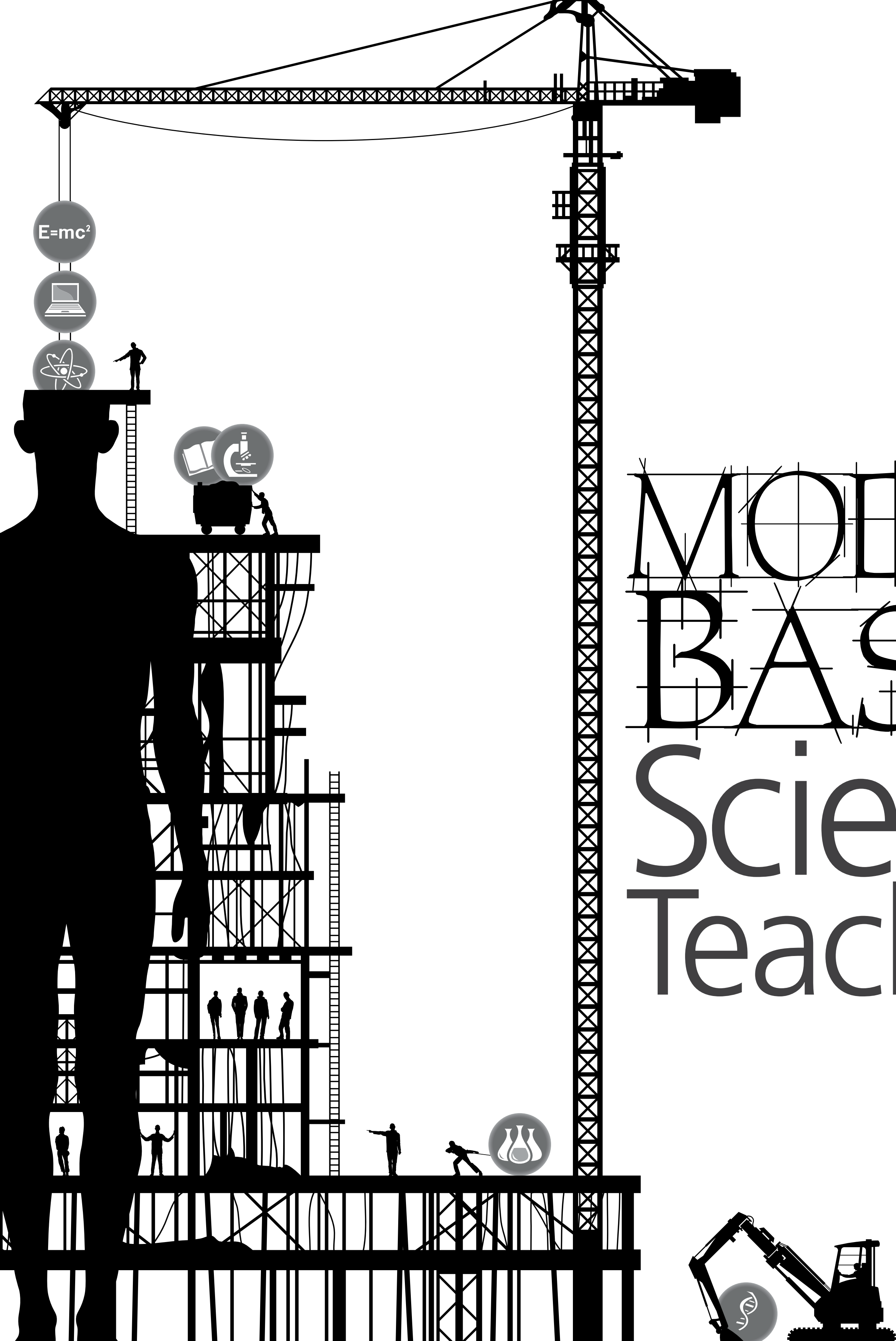

MODELS-BASED Science Teaching

Steven W. Gilbert

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Science Teaching

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PREFACE

Philosophy is dead.

—Hawking and Mlodinow, *The Grand Design*

The idea that philosophy is dead seems to be shared by many scientists and science teachers who believe that science has somehow supplanted all other approaches to the study of existence, knowledge, values, reason, mind, and language. In my view, however, nothing is further from the truth. Science is based on a commonly held philosophy, as are many other modes of formal human inquiry. Is philosophy dead in law? Economics? Politics? I think not. There are, in fact, many philosophies in the world today (probably as many as there are people, for we all have our personal philosophies). Unless we recognize and understand the strengths and weaknesses of those philosophies, we may be prone to make unnecessary errors in our interactions with the universe.

Models-Based Science Teaching (MBST) is not a primer on how to construct and use physical models for teaching. Instead, it builds upon the concept of mental models—simplified cognitive representations of what we think we know. From there, it seeks to demonstrate how we might lead our students to better define and frame the enterprise of science though models-based discourse, and thus how we might give more meaning to the processes and products of inquiry and discovery, research, and experimentation.

The key concept in this approach is mental modeling. Mental models are the essential elements—the building blocks—of intelligent communication, learning, knowledge, understanding, and action; and yet we pay only scant attention to them when we talk about science. This does our students a grave disservice. It deprives them of the deeper understanding of science they could acquire were we to incorporate mental modeling overtly into our approach to teaching and understanding science. This book explores how to do just that.

The philosophical concept underlying MBST—which I will call models-based science (MBS)—challenges conventional ideas about the nature of reality. The concept is not new or original, nor are its implications widely accepted by the general population, despite support for its premises from the medical, cognitive, and computer sciences. It would be understandable, then, for some science teachers to object to bucking their students' traditional ideas about the nature of reality in order to incorporate newer and potentially more controversial ideas into their science curriculum.

I was pleased, therefore, to find a model supporting MBS in Stephen Hawking and Leonard Mlodinow's recent book, *The Grand Design* (2010). In their work, they introduce a philosophical approach called "model dependent realism," or what I will refer to as MDR. MDR is very similar in it arguments and implications to MBS. You will not find references in this book to MDR by name, but you would recognize similar ideas if you read both books.

Both philosophical approaches focus on mental models and regard models as far more than convenient representational tools. Mental models are the heart and soul of conscious thought. All higher animals create and use them when thinking; humans, however, are consummate model builders, creating mental models with our minds and physical models with our hands, our voices, and our gestures. Through these models we create and represent our internal (subjective) realities. This is a simple idea, but it has profound implications—implications we must convey to our students if we are truly concerned with developing their science literacy.

Absent such learning, students may well grow up believing that reality is exactly what they perceive it to be: that their perceptions are real in an absolute sense. From that personal conviction, they may find it easy to believe that scientific knowledge is real in the same certain sense. And yet one of the central tenets of the nature of science is that nothing is absolutely knowable or provable. Why not? Well, that is what this book is about.

I have crafted this book for preprofessional students preparing to be specialized elementary/middle/high school teachers, elementary teachers of science, practicing science teachers at all levels who want to explore new and better ways to frame and model science, and parents or guardians who are homeschooling their children. Of course, anyone who educates or mentors new or practicing science teachers should also read this book.

Several short readings, suitable for secondary-level students, have been included in the appendix. While elementary- and middle-level students should learn MBS ideas through the discourse their teacher uses to guide inquiry and frame discussion, high school students may be introduced to the central tenets of this book in a more direct and thoughtful way, through these readings and subsequent discussions. Open discussion is always preferable to rote memorization, and students should be free to disagree or dispute some of the assertions in the readings.

In the end, the success of models-based science teaching will depend on your willingness as a professional science teacher to understand the underlying concepts of MBS/MDR and apply them as you direct, guide, discuss, lecture, or otherwise interact with your students. Consistency in application is most important if you expect students to understand and adopt a similar model as their own.

Reference

Hawking, S. and L. Mlodinow. 2010. *The Grand Design.* New York, NY: Bantam Books.

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Steven W. Gilbert received his PhD in science education from Purdue University in 1985 and has written extensively on models and modeling as a way to understand science. In addition to eight years of high school science teaching, he has been a professor of elementary and secondary science teacher education in Texas, Michigan, Indiana, and Virginia. He currently resides in Bloomington, Indiana, where he writes on science education and other topics. He can be reached at *stevengilb@gmail.com*.

Chapter 4

Models and Science Teaching

All models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind…

—George Edward Pelham Box

We've spent some time now creating a model of science based in the concept of mental modeling. Hopefully, I've made the case that mental models are more than just imaginative metaphors. In order to know something, you have to build a mental model of it. We see evidence of this all the time, but we have not recognized its importance as a key to understanding learning.

The example of Models-Based Science Teaching (MBST) I present in this chapter is built upon the guided inquiry model. Inquiry has shown itself to be at least as effective as traditional approaches for content acquisition and better in creating positive student attitudes toward science. On its face, inquiry also better mirrors the practice of science than traditional approaches. Our purpose is to impose a framework that develops other elements of science literacy as well, specifically understanding of the nature of science and its personal and social contexts. Building upon inquiry makes good sense, but you could infuse elements of MBST into a more traditional curriculum.

MBST is largely a matter of discourse—of how you present and explain the components of science to your students. It does entail learning a new set of skills, but these skills are readily learned by anyone who accepts the premises of MBST. Ideally, the language of MBST would suffuse the science curriculum from elementary school through college, but even if it doesn't—if it is used only in your classroom—it can do some good.

Content to Inquiry to Model Building

The National Science Education Standards define inquiry in science teaching as:

> . . . a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations. (NRC 1996, p. 23)

Skill in inquiry is one of the four important dimensions of science literacy referenced in the Standards, along with learning of science content ("subject matter"), understanding of the nature of science, and ability to view science in a greater social and personal context.

Inquiry differs from more traditional lab approaches in a number of ways. In the traditional lab activity, the focus is more heavily upon learning the content. Processes of investigation tend to be limited to manipulative and data collection skills (Table 4.1). Lab and field activities are usually prescriptive (sometimes called "cookbook labs") and are intended to lead students to correctly understand the phenomenon under study, which has usually already been discussed in class. For the most part, the students are not creatively involved in the development of the activity. Often they simply fill in the blanks on a printed sheet to complete their lab.

Inquiry, in contrast, focuses more on the development of the scientific process skills, as shown in Table 4.2. Content is developed with a conscious focus on developing a conceptual network, rather than being given as information. Guided inquiry, which involves teacher participation, is most common in schools.

In guided inquiry, students examine a new phenomenon (often in the form of a problem) before the teacher discusses the underlying concept with them, although the teacher usually involves the student in the design of the inquiry and interpretation of the results. The amount of guidance provided by the teacher varies with the subject and the age and experience of the students.

TABLE 4.1

Traditional vs. Inquiry Curricula

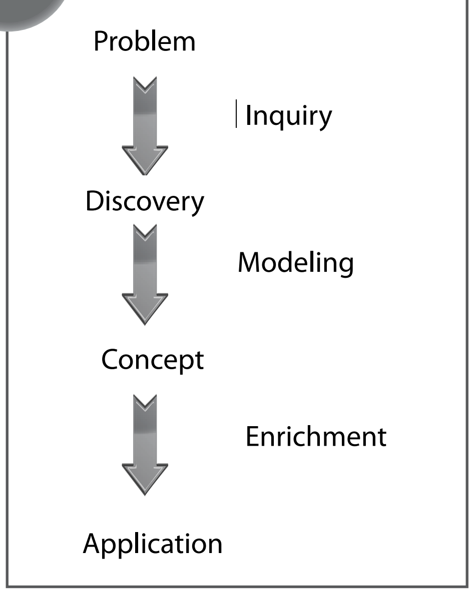
Traditional	Inquiry
Content comes before activity	Activity leads to content
Content is information	Content is concept-focused
Activities confirm content	Activities lead to discovery of content
Little student involvement in planning	Some or much student involvement in planning
Heavily teacher directed	Some teacher direction
Focuses on obtaining answers	Focuses in part on processes
Emphasis on developing physical techniques	Emphasis on exploration and inquiry
Saying little about nature of science	Partly mirrors technical nature of science
Provides little context for science	Provides some context for science

TABLE 4.2

Basic and Integrated Process Skills of Science

Basic science process skills:	Observing
	Measuring
	Inferring
	Classifying
	Predicting
	Communicating
Integrated science process skills:	Formulating Hypotheses
	Identifying Variables
	Defining Variables Operationally
	Describing Relationships Between Variables
	Designing Investigations
	Experimenting
	Acquiring Data
	Organizing Data in Tables and Graphs
	Analyzing Investigations and Their Data
	Understanding Cause-and-Effect Relationships
	Formulating Models

FIGURE 4.1



The process of inquiry as viewed through the MBST framework.

In contrast with the traditional approach, in which the activity follows the introduction of the target content, inquiry leads the students to the target from the initial activity. This means that students develop a mental model of the target concept *before* the teacher labels it. In the MBST format, the model for inquiry is similar to that shown in Figure 4.1.

Research to date indicates that students studying science through guided inquiry learn as much or slightly more science content than those following a more traditional curriculum and, importantly, report a greater liking for science. However, we have little evidence to show that students using inquiry gain a better understanding of the nature or context of science than those using a more traditional approach. This may in part be due to a lack of an *organizing framework*—a model that would provide inquiry with more meaningful form and focus.

All good therapists know how important a framework is. The same problem, seen through two different frameworks (some people prefer the metaphor of lenses), takes on different meanings. If we "do" activities without a framework, they are simply class assignments. They have no larger meaning. Part of the reason inquiry may not live up to its full potential is that the activities are often focused—like traditional labs—on content and may be too carefully guided by teachers. They do not involve students in anything much like science.

MBST provides you and your students with a thematic structure for inquiry. It does so by overtly defining science as the construction of descriptive and theoretical models. Building a model is different from "doing" a lab. It is different from inquiry alone.

A model is a *product* with a distinct purpose. We design models selectively, systematically, and deliberately. Building a model is an end in itself. You have a purpose for every model that you build; every sentence that you utter, for example, is a model.

Awareness of this process is the key to making science more meaningful and challenging for your students. And this awareness if often missing, right up through graduate school. Graduate students of science writing theses for their master's degrees or doctorates frequently have trouble with their research projects precisely because they do not have this end in mind. Stephen Covey's admonition to "begin with the end in mind" (1989) would be helpful. But what is the end? To build a model, of course. The ultimate goal of all learning and communications is to build an effective model. Learning how to build such models is in part what education is all about. Why do scientists build models? To describe and explain phenomenon.

In other words, science does not end at discover. It begins there. Inquiry is a means to an end, not an end in itself. Even if we keep our mental model to ourselves and never share it, we are still engaged in model building.

If we impart subject matter content and technical skills to our students without a firm grasp of the product, we will rob our students of a deeper understanding of science. I was reminded of the need for this kind of understanding when I described this models-based approach to a retired physician who had done science at one time as a grad student. I was stunned when he took vehement issue with the model I presented. When I pressed him to clarify what he was doing when he did science, he could go no further than to say he was discovering things. My effort to convince him that he was building a model failed. But then, I hadn't given him the background I've given you. Hopefully, you will be more receptive to the benefits of knowing about science as well as how to practice it!

Modeling Science at Different Grade Levels

What additions or changes do you have to make in your teaching in order to use MBST? The good news, if you use inquiry already, is not many. To make these changes, though, you must be thoroughly familiar with the concepts we have developed in the first three chapters.

The changes MBST requires are largely semantic—the product of a different way of conceptualizing science. Following from the axiom of beginning with the end in mind, what would a scientifically literate student know at the end of their student career if he or she was taught using MBST regularly and consistently in grades 4–12? The student would presumably

- know how to create descriptive or explanatory models of phenomena through inquiry;
- view science as the construction of descriptive and explanatory models;
- distinguish science from technology according to the purposes of each;
- understand learning as the creation of mental and expressed models;
- understand that knowledge is a variable structure of simplified mental models;
- understand the subjective nature of knowing and learning;
- know the difference between scientific and nonscientific model building; and
- understand on a practical level why science can never explain all things.

The principles underlying MBST are the same as those that frame our contemporary understanding of the nature of science and human thinking. As a teacher of science using models-based science teaching, you engage students in constructing a web of science concepts while also developing their understanding of

- how humans learn by constructing mental models (nature of learning);
- the nature and limitations of all mental models (nature of knowledge);
- the nature and limitations of expressed models (principles of communication);
- the processes for building models in science (scientific investigation and learning); and
- the differences between scientific and nonscientific models.

Clearly, these dimensions of MBST cannot be addressed in the same ways at all grades and ages, but let's examine how to adapt the method to each grade level.

MBST at the Elementary Level

Most elementary age children would be unable to comprehend models of the philosophical and scientific basis for human thought. They are just coming to grips with the nature of their own realities and have no idea how the brain works. Students at this age would not benefit from any but the most superficial references to the subjective nature of reality (e.g., "that's how you see it, but other people might see it differently").

However, elementary students can be given a broad definition of what a model is, and they can understand that they are creating models when they make something to represent something else. If they write a poem, for example, you can tell them they are creating a model of what they are thinking. If they draw and write a description of a leaf, you can remind them that they are creating a model in words and pictures of a leaf. You can introduce the word *target* to identify the thing they are describing or explaining. In this way, elementary teachers can lay the foundations for MBST and for understanding through model building.

As a simple example, suppose you as an elementary teacher want to engage your third graders in a study of insects. The goal of the exploration is to describe (create a model of) a typical insect. You give your students three pictures of insects and three pictures of noninsects (e.g., spiders and centipedes) and put your class in the role of scientists. You ask them to pick out the three and tell why they chose them.

Once the class agrees on the three candidates (with your help) you go on to help them build a model they could use to identify other members of the group called insects. The students could then compare the insects and noninsects and suggest features peculiar to insects to include in their model. While this seems like a simple activity, it actually mirrors the activities of early natural philosophers as they put together classification systems based on appearance.

It's not enough to stop there, though. The students will not understand anything about science by just constructing this model. You must explain to them that they, like scientists, are looking for patterns—common features the insects share that the noninsects don't have. You remind the class that they are creating a "model in their heads" of what an insect is and is not. When they write or draw the model on paper, they are doing what scientists do by creating a model to share with others from the ones in their heads.

Once the children have collected data, you work with them (or let them work together) to create the model. Once the model is created, they test it by looking at more insects, refining what they have created. Scientists, you tell them, have to test their models too.

You could do the same activity without MBST, but notice how the focus is shifted from content to building and testing a good model. That is the difference between having a framework and not having one.

MBST in elementary science focuses on

- broadening and developing the models concept to include mental and physical models,
- expanding the range of constructs that students view as models,
- engaging students in simple model building and testing based on existing inquiry activities, and
- framing activities with simple but valid ideas about what scientists do.

Keep in mind that all learning activities across subjects involve model building. When students do arithmetic, they are building models of the relationships of quantities. When they spell and write, they create symbolic models representing concepts and propositions. As an elementary teacher, you can apply the language of modeling across subjects.

MBST at the Secondary Level

By the time your students get to middle school, they could have a good grasp of models and modeling, assuming the exposure in elementary is similar to what we have just discussed. At this level, they should be ready to understand that

- scientists construct and share models of the natural world;
- scientific models are based on data that we can see and confirm;
- the data for a scientific model must be replicable and consistent;
- scientific models are what experts in an area agree upon;
- scientific models are accepted because they are useful and predictive;
- scientific models are simplified and do not describe or explain everything;

- scientists seek to know and explain;
- technologists invent and apply; and
- many of the models we commonly use are not scientific, but that does not mean they are wrong.

These ideas should grow naturally from your reframing of inquiry but, as we pointed out for the elementary grades, the ideas should be repeatedly included in your discussion of science with your students.

By high school, most students can think abstractly enough to handle deeper technical explanations of mental and scientific models. They should be mature enough to

- understand the theoretical basis for mental modeling and human thinking;
- understand science as a process of model building;
- understand the limits of theoretical models as both shared and individual constructs;
- design and construct scientific valid models of selected phenomena;
- use basic statistics or statistical presumptions to assess outcomes;
- critique scientific models as to their reliability and validity;
- critically relate their models to a range of targets;
- find new problems as the construct models;
- distinguish scientific from nonscientific and pseudoscientific models; and
- understand science in personal, social, cultural, and historical contexts.

While MBST may require expenditures of time to address some of these issues, such as the theoretical basis for mental modeling and human thinking, many of the principles of MBST can be infused into existing activities.

Since only one hour per week is devoted to lab work in the average high school classroom (NAS 2005), the approach should be infused into other modes of instruction. In biology, for example, you can talk about the Darwin/Wallace model (or theoretical model) rather than theory. You can refer to models of force, bonding, and plate tectonics and refer to factual models rather than calling them facts. And there are always opportunities in the course of instruction to talk about how scientists build and test models, and how the models are simplified, and to point out that not everything is known or certain. MBST requires a commitment to the development of scientific literacy. Without that commitment, it will go nowhere.

Examples of MBST at Several Grade Levels

The steps you use to construct a scientific model are similar to doing inquiry activity, but with certain modifications. A full MBST-based inquiry usually includes the following steps:

- Introduce a problem of description or explanation
- Frame a solution to the problem in model-building terms by identifying the target
- Plan the model
- Construct the model by collecting and evaluating data and making inferences
- Evaluate the fit of the model to the target

In guided inquiry, the teacher usually poses the problem (open inquiry is more student focused). A *problem* is any situation or question for which we do not have an immediate solution, explanation, or answer. In the insect classification activity we discussed in the previous section, the problem was to identify the characteristics of the insects that distinguished them from noninsects.

Elementary students are usually more concerned with solving descriptive categorical and ordering problems than in constructing explanations for phenomena, although we should by no means exclude them from constructing simple explanatory models appropriate for their level of understanding and development.

By the middle grades (variously defined as grades 4–8), most students have the capacity for modeling concrete cause-and-effect relationships to explain a thing. For example, they can understand the causal explanation for winds and ocean currents by applying concrete convection models to these larger targets.

They are also able to understand abstract concepts such as density when the concept is presented in a concrete activity. In text box 4.1 is a classroom activity that uses differences among cereals to develop a mental model of density.

In this activity, the teacher provides the framework for the inquiry by suggesting a goal to the students. The problem is to explain why equal volumes of three different flake cereals weigh different amounts.

As we have pointed out, MBST depends upon regular and consistent use of models terminology. You never just "do" an activity without framing it in a models context:

> *Wrong:* Today we are going to do an activity (or lab) investigating how the color of light influences the growth of bean plants.
>
> *Correct:* Today we are going to practice science by developing a research-based model showing how the color of light influences the growth of bean plants.

TEXT BOX 4.1

The Density of Cereals

Purpose: To use differences in common cereals to develop the concept of density.

Students must be able to:

- Determine mass on a simple scale or balance
- Measure volume

Materials

- Three different flake cereals of distinctly different densities

Introduction
Put the students into the role of scientists who have never seen cereals. Their goal is to create a model to report back to their other scientists what they have found, providing as much information as they can. Ask what characteristics they might include in their models. Come to an agreement about what their models will include (making sure flake, compactness, weight of a cupful, texture, and so forth are included).

Procedure

- Give each group one cup of the cereal to work with.
- Allow them to collect the data agreed upon.
- Put numerical data on the board and calculate averages for the model.

Discussion

T: *Look at your data model carefully. What does it show you? What things that you say seem to be true?*

[They might see that the cereal with the smallest flakes weighs the most per cup. If they do, ask them to explain why this might be. Give them time to think. If they get stuck, guide them.]

T: *Do you see any relationship between the size of the flakes and the weight of the cup?* They do. They state it correctly). *Why do you think the cereal with the smaller flakes weighs more per cup?*

S: *'Cause you can get more flakes in. So there's more stuff in the cup.*

T: *More mass?*

T: Yeah, more mass.

T: *So there's more mass in the heavier cup than the lighter one?* [They agree]. *Weight comes from gravity acting on mass. You have the same amount of cereal by volume but different amounts by mass. So can you tell how much mass something has just by looking at it?* [They say no]. *So let's say we know how much a cup of each of five cereals weighs. They look the same but they are different in weight—in mass per cupful. If you were given a cupful of one of the cereals but didn't know which one it was, how could you figure that out?*

S: *You could weigh it.*

T: *So you could use your model to figure out—to predict—what cereal you have.* [They agree]. *Scientists build predictive models just like the one you just made. They use the weight per cupful to help figure out what an unknown substance is. The part of your model that we've just discussed—mass per unit of volume—is a model of a concept called density. We would say these cereals have different densities because they have different masses in the same volume. You'll want to keep that model of density in your heads so we can add to it and make it grow.*

The script below imagines the teacher, who is overseeing the density lab described in the text box, guiding her students from that activity to another activity that will build upon the concept of density that the students have just learned.

T: *Okay, so we've created a neat scientific model of this thing called density. And if we knew the densities of all the cereals in the world, you could tell what kind of cereal you had just by measuring its weight per cup. Scientists like this kind of predictive model. It makes their job easier. Now we have this model in our heads we call density. It's basic, so we might want to make it better by enriching it. We've been talking about how much our cereal weighs per cup. What's wrong with using weight for our model?*

Ss: (blank looks)

T: *Is the* <u>*weight*</u> *of something always the same everywhere?*

S1: *No! You can be weightless in outer space.*

T: *But the amount of you doesn't change in outer space, does it? Do you remember what weight is?*

S2: *It's the pull of gravity on mass.*

T: *So the amount of material in the cereal is its mass. It stays the same no matter what it weighs?*

S1: *Unless you eat it!*

T: *Let's say we don't eat it. When you weighed the cereal, you found out how many grams it weighed because weight and mass are the same at sea level. So our weight in grams is okay as long as we are on the ground. But out model would be better if we used mass instead of weight. Agree?*

S2: *Okay.*

T: *How about our using a cup for the measurement? Is there any problem with that?*

Ss: (blank looks)

T: (takes out two cups of different sizes): *Here are two cups. Which one is the right size?*

S3: *I don't know. Either one could be right.*

T: *Exactly. To make a model that we can always use and understand with fewer mistakes, we will need a volume that always stays the same.*

S1: *Right.*

T: *Scientists want to create models that everyone can understand and duplicate if they want to. So even though we're okay with the grams per cup measure, we might want to use standard measures next time we build a* *model: measures that everyone knows. Now, here's an interesting question. You know there are different kinds of woods: oak, maple, pine, and so forth. Do you think they all have the same density or different densities?*

S1: *Different!*

S2: *The same!*

T: *What does the model we just created tell us about how we can find out?*

This dialogue, although obviously contrived, illustrates how you reference models and the nature of science in your conversations with students. You may focus on different aspects of science, of course.

Once the students have enriched their models of density by discovering that different woods have different densities, they could enrich their models by creating a link to the concept of buoyancy (denser woods float lower in water—are less buoyant—than less dense woods). If you are familiar with *learning cycles*, you will recognize the pattern. Let's pull another simple example from the field of chemistry, specifically endothermic reactions that absorb heat and feel cold as they occur, and exothermic reactions that emit heat and thus feel warm or hot.

In a traditional lesson plan, the concepts of endothermic and exothermic reactions are introduced to the students prior to them doing the lab. This is not so in guided inquiry. In the latter, students "discover" the differences before formally building a model by mixing the reactants and measuring temperature changes. The terms *endothermic* and *exothermic* are applied after they have constructed a mental image—a mental model—of the reactions.

Students can then enrich their model through a series of measurements of other reactants to create patterns that would predict endothermic and exothermic reactions.

This lab is a variation and extension of a typical "cookbook" lab, but poses a problem (to find a pattern in the model being created) and so is more interesting than most prescriptive lab activities. But MBST goes beyond inquiry. Having raised at least some interest and curiosity, the teacher assigns the students the role of scientists. The problem is stated after the "discovery," which is how to build a valid databased model of the phenomenon. By way of introducing the whole activity, the chemistry teacher might say something like this:

> *I've discovered an interesting phenomenon I'd like to share with you. It's so interesting that I think it deserves some investigation, but first I want you to see what it is for yourselves. This is what I did.*

The teacher then gives students minimal directions on what to do and they discover as-yet unnamed exothermic and endothermic reactions. After they have discussed the phenomena and named the reactions, the teacher continues, saying:

Your job will be to work together as scientists to collect and pool your data to create a descriptive model of this phenomenon. I also want to see whether we can enrich our model by testing other similar materials to see whether they show the same or similar reactions. We will work out which materials to test in just a moment.

I also want you to think about why these differences appear. In other words, what could be going on inside the systems to cause this effect? These will be hypothetical models, of course, since they are speculative. But as we've said before, scientists often include their speculations in their descriptive models to suggest explanations for what they observe.

Since we will pool our data to help ensure its reliability, we first need to talk about, and agree upon, what you will include in your model.

In this brief introduction, you can see our emphasis upon building a model—not just completing an activity and finding right answers. Inquiry and discovery are part of the process but are a means to an end. That end is the final expressed model.

The teacher has laid out the parameters for the inquiry but has also left room for input from his students: that is, they plan the model together. In chemistry, of course, the teacher has to exert more control over most inquiries due to the inherent dangers in that subject. But students always know they are being guided in school science. Your goal is to use questions and suggestions to help them get a sense of how to shape a model—what variables to consider—even if you cannot give them freedom to inquire.

Almost all traditional labs can be transformed into opportunities for problem solving and model building. Although you may object that inquiry takes too much time, keep in mind that our goals have changed.

In the chemistry activity we just discussed, students will find that some chemical reactions absorb energy while others release it. They may hypothesize then that "all chemical reactions either absorb or release heat." When questioned about where the energy may come from or go, students may puzzle out the involvement of chemical bonds. This speculation can be included in their models *as speculation*. The postlab discussion might go something like this (in part) where the teacher uses the notion of the target:

T: *The targets for our model are the reactions that we actually investigated. But can we honestly say that all chemical reactions are either endothermic or exothermic?*

S1: *Sure, if the energy is in the bonds, it gets released. Or it takes energy to break a bond.*

T: *So what do we know for sure?*

S1: *If there's a reaction, bonds must be broken or formed.*

S2: (points to paper) *Or both. But all we know for sure is that the reactions we tested either released heat or took it in.*

T: *How reliable were our data?*

S3: *They were good.*

T: *How certain are we that our model includes all chemical reactions?*

S2: *Kinda certain. I mean, we can generalize from our model but we would have to look at all reactions if we wanted to be sure.*

T: *So we can't be sure from our model that all chemical reactions are either exothermic or endothermic?*

S1: *No, not really. Some we haven't seen might be different.*

T: *But it seems likely?*

S3: *Yeah.*

T: *So our model is useful but incomplete. Still, it's useful. And the explanation you proposed for why the reactions feel hot and cold is consistent with the existing scientific model for chemical bonding that's already part of our theoretical model.*

Ss: *Yeah.*

In guided inquiry, you provide the leadership needed for your students to make sense of their work. Students can enrich their models by searching out background information on endothermic/exothermic reactions once the concepts are introduced.

Now let's look at a third scenario, this time in biology. Our goal is to develop models describing and explaining adaptation in flowers. Our first step is to develop descriptive models of flowers. So we give our biology class several morphologically and ecologically distinct flowers and set up a problem using MBST terminology. The teacher says:

> *We've learned already that scientists create descriptive and explanatory models. Even today, there are scientists creating models of new species just as Ray, Linnaeus, Darwin, and others did several centuries ago. Genetics are used more now, but we usually rely first upon differences in form to create preliminary models.*
>
> *Naturalists have always being interested in creating models of why particular creatures have particular forms and functions: for example, why a leaf is shaped the way it is, or why bark on a bush has certain textures. Over time, they have created a theoretical model relating form and function.*
>
> *Here is the situation. Each team of naturalists has two newly discovered flowers. Now you are already familiar with flower anatomy from our work with the lily. Your task is to enrich your model of a flower by creating*

> *descriptive models of your two flowers, using the lily as a reference. In the end, you will want to be able to speculate on the causes of any differences you see among the flowers. Now let's consider what we might include in our models to make them useful. What should we do to make our models most meaningful and how should we record data?*

Note in this monologue how the teacher tries to engage her students in role-playing. She gives them a situation and a task, which is to build a model. Of course, the students are well aware that they are not scientists, but they can still benefit by pretending to be. Role-playing can be a powerful way to develop their understanding of the nature of science, if you use it regularly and consistently, and are careful to model science well.

Part of your role as a teacher is to create a scene or role for your students. In many classrooms, that role is one of passive learner. In the best science classrooms, the learner is active and engaged, and has a sense of purpose. MBST is primarily about developing purpose.

Introducing Your Students to MBST

In the book, *Learning How to Learn,* Novak and Gowin (1984) stated their purpose as "educating people and… helping people learn to educate themselves. We want to help people get better control over the meanings that shape their lives." The authors felt that knowing how to learn is just as important as knowing what is learned.

MBST is likewise concerned with building a model of learning that helps students of all ages understand that when they learn something,

- they are constructing mental models that are by nature simplified and subject to change;
- these models are adopted because they work and not necessarily because they are the only true and most effective ways of understanding the world;
- no one has a complete grasp of any model, and most of the time we are working with approximations of a situation; and
- what we create when we communicate are expressions of our inner mental models alone.

These basic principles have implications that go well beyond our understanding of science. Learning how to learn (by building models) is in MBST supplemented by learning *what* we learn.

If you are an elementary- or middle-level science teacher, you will generally infuse MBST into your science activities without referring much to the underlying rationales we developed in Chapter 1 through Chapter 3. Young children are attuned to learning by doing. They would not understand such rationales. But if you are a high school teacher, you could more overtly include some of the

TABLE 4.3

Stereotypes of Science vs Alternative Tenets of Science

Stereotypes	Alternative Tenets
Science is a search for unchanging truth.	Science is a quest for predictive explanations.
Reality is objectively knowable.	Reality can only be known and understood subjectively.
Once something is proven, it doesn't change.	All scientific models are subject to change if change is warranted.
Scientists are inventors bent on controlling things.	Scientists build descriptive and theoretical models.
Scientists are objective and dispassionate.	Scientists think subjectively and are motivated by curiosity and desire for success.
Scientific knowledge is objectively proven reality.	Scientific knowledge is models accepted by the agreement of experts in a field.
Scientists are atheists opposed to religion.	Scientists need not be atheists but may reject some beliefs of established religions.
Knowledge is contained in books, journals, and other media.	Knowledge exists in the collective of human minds.

philosophical and conceptual ideas that underlie our modern understanding of science and learning. How you would introduce these ideas would depend upon the curriculum you use. If you design your own, you have more options than if you are forced into a lockstep with other teachers in your district. Even then, however, you can infuse many of these ideas into your explanations and discussions.

The model most adults have constructed of science contains many stereotypes held over from the recent and distant past. These stereotypical models need to be reexamined in light of developments in the late 20th and early 21st centuries, because they pop up regularly in the science reports of popular media (and even sometimes in professional literature). Some of these stereotypes and rebuttals are presented in Table 4.3.

Students need to think about what happens when we think. One way to introduce science to your (high school) students is to present them with examples of the products of science, such as copies of research papers from journals like *Nature* or *Science*.

In very short order, you can develop many of the ideas of science as model building; first, by considering what these papers represent and getting into the heads of the authors; second, by thinking back about how they were constructed.

This approach puts a human face on scientific model building. Although it is best to select articles that are reasonably transparent, transparency is not as important as the discussion about the nature of the papers themselves.

This approach is nothing more than an application of the principle of beginning with the end in mind. If students don't know the products of science, how can they be expected to understand what science is about? By examining real scientific models, they begin to understand how a scientist represents a target by using graphs, pictures, descriptive narrative, and so forth.

As students examine the papers, the idea that these models are simplifications of real systems can take hold. It also becomes easy for them to understand the limits of these models when they have the real thing before them; that models have to be interpreted to have meaning, and that what they have is a representation in symbols of some real target.

I am suggesting, then, that starting out the year by examining the nature of the products of science—research papers—in the greater context of how humans learn and know a thing is essential if we want our students to understand themselves and science better.

Lesson Planning for MBST

Good lesson planning is as essential to MBST as it is to any other approach to teaching and learning. If you don't know where you are going, you cannot know if you have arrived.

Each time you plan a class, you must ask yourself how the content can be presented within the framework we have developed. Keep in mind that you are not being asked to add new activities to your curriculum; rather, you are being prompted to create an explanatory framework for those activities that better describes the processes and products of human thought.

If we apply our MBST model to lesson planning, we find we can be effective by following certain simple rules and principles:

- Construct models, don't just give out information
- Be parsimonious: develop the most important elements of the model solidly
- Create familiar imagery to anchor propositional elements (develop pictures in the head to anchor spoken or written ideas)
- Link parts of the models and models themselves systematically and hierarchically
- Teach students how to create and evaluate scientific models through inquiry
- Create a model of what science is first by examining the products of science
- Engage your students in the role of the scientist as model-builder

- Always refer to the nature and context of science during discussion (always have in mind that you are teaching about science and not just science content)
- Always open and close your activities: Don't stop until you have developed a complete model of whatever phenomenon you are investigating or discussing.

As of this writing, I am not aware of any published instructional materials that incorporate MBST terminology. Your success depends upon your ability to frame and explain contextualized science to your students in your own words, using appropriate terms. Because of the power of language to shape our thoughts, regular thinking in MBST terms actually can change the way we design the science curriculum; which, of course, is the primary point of this book.

Summary

MBST is most consistent with, and builds upon, the principles of inquiry defined by the National Science Education Standards (NRC 1996). Implementation of MBST requires you as a teacher to plan and administer your science curriculum using a specific terminology—what we might call the "language of models"—at a level that is appropriate for the age and maturity of your students. If your students can do inquiry, they can understand MBST ideas about the nature and context of science at their level. It is better to infuse ideas about human thinking and learning into the curriculum as part of the process of scientific model-building than it is to treat it as a separate topic.

As a rule, you will be most successful with MBST if your primary goal as a science teacher is to teach students how to construct and evaluate scientific models, both mental and expressed. Learning of content and processes will follow from this goal.

Practical work in the lab or field should always pose a problem, and that problem should be how to construct a reliable, valid model of a natural phenomenon. Students assuming the role of problem solvers and model-builders focus their attention on planning and constructing the best possible descriptive and/or explanatory model of the phenomena they study. Students so engaged will necessarily learn the desired conceptual content.

Even if you can only lecture, you can still infuse MBST terminology and explanation into your discourse by referring to scientific models, theoretical models, and the creation of research based models. Because most students, especially at the higher grade levels, have some reasonably accurate notion of what a model is, the constant and consistent use of the term *models* can be expected to carry over to their understanding of the content you are presenting. While lecture-only science is not recommended, it does necessarily preclude the understanding that comes from using MBST.

In the next chapter, we will continue developing ideas about how to implement MBST in the classroom.

For Discussion and Practice

1. Analyze the idea that MBST principles regarding the nature of science and human thought should be commensurate with students' ability to grasp principles of inquiry. What does this mean to you in terms of students you have worked with or are preparing to work with?
2. How does the idea of *building a model* of a concept such as density differ from the notion of *teaching the concept* of density? Does the idea of modeling change your approach to planning in any way? How?
3. Some teachers might be concerned about introducing their students to the uncertainties of science. Review some of these uncertainties (the uncertainties of models and limitations of model building in general) and discuss how they might best be addressed during discussions with your students.
4. Our goal in MBST is to engage our students as model builders. How can you do this consistently, so that building a good model becomes the focus of their efforts?
5. A rather simple science activity, often used in teaching physical science, involves shining white light through a slit, and then through a prism to project a full spectrum. Filters are then used to change the color of the light, and students note changes in the projected spectrum. From this they can infer that the filters are absorbing certain colors (wavelengths) and allowing others to pass through. Discuss how you would frame this activity to make it a model-building activity. What would you tell students? How would you introduce the activity and pose the problem using MBST terminology?

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