Benchmarks for Science Literacy Concept Introductions

The Universe

In earlier times, people everywhere were much more aware of the stars and were familiar with them in ways that few people today are. Back then, people knew the patterns of stars in the night sky, the regularity of the motions of the stars, and how those motions related to the seasons. They used their knowledge to plan the planting of crops and to navigate boats. The constellations, along with the sun, the moon, and the "wanderers"-the planets-have always figured in the efforts of people to explain themselves and their world through stories, myths, religions, and philosophies.

For all of that, and for the sheer wonder the stars provoke on a clear, moonless night far from city lights-awe that has inspired the expressive powers of poets, musicians, and artists-science is not needed. Why, then, insist that everyone become familiar with the heavens as portrayed by science? Consider that in cities the night sky is no longer a familiar part of a person's neighborhood. Many people today live in circumstances that deprive them of the chance to see the sky often enough to become personally familiar with it. Fortunately, telescopes, photography, computers, and space probes make up the difference by revealing more of the cosmos in greater detail than ever before. Thus, science education can bring back the sky-not the same sky, but one that is richer and more varied than people's eyes alone had ever led them to imagine.

Finding our place in the cosmic scheme of things and how we got here is a task for the ages-past, present, and future. The scientific effort to understand the universe is part of that enduring human imperative, and its successes are a tribute to human curiosity, resourcefulness, intelligence, and doggedness. If being educated means having an informed sense of time and place, then it is essential for a person to be familiar with the scientific aspects of the universe and know something of its origin and structure.

In thinking about what students should learn about the heavens, at least three aspects of the current scientific view ought to be taken into account: (1) the composition of the cosmos and its scale of space and time; (2) the principles on which the universe seems to operate; and (3) how the modern view of the universe emerged. The benchmarks in this section deal primarily with composition and scale; principles are dealt with in subsequent sections of the chapter, and some rudiments of the history of the scientific picture appear in Chapter 10: Historical Perspectives.

The Earth

An integrated picture of the earth has to develop over many years, with some concepts being visited over and over again in new contexts and greater detail. Some aspects can be learned in science, others in geography; some parts can be purely descriptive, others must draw on physical principles. The benchmarks in this section complement those of the previous section that locate the earth in the cosmos and those of the following section that focus on the surface of the earth. This arrangement does not imply any particular order of teaching. Often, teaching near-at-hand phenomena before teaching the far-distant ones makes sense; on the other hand, sometimes the near-to-far progression that makes sense cognitively may not correspond to what interests children.

Perhaps the most important reason for students to study the earth repeatedly is that they take years to acquire the knowledge that they need to complete the picture. The full picture requires the introduction of such concepts as temperature, the water cycle, gravitation, states of matter, chemical concentration, and energy transfer. Understanding of these concepts grows slowly as children mature and encounter them in different contexts.

The benchmarks here call for students to be able to explain two phenomena-the seasons and the phases of the moon-that are usually not learned well. Most adults are unable to give even approximately correct explanations for them. Most students are told by teachers what causes the seasons and the phases of the moon, and they read about them without understanding. Moon phases are difficult because of students' unfamiliarity with the geometry of light and "seeing." To help figure out the geometry, students can act out the sun-earth-moon relationships and make physical models. In trying to understand the seasons, students have difficulties regarding geometry and solar radiation. Students need direct experience with light and surfaces-shadows, reflection, and warming effects at different angles.

Processes that Shape the Earth

Students should learn what causes earthquakes, volcanoes, and floods and how those events shape the surface of the earth. Students, however, may show more interest in the phenomena than in the role the phenomena play in sculpting the earth. So teachers should start with students' immediate interests and work toward the science. Students may find it harder to take seriously the less-obvious, less-dramatic, long-term effects of erosion by wind and water, annual deposits of sediment, the creep of continents, and the rise of mountains. Students' recognition of those effects will depend on an improving sense of long time periods and familiarity with the effect of multiplying tiny fractions by very large numbers (in this case, slow rates by long times).

Students can start in the early grades with the ways in which organisms, themselves included, modify their surroundings. As people have used earth resources, they have altered some earth systems. Students can gradually come to recognize how human behavior affects the earth's capacity to sustain life. Questions of environmental policy should be pursued when students become interested in them, usually in the middle grades or later, but care should be taken not to bypass science for advocacy. Critical thinking based on scientific concepts and understanding is the primary goal for science education.

The Structure of Matter

This section may have the most implications for students' eventual understanding of the picture that science paints of how the world works. And it may offer great challenges too. Atomic theory powerfully explains many phenomena, but it demands imagination and the joining of several lines of evidence. Students must know about the properties of materials and their combinations, changes of state, effects of temperature, behavior of large collections of pieces, the construction of items from parts, and even about the desirability of nice, simple explanations. All of these elements should be introduced in middle school so the unifying idea of atoms can begin by the end of the 8th grade.

The scientific understanding of atoms and molecules requires combining two closely related ideas: All substances are composed of invisible particles, and all substances are made up of a limited number of basic ingredients, or "elements." These two merge into the idea that combining the particles of the basic ingredients differently leads to millions of materials with different properties.

Students often get the idea that atoms somehow just fill matter up rather than the correct idea that the atoms are the matter. Middle-school students also have trouble with the idea that atoms are in continual motion. Coming to terms with these concepts is necessary for students to make sense of atomic theory and its explanatory power.

The strategy here is to describe the complexity of atoms gradually, using evidence and explanations from several connected story lines. Students first learn the notion that atoms make up objects, not merely occupy space inside them; then they are introduced to crystal arrays and molecules. With this understanding, they can imagine how molecules and crystals lead to visible, tangible matter. Only then should the study of the internal structure of atoms be taken up.

Bringing atomic and molecular theory into the earlier grades is a great temptation, but most students are not ready to understand atomic theory before adolescence. The theory is certainly essential to much of modern scientific explanation, but moving atomic/molecular theory forward to the earlier grades should be resisted. The tiny size and huge number of atoms in even a sand grain are vastly beyond even adult experience. Having students memorize the names of invisible things and their parts gets things backward and wastes time. Concrete perceptions must come before abstract explanations. Students need to become familiar with the physical and chemical properties of many different kinds of materials through firsthand experience before they can be expected to consider theories that explain them.

There seems to be no tidy and consistent way to relate the terms atom, molecule, ion, polymer, and crystal. A facility in discussing these terms will grow slowly over time. Students should also not rush into discussions of nuclear theory. The abstractions are too formidable. The emptiness of the atom and its electrical balance, isotopes, decay, and radiation challenge the human mind. The preparations for these concepts should be developed carefully over several years so they can converge in high school.

Energy Transformations

Energy is a mysterious concept, even though its various forms can be precisely defined and measured. At the simplest level, children can think of energy as something needed to make things go, run, or happen. But they have difficulty distinguishing energy needs from other needs-plants need water to live and grow; cars need water, oil, and tires; people need sleep, etc. People in general are likely to think of energy as a substance, with flow and conservation analogous to that of matter. That is not correct, but for most people it can be an acceptable analogy. Although learning about energy does not make it much less mysterious, it is worth trying to understand because a wide variety of scientific explanations are difficult to follow without some knowledge of the concept of energy.

Energy is a major exception to the principle that students should understand ideas before being given labels for them. Children benefit from talking about energy before they are able to define it. Ideas about energy that students encounter outside of school-for example, getting "quick energy" from a candy bar or turning off a light so as not to "waste energy"- may be imprecise but are reasonably consistent with ideas about energy that we want students to learn.

Three energy-related ideas may be more important than the idea of energy itself. One is energy transformation. All physical events involve transferring energy or changing one form of energy into another-radiant to electrical, chemical to mechanical, and so on. A second idea is the conservation of energy. Whenever energy is reduced in one place, it is increased somewhere else by exactly the same amount. A third idea is that whenever there is a transformation of energy, some of it is likely to go into heat, which spreads around and is therefore not available for use.

Heat energy itself is a surprisingly difficult idea for students, who thoroughly confound it with the idea of temperature. A great deal of work is required for students to make the distinction successfully, and the heat/temperature distinction may join mass/weight, speed/acceleration, and power/energy distinctions as topics that, for purposes of literacy, are not worth the extraordinary time required to learn them. Because dissipated heat energy is at a lower temperature, some students' confusion about heat and temperature leads them to infer that the amount of energy has been reduced. On the other hand, some students' idea that dissipated heat energy has been "exhausted" or "expended" may be tolerably close to the truth.

Similarly, units and formulas for kinetic and potential energy are more difficult than they are worth for the semi-quantitative understanding that we seek here. But the notion of potential energy is still useful for some situations in which motion might occur (for example, gravitational energy in water behind a dam, mechanical energy in a cocked mousetrap, or chemical energy in a flashlight battery or sugar molecule).

Work, in the specialized sense used in physics, is often considered a useful, even necessary, concept for dealing with ideas of energy. These benchmarks propose to do without a technical definition of work for purposes of basic literacy, because it is so greatly confused with the common English-language meaning of the word. The calculation of work as force times distance is not essential to understanding many important ideas about energy. Running makes you tired; rubbing your hands together makes them warmer; coming out of water makes you feel cool.

Older students can grasp these ideas in a general way, but even they should not be expected to understand them deeply. For young students, it may be enough at first to convince them that energy is needed to get physical things to happen and that they should get in the habit of wondering where the energy came from. Then, as they study physical, chemical, and biological systems, many opportunities arise for them to see the many different forms energy takes and to find out how useful the energy concepts are.

Teachers have to decide what constitutes a sufficient understanding of energy and its transformations and conservation. As the benchmarks below indicate, in harmony with *Science for All Americans*, qualitative approximations are more important and should have priority. Much time can be invested in having students memorize definitions-for heat, temperature, system, transformation, entropy, and the like-with little to show for it in the way of understanding.

Motion

Nothing in the universe is at rest. Motion is as essential to understanding the physical world as matter and energy are. Following the organization of *Science for All Americans*, the benchmarks for motion constitute a wide range of topics, from the movement of objects to vibrations and the behavior of waves. Rotary motion, as interesting as it is, poses much greater difficulties for students and is not included in the benchmarks.

The benchmarks for understanding the motion of objects and repeating patterns of motion do not demand the use of equations. For purposes of science literacy, a qualitative understanding is sufficient. Equations may clarify relationships for the most mathematically apt students, but for many students they are difficult and may obscure the ideas rather than clarify them. For example, almost all students can grasp that the effect of a force on an object's motion will be greater if the force is greater and will be less if the object has more mass-but learning $a=F/m$ (which to many teachers seems like the same thing) is apparently much harder.

Newton's laws of motion are simple to state, and sometimes teachers mistake the ability of students to recite the three laws correctly as evidence that they understand them. The fact that it took such a long time, historically, to codify the laws of motion suggests that they are not self-evident truths, no matter how obvious they may seem to us *once we understand them well.* Much research in recent years has documented that students typically have trouble relating formal ideas of motion and force to their personal view of how the world works.

These are three of the obstacles:

1. A basic problem is the ancient perception that sustained motion requires sustained force. The contrary notion that it takes force to change an object's motion, that something in motion will move in a straight line forever without slowing down unless a force acts on it, runs counter to what we can see happening with our eyes.
2. Limitations in describing motion may keep students from learning about the effect of forces. Students of all ages tend to think in terms of motion or no motion. So the first task may be to help students divide the category of motion into steady motion, speeding up, and slowing down. For example, falling objects should be described as falling faster and faster rather than just falling down. As indicated earlier, the basic idea expressed in Newton's second law of motion is not difficult to grasp, but vocabulary may get in the way if students have to struggle over the meaning of force and acceleration. Both terms have many meanings in common language that confound their specialized use in science.
3. Like inertia, the action-equals-reaction principle is counterintuitive. To say that a book presses down on the table is sensible enough, but then to say that the table pushes back up with exactly the same force (which disappears the instant you pick up the book) seems false on the face of it.

What is to be done? Students should have lots of experiences to shape their intuition about motion and forces long before encountering laws. Especially helpful are experimentation and discussion of what happens as surfaces become more elastic or more free of friction.

Vibrations treated only descriptively bring no special problems, other than the occasional confusion caused by the word speed being used in English for both frequency and velocity. Does a guitar string move quickly (back and forth a thousand times a second) or slowly (only 15 miles or so per hour)? Similarly, is the earth's rotation slow (once a day) or fast (1,000 miles per hour at the equator)? In the overall story of motion, vibrations serve in good part to introduce the ideas of frequency and amplitude. Because there are so many examples of vibrating systems that students can experience directly, they easily see vibration as a common way for some things to move and see frequency as a measure of that motion.

Waves, on the other hand, present a greater challenge. Wave motion is familiar to children through their experience with water. Surface waves on water provide the standard image of what waves are, and ropes and springs can also be used to show some of the properties of waves. Without formal schooling, young people learn that many other kinds of waves exist: radio waves, x rays, radar, microwaves, sound waves, ultraviolet radiation, and more. But they still might not know what these things are, how they relate to one another, what they have to do with motion, or in what sense such waves are waves.

Forces of Nature

For a good many school years, force may be treated as the originator of motion, and an explanation of force itself may be postponed. But the force between a bat and a ball has an entirely different origin than that between the earth and the moon. In helping students broaden their understanding of the fundamental forces of nature, the emphasis should be on gravitational and electromagnetic forces.

The general idea of universal gravitation and how weak it is compared to other kinds of forces is sufficient. Working out numerical problems adds little and is very likely to leave many students behind. The math is not hard but the units are baffling. A paradoxical idea for students is how weak gravity is compared to electric and magnetic forces. Gravity becomes appreciable only when very large accumulations of matter figure, such as that of a student and the entire earth. To students, gravitational forces seem strong compared to the trivial electric forces on dry hair charged by combing. But they can be led to see quite the opposite: The whole earth is required to pull a hair down by gravity, while only a small amount of charge is needed to force it up electrically against gravity.

Electric and magnetic forces and the relationship between them ought also to be treated qualitatively. Fields can be introduced, but only intuitively. Most important is that students get a sense of electric and magnetic force fields (as well as of gravity) and of some simple relations between magnets and electric currents. Direction rules have little importance for general literacy. The priority should be on what conditions produce a magnetic field and what conditions induce an electric current. Diagrams of electric and magnetic fields promote some misconceptions about "lines of force," notably that the force exists only on those lines. Students should recognize that the lines are used only to show the direction of the field.