The Nature and Structure of Scientific Models

Prepared by

Jennifer Cartier, John Rudolph, and Jim Stewart

The National Center for Improving Student Learning and Achievement in Mathematics and Science (NCISLA)

January 2001

Working Paper

NCISLA • Wisconsin Center for Education Research • School of Education, University of Wisconsin–Madison • 1025 West Johnson St. • Madison, WI 53706
Phone: (608) 263-3605 • E-mail: ncisla@education.wisc.edu • Web site: http://www.wcer.wisc.edu/ncisla

The Nature and Structure of Scientific Models

Models are a central topic of discussion in contemporary science education with debates centering on the pros and cons of including a modeling perspective in science curricula and on pragmatic strategies for designing classrooms that enable students to learn about science as a modeling endeavor. Although we find all this attention to scientific models exciting, it is sometimes confusing. At the core of the confusion lie the many (sometimes mutually exclusive) ways in which the term "model" is used. In an effort to avoid contributing to the confusion, it has been helpful for us to clearly articulate what we mean by "scientific model" prior to collaborating with teachers to design modeling curricula.

As the term "s*cientific* model" indicates, we are most interested in models from the perspective of what scientists actually do. And, despite all that makes up or contributes to scientific practice***, the most important overall goal of scientists is the development of an understanding of how the natural world works***. In all scientific disciplines, this understanding is most often accomplished through the conceptualization of models of various natural processes. It is this broad goal of science—the conceptualization of process models—that we feel is most important to convey to students. Other aspects of science may color and no doubt contribute to this overall goal, but student understanding of this big picture remains for us a primary learning outcome and provides the focus for the work described at the Modeling for Understanding in Science Education (MUSE) website.

What is a Scientific Model?

Perhaps the simplest way to begin defining what a scientific model is would be to point out what it is *not*. The term "model" is often used to describe (among other things) physical replicas of objects or systems. A space-filling molecular model made of plastic as well as the material globes and light bulb that make up a "model" of the solar system are examples of

The preparation of this working paper was supported, in part, by the National Science Foundation (Grant No. REC-9554193) and by the National Center for Improving Student Learning and Achievement in Mathematics and Science (funded by the Educational Research and Development Centers Program, PR/award Number R305A960007, as administered by the Office of Educational Research and Improvement, U.S. Department of Education). Any opinions, findings, or conclusions are those of the authors and do not necessarily reflect the views of the supporting agencies.

physical models. Representational systems, such as maps or diagrams, and mathematical algorithms or formulae are also referred to as models.

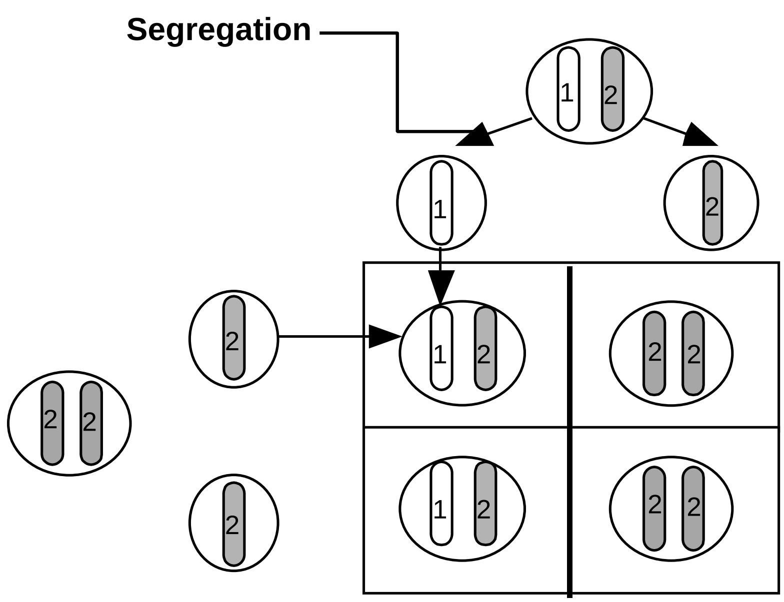
Not surprisingly, researchers characterizing students' views on models have found that many students cite examples of models that are physical replicas, verbal or visual entities, and mathematical formulae (see Grosslight et al., 1991). In our own research, we have also heard high school students use the term broadly. Students tend to think of physical objects that are constructed to convey an idea as models themselves. For instance, students asked to produce a model to explain the phenomena associated with a black box—such as a detergent container that always pours a set amount of detergent when tipped—are likely to identify the butcher paper drawings that result from that activity, rather than the ideas about the underlying mechanism for the phenomenon, as models.

We recognize that these types of entities, namely representations, formulae, and physical replicas, play important roles in science curricula (and science itself) and are sometimes prerequisites to the formation of scientific models. In fact, representations of models are essential tools for communicating and conversing about the scientific models underlying them. However, we take the position that represenations are not models themselves. In our view, a scientific model is a set of *ideas* that describes a natural *process*. A 'scientific' model so conceived can be mentally run, given certain constraints, to explain or predict natural phenomena. It is in this way that scientific models are both desirable *products* of scientific research and useful as *guides* to future research. The following discussion provides of some examples of scientific models and how they are used in scientific inquiry and instruction.

- **A scientific model is a set of *ideas* that describes a natural *process.***

In Biology, the meiotic model describes the process by which alleles segregate and independently assort during gamete formation. Given this model and some background knowledge about certain genes of interest, it is possible to predict the possible allele combinations resulting from meiosis in a given sex cell or class of sex cells. The processes of meiosis and fertilization are frequently represented using Punnett squares (see Figure 1). The Punnett square representation is an effective graphical tool for generating the possible gametes that might result from a particular meiotic event. In order to use such a diagram, it is necessary to move the alleles in question through the processes (segregation and assortment) involved in meiosis. It is important to note, however, that the Punnett square diagram is simply a *representation* of selected aspects of the meiotic model (with alleles specified) and not the model itself.

FIGURE 1. Punnet Square Diagram



Meiotic processes:

Segregation: separation of chromosome pairs during sex cell formation.

Independent Assortment: Mendel's law stating that members of chromosome pair segregate independently from members of any other pair.

- **Models are constituted by empirical or theoretical *objects* and the *processes* in which they participate.**

For the meiotic model mentioned above, the set of objects includes chromosomes, genes, alleles, mother and daughter cells, and so on, and the principle processes of segregation and assortment. A similar set of objects and processes forms the basis for the Mendelian model of simple dominance—a model that seeks to explain a particular pattern of trait inheritance (see Figure 2). Notice that objects in the simple dominance model also include phenotypes and genotypes in specific pairings and that the processes include fertilization. Notice also that there is some overlap between the meiotic model and the model of simple dominance. The process of

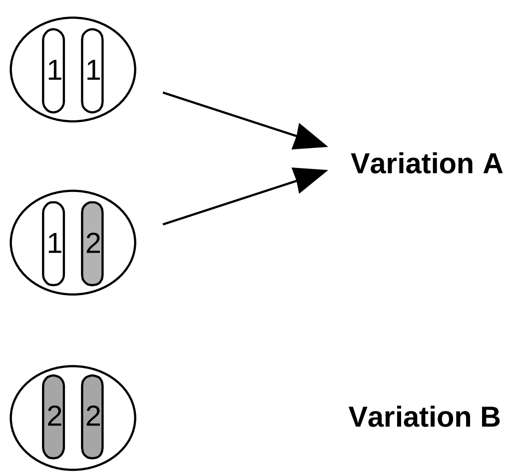
FIGURE 2. Mendel's Model of Simple Dominance

Variations 2

Alleles 2

Relationship between genotypes and phenotypes:

Genotype (allele combinations)	**Phenotype** (appearance)



Representation of Mendel's Simple Dominance Model. The simple dominance model accounts for the inheritance of discrete traits for which there are two variants (designated A and B). Each individual in the population possesses two alleles (designated 1 and 2) for the trait and one allele (1) is completely dominant over the other (2). There are only two different alleles in the population. The underlying processes simple dominant inheritance are Mendel's law of **segregation** (the meiotic process of sex cell formation during which half of all parental genetic information is packaged into sperm or egg cells) and **fertilization** (during which genetic information from both parents combines in the offspring).

segregation, for example, is a component in both. In fact, the objects and processes of the meiotic model essentially make up one component of the simple dominance model.

- **Models can be used to explain and predict natural phenomena.**

One can use the simple dominance model to explain and predict inheritance phenomena in given organisms. One could explain why a true-breeding tall pea plant crossed with a true-breeding short pea plant always produces tall progeny and also why these tall progeny, when cross-bred with one another, produce tall and short progeny in a 3:1 ratio. Using the simple dominance model, an explanation for such phenomena would take the form of specifying genotype to phenotype mappings (the relationships between alleles is already specified in the model as one of simple dominance) and describing how parent organisms with a given genotype might contribute particular alleles to their offspring, via meiotic processes, leading to organisms with particular genotypes (and the consequent phenotypes).

- **Models are consistently assessed on the basis of empirical and conceptual criteria.**

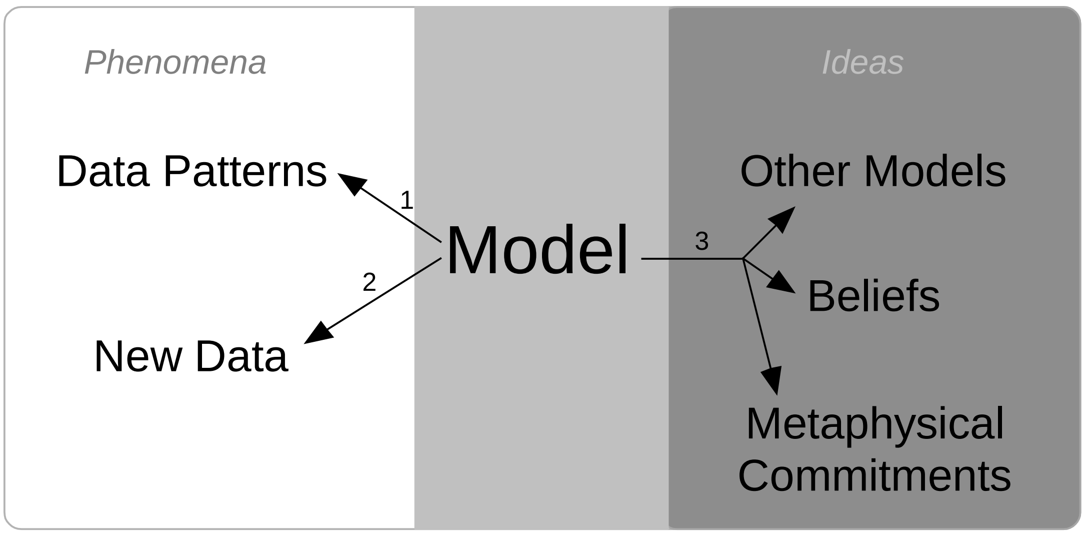
Specifically, scientists assess whether a particular model can explain all of the data at hand and predict the results of future experiments (empirical assessment). They also evaluate how well a model fits with other accepted models and knowledge (conceptual assessment—see Figure 3 for a summary). For example, since the meiotic model is at some level a component of the simple dominance model, it is important that there be no conceptual conflicts between them. Models that fail to satisfy some or all of the assessment criteria are discarded or (more commonly) revised until they are deemed acceptable. In practice, models are continuously revised as they are used to probe new phenomena and collect additional data.

- **Models are useful as guides to future research.**

Once constructed, models influence and constrain the kinds of questions scientists ask about the natural world and the types of evidence they seek in support of particular arguments. They guide a researcher's perception of what is involved in the natural processes of the world.
The belief of early geneticists that genotypes controlled discrete phenotypes only led them to see organisms as mere aggregates of discontinuous traits. Important research for these scientists included identifying just which characteristics could be identified as 'traits' and how such traits

were inherited. Later, when geneticists began to recognize the complexity of inheritance phenomena, they revised their earlier models in order to account for inheritance of continuous characteristics as well. Their revised models led to new conceptions of how inheritance worked and, subsequently, new research questions as well.

FIGURE 3. Assessment of Explanatory Models



Generally, explanatory models are assessed based upon whether they can (1) explain patterns in data; (2) correctly predict the results of new experiments or observations; and (3) are consistent with other ideas (models, beliefs, and metaphysical commitments).

Implications for the Teaching of Science

We believe that organizing curricula around sets of scientific models provides students with opportunities not only to learn about the conceptual subject matter of particular disciplines, but also about the nature of scientific knowledge—how it is constructed and justified. Grosslight, Unger, Jay & Smith's (1991) study pointed out deficiencies in students' understanding of scientific models as conceptual tools used by practicing scientists. In our own research, we have also heard high school students use the term "model" broadly and demonstrate a tendency to think of physical objects that are constructed to convey an idea as models themselves. In contrast, the scientists interviewed by Grosslight et al. readily identified models as theoretical entities, acknowledging the central role they play in defining research questions and shaping interpretation of data. They suggested that students might come to appreciate the conceptual nature of scientific models given opportunities to examine multiple models (some of their own construction) purporting to explain the same set of phenomena. Students might also develop an appreciation for models after revising such models to account for new data.

In our own research and work with teachers, we have found that providing students opportunities to work with models can support their understanding of scientific models and inquiry (see Cartier, 1999). When models have been a focus of classroom attention, students have learned that they are tentative constructions that explain the natural world and that their usefulness is dependent upon the kinds of questions they enable scientists to ask and answer. Moreover, students have learned that models must be consistent with other scientific knowledge in order to be considered acceptable. The instructional materials found on MUSE have been developed in order to provide students with some understanding of important models in diverse disciplines as well as an understanding of what is involved in the development, use, revision, and assessment of scientific models.

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