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Author: Raghavan, Kalyani; Kesidou, Sofia & Sartoris, Mary

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A Model-Centered Curriculum for Model-Based Reasoning in Science

Kalyani Raghavan, Sofia Kesidou, & Mary Sartoris
Learning Research & Development Center, University of Pittsburgh
Pittsburgh, PA 15260,U.S.A.

ABSTRACT

Researchers have found that physicists and skillful problem solvers possess a hierarchically organized knowledge base, and typically use qualitative model-based reasoning to analyze and explicate real world phenomena. To facilitate students' use and understanding of models as a primary disciplinary resource, we designed a model-centered curriculum. This curriculum focuses on a network of concepts important for understanding hydrostatics. Traditional curriculums have students perform experiments with concrete materials in the laboratory, immersing objects in a liquid and measuring the displaced volume of the liquid to verify Archimedes' principle. But these experiments do not readily provide sufficient explanatory leverage because many of the important elements of a full explanation (for example, buoyant force), cannot be directly observed. The curriculum includes many of these traditional-style experiments with laboratory materials, but coordinates them with a set of interactive computer programs that support inspection and direct manipulation of the underlying theoretical entities. This paper reports results of a pilot study conducted with middle school students that tracked their initial ideas about forces in fluids and the conceptual changes and development that occurred as they progressed through the last three units of the curriculum.

INTRODUCTION

National projects working to reform science education, like the Scope, Sequence, & Coordination Project, the National Science Education Standards Project, and Project 2061, recommend that science education become less concerned with details and facts and more concerned with overarching themes or the "big ideas" of science. It is generally agreed that students should learn more about less. That is, it is more important to empower students to think and to build understanding than to present them with a wide variety of information at the acquaintance level.

Many of these projects explicitly advocate model-based reasoning as a means of facilitating analysis and comprehension. Studies have shown that physicists and skillful problem solvers possess a substantial, hierarchically organized knowledge base, and typically use qualitative, model-based reasoning to analyze and explicate real world phenomena (Chi, Feltovich, & Glaser, 1981; Clement, 1991; Larkin, 1983; Mestre, 1992). Hestenes (1987, 1992) has advocated a model-centered approach to science teaching, and researchers have found it to be a successful teaching strategy (Andaloro, Donzelli & Sperandeo-Mineo, 1991; Halloun & Hestenes, 1987; Heller & Reif, 1984).

In cognitive psychology, research on modelling has focused on how learners' mental models can affect subsequent learning (Gentner & Stevens, 1983; Johnson-Laird, 1989; White & Frederiksen, 1986) and on how physical or pictorial models can be used in instruction to facilitate comprehension (Clement, 1982; Mayer, 1989). Research has shown that children often have undifferentiated concepts that are difficult to correct. Much of the recent research on the use of interactive models for learning science has been aimed at conceptual differentiation, for example distinguishing weight from density (Smith, Snir, Grosslight, & Frenette, 1986), heat from temperature (Wiser, 1987), and velocity from acceleration (White & Horwitz, 1987). Such work has focused on a single difficult concept or pair of concepts and not on a set of interrelated concepts that comprise an explanatory system. Dynamic causal models are introduced as intermediate abstractions, designed to serve as temporary conceptual anchors for explicating the target concept.

Project MARS (Model-based Analysis and Reasoning in Science) has been involved in the development and implementation of a model-centered science curriculum for middle school students. Unlike previous interactive models that focused on a single difficult concept or a pair of concepts, this curriculum focuses on a rich network of concepts important for understanding hydrostatics. The curriculum provides students with the opportunity to learn how to use models to engage in extended and increasingly complex forms of reasoning within a rich but bounded topic area. Using this curriculum, we have begun to investigate how students come to understand and use models as a primary disciplinary resource to engage in complex chains of reasoning that require integrating concepts into networks of relations and transferring models to novel situations within the same explanatory system.

There are a few important concepts that have great explanatory power across a variety of situations such as balance of forces or conservation of energy in physical science. These foundational ideas, therefore, need to be conveyed and carefully developed as intellectual anchors. However, an emphasis on developing such ideas as conceptual anchors does not appear to be typical of standard science texts for elementary and secondary school levels. Rather these texts, while filled with information, lack coherence, placing more emphasis on facts than understanding, whereas in science, as in many fields, meaning and understanding emerge from the patterns and relationships that link isolated observations and facts. For example, although middle school science texts use floating and sinking to motivate discussion about relative density, the underlying mechanism that links density with the observable phenomena of floating or sinking is not typically considered. Prerequisite concepts are often introduced in unrelated portions of the text, separated from the discussion of floating and sinking by as many as 100 pages. In addition, textbook explanations generally include several “holes” that a student would have to fill, either by relying on prior knowledge or by generating inferences. One text, for example, interrupts its discussion of why some things float and others sink with a brief paragraph that tells the usual story of how Archimedes jumped out of the bathtub when he solved the “problem of buoyancy.” However, the text never explains what the problem of buoyancy is or what it has to do with floating and sinking. The “explanation” of floating and sinking is that objects denser than water sink. What forces are exerted on objects that are immersed in fluids, and why? What factors make a difference in the magnitude of these forces? How are the densities of the object and liquid related to these forces? These questions are typically not addressed, and, consequently, the explanations of floating and sinking provided in most middle school texts are largely at a very superficial level. Furthermore, the diagrams used in these books are static, inert representations of specific states of the phenomenon and are inadequate to motivate chains of inference or to link the theory with intuitive, qualitative understanding. They depict one state of the phenomenon whereas multiple states may be needed to clarify the changes in the phenomenon.

In the traditional science classroom, students perform experiments with concrete materials in the laboratory, immersing objects in a liquid and measuring the displaced volume of the liquid to verify Archimedes’ principle. But such experiments do not readily enable students to *understand* Archimedes’ principle because many of the important elements of a full explanation (for example, buoyant force, density of objects and fluids) cannot be directly observed.

Fostering the kind of conceptual understanding needed to appreciate science requires that students be able to redefine, reorganize and elaborate their existing concepts through interactions with objects and events in the environment. They should interpret objects and phenomena and subsequently explain phenomena in terms of their current conceptual understanding. This involves identifying their current conceptions and providing a means of challenging them through discrepant events, experiences that conflict with students’ existing ideas leading to a realization that their current explanations are inadequate, and providing students with experiences that suggest alternative ways of thinking about the phenomenon and with opportunities and time to construct a conception more adequate than the previous one.

In the MARS curriculum, we are attempting to create an environment conducive to fostering conceptual understanding and reasoning sensibly about scientific phenomena that involve “balance of forces” by creating visual representations that concretize abstract ideas, and by making them dynamic and interactive. The curriculum includes many of the traditional-style laboratory experiments, but coordinates them with a set of interactive computer programs that support direct inspection and manipulation of the underlying theoretical entities. The programs introduce and make available as tools a library of manipulable representations for such basic constructs as surface area, volume, mass and force. These "primitive level" models can be used to generate predictions and explanations about the results of changes in simple systems (cf., Sherwood, Chabay, Larkin, Reif, & Elyon, 1991). For example, in one unit, a student uses the force arrow model on the computer to depict the applied forces and the resultant force when magnets are brought near a magnet held in place by springs on a forceboard. The student learns to manipulate the arrow to make and test predictions about how the mounted center magnet will move. Such model primitives can in turn be combined to support inferences about the behavior of more complex systems. For example, a model depicting an object immersed in a liquid incorporates simpler models as components. Students are free to inspect and manipulate familiar models of volume, surface area, density and force as they work to build predictions and explanations of floating and sinking.

Thus, an important and unique feature of this curriculum is the notion that models can be combined into more complex models. This feature was adopted because it accurately reflects the structure of the subject matter. In addition, such a structure supports the development of model-based reasoning. Traditional science instruction rarely uses models beyond the purpose of illustration. Students are not taught how to *use* models to analyze and solve problems. Without a context to motivate transfer and application of learned models, model-based reasoning can scarcely develop. The MARS curriculum has therefore been structured deliberately so that a student will learn a model in one of the simpler contexts and go on to encounter new and more complex situations where the application of that model continues to provide conceptual leverage. Therefore students encounter models not merely as instructional illustrations, but as reasoning tools which give them the power to solve problems in a variety of contexts.

The organization of the curriculum units is illustrated in Figure 1. The experimental curriculum devotes three units of instruction to each of the three central concepts, and, in addition, certain units portray important relationships among two or more concepts as illustrated by Figure 2. The numbers in Figure 2 correspond to the units where these concepts are presented. In the mass unit, for example, students must coordinate density and volume in order to decide which of two objects has more mass.

The MARS curriculum represents an attempt to provide model-centered science instruction which teaches students how to use models to understand a complex network of concepts and to analyze phenomena involving a balance of forces. This paper describes the motivation for and design of the curriculum units on forces in fluids, buoyancy, and floating and sinking and reports the results of preliminary testing of these units.

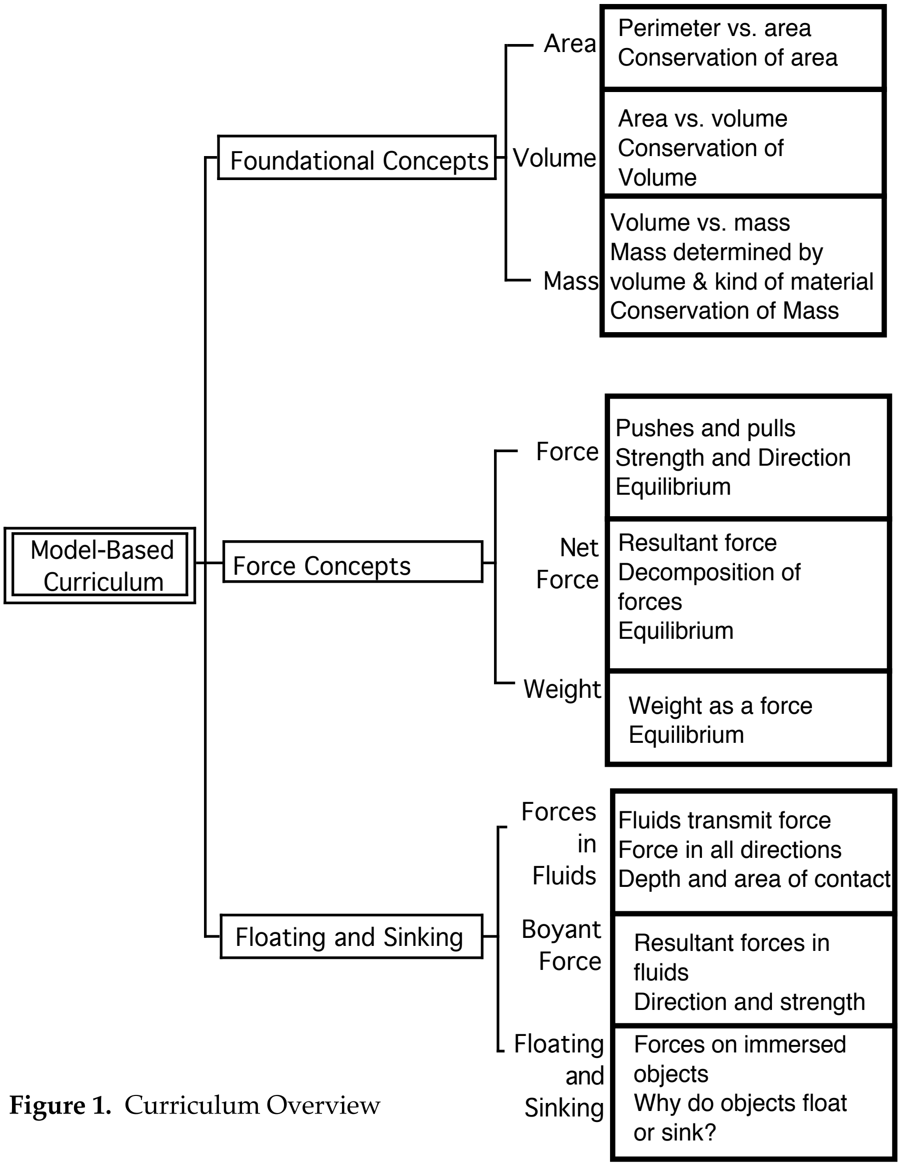


Figure 1. Curriculum Overview

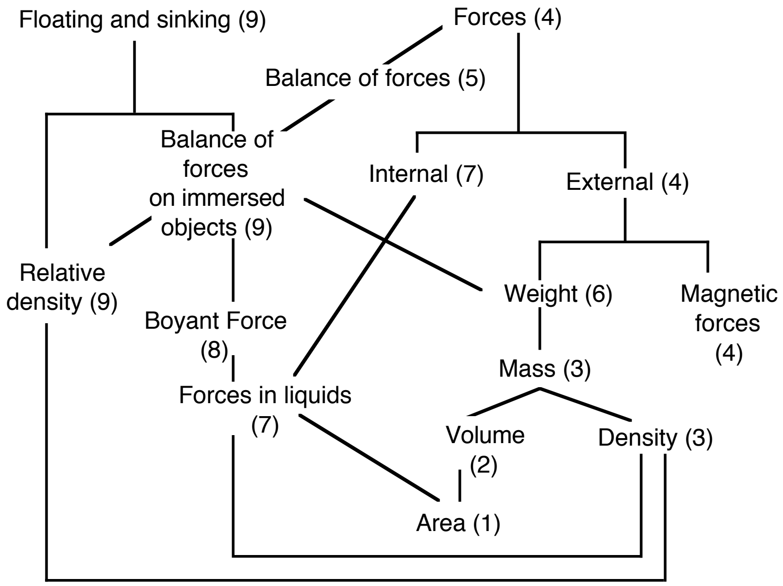


Figure 2. Concept Map

CHILDREN'S CONCEPTUAL UNDERSTANDING OF FORCES IN FLUIDS

An understanding of forces in fluids is necessary in order to explain floating and sinking using the idea of balance of forces. Although there are no studies specifically on students' understanding of forces in fluids, there have been a number of studies on a closely related topic, children's understanding of fluid pressure. These studies typically explore students' conceptions of the idea that pressure in liquids increases with depth and is equal in all directions. Further, in studies on air pressure, students' conceptualizations of the word "pressure" are investigated.

Sere (1982) reviewed some of the frameworks used by 11 to 13 year olds in the interpretation of air pressure prior to instruction on physical properties of gases. She found that most students could not imagine pressure without associated movement; they did not "believe that air, when immobile, exists, is present, and acts" (Sere, 1982, p 308). Sere interprets these results as indicating that students conceive of a direct, causal relationship between force and motion and therefore cannot imagine that air exerts forces in the absence of visible movement.

Clough and Driver (1985, 1986) investigated 12 to 16 year old students' understanding of pressure in a liquid, particularly that it increases with depth but is the same at any given depth. The majority of students had the notion that pressure increases with depth in liquids, but they tended to view pressure as a vector, or unidirectional, only acting downward. Only a small proportion of students correctly thought of pressure as a scalar quantity, acting equally in all directions. Some students asserted that the downward pressure is greater than the horizontal pressure, and a considerable number of students thought the total volume of liquid influences the pressure in that liquid. Excerpts from the student interviews provide some insights into the models that students possessed of the causes of pressure in liquids. For example, students often identified the air on the water as the main cause of downward pressure. In addition, students frequently associated horizontal pressure with movement in the liquid. In general, students possessed a dynamic model of pressure, rather than a static model; that is, pressure was viewed as involving action or motion. Their explanations frequently included such expressions as "pushes through," "hits," "comes up" or "gets down."

Giese (1987) reported similar results with 14 year olds. She found that many students thought that pressure increases with depth. However, only very few students thought that pressure at a given depth is equal in all directions. She also encountered the belief that horizontal pressure at a point on an object is directly proportional to the horizontal distance from that point to the nearest boundary of the container of water.

Kariotogloy, Psillos, and Valassiades (1990) asked lower secondary-school students to predict and/or interpret phenomena related to liquids. They classified the results according to the properties and features students attributed to the word "pressure." They list three conceptualizations of pressure that their students possessed:

(i) the packed or anthropomorphic conceptualization, according to which pressure is greater in a narrow container than in a wide one;

(ii) the pressing-force conceptualization in which "pressure" is used as a synonym for "force;" and

(iii) the liquidness conceptualization according to which pressure is conceived as a property of liquids.

The pressing force conceptualization was the most widely used by students whereas the liquidness conceptualization appeared least frequently in students' work.

In summary, middle-school and junior-high students appear to conceptualize air and water pressure as something dynamic, associated with movement, and to use "pressure" as a synonym for "force." Students who believe forces do indeed exist in the absence of movement are likely to say such forces are downward only. Those who think horizontal forces exist are likely to assert that downward forces are stronger. These ideas apparently persist despite relevant instruction.

THE EXPLANATORY SYSTEM

In the history of science, at least three alternative explanations of floating and sinking have been posed (Snir, 1991). However, our emphasis in this instructional context is an explanation based on "balance of forces." This explanation requires a qualitative understanding of water pressure at different depths, buoyancy, density, and the relations among these concepts. It is, therefore, necessary that students recognize that fluids transmit forces, that these forces are transmitted equally in all directions, and that the strength of forces in liquids increases with depth and with the density of the liquid.

Once students grasp these fundamental ideas, they can realize that, because the bottom surface of an immersed rectangular object is always at a deeper level than the top surface, the upward force due to the liquid on the bottom will always be stronger than the downward force on the top. The resultant of forces exerted by fluids on an immersed object will therefore always be upward. The strength of that resultant force will depend on the volume of the object and the density of the liquid. When an object is immersed in a liquid, there is a buoyant force upward and a gravitational force downward. The buoyant force will be greater than the gravitational force on the object when the density of the liquid is greater than the density of the object, and the object will float. The gravitational force will be greater than the buoyant force when the density of the object is greater than the density of the liquid, and the object will sink.

Accordingly, the explanatory system underlying the units on forces in fluids, buoyancy, and floating and sinking in the MARS curriculum is based on such concepts as force and gravity (weight), the transmission of forces in liquids, and the equilibrium of forces. The concepts of force and gravity and the equilibrium of forces are introduced in earlier units. From these elements of the explanatory system, further inferences can be drawn and predictions can be made about properties of forces in liquids.

The MARS curriculum deviates from traditional instruction in hydrostatics by focusing on the concept of force instead of the concept of pressure. This approach reflects a commitment to emphasize the central concept of "balance of forces," to limit the number of new concepts and terms introduced, and to try to build upon students' prior conceptions. As evidenced by previous studies, when students interpret phenomena involving liquids, they typically ascribe to pressure the meaning of force. Moreover, by focusing on a few basic but powerful concepts, our goal is to provide students with the tools that will allow them to not only build coherent models of hydrostatics, but which can also be repeatedly applied to a broad range of phenomena. Force is such a basic and powerful concept, and so a significant portion of the curriculum is devoted to introducing, modelling and providing students with opportunities to reason with the concept of force in a variety of contexts.

A second basic but powerful component of the explanatory system is the idea of transmission of forces in liquids. The Forces in Fluids unit introduces the idea that when a force is applied to some portion of a liquid, this force is transmitted to every other portion of the liquid. To illustrate this concept and to help dispel some student misconceptions about the magical properties of air, computer activities require students to predict the force due to air or atmosphere on an imaginary boundary considered at different depths within a container of a liquid. Students receive feedback on their predictions which show that this force is the same everywhere as long as the boundary area remains the same. Transmission of force is thus presented as an essential property of liquids, and it is used extensively in all of these units.

An important feature of the Forces in Fluids unit is the *column model*, which is used for explaining the different component forces exerted by liquids. The column model provides students with a visual representation of the downward force due to a liquid on a bounded area as a result of the weight of the liquid above that area, and that the magnitude of this force is directly proportional to the area of the boundary, the depth of the boundary below the surface, and the density of the liquid. Students are first introduced to the computer column model in response to their prediction about the downward force due to a liquid on a boundary surface. Students drag rectangles which serve as boundaries, delineating specific areas of liquid(s) at a selected depth into containers of the liquid(s) and predict the downward forces on these areas at the selected depths. They are then shown the column models as illustrated in Figure 3. Each column model depicts the column of liquid above this bounded area and students can deduce the weight of the column of liquid using previously learned relationship between volume , density, mass, and weight.

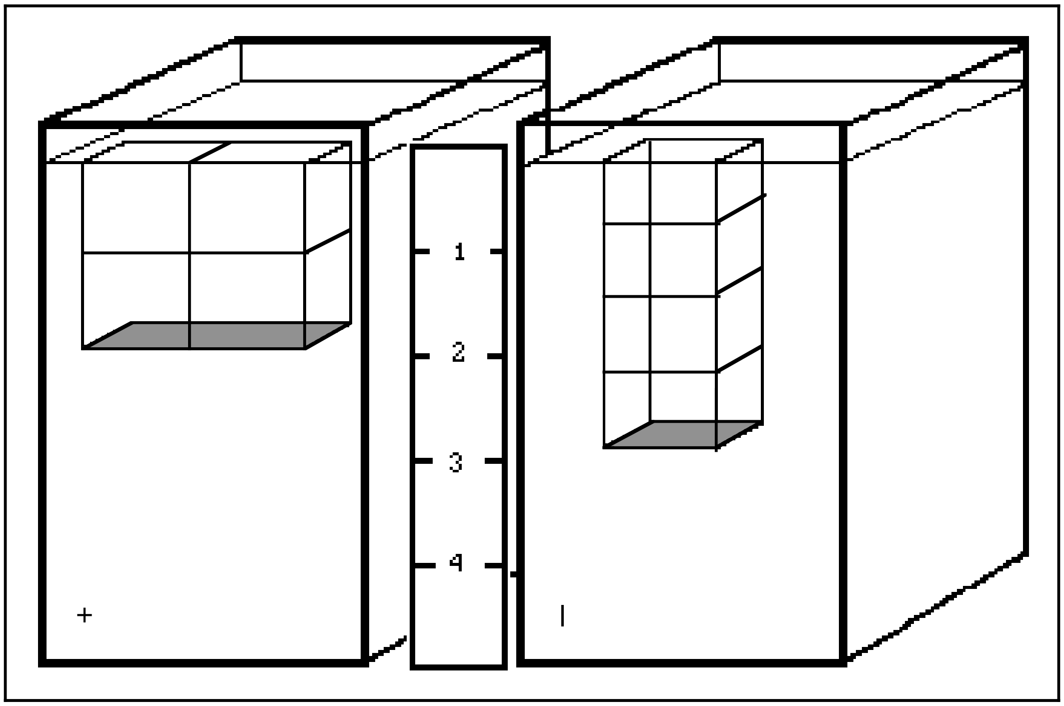


Figure 3. Column model (| and + indicate densities of liquids)

The equilibrium of forces model introduced in the earlier units is then exploited to derive other properties of forces in liquids. For example, the equilibrium model supports the inference that the magnitudes of the downward and upward forces on a specified area of a motionless liquid are equal. Students can use this model to explain that the magnitudes of upward and downward forces on liquid boundaries of the same surface area and at the same depth are equal. The column model, in conjunction with the equilibrium of forces model then provides the explanatory leverage needed to understand buoyant force and to realize why an object floats or sinks in a liquid.

METHODS AND ACTIVITIES

A science teacher from a cooperating middle school provided a site for the formative evaluation of the curriculum as each unit was developed. These prototype tests helped us not only to iron out design problems but also to explore instructional interventions that were particularly helpful in enabling students to develop robust mental representations of abstract concepts. These evaluative sessions have permitted us to observe how students learn to map observations of actual objects and events onto isomorphic objects and events in the computer environment, how students use alternative representations of the same constructs, and how they generate strategies for solving problems with these representations. Eight student volunteers participated in all of the unit pilot tests, which were conducted individually in seven 40-minute sessions over a period of two months. An experimenter introduced the tasks and provided support and scaffolding through questions.

The instructional materials for all units included: (1) a set of coordinated demonstrations and experiments with physical objects. These activities were designed to provide students with experiences that would enable them to infer that forces in liquids are exerted in all directions and that the magnitude of these forces change with depth. (2) a set of interactive computer programs which provided manipulable representations of abstract concepts underlying real-world phenomena. In the computer activities, students can use arrows to predict or explain forces acting on the system. The program then simulates a model of the student's view of the system and a model of the actual view. These activities focus on forces due to air, forces due to liquid, buoyant force, and how the buoyant force counteracts with the gravitational force. The screen interface for each activity consists of two rectangular containers filled with water or a fictitious yellow liquid. Students can drag one of four rectangular surface boundaries or one of eight rectangular solid objects into each container. By selecting Model World, students can see the bounded areas of liquid divided into area units, the objects divided into volume units, and/or representations of the density of the liquid and objects. Students make predictions by placing force arrows and adjusting their magnitude and direction. When a student's model is "run," the computer responds with appropriate feedback.

The Forces in Fluids unit consists of four parts, including transmission of forces in liquids, downward forces in liquids, upward forces in liquids, and horizontal forces in liquids. This is followed by units covering buoyant force as the resultant of the forces exerted by a liquid on the different faces of an immersed object and floating and sinking as determined by the net force on an immersed object.

Prior to instruction, students were asked a series of questions designed to probe their initial ideas regarding forces in fluids. As they worked through the units, students were periodically asked to explain their conclusions and to describe the differences and similarities between the phenomena presented to them.

Hands-on activities

This section briefly describes the hands-on activities in which students participated. These activities were coordinated with appropriate computer activities to encourage mapping between the two sets of activities and were used to elicit student explanations.

1. Waterbed. In this demonstration activity, students are introduced to the idea of transmission of forces in liquids. As the experimenter pushes downward on a plastic bag filled with water, the student is asked to place her hand at various locations on the top, bottom and sides of the bag to feel a corresponding force.

2. Tubes with holes. In these activities students explore the idea that downward and horizontal liquid forces exist, and that the magnitude of these forces increases with depth. A transparent plastic graduated cylinder with four tiny holes plugged by toothpicks is filled with a certain amount of water. Three of the holes are vertically spaced near the bottom, middle and top of the jar. The fourth hole is diagonally across from the middle hole. When the

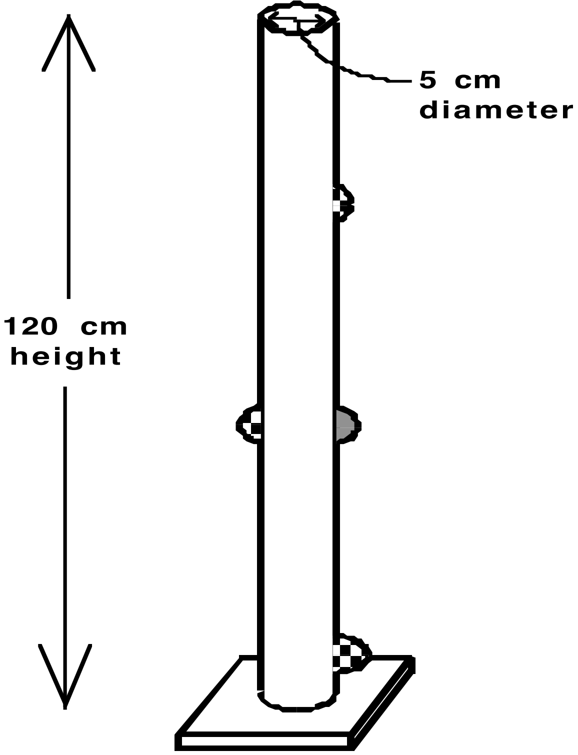


Figure 4. Tube with membranes

toothpicks

are removed, water spurts out of the holes. In one activity, students observe differences in how the water spurts out of the holes with different levels of water in the jar. In a related activity students are shown a tall Plexiglas tube with circular holes near the top, middle and bottom of one side, and with a fourth hole at the middle level on the opposite side as shown in Figure 4. The holes are covered with rubber membranes which bulge when the tube is filled with water. The membrane at the bottom bulges most, the two membranes in the middle bulge less, and the top membrane bulges least. Although the two activities are similar in structure, the second activity seems to make it easier for students to infer the forces that are exerted by the water.

_**3. The funnel**. In this activity, students explore the idea that upward and horizontal forces are exerted in liquids and that the magnitude of such forces increases with depth. The wide end of a glass funnel is covered with balloon material, and a length of transparent plastic tubing is attached to the narrow end as shown in Figure 5. The funnel and tubing are partially filled with colored water. Students press on the balloon material and observe a rise in the level of the colored water inside the tubing. Next, the wide end of the funnel is pointed downward and gradually lowered into a container of water so students can observe the rise in the level of the colored water. The deeper the funnel is immersed, the higher the colored water rises. Last, the funnel is held in a horizontal position and gradually lowered into the container. Again, the level of the colored water inside the tube rises.

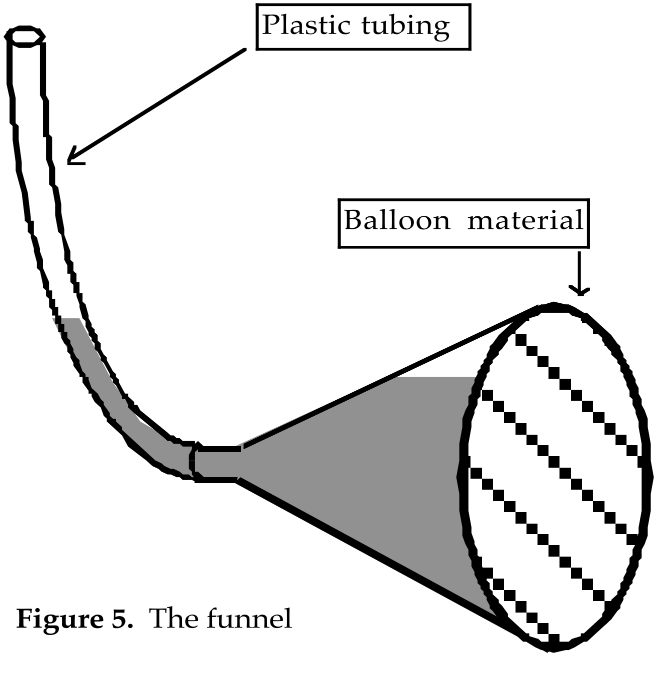


Figure 5. The funnel

4. The coin and tube. This activity provides a second demonstration of the existence of upward forces in liquids. In addition, this activity invites students to reason with the equilibrium of forces model. The experimenter holds a hollow glass tube, approximately 1 cm in diameter, with a coin pressed securely against the bottom opening. As the student watches, the experimenter holds the coin in place with one finger and slowly lowers the tube into a container of water until it is almost fully immersed. The experimenter's finger is then taken away from the coin, yet the coin does not sink. Even when the experimenter raises the tube a bit, the coin remains securely pressed against the bottom of the tube. The experimenter slowly continues to raise the tube, and students see that, at some point before the coin reaches the surface of the water, it dislodges and sinks.

Computer activities

The computer activities provide an exploratory environment in which students can manipulate visible representations of abstract ideas and concepts. Students view liquid-filled containers and perform experiments to determine whether and how forces in liquids are influenced by such factors as container size, depth and kind of liquid. Students use force arrows to represent their predictions about what forces are exerted and the magnitude and direction of these forces.

1. Modelling forces in liquids. Students view two liquid-filled containers. Rectangular boundaries permit students to "draw lines in water," *delineating specific 2-dimensional portions of the liquid*. By selecting a boundary and positioning it within one of the containers, students can explore the forces acting on that bounded area of liquid (see Figure 3). The boundaries come in two sizes--one has twice the surface area of the other. They can be placed at different depths, in different positions relative to the sides of the container, in different-sized containers and in different kinds of liquid.

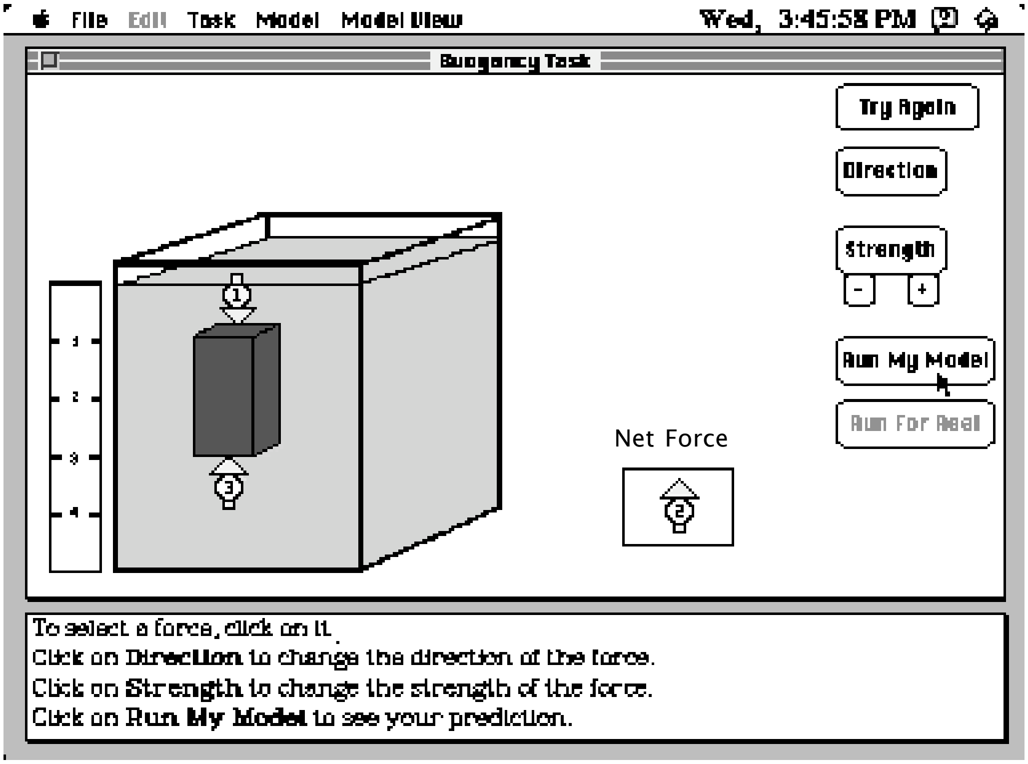
Students are provided with force arrows, one color representing forces due to air, and another to represent forces due to liquid. Students can adjust the direction of the arrow to model an upward or downward force, and they can increase or decrease the strength, indicated by a number in the center of the force arrow. Students use force arrows to represent a prediction, and they receive feedback indicating whether or not the prediction is correct. As additional feedback, the column model is displayed, encouraging students to think about where the forces come from (i.e., the weight of the column of liquid above a bounded area) and why their prediction is correct or incorrect. Students are given two opportunities to revise incorrect models before the correct forces are displayed.

One segment of the program provides vertically-oriented boundaries with which students can explore horizontal forces due to air and liquid. The purpose of this segment is to demonstrate to students that the horizontal forces (left, right, front, or back) exerted by a liquid on surfaces of the same area at the same depth are all equal and depend only on the area of the surface.

Instead of force arrows, students use representations called push/pull puppies to depict horizontal forces. These can be pointed toward the left or right (depicting the direction of the force), and the strength can be adjusted qualitatively by selecting one of two sizes, large or small (depicting the magnitude of the force). Students are thus able to make qualitative predictions regarding horizontal forces in liquids.

As students set up experiments, model their predictions and receive feedback, they are able to see that forces in liquids are exerted in all directions. They are able to observe that forces due to liquid do not change with container size, but do increase with surface area, with depth and with the density ("heaviness") of the liquid. They can also see that force due to air does not change with depth, size of container or kind of liquid, but does increase with surface area. Finally, they are able to see that the upward and downward forces on a horizontal boundary and the leftward and rightward forces on a vertical boundary are equal in strength and opposite in direction. In other words the model demonstrates that in a stationary liquid, the forces on any bounded area are in equilibrium.

2. Modelling buoyant force. In this component of the unit, the computer screen depicts a single liquid-filled container and four rectangular solid objects. Students select one of the objects and drag it into the container. They are asked by the experimenter to ignore the weight of the object itself for the time being and to focus only on the forces due to the surrounding liquid acting on the object and to investigate how all those forces combine. The activity is divided into three parts. First, students predict the horizontal forces, then they predict the vertical forces, and, finally, they are asked to figure out the resultant of all of the forces (Figure 6). The term "buoyant force" is introduced in the feedback message as the resultant upward force exerted by the surrounding liquid on the object. Students are thus shown that liquids always exert an upward force on immersed objects.



To select a force, click on it.
Click on **Direction** to change the direction of the force.
Click on **Strength** to change the strength of the force.
Click on **Run My Model** to see your prediction.

Figure 6. Sample screen from Buoyant Force computer task

3. Modelling floating and sinking. The final unit integrates all the features of the previous units. Students use the computer model to perform experiments to figure out why objects float or sink when they are immersed in a liquid. The objects vary in volume and kind of material, and there are two liquids. Students use force arrows to indicate the magnitude and direction of the forces exerted on the immersed object (the buoyant force and the gravitational force). They then predict whether the object will float or sink by specifying the magnitude and direction of the net force (Figure 7). Feedback consists of an animated simulation of the student's model--the object floats up or sinks down in accordance with the student's predicted net force--and a simulation of what would happen in the real world. Students then have the opportunity to either revise their model or to proceed with another experiment.

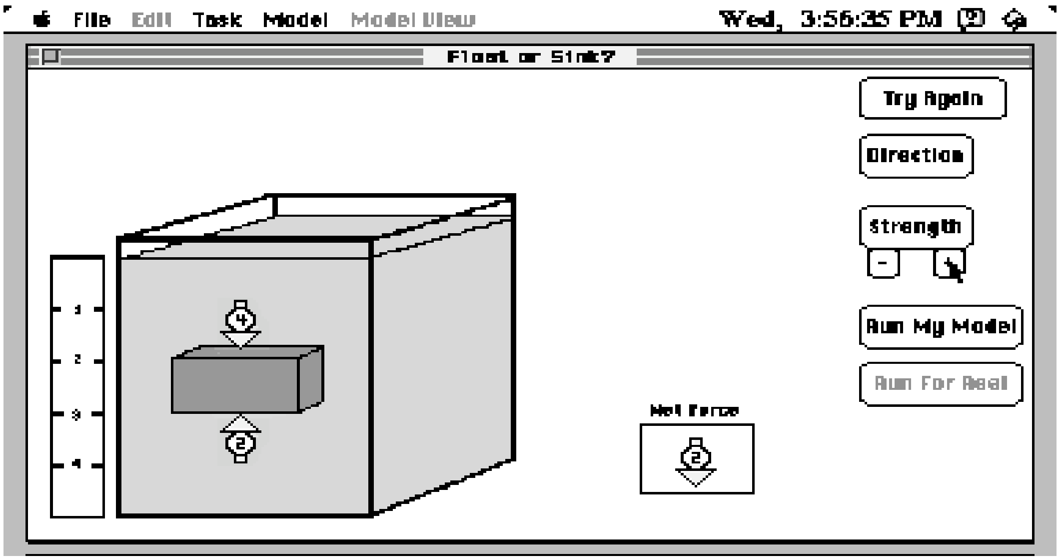


Figure 7. Sample screen from Floating and Sinking computer task

Procedure

The purpose of the hands-on activities was to encourage students to develop an initial understanding of the concepts and terminology underlying the computer activities. The hands-on tasks typically followed a "predict-explain/observe/explain" sequence. This included presenting the students with a physical situation, asking them to predict and explain what will happen if a certain action is taken, then demonstrating the action and requiring the students to observe and explain any discrepancy with their initial ideas.

Each task started with open questions. For example, before the buoyant force unit, students were shown a drawing of a cube suspended from a spring and asked to draw a picture of the same spring and the cube when immersed in water and to explain their drawing. Our main intention was to help students articulate their own models. However, in the second part of the task, we also guided students' attention by particular "leading" questions towards the aspects we were interested in because of our interest in identifying probes that would help students to develop or revise their models. Three types of interventions were attempted. First, at specific points in the interview we asked the students to explain a phenomenon using the concepts and models explored in previous units of the curriculum. For example, if students had not explained the situation presented to them using the concept of balance of forces, the experimenter reminded them to do so. Second, we encouraged students to evaluate new data they collected or new observations they made in light of their current conceptions. Third, we encouraged students to construct analogies between experiments similar in structure, and to draw inferences in the form of predictions or explanations from these analogies.

The purpose of the computer activities was to observe if and how students developed or revised these ideas as they explored the units. We were particularly interested in students' strategies for predicting forces and their interpretations of the computer models. Students initially worked on each computer activity in an exploratory mode for a certain period of time. They were then asked to work through a predefined set of problem situations. At the end of each session, the interviewer probed the student's understanding by asking questions focusing on an analogous hands-on activity. Subsequent to the forces in liquids activities, for example, students were asked the following questions about the differences in the bulging of the membranes in the tall Plexiglas tube (Figure 4):

1. Why do the two membranes at the middle level bulge the same amount?

2. Why do the membranes at different levels bulge more or less than the middle membranes?

3. How would the amount of bulging differ if there were two tubes of different diameters which were otherwise identical?

4. How would the amount of bulging differ if there were two identical tubes filled with different liquids? In addition, we wanted to investigate how students' strategies and interpretations of the models developed during the tasks.

Such questions were designed to see whether students were able to apply their newly-acquired models to reasoning about real-world phenomena. Finally, students were asked to explain how they can decide if an object will float or sink in a given liquid using the column model. Students were thus encouraged to see that whether an object floats or sinks depends entirely on the relative densities of the object and the liquid in which it is immersed.

RESULTS AND CONCLUSIONS

In this section we will first describe students' initial ideas about forces in liquids, buoyancy, and floating and sinking. Particular attention will be devoted to describing students' explanations regarding the origin of the downward, upward and horizontal forces in liquids. This will be followed by an examination of changes in students' ideas which occurred during the course of their experience with the curriculum and a discussion of likely reasons for those changes.

Students' initial conceptions about forces in liquids

As mentioned earlier, many of the initial activities were designed to elicit students' ideas about forces in fluids including whether or not such forces exist, in what directions they act, and what factors make a difference in the strength of these forces. The ideas these students expressed are quite consistent with results reported in related literature. Most students said there are downward forces in liquids, and that their magnitude increases with depth. Only a few said there are upward or horizontal forces. Of those, some thought the upward force will decrease with depth. Some said the horizontal forces are not affected by depth, but are affected by the distance from the container wall. Many students thought the size of the container made a difference in how strong the forces in liquids were. Some students said a larger container would result in greater force. However, a few said just the opposite, explaining that, in a smaller container, the liquid is more compact, resulting in greater pressure.

One particularly informative question required students to explain where the forces in liquids come from. Some had dynamic models of forces in water, explaining that without motion, such as bubbles or currents, there are no forces in water. Several students said the forces in liquids come from water pressure, but they did not know where water pressure comes from. Some explained that forces arise because liquid in a container is compressed. These same students expected smaller containers to have greater force, and many of them also expected proximity to the container wall to make a difference, because forces are stronger near the sides and bottom of the container.

Many students described the downward force as resulting from the air pushing down on the surface of the liquid. Some of these students explained that gravity is in the air or "comes from the atmosphere" or "is all around us," confounding gravity with air pressure. A few described the air as pushing down into the liquid to the bottom of the container and bouncing off the bottom upwards. Consider, for example, the following attempt to explain why the funnel shows pressure increasing with depth (see Figure 5): "When the air is pushing on the top, it (the air) all goes down to the bottom and then pushes it(the funnel) up, but when it (the funnel) is on the top of the water, there is not as much pressure, because it (the air) all, it went, like, it used up all its energy on the bottom."

Only one student correctly explained that forces in liquids result from the weight of the water above pushing down on the water below. Asked about the tube-with-membranes (Figure 4), he explained that the bottom membrane bulges more because it has more weight on it. However, when asked what would happen if the middle level had only one hole instead of two, he said it would bulge more than it did, explaining that the amount of pressure depends not only on the weight of water on top, but also on the amount of space available.

Students' initial conceptions about buoyancy

To get at their concepts of buoyancy, students were shown a cube suspended from a spring and asked what would happen when the cube-on-a-spring were immersed into a container of water. Most students predicted that the spring would stretch less in water than in air, and several stated that the water would push the cube upward. However, only few students could offer coherent explanations as to why this occurred. Some students explained that the spring will stretch less in water than in air in terms of changes in gravity which occur under water. One student, for example, said that, in water, "the gravitational pull would not be as strong." Another student said that the gravity pulling on the cube would "have more energy" in water "because it has the water with it, too." Immediately thereafter, she said that water pressure is upward and said she wasn't sure what would happen to gravity because she didn't know "how the water pressure and the gravity go together." A third student stated that water pressure pushes on all faces of the immersed cube and that the upward pressure on the bottom is greater. When asked to elaborate he explained that the forces on the sides and downwards were all the same strength but the upward force is greater and "there is not gravity under water."

Students' initial conceptions about floating and sinking

The coin and tube activity examined students' ideas about floating and sinking. Most students had no trouble deciding that the coin alone would sink in water, explaining that the coin is heavier than water. Some even stated that the coin is made of a denser kind of material than water. However, asked to explain why the coin does not sink in the second case when the coin and tube were held together under water, students could often offer no explanation. One boy tried, explaining that the coin sticks to the bottom of the tube because "the oxygen in the water pushes up" and "traps it when it is rising," but he couldn't explain why the oxygen pushes harder when the tube is present than when the coin is alone. Another student explained that the coin stays "because of the pressure pushing down on it (water), and the water is trying to find every other way to get out from the pressure."

In summary, students made accurate predictions but they had specific misconceptions about forces in fluids and gravity as evidenced from their explanations. They were not always initially aware that upward and horizontal forces are exerted. Even the few students who were aware had incorrect notions of the magnitude of these forces. Some thought that the magnitude of the upward forces increased with the amount of liquid below an object and some students thought that the magnitude of the horizontal forces increased with the amount of liquid between an object and the nearest container wall. A large proportion of students thought downward forces in liquids were exerted mainly by the air pushing down on the liquid. The idea was often due to students' lack of differentiation between air pressure and gravity. A large proportion of students thought the magnitude of forces, in particular horizontal forces, in liquids depended on the amount of space available for the liquid to occupy. Thus, forces in liquids were stronger when the liquid had less space available. Again, although intuitively most students knew that objects weigh less in water than in air, they attributed this to some property of gravity or air.

Students’ conceptions after instruction

The explanations students offered at the end of these three units reflect changes in a number of ideas. None of the students, for example, asserted that there are no forces in liquids without motion, currents or bubbles. Fewer students identified air or air pressure as the agent of forces in liquids. And more students explained that forces in liquids are caused by the weight of the liquid or by gravity pulling on the liquid.

All students appear to have benefitted from the activities of the units. In particular, six out of eight students developed the target model for downward forces in liquids, namely that forces on a surface within a liquid are due to, and depend upon, the weight of the column of liquid directly above the surface. In addition, five students developed an understanding of the connection between upward forces and downward forces in liquids; that is, that upward forces counter-balance the downward forces exerted in liquids due to the air and due to gravity. This idea is consistent with the idea of transmission of forces in liquids. Furthermore, all eight students developed strategies and heuristics for making quantitative predictions about downward and upward forces in liquids. In some cases, students’ quantitative predictions were made on the basis of the column model presented and the deep understanding they had developed during the unit on forces in liquids. In other cases, students manipulated the model to come to correct quantitative predictions without a clear understanding of the model and the concepts involved.

Although all students realized that upward and horizontal forces are exerted in liquids, some still could not offer coherent or consistent explanations for *why* such forces are exerted. Some students continued to believe that the strength of the upward force depends on the amount of liquid beneath the area in question, apparently envisioning the column of liquid under the boundary even though the feedback on the computer always displayed only the column above.

Even some of the students who learned to consider the column of liquid above the boundary when calculating the upward force did not seem to understand why. One student, for example, explained that the column above the boundary shows “how much it has to push up through.”

During the computer activities, students were quite adept at learning the quantitative “rules of the game.” Seven of the eight students learned to make consistently correct predictions, appropriately adjusting the strengths of the force arrows to account for depth, surface area and density of the liquid. They were much less proficient at grasping the qualitative point of the model. Asked if the column model made sense, most said yes, and proceeded to describe the quantitative procedure they used to get the correct answer. Asked, however, to explain what the column model represents or why the procedure works, some students were unable to offer coherent explanations or to connect the computer model to the real-world phenomena it is supposed to represent.

The hands-on activities and the interventions facilitated an understanding of the computer representations. Some students appeared to have acquired mental models about forces in liquids which were close to the models presented on the computer. These students developed their models as they were prompted to give predictions on the basis of thir current models, to revise their models on the basis of new observations, to construct analogies between phenomena of similar structure, and to reason with concepts and models taught in previous units in the curriculum. In contrast, students who had not developed such ideas before working with the computer activities could not construct adequate mental models of forces in liquids only on the basis of the computer activities.

One student, for example, learned to correctly predict upward and downward forces due to air and water. She explained that depth doesn’t make a difference to the force due to air. When asked why, she offered the following explanation:

“I don’t think it would matter for depth, because for air...when air pushes down on it (the imaginary boundary in water), it doesn’t matter how...um...it--it matters how much...the unit is, but...the depth doesn’t matter because it doesn’t take...any more force from the air to push down on it then it would...for...low depth--er...high depth.”

However, she contradicts herself a little later when the interviewer showed her a drawing of the tube with membranes (Figure 4):

I: Can you explain, on the basis of what we just did, why these pop out less and these more?

S: OK. Well, I think, um...that this one would--that’s all water, isn’t it?

I: Yes.

S: So, I think that this one would...Gee, this is hard. Um...Um...the air pressure would be greater there, I know. I don't know why. I'm trying to think.........I don't remember. I don't remember things very well.

I: Why is force due to the air higher here than here?

S: Well, let's see...I know it's higher, but...well, if I had a hypothesis, I would say that this (top membrane) would be bigger than this (bottom membrane).

I: Why?

S: Because, um...the air would...um...it gets to here first (top membrane) so...

I: Let's try to see how what we learned here (computer model) applies. What did you learn about force due to air?

S: That it doesn't matter about the depth. Just how many units.

I: So does force due to air explain this tube?

S: Um........for the depth...well...for this one...it sort of looks like it *does* matter because...this one is...it...it differs by depth. It differs by depth.

I: But we learned here (computer) that air doesn't change with depth. So if we were to stick to that and really believe it, would air explain what's happening with the tube?

S: Mmmmmm.....

I: Yes or no?

S: Well, it...I think so.

I: How? If air doesn't change with depth?

S: Oh! I see! Then it wouldn't matter about the air--it would be the water pressure that would explain...

I: Exactly. And why does water pressure change with depth, do you remember?

S: Oh! I remember now!

I: Tell me.

S: Because there's more...um...there's more water up here (above bottom membrane) than there is here and here.

I: Which water are you counting? At this (bottom) level, which water are you thinking of?

S: The water above it.

I: And here (middle)?

S: And there's less water above that one. I get it. I remember.

The above interchange leads to an interesting question: What causes students' ideas to change?

Instructional strategies for supporting conceptual change

Based on our interviews during these sessions, we have identified three instructional strategies that can facilitate conceptual change.

1. Accounting for observable phenomena based on current conceptions.

Students developed their models of phenomena as they attempted to resolve discrepancies between predicted and observed outcomes about phenomena. For example, in the tube with holes activity, most students predicted that the water would travel less far if both toothpicks at the same level were removed than when only one toothpick was removed. After observing that the water travelled the same distance in both cases some students could not come up with an alternative explanation to account for the discrepancy, or they did not understand why their prediction was wrong and ended up confused. However, when students were reminded of a previous explanation they had provided, they appeared to resolve the conflict between their predictions and the observed outcome as illustrated by the following dialogue between the experimenter and a student:

S: Well, it is coming out of one hole, it has only a small place to come out, so it is forcing it a lot more, there is no other place to go, but if there are two holes, it has two places to come out.

E: Let's see (demonstrates)

S: It's the same. That's weird. I was wrong.

E: Before you said that gravity is pushing down on the water and then the water is pushing out. Would the force of gravity change if we had two holes there or would it be the same?

S: It is the same.

E: So, does this tell you something about the two pushes?

S: Oh well. If gravity stays the same then it wouldn't be different amount of pressure.

2. Reasoning with previously learned concepts.

In some activities, students were prompted to think through the equilibrium of forces model to make predictions and give explanations about whether upward forces were exerted on given boundaries in liquids, and if yes, what was the magnitude of these forces. For example, if a student thought there were no upward forces exerted on a given boundary in a liquid, the experimenter asked what would happen to this boundary if only a downward force was exerted on it. Similarly, if a student recognized that an upward force was exerted on a boundary, but thought its magnitude was different from the magnitude of the corresponding downward force, the experimenter asked what would happen to the boundary if two forces with different strength but opposite direction were exerted on it.

As a result of this prompt, several students developed their ideas about upward forces in liquids. For example, four out of eight students in the context of forces due to the liquid concluded, after this prompt, that forces in liquids balance out and downward forces on a surface area are equal to upward forces on the same surface area. In fact this intervention may also be useful in encouraging students to develop their ideas about horizontal forces. For example, a student initially predicted that the magnitude of horizontal forces in liquids increased with distance from the nearest container wall. However, after thinking through the equilibrium model, she concluded: "If that was the case, then the liquid would not be in balance since two opposite forces of different strength would be exerted on the surface area." Evidently, taking students through similar argumentations may prompt them to revise quite persistent ideas such as that the magnitude of horizontal forces in liquids increase with the size of the liquid container.

However, it is worth noting that although some students appeared to recognize the logical necessity of upward forces in stationary liquids balancing the downward forces, they indicated they were confused because they did not understand where these forces came from. It appears that, although the equilibrium model made ideas about upward forces intelligible, it did not always make them plausible to students (Posner, Strike, Hewson, & Gertzog, 1982). This is because the equilibrium model does not entail an explanation of how forces arise in liquids.

3. Constructing analogies between phenomena.

At specific points in the interview, we encouraged students to draw inferences from phenomena they understood in order to make predictions or construct explanations about phenomena which they could not yet explain. For example, we asked the students to identify similarities between the following phenomena:

When a downward force is exerted on a plastic bag filled with water, upward

and horizontal forces are exerted from the water on the bag (source analog nitially presented).

When a funnel covered with elastic material at its bottom and filled with
colored water is immersed in water, the colored water rises in the funnel
(target analog presented later).

The purpose was to encourage students to infer that the upward force on the bottom of the funnel arises as a result of a downward push on the water. Four out of five students who initially did not believe that upward forces were exerted in liquids due to the air, inferred that such forces were exerted in liquids after thinking about the transmission of forces in the plastic bag filled with water. Secondly, students who did not think there were upward and horizontal forces in liquids realized that upward and horizontal forces are exerted in liquids as a result of downward forces.

To summarize, there are at least three kinds of interventions which lead students to change their ideas: reminding about their current conception, asking questions which cause them to focus on and think about a key concept they know, and using analogies. These interventions exposed students to phenomena that their current ideas cannot explain, to view phenomena from alternative perspectives, to explain phenomena logically, and to apply a key concept to different situations.

An important conclusion to be drawn from these results is that hands-on activities need to be carefully integrated with computer activities. Although the curriculum design included integration of hands-on activities with appropriate computer activities, due to time constraints in this trial, most of the hands-on activities were grouped together in the first session. Consequently, the insights gained from them were forgotten by the time students encountered the relevant computer model. The funnel task, for example, contradicted some students' notion that upward forces decrease with depth. Two sessions later, however, when students encountered upward forces in the computer model, they had apparently forgotten the funnel experience, because they again expected upward forces to decrease with depth. It is therefore important that the hands-on activities be carefully integrated with the tasks involving computer models.

Integrating the hands-on and computer model activities would also help students transfer the computer model back to the real world. Students often learned the "rules" of the computer model but were not inclined to apply them in the real world. It might help to devise some bridging activities which would help students build connections between the computer models and real-world phenomena. To provide this link, students should be made to answer the questions asked initially during the hands-on activities on the basis of the knowledge they have since developed.

Our work with the students also suggested some content-specific implications for the curriculum. First, we were successful at encouraging students to use the idea of transmission of forces to draw inferences about forces exerted in liquids in all directions. Indeed, reasoning with this idea made plausible for students the idea that upward and horizontal forces both due to the air and due to the liquid's weight are exerted in liquids.

Second, students had deep-rooted misconceptions about gravity and air pressure. Students frequently confused the two-. In the units dealing with force concepts, further effort should be made to help students distinguish between weight as a force exerted by the earth and not by air. Experiments which separate the effects of gravity from the effects of the surrounding air would be helpful (see for example, Minstrell, Stimpson & Hunt, 1992). Introducing an air-column model in the forces in fluids unit may also help students overcome this confusion. As noted earlier, students sometimes thought the force due to air increased with depth. Displaying the same column of air pushing down on the liquid, regardless of the depth of the surface, may reinforce the idea that the force due to air does not change with depth. It may also help students who do not think a force is exerted from air to develop their ideas about the weight of air pushing down.

Third, more time should be devoted to horizontal forces in liquids. Our work indicates that misconceptions associated with these forces persist. Introducing a column model for horizontal forces may be helpful. The model would indicate that horizontal forces depend on the weight of the liquid column on a surface which has a depth equal to the "average" depth of the surface area on which the force is exerted. The area of the two surfaces, of course, should be the same.

In conclusion, this evaluative study yielded some very encouraging results. Through the course of exposure to the MARS curriculum, students did experience some conceptual changes and development. While the changes were not as long-lived as we would like to have seen, nor the developments as far-reaching, there is sufficient reason to hope that a model-centered curriculum such as this can help students learn to use models as tools for analyzing and understanding scientific phenomena.

IMPLICATIONS AND FUTURE DIRECTIONS

Our studies to date have focused on how students use the models within individual units of instruction. Since the units are designed to be cumulative, however, more interesting questions can be addressed once the instrumentation is completed. At that time, we will be in a position to conduct one or more short-term longitudinal studies to learn how students negotiate the entire instructional sequence, beginning with models of basic concepts which are then used to model predictions and explanations of novel and increasingly complex situations. The MARS curriculum offers an extended reasoning context that will afford the opportunity to study not only how students learn new models, but also how they learn to use those models as reasoning tools and to transfer them to new contexts. Short-term longitudinal studies will permit investigation of how students coordinate such basic concepts as area, volume, density and force in reasoning about more complex situations embodying Archimedes' Principle. Equally important, we will have the opportunity to observe students as they gradually acquire an understanding of the characteristics and usefulness of scientific models themselves.

Working in the classroom, we will be able to supplement the observational focus of this work with some experiments on instructional manipulation. This experimentation will be directed toward exploring instructional strategies that promote model-based reasoning. Researchers in the area of analogical reasoning have been experimenting with various strategies for promoting what Brown (1989) calls "cognitive flexibility," the spontaneous access and use of an analogy in a novel but appropriate context. Such work obviously parallels our goal of promoting the appropriate utilization and transfer of a model.

This work holds promise both as educational practice and as psychological method. From the perspective of educational practice, we have already noted the growing national consensus on the importance of developing educational contexts that can support significant reasoning in science. Such contexts must go beyond reciting facts and equations to engaging students in extended thought and creative problem solving. Moreover, model-based reasoning, although frequently used by scientists, is rarely the direct focus of science instruction. Much remains to be learned about not only how this form of reasoning develops, but also how to encourage it. Our work is an integrated exploration linking the design and development of an instructional intervention with the detailed and deliberative study of the processes by which students gain the ability to reason with science models.

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