

USING MODELS TO EXPLAIN SCIENCE

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Could your students state a good operational definition of science in twentyfive words or less? Most of us realize that meaningful definitions to a large extent determine a person's expectations and responses to stimuli. Stated or implied definitions of science in our curriculum determine the quality of responses we receive when we ask our students to discuss and analyze science. For example, if your teaching materials reflect the idea that science is the study of the natural world, they will probably favor textbook learning (study) and restrict the students to the natural sciences at the expense of other scientific domains. This definition favors the teaching of content and is the basis for the approach used in many classrooms at the present time.

If you use the definition of science as "... the system of knowing about the universe through data collected by observation and controlled experimentation,"⁵ you may be getting away from such a strong emphasis on content, but you may still not be focusing on some very important components of the scientific process, such as mathematical-ly-based theory, intuition, and creative insight. This definition transmits a false impression of science as a linear, highly logical process. As a result, students may emerge with a false image of science that does not correspond with what those who have studied scientists say actually goes on.³⁴⁷ Because the "universe" is generally associated with the natural world, the restrictions on thinking imposed by the first definition may also apply here. The problem of how to define science has been given less attention than it deserves, and it is possible that the difficulty some teachers have in accepting innovative curricula may stern from a failure on the part of curriculum developers to address this issue. An alternative definition of science tends to account for some of the relationships missing in traditional conceptualizations. This definition may be used to explain the structure of



science. Also, this alternative definition is based on an understanding of science as a process of model-building.

Models are representations of one system by another system in a different medium. They are an integral part of human communications. In a real sense, all human experience must be translated into models of one sort or another. A simple description of a leaf, for example, is a verbal model if it permits a reader to visualize the object, or target, the description refers to. The correspondence between the description and the actual leaf is the "fit" of the model to its target. By the same token, any system whose function is to represent a target system is a model; maps, graphs, and theories are models, as are many other systems used in science and our everyday life (Table I). Our memory may itself be conceptualized as a set of neural representations of past events, relationships, and directives. Science without model-building could not exist because there would be no mechanism for communication or thought. Of course, the same principle underlies any human endeavor relying on communication. What specific kind of models does the scientist construct?

The following definition contains the answer to that question. This definition is proposed as a conceptualization which has enough consistency and explanatory power to make it very useful to the curriculum designer and classroom teacher:

Science is a process of constructing conceptual models through the identification and testing of predictive relationships.

Data Bases	Data tables, diagrams, pictures, figures, drawings,
Representations	Concrete scale, concrete non-scalar, replicas, copies, examples, samples, demonstrations.
Analogues	Concrete analogues such as friction carts and stream tables, analogical imagery.
Simulations	Computer simulations and projections, simulation games.
Procedures	Verbal or written directions, systems of rules, cognitive executive systems, schemata, guidelines, matrices.

Table I: Model Types and Nominal Classifications



Concepts/Theories Verbal and written descriptions of presumed reality, mathematical formulae, ideals, predictions, hypotheses, conceptual networks, semantic maps, "Vee" diagrams, integrative reports, outlines.

For educational purposes, this operational definition has several advantages over more traditional definitions: 1) it reinforces the idea that models are a fundamental part of our communications system; 2) it identifies predictivity as the criterion upon which the validity of a scientific model is based; 3) it puts stress on relationships rather than on isolated objects or events; 4) it implies that knowledge is constructed rather than discovered; and 5) it is equally applicable to natural and social science domains, as well as to the student's individual life.

The Hierarchy of Scientific Models

The definition of science as model-building leads to a hierarchy of models which can be used to explain scientific knowledge and knowledge in general. For the sake of clarity, several new terms have been created and applied in the following discussion. Other terms are commonly used in the existing literature of science.

The purpose of any research project is to construct an <u>outcome model</u> of some sort. Each outcome model consists primarily of the assumptions, methods, results, and knowledge claims of a single research report. Whether this model is constructed inductively or deductively, with verbal descriptions or statistics, its purpose is to identify a system of concepts and relationships that can predict subsequent models. The outcome model is the "unit of exchange" in the economy of science.

An outcome model is only worth something if it is predictive. Predictivity can manifest itself in several ways: 1) as an anticipated similarity between models produced under similar conditions (reliability); 2) as consistency within a set of data (reliability); 3) as a correspondence between a prediction (hypothesis) and an outcome model; 4) as the fit of a model into an existing knowledge structure; or 5) as the capacity of the model can give rise to subsequent predictive models. Most scientists prefer to rely on direct observations for their



models, but sometimes direct observation is not possible. In that case, the consistency of the outcome model within a larger context may be the only standard available for judging the validity of the model. The paleobiologist, for example, can interpret a new fossil only by relating it to known fossils and modern analogues. The meaning of fossils themselves is purely inferential. If current models do not predict the existence of this fossil, and the fossil does not predict subsequent finds, then it will either remain an anomaly, or the fossil will necessitate changes in the model. Direct observations are also difficult in the sciences dealing with very large or very small phenomena. A theoretical physicist or an astronomer may develop mathematical models which are internally consistent to predict phenomena. Subsequent observations may then support these ideas. The idea of "black holes" in space is such a mathematical construct. Electromagnetic wave/particle phenomena are also mathematical constructs.

A comprehensive knowledge structure in science is developed by linking outcome models to each other. As a simplified example, suppose that studies have been done of alarm behavior in six species of ground squirrels. Scientists use these models to construct a generalized model of ground squirrel alarm behavior. The comprehensive representation thus created includes the common elements of the six individual studies and general principles which none of the studies could supply alone. These elements form a matrix within which new ground-squirrel studies may be formulated, and against which they are likely to be assessed. An idea created in this manner is a <u>theoretical model</u> or theory.

As new outcome models are added, theoretical models grow in scope and stature. Most become integrated into progressively larger theories to form a hierarchy. A theory of alarm behavior in ground squirrels may be integrated into a theory of alarm behavior in mammals, which itself forms a part of a theoretical model of alarm behavior in animals. Eventually, some theoretical models become consistent and predictive enough to guide the normal research in a field and assume the role of the <u>paradigm model</u>: an example"... which include(s) law, theory, application and instrumentation together ... (and which)... provide(s) models from which spring coherent traditions of scientific research."² Models such as the theories of evolution, relativity, and atomic structure are examples of paradigm models. Normal research in each of these



fields is based on the assumption that the paradigm model will be predictive and productive.

For a theoretical model to be accepted, it must prove itself to be useful as a source of new models. In the competitive economy of science, unproductive models are eventually discarded. When gaps in the present model are apparent, researchers will sometimes propose predictions, called <u>hypothetical models</u>, that are consistent with known facts and assumptions. Successful hypothetical models become part of new outcome models, and so the process of science continues.

Application of the Models-Based Definition to Education

An effective explanatory definition of science is important if there is to be an acceptance of new curriculum developments and subsequent improvement of education in science. In the definition of science as the building of predictive models, science is regarded neither as a study, a body of facts, a method, or a set of processes per se. Science is an activity with a social role and a definable product. The variables involved in teaching science have been identified as facts, concepts, and the processes "through which science uncovers facts and develops models."¹ The recent literature of science education has favored more emphasis on processes and concepts and less on facts. But to what end are these processes directed? How are concepts to be united into a meaningful system? A fourth emphasis is needed -- an emphasis on developing the students' understanding of the nature of the knowledge that science produces.

Focusing the science curriculum on the construction of models helps to ensure that processes are not taught and learned as ends in themselves. Process skills are a means to an end. Science education activities are needed which use investigative processes to develop conceptual models representing sets of predictive relationships. The validity of scientifically-developed models depends upon the reliability (cohesiveness) of the data and the confidence which students and teachers are able to invest in the outcome. Reliability and validity should be the main criteria against which a laboratory activity is adjudged a success or failure. This means data must be pooled and examined cooperatively. When an outcome model contradicts established theory, then one must look carefully at the model-building (research) procedures and make a subjective judgment about what the results actually mean. This approach is



not an open invitation to accept misconceptions when the models do not agree with the expectations of the students and teacher, rather it is an invitation to think about how scientists evaluate their results and develop their research.

In elementary and junior high school, most of the focus should be on the development of primary conceptual models which can be constructed, classified, and ordered with hands-on activity. Since the purpose of learning is ". . . largely a process of refining models so they correspond better with the real world,"⁸ careful planning to link one concept to another is essential. The concept of the model should be developed in its broadest sense and should be used as a unifying theme to give purpose and continuity to science as an activity.

In high school and college, students become more formal operational and, hence, are able to begin adding to their conceptual map of the world through abstract thinking. Even at this level, however, 50% or more of high school students may require concrete experiences in order to understand certain new science concepts.6 During this time of emerging abstract thought, conceptual structuring models such as concept mapping, semantic webbing, and diagrams will help to clarify the elements of the students' general knowledge structure and make it easier to conceptualize abstract or derived relationships.

A curriculum which develops a distinct model of a concept, such as density or photosynthesis, is likely to be more effective than one which presents these same concepts as lecture or textbook information or in the form of mathematical and chemical expressions. Developing multiple models focused on a limited number of important concepts has been suggested as a highly constructive approach to teaching science.8

Because a model is a human construct, a model is tentative and usually simplified. A models-based definition of science implies, therefore, that knowledge is also tentative and often simplified. Conceptual models are developed as they are linked, modified, simplified, manipulated, and evaluated. Knowledge is developed in the same way. Teaching science as a process of constructing models carries a message about the way knowledge is obtained, how it is evaluated, and why it is valued.



Suggestions for Teachers

- Present the definition of science as model-building early and build on that definition as the school year progresses.
- Include an introductory unit on science and use that unit to develop a broad conceptualization of the model (Table I).
- Use the definition as the basis for designing instructional opportunities and as a way of focusing student efforts on learning concepts.
- Present concepts, facts, and relationships only as they are needed to develop a conceptual model. Eliminate excess information.
- Become familiar with the concepts of reliability and validity, and apply them in a nonstatistical manner.
- Use and require diagrams, concept maps, semantic webs, and similar structuring devices as often as possible.
- Present and discuss the relationships among outcome, hypothetical, theoretical, and paradigm models.
- Understand the relationships between scientific and technological models as the basis for evaluating science/technology/society interactions.
- Develop multiple models of the same concept.

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