In the Beginning, There Were Sun and Shadows: Using Stories in Science Teaching

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Abstract. Since the dawn of humanity, our understanding of the world around us has been grounded in storytelling: *Once upon a time... Before the beginning of time... Before people invented the concept of time...* People in the earliest societies paid attention to nature and told stories about what they experienced. Through their careful observation of the sun, moon, planets, and stars, and assisted by their creation of simple tools for measurement and record keeping, people all over the earth developed concepts of time and space. In our time, stories of how people developed mathematics, science, and technology can provide sparks to motivate students to engage in investigations through which they themselves can develop foundational capabilities in these disciplines. This paper describes *Sun & Shadows*, an experiential program in which students use systematic observation and model the patterns of sun and shadows over the course of the school year. *Sun & Shadows* is enriched by the use of stories that provide a framework within which students (and teachers) can relate to nature and science in a more personal way.

The Story of Eratosthenes

Once upon a time, more than two thousand years ago, no one knew how large the earth was, and many people didn't even know that it was round. But there was someone who not only believed it was round but found a way to determine its size.

Eratosthenes was born around 276 B.C.E. near the Mediterranean Sea in north Africa. Later, he lived in ancient Alexandria, where he served as the chief librarian of the greatest library of the time. At that time, sailors on the Mediterranean had observed the night sky, and for over two hundred years they had thought that the earth might be round.

Eratosthenes was known for his curiosity, his careful attention to details, and his record keeping. He became very interested when he heard a surprising story about an annual occurrence in a town south of Alexandria, a town called Syene. There, on one day of the year, the sun at noon shone all the way down into a deep well and reflected straight up off the water at the bottom, making no shadows at all. The day of the year on which this happened was called the summer solstice.

Eratosthenes had never seen a sunny day without shadows. Where he lived, he had seen that when sunlight touched anything, it always cast a shadow. He had noticed that at some times of year the sun was lower in the sky and at other times of year it was higher, and he'd noticed also that shadows were sometimes longer and at other times shorter. The difference in the shadows cast where he lived and in Syene interested him. He thought that if the light from the sun came to earth in parallel lines, if the earth was curved, and if he knew how far north Alexandria was from Syene, the difference in the shadows might help him to demonstrate that the earth was round and perhaps even to show how large it was.

So Eratosthenes himself went outdoors in Alexandria and measured shadows at noon on the summer solstice. He also hired a person to walk many days from Alexandria to Syene and measure the distance very, very carefully. When this was done, Eratosthenes used his understanding of geometry *to compute the circumference of the earth. Nowadays, NASA uses satellites to compute that same circumference.*

How did Eratosthenes make his observations? How was he able to make his computations over two thousand years ago? How close to NASA's measurements were his?

Over the course of this year, you and I will watch the sun and measure shadows. We'll work to perform experiments like those of Eratosthenes and others. We'll see what we can learn from shadows.

The Value of Stories

Stories prime students for learning. Our telling of the story of Eratosthenes—inspired by a variety of sources (Crease, 2003; Hakim, 2004; Sagan, 1980)—is crafted to spark students' curiosity and to set them on a path toward acquiring specific understandings in earth science, mathematics, geometry, and technology. Sparking curiosity is an essential first step; as experienced teachers know, students are much more likely to learn what their teachers are hoping they'll learn if they are genuinely curious about the topic—if their interest has been aroused at the outset. Regardless of what the instruction afterward consists of, a student who wonders about the story—How could Eratosthenes figure out anything about the size of the earth that way? How many days did the walk take? How close *was* Eratosthenes' calculation to NASA's measurement? What kind of shadow is usually cast by a well? How long is *my* shadow at noon?—will be more engaged in the exploration to come.

Stories provide a basis for developing problem-solving skills. The story of Eratosthenes gives students a framework for thinking about how to solve problems. Hearing about his desire to fully understand properties of the earth and his care in noticing discrepancies encourages students to keep accurate records of their own observations. Hearing about his invention of a way to make measurements that will allow him to calculate the size of the earth (shown in Figure 1) and his use of a measurement technique that is no longer standard (using the length of a stride to measure large distances) contributes to students' interest in making measurements and a consideration of standard and nonstandard units. The calculation that Eratosthenes made requires simple measurements and straightforward geometry, easily duplicated by students once their attention is engaged. The story also introduces—or hints at—important concepts like circumference, the summer solstice, and consideration of error. Eratosthenes' conclusions, as students will discover later during their study of sun and shadows, were quite accurate—more accurate, in fact, than any others made in the next two thousand years. All aspects of the story contribute to wonderment. How did Eratosthenes figure it out? How might *we* be sure that the earth is round?

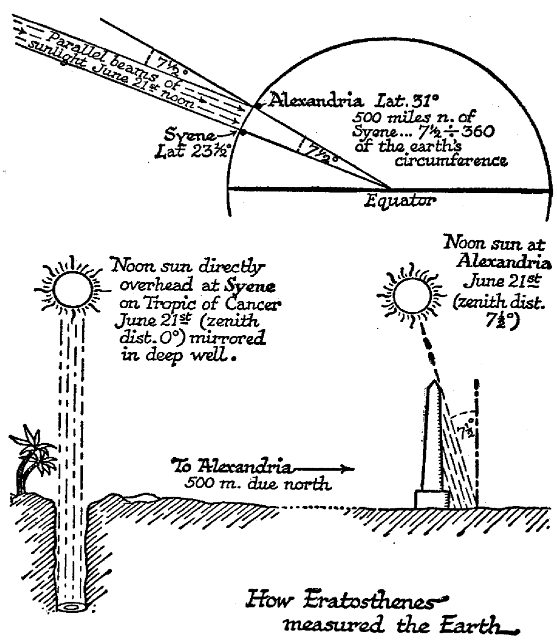


FIG. 107

Note that at noon the sun lies directly over the observer's meridian of longitude. Syene and Alexandria have nearly the same longitude. So the sun, the two places, and the earth's centre may be drawn on the same flat slab of space.

Figure 1: Eratosthenes' Geometric Calculations
(Hogben, 1937, p. 348)

<u>Stories provide a basis for inquiry</u>. In our *Sun & Shadows* unit, we use the story of Eratosthenes to motivate students to work directly with natural phenomena having to do with the sun and the shadows it casts. Students observe, represent, and make inferences about shadows—their sizes, shapes, and movements—over the course of the day and the year. In doing so, students grapple with the approximations, uncertainties, and threats of error that characterize scientific investigations. Their work can become more fruitful by the introduction of simple tools that allow them to pay careful attention, keep records, and develop accurate ideas about how to measure time and space. In this way students find themselves engaged in investigations of the nature of time and space of the very type that led to the emergence of math, science, and technology in ancient times. In fact, children may be brought to discover the facts and laws associated with these phenomena through their own investigations, and the experience of 'scientific discovery' may become a legitimate expectation for educational programs (Zachos, Hick, Sargent & Doane, 2000).

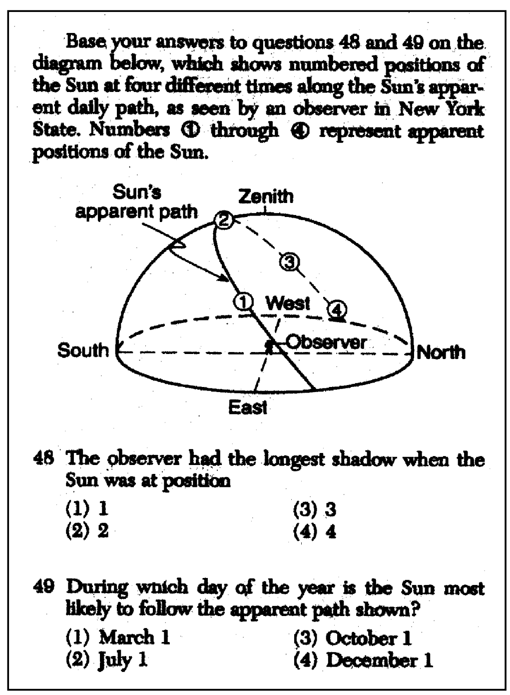
<u>A note on personal vs. historical discovery.</u> Stukeley (1752) tells the story of how Isaac Newton as a boy engaged in a study of sun and shadows of exactly the kind that we are describing here. The story illustrates how personal discovery can recapitulate historical discovery.

> Besides the clocks which Sir Isaac made, he showd another method of indulging his curiosity to find out the suns motion, by making dyals of divers forms and constructions every where about the house, in his own chamber, in the entrys and rooms where ever the sun came. He… show'd the greatness and extent of his thought by drawing long lines, driving of pegs into the wall to show the hours, half hours and quarters; tying long strings with running balls upon them, and the like contriveances, in order to find out the periods and conversions and elevations of the luminary: and made a sort of almanac of these lines, knowing the day of the month by them, and the suns entry into signs, the equinoxes and solstices. So that Isaacs dyals, when the sun shined, were the common guide of the family and neighbourhood. (Stukeley, 1752, ed. White, 1936, p. 43)

Stukeley chose to focus on these studies as an early manifestation of Newton's genius. We believe that the story—colorfully narrated also by Gleick (2003, pp. 11-13)—attests as well to the age-old fascination with sun and shadows, a fascination that can be used to capture the attention and imagination of young people in our own time just as it has throughout history.

In the Beginning: A Story of Educational Failure

One day, not so very long ago, we were invited by a teacher to help a group of unsuccessful students at Galileo High School in a small city in the northeastern part of the United States. (Names have been changed to protect schools' privacy.) These students had failed the state examination in earth science, three times. Our analysis of test items (a typical one is shown in Figure 2) indicated that a rich array of capabilities related to math, science, and technology was needed for success. Among the needed capabilities were measurement of angles, elements of geometric thinking, and understanding of scale and proportionality in interpreting diagrams. To be successful, students would have to relate their personal experiences of celestial events to the diagrams in the test. Because of the need to prepare for the test, instruction at Galileo High School—and indeed in the state as a whole—had been characterized by the use of plastic hemispheres. The teacher had been unable to spark their interest in seasons, in the sun, in shadows, in the earth itself.


Base your answers to questions 48 and 49 on the diagram below, which shows numbered positions of the Sun at four different times along the Sun's apparent daily path, as seen by an observer in New York State. Numbers ① through ④ represent apparent positions of the Sun.

48 The observer had the longest shadow when the Sun was at position
(1) 1 (3) 3
(2) 2 (4) 4

49 During which day of the year is the Sun most likely to follow the apparent path shown?
(1) March 1 (3) October 1
(2) July 1 (4) December 1

Figure 2: State Earth Science Test Item

We administered some simple practical assessments and found that most of the students had none of the needed capabilities, except for the most rudimentary measurement skills. Conversations with students revealed that they had little or no experience in observing and thinking about natural phenomena and that a relationship to these had not been emphasized. Additionally, students were tired of teachers' repetitive efforts to get them to understand the material; they were disheartened.

After analyzing the state test and hearing from the teacher about her goals for her students, we established learning goals and developed assessments for judging success in meeting the learning goals. An instructional intervention was designed, premised upon involving the students in developing *Sun & Shadows* teaching tools so they might be motivated to make multiple measurements and drawings. First we told students a version of the story of Eratosthenes. They imagined shadows in distant places, and they imagined the sunlight reflecting, streaming up from the deep well in Syene, providing clues to solving a mystery. Their imagination kindled, we introduced them to a homemade measurement tool—a set of three colorful oversized wooden boards we call 'shadow boards'—accompanied by a variety of gnomons, rulers, protractors, compasses, and drawing materials. In order to encourage repeated and methodical measurements, we requested their design assistance: which of these boards (shown in Figure 3) would other students find most useful for making accurate measurements? The students learned to make accurate measurements, to choose units consistently, to measure angles, to accurately reproduce angles, to create scale drawings. We could see the students' skills improve, but we wondered if students understood the scientific principles behind their measurements. To find out, one day we asked students to find a way to teach a guest everything they had learned about sun and shadows, without making it too easy for him. Students took a flashlight, handed it to the guest, and asked him to show them on the shadow board the path the sun had likely followed the previous day. To help with this task, they provided data in the form of technical drawings they had produced, showing the lengths and angles of shadows at various times of day. This innovation on their part—they had never used a flashlight in their work with us before—and the specific assignment they created, demonstrated to us that they had attained competence in modeling the pattern of lengths of sun shadows over the course of a day and the sun's apparent path in the sky during that period as well. We were intrigued by the Galileo High School students' method of assessing these capabilities, and we now use their assessment method ourselves, both with other students and when working with teachers in professional development activities.

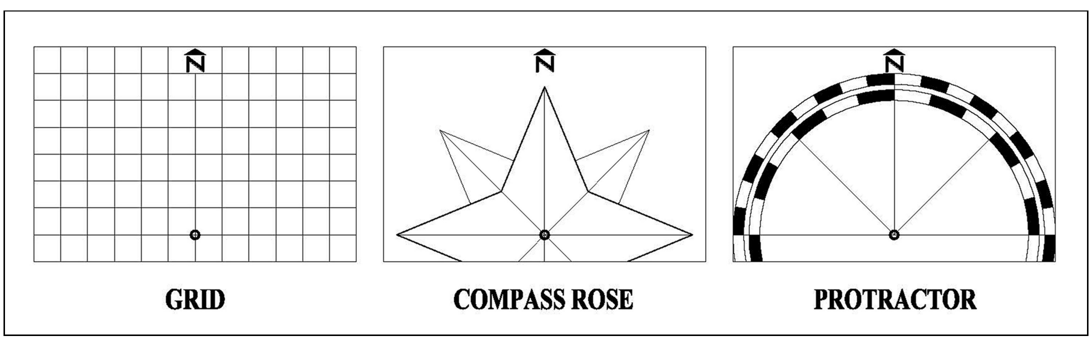


Figure 3: Shadow Boards (each board is 120 cm x 80 cm, designs available at no charge on www.acase.org)

Further Development of *Sun & Shadows*

<u>Learning goals, assessment, and instruction</u>. We have alluded to learning goals, assessment, and instruction. To be most effective, instruction must be efficiently directed toward the achievement of targeted learning goals (Johnson, 1977; Mager, 1962; Tyler, 1949). Assessment is the means for finding out the degree to which these goals are being achieved. Often learning goals are implicit; sometimes teachers cannot even articulate what their learning goals are. Instruction cannot be efficiently directed toward achievement in such situations. The value of explicit learning goals is that they permit thoughtful and even empirical answers to the three fundamental educational questions:

1. Is the educational program directed toward achievement of the most valued outcomes?
2. To what degree are these outcomes being achieved?
3. To what degree is instruction contributing to the achievement of the desired outcomes?

Without clear learning goals, it is difficult to answer any of these questions.

Recently Grant Wiggins (2005) has brought to the fore the importance of what he calls 'backward design' in relating the three fundamental features—learning goals, assessment, and instruction— of the educational process. The idea of backward design is to immediately follow the identification of educational goals with the development of appropriate assessments and only then to begin the process of planning and carrying out instruction. There are several virtues to this order. First of all, it permits pre-testing and provides empirical data on which to base instructional design decisions. Second, it tends to ensure that the learning goals will be attended to and that instruction will not just become a matter of 'covering the topic' or 'getting through the curriculum'. But if instruction is to truly meet the learning goals, assessment must be carefully designed. If it is not, the assessment may fail to fully capture what is essential in the learning goals, thus trivializing the goals and lowering expectations for learners.

Building on our experience with the Galileo High School students, we began to imagine an educational program built intentionally on learning goals targeting the very concepts and capabilities that characterized the ancient investigations of sun and shadows—investigations that set the foundations for our math, science, and technology, and our modern concepts of space and time. In our view, it is these capabilities that provide a solid foundation for competent performance in math, science, and technology education in secondary school, and afterward in solving life problems. A science teacher who had become intrigued with the first fruits of our design efforts expressed an interest in seeing how her classes responded to *Sun & Shadows*. She obtained a grant from an educational foundation in her town to work with us on this project. What we did over the next year at her school, Maria Mitchell Middle School in a northeastern U.S. suburb, is described below.

Identify learning goals. Using backward design, we first analyzed AAAS benchmarks (Project 2061, 1993), the school's goals, and the teacher's personal goals in order to identify valued outcomes appropriate for her students (generally high-achieving sixth graders). We then created a set of operational learning goals (goals that represent teachable outcomes), emphasizing higher-order capabilities—application, analysis, synthesis, and evaluation, in Bloom's taxonomy (Bloom, 1956). In the course of the year some additional learning goals were identified; these will be assessed next year and are discussed briefly in our 'next steps'. The learning goals that were used during this pilot year are as follows:

- Coordinates direction of sun with direction of shadow
- Coordinates sun altitude and shadow length
- Identifies pattern of change in length of shadows over the course of the day
- Identifies pattern of change in length of shadows at noon over the course of the year
- Shows understanding of the word *equinox*
- Shows understanding of the word *solstice*
- Labels orienting directions
- Models path of sun over the course of the day
- Models changes in path of sun over the course of the year
- Models pattern of change in length of day over the course of the year
- Supplies units of measure in data presentations
- Creates a drawing to scale
- Provides a scale for a drawing
- Solves problems of proportionality geometrically
- Solves problems of proportionality mathematically

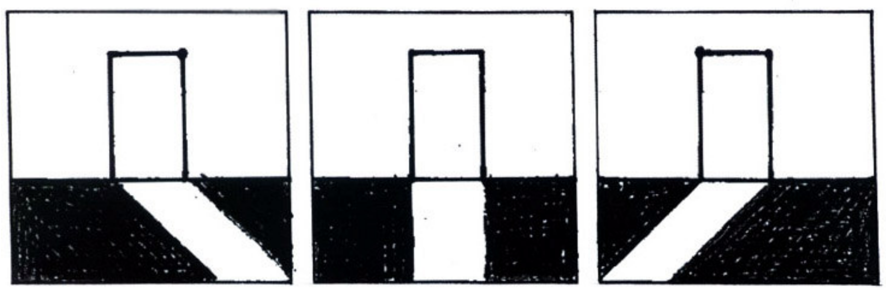
Create assessments. Next, we created assessments aligned to the learning goals. Some are activities that permit simultaneous assessment of two or more learning goals while still permitting clarity regarding the attainment of each particular goal. These assessments can be used at the beginning of a unit both to give the teacher information about what the students have already attained and to serve as instruction for the students. For example, in the assessment activity shown in Figure 4, the students have the opportunity to think about what types of information are important on a diagram, and the teacher has the opportunity to see what the students already know.

> An elementary class in Massachusetts decided to investigate shadows, and found a class in Ecuador that wanted to do so also. One day, both classes measured their flagpole's shadow. The Massachusetts class, with a 25-meter flagpole, found the shadow was 15 meters long. The class in Ecuador, with an 18-meter flagpole, found the shadow was 5 meters long. Your job is to make a diagram including everything that is important for showing how the flagpoles with their shadows are different.

Figure 4: Assessment Activity

The assessment questions shown in Figure 5 generally leave students curious and aware that they have something they need to learn.

This diagram shows sunlight entering a room through the same door at three different times one day in a building near here.



just after sunrise | at noon | just before sunset

1. **What direction does the door face? (Circle one: north, south, east, west) Explain your reasoning.**
2. **Look again at the diagram. Near what date or dates do you think this could have occurred? (Circle: March 21, June 21, Sept. 23, Dec. 21) Explain your reasoning.**

Figure 5: Assessment Questions

These assessment activities and questions provide information on the extent of student attainment of the learning goals. We are not interested in ranking students, so the assessment results for all learning goals are not summed to obtain an overall score for each student. Rather, each learning goal is considered separately so as to provide the teacher with information that will be useful for planning and evaluating instruction.

In the assessments, a student's performance on each learning goal is characterized as either *attained* or *no evidence of attainment*. The reason for using the phrase *no evidence of attainment*, rather than *not attained*, is that there is often legitimate concern over the distinction between cases where competence is absent and those where the assessment has simply not successfully demonstrated student competence. For some learning goals, an intermediate level, *under development*, provides a more precise way to characterize student attainment.

Over time, rules and examples are provided to help teachers (and others who are assigning ratings) to accurately identify the appropriate level of student performance for each rating. For example, we assess performance on the learning goal 'Coordinates sun altitude and shadow length' by asking students to explain what they could say about the sun if their shadow is short (for someone at about latitude N 43^0). Evidence of attainment requires some indication that the sun is high in the sky. Acceptable answers include ‘The sun is high in the sky’, ‘It is noon’, ‘The sun is above you’, and ‘It is not winter’. Student performance is displayed to allow the teacher to see the relative levels of attainment (before and after instruction) of students in a class. As the display in Figure 6 shows, the majority of students in one of the pilot classes had not attained this concept when an assessment was carried out in September. By June, most students had reached attainment.

The information system that generates these reports also identifies the specific students at each level of performance indicated by the bar graph, thus permitting targeted instructional planning.

What is the quality of the information obtained from these assessments? We place a premium on reliable rating of student performance. When we communicate a judgment of student attainment to a student, parent, colleague, or school administrator, our judgment must—in the interests of clarity, objectivity, and fairness—be dependable. Reliability verification is one of the most powerful means of ensuring that dependability. Those who are assigning the ratings—that is, characterizing students’ answers as *attained*, *no evidence of attainment*, or, in some cases, *under development*—must have engaged in systematic preparation so that their ratings will be reliable. The reliability of an individual’s ratings is calculated as the percentage of matches between her or his ratings and a standard that we have established. When the percentage exceeds 90%, we consider the individual to be rating reliably. This level was attained on all of the data presented here.

Design instruction. By the time the school year began at Maria Mitchell Middle School, we had developed assessment activities that would also serve to introduce instruction. To engage students’ interest and pique their curiosity, we planned to use stories such as that of Eratosthenes. And we had already created tools for the project, including the shadow boards that had proved so successful in engaging the older Galileo High School students in direct investigations of the patterns of sun and shadow.

Working directly with natural phenomena provides an instructional efficiency that is typically not possible with simulations. In investigating natural phenomena, students can discover, immediately or over time, whether their concepts and explanations are working and can adjust them to fit new evidence. By concentrating on concepts that students can verify through their own investigations, we are also able to capitalize on the students’ motivation to uncover the mysteries implicit in everyday events, such as changes in where the sun and moon rise and set over the course of the year.

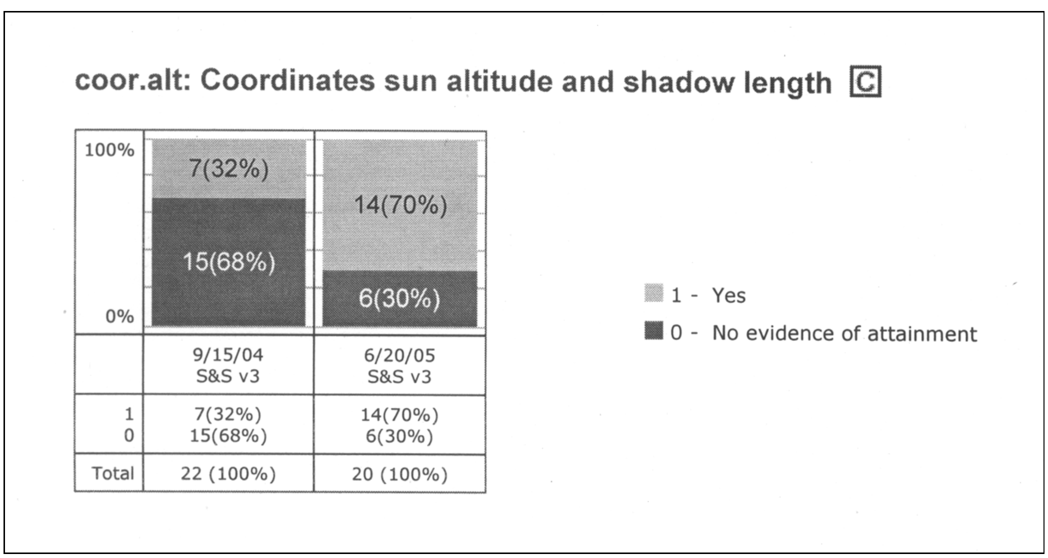


Figure 6: Maria Mitchell Middle School Student Performance
‘Coordinates Sun Altitude and Shadow Length’

In *Sun & Shadows*, the teacher presents tasks, problems, and questions that students address through their own investigations, often over a period of time. These investigations require careful observation, record keeping, and the development of explanations and mental models by students working sometimes individually and sometimes in groups.

Sun & Shadows in the Classroom

Autumn. At the beginning of the school year, the teacher told her students a myth about the sun (Lester, 1989; Pilling, 1993). Sixth graders at Maria Mitchell study myth in their language arts classes, and she wished to coordinate with other teachers. Additionally, she wanted her science program—like Egan's—to reflect 'the human adventure that began in magic and myth and gradually, through individuals' courage, ingenuity, hopes, beliefs, and so on, became science' (Egan, 1986, p. 97). With Moyers, she feels that 'myths are stories of our search through the ages for truth, for meaning, for significance' (Campbell, Moyers, 1988, p. 4). Most of all, she wanted to start with a story that would provide flexibility. 'I knew that I didn't know exactly where I was going to go, didn't know exactly what to emphasize in the Eratosthenes story, didn't know which aspects of the story would prove to be absolutely essential', the teacher commented in her journal. The power of telling a story that is fully integrated with learning goals is enormous; as the teacher put it:

> I didn't want the students to grow weary of the story, didn't want to waste it. In fact, I did use the story of Eratosthenes myself, in my head, to frame what I wanted to do with my students. For instance, before I knew the story I didn't recognize the importance of scale drawings. I decided having students create scale drawings of themselves would be a good way to start the school year, and I found that the concept of scale is foundational for a study of the solar system AND for graphing AND for map work AND for geometry—as well as for understanding how Eratosthenes accurately determined the circumference of the earth 2,200 years ago.

After hearing the story, students were given a complete assessment, the results of which were not shared with them. Most students were able to coordinate the direction of the sun with the direction of their shadow. Most students were able to apply orienting directions, placing the four cardinal directions and four intermediate directions in the conventional Northern Hemisphere pattern on a blank compass rose (it was not a multiple choice; students were not given possible answers). None of the students were able to model the path of the sun over the course of the year, and 65% were unable to model the course of the sun over the course of the day. This was not surprising, as the students were eleven years old and had had no known exposure at school to these concepts and skills.

Students were introduced to scale drawings by being taught to create measured self-portraits, several of which are shown in Figure 7**.** The *Sun & Shadows* boards were used to create outlines of shadows throughout the day on the autumn equinox, with each group adding to the work of others. Students measured the lengths of shadows: their own, the shadow at the flagpole, the shadows on the board. They compared their drawings to drawings done at different times of day by other groups. Students learned—either then or later in the year—to make scale drawings of the side view of a blocking object and its shadow, learned to make drawings with accurately constructed sun angles, and learned to use scale drawings to solve problems in geometry (such as working backwards from the length of a flagpole's shadow and the sun angle to discover the height of the flagpole).

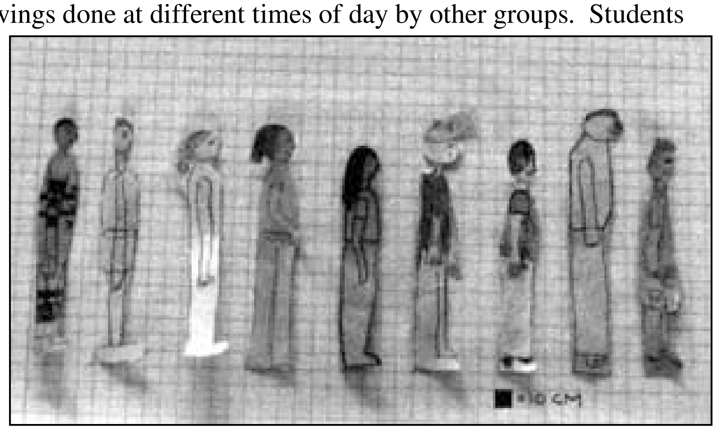


Figure 7: Self-Portraits—Scale Drawings

Winter. In preparation for going outside to record the shadows on the winter solstice, students were reminded about the autumn shadow tracings they had done and were shown samples. Working individually this time, students sketched the autumn shadows freehand while viewing the recorded data, and then they thought about the shadows they expected to see at the winter solstice, using a second color to show their predictions. Meeting in small groups, they brainstormed and discussed possibilities. Trying to reach consensus on what might be the path of the sun during this particular day and what might be the effect of that path on the shadows, they revealed what they had already observed. Some groups couldn't reach agreement on what to expect. The teacher invited careful consideration of differences in shadow length and position, but some students turned out to be most interested in how wide or narrow, how crisp or fuzzy the shadow was. One group of students spontaneously fetched the blocking object and a meter stick and then held them over the page of autumn shadow tracings with the meter stick positioned to show each other the sun angle, in order to predict the December shadows.

On the occasion of the winter solstice, something very wonderful occurred. Students were asked to observe and reflect on any discrepancies between what they were observing and what they had predicted. One young boy became excited during this process. He remembered very clearly his answers on the autumn assessment, and he had been eager since then to find out whether he was right or not. On this day, the shadows themselves answered his question. Now, it is not an easy thing for a teacher to do, to allow a student's questions to remain unanswered over a long period of time before being answered by the student's own efforts. In her journal, the Maria Mitchell teacher reflected on the contrast between teaching in this way and teaching in what she describes as a more teacher-centered way:

> I am kind of blown away by how relaxed I feel about the degree of seeming chaos there is in my room. Although I believe (theoretically) in *non*-teacher-centered teaching, it usually makes me uncomfortable. But it seems that students are on task, doing different things, handling their issues, etc.

Spring. Shortly before the spring equinox, students were asked to write their hypotheses about the shadows they were likely to see when they went outside. Some students clearly had misconceptions about the relationship between sun and shadow. One boy wrote:

> I think the shadow will be longer because the closer the sun is to us the shorter the shadow and the farther away should be a longer shadow.

Other students were beginning to pay more careful attention to what they saw, and were beginning to understand the patterns. One girl wrote:

> On September 22, most of the shadows were short (the sun was overhead and high in the sky) and on December 21 the shadows were much longer, (the sun was lower in the sky and not right above). I am guessing that now, March 15, about the same amount of time away from Dec 21 as September 22, the data will either be similar to those of September or equally taller than December's. My guesses are just based on possible patterns, not on strong knowledge.

Another student spontaneously provided sketches for shadow patterns for 'Now', Spring, Winter, Fall, and Summer, and also created a diagram of the relationship of earth's tilt in relation to the sun at the different seasons. He wrote:

> I think that the shadows will be much like the ones on September 22 because from when we learned about astronomy, we learned that the shadows on the two equinoxes (and March 21 or 22 is one), the shadow's angles are in the middle of Winter and Summer shadows, (Winter being the longest) because of the angle of the sun in relation to the earth's tilt. I also think that they will be a little longer than September 22, because March 15 is closer to Winter Solstice and farther from Summer Solstice.

When students went outside to make their shadow drawings, they had the opportunity to use a new tool we had developed, a giant protractor, 120 cm x 60 cm. The shadow boards are of similar size—all are durable, brightly painted, and large enough to enable students to make precise measurements easily. Figure 8 shows the tools in use, as students puzzle through the use of the protractor.

Later in the spring, the teacher had these thoughts:

I'm musing on the issue of discomfort. It seems to me that students need to be uncomfortable when they are really learning something the teacher has decided is important. I mean, some students may immediately make it their own choice to understand something complex (such as how Eratosthenes determined the circumference of the earth) and many are willing to follow a procedure because the teacher has asked them to do so, but when taking a big step like understanding why a scale drawing enables them to determine the sun angle, it seems that they need to struggle with that themselves. I can tell them they have to make a scale drawing, I can show them how to measure the angle on it, I can teach them how to construct an angle, but it seems like I can't *teach* them how to figure out what they need to do to solve a new and different problem. This whole business of teaching is somewhat circular: I can't get them interested in learning to measure angles unless there's a good reason, and I can't get them to understand the reason unless they have the concept of angles. So I was extremely pleased with yesterday's assignment, in which I asked them to show where shade from a picnic-table canopy would fall at noon on the summer solstice. I felt that I was able (with it) to leave students with their discomfort long enough for them to solve it. (They had to realize that they needed to construct an angle, and then they had to figure out where to construct the angle, and finally they had to do so.) In the past I think I haven't left students in their discomfort long enough for them to make discoveries. I'm pretty uncomfortable forcing students into discomfort.

Figure 8: Students Measuring Solar Altitude

Summer. On the summer solstice, students went outside to make shadow tracings. The final assessments for the school year were made several days later. This provided an opportunity to study growth (or lack of it) in student performance over time. Before discussing what trends emerged, we will use test item #1 (shown earlier in Figure 5), an assessment of students' attainment of the learning goal 'Models path of sun over the course of the day', as an illustration of the end-of-year results. *Attainment* on this learning goal is evidenced by the choice of 'south' as the direction toward which the door faces, buttressed by correct reasoning. Students wrote:

- 'Because the sun rises in the east so you would turn it around and see it is south.'
- 'Because if you are facing north the east is on the right but here the east is on the left because sunrise is in the east so you must be facing south.'
- 'The sun rises from the east so the door shadow goes west and the sun sets from the west so the door goes west. At the middle it it's even. So the door must be facing south.'

Students who chose the correct direction but failed to provide appropriate reasoning (and yet did not submit faulty concepts or reasons) were characterized as being *under development* with regard to this learning goal. They wrote:

- 'I be looking in the south because that is where the sun is.'
- 'The sun always sets in the west #3 door'
- 'because you would be looking forward'

An incorrect answer or a correct answer with incorrect reasoning was scored as having *no evidence of attainment*. These responses included:

- ‘North: At noon the sun is overhead’
- ‘North: because at noon the sun is in the middle of the sky.’
- ‘North: the earth is at its middle course in orbit’
- ‘East: If the sun rises in the east, at sunrise it’s east, the door is basically facing east.’
- ‘South: The door would be facing south because the sun rises in the west.’

All four of the classes that took part in the *Sun & Shadows* course of instruction experienced growth in performance on this learning goal. Figure 9 shows the aggregated pre- and post-instruction performance on ‘Models path of sun over the course of the day’ for the four classes.

In looking for trends, we discovered that *Sun & Shadows* students progressed on all of the learning goals, to varying degrees. ‘Models path of sun over the course of the day’ was actually *not* one of the most dramatic examples of growth. On ‘Models pattern of change in length of shadows at noon over the course of the year’, the percentage of students who had shown *no evidence of attainment* on the pre-test dropped from 55% to 21% on the post-test, and on ‘Models pattern of change in length of shadows over the course of the day’, the percentage of students who showed *no evidence of attainment* dropped from 54% to 29%. Learning goals with the highest levels of attainment at the beginning of the year tended to show the least amount of growth over time. Students who were successful at ‘Shows understanding of the word *equinox*’ increased from 10% to 67%, while those who were successful at ‘Shows understanding of the word *solstice*’ increased from 5% to 49%.

Could the growth have been greater? What factors might have interfered with growth? Could some of the learning goals have been less well suited than others to the developmental level of particular students? Were there problems in the way the instructional program was carried out? These are central questions, and the assessment instruments provide tools that can be used to answer them in subsequent research. Why particular students did not move forward should be a fruitful path of inquiry for action research and cognitive research in future uses of *Sun & Shadows*.

As it turned out, the assessments were also administered to three additional classes taught by other teachers in the Maria Mitchell school district—classes with roughly equivalent students who had studied the same subject matter, but without the experiential *Sun & Shadows* instructional activities. We will refer to these classes as the ‘B Group’. A comparison of the results provides hints of the possible effects (and effectiveness) of *Sun & Shadows*. They are, however, merely hints, given the lack of information about the instructional activities in the other classrooms and the possibility of teacher effects. We do know that the learning goals we measured are consistent with the district’s learning goals for these students.

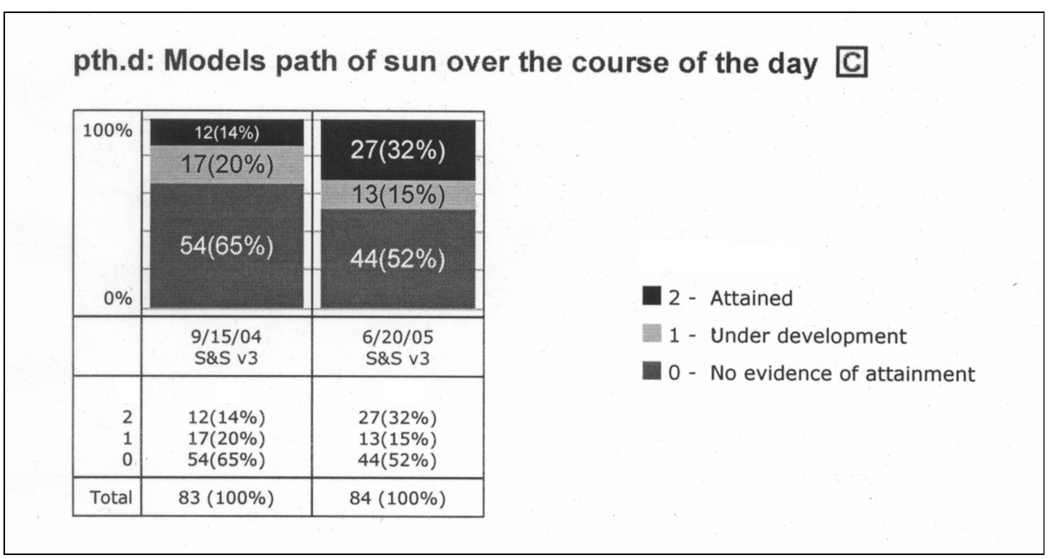


Figure 9: Maria Mitchell Middle School Student Performance - *Sun & Shadows* Group

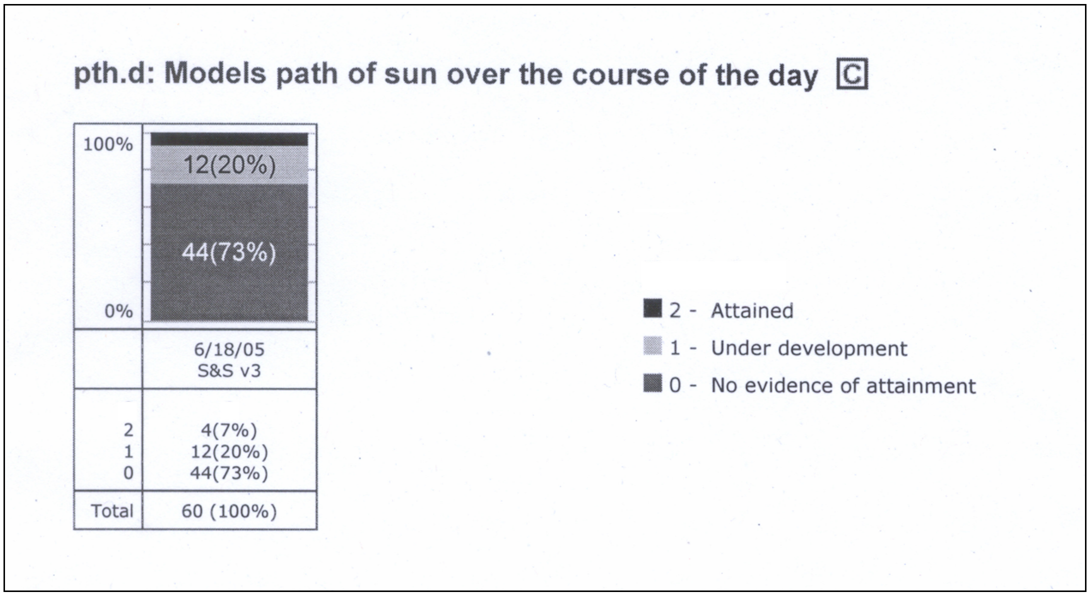


Figure 10: 'B Group' Student Performance

Figure 10 shows the June performance of the B Group on 'Models path of sun over the course of the day'. These scores are even lower than the *September* scores of the classes that did use *Sun & Shadows*, leaving us with an array of unanswered questions we hope to have the opportunity to explore in the future. Is it possible for performance to regress over the course of a school year?

In other comparisons between the B Group and the classes in which *Sun & Shadows* was used, it appears that performance was roughly equivalent for learning goals that involved learning simple facts (e.g., different lengths of day over the course of the year, cardinal compass points). Yet, surprisingly, B Group students had lower attainment on understanding *equinox* and *solstice*— 34% on each learning goal. For learning goals that required the organization of patterns of phenomena and events (e.g., the change in shadow length over the course of the day, modeling the sun's path over the course of the day), the students who had taken part in the *Sun & Shadows* curriculum were clearly at an advantage, with the scores of the B Group similar to the September scores of the classes in which *Sun & Shadows* was used.

We suspect that the important factors in these differences are the attention paid in *Sun & Shadows* to students' personal experiences of sun and shadow phenomena, the systematization of those experiences through observation and communication (e.g., scale drawing), and the exercise of mentally coordinating the experiences in class and in homework. Our hunches constitute hypotheses both for action research by teachers working with this subject matter, and for more carefully controlled studies by researchers on these factors' effects.

A full analysis of the assessment results can be viewed at:
http://acase.org/tasks/sunshadows/04-05assessment results/

Sun & Shadows Next Steps

As we have indicated above, we have a number of unanswered questions about the use of *Sun & Shadows* in the classroom. This coming year several of the other sixth-grade science teachers in the Maria Mitchell school district will be using *Sun & Shadows* with their students, giving us the opportunity to see the results with over two hundred students. As the work moves forward, we are imagining an extended educational program moving into the higher grades, built intentionally around the learning goals we see in other stories associated with sun and shadows. Figure 11 shows some of these possibilities, from Pythagoras to Newton. (As always, teachers who would like to do so may freely use the materials available on our website, www.acase.org.)

Person/ Event	**Story**	**Learning Goals**
Pythagoras (582-497 B.C.E.)	Known to have taught that the earth was spherical	• Understand that earth is (roughly) a sphere • Geometry
Aristarchus (320-250 B.C.E.)	Heliocentric hypothesis, geometry of earth, sun, and moon	• Understand the heliocentric model • Understand that a good hypothesis may be disbelieved for non-scientific reasons
Euclid (~300 B.C.E.)	Geometry	• Solve problems using geometry • Scale drawings
Eratosthenes (276-196 B.C.E.)	Desire to understand properties of earth, noticing discrepancies, inventing a way to make measurements	• Create a way to make measurements to obtain accurate data • Create accurate graphic communication • Provides accurate technical diagrams • Create conceptual model that incorporates observed data • Refine model in response to additional data
Apollonius (250-220 B.C.E.)	Conic sections: ellipses, parabola, hyperbola	• Circles • Ellipses
Hipparchus (190-120 B.C.E.)	Invention of Parallax Gridwork of latitude and longitude and star maps with 6 magnitudes of brightness	• Solve geometry problems using parallax • Understand seasons in relation to earth tilt • Understand latitude
Poseidonius (135-50 B.C.E.)	Measuring the earth inaccurately and convincing others	• Distinguish quality of data
Copernicus (1473-1543)	Sun at the center of the planets, worked out mathematically	• Understand the heliocentric model
Kepler (1571-1630)	Elliptical orbits	• Refine the heliocentric model
Newton (1642-1727)	Law of universal gravitation	• Understand role of gravity in relation to solar system.

Figure 11: *Sun & Shadows*, Additional Stories and Learning Goals (dates based on Asimov, 1964)

Concluding Thoughts: *Sun & Shadows* and Its Relation to Other Curricula

Inhelder and Piaget (1958) have shown that shadow reckoning can be used as a rigorous tool for assessing what they call 'formal operational' capabilities of children. Piaget has highlighted the importance of such capabilities for a general scientific world view and competence (1972). We believe that the attainment of the learning goals associated with *Sun & Shadows* provides a critical foundation for competent performance in math, science, and technology in the secondary school classroom. Just as the capabilities associated with these learning goals became the foundation of our modern science, mathematics, and technology, so too are they the logical foundation to underlie competence in the modern disciplines.

We believe, moreover, that engagement with the investigation of sun and shadows provides a rich opportunity to assess the attainment of foundational higher-order cognitive abilities. Practical shadow reckoning can be a powerful medium for developing these capabilities. Sun and shadow studies provide a natural link to subsequent and larger questions of the measurement of time and space—for instance, those in which the pendulum has played a critical role (Matthews, 2000). In another context we have addressed the importance of competence in notions of error and uncertainty if students are to engage in empirical studies of pendulum phenomena (Zachos, 2004). It is reasonable to explore the possibilities of sun and shadow work as a prerequisite to these studies.

We have presented our case as a series of stories, stories about great scientists and their discoveries, stories about teachers and students, stories about our own efforts and interests. Stories are a quintessentially human sort of information. They can engage interest, spark essential questions, and set themes for inquiry. Stories of space and time are a central feature of the *Sun & Shadows* activities. They give students a connection to ancient and faraway places and to adventurous individuals whose work with sun and shadows led to important contributions to civilization. Stories from the world's mythologies infuse our relationship to time and space with feeling and imagination. Such stories—and direct work with natural phenomena—spark students' curiosity and motivate them to engage in learning and to broaden their horizons, taking them beyond the limitations of conventional classroom practice.

We know that we have only touched the surface of the role of stories and of the implications and possibilities for sun and shadow study as the center of an integrated curriculum. We look forward to working with colleagues in the fields of math, science, technology, philosophy, history, and the arts to enrich this educational initiative.

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