Benchmarks for Science Literacy High School Science Descriptions

Earth Sciences

This is the time for all of the pieces to come together. Concepts from physics and chemistry, insights from history, mathematical ways of thinking, and ideas about the role of technology in exploring the universe all contribute to a grasp of the character of the cosmos. In particular, the role of gravity in forming and maintaining planets, stars, and the solar system should become clear. The scale of billions will make better sense, and the speed of light can be used to express relative distances conveniently.

Two important strands of understanding can now be pulled together to enrich students' views of the physical setting. One strand connects such physical concepts and principles as energy, gravitation, conservation, and radiation to the descriptive picture that students have built in their minds about the operation of the planets. The other strand consists of the Copernican Revolution, which illustrates the place of technology, mathematics, experimentation, and theory in scientific breakthroughs. In the context of thinking about how the solar system is put together, this historical event unites physics and astronomy, involves colorful personalities, and raises deep philosophical and political issues.

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).

The thrust of study should now turn to modern explanations for the phenomena the students have learned descriptively and to consideration of the effects that human activities have on the earth's surface. Knowledge of radioactivity helps them understand how rocks can be dated, which helps them appreciate the scale of geologic time.

Life Sciences

Diversity of Life

Two aims dominate at this level. One is to advance student understanding of why diversity within and among species is important. The other is to take the study of diversity and similarity to the molecular level. Students can learn that it is possible to infer relatedness among organisms from DNA or protein sequences. An investigation of the DNA-fingerprinting controversy may provide an interesting way to approach the question of the nature and validity of molecular evidence.

Heredity

DNA provides for both the continuity of traits from one generation to the next and the variation that in time can lead to differences within a species and to entirely new species. Understanding DNA makes possible an explanation of such phenomena as the similarities and differences between parents and offspring, hereditary diseases, and the evolution of new species. This understanding also makes it possible for scientists to manipulate genes and thereby create new combinations of traits and new varieties of organisms.

Cells

The individual cell can be considered as a system itself and as part of larger systems, sometimes as part of a multicellular organism, always as part of an ecosystem. The cell membrane serves as a boundary between the cell and its environment, containing for its own use the proteins it makes, equipment to make them, and stockpiles of fuel. Students should be asked to consider the variety of functions cells serve in the organism and how needed materials and information get to and from the cells. It may help students to understand the interdependency of cells if they think of an organism as a community of cells, each of which has some common tasks and some special jobs.

The idea that protein molecules assembled by cells conduct the work that goes on inside and outside the cells in an organism can be learned without going into the biochemical details. It is sufficient for students to know that the molecules involved are different configurations of a relatively few kinds of amino acids, and that the different shapes of the molecules influence what they do.

Students should acquire a general picture of the functions of the cell and know that the cell has specialized parts that perform these functions. This can be accomplished without many technical terms. Emphasizing vocabulary can impede understanding and take the fun out of science. Discussion of what needs to be done in the cell is much more important than identifying or naming the parts that do it. For example, students should know that cells have certain parts that oxidize sugar to release energy and parts to stitch protein chains together according to instructions; but they don't need to remember that one type of part is a mitochondrion and the other a ribosome, or which is which.

Interdependence of Live

The concept of an ecosystem should bring coherence to the complex array of relationships among organisms and environments that students have encountered. Students' growing understanding of systems in general can suggest and reinforce characteristics of ecosystems-interdependence of parts, feedback, oscillation, inputs, and outputs. Stability and change in ecosystems can be considered in terms of variables such as population size, number and kinds of species, and productivity.

Flow of Matter and Energy

Now students have a sufficient grasp of atoms and molecules to link the conservation of matter with the flow of energy in living systems. Energy can be accounted for by thinking of it as being stored in molecular configurations constituted during photosynthesis and released during oxidation. Although there is no need to account for all the energy, students should observe heat generated by consumers and decomposers. Discussions of ecosystems can both contribute to and be reinforced by students' understanding of the systems concept in general. The difficulty of predicting the consequences of human tinkering with ecosystems can be illustrated with examples such as the ill-considered fire-prevention efforts in national forests.

This level is also a time to ask what this knowledge of the flow of matter and energy through living systems suggests for human beings. Issues such as the use of fossil fuels and the recycling of matter and energy are important enough to pay considerable attention to in high school.

Evolution of Life

Knowing what evolutionary change is and how it played out over geological time, students can now turn to its mechanism. They need to shift from thinking in terms of selection of individuals with a trait to changing proportions of a trait in populations. Familiarity with artificial selection, coming from studies of pedigrees and their own experiments, can be applied to natural systems, in which selection occurs because of environmental conditions. Students' understanding of radioactivity makes it possible for them to comprehend isotopic dating techniques used to determine the actual age of fossils and hence to appreciate that sufficient time may have elapsed for successive changes to have accumulated. Knowledge of DNA contributes to the evidence for life having evolved from common ancestors and provides a plausible mechanism for the origin of new traits.

History should not be overlooked. Learning about Darwin and what led him to the concept of evolution illustrates the interacting roles of evidence and theory in scientific inquiry. Moreover, the concept of evolution provided a framework for organizing new as well as "old" biological knowledge into a coherent picture of life forms.

Finally there is the matter of public response. Opposition has come and continues to come from people whose interpretation of religious writings conflicts with the story of evolution. Schools need not avoid the issue altogether. Perhaps science courses can acknowledge the disagreement and concentrate on frankly presenting the scientific view. Even if students eventually choose not to believe the scientific story, they should be well informed about what the story is.

Physical Sciences

The Structure of Matter

Understanding the general architecture of the atom and the roles played by the main constituents of the atom in determining the properties of materials now becomes relevant. Having learned earlier that all the atoms of an element are identical and are different from those of all other elements, students now come up against the idea that, on the contrary, atoms of the same element can differ in important ways. This revelation is an opportunity as well as a complication-scientific knowledge grows by modifications, sometimes radical, of previous theories. Sometimes advances have been made by neglecting small inconsistencies, and then further advances have been made later by attending closely to those inconsistencies.

Students may at first take isotopes to be something in addition to atoms or as only the unusual, unstable nuclides. The most important features of isotopes (with respect to general scientific literacy) are their nearly identical chemical behavior and their different nuclear stabilities. Insisting on the rigorous use of isotope and nuclide is probably not worthwhile, and the latter term can be ignored.

The idea of half-life requires that students understand ratios and the multiplication of fractions, and be somewhat comfortable with probability. Games with manipulative or computer simulations should help them in getting the idea of how a constant proportional rate of decay is consistent with declining measures that only gradually approach zero. The mathematics of inferring backwards from measurements to age is not appropriate for most students. They need only know that such calculations are possible.

Energy Transformations

The concepts acquired in the earlier grades should now be extended to nuclear realms and living organisms. Revisiting energy concepts in new contexts provides opportunities to improve student understanding of the basic concepts and to see just how powerful they are.

Two other major ideas merit introduction during these years, but without resort to mathematics. One of these is that the total amount of energy available for useful transformation is almost always decreasing; the other is that energy changes on the atomic scale occur only in discrete jumps. The first of those is not too difficult or implausible for students because they can experience in many ways a wide variety of actions that give off heat. The emphasis should probably be on the practical consequences of the loss of useful energy through heat dissipation.

On the other hand, the notion that energy changes in atoms can occur in only fixed amounts with no intermediate values is strange to begin with and hard to demonstrate. Some evidence should be presented for this scientific belief but not in great detail. The easiest phenomenon to show, which is also a major reason for including quantum jumps in literacy, is the discrete colors of light emitted by separate atoms, as in sodium-vapor or mercury-vapor lights. Another major reason for having students encounter the quantum idea is to illustrate the point that in science it is sometimes useful to invent ideas that run counter to intuition and prior experience.

An important application of the atom/energy relationship to bring to the attention of students is that the distinctive light energies emitted or absorbed by different atoms enable them to be identified on earth, in our sun, and even on the other side of the universe. This fact is a prime example of the "rules are the same everywhere" principle.

Motion

At this level, students learn about relative motion, the action/reaction principle, wave behavior, the interaction of waves with matter, the Doppler effect now used in weather observations, and the red shift of distant galaxies. Relative motion is fun-students find it interesting to figure out their speeds in different reference frames, and many activities and films illustrate this principle. Learning this concept is important for its own sake and for the part it plays in the changing reference frames of the Copernican Revolution, and in simple relativity.

This level is also a time to show the power of mathematics. Once students are fully convinced that change in motion is proportional to the force applied, then mathematical logic requires that when F = 0, there be no change in motion. (So, Newton's first law is just a special case of his second.) Students can move from a qualitative understanding of the force/motion relationship (more force changes motion more; more mass is harder to change) to one that is more quantitative (the change in motion is directly proportional to the amount of force and inversely proportional to the mass). Experimentally, they can learn that the change in motion of an object is proportional to the applied force and inversely proportional to the mass-a step beyond knowing that change in motion goes up with increasing force and down with increasing mass.

Students should come to understand qualitatively that (1) doubling the force on an object of a given mass doubles the effect the force has, tripling triples the effect, and so on; and (2) that whatever effect a given force has on an object, it will have half the effect on an object having twice the mass, a third on one having triple the mass, and so on. This need not entail having students solving lots of numerical problems.

The qualitative principle also applies to waves. Even as simple a relationship as speed = wavelength x frequency poses difficulties for many students. A sufficient minimum is that students develop semi-quantitative notions about waves-for example, higher frequencies have shorter wavelengths and those with longer wavelengths tend to spread out more around obstacles.

The effect of wavelength on how waves interact with matter can be developed through intrinsically interesting phenomena-such as the blueness of the sky and redness of sunsets resulting from light of short wavelengths being scattered most by the atmosphere, or the color of grass resulting from its absorbing light of both shorter and longer wavelengths while reflecting the intermediate green. Electromagnetic waves with different wavelengths have different effects on the human body. Some pass through the body with little effect, some tan or injure the skin, and some are absorbed in different amounts by internal organs (sometimes injuring cells).

Forces of Nature

Students should now learn how well the principle of universal gravitation explains the architecture of the universe and much that happens on the earth. The principle will become familiar from many different examples (star formation, tides, comet orbits, etc.) and from the study of the history leading to this unification of earth and sky. The "inversely proportional to the square" aspect is not a high priority for literacy. Much more important is escaping the common adult misconceptions that the earth's gravity does not extend beyond its atmosphere or that it is caused by the atmosphere.

Study of the nature of electric and magnetic forces should be joined to the study of the atom. What is likely to surprise many students is how much more powerful electromagnetic forces are than the gravitational forces, which are negligible on an atomic scale. Some students may have trouble seeing mechanical forces, such as pushing on an object with a stick, as being produced by electric charges on the atomic scale. It may help for them to recognize that the electric forces they do observe commonly (such as "static cling") result from extremely slight imbalances of electric charges. As students come to believe in the action/reaction principle, they will expect forces to be mutual.