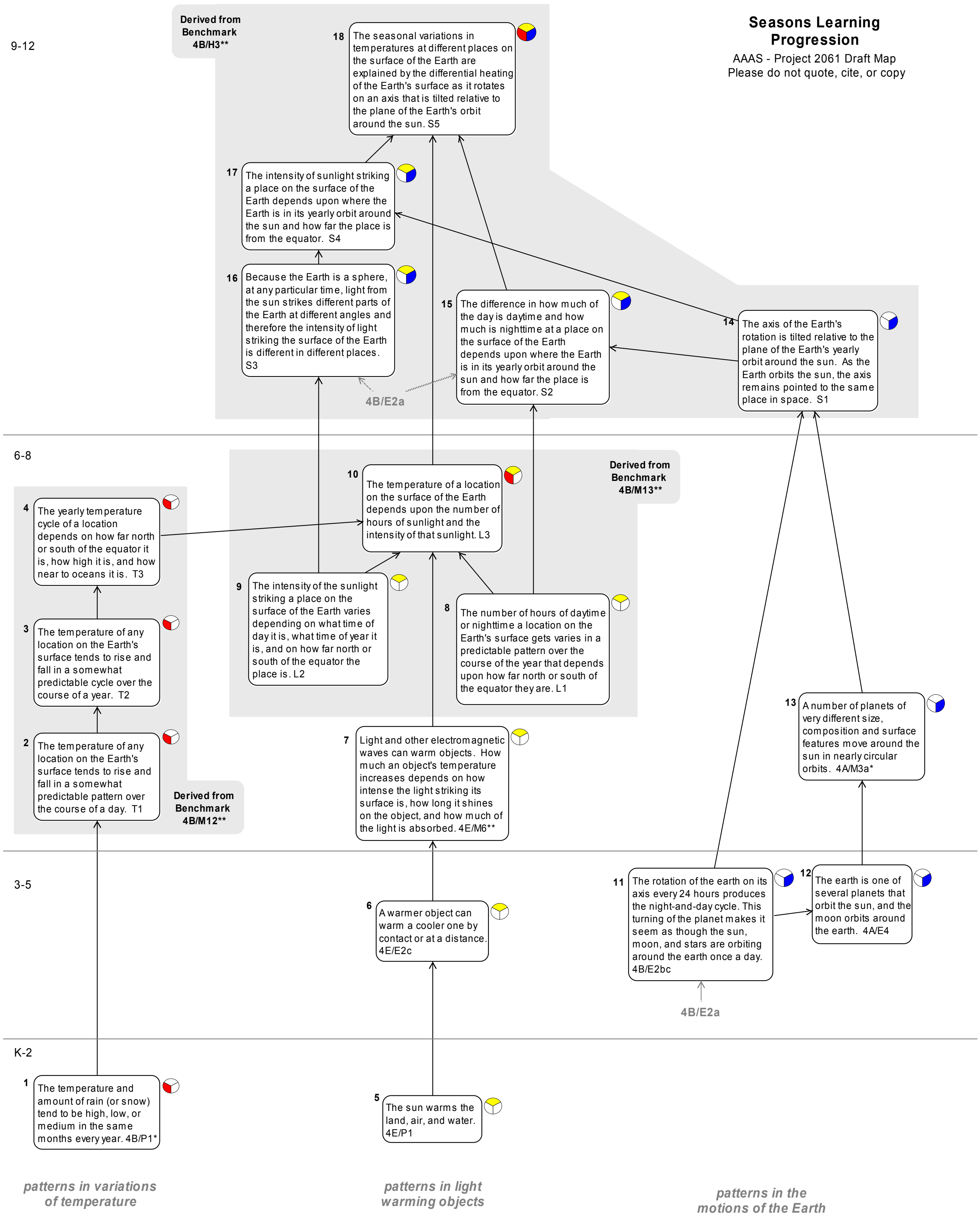
Our own examination of the unit revealed additional weaknesses (Roseman, 2006) and gave us further insights into the story lines that would need to be developed in the learning progression. A fundamental weakness is the short amount of time (two weeks) that is allocated to teach several conceptually difficult ideas. (In contrast, the chemistry unit used in the study described below focused six to eight weeks of instruction on two or three key ideas.) No more than a single activity of the *Seasons* unit (each designed for a class period) is focused on any key idea and no support is provided to teachers who might want to devote additional time, such as a) providing further clarification about common student misconceptions, b) illustrating how they might be reflected in student work, and c) providing tasks that encourage students to express, clarify, justify, and represent their ideas both to push them to make their ideas explicit and to provide teachers with a window to their thinking.

Research on elementary students' conceptions of key ideas in astronomy, such as the day-night cycle or the phases of the moon, has shown that not only are students mental models of the phenomena often incorrect, but so is their knowledge of the phenomena themselves (Vosniadou, 1991; Vosniadou, & Brewer 1994). For example, students may believe that the moon is only seen at nighttime. This has been shown to occur on other topics as well (Herrmann Abell & DeBoer, 2007). The first step in helping students form a correct mental model is helping them gain a more accurate understanding of the phenomena in question. Students might then be ready to wrestle with and connect the models to the phenomena.

We realized that in developing a learning progression leading to an understanding of the reasons for seasons, it was as important for us to think through the development of students' understanding of temperature data and patterns in the data as it was for us to think through the development of students' understanding of the explanatory models.

Framework and Progression

The framework for the learning progression is organized around three sets of patterns in data that are needed to understand the reasons for seasons: 1) patterns in temperature variation across the earth and over time, 2) patterns in light warming objects, and 3) patterns in the motions of the Earth. The first two patterns are reflected in benchmarks from the Weather and Climate map in *Atlas* 2 (p. 21) and the third is reflected in benchmarks from the Solar System map in *Atlas* 1 (p. 45). Three of these benchmarks—4B/M12**, 4B/M13**, and 4B/H3**—have been unpacked into eleven key ideas and the relationships among those key ideas have been made explicit in the map in Figure 1.

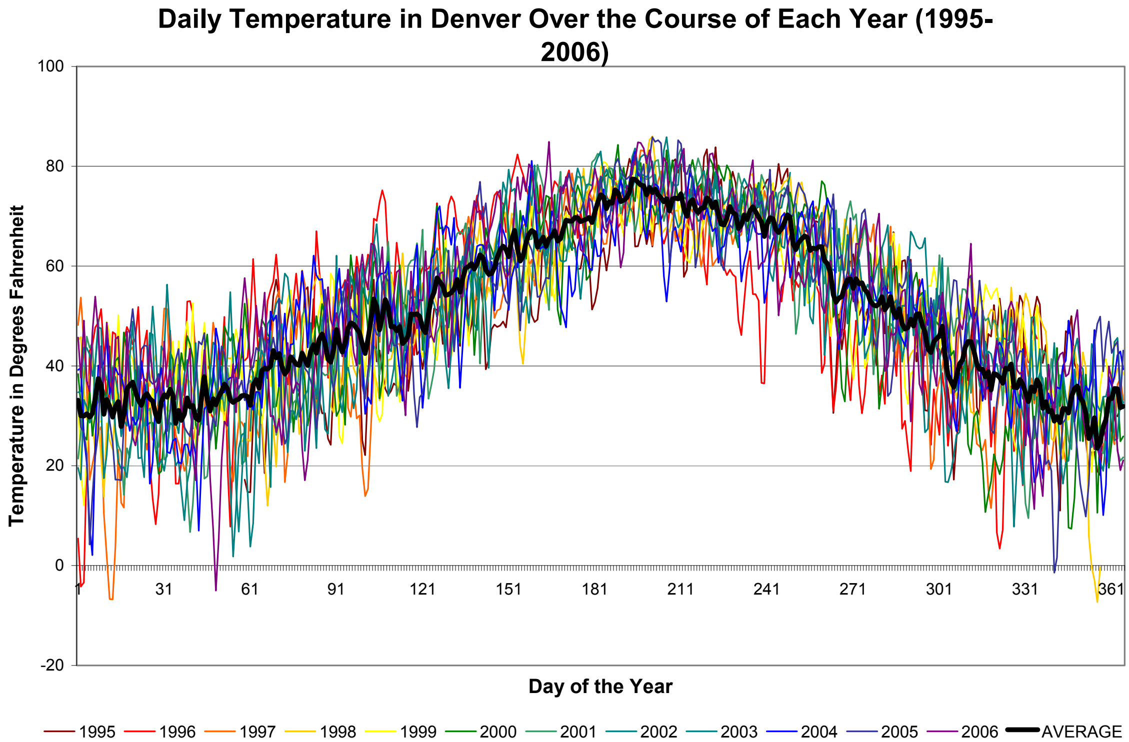

Seasons Learning Progression
AAAS - Project 2061 Draft Map
Please do not quote, cite, or copy
9-12
6-8
3-5
K-2
Derived from Benchmark 4B/H3**
18 The seasonal variations in temperatures at different places on the surface of the Earth are explained by the differential heating of the Earth's surface as it rotates on an axis that is tilted relative to the plane of the Earth's orbit around the sun. S5
17 The intensity of sunlight striking a place on the surface of the Earth depends upon where the Earth is in its yearly orbit around the sun and how far the place is from the equator. S4
16 Because the Earth is a sphere, at any particular time, light from the sun strikes different parts of the Earth at different angles and therefore the intensity of light striking the surface of the Earth is different in different places. S3
15 The difference in how much of the day is daytime and how much is nighttime at a place on the surface of the Earth depends upon where the Earth is in its yearly orbit around the sun and how far the place is from the equator. S2
14 The axis of the Earth's rotation is tilted relative to the plane of the Earth's yearly orbit around the sun. As the Earth orbits the sun, the axis remains pointed to the same place in space. S1
4B/E2a
Derived from Benchmark 4B/M13**
10 The temperature of a location on the surface of the Earth depends upon the number of hours of sunlight and the intensity of that sunlight. L3
4 The yearly temperature cycle of a location depends on how far north or south of the equator it is, how high it is, and how near to oceans it is. T3
9 The intensity of the sunlight striking a place on the surface of the Earth varies depending on what time of day it is, what time of year it is, and on how far north or south of the equator the place is. L2
8 The number of hours of daytime or nighttime a location on the Earth's surface gets varies in a predictable pattern over the course of the year that depends upon how far north or south of the equator they are. L1
3 The temperature of any location on the Earth's surface tends to rise and fall in a somewhat predictable cycle over the course of a year. T2
13 A number of planets of very different size, composition and surface features move around the sun in nearly circular orbits. 4A/M3a*
2 The temperature of any location on the Earth's surface tends to rise and fall in a somewhat predictable pattern over the course of a day. T1
Derived from Benchmark 4B/M12**
7 Light and other electromagnetic waves can warm objects. How much an object's temperature increases depends on how intense the light striking its surface is, how long it shines on the object, and how much of the light is absorbed. 4E/M6**
11 The rotation of the earth on its axis every 24 hours produces the night-and-day cycle. This turning of the planet makes it seem as though the sun, moon, and stars are orbiting around the earth once a day. 4B/E2bc
12 The earth is one of several planets that orbit the sun, and the moon orbits around the earth. 4A/E4
6 A warmer object can warm a cooler one by contact or at a distance. 4E/E2c
4B/E2a
1 The temperature and amount of rain (or snow) tend to be high, low, or medium in the same months every year. 4B/P1*
5 The sun warms the land, air, and water. 4E/P1
patterns in variations of temperature
patterns in light warming objects
patterns in the motions of the Earth

As shown, the progression involves the development and linking of the three patterns in observations over K-12. Development of all three patterns begins in the elementary grades. Patterns in temperature variation is linked to patterns in light warming objects in middle school and both are linked to patterns in motions of the Earth in high school.

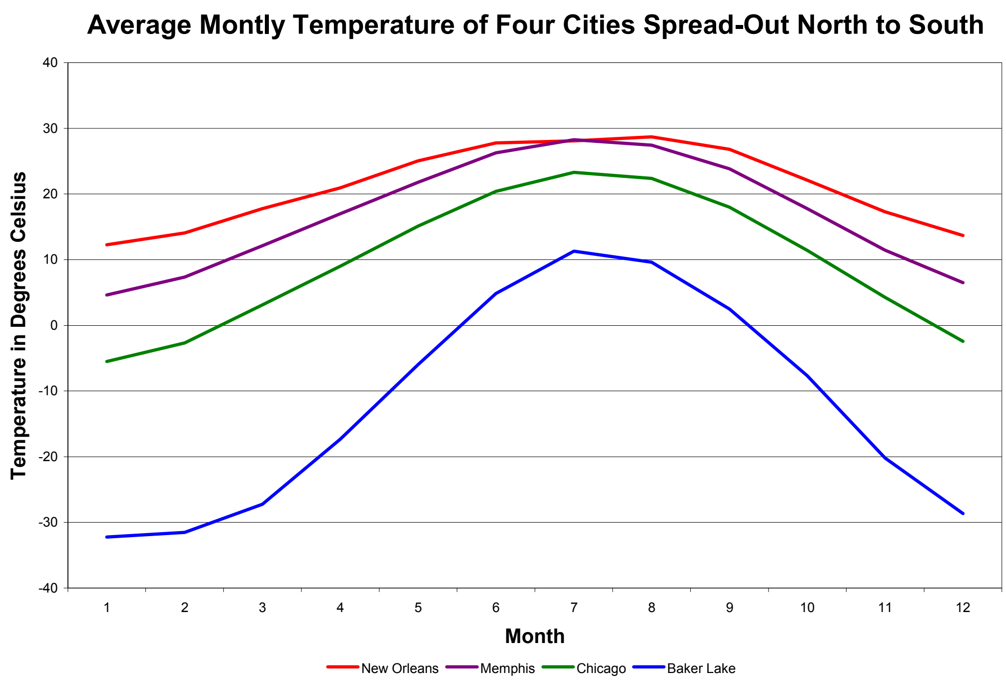
The progression is based primarily on a careful analysis of the logic of the discipline. Most of the learning research on seasons focuses on misconceptions students have, rather than on what students might learn with carefully designed instruction. The failure of the GEMS curriculum unit to outperform the comparison unit in the O'Donnell study (O'Donnell, et al., 2006) points to the need to think through more carefully what ideas are needed for students to understand how the motions of the Earth with respect to the sun cause the seasons and to reconsider where each step in the progression of understanding might reasonably take place.

Patterns in variation of temperature. This story line focuses on generalizations about daily and yearly temperature patterns on the surface of the Earth. Student understanding of these patterns begins in grades K-2 with the idea that the temperature of a place tends to be high, low, or medium in the same months every year (Box 1). In middle school, students are expected to learn more precisely how temperature varies. Benchmark 4B/M12** has been broken into three separate ideas. First students are asked to recognize that the rise and fall of the temperature during the day tends to follow a consistent pattern. (Box 2) For example, the warmest time of day is usually in the late afternoon.

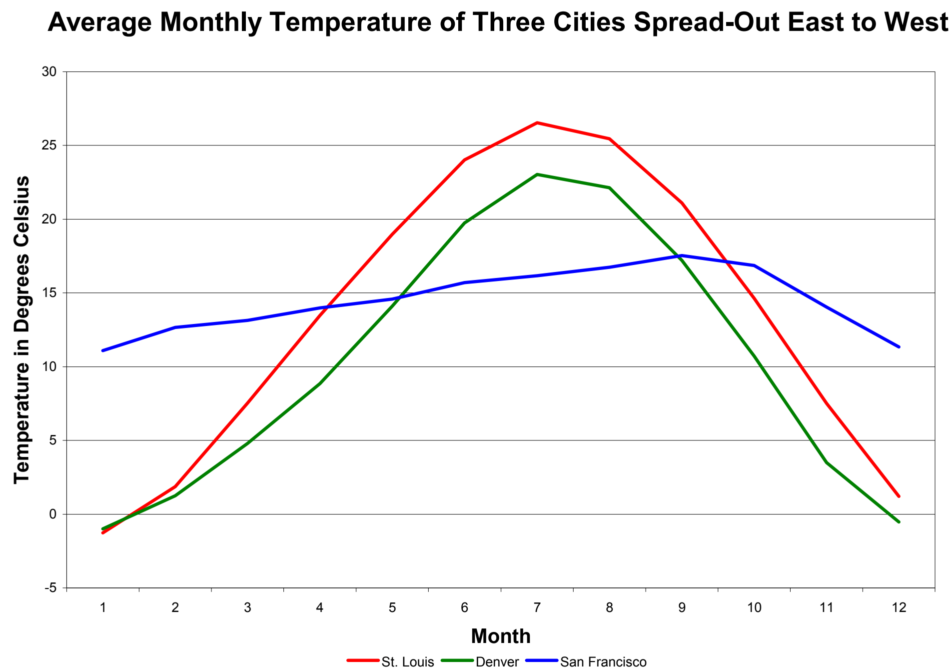
Students also need understand the pattern of temperature changes over the course of the year. (Box 3) For example, temperatures in the Denver, Colorado are highest in the summer months of June, July, and August and lowest in December, January, and February (see graph below)



Students also need to know that in general, locations farther from the equator have more extreme variations in temperature and cooler temperatures on average than locations closer to the equator. The graph below illustrates the variation in pattern with the distance north of the equator. A comparable graph would be needed to illustrate the variation in pattern with the distance south of the equator.



because there are several other factors that influence the temperature of a location on Earth. For example, locations closer to oceans or other large bodies of water tend to have more moderate temperatures and locations at higher altitudes tend to be cooler (see graph below). Project 2061's suggestion in addressing this is to have students gain an understanding that all of these factors play a role in determining typical temperatures of a location, by focusing instruction on each factor separately. (Box 4)



Patterns in Light Warming Objects. Student understanding of patterns in light warming object begins in grades K-2 with the idea that "The sun warms the land, air, and water." (Box 5) In grades 3-5, students are expected to learn that "A warmer object can warm a cooler one…at a distance." (Box 6)

In middle school, students are expected to relate the observed patterns in temperature variation to their increased understanding of light warming objects as they realize that the reason for the temperature patterns has to do with the amount of sunlight different locations receive. Benchmark 4B/M13** has been divided into three separate ideas that describe different ideas students need to know: Students need to recognize how the number of hours of sunlight a place receives each day varies throughout the course of the year (Box 8), how the intensity of sunlight varies over the course of the year (Box 9), and that both of these phenomena are influenced by how far north or south a place is from the equator.

However, their recognition of this correlation between the amount of sunlight (including both hours of daylight and intensity of the sunlight) a place receives and the temperature of that place is not sufficient for them to gain a firm grasp of how the amount of light a place receives affects its temperature. They also need to have the mechanism for the effect of the amount of sunlight on the temperature. Therefore, it is necessary for students to learn the idea that light can warm an object and that the amount of warming is dependent on the intensity of the light striking the object and the length of time that the light is striking the object (Box 7). With the idea of a mechanism in place, students have sufficient evidence to support the idea that variations in the amount of sunlight cause yearly variations in temperature. (Box 10)

Patterns of the Earth's Motion. The link between sunlight and temperature provides one of the essential prerequisites to understanding how the motions of the Earth with respect to the sun cause the seasons. The other essential prerequisite is an accurate understanding of how the Earth moves with respect to the sun. Student understanding of the Earth's motion begins in grades 3-5 with the idea that the spinning of the Earth explains the apparent motion of the sun, moon and stars across the sky (Box 11). In this grade range, they also learn that the Earth goes around the sun once a year (yearly), which is why different stars can be seen in different seasons (Box12). In middle school, students are expected to build on the ideas in this strand towards by gaining a greater understanding of the scale and organization of the solar system including the idea that the orbit of most planets, including Earth's, is nearly circular (Box 13). Finally, in high school, before students are ready to explain the seasons, they must understand that the Earth's axis of rotation is not perpendicular to the path of its orbit around the sun, but it is tilted. This includes knowing that as the Earth orbits the sun, the axis of rotation always has the same rotation so that it is oriented toward the same point in space (Box 14).

Thus, Polaris, the north star, does not appear to move as the Earth spins even though all the other stars in the sky appear to. No matter what time of year it is, Polaris appears fixed because it is nearly directly above the north pole.

Putting it All Together: Seasons at Last. The overall progression then culminates 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 the year. Since the orientation of its axis with respect to the stars remains fixed as the Earth goes around the sun, the orientation of the axis with respect to the sun must change. There are two effects of this change in orientation between the Earth's axis and the sun that students need to know. The first is that when one pole (either north or south) is directed toward the sun, places in that hemisphere get more than twelve hours of daylight and places in the other hemisphere get less than 12 hours. The closer a place is to the pole and the more the respective pole is aligned toward the sun, the more hours of daylight the place gets, up to a maximum of 24 hours of daylight (Box 15).

Students need to know that the orientation of the Earth's axis with respect to the sun also affects the maximum intensity of the sunlight any given place on the Earth can receive. (Box 17) As a step in appreciating the geometry of this situation, students need to know that since the Earth is spherical, its curvature causes the sun's rays to hit different places on the surface at different angles at any given time. (Box 16).

Once student appreciate that the Earth's motions with respect to the sun influence the number of hours of daylight a place receives at different times of the year and the intensity of that light at any given point in the day, they can link it to the connections they made in middle school between the amount of light a place receives and the temperature of that place. At last, the connection between the motions of the Earth around the sun and the seasonal variations in temperature has been made (Box 18).

Testing the Progression

Before a learning progression can be fully tested, two kinds of tools are needed: 1) a set of assessment items that align with each of the key ideas in the progression and effectively probe students' understanding of them and 2) a set of instructional interventions that could plausibly move students from one step in the progression to another.

Assessment items. Project 2061's assessment work (presented in the Assessment Plenary) is developing assessment items that align with key science ideas in *Benchmarks for Science Literacy* (AAAS, 1993) and the National Science Education Standards (NRC, 1996) and can be used to monitor student progress along a progression (NSF #..ESI-0352473). Just as the progressions make significant use of the research on students learning, so too should the assessments. They need to check not only do students have the desired understanding, but whether students hold any of the common misconceptions related to the key idea. The work is summarized in the KSI Assessment Plenary and presented in more detail in the accompanying paper (DeBoer, 2007). Findings from pilot and field test of items is also informing the design of curriculum components, described below, and the suggestions being made to guide their effective use (Herrmann Abel and DeBoer, 2007).

Curriculum components. Project 2061 is also designing a set of components of instructional interventions that meet indicators of Project 2061's content and instructional criteria (Roseman, Kesidou, and Stern, 1996) (NSF#.ESI-0103678). The set of research-based criteria used in Project 2061's Curriculum Evaluation Studies (Kesidou and Roseman, 2002; Stern and Roseman, 2004) provides a way to gauge the plausibility of the instructional interventions. Empirical studies, involving a quasi-experimental design, showed that students learned chemistry concepts better in classrooms using a "highly rated" curriculum unit, according to the Project 2061 criteria, than in classrooms using other curriculum materials to teach the same concepts (Lynch, et al., 2006). The findings, which held across sub-populations of students, provide empirical evidence of the usefulness of the criteria in curriculum design. A key element of instruction that is reflected in the criteria is a set of well-aligned and comprehensible phenomena that can be used to illustrate or provide evidence for the key ideas. Representations are also crucial for helping to clarify both ideas and phenomena. And guidance is needed, in the form of structured tasks or question sequences, to help students make sense of the phenomena and link them to the key ideas. Examples of phenomena related to the idea of a spherical earth and to the idea of seasonal patterns in temperature, along with some suggestions for guiding student interpretation of them, are presented in the KSI session Phenomena: Interactive Poster Session and the posters are available on the ctools website.

References

American Association for the Advancement of Science. (1989). *Science for all Americans*. New York: Oxford University Press.

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

American Association for the Advancement of Science. (2001). *Atlas of science literacy, volume 1*. Washington, DC, Author.

American Association for the Advancement of Science. (2007). *Atlas of science literacy, volume 2*. Washington, DC: Author.

Atwood, R. K., & Atwood, V. A. (1996). Preservice elementary teachers' conceptions of the causes of seasons. *Journal of Research in Science Teaching*, 33, 553-563.

DeBoer, G. E. (2007, July). *Developing assessment items aligned to middle school science learning goals*. Paper presented at the annual Knowledge Sharing Institute of the Center for Curriculum Materials in Science, Washington, DC.

Dove, J. (1998). Alternative conceptions about the weather. *School Science Review*, 79, 65-69.

Galili, I., & Lavrik, V. (1998). Flux concept in learning about light: A critique of the present situation. *International Journal of Science Education*, 82, 591-613.

Herrmann Abell, C. F., & DeBoer, G. E. (2007, April). *Probing middle school students' knowledge of thermal expansion and contraction through content-aligned assessment*. Paper presented at the annual conference of the National Association for Research in Science Teaching, New Orleans, LA.

Kesidou, S., & Roseman, J. E. (2002). How well do middle school science programs measure up? Findings from Project 2061's curriculum review. *Journal of Research in Science Teaching, 39*(6), 522-549.

Kikas, E. (1998.) The impact of teaching on students' definitions and explanations of astronomical phenomena. *Learning and Instruction*, 8, 439.

Lynch, S., Kuipers, J. C., Pyke, C., & Szesze, M. (2005). Examining the effects of a highly rated science curriculum unit on diverse students: Results from a planning grant. *Journal of Research in Science Teaching, 42*(8), 912-946.

Lynch, S., O'Donnell, C. L., Hatchuel, E. E., Rethinam, V., Merchlinsky, S., & Watson, W. A. (2006, April). *What's up with the comparison group? How large quasi-experimental study of highly rated science curriculum units came to grips with unexpected results*. Paper presented at the annual meeting of the American Educational Research Association, San Francisco, CA.

Lynch, S., Taymans, J., Watson, W., Ochsendorf, R., Pyke, C., & Szesze, M. (2007). Effectiveness of a highly-rated science curriculum unit for students with disabilities in general education classrooms. *Exceptional Children, 73*(2), 202-223.

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

O'Donnell, C. L., Watson, W. A., Pyke, C., & Lynch, S. (2006). Understanding a quasi-experimental study of a seasons unit: Examining the intended, implemented, and attained curriculum. Manuscript submitted for publication.

Philips, W. (1991). Earth science misconceptions. *Science Teacher*, 58, 21-23.

Roseman, J. E. (2006, April). *Are "highly-rated" middle school science curriculum materials effective and for whom? Results from a set of implementation studies*. Discussant remarks for the session at the annual conference of the National Association for Research in Science Teaching, San Francisco, CA.

Roseman, J. E., Kesidou, S., & Stern, L. (1997). Identifying curriculum materials for science literacy: A Project 2061 evaluation tool. Based on a paper prepared for the colloquium *Using the* National Science Education Standards *to guide the evaluation, selection, and adaptation of instructional materials* held at the National Research Council, November 10–12, 1996, Washington, DC.

Sadler, P. (1987). Misconceptions in astronomy. In J. Novak (Ed.), *Proceedings of the second international seminar misconceptions and educational strategies in science and mathematics* (Vol. III, pp. 422-425). Ithaca, NY: Cornell University.

Sadler, P. (1998). Psychometric models of student conceptions in science: Reconciling qualitative studies and distractor-driven assessment items. *Journal of Research in Science Teaching*, 35, 265-296.

Salierno, C., Edelson, D., & Sherin, B. (2005). The development of student conceptions of the Earth-Sun relationship in an inquiry-based curriculum. *Journal of Geoscience Education*, 53, 422-431.

Stern, L., & Roseman, J. E. (2004). Can middle-school science textbooks help students learn important ideas? Findings from Project 2061's curriculum evaluation study: Life science. *Journal of Research in Science Teaching*, *41*(6), 538–568.

Vosniadou, S. (1991). Designing curricula for conceptual restructuring; lessons from the study of knowledge acquisition in astronomy. *Journal of Curriculum Studies*, 23, 219-237.

Vosniadou, S., & Brewer, W. F. (1994). Mental models of the day/night cycle. *Cognitive Science*, 18, 123-183.