ED 303 352 SE 050 336

AUTHOR Linn, Marcia C.; Songer, Nancy Butler
TITLE Curriculum Reformulation: Incorporating Technology into Science Instruction.
SPONS AGENCY National Science Foundation, Washington, D.C.
PUB DATE 88
GRANT NSF-MDR-8470514
NOTE 53p.; Paper presented at the Annual Meeting of the American Educational Research Association (New Orleans, LA, April 1988).
PUB TYPE Speeches/Conference Papers (150) -- Reports - Research/Technical (143)

EDRS PRICE MF01/PC03 Plus Postage.
DESCRIPTORS *Computer Assisted Instruction; Computer Graphics; Computer Software; *Computer Uses in Education; *Curriculum Development; *Laboratories; Microcomputers; Physics; Science and Society; *Science Instruction; Sciences; Secondary Education; *Secondary School Science; Technology; Thermodynamics
IDENTIFIERS *Microcomputer Based Laboratory

ABSTRACT

To increase the connection between educational research and educational practice, a process called "curriculum reformulation" was used to incorporate recent advances in research on learning and instruction into science classroom experiences. The cognitive demands of a thermodynamics curriculum were successively refined while maintaining the same microcomputer based laboratory (MBL) software and the same basic experiments. The 13-week curriculum was reformulated four times, and each version was evaluated using the same criteria. Overall, a four- to ten-fold increase in student learning (depending on the criteria applied) was achieved as a result of reformulations based on cognitive research. The results showed that some suggestions from research offer promise for use in realistic settings and that other suggestions such as "offer multiple representations" are wrong or incomplete when applied in realistic settings. Includes a bibliography of 75 references. (Author/MVL)

Curriculum Reformulation: Incorporating Technology into Science Instruction

Marcia C. Linn

Nancy Butler Songer

Graduate School of Education
Tolman Hall
University of California
Berkeley, California 94720

Paper presented at the American Educational Research Association meeting.
In symposium entitled
Conceptual Models of Science Learning and Science Instruction
Session 23.28
New Orleans, April, 1988.

Acknowledgements:

This material is based upon research supported by the National Science Foundation under grant No. MDR-8470514. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the National Science Foundation.

We appreciate contributions of software and equipment from Bob Tinker and Technical Education Research Centers (TERC). We gratefully acknowledge the donation of equipment and software from Apple Computer, Inc. Special thanks go to Jim Greeno and Dana Kay for their comments on an earlier version.

We were fortunate to collaborate with experts on physics, technology and education. We would like to thank: Doug Kirkpatrick, Foothill Middle School, Phil Dauber, Foothill Middle School, Robert Tinker, TERC, Rafi Nachmias, Post-Doctoral Scholar from Israel (Tel Aviv University), Yael Friedler, Post-Doctoral Scholar from Israel (Hebrew University), Joanne Striley, Graduate Student, University of California, Berkeley (now at University of Pittsburgh), and John Layman, Professor, University of Maryland.

Curriculum Reformulation:
Incorporating Technology into Science Instruction

Abstract

To increase the connection between educational research and educational practice, we used a process called "curriculum reformulation" to incorporate recent advances in research on learning and instruction into science classroom experiences. We successively refined the cognitive demands of a thermodynamics curriculum while maintaining the same microcomputer based laboratory (MBL) software and the same basic experiments. We reformulated the 13 week curriculum four times, and evaluated each version using the same criteria. Overall, we achieved a four- to ten-fold increase in student learning (depending on the criteria applied) as a result of reformulations based on cognitive research. Our results showed that some principles from research offer promise for realistic settings and others such as "offer multiple representations" are wrong or incomplete when applied in realistic settings.

Curriculum Reformulation

Educational leaders frequently call for closer collaboration between educational research and educational practice. Recent reports stress the need for investigations testing ideas from educational research in realistic settings (Linn, 1987-a, 1987-b; Pea & Soloway, 1987). Two major problems thwart efforts to couple educational research with educational practice. The first is methodological. Studies in realistic settings are influenced by numerous factors, and often the effect of research-based innovation cannot be detected. The second is conceptual. Although research on learning and instruction has advanced substantially in recent years, curricular prescriptions remain imprecise. In fact, at times different research perspectives recommend conflicting educational practices.

In these investigations, we combined advances from research on learning and instruction with advances in educational technology. Our goal was to improve students' understanding of aspects of thermodynamics, in particular the distinction between heat energy and temperature. The technological advance we studied, real-time data collection, is the ability to collect, record, and instantaneously display laboratory data. Use of such a tool frees students from the tedium of recording, analyzing, and displaying data. The challenge to curriculum designers involves taking full advantage of this capability in teaching students about thermodynamics. The advances in research on learning and instruction we incorporated characterize the learner as a) actively constructing a view of the natural world, b) coming to science class with isolated conceptions rather than integrated ideas, c) benefitting from robust models of scientific phenomena, and d) capable of learning self-monitoring skills (Eylon & Linn, in press). We used the process of curriculum reformulation to evaluate our effects.

We employed curriculum reformulation to address the methodological and conceptual problems of conducting investigations in realistic settings. Methodologically, rather than contrasting the "traditional" curriculum with the "innovative" curriculum, we contrasted successive reformulations of the innovative curriculum with each other. Conceptually, we evaluated each version of the curriculum, analyzed its shortcomings, sought guidance from research on learning and instruction to improve the curriculum, and evaluated the reformulated version.

Methodology

Methods used for comparisons of traditional and innovative curricula generally place the innovation at considerable disadvantage. Often these studies attempt to "keep everything else the same" and therefore they retain the goals of the traditional curriculum while adding some innovation. For example, studies add real-time data collection to a unit on thermodynamics but otherwise do not take advantage of the technique. Alternatively, studies change many aspects of the instruction making causal attributions problematic. As Cronbach (1963) discussed, comparisons of innovative curricula to established approaches often provide weak or useless information about the innovation. Essentially, hundreds of factors influence performance in realistic settings. Many of these factors interact with the innovation. If these interactions are suppressed, the innovation has very little effect. If these interactions are permitted, the nature of the innovation changes, and the goals of instruction may change.

For example, consider the familiar debate about using calculators to teach long division. If the "innovative" curriculum adds calculators and makes no other changes, students in the innovative program will spend less time learning division and will be faster and more accurate than those in the traditional program on tests where calculators are permitted. Of course, when required to solve division problems without calculators, those who never used calculators will probably excel. However, students who use the time saved from drill on long division to learn estimation and answer verification may excel at solving naturally-occurring division problems under pressure, with or without calculators. Investigations of the effectiveness of instruction in realistic settings must be sensitive to the trade-offs between one instructional approach and another. Curriculum reformulation allows investigation of each instructional approach.

Results from investigations in realistic settings can inform policy makers and other decision makers. All such studies must be evaluated in conjunction with the goals of instruction. Thus, adding calculators to instruction in division offers an opportunity to change the goals of instruction to include estimation and answer verification. Naturally, policy makers ultimately select from several possible instructional goals and alternative versions of curricula. Besides evidence from trials in realistic situations, such decisions are based on costs, availability of trained personnel, and a variety of other evidence.

Conceptualization

Applying educational research to curriculum design involves complex decision making. Curriculum design involves thousands of decisions that ideally follow from research on learning and instruction. Furthermore, principles of learning and instruction are constantly evolving. The principles enumerated here have empirical support, but are not fully understood. For example, the motivational value of hands-on learning is well documented, but the mechanism leading to increased motivation in hands-on situations has not been fully specified (Lepper, 1985). Educational principles, therefore, provide guidance for the design of a physical science curriculum but leave many questions unanswered.

Several models for combining research principles with curriculum design are possible. We chose to combine the expertise of our project team to define the initial version of the curriculum and then to seek guidance from research after evaluation of the outcomes. Thus, the first version of the Computer as Lab Partner curriculum incorporated principles from research and insights from educational practice. A more theory-driven approach was taken by Anderson's group at Carnegie Mellon University for devising computer tutors. They started with the principles from ACT* theory (Anderson, 1983) and used these principles to govern instructional design as much as possible. (ACT* is "the most recent in a series of theories denoted by the acronym ACT. The acronym stands for Adaptive Control of Thought, a name that has only historical significance." (Anderson, Boyle, & Reiser (1985)) Nevertheless, both Anderson's group (Lewis, 1987) and our group report that curriculum design involves thousands of decisions, many of which are not addressed by relevant research or theory.

The Computer as Lab Partner Curriculum

The first of four versions of the Computer as Lab Partner Curriculum combined the teacher's commitment to hands-on, interactive learning and the researcher's perspective of the learner and of instruction. This section describes the rationale for the initial curriculum. Preliminary versions of the student activities used hardware and software donated to the project and were devised jointly by the teacher, researchers, and physics experts who participated in the project. The science topic, experiments, technological environment, and classroom environment remained constant through all of our investigations, as did the teacher role and student characteristics. We varied the intellectual demands on students as we refined the curriculum in light of principles from research.

Science Topic

We focused our investigation on an important scientific domain -- thermodynamics. Science educators and cognitive researchers generally agree that efforts to understand and improve science education should focus on fundamentally important knowledge domains. Since much of scientific knowledge is specific to the problem context, students develop conceptions of scientific problems that can inhibit or enhance subsequent learning (e.g., Gentner & Stevens, 1983; Larkin, McDermott, Simon, & Simon, 1980; Linn & Swiney, 1981). Furthermore, instructional provisions, including the strategies necessary for problem solution, vary with the scientific domain (e.g., Reif, 1987; Brown, Kane, & Echols, 1986).

We selected thermodynamics for several reasons. First, thermodynamics is fundamental to much of physical science. The concept of energy and the distinction between intensive and extensive properties contribute to many domains. Second, students encounter many naturally-occurring problems involving thermodynamics, such as conservation of energy in home heating and cooling, maintenance of body temperature, and cooking with microwaves, which primarily add energy to water and fat molecules. Third, thermodynamics involves many observable influences and is readily accessible to experimentation. Students can use microcomputer-based laboratories to collect information about heating and cooling and can easily conduct experiments involving state changes such as the freezing and boiling of water or alcohol. For eighth-grade physical science, we sought a topic familiar to students, readily encountered in natural settings, appropriate for middle school, and amenable to available technology. The general topic of thermodynamics met these criteria.

Activities

We devised a series of hands-on experiments that were feasible in the classroom and relevant to thermodynamics. The actual curriculum focused on the distinction between heat energy and temperature and on the process of state change. Examples of state change included (a) freezing of paradichlorobenzine, (b) the freezing of water, (c) boiling of water, and (d) boiling of alcohol. Activities were selected from experiments used previously by the instructor or devised by the research team. As can be seen in the summary in Table 1, the activities were modified slightly from version to version of the curriculum, but major changes were not made.

Our choice of hands-on learning experiences reflected the considerable research demonstrating that students devote their full attention to hands-on learning experiences and report enthusiasm for these activities (National Assessment of Education Progress [NAEP], 1979a). Hands-on approaches to science instruction maintain high motivation among students and often teach science effectively (Shymansky, Kyle, & Alport, 1982). On balance, hands-on learning requires considerable instructional time and may fail to communicate the appropriate problem representation and fail to encourage integration of knowledge. Often students in hands-on classes learn to break glassware or create bubbly mixtures, but not to relate their experiments to any scientific principle (Linn, 1980). Furthermore, many important scientific phenomena are not amenable to in-class experiments. In light of this situation, we sought guided discovery experiences that combined real-time data collection with n emphasis on an effective representation and integrated understanding to achieve effective learning.

It should be noted that the curriculum devoted 13 weeks to heat energy and temperature. In contrast, the textbook for middle school physical science recommends devoting approximately one week to this topic. Furthermore, the textbook treatment involves the distinction between heat energy and temperature as well as state change, specific heat, thermoconductivity, and kinetic theory. The textbook approach is fundamentally in conflict with the principles of learning and instruction governing our investigation: The textbook overloads students' processing capacity, focuses on isolated facts, and fails to provide an appropriate representation for the distinction between heat energy and temperature. Although our approach differed substantially from that recommended by the textbook, it was not a radical change for the participating teacher, who generally focused on a few topics and used hands-on experiments.

Technological Environment

To study thermodynamics at normal pressure, expert scientists often use real-time data collection. This tool is available to students through software developed by Technical Education Research Centers (TERC) in Cambridge, Massachusetts, and (originally) published by Human Resource Media [now Queue] (1987). Other companies also offer similar software (e.g., Broderbund, 1987). Adaptation of technological tools used by experts for classroom instruction offers considerable promise over earlier approaches for using technology in education (Linn, 1987b; Linn, 1988).

In our curriculum, the computer becomes a silent lab partner. Students can conduct heat and temperature experiments, collect data in real-time, display the data, and print graphs of the data using the Apple IIe computer (see Figure 1). This environment resulted from an equipment grant from Apple Computer and a gift of pre-released software from TERC, as well as an Educational Technology grant from the State of California to buy final versions of the software.

The real-time data collection environment supports the active, constructing nature of the learner. First, real-time data collection provides memory support and frees the student to concentrate on integrating ideas. Real-time data collection speeds up experimentation and increases efficient use of limited classroom time, allowing students to repeat their experiments to resolve ambiguities even in a single class period.

Second, real-time data collection encourages understanding of graphs of heating and cooling by dynamically displaying changes over time. Students note when the temperature changes rapidly and when it changes slowly or does not change at all, often remarking, "Look, now the temperature is changing fast; now it's slowing down."

Third, real-time data collection helps students develop robust understanding of heat energy and temperature by providing multiple representations of heating and cooling. Students have a concrete representation of their experiment and they have graphic representations of the data. In addition, by representing many different experiments on the same axes and with the same format, students can easily compare one experiment to another and potentially integrate their understanding of thermodynamics.

Fourth, using real-time data collection enhances hands-on interactive learning. A long research tradition demonstrates that feedback helps students learn (e.g., Greeno & Simon, 1984). Traditionally, science teachers have provided feedback for students through tests and worksheets and through class discussions. Using real-time data collection, students gain feedback through graphic representation of their data, and opportunities to re-display information gathered from varied experiments.

Real-time data collection also makes it easy for students to give feedback to peers. When using computers in the science classroom, opportunities for peer interaction include collaborative reports using the wordprocessor and easy access to computer screens displaying data collected by other students. As yet, this feedback is not well understood (Webb & Lewis, in press) and techniques to take advantage of peer interaction are still developing (e.g., Lambiotte, et al. 1987; O'Donnell, Dansereau, Hall, & Rocklin, 1987, Brown & Palinscar, 1987).

Fifth, real-time data collection provides opportunities to learn about scientific measurement. By calibrating the probes used for real-time data collection, students learn about error of measurement. When reconciling their results with those of other students, they realize that some differences in outcome are attributable to calibration. Students also confront the problem of accuracy of measurement when they note irregularities in heating and cooling curves caused by the pixel density on the computer screen. Real-time data collection allows students to examine effects not often studied in science classes. For example, they can investigate the effect of stirring a heated liquid on the uniformity of temperature throughout the material.

In summary, the technological environment facilitates experimentation, helps students build robust representations of the phenomena under investigation, and supports effective hands-on learning.

Classroom Environment

Instruction took place in a one-semester (20 week) physical science class, with each class period about 55 minutes long. Classes met six out of every seven school days. The district follows a modular schedule which allows students to participate in seven classes even though they only schedule six class periods daily. Four classes participated each semester.

Students learned science using a double classroom. One classroom was used for written assignments and class discussion. The other was used for experimentation. The computers were arranged around the room, one to a table. Printers were located centrally. Students needed to save their results and then take them to a computer with a printer.

Students conducted experiments using the computers as lab partners about every other day. Apparatus for experiments included bunsen burners for heating liquids, insulated containers, and containers of many different sizes. Students experimented with hot water, ice water, ice, and a variety of different substances including oil, alcohol, and paradichlorobenzine. They gathered equipment needed for their experiments from a central location, set up their experiments, and collected their data. Then they prepared written reports and participated in discussions about their findings.

Teacher role

Initially, the teacher maintained his usual role. The teacher was experienced in managing hands-on learning, and found that real-time data collection simplified experimentation. The teacher modeled effective problem solving, encouraged student pairs to discuss their plans and their results, devised team response sheets to encourage interaction, and monitored student behavior during experimental sessions. The real-time data collection techniques made monitoring student performance easier because results were displayed on 16 computer screens around the room.

Self-Monitoring. This teacher role is compatible with recent research on instruction, demonstrating that students' self-monitoring skills contribute to learning (Brown & Palinscar, 1987). Brown and her colleagues have demonstrated that teachers can model self-monitoring skills and, with appropriate scaffolding, can instill them in students. As students develop skills in self-monitoring, they learn to analyze different perspectives on the same underlying phenomena, test their ideas, and eliminate conceptions that lack predictive power.

In the Computer as Lab Partner curriculum, several factors encouraged effective self-monitoring. First, the teacher modeled his own problem-solving processes, describing how he monitored his ideas and compared results from different experiments. Second, the hands-on experience available in the classroom also encouraged self-monitoring because students had concrete results to compare to their verbal explanations for concepts from thermodynamics. Third, real-time data collection procedures encouraged self-monitoring in that they provided a new representation of valid data for students to examine.

Student Characteristics

The participating students came from a middle class, racially and ethnically mixed community. About one-third of the students reported some access to computers outside of school.

Thermodynamics is appropriate for 12- to 13-year-olds, in that they have many concrete experiences relevant to it. Furthermore, students of this age should be transitional between concrete and formal operations, and therefore receptive to instruction which attempts to provide a more systematic understanding of heat energy and temperature (Inhelder & Piaget, 1958).

Requisite Knowledge. Most would agree that there are prerequisites to any instruction (e.g., Gagne, 1968). To use real-time data collection, students need skill in interpreting graphs presented on the computer as well as skill in evaluating the reliability and validity of computer presented information. Thus, we focused on this information at the beginning of the course and assessed whether students had acquired it.

Domain Knowledge. Much research reveals that students need appropriate knowledge about the situations in which concepts or principles are applied in order to reason effectively about those concepts (Greeno,1986). In particular, students cannot design fair comparisons when they do not know which variables to keep the same (Linn & Swiney, 1981). Our curriculum focused on experiments conducted in the science classroom. To ensure that students understood the situation, we emphasized each of the variables that they could investigate. Thus, they learned about the problem situation including the role of each variable influencing aspects of heat transfer and temperature. In general, students found these situations unique and had few expectations about outcomes.

Classroom teachers, philosophers, developmental psychologists and others agree that learners actively construct an understanding of scientific phenomena (Resnick, 1983) and enter science classes with well-established ideas about scientific phenomena, including thermodynamics. Effective instruction must take advantage of the active constructing nature of the learner in order to improve scientific reasoning and problem solving. In thermodynamics, students have difficulty distinguishing heat energy from temperature (e.g. Wiser & Carey, 1983) and have isolated ideas that are not readily integrated (Brook, Briggs, Bell, & Driver, 1984; Tiberghien, 1983).

In addition, many studies reveal that students construct specific ideas about scientific phenomena which govern their reasoning in naturally-occurring situations, even if instruction offers a different perspective (e.g., West, Pines, & Sutton, 1984; Driver, 1983). Students have very clear ideas about naturally-occurring problems involving heat energy and temperature (Table 2) but do not necessarily apply these ideas to classroom experiments. Thus, students believe that a larger cup of hot chocolate has a higher temperature than a small cup of hot chocolate, and that sweaters keep people warm and therefore cannot be used to keep an ice cube from melting. Initially, our curriculum emphasized understanding of heat and temperature experiments students conducted in class since these were accessible to experimentation. Ultimately, we intend to help students apply their understanding to naturally-occurring problems. (see Songer & Linn, 1988a).

The Computer as Lab Partner: Version One

The goal of the first version of the Computer as Lab Partner curriculum was to impart integrated knowledge of heat energy and temperature. Based on research on scientific understanding, it is clear that neither requisite knowledge nor domain knowledge are sufficient for learning to distinguish heat energy and temperature. Researchers generally agree that students need coherent understanding of a class of problems rather than isolated understanding of individual problems in order to garner knowledge (e.g. Linn, 1987a). In contrast, students often develop separate representations for problems that have the same underlying structure (di Sessa, in press;

Eylon & Linn, in press). Essentially, students learn to solve a problem in a particular context or situation and fail to recognize which information is essential and which is peripheral. Therefore, they treat problems as dissimilar that, in fact, could be integrated. By integrating understanding of several problems, students not only recognize the essential features, but also build representations that more readily incorporate subsequent related problems.

Although researchers stress integration, they offer minimal guidance on how to achieve it. Many researchers believe that effective instruction involves integrating domain knowledge by providing students with an appropriate "mental model" of the phenomenon under study (Gentner & Collins, 1985; Rouse & Morris, 1986). Mental models include domain knowledge as discussed above (e.g., the relative insulating value of different materials), procedures (e.g., techniques for separating intensive and extensive properties), and plans that combine domain knowledge and procedures to yield problem solutions (e.g., predicting whether a small glass casserole or a larger metal casserole will stay warm longer). Thus, mental models help students relate the various aspects of heat energy and temperature into a coherent view and provide systematic ways to use this coherent view to solve problems.

In designing this course, we considered four possible models or representations (summarized in Table 3) to help students develop integrated understanding of heat energy and temperature. Three of these models appeared in textbooks for students in middle school: measurement, variables, and kinetic theory. The fourth, based on heat flow, is similar to the historic view of heat as the calorie, but stresses that heat lacks mass.

Initially, the teacher retained the <u>measurement</u> representation, having students compute changes in degrees and changes in calories. This was accompanied by a verbal description of the <u>kinetic theory</u> model In all versions of the curriculum, we emphasized the <u>variables</u> involved in changes in heat energy and temperature to provide domain knowledge but not as an explanation of the distinction between heat energy and temperature. Fundamentally, only the kinetic theory and heat flow models offer an adequate explanation of the heat energy and temperature distinction.

Method

Using the activities, technological environment, and classroom environment described above, and starting with the teacher role and student characteristics defined above, we tested and refined the first version of the Computer as Lab Partner curriculum. Four separate cohorts of 128 eighth-graders participated in the four investigations. Between curriculum versions, we modified the intellectual demands on students, but not the experiments or the software, in order to improve learning outcomes.

The first version of the curriculum included the hands-on experiments listed in Table 1. The curriculum emphasized knowledge required to take advantage of real-time data collection. Activities designed to teach students how to interpret computer-presented graphs and how to analyze the reliability and validity of computer-presented information were included. This effort has been reported elsewhere and is summarized here (see Linn, Layman, & Nachmias, 1987; Nachmias & Linn, 1987).

In addition, the curriculum helped students acquire domain knowledge relevant to thermodynamics because students conducted experiments investigating how each variable influenced heating and cooling.

Assessment. To assess student understanding of thermodynamics, we used the Heat and Temperature Assessment (HTA) each semester we offered the Computer as Lab Partner curriculum. This assessment consisted of questions about domain knowledge, as well as a general question about the distinction between heat energy and temperature. See sample item in Figure 3.

Scoring. HTA items were coded according to qualitative distinctions agreed upon by several members of the research team. To score domain knowledge, questions about "volume" and "insulation" and their influence on heating and cooling were marked as pass or fail. Responses to the heat energy and temperature distinction question were classified into seven categories. These categories were: (1) very good distinction (including at least two clear and accurate qualitative distinctions and/or good example), (2) complete distinction (at least one clear and accurate qualitative distinction), (3) some distinction (one vague but correct qualitative distinction), (4) single thermal distinction, (5) textbook definition or terms only, (6) no difference, confused, or wrong and (7) no response. Ambiguous answers were reviewed by at least two coders and resolved by group discussion.

In order to fully characterize understanding of the distinction between heat energy and temperature, two levels of coding criteria were realized: a weak criteria and a strong criteria. In the weak criteria, the seven categories of student answers were divided into four groups: no response, wrong, incomplete, and good. Wrong responses were those characterized as "no difference" or "confused" (6 and 7 above). Incomplete responses were those characterized as single thermal and textbook terms only (4 and 5 above). Good responses included at least one accurate qualitative distinction (1, 2, and 3 above). Sample responses appear in Table 4. The second criteria, the strong criteria, placed students in two groups. All students who were able to make at least one clear and accurate qualitative distinction, and/or cite an example of their distinction, were characterized as successful (1 and 2 above).

Design. During the first semester of the Computer As Laboratory Partner (CLP) curriculum, we established a performance baseline by administering the assessment to students slated to take the course during the second semester. Subsequently, we administered the assessment at the end of the course.

Results and Discussion

Before determining whether students gained integrated knowledge, we assessed whether the curriculum was implemented as planned, whether students could interpret the graphs presented by the software, and whether the computer-presented information made sense to the students. We then assessed students' domain knowledge and their ability to distinguish heat energy and temperature, our measure of integrated understanding.

Implementation. During the first semester we were successful in implementing the interactive and hands-on aspects of the classroom environment. In contrast, the technological environment presented difficulties. Probes broke, software crashed, and computers needed repair. These problems distracted both the teacher and the students, and no doubt interfered with acquisition of robust understanding.

Knowledge of Graphing. As reported by Linn, Layman, and Nachmias (1987), students acquired understanding of graphing from the curriculum. Students became proficient at interpreting computer-presented graphs, explaining 80% of the heat and temperature graphs correctly. These results are consistent with other studies of real-time data collection (e.g., Brasell, 1987; Mokros & Tinker, 1987). Remarkably, students transferred their understanding of graphing to motion experiments. Students using real-time data collection were significantly better than others at interpreting graphs of, for example, the speed of a bicycle going up and then down a hill over time, even though no instruction on interpreting graphs involving motion was offered (see Linn, Layman, & Nachmias, 1987 for details).

Interpreting computer-presented information. Students also became more proficient at recognizing reliable and valid information as a result of experience with the Computer as Lab

Partner curriculum. As reported by Nachmias and Linn (1987), students learned (a) to recognize when their experimental set-ups were incorrect and (b) to detect when graphs had gone off either the upper or lower scale on the screen. Students had greater difficulty interpreting fluctuations in graphs due to pixel density on the screen or due to the calibration of the measuring device. As a result, subsequent versions of the curriculum increased emphasis on these topics.

Domain knowledge. Students acquired domain knowledge in that they recognized the role of the variables they investigated. As shown in Figure 4, over 75% of the students understood the role of the variables they had studied in heating and cooling, compared to a baseline of 50%.

Distinguishing Heat Energy and Temperature. Students made little progress in distinguishing heat energy and temperature, as shown in Figures 5 & 6. Prior to instruction, students had virtually no understanding of this distinction: Only 3% of students met the strong criteria (Figure 6). This finding is consistent with a wide range of investigations of students' conceptions of heat energy and temperature (e.g., Tiberghien, 1980, 1983; Wiser & Carey, 1983). After instruction, 11.7% of the students met the strong criteria for distinguishing heat energy and temperature (Figure 6). Close to 40% of students gave incorrect or confused answers and 17% gave no response at all (Figure 5). Of those who responded, 14% indicated that heat and temperature comprised a single thermal concept, perhaps suggesting that heat measured the temperatures above warm and that temperature was all the degrees on the spectrum (see Table 4 for examples). A small percent (10%) of students hinted at the intensive versus extensive properties of heat and temperature by saying things like "Heat is what is given off by something, and temperature is the measure of heat in °C or °F." Clearly, this distinction presents difficulties for students.

In summary, the first version of the Computer as Lab Partner curriculum implemented the desired classroom environment, providing an interactive, hands-on approach to learning. Results for this version demonstrated that students have no difficulty learning to interpret real-time data collection experiments, consistent with other investigations. As expected, students gained familiarity with the variables involved in heat energy and temperature, but made limited progress in achieving a coherent, integrated understanding of the distinction between heat energy and temperature. An unanticipated result was that investigations of heating and cooling communicated robust understanding of graphing that generalized to experiments concerning motion.

The Computer as Lab Partner: Version Two

Continuing with our goals of imparting integrated understanding of heat energy and temperature and using results from version one, we reformulated the Computer as Lab Partner curriculum and tested the effectiveness of the revised version with a new group of students. We increased emphasis on areas where requisite knowledge was weak, expanded domain knowledge, and sought new ways to help students to integrate their understanding and develop a robust representation for heat energy and temperature.

In version one, we found that the kinetic theory representation, combined with the measurement representation, was not sufficient to help students distinguish heat energy and temperature. We sought a more powerful representation of this distinction, adding both qualitative and quantitative components. In designing an appropriate representation for heat energy and temperature, we sought a qualitative model that would be accessible to middle school students and would unify the experiences in the curriculum. We focused on heat flow and offered a definition of heat reminiscent of the historical concept of the caloric. In contrast to the historical notion that the caloric had mass, we stressed that heat was massless. Quantitatively, we continued to emphasize computation of changes in calories, and the implications of these changes on computation of changes in degrees centigrade.

In version one of the Computer as Lab Partner curriculum, the teacher had difficulty implementing his usual techniques for encouraging students to integrate their ideas due to logistic problems. In version two, he instituted the techniques he generally uses to help students integrate their understanding of scientific principles. He presented challenging questions at the beginning of each lesson, encouraged group discussion, and modeled his own thought processes. He encouraged joint problem-solving and group reports. Response sheets were revised to reinforce integration of understanding.

In summary, version two of the curriculum addressed the difficulty of understanding calibration, extended coverage of variables relevant to the domain, and encouraged students to develop robust models and integrated understanding of heat energy and temperature. The other effective components of the curriculum were retained.

Method

Technological Environment. For version two, the project received a donation of wordprocessing software from Apple Computer. As a result, several student activities were altered so that partners could generate joint reports using the wordprocessor.

In addition, calibration activities were increased.

Domain Knowledge. Because students readily learned about the variables influencing the situations they were studying, we added starting temperature to the variables studied. Knowledge of the role of these variables was not sufficient to explain the distinction between heat energy and temperature.

Assessment. The assessments used for version two were the same as those for version one except that the domain knowledge assessment was expanded to include starting temperature.

Scoring. Consistent with the scoring of the other domain variables, knowledge of starting temperature and its influence on heating and cooling was coded on a pass/fail basis.

Results

Domain and Requisite Knowledge. Before assessing student gains in integrated understanding from the reformulated version of the curriculum, we first assessed domain and requisite knowledge, implementation, and the effects of using the wordprocessing. Results from version two replicated those from version one concerning domain knowledge (see Figure 4), knowledge of graphing, and knowledge of computer presented information. The revised activities succeeded in improving students' understanding of calibration, as reported by Nachmias and Linn (1987). As shown in Figure 4, students made good progress in understanding the effect of starting temperature introduced in version two.

Implementation. To assess implementation of the curriculum during this version, Striley (1988) closely observed dyads of students conducting experiments. She found that students were almost always on-task in spite of the many potential distractions: Students needed to collect the materials for their experiments, to set up their experiments, and then to respond to questions on their activity sheets. During all of these activities, less than 1.5% of the time was spent off-task. Of the remaining time, 10.3% of student interaction was composed of discussion of experimental results and negotiation of understanding of investigations. The remaining 88% of the time students spent on the activities needed to conduct empirical investigations, including gathering equipment, setting up experiments, and recording results.

Technological Environment. Students, working in dyads, took turns at the keyboard and both contributed to the final report. Striley (1988) observed students preparing reports by hand and using the wordprocessing software available during this semester. One unanticipated effect was that students collaborated more when preparing reports on the wordprocessor than they did when preparing reports by hand. Typically, when students used pencil and paper to make reports, one student answered the questions while another wrote down the answer. Often we heard students say, "You write, I'll think." When using the wordprocessor, students were more likely to work jointly to answer questions and were also more likely to revise their responses.

Thus, using the wordprocessor to prepare lab reports facilitated knowledge integration. First, the wordprocessor permitted collaborative report preparation. Second, the wordprocessor made revision easier and increased its frequency. Third, report preparation on the wordprocessor allowed the teacher to observe the process and discuss statements with students. The teacher modeled question-asking strategies that students began to implement as they prepared their laboratory reports.

Observations of students working in the classroom revealed another unanticipated effect of the technological environment. Students frequently compared the results of their experiments to those of other students by glancing around the room at the computer screens. Furthermore, when students observed anomalous findings on another screen, they frequently gathered around to analyze the results. Thus, at times a community of scholars emerged as groups formed to discuss aberrant results.

Integrating Understanding. In spite of reformulations, students made little gain in distinguishing heat energy from temperature from version one to version two. The teacher was able to implement techniques used in the past to encourage students to integrate their understanding, yet only slight gains over version one of the curriculum were recorded (see Figures 5 & 6).

In version two of the curriculum, two representations for the distinction between heat energy and temperature were offered: one quantitative, involving measurement of calories and degrees, and one qualitative, involving heat flow. Some researchers believe that multiple representations of the same phenomenon facilitate learning. In our curriculum, the opposite seemed to be the case. Rather than integrating the two representations for heat energy and temperature, students appeared to prefer the quantitative approach, which in fact, offered a limited representation of the underlying phenomenon. Students seemed satisfied with their ability to compute a change in calories or a change in degrees and were not motivated to go beyond these changes to find a mechanism to explain the difference between heat energy and temperature. As a result, a significantly higher number of students in version two were able to describe some distinction between heat energy and temperature (see Figure 5). However, the distinction was superficial, a common answer being "Heat is calories, temperature is degrees."

Discussion

The second version of the curriculum revealed serious difficulties in imparting integrated understanding. First, students selected the simplest representation, rather than integrating the available representations. Students preferred the quantitative representation for its simplicity, not for its robustness. As Lewis (1987) concluded in evaluating the effectiveness of the algebra tutor developed at CMU, students are "cognitive economists". If a simple solution is available, they resist a more complex one. It seems that the quantitative representation for heat energy and temperature provided an easy answer and stood in the way of students' serious analysis of the distinction. Many textbooks emphasize computation of gains or losses in calories and in degrees centigrade to represent heat and temperature. Our results suggest that this quantitative representation of thermodynamics throws a veil of numbers over the distinction between heat energy and temperature and stands in the way of qualitative understanding because students fail to analyze the qualitative relationships. In contrast, experts tend to think qualitatively about physics problems while novices often think quantitatively (Larkin, et al, 1980). As a result, we limited our presentation to qualitative representations in subsequent versions of the curriculum.

Second, in this version of the CLP curriculum, the teacher's proven techniques for helping students integrate their ideas did not succeed. In the traditional classroom, students spend considerable time translating data collected from experiments onto graphs. In the real-time data collection environment, such translation is unnecessary. Thus, traditional techniques do not take full advantage of real-time data collection. While data was being collected, students rather passively watched the graphs appear on the screen although they were free to concentrate on other aspects of the experiment. The third version of the curriculum sought to correct this situation.

The Computer as Lab Partner: Version Three

The first two versions of the CLP curriculum did not enhance integrated understanding in the form of improved ability to distinguish between heat energy and temperature, although they did instill (a) knowledge of graphing, (b) understanding of and computer-presented information and (c) domain knowledge appropriate for thermodynamics. Furthermore, although the program implemented efficient hands-on, interactive experiences and encouraged students to compose laboratory reports at the wordprocessor, it did not create robust understanding.

It is exactly this lack of integration of understanding that many implicate in the poor performance of American students on national science assessments. Furthermore, much research demonstrates that students rarely change their concepts about scientific phenomena (Eylon & Linn, 1987; Champagne, Klopfer, & Gunstone, 1982). It appears that students "learn" new scientific principles in class, but fail to apply them to subsequent problems.

In spite of extensive research, we had limited success in the classroom. First, we sought inspiration from philosophers of science to understand conceptual change and find effective strategies for instruction. This research clarified the dilemma, but did not offer clear guidelines. Carey (1985) compares changes in student's ideas during development to change in scientific understanding as described by philosopher of science Kuhn (1963). Several researchers have compared students' attempts to understand scientific phenomena with the description of progressing and degenerating research programs offered by Lakatos (1972, 1976). These researchers argue that students selectively incorporate information much as scientists in the history of science have dealt with new results (Strike & Posner, 1983; Linn & Siegel, 1984). These views suggest the importance of offering an integrated, robust alternative view to the learner and are consistent with the observation that apparent contradictions to students' ideas are not sufficient to lead to conceptual change (Burbules & Linn, 1988).

This research reiterates the importance of an appropriate representation for heat energy and temperature, and suggests how our representation could be augmented. Thus, we focused on the heat flow representation of heat energy and temperature in version three to (a) offer a robust alternative to students' ideas, (b) avoid simplistic options like the measurement representation, and (c) avoid abstract options like kinetic theory.

The research tradition informing our reformulations was our second focus on the constructing nature of the learner. In version three we reformulated the curriculum to encourage students to actively integrate their understanding of heat energy and temperature. We observed that students could tolerate greater cognitive demands while conducting their experiments because real-time data collection took over functions that would have occupied them in a traditional class. We based our reformulations on two principles from research: active learning and self-monitoring.

Research results recommended that students be actively involved in analyzing and integrating their experiences (Palinscar & Brown, 1984; Bereiter & Scardamalia, 1986). The teacher had attempted to achieve active, reflective learning through class discussion and work sheets. Students could also be actively involved in their experiments. For version three we generated two hypotheses about how students could actively analyze and integrate their experiences. First, rather than passively conducting experiments, students could actively record their observations just as expert scientists do. Second, rather than treating each experiment as unique, students could use the results of one experiment to predict the outcomes of the next. Essentially, students could base their first prediction on conceptions they brought to science but would construct their second prediction by integrating the results of their first experiment. Thus students would be encouraged to engage in a progressing research program as described by Lakatos (1972,1976).

Research also stresses the importance of self-monitoring for achieving integrated understanding (Brown & Kane, in press, Schoenfeld, 1985). Self-monitoring involves assessing one's progress and redirecting one's energy based on feedback. Self-monitoring skills include a) recognizing incomplete or inaccurate conclusions, b) locating the causes of errors, and c) anticipating future problems. Both the prediction and observation conditions provided opportunities for self-monitoring in that students could compare their observations or predictions to other information they had about thermodynamics. To encourage self-monitoring in version two, the teacher described his own self-monitoring activities. In version three he also encouraged students to engage in trial and refinement of ideas, and provided feedback on self-monitoring activities.

Prediction and Observation Conditions

To encourage trial and refinement, both the prediction and the observation approaches can take advantage of real-time data collection because students receive valid feedback on their investigations. The graphs of the experimental data that students print out are almost always valid. As a result, it is appropriate to reconcile predictions with outcomes and revise ideas. In contrast, when students write down measurements and then construct graphs, often the data lack validity. Furthermore, with real-time data collection, observations linking experimental events to changes on the graph are possible. Students can observe water boil and immediately note that the graph levels off.

Both prediction and observation can also encourage self-monitoring. For prediction, self-monitoring results from encouraging students to explain discrepancies between predictions and outcomes, requiring pairs of students to reconcile their ideas. For observation, self-monitoring results from encouraging students to explain the relationship between changes in the experiment and changes in the graph.

Representation of Heat and Temperature

As mentioned above, in version three we modified the representation of heat and temperature we offered students by increasing emphasis on the qualitative relationships between the variables and dropping the emphasis on the quantitative relationships. Results for version two suggested that quantitative relationships were not integrated with qualitative relationships and that the quantitative relationships we offered were selected over the more powerful qualitative representations.

Gildea, Miller, and Wurtenberg (1988) report similar results from their attempt to provide multiple dictionary definitions. Rather than integrating the various definitions offered, students tend to select a single definition. Furthermore, rather than selecting the most useful definition, students tend to select whatever they perceive as the easiest definition. They tend to ignore definitions that place the word in the context of a sentence and instead select prototypic dictionary definitions.

Method

Design. In version three of the CLP curriculum, we instituted two conditions: the **observation condition**, where students carefully observed what happened in their experiments; and the **prediction condition**, which required students to predict outcomes based on previous results and reconcile their predictions with the results they observed. Because both of these conditions seemed promising, we randomly assigned the four classes to either the prediction condition or the observation condition. Recall that classes rotate so students do not always have science at the same time of day, making this random assignment independent of time of day.

Activities. We designed new versions of each activity to emphasize either prediction or observation. Examples appear in Table 5.

As shown in Table 1, to increase emphasis on qualitative relationships, we included the surface area variable. We also increased emphasis on state changes and on more complicated situations, such as rate of cooling when a substance to be cooled was modified at several different points during the experiment.

Assessment. To assess the effectiveness of the observation and prediction conditions, we added an activity called the swimming pool problem. In this problem, students were required for the first time to design and conduct their own experiment prior to describing their results. As a design and implementation activity, the swimming pool problem was a good assessment of students' integration of knowledge and their ability to apply general problem solving skills such as controlling variables. The activity is shown in Figure 8.

Scoring. As with the previous domain knowledge variables, starting temperature and its influence on heating and cooling was scored as pass or fail.

Administration and scoring of the swimming pool problem is described in Friedler, Nachmias, & Linn (in press).

Results and Discussion

In assessing version three of the CLP curriculum, we continued to find that domain knowledge was acquired, we were again able to effectively implement our plans, and we discovered that our efforts to incorporate principles of research into classroom instruction finally paid off in imparting increased integration of understanding.

Domain Knowledge. In the third version of the curriculum, students again demonstrated understanding of the role of variables encountered in their experiments. As shown in Figure 4, students could effectively distinguish the role of insulation, starting temperature, mass, and surface area. Analysis of performance on the swimming pool problem revealed that students were quite proficient at controlling these variables when designing experiments to test the energy efficiency of various swimming pool designs (see Friedler, Nachmias, & Linn, in press).

Implementation. The observation and prediction conditions were implemented effectively. On the swimming pool problem, students in the observation condition made considerably more observations during their experiments, while students in the prediction condition made more accurate predictions of the outcomes of the experiment (Friedler, Nachmias, & Linn, in press).

Student acquisition of prediction skill is apparent in Figure 7. Students initially had difficulty predicting results for heating or cooling experiments. In the case of heating, encountered first in the curriculum, predictions became quite successful after a few trials. Although this skill was not immediately generalized to cooling experiments, there were savings. Experience with heating shortened the time required to make accurate predictions for cooling. As can be seen, after two experiments almost all the subjects learned to make accurate predictions for cooling. This lack of immediate transfer illustrates the difficulty in generalizing these complex ideas to new situations.

Integrating understanding. Both prediction and observation significantly influenced ability to integrate understanding of heat energy and temperature (semester 1 versus 3, F(1, 213)=3.0, p≤.0002), resulting in a two-fold increase in students who were able to meet the strong heat energy and temperature distinction criteria (see Figure 6). Furthermore, the prediction condition was significantly more effective than the observation condition in achieving integration of understanding ($F(1, 101)=6.2$, $p<.01$). Analysis of specific responses revealed several trends. First, students did not refer to calories and degrees centigrade because quantitative models were not introduced. Second, students in the observation condition were more likely to give explanations that emphasized descriptive aspects of their experiments such as, "They are the same because heat energy is if it's hot or cold and temperature is just leveling out for you," while students in the prediction condition were more likely to give integrated explanations such as, "A piece of pizza might have the same temperature as a whole pizza, but not as much heat energy, because a whole pizza is bigger and has much more mass and heat energy." Third, most of the students (95%) had some idea about the distinction between heat energy and temperature, compared to 87% for version 2.

As can be seen in Figure 6, both prediction and observation increased student ability to meet the strong criterion for distinguishing heat energy and temperature. Looking at the weak criteria, we see that only prediction increased student ability to meet the "good" criteria. Thus, observation was most helpful for students who had attained quite sophisticated understanding, but it did not help the others. It appears that observation helps those who know what to look for but does not help others. It may be that students can integrate the information from observations only when they have a structure to guide their activities.

Thus, both prediction and observation enhanced students' ability to distinguish heat energy and temperature and therefore their ability to build a robust understanding of thermodynamics. If observation and prediction are effective separately, would students learn more about heat energy and temperature with both?

The Computer as Lab Partner: Version Four

To encourage integration of understanding as well as self-monitoring, we combined observation and prediction in version four of the Computer as Lab Partner curriculum. If both observation and prediction encourage active learning and self-monitoring when used separately, together they might have a greater impact. Alternatively, would employing both observation and prediction overload students and distract them from learning the material? Version four of the curriculum investigates this question.

In addition, a common concern is how easily other instructors can use new curricula. Conveniently, for version four, a student teacher took over two of the four classes, allowing us to determine whether the CLP curriculum could be used by other instructors.

Method

Activities. Version four of the curriculum was identical to version three of the curriculum, except that each activity was rewritten to include both observation and prediction. Naturally, by including both components, it was necessary to shorten the time spent on each.

Assessment. Evaluation instruments used for version four were the same as those used for version three. In addition, since the curriculum now helped over half the students to distinguish heat energy from temperature, we assessed the transfer of this understanding to naturally-occurring problems. We measured spontaneous transfer to these problems since no explicit instruction was devoted to naturally-occurring problems. To measure transfer, a survey of students' ability to interpret naturally-occurring problems was added to the evaluation battery.

Scoring. The naturally-occurring problems were scored pass or fail.

Results

In assessing version four of the CLP curriculum, we again found that students had mastered the domain knowledge, we assessed whether the student teacher was as effective as the regular teacher, and we found that integrated understanding was sustained when both observation and prediction were combined.

Domain Knowledge. As was the case for earlier versions of the curriculum, students accurately explained how each variable influenced heating and cooling (Figure [illegible]). In addition, students could give convincing examples to illustrate their views about heat energy and temperature (see Table 4).

On the swimming pool problem, performance of students in version four paralleled that of students in version three. However, classes performed equally on observation and prediction since all students learned both techniques.

Effect of Teacher. Outcomes for classes taught by the regular teacher did not differ from those taught by the student teacher. This evidence indicates that the curriculum can generalize to different instructors.

Integrated understanding. The combination of observation and prediction increased students' ability to distinguish heat energy from temperature (semester 2 versus 4 F(1, 22[illegible])=2.65, p≤.0002). As shown in Figure 5, students in version four were significantly more successful at distinguishing heat energy and temperatu..e than those in the observation condition, but not more successful than those in the prediction condition from version three. Analysis of student responses to the question about distinguishing heat energy and temperature revealed that students had reasonably integrated understanding of the concepts.

Two trends are notable. First, numerous students were beguiled by an erroneous idea that emerged from the discussion of a textbook definition for the distinction between heat energy and temperature. Overall, 19.4% of the students responded, "Heat is all kinetic energy, temperature is the average." Again, students acted as cognitive economists, preferring a simple, available explanation that they did not completely understand. Second, very few students (11.2%) were completely wrong in their response to the question about heat energy and temperature -- fewer than had been wrong in the past.

Overall, there was a fourfold increase in deep understanding of heat energy and temperature and a t· .old increase in adequate understanding of the instruction. Clearly, curriculum reformulation can substantially improve learning even when the current constraints of instruction such as the 30-student class and 55-minute class period are sustained.

Naturally-occurring problems. Assessment of students' ability to transfer their understanding of heat energy and temperature to naturally-occurring problems paralleled results for other transfer studies and are discussed in detail elsewhere (Songer & Linn, 1988a). Essentially, ability to apply concepts of heat ·· ergy and temperature to classroom experiments does not help students apply this knowledge to naturally-occurring problems. Students perceive naturally-occurring problems involving heat energy and temperature as being distinct from those studied in class and therefore do not apply the concepts learned in class to the naturally-occurring problems.

Discussion

By reformulating the CLP curricula, we were able to effectively incorpo te principles from research on learning and instruction and to document how these work in a realistic setting for a large population of students. The observation and prediction conditions were used to implement research demonstrating that learners actively construct an understanding of the material world. The choice of a heat flow representation reflected research on mental models. On ba'· ce, these principles were not sufficient to impart integrated understanding to all students and did not result in generalization of understanding to naturally-occurring problems.

Active Learner. How did the observation condition implemented in versions three and four of the curriculum take advantage of the active nature of the learner and help students acquire deep understanding of the distinction between heat energy and temperature? First, by acquiring detailed evidence about each experiment, students gained a more concrete understanding of heat and temperature. For example, by observing change in temperature from room temperature up to boiling point and noting that, at the boiling point, the temperature does not change, students develop a continuous representation of heat change. We hypothesize that students are less likely to represent a variable continuously when they set up the experiment and then look at the graph. Rather, they may focus primarily on the endpoints of the experiment.

How did the prediction condition take advantage of the active nature of the learner and influence students' ability to integrate their understanding? Skill in prediction involves using domain-specific knowledge. When first encountering a new variable, students are unlikely to make effective predictions. However, when required to use feedback from experiments, students make reasonable predictions and determine a practical application for the knowledge. Self-monitoring was certainly enhanced by requiring students to reconcile their predictions with the results of their experiments. Students' comments, when writing explanations for the differences between their predictions and their results, clearly indicated that they were reflecting on their own thought processes.

Should observation and prediction be combined? Both observation and prediction take advantage of the active nature of the learner by encouraging integration of feedback and self-monitoring. Taken together, results for versions three and four of the CLP curriculum suggest that combining observation and prediction results in the most robust understanding of heat energy and temperature. Although combining observation and prediction in version four was not significantly better than prediction alone in version three for improving performance on the distinction between heat energy and temperature, students had more integrated ideas as a result of experiencing both conditions. In particular, students in the observation condition pay attention to details of the experiments that may consolidate their understanding. For example, students who carefully observe boiling note when bubbles appear and relate this phenomenon to temperature change and state change.

Mental models. While researchers agree that students need powerful representations of scientific phenomena, ideal models have not been identified. Our investigations revealed that students readily accept superficial models and resist efforts to encourage deep understanding.

Thus students were satisfied with (a) computation of changes in calories or degrees centigrade, (b) understanding the variables influencing heating and cooling separately or (c) a scientific-sounding explanation they could not comprehend. One solution to keep students from adopting these incomplete explanations was not to offer them. Ultimately, however, effective self-monitoring skills should help students recognize when their explanations are incomplete or superficial. This is a goal for subsequent reformulation of the curriculum. Curriculum developers should be prepared for students seeking simple answers, and ensure that instruction encourages deep understanding.

Robust understanding. In spite of the dramatic gains in student success from versions three and four of the CLP curriculum, many students still failed to gain deep understanding of heat energy and temperature.

Nevertheless, they learned a great deal compared to others. First, although some students had serious gaps in their knowledge of thermodynamics, they have learned as much or more than young adults typically learn. Songer & Linn (1988b) show that they always perform better than 17-year-olds in a national sample NAEP (1979). Second, almost all students have some understanding of the distinction between heat energy and temperature after instruction. Third, students have acquired understanding of the variables influencing rate of heating and cooling (Figure 4).

In spite of these gains, few students achieved the robust understanding experts have of thermodynamics. Most students did not generalize their understanding of heat energy and temperature to naturally-occurring problems. Rather, they maintained that naturally-occurring problems were governed by different principles such as those in Table 2. To achieve change, students need (a) an alternative view and (b) reason to replace their current perspective. Only by the third version of the curriculum had many students acquired an alternative. In general, the models that students developed differed from those of experts in that they were less integrated and could not be applied to naturally-occurring problems. Furthermore, the curriculum did not emphasize thermoconductivity or specific heat, two concepts prominent in naturally-occurring problems. In the future, we hope to motivate change by making naturally-occurring problems more accessible to experimentation and to impart more robust, integrated models of thermodynamics.

Conclusions

In conclusion, reformulation of the CLP curriculum, in light of research on learning and instruction, succeeded on a broad range of goals. It helped students a) gain robust understanding of graph interpretation--a skill required in many standardized tests, b) evaluate computer-presented data, c) understand experimentation and d) distinguish heat energy and temperature. For distinguishing heat energy and temperature, performance doubled on the weak criteria, and increased fourfold on the strong criteria as the result of reformulations of the curriculum. These investigations demonstrate that by changing the intellectual demands on the students, but not the experiments or the software, substantial improvement in student understanding can result. They provide support for using the principles of learning and instruction to guide curriculum design. They demonstrate a) the advantages of spending increased instructional time on one topic, b) the possibility of generalizing these results to other teachers and classes and c) the advantages of using research to improve practice in realistic settings, as well as some shortcomings and limitations of current research on instruction.

Instructional Time

The CLP curriculum demonstrated cognitive, motivational, and practical advantages of spending increased instructional time on a few science topics. First, the cognitive advantages included a) middle school students achieving understanding of heat energy and temperature and important scientific concepts at levels comparable to those of young adults, and b) almost universal understanding of an important scientific technique, the graphing of experimental results. In contrast, recent national reports indicate that the vast majority of middle school students gain virtually no knowledge of scientific concepts and principles from middle school courses. Second, deep coverage of scientific topics has the added benefit that students are highly engaged in their scientific experiments and have a remarkable level of task-oriented behavior. As might be expected, formal comments by students were overwhelmingly favorable. One student even commented that she hated the weekend because she couldn't work with the computer in science class. The vast majority of students indicated that science was their favorite subject while the Computer as Lab Partner curriculum was offered.

Third, the increased instructional time spent on thermodynamics in the CLP curriculum had the practical advantage of providing learning likely to contribute to good standardized test performance. Clearly, improved understanding of graphing will help students on a broad range of standardized test items. In addition, evaluations of the hands-on curricula developed in the 1960's that also featured deeper coverage of a smaller number of topics revealed that these curricula prepared students for standardized tests at least as well as more traditional approaches (Shymansky, Kyle, & Alport, 1982), no doubt, in part, because students gained integrated understanding of some aspects of science.

These practical advantages of spending considerable instructional time on a few scientific topics contradict the many state guidelines listing numerous topics, the textbook emphasis on numerous topics (thermodynamics is typically covered in one week), and the ostensible focus on many topics of state testing programs. Yet, we argue that the recommendation to cover a wide range of topics is in conflict with the goals of instilling coherent understanding of scientific phenomena and encourages students to believe that science consists of a collection of unrelated facts.

Generalizing to other classes

These investigations provide evidence for the possibility of generalizing this curriculum to different populations. When the student teacher was fully responsible for two of the four classes, the curriculum was just as effective as when the master teacher presented it. Yet, few training programs are as intensive as student teaching. Our observations suggest that the intricacies of real-time data collection are easiest for teachers familiar with hands-on learning and that the process of modeling self-monitoring strategies required both domain knowledge and considerable trial and refinement in the classroom. To encourage this approach, the teacher has provided workshops for over a thousand teachers. Response to his techniques has been overwhelmingly favorable.

Curriculum Reformulation

Our investigations demonstrated that curriculum reformulation, guided by principles from learning and instruction, is reasonable and effective for improving instruction in realistic settings. Investigations conducted in realistic settings have constraints but also offer opportunities. For example, the 55-minute class period required the developers to abandon some plans but the use of real-time data collection made the class period more efficient. A similar approach has been used successfully by others developing curriculum materials. Brown's (Brown & Palinscar, 1987) reading comprehension instruction was developed through numerous reformulations of the reciprocal teaching technique. Anderson's tutoring programs for LISP, Algebra, and Geometry were initially devised to reflect the ACT* theory but have undergone transformations following realistic trials in classrooms. Earlier work in science education and reading reveals benefits of curriculum reformulation in many domains (see Karplus, 1975; Tharp, et al., 1984). This paper illustrates the promise and limitations of using principles of learning and instruction for curriculum reformulation.

Promise of Principles of Learning and Instruction

Fundamentally, the continuous improvement in learning outcomes as the result of curriculum reformulation suggests that the educational principles governing refinement have value. These principles are sufficient to establish a progressing research program in the terms of Lakatos (1972). Furthermore, as discussed above, they suggest directions for continued refinement.

Two principles led to a two- to four-fold gain (depending on the criteria employed) in ability to distinguish heat energy and temperature. The first was to channel the active, constructing nature of the learner to integrate information from a series of experiments. The second was to model and encourage self-monitoring skills. The development team translated these principles into an emphasis on predicting results and observing outcomes during experimentation. Essentially these are the activities performed by expert scientists when they conduct experiments. However, guidance from the principles of research helped the developers select, from among the many behaviors of experts, those likely to help students integrate their experiences. In addition, the principles of research emphasized the mode of instructional delivery. Both of these principles made it clear that students must be guided to actively analyze their experiences rather than be told what the experiences mean. These principles suggest that students should not read about the distinction between heat energy and temperature, but rather figure out this distinction by combining information from a series of experiments, and by analyzing and refining their own ideas.

Limitations of Principles of Learning and Instruction

Efforts at curriculum reformulation also revealed some shortcomings of instructional research and suggested some directions for refinement of principles. Although many believe that students benefit from multiple representations of the same phenomena, and we argued that real-time data collection may help students because it provides another representation of the same phenomena, our experience suggests that this principle requires refinement. We initially provided multiple representations of the distinction between heat energy and temperature. We found that rather than integrating these separate representations, students chose the one they found easiest to learn. Many students focused on what could be called the "measurement distinction" and concluded that heat was calories and temperature was degrees centigrade. When we omitted this option, more students acquired sophisticated explanations.

Several conjectures for research are suggested by this finding. One hypothesis is that the multiple representations needed integration and that students would benefit from several explanations for the distinction, including the measurement distinction, if they were required to map one explanation on to the other. This is the hypothesis White and Frederickson (1987) represented in their progressions of mental models. However, as yet no evidence exists for procedures that succeed in achieving integration.

Another conjecture is that some explanations form poor mental models. This view says that the measurement distinction is incomplete (and does throw a veil of numbers over the important information) because it does not explain the phenomenon under investigation. This is the point of work comparing mental models (Collins & Gentner, 1983). This conjecture is also consistent with the effectiveness of the dynamic representation communicated by real-time data collection. In summary, our efforts at curriculum refinement revealed that multiple representations do not always advance learning.

Another educational principle that requires refinement concerns the role of domain knowledge in reasoning. Researchers have argued that reasoning has important domain-specific components that must be addressed in instruction. Our investigations suggest that domain knowledge is far from sufficient for learning about complex concepts like heat energy and temperature. Students readily mastered the role of variables such as surface area, insulation, starting temperature, and mass in heating and cooling but did not improve in ability to distinguish between heat energy and temperature. Students acquired understanding of these variables much as they acquire isolated information from textbooks and failed to apply it to more complex problems. The skills students use to learn about the variables are not sufficient for understanding the distinction between heat energy and temperature. This distinction was only acquired when students were required to combine the isolated experiments that yielded information about each of the variables in the domain.

It appears that students interpret science incorrectly when lots of domain knowledge is present, and assume that science consists of memorizing this information instead of understanding the principles that lead to the information. This conjecture is consistent with research showing that students learn the formulas for elementary mechanics rather than learning the principles that govern the formulas (Larkin, et al., 1980) and that students learn the syntax of programming rather than design skills (Linn, 1985). This hypothesis raises several research questions. First, to encourage understanding, instruction could emphasize self-monitoring skills and explicitly show that the domain knowledge is not sufficient for understanding. Alternatively, instruction could expand the notion of domain knowledge and teach much more complex templates or procedures for solving problems. Ultimately the nature and boundaries of domain knowledge become issues.

A final limitation of principles of learning and instruction for curriculum refinement concerns precision. Current principles are not sufficiently developed to provide answers to questions concerning choice of topic, duration of instruction, classroom organization, etc. Furthermore the field itself suffers from domain specificity. Commonly, principles concerned with classroom management are unintegrated with principles of learning. Presumably, efforts at curriculum refinement will help to resolve some of these questions and integrate some domains of knowledge.

Considering that understanding of principles of instruction is just emerging, it is encouraging that some insights from research can be used to guide curriculum design. A closer coupling between research on instruction and experience in realistic settings offers promise. The Centers for Collaboration on Science Education proposed by many recent national groups (e.g., Linn, 1987; Pea and Soloway, 1987) would foster effective curriculum reformulation projects by bringing together all those concerned about effective instruction.

Overall, the investigations reported here look broadly at instruction, and the resulting recommendations are reasonably general. There remain multiple explanations for the outcomes because the teaching situation is complex. However, use of curriculum reformulation suggests mechanisms that govern learning, and offers possibilities for replication and extension. Combined with similar efforts, these investigations promise a systematic understanding of learning in realistic settings.

Bibliography

Albert, E. (1978). Development of the concept of heat in children. *Science Education, 62*, 389-399.

Anderson, J. R. (1983). *The architecture of cognition.* Cambridge, MA: Harvard University Press.

Bereiter, C. & Scardamalia, M. (1986). *The psychology of written composition.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Brasell, H. (1987). The effect of real-time laboratory graphing on learning graphic representations of distance and velocity. *Journal of Research in Science Teaching, 24*(4), 385-95.

Brook, A., Briggs, H., Bell, B., & Driver, R. (1984). *Aspects of secondary students' understanding of heat: Full report.* England: The University of Leeds, Centre for Studies in Science and Mathematics Education, Children's Learning in Science Project.

Brown, A. L. & Kane, M. J. (in press). *Preschool children can learn to transfer: Learning to learn and learning from example.* Urbana-Champaign: University of Illinois, Center for the Study of Reading.

Brown, A. L., Kane, M. J., & Echols, K. (1986). Young children's mental models determine analogical transfer across problems with a common goal structure. *Cognitive Development, 1*(2), 103-22.

Brown, A. L. & Palincsar, A. S. (1987). Reciprocal teaching of comprehension strategies: A natural history of one program for enhancing learning. In J. G. Borkowski & J. D. Day (Eds.), *Cognition in special children: Comparative approaches to retardation, learning disabilities, and giftedness.* Norwood, NJ: Ablex Publishing.

Burbules N. C. & Linn, M. C. (1988). Response to contradiction: Scientific reasoning during adolescence. *Journal of Educational Psychology, 80*(1), 67-75.

Carey, S. (1985). *Conceptual change in childhood.* Cambridge, MA: Harvard University Press.

Champagne, A. B., Klopfer, L. E., & Gunstone, R. F. (1982). Cognitive research and the design of science instruction. *Educational Psychologist, 17*(1), 31-53.

Cronbach, L. J. (1963). Evaluating course outcomes. *Teacher's College Record, 64*, 672-83.

di Sessa, A. (in press). Knowledge in pieces. In G. Forman & P. Pufall (Eds.), *Constructivism in the computer age.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Driver, R. (1983). *The pupil as scientist?* England: Open University Press.

Erickson, G. L. (1979). Children's conceptions of heat and temperature. *Science Education, 63*(2), 221-30.

Erickson, G. L. (1980). Children's viewpoints of heat: A second look. *Science Education, 64*, 323-36.

Eylon, B. & Linn, M. C. (in press). Learning and instruction: An examination of four research perspectives in science education. *Review of Educational Research.*

Friedler, Y., Nachmias, R., & Linn, M. C. (in press). Using microcomputer-based laboratories to foster scientific reasoning skills. *Journal of Research in Science Teaching.*

Gagne, R. (1968). *Instructional variables and learning outcomes.* Los Angeles: University of California Press.

Gildea, P. M., Miller, G. A., & Wurtenberg, C. L. (1988). *Contextual enrichment by videodisc: A first report* (CSL report no. 12). Princeton: Princeton University, Cognitive Science Laboratory.

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

Greeno, J. G. (1986). Advancing cognitive science through development of advanced instructional systems. *Machine Mediated Learning, 1*(4), 327-43.

Greeno, J. G. & Simon, H. A. (1984). Problem solving and reasoning. In R. C. Atkinson, R. Herrnstein, G. Lindzey, & R. D. Luce (Eds.), *Steven's handbook of experimental psychology* (Revised ed.). New York: John Wiley & Sons.

Guesne, E., Tiberghien, A., & Delacote, G. (1978). Methods et resultats concernant l'analyse des conceptions des eleves dans differents domains de la physique. Deux exemples: Les notions de chaleur et lumiere. *Revue Française de Pedagogie, 45,* 25-36.

Hewson, M. G. & Hamlyn, D. (1983). The representation and analysis of conceptions of heat. Research on physics education. In *Proceedings of the First International Workshop* (pp. 347-54). La Londe les Maures.

Human Resources Media. (1987). *Heat and temperature* [Computer program]. Pleasantville, NY: Author.

Inhelder, B. & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence.* New York: Basic Books.

Johnstone, A. H., McDonald, J. J., & Webb, G. (1977). Misconceptions in school thermodynamics. *Physics Education, 12*(4), 248-51.

Karplus, R. (1975). Strategies in curriculum development: The SCIS Project. In J. Schaffarzick & D. H. Hampson (Eds.), *Strategies for curriculum development.* Berkeley, CA: McCutchan Publishing Corp.

Kuhn, D. (1963). *The structure of scientific revolutions.* Chicago, IL: University of Chicago Press.

Lakatos, I. (1972). Falsification and the methodology of scientific research programs. In I. Lakatos & A. Musgrave (Eds.), *Criticism and the growth of knowledge.* Cambridge, England: Cambridge University Press.

Lakatos, I. (1976). *Proofs and refutations: The logic of mathematical discovery.* Cambridge, England: Cambridge University Press.

Lambiotte, J. G., Dansereau, D. F., O'Donnell, A. M., Young, M. D., Skaggs, L. P., Hall, R. H., & Rocklin, T. R. (1987). Manipulating cooperative scripts for teaching and learning. *Journal of Educational Psychology, 79*(4), 424-30.

Larkin, J., McDermott, J., Simon, D. P., & Simon, H. A. (1980). Expert and novice performance in solving physics problems. *Science, 208*(20), 1335-42.

Lepper, M. R. (1985). Microcomputers in education: Motivational and social issues. *American Psychologist, 40*, 1-18.

Lewis, E. (1987). *A study of knowledge elements present in the heat and temperature concepts of adolescents and naïve adults*. University of California, Berkeley; Computer as Lab Partner Project.

Linn, M. C. (1980). Teaching children to control variables: Some investigations using free choice experiences. In S. Modgil & C. Modgil (Ed.), *Toward a theory of psychological development within the Piagetian framework*. Windsor, England: National Foundation for Educational Research Publishing Co.

Linn, M. C. (1985). The cognitive consequences of programming instruction in classrooms. *Educational Researcher, 14*(5), 14-29.

Linn, M. C. (1986). Science. In R. Dillon & R. J. Sternberg (Eds.), *Cognition and instruction* (pp. 155-204). New York: Academic Press.

Linn, M. C. (1987a). Establishing a research base for science education: Challenges, trends, and recommendations. *Journal of Research in Science Teaching, 24*(5), 191-216.

Linn, M. C. (1987b). *Education and the challenge of technology*. Cupertino, CA: Apple Computer, Inc.

Linn, M. C. (April, 1988). *Technology and science instruction* [Proceedings of a conference on Technology and Teacher Education]. Cupertino, CA: Apple Computer, Inc.

Linn, M. C., Layman, J., & Nachmias, R. (1987). The cognitive consequences of microcomputer-based laboratories: Graphing skills development. *Journal of Contemporary Educational Psychology, 12*(3), 244-253.

Linn, M. C. & Siegel, H. (1984). Postformal reasoning: A philosophical model. In M. Commons, F. A. Richards, & C. Armon (Eds.), *Beyond formal operations: Late adolescent and adult cognitive development* (pp. 239-257). New York: Praeger Publishers.

Linn, M. C. & Swiney, Jr., J. (1981). Individual differences in formal thought: Role of expectations and aptitudes. *Journal of Educational Psychology, 73*(2), 274-286.

Miller, G. (March, 1984). *Natural language access to intelligent systems*. Princeton, NJ: Princeton University.

Mokros, J. R., & Tinker, R. F. (1987). The impact of microcomputer-based labs on children's ability to interpret graphs. *Journal of Research in Science Teaching, 24*(5), 369-383.

Nachmias, R. & Linn, M. C. (1987). Evaluations of science laboratory data: The role of computer-presented information. *Journal of Research in Science Teaching, 24*(5), 491-506.

National Assessment of Educational Progress (NAEP). (1979a). *Attitudes toward science: A summary of results from the 1976-77 national assessment of science* (Report No. 08-S-02). Denver: Education Commission of the States.

O'Donnell, A. M., Dansereau, D. F., Hall, R. H., & Rocklin, T. R. (1987). Cognitive, social/affective, and metacognitive outcomes of scripted cooperative learning. *Journal of Educational Psychology, 79*(4), 431-437.

Palincsar, A. S. & Brown, A. C. (1984). Reciprocal teaching of comprehension-fostering and comprehension-monitoring activities. *Cognition and Instruction, 1*, 117-175.

Pea, R. D. & Soloway, E. (1988). *The state of the art in educational technology R & D: Issues and opportunities*. Report to the Office of Technology Assessment, Washington, D. C.

Reif, F. (1987). Instructional design, cognition, and technology: Applications to the teaching of scientific concepts. *Journal of Research in Science Teaching, 24*(4), 309-324.

Resnick, L. B. (1983). Cognition and instruction: Issues and agendas. Hillsdale, NJ: Lawrence Erlbaum Associates.

Rogan, J. H. (1985). The development of a conceptual framework of heat. *Science Education, 10*.

Rouse, W. B. & Morris, N. M. (1985). *On looking in the black box: Prospects and limits in the search for mental models* (Center for Man-Machine Systems Research Report No. 85-2). Atlanta, GA: Georgia Institute of Technology.

Schoenfeld, A. H. (1985). *Mathematical problem solving*. Orlando, FL: Academic Press.

Shayer, M. & Wylam, H. (1981). The development of the concept of heat and temperature in 10 - 13-year-olds. *Journal of Research in Science Teaching, 18*(5), 419-434.

Shumway, S. & Elliot, L. (1987). *Science toolkit* [Computer program]. San Rafael, CA: Broderbund Software.

Shymansky, J. A., Kyle, W. C., & Alport, J. M. (1982). How effective were the hands-on computer programs of yesterday? *Science & Children, 20*(3), 14-15.

Songer, N. B. & Linn, M. C. (1988a). *Thermodynamics and everyday problem solving*. Berkeley: University of California, Computer as Lab Partner Project.

Songer, N. B. & Linn, M. C. (1988b). *Performance of 13-year-olds trained on thermodynamics in NAEP items*. Berkeley: University of California, Computer as Lab Partner Project.

Stavy, R. & Berkovitz, B. (1980). Cognitive conflict as a basis for teaching quantitative aspect of the concept of temperature. *Science Education, 64*(5), 679-692.

Stevens, A. L. & Gentner, D. (1983). Introduction. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 1-6). Hillsdale, NJ: Lawrence Erlbaum Associates.

Strike, K. A. & Posner, G. J. (April, 1983). *Understanding from a conceptual change point of view*. Paper presented at the annual meeting of the American Educational Research Association, Montreal, Canada.

Striley, J. (1988). *How students negotiate understanding: Characterizing the problem-solving processes of dyads during microcomputer-based science labs*. Unpublished dissertation, University of California, Berkeley.

Summers, M. K. (1983). Teaching heat -- An analysis of misconceptions. *School Science Review, 64*(229), 670-676.

Tharp, R. G., Jordan, C., Speidel, G. E., Au, K. H., Klein, T. W., Calkins, R. P., Sloat, K. C. M., & Gallimore, R. (1984). *Product and process in applied developmental research: Education and the children of a minority*. Honolulu, HI: The Kamehameha Schools.

Tiberghien, A. (1980). Modes and conditions of learning. An example: The learning of some aspects of the concepts of heat. In W. F. Archenhold, R. H. Driver, A. Orton, & C. Wood-Robinson (Eds.), *Cognitive development research in science and mathematics* (pp. 288-309). Leeds, UK: University of Leeds Printing Service.

Tiberghien, A. (1983). Critical review on the research aimed at elucidating the sense that notions of temperature and heat have for the students aged 10 to 16 years. Research on Physics Education. In *Proceedings of the First International Workshop* (pp. 75-90). La Londe les Maures.

Tinker, R. (1988). *Heat and temperature probeware and software*. Queue, Bridgeport: CT.

Webb, N. & Lewis, S. (in press). The social context of learning in computer programming. In R. Mayer (Ed.), *Research on teaching and learning computer programming*. Hillsdale, NJ: Lawrence Erlbaum Associates.

West, L. H. T., Pines, A. L., & Sutton, C. R. (1984). In-depth investigations of learner's understandings of scientific concepts and theories. In A. L. Pines & L. H. T. West (Eds.), *Cognitive structure and conceptual change*. New York: Academic Press.

White, B. Y. & Frederiksen, J. R. (1987). Causal model progressions as a foundation for intelligent learning environments (Report No. 6686). Cambridge, MA: BBN Laboratories Incorporated.

Wiser, M. & Carey, S. (1983). When heat and temperature were one. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 267-298). Hillsdale, NJ: Lawrence Erlbaum Associates.

topic:	Semester 1 duration	Semester 2 duration	Semester 3 duration (Obs./Pred.)	Semester 4 duration (Obs.& Pred.)
temp. &cooling curves	2 weeks	1.5	1.5	1.5
& changes in volume	0.5	1	0.5	0.5
& changes in insulation	0.5	1	0.5	0.5
& changes in starting temperature	no	1	0.5	0.5
& changes in surface area	no	no	1	1
calibration	no	1	1	1
graph interpretation	1	1	1	1
total on temperature	4	6.5	6	6
heat energy/calories	4	5.5	4	4
energy efficiency	1	no	no	no
total on heat energy	5	5.5	4	4
boiling water/state changes	2	1.5	1	1
boiling point/evaporationof alcohol	no	no	1	1
rates of cooling (coffee&cream)	no	no	1	1
total on temperature& heat energy integration	2	1.5	3	3
total on temperature & heat energy	11	13.5	13	13

Table 1: Curriculum Over Four Semesters

TABLE 2
Naturally-Occurring Ideas About Thermodynamics

1. "Your cup of hot chocolate is larger, so yours has a higher temperature."
2. "You only have a temperature if you are sick."
3. "The ice cools the water."
4. "It's cooler in the shade."
5. "It's hot on the asphalt, so walk on the grass."
6. "Metal attracts coolness."
7. "Larger ice cubes are cooler than small ones."
8. "Wood absorbs heat. It's cool outside but warm inside."

TABLE 3 Alternative Representations of Heat Energy and Temperature Distinction

1. Measurement

Heat change is measured in calories, temperature change is measure in degrees centigrade or fahrenheit.

2. Variables

Heat and temperature changes are influenced by mass of substance, surface area of substance, presence of insulators around substance, and starting temperature of substance relative to surround.

3. Kinetic Theory

Heat is transferred by the collision of particles between substances in physical contact until equilibrium is achieved. The total heat energy present in an object is a function of the number of particles present in the object and the object's temperature. Temperature is a quantitative measure of the average energy of motion per particle within a substance.

4. Heat Flow

Heat is distributed in substances and flows from warmer to cooler substances until equilibrium is reached. Heat lacks mass. Temperature is a measure of the intensity at a given point.

TABLE 4: Sample Responses to the Heat Energy/Temperature Distinction Question, "In general, are Heat Energy and Temperature the same or different? What is the main reason for their similarity or difference?"

1. Very good distinction

"the amount of heat energy in something keeps it at a temperature. A larger object needs more heat energy to keep it at a certain temperature than a smaller object needs to keep it at the same temperature. A glass of water at 20°C has less heat energy than full bathtub at 20°C because it has less water."

"temperature defined as-a measure to see how hot or cold an object is. heat energy-amount of heat and energy an object has measured in calories. The more mass the more heat energy an object will have, even if the temp. of the object doesn't change. A piece of pizza might have the same temp. as a whole pizza, but not as much heat energy, because a whole pizza is bigger and has much more mass and heat energy.

2. Complete distinction

"The difference between heat and temperature is there can be more heat in a cup than in another but both are the same temperature. If there were two cups one with 100 ml and one with 20 ml they can both be still 50°C."

3. Some distinction

"Heat is an amount of energy expressed in calories. Temperature is the degree at which something is. For example, an ice cube may be 0°C but it still has and gives off heat energy."

4. Single Thermal distinction

"Temperature is the measure of heat energy"

"Heat is like a fire burning and temperature is to tell how hot the fire is."

5. Textbook definition/Terms only

"heat is the total kenetic energy in the area. Temp. is the average kenetic energy in the area."

"temperature is measured in °C heat energy is measured by calories."

6. Confused/Wrong/Incomplete

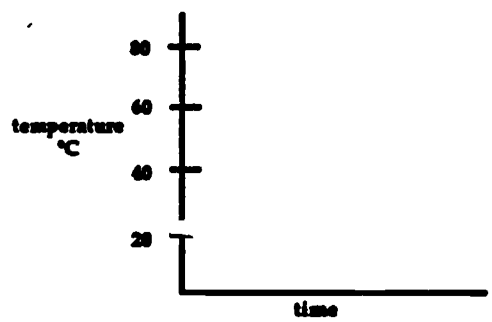
"The difference between heat and temperature is like a baby's bottle is hot with heat and when a baby is sick he has a temperature."

7. No response

TABLE 5
Sample Prediction and Observation Activity Questions

Sample Prediction Activity Questions: Cooling Water - First Experiment
In this experiment 200 ml of hot water will be allowed to cool to room temperature. The computer will record the temperature and will draw the graph. Before doing the experiment predict some of the experiment's outcomes. At the end of the experiment, you will be able to check whether your predictions were right.

Before doing the experiment give your predictions for:
The water temperature at the <u>beginning</u> of the experiment..........................
The water temperature at the <u>end</u> of the experiment.................................
The change in the volume of the water...
The length of time it will take the water to cool...
Predict what the graph will look like (draw your prediction below)



Now do the experiment
For your lab report please draw the graph from the data you have recorded on the graph paper and answer the questions on the other side of this page.

After doing the experiment write down which of your predictions you were right, and which were wrong. Try to explain why your predictions were wrong.
I was right about:
I was wrong about:
Why:
My conclusions about the shape of a cooling curve of water are:
(Include information about the initial temperature of the water, whether the graph went up or down and at what rate. When the change in temperature was rapid, when it was slow)

Sample Observation Activity Questions: Cooling Water - First Experiment
Cooling of Water
In this experiment 200 ml of hot water will be allowed to cool to room temperature. The computer will record the temperature and will draw the graph. While doing your experiment, observe carefully and report as many details as possible in your log. This log will be collected as your lab report.

Before heating the the water
Report all the details you observed concerning the experimental setup, such as: the volume of water, the description of the container etc. Describe also the conditions at the beginning of the experiments such as: air temperature, water temperature etc.
Draw: a sketch of your set up.

While heating the the water
Pay attention to the temperature change as well to any changes in the water condition (e.g. bubbles, change in the volume of the water)
Remember to report <u>what</u> happens and <u>when</u> it happens.
Pay attention and report about the changes in the water condition in relation to the changes of your graph on the computer screen.

After doing the experiment
a) Draw the final graph you have on your screen on the graph paper.
b) Describe how the temperature of the water changes. Start with reporting the initial temperature of the water, then describe whether the temperature went up or down and at what rate, when the change in temperature was rapid, when it was slow and when the temperature was constant. Report how long the experiment took and the temperature of the water at the end of the experiment.

In the next periods you will conduct experiments to investigate the following questions:
1. What is the effect of different volumes of water on it's cooling rate.
2. What is the effect of different insulators on waters' cooling rate.
In each one of these experiments write down a detailed log that will consist all the information mentioned above.

FIGURE 1 Example of a Screen Display from an Evaporation Experiment Conducted with Real-Time Data Collection

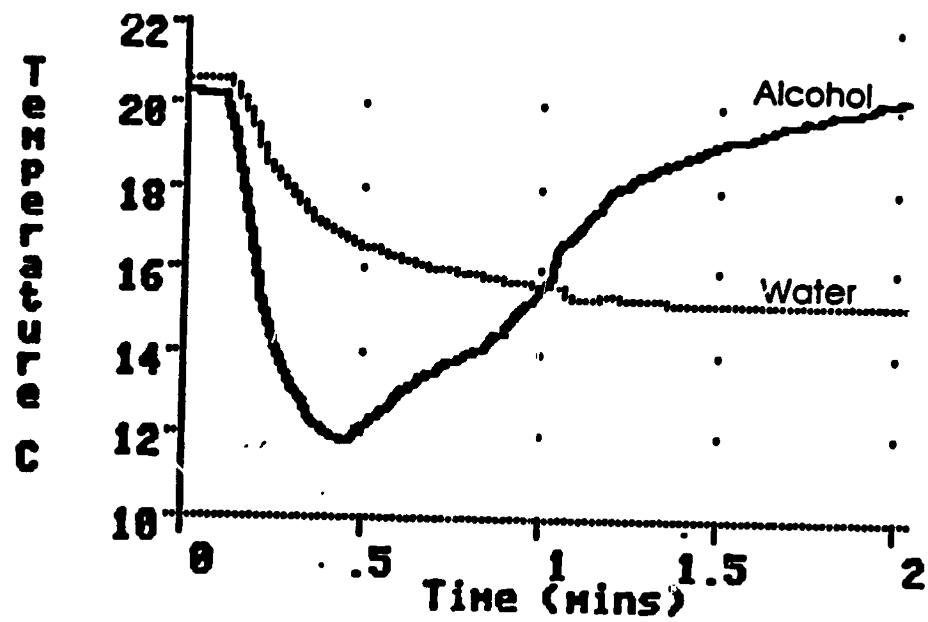


FIGURE 2 Sample Students' Responses to a Question About Heat Energy and Temperature

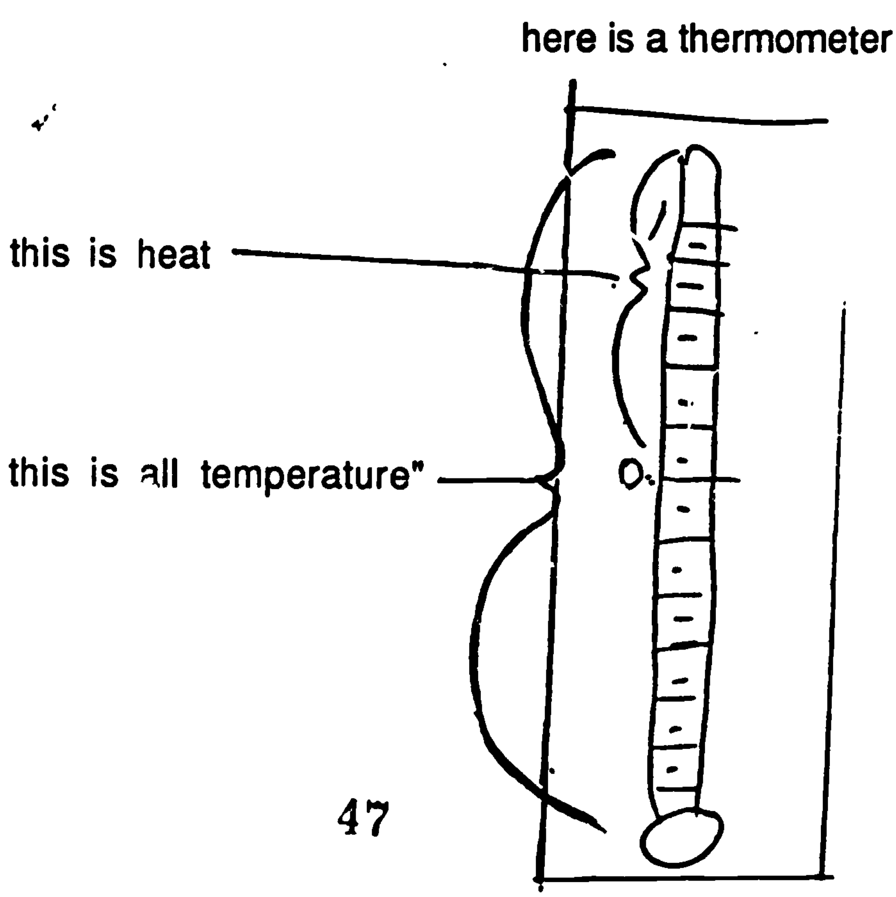
example 1

"The difference between heat and temperature is like a baby's bottle is hot with heat and when a baby is sick he has a temperature"

---

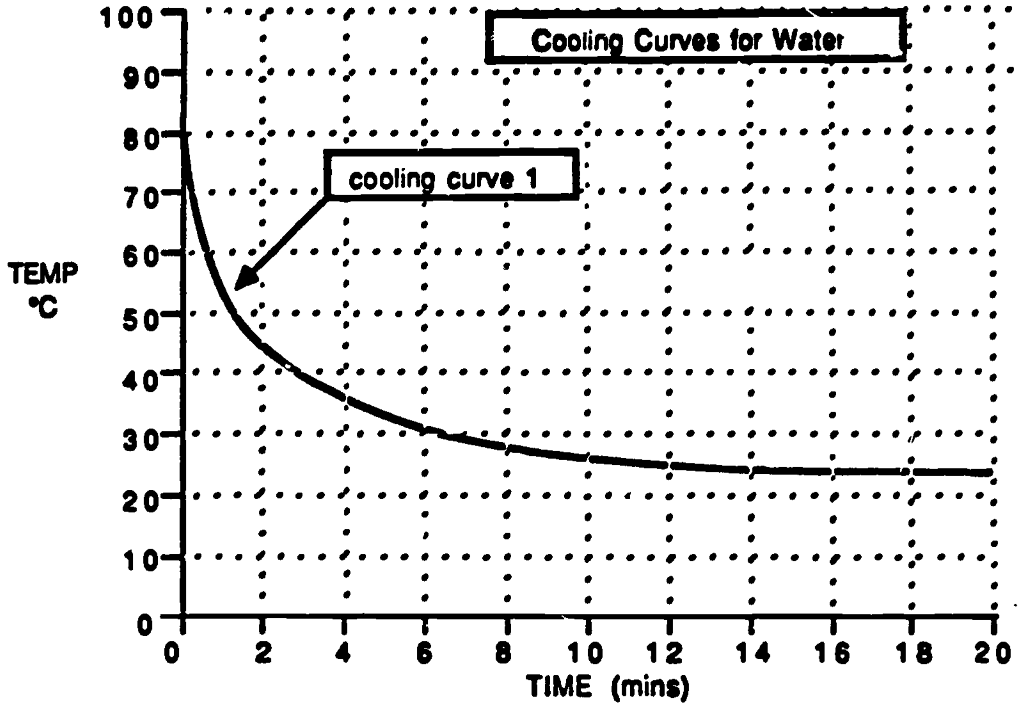
example 2

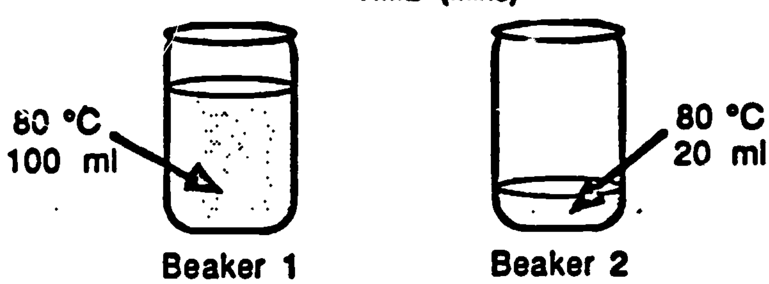
"Temperature registers everything but heat is the hot part. For example...



Domain Knowledge Question About Volume

1. This graph shows the change in temperature when 100 ml of 80 °C water in glass beaker 1 is allowed to cool in a 23 °C room. It is labeled "cooling curve 1".





a) On the same graph, show the change in temperature for 20 ml of 80°C water which cools in glass beaker 2 in the same room. Label it "cooling curve 2"

b) What is the main reason why "cooling curve 1" is different from (or the same as) "cooling curve 2"?

c) What experience have you had (either an experiment from class, or an instance from everyday life) that convinces you of your answer?

Heat Energy and Temperature Assessment Question

1. a) In general, are heat energy and temperature the same or different?

(circle one) same different

b) What is the main reason for their similarity or difference?

c) Give an example that explains your answer.

Figure 3: Sample Questions

FIGURE 4 Students' Understanding of Four Variables Associated with Classroom Experiments

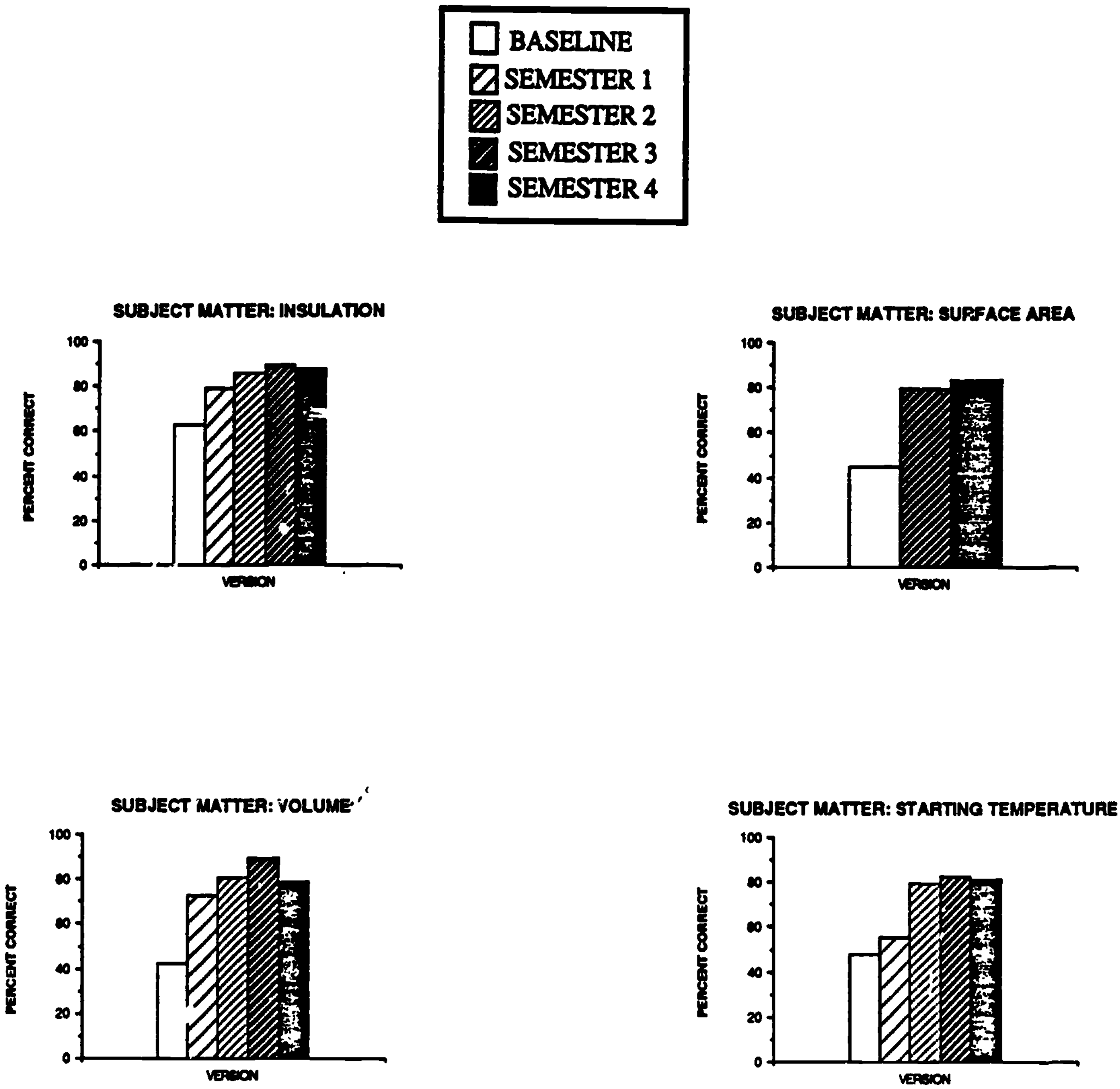


FIGURE 5: Weak Criteria for Heat Energy/Temperature Distinction

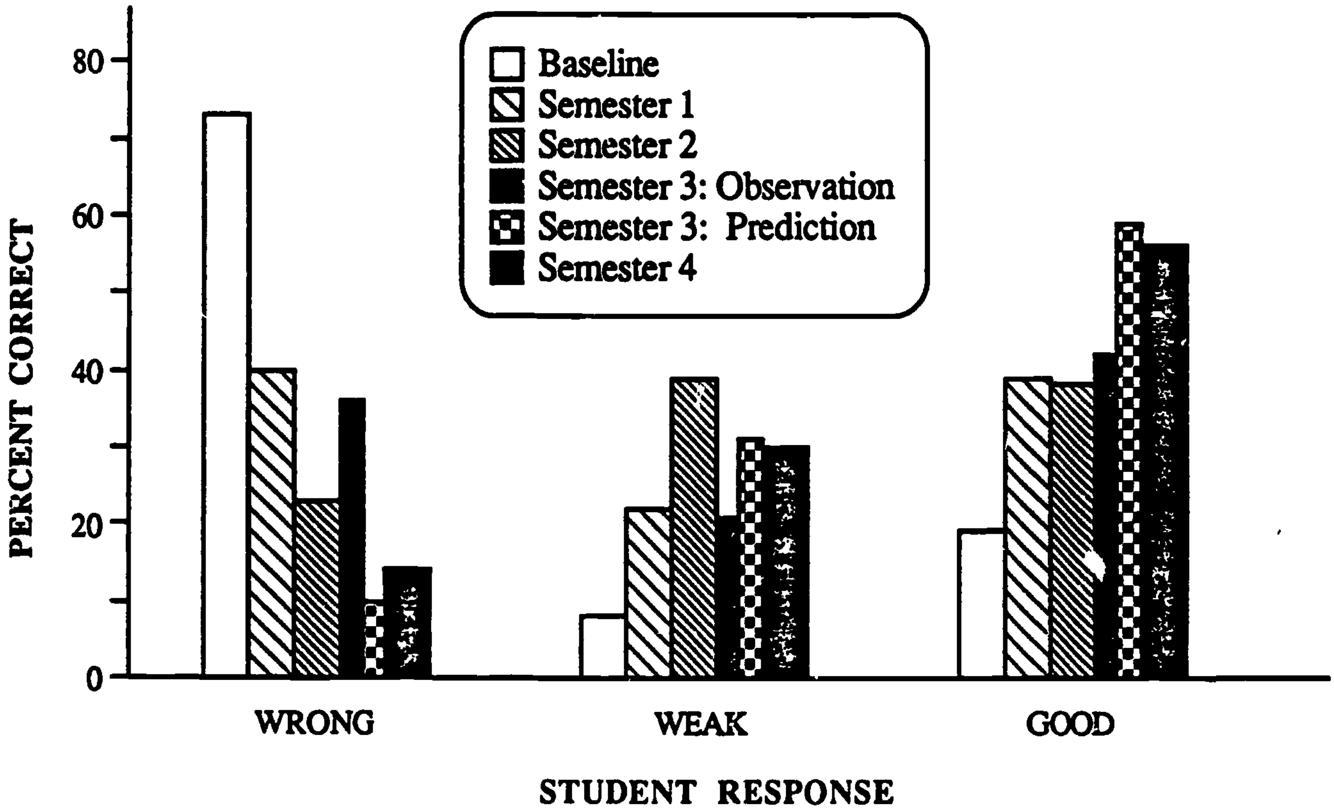


FIGURE 6

Strong Criteria for Heat Energy/Temperature Distinction

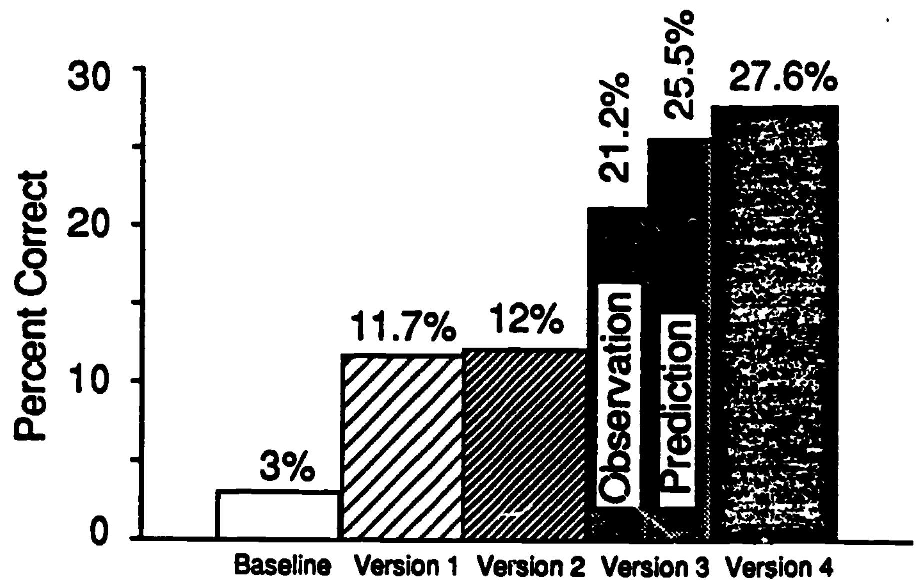
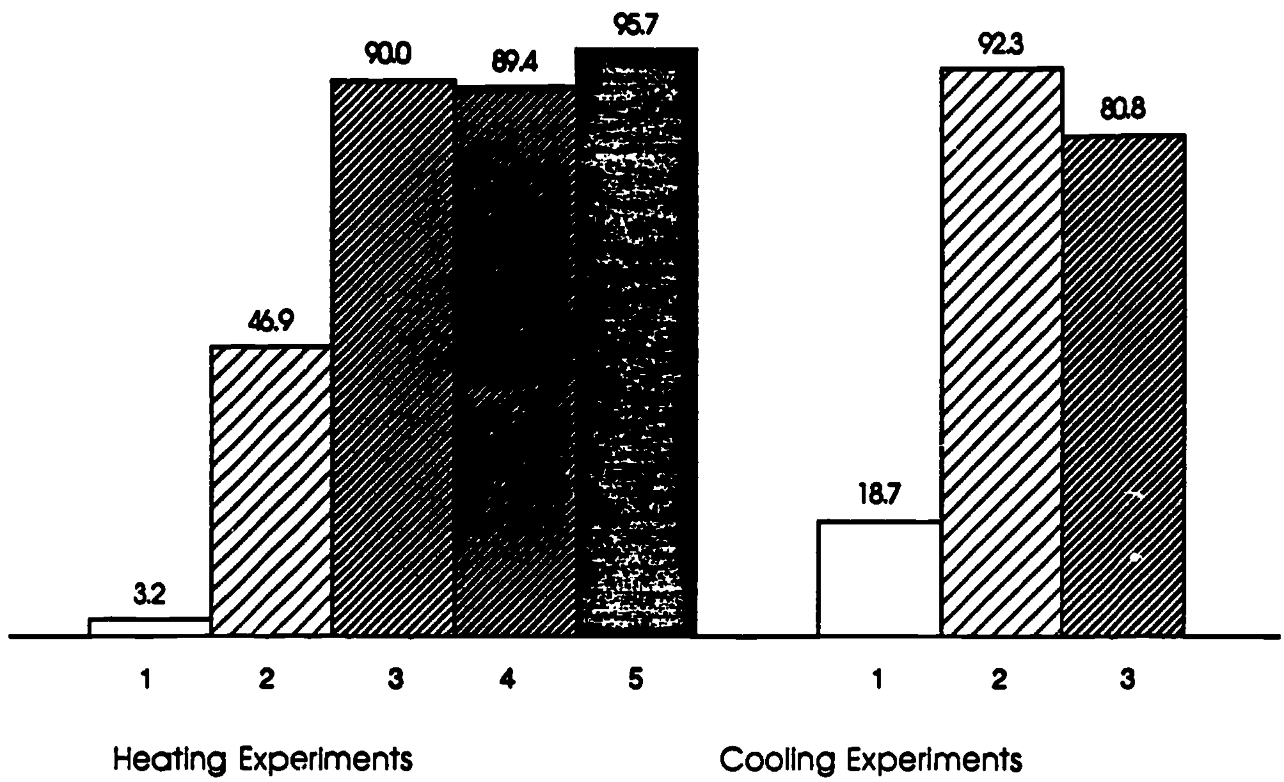


FIGURE 7 **Percent of Valid Predictions**



Name _______________
period _______

The Swimming Pool Activity

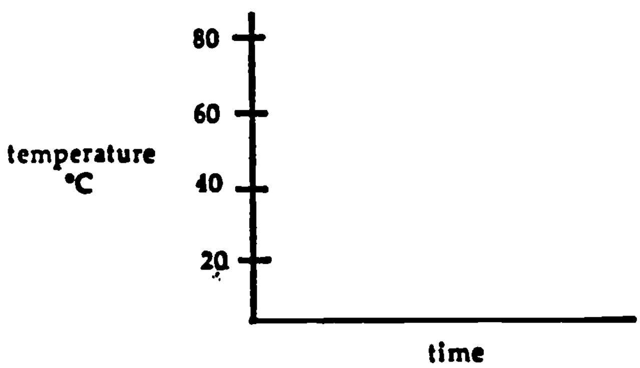
In the next two periods you will be hired as an independent researcher by a swimming pool company. The company started to design a new series of swimming pools for customers all over the country. One very important factor of the design is how fast the water in various swimming pools cools. The question that the designers asked is: **How does the surface area of a swimming pool affect the cooling rate of its water?** (surface area is the size of the surface of the water that is exposed to air). Of course they want the answer before building a real swimming pool. Your job will be to design and carry out an experiment to answer this question.

Your work will consist of two main parts. The first part will be done before you start the experiment and will include a plan of your experiment. The second part will be done during and after the experiment and will include a detailed log of your observations and your conclusions from the experiment.

Part 1

1. Do you think different surface areas will make a difference in cooling? If you do, what do you think will happen?

2. If you graphed two pools cooling which have different surface areas, what do you think the graph would look like?



Part 2

Congratulations! Your plan has been approved by the swimming pool company and they want to see the results of your experiment as soon as possible. They will expect to see a graph of your results and would like you to submit a statement of your observations and your conclusions.

Observations

Comment on what your graph looked like. Was there one line or two? Were the lines straight or curved? If they were curved, when were they steepest? Did they get steeper or less steep as time went one? Were there any sudden drops or rises? What was happening when those drops occurred? Write your comments below. Don't just answer these questions. Write in full sentences. You can use these questions as guides to help you decide what to look for. Add anything else you think is important.

Figure 8: The Swimming Pool Activity