Linking Phenomena with Competing Underlying Models: A Software Tool for Introducing Students to the Particulate Model of Matter

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ABSTRACT: Helping students understand the general nature of scientific models is increasingly regarded as an important goal of the middle and high school science curriculum (e.g., J. K. Gilbert & C. Boutler, 1998. International Handbook of Science Education; Kluwer, London; A. G. Harrison & D. F. Treagust, 2000. Science Education, 352–381). In addition, beginning in middle school, students are introduced to one of the most central models in modern science—the particulate model of matter. Thus, teaching students about this model is an ideal opportunity to help students develop an understanding of the nature of models in the context of learning a central scientific concept—the discontinuity of matter. In this article, we present a software tool that was designed for this purpose. The software engages students with investigating and evaluating competing models of matter in order to help them see the particulate model as a plausible model that can explain a wide range of facts about diverse phenomena. The first and second parts of the paper describe the scientific content of the particulate model and the main ideas about scientific models that we would like to teach, as well as the educational challenges of teaching these ideas to middle school students. The third part describes the structure of the software and the three phenomena we chose to have students explore. These are all phenomena that should be puzzling to students if they assume that matter is continuous, but that can be easily explained if they assume that matter consists of discrete particles. The paper concludes with a description of two studies evaluating the effectiveness of the software in promoting students' understanding of models

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in general and the particulate model of matter in particular. We found that middle schoolers can engage with fundamental ideas about the nature of models, and that engaging them with these ideas helps them internalize the assumptions of the particulate model of matter. This happened especially for students who had developed relevant macroscopic conceptions of matter based upon quantified and interrelated conceptions of volume, weight, and density.
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INTRODUCTION

The particulate model of matter is one of the central ideas in modern science. It is also a central subject in the middle and high school science curriculum. Yet, as is well known, this topic is very hard for students to learn and internalize (e.g., Ben-Zvi, Eylon, & Silberstein, 1986a, 1986b; Berkheimer, Anderson, & Spees, 1990; Griffiths & Preston, 1992; Lee et al., 1993; Novick & Nussbaum, 1978; Nussbaum, 1985; Wiser, 1994). We believe that understanding the particulate model of matter is difficult because it requires that students develop an understanding of two profoundly important, but counterintuitive, ideas. The first one is the idea of the *discontinuity of matter* and the second is the idea of an *explanatory model* as a metaconcept in science.

In this paper, we describe a software tool we have developed to help students begin to understand these important ideas. The software is one element of a more complete curriculum unit designed by us to support the beginning stages of learning the particulate model of matter among middle school students. The main goal of the curriculum unit was to create an environment in which students would be able to construct some key elements of the model and to see its explanatory power and usefulness, rather than to memorize isolated tenets of the model as absolute truths or simple facts.

In the first part of this paper, we define, from the scientific point of view, the complexity at which we would like to teach these two main ideas to middle school students. In the second part, we discuss the pedagogical problems encountered when teaching these two ideas. In the third part, we discuss the structure of the software and how it was designed to meet the goals and challenges posed by the previous parts, that is, the scientific and didactic considerations. Finally, in the fourth part, we report the results of two small-scale studies that assessed the effectiveness of this software tool.

PART 1: THE PARTICULATE MODEL OF MATTER—THE SCIENTIFIC ASPECTS

The centrality of the particulate model of matter in modern science is well-captured in Richard Feynman's famous remarks (Feynman, Leighton, & Sands, 1963, Ch. 1, p. 2):

> If, in some cataclysm, all the scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* . . . that *all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another*. In that one sentence, you will see, there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied.

Indeed, most of today's science is centered on the molecular-atomic and subatomic levels—from elementary particle theories through electronics to molecular biology.

The particulate model of matter is also a central idea in middle, high school, and college science curricula. It is typically first introduced in the middle school science curriculum, because subsequent studies of physics, chemistry, and biology are based on a microscopic description of matter and therefore depend on a good understanding of this model. But perhaps Feynman was optimistic in assuming that one needs only a little imagination and thinking in order to see the power of this model. It is well known that this idea is very hard for students to learn, in part because it conflicts with many intuitive ideas students have about matter and about models. It is thus extremely important to help students overcome these difficulties, because their failure to learn the particulate model will impair their learning of science in subsequent years.

In this part of the paper, we analyze from the scientist's perspective both specific elements of the particulate model and general ideas about the nature and purpose of explanatory models. Such analysis of the scientist's perspective is a prerequisite to any attempt to bring about conceptual change in the learning of scientific concepts. Clearly, any scientific concept can be thought about at different levels of complexity. By analysing these concepts, we can define the endpoint we wish students to achieve, and the scope of the materials needed to support their learning process. This analysis will also allow us to specify which aspects of the scientific model we are ignoring or avoiding consciously in our teaching and why we choose to do so.

Some Elements of the Particulate Model of Matter

Scientists use a complex web of ideas when thinking about the particulate nature of matter, each carefully supported by the findings of a large number of experiments. These ideas include the very general notion that matter is discontinuous and made up of discrete particles. They also include conceiving of these particles—atoms—as having a complex, internal structure, i.e., being made of subparticles which in turn have their own internal structure. Further, they include assuming a variety of forces are involved in the system, whose nature and mathematical description have been worked out through extensive experimentation. Finally, they include assuming the elements of the microscopic world are in constant motion at many levels—the particles themselves and the elements in the particles, to mention only two.

Even more basically at a macroscopic level, scientists have a notion of the mass of matter as an invariant of the system in all its transformations, such as phase changes or temperature changes. Scientists also distinguish between the additive properties of matter, such as mass, and its intensive properties, such as density. They have a battery of metaconceptual tools, such as understanding the nature of measurements and definitions of units, and the nature of models and scientific theories. Finally, as mentioned above, scientists have extensive and detailed knowledge of a long list of physical phenomena that both support these assumptions and are well explained by them.

Thus, when thinking of matter scientifically, scientists use a mental model of an unseen world that has its own "life" at the microscopic level. Even though the particles of matter cannot be seen or touched at a macroscopic level, scientists assume that these particles exist and they become an important reality for their mind. In so doing, the science expert relates to an unseen conceptual level that is very much at odds with surface appearances. In contrast, the novice relates either to the concrete world of objects themselves or to a conceptual level that corresponds more directly to surface appearances (e.g., matter is continuous because it looks continuous). This creates a gap between the views of experts and novices that is similar to other described cases (Larkin, 1983).

All of the scientists' ideas about the nature of matter, and the detailed knowledge supporting these ideas, were developed through a long history of human thought, experimentation, and collaboration, sometimes with lapses of hundreds of years between stages. Although some thinkers even in antiquity had proposed that matter might be fundamentally particulate in structure (Toulmin & Goodfield, 1962), the particulate theory did not gain ascendancy as a powerful explanatory, scientific theory until the 1800s. A variety of changes in scientists' macroscopic understandings of matter as well as detailed knowledge of puzzling real-world phenomena were needed in order for this theory to emerge as a well-grounded theory. For example, after Newton had formulated (in 1687) the concept of amount of matter (mass), it took almost another 100 years before Lavoisier formulated (in 1789) the law of conservation of mass in chemical transformation. This law states that there is no creation of matter from nothing and that the amount that goes in and comes out of a system is constant under transformations such as burning or combining into compounds. To quote a translation of his writing: "... in all the operations of art and nature, nothing is created; an equal quantity of matter exists both before and after the experiment ..." (Holton, 1985, p. 231). A few years later (in 1808) Dalton formulated the law of definite proportions. In formulating this law, he proposed an explanation for why certain amounts of materials make compounds only in certain proportions: namely, that matter consists of small, discrete particles which combine in fixed proportions. Then (in 1827) Brown provided convincing evidence that these small particles called atoms are in constant motion. This work was done only after the concepts of energy, the conservation of energy, the nature of heat as a form of energy and the kinetic theory of gases were established. Thus, it was an enormous effort, based on findings from many branches of science like mechanics, heat theory, and chemistry, to get to the statements that we often try to convey to our students in just a few lessons.

Perhaps we should remember this complicated historical path when designing our modern-day curriculum. Which key ideas should we introduce to students, in their first encounter with the model? We discuss our answer to this question in the second part of the paper.

The General Conception of an Explanatory Model

Let us now briefly examine some important aspects of scientists' general conception of an explanatory model. We believe it is as important to carefully examine the components of this scientific metaconcept before trying to teach it, as it is to examine the elements of the particulate model of matter itself.

First, for scientists, a model is not a true description of a system, but rather a set of assumptions that include theoretical entities and relations among them, that are designed to help them think about how to explain some aspect of reality. As we will see later, this basic assumption about models is not made by students, who typically think of models as little replicas or pictures of reality (Grosslight et al., 1991).

Second, for scientists, every model is limited in its scope, capable of helping them think about only a limited aspect of a complex reality. Usually when dealing with models in the scientific world, the discussion is centered on these very limitations, because scientists are trying to understand the boundaries of each model and how different assumptions are limiting its power. They need to understand these boundary conditions in order to move flexibly among models, selecting a model of appropriate complexity for a given phenomenon or a model that explains different aspects of that phenomenon.

For example, in formulating the particulate model of matter, one can assume—and model—the particles as perfect spheres. This formulation ignores the complex internal structure of the particles from which matter is constructed, but is sufficient to explain many phenomena, such as Dalton's law of definite proportions. By assuming this, one understands that this formulation of the model does not apply to other phenomena, such as the structure of ice crystals, whose explanation depends on the specific, nonspherical, internal charge distribution within molecules or atoms. Thus it is clear that for scientists a model is not the truth, but a flexible temporary tool for visualizing and interpreting limited aspects of reality.

Third, embedded in the idea that models are limited in scope is an assumption about the standards scientists use for the evaluation of models. Models are evaluated according to their power to explain a set of experimental phenomena, their ability to predict the outcome of not-yet-experienced phenomena, and by their internal consistency. When there is a conflict between the model's prediction and the observed results of an experiment, one looks for ways to expand the model so that is will account for more phenomena with the new set of assumptions; that is, the model is not proclaimed as wrong—as it provides a sufficient explanation of some aspects of reality—but as inadequate or partial.

For example, assuming that matter is made of discrete particles was historically enough to explain the law of definite proportions, but it was not enough to explain the fact that when a bottle of perfume is opened in one corner of the room, it can be smelled throughout the room. For these phenomena, one needs to add the assumption that matter is not only made of particles, but also that these particles are in constant motion. This new assumption is added to the particulate assumption as an extension of the original. Even when there are two conflicting models, such as the particulate and wave nature of light, one cannot say that one of them is wrong, but rather that each model helps us look at a limited aspect of the phenomena of light. Thus, the discussion centers on where exactly one model falls short in its explanations.

A fourth aspect of models is that the same reality can be modeled in more than one way. Although mathematically the two different models can be isomorphic, they might differ in the visual or conceptual tools they use to depict different aspects of the same reality (e.g., the action-from-a-distance and the field models for gravitation discussed in Feynman, 1967, pp. 50–53).

In the next part, we discuss the ways students think about matter and models. Because there are major differences in the perspectives of scientists and students, we need to think of ways to bridge between the starting conceptions of students and the conceptions of experts.

PART 2: THE PARTICULATE MODEL OF MATTER—THE EDUCATIONAL CHALLENGES

There have been a variety of approaches to teaching middle school students about the particulate model of matter. In our view, no approach has been fully satisfactory in its responses to key educational challenges. Indeed, the literature documents that students have many misconceptions both about the specific assumptions of the particulate model of matter and its status as an explanatory model that typically persist even after explicit instruction. In this section we will describe some of the problems encountered with previous approaches in an effort to contextualize the contribution we are trying to make with our own efforts.

In many textbooks, the particulate model is presented to students as a known fact (Dori et al., 1989; Hurd et al., 1988). For example, the text used by the Israeli schools in Grade 7 presents the model as three known facts: (a) matter is particulate (i.e., made of atoms, or molecules); (b) there is a vacuum between the atoms or molecules; and (c) these atoms or molecules are in perpetual motion (Dori et al., 1989, p. 124). After stating these facts the text moves on to the explanation of various phenomena on the basis of these facts. Many of the phenomena discussed have to do with matter in the gaseous state. For example, the diffusion of gases is brought up as an example showing the constant movement of the particles. The idea of a model, as an abstract construct in science, however, is usually not discussed at all or is only mentioned briefly in a few sentences. For example, in both textbooks mentioned here, there is a short, general chapter on the scientific method as a system that uses experimentation to confirm or reject scientific assumptions, but no explicit discussion of scientific models.

We believe there are several problems with this approach. First, it fails to consider that the scientific knowledge needed to understand these ideas about the particulate model of matter is enormous and that students may have alternative conceptions about matter and related concepts that might prevent their understanding of these facts.

For example, in using experiments that are based on the gaseous state, texts assume that students this age conceive of gases as matter. Prior research, though, has shown that this is often not the case (Lee et al., 1993; Smith et al., 1997; Stavy, 1991). Because students think that matter is something that they can see, touch, and feel, they have problems conceiving of gases as matter. Thus, by using gases for teaching about the particulate model of matter, one is using obscure, not well-understood materials in the eyes of the students to make statements about an even more obscure abstract structure (i.e., the structure of this material at a microscopic level).

In addition, the particulate model of matter assumes that matter is discontinuous, and that the discrete particles have mass and take up space. Prior research, however, indicates that students may conceptualize weight as felt weight rather than as a fundamental property of matter (Smith et al., 1997); that is, they think that some material objects, such as a piece of Styrofoam or grains of sugar, weigh nothing at all because they have no felt weight. Further, some may fail to comprehend that matter continues to exist on a small scale. When faced with a thought experiment about what happens to a piece of matter with repeated division, they argue that it gets too small and eventually disappears. Clearly, students will have difficulties accepting the existence of atoms as valid materialistic entities that have mass and volume without being convinced that all macroscopic objects (such as pieces of Styrofoam or shavings of sawdust) have mass and take up space. Without these ideas being in place, students have no way to see how the particulate model of matter creatively unites and extends them. Instead, the ideas of the particulate model will not make sense to them and they can only learn the ideas of the particulate model by rote learning.

A second problem with this approach is that it presents the assumptions of the model as known fact rather than as conjectures that might explain a pattern of evidence. Thus students are not given an opportunity to develop an understanding of what type of thing the particulate theory really is (i.e., an abstract model, not a set of facts) nor to appreciate its tremendous power and scope.

Some curricula have tried to develop student understanding of the particulate model through more open-ended inquiry activities: presenting students with interesting phenomena to explain and encouraging them to generate and evaluate competing explanations for those phenomena. However, they have been beset with problems either in convincing students that the particulate model is a better model than the alternative models students themselves create, or in helping students come up with a robust understanding of the multiple, complex elements of the particulate model.

For example, "The Models of Matter" curriculum (Berger et al., 1979) involved students in evaluating how well different models explained the process of mixing and dissolving. A variety of models were considered including the "push" model (things mix because one material pushes its way into another), the "shake" model (things mix because they are shaken together), and the "small particles" model (things mix because they consist of small particles that are moving). The assumption of the curriculum developers was that students would clearly see the advantages of the small particles model in explaining these phenomena. However, careful research about how students responded to the curriculum unit revealed that this did not happen (Berkheimer, Anderson, & Spees, 1990). Students preferred the conceptually simpler "push" model of mixing and dissolving to the "small particles" model, and continued to use this model (and make adjustments to it) rather than abandon it in light of experimental evidence. This created an awkward moment for teachers as the remainder of the curriculum presupposed that students initially had "bought into" the small particles model and was devoted to having them explore its ability to explain a wide range of other phenomena. Consequently, teachers often had to simply tell students that the small particles model was the better model in order to proceed with the rest of the unit (Berkheimer, Anderson, & Spees, 1990).

The extensive inquiry-based introduction to the particulate model of matter that Driver and her colleagues have developed and used with eighth-grade students in England (Children's Learning in Science Project, 1987) appears to lead students much more naturally to the conclusion that matter is particulate based on its ability to account for empirical evidence. One of the strengths of this curriculum is the tremendous respect it has for students' initial ideas and the care it gives to "preparing the ground" for constructing a particulate theory by (a) involving students in generating their own explanations for a diverse set of phenomena about matter; (b) involving students in a murder mystery exercise designed to make the metapoint that a good explanation accounts for a wide range of evidence or "clues"; and (c) having them initially explore the ways that solids, liquids, and gases differ from each other and identify a pattern of properties that distinguishes them. After these initial exercises, students are challenged to develop a theory to explain why matter in different states has different properties and what happens when water changes state. Students work in small groups to make posters of their ideas about what is "inside" a solid, liquid, and gas, and then present and debate their ideas in the whole class. Although it is common for "particulate" ideas to emerge in at least some student posters, some students only give macroscopic explanations and for others many key elements of the particulate model are either entirely missing or misunderstood. For example, it is common that students think that there is air between the particles (rather than empty space), confuse the particles of air with specks of dust (rather than see them as the air itself), do not consider the particles to be in motion, and do not have any idea what holds the particles together. At this point, the teacher engages students in trying to reach consensus about certain issues and has the challenging task of trying to move students toward the accepted scientific model. In our view, the curriculum only offers limited guidance on how to proceed with these issues—especially the issues about space between particles. Indeed, it acknowledges that many students consider it a philosophical point whether there is air between the particles and argue that there is no way to prove there is not. Further, the curriculum never engages with the core issues of whether each particle has mass and takes up space. Finally, no detailed posttest assessment is provided of how convincing the curriculum is to individual students. Nonetheless, the curriculum is exemplary in many respects, especially in attempting to have students explore how the particulate theory provides explanations for a wide range of phenomena.

The problems that sixth-grade students experienced with the "Models of Matter" curriculum (Berger et al., 1979) led Berkheimer and his colleagues to propose yet another approach to teaching students about the particulate model of matter: one that they regarded as more deeply grounded in conceptual change principles (Berkheimer, Anderson, & Spees, 1990). They argued that a common problem with both traditional text-based and more open "inquiry" based presentations of the particulate theory is that neither had considered the nature of students' initial macroscopic conceptions of matter. Their own careful research richly documented that middle school students have many misconceptions about matter at a macroscopic level that prevent them from understanding the particulate model of matter. Consequently, they developed a revised curriculum unit entitled "Matter and Molecules" (Berkheimer et al., 1988) that devoted almost as much time to teaching these macroscopic understandings as to teaching students about the particulate model of matter.

However, in developing this new unit they took a much more directed approach—directly teaching students how to give well-formed explanations of phenomena in terms of the assumptions of the kinetic molecular theory—and abandoned the idea of having students compare different models of matter in terms of their explanatory adequacy. They argued that middle school students were epistemologically unprepared to deal with these complex issues and that the consideration of alternative models would simply generate more conceptual confusion than epistemological insight. Further, they argued that because scientific models develop in response to a wide range of evidence, rather than based on data from single critical experiments, it is naïve to expect that students will accept the particulate model through consideration of limited experimental evidence (Berkheimer, Anderson, & Spees, 1990).

We agree that a pure inquiry-oriented approach is naïve and that any approach to teaching should take account of student preconceptions. However, we believe students should not be introduced to the particulate model without providing them with some compelling evidence that favors this model over alternatives, and think that these researchers may have underestimated middle schoolers' readiness to deal with these important epistemological issues.

In our view, a problem with previous curricula is that they have tried to introduce too many features of the particulate theory of matter all at once, without sufficient attention being paid to the phenomena that might best motivate the development of each feature. Further, as has already been pointed out (Berkheimer, Anderson, & Spees, 1990), many curricula have used phenomena that students may not yet understand or find puzzling at a macroscopic level. In addition, most curricula about the particulate theory do not engage students with explicit metaconceptual discussion of the nature of models or involve them with considering alternative models. Finally, in the few cases where students have been invited to consider competing models, it is assumed that students are able to "envision" what each model implies would happen in a macroscopic situation, even though some aspects of this envisionment may not be obvious. We believe, however, that a conceptual change curriculum has to give careful attention to all these issues. We hypothesize that middle school students would be able to engage with the task of evaluating competing models in light of empirical adequacy if more attention were paid to all these issues. The advantage of such a curricular approach would be that it not only developed an understanding of the particulate model, but of the important metaconcept of an explanatory scientific model.

Thus, we were looking for ways to help students arrive at the idea of the discontinuity of matter by creating an environment in which students can gradually develop elements of the particulate model of matter as part of a process of trying to explain puzzling phenomena. By presenting students with phenomena that are puzzling if one assumes that matter is fundamentally continuous, we hoped that they would become dissatisfied with this idea and would look for alternative ideas that can provide a better account of all the data, as was done in the development of science.

To begin, we wanted to introduce the most fundamental assumptions of the model that would also be the simplest to understand. Therefore we decided to limit our discussion, in the introduction of the model, in the following way: First, we limited the description of the discontinuity to simple particles and we did not specify the nature of these particles. We limited our description in this way because we believe that it does not make sense to talk about the nature of particles to someone who is not yet convinced that particles exist at all. Second, we decided to ignore, in the introduction, the perpetual movement of the particles from which matter is made. We also ignored any detailed discussion of forces between the particles. In other words, we thought that it would be better to concentrate first on the difficult transition from the assumption that matter is continuous to the assumption that matter is particulate, without elaborating on any other elements of the model. In this way, our approach is different from other curricula dealing with this subject.

In this way, we were also following, to some extent, the historical path of science in establishing the particulate model. Further, when one studies these historical steps, one sees that the necessary prerequisite concepts were the definition of matter as something that has mass and takes up space—even in very small, unseen, quantities. The ability to attribute materialistic properties to an unseen entity is very hard for many students and one should pay attention to this point before moving on to build the particulate model. We believe that students should have the concepts of volume, mass, and of basic measurements as a prerequisite for learning the model. In our curriculum units, therefore, we invested a long time on these prerequisites, but will not discuss this part here.

Because we wanted to help students make the transition from a tangible, observable continuous world to an abstract unseen one that consists of discrete particles at a microscopic level, we were looking for experimental phenomena that occur in the solid or liquid states. These are the two states of matter which students most clearly recognize as "matter" (Lee et al., 1993; Smith et al., 1997; Stavy, 1991). In these two states, matter is basically incompressible, visible, and tangible, unlike the gaseous state where matter is compressible, invisible, and intangible. We assume that the particulate model most clearly violates students' conceptions about the nature of solids and liquids, and it is best to confront these issues head on. We also assume that students may better understand the constraints of explanatory model building if they are faced with the task of imagining unseen elements that explain a tangible aspect of reality than if they are imagining unseen elements to explain an intangible aspect of reality.[1]

Finally, let us turn now to the "model as a concept" element of the curriculum. We believe, along with many others in science education (e.g., Abell & Roth, 1995; Brown & Campione, 1994; Carey et al., 1989; Driver et al., 1996; Gilbert & Boutler, 1998; Grosslight et al., 1991; Harrison & Treagust, 1998, 2000; Hennessey, 1999; Lehrer et al., 2000; Ragavan & Glaser, 1995; Schwartz, 1998; Snir, Smith, & Grosslight, 1993; White & Frederickson, 1998, J. Stewart, J. Cartier, & C. Passmore, Developing understanding through model-based inquiry, unpublished manuscript), that a central element of science teaching should be about metaconcepts as well as the set of relevant concepts. That is, students should understand what a model is and how it is used in science. We believe that if this is done constantly as each new concept is introduced in science, students will not only better understand important scientific concepts, but will be able to understand science as a way of thinking which they can apply to their everyday world. Perhaps this is the most important goal in teaching science. The particulate model is ideally suited for this purpose because the notion of an explanatory model is an integral part of the theory.

There are several elements from the many ideas about models mentioned in Part 1 that we would like to include in our teaching. To start with, we would like our students to understand that models are a representation of reality, not a picture of it. Prior research has showed that students think about models as little replicas or pictures of reality (Grosslight et al.,

[1] Nussbaum (1997) has recently reported on the development of an extensive curriculum for seventh-grade students about the particulate theory of matter, which centers on explaining the compression and elasticity of air. He argues that a central conceptual difficulty that prevents students from grasping the fundamental idea that matter consists of discretely spaced particles is that they lack a scientific understanding of a vacuum. We agree that a full curriculum about the particulate theory would need to tackle this important issue and applaud his attempts to engage students with many of the most fundamental assumptions underlying the particulate theory of matter. Our proposal is that at the beginning stages of debating whether matter is continuous or particulate, it is important to focus on central instances of matter, such as solids and liquids, and to engage students with the general idea of an explanatory model.

1991). Therefore an explicit discussion about the differences between a representation and a picture (or scaled replica) and between explaining something and showing something should be included. We would like our students to think of models as helpful tools for thinking about observed phenomena. We would like them to understand the standards used in science for evaluating the validity of a model by examining the facts it explains and the model's internal consistency. We would like them to see how models are developed and become more sophisticated and complex to account for more data. This experience would also help students understand that models are only temporary. And lastly we would like them to treat models not as right or wrong but as more or less adequate. We believe that in doing so we are letting students take part in the process of scientific development the way scientists do, even though it is in a structured and limited environment designed by us specifically for these purposes.

Thus, the educational challenges involve not only deciding what part of the particulate model to teach first and what prerequisite conceptions must be in place to create these conceptual puzzles, but also how to build students' general understanding of what a model is. We believe the best approach is to involve students in explaining a series of phenomena and in evaluating the explanatory adequacy of alternative models. This approach gives students the opportunity to construct the particulate model slowly in their mind in response to puzzling, but concrete phenomena. We turn now to a description of the specific phenomena we chose, and the structure and function of the software tool we designed in order to guide student thinking.

PART 3: DESCRIPTION OF THE THREE CORE PHENOMENA AND THE SOFTWARE

As mentioned earlier, we limited the scope of the curriculum unit to a subset of selected elements of the particulate model of matter. Therefore, we carefully selected a few core phenomena to motivate the construction of these elements of the model.

We start this section by describing these core phenomena and explaining our reasons for choosing them. We then discuss the specific structure of the software and our reasons for having this structure. Finally, we conclude by discussing the pedagogical rationale for using software at all. We believe that the design of the software not only permits greater scaffolding of the model evaluation process, but also highlights the distinction between the basic facts about a phenomenon and its explanation in a way that is impossible to do in the lab or a demonstration. In this way, the software is used as an added tool to facilitate the conceptual change process, not to replace students' exploration of the real-life phenomena or their attempts to construct and debate their own personal models.

Which Phenomena Were Selected and Why?

Three demonstrations are simulated and analyzed by the software: the mixing of water and alcohol, thermal expansion of a metal ball, and the combining of sulfur and copper in different proportions. Each phenomenon has an unexpected result, which poses a puzzle for a student who believes that matter is continuous, but which can be explained easily by someone who assumes that matter consists of discrete particles.

The demonstrations involve phenomena from different branches of physics and chemistry. Thus, they can be used to reflect on the strength of the particulate theory: its ability to explain a wide variety of different phenomena. It is important to note that all the demonstrations relate to the solid and liquid states of matter. For reasons discussed in the previous section, we refrained from using gaseous phenomena at this stage. Let's consider in greater detail the basic facts of each phenomenon, and the basic puzzles that are posed by each.

Mixing Water and Alcohol. When water is added to alcohol, the two liquids mix, but, surprisingly, the volume of the mixture is less then the sum of the volumes of the water and the alcohol, although the mass of the mixture is equal to the sum of the mass of the parts. Here the three basic facts are (a) the liquids intermix, (b) the masses add, and (c) the volumes do not add. The key puzzles are: How can two noncompressible liquids mix at all? In addition, how can they combine to produce a mixture whose volume is less than the sum of the two parts?

This demonstration is done twice, first with the colorless liquids and second with the water colored blue and the alcohol red. The coloring helps students see that the two liquids intermix instead of staying in layers. Comparing the mass of the two liquids against the mass of the mixture on a balance scale shows them that the masses are the same, as no matter got lost. The volume discrepancy is made quite salient for students by using volumetric flasks with a narrow tube at the top.

Thermal Expansion of a Metal Ball. An unheated metal ball, which easily passes through a metal ring, is then heated. After heating, the ball no longer can pass through the ring. A comparison of a heated and unheated metal ball on the balance scale shows that the mass of the ball did not change. Here the basic facts are (a) heating increases the volume of the ball, (b) heating does not change the mass of the ball, and (c) the mass and volume of the ring remain the same because it has not been heated. The basic puzzle is: How can the volume of the ball increase while its mass stays the same?

Combining Sulfur and Copper in Different Proportions. Heating copper (an orangish metal) with sulfur (a yellowish powder) forms a new substance called copper sulfide (a crispy black powder). Only when one uses a certain amount of copper and sulfur does one get the formation of copper sulfide without any residue. If the amount of copper or sulfur is increased above the nonresidue case, one gets a residue of copper or sulfur accordingly. These extra amounts of materials do not take part in the reaction at all. The mass of the materials is preserved in the process.

Here the basic facts are: (a) heating leads to the formation of a new substance; (b) sometimes there is a copper residue, sometimes there is a sulfur residue, and sometimes the copper and sulfur are completely used up in the reaction; and (c) mass is conserved across the reaction. The basic puzzles are: Why can't the two materials completely combine in any proportion? Why is there sometimes copper left over, sometimes sulfur left over, and sometimes nothing left over?

The Structure of the Software

In the opening screen, students can choose which demonstration out of the above three that they would like to simulate and analyze (see Figure 1, screen dump from opening screen). Once students have selected the phenomenon to work on, they get a screen that allows them to open one of the following windows: (a) *Laboratory Work*, (b) *Stop and Think*, (c) *Models*, and (d) *Investigate Models*. Students can open these windows in any order and move freely among them. Further, the first three windows can be simultaneously activated on the same screen, to facilitate comparison among them. Let us now describe

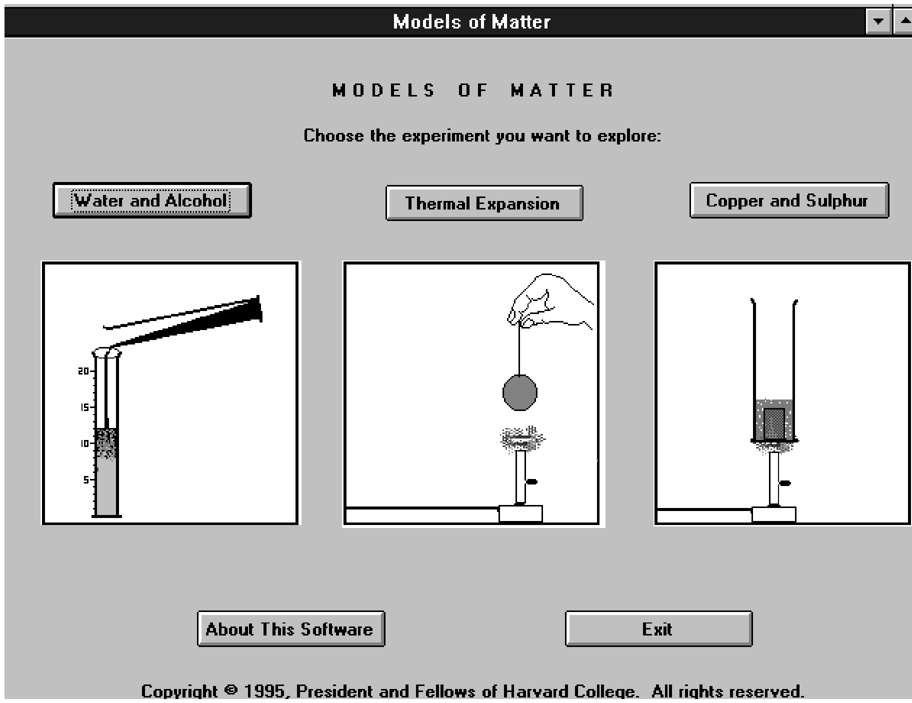


Figure 1. The opening screen from the software *Models of Matter* allows students to choose which of three experiments they want to explore.

these four windows in greater detail and the general functions that each was designed to serve.

Laboratory Work: Simulating the Experiments. Activating this option opens a window (on the left-hand portion of the screen) that lets students scroll through a brief simulation of the demonstration. The demonstration is depicted by a small set of comprehensive slides. These include schematic pictures of each main phase of the demonstration and a brief description of what happens in that phase written beneath. For example, when exploring the phenomenon of mixing water and alcohol, students first see the demonstration as two colorless liquids; then with the water colored blue and the alcohol red. Figures 2 and 3 show two slides from this sequence in which the mixtures are colored. Note that the demonstration concludes by putting the beakers on a balance to show the conservation of mass.

Students can navigate freely forward and backward to control the presentation. This feature of allowing students to go back and forth while watching the demonstration is a unique contribution of the software that cannot be done in the laboratory. The schematic presentation of the demonstration also helps students to concentrate on its important elements. All the "noise" that is usually a part of a real experiment is avoided. In spite of this we would like to stress that the simulation is not designed to replace the laboratory, but rather to provide another means to understand more deeply what was done and observed there.

Stop and Think: Ensuring that Students Noticed the Central Facts. Activating this option opens a center-screen window that presents three multiple-choice questions. After answering these questions students can choose the option "Check my answers," which

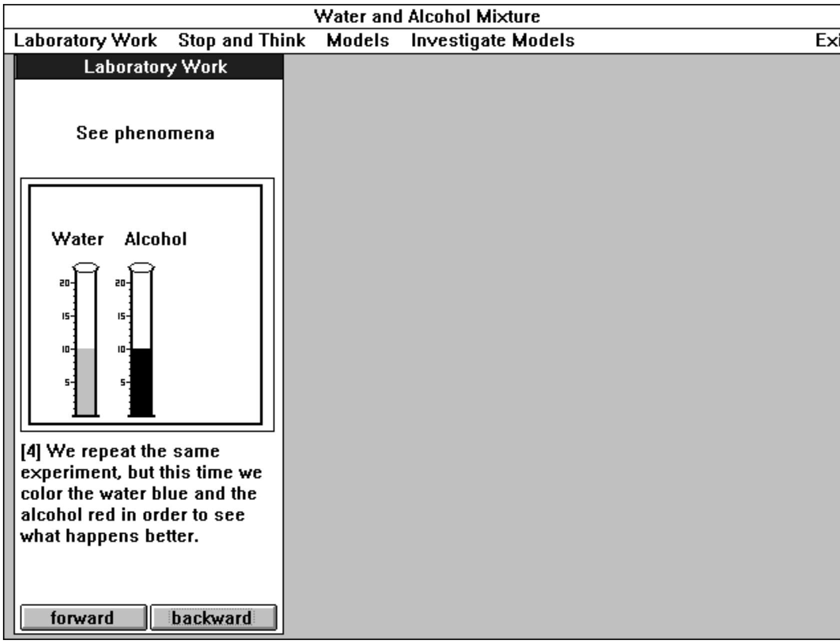


Figure 2. This screen dump shows the fourth screen of the *Laboratory Work* window for the phenomenon of Water and Alcohol, in which the water and alcohol have been colored. Note that we use shading intensity differences to show color differences in all of our screen dumps, because we are limited to creating black and white figures. The actual computer screens use colors.

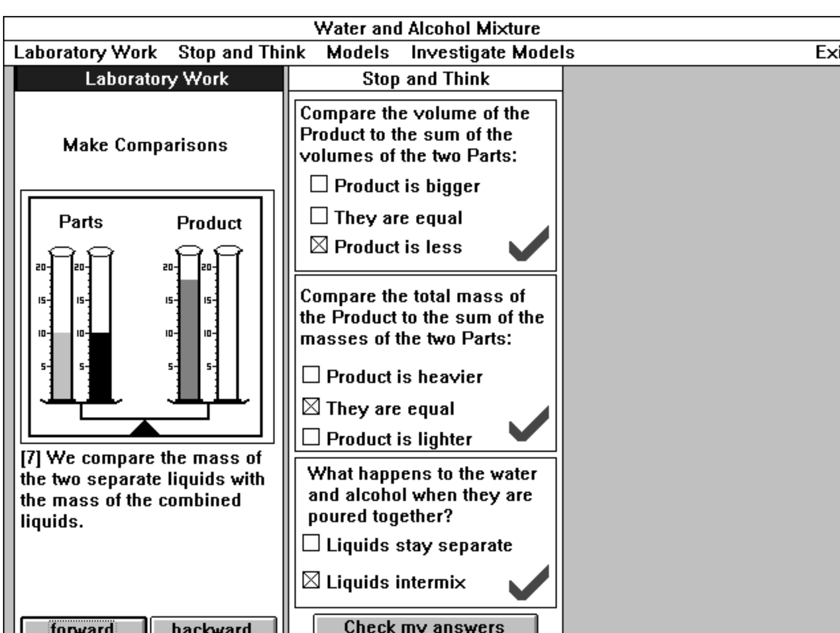


Figure 3. This screen dump shows the last screen of the *Laboratory Work* window for the phenomenon of Water and Alcohol, along with the opened *Stop and Think* window in which answers have been entered and checked.

asks the software to give feedback on the correctness of each answer. The purpose of this part is to ensure that the student knows the puzzling facts. If the student is correct, a large check mark appears. If the student is incorrect, the software gives the message "one of your answers in not correct, please go back to the laboratory work and check the experiment again." As the left-hand *Laboratory Work* window is still open, the student may freely return to that window to search for relevant facts (see Figure 3).

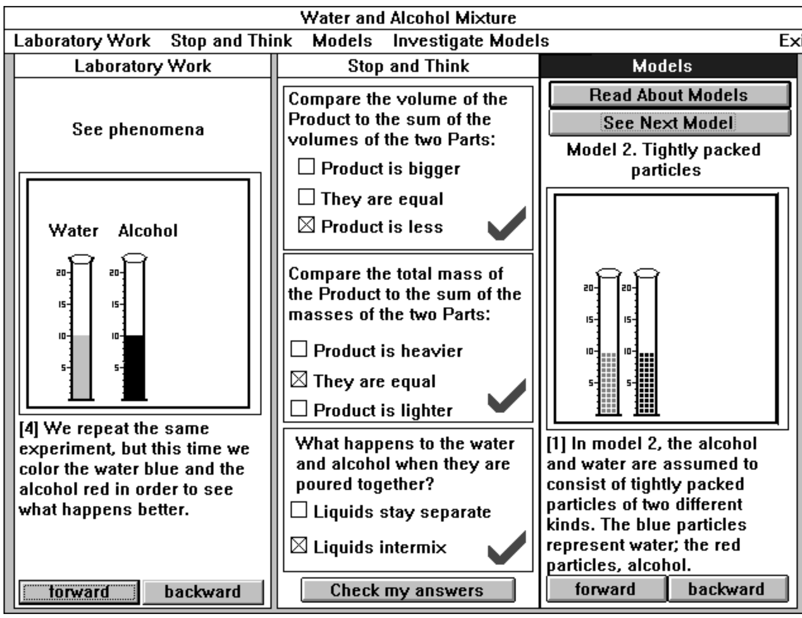
Models: Giving Students the Opportunity to Choose a Satisfactory Explanatory Model. Activating this option opens a new right-hand window on the screen from which students can choose two options: "Read About Models" and "See Next Model." If students select "Read About Models," they scroll through several screens of text which present ideas about the nature and purpose of models. Because we know that students' ideas about models are quite limited and often at odds with scientists' ideas, we wanted to make some of the scientists' most fundamental ideas about models salient and explicit to students. For example, students are told that the purpose of a model is to explain a set of facts, that a model can make assumptions about what is unseen in order to explain what is seen, and that we are looking for a model of matter that can explain the behavior of matter in diverse circumstances. The purpose of including such text in the software is to reinforce important metapoints about models that are also extensively explored in class discussion.

In the same window in which students are able to read about models, they can view alternative explanatory models for these demonstrations. These models are billed as ideas presented by different students. By selecting the "See Next Model" option, students can view four sets of different models that the software presents in a successive way. Each model makes different assumptions about the underlying structure of matter, based on different ideas that students can have about matter (e.g., that matter is continuous, that matter consists of discrete, but tightly packed particles, or that matter consists of discrete particles with spaces between them). Each model then proposes different explanations for the phenomenon that is consistent with its assumptions. Each model can account for at least one of the basic facts about each phenomenon. However, only one model (in the cases of mixing water and alcohol and combining copper and sulfur) or two models (in the case of thermal expansion) can account for *all* the facts of a particular phenomenon. Further, only the particulate model can give a satisfactory explanation for all three phenomena.

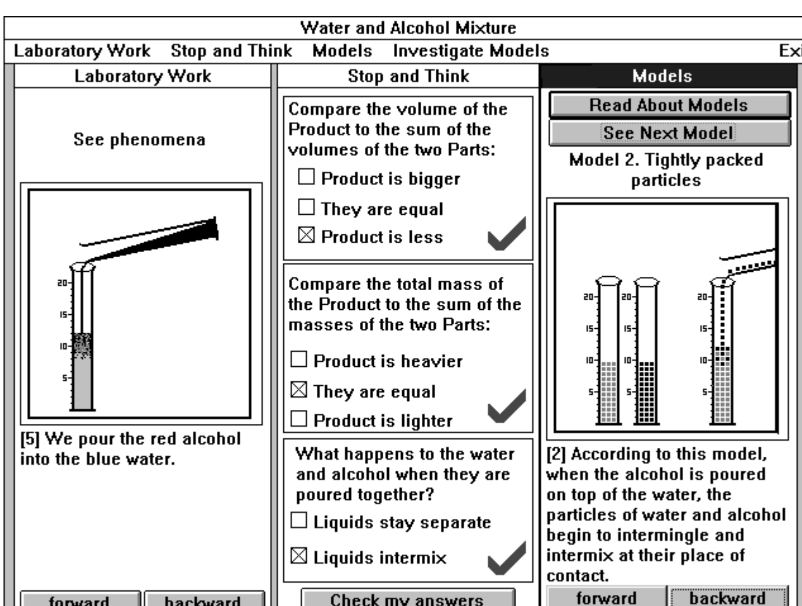
The presentation of each model is very similar to the way the Laboratory Work is presented. The student watches the demonstration unfold step by step, but this time the materials are drawn according to the way the model defines them. For example, suppose the student chooses a model for the mixing of water and alcohol that assumes that matter consists of loosely spaced, discrete particles. Then in the step where one liquid is poured into the other, the presentation will show a stream of particles of one material being poured into the particles of the other material. The wording, beneath, explains the basic assumptions of the model, how each material is represented, and how it proposes to explain the phenomenon.

Figure 4 shows three screens from *Model 2. Tightly packed particles* for the phenomenon of mixing water and alcohol. The first screen (Figure 4a) announces the model's basic assumption about matter and explains how it represents the water and alcohol. Subsequent screens show what would happen during the pouring process, given these assumptions. Because the particles are discrete, they would intermingle and intermix (Figure 4b). Further, because they are tightly packed, they would be in the same tight packing before and after pouring the liquids together; hence the two volumes would sum (Figure 4c). Note the *Models* window appears on the right, allowing the student to leave open and freely navigate within the *Laboratory Work* and *Stop and Think* windows at the left and center.

Figure 5 shows three screens from *Model 3. Loosely packed particles of different sizes* for the phenomenon of mixing water and alcohol. The initial screen (Figure 5a) announces the model's basic assumption about matter and explains the way it represents water and alcohol. Subsequent screens show what this model implies would happen in the pouring process.

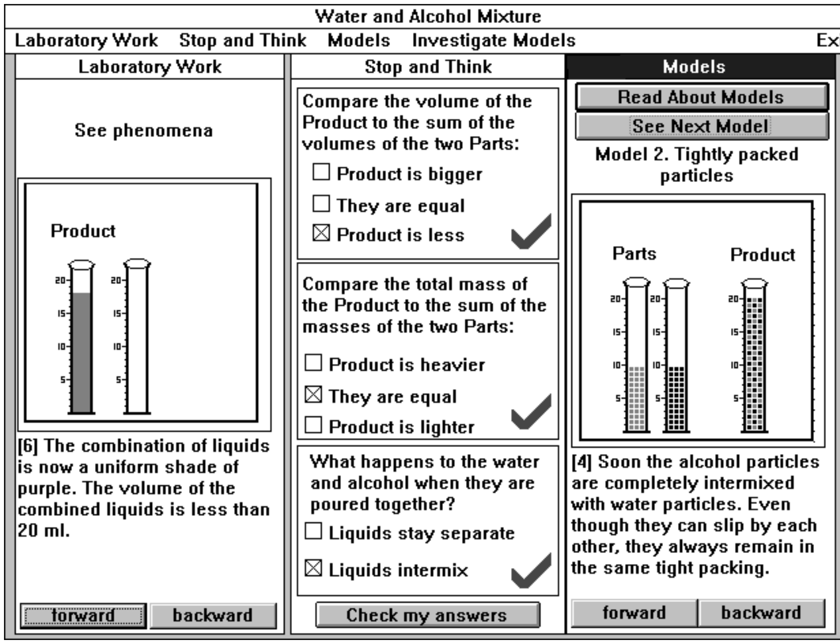


(a)



(b)

Figure 4a–c. Three screen dumps show the opened *Models* window for the phenomenon of Water and Alcohol in which *Model 2: Tightly packed particles* has been selected for viewing. As students scroll through these screens, they see the two liquids being poured together, the tightly packed particles intermixing, and summing to a volume of 20 ml. (*Continued on next page*.)



(c)

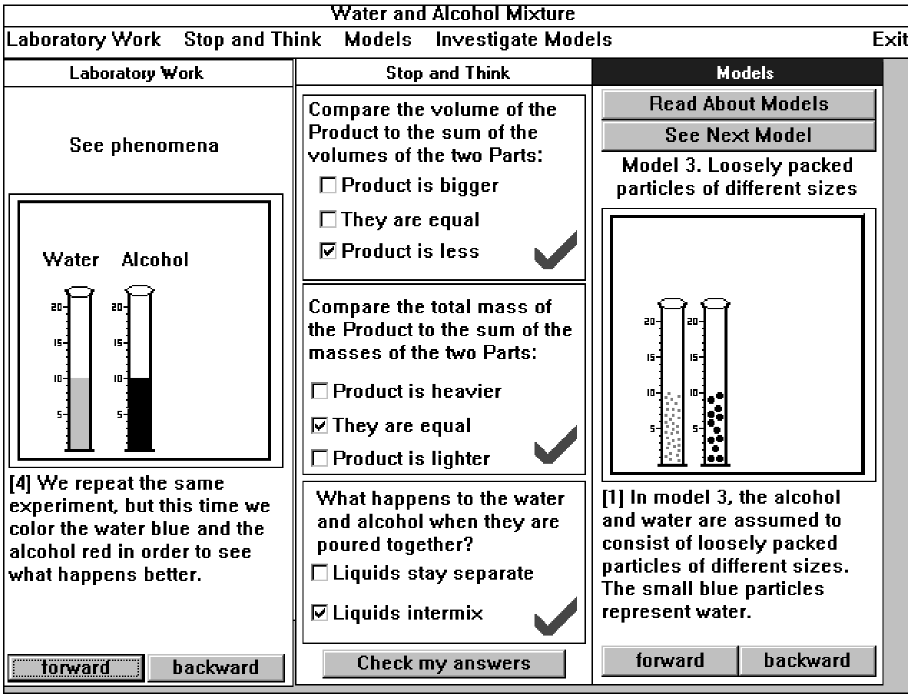
Figure 4a–c. *Continued.*

Not only would the two types of particle intermix, but also some of the smaller particles would fit in the spaces between the larger particles (Figures 5b and 5c). Thus, the particles in the mixture would be more tightly packed than they are for the pure substances, explaining why the volume of the mixture is somewhat less than the additive sum of the volume of the parts, although the number of particles does not change.

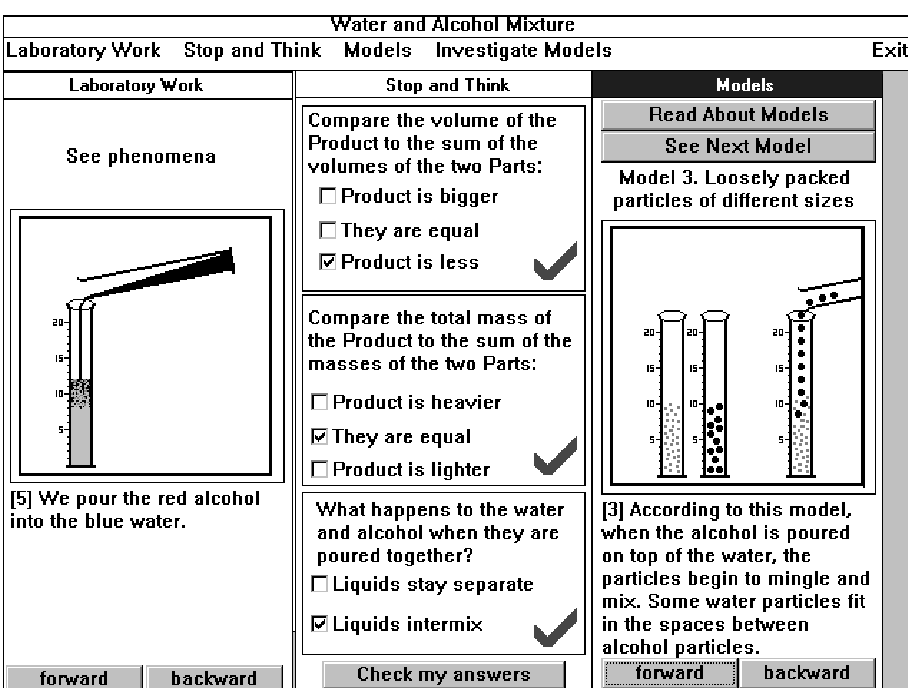
Several features of the Models option are important. First, students are presented with a variety of competing models that make different assumptions about the nature of matter. This feature highlights the fact that there can be competing explanations proposed for a given phenomenon. It also allows students to consider a broader range of explanatory options than they might initially generate themselves.

Second, each model makes assumptions about the underlying structure of matter that go beyond what is physically observable. The models attempt to represent these unseen entities and relationships and hence do not look exactly like the phenomenon itself. This feature helps to highlight that the purpose of a model is to explain a phenomenon at a deeper level rather than simply to capture its surface appearance.

Third, each model is designed to be internally consistent. By taking students through a series of steps, it forces them to consider the logical (and sometimes surprising) consequences of making certain assumptions about matter. For example, the first model for water and alcohol assumes that matter is continuous. It is explained to students that this means there are no gaps in the matter, an assumption students find initially quite commonsensical and appealing. However, as the experiment unfolds, it shows that if there were no gaps, there would be no way for the two liquids to intermingle and intermix; thus, the two liquids should stack. As students think about this, they tend to agree that the model is being consistent: if there were no gaps, this is indeed what would happen. Because they know that the two liquids do mix, they immediately see that there are problems with this assumption. Thus, the software helps students not only to think about different assumptions of what matter

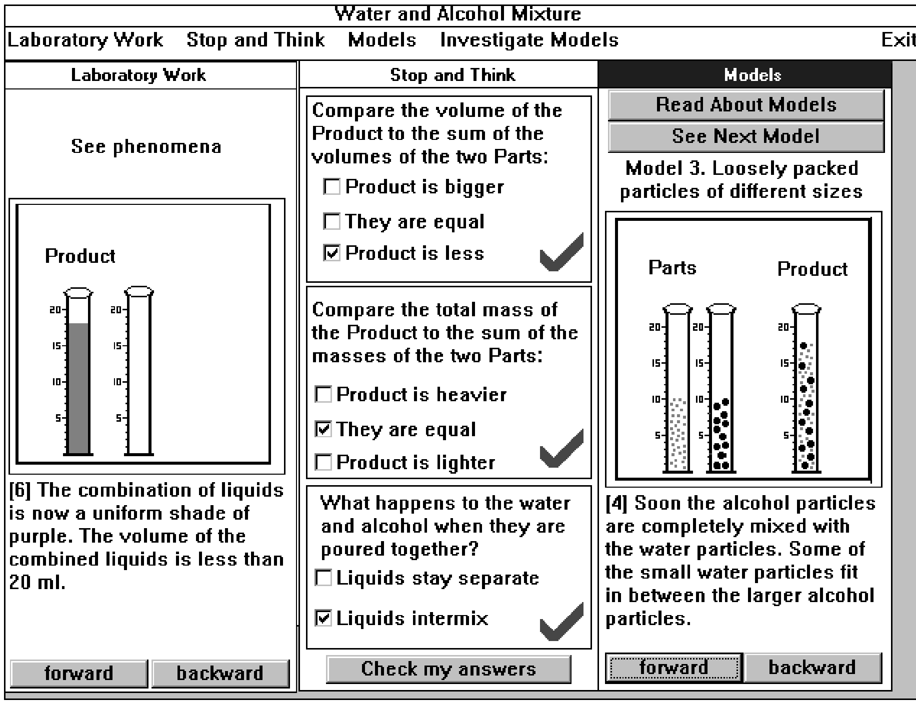


(a)



(b)

Figure 5a–c. Three screen dumps show the opened *Models* window for the phenomenon of Water and Alcohol in which *Model 3: Loosely packed particles of different sizes* has been selected for viewing. As students scroll through these screens, they see the two liquids being poured together, the loosely packed particles intermixing, and summing to a volume of less than 20 ml. (*Continued on next page*.)



(c)

Figure 5a–c. *Continued.*

might be like, but also helps them concretely imagine what those assumptions imply; that is, it forces them to take those assumptions seriously and to follow those assumptions to their logical conclusions. Without the scaffolded envisioning provided by the software, students might not have thought about what a given model implied, and thus may not have found any problems with it.

Fourth, we included models that make assumptions students might find initially appealing, but that upon further reflection would not be explanatorily adequate. This feature allows students to explicitly consider these "wrong" assumptions and reason their way out of them and is in keeping with important findings about conceptual change. That is, it is not harmful for students to consider "wrong" ideas, especially if they are engaged in a reasoning process about these ideas. Rather, taking initial ideas, making them explicit, comparing these ideas to others, and reasoning about their adequacy is the very best way to get students to abandon (or modify) them! (See the Appendix for a description of the four competing models we presented for each of the three phenomena. In generating these models, we not only thought about the particulate ideas that we wished to teach, but also thought about the common "misconceptions" that students might have that we wanted them to take time to reconsider.)

Finally, the models are presented in open-ended fashion. No one model is presented as "correct" or as the "scientists'" model, just as models don't come prelabeled as "correct" in science. Rather each is an explanatory possibility and it is the students' task to think about which model they think does the best job explaining the observed facts. Further, although the text about each model identifies its core assumptions and begins to describe what each implies would happen macroscopically, it does not spell out all features of the mapping between the model and the phenomenon in words. Some features are initially left for students to infer from the visual depictions of each model. For example, the text for Water and Alcohol only explicitly says what each model implies about whether or not the two liquids would mix. The implication of each model for what happens to the volume is only visually depicted, not verbally stated. Finally, the implication of each model for what happens to mass is only implicitly represented: based on whether the total number of particles is the same or different. The final option of the software, opening the *Investigate Models* window, is included to scaffold their exploration of the explanatory adequacy of each model, in part by giving them more direct clues about what each model implies about mass changes by placing the modeled objects on a balance scale.

Investigate Models: Allowing Students to Investigate the Models They Choose. Activating this option opens a full screen window (see Figure 6). Students can choose which model they want to investigate. Once a model is selected, the conceptual representation of the model is represented on the left-hand side of the screen. On the right-hand side of the same screen, there are two additional frames: the upper entitled “Lab Observations” and the lower “Model Implications.” The “Lab Observations” frame shows the actual experimental results. The “Model Implications” frame shows the results that are implied from the currently selected model. Conflicts between the laboratory observations and the model implications mean that the model does not explain all of the results.

For example, let’s assume that the student is choosing to investigate the tightly packed particles with “evaporation” explanation for the water and alcohol experiment, as depicted in Figure 6. This model assumes that water and alcohol each consist of discrete, but tightly packed particles. It also assumes that after they are combined, some of the alcohol evaporates in order to explain the slight loss of volume.

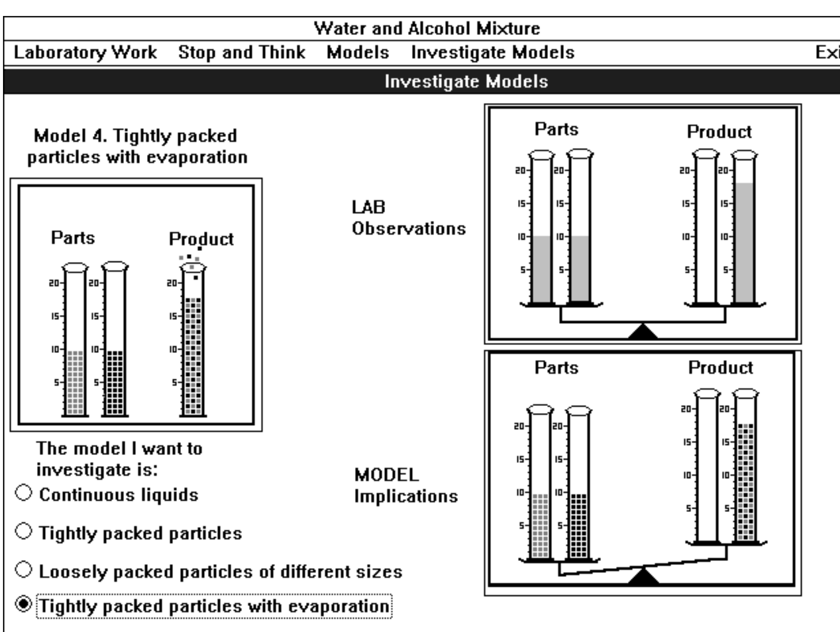


Figure 6. This screen dump shows the opened *Investigate Models* window for Water and Alcohol. *Model 4: Tightly packed particles with evaporation* has been selected for investigation. Students can compare the Lab observations with the Model implications.

In the upper-right-hand side one can see the actual "Lab Observations." Immediately beneath one sees the "Model Implications." The discrepancy between the two is very salient. One can see that in the real experiment the mass is conserved but the model predicts a loss of mass. So although the model is able to account for the change in volume and the intermixing of two liquids, it is not satisfactory because it does not account for all the facts.

We included this "Investigate Models" window for two reasons. First, it serves to highlight two important meta-points about models, namely (a) that the model predictions and lab observations are distinct, and (b) that a good model should be consistent with lab observations. Second, it provides an even more scaffolded environment for model evaluation, by helping students to think through the full consequences of each model. For example, in earlier screens some students may think that the tightly packed particles with "evaporation" model is a good one because it explains why the volume of liquid is less. At that point, they may fail to spontaneously consider that if some molecules escape then the mass would be less, contradicting the known conservation of mass. By explicitly showing the change in mass before and after the evaporation in the "Model Implications" frame, this screen encourages students to think more deeply about what this model implies and use this deeper understanding of the model to inform their model evaluation.

Some General Considerations in the Software Design, or When and Why Use Computers

When introducing computer software in the science curriculum, one should make sure that there is a specific reason for doing so and that the software has an added value to the learning process. In this section we will elaborate on the general rationale informing our software design. One can distinguish between two main modes for using computers in education, which are in some ways opposite modes: the tutorial-drill mode and the tool-for-investigation mode (Taylor, 1980). In the first mode, the computer controls the contents presented to the student and is used mainly for training and introducing students to factual information. In the second mode the student is in control and the computer is used as a tool to investigate the world or environment created on the screen. When using this mode, computers have a specific power that no other media have: the ability to present synchronized, multiple representations of the same event on one screen. This feature is central in science education where one would like to help students connect between the surface features of phenomena and the underlying models and conceptual network that can be used for thinking about them (Larkin, 1983; Snir, Smith, & Grosslight, 1993; White & Frederikersen, 1998). In our case, we want students to connect macroscopic observations about the observed mass and volume of solids and liquids under changing conditions and the microscopic particulate model that helps explain them, as well as distinguish between an observation-level and model-level of representation and description. This consideration was our main reason for introducing the software.

In designing the software, we made use of both modes mentioned earlier. We used the tutorial mode to make sure that the students were aware of the main experimental facts that needed to be explained by a given model and to present the basic assumptions of each model about what was happening on a microscopic scale. We then used the tool mode to allow students to search for the best model and to develop the criteria needed for such a choice. Apart from using the technology as an organizing device that has all the information needed to conduct the investigation, the software creates an environment in which the student can interactively investigate a problem while being able to recall the information stored to make decisions concerning the problem they are investigating. Only some aspects of the mapping between macroscopic and microscopic levels are presented explicitly in the written descriptions of each model. The student has to infer other aspects from the screens presented as the student interacts with the computer. Even in the Investigate Models part of the software, the student must decide which models to investigate and must interpret the screens that are presented as a result of his/her actions. This ability to connect student actions to a screen reflection is unique to the technology and was an important reason for integrating it in the teaching unit that also included real-life experiments and other noninteractive presentations such as video and worksheets. Actually, in practice we observed that the students used the software with much enthusiasm and found the search model part quite challenging as it is. The activity with the software was followed by lively class discussion in which students discussed the different models and presented their reasons for choosing one model rather than another.

Summary of Key Design Features of the Software

In summary, we believe there are several important design features of our software:

1. It is designed to help students filter central facts from many experimental details.
2. It combines both tutorial and tool elements, while adjusting the mode to the nature of the learning. If one conceives of learning science on three levels—factual, conceptual, and metaconceptual (Snir, Smith, & Grosslight, 1993)—then we used the tutorial mode for the factual level and the tool mode for the conceptual and metaconceptual levels.
3. It allows students to compare, on the same screen, surface and model levels of description.
4. It acknowledges the existence of alternative models and students' initial ideas.
5. It facilitates the introduction of model evaluation based on consistency with a range of facts, rather than simply one observation, as a central part of the curriculum.

PART 4: SMALL SCALE RESEARCH ON THE EFFECTIVENESS OF THE SOFTWARE

We have undertaken two studies of the effectiveness of this software. In one, we worked individually with fifth- and sixth-grade students and gathered in-depth data on all aspects of their thinking about these phenomena before, during, and after work with the software. In the other, the software was presented in a classroom teaching context to two classes of seventh-grade students. Data about student thinking was gathered via group tests (immediately before and 1 year after the teaching) and via individual interviews (immediately after the teaching). Both studies addressed a number of important questions: (a) Would students find these phenomena puzzling and hard to explain prior to their encounters with the software? (b) Would the software scaffold student understanding of the task of evaluating competing models based on how well they accounted for all the facts, and would students find explanations in terms of particulate models both satisfying and compelling? (c) Would work with the software lead to general changes in students' understanding of the nature and purpose of scientific models? (d) Would work with the software lead to specific changes in student understanding that matter is fundamentally particulate (rather than continuous) in structure?

In this part, we briefly summarize the main findings. These findings support the conclusion that for students who have strong macroscopic conceptions of matter, working with the software not only promotes their internalization of the assumption that matter is fundamentally particulate, but also leads them to develop a deeper understanding of the explanatory nature of scientific models.

Study 1: Use of the Software in Individual Sessions with Fifth- and Sixth-Grade Students

Our first study involved a series of individual interviews with 9 fifth- and sixth-grade students from an urban U.S. public school with a strong science education program. The students were selected from a larger group of students in the same grades who had volunteered to stay after school for some science interviews about their conceptions of volume, weight,[2] density, and matter. They were selected to represent a range of background understandings about the nature of matter, although we focused on selecting students who were at least beginning to develop the relevant macroscopic theory. Thus, we were not interested in testing whether all fifth and sixth graders could understand our software, but rather whether those who were beginning to have the relevant macroscopic conceptions could. Four had strong macroscopic understandings of matter in that they thought weight and volume were fundamental properties of matter, had relevant procedures for quantifying the weight and volume of objects, and qualitatively differentiated weight and density, conceptualizing density as an intensive characteristic of specific materials. Four had intermediate understandings in that they understood that weight and volume were fundamental properties of matter and had some procedures for quantifying the weight and volume of objects. They did not, however, differentiate weight and density. Only one had a weak macroscopic understanding of matter in that she did not conceive of weight and volume as fundamental properties of matter, did not quantify these properties, and did not differentiate weight from density.

In our initial interviews, we found that all three phenomena were discrepant events for students in that they overwhelmingly made incorrect predictions about what would happen. In particular, all nine predicted that mixing 25 ml of water and 25 ml of alcohol would result in 50 ml of fluid and were surprised when the mixture had a volume of only 48 ml. The majority also thought that a heated metal ball would still pass through a metal ring and were surprised to find that it would no longer pass through the ring. Finally, after seeing a certain amount of copper and sulfur completely combine to form copper sulfide, all nine predicted that a different, starting amount of copper and sulfur would also completely combine to form copper sulfide, rather than having some pure copper or sulfur left over.

We also found that students could readily remember the two or three basic facts about what had happened in each phenomenon. They were, however, hard pressed to come up with satisfying explanations for any of the phenomena, and no one came up with clearly formulated explanations for these phenomena at an atomic or molecular level. Instead, their explanations tended to be on the macroscopic level (e.g., the liquids compressed; the metal ball swelled and got air in it) or quite vague (e.g., there was some kind of chemical reaction).

Overall, we found that students were most deeply puzzled by the mixing of water and alcohol and generally did not find their own attempted explanations satisfactory. Many were genuinely puzzled by thermal expansion as well. Students were least puzzled by the fact that sometimes there was a residue in the copper and sulfur experiment and at other times not. Some even came up with macroscopic analogies that they found fairly satisfying. For example, one student said, "it's like painting your house: you have to have the right amount of paint to cover the whole house. If you have too much paint, some paint will be left over. If you have too little paint, some of the house will be unpainted."

Students looked forward to the software sessions, which we billed as an opportunity to consider other students' ideas about how to explain these phenomena. Students had been

[2] We asked students about the "weight" rather than "mass" of objects because this word is more meaningful to them from everyday experience. In general, students do not differentiate weight and mass, and their intuitive concept of weight is closer to the scientists' concept of mass (in that they consider it a property of matter) than to the scientists' concept of weight.

frustrated with their own lack of ideas and were eager to hear about other ideas. Immediately prior to working with the software, students were asked some general questions about their conceptions of models: What is a scientific model? Why do scientists make models? What makes something a good model? Their answers to these questions showed they generally had a very limited conception of models, similar to those reported by Grosslight et al. (1991) for students this age; that is, they described models concretely as an example or little replica of something, whose purpose is to show or illustrate something, or to be a little copy.

Students then began working with the software, beginning with the phenomenon of mixing water and alcohol. After viewing a cartoon of the actual experiment in the *Laboratory Work* window and reviewing the basic facts of what happened in the *Stop and Think* window, students moved to the *Models* window that contained four competing models of the phenomenon. In this window, students first read some introductory text about the purpose of models and were asked to discuss whether the ideas in the text made sense to them or not. These statements included: (a) that the purpose of scientific models was to explain a set of facts, rather than to show how something looks; (b) that models can make assumptions about what matter is like at a level that you cannot see, in order to explain facts that you can directly observe; and (c) that a good model accounts for *all* the relevant facts about a situation. These ideas were quite different from those the students had spontaneously expressed and students frequently raised some questions about them. We clarified the meaning of difficult words and discussed with them how the surface appearance of things might be different from the underlying reality (e.g., photos in newspapers look continuous to our eye, although they are really made up of very small dots when viewed with a magnifying glass). After these discussions, students generally acknowledged that these ideas made sense. They then launched into considering the competing models presented in the software.

At this point, students were asked to think aloud as they considered the assumptions made by each model. They were asked whether they understood what each model was claiming and whether they thought it provided a good explanation for the phenomenon in question. At issue was what models would make sense to students and how they would approach the model evaluation task. Would they focus on how well the models accounted for the underlying facts, such as the fact that the volume changed, but the mass was conserved? Or, would they consider the models inadequate because they did not match the surface appearance? In fact, all the models made some assumptions about matter that went beyond surface appearances. They varied, however, in specific assumptions that were made about the nature of matter (e.g., matter is continuous vs. particulate; matter particles are tightly packed vs. widely spaced) and how well they were able to account for all the facts. For both mixing water and alcohol and combining copper and sulfur in different proportions, only one of the four models was able to account for the entire set of facts about that phenomenon. This was the model that assumed matter consists of discrete, widely spaced particles. For the phenomenon of thermal expansion, two models—*Continuous matter stretches* and *Discrete particles move apart*—were consistent with the basic facts. (The Appendix provides a detailed description of each of the models and what facts were accounted for by each.)

Students' reaction to the models generally evolved as they worked through the software for each phenomenon and they were given multiple opportunities to revise their views. Some models whose assumptions they initially liked lost favor as they considered their deeper implications, while other models that they had initially questioned gained in status as they considered how well they accounted for what happened. In general, students were comfortable with revising their evaluation of models as they considered alternatives and deepened their understanding of what each implied.

We were pleasantly surprised to learn that, in the scaffolded environment provided by the software, students were able to evaluate models based on their consistency with a set of known facts. All took great pleasure in catching the "mistakes" made by a number of the models when they failed to account for some critical fact. Further, the majority of the students (seven of nine) ultimately selected models as acceptable and best *only* if they were consistent with *all* the key facts about a given phenomenon (see Table 1). That students evaluated the acceptability of models based on consistency with facts for all three problems and were not bothered by surface appearance differences argues that they really understood that the purpose of a model is to explain a set of facts rather than to show what something looks like. The remaining two students were less consistent in evaluating models based solely on their fit with the selected set of facts throughout the session, being at times more lax and at other times more stringent in their evaluations. In their more lax evaluations, they judged models as acceptable if they accounted for at least some of the basic facts. This led them to consider a greater number of models as "acceptable." In their more stringent evaluations, they wanted the model to look like the phenomenon. This led them to reject all the models for their failures to match the surface appearance of the phenomenon. But even these students were interested in and engaged with the task of model evaluation.

Postinterviews, given a few days to a week after they worked with the software, revealed that students had made progress both in their general understanding of models and in their specific understanding of the particulate nature of matter (see Table 1). All students now gave particulate explanations for the water and alcohol problem. Recall that this was the problem for which students found their initial macroscopic explanations most unsatisfying and the microscopic explanations suggested in the software most satisfying. Further six of the nine students now acknowledged the discontinuity rather than continuity of matter (at a microscopic level), in response to a direct probe on this issue. All were students who had focused on evaluating the models based on their consistency with an entire set of facts. Finally, six of the seven students who were given the posttest questions about the nature of models[3] now explicitly stated that the purpose of models was to explain a set of facts rather than to show or illustrate a phenomenon. Taken together, these results show the promise of the software in scaffolding student understanding both of the nature of explanatory model construction and of the particulate nature of matter.

Given that students' initial conceptions of models were so limited, why were they able to respond so positively to the think-aloud software session? First, we would argue that although students did not initially connect model building with explanation, most did, in fact have a rich sense of explanation that was embedded in their commonsense matter theories. For example, all but one believed that weight is an extensive property of matter and were thus committed to explaining the weight of an object in terms of the weight of its smaller, component parts. Those who differentiated weight and density had an even finer-tuned theory that allowed them to explain the weight of an object in terms of its volume and the density of material of which it is composed. Second, by engaging students in evaluating how well explicit models explained new phenomena in this domain, they were able to connect their pursuit of explanation to the process of modeling. Indeed, all the models we presented encouraged them to think about what might be happening at a level they could not see in order to explain what they could see (i.e., to model an underlying mechanism rather than a surface appearance).

Although the numbers of students involved are small, our data also suggested that students' macroscopic understandings of matter affected their readiness to engage in explana-

[3] Unfortunately, the first two students in our study were not asked these general posttest questions about models. One had been among the most sophisticated students in our sample; the other one of the least sophisticated.

TABLE 1
Reactions to the Software and Posttest Responses for the Three Groups of Students (Study 1)

	Software Model Selected as Best[a]				Type of Posttest Models[b]			General Posttest Comments	
Macroscopic Understanding	Water and Alcohol	Thermal Expansion	Copper and Sulfur	Only if Fits All Facts	Water and Alcohol	Thermal Expansion	Copper and Sulphur	Matter is Particulate	Models are Explanatory
Strong ($N = 4$)									
S1	3	2	3	√	P	P	Qn	√	(Not asked)
S2	3	2	3	√	P	P	P	√	√
S3	3	1, 2	3	√	P	P	P	√	√
S4	3	2	3	√	P	P	P	√	√
Intermediate ($N = 4$)									
S5	3	2	3	√	P	P/Macro	P	√	√
S6	3	1, 2	3	√	P	P	Macro	√	√
S7	None	1, 2	2, 3	–	P	C	Macro	–	(Not asked)
S8	3	1	3	√	P	C	P/C	Some	√
Weak ($N = 1$)									
S9	None; then 3 best, 2, 4 good	1	3?	–	P	C(p)	Macro	–	–

[a]See Appendix for description of models. Models that were consistent with all key facts for a given phenomenon were Model 3: Loosely Packed Particles of Different Sizes (Water and Alcohol), Model 1: Continuous Matter Stretches and Model 2: Matter Particles Spread Apart (Thermal Expansion), and Model 3: The Bonding of Particles (Copper and Sulfur).

[b]Student posttest models were categorized as P (Particulate), C (Continuous), Macro (Macroscopic), P/C (Particulate for one substance, continuous for other), P/Macro (Particle swelling rather than spreading model for thermal expansion), C(p) Continuous substance with particles inside, Qn (quantitative representation of fixed relation between Cu and S, but not at a particulate level).

tory model construction about the particulate nature of matter, a finding in keeping with the above interpretation. Among the four students with strong macroscopic understandings of matter, each evaluated the models in the software based on their consistency with all the facts, selected particulate models as the "best" models, and expressed the belief at the end that matter consists of discrete particles. In contrast, among the students with intermediate macroscopic understandings of matter, only half responded in this consistent fashion. Finally, the one student with weak macroscopic understandings of matter did the least well in understanding both the particulate theory and the idea of an explanatory model.

Study 2: Use of the Software in a Classroom Teaching Study with Seventh-Grade Students

In our second study, we used this software in a short classroom teaching unit for two classes of seventh-grade students who attended a regional school in rural Israel.[4] In this study we were examining the software's effectiveness with a broad (unselected) group of students. We felt it was of interest to test this age group because this is the age when Israeli students are typically introduced to key aspects of the macroscopic theory of matter as well as key elements of the particulate theory of matter. Thus, it was of interest to assess whether students of this age were generally ready to engage with the challenge of constructing and evaluating competing microscopic models of matter, and whether our curricular approach was more effective than the standard text-based approach used in the Israeli curriculum.

The experimental unit involving our new software was designed to start them thinking about what matter might be like at a microscopic level. It came immediately after a much longer unit (14 double-class periods) designed to enhance students' macroscopic understandings that all matter had volume and weight and that material kinds varied in density. The prior unit also began to develop their measurement skills and their metaconceptual understanding of the nature of models and the process of measurement.[5] Joseph Snir and Gila Raz taught both units.

At the start of the microscopic unit, written group tests revealed that 42% of the students had fairly strong macroscopic understandings of matter. They judged solids, liquids, and gases to be matter. They also believed that even small, light pieces of matter (such as sawdust or air) take up space and have weight. Finally they gave evidence of differentiating and beginning to quantify the three properties of weight, volume, and density. Another 42% of the students had intermediate macroscopic understandings of matter. These students also judged solids, liquids, and gases to be matter and believed that small, light pieces of matter take up space and have weight. However, they were more limited in their differentiation and quantification of the properties of weight, volume, and density. Some had differentiated and quantified their concepts of weight and volume, but had not yet formulated a fully differentiated (or quantified) concept of density. Others had qualitatively differentiated the properties of weight, volume, and density, but had correctly quantified only one of these properties (either volume or weight). The remaining students had even weaker macroscopic understandings and could not correctly quantify any property of matter.

[4] Twenty-eight students participated in these innovative lessons. Here we report on the data of 19 of these 28 students for whom we have both immediate and delayed posttest data.

[5] The macroscopic unit included another software tool, *Archimedes and Beyond*, which was developed by us earlier. A more complete description of this tool and some teaching units that were based on it can be found elsewhere (Snir & Smith, 1995; Smith et al., 1997). Basically this tool allows students to manipulate a computer representation of volume, weight, and density in order to see how these quantities are interrelated. The software allows students to build and model objects, measure their volume and weight, change their material kind, and do sinking and floating experiments with the objects they build.

The first half of the microscopic unit involved a written group pretest that elicited student thinking about six different phenomena: the three core phenomena that students would subsequently explore using the software and three additional phenomena that were not going to be discussed in the teaching unit. This pretest took three double-class periods, with students observing and explaining one phenomenon per single 50-min period. For the three core phenomena (Water and Alcohol, Thermal Expansion, and the formation of Copper Sulfide), students were shown a video of the three core phenomena being demonstrated in a lab. The video was stopped at numerous points for students to make predictions about what would happen next. For both Water and Alcohol and Thermal Expansion, students also saw a first-hand demonstration of the phenomenon. At the end of each presentation, students were asked to write their explanations for what happened and to draw a model showing their main idea. The three additional phenomena included to assess transfer were the following: (a) why, when rock salt dissolves in water, the volume of the mixture goes down but the mass remains the same (a phenomenon similar to the mixing of water and alcohol); (b) why a balloon filled with air expands when it is placed in hot water (a phenomenon similar to the expansion of a metal ball but involving a gas); and (c) why air can be added to a container already full of air (another phenomenon involving matter in the gaseous state). After each of these transfer phenomena were demonstrated or described, students were asked to state what happened and to explain why it happened.

Students were somewhat frustrated in these opening class sessions as they were used to being given "answers," not being asked to think for themselves. Further, they could not think of satisfying explanations for these phenomena. Students generally gave macroscopic re-descriptions of the phenomena (i.e., restated the core facts) and drew pictorial models of what the phenomena looked like on a macroscopic level, rather than attempting any deeper explanation of them. A few said that perhaps the density changed in the mixing of water and alcohol or thermal expansion, because the volume had changed while the weight remained the same. None, however, offered any explanations at a microscopic level in terms of the spatial rearrangement of discrete particles of matter. This suggests that these students did not yet conceive of matter as fundamentally particulate. At the very least, they did not use this fundamental assumption to explain an observed pattern of results.

During the second half of the microscopic unit (again, three double-class periods), students worked with the software. They were eager to work with the software, as they were told the software would help give them ideas about how to resolve the puzzles. Each double-class period was devoted to one phenomenon. The first half of the double period, students worked with the software, completing structured worksheets about the phenomenon and the models presented. During the second half of the double period, they discussed their ideas and performed additional demonstrations.

More specifically, students began by considering the mixing of water and alcohol. A structured worksheet directed them to review the phenomenon in the *Laboratory Work* window and to answer the critical questions about it in the *Stop and Think* window. Next they were directed to open the *Models* window, read about the general purpose of models, and then answer a general question about the purpose of models. After that, they examined each of the four models for water and alcohol and answered questions about how each model represented water, alcohol, and the water–alcohol mixture. Finally, they opened the *Investigate Models* window and answered questions about which facts each model could account for. They were also asked to reflect on whether any model could account for all the facts and to make an explicit judgment about what they thought was the best model.

This first class went extremely well, as assessed by the classroom teachers Snir and Raz. Students found the software easy to use and really liked being put in the position of judging the models themselves. Overall, the particulate explanation of this phenomenon emerged as the most satisfying and compelling model, based entirely on student discussion of which model best accounted for all the facts. To reinforce student understanding of the nature of this explanation, we then performed a follow-up demonstration of the mixing of nuts and sugar. In this demonstration, students saw how mixing a half cup of nuts and a half cup of sugar resulted in a mixture with a volume less than one full cup. Again, students found this demonstration very helpful and convincing.

In the second class, students turned to consideration of the four models for thermal expansion. Much to their surprise, they found that two models could account for all the facts. This puzzled them, as they had not encountered such situations in their previous teaching. We used this puzzlement to reiterate that a good model should account for all the facts—which means looking at a pattern of results across a series of experiments. They were encouraged to withhold final judgment until they had considered the last experiment.

In the final class, students considered the phenomenon of combining copper and sulfur in different proportions. The copper and sulfur experiment was quite complex, having three different experimental conditions. This was students' first encounter with the concept of a compound, and we gave them a brief introduction by saying that when two materials get combined they lose their specific properties and become a new substance. The most puzzling and intriguing aspect of this phenomenon to students seemed to be the process of compound formation itself and not the fact that sometimes there was no residue and at other times there was. However, students came to more deeply understand the particulate explanation both by working with the computer software and by engaging in a demonstration of couple formation in class. In this demonstration the starting number of girls and boys affected whether they were all paired off or whether there were some boys or girls remaining. At the conclusion of the class, students could see how a particulate model of matter could account for all three phenomena. At this point, we noted that these three experiments are from different areas of science. Because the model explains these phenomena and many others very well, scientists believe that matter is made up of discrete particles.

Following the teaching, students were given individual post-interviews in which they were reminded of the basic facts that occurred for the three core and three transfer phenomena and were asked, in open-ended fashion, to draw a model that provided an explanation for the phenomena.

For each of the three core phenomena explicitly discussed in class, about 60% of the students spontaneously provided clear and appropriate explanations at a particulate level. These explanations were as follows: (a) smaller particles fitting in the spaces between larger particles (for Water and Alcohol), (b) same size particles moving farther apart (for Thermal Expansion), and (c) particles of copper being paired with particles of sulfur, with either no unpaired or some unpaired particles remaining depending upon the starting number of particles of each type (for Copper and Sulfur). About 40% of the students provided appropriate particulate drawings and explanations for all three phenomena; about 75% for two of the three phenomena; and almost 90% of the students for at least one phenomenon. When students did not draw an appropriate particulate model, they provided simple macroscopic explanations, gave no explanation at all, or generated an alternative particulate explanation that showed failure to internalize key aspects of the model. Examples of such alternative particulate explanations were showing alcohol getting inside particles of water (for Water and Alcohol) or showing individual particles of metal swelling up and becoming larger, rather than further apart (for Thermal Expansion).

We also assessed whether students could use the assumptions of the particulate model of matter generatively to explain the three transfer phenomena that had not been specifically discussed in class. Again, the majority of students were able to generate an appropriate particulate explanation for at least one of the three transfer phenomena; 30% were able to generate appropriate particulate explanations for all three of the transfer phenomena. The two transfer problems about the compression and expansion of air were the easiest for students to explain in particulate terms, even though they had never discussed the particle model in class vis-à-vis gases. In these cases, students noted the particles were more tightly packed when adding air to a fixed size container and less tightly packed when the balloon expanded in hot water. The rock salt and water phenomenon was harder for students to explain in particulate terms. For example, some students only represented the salt as particulate and the water as continuous and showed salt particles breaking apart and dispersing through the (continuous) fluid. Even here, however, over one-third of the students represented both salt and water as particulate and talked of one particle getting in between the spaces of the other type of (larger) particle. Many also explicitly noted the analogy with the phenomenon of mixing water and alcohol. The strong performance of students on these transfer tasks is one indication that they were internalizing the assumptions of the particulate model at a conceptual level and beginning to explore its explanatory potential.

Another indication that some students were able to deeply internalize the assumptions of the particulate model of matter came from data about their long-term retention of the lessons of this unit. Over 1 year after the completion of this unit—at the end of their eighth-grade year—we gave these same students and a control group of students a follow-up written test. This test assessed (a) their macroscopic conceptions of matter, weight, density, and volume; (b) their general beliefs that matter consists of discrete particles; (c) their ideas about what makes the particulate model a good model of matter; and (d) their ability to explain two phenomena in particulate terms. Both groups of students had covered the same curriculum units in the same amount of time in the seventh and eighth grades. The only difference was in the way the two groups had been taught the two units on the macroscopic and microscopic nature of matter, which comprises the first half of the seventh-grade Israeli science curriculum.

Joseph Snir and Gila Raz had taught the experimental group in a way that involved students in thinking about metaconceptual issues about model construction and evaluation, using two innovative kinds of software (*Archimedes and Beyond*, for the macroscopic unit, described in Snir & Smith, 1995; and *Models of Matter* software, discussed above, for the microscopic unit).

The control group received the traditional Israeli curriculum on these topics taught by their regular science teachers, although they were involved in all the same pretesting and posttesting as the experimental group. In the macroscopic unit, students learned about the three states of matter and were involved in a series of experiments demonstrating the properties of matter and conservation of mass. In the microscopic unit, students spent the first half (three double-class periods) writing their initial ideas about the same six phenomena that were presented to students in the experimental group. In the second half of the unit, students considered three of the six phenomena in greater detail: the dissolving of rock salt in water, the expansion of a balloon in hot water, and the formation of copper sulfide.[6] Their

[6] The Israeli curriculum does not use the mixing of water and alcohol and the thermal expansion of a metal ball—two core phenomena used in our software—in teaching the particulate model. Thus, for the control group these two phenomena were used as transfer items, and the related phenomena concerning the dissolving of rock salt and the thermal expansion of a gas were directly taught instead.

teacher didactically presented the three core assumptions of the particulate model—matter consists of particles, there is a vacuum between the particles, the particles are in constant motion—and then showed them how the model applies to the three phenomena. Students then completed detailed worksheets about the particulate explanation of these phenomena. Students were not, however, involved in the process of considering competing models for these phenomena or evaluating which model provides the best account of all the facts.

We found that there was much greater understanding of the core assumptions of the particulate model of matter and of the explanatory value of the model among the experimental group of students on our delayed posttest, although both groups had down well on the immediate microscopic posttest. In one portion of the delayed posttest, we assessed whether students understood seven assumptions of the model which had been clearly taught in both curricula: (1–4) that solids, liquids, gases, and powders are each composed of particles; (5) that even in solids, the particles of matter are discretely spaced; and (6–7) that the particles of matter both take up space and have weight. In the experimental group, we found that 30% of the students had a perfect understanding of these seven simple points, compared to none in the control group. If we allow students one error, we find that 47% of the experimental students understood at least six of the seven points compared to 22% of the control students.

In addition, within the experimental group, 30% of the students clearly used the assumption of spaces between particles in both their drawings and explanations of the loss of volume in the mixing Water and Alcohol, a phenomenon they had been taught, and the Dissolving of Rock Salt, a transfer phenomena. In contrast, none of the students in the control group did this in their explanations of the Dissolving of Rock Salt, the phenomenon for which they had been directly taught the particulate model.

Finally, 30% of the students in the experimental group wrote open-ended responses indicating that what makes the particulate model a good model is its ability to explain a wide range of phenomena (see Table 2 for examples of student responses). In contrast, none of the students in the control group answered in this way. Most said they didn't know what makes it a good model or left the question blank. The few who did write something seemed to confuse the claims of the model with what makes it good—showing a failure

TABLE 2
Contrasting Comments about What Makes the Particulate Theory a Good Model

Experimental Group: Comments that Focused on Explanation	Control Group: Sample Comments
E1: Because it can explain for us phenomena like how the volume decreases and the weight does not change and other strange phenomena.	C1: Since it turns things into solids and they can be used
E2: Since it can explain many phenomena	C2: It gives many examples
E3: Since it depicts matter in a more tangible way and it helps to explain all these problems that we saw in these pages	C3: Since this way you can change materials
E4: It helps us to solve and know answers that bother us for a long time and cannot be explained rationally without the particulate model.	C4: I think that it is not a good model

to understand the metaconceptual question about models that was being asked (see sample comments, also in Table 2).

Significantly, an individual pattern analysis revealed that students in the experimental group who remembered the core assumptions of the model were also the ones who understood its explanatory potential (see Table 3). For example, the students who showed in the initial questions that they had internalized at least six of the seven core assumptions of the particulate model (47% of the sample) were also the ones who were able to use the model in explaining one of the two phenomena. Further, the students who used the particulate model generatively to explain *both* Water and Alcohol and Dissolving of Rock Salt (30% of the sample) all spontaneously commented that what makes it a good model is its explanatory potential.

TABLE 3
The Relation Between Student's Macroscopic Understanding of Matter, Retention of Key Assumptions of the Particulate Model of Matter, Use of the Particulate Model in Explaining Phenomena, and Valuing the Model as an Explanatory Tool at the time of the Delayed Posttest 1 Year after Teaching (Study 2, Experimental Group)

Macroscopic Understanding	Retention of Key Ideas (At Least 6 Out of 7)	Use Idea of Spaces Between Particles to Explain Water–Alcohol Mixture	Use Idea of Space Between Particles to Explain Dissolving of Rock Salt	Particulate Model is Good Because of Explanatory Scope
Strong				
S1	√ (7)	√	√	√
S2	√ (7)	√	√	√
S3	√ (7)	√	√	√
S4	√ (7)	√	√	√
S5	√ (6)	√	√	√
S6	√ (6)	√	√[a]	√
S7	√ (7)	–	–	–
S8	–	–	–	–
S9	–	–	–	–
Intermediate				
S10	√ (7)	√	–	–
S11	–	√	–	–
S12	–	–	–	–
S13	–	–	–	–
S14	–	–	–	–
S15	–	–	–	–
Weak				
S16	√ (6)	–	–	–
S17	–	–	–	–
S18	–	–	–	–
S19	–	–	–	–

[a]This student represented salt and water as particles, but then explained the dissolving of rock salt as the salt going inside the water particle.

Finally, the data provided evidence that students' macroscopic and microscopic understandings of matter mutually support one another.[7] Students who by the time of the delayed posttest showed that they had a strong macroscopic understanding of matter were the ones most likely to have internalized the assumptions of the particulate model. Seventy-eight percent of students with strong macroscopic conceptions on the delayed posttest showed they had internalized the assumptions of the particulate model. Further, all of the students who used the model generatively and who made metacomments about its explanatory potential had strong macroscopic understandings of matter.

GENERAL CONCLUSIONS

We conclude, then, that our software and teaching approach not only helps middle school students internalize basic assumptions of the particulate model, but also helps them understand a more general point about models: that a good model should explain a wide range of facts, not simply illustrate a given phenomenon. For the most part during the teaching itself, students were able to understand that models can make assumptions at a level we cannot see in order to explain what we do, and they were able to engage with the task of evaluating competing models in terms of their ability to explain a pattern of results. Further, students who were asked to "think their way" through to the particulate model by comparing its ability to explain a set of facts against alternatives were more likely to have long-term internalization of its assumptions than those who had been instructed in those assumptions in a more traditional way.

What features of our intervention were particularly critical in promoting the growth of thinking about models and matter? We believe that it is the complex integration of multiple aspects that were important, rather than a single feature alone. Further, the kind of dialogue that students are asked to engage in throughout each activity is critically important. These aspects include first exposing students to phenomena slowly, where they are asked to make predictions along the way and are given the opportunity to become highly engaged with finding out what happens. This was the approach that we took in showing them the video, where we stopped it along the way and constantly asked them to make predictions, to consider the reasons for their predictions and then to reflect on whether the actual results of the demonstration were surprising. This phase awakened their curiosity and allowed them to be puzzled by something that they observed. Second, we asked them to generate explanations for these phenomena. This allowed them to activate their current ideas, as well as experience some dissatisfaction with them. Third, we engaged them in sustained dialogue in working with our software tool that introduced them to competing models of matter. This dialogue centered on considering and evaluating these models, by asking questions such as: What is that model assuming? Does it make sense? Is the model being consistent with itself in its predictions? Can it account for the basic data? Do you think one model does a better job explaining the basic facts than another does? Why?

[7] We describe the relationship between macroscopic and microscopic understandings as involving "mutual support" because we believe there can be two-way interactions. Macroscopic understandings can enable one to be ready to develop certain microscopic understandings. At the same time, microscopic understandings can enable one to consolidate certain macroscopic understandings. Evidence for two-way rather than one-way interactions comes from the fact that students' macroscopic understandings at the time of the immediate posttest were not as predictive of their understanding of the particulate model on the delayed posttest as their macroscopic understandings at the time of the delayed posttest. Thus, some "settling out" occurred: students who understood the particulate model sometimes consolidated their macroscopic understandings while those who did not sometimes got worse in their macroscopic understandings.

Finally we believe that several features of our software tool helped support student dialogue about these kinds of issues. Perhaps the most important feature is its capacity to have multiple representations that are synchronized by the software. One representation reflects facts and the second represents the models proposed to explain these facts. The software has separate windows for Lab Observations and Model Implications that can be simultaneously opened and compared. In this way, students can compare the predictions of each model with the actual lab observations to check how well the model was accounting for all the data.

Another advantage of the multiple synchronized representations, which is the interactive tool part of the software, is that it allows students to work with internally consistent models and helps them envision the logical consequences of each model, thus permiting each model to be tested in subtler ways. For example, an idea that may be initially appealing—such as that water and alcohol are each continuous—may have logical consequences that don't fit the data—such as that the two liquids intermix and that the volumes do not sum. If left to their own devices students may not have envisioned the consequences of assuming that the liquids are continuous and thus may not have become dissatisfied with this model of matter. Yet when working in the scaffolded environment of our software, students were able to test models in these subtler ways. Further, we found they were able to distinguish whether a model was being "internally consistent" from whether it "was consistent" with a pattern of data. Thus, the software allowed us to discuss these important metaconceptual points about models with students as well.

In addition, the software included multiple models for each phenomenon, to acknowledge that one could try to explain a phenomenon by making very different assumptions. These alternative models presented students with a variety of visually and verbally presented "new ideas" with which to try to understand the domain—thus extending the representational resources that students bring to the explanatory task. Further by deliberating building into the software "partial models"—models that not only vary in their assumptions but how many facts are accounted for—we called student attention to this important issue and allowed them to see not only how models have testable consequences but also how some may explain more facts than others.

Of course, at present, the software is limited to engaging students with a few of the most basic assumptions of the particulate model: that matter is particulate rather than continuous and that those particles take up space and have weight. Yet it fills an important void in existing curricular materials as students are rarely asked to engage with these most fundamental assumptions in other curricular materials. Other central aspects of the model—such as that those particles are in constant motion, that they have internal structure, and that they are held together by different kinds of forces—would need to be addressed with the selection of additional phenomena. We suspect that students would be more ready to engage with adding these additional features to their model if they deeply believed that matter was particulate in the first place. Further, students would have the opportunity to learn about how models can be elaborated and revised to account for more phenomena through the progressive construction of more complex models.

In closing, let us mention one final caveat. Although we believe that middle school students are ready to deal with important epistemological issues about models when being introduced to the particulate model of matter, we do not believe it is profitable to engage them with these issues until they have developed a sound macroscopic understanding of matter. Both Driver and colleagues (Children's Learning in Science Project, 1987) and Berkheimer, Anderson, and Spees (1990) share this assumption with us, although they have focused more on developing students' macroscopic understandings of changes in state rather than their macroscopic understandings of the physical quantities of weight, volume, and density. In our view, it is essential that students think of weight as an additive physical quantity that is distinct from volume and density, that matter is something that continues to exist as it is repeatedly divided into smaller pieces, and that those tiny pieces take up space and have weight if they are to understand the particulate theory as an explanatory model.

In our current research, we found that students who had strong macroscopic understandings of matter were more likely to consider the particulate model a good model (Study 1 and 2) and to have long-term internalization and retention of its key assumptions (Study 2). At the same time, we found that less than half the students had achieved strong macroscopic understandings of matter, which included a basic understanding of measurement procedures, even after a curriculum unit devised to teach these understandings. Taken together, these findings suggest that for many students a large part of the problem in accepting or understanding the particulate theory may come from more basic problems in conceptualization of matter at a macroscopic level. At present there are a number of innovative proposals about how to approach teaching about measurement and matter from a modelling perspective (Lehrer et al., 2001; Ragavan & Glaser, 1995; Smith et al., 1997). Future research should compare the effectiveness of these different approaches not only in developing students' macroscopic understandings of matter but also in preparing them to understand the particulate theory of matter as an explanatory model.

APPENDIX: ALTERNATIVE MODELS AND EXPLANATIONS USED IN THE SOFTWARE

Mixing Water and Alcohol

Model 1: Continuous Liquids. Each liquid is portrayed as a continuous material with no gaps. In working with this model, students see the implications of this assumption: the two separate liquids cohere as a unit and the volume of the combined water/alcohol mixtures equals the sum of the volume of the two parts. Thus, this model fails to account for two of the three observed facts about water–alcohol mixture: that the two liquids do intermix and that the volumes do not simply add.

Model 2: Tightly Packed Particles. Each liquid is portrayed as a grid of tightly packed particles, with essentially no spaces between the particles. When the liquids combine, the particles can push by each other and intermix. However, they remain in the same tight packing and the volumes sum. Thus, this model fails to explain the nonadditivity of volume (but can explain the mixture of liquids and the additivity of mass).

Model 3: Loosely Packed Particles of Different Sizes. Each liquid is composed of loosely packed particles of different size. When the two different liquids combine, the particles intermix with some of the smaller water particles fitting in between the larger alcohol particles. This model thus provides an explanation of all three basic facts about this phenomenon.

Model 4: Tightly Packed Particles with Evaporation. This model makes the same assumption about the structure of matter as Model 2 does. It also assumes that some water and alcohol evaporate in the pouring process, to explain the loss of volume. However, this new assumption implies that the masses do not add, which contradicts another one of the basic facts about this phenomenon.

Thermal Expansion of a Metal Ball

Model 1: Continuous Matter Stretches. Matter is portrayed as a continuous substance, which stretches and "thins" as the ball is heated. This model can explain all the basic facts of the phenomenon, but cannot explain the facts about water–alcohol mixture as well.

Model 2: Matter Particles Spread Apart. Matter is portrayed as discrete particles held together by forces and separated by empty space. These particles spread apart as the ball is heated. This model can explain all the basic facts of this phenomenon and the facts of water–alcohol mixture.

Model 3: Matter Particles Are Added to the Ball. This model makes the same assumptions about matter as Model 2 does. However, it explains the change in volume in terms of adding more particles, which is inconsistent with the fact that the mass of the ball is unchanged.

Model 4: Air Is Added to Continuous Matter. This model makes the same assumptions about matter as Model 2 does. However, it explains the increase in the ball's volume in terms of the addition of air pockets with heating, which is inconsistent with the fact that the mass of the ball is unchanged.

Combining Copper and Sulfur in Different Proportions

Model 1: Mixing of Substances. This model portrays the copper and sulfur as tightly packed particles that intermix freely in any proportions. It thus fails to account for two of the basic facts of the phenomenon: that a new substance is formed and that sometimes there is a copper residue, sometimes a sulfur residue, and sometimes no residue.

Model 2: Burning of Substances. This model again portrays the copper and sulfur as tightly packed particles, which turn black when exposed to heat (a kind of charring or burning). This model can explain the appearance of the black substance, but cannot explain why sometimes there is a residue of copper or sulfur. Presumably, if one continues heating the substances, they will both become completely charred.

Model 3: The Bonding of Particles. This model portrays the copper and sulfur as differently shaped particles, which can bond and form a new substance (consisting of one particle of copper and one of sulfur). This model explains all three basic facts (the formation of a new substance, the conservation of mass, and the facts about residues—there will be a residue only when there are unequal number of particles of both substances). This model can also explain the mixing of water and alcohol and thermal expansion experiments.

Model 4: Burning of Substances and the Creation of Smoke. This model makes the same assumption as Model 2 does, except that it assumes some material is lost as "smoke" in the burning process. This assumption is inconsistent with the fact that mass is conserved across the reaction.

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