

involving scale diagrams and models can support students in developing facility with this important concept.

Once students become familiar with measurements of length, they can expand their understanding of scale and of the need for units that express quantities of weight, time, temperature, and other variables. They can also develop an understanding of estimation across scales and contexts, which is important for making sense of data. As students become more sophisticated, the use of estimation can help them not only to develop a sense of the size and time scales relevant to various objects, systems, and processes but also to consider whether a numerical result sounds reasonable. Students acquire the ability as well to move back and forth between models at various scales, depending on the question being considered. They should develop a sense of the powers-of-10 scales and what phenomena correspond to what scale, from the size of the nucleus of an atom to the size of the galaxy and beyond.

Well-designed instruction is needed if students are to assign meaning to the types of ratios and proportional relationships they encounter in science. Thus the ability to recognize mathematical relationships between quantities should begin developing in the early grades with students' representations of counting (e.g., leaves on a branch), comparisons of amounts (e.g., of flowers on different plants), measurements (e.g., the height of a plant), and the ordering of quantities such as number, length, and weight. Students can then explore more sophisticated mathematical representations, such as the use of graphs to represent data collected. The interpretation of these graphs may be, for example, that a plant gets bigger as time passes or that the hours of daylight decrease and increase across the months.

As students deepen their understanding of algebraic thinking, they should be able to apply it to examine their scientific data to predict the effect of a change in one variable on another, for example, or to appreciate the difference between linear growth and exponential growth. As their thinking advances, so too should their ability to recognize and apply more complex mathematical and statistical relationships in science. A sense of numerical quantity is an important part of the general "numeracy" (mathematics literacy) that is needed to interpret such relationships.

## **Systems and System Models**

As noted in the *National Science Education Standards*, "The natural and designed world is complex; it is too large and complicated to investigate and comprehend all at once. Scientists and students learn to define small portions for the convenience

of investigation. The units of investigations can be referred to as ‘systems.’ A system is an organized group of related objects or components that form a whole. Systems can consist, for example, of organisms, machines, fundamental particles, galaxies, ideas, and numbers. Systems have boundaries, components, resources, flow, and feedback” [2].

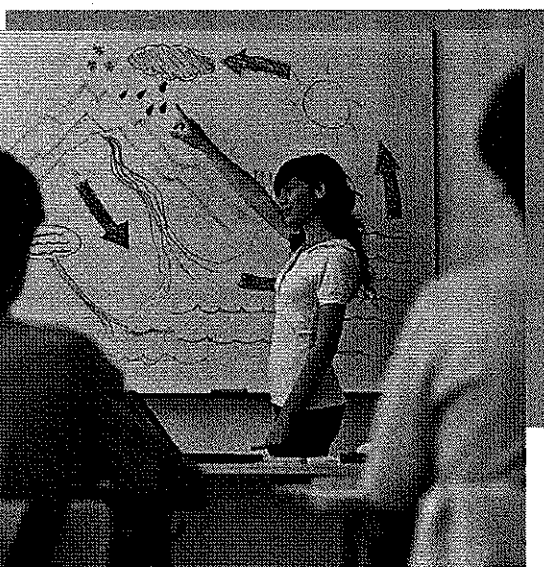
Although any real system smaller than the entire universe interacts with and is dependent on other (external) systems, it is often useful to conceptually isolate a single system for study. To do this, scientists and engineers imagine an artificial boundary between the system in question and everything else. They then examine the system in detail while treating the effects of things outside the boundary as either forces acting on the system or flows of matter and energy across it—for

example, the gravitational force due to Earth on a book lying on a table or the carbon dioxide expelled by an organism. Consideration of flows into and out of the system is a crucial element of system design. In the laboratory or even in field research, the extent to which a system under study can be physically isolated or external conditions controlled is an important element of the design of an investigation and interpretation of results.

Often, the parts of a system are interdependent, and each one depends on or supports the functioning of the system’s other parts. Yet the properties and behavior of the whole system can be very different from those of any

of its parts, and large systems may have emergent properties, such as the shape of a tree, that cannot be predicted in detail from knowledge about the components and their interactions. Things viewed as subsystems at one scale may themselves be viewed as whole systems at a smaller scale. For example, the circulatory system can be seen as an entity in itself or as a subsystem of the entire human body; a molecule can be studied as a stable configuration of atoms but also as a subsystem of a cell or a gas.

An explicit model of a system under study can be a useful tool not only for gaining understanding of the system but also for conveying it to others. Models of a system can range in complexity from lists and simple sketches to detailed computer simulations or functioning prototypes.



Models can be valuable in predicting a system's behaviors or in diagnosing problems or failures in its functioning, regardless of what type of system is being examined. A good system model for use in developing scientific explanations or engineering designs must specify not only the parts, or subsystems, of the system but also how they interact with one another. It must also specify the boundary of the system being modeled, delineating what is included in the model and what is to be treated as external. In a simple mechanical system, interactions among the parts are describable in terms of forces among them that cause changes in motion or physical stresses. In more complex systems, it is not always possible or useful to consider interactions at this detailed mechanical level, yet it is equally important to ask what interactions are occurring (e.g., predator-prey relationships in an ecosystem) and to recognize that they all involve transfers of energy, matter, and (in some cases) information among parts of the system.

Any model of a system incorporates assumptions and approximations; the key is to be aware of what they are and how they affect the model's reliability and precision. Predictions may be reliable but not precise or, worse, precise but not reliable; the degree of reliability and precision needed depends on the use to which the model will be put.

### *Progression*

As science instruction progresses, so too should students' ability to analyze and model more complex systems and to use a broader variety of representations to explicate what they model. Their thinking about systems in terms of component parts and their interactions, as well as in terms of inputs, outputs, and processes, gives students a way to organize their knowledge of a system, to generate questions that can lead to enhanced understanding, to test aspects of their model of the system, and, eventually, to refine their model.

Starting in the earliest grades, students should be asked to express their thinking with drawings or diagrams and with written or oral descriptions. They should describe objects or organisms in terms of their parts and the roles those parts play in the functioning of the object or organism, and they should note relationships between the parts. Students should also be asked to create plans—for example, to draw or write a set of instructions for building something—that another child can follow. Such experiences help them develop the concept of a model of a system and realize the importance of representing one's ideas so that others can understand and use them.

As students progress, their models should move beyond simple renderings or maps and begin to incorporate and make explicit the invisible features of a system, such as interactions, energy flows, or matter transfers. Mathematical ideas, such as ratios and simple graphs, should be seen as tools for making more definitive models; eventually, students' models should incorporate a range of mathematical relationships among variables (at a level appropriate for grade-level mathematics) and some analysis of the patterns of those relationships. By high school, students should also be able to identify the assumptions and approximations that have been built into a model and discuss how they limit the precision and reliability of its predictions.

Instruction should also include discussion of the interactions *within* a system. As understanding deepens, students can move from a vague notion of interaction as one thing affecting another to more explicit realizations of a system's physical, chemical, biological, and social interactions and of their relative importance for the question at hand. Students' ideas about the interactions in a system and the explication of such interactions in their models should become more sophisticated in parallel with their understanding of the microscopic world (atoms, molecules, biological cells, microbes) and with their ability to interpret and use more complex mathematical relationships.

Modeling is also a tool that students can use in gauging their own knowledge and clarifying their questions about a system. Student-developed models may reveal problems or progress in their conceptions of the system, just as scientists' models do. Teaching students to explicitly craft and present their models in diagrams, words, and, eventually, in mathematical relationships serves three purposes. It supports them in clarifying their ideas and explanations and in considering any inherent contradictions; it allows other students the opportunity to critique and suggest revisions for the model; and it offers the teacher insights into those aspects of each student's understanding that are well founded and those that could benefit from further instructional attention. Likewise in engineering projects, developing systems thinking and system models supports critical steps in developing, sharing, testing, and refining design ideas.

## **Energy and Matter: Flows, Cycles, and Conservation**

One of the great achievements of science is the recognition that, in any system, certain conserved quantities can change only through transfers into or out of the system. Such laws of conservation provide limits on what can occur in a system, whether human built or natural. This section focuses on two such quantities,