Appendix

Problem Set Answers

Action Research Guide

Related Reading List

Credits

Course Readings

Problem Set Answers

Session 2

1. Session 2 introduces the four basic principles of the particle model of matter. Explain how each of these contributes to a microscopic explanation of what happens when you compress a closed syringe filled with air.

The four principles of the particle model are as follows:

Principle	Relation to compressing a closed, air-filled syringe
All matter is made of tiny, invisible particles.	Air is transparent, which explains why you can't see it in the syringe.
There is empty space between particles.	When the syringe is compressed, the particles are simply squeezed closer together. There is less empty space, but all the particles are still there.
Particles are in constant motion.	Particles of the air will move in straight lines until they collide with another particle or the walls of the container. It is the pressure that results from these collisions which you feel as resistance to compressing the syringe past a certain point.
There are forces between particles.	Without these forces—attractive at large distances and repulsive at short distances—particles will not "bounce" off each other when they get close to each other. If the forces were only attractive and the particles were not in motion, all the particles would gather into a clump inside the syringe.

2. What are the characteristics of a good scientific model and how does the particle model show these characteristics?

A good scientific model represents something too big, small, or complex to easily comprehend, explains a range of phenomena beyond the ones used to develop it, and is as simple as possible. The particle model represents the behavior of particles too small for us to experience directly. As we will see in later sessions, it aids our understanding of many phenomena, including physical and chemical changes, rising and sinking behavior, and the changes that result from the addition of heat.

3. Why does water "beading" on a windshield help support the idea that there are forces between particles?

We see the macroscopic phenomenon of different drops being "pulled" together as they move down the windshield. If we accept the existence of particles, this macroscopic phenomenon must have some microscopic explanation. The simplest explanation is that there are forces between all particles of water, even those in different macroscopic drops. The small forces between individual particles add up into the (relatively) larger force that pulls drops together.

4. In the video, Russell Springer's students, with the help of another teacher "Mr. O," acted out a life-sized model to help them understand the microscopic phenomenon of Brownian motion. Explain how Brownian motion works using this model.

In the classroom model, the students represented the water molecules, which are invisible even under the microscope. They moved around in random directions, as we assume water molecules do in a drop of water. "Mr. O" represented the larger oil particles, which we could see under the microscope. As the students moved around and bumped into him, Mr. O traced out an erratic pattern similar to that of the oil drop seen under the microscope. Thus, the zigzag pattern (Brownian motion) of oil droplets is a result of collisions with constantly moving, invisible water molecules.

Session 3

1. In Session 3, a distinction is made between boiling (a physical change) and burning (a chemical change). On a particle level, how would you describe the difference between boiling and burning?

Boiling is a physical change, and therefore involves only a rearrangement of the original particles. In the case of boiling water, the water particles go from being packed closely together to being more spread apart because they are moving faster. All the particles that were there originally are still there. In contrast, burning a piece of wood changes something about the particles—the original particles are *not* still there. As we shall see, a chemical change involves tearing particles apart and combining them into new substances.

2. At the end of Session 3, an equal amount of alcohol and water are combined and then shaken in a container, resulting in a liquid with less volume but the same weight as before they were mixed. Is this an example of a physical or a chemical change?

Dissolving alcohol into water is an example of a physical change. Although it may seem different from dissolving a solid like salt into water, the particles of each substance (salt or alcohol) are all still present, but are just mixed into the spaces between the water molecules. Thus, the change conforms to the microscopic definition of a physical change. This change is also reversible: in a way similar to desalinization—water is evaporated and salt is left behind—if the alcohol/water solution is heated, the alcohol will evaporate first and leave the water behind. Therefore, the change conforms to the macroscopic definition of a physical change.

3. An iron rod is sealed inside a mold that is put in a high temperature furnace. The rod melts inside the mold and turns into liquid. The hot liquid iron is then allowed to cool until it becomes a solid rod again. The new rod is then removed from the mold. What difference do you think there is between the original rod and the new rod? Explain your answer.

a. **The new iron rod is lighter than the original rod.**
b. **The new iron rod is heavier than the original rod.**
c. **The new iron rod is the same weight as the original rod.**
d. **The iron rod is lighter when it's a liquid than when it's a solid.**
e. **The weight of the rod depends on how long the iron took to cool.**

The answer is c. This is an example of the reversibility of a physical change. All the original particles were simply rearranged into a liquid (by adding heat) and then rearranged again into a solid (by allowing the matter to return to room temperature). Since no particles were added or lost (the mold was sealed), the mass and therefore the weight would not change at any step along the way. Mass conservation holds in a physical change.

4. A copper wire is heated and turned into liquid. After a while, it cools down and becomes solid again. What changes do you think have taken place? Explain your answer.

a. **The copper turned into another metal after melting.**
b. **Some of the copper turned into another metal after melting.**
c. **A large amount of copper turned into another metal after melting.**
d. **The solid is still all copper.**
e. **There is not enough information to answer the question.**

The answer is d. Again, this is an example of a physical change. If the material had changed into another metal, this would mean that the particles were no longer copper particles and we'd classify the change as a chemical change.

Session 4

1. Explain the differences and relationships among these terms: element, molecule, atom, and compound.

An element is a substance wherein the smallest particle that still can be considered that material is an atom. A compound is a substance wherein the smallest particle which still can be considered that material is a molecule. Molecules are made of two or more atoms of different elements. Simply put, the particles which that make up a pure substance, which we defined in the video as substance that can not be separated into simpler substances, are either atoms or molecules, but not both.

2. In the video, the hosts mixed plaster of Paris with water, let it harden, and then tried to repeat the process with this hardened product and water. What was the macroscopic evidence that a chemical reaction had taken place? If we had a powerful microscope, would we see microscopic evidence that a chemical reaction had taken place? Answer the same questions for the "cheese candle" that the hosts burned at the end of the program.

Macroscopically, the mixture heated up and it started to change consistency, becoming rigid. If we could observe the microscopic process, we'd see the particles of plaster either combining or swapping particles with water molecules, leaving behind different particles than were there originally. (The total number of atoms would be the same, however, so mass is still conserved.)

In the case of the burning cheese candle, the release of heat (as well as smoke) and the fact that the candle slowly gets smaller are both indicators of a chemical change. On a microscopic level, we would observe particles of cheese being broken down and combined with particles of oxygen from the air. As with the plaster of Paris, we would end up with different particles than we started with, but the total number of atoms would be conserved.

3. How is Geoffroy's affinity table different from Mendeleev's periodic table? What is the usefulness of each?

The affinity table shows how two substances will react when they are placed together. This allows us to predict the outcome of particular interactions. The periodic table is a chart of individual elements, organized by the structure of that element's atoms. Although there is no explicit statement of how the elements would react with other materials, their placement in the chart is indicative of their general chemical behavior. As a result, the periodic table could be considered to be more general and useful than an affinity table, since it enables us to make predictions about how an element will react with all other elements, rather than just one element at a time.

4. Why is the example of electrolysis of water a good demonstration of the law of fixed proportions? How can we be sure that this ratio of two hydrogen to one oxygen holds true even down to the smallest particle?

The law of fixed proportions states that all materials are composed of a simple ratio of different atoms. In our particle language, this means that every particle of a particular material is made of a specific number of whole atoms. Therefore, if we take a substance—for example, water—and break it down into its constituent elements, we will have perfect ratios of the new elements. Since water breaks down into two gases (oxygen and hydrogen), the volume of the gases reflects the number of particles that we have of each. If every water molecule has twice as many hydrogen atoms as oxygen atoms, the products of our chemical reaction, electrolysis, should also have twice as much hydrogen as oxygen. We believe this ratio to hold down to the smallest particle because we can repeat the electrolysis experiment with any amount of water, and still always have the same 2:1 ratio.

5. Tony has a double-pan balance. On one pan he places a container of water and an Alka-Seltzer tablet. On the other pan he places a container of water and puts an Alka-Seltzer tablet in the water. What do you think will happen to the pan holding the fizzing Alka-Seltzer?

Although mass is conserved in any chemical reaction, the pan with the fizzing tablet is changing some of its mass into gas, which then floats away into the air. Since the weight of the escaped mass is no longer pressing down on the pan, the other pan is heavier and goes down, while the pan with the fizzing tablet goes up. As more gas escapes into the room, the weight of the fizzing container of water will continue to decrease.

Session 5

1. As official crown inspector for the kingdom of Kerplackistan, you are asked to determine if R. Fink, the king's new crown maker, really used the 500 grams of gold given to him to craft a crown for the king. When you receive the crown, it does indeed have a mass of 500 grams, but you suspect R. Fink of mixing lead with the gold. You measure the volume of the crown by immersing it in water and find it to be around 33 cubic centimeters, and you know that the density of gold is 19.3 grams/cubic centimeter. Did R. Fink cheat the king by mixing his gold with lead?

We know the density of lead is less than the density of gold if R. Fink really used some lead as well as gold, then the density of the crown is less than 19.3 g/cm^3 and we've caught a rat.

$$D = M / V$$
$$D = 500 \text{ g}/33 \text{ cm}^3$$
$$D = 15.1 \text{ g/cm}^3$$

The density of the crown is less than pure gold, so we know R. Fink did cheat the King.

2. In the video, Steve Bailey explains how some fish use a swim bladder to change their behavior from sinking to rising. When they do this, are they changing mostly their mass or volume? How does a submarine change its behavior from sinking to rising? Does it change its mass or volume?

Changing behavior from sinking to rising involves decreasing the density of an object. Recall density = mass/volume, so either mass, volume, or both can change to cause a change in density. A fish changes its density mostly by increasing its volume. (Adding air to its swim bladder does add mass, but not a significant amount.) By making its volume greater, it lowers its density and the fish rises. A submarine, on the other hand, is made of metal and cannot change its volume. Thus, it must change its mass and does so by pumping water in or out of its holding tanks. Pumping water out of the submarine makes its mass decrease which lowers its density, causing the submarine to rise.

3. How would you explain why it takes the same amount of force to hold an object under the water at any depth?

A liquid, like all matter, has weight, which is the force with which the Earth pulls the liquid downward. If we think of this liquid in terms of particles, the particles on the top layer are pulled downward by their own weight. The particles in the layer underneath get pulled downward by their own weight, but also have an additional downward push on them from the layer above. Thus, as an object is taken to a deeper level, the weight of more and more liquid above it causes the pressure on the object to increase. (If you don't like this explanation, put a bunch of marshmallows in a tall cylinder as a physical demonstration. The marshmallows near the top are not crushed because there is only pressure on them from the few marshmallows above them, whereas the marshmallows near the bottom are compressed by the weight of all the marshmallows above them.)

Session 6

1. Restate Archimedes' Principle in your own words. What role does density play?

Archimedes' Principle states that the upward buoyant force felt by an object in a fluid is equal to the weight of the fluid displaced by the object. Density, calculated from the mass of an object divided by its volume, is used to calculate the buoyant force. The force is the volume displaced (in cm^3) times the density of water (1 g/cm^3 at room temperature).

2. What is a "watery ghost" and how does it relate to Archimedes' Principle?

A "watery ghost" is simply a representation of the volume of water displaced by an object when that object is submerged in water. It is the same shape and size as the object but is made of water. "The weight of the water displaced by an object" in Archimedes' Principle is the weight of the watery ghost.

3. A. Imagine you have a wooden ring that is 50 cubic centimeters in volume and 42 grams in mass. What would be the mass of the "watery ghost" of this ring? (Recall the density of water at room temperature is about 1 gram/cubic centimeter.)

B. If we put the ring on the left side of a balance scale and its watery ghost on the right side, which side of the balance would go down? Does this mean the ring will rise or sink when submerged in water?

C. Would you agree or disagree with the statement below? Why?

> **"If rising happens when the weight of an object (downward) is less than the buoyant force (upward), and the buoyant force is equal to the weight of the watery ghost, I think a smaller ring would float because its weight would be less."**

A. The watery ghost of the ring also has a volume of 50 cubic centimeters. Its mass can be calculated using the definition of density:

$$D = M/V$$
$$D * V = M$$
$$1 \text{ g/cm}^3 * 50 \text{ cm}^3 = M$$
$$50 \text{ g} = M$$

B. The right side of the balance (the side with the watery ghost) will drop. The weight of the watery ghost of the ring is more, thus the buoyant force on the ring is more than its weight (from Archimedes' Principle) and the ring will rise.

C. You should disagree with your friend because, although decreasing the volume of the ring will decrease its weight, you must compare this weight to the weight of a correspondingly smaller "watery ghost." In other words, the buoyant force on an object decreases as its volume decreases.

4. Why is it surprising that the solid form of water (ice) floats in liquid water?

In solids, the particles are usually packed closer together than in liquids. Thus, most solids should be more dense than the same matter in liquid form. However, water is a special case because the shape of the particles is such that they can stack closer together in liquid form than the rigid structure they create when in solid form.

5. We know that a helium balloon rises on Earth because the buoyant force from the air around it is greater than its weight. Similarly, an air-filled balloon sinks because the buoyant force is less than the balloon's weight. How might the behavior of these balloons change if we were able to get a

container full of atmosphere from Mars, which is much less dense than Earth's atmosphere, and put the balloons inside it? What if we did the same with a container filled with the atmosphere of Venus, which is much more dense than Earth's atmosphere?

The density of the gas is much less in the Martian atmosphere than the density of the gas in the two balloons. Therefore, the balloons would sink. The density of the gas in the Venusian atmosphere is more than the density of the gas in the two balloons. Therefore these balloons would tend to rise.

Session 7

1. In the video, we saw that water and alcohol boil at different temperatures at sea level. How would you explain why this is so?

The strength of the forces between particles of different liquids varies. When the forces between particles are weak, the boiling points are low. When the forces between the particles are strong, the boiling points are high.

2. In your own words, why doesn't the temperature of melting ice go up until all the ice has melted?

Temperature is a measure of the average energy of motion of the particles that make up an object. By adding heat during a phase change (as in melting an ice cube), particles begin to go faster. However, when any molecule gains enough energy (related to the speed of the particle) to break away from the surface of the ice, it will do so but be slowed down as a result. Thus, the average energy of the particles does not increase until all the molecules still in the ice phase have been "freed," and the temperature remains steady.

3. When heating an object changes its density (as when the hot water balloons rose in the cold water), have we changed the mass, the volume, or both? Explain your answer.

The volume increases. Recall that all particles are in motion and that, in most cases, when their temperature is increased, the average energy of motion in particles increases as well. This means that the particles move faster and collide more frequently. As a result, there is an increase in the average distance between particles on a microscopic level and an overall increase in volume at the macroscopic level. This is what happened with our ball and ring experiment in the Science Studio of this session. Heating the ring caused the particles to vibrate faster, and thus increased the volume of the ring—including the volume of the opening in the ring—which enabled the ball to pass through the ring when it was hot.

4. Why do you think the traffic department uses a rubbery material instead of regular asphalt to fill in cracks in the road?

As the road expands and contracts during the hot and cold seasons (or even between day and night), the road, including the cracks in the road, expand and contract. In fact, it is this expansion and contraction which led to the cracks in the first place. By using a rubbery material, the filler will not "pop out" during hot conditions when the road expands and the cracks get smaller, as might happen with asphalt.

Action Research Guide

The Action Research Process:

Identify your starting point for research

↓

Refine your thinking

↓

Formulate a research question

↓↑

Develop and implement strategies for action

↓↑

Collect and analyze data

↓↑

Reflect on action

↓

Generate practical knowledge

One of the primary reasons for doing action research is to generate knowledge that can inform classroom practice. Your research for the *Essential Science for Teachers: Physical Science* course should focus on some aspect of science teaching and learning in your classroom. Issues involving content, pedagogy, assessment, management, or using children's ideas are all possibilities for productive research. The following is an outline of stages of action research tailored for a 15-week graduate-level course. For more information refer to the following list of readings related to action research.

Weeks 1-3: Identify Your Starting Point

Begin your action research by reflecting on your current practice and identifying an area of special interest to you. Ask yourself these questions to organize your thinking:

- What science content presents problems for my students?
- Which pedagogical approaches help or hinder me in addressing children's science ideas?
- How do I use assessment to guide my science teaching?
- Which educational situations make teaching science content difficult for me?
- What strengths related to addressing children's ideas would I like to develop?

Gather preliminary data through classroom observations and note taking. Your notes should include detailed descriptions and interpretations, explanatory comments, summaries of conversations, hunches, and insights. Reflect on your role within your area of interest to help you think about alternative courses of action.

Think about your current situation and one that would represent improvement. This can help you understand the sources of problems that your action research will address.

Weeks 4-5: Refine Your Thinking

Phrase a preliminary research question that has emerged from a review of your notes. Think about what possible action you could take to better understand this question, as well as aspects of your classroom practice you could change to better address issues raised by your question.

Collect additional information and reflect on how this knowledge will impact your research question. Revisit and adjust the research question you phrased earlier to reflect any changes in thinking.

Week 6: Formulate a Research Question

Reconstruct your research question into a question with two variables in mind—a strategy and an outcome—to help you be more specific about your research and to make it more focused and manageable.

Week 7: Develop Strategies for Action

Identify several possible strategies for action ranging from radical changes in pedagogy to slight behavior modifications. Determine what kinds of data to collect that are appropriate to your question.

Week 8: Implement Strategies for Action and Begin Collecting Data

Begin to implement your chosen strategy and collect the appropriate data.

Weeks 9-12: Refine Action, Continue Data Collection, and Begin Data Analysis

Begin to interpret and draw conclusions from your data about the success of your strategy for action. Writing data summaries after reviewing sections of your data is an effective method for organizing and informing your analysis. Check the validity of your perceptions of your progress by establishing a consensus view of the results. You might interview students, ask a neutral party to observe your class, or choose a colleague to be a "critical friend." Consider the reliability of the data you are collecting. If you come across data that substantiates an important finding for your research, search the rest of the data for conflicting evidence that could refute the finding. It is important that you are open to data that both questions and supports your hypothesis.

Begin a theoretical analysis to take your data analysis to another level. After reviewing a section of your data, try writing a summary in which you identify and interpret themes, contradictions, relationships, and different perspectives that are represented in the data. Developing these ideas can lead to establishing practical theories about teaching.

Week 13: Conclude Strategy Implementation and Continue Data Analysis

Draw the implementation of your chosen strategy to a close. Begin to organize information about your methods of data collection and analysis, and bring your interpretations of the meaning of your data to some kind of conclusion.

Week 14: Generate Practical Knowledge

Draw conclusions from the activity of your research. Begin to work on organizing a research report that should minimally include an introduction that explains the context of the research and the research question, a description of methods of data collection and data analysis, results of the data analysis, conclusions you have drawn from the study, and the implications of your findings for your teaching.

Week 15: Generate Practical Knowledge

Complete the research report.

Readings on Action Research

The following resources will provide you with additional guidance to conduct your action research project:

Altrichter, H. Posh, P. and Somekh, B. (1993). *Teachers Investigate Their Work: An Introduction to Methods of Action Research*. NY: Routledge.

Hubbard, R. and Power, B. (1993). *The Art of Classroom Inquiry*. Portsmouth, NH: Heinemann.

If neither of those resources is available, choose any of the following readings:

Bogdan, R. and Biklen, S. (1998). *Qualitative Research in Education. An Introduction to Theory and Methods*. Third Edition. Needham Heights, MA: Allyn & Bacon.

Burgess, R.G. (1981). Keeping a Research Diary. *Cambridge Journal of Education*, 11, 1, 75-83.

Denzin, N. and Lincoln, Y. (Eds.). *Handbook of Qualitative Research*. Thousand Oaks, CA: Sage Publications.

Duckworth, E. (1986). Teaching As Research. *Harvard Educational Review*, 56, 481-495.

Jenkins, D. (2003). Action Research with Impact. *EncFocus*, 10(1), 35 - 37.

Kemmis, S. and McTaggart, R. (Eds.). (1988). *The Action Research Planner*. B.C. Canada: Deakin University Press.

LeCompte, D. (2000). Analyzing Qualitative Data. *Theory into Practice*; 39(3), 146 - 154.

McNiff, J. (2003). Action Research in the Classroom: Notes for a Seminar. Available at http://www.leeds.ac.uk.educol/documents/00002397.htm

Oberg, A. (1990). Methods and Meanings in Action Research: The Action Research Journal. *Theory Into Practice*, 29(3), 214 - 221.

Schon, D. (1983). *The Reflective Practitioner: How Professionals Think in Action*. New York: Basic Books.

Scott, P. and Driver, R. (1998). Learning About Science Teaching: Perspectives from an Action Research Project. In Fraser, B.J. and Tobin, K.G. (Eds.). *International Handbook of Science Education*. London: Kluwer Academic.

Simpson, M. and Tuson, J. (1995). Using Observations in Small-Scale Research: A Beginner's Guide. Eric Clearinghouse Document ED394991

Spiegel, A., Collins, and Lappert, J. (Eds.). (1995). Action Research: Perspectives from Teachers' Classrooms. Tallahassee, FL: SERVE Eisenhower Consortium for Mathematics and Science Education.

Related Readings by Session

Session 1: What is Matter? Properties and Classification of Matter

Andersson, B. R. (1990). “Pupils' conceptions of matter and its transformations (age 12-16).” *Relating macroscopic phenomena to microscopic particles: A central problem in secondary Science Education*. P. L. Lijnse, Licht, P., Vos, W. de, Waarlo, A. J. Utrecht, CD-ß Press**:** 12-35.

Andersson, B. R. (1990). "Pupils' conceptions of matter and its transformations (age 12-16)." *Studies in Science Education* **18**: 53-85.

Cobern, W. (1990). "Understanding the world as others do." *Newsletter (No.13) of the SIG "Subject Matter Knowledge and Conceptual Change" of the American Educational Research Association.*

Comber, M. (1983). "An analysis of Nuffield Combined Science 5-13 in terms of concepts related to the theory of matter." *School Science Review* **64**(228): 556-561.

Hellden, G. (1993). “Pupils' understanding of ecological processes and their conceptions of matter.” *Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics*. J. Novak. Ithaca, New York, Cornell University (distributed electronically).

Krnel, D., Glazar, S. and Watson, R. (2003) “The Development of the Concept of ‘Matter’: A Cross-Age Study of How Children Classify Materials.” *Science Education* 87: 621-639 2003

McPhan, G. (1993). “Acquiring concepts about the structure and behaviour of matter: Productive process or undesirable outcome?” *Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics.* J. Novak. Ithaca, New York, Cornell University (distributed electronically).

Rennstroem, L. (1987). “Pupils conceptions of matter. A phenomenographic approach.” *Proceedings of the Second International Seminar "Misconceptions and Educational Strategies in Science and Mathematics," Vol. III*. J. Novak. Ithaca, Cornell University**:** 400-414.

Scott, P. H. (1990). "Conceptual change in the science classroom a case study of the development of one pupil's ideas relating to matter." *Occasional paper from the Children's Learning in Science Research Group. Centre for Studies in Science and Mathematics Education. The University of Leeds*: 1-28.

Stavy, R., Stachel, D. (1985). "Children's conception of changes in the state of matter: From solid to liquid." *Archives de Psychologie* **53**: 1-29.

Stavy, R. (1989). “Students' conceptions of matter.” *Adolescent development and school science*. P. Adey. London, Falmer Press**:** 273-282.

Stavy, R., Rager, T. (1990). “Students' conceptions of the three dimensions of the quantity of matter - Volume, mass and number of particles: static systems.” *Relating macroscopic phenomena to microscopic particles*. P. L. Lijnse, Licht, P., Vos, W. de, Waarlo, A. J. Utrecht, CD-ß Press**:** 233-246.

Session 2: The Particle Nature of Matter: Solids, Liquids, and Gases

Aalst, J. (1997). "Learning about heat and matter with CSILE: An inquiry into conceptual change." *Occasional paper: Department of Curriculum, Teaching, and Learning, University of Toronto*: 1-32.

Andersson, B. R. (1990). “Pupils' conceptions of matter and its transformations (age 12-16).” *Relating macroscopic phenomena to microscopic particles: A central problem in secondary Science Education*. P. L. Lijnse, Licht, P., Vos, W. de, Waarlo, A. J. Utrecht, CD-ß Press**:** 12-35.

Brook, A., Briggs, H., Driver, R. (1984). *Aspects of secondary students' understanding of the particulate nature of matter*. Leeds, University Leeds, Centre for Studies in Science and Mathematics Education.

Calvelli, G., Capitanio, M., Di Blasi Burzotta, R., Furlan, D., Merlo, A. (1996). “Teaching the changes of state of matter in the primary school.” *Teaching the science of condensed matter and new materials*. M. Michelini, Jona, S., Cobai, D. Udine, Forum**:** 429-433.

Comber, M. (1983). "Concept development in relation to the particulate theory of matter in the middle school." *Research in Science and Technological Education* **1**(1): 27-39.

Dawson, C. (1998). "Modeling the states of matter and changes of state." *Australian Science Teachers' Journal*. **44**(2): 54.

de Vos, W., Verdonk, A. (1996). "The particulate nature of matter in science education and in science."

Journal of Research in Science Teaching **33**(6): 657-664.
Driver, R. (1983). "An approach to documenting the understanding of 15 years old British children about the particulate theory of matter." *Research on Physics Education. Proceedings of the first international workshop*. La Londe les Maures: 339-346.
Epsimos, G., Fassoulopoulos, G., Kariotoglou, P. (2001). “Pupils' conceptions about intensive variables across the states of matter.” *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society, Vol. 2*. D. Psillos, Kariotoglou, P., Tselfes, V., Bisdikian, G., Fassoulopoulos, G., Hatzikraniotis, E., Kallery, M. Thessaloniki, Greece, Aristotle University of Thessaloniki**:** 730-732.
Mortimer, E. F. (1994). “The evolution of students' explanations for physical state of matter as a change in their conceptual profile.” *European research in Science Education - Proceedings of the first Ph. D. Summerschool*. P. L. Lijnse. Utrecht, CD-ß Press, Centrum voor ß-Didactiek**:** 281-287.
Gabel, D. L. (1993). "Use of the particle nature of matter in developing conceptual understanding." *Journal of Chemical Education* **70**(3): 193-194.
Gabel, D. L., Samuel, K. V., Hunn, D. (1987). "Understanding the particulate nature of matter." *Journal of Chemical Education* **64**(8): 695-697.
Haidar, A. H., Abraham, M. R. (1989). *A comparison of applied and theoretical knowledge of concepts based on the particulare nature of matter*. University of Oklahoma, Department of Chemistry and Biochemistry.
Hibbard, K. M., Novak, J. D. (1975). "Audio-tutorial elementary school science instruction as a method for study of children's concept learning: Particulate nature of matter." *Science Education* **59**(4): 559-570.
Johnston, K. (1990). “Students' responses to an active learning approach to teaching the particulate theory of matter.” *Relating macroscopic phenomena to microscopic particles: a central problem in secondary Science Education*. P. L. Lijnse, Licht, P., Vos, W. de, Waarlo, A. J. Utrecht, CD-ß Press**:** 247-265.
Kokkotas, P., Vlachos, I., Koulaidis, V. (1998). "Teaching the topic of the particulate nature of matter in prospective teachers' training courses." *International Journal of Science Education* **20**(3): 291-303.
Lichtfeldt, M. (1996). “Development of pupils' ideas of the particulate nature of matter: Long-term research projekt.” *Research in Science Education in Europe*. G. Welford, Osborne, J., Scott, P. London, The Falmer Press**:** 212-228.
Meheut, M., Chomat, A. (1990). “The bounds of children's atomism: An attempt to make children build up a particulate model of matter.” *Relating macroscopic phenomena to microscopic particles: a central problem in secondary Science Education*. P. L. Lijnse, Licht, P., Vos, W. de, Waarlo, A. J. Utrecht, CD-ß Press**:** 266-282.
Novick, S., Nussbaum, J. (1978). "Junior High School pupils' understanding of the particulate nature of matter: An interview study." *Science Education* **62**: 273-281.
Novick, S., Nussbaum, J. (1981). "Pupils' understanding of the particulate nature of matter: A cross-age study." *Science Education* **65**: 187-196.
Rafel, J., Mans, C. (1987). “Alternative frameworks about the learning of changes of state of aggregation of matter: Sorting of answers into models.” *Proceedings of the Second International Seminar "Misconceptions and Educational Strategies in Science and Mathematics", Vol. III*. J. Novak. Ithaca, Cornell University**:** 392-399.
Rafel, J., Mans, C., Black, P. (1992). “Pupils' conceptions around changes of state of aggregation of matter.” *The history and philosophy of science in Science Education. Proceedings of the international conference on the history and philosophy of science and science teaching. Volume II*. S. Hills. Kingston, Ontario, The Faculty of Education, Queens University**:** 335-346.
Rohr, M., Reimann, P. (1997). "Reasoning with multiple representations when acquiring the particulate model of matter." *Occasional paper, University of Heidelberg, Germany*: 1-29.
Rohr, M., Reimann, P. (1999). “A cognitive model to describe the process of learning the particulate model of matter and its instructional consequences.” *Research in Science Education - Past, Present, and Future Vol.1*. M. Komorek, Behrendt, H., Dahncke, H., Duit, R. , Graeber, W. , Kross, A. Kiel, IPN Kiel**:** 195-197.
Stavy, R., Rager, T. (1990). “Students' conceptions of the three dimensions of the quantity of matter - Volume, mass and number of particles: static systems.” *Relating macroscopic phenomena to microscopic particles*. P. L. Lijnse, Licht, P., Vos, W. de, Waarlo, A. J. Utrecht, CD-ß Press**:** 233-246.
Wightman, T., Green, P., Scott, P. H. (1986). *Children's learning in science project. The construction of*

meaning and conceptual change in classroom settings: Case studies on the particulate nature of matter. Leeds, University of Leeds, Centre for Studies in Science and Mathematics Education.
Shepherd, D. L., Renner, J. W. (1982). "Student understandings and misunderstandings of states of matter and density changes." *School Science and Mathematics* **82**(8): 650-665.
Sormunen, K., Hirvonen, P. E. (2001). “Seventh-grade pupils' epistemic views in the context of modeling the states of matter.” *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society, Vol. 2*. D. Psillos, Kariotoglou, P., Tselfes, V., Bisdikian, G. , Fassoulopoulos, G. , Hatzikraniotis, E. , Kallery, M. Thessaloniki, Greece, Aristotle University of Thessaloniki**:** 640-642.
Stavy, R. (1987). "Children's conception of change in the state of matter: From liquid (or solid) to gas." *Paper of the School of Education, Tel-Aviv University*.
Stavy, R. (1994). “States of matter **-** pedagogical sequence and teaching strategies based on cognitive research.” *The Content of Science*. P. Fensham, Gunstone, R., White, R. London, The Falmer Press**:** 221-236.
Stavy, R., Stachel, D. (1985). "Children's conception of changes in the state of matter: From solid to liquid." *Archives de Psychologie* **53**: 1-29.

Sessions 3: Physical Changes and Conservation of Matter and Session 4: Chemical Changes and Conservation of Matter

Haidar, A. (1997). "Prospective chemistry teachers' conceptions of the conservation of matter and related concepts." *Journal of Research in Science Teaching* **34**(2): 181-197.
Holding, B. (1987). *Investigation of schoolchildren's understanding of the process of dissolving with special reference to the conservation of matter and the development of atomistic ideas*. Leeds, The University of Leeds, School of Education.
Kircher, E. (1981). “Research in the classroom about the particle nature of matter (grades 4-6).” *Proceedings of the international workshop on "Problems Concerning Students' Representation of Physics and Chemistry Knowledge"*. W. Jung, Pfundt, H., Rhoeneck, C. von. Ludwigsburg, Paedagogische Hochschule**:** 342-364.
Ryan, C. (1990). "Student teachers' concepts of purity and of states of matter." *Research in Science and Technological Education.* **8**(2): 171-183.
Stavy, R. (1991). "Using analogy to overcome misconceptions about conservation of matter." *Journal of Research in Science Teaching* **28**(4): 305-313.
Stavy, R., Cohen, M. R. (1989). "Overcoming students' misconceptions about conservation of matter by conflict training and by analogical reasoning." *Paper presented at the Jerusalem Conference*.

Session 5: Density and Pressure

Ahtee, M. (1995). "Pupils' understanding of density at secondary level." *Paper presented at the First European Conference on Research in Science Education, Leeds, UK, April 7-11, 1995*.
Anderson, C., Kurth, L., Palincsar, A. (1998). "Design principles for collaborative problem solving in science." *Paper presented at the annual meeting of AERA, San Diego, 1998*: 1-13.
Dawson, C. J., Rowell, J. A. (1977). "Yes, children are different! The concept of relative density and the conservation of quantities." *The Australian Science Teacher Journal.* **23**(1): 94-96.
Gennaro, E. D. (1981). "Assessing Junior High Students' understanding of density and solubility." *School Science and Mathematics* **81**: 399-404.
Hewson, M. G. (1986). "The acquisition of scientific knowledge: Analysis and representation of student conceptions concerning density." *Science Education* **70**(2): 159-170.
Shepherd, D. L., Renner, J. W. (1982). "Student understandings and misunderstandings of states of matter and density changes." *School Science and Mathematics* **82**(8): 650-665.
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**(3): 177-237.
Smith, C., Snir, J., Grosslight, L. (1987). *Teaching for conceptual change using a computer-based modeling approach: The case of weight/density differentiation*. Cambridge, Educational Technology Center.

Smith, C., Snir, J., Grosslight, L. (1992). "Using conceptual models to facilitate conceptual change: the case of weight-density differentiation." *Cognition and Instruction* **9**(3): 221-283.
Smith, C., Maclin, D., Grosslight, L., Davis, H. (1997). "Teaching for understanding: A study of students' preinstruction theories of matter and a comparison of the effectiveness of two approaches to teaching about matter and density." *Cognition and Instruction* **15**(4): 317-393.
Taagepera, M., Potter, F., Miller, G., Lakshminarayan, K. (1997). "Mapping students' thinking patterns by the use of the knowledge space theory." *International Journal of Science Education* **19**(3): 283-302.

Session 6: Rising and Sinking

Filho, F., Gomes, M., Bastos, L. "A teaching strategy to physics conceptual change in elementary grades." *Paper presented in the Annual Meeting of the American Educational Research Association held in San Francisco, April 1989*.
Gang, S. (1995). "Removing preconceptions with a 'learning cycle'." *The Physics Teacher* **33**(6): 346-354.
Havu, S. (2000). *Changes in children's conceptions through social interaction in pre-school science education*. Joensuu, Finnland, University of Joensuu.
Raghavan, K., Sartoris, M., Glaser, R. (1998). "Why does it go up? The impact of the MARS curriculum as revealed through changes in student explanations of a helium balloon." *Journal of Research in Science Teaching* **35**(5): 547-567.
Varelas, M. (1996). "Between theory and data in a seventh-grade science class." *Journal of Research in Science Teaching* **33**(3): 229-263.
Westbrook, S., Rogers, L. (1996). "Doing is believing: Do laboratory experiences promote conceptual change?" *School Science and Mathematics* **96**(5): 263-271.

Session 7: Heat and Temperature

Aalst, J. (1997). "Learning about heat and matter with CSILE: An inquiry into conceptual change." *Occasional paper: Department of Curriculum, Teaching, and Learning, University of Toronto*: 1-32.

Gabel, D. L., Samuel, K. V., Hunn, D. (1987). "Understanding the particulate nature of matter." *Journal of Chemical Education* **64**(8): 695-697.
Gabel, D. L. (1993). "Use of the particle nature of matter in developing conceptual understanding." *Journal of Chemical Education* **70**(3): 193-194.
Stavridou, H., Solomonidou, C., Papadimitriou, V. (1993). "Student-teachers' conceptions about physical and chemical transformations of matter." *Proceedings Atti - Second European Conference on Research in Chemical Education, 11-14, September 1993, University of Pisa, Pisa, Italy*. A. Bargellini, Todesco, P. E. Pisa, University of Pisa**:** 235-240.

Session 8: Extending the Particle Model of Matter

Andersson, B. R. (1990). "Pupils' conceptions of matter and its transformations (age 12-16)." *Relating macroscopic phenomena to microscopic particles: A central problem in secondary Science Education*. P. L. Lijnse, Licht, P., Vos, W. de, Waarlo, A. J. Utrecht, CD-ß Press**:** 12-35.
Holding, B. (1987). *Investigation of schoolchildren's understanding of the process of dissolving with special reference to the conservation of matter and the development of atomistic ideas*. Leeds, The University of Leeds, School of Education.
Johnston, K. (1990). "Students' responses to an active learning approach to teaching the particulate theory of matter." *Relating macroscopic phenomena to microscopic particles: a central problem in secondary Science Education*. P. L. Lijnse, Licht, P., Vos, W. de, Waarlo, A. J. Utrecht, CD-ß Press**:** 247-265.
Maskill, R., Cachapuz, A., Koulaidis, V. (1997). "Young pupils' ideas about the microscopic nature of matter in three different European countries." *International Journal of Science Education* **19**(6): 631-645.
Meheut, M., Chomat, A. (1990). "The bounds of children's atomism: An attempt to make children build up a particulate model of matter." *Relating macroscopic phenomena to microscopic particles: a central problem in secondary Science Education*. P. L. Lijnse, Licht, P., Vos, W. de, Waarlo, A. J. Utrecht,

CD-ß Press: 266-282.
Stavy, R., Rager, T. (1990). “Students' conceptions of the three dimensions of the quantity of matter - Volume, mass and number of particles: static systems.” *Relating macroscopic phenomena to microscopic particles*. P. L. Lijnse, Licht, P., Vos, W. de, Waarlo, A. J. Utrecht, CD-ß Press: 233-246.
Stavy, R. (1996). “Children's conceptions of the states of matter.” *Teaching the science of condensed matter and new materials*. M. Michelini, Jona, S., Cobai, D. Udine, Forum: 81-94.

Credits

Series Producer
Clive A. Grainger

Course Content Developers
Jamie Bell
Dr. Noah Finkelstein

Hosts
Dr. Sallie Baliunas, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts
Robin Moriarty, Education Development Center, Inc., Newton, Massachusetts

Featured Classrooms
Rosinda Almeida, Grade 2, Benjamin Banneker Charter School, Cambridge, Massachusetts
Christina Bash, Grade 5 / Science Specialist, Saltonstall School
Salem, Massachusetts
Monique Brinson, Grade Three, Young Achievers Science and Math Pilot School, Jamaica Plain, Massachusetts
Linda Block, Grade 5, Independent Elementary School, Castro Valley, California
Rebecca Cituck, Grade 5, Portsmouth Middle School, Portsmouth, Rhode Island
Joanie Grisham, Grades 1/2, Fayerweather Street School, Cambridge, Massachusetts
Tina Grotzer and Nicole Scalzo, Grade 5, Thompson Elementary School, Arlington, Massachusetts
Linsey Newton, Grade 3, Joseph L. Mulready School, Hudson, Massachusetts
Cindy Plunkett, Grade 1, Blanchard Memorial School, Boxborough, Massachusetts
Paula Proctor and Gina Robertson, Grade 6, Roosevelt School, Worcester, Massachusetts
Joe Reilly, Grade 1, W.H. Lincoln Elementary School, Brookline, Massachusetts
Russell Z. Springer, Grade 5, Cabot Elementary School, Newtonville, Massachusetts

Series Advisors
Dr. Sallie Baliunas, Harvard-Smithsonian Center for Astrophysics
Christina Bash, Salem, Massachusetts Public Schools
MaryAnn Bernstein, Fox Hill Elementary School, Burlington, Massachusetts
Rich Carroll, Marshall Simonds School, Burlington, Massachusetts
Dr. Scott Franklin, Rochester Institute of Technology, New York
Dr. Anita Greenwood, University of Massachusetts Lowell, Massachusetts
Joanie Grisham, Fayerweather Street School, Cambridge, Massachusetts
Dr. Tina Grotzer, The Understandings of Consequence Project, Project Zero, Harvard Graduate School of Education
Dr. Apriel Hodari, The CNA Corporation
Dr. Bernard Hoop, The Benjamin Banneker Charter School, Cambridge, Massachusetts
Robin Moriarty, Education Development Center, Inc., Newton, Massachusetts
Maria Nieves, McCormack School, Boston, Massachusetts
Mary Rizzuto, Tobin School, Cambridge, Massachusetts
Dr. Philip Scott, University of Leeds, UK

Nadine Solomon, Arlington Public Schools, Arlington, Massachusetts
Russell Z. Springer, Cabot School, Newtonville, Massachusetts
Dr. Irwin Shapiro, Harvard-Smithsonian Center for Astrophysics
Dr. Carol Smith, University of Massachusetts Boston
Jeff Winokur, Education Development Center, Inc., Newton, Massachusetts

Support Materials Developers
Jamie Bell
Mark Hartman

Series Researchers
Mark Hartman
Abby Paske

Research Assistant
Emily Lu

Series Editors
Ian Albinson
Steven J. Allardi
Michel Chalufour
Neal Duffy
Thomas Lynn
Douglas K. Plante
Sandeep Ray
Ivan Rhudick
Memo Salazar

Audio Mixer
Lisa Haber-Thomson

Videographers
Ian Albinson
Carla Blackmar
Yael Bowman
Scott Crawford
Thomas Danielczik
James Day
Robert Duggan
Clive A. Grainger
Alex Griswold
Milton Kam
Franchot Lubin
Thomas Lynn
Tobias McElheny
Lauren Peritz
Douglas K. Plante
David Rabinovitz
Sandeep Ray

Audio
Robert Duggan

Original Music
Alison Reid, Treble Cove Music

Graphic Design/Animation
Ian Albinson
Steven J. Allardi
Chi-Yun Lau
Douglas K. Plante
Raedia Sikkema
Leonard Wikberg III, www.ScienceData.com

Web Design
Alison Reid

Support Materials Coordinator
Jeff Peyton

Associate Producer
Yael Bowman
Shannon Densmore

Production Assistants
Carla Blackmar
James Day
Lisa Haber-Thomson
Lauren Peritz

Curriculum Resources

Causal Patterns in Density (copyright 2004)
Presidents and Fellows of Harvard College
Available through Project Zero:
Note: instructional materials were developed as part of The
Understandings of Consequence Project, developed with funding from the National Science Foundation (Grant No. REC-9725502 and REC-0106988). All opinions, findings, conclusions or recommendations expressed therein are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Delta Science Modules: States of Matter
Delta Education

EDC Insights: Changes of State
Kendall/Hunt Publishing Company

EDC Insights: Liquids
Kendall/Hunt Publishing Company

EDC Insights: The Mysterious Powder
Kendall/Hunt Publishing Company

FOSS: Water
Delta Education

FOSS: Air and Weather
Delta Education

NSRC STC: Changes Unit
Carolina Biological Supply Company

NSRC STC: Solids and Liquids
Carolina Biological Supply Company

Field Trip "Open Pathways"
The Exploratorium, San Francisco

Channel Operations Manager
Bev King

Director of Outreach
Joyce Gleason

Outreach/Scheduling Consultant
Dana Rouse

Outreach Assistants
Amy Barber Biewald
Zenda Walker

Education Coordinators
Jeff Peyton
Alexander D. Ulloa

Financial Manager
Oral Benjamin

Administrator
Linda Williamson

Project Manager
Nancy Finkelstein

Executive Producer
Alex Griswold

Executive Director
Dr. Matthew H. Schneps

Course Readings

Third Misconceptions Seminar Proceedings (1993)

Paper Title: Teaching about Vacuum and Particles, Why, When, and How: A research report
Author: Nussbaum, Joseph

Abstract: Most curricula in many countries introduce the idea that matter is formed from particles, to students when they are approximately 13-14 years of age. The reasoning for studying the subject in this age is the assumption that the cognitive development of younger students is not yet ripe enough to handle such "abstract" ideas, while older children already need the particulate model as applied in more advanced subjects as physics, chemistry and in biology.

Keywords:
General School Subject:
Specific School Subject:
Students:

Macintosh File Name: Nussbaum - Particles
Release Date: 10-13-1994 I

Publisher: Misconceptions Trust
Publisher Location: Ithaca, NY
Volume Name: The Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics
Publication Year: 1993
Conference Date: August 1-4, 1993
Contact Information (correct as of 10-15-93): Joseph Novak (Education Department, 4th Floor Kennedy Hall, Cornell University, Ithaca, NY 14853 USA/607-255-3005) or Robert Abrams (rha2@cornell.edu)

A Correct Reference Format: Author, Paper Title in The Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics, Misconceptions Trust: Ithaca, NY (1993).

form as they are in traditional print media. We feel that page numbers have always been an approximate measure at best, so that the fraction of desynchronization that the electronic form adds to the measure is not a debilitating concern. If you are concerned about this issue, we suggest that you use range guides: create an index, consisting of a three column array, immediately following the reference to this paper in your bibliography, where the first column is the page number(s) cited, the second column is the first five words on that page, and the third column is the last five words on that page. Finally, a great deal of effort has been invested in bringing you this proceedings, on the part of the many authors and conference organizers. If you have found this collection to be of value in your work, consider supporting our ability to support you by purchasing a subscription to the collection.

----- -----

Teaching about Vacuum and Particles, Why, When, and How: A research report

Joseph Nussbaum
Jerusalem College for Women
P.O.B. 16078
Bayit Vegan, 96383 Jerusalem, Israel

Presented
at the Third International Seminar on
Misconceptions and Educational Strategies
in Science and Mathematics
Cornell University, Ithaca, NY
August 1993

This research was supported by Machon MOFET
Teacher Education Department
Ministry of Education
Jerusalem, Israel.

INTRODUCTION

Most curricula in many countries introduce the idea that matter is formed from particles, to students when they are approximately 13-14 years of age. The reasoning for studying the subject in this age is the assumption that the cognitive development of younger students is not yet ripe enough to handle such "abstract" ideas, while older children already need the particulate model as applied in more advanced subjects as physics, chemistry and in biology.

For approximately 15 years, there has been a growing awareness among science educators of the difficulties that students experience in studying the particulate model and applying it in different scientific areas. Many research studies have shown that students develop various misconceptions regarding the particulate structure of matter and the interactions between particles in physical, chemical and biological phenomena (see the reviews of Nussbaum, 1985; Andersson, 1990). Misconceptions among students in various scientific fields are recognized today as a general and basic phenomenon requiring theoretical revisions in the psychology of learning and in teaching strategies.

In a recent international conference[1] devoted wholely to the issue of relating micro to macro in science education, a number of researchers reported on their projects, in which they applied their unique approaches to teaching particulate theory. All of these projects began in the eighties, as a result of an awareness of the difficulties of teaching the subject as mentioned above. Each researcher presented his own rationale.

The rationales were developed from considerations drawn from various areas, such as the history and philosophy of science, psychology, as well as from didactic principles and educational practice. Each rationale was based upon different combinations and different degrees of emphasis of those considerations.

It is important to remember that although two people may recognize that considerations should be drawn from a certain area, the specific considerations drawn by each of them, as well as the conclusions which each one reaches, may not necessarily be identical, and may even contradict each other. A brief review of some of these reports would be worthwhile in this introduction.

---

[1]in Utrecht, The Netherlands, 1990.

Millar (1990)[2] presents mostly psycho-didactic and practical considerations. He recommends that science be taught "from everyday contexts to scientific concepts". He promotes distributing the introduction of ideas of the particulate model across the general program in science, for ages 14-16. He further promotes the concept of introducing parts of particulate-kinetic theory - but only in places in the curriculum which can contribute to an additional understanding, and not as instruction in discrete subjects. He opposes the teaching of the theory in its entirety as a single educational unit. Millar recommends the introduction of particular ideas, in the first stage, when it is necessary to explain the behavior of solids. He strongly recommends postponing the use of particulate model of gases for a later stage. His arguments are that research findings have shown that children have difficulties understanding that *gas* is *matter*, and that it is comprised of constantly moving particles in a vacuum. From a psycho-didactic point of view, he recommended that students be convinced of the existence of particles which so tiny that they are imperceptible. He used a method which he called *ostention* - "showing" - rather than by abstract discussions about the behavior of imperceptible particles. For example, they bring the student from the macroscopic world to the microscopic, by studying threads of clothing with a magnifying glass, and only then do they continue to the ultra-microscopic level of particles.

Meheut and Chomat (1990)[3] presented considerations resulting from the identification of a basic aspects of atomistic theory, i.e., the conceptualization of particles as invariant constituents of matter (which themselves never change), while the empty spaces between the particles and the motion of the particles are variable factors of matter (appearing in different magnitudes in different circumstances). They demonstrate that these dinstinctions existed among the first Greek atomists. Their historical and content analysis did not extend much beyond this, and the historical difficulties and misgivings were not discussed in the rationale which they presented. In their instruction, as opposed to Millar's recommendation, the experiments dealt entirely with air and other gaseous behavior; they have demonstrations of pressure and change in volume as well as the diffusion of two gases in each other. The decision to begin with gases results from the assumption that the attempt to explain the behavior of gases will bring about the identification of variables of space and motion. They criticize Piaget's analysis of the development of "atomism" among children because his definition of an "atomistic view" is superficial, and does not include all of the essential

---

[2]His project has produced a textbook - *Salter's Science* (1989). York: University of York, Science Education Group.
[3]From LIRESPT, Universite Paris 7

attributes of the scientific model. They feel that even if a child thinks about particles in the Piagetian manner, he would have no reason or need to see those small pieces of matter as invariant. They present the children with phenomena and expect them to construct a particulate theory which would explain that which is observed. However, the very idea of the existence of invariant particles was not elicited from the students, but was presented from the outset in given propositions.

Johnstone (1990)[4] describes an experiment in instructing the particulate model to children aged 13-14. It is based upon the psychological constructivist approach, which converged with the constructivist approach in the philosophy of science. Their teaching scheme includes three phases of instruction as proposed by Driver and Oldham (1986)-

An elicitation phase: In which students are provided with opportunities to put forward their own ideas and to consider the ideas of their peers.

A restructuring phase: In which the teacher introduces activities which interact with students' prior ideas, and which encourages students to move their thinking towards the school science review program.

A review phase: In which students are asked to reflect on the ways in which their ideas have changed.

They began the first phase of their project by asking the students to compare the characteristics of gases, liquids, and solids, and to propose a theory which would explain the differences.

Johnstone indicates that many students showed in the first phase that concepts such as atoms and molecules are familiar to them from elementary school or from television programs. However, they soon showed all of the familiar misconceptions shown in the research literature.

The last phase of the teaching scheme was to have been meta-learning, a kind of lesson in epistemology, in which the students reflected upon their experiences during their initial phases of instruction. Thus, the activities during this phase were related more to the philosophy of knowledge than to the particulate model. According to the report, some students had difficulty connecting prior learning with this reflective activity.

---

[4]CLIS, Children Learning in Science Project. (R. Driver - director). University of Leeds, UK.

Despite the fact that Johnstone mentions Driver's proposal (1989) that a strategy for promoting conceptual change in science classrooms "needs to be investigated in the context of particular domains of knowledge", her report did not have a focussed attempt to analyze the source of the specific problems of this area of particulate theory. It seems that their effort focussed more on creating a general constructivist trend, without a clear innovation in the specific contextual area.

de Vos, 1990[5] integrates a psychological and content-oriented analysis in a relatively highly-developed manner. He also integrates references to the distant and recent history of the atomistic theory. In content-oriented analysis, he shows how the definitions of textbooks are imprecise and how they contribute to the formation of misconceptions. He emphasizes how important it is to identify and formulate which qualities which are known on the *macroscopic* level are to be used to explain the *microscopic* world, and which ones should be avoided. He identifies certain misconceptions from the history of science and describes the intuitive processes which apparently influenced those scientists. He emphasizes that it would be quite natural for the intuition of the modern student to operate in the same way.

In a fine analysis, he identifies five characteristics of the macroscopic world, and stipulates that they are the only ones which can be used in the particulate theory. These five unique qualities are *mass, space, time, mechanical energy* and *electric charge*. de Vos indicates that these five elements are really seen as quite structured and simple for instruction, yet "..would it be obvious to students why the elements from which a corpuscular model is to be built, should be mass, space, time, energy and electric charge? Or would they prefer to choose, say, colour, taste, toxicity, temperature or malleability?"

Despite the fact that the rationale of de Vos seems to the present author as richer and more comprehensive than that of all of the others, its considerations do not yet hint how they influenced their teaching unit. At any rate, the last section of his article, describing their strategy in general, is worthy of note:

> "In science lessons at lower secondary school level, it is not very important which corpuscular model a child learns. It is much more important to preserve something of the uncertainty and the tentativeness which are characteristic of models...It means that children should experience

---

[5]Vos, W de (1989), *Chemie in Duizend Vragen (Chemistry in a Thousand Questions)*. Utrecht: The University of Utrecht.

how it feels to work with ideas without being sure whether they are correct or not. Working with models is not just an intellectual affair, but also an emotional one. It requires creativity as much as discipline, and it may lead to frustration as well as to satisfaction. This way of learning to work with models is encouraged if the teacher does not present corpuscular models as facts discovered by famous scientists, but instead asks students about their own ideas, stimulating them to discuss these and test their consequences in suitable experiments."

Sources for our Rationale for the Teaching of the Particulate Model

The rationale of our[6] teaching strategy is heavily based on implications drawn from analyses of (1) the historical development of the particulate model; (2) current basic issues in the philosophy of science; and (3) current views in cognitive psychology. The analysis and the implications will be presented according to these source areas.

(1) ***The historical development of the particulate model*.**

We do assume that each conception in science presents the student with cognitive difficulties which are unique to the nature of the subject. For in designing effective teaching one must first identify the difficulties. One important way of identifying these difficulties in advance is by identifying and analyzing the cognitive difficulties which the scientists of the past faced during the course of the historical development of relevant scientific ideas. This paper has no intention of arguing that the development of the scientific understanding of the student precisely recapitulates the historical pattern. The argument is that if the basic cognitive difficulty which appeared in the history of particulate theory is indeed so significant, that there is reason to be concerned that it would also appear today among our students. Despite the fact that the survey and analysis of the historical processes demand extensive room, we feel that the matter is worth doing for the reader who is seriously interested in the matter.

We do not know how the first Greek atomists arrived at their brilliant ideas and we are amazed that the first ones forming the bases of theory, Leucippus (450 BCE) and Democritus (410 BCE), propounded nearly all of the essentials of the atomistic theory: (a) the material is constructed of separate particles, which are full, indivisible corpuscles[7] and they comprise together the mass of material; (b) The particles exist within an absolute vacuum; (c) The particles move freely and continously within the vacuum and interact with each other. (d) The interaction of the particles creates the macroscopic changes which we see. The interactions include situations of *association* (condensation, solidification, and the creation of new compounds) as well as

---

[6]The use of the plural form (the editorial we) includes my close colleague, Dr. Shimshon Novick, with whom I started this project. He unfortunately passed away in 1983.

[7]Even today, when we know about subatomic particles, the basic idea remains that we always arrive in our research to particles which in this stage of the research are for us indivisible.

disassociation (breaking down of the existing compounds by attack from outside) and situations of *creating pressure* such as with gas.

The Greek sources quoted in Sumbursky's Anthology (1965) indicate that

> "Democritus thinks that the nature of the perceptual things consist of small particles infinite in number. For these he postulates another space of infinite size. He designates space by the term `the void', `Nothingness' and `the infinite', and each of the particles by the terms `the something', `the solid' and `the being'. He thinks the particles are so small as to be imperceptible to us, and take all kinds of shapes and all kinds of forms and differences of size. Out of them, like out of elements, he now lets combine and originate the visible and perceptible bodies. They move in confusion in the void..., and while in motion they collide and become interlocked in entanglement of a kind which causes them to be juxtaposed and in proximity to one another without actually forming any real unity whatsoever.... The cause of the continuance of aggregations of particles for some period of time, he says, is their fitting into one another in bondage - for some of them are uneven, others barbed, some concave and some convex.... He thinks they hold together and continue to do so until the time when some stronger force coming from the environment disrupts and disperses them in different directions." (p.55).

Democritus' atomistic concept postulates the existence of vacuum as necessary to allow movement of particles, and thus also allows interaction and changes. It is worth noting that the atomistic view is a *reductionistic* and *mechanistic* model for understanding reality. The model is *reductionistic*, because it reduces the number of components and factors relating to all complex phenomena to an interaction of the simplest microscopic particles. The model is *mechanistic*, because he assumes that these basic particles move, bump into each other, and rebound according to mechanistic laws. This model is therefore causal rather than teleological. This mechanistic model was applied by the atomists, such as Epicurus (350 BCE), in all areas of existence, including cosmology, physiology and mental processes in man. Reductionism combined with mechanism is the characteristic of all of our natural sciences. The acquisition of this approach is a meta-goal of science education.

Each of the four basic essentials of the model mentioned in the previous page are combined and strengthened by the existence of the other factors. Change in matter means a change in the arrangement of the particles, which requires the existence of movement, which in turn requires the existence of vacuum in order to occur. As a result, the existence of vacuum is a the most substantial part of the entire model. This idea is expressed in the original writings of Epicurus:

> "the atoms are in continual motion through all eternity. Some of them rebound to a considerable distance from each other, while others merely oscillate in one place when they chance to have got entangled or to be enclosed by a mass of other atoms shaped for entangling.
>
> "This is because each atom is separated from the rest by a void, which is incapable of offering any resistance to the rebound; while it is the solidity of the atom which makes it rebound after a collision, however short the distance to which it rebounds, when it finds itself imprisoned in a mass of entangling atoms." (ibid p.84).

Apparently, just after the generation of Democritus and Leucippus there was a debate between those who agreed with and those who opposed atomism. The head of the opposing faction was Aristotle (350 BCE). The main aspect of the debate of Aristotle was not the actual possibility of the existence of the minuscule imperceptible particles, but rather the possibility of the existence of a vacuum.

The concept of the vacuum created the major philosophical obstacle, and therefore it faced most of the effort of refutation (although there were other arguments against the notion of the indivisibility of elementary particles). Aristotle gives a long series of philosophical-physical arguments why the existence of a vacuum is not substantially possible.[8] For the duration of an entire lengthy series of arguments Aristotle attempts to reverse the arguments of the atomists' arguments and to argue that the existence of a vacuum is not essential for the existence of movement, but rather the existence of the vacuum would actually *prevent* movement or would create movement which would have no specific direction. Two exemplary arguments in

---

[8] I do not want to enter into the roots of the argument relating to the opposing arguments of the concept of the "space". Whereas the atomists (such as *Democritus* and *Newton* conceive of space as an infinite vacuum into which bodies are placed, *Aristotle* conceives of space as one of the basic concepts of the bodies themselves. Therefore, space and matter are indivisible, and therefore the world, which has spatial dimensions, is *full* of *continuous* matter.

the original formulation as proposed by Aristotle are presented here:

> "...not a single thing can be moved if there *is* a void; for as with those who for a like reason say the earth is at rest, so, too, in the void things must be at rest; for there is no place to which things can move more or less than to another; since the void insofar as it is void admits no difference..."
>
> "Further, in point of fact, things that are thrown move though that which gave them the impulse is not touching them, either by reason of mutual replacement, as some maintain, or because the air that has been pushed pushes them with a movement quicker than the natural locomotion of the projectile wherewith it moves to its proper place. But in the void none of these things can take place, nor can anything be moved save as that which is carried is moved." (*ibid.*, p.71).

Greek atomism remained strong among its supporters for about five hundred years. In the first century BCE it is described in vivid detail in the great poem of the Roman poet Lucretius (*ibid.*, p. 88 and it is also the basis for scientific and technological experiments in the behavior of the air performed by Hero of Alexandria (60 CE) (See Toulmin and Goodfield, 1962, p.222).

However, in the middle ages it was clearly rejected, and Aristotle's position apparently took hold firmly. His philosophy was adopted in nearly all areas of thought and science, both by the Christian Church and by many Arab philosophers. Regarding the notion of vacuum, it was accepted for the duration of the Middle Ages that vacuum is implausible and that "Nature abhors a vacuum".

In the beginning of the 17th Century, a clear return to atomism began. It rested to some degree on experiments, but was rooted in speculative philosophical considerations. Toulmin and Goodfield (1962) in their historical survey argued that Galileo (1564-1642)

> "adopted atomism for general philosophical reasons: It was the intellectual instrument by which he hoped to bring matter theory within the field of mathematics (*ibid.*, p.194)..."A truly scientific account of behavior of things should therefore refer only to shapes and motions - mathematically analyzable properties, which Galileo called the `primary' qualities of things. Characteristics such as colour and warmth, by contrast, had no place in scientific theory: such `secondary' qualities were no more than by-products of the interaction between our bodies and the atoms of the outside world (*ibid.*, p.194-5).

"Galileo was happy to follow Democritus in most respects, differing from him only in the central importance he attached to mathematics (*ibid.*, p.196) ... (He) and his pupils began to experiment on the physical properties of elastic (i.e., compressible or gaseous) fluids - notably, on the air of the atmosphere. This choice of starting-point was no accident. *Atomism had always appeared most plausible when applied to the physics of gases*, and Hero of Alexandria's treatise on the subject was familiar both to Galileo in Italy and a generation later, to Robert Boyle in England." (*ibid.*, p.196) [emphasis mine, J.N.].

The experiments carried out by the student of Galileo, Toricelli (1608-1655) on the air in the atmosphere brought about the invention of the first barometer. The barometer, which demonstrated the natural formation of a vacuum at the top of the pipe, and subsequently, Toricelli's explanation of air pressure, created a wave of excitement which spread among the European scientists.

It was clear that Toricelli's experiments challenged Aristotle's claim that "Nature abhors a vacuum". Pascal (1623-1662) continued Toricelli's experiments and showed that the column of mercury in the barometer is shorter when measured on the top of hills, since it left more vacuum at the top of the glass tube. These breakthrough experiments with the barometer resulted in a situation in which atomism was more receptive and which therefore could be brought to the center of scientific thinking after 2000 years of opposition. It should be pointed out that despite this great jump forward, no effort had yet been made to clarify the "true" form of corpuscles or atoms, but rather of the very existence of vacuum and of its being an important part of the world of matter.

Pascal is interesting here:

"It is not difficult to demonstrate...that nature does not abhor a vacuum at all. This manner of speaking is improper, since created nature .. is not animated, and can have no passions.... [Nature] is supremely indifferent to a vacuum, since it never does anything either to seek or to avoid it" (Sambursky, p.261-2).

This article of Pascal concludes with a pathos emphasizing the stormy depth of the historic argument over vacuum.

"Does Nature abhor a vacuum more in the highlands than in the lowlands? In damp weather more than in fine? Is not its abhorrence the same on a steeple, in an attic, and in the yard? Let all the disciples of Aristotle collect the profoundest writing of their

> master and of his commentators in order to account for these things [the barometer's changes] by abhorrence of vacuum if they can. If they can not, let them learn that experiment is the true master that one must follow in physics; that the experiment made on the mountains has overthrown the universal belief in nature's abhorrence of a vacuum, and given the world the knowledge, never to be lost, that nature has no abhorrence of a vacuum, nor does anything to avoid it; and that the weight of the mass of the air is the true cause of all effects hitherto ascribed to that imaginary cause" (*ibid.*, p.263).

Boyle (1627-1691) continued the line of research of Toricelli and Pascal and carried out experiments on "the spring of air". In his summary, Boyle writes:

> "the notion I speak of is that there is a spring or elastic power in the air we live in." (*ibid.*, p.281)..."this notion may perhaps be somewhat further explained, by conceiving the air near the earth to be such a heap of little bodies, lying one upon the other as may be resembled to *a fleece of wool* [J.N.]. For this ... consists of many slender and flexible hairs; each of which may indeed, like a little spring, be easily bent or rolled up; but will also, like a spring be still endeavouring to stretch itself out again." (*ibid* p.282).

Thus, as we see, Boyle did not explain the springiness of air by a kinetic model with invisible corpuscles bumping into each other and into the walls. Even his particles are not necessarily ball-shaped, as we have gotten used to thinking of them. He is prepared to compare them to a fleece of wool. Why, if such is the case, is his model worthy of being considered atomistic?

It is indeed atomistic, since he assumes a vacuum area similar to the "empty" space which surrounds and impenetrates the wool, and also because he assumes that the matter of the air *is not* continuous, but composed of discrete particles. Note the following statements made by Boyle:

> "This power of self-dilation is somewhat more conspicuous in a dry sponge compressed, than in a fleece of wool. But yet we rather chose to employ the latter [the wool model] on this occasion, because it *is not*, like a sponge, *an entire body*, but a number of slender and flexible bodies, loosely complicated, as the air itself seems to be (*ibid.*, p.282).

It may be assumed that Boyle, who considered himself to be an empiricist, did not want in this article (1660) to make too much of a strong statement or to return to the model of Democrates in its entirety (separate atoms moving and interacting within an infinite vacuum). He adopted the atomistic model only insofar as experiments "compelled" him to do so. Thus, it is certain that the empty space contains discrete particles crowding together under pressure. The less bold explanation seemed to be that each particle behaves like a spring. Kinetics, which was part of the Democrates' model, did not seem compelled from within the experiment, and therefore he took pains not to use it at this stage. However, we find that Boyle had a full kinetic model from his writings in 1666 (Toulmin and Goodfield, p.201).[9]

Boyle recognized that there is an alternative, Cartesian explanation to his experiments with the air, and yet he preferred the atomistic explanation because of its simplicity (Sambursky, p.283).

Toulmin and Goodfield summarize these historical stages as follows:

> "The basic appeal of atomism to seventeenth century corpuscular philosophers remained general and philosophical: their experimental work on air did not, by itself, provide compelling evidence of the truth of the atomic doctrines. It carried conviction only to the convinced. (p.199).

Atomism, in its physical view, before the modern chemical period, reached the peak of its development with Newton (16--) who added the concept of the existence of attracting and repelling forces among the particles. By using this idea, Newton explained physical and chemical concepts such as cohesion, capillary attraction, absorption of water vapor by hygroscopes, the warming of a mixture in a salt solution with water, or with the reaction of acids upon different material. Despite the fact that the promotion of Newton's atomic theory was very significant, the very transfer of his concept from the macro world of magnetism and gravitation to the micro world of atomic interaction, brought Newton to propose also a *misconception* which remained in force until the beginning of the nineteenth century.

Newton's general assumption regarding the attractive forces among atoms is accepted and the basis of our understanding today of matter. However, Newton continued another assumption regarding the forces of *repulsion* between gaseous atoms (which act for a large distance) which create

---

[9]It is interesting that kinetics, which is responsible for the flexibility and springiness of the air, was missing from Boyle's first explanation, but it appeared in the opposing concept of Descartes. However, Cartesian movement differed from the linear displacement concept proposed by Democritus, because the former espoused a rotation of bodies moved by a continuously whirling celestial fluid - ether - which was assumed to fill the entire universe.

the springiness of air which Boyle described. Dalton (1766-1844) retained this misconception and argued that the forces of repulsion exist only between atoms of the same gas and do not exist between atoms of different gases. In this way, Dalton explained how it is possible to achieve homogenic diffusion of two gases with each other, rather than achieving two separate layers.

The noting of this misconception here emphasizes the point that the scientists' return to Democritus' model began from the acceptance of the existence of vacuum, while it took additional time to convince others of the movement of particles.

We propose several implications from the historical review discussed above:

i. *Instruction by philosophical discussions*. Historical analysis shows that experiments by themselves cannot convince everybody by themselves of the correctness of a theoretical explanation. Also the very knowledge and understanding of theory is no guarantee of the adoption by a person who studies it. Aristotle and Descartes were would have received a high mark if they had been tested on the details of the arguments of the atomists, but nonetheless Aristotle and Descartes absolutely rejected the atomic theory. Therefore we see no way to bypass the basic philosophical discussion regarding the quality of matter. Only as a result of a philosophical discussion is it possible to achieve a true and significant level of convincing.

ii. *Beginning by explicit and elaborate discussion of the concept of vacuum*. The main philosophical aspect which presents innovative material in the atomic theory is the fact that vacuum is a significant part in physical existence. Only if there is a vacuum could matter be non-continuous, and thus particulate. Only if there is a vacuum is there a possibility of a movement of particles which can be described in Newtonian mechanics. The "correct" form of the particles and the kinetic concept are less important or primary. The quality of instruction will be tested by its ability to create a true philosophical discussion of concepts of vacuum.

iii. *Entering into the particulate model by an investigation of the behavior of gases, mainly air*. Since it was demonstrated historically that the gas phase calls for the idea of the existence of vacuum and thus *ipso facto* particulate matter, more than a phase of liquid and a solid, it is worth beginning also with students from an investigation of the air.

iv. *A study of the particulate model is a lengthy process of conceptual change*. The history of science has shown in various areas that a conceptual change is a lengthy process accompanied by coping with different types of misconceptions and it includes alternating stages of advance and retreat. It is not reasonable to expect our students to internalize the subject in a meaningful manner while studying it for several weeks. The educational process which applies Points (1) through (3) above has to be given time, and it must be developed in a spiral fashion over the course of several years of study.

(2) ***Implications from the philosophy of science.***
A previous article (Nussbaum, 1989) pointed out the possible significance of the philosophy of science on the teaching of science in schools. That article presented these matters in detail while this paper will present only a brief summary, with references to that source.

The broad trend predominating today in philosophy is constructivism, which replaced the two classical trends - empiricism and rationalism. The two traditional trends believed in absolute knowledge, while the current trend emphasizes the building of knowledge by a person, as well as the fact that the basis of science is a process of revised constructs and reconstructions of models for the existential structure. The main issue which separating constructivist philosophers is whether there is (and whether it is proper that there be) clear criteria for abandoning an older theory and the adoption of another theory. From Popper it is clear that scientists abandon a theory when a critical experiment refutes it. Kuhn argues, quite uncompromisingly, that the inclusive theories, or paradigms, are not necessarily replaced because of a critical experiment, but to a great extent because of social and psychological reasons which affect the individual scientist and the community of scientists. Lakatos (196-) and Toulmin (1972) take intermediate stands, both of them emphasizing that it is not a critical experiment which creates a conceptual change. Lakatos argues that the abandonment of a theory occurs not with a conflict between the theory and a new experiment, but only whit an open conflict between this theory and an alternative theory. A theory is abandoned only when its proponents gradually realize the advantages of an alternative theory and the disadvantages of continuing to reconsider of their own theory. Toulmin emphasizes the gradual and evolutionary change in the meaning of the concepts. These two philosophers emphasize that the conceptual change among the community of scientists is not a purely intellectual process but rather includes a process of social negotiation.

This writer is more convinced by the philosophical approaches espoused by Lakatos and Toulmin, and believes that during the course of conceptual change in the classroom, the process must include negotiations among the alternative models, as a main part of the instructional strategy. The teacher guiding the process must be patient and tolerant, and to be prepared not only for slow progress among some of the students, but also for a possible retreat among some of them.

(3) ***Implications from the area of cognitive psychology***

The writings of various people in cognitive psychology, beginning in the Sixties, shows a psychological concept reminiscent in its principles of the constructivist concept in the philosophy of science. After studying the convergence of the current concepts in philosophy and psychology, those involved in teaching science began to speak of a constructive approach to education (Driver, 1985; Novak, 1988). From a certain point of view, also Piagetian theory is constructivist, but Piaget's intellectual construction of reality is created only through logical operations. Since the development in stages of logical operations is an immanent component of Piaget, it results that a young child cannot study abstract concepts. Logic has lost a great deal of its centrality when conceptualizing the essence of science among recent philosophers (Brown, 1988). In addition, various psychologists have challenged the centrality of logic as the primary criterion determining the quality of thought (Donaldson, 1979) and Piaget's gradual development model.

With certain variations many psychologist agree today that the thought of the child is affected by their existing context-oriented and context-dependent concepts.

Writings such as Matthews (1984) and others have shown that very young children are capable of true philosophical discussions. It has become clear from these projects that it is not the age of the children which is a limiting factor for their ability to philosophize. It is rather the ability of the adult guiding the discussion to stimulate them and to assist them to draw out their hidden potential.

According to these considerations, we have hypothesized that philosophical discussions can be carried out regarding the particulate model of matter also with children of a relatively young age - and younger than the age that the subject is generally taught in schools. If it could be studied at an earlier age then it would certainly be worthwhile, as noted in the previous section indicating that the conceptual change is an extended process.

Our argument is that because the subject is not introduced until age 13-14 and up, and that furthermore it is introduced in insufficient methods, we find that high school students still cannot operate with the particulate model in a meaningful manner in advance subjects such as chemistry and biology.

In some of our previous articles (Nussbaum & Novick, 1981,1982) we attempted to apply the considerations which we brought above for instructing the subject to students aged 13-14, and we found that the strategy which we proposed was very successful.

The present research presented an attempt to investigate whether it was possible by means of some modifications to teach the subjects to students aged 9 (third graders).

Structure of the instructional unit

Since we cannot expand on the process of education which includes 30 propositions, the structure will be described following in the form of expressions or questions. In most of the classes each expression or question will be accompanied by experimental activities.

Generating concepts and primary factual knowledge regarding air and pure gases	☺ Is air matter? Air takes up room; air carries out activities. ☺ Various gases, such as carbon dioxide and oxygen, are colorless and clear. How can carbon dioxide be identified? How is oxygen identified? Air is a mixture of carbon dioxide, oxygen, and nitrogen.
Preparation for the cognitive need for vacuum	☺ If we had magic eyeglasses, how would air remaining in a closed flask look after part of it was pumped out. From what place within the flask would air be missing after it was pumped out? ☺ Why is air compressible whereas water is not compressible?
Preparation of an "analogy" for the following discussion	☺ Air behaves like a spring or like a sponge. Given a block of iron, steel wool, a steel spring, a rubber stopper, and foam rubber, which is compressible? Which is not? The structure of the material, rather than the material itself, determines whether it will be compressible. Steel wool, a spring, and a rubber sponge have empty spaces in them, and this is why they are compressible.
"Feeling" the applicability of the new model	☺ Are there empty spaces in the air surrounding us? What can explain the compressibility of air? Air is made of particles in a vacuum - the teacher's preferred proposal.
Debating the plausibility of natural vacuum	☺ Given acetone, alcohol, and water - which has the strongest smell? Which evaporates and disappears first? Where are the acetone particles which left the liquid? How are the acetone particles distributed in the air?

Supporting experience	☺ Acetone, alcohol and water: Which was has the strongest smell? Which one evaporates and disappears first? Where are the acetone particles which left the liquid? How are the particles of acetone distributed in the air?
Debating animism vs. mechanism. Smell is a substance.	☺ Do the acetone particles "want" to reach our noses? ☺ "Smell" is a substance which changed from a liquid (or solid) form to a gaseous form. Smell is vapors. Vapors are caseous matter. Water vapor has no smell. Where are the naphthalene particles which evaporated?
Temperature and particles kinetics animism vs. mechanism	☺ A flattened plastic bottle with some liquid acetone expands when heated. What did the heating do to the particles of acetone in the bottle? What did the particles of gaseous acetone do to the walls of the bottle? ☺ The connection between the heating and the movement of particles ☺ The rising of a bubble of soap which seals off the mouth of the test tube - by heating the air in the test tube. ☺ The lowering of that bubble by cooling of the test tube. ☺ What is the particulate explanation? Do particles escape from the heat? What pushes the bubble harder - the air inside or the air outside?

Bibliography

Andersson, B (1990). Pupils' conceptions of matter and its transformations (age 12-16). In: Lijnse, P.L., Licht, P., Vos, W. de, Waarlo, A.S. *Relating Macroscopic phenomena to microscopic particles: A central problem in secondary science education.* Utrecht: CD-ß Press, 81-104.

Brown, H.I. (1988) *Rationality.* London: Routledge.

Donaldson, M. (1978). *Children's Mind.* New York: W.W. Norton & Company.

Driver, R. and V. Oldham (1986). A constructivist approach to curriculum development. *Studies in Science Education,* 13, 105-122.

Driver, R. (1989). Theory into practice II: A constructive approach to curriculum development. In: P. Fensham (ed.). *Development and dilemmas in science education.* London: Falmer Press.

Johnston, K (1990). Students' responses to an active learning approach to teaching the particulate theory of matter. In: Lijnse, P.L., Licht, P., Vos, W. de, Waarlo, A.S. *Relating Macroscopic phenomena to microscopic particles: A central problem in secondary science education.* Utrecht: CD-ß Press, 81-104.

Lakatos, I (1970). Falsification and the methodology of scientific research programmes. In: I. Lakatos and A. Musgrave (eds.), *Criticism and the Growth of Knowledge.* Cambridge: Cambridge University Press.

Matthews, Gareth B (1984). *Dialogues with Children.* Cambridge, Harvard University Press.

Meheut, M. and A. Chomat (1990). The bounds of children's atomism; An attempt to make children build up a particulate model of matter. In: Lijnse, P.L., Licht, P., Vos, W. de, Waarlo, A.S. *Relating Macroscopic phenomena to microscopic particles: A central problem in secondary science education.* Utrecht: CD-ß Press, 81-104.

Millar, R. (1990). Making sense: What use are particle ideas to children? In: Lijnse, P.L., Licht, P., Vos, W. de, Waarlo, A.S. *Relating Macroscopic phenomena to microscopic particles: A central problem in secondary science education.* Utrecht: CD-ß Press, 81-104.

Nussbaum, J. (1985). The particulate nature of matter in the gaseous phase. In R. Driver, E. Guesne and A. Tiberghien (eds.). *Children's Ideas in Science*. Open University Press, Milton Keynes.

Nussbaum, J. (1989). "Classroom conceptual change: Philosophical perspectives". *International Journal of Science Education*. 11:(Special issue), 530-540.

Sambursky, S. (1960). *The evolution of physical thought: From the presocratics to quantum physics; An anthology*.

Toulmin, S.E. and J. Goodfield (1962). *The architecture of matter*. Harmondsworth: Penguin.

Toulmin, S.E. (1972). *Human Understanding*.

Vos, W. de (1990). "Seven thoughts on teaching molecules." In: Lijnse, P.L., Licht, P., Vos, W. de, Waarlo, A.S. *Relating Macroscopic phenomena to microscopic particles: A central problem in secondary science education*. Utrecht: CD-ß Press, 81-104.

ACQUISITION OF CONSERVATION OF MATTER

Ruth Stavy, School of Education, Tel-Aviv University

According to Piaget, quantitative conservation is possible at the concrete operational stage when children possess reversible logical operations (compensation, negation, identity or additivity). In our previous research (Stavy and Stachel 1985.), as in many others (Lovell and Ogilvie, 1961-62; Uzigris, 1964), it was found that, as opposed to what is expected according to Piaget's stage theory, children can conserve weight in some tasks but not in others.

Lovell and Ogilivie explain this horizontal decalage by saying that although logical thinking is an essential condition for weight conservation, it is not enough. Experience in the physical world has a much larger role than expected, therefore conservation does not develop in an all or none process but is developed gradually, Inheider Sinclair and Bovet (1974) claim that during the process of constructing their knowledge, children come across much risistance from their surrounding which is the cause for horizontal decalage.

Another approach to conservation of weight problems will be presented in this paper. Misconservation will be presented and interpreted in terms of specific alternative conceptual framework. Thus, the development of conservation of weight in different transformations of matter will be described and discussed. Educational implications will also be discussed.

Methodology

The Sample

The sample included students of middle class population from the first grade (ages 6-7) until the ninth grade (ages 14-15). Each age group comprised 20-25 students. Each student was interviewed independently while being showed the materials and the processes. Each student was asked only two of the tasks.

In the seventh grade students in Israel study the chapter "The Structure of Matter" (Orpaz, Ben-Zvi) which deals with the particulate theory of matter, in the eighth grade they study the chapter "From Elements to Compounds" (Arazi, Sivan) which deals with elements and compounds, the periodic table of the elements and electrical phenomena of matter.

The Tasks

a. Melting task:

Candles: Two indentical candles were given to the child who was asked to judge the equality of weight. One of the candles was then melted and the child was asked about the equality of weight and about the reversibility of the process.

Ice: The child was presented with two identical test tubes. Each contained an equal amount of ice. The child was asked to judge the equality of weight. The ice in one of the test tubes was melted and the child was asked about the equality of weight and about the reversibility of process.

b. Evaporation tasks:

1. Acetone: The subject was presented with two closed identical test tubes. Each contained an equal amount of acetone (one drop). The subject was asked to judge the equality of weight. The acetone in one of the test tubes was heated until it completely evapoatated. The student was asked about the equality of weight and about the reversibility of the process.
2. Iodine: The subject was presented with two closed identical test tubes, each containing an iodine crystal (two equally sized crystals). The subject was asked to judge the equality of weight. The iodine in one of the test tubes was heated and turned completedly into purple gas which filled the whole volume of the test tube. The subject was asked about the equality of weight and about the reversibility of the process.

c. Dissolving of sugar task:

The subject was presented with two identical cups containing equal amounts of water and with two identical tea spoons containing equal amounts of sugar. The child was asked to judge the equality of weight of the two systems. One tea spoon of sugar was put next to one of the cups and the second was dissolved in the water in the second cup. The child was asked about the equality of weight of the two systems.

d. Expansion of Water task:

The subject was presented with two small vials each of which was filled to the top. A rubber stopper with a hole in it was placed in the vial's opening and a thin glass tube was inserted into the hole of the stopper, so that it slightly entered the vial. One of the vial was heated and the water rose into the tube. The child was asked about the equality of weight of the two vials.

Results

A. Conservation of Weight in different types of transformations of matter.

The classic task concerning weight conservations developed by Piaget, is that of the plasticine ball deformation. Six to seven year old children succeed in this task using explanations of: identity (it is the same plasticine); reversibility (the ball can be changed back); compensation (there are more pieces but they are smaller); additivity (nothing was added or substracted). This means that children at this age have the logical ability to deal with certain weight conservation tasks.

When children are presented with weight conservation tasks which involve change of state their responses are different. As opposed to the linear curve of development in the success of the plasticine conservation task (with a rise from 20% to 80% in the second grade), the development curve with regard to the success of the melting of ice task is not linear, but rather is an S - shaped curve with a sharp rise at the third grade (5% - 45%), a shoulder and a second rise at the fifth grade (55% -75%). The evaporation of acetone task shows a linear rise from 0% - 80% from fourth to ninth grade. It seems, therefore, that the capacity to conserve wieght depends on the nature of the transformation. It is first expressed in the case of the simple change of translocation, then in the process of change of state from solid to liquid and finally in the process of change from liquid to gas. (see fig. 1).

Insert Fig. 1.

The majority of students who did not answer correctly the melting of ice task believed that ice is heavier than water or that water has no weight. Few of the younger ones believed that water is heavier than ice. With regard to the evaporation of acetone task the younger students in the sample tended to believe that gas has no weight and the older ones that liquid is heavier than gas.

The development of conservation of weight in the processes of dissolving sugar in water and expansion of water by heat are very similiar to the development of conservation in the melting of ice task (Fig.2)

Insert Fig. 2

The younger students who did not respond correctly to the sugar water task believed that the sugar water is heavier than the sum of the weights of sugar and water because "sugar is heavy and it makes the water heavier". The older ones tended to believe that the sugar water is lighter than the sum of the weights of sugar and water because "the sugar becomes smaller and smaller until it disapears."

In the expansion of water task the majority of students thaught that the hot water is heavier because its volume is expanded. But few of the older student (grades eight and nine) thought that "cold water is always heavier" and some even explained that the density of cold water is larger.

It seems that children construct a set of intuitive rules or propositions regarding the correlation between the weight of matter and its state. The rules found in the case of evaporation were : I - gas has no weight; II - gas always weighs less than liquid; III - the weight of gas is equal to the weight of the liquid from which it was made. The following rules were found in the case of melting:

I - liquid weighs more than solids; II - liquids has no weight; III - liquids weigh less than the solids; IV - the weight of a liquid is equal to that of the solid from which it was formed.

Similar rules were found regarding dissolving of sugar in water (which might be percieved by students as melting): I - sugar water is heavier than the total weight of sugar and water; II - the dissolved sugar has no weight; III - the weight of the sugar water is smaller than the total weight of sugar and water; IV - the weight of the sugar water is equal to the sum of the weights of the sugar and water.

All these rules stem from intuitive feeling that children have regarding "lightness" and "heavyness" of matter (or qroups of materials) which is an intensive "quantity" or property. The child refers to the intensive quantity instead of the extensive quantity, weight, about which he was asked. Can it be assumed that the child does not properly understand the meaning of the term weight and thinks that weight refers to the specific weight of the material? This is almost definitely not the case. It is clear that from a very young age children understand what the weight or heaviness of an object is, and know that a large body of a certain material is heavier than a smaller body of the same material. A reversed behavior was observed by Piaget and Inhelder (1974) and Megged (1978) who studied the development of children's concept of density. (see Fig. 3).

Insert Fig. 3

Children were asked about floating or density - an intensive property of matter, and they responded as if they had been asked about weight which is an extensive property of matter.For example, children were presented with two pieces of iron, one was a large and heavy cube and the other was a pin. The child was asked to predict whether the object would sink or float. Children under the age of twelve thought the pin would float since it was light and "light things float". It is possible to explain this difference between the responses as follows. The major change in the case of evaporation is change in the state of matter which is expressed as a change in density. While in the case of floating the main change is in the size or weight of the piece of matter. It is possible that children's cognitive system is affected by the changing dimension, such as density, and regards it as the significant dimension in the problem and looks for ties which are appropriate to the situation. And indeed, some of the rules presented here are correct in other situations. There is no doubt that studying chemistry in the seventh and eighth grades might reinforce these rules (for instance "gas weighs less than liquid" or "liquid weighs less than a solid"). Apparently the term "weight" is connected in the child's congnitive system with "specific weight" and "absolute weight" (and probably also with other "weight" aspects such as swings, balance scales, free fall, etc.) These terms are not defined well enough and as long as they are not fully differentiated the child can use them according to the specific characterictics of the situation.

B. <u>The effect of context on weight conservation.</u>

Children's responses to tasks which are essentially identical such as evaporation of acetone and evaporation (or sublimation) of iodine were compared. The iodine, as opposed to the acetone has color and can be seen in its gaseous state. As can be seen from Fig.4. many more students in the fourth to seventh grade conserved the weight of iodine, than they did with regards to acetone.

Insert Fig.4

Children in this age group who conserved the weight of iodine and not that of acetone were clearly relating to the fact that they could see the material. They explained their answers with explanations similar to those given for the weight conservation of the clay ball task (Piaget): "the crystal becomes crumbs so it is exactly the same thing" or "the same thing that was in the crystal is in the test tube" or "since the crystal dissolved".

From the seventh grade on, children begin to regard weight conservation of iodine in the same fashion that they regard acetone and their explanations are similar, "only the state of matter was changed" or "nothing was added or subtracted". A few children refered to particles and said, "the particles only got farther apart". Explanations to incorrect answers among this age group were also similar "gas is weightless" or "gas always weighs less than a solid".

Apparently specific perceptual input from the task affects children's judgements. Beginning in the seventh grade the effect of perceptual input disappears and the percentage of success in the two different tasks become parallel. One can assume that at that age all tasks of change of state, are represented in the same way and this may symbolize the beginning of formal conservation.

However, two melting tasks, the melting of ice and the melting of candle wax show closer developmental curves (Fig.5).

Insert Fig. 5

And the developmental curves of success in the sugar water task, expansion of water task and evaporation of iodine task are similar to them. All these tasks are perceptually similar: they are concrete and involve change in the volume or organization of matter. Apparently, students relate to all of them in a similar way.

C. <u>Conservation of weight and Reversibility</u>

The understanding of reversibility was not found to be prerequisit to the capability of weight conservation. There were cases in which children conserved weight without understanding the reversibility of the process (melted candle, iodine sublimation) and (rare) cases in which the children understood the reversibility of the process but did not conserve weight.

It turns out that the two developmental curves of the success in the reversibility tasks - (the evaporation of acetone and sublimation of iodine) - are very similar (see figure 6). The curves are linear and have a sharp rise around age twelve-the seventh grade (at age fourteen a fall appears which is different for each of the tasks apparently because of over sophistication and attention to technical details regarding the reversibility of the process). These facts suggest that children represent the reversibility tasks related to the process of change of state from liquid to gas in the same way and are not affected by perceptual elements of the task. It is possible that the understanding of the reversibility of the process which emerges at the age of 12 is a result of school learning in addition to the development of formal thinking. (The structure of matter, which deals with changes in states of matter, is taught in the seventh grade). The reversibility curve is almost identical to that of the conservation of weight in the acetone evaporation task, which is the most difficult of the task presented here. It is therefore possible that there is

Insert Fig. 6

some correlation between understanding of reversibility and the capability to conserve weight in cases in which there are no supporting perceptual elements, or during ages when these elements do not serve as supporting entities. The developmental curve of success in the reversibility of melting a candle also develops gradually from kindergarden until age fourteen. (see fig. 7). This curve proceeds that of reversibility of evaporation by approximately four years.

In the case of meting ice majority of children betweeen the ages of six and fourteen understand the reversibility of the process although many of them do not conserve weight during this process. It is possible that children of these ages do not have a general conception of the reversibility of the melting process but judge each case specifically.

Insert Fig. 7

Discussion

Piaget relates the capability of conservation at the stage of concrete operations to the development of logical operations. As it turns out these logical operations do not suffice to enable dealing with certain conservation tasks. Specific knowledge about the change, and about the properties of the quantity in question and about the boundaries within which it is conserved is necessary. For instance, the mass and weight of matter are conserved during a change of state though its volume is not. From a logical point of view the same logical claims of reversibility, identity and additivity can be made regarding mass weight and volume. In addition, in many cases of chemical changes considerations of reversibility or identity cannot be made (there are irreversible processes and the identity of matter is not conserved during chemical processes); none the less, matter is conserved.

Many scientists regard the laws of conservation as empirical laws which state that for a given system of objects there exist measurable quantities whose total amount does not change. The laws determine the conditions in which each quantity is conserved.

In his book "The Various Language", A. Arons (1977) wrote: "The law of conservation of matter cannot be proved to be true by some system of deductive reasoning from more fundamental principles...it is induced from a limited amount of empirical data. We have, however, over a period of 200 years come to hold a very deep belief of its validity".

Obviously children do not have directed empirical experience which would lead them to the laws of conservation. Apparently the logical operations which develop with the development of concrete operational thought, are those which enable children at ages six and seven to solve certain problems of conservation. The question arises: Why don't children use these logical operations in order to solve other conservation problems?

In this paper we have demonstrated that children solve certain conservation problems without being able to solve others. We have also shown that in addition to the logical operations related to conservation, children have much factual knowledge about matter which changes with age and possibly as a result of formal schooling. We will try now to answer the question posed above.

As a result of an internal representation of a problem a person (or a child) is faced with, many different bits of his knowledge are activated or aroused. These bits of knowledge compete with one another over the problem solving mechanism in such a way that the strongest knowledge relevant to the problem, at a given moment, overcomes all other bits of knowledge. The strongest knowledge relevant to the problem will be that which will affect the person in his solution of the problem. So even if the appropriate knowledge exists in the cognitive system it will not always be expressed in solving the problem. This explanation enables us to understand the horizontal decalage found in this research and others regarding weight conservation problems, and the non-linear development of the success in these tasks. For instance, half of the children above the age of seven conserved weight in the melted candle task using logical additivity justifications, the other half used their knowledge that a solid candle was heavier, whereas they all responded correctly to the weight conservation task with the plasticine. In the case of the plasticine apparently no competitive knowledge is activated which explains the high degree of success. In the case of the candle two sets of knowledge of equal strength are probably used.

Among the older children (ages eight to nine) the knowledge that the solid candle is heavier strengthens as the result of experience in the physical world and successful use of this knowledge in solving other types of problems (solids usually have higher specific weights than the corresponding liquids), so the percentage of success drops and then rises again in the sixth and seventh grades (ages eleven and twelve) when the knowledge that solids are heavier is channeled to relevant problems and no longer competes with the logical operations relevant to conservation. This process of finding the boundaries within which one's knowledge is applicable may lead one to identify (even unconsciously) a problem and relate to it according to its type or category (even if the response is incorrect). In such a case the person's response will not be affected by irrelevant perceptual information and the solution will deal with the type and essence of the problem – that is a more formal or abstract response. In addition, the different bits of knowledge may get temporary support from immediate perceptual inputs of the task verbal, visual or that which is related to the dynamic aspect of the task. In summary the different types of knowledge that exist in the cognitive system of the child regarding certain physical entities compete with one another and with the correct knowledge which also may exist in the cognitive system. This is a dynamic competition between the different knowledge systems in which the strongest knowledge prevails. In our case the children have the operative knowledge necessary to solve the weight conservation problems but instead they use irrelevant knowledge which, at certain ages or situations, is quite strong.

This reciprocal game between the different knowledge systems is a progressing process through which the child gradually learns the boundaries within which his knowledge is applicable. It is possible that the expansion of knowledge starts with instances in which positive reinforcement exists for correct knowledge from immediate perceptual input and from those transfered by analogy to similar cases in which it does not.

Applications for science instruction

We will divide the discussion on instructive applications into two parts: The first part will deal with specific applications regarding educaiton in the subject of "The states of matter". The second part will be more encompassing and will deal with science teaching in general.

a. Specific applications

The law of conservation of matter was a breakthrough to the particulate theory of matter and modern chemistry and one can assume that it is basic knowledge that should be used to develop the particulate theory and modern chemistry among students also. Results of this research show that only 50% of the seventh grade students understand the conservation of matter in the process of evaporation; The particulate theory of matter is taught on the basis of this faulty knowledge. This may be the reason that no students in the seventh grade and only 15% in the eighth and ninth grades used the terms from the particulate theory in their explanations. In light of these results we recommend teaching the conservation of weight, at least regarding changes of states of matter, <u>before</u> beginning to deal with the particlulate theory and with chemistry and while teaching these subjects to emphasize, and expand the conception about conservation of matter regarding chemical proceeses also.

Instruction of conservation of weight should be done in the following sequence: (1) conservation in translocation - crumbling a lump of solid into powder, (2) conservation during melting, dissolving and in changes of volume (of solids and liquids) during heating (or cooling) (3) changes of solids or liquids to gas (one should start with materials which have clear perceptual properties in the gaseous state), and changes of volume of gas (heating or compressing) (4) chemical reactionsins which do not involve evolution or absorption of gases, (5) chemical reactions in which gas is evolved or absorbed.

In all these transformations the reversibility of process must be regarded as must the conservation of qualitative properties both in processes in which the identity of the matter is conserved and they are reversible and in those that the identity of the matter is not conserved, nor are they reversible.

B. Pedagogic applications

When a new phenomenon, term, law or theory is being taught one should try to begin with an example for which there is maximal perceptual reinforcement for correct intuitive knowledge. For instance, in weight conservation in the process of evorporation one should start (at an appropriate age) with colored matter (such as iodine) in order to reinforce the intuitive knowledge that exists, that weight is conserved in this case. Only then should one proceed by analogy to cases in which the perceptual reinforcements are diminished (for instance colorless matter with smell and then colorless matter with no smell). When instructing science it is common to present ideas or new phenomena with the most characteristic examples isntead of those with the most perceptual elements. For instance in the subject of gases examples of oxygen, nitrogen, carbon dioxide, ammonia, etc. are given but not iodine, bromine, chlorine or nitrogen oxide which are colored. The opposite is also true - in cases in which the common typical exemplars have strong perceptual reinforcements other examples are not usually given. For instance, while teaching the term liquid the common examples of water, oil, etc. are given. These have strong perceptual elements which help classifying them as liquids. If this is not augmented with examples of viscous liquids or powders nothing is added to the existing intuitive knowledge. This type of instruction should be tried and tested. It demands knowledge about the intuitive ideas that children have at different ages about phenomena, terms or ideas related to science.

2. Since we saw that the success of solving a problem depends on the dynamic competition between the different bits of knowledge in which the stronger knowledge prevails, it is clear that the child should be assited in strengthening the correct bits of knowledge in his cognitive system, and should be helped

to find the boundaries within which this knowledge can be applied. This can be done by giving the students chances to use their knowledge in solving different problems and to allow them to propose hypotheses and examine them in light of the physical reality.

3. We have seen that during the process of acquiring conservation of weight skills the child goes through a stage in which he reacts and responds to all evaporation problems in the same fashion (even if incorrectly so) and does not relate to any irrelevant elements. This attitude enables correct responses to this to type of question at a later stage. From this we see that the relation to the type and the essence of a problem and relating it to the characteristic category of problems can be an important stage towards the capability of solving such problems and towards acquiring the general knowledge relevant to them.

Bibliography

Arazi, J., Sivan, I. (Undated). From Elements to Compounds, TL (In Hebrew).

Arons, A., The Various Language, New York: Oxford University Press, 1977, p. 39.

Inhelder, B., Sinclair, H. & Bovet, M., Learning and the Development of Cognition. Cambridge: Harvard University Press, 1974.

Lovell, K., & Ogilvie, E., A Study of the Conservation of Weight in the Junior School Child. British J. Educational Psychology, 1961-1962, 31, 138-144.

Megged, C., The Development of the Concept of Density in children from ages 6-16. M A Thesis Tel Aviv University, 1978.

Orpaz, N., Ben-Zvi, R., undated, The Structure of Matter, TL (In Hebrew).

Piaget, J. & Inhelder, B. The Child's Construction of Quantity: London: Routledge and Kegan Paul, 1974. (Original, 1941).

Stavy, R., and Stachel, D. Children's Conception of Changes in the State of Matter: From Solid to Liquid. Archives de Psychologie, 1985, 53, 331-344.

Uzigris, I. C., Situational Generality of Conservation. Child Development, 1964, 35, 831-841.

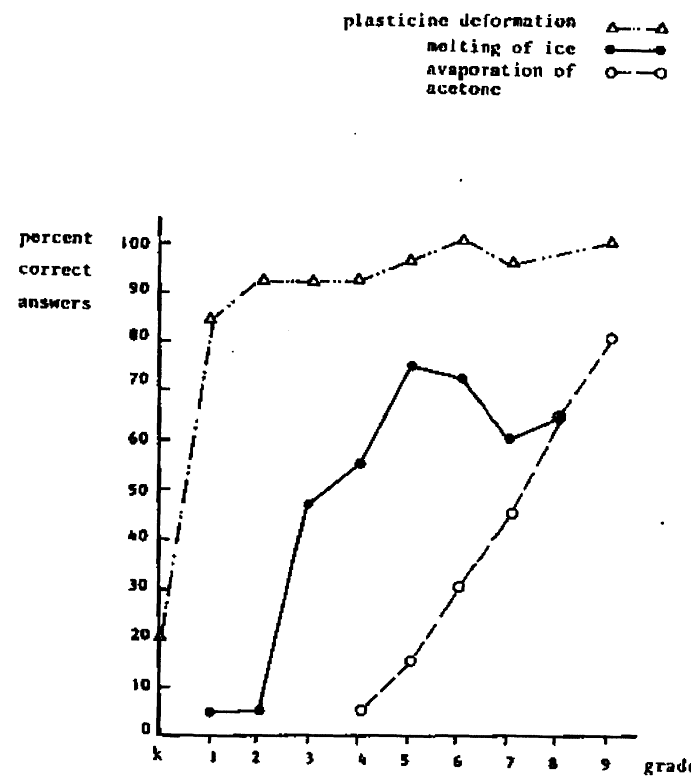


Fig 1: precent correct answers across age for different conservation of weight tasks.

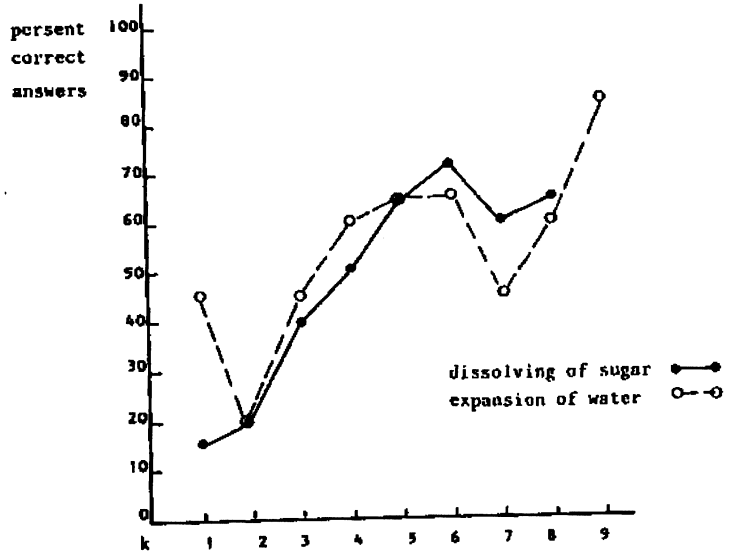


Fig 2: Percent correct answers across age for conservation of weight in dissolving of sugar and expansion of water tasks

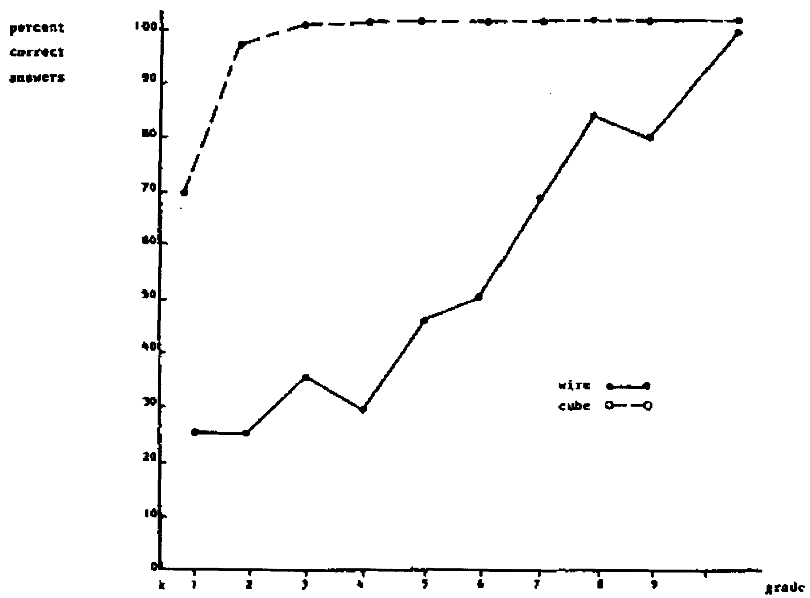


Fig 3: Percent correct predictions across age for floating and sinking of iron cube and iron wire
From Megged (1974)

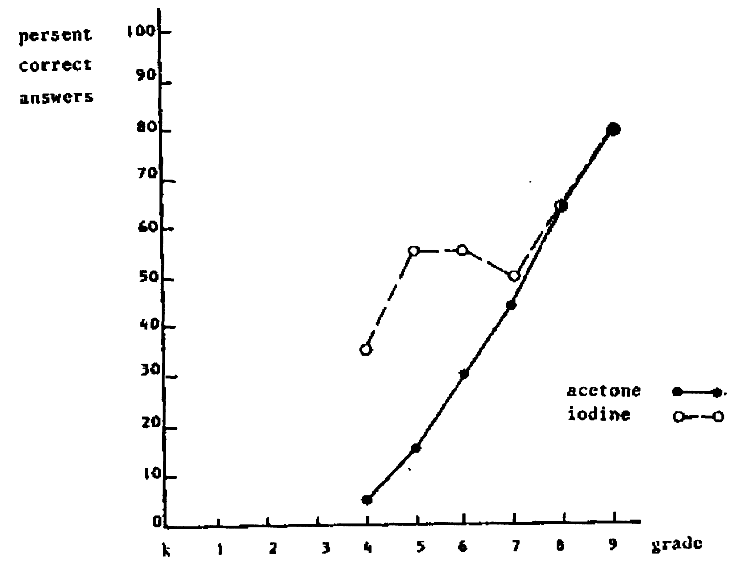


Fig 4: Percent correct answers across age for conservation of weight in different evaporation tasks.

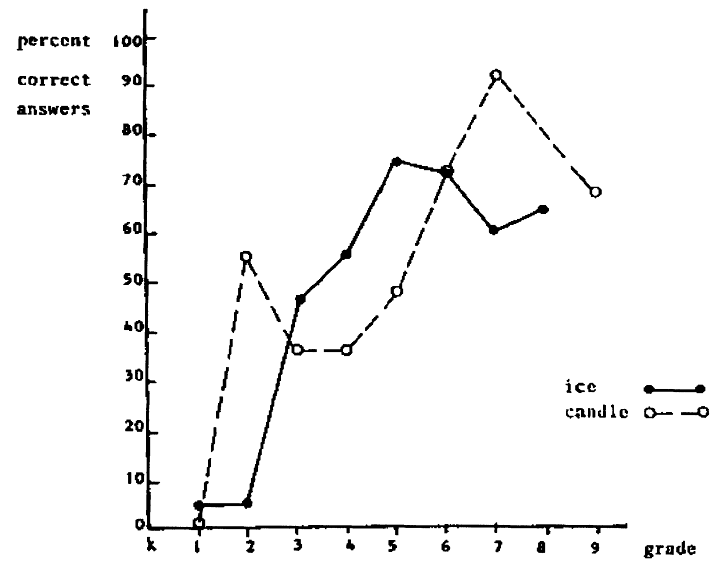


Fig 5: Percent correct answers across age for conservation of of weight in different melting tasks.

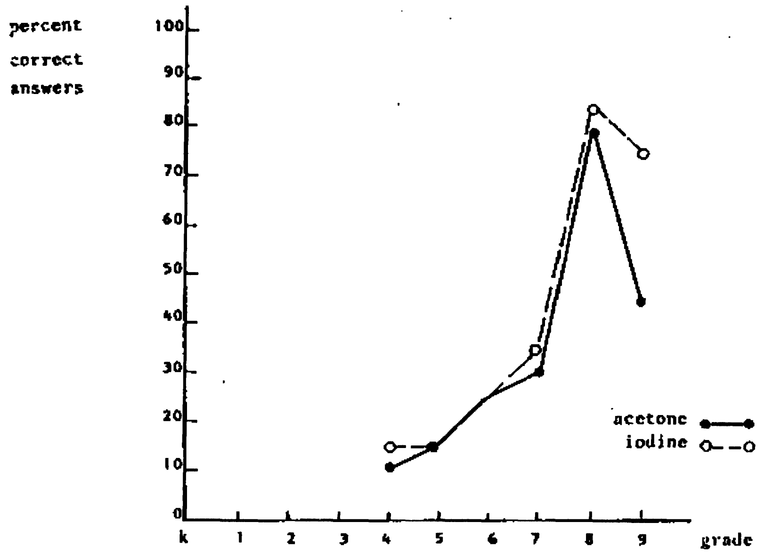


Fig 6: Percent correct answers across age for reversibility of evaporation taskes.

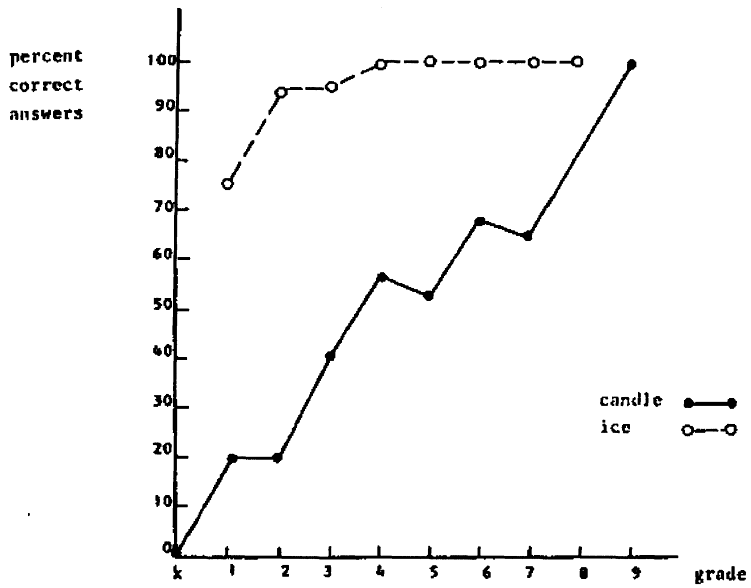


Fig 7: Percent correct answers across age for reversibility of melting tasks.

Third Misconceptions Seminar Proceedings (1993)

Paper Title: **A Model-Centered Curriculum for Model-Based Reasoning in Science**

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

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.

Keywords: Educational Methods,Concept Formation,Educational Technology,Empowering Students,Learning Activities,Thinking Skills,Abstract Reasoning,Scientific Concepts,Educational Innovation
General School Subject: Physics
Specific School Subject: Fluid Mechanics
Students: Middle School

Macintosh File Name: Raghavan - Science
Release Date: 7-5-94, 11-10-1994 I

Publisher: Misconceptions Trust
Publisher Location: Ithaca, NY
Volume Name: The Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics
Publication Year: 1993
Conference Date: August 1-4, 1993

Contact Information (correct as of 10-15-93): Joseph Novak (Education Department, 4th Floor Kennedy Hall, Cornell University, Ithaca, NY 14853 USA/607-255-3005) or Robert Abrams (rha2@cornell.edu)

A Correct Reference Format: Author, Paper Title in The Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics, Misconceptions Trust: Ithaca, NY (1993).

Note Bene: This paper is part of a collection which pioneers the electronic distribution of conference proceedings. We are conducting an evaluation study of this collection so that we can highlight the advantages and correct the disadvantages of electronic publishing, funded in part by the National Science Foundation. If you would like to participate, please contact us. Academic livelihood depends upon each person extending integrity beyond self-interest. If you pass this paper on to a colleague, please make sure you pass it on intact. If you reference this paper, please be aware that page numbers are not as precise a measure in an electronic form as they are in traditional print media. We feel that page numbers have always been an approximate measure at best, so that the fraction of desynchronization that the electronic form adds to the measure is not a debilitating concern. If you are concerned about this issue, we suggest that you use range guides: create an index, consisting of a three column array, immediately following the reference to this paper in your bibliography, where the first column is the page number(s) cited, the second column is the first five words on that page, and the third column is the last five words on that page. Finally, a great deal of effort has been invested in bringing you this proceedings, on the part of the many authors and conference organizers. If you have found this collection to be of value in your work, consider supporting our ability to support you by purchasing a subscription to the collection.

----- -----

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 usequalitative, 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.

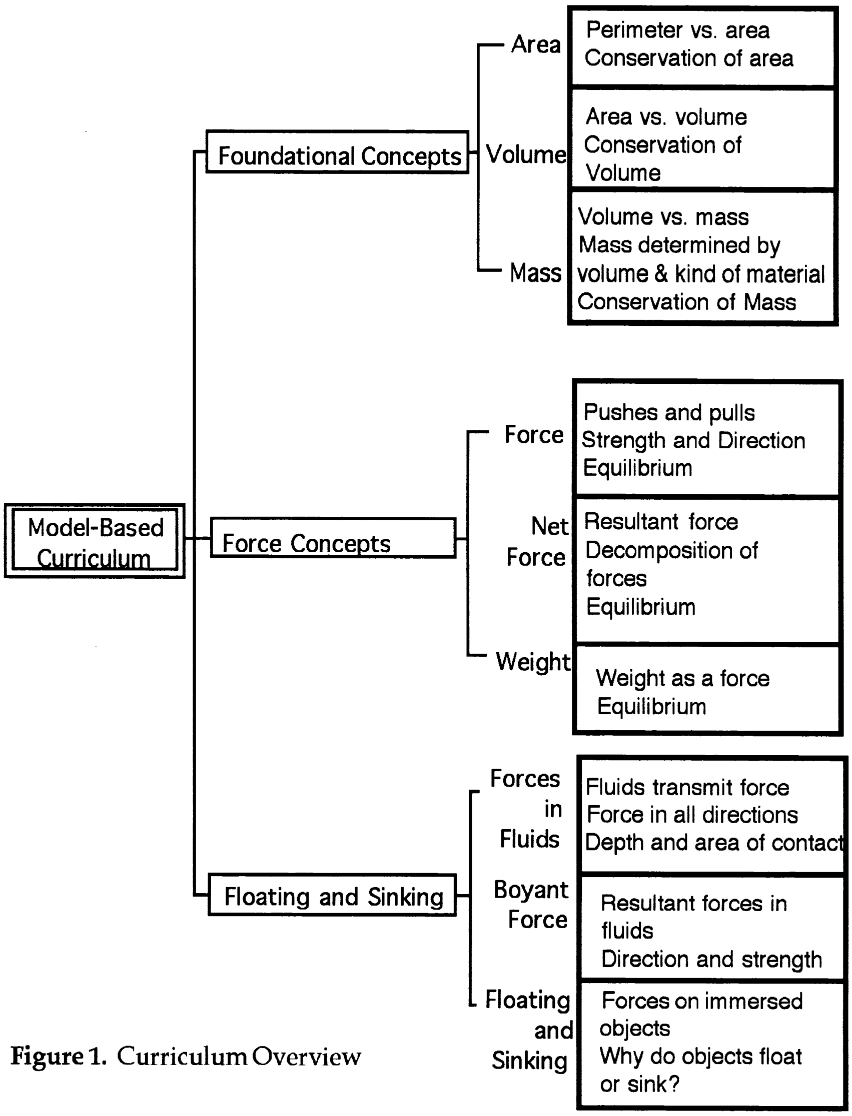


Figure 1. Curriculum Overview

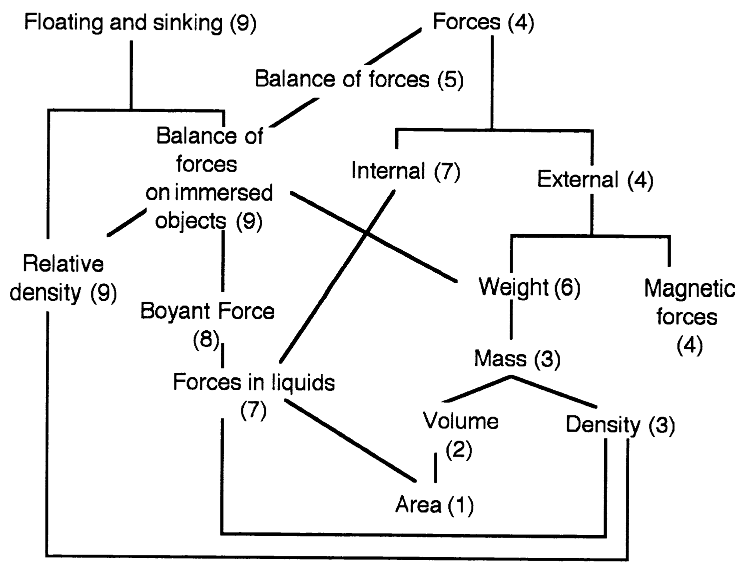


Figure 2. Concept Map

9

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.

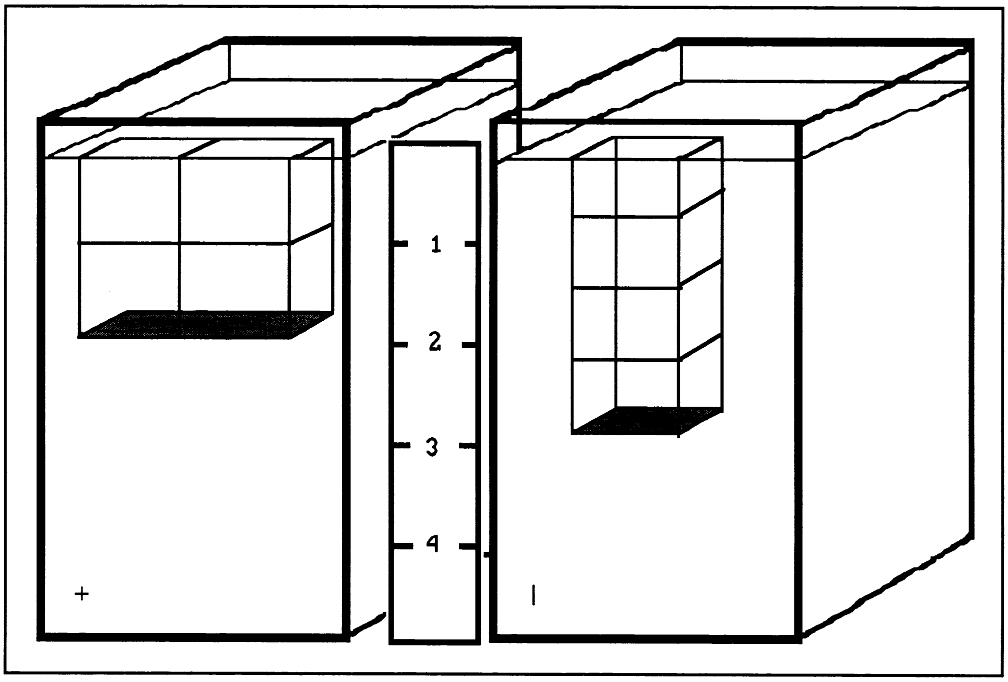


Figure 3. Column model (I and + indicate densities of liquids)

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.

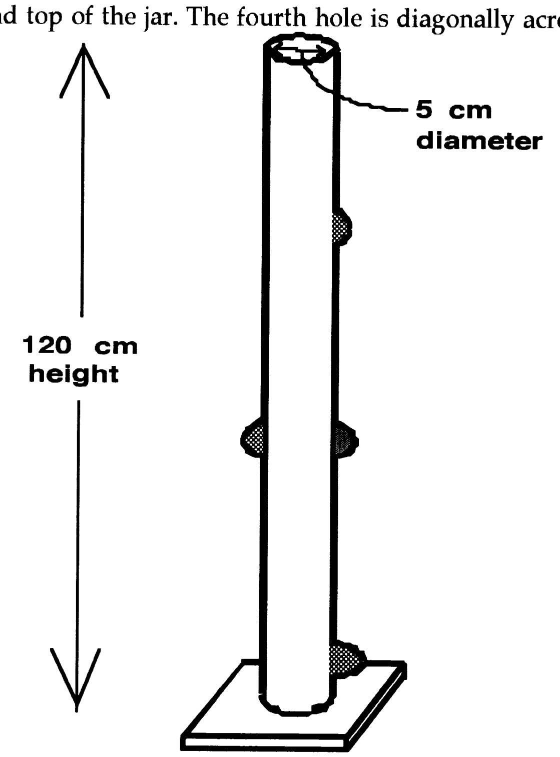
Prior to instruction, students were asked a series of questions designed to probe their initial ideas regarding forces in fluids. As they worked through the units, students were periodically asked to explain their conclusions and to describe the differences and similarities between the phenomena presented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



toothpicks **Figure 4.** Tube with membranes 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.

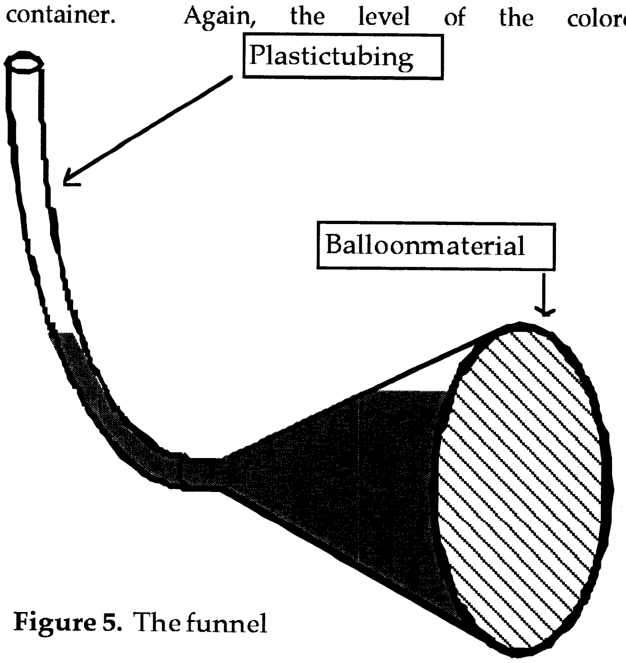


Figure 5. The funnel

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.

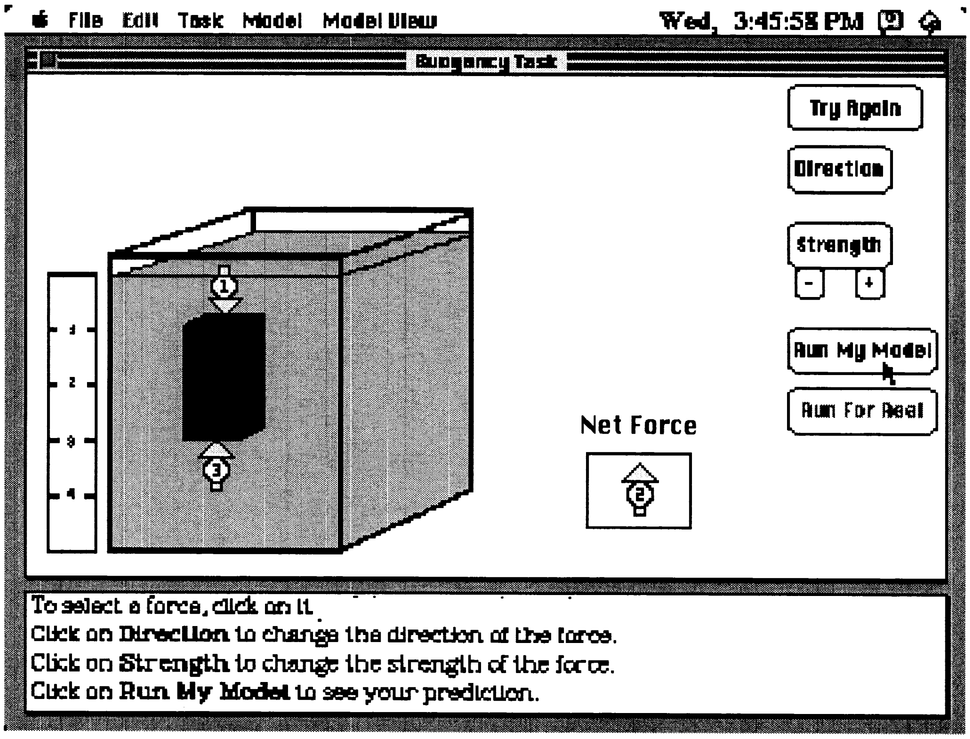


Figure 6. Sample screen from Buoyant Force computer task

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.

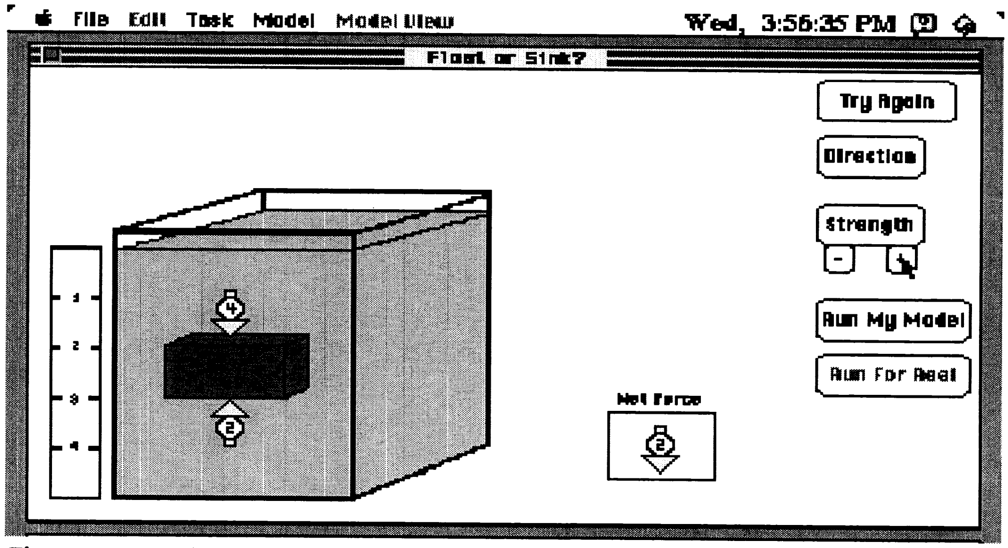


Figure 7. Sample screen from Floating and Sinking computer task

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 computeractivities 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.

ACKNOWLEDGMENTS

The authors wish to thank Robert Glaser, Leo Klopfer and Anne Fay for their helpful suggestions.

REFERENCES

Andaloro, G., Donzelli, V., & Sperandeo-Mineo, R. M. (1991). Modelling in physics teaching: The role of computer simulation. *International Journal of Science Education, 13*(3), 243-254.

Brown, A. L. (1989). Analogical learning and transfer: What develops? In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 369-406). Cambridge, England: Cambridge University Press.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5,* 121-152.

Clement, J. J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics, 50,* 66-71.

Clement, J. J. (1991). Non-formal reasoning in experts and in science students: The use of analogies, extreme cases, and physical intuition. In J. Voss, D. Perkins, & J. Siegel (Eds.), *Informal Reasoning and Education* (pp. 345-362). Hillsdale, NJ: Lawrence Erlbaum Associates.

Clough, E.E., & Driver, R. (1985). What do children understand about pressure in fluids? *Research in Science & Technological Education, 3*(2), 133-144.

Clough, E.E., & Driver, R. (1986). A study of consistency in the use of students' conceptual frameworks across different task contexts. *Science Education, 70*(4), 473-496.

Gentner, D., & Stevens, A. L. (1983). *Mental Models.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Giese, P.A. (1987). Misconceptions about water pressure. 142-148.

Halloun, I. A. & Hestenes, D. (1987). Modeling instruction in mechanics. *American Journal of Physics, 55*(5), 455-461.

Heller, J. I. & Reif, F. (1984). Prescribing effective human problem solving processes: Problem description in physics. *Cognition and Instruction, 1,* 177-216.

Hestenes, D. (1987). Toward a modeling theory of physics instruction. *American Journal of Physics, 55*(5), 440-454.

Hestenes, D. (1992). Modeling games in the Newtonian world. *American Journal of Physics, 60*(8), 732-748.

Johnson-Laird, P. N. (1989). Mental Models. In M. I. Posner (Ed.), *Foundations of cognitive science* (pp. 469-499). Cambridge, MA: The MIT Press.

Kariotogloy, P., Psillos, D., & Valassiades., O. (1990). Understanding pressure: didactical transpostions and pupils' conceptions. *Physics education* 25 (2), 93-96.

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

Mayer, R. E. (1989). Models for understanding. *Review of Educational Research, 59*(1), 43-64.

Mestre, J. P. (1992). Cognitive aspects of learning and instruction in science. *Pre-College Teacher Enhancement in Science and Mathematics: Status, Issues and Problems.* National Science Foundation. (To appear)

Minstrell, J., Stimpson, V., & Hunt, E. (1992). Instructional design and tools to assist teachers in addressing students' understanding and reasoning. Paper presented at the annual meeting of the American Educational Research Association, April.

Posner, G., Strike, k., Hewson, P., & Gertzog, W. (1982). Accomodation of a scientific conception: Toward a theory of conceptual change. *Science Education* 66(2), 211-227.

Sere, M. G. (1982). A study of some frameworks used by pupils aged 11 to 13 years in the interpretation of air pressure. *European Journal of Science Education*, 299-309.

Sherwood, B., Chabay, R., Larkin, J., Reif, F., & Eylon, B. (1991). *An integrated treatment of electrostatics and circuits.* Unpublished manuscript, Carnegie Mellon University, Pittsburgh, PA.

Smith, C., Snir, J., Grosslight, L., & Frenette, M. (1986). *Promoting 6th graders' understanding of density: A computer modeling approach.* (Tech. Rep.). Cambridge, MA: Harvard Graduate School of Education, Educational Technology Center.

Snir, J. (1991) Sink or float--What do the experts think? The historical development of explanations for flotation. *Science Education, 75*(5), 595-609.

White, B. Y. & Frederiksen, J. R. (1986). Qualitative models and intelligent learning environments. In R. Lawler & M. Yazdani (Eds.), *AI and Education: Learning Environments and Intelligent Tutoring Systems.* Norwood, NJ: Ablex Publishing.

White, B. Y. & Horwitz, P. (1987). *ThinkerTools: Enabling children to understand physical laws* (Tech. Rep. No. 6470). Cambridge, MA: BBN Laboratories.

Wiser, M. (1987). The differentiation of heat and temperature: History of science and novice-expert shift. In D. Strauss (Ed.), *Ontogeny, phylogeny, and historical development* (pp. 28-48). Norwood, NJ: Ablex.

Third Misconceptions Seminar Proceedings (1993)

Paper Title: **Diagnosing Students' Conceptions Using Portfolio Teaching Strategies: The Case of Flotation and Buoyancy**
Author: Duschl, Richard A. & Gitomer, Drew H.

Abstract: The adoption of performance-based or portfolio assessment strategies is a commitment to the reform of education that, by intent, will hopefully extend into the schools and the classroom. By changing the standards of performance expected of children we are indirectly changing the standards of performance expected of curriculum writers, supervisors and teachers. Consequently, changing the procedures and the standards for determining students' success in science will require that these assessment changes be supported by and be evident in changes in the learning environment of classrooms. Most would agree that if the performance assessment is the first instance where a student encounters new expectations and standards of learning, then the system of education for that child is inadequate. It isn't surprising, then, that educational standards initiatives like the New Standards Project are seeking school delivery standards or social contracts with school districts. The basic and compelling issue is what good is raising standards if the curriculum and instructional practices in schools do not contribute to the preparation of students to achieve the new standards.

Keywords: Concept Formation,Teaching for Conceptual Change,Thinking Skills,Empowering Students,Feedback,Informal Assassment,,,
General School Subject: Physics
Specific School Subject: Fluid Mechanics
Students: Middle School (6,7,8,)

Macintosh File Name: Duschl - Flotation & Bouyancy
Release Date: 7-6-94 H, 11-10-1994 I

Publisher: Misconceptions Trust
Publisher Location: Ithaca, NY
Volume Name: The Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics
Publication Year: 1993
Conference Date: August 1-4, 1993
Contact Information (correct as of 10-15-93): Joseph Novak (Education Department, 4th Floor Kennedy Hall, Cornell University, Ithaca, NY 14853 USA/ 607-255-3005) or Robert Abrams (rha2@cornell.edu)

A Correct Reference Format: Author, Paper Title in The Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics, Misconceptions Trust: Ithaca, NY (1993).

Note Bene: This paper is part of a collection which pioneers the electronic distribution of conference proceedings. We are conducting an evaluation study of this collection so that we can highlight the advantages and correct the disadvantages of electronic publishing, funded in part by the National Science Foundation. If you would like to participate, please contact us. Academic livelihood depends upon each person extending integrity beyond self-interest. If you pass this paper on to a colleague, please make sure you pass it on intact. If you reference this paper, please be aware that page numbers are not as precise a measure in an electronic form as they are in traditional print media. We feel that page numbers have always been an approximate measure at best, so that the fraction of desynchronization that the electronic form adds to the measure is not a debilitating concern. If you are concerned about this issue, we suggest that you use range guides: create an index, consisting of a three column array, immediately following the reference to this paper in your bibliography, where the first column is the page number(s) cited, the second column is the first five words on that page, and the third column is the last five words on that page. Finally, a great deal of effort has been invested in bringing you this proceedings, on the part of the many authors and conference organizers. If you have found this collection to be of value in your work, consider supporting our ability to support you by purchasing a subscription to the collection.

----- -----

Diagnosing Students' Conceptions Using Portfolio Teaching Strategies: The Case of Flotation and Buoyancy[1]

Richard A. Duschl, University of Pittsburgh, USA

Drew H. Gitomer, Educational Testing Service, USA

Technical Editor's Note: Tables and Figures have been left as supplied by the author, and can be found at the end of this article.

Introduction

The adoption of performance-based or portfolio assessment strategies is a commitment to the reform of education that, by intent, will hopefully extend into the schools and the classroom. By changing the standards of performance expected of children we are indirectly changing the standards of performance expected of curriculum writers, supervisors and teachers. Consequently, changing the procedures and the standards for determining students' success in science will require that these assessment changes be supported by and be evident in changes in the learning environment of classrooms. Most would agree that if the performance assessment is the first instance where a student encounters new expectations and standards of learning, then the system of education for that child is inadequate. It isn't surprising, then, that educational standards initiatives like the New Standards Project are seeking school delivery standards or social contracts with school districts. The basic and compelling issue is what good is raising standards if the curriculum and instructional practices in schools do not contribute to the preparation of students to achieve the new standards.

In science classrooms, a compelling and persistent problem is that of conceptual change. Raising educational standards in science programs to embrace conceptual change cognition or thinking demands that changes also occur with how science is taught. Our position is that an effective conceptual change science classroom will be one that provides teachers and students with information about the construction of knowledge in three different arenas of classroom dynamics. The three dynamics are scientific knowledge or epistemic dynamics, thinking,

[1] Funding for this project is provided by a grant from the National Science Foundation (MDR-90055574). The opinions expressed do not necessarily reflect the positions or policies of NSF and no official endorsement should be inferred.

meaning making and reasoning or cognitive dynamics, and representing and communcating information or social dynamics. Having access to and learning to employ information from each of these three arenas is, we feel, critical to empowering teachers and students to take control of their learning. It follows, then, that conceptual change science teaching should involve the use of those instructional activities and tasks that make available information about the epistemic, cognitive and social dynamics of individual students and groups of students doing science.

Questions and recommendations about school reform and restructuring must reach into the classrooms and must involve teachers in monitoring the construction of knowledge by their students. We must ask of all educational innovations, what does this mean at the level of the classroom? We must ask of conceptual change learning environments, then, how do teachers acquire the necessary information to monitor, assessment, and give feedback on students' meaning making, thinking, and communication of knowledge. In our work with the reform of science instruction at the middle school grades, we are examining ways to create a classroom learning environment that can provide this information for assessments. Evidence from our investigations and our work with teachers suggests that assessment information from each of the three dynamic domains mentioned above should be made available and used to facilitate learning science and how scientists learn.

There are,then, three assessment domains:

(1)*scientific knowledge* - the epistemic domain,

(2) *thinking skills* - the cognitive domain, and

(3) *communication skills* - the social domain.

Respectively, each domain seeks answers from teachers and students to the following questions:

What knowledge evidence or data do we choose to use and toward what goal?

What reasoning and meaning making strategies do we choose to monitor and to use?

What classroom actions support acquiring information to address the first two questions?

The domains and questions are presented in Table 1. The process of obtaining, recognizing, analyzing and deploying information to get at the answers to these questions is what shapes the instruction that fosters a learning environment guided by assessment information and decisions.

Taken together these three domains when executed as co-construction activities begin to develop a portfolio culture learning environment.

~~~~~~

Insert Table 1 About Here

~~~~~~

Project SEPIA - Science Education through Portfolio Instruction and Assessment - seeks to make assessment in classrooms an integral component of instruction. A goal is to provide the teacher, and we hope eventually the students as well, with instructional strategies and curriculum approaches that generate information about the cognitive procedures students are using to solve authentic problems, to reason, and to apply what they know. In brief, we seek to provide teachers with new kinds of information they can use to make informed decisions about the instruction and activities that support student learning. What is sought is a radical and comprehensive change in the character and the dynamics of the feedback students receive.

Given this orientation toward effective feedback, we must by necessity be concerned with the three classroom level dynamics outlined in Table 1. In turn, we must also be concerned about the criteria that set the standards for guiding and assessing students' performance in these three domains. In general this means creating and then applying criteria that focus on

- what counts as scientific knowledge and evidence in the epistemic domain,

- the reasoning and meaning making of students in the cognitive domain, and

- the characteristics of the classroom learning community that support dialogue and conversations about personal and scientific ideas and information in the social domain.

It is fundamentally important for us is to create a classroom that provides for and supports the communication and representation of ideas from students, from texts, and from teachers. Recall that a goal of assessment-driven instruction is to gain access to information that can be used to give students feedback. But this information is more often than not a kind of information that has not previously been made available to or recognized by middle-school science teachers as relevant to science teaching. Moreover, the management of students' ideas and information represent a very different challenge to teachers who are more adept at the management of activities, materials, and students' behaviors.

To date, we have had some success with teachers to employ activities that get students to tell us what they know in a variety of ways(e.g., letter writing, journals, drawings, oral presentations, etc.). But there are still many unanswered questions about how to interpret this information and then use it to inform instructional decision making that raises the standards of performance in science classrooms. What does meaning making and reasoning look like in these student products? What are the best sources of assessment information? Are there different kinds of assessment information? Where do we look and listen for assessment information while teaching? If we find the information, what are the types of actions teachers and students should take to use this information? How do we feed the assessment information back into instructional activities? How do we structure the learning environment such that assessment in the service of meaningful learning and higher standards is possible?

STATEMENT OF PURPOSE

The purpose of this paper is to report on the results of a portfolio assessment curriculum and instructional intervention in middle school science classrooms that provided information about students meaning making and reasoning in the construction of a causal explanation. It signals to us that information about students conceptions and the impact these have on the growth of knowledge can be obtained by teachers.

Conducting interviews with students around a body of work produced by the students during a specially designed curriculum revealed that the 6th and 7th grade students' hold an alternative theory students' for explaining why vessels float when carrying a load. Specifically, our research data indicate students have a conception about flotation and buoyancy that inhibits the development of a causal explanation for flotation. The interviews conducted with students on the work they produced suggest that these student interviews can be used as a source of information for identify student misconceptions about scientific explanations.

The first section of the paper describes our prototype curriculum approach which is organized around the implementation of assessment conversations. The science subject matter context is flotation and buoyancy. The instructional context is a design problem task that challenges students to construct an aluminum vessel that maximizes load carrying capacity. The second section examines and discusses the character of the student work generated by the Vessels Unit and how this work can be used to provide assessment information. In the last section, implications for classroom teachers and recommendations and challenges for teachers and researchers working in the reform of classrooms and schools are discussed.

VESSELS UNIT CURRICULUM

When we think of instructional tasks and the classroom social organizations being designed in the service of providing assessment information, we get a very different image of classroom management and of what counts as important learning activities. In our Project SEPIA classrooms, we try to organize instruction such that we gain information about the development of learners' reasoning and meaning making, and their use of skills like communication, explanation and argumentation. Obtaining information about each of these cognitive activities in order to make an assessment and then give feedback requires, however , that there exists a classroom learning environment in which students get the chance to practice these tasks. We refer to this specialized learning environment as a portfolio culture and have written a special curriculum unit - The Vessels Unit.

One approach to reform science classroom learning environments is to adopt alternative assessment strategies like portfolios that serve to inform both teachers and learners about what ought to be the next step of instruction. The ultimate goal is the creation of portfolio culture science classrooms. The term culture is purposely used to reflect the complex nature of the enterprise since the use of portfolio assessment techniques requires that both subtle and fundamental changes occur in teachers, students, and curriculum. Hence, a portfolio is not just a collection of work that documents the sequence of instructional activities performed by students. Nor, is a portfolio a collection of work judged or graded only by the teacher. Rather, a portfolio is a **select sample** of a student's work that serves to demonstrate how that student understands, communicates, reasons with , and constructs scientific knowledge. The sample is selected by teachers and by students according to publicly shared and negotiated criteria. In this sense, a portfolio culture and the assessments that take place in this culture are said to be criteria-driven.

The application of the criteria to instructional activities and tasks, and thus to the construction of a folder of work, is an endpoint of a long and involved set of activities. It is vitally important that the day-to-day actions of teachers and students and the structure of the curriculum reflect a strong commitment to the criteria or standards of a portfolio culture science classroom. Thus, the criteria are an integral component of instruction; components that should under gird everything that takes place in the classroom. The criteria must become the standards of the classroom, the currency of exchange, and the commodity that is most valued.

The criteria themselves, and the vision of how we see the criteria being used, even at this early stage of development, reflect a dual commitment. The dual commitment is a distinction and a balance between science as exploration and science as argument. It is that dual relationship between conceptual development and the skills and logic of reasoning that we want. On the one hand, we need to monitor, assess, and develop forms of reasoning, i.e., making connections. On the other hand, we need to monitor, assess, and develop the precise ways in which scientific knowledge is explored, represented, modified and justified - the target cluster of science concepts and the goals of investigation if you will. In Project SEPIA we are focusing on getting students to use and understand the use of explanations, experimentation, and models in science.

At present our working criteria reflect a commitment to these two important elements: (1) criteria that emphasize the development of reasoning skills, and (2) criteria that stress meaning making and sense making of scientific knowledge claims. It is working list because the criteria should change over time as the students develop the capacity to engage in higher and higher levels of cognitive processes or as the class decides examine other contexts of science that then require other criteria (i.e., statistical significance). Our present list of working list of criteria is provided in Table 2 and a schematic that places the individual categories of criteria on a 'Meaning Making - Reasoning' continuum is given in Figure 1.

~~~~~~

Insert Table 2 and Figure 1 about here

~~~~~~

The title of the unit is Vessels and an outline of the unit is presented in Appendix A. The unit involves students in a problem solving task, namely, the design of a vessel hull out of aluminum foil that maximizes load carrying capacity. The task is introduced through a letter from a fictitious mayor of Pittsburgh but the task is authentic. The letter outlines the problem as well as the expectations of student work. In brief, the purpose of the investigation and the goals of the investigation are given to the students. Here is how the letter finishes:

After completing your investigation, the packet of information you submit to the City should contain the information and materials in the items listed below. Only complete packets will be considered. We want to hire the firm that can design the best hull. But the City must have confidence that the designers understand and can explain why a vessel will float and carry a load. Without this explanation, the City can't be certain the design model you submit will work.

Design Packet Items

1. A sketch of the vessel hull.

The sketch should be neat and have the height, length and width of the vessel labeled.

2. A scale model of the vessel.

The scale model should be made of aluminum foil. It will represent the hull of the vessel. It should be made as best as you can to look like the sketch you submit.

3. Sketches of the vessel hull in water with and without a load

These two sketches should be side by side on the same piece of paper. Using arrows, science terms and the names of forces, label the sketches to explain the forces that keep the vessel afloat. Please mark the water line.

These sketches are a very important part of the design packet. We want to hire the firm that understands and can best explain why vessels float.

4. A report of tests and results.

Please list the tests, experiments, and investigations you performed. Then provide the a report of results. For example, what is the mass in grams (g) that it took to sink your vessel. Include in your packet any tables, graphs, or test design sketches you think will demonstrate you have thought through the problem carefully.

The conceptual ecology of the unit is buoyancy and flotation - See Appendix B. Inasmuch as we are interested in helping students construct a *causal explanation* for flotation the curriculum plan is designed around the differential pressures model. That is, the difference in water pressures at two depths produces a total net upward force called the buoyant force. It is the balance between the upward buoyant force and downward gravitational force that causes an object to float. It is an imbalance in favor of the gravitational force that causes an object to sink and an imbalance in favor of the buoyancy force that causes an object to rise. For example, if you take a small block of wood and place it at the bottom of a tub of water, when you release it the difference in water pressure between the top of the block (low) and the bottom of the block(high) will push the block up. It continues upward until the buoyant force up equals the gravitational force down. Now if we perform the same activity but this time substitute a helium balloon for the block of wood, the balloon will rise to the top of the water and then continue rising into the atmosphere since the buoyant force is now large enough to lift the balloon and push it out of the water and continue pushing it up into the air. The 'pressure below/pressure above' principle applies to all fluids and air is a fluid.

Now the problem in the design of the vessel, then, can, and should, be understood in terms of increasing the buoyant force. If you increase the buoyant force, then you increase the carrying capacity (i.e., weight the vessel can hold and still remain afloat). There are two ways to increase the buoyant force. You can increase the bottom surface area of the vessel or you can increase the height of the sides of the vessel. But in either case - bottom or height of sides - there is a limit to which the increase is beneficial when your problem is restricted by the amount of material with which you have to work - one sheet of aluminum foil. Thus, another and an important characteristic of the vessels unit is that it involves students in a trade-off problem. How much foil should one invest in the height of the sides? How much foil should one invest in the bottom?

The Vessels Unit allows students the opportunity to **do** science in the full sense of what it means to **do** science. And, this full sense means (1) the construction of explanations and models based on experiments and experiences - the epistemic dynamics of the domain; (2) reasoning about the relation of evidence to explanation - the cognitive dynamics; (3) communicating and discussing knowledge claims and evidence with members of the class - the social dynamics. In the Vessels Unit students individually construct a vessel , test its carrying capacity, compare and contrast the diversity of designs against performance by all students, identify via conversations design features associated with performance, explore via demonstrations and conversations what occurs with changes in depth of water, design and conduct experiments that test the specific design features, report via conversations the results of the experiments and then be given the opportunity to construct a second and third vessel. And, all along the way be encouraged to think about and communicate their thoughts about why things float, and why it is that one design can hold more weight than another design.

Traditionally, our assessment and evaluation of student learning has emphasized measuring students acquisitions of declarative knowledge. The research shows though that the development of strategic or procedural knowledge frameworks is what seems to distinguish superior knowers from novices knowers. Thus, one desired outcome of alternative assessment tasks is to get information on how learners use strategic knowledge. Such information can then be used to provide feedback on reasoning and on the development of procedural knowledge frameworks.

Consider the following example that involves a procedure for reading information off of a graph. In a special curriculum unit that we've design to help promote assessment opportunities in classrooms, students were asked to make and then test the carrying capacity of aluminum vessels. The class set of vessels was then plotted on a bulletin board graph and a discussion then followed that gets students to think about what features of the vessels seems to correlate with performance. Students will naturally focus on the extreme vessels in the graph - the best and worst - and will quickly conclude "Make it bigger!"

A different procedure for obtaining information from the graph, however, is to get students to focus on the vessels in the same column of the graph - say all those that held between 300 and 400 grams. This graph reading strategy reveals that different designs can produce the same performance and it shows that the features of the vessels which need to be bigger are the height of the sides and the bottom surface area. The use of the graph reading procedure 'look within a category' can be modeled and taught. A performance assessment task might then probe a student's ability to use this is important scientific way of knowing.

Research on learning has also made it quite apparent that the acquisition of knowledge - declarative and procedural - is a social activity. So much of what any individual comes to know takes place in social learning environments. In particular, it is out of social situations that the criteria and standards for performance are learned. The research shows that when the opportunities for conversation and argumentation increase so too does the ability of learners to comprehend and understand the topics under investigation and the reasoning procedures. In short, it is the public display and reporting of information and strategies and the opportunity to act on this information and strategies that contributes to the growth of knowledge.

For an example of how social situations effect learning, consider the graphing of the vessels once again. From this public display of information it is possible for students to quickly see some of the ways to redesign their vessel so as to improve the load carrying capacity. The conversation about what design features of vessels seem to effect performance is also made public and social. Posing the question "How do we know which of these design features is most important in determining carrying capacity?" invites the opportunity for conversation and argumentation about competing explanations and designs for how and why vessels float, rise and sink.

By shifting the aim of instruction from activities and tasks that ask learners to merely display what they know (declarative knowledge) on individual reports or exams to activities and tasks that require students to use apply, and publicly report what they know (procedural knowledge) , we contend, windows are opened into students' reasoning. We are working to create a classroom learning environment that supplies teachers and students with information about students' reasoning and meaning making. The core features of our instructional approach are:

- engaging in an authentic task
- employing criteria-driven assessment conversations
- publicly communicating and displaying ideas, explanations, and information
- involving students in portfolio tasks around the work they produce.

CONCEPTIONS ABOUT BUOYANCY

An analysis of student drawings, labels of drawings, interview statements, and presentation statements indicates that students are constructing an incomplete explanation for flotation with and without a load. Through the practices arranged by teachers (e.g., assessment conversations, demonstrations, questions and answer) and those given to students (e.g., drawings, warm-ups, presentations, writings) information about how students are relating concepts and how they are reasoning is made available. In particular, steps have been taken to provide a sequence of activities, such that, sources of assessment information to teachers about students' learning and reasoning can emerge. Such activities involve students in doing drawings, writing explanatory statements, labeling models and sketches, participating in conversations, and giving oral presentations.

The conceptual ecology of the unit is summarized and presented in the concept maps found in Appendix B. Although the unit begins with the concepts of gravity and buoyancy, the core concept is water pressure for it is the causal link that explains why a vessel with higher sides or a larger bottom is able to carry more load. The label used by the students to explain floating is buoyancy or buoyant force but the causal link that explains why a vessel remains afloat when weight is added has do to with the fact that water pressure increases with depth. The subject matter objectives for the unit as written in the teacher background materials are:

1) Floating is a state of balance; gravity = buoyancy. Objects that float do so because the force of gravity pulling the object down is equal to the buoyant force pushing the object up.

2) Sinking is a state of imbalance; gravity > buoyancy. Objects that sink do so because the force of gravity pulling the object down is greater than the buoyant force pushing the object up.

3) Buoyancy is a force caused by water pressure. The pressure in the water at a given point is caused by the weight of the water above that point and acts in all directions equally around that point. The lower the vessel can go without sinking the greater the water pressure which causes the buoyant force.

4) The buoyant force (upward) is caused by differences in water pressure at the top (lesser pressure) and bottom (greater pressure) on the object. Floating is a special case where the top pressure, being above water, is equal to zero. The larger the buoyancy the more weight the vessels can hold.

5) Buoyancy is a force affected by surface area. The larger the surface for the buoyant force to act on, the greater the force at a given depth.

6) Water displacement is the amount of water pushed aside when an object is placed in water. When an object floats, the weight of the displaced water is equal to both the force of gravity pulling down and the buoyant force pushing up. The more water a vessel can displace, the more load it will be able to carry.

The information from the portfolio interviews indicates that students can tell you why something floats and typically do so in terms of gravity being equal to buoyancy. Students can also tell you why something sinks and typically do so in terms of gravity being greater than buoyancy. The student drawing in Figure 2 is representative of that produced by most students.

When students are asked though to explain floating without a load and compare it to floating with a load a misconception emerges. Again, the drawing in Figure 3 is representative. The problem that emerges is that students interpret floating lower and lower in the water as a 'kind of sinking' process. Thus, rather than preserving the notion of gravity equal to buoyancy as the vessels float lower and lower in the water, the students use the notion of gravity getting greater and buoyancy getting less as the vessel floats lower and lower in the water. In their minds, the process appears to be a zero sum game. The problem that exists here is that the students conception of floating with buoyancy getting less blocks the need to develop a sense of water pressure changing with depth. If the equal and opposite forces of gravity and buoyancy idea is preserved, then we must ask what it is that is causing the buoyant force to increase as we add weight to the floating vessel. With the students present conception of the buoyant force getting less or weaker, there is no compelling reason to investigation changes in water pressure with depth and, consequently, no compelling reason to think about the importance of the height of the sides in the design of the vessel.

~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

Name

Date

Teacher

Portfolio Item 2

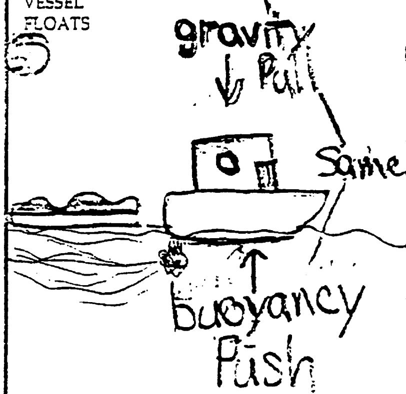
Explain then Draw
Number (1,2,3) the order in which you complete the three tasks.

EXPLAIN WHAT MAKES A VESSEL FLOAT AND WHAT MAKES IT SINK

1 A vessel floats because the force of gravity and the force of buoyancy are the same. When the force of gravity is greater the vessel will sink.

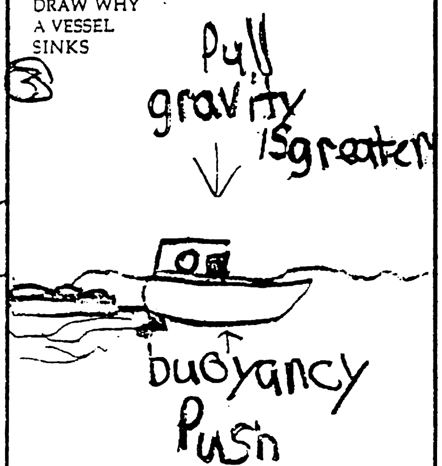
DRAW WHY A VESSEL FLOATS

2



DRAW WHY A VESSEL SINKS

3



Criteria:
Clarity
Relationships
Consistency with evidence

Project SEPIA - Fall 1992
Figure 2 - Relation of Buoyancy and Gravity for Floating and Sinking

Figure 2. Relation of Bouyancy and Gravity for Floating and Sinking

Portfolio Item C
Design Packet - What keeps the vessel afloat?

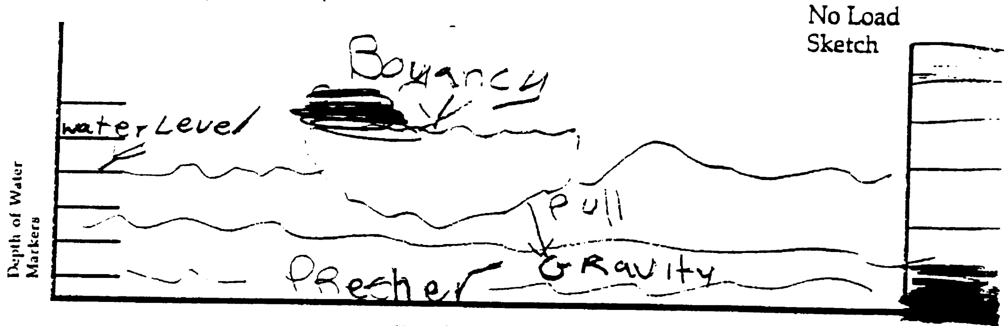
Name

Date

Teacher

Sketch the vessel. Use arrows, science terms, and the names of forces to label the sketches. The sketch and labels should explain what keeps the vessel afloat.

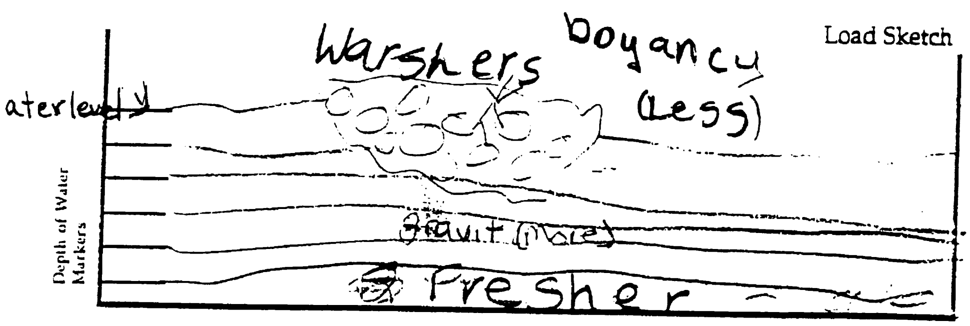
No Load Sketch



Vessel without a load
Mark the water line

Sketch the vessel. Use arrows, science terms, and the names of forces to label the sketches. The sketch and labels should explain what keeps the vessel afloat.

Load Sketch



Vessel with a load
Mark the water line

Criteria:
Accuracy
Clarity & Precision
Relationships

Project SEPIA - Fall 1992

Figure 3 - Relation of Buoyancy and Gravity when Floating with and without a Load

52

Figure 3. Relation of Bouyancy and Gravity when Floating with and without a Load.

~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

Now we want to emphasize that this is a wonderful problem for us to discover. For one it tells us that our portfolio culture instructional process and materials are making it possible to locate and use assessment information that can be used as feedback. Let's look at the two arguments for floating - the curriculum argument and the students' argument - in more detail. The two instructional arguments are as follows:

Instructional Argument in Curriculum:

1a. Flotation is a state in which the gravitation force (G) is equal to the buoyant force (B).

1b. Sinking is a state in which the gravitation force (G) is greater than the buoyant force (B).

2. An aluminum vessel with no load will float on or near the surface of the water. G=B.

3. When a load is added to the vessel is floats lower in the water. G=B

4. The additional mass increases the gravitational force acting on that mass pulling the vessel down into the water.

5. Since the vessel is still floating then G=B, therefore B must increase as G increases.

6. The increase in B is caused by the increase in water pressure as the vessel floats lower in the water.

Instructional Argument among some Learners

1a. Flotation is a state in which the gravitation force (G) is equal to the buoyant force (B).

1b. Sinking is a state in which the gravitation force (G) is greater than the buoyant force (B).

2. An aluminum vessel with no load will float on or near the surface of the water. G=B.

3. When a load is added to the vessel it sinks lower in the water. G>B

4. The additional mass increases the gravitational force acting on that mass pulling the vessel down into the water.

5. Since the vessel is sinking then G>B, therefore B must decrease or remain the same as G increases.

The curriculum argument requires that an appeal be made to what causes the buoyant force to increase (i.e., water pressure) in order to preserve the equality needed between G and B when the vessel continues to float. In contrast, the student argument need not invoke an appeal to water pressure since their model of flotation employs a 'partial sinking' mechanism for floating lower in the water when weight is added. Applying the sinking rule G>B to this partial situation, it makes sense to think and talk about getting lower in the water being an increase in gravity and a decrease in buoyancy, relative or otherwise.

The dilemma is that students do not need to think about the evidence related to things changing with the depth of water. As stated above, the explanation given by students is one that ignores water pressure changing with depth. Getting students to recognize that B=G when ever an object floats and to then adopt the correct explanation that buoyancy increases when the gravity increases as a load is added opens up the instructional opportunity to ask what is causing the buoyancy force to increase. The epistemic dynamics of the class and of our instructional approach were found to be inadequate.

The opposite of sinking is not floating. It is rising. We do not talk about nor do we give students experiences with things that rise. We could, for example, ask students to monitor what happens to a vessel floating with a load when you take weights out of the vessel. We can ask then what is pushing it up? There also is a semantic concern. We hear students talking about the vessel sinking lower as you add a load. A clearer distinction between floating and sinking needs to be made in our classrooms and a conscious effort to use say floating lower in the water with a load should be made. The semantic understanding by students and used by teachers of floating, sinking, rising, and balance would seem to be an important issue. Thus, the data from the student interviews has provided us with information about how to assess students meaning making and it has given us a window into how to change our curriculum design and implementation strategies to make it more epistemically sound.

CONCLUSION

Properly construed instructional activities and classroom practices can be designed and implemented to provide access to student meaning making and reasoning. It requires a curriculum balance between the epistemic, cognitive and social dynamics of the classroom. Key to the process is giving students the opportunity to communicate and discuss what they know. The portfolio interview is one such opportunity. When students are given access to the work they produce and then asked to interpret and use the information we get insights into students meaning making and reasoning.

Engaging students in individual interviews that take them through a reflective conversation about the work they do, however, while certainly a rich source of information is nonetheless an 'after-the-fact' source of information for classroom teachers. A challenge we face in our research program is how to bring this kind of assessment information on-line. That is, how do we begin to make it part of the social dynamics of the classroom that teachers and students do as part of the culture of the classroom. When we look at classroom transcripts we discover that the assessment information is subtle, very subtle. It often occurs in comments, gestures, and in notations not presently consider relevant to instructional goals. It is an arrow in this drawing, a word in that drawing, a comment in response to this or that question. Locating the information requires:

1) the employment of astute listening. observing and reading skills,

2) constant attention be given to the target conceptual ecology; e.g., concept maps in Appendix B,

3) attention to the representation and capture of information **learners** can use to reason to or construct the appropriate conceptual framework.

All of this must take place along with all the other decision making events in the classroom like who's on task or off task, who is behaving and misbehaving, when do you begin closure on the lesson, or make a transition from the warm-up to the lab activity.

We know, for example, how powerful it is to have students examine the diversity of responses or products from their own efforts. We also know that the examination of student work to arrive at relevant information to make assessments occurs best when it is carried out with that group. For example, when we graph the vessels and have a conversation with students this single act enables students to see the features of the vessels that contribute to its ability to carry a load. While the initial information emerges more often than not from individuals, the complex information like explanations must become part of the community dialog to enable conceptual change to occur. This appeal to the community is also needed to motivate the learners to deal with science understanding and representation at this deep level of knowledge, knowing, meaning making, and reasoning. These are complex changes and require teachers to listen and look for new forms of information. The problem, then, is to develop effective and manageable strategies teachers and students can use for looking, listening, and assessing.

Our interview data indicate that instructional tasks and activities can be designed and implemented to support the assessment of students' meaning making and reasoning. The results also indicate that portfolio assessment information can be used to evaluate curriculum scope and sequence and instructional strategies. Information about the learned curriculum can be used as a window to guide in the modification of the designed and implemented curriculum. The portfolio interviews provided a window into the kinds of changes needed to support alternative assessment in science classrooms. We discovered that in addition to talking about floating and sinking we must also talk about rising. We now know that we need to pay careful attention to the way in which we speak about flotation with students. In addition to having demonstrations and activities that focus on the lowering of the vessel when a load is added we need to also have demonstrations and activities that focus on the rising of the vessel when a load is removed. Employing portfolio assessment instructional practices makes it possible to monitor the epistemic, cognitive and social dynamics of science classrooms.

Table 1

Co-Construction Domains in an Assessment Driven Learning Environment:

Central Questions

Domain	Central Question
Epistemic/Scientific Knowledge	What knowledge, evidence, or data do we choose to use and to what goal do we use it?
Cognitive/Thinking Skills	What reasoning and meaning making strategies do we monitor and use?
Social/Communication Skills	What actions support getting information about scientific knowledge, thinking skills, and communication skills?

Table 2
SEPIA Criteria for Guiding Design and Assessment of Student Work
Criteria and Sample Questions Posed to Students

Relationships

What goes together?
How do they go together?
Is there a name we can give to the relationship?
Is there anything that does not belong?
How are things alike?

Clarity

Is it clear?
Does it tell what you want it to tell?
Will it be clear to someone else?

Consistency with Evidence

Is the statement supported by observations? If so, what?
Is it supported by the observations of others? If so, what?
Is the statement consistent with lab data? If so, what data?
Can you identify evidence from nature that supports the statement?
Does your statement reflect the data?

Use of Examples

Can you give an example?
Is it a good example for this purpose?
Is there a better example for this purpose?
Can you think of an original example?

Making Sense

Is this what you expected?
Are there any surprises here?
Is there anything that does not fit?
Does your hypothesis make sense with what you know?
Can you predict what will be the outcome?

Table 2 - cont.
SEPIA Criteria for Guiding Design and Assessment of Student Work
Criteria and Sample Questions Posed to Students

Acknowledging Alternative Explanations

Is there another way to explain this?
Is your explanation or hypothesis plausible - can it happen?
What does this explanation say that the other doesn't?

Elaboration of a Theme

Is this term related to something we did before?
Is it familiar? If so, how?
Is it related to anything you did in another class?

Accuracy

Is the statement consistent with other information on the same topic?
How does the model compare with other models?
How does it compare with other representations?

Making Sense

Relationships

Elaborating a Theme

Acknowledging Alternative Explanations

Accuracy

Use of Examples

Clarity

Consistency with Evidence

Sense Making

What is Known

|
|
|
|
|
|
|
|
|
|
|
|
|
|

Reasoning

How it is Known

Figure 1. SEPIA Criteria Continuum

Appendix A
Vessels Unit Outline

1. Engaging Authentic Problem/Question

Letter/ Reading the Letter

Emphasize the goals - to build a model that helps in the design of a vessel; to explain why and how the design works - the packet

Emphasize the function of the model - to maximize how much a vessel can carry

Emphasize the performance variable - interactions with water, what matters in the letter - what doesn't matter in the letter

Capture Prior Knowledge about Vessels
- Diversity of Vessels
- Design of Uses

Why do things float?
Why do things stay afloat when a load is added?
Why do things sink?

****

The development of lists of important concepts from the discussion of the letter should be captured and displayed publicly as word banks, concept map, cards.

****

2. Assessment Conversation related to 1

Models

Student Work (Portfolio item)
- Sketch of a vessel
- Label or otherwise explain:
  - Why a vessel floats?
  - Why a vessel sinks?

Teacher Led SEPIA Criteria Discussion of Student Work
- Performance Criteria; i.e., clarity & precision
- Subject Matter Content Focus;

3. Perform the Task - 1st Effort

Individually students sketch-plan-do

Ss build 1st vessel
Sketch vessel (Portfolio Item) - relate to goals in letter

4. Assessment Conversation related to 3

SEPIA Criteria Discussion gives rise to
Performance Predictions (Which vessels will work best? Why?)
Initial conversation about contrast features
Need to capture details about vessel design - acquire bottom surface area and height of sides

****

Do all the boats weigh the same?

Teachers can pursue this question as either a warm-up activity or as a demonstration. Take one S's vessel. Ask if anyone thinks their vessel will weigh a significantly different amount (± 2 g). If a Ss volunteers, then take that vessel and place it on a double pan balance with the first vessel. Compare and point out they weigh the same. Continue this procedure until you have convinced the students that all of the vessels regardless of shape are in the same narrow weight range.

****

5. Test/Solve

Students reminded to "keep an eye on things" - boat down water up why my boat sinks, how my boat sinks

Students reminded to "keep a record"; surface area value, weight it took to sink the vessel, design features of the vessel

****

Group students so that there is a distribution of vessels according to size. This will facilitate completion of the vessel testing within one class period. It will also facilitate the acquisition of evidence for the ensuing assessment conversation.

****

6. Look-for-Contrasts/Patterns Assessment Conversation related to 3,4,5

Review performance predictions and explanations during warm-up

Graph Display of Vessels
Student work (Portfolio Item)
Visual representation of graph

Locate examples of contrasts and patterns
Same performance different design (within same category)

Different performance same design (bottom area)
Different performance different design (extreme categories)

Summarize contrasts and patterns
Return to Subject Matter Focus - why things float and sink?
Apply SEPIA criteria to:
review and critique of performance/strategy/plan
Student Work (Portfolio Item)
Provide sketch and explanation of performance/strategy/plan
Capture diversity of ideas and knowledge claims
Acquire evidence that support ideas and knowledge claims
interaction with water
Name the forces buoyant force - gravity force
pressure increases with depth

****

Demonstrations can be used to assist in establishing and/or reviewing the concepts and evidence involved in flotation and buoyancy.

1) level of water
2) pressing cups/tubs into a trough/sink/aquarium of water
3) coffee can with holes (the taller the object the better)
4) manometer (thistle tube with rubber diaphragm attached to glass u-tube.

****

Student work

Compare and relate cup pressing in water with adding weight to vessel. Sketch, draw or other wise explain how the demonstration with the cup is related to the performance of the vessel. (Portfolio Item)

7. Nested Unit on Models, Experimentation, or Explanation

a. Class discussion of criteria for plan and a fair test
b. Groups of Ss design individual plans
c. Class discussion of exemplary plans; i.e., those that address SEPIA and Fair Test criteria
d. Implement the Plan
e. Report the results
f. Post the results

Experiments on contrasts to include but not be limited to:
- shape of vessel
- bottom size of vessel

- height of sides of vessel
- distribution of weight in the vessel
- measurement of change in depth of water

8. Assessment Conversation related to 7; particularly e and f

Return to contrasts and patterns; what counts and what doesn't count
Apply SEPIA Criteria to guide this dialog
Relationships
Alternative Explanations
Evidence for Explanations

****

The purpose of this assessment conversation is to highlight the elements of vessel design that help to meet the goal of the project - design a model that maximizes the load a vessel can carry and provide an explanation of why it works

****

9. Perform the Task - 2nd Effort

Review goals and SEPIA Criteria
Plan of Action by Groups of Ss
Sketch of Vessel Design with Performance Explanation (Portfolio Item)
Construct vessel - each student makes a vessel (Portfolio Item)
Performance Packet (Portfolio Item)

****

The test of the vessels can be done as a large group activity with each vessel being tested at the front of the class. The vessel that has the best results will be the one submitted to the 7th grade competition. Stress that the effort was a group effort - whole class effort.

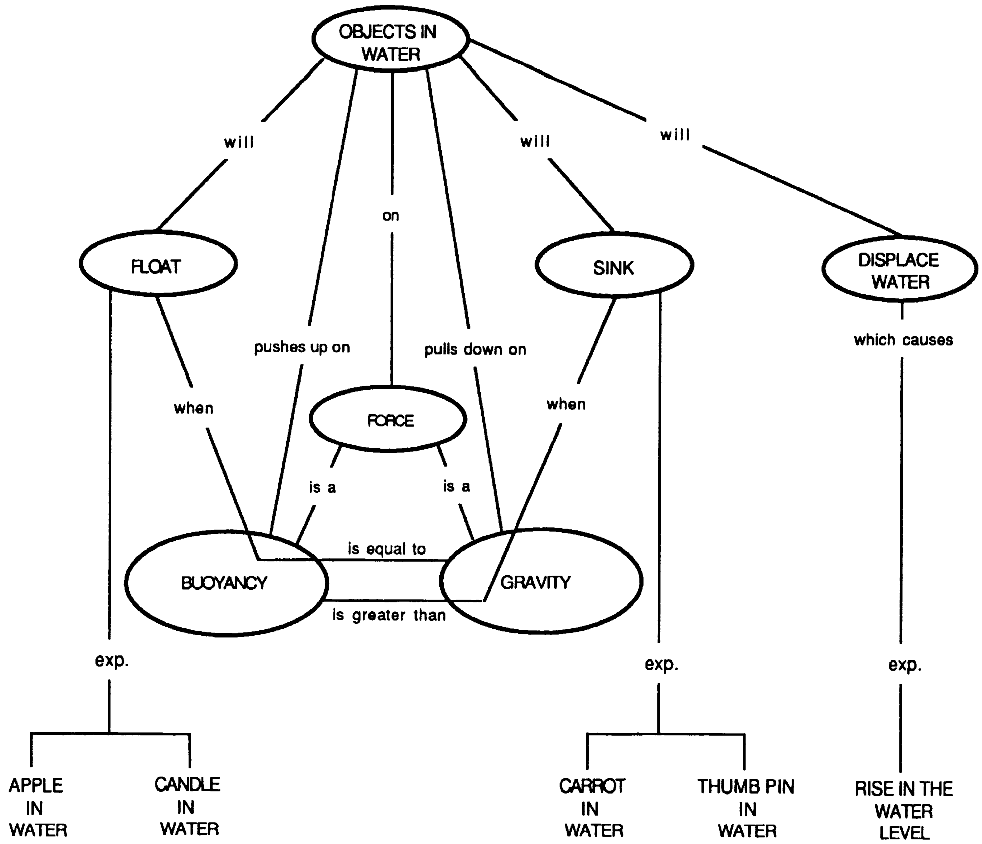
****

10. Assessment Conversation related to 9

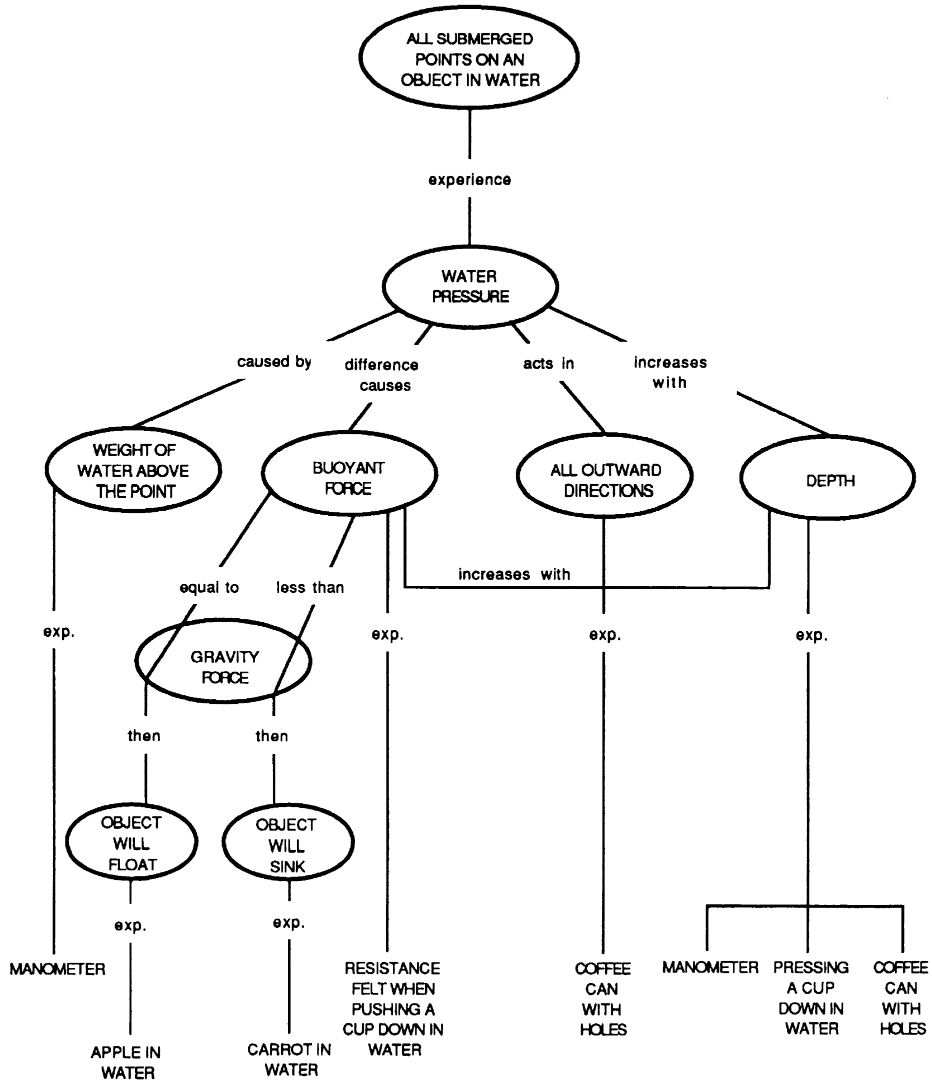
Submission of Final Plans and Packet
Assemble portfolio of work

Appendix B

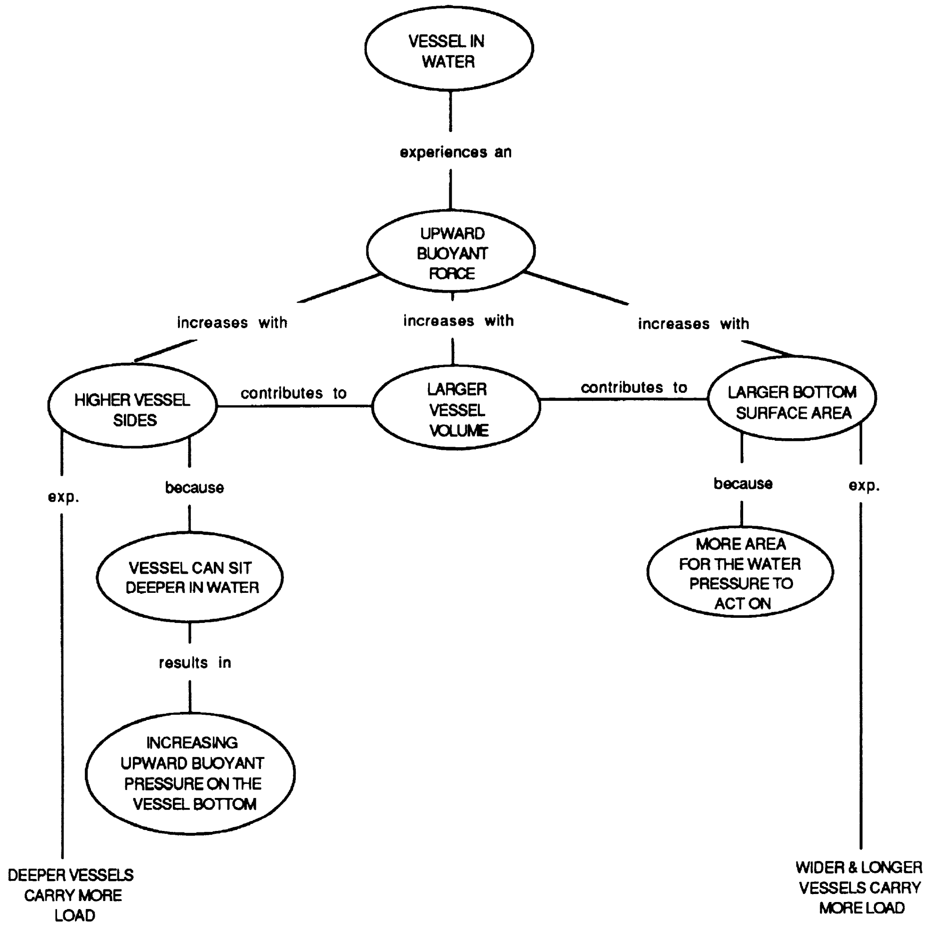
Conceptual Ecology of the Vessels Unit
in
Three Parts



CONCEPT MAP
PARTS 1 & 2



**CONCEPT MAP
PART 3**



CONCEPT MAP
PART 4

32

References

Anno, M. (1979). Anno's medieval world. New York: Philomel Books.

Branley, F.M. (1986a). Gravity is a mystery. New York: Thomas Y. Crowell.

Branley, F.M. (1986b). What makes day and night. New York: Thomas Y. Crowell.

Brewer, W.F., Hendrich, D.J. & Vosniadou, S. (1988). A cross-cultural study of children's development of cosmological models: Samoan and American data. Unpublished manuscript.

Bruer, J.T. (1993). The mind's journey from novice to expert. American Educator, 6-46.

Delta Education, (1993). Orbiter planetarium.

Dillon, D.R. (1989). Showing them that I want them to learn and that I care about who they are: A microethnography of the social organization of a secondary low-track English-Reading classroom. American Educational Research Journal. 26, 227-259.

Duschl, R.A., Hamilton, R.J. & Grandy, R.E. (1992). Psychology and epistemology: Match or mismatch when applied to science education? In R.A. Duschl & R.J. Hamilton (Eds.) Philosophy of science, cognitive psychology, and educational theory and practice (pp. 19-47). Albany: State University of New York Press.

Fowler, A. (1991). The sun is always shining somewhere. Chicago: Children's Press.

Gardner, H. (1983). Frames of mind. New York: Basic Books.

Gardner, H. (1991). The unschooled mind. New York: Basic Books.

Gega, P.C. (1986). Science in elementary education. Fifth Edition. New York: Macmillan.

Glaser, B.G. & Strauss, A.L. (1967). The discovery of grounded theory: Strategies for qualitative research. New York: Adline Press.

Goldschmid, M.L., & Bentler, P.M. (1968). Concept assessment kit -Conservation. San Diego. CA: Educational and Industrial Testing Service.

Gordon, C. (1992a). A case study of conceptual change. In C.K. Kinzer 8 D.J. Leu (Eds.) Literacy research, theory, and practice: Views from many perspectives. Forty-first Yearbook of the National Reading Conference (pp 161 - I68). Chicago: National Reading Conference.

Gordon, C. (1992b, December). A case study of conceptual change: A follow-up. Paper presented at the annual meeting of the National Reading Conference, San Antonio. TX.

Guzzetti. B.J., Snyder. T.E., Glass. G.V., & Gamas. W.S (1993). Promoting conceptual change in science: A comparative meta-analysis of instructional interventions from reading education and science education. Reading Research Quarterly, 28. 117-159.

Hazan, R.M., & Trefil, J. (January 13, 1991). Quick! What's a quark? New York Times Magazine.

Ingoglia, G. (1991). Look inside the earth. New York: Grosset & Dunlap.

Jeunesse. G., & Verdet, J.P. (1989). The Earth and Sky. New York: Scholastic.

Kaufman, A.S., & Kaufman, N.L. (1990). Kaufman Brief Intelligence Test. Circle Pines. MI: American Guidance Service.

Kitamura, S. (1989). UFO diary. New York: Farrar, Straus & Giroux.

Klein. C.A. (1982). Children's concepts of the earth and the sun. Science Education, 65, 95-1()7.

Lauber, P. (1990). How we learned the earth is round. New York: Harper Collins.

Lemke, J.L. (1990). Talking science: Language, learning and values. Norwood, NJ: Able Publishing Company.

Linn, R.L. & Meyer, L.A. (1991). How American teachers teach science in kindergarten and first grade. (Tech. Rep. No. 544). Champaign, IL: Center for the Study of Reading.

Mant, J. & Summers, M. (1992). Some primary school teachers' understanding of the Earth's place in the universe. (Working Paper No. 16) Oxford: Primary School Teachers and Science Project.

Maria, K. (1988, Decembcr). Helping fifth graders learn with science text. Paper presented at the annual meeting of the National Reading Conference. Tucson, AZ.

Maria, K. & Hathaway, K. (1991, December). Conceptual change through reading: The effect of instructional support. Paper presented at the annual meeting of the National Reading Conference, Palm Springs, CA.

Maria, K. & Johnson, J. (1990). Correcting misconceptions: Effect of type of text. In S.J. McCormick & J. Zutell (Eds.) Literacy theory and research: Analysis from multiple paradigms. Thirty-eighth Yearbook of the National Reading Conference (pp. 329-339). Chicago: National Reading Conference.

Maria, K. & MacGinitie, W.H. (1987). Learning from texts that refute the reader's prior knowledge. Reading Research and Instruction, 26, 222-238.

Martin, K. & Miller, E. (1988). Storytelling and science. Language Arts, 65, 255-259.

Mayer, M. (1987). Common sense knowledge versus scientific knowledge: The case of pressure, weight and gravity. In J. Novak (Ed.), Proceedings of the second international seminar on misconceptions in science and in mathematics. (pp 299-310). Ithaca. NY: Cornell University.

McGraw-Hill (1989). Comprehensive Test of Basic Skills.

Minstrell, J. (1989). Teaching science for understanding. In L.B. Resnick & L.E. Klopfer (Eds.) Toward the thinking curriculum, Alexandria. VA: Association for Supervision and Curriculum Development.

Nelson, J. (1990). Day and night. Cleveland: Modern Curriculum Press.

Novak. J.D. (1972). The use of audio-tutorial methods in elementary school instruction. In S.N. Postlethwait, J.D. Novak & H. Murray (Eds.) The audio-tutorial approach to learning. (pp. 110-130). Minneapolis, MN: Burgess.

Novak, J.D. & Musonda, D. (1991). A twelve-year longitudinal study of science concept learning. American Educational Research Journal, 28, 117-153.

Nussbaum, J. (1971). An approach to teaching and assessment: The earth concept at the second grade level. Unpublished doctoral dissertation. Cornell University, Ithaca, NY.

Nussbaum, J. (1979). Children's conceptions of the earth as a cosmic body: A cross age study. Science Education, 63, 83-93.

Nussbaum, J. & Novak, J.D. (1976). An assessment of children's concepts of the earth utilizing structured interviews. Science Education, 60, 535-550.

Nussbaum, J. & Sharoni-Dagan, N. (1983). Changes in second grade children's preconceptions about the earth as a cosmic body resulting from a short series of audio-tutorial lessons. Science Education. 67. 99-114

Ogle, D.M. (1986). K-W-L: A teaching model that develops active reading of expository text. The Reading Teacher, 39. 564-570.

Patton, M.Q. (1990). Qualitative evaluation and research methods. Second Edition. Newbury Park, CA: Sage Publications.

Reardon, J. (1993). Developing a community of scientists. In Science workshop: A whole language approach (pp. 19-38). Portsmouth. NH: Heinemann.

Roth, K.J. & Rosaen, C.L. (1990, April). Writing activities in a conceptual change science learning community: Two perspectives. Paper presented at the annual meeting of the National Association for Research in Science Teachers, Lake Geneva, IL.

Rutherford, F.J. (1991). Vital connections: Children, science and books. In W. Saul & S.A. Jagusch (Eds.) Vital connections: Children. science and books (pp.21-30). Portsmouth, NH: Heinemann

Santa, C.M. & Havens, L.T. (1991). Learning through writing. In C.M. Santa & D.E. Alvermann (Eds.) Science learning: Processes and applications (pp. 122-133). Newark, DE: International Reading Association.

Schollum, B. & Osborne, R. (1985). Relating the new to the familiar. In R. Osborne & P. Freyberg (Eds.) Learning in science: The implications of children's science (pp. 51-65). Portsmouth. NH: Heinemann.

Shayer. M. & Adey, P. (1981). Toward a science of science teaching: Cognitive development and curriculum demand. London: Heinemann.

Silver Burdett & Ginn (1987). Science workbook - Grade 1. Lexington, MA.

Sneider, C. & Pulos. S. (1983). Children's cosmographies: Understanding the earth's shape and gravity. Science Education, 67, 205-221.

Strike, K.A.. & Posner, G.J. (1992). A revisionist theory of conceptual change. In R. Duschl & R. Hamilton (Eds.) Philosophy of science, cognitive psychology, and educational theory and practice (pp. 147-176). Albany: State University of New York Press.

Time Magazine (March 8. 1993) Lunar mission (pp. 21-22).

Vosniadou. S. (1987, April). Children's acquisition and restructuring of science knowledge. Paper presented at the annual meeting of the American Educational Research Association, Washington, DC.

Vosniadou, S. (I989). On the nature of children's naive knowledge. Proceedings of the 11th Annual Conference of the Cognitive Science Society, Ann Arbor, Ml.

Vosniadou, S. (1992). Designing curricula for conceptual restructuring: Lessons from the study of knowledge acquisition in astronomy (Tech. Rep. No. 546). Champaign, IL: Center for the Study of Reading.

Vosniadou, S. & Brewer, W.F. (1987). Theories of knowledge restructuring in development. Review of Educational Research. 57, 51-67.

Wolfman, I. (1991). My world. New York: Workman Publishing.

Wood, T. (1992). Our planet Earth. New York: Macmillan.

HEATING

THE TEACHER'S VIEW

This section outlines those aspects of a deeper understanding which the teacher needs to have in mind whilst working with pupils. Ideas in any aspect of science are constructed at ever increasing levels of sophistication and there are inevitably more sophisticated understandings than can be represented in these brief notes.

The scientific perspective on heat has changed substantially during the last three hundred years. The notion that heat is a material substance was evident in writings of the seventeenth century, such as Robert Boyle's 'Essay of Effluviums'. However, the idea is much older, possibly stemming from Greek philosophy. The caloric theory, which was constructed around the material characteristics of heat, came into general use in the eighteenth century. It proved to be more useful in explaining the phenomena known at the time than was the view that heat is associated with particulate motion, which was relatively underdeveloped. The theory included the postulates that caloric (or 'matter of heat') is an elastic fluid, the particles of which are attracted by the particles of ordinary matter and which, like all matter, can neither be created nor destroyed.

In the latter part of the eighteenth century, attempts to discover the effect of heat on the mass of bodies were proving inconclusive, (if heat had material characteristics, cooling should cause loss of mass) and the idea that heat is a mode of motion of the particles in a substance was gaining ground. Attempts were also being made by Rumford, Lavoisier, Laplace and others, to find quantitative relations between phenomena. For instance, Rumford compared the heat evolved by burning candles with that evolved by friction. These phenomena later became recognised as representing conversions of energy from one form to another, or transfers of energy from one location to another.

It was not until some 40 years later that Mayer, Joule and others re-investigated the subject of heat produced by friction, and established that heat is not a separate substance, but that it is associated with the motion of particles of ordinary matter.

By the second half of the nineteenth century, heat was considered by most scientists to be the energy of particles in substances, which is transferred due to a temperature difference. This definition is in agreement with the more modern thermodynamic definition, except that in the latter, the energy of particles is not thought of as a form of energy called 'heat', but as internal energy.

Internal energy

The particle constituents of a sample of matter possess some energy from their motion relative to one another (kinetic) and, they possess some energy from their positions relative to one another (potential).

The total energy arising from the relative motion and the relative positions of the particle constituents is called the internal energy of the sample. (The internal energy does not include contributions from the motion of the sample as a whole or from the position of the sample as a whole.)

Heat and heating

Current scientific ideas about energy focus upon heating as a process. The idea of 'heat' as an energy form is not consistent with current ideas about energy.

From a scientific point of view, heating is a process of energy transfer between two bodies because of a temperature difference. When objects at different temperatures are brought into contact such that their temperatures equalise, energy is transferred from the object at the higher initial temperature (thus reducing its internal energy), to the object at the lower initial temperature (thus increasing its internal energy).

The internal energy of the object (the aggregate of the kinetic and potential energies of the atoms in the object), cannot be equated to heat, since it is possible to increase the internal energy of a substance without exposing it to a body at a higher temperature. This can result from other ways of transferring energy. For example, the temperature of a gas is increased by compressing the gas. It follows that we can discuss internal energy in a body, but not 'heat' in a body.

In practice the objects which we experience are usually at a different temperature to ourselves, so heat transfer occurs and we are conscious of 'heating'.

Heating is the process of energy transfer due to a difference in temperature.

Temperature

Temperature can be thought of as an indicator of how readily an object will gain or lose energy. A difference in temperature between two objects means that energy will flow between them if they are placed in thermal contact. The temperature of an amount of material is an indication of the 'concentration' of its energy. A material at a higher temperature has more energy per volume than the same material at a lower temperature.

Convection, conduction and radiation

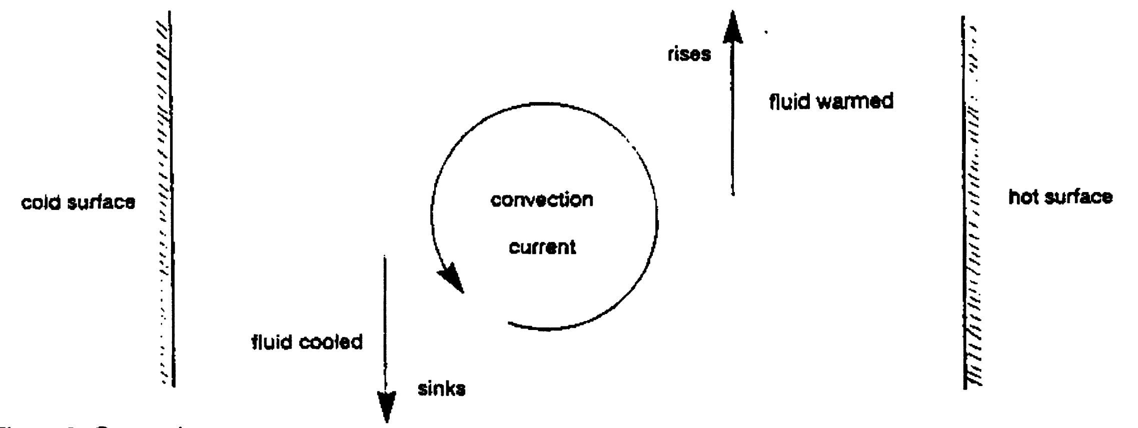


Figure 1: Convection

Convection is the transfer of energy between two surfaces when the surfaces are separated by a fluid (liquid or gas) which is free to move. The hotter surface warms the fluid in contact with it. The fluid then, being warmer than the surrounding fluid, has a lower density and thus rises. Fluid in contact with the colder surface is cooled. It therefore has a greater density than the surrounding fluid and it sinks. The rise on one side and sinking on the other results in a circulation of the fluid - a convection current. (See Figure 1.)

Conduction is the principal mechanism by which energy is transferred through solid materials, where the medium is not free to move. It can also occur in liquids and gases, accompanied by convection. Energy transfer in conduction occurs by the transfer of vibrational energy when the particles collide. Energy is also transferred as the kinetic energy of the electrons of the conducting substance. Conduction in metals is predominantly due to the movement of electrons through the material. Being light the electrons move through the material quickly: metals, having electrons which are free to move, are good conductors whilst non-metals are poor conductors.

Radiation is an energy transfer between two surfaces at different temperatures, which does not rely on the presence of a medium between the surfaces. If an object is heated to a sufficiently high temperature it begins to glow red: it emits red light. If heated to still higher temperatures, it glows white and is found to be emitting light of all colours.

(Indeed in the ordinary electric light bulb, the tungsten filament is electrically heated to about 2200 K.) All objects emit radiation all the time, but most of it is not visible radiation. The invisible radiation emitted by bodies as a result of their temperature is known as infra-red radiation. Infra-red radiation behaves in a similar manner to visible radiation; thus using film sensitive to infra-red radiation, it is possible to take infra-red photographs. Our eyes are not sensitive to infra-red radiation, but some animals and plants can sense it.

Radiation of all types carries energy from the emitter of the radiation to objects that can absorb the radiation. The most important example of this is the energy received by the Earth from the Sun. This is an example of radiation travelling through space, not requiring any medium for its transmission. The radiation from the Sun carries energy. When this is transferred to the Earth, the Earth's temperature rises. The Earth also emits radiation into space. As the Earth warms, so the amount of radiation emitted increases. (Hot bodies emit more energy by radiation than cold bodies.) Since the Earth has a more or less steady temperature, the radiant energy received from the Sun must be exactly balanced by the energy radiated by the Earth back into space. In this steady state there is a balance between the energy gained and lost by radiation.

The radiation emitted by an object depends upon its temperature and on the nature of its surface; the nature of the surface also determines the efficiency with which a body absorbs radiation.