ASTRONOMY LEARNING AND STUDENT THINKING

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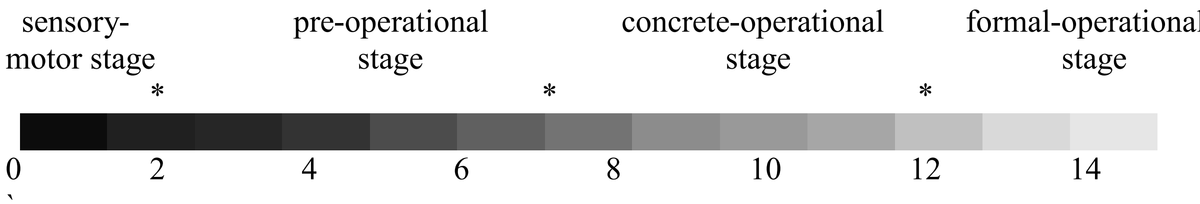
Each year the ASP honors an educator for special achievements in teaching astronomy. The 1995 winner was Jeanne Bishop, known for her professional dedication and research into how children learn at different ages.

You would have sworn that they really understood lunar phases. I had each sixth-grader hold a ping-pong-ball “moon” and watch how it was lit by a 100-watt “sun,” I explained that the ping pong phases they saw were like the lunar phases we see from earth. When I asked questions about the sun's direction and each phase, all the students answered them correctly.

And yet they did not really understand. When I asked the students to match the orbital position of the moon with the phase that we would see, half of them failed to get even 40 percent of the questions right. Too often, we educators blame ourselves for this. We think that if we can just explain something right, using great teaching methods such as hands-on modeling and planetarium observations, students are sure to get it. It isn't so. My sixth-graders simply had not yet developed the mental ability to switch back and forth between earth-based and space-based perspectives of the phases.

Although I have done my own research into spatial-concept learning by students of different ages, I have been strongly guided in both my teaching and my research by the theories of the Swiss psychologist Jean Piaget. For half a century, Piaget designed experiments to see how children think and how their thinking matures. His conclusions guided physicist Robert Karplus of the Lawrence Hall of Science when he designed the “Learning Cycle” and incorporated it into the Science Curriculum Improvement Study in the 1960's.

Piaget's ideas, as restated by Karplus, have found expression in the current educational trend of constructivism [see "Constructing Constructivism," July/Aug. 1995 issue of *Mercury*, p. 7]. They have also been supported by neurological research: The brain grows in spurts that are close to the transitional times identified by Piaget – 2 to 4, 6 to 8, 10 to 12, and about 14 years old (see diagram next page). By knowing what children of different ages are able to comprehend, teachers and parents can be more effective in helping them to learn. Astronomy, it turns out, is an ideal way to promote many of the skills that children will need in every area of life.



Stages of thinking. *These stages and transitions emerged in the clinical studies of Jean Piaget, but have also been observed by neurologists. Toddlers are just learning what it is like to look and move around, young children develop language skills, older children gobble up information and learn to categorize it, and teenagers pick apart arguments and make plans on their own. A spurt in brain growth propels children from one stage to the next. From the age of 8 onwards, children develop their ability to think abstractly about spatial orientation. Of course, not every child goes through the transitions at precisely the same age.*

Preschool: fun with names.

Piaget called young children pre-operational thinkers. Their language skills, perception, and symbolism are developing. Their thinking is often intuitive.

The abilities of the preschool child can be nurtured through exploration or interaction with the world: observing, relating accurately what was observed, making predictions, checking predictions, differentiating right from left in a variety of situations, being alert to the relativity of motion, telling how size varies with distance, and realizing that time moves forward at a constant rate.

Children at these ages learn astronomical names easily, and find the sounds fascinating. Observations of the stars, bright planets, and moon are great activities for a young child as soon as he or she can perceive them. My son at age 2 was delighted by the appearance of the moon in both the day and night sky. At age 3, he could name many lunar craters.

Early elementary: fact explains fact.

Ask an average 6-year-old why the sun stays up, and he or she will reply with something like, "Because it's bright," or "Because it's daytime." For kids at this age, one fact explains another. Piaget called this transductive reasoning, which characterizes children younger than 7 years old, or about second-grade.

If you explain to a child of this age that earth turns around on an axis to face the sun sometimes and away from the sun other times, the words will get stored in the brain – but the child will make little or no logical connection of explanation to fact. If the child repeats the explanation, he or she is simply parroting (unless he or she has moved ahead of normal development).

I have heard children, to whom a fine lesson has been given with an earth model and stick person, repeat the explanations, and then give completely wrong answers to pointed questions. "Where is the sun after sunset here?" usually elicits "Behind a mountain" or "In a cave." Until third-grade or later, the ability to unite the view of the earth in space with the person's view is absent. And even then, probing questions usually are answered wrong. The flexibility to switch between earth-based and space-based views for more difficult concepts, such as lunar phases, comes much later.

Children in the lower elementary grades need action and sensory input – the more the better. Discuss with young children what they are doing and listen for any wrong ideas they hold. If a 7-year-old tells you that the sun goes behind a mountain or into a cave after sunset, probe with, "Why do you think that happens?" Let the child try different things with the model materials.

Piaget's findings also can guide constellation study, an opportunity for everyone to become familiar with astronomy without instruments. Before age 3, most children cannot distinguish closed shapes such as triangles, circles, and squares from one another. At age 5 to 6, children can tell circles from rectangular shapes and straight lines from curved; they can discern angles of different relative sizes and explain relationships between sides of a figure. The words *shorter* and *longer* become a part of their vocabulary. At age 7, children begin to differentiate a six-pointed star from a hexagon.

Therefore, it is pointless to try to teach a constellation shape to most children under 6 years old. They will not see one constellation shape as being different from any other. By about first-grade, children can learn simple sky patterns. Their constellation learning can be helped along with line drawings that indicate differences in side length and angle size. By about third-grade, children become more discerning in picking out different constellations. But the ability to recognize a complex pattern in a radically different orientation is an advanced ability. As an adult visiting Australia, I had difficulty recognizing the same constellations I had viewed frequently from Ohio.

Late elementary: weaving a web of ideas.

At age 7 to 8, children move into a concrete-operational state of thinking, which lasts until about age 12 to 13. They can define, order, and classify. But they need step-by-step instructions and references to familiar objects and actions. For instance, my sixth-grade planetarium class was comfortable with answering questions about the lunar phases as long as the ping-pong ball and light bulb were still present.

Elementary schoolchildren find facts absorbing. As they sort and classify them, they build up knowledge that will be put together in more advanced ways when the thinking mechanisms are ready. Children at this age can form groups and subgroups with "planets," "stars," and "galaxies." They can identify sequences of observations of lunar phases, sunset positions, and shadows. The planetarium is a wonderful supplement, although not a substitute, to the real sky for observations by grade-school students.

Until the age of 11 or 12, children can imagine to a certain size and then no larger. Third- and fourth-graders love facts like, "It is 93,000,000 miles from earth to sun" and, "The earth formed between 4 and 5 billion years ago." But they cannot grasp the idea that time could go on "forever" or that there are "infinite number" of anything. I remember hearing of the steady-state model of cosmology while in elementary school. My father tried to explain it, but I could not imagine that time might never start.

The concepts of horizontal and vertical, based on the earth's surface and gravity, are mastered at about age 9; the correct relationship between left and right in different situations, a few years later. The child then advances to a stage of spatial thinking called projective representation, the ability to visualize what an object or event would look like from different points of view. The sixth-graders in the planetarium lacked this ability.

Such limitations intimidate many teachers and parents. How can you give meaningful answers to the questions kids ask? In the planetarium, children of all ages ask me about things that are very important to them: What makes the stars shine? What is a black hole? How was the solar system formed? How old is the universe? I think that it is possible for a teacher or parent to give accurate answers to children of any age by knowing some of the features and limitations of their thinking (see table below). I do not think that a teacher should ever say to a child, "This subject is too complicated for you."

Why do stars shine?

Age: 5
Explanation: "A star shines because one kind of hot gas inside is turning into another kind of hot gas. When the change takes place, this gives off energy."
Comment: Children may not really understand gas or even the sequential reason for the change, but the explanation is correct, it satisfies them that someone knows an answer, and they file away one or more retrievable facts – important to them because they had asked about it.

Age: 8
Explanation: "The temperature of the center of the sun is over 10 million degrees. Small particles of hydrogen bump into each other with great force and sometimes stick. They change into a different gas called helium and give off a lot of energy."
Comment: It helps if you act, gesture, and emphasize some words.

Age: 11
Explanation: "The sun's center is about 20 million degrees Fahrenheit. Six hundred million tons of hydrogen are converted to helium each second, while 4 million tons of hydrogen are changed into energy. If the sun were wrapped in a shell of ice that was 40 feet thick, the sun would melt all of the ice in one minute."
Comment: The 11-year-old is hungry for facts and considers you to be a good teacher who will have credibility in other lessons if you can cite numbers.

Teen-age: thinking about thinking.

Children between second- and eighth-grade learn mainly by inference rather than deduction. Not until adolescence do most students become able to think abstractly. Piaget prefers to thinking at this highest level as formal operational. Children at age 13 are starting to consider different hypotheses, figure out their implications, use symbols to express ideas, and disentangle related concepts. They are aware of their own thinking. They can understand time and distance simultaneously and hence grasp, say, the concept of a light-year. Piaget found that people with such abilities also have reached the spatial stage he called Euclidian abilities.

Advanced spatial thinkers recognize that a value does not change when it is represented in a different form. They can measure distance, length, area, volume, and angle. The stellar color-magnitude diagram and mass-luminosity relationship require both projective representation and Euclidean abilities. There is a widespread practice in the United States of teaching earth and space science in eighth- or ninth-grade, and stopping there. Yet many students taking these classes may not have yet reached the necessary thinking level. When I talk with adults who were unsuccessful bat earth science in high school, I sometimes hear, "Astronomy! I am so interested in it. We had earth science in ninth-grade, but I didn't understand it. Now I'm reading astronomy books, and the ideas don't seem very difficult. I don't know what was wrong with me in high school."

I believe these adults just had slowly developing formal and spatial thinking. Although astronomy cannot be understood fully without these advanced abilities, high-school teachers can maintain students' interest by improving the quality of concrete experiences, which will prepare students for complete understanding of abstract topics when the right time comes for them. In my own research, I found that children who had worked with models and observations in sixth-grade were more likely to understand lunar phases when they encountered that topic in eighth-grade.

The Learning Cycle

Thirty years ago, Karplus distilled Piaget's conclusions into a practical method for teaching: the Learning Cycle. He assumed that experience with the physical environment is important, that ideas are transmitted by social processes, and that there is self-regulation, or construction, of the ideas one holds. The cycle involves three basic steps:

- *Exploration*, in which students in groups explore cause-and-effect relationships with materials – with minimal guidance.

- *Concept Introduction*, in which teachers formally talk about the idea. The students need to see the relationship between the exploration and the idea.

- *Concept Application*, in which students apply the idea to similar but new situations.

Recent efforts at science-education reform, such as the American Association for the Advancement of Science's Project 2061, also have emphasized the importance of direct experience and personal inquiry.

I have used the Learning Cycle as the basis of an astronomy curriculum. My ideas was to get 13-year-olds, who were at a transition time predicted by Piaget, to understand projective concepts – the celestial sphere, earth rotation, seasons, lunar phases, and planet positions and motions – from both earth and space viewpoints. Sad to say, although there were some gains from the Learning Cycle and the other interactive techniques I used, most students who went through the curriculum were unable to answer three-fourths of the post-test. The kids were not yet capable of understanding the topics as projective concepts. And their performance worsened as the astronomy concepts became more complex. So what happened? Some researchers have found that American children lag one or more years behind the European children whom Piaget examined. This difference may simply be a selection bias in Piaget's sample, or it may have a deeper cultural reason. My array of the latest teaching techniques could not overcome the fact that my 13-year-olds were not ready.

The bottom line is that it is probably useless to spend much time on the introduction and application steps of the Learning Cycle until a child is near or beyond the level needed to understand a particular concept. An important process in learning, one that Piaget called accommodation, will occur if a child is ready to learn an idea. If not, the experiences -- or lecture, if it was especially important to the child -- will be stored away to help in learning the concept at a later time.

Accommodation is hard work and often unpleasant. The individual must abandon an old way of viewing something. Accommodation can make teenagers moody, distracted, or even surly as they defend their old thinking. When a teenager is grappling with new ways of seeing things, the teacher and parent need to be patient. An adult who becomes exasperated with the teenager's accommodation – and conveys this with incessant questioning or prolonged arguing -- is defeating the process. An authoritative declaration, "This is right and that is wrong," can even turn the student away from the teacher and from future lessons.

Mellowing Out

Actually, I think it is exciting to identify, observe, and assist teenagers in accommodation. The best approach is to answer questions, provide evidence that students can understand, formulate thought-provoking questions, and quietly wait. When adults are more relaxed and receptive, teenagers feel freer to do what they think they must to learn.

This is not to say that students won't forget the concept and revert to a previous misconception. In Philip Sadler's now famous film "A Private Universe," Harvard students incorrectly explain the cause of the seasons with great confidence [see "The Universe in the Student's Mind," May/June 1994 issue of *Mercury*, p. 28]. The film gave my high-school astronomy students a good laugh. They had studied models in small groups, taken data of the earth-based view in the planetarium, sketched their observations, and written essays about the reasons for the seasons. Almost everyone in the class had correct explanations on the unit exam. And then, on the final exam, only half the students correctly explained the seasons!

Teaching is further complicated, of course, by the fact that different people learn best in different ways. An aural learner likes detailed explanations, the viewer likes to watch carefully, and the kinesthetic learner likes to move around in a dynamic model. The Learning Cycle can be modified with a procedure known as "Cognitive Style Mapping" to tailor the learning techniques to each student.

Gender is another factor. I know it has been hotly debated, but there is very good evidence for a gender difference in spatial thinking. Teenage boys generally have an edge on girls in their ability to manipulate objects mentally. My study with eighth-graders showed that boys improved significantly more than girls in understanding the seasons, lunar phases, and planet motions. This difference in improvement occurred when I used the Learning Cycle and hands-on activities, but not when I took a traditional approach to planetarium and classroom lessons.

The best approach to gender difference is to ensure that students receive a solid foundation in astronomy in the sixth-grade, when boys and girls still learn spatial concepts equally well. If good opportunities for spatial thinking and growth occur in the pre-teen years, girls will enter their teens with past experiences to compensate for their slower development.

Astronomy is a perfect vehicle to give elementary students those experiences -- experiences that will help girls and boys in all subjects. Even though most students cannot grasp formal and projective astronomy concepts until high school, this fact should never be taken as an excuse to eliminate astronomy from the curriculum.

Editor's Note: Jeanne Bishop was the one who, in the 1970s, discovered that astronomy was once common in American school curricula, but vanished because the Committee of Ten, an educational standards panel that met in 1892, gave it such low priority.