ED 295 832 SE 049 213

AUTHOR Snir, Joseph; And Others
TITLE The Truth, but Not the Whole Truth: An Essay on Building a Conceptually Enhanced Computer Simulation for Science Teaching. Draft Article. Technical Report 88-18.
INSTITUTION Educational Technology Center, Cambridge, MA.
SPONS AGENCY Office of Educational Research and Improvement (ED), Washington, DC.
PUB DATE Jun 88
CONTRACT 400-83-0041
NOTE 31p.; Drawings may not reproduce well.
PUB TYPE Viewpoints (120) -- Reports - Descriptive (141)

EDRS PRICE MF01/PC02 Plus Postage.
DESCRIPTORS *Computer Simulation; Computer Software; *Computer Uses in Education; *Concept Formation; Educational Improvement; *Educational Innovation; *Educational Objectives; Elementary School Science; Elementary Secondary Education; Misconceptions; Physical Sciences; Science Education; Science Instruction; *Secondary School Science; Teaching Methods
IDENTIFIERS *Science Education Research

ABSTRACT

Many feel that an advantage to using computer simulations in science teaching is that they give students the opportunity to witness or perform experiments which might otherwise be too expensive, time consuming, or dangerous for them to do. Simulations attempt to mimic the kind of experience students get in a laboratory and help students learn new facts. It is held that simply providing students with laboratory experience does not help them to understand the ideas of scientists. This paper urges researchers, educators and software designers to consider how computer simulations can be used to bring about conceptual change and understanding. The purpose of this paper is to provide a rationale for designing conceptually enhanced simulations and describe their underlying structure. Part one discusses natural pnenomena and defines the problem. Part two discusses model systems and identifies the kinds that may play a role in helping students understand the theoretical frameworks of scientists. The third part shows how these ideas were applied in developing a simulation to teach the concepts of weight and density. Twenty-five references are listed. (CW)

TR88-18

THE TRUTH BUT NOT THE WHOLE TRUTH: AN ESSAY ON BUILDING A CONCEPTUALLY ENHANCED COMPUTER SIMULATION FOR SCIENCE TEACHING

June 1988

Educational Technology Center
Harvard Graduate School of Education
337 Gutman Library   Appian Way   Cambridge MA 02138
(617) 495-9373

The Truth, but not the Whole Truth: An Essay on Building a Conceptually Enhanced Computer Simulation for Science Teaching

Draft Article
June 1988

Prepared by:

Joseph Snir
Haifa University
and
Educational Technology Center

Carol Smith
University of Massachusetts, Boston
and
Educational Technology Center

Lorraine Grosslight
Educational Technology Center

Weight and Density Project
Group Members

Micheline Frenette
Joel Giampa
Lorraine Grosslight
Grace Marie LeBlanc
William Radomski
Judah Schwartz
Carol Smith
Sandra Smith
Joseph Snir

Preparation of this report was supported in part by the Office of Educational Research and Improvement (Contract # OERI 400-83-0041). Opinions expressed herein are not necessarily shared by OERI and do not represent Office policy.

INTRODUCTION

The use of computer simulations for science teaching is increasing steadily (Gallagher, 1987). To date, a primary argument for using computer simulations has been that they give students the opportunity to witness or perform experiments which might otherwise be too expensive, too time consuming, or too dangerous for them to do. Typically such computer simulations represent real world events in a cartoon-like fashion, with a program code based on the retrieval of predetermined screens. For example, if an experiment is being performed with a beaker of liquid, the screen displays a beaker-like shape filled with a colored fluid. The simulation then depicts observable changes--if the fluid expands when heated, the level of the fluid is shown to rise on the computer screen--usually by calling up predesignated screens. Such simulations attempt to mimic the kind of experience students get in a laboratory and are well designed to help students learn new facts. Indeed recent research (Choi & Gennaro, 1987) supports the claim that students can gain an equivalent level of factual knowledge by working either with computer simulations or the actual laboratory experiments.

Science education, however, does not involve simply teaching students some basic facts which they can observe. It also involves introducing students to new ideas which they cannot observe directly--the theories that scientists have developed to understand and explain those basic facts. There is now considerable evidence that students have great difficulty in understanding these new theories, in part because they come to science class with their own ideas, which are different from the ideas of scientists in many respects. A central challenge for science educators is to develop ways of helping students understand the ideas of scientists, which often means that students must be helped to make fundamental changes in their own pre-existing ideas. Simply providing students with laboratory experiences (or cartoon-like computer simulations) does not suffice, because students typically try to understand these situations in terms of their pre-existing ideas.

In this paper, we urge researchers, educators, and software designers to consider a way computer simulations can be used to address the problem of teaching for conceptual change and understanding. To address this problem, a new kind of computer simulation is called for. Instead of simulations which merely mimic what a laboratory experiment looks like, we need simulations that allow students to observe what can't be directly observed in laboratory experiments: some of the theoretically based concepts and ideas used for interpreting the experiments. We will call such simulations "conceptually enhanced simulations" because they are based on models which provide an explicit representation of a set of interrelated concepts. Students can then perform experiments using these simulations, enabling them to reflect about the experiments they perform with real world materials. Thus, the advantages of such conceptually enhanced simulations are not only that they allow students to perform experiments which cannot be performed in the classroom, but also that they help students understand experiments they can perform in terms of the scientists' concepts and theories.

The purpose of this paper is to provide a rationale for designing such conceptually enhanced simulations as well as to describe their underlying structure. It is organized into three main parts.

The first part discusses the natural phenomena themselves, identifying three levels of understanding of these phenomena which need to be addressed in school science. In this part, we define the problem we want the computer simulation to help us solve, by showing how students can observe or experience a phenomena but not understand it in terms of the scientists' theories and concepts.

The second part discusses model systems and simulations more generally and identifies the kinds of model systems that can play an important role in helping students understand the theoretical frameworks of scientists. We argue that computer simulations which build mathematical laws and relationships (expressing physical principles) into the program code are more powerful than simulations based on the retrieval of a series of predesignated screens, because they permit the discovery of new consequences of known physical principles. Further, computer simulations which give visual representations for a set of interrelated (normally unobservable concepts) guide students in thinking about the phenomena at a more theoretical level.

The third part of the paper shows how we applied these ideas in developing computer simulations for a particular set of purposes: to help students grasp the distinction between weight and density, to understand the phenomena of flotation, and to understand the changes in density that result from thermal expansion. These topics are notoriously difficult for 7th and 8th grade students, in part because students frequently come to class with a conceptual framework which unites distinct senses of heaviness (including heavy and heavy for size) into one concept of weight. Students embed this concept of weight in a framework which interrelates the notions of size, weight, and material kind. They know, for example, that the weight of an object is a function of both its size and the kind of material it is made of. But this framework does not yet contain a concept of density that is distinct from weight which would allow students to distinguish, for example, between the total weight of the object and the density of the material of which the object is made. Thus, this is a clear case where science teaching needs to help students make conceptual changes (in this case, differentiate the concepts of weight and density) and restructure their understanding of these new conceptual entities. And it is a good case to show how "conceptually enhanced simulations" integrated with other more standard science education tools can provide special assistance in the process.

The paper concludes with an epilogue, in which we reflect on the kinds of activities such conceptually enhanced simulations allow, and in turn, the ways planned activities may affect the overall design of simulations. An exciting challenge for future research is to examine how the effectiveness of conceptually enhanced simulations depends upon the ways in which they are used, in addition to their basic structure and design.

THREE LEVELS OF LEARNING ABOUT NATURAL PHENOMENA

Science education should deepen students' understanding of natural phenomena at three different levels.

At the first level, students need to learn some directly observable facts about natural phenomena, and form some simple generalizations based on these facts. These facts are considered directly observable in the sense that they are about attributes and relationships of largescale physical objects which can be directly perceived by the person's unaided senses. For example, students can directly observe that an object is red, large, hot, heavy, or made of wood. They can also directly observe simple relationships between objects: one object moves faster than another, one object is larger than another, one object floats in a given liquid. Based on such observations they might form simple generalizations like: "wooden objects float on water," or "metal objects expand when heated." We call this a "surface" or "object" level, because it is grounded in everyday observation of concrete objects.

At the second level, students need to learn the scientific theories by which the facts observed at the first level can be explained. These theories make use of a series of interrelated concepts, which are mutually interdefined and cannot be simply or directly observed. For example, density, a property of different material kinds, is defined as mass per unit volume. As such, it cannot be directly observed, but must be inferred by relating other observations and measurements. Further, concepts such as density (along with other important notions) emerge in explanations of why objects weigh what they do and why some objects float and others sink in certain liquids. We call this a "theoretical" or "conceptual level" because it is concerned with relations among a set of theoretical (conceptual) entities rather than simply the relations among the objects themselves.

At the third level, students need to learn about the purposes and methods of science. For example, they need to learn that scientists develop models and theories to help them understand phenomena; and, of course, they need to learn what a model or theory is. They also need to become aware of some of the methodological principles scientists use in deciding what is good science (e.g., what makes something a better law or better model than something else; what kinds of criteria scientists use in making these judgments). We call this third level a "metatheoretical" or "metaconceptual level," because it involves reflection about the epistemological basis of the theoretical conceptual level.

These three levels are not independent for scientists. The very choice of a given phenomenon as a subject for examination might be a consequence of the basic paradigm held by the scientific community (Kuhn 1960). Further, the kinds of theories one constructs are affected by the range of phenomena one is trying to explain, the principles one holds about what counts as a good explanation, and the set of concepts that are used for the explanation. Thus, good science involves an interplay among all three levels.

We believe that students have preexisting ideas at all three levels, as well. Thus, the interplay of ideas from all levels is important not only for good science, but also for good science education. No one disputes that children work with basic objectlevel descriptions (the first level). Larkin's work (1983), for example, clearly shows that novice physics students exploit such object level descriptions in solving certain kinds of physics problems. With respect to the second theoretical level, a number of researchers have argued that children organize their basic knowledge of how objects behave by using intuitive theories (Carey, 1985; Driver & Erikson, 1983; and Wiser, 1986) and they have given numerous arguments about why intuitive theories are important in conceptual organization. For example, they argue that cognitive psychologists must understand the role concepts play in theory-like structures in order to understand the nature of constraints on induction (see Goodman, 1965; and Keil, in press), to answer questions about what holds concepts together and makes them coherent (Murphy and Medin, 1985) and to understand the process of conceptual change (Carey, 1985; Smith, Carey and Wiser, 1985). Finally, recent work suggests that children have some metaconceptual ideas about how knowledge is generated in everyday life and in science (Carey et al, 1988; Wellman, 1986). Students believe essentially that scientists as well as other people learn by making observations (and developing instruments to help them make finer and finer observations). Knowledge is thus acquired by forming mental "copies" of what one has observed. While such a copy theory of knowledge seems highly simplistic (totally overlooked, for example,is the constructive nature of knowledge acquisition and the role of hypotheses and hypothesis testing in knowledge generation), it has a certain coherence and serves to explain some phenomena students have noted about learning.

If we are right in assuming that students have existing ideas at all three levels, then successful science instruction does not involve simply communicating new facts and superordinate concepts to students. Rather, it involves modifying the student's existing conceptual and metaconceptual organization. Because the meanings of concepts are so interdependent, they cannot be revised in isolation: changing one concept involves making changes in many other concepts and explanatory principles as well.

Unfortunately, given current educational practice, we believe students rarely make changes at more than the first level. There is extensive evidence that they have difficulties in relation to the second level (frequently trying to assimilate the new facts they are learning in science class to their old conceptual frameworks). And they are seldom explicitly introduced to a constructivist epistemology at the third level. Thus, their copy theory of knowledge remains unchallenged and intact, and they simply add to their store of observations and memorized facts.

In this paper, we shall argue that properly designed computer simulations (exploited in a teaching context which encourages discussion and reflection) can help students make changes at all three levels. In order to explain more completely how simulations may help in these ways, however, we first need to consider more precisely what we take models and simulations to be.

MODEL SYSTEMS AND SIMULATIONS FOR SCIENCE TEACHING

Pictures, graphs, models, analogies, and metaphors have one thing in common. All can be used as tools to help understanding. By serving as "model systems," they let one use something that is known or more accessible to understand something that is less well known or less accessible. In this section, we describe aspects of the structure of model systems that we think are useful for science education, distinguish between two basic kinds of model systems, and then describe some of the special advantages of using computer-based model systems.

MODEL SYSTEMS AS STRUCTURE MAPPINGS

Gentner (1983) has developed a framework for thinking about how analogies work in science. This framework describes analogies in terms of a structure mapping between two domains. She views any domain as an organized system of objects, object-attributes, and relations between objects. Thus, in making a structure mapping between two domains, one can ask what elements of the two systems are mapped: objects, object-attributes, or object relationships.

In Gentner's framework, attributes are defined as predicates which take one argument (e.g., RED (x), or LARGE (x)), while relations are defined as predicates taking two or more arguments (e.g., LARGER (x, y), or COLLIDE (x, y)). Predicates vary not only in the number of arguments that they take, but also in the kind of arguments they take. Some predicates simply take objects as arguments, as in the examples above (Gentner terms these first-order predicates). Other predicates, however, can take entire propositions as arguments. For example, predicates concerned with causal relations (e.g , CAUSE (COLLIDE (x, y)) (STRIKE (x, y))) and with quantitative relations (EQUAL (WEIGHT (x), WEIGHT (y)). Thus, predicates can be nested within each other and form an inter-related system: the predicates themselves are mutually inter-defined and changes in the value of one predicate can result in changes in the value of others. The degree of nesting determines the order of the predicate (i.e., whether it is second or higher-order). Mathematical equations are a means of formally connecting a set of predicates into a mutually constraining system, and are thus higher-order relational predicates.

Using Gentner's basic framework, we can distinguish between two different types of model systems: (1) object-attribute models, in which it is important that the model resembles the object modeled in some aspects of its basic appearance; and (2) relational models, in which it is important that the same systematic pattern of relationships between predicates holds in both the model system and the system modeled.

Pictures, some [illegible]le models, and some metaphors are all examples of object-attribute model systems. In such model systems, more attention is paid to mapping object-attributes than object relationships, and there is no attempt to map higher-order relationships among predicates. For example, one can order food in Japan by calling the waiter to the restaurant display window and pointing to the plastic replicas of food there. These plastic models serve as examples for the real food served in the restaurant, and capture many attributes of the food's appearance (e.g., color, size, shape). However, there is no attempt to portray information about the inter-dependent nutritional aspects of the food. Similarly, one can make a little replica of an airplane which depicts many features of what the plane looks like, but which fails to capture the way it really flies because it has no engine or other working parts.

In contrast, the power of scientific models lies in their having a network of relationships in common with the system they model. In making scientific models, it is a set of relational predicates rather than the attributes of objects which are mapped from one domain to another. Further these relational predicates (typically) are themselves abstract theoretical entities, defined originally as a pattern of relationships and not in terms of simple object attributes. Finally the two systems may even share a common abstract mathematical description.

For example, scientists have used the waves in a ripple tank as a model system for sound waves. Clearly, the two systems are not alike in basic object attributes. However, if one thinks about the underlying causes of wavelike motion in the two domains, and analyses the system in terms of the abstract relations of force and energy, one can see that there is a common process at work in the two systems. Water molecules relate to each other in the same way as air molecules do. In both cases, there exist inter-molecular forces of the same kind. And in both cases, when an outside force is applied to the system at rest, the system is perturbed, and there is a resultant transfer of energy throughout the system. In particular, the air particles and water molecules serve as carriers for transferring energy from one point to another. The perturbance of one molecule results in the perturbance of another (and the transfer of energy) because of the existence of those inter-molecular forces. Indeed, the same set of mathematical equations describing the relation between inter-molecular forces, the mass of the particles, the investment of energy and the resulting wave motion apply in both domains.

Another example of a relational model is using a pendulum as a model of an LC circuit. (An LC circuit is an electric circuit which contains a coil of self-inductance "L" and a capacitor of capacity "C"). In using the pendulum as a model of an LC circuit, the instructor and student are quite aware that pendulums and circuits are not alike in basic appearance. The ability to make an analogy between the two systems stems from the ability to map similar relations in the two systems, despite differences in object attributes. Again, the relations involve the abstract concepts of force and energy. This time, however, the forces involved in the two systems are not the same (the pendulum involves mechanical forces, while the LC circuit involves electrical forces). Yet the mathematical description of these forces is identical for both kinds of forces.

For example, when energy is invested in the pendulum system (by moving the pendulum bob from equilibrium), the bob is set in motion and will move back and forth until the energy is dissipated. Similarly, when energy is invested in the LC circuit by charging the capacitor, electrical charges move back and forth from the capacitor to the coil, until the energy is dissipated. In both systems the variables of force and energy are related in the same way: there are restoring forces which need to be overcome if the systems are to be set in motion, and one must invest energy (do work) to overcome these forces. Thus, although the basic restoring forces which one must do work to overcome when perturbing the system are fundamentally different (gravitational force in the case of the pendulum and electrical force in the case of the LC circuit), the same equations describe the way energy relates to the mechanical forces in the pendulum as describe the way energy relates to electrical forces in the LC circuit. Thus, the two systems are isomorphic. Since the systems are analogous in terms of descriptions of force and energy relations, other elements that are relevant to descriptions in terms of force and energy can also be mapped.

Scientists have used model systems not only to help them understand new phenomena and to explain these phenomena to others, but also to do simulations of actual experiments. Given that the same mathematical description underlies the behavior of both systems, scientists can do experiments with the relevant variables of the model system to learn about the behavior of the modelled system. In simulations, the performance of the model systems is examined when some process takes place in it. The simulation is, then, defined as the dynamic execution or manipulation of the model system (Barton, 1970).

Continuing with our two examples, scientists can use the ripple tank to understand the phenomena of interference of waves, and to study how wave interference is affected by parameters such as the wave length of the interfering wave, in a domain which is easier to work with and in which the interference is observable. By doing these experiments in the ripple tank, they can make predictions about and understand interference phenomena for sound waves (or even light waves). Similarly, both scientists and students can use the pendulum to study parameters that affect the behavior of the LC circuit. Putting the pendulum in motion provides a simulation of the phenomenon of oscillations in the LC circuit. By manipulating the variables of the length of the string or mass of the bob in the pendulum system and noting their effects on the oscillation frequency of the bob, they can reach conclusions about how manipulation of analogous variables in the LC circuit would affect the oscillation frequency of the charge.

In summary, we believe it is important to distinguish two types of model systems: object-attribute models and relational models. Students are familiar with object-attribute models from their previous everyday experience. However, they may be less familiar with the relational models that are important in science. For students to understand one system as a relational model for another, they must both (1) identify the relevant set of relationships to be mapped, and (2) figure out how those relationships apply to non-identical elements. Significantly, Gentner and Toupin (1986) has found that at least by age 8 children are able to understand such relational models in a non-scientific context. This finding suggests that students may be ready to understand appropriate relational models in science and that such models can be used as an important tool in science education.

In the past, scientists have most typically used one physical system as a relational model for another one, and used these physical systems in running simulations. With the advent of computers, there are new possibilities and issues about how relational model systems can be created. In the next section we explore some of the issues in using computer-based model systems as well as describe some of the special advantages of using computer-based models.

COMPUTER-BASED MODEL SYSTEMS

In searching for analogous physical systems, one is looking for two systems which share a common relational structure. One is constrained by what naturally occurs, and has no control over the surface appearance of the two systems. One tries to find a more familiar system to use as a model for a less familiar system -- one in which the underlying relational structure is easier to see. Yet typically, the relational structure of even familiar systems is not transparent or directly observable. For example, although one can see the pendulum bob and watch or even measure its changing velocity and oscillating movement, one has to infer the forces and energy involved in the system as well as the underlying relationships between these elements.

Advantages of Computer-based Models

One advantage of using computer-based models is that they allow more freedom in structuring the visual aspects of the model system. Thus, more attention can be paid to creating model systems in which entities (elements) to be mapped and their relationships are themselves directly observable. This in turn can make it more likely that the student makes the mapping that the teacher intended (rather than a less relevant and revealing attribute based mapping).

There are, of course, several kinds of screen visuals computer-based models might provide to extend the range of what is normally observable in the real world. We feel it is important for software developers to be aware of the full range of options in using visuals, so that they can exploit the full power of the computer in providing visual representations. One could, for example, depict real entities or "objects" which are usually observable only with special equipment (e.g., planets, cells). Furthermore, one could portray their behavior in speeded up or slowed down time so their motion is observable. Their motion can also be marked, or a trail left, so that the user has a record of the motion and does not have to rely on memory when analyzing or reflecting about such motions.

One could also depict entities which one can imagine as objects, even though these entities have in fact a theoretical status (e.g., atoms, molecules). The behavior of these "imagined objects" can be shown in a way which provides an explanation for some phenomena (e.g., movement of an electron from one atom to another as an explanation for the creation of a chemical bond). These are some of the approaches to visuals (above and beyond real-world cartoons) which have been most frequently used.

However, we propose still another way to use visuals: a case in which the representation is a conscious attempt to depict particular conceptual relationships or sets of relations which form a system. In this case, there is no assumption that the objects on the screen must correspond directly to pointable objects. Instead, a "screen-object" can represent some attribute or quantity (e.g., weight, kinetic energy). (Note these attributes may have themselves been formed through relations and have become new primitives). The "screen objects" can be designed to depict ways of thinking about phenomena so that important concepts and relationships are highlighted. We have termed models and simulations which use visuals in this way "conceptually enhanced models and simulations" and will develop an extended example later in the paper.

A second advantage of the computer is that it can be programmed to display several different kinds of representation simultaneously or sequentially. In this way students can move between multiple representations of a phenomenon. These linked representations can be different kinds of visual representations (e.g., real world cartoons, conceptual representations and grasphs), as well as verbal, numeric, and even algebraic representations.

Design Issues

An interesting issue in the design of computer model systems concerns what the underlying program code is like. The program code is itself not directly visible, but determines how the computer actually models the situation. The program designer has several important kinds of choices to make in constructing a code.

The first kind of choice concerns whether or not the program designer embeds the underlying physical laws directly into the program. There are at least two contrasting ways to design a computer simulation. In one, the program designer creates a discrete set of screens that the user will see later. When users run the program, they are essentially signalling the computer to display particular pre-determined screens. The number of these screens is limited and the program code contains a set of rules by which the computer will generate the particular screen in response to a particular student action (see, for example, Operation: Frog).

This is in contrast to a simulation which generates screens in a very different way: one in which the program code embodies relevant physical laws as a set of mathematical formulas. The behavior of objects on the screen is a direct result of the program's rules for their behavior in accordance with the physical laws. In the initial screen, the system is in one of its equilibrium states. As students interact with the program, they perturb this initial state. When this occurs, the program reacts by searching for a new state of equilibrium.

Given that a program designer chooses to embed the underlying physical laws, the second choice he/she faces concerns which aspects of the simulated physical system to make visible. We have already mentioned that different types of objects can be made visible as well as different types of behavior for those objects. It is up to the program designer to decide what kind of representation will be best for portraying the system in action. Cartoons may suffice or explicit representations for mental constructs may be necessary to convey the software's intended message. A variety of considerations will affect these choices including the scope of the curriculum, the student's readiness to understand the concepts involved, and design choices about which set of relationships can be presented in a rich and clear way.

Again, we stress that the computer offers the unique advantage of being able to represent entities which would otherwise not be visible. Furthermore, we shall show how the interdependent relationships among specific entities in a given system can be made observable. Because of its interactive capacity and ability to run simulations according to mathematically expressed physical laws, the computer affords an environment which allows the student to discover, explore and reflect upon new conceptual territories.

ALTERNATIVE MODEL SYSTEMS FOR TEACHING STUDENTS ABOUT DENSITY: WHAT CAN HELP WITH WHAT

Although understanding natural phenomena is an important focus in science teaching, students rarely observe these phenomena in complex everyday settings for science class. Instead, teachers construct simplified model systems to enable students to understand the real world phenomena. Typically, these model systems take the form of demonstration or laboratory experiments, but more recently they have also involved work with computer simulations.

In this section, we consider different kinds of model systems used in teaching students about density and flotation, ranging from more traditional laboratory based models to some newer kinds of computer based models. The purpose of this section is to provide concrete examples of these different kinds of model systems as well as to analyze their strengths and weaknesses in helping students understand phenomena. We believe that computer based conceptual simulations may be especially helpful when students must change their underlying concepts. However, we would argue that an ideal curriculum would not rely on one type of model system alone, but rather would involve a judicious combination of systems.

LEARNING SYSTEMS BASED ON LABORATORY EXPERIMENTATION

Consider for example, two kinds of laboratory based learning systems that have been used in teaching students about density and flotation: the ESS curriculum unit on clay boats (1969), and the curriculum unit on density and flotation developed by Rowell and Dawson (1977)

In the clay boats unit, students are given a lump of clay, and a container of liquid, and are challenged to figure out a way to make the piece of clay float. Students who invent the solution of making a clay boat are given additional materials (little weights to put in the boat) and additional challenges (for example, design a boat that will hold the most cargo.)

While this unit uses the clay and water as a model system for understanding the behavior of real life boats, the model system itself is very open-ended and complex (e.g., students are free to vary the shape of objects in unlimited ways). Such model systems may be particularly effective in arousing student interest and curiosity and can also lead students to discover new facts about what kinds of objects will float. This in fact was probably the principal aim of the curriculum since it was intended for use with very young children. However, because there is so much freedom in defining the variables in the clay boats system, it is almost impossible to construct any quantitative laws from it or develop an explicit concept of density. Thus, although elementary age students have fun with this unit and can figure out ingenious ways to make clay boats, they rarely formulate conclusions in terms of general laws or use a concept of density to understand flotation. This illustrates an important limitation of such a model system for concept learning: it is too open and complex to allow students to discover the relevant physical laws. Students need more explicit guidance about the concepts they should use in understanding a phenomenon if they are to go beyond merely learning some new facts.

Rowell and Dawson present a second more structured approach to using laboratory experimentation in order to learn about density and flotation (1977). Students are presented with a set of steel bars of differing length. They are instructed to record measurements of the lengths of the bars and to calculate their volume. The students are then asked to construct a graph which represents the data obtained from measuring the volume and weight of the set of bars. Such a structured system limits the variables under consideration to enable students to focus on those that are relevant (i.e., students focus on volume and weight, while shape is held constant). This learning system was specifically designed to help students grasp that although objects made of a given material can vary in volume and weight, the density of the material is a constant (the graph relating volume and weight is a straight line). The hope is that experimentation with specific cases will help the student to formulate a general hypothesis about the density of the material which they can then apply to new instances. However, even in this situation, it was found that many students had difficulty extrapolating a general rule from their limited data.

Regardless of the teaching methods employed, children's activities with real life materials, accompanied by their careful observations, will, undoubtedly, contribute to their knowledge of the observable facts about the phenomenon: facts, such as, that different objects behave differently in the same liquid; that the same object can behave differently in different liquids; and that objects made of different materials can have different weights although they are the same size. However, it is less likely that these activities alone will be successful in bringing about conceptual change. Instead, students will try to understand these situations with their initial concepts (in this case, the concepts of size, weight, shape, and material), and will resist restructuring their conceptual system in a way that makes a fundamental distinction between weight and density. For example, in the clay boats unit it is easy for students to explain the fact that clay boats float by simply noting that the shape as well as the weight of objects or the kind of material an object is made of affects whether it will sink or float.

One way that Rowell and Dawson attempt to overcome the limitations of laboratory experimentation in their unit is to have students work with graphing given variables as well as using explicit mathematical formulas. The hope is that seeing the linearity of the graph that represents the experimental data will convince students about density being an intensive quantity. However, it is not clear that graphical models are "transparent" to children of this age. Further, mathematical formulas are things that students frequently try to learn by rote. Thus, students often correctly solve some problems with the formula, but they lack any understanding of the phenomenon on the conceptual level. Density for them is simply a number derived from certain mathematical operations; it is not a meaningful physical quantity. The only meaningful physical quantities for them are still weight and size. More experimentation with objects or practice with computational problems is not likely to be of much help in deepening their conceptual understanding. It is not that the students do not know the facts, but rather that they do not possess the network of concepts needed for thinking about these facts: a network in which weight and density are differentiated as physical quantities.

Thus we see that laboratory experimentation provides an opportunity for students to experience and explore certain interesting phenomena and even to induce some general rules about those phenomena (through interaction with simplified physical model systems), but does not provide explicit guidance about the concepts which must be used in those laws. In the sections that follow we will describe two ways that computers can be used to enhance this process.

LEARNING SYSTEMS BASED ON COMPUTER MODELS

In building a computer simulation, the program designer makes choices both about what the screens should look like (the nature of the visuals) and how those screens will be controlled by the program designer and user (the nature of the program code). Part of the flexibility of computers as modeling systems stems from the fact that these decisions are somewhat independent: the same kind of visuals can be created from two different kinds of program code, and the same kind of program code can be used to support two different kinds of visuals. The purpose of this section is to clarify the nature of these choices and discuss the possible implications for learning from the resulting model systems.

Pictorial Simulations

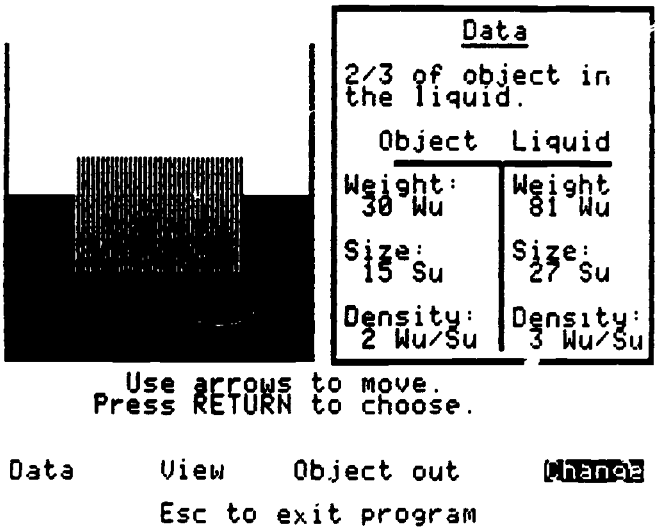
The most common type of visual used in computer simulations gives a cartoon-like representation of the object and its behavior. We call such simulations "pictorial" simulations since they depict observable attributes of objects and show the observable interactions of objects. In this respect the computer simulation corresponds to what students can visually observe in the laboratory and directly mimics some of the visual aspects of the laboratory experience.

Given that the program designer has chosen to use screens with pictorial visuals, there are two contrasting ways of determining how those screens should be created. In one approach, there is no attempt to build the mathematical laws which are relevant to the phenomenon into the computer code. We shall call this a "non-analytic simulation." In this design, essentially the program designer creates a discrete set of screens that the user will see later. The user, when running the simulation, is sending signals to the computer to display the different screens. The predetermined screens are stored in the computer memory and the program contains a set of rules by which the computer produces a certain screen in response to a specific student action. Most of the authoring languages, such as Super-pilot or Quest, are based on this approach and provide flexible tools for the creation of such screens. Although this kind of program can be very instructive, the software can never produce an unexpected situation because all the screens are predetermined (e.g., Operation Frog, 1984; Measurements: Length, Mass, & Volume, 1984).

A different approach to software design builds mathematical relationships into the program code and the screens reflect states of the simulated system as it evolves dynamically. We shall call this an "analytical" simulation because it is based on a series of mathematical equations. The program designer defines a set of objects (parameters) and a set of mathematical relations (procedures) between these objects in the underlying code which is used to generate the pictorial representation of those objects on the screen. Thus, the system of objects and the underlying mathematical relations form an isomorphic system.

That is, all the relations and operations that are true in the mathematical system are true for the objects on the screen. In the initial screen the system is in one of its equilibrium states. As students interact with the program, they perturb this initial state. When this occurs, the program reacts by searching for a new state of equilibrium.

To illustrate these points, consider the software concerning flotation which we have developed. In this program, the user can choose the densities of a solid material object and a liquid in a container. In the initial screen, the system is depicted in a state of equilibrium. For example, an object made of some low density material is shown floating in a high density liquid. When the user perturbs the equilibrium (e.g., by changing the density of the liquid in the container), the program reacts by searching for a new equilibrium according to selected physical laws which we describe below. The screen output is a representation of the object moving according to these laws until the new equilibrium has been reached. Each screen is produced as the computer calculates the successive stages of the system. (Note that the equilibrium state is not first calculated and then displayed only at the endstate.)



Data

2/3 of object in the liquid.

Object	Liquid
Weight: 30 Wu	Weight 81 Wu
Size: 15 Su	Size: 27 Su
Density: 2 Wu/Su	Density: 3 Wu/Su

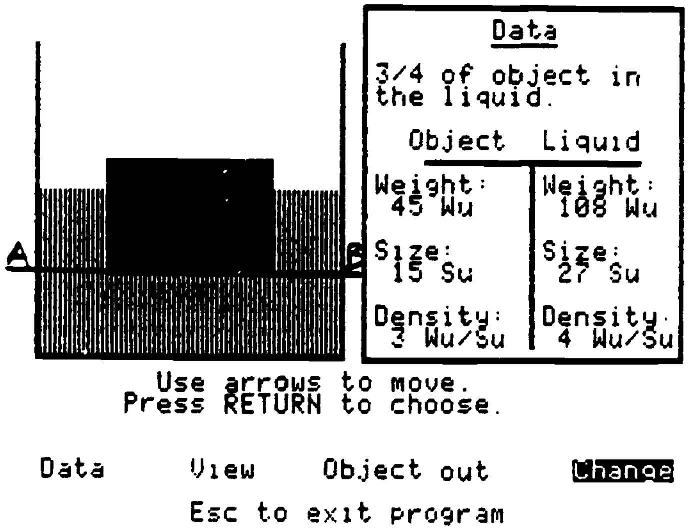
Use arrows to move.
Press RETURN to choose.

Figure 1

The elements of the system are represented on the screen in the following way (see Figure 1). One sees an object and a container with liquid. There is no attempt to make the object or liquid look three-dimensional. The object (corresponding to a chunk of homogenous material in the real world) is shown as a colored rectangle of varying size. There are five possible colors for the rectangle, corresponding to five different materials with different densities. The container of liquid is shown as a cross-section of an open rectangular container. It is filled to a specified level with one of five different color liquids. Thus the liquid is also represented as a colored rectangle. In this way information about the size of objects and the kind of material they are made of is directly presented.

Two laws are built into the flotation simulation to account for the behavior of the object placed in the confined liquid. One concerns conservation of matter. When the object is lowered into the liquid, some liquid is pushed aside. The liquid's shape changes to accommodate the object, but its total amount (represented as area) remains constant.

The second law concerns hydrostatic pressure. If the system is in equilibrium, the hydrostatic pressure will be constant at every point of a given horizontal plane through the liquid. (This is obvious when there is only liquid in the container, since identical conditions exist at every point of the given plane). When there is an object floating in equilibrium, however, consider what this law says about the plane tangent to the bottom of the object (see Figure 2). This law means that the pressure generated by the object on a unit area of this plane should be equal to the pressure generated by the column of liquid on a unit area around the object. Pressure of a [illegible] material on a unit area of a certain plane is a function of the height of that matter above this plane and the density of that material. Thus, the object will sink until such a pressure equilibrium is reached: the exact depth of the tangent plane for which the flc [illegible] object system is in equilibrium depends on the ratio of object and liquid densities.



Data

3/4 of object in the liquid.

Object	Liquid
Weight: 45 Wu	Weight: 108 Wu
Size: 15 Su	Size: 27 Su
Density: 3 Wu/Su	Density: 4 Wu/Su

Use arrows to move.
Press RETURN to choose.

Esc to exit program

Figure 2. The plane AB is tangent to the bottom of the object

In summary, equivalence of pressure and conservation of matter are two specific physical laws embedded in the program. They alone dictate the process of searching for the new equilibrium. The screens are actually created by this search process rather than being predesignated by the programmer.

An intriguing aspect of programs of this type is that it can allow even the program designer to discover consequences of the physical (mathematical) laws that he or she had not worked out before. In a sense, the program operates by itself, according to simulated physical laws, and it can, therefore, create novel situations that were not directly programmed. Such a case of new discovery and deepened understanding was actually experienced by one of us after creating this program. In particular, working with the computer simulation he had developed, Snir noted he could make a large heavy object float in a small container of liquid, where the total weight of the liquid was less than the total weight of the object. This is understandable when one thinks of flotation in terms of pressures but seems to contradict the way that Archimedes' law is typically formulated in textbooks and in Archimedes' writing. According to Archimedes, an object sinks to the point where the weight of the water displaced is equal to the total weight of the object and therefore an object cannot float when the total weight of water is less than the weight of the object (see Snir, 1988, for further details about how this contradiction should be explained and its historical roots).

In summary, an important choice for the program designer concerns how to generate the screens used in the simulation: by using predetermined screens or by embedding the mathematical laws into the underlying program code. Only if the programmer embeds the mathematical laws into the underlying program code is the computer simulation as powerful as laboratory models (i.e., allows for genuine inquiry and new discovery). Thus, laboratory models and pictorial computer simulations based on analytic models are alike in two respects: (1) the same kinds of visual events are observable in both systems and (2) both kinds of models capture mathematical regularities and relationships and allow for new discovery.

A possible advantage of such pictorial simulations based on analytical models is that they allow students to perform a wider range of experiments more easily, with a larger range of parameters than would be possible in traditional laboratories. This is turn increases chance of novel discoveries. However, we believe simply more experience is not necessarily enough to ensure conceptual change. We believe that the student needs something different, something which will provide direct contact, not with the objects and observable attributes alone, but with representations of unobservable attributes relevant to the understanding of a particular phenomenon as well. Hence, in the next section we propose a new dimension be added to pictorial simulations, a direct simulation of a network of concepts needed for understanding the natural phenomena.

Conceptually Enhanced Simulations

Although computer simulations typically use visuals which provide simply a cartoon-like picture of phenomena, the program designer can choose to create other kinds of visuals as well: visuals that make "observable" what is in nature "unobservable." One important kind of "unobservable" is a set of inter-related concepts. In a conceptually enhanced simulation, we add a visual representation of the concepts used in explaining a specific phenomenon (the theoretical level) to the representation of the observable features of the objects (the object level). This enables students to observe, simultaneously on the same screen, two levels of thinking about the same phenomenon and to live in (or experience) the conceptual space in which the expert thinks. Synchronization of these two kinds of visual representations on the same screen gives students direct access to abstract concepts which they could not manipulate in the laboratory or the pictorial simulation alone. Thus the students gain not only more experience with a specific phenomenon, but have the opportunity to restructure their conceptual understanding of it.

In this section, we describe conceptually enhanced models and simulations that we have developed for teaching about the concept of density and the related phenomena of flotation and thermal expansion. In presenting this example, we first describe some of the main choices we faced as program designers in creating such conceptually enhanced models, and then describe the series of simulations we developed which are based on these models.

Design Issues and Choices

Educational models and simulations are created by curriculum designers not so much for their power to lead to the discovery of new scientific facts, as for their ability to illuminate known aspects of a phenomena (Nesher, 1987). Thus, a first choice faced by a software designer concerns what known aspects of a phenomena the model should account for. The answer to this question in part depends upon the age and background of the students being taught.

Our density curriculum was intended for 6th and 7th grade students, and our decisions about what to include in the model were guided by didactic as well as scientific considerations. We deliberately chose not to tell the whole truth, but to limit attention to a well defined segment of reality. There were four concepts which we decided to represent explicitly: weight (or mass) of objects, volume, density, and material kind. Later, we shall describe the specific visual representations used for each of these concepts, but first we must discuss some of the issues involved with choosing these four specific elements.

As we mentioned before, research has shown that students of this age come to science class with distinct, yet inter-related concepts of size, weight, and material kind. They know that the weight of objects is a joint function of their size and material kind; they have a good grasp of the intensive nature of material kinds; further, they believe that some materials (like steel) are heavier kinds of materials than others (like wood). However, they use two different senses of weight in these generalizations about materials (heavy and heavy for size), and in fact unite these two senses of weight into one weight concept. Therefore, in designing our curriculum, we decided to build on the strengths in students initial understandings (their grasp of the intensive nature of material kinds) and push them to see density as an intensive quantity associated with given material kinds. Thus, we initially present them with situations where weight and density do not covary, but material kind and density do (temperature is held constant). Only later do they consider situations where the density of a given material varies with temperature changes.

Density, as it is usually defined, is the relation mass/ volume. However, mass is an abstract concept with which most of the 6th and 7th grade students are not familiar. On the other hand, even very young students are familiar with the concept of weight. Therefore, we chose weight, which is proportional to mass, as the predicate for mapping. In some versions of the software, teachers can choose whether they want to use the label "mass" or "weight."

Temperature is another parameter which affects an object's volume and its density. We chose to ignore this parameter in initial models (by assuming constant temperature) but to explicitly map this variable in models used at a later point in the curriculum. (Note: At that point this variable is only represented with a written verbal label and number; it is never given a visual representation.) We did not map the parameter of pressure in our visual models at any point. Because we were modelling only non-compressible solids and liquids, pressure is not a variable which affected the density of materials. (Note: Pressure was, however, an important variable in the program code for the flotation simulation. This illustrates how a variable in the program code need not be given visual expression.)

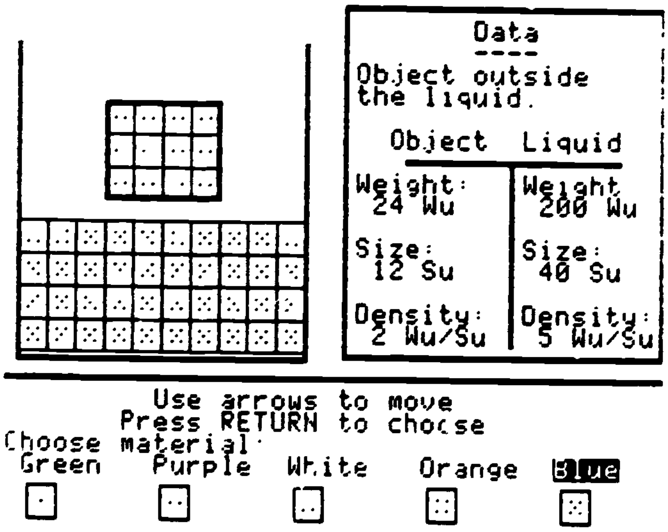
A second decision in model building concerns whether the entities represented visually should correspond to real objects (i.e., blocks, cylinders), to complex theoretical constructs which can be imagined as objects (i.e., atoms, protons, neutrons) or to abstract (relationally defined) attributes of real objects and object-like entities (i.e., weight units). If the visual entities correspond to real objects (as in the pictorial simulations described above), the density of materials is not observable. Density can only be found empirically by taking a sample of material, measuring its mass and volume and then performing the operation mass/volume. Although the resultant number should be viewed as a property of the material kind rather than the object, students are provided with little insight as to why this should be.

If one moves to a microscopic level and makes the visual entities (e.g. dots) correspond to subatomic particles like protons and neutrons, students might understand density as a property of material kinds by associating it with the numbers of the atomic elements and the distance between atoms. Such a conceptualization gives real meaning to the numbers, but the entities themselves (protons) may be unfamiliar to the student. Although these entities can be thought of concretely as microscopic "objects," they are in fact theoretical constructs embedded in a complex theory of matter which is not yet known by 6th and 7th grade students.

This brings us to our third option: to have the visual entities in the model correspond to abstract attributes of objects, not the objects themselves. If we assign accessible analogs for each of these attributes (boxes for size units, dots for weight units), we create a visual referent for density as well (dots per box). Like the microscopic model, this model helps the student see density as a property of material kind. Students can see that they can construct objects out of different materials and that different materials have different densities. Further they can see that adding material to an object changes the size and weight of objects, while the density of the material remains the same. One advantage of making density "visible" using a conceptual model rather than a microscopic model is that the attributes of weight and size are accessible to students in this age range, while the notion of atoms and protons are not. Indeed, historically, Archimedes and Galileo were able to distinguish weight and density, although they did not have an atomistic framework for understanding those concepts. Thus, here, too, we decided not to tell the whole truth, but to stop with a macroscopically accessible definition of density.

Once the program designer has decided on the level of complexity of the model and the kinds of entities the model will refer to, a third major choice concerns the actual visual symbols that will be used in the model. The visual symbols must, of course, be valid, embodying the same mathematical relations as the real world analogs. Thus, although we choose not to tell the whole truth we do tell the truth by creating a valid model in the sense defined above. And, the visual symbols must be ones which the child can intuitively understand at the relevant age, since these visual symbols serve to anchor the child's understanding of the concept (Clement, 1987). Thus, the model should not only be valid and precise, but also be readily transparent to the student.

In our model, a size unit is represented by a square of constant area; a weight unit is represented by a dot; and density is represented by the number of dots in each square. Thus, the total size of a block of solid or liquid (i.e., its volume) can be seen as the total number of squares in the object, and the total weight of the solid or liquid can be seen as the total number of dots in the object (see Figure 3). Different materials of different density look more or less crowded according to the number of dots in the square size units. In this way, the model exploits the visual spatial relationship "in each" to portray directly the abstract relationship "per" (i.e., weight per size unit).



```
Data
----
Object outside
the liquid.

 Object   Liquid
Weight:   Weight
 24 Wu     200 Wu

Size:     Size:
 12 Su     40 Su

Density:  Density:
 2 Wu/Su   5 Wu/Su

      Use arrows to move
    Press RETURN to choose
Choose material:
 Green    Purple   White    Orange   Blue
```

Figure 3

Having chosen the visual symbols, the program designer's final choice concerns what other types of representations to include in the model system (written verbal labels, numbers) and how to coordinate different representations within the model system. As mentioned earlier, a special advantage of computer-based model systems is that they permit the linking of multiple representations. Thus, we believe the program designer should interconnect verbal and numerical representations to the two kinds of visual representations already described.

For example, in working with the pictorial simulation, the student can build objects of different sizes and materials in three windows on the computer screen. The building process is carried out by choices in verbal representation, i.e. children are presented with a given set of terms which they can use to describe the activities they wish to carry out, such as: "change size" or "change material." In this way, children are introduced to specific terms needed to think about the concepts involved. They can choose materials from which to build the blocks, they can change their size and can arrange the blocks on the screen by different criteria.

In working with the pictorial simulation, students can also use a third form of representation: numerical representation. They can collect data about the objects and display them numerically in a window immediately above the object created. This allows students to get quantitative data about the specific sizes, weights, and densities of the three objects created. Thus, the numerical representation gives quantitative information about size weight and density that was not present in the pictorial representation. If the child is working only with data gathered while in the pictorial mode, the weight and density relations between objects can be seen only in their numerical values. The pictorial representation does not show these relationships.

Finally, the program is designed so that the child can not only link verbal and numerical representations but also shift between two types of visual models for the phenomenon (pictorial and conceptually enhanced). In this way, the description of a phenomenon in terms of observable features is readily linked to a conceptual description.

In summary, we have argued that there are four important kinds of design choices faced by developers of model systems: (1) the level of complexity of the model; (2) the kind of entity referred to in the model; (3) the specific visual symbols that will be used (they should be both valid and transparent); and (4) the other kinds of representations that will be used and the ways they will be linked. In all cases, it is important to make these choices based on a sound analysis of student starting points and desired scientific endpoints.

Ultimately, in the evaluation of the usefulness of a model we should consider not only its design but also its scope. Although the above mentioned model was created for teaching about the concept of density, it can serve to represent the relation between any two extensive quantities and a related intensive quantity. For example, the dots might represent units of money, the boxes units of merchandise and the dots per box the price. Or, more relevantly for work in science education, total dots can represent amount of heat, the area can represent the amount of mass, and the dot crowdedness can represent temperature. Interestingly, the recent work of Wiser and Kipman extends the model in certain ways to provide a series of ingenious conceptually enhanced simulations to help students understand the distinction between heat and temperature (see Wiser & Kipman, 1988).

Interactive Simulations

Once decisions have been made about how to construct a conceptual model for a given phenomenon, we can proceed to design interactive simulations which permit dynamic manipulation of that model. In our work, we have developed five such interactive simulations. The first four simulations build on the conceptually enhanced model which has already been described. The fifth simulation, however, required some revision in the model itself.

The first simulation permits students to build objects using a conceptual as well as pictorial representation. It also provides representations using verbal labels and numbers (i.e., students can request data about the objects they have built). In addition to building objects and switching back and forth between different representations of those objects, students can order the objects they have built according to different dimensions or change an object they have built in some way. They also can use the simulation to create models of real life objects on the computer screen.

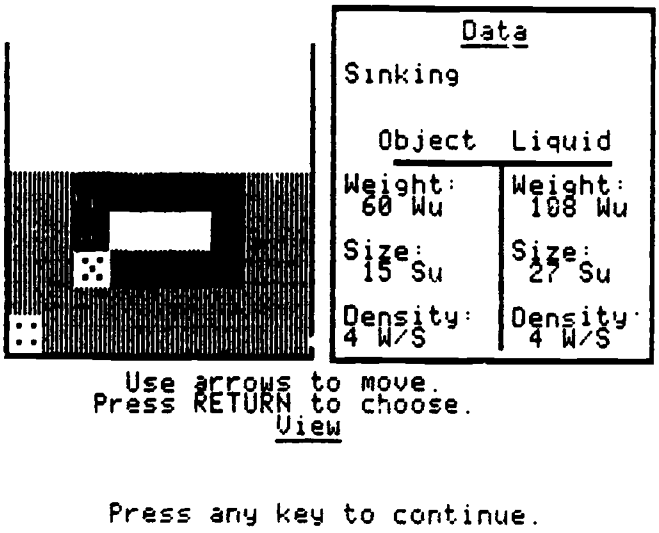
Three additional simulations allow students to do experiments about sinking and floating. In the flotation programs, the child can build objects of different materials and place them in different liquids. The three different flotation programs, progressively complicate the phenomena that are simulated.

In the first flotation program, the size of the object and the liquid are constant. The only variable which can be changed is the kind of material the object or liquid is made of. The student interacts with the program by selecting among written menu choices. However, the objects and liquid can be seen in terms of the two kinds of visuals described above. When the student changes the material kind of the object or liquid, the program seeks a new equilibrium state for the system.

In the second flotation program, students have more freedom to vary parameters. They can change not only the material the object and liquid are made from, but also the size of the object. In this way they can learn that flotation is independent of size, and that the proportion of an object which is submerged in a liquid is constant for all objects made of the same material kind immersed in the same kind of liquid.

In the third part of our flotation simulation, the student can put a fixed size empty space in the middle of any object. This option opens up a rich, new field for exploration and allows the introduction of a new concept -- average density. Here, the learner can observe how an object made of a dense material can float in a less dense liquid if the size of the empty space is big enough relative to the object's total size (see Figure 4). That is, if the empty space is big enough to make the average density of the object less than that of the liquid. In interacting with this simulation, the student can also analyze Archimedes' dilemma about the Heiron crown and his brilliant solution to the problem of whether or not the crown was made of pure gold.

To enhance their educational impact, these conceptual simulations of flotation should be used in conjunction with laboratory activities with real materials. For example, the student should be asked to use the computer to model real life situations. In this way, students are encouraged not only to link the two modes of representation on the screen (pictorial and conceptually enhanced) but also to link the relationship of the representations to real materials. Thus, the conceptually enhanced simulation is not used to create new experiments which cannot be performed in the laboratory; on the contrary, it is used to represent experiments which can be carried out in the laboratory in such a way as to reveal conceptual structure and to foster a deeper understanding of a particular phenomenon.



Data

Sinking

Object	Liquid
Weight: 60 Wu	Weight: 108 Wu
Size: 15 Su	Size: 27 Su
Density: 4 W/S	Density: 4 W/S

Use arrows to move.
Press RETURN to choose.
View

Press any key to continue.

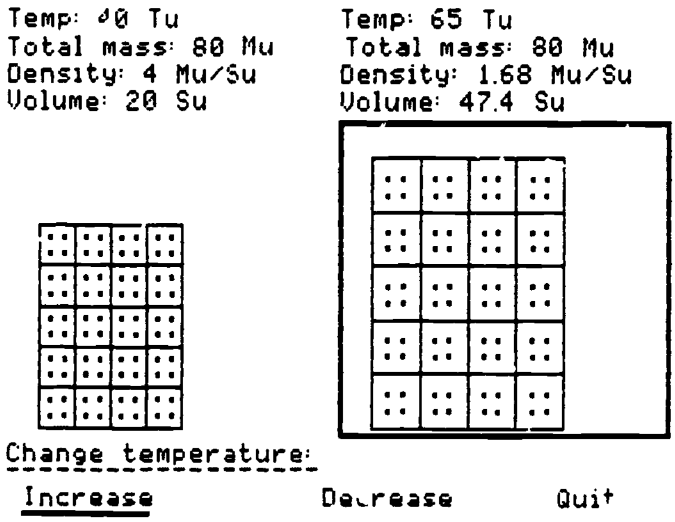
Figure 4. An object made of blue material (density 5wu/su) that has a space inside it is suspended in orange liquid (density 4wu/su)

Our fifth simulation focuses on the effect of thermal expansion on the density of materials and required some revisions to our conceptually enhanced model. The process of revising our model to accommodate this new phenomenon illustrates again some of the choices faced by model builders in the selection of the elements of a visual representation.

We decided that the new model should be built so that the previous model was included in it as a special case, to facilitate understanding of the new model by students. A new option in the menu allows for temperature change. When the temperature is changed, the pictorial representation shows a change in the size of the object in a relatively straightforward manner (i.e., the block which represents the object grows larger). Since it is still made of the same material, its color stays the same; and since it is still the same weight, the number which represents the block's weight also stays the same. Thus, these aspects of the visual and numerical representations allow students to observe what they can observe in parallel classroom experiments. No changes in the pictorial or numerical model systems are necessary.

It is at the level of the conceptually enhanced representation, however, that changes in the model are called for. In our earlier model, we had discrete quantitative representations for size, weight, and density. In addition, material kind was also represented in terms of density (the number of dots per unit size). In our new model, all three quantities are still precisely (and quantitatively) represented, but only the representation of weight remains discrete. Further, there are now distinct representations for material kind and density.

More particularly, when an object expands due to changes in temperature, our revised model shows the number of dots stays the same, but they are spread out in a bigger object (see Figure 5). There is no longer an explicit representation of standard size units. Hence, differences in both size and density can be visually apprehended but not discretely counted (bigger objects look bigger, but one can't directly count a symbol on the screen to tell exactly how much bigger; denser objects are more crowded with dots, but again, one can't directly count some symbols to determine density). Weight is still represented quantitatively as the total number of dots in the block; and material kind is still represented as the number of dots per block. Although different from the previous model, this representation is valid in the sense that, as before, there is a precise mapping of the relations between the visual symbols (and program code) and the real entities.

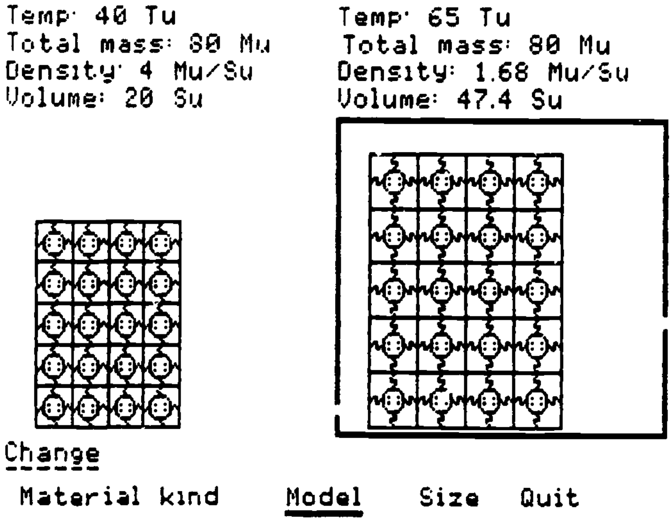


```
Temp: 40 Tu               Temp: 65 Tu
Total mass: 80 Mu         Total mass: 80 Mu
Density: 4 Mu/Su          Density: 1.68 Mu/Su
Volume: 20 Su             Volume: 47.4 Su
```

Figure 5

We did not represent size units explicitly in our new model because we thought it would unduly clutter the screen and even obscure the main points we wanted to convey to students. These main points were that size becomes larger and density decreases when an object expands while being heated. This can be shown in a qualitative way (as mentioned above) by having the outline of the box expand and the dots in the box spread out. In contrast, if one were to superimpose a grid of standard size units on the enlarged object, one has the problem that the boxes would not contain the same number of dots. This is because the density calculations for some of the objects now involve fractions instead of simple whole numbers, and these fractional values cannot be simply portrayed in terms of dots per box. Thus, we chose to keep the visual depiction simple and qualitative and to rely on numerical representations for quantitative information about size and density.

As students consider how the computer model needs to be revised to account for thermal expansion, questions naturally arise about the choices we made in model building. To highlight these issues about choices in model building, we also created a different model of thermal expansion. In this second model, objects are depicted as being made of different materials (where different materials are represented as standard size circles filled with different numbers of dots). The circles represent units of material and are connected to other units with spring-like links. When the temperature changes, the units stay the same, but the distance between these units becomes larger (see Figure 6). In this new model, matter is made of units; each unit has a different weight and the overall density of an object is a function of two parameters (the distance between the units and the number of dots per unit, or kind of unit). This model essentially provides students with a microscopic model of the phenomenon of thermal expansion. Since our program contains both models, and allows students to choose the type of model they wish, it essentially allows students to move among three types of models: pictorial models and two types of conceptually enhanced models (microscopic models and models representing a set of interrelated concepts).


Temp: 40 Tu
Total mass: 80 Mu
Density: 4 Mu/Su
Volume: 20 Su

Temp: 65 Tu
Total mass: 80 Mu
Density: 1.68 Mu/Su
Volume: 47.4 Su

Figure 6

EPILOGUE: ON DESIGNING ACTIVITIES TO INCREASE THE EDUCATIONAL VALUE OF CONCEPTUALLY ENHANCED SIMULATIONS

The purpose of this paper has been to analyse the types of model systems typically used in science education and to alert educators to the potential importance of a new type of model system: a computer-based analytic model which provides an explicit representation of the concepts that scientists use to understand a phenomena. The dynamic model is implemented in such a way to let students directly manipulate these conceptual entities. In the preceeding section we have discussed the structure of such a model system. There, we also proposed that the conceptually enhanced simulation should have other modes of representation (e.g., pictorial, verbal, numerical) for relevant aspects of the phenomena. These should all be synchronized in order to maximize the simulation's effectiveness in facilitating the process of conceptual change. Indeed, we believe one of the unique advantages of building computer-based simulations lies in their ability to have such multiply linked representations and hence in their ability to help students create links between different representations for a phenomenon in their own minds.

However, simply providing the availability of a conceptually enhanced model or multiply linked representations as a tool for science teaching does not guarantee its effectiveness or proper use by students . In fact, a crucial aspect of their design concerns detailed thinking about the ways students will use (or potentially misuse) such simulations in classroom activities. In concluding, therefore, we would like to highlight three aspects of curricular design that we think will prove crucial to ensuring the effectiveness of such simulations as tools for provoking conceptual change, consolidation and elaboration. (Note: a more detailed discussion of the important ways of teaching with these computer models will be provided in a subsequent paper. This paper will describe the curriculum units we have developed for use with this software.)

A first crucial element in activity design concerns integrating (interrelating) computer and laboratory model systems. As mentioned above, the computer is designed to add another dimension to the laboratory activities: one in which the concepts involved in understanding a phenomenon are made explicit. Students therefore need activities in which they use the computer to model real life laboratory situations, and, conversely, where they construct laboratory situations to match what they have observed on the computer screen. For example, students might experiment with making a real object float in a given liquid and then create an analogous situation on the screen by choosing the right combination of materials for the liquid and the object to make it float. Or they might examine the effects of changing an object's size first in the lab and then using the computer simulation. Conversely, beginning with the computer simulation, students can be introduced to a situation in which an object floats even though its total weight is greater than the total weight of the liquid in which it floats. Their challenge is then to create a situation in the real world where this happens, finding the special combination of materials and container size and shape necessary for this to occur. In these ways, the student may come to understand more deeply the importance of density rather than weight or size alone in flotation.

One second set of activities concerns the interplay among the verbal, pictorial and conceptual representations on the screen. First, students manipulate the simulated events through the verbal dimension. Since all the user options offered by the software are displayed through written verbal commands, the student needs to relate to the terminology in order to control the program. By itself, this will not make them understand the concepts involved, but we believe that developing a precise and more differentiated vocabulary supports the process of making conceptual change. For example, in a simple activity, students are asked to build objects and then change the SIZE or DENSITY by using the right verbal menus. In a more complicated task, they are asked to make an object that is less DENSE than a given object presented on the screen but which WEIGHS more.

Another set of activities involving the interplay of multiply linked representations concerns the interplay between the pictorial and the conceptual representations on the screen. Although we have designed our software so that students can go back and forth between conceptual and pictorial representations of the same phenomena, we have found that students (if left to their own devices) may not use the software in this way. Rather, they may stay simply in the pictorial representation (perhaps because it is pretty and has nice colors). Thus, we think it is critical to design activities in which students need to coordinate the different representations in order to be successful. For example, they need to be given tasks in which they must manipulate the pictorial object WITHOUT SEEING THE PICTURE, but instead seeing only the conceptual representation . In this way the student must constantly translate between conceptual and pictorial representations of a phenomena. In our own sink/float software, for example, students can be given the task of making objects that will float in a liquid. They may first design the objects (using the conceptually enhanced representation of object and liquid) and then experiment to see whether their object really floats. Another nice example of such an activity is found in the Thinkertools software (White and Horwitz, 1987) where students have to move an object from one place to another by using only the information given in the data cross that provides a conceptual representation of the number and direction of past shots of momentum that have been applied to an object. Significantly, White and Horwitz found in their work that their simulation was effective in bringing about conceptual change only when students were forced to link representations in this way. Simply providing them with multiple representations was not enough, since students frequently did not use them.

A final crucial element in activity design concerns the need to discuss explicitly with students how one goes about building and interpreting models, and the choices one makes in model design. The models we chose, like any model, are arbitrary in certain respects and highly constrained in others. The models are designed to capture relational rather than surface similarities. One danger in using such relational models is that the learner may take the elements of the model at face value and think that they provide a direct "picture" of reality.

This problem is fundamental to any use of models, especially models which are portraying theoretical entities or conceptual relationships. For example, in the case of our conceptually enhanced simulation, students might erroneously believe that steel is a material kind made up of three fundamental particles (because we represent steel as the three dots per box material) while alumunium is a material kind made up of one basic particle (because we represent aluminum as a one dot per box material) . Thus, any serious science teaching which implements the tools of models and analogies must include discussion of the very nature of models as an integral part of the subject matter. In science classes, students should be expected to examine the questions: What is a model? Is the model the truth? What kinds of entities is the model designed to represent? What makes something a useful, or valid model?

In other words, in presenting models, we are telling only part of the truth, and we have an obligation to tell the truth about that. We must make it clear that a model is not the whole truth. The fact that one can build computer simulations which are based on different, equally valid models provides an excellent opportunity for teaching students about the constructive nature of scientific inquiry and highlighting how different models and frameworks can be used to guide inquiry.

REFERENCES

Barton, R.F. (1970). Simulation and Gaming (p.6). Englewood Cliffs, New Jersey: Prentice Hall

Carey, S. (1985). Conceptual Change in Childhood. Cambridge, MA: MIT Press.

Carey, S., Evans, R., Honda, M., Jay, E., Unger, C. (1988). What junior high school students do, can and should know about the nature of science and scientific inquiry. Educational Technology Center Technical Report No TR88-2. Cambridge, MA: Harvard Graduate School of Education.

Choi, B., & Gennaro, E. (1987). The effectiveness of using computer simulation experiments on junior high students' understanding of the volume displacement concept. Journal of Research in Science Teaching, 24(8), 539-552.

Clement, J. (1987). Overcoming students' misconceptions in physics: The role of anchoring intuitions and analogical validity. Proceeding of the Second International Seminar on Misconceptions and Educational Strategies in Science and Mathematics. Ithaca, New York: Cornell University.

Driver, R. & Erikson, G. (1983). Theories in action: Some theoretical and empirical issues in the study of students' conceptual frameworks in science. Studies in Science Education, 10, 37-60.

Gallagher, J. (1987). A summary of research in science education - 1985. Science Education, 71(3), 307-457.

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. Cognitive Science, 7, 155-170.

Gentner, D. & Toupin, C. (1986). Systematicity and surface similarity in the development of analogy. Cognitive Science, 10, 277-300.

Goodman, N. (1965). Fact, Fiction, and Forecast. Indianapolis: Bobbs-Merrill.

Keil, F. (in press). Concepts, Word Meanings, and Cognitive Development. Cambridge: MIT Press.

Kuhn, T.S. (1960). The Structure of Scientific Revolutions. Chicago: University of Chicago Press.

Larkin, J. (1983). The role of problem representation in physics. In D. Gentner & A.L. Stevens (Eds.), Mental Models. Hillsdale, N.J.: Lawrence Erlbaum. pp 75-98.

Murphy, G.L. & Medin, D.L. (1985). The role of theories in conceptual coherence. Psychological Review, 92(3), 289-316.

Nesher P. (1987). Microworlds in mathematical education: A pedagogical realism. In L.B. Resnick (Ed.), Knowing and Learning. Issues for a Cognitive Science of Instruction. Hillside, NJ: Lawrence Erlbaum Associates.

Rowell J.A. & Dawson C.J. (1977). Teaching about floating and sinking: An attempt to link cognitive psychology with classroom practice Science Education, 61(2), 243-251.

Smith, C., Carey, S., & Wiser, M. (1985). On differentiation: A case study of the development of the concepts of size, weight and density. Cognition, 21, 177-237.

Snir, J. (1988). Sink or float? What do the experts think? or: The historical development of explanation for floatation. (submitted for publication)

Wellman, H. (1986). First steps in the child's theorizing about the mind. Paper presented at the International Conference on Developing Theories of Mind, Toronto.

White, B.Y. & Horwitz, P. (1987). Thinker Tools: Enabling children to understand physical laws. Cambridge: BBN Laboratory Report.

Wiser, M. (1986). The differentiation of heat and temperature: An evaluation of the effect of microcomputer teaching on students' misconceptions. Educational Technology Center Technical Report No TR87-5. Cambridge, MA: Harvard Graduate School of Education.

Wiser, M., Kipman, D., & Halkiadakis, L. (1988). Can models foster conceptual change? The case of heat and temperature. Educational Technology Center Technical Report No TR88-7. Cambridge, MA: Harvard Graduate School of Education.

SOFTWARE AND CURRICULUM REFERENCES

Clay Boats Unit: Teachers Guide for Clay Boats, (orig. 1969). Education Development Center (Copyright). Webster Division of McGrawHill Book Co. (republished 1986). Delta Education, Inc. (Copyright). Nashua, NH: Delta Education, Inc.

Measurements: Length, Mass, and Volume, (1984). Blake, J. & Grenetz, C.S. (Authors). Garden City, New York: Focus Media Inc.

Operation: Frog, (1984). Goldhamer, A. & Isenberg, S. (Authors). New York: Scholastic, Inc.