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ABSTRACT

Research offers important suggestions concerning science curriculum design, and real-time data collection technology offers great opportunities. This paper discusses how recent increases in understanding the nature of the learner and the process of instruction combined with recent advances in technology might lead to improved science instruction. Results from the Computer as Lab Partner project illustrate how curriculum developers might take advantage of these understandings to create effective materials for science education. (27 references) (Author)

PERSPECTIVES FOR RESEARCH IN SCIENCE TEACHING:
USING THE COMPUTER AS LABORATORY PARTNER

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Abstract

Research offers important suggestions concerning science curriculum design, and real-time data collection technology offers great opportunities. This paper discusses how recent increases in understanding the nature of the learner and the process of instruction combined with recent advances in technology might lead to improved science instruction. Results from the Computer as Lab Partner project illustrate how curriculum developers might take advantage of these understandings to create effective materials for science education.

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Research offers important suggestions concerning science curriculum design, and real-time data collection technology offers great opportunities. At present, these suggestions and opportunities are not precise enough ensure that curricula will succeed. Rather, significant trial and refinement is required to achieve a curriculum that reflects the results of recent research, uses technology effectively, and meets the needs of students. The Computer as Laboratory Partner (CLP) project has employed trial and refinement over a period of four semesters to improve the thermodynamics curriculum for 13-year-old science students. Each semester, the curriculum was reformulated based on both research in controlled settings and data collected in the classroom. The CLP project sought to take full advantage of real-time data collection using Apple II computers to help students construct understanding of thermodynamics. This paper describes (a) the cognitive goals of the curriculum, (b) the instructional philosophy, and (c) the role of curriculum reformulation in accomplishing the cognitive goals.

As many have noted, technological innovations are not self-implementing. Real-time data collection is no exception. Scientists use real-time data collection to improve the efficiency and accuracy of their experiments, but this technique does not help them design better experiments nor does it help them interpret the results of their experiments. Scientists have already developed the thinking and reasoning skills necessary to design experiments and interpret the results. Teaching these skills is a goal of the science curriculum for 13-year-olds. Real-time data collection allows students to observe relationships dynamically and concentrate on the results of their experiments (Linn, 1987a). Our objective in the CLP project was to exploit real-time data collection to improve student understanding of thermodynamics.

COGNITIVE GOALS

The CLP curriculum addresses the distinction between heat energy and temperature. 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 develop some fairly robust and uniform ideas about observable phenomena. As many have shown, students have difficulty distinguishing heat energy from temperature (Wiser & Carey, 1983; Linn & Songer, 1988). In addition, students come to science class with many unrelated ideas about the distinction between heat energy and temperature. For example, many students believe "you only have a temperature if you are sick," or "you have more hot chocolate, so yours is hotter than mine," or "temperature is all the degrees, but heat only refers to temperatures that are above warm," or "wind lowers the temperature." In contrast, students have reasonable intuitions about such events as (a) the effect of insulation on the temperature of a liquid, gained from using styrofoam cups and (b) the relationship between the volume of a liquid and the amount of heat energy that needs to be added to make it boil, gained from heating large and small quantities of liquid in the kitchen.

Our first goal was to capitalize on these accurate intuitions to help students gain cohesive and robust understanding of heat energy and temperature. Robust understanding refers to knowledge that can be successfully applied to new, related problems. In contrast, students entering science classes for the first time have fragile knowledge that often applies only to one small problem. Cohesive understanding refers to knowledge that captures the nuances that differentiate problem solutions. Students entering science classes often cannot determine which science ideas apply to which problems. Thus our task was to help students organize their knowledge of thermodynamics and to standardize their use of potentially confusing terminology.

Analysis of thermodynamics, as presented in pre-college texts, demonstrates the need for a qualitative, integrated representation of thermodynamics (Alexander, 1986; Heimler & Price, 1984; Magnoli & Shymansky, 1985). Many textbooks emphasize computation of gains or losses in calories and in degrees centigrade to represent heat and temperature. This quantitative representation may throw 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. Other texts describe the many variables that influence heat gain and loss, such as insulation, mass, starting temperature, and surface area, emphasizing isolated views and preventing students from constructing a coherent model of thermodynamics. A third model for thermodynamics common in texts involves molecular kinetic theory. Molecular kinetic theory depends on hidden mechanisms that are difficult to understand and remarkably abstract. Our second goal was to provide an adequate model of thermodynamics. Initially we presented all of these explanations to students.

Considerable research on conceptual change and on effective instruction reveals that students do not so much reject incomplete or inaccurate ideas as embrace more powerful ideas about science (Lakatos, 1972; Hawkins, & Pea, 1987; Linn & Siegel, 1984; di Sessa, 1988). Furthermore, research confirms that students develop mental models of scientific phenomena (e.g., Gentner & Stevens, 1983), and that powerful models help students learn (e.g., White & Frederiksen, 1986a,b; 1987). Mental models include factual details or declarative knowledge (e.g., the relative insulating value of different materials), procedures (e.g., techniques for separating intensive and extensive properties), and plans that combine declarative 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 our approach was to attempt to impart more powerful models by integrating all the alternatives. We hypothesized that this approach would also help students who held one or the other of these ideas see how it could be elaborated by considering another perspective.

INSTRUCTIONAL PHILOSOPHY

The CLP curriculum draws upon recent successful examples of instruction in a variety of domains. Taken together, these have been referred to as "apprenticeship" teaching. First, Brown and her colleagues have succeeded in helping students develop robust understanding of reading comprehension through a technique called "reciprocal teaching" (Palinscar & Brown, 1984). Key features of this technique include: (a) providing a new conceptual model of the reading task; (b) having teachers model the complex problem-solving processes that they employ; (c) reducing the cognitive load in reading comprehension by providing specific skills, such as formulating questions and predicting outcomes; (d) encouraging students to reflect on their knowledge by devising solutions and by evaluating solutions devised by others; and (e) encouraging students to take responsibility for their own learning by turning instruction over to groups of students.

In addition, the approach of Brown and her colleagues is cognizant of developmental constraints and domain characteristics. Thus, Brown discusses what Vygotsky (1986) has called the "zone of proximal development," and points out that students have limitations in the amount of progress they can make at one time. This point is consistent with the general notion that learning proceeds by successive approximations and refinements rather than by leaps and bounds. Brown also notes that instruction must be tailored to the knowledge domain. She has refined the approach for reading as the result of numerous trials in real settings.

In the area of writing, Bereiter and Scardamalia (1986) have pioneered an approach that has many features in common with that of reciprocal teaching, but is tailored to the knowledge domain of writing. This approach features (a) having teachers model the expert writing process for students, (b) providing techniques that reduce the complexity of writing by focusing the students on a limited number of options, such as generating a new idea, elaborating an idea, or integrating the idea with others, and (c) encouraging students to reflect on their writing and that of other students by a process called co-investigation.

Schoenfeld has investigated mathematics instruction and demonstrated similar principles of effective programs (Schoenfeld, 1985). Schoenfeld's approach emphasizes re-analysis of the knowledge required for problem solving. He addresses students' beliefs about the nature of the physical world, about their own ability to learn mathematics, and about the trial and refinement inherent in realistic problem solving. For example, Schoenfeld emphasizes that problems can be ambiguous and that experts flounder on the way to solving complex problems.

Reif and his colleagues have identified knowledge representations that help students achieve a robust understanding of mechanics (Reif & Heller, 1982). This approach emphasizes developing easy-to-implement representations of scientific concepts that generate useful explanations for novel problems. These can be compared to the templates found to be effective in programming instruction.

Consistent with the results described for reading, writing, mathematics, and science, Linn, Sloane, and Clancy (1987) found that, in teaching program design, teachers who model their own design processes at a level accessible to students are far more effective than those who provide abstract discussions of problems. Thus, teachers who talk through how they solve problems and include in their discussion some re-interpretation of the problem statement, some backtracking from initial conjectures, and some clear examples of how they use prior problem solutions to solve new problems are more effective than those who provide a tightly-knit presentation of the subject matter but fail to communicate how the subject matter can be applied to a problem.

In summary, research investigations suggest principles of instruction for improving students' understanding, including: a) provide a powerful conceptual model of the domain, such as the pragmatic model described for heat energy and temperature; b) teach techniques and strategies to reduce the complexity of problem solution; c) develop a "way in" or prototype to help students recognize the essential features of new problems; d) explicitly model complex problem -solving skills appropriate for students; e) establish an orderly transfer of responsibility for explaining complex procedures from the teacher to the student; f) encourage reflection on new problems to help students develop a more coherent understanding of the subject matter; and g) capitalize on joint exploration of problem solutions, encouraging students to form a community of scholars.

CURRICULUM REFORMULATION

The experimental studies of the Computer as Lab Partner curriculum used curriculum reformulation, a process which involves refining materials in light of evidence from trials in real settings. As noted above, curriculum reformulation is necessary because our knowledge of effective learning environments is imprecise. As a result, developers come up with a reasonable plan for curriculum materials and improve it by using feedback from classroom observations, interviews, assessments of student progress, and other sources.

In the CLP curriculum the feedback was analyzed by a multidisciplinary team. The diverse perspectives of the team enhanced the final version of the curriculum. The team included classroom teacher Doug Kirkpatrick, who has developed science curriculum materials and is committed to hands-on science; Robert Tinker, of Technical Education Research Centers, who developed software and laboratory equipment; John Layman, a physicist from the University of Maryland, who helped design laboratory experiments for classroom use; and professors, post-doctoral scholars, and graduate students in science education.

Our process was to design the best possible curriculum using the cognitive goals and instructional philosophy described above, to identify potentially problematic goals of the curriculum, and finally to design some evaluation instruments to assess whether these problematic goals were achieved. Once a goal was achieved the evaluation effort turned to other issues.

Selection of goals for evaluation resulted from group discussion. Criteria for goal selection were both theoretical and pragmatic. In the first trials of the curriculum we were guided by the pragmatic concern that the students might not understand the nature of real-time data collection and might fail to interpret the graphs that were produced by the software. We evaluated student understanding of graphs, student interpretation of computer-presented data, and related issues.

Later trials of the curriculum focused on whether or not students were actually reflecting on the information they collected and on whether the potential benefits of collaboration were being achieved. We evaluated whether students understood each experiment and whether they could combine the results of the experiments to achieve cohesive and robust understanding.

Methods

Subjects in these investigations were 12- to 13-year-olds enrolled in a middle school that served students between about 11 and 14. Each semester four science classes used the curriculum materials. Different students participated each semester. Each class had about 32 students, so each semester about 120 students used the curriculum materials. Since the study was conducted over a four semester period, a total of about 500 students were involved.

The classes were all taught by the same teacher but during the fourth semester primary responsibility for two of the classes was assumed by a "student teacher" who was training to become a certified teacher. As a result during the fourth semester we were able to determine whether the curriculum generalized to different instructors.

The topics covered by the curriculum are summarized in Table 1. As can be seen, changes were made following the first two trials of the materials. Note that the curriculum lasted 11 to 13 weeks, much longer than is typical for coverage of thermodynamics. This duration of instruction was consistent with our effort to achieve depth of coverage and was acceptable to the classroom teacher and to the school district (see, Linn 1987b for a discussion of the depth of coverage issue).

- - - Table 1 about here - - -

Evaluation measures included both formal and informal techniques. A primary method was observation in the class and discussion with the students. Project staff members were present for most class sessions. Their observations were summarized at project meetings.

In addition, assessment devices were pilot tested and used in the more formal investigations. Many of these are described in detail in other project reports (e.g., Linn Layman, & Nachmias, 1987; Nachmias & Linn, 1987; Striley, 1988; Linn & Songer, 1988).

The primary measure of cohesive and robust understanding was the "heat energy and temperature assessment." This was an essay question administered to all the students who participated in the study. Students were asked to indicate whether heat energy and temperature were different, to justify their answer, and to give several examples to clarify their point of view.

Project staff members categorized each answer and also analyzed the specific responses that students gave. The most sophisticated students (a) differentiated between heat energy and temperature by pointing out that heat energy extends throughout the material under study while temperature is a measure of intensity at a given point and (b) convincingly applied their ideas in two diverse examples. The least sophisticated students indicated that heat energy and temperature were identical or that heat energy was present only when the temperature was above some level. Other students gave no answer at all or gave some intermediate response such as indicating that heat was measured in calories and temperature was measured in degrees centigrade. We judged only the most sophisticated students to have achieved robust and cohesive understanding.

Results

Initial discussion by the project staff revealed a list of pragmatic and theoretical concerns about the program. During the first two semesters of the program the pragmatic concerns were addressed. During all four semesters the theoretical concerns were evaluated.

Pragmatic Concerns

The pragmatic concerns raised by the project team included (a) would students be able to interpret computer-presented graphs, (b) would students correctly evaluate the reliability and validity of computer presented information, and (c) would students stay on-task in a classroom filled with computers.

Graphing. The CLP curriculum relies heavily on student interpretation of graphs. All the results of experiments are presented graphically, as shown in Figure 1. Since students have considerable difficulty interpreting graphs, the project assessed student understanding of heat and temperature graphs as well as whether they could apply this understanding to time and motion graphs. Students frequently think that graphs are pictures representing a hill, for example, instead of representing a functional relationship. The project assessed whether the curriculum would change students' ideas about graphs.

- - - Figure 1 about here - - -

Students in the CLP project gained considerable understanding of graphing and extended this to interpretation of motion graphs even through they had not studied motion. For example, as a result of studying graphs about heat and temperature, students could correctly interpret a graph showing the speed of a bicycle when the bicycle ascended a hill and then descended the hill. Prior to instruction, many students assumed that when the graph increased, the bicyclist was going up the hill. After instruction, these ideas were reversed. See Linn, Layman, and Nachmias (1987) for more details.

Students also learned to construct graphs correctly and interpret their features. Students were better able to label graphs, to read numbers off graphs, and to construct graphs, as a result of participation in the CLP curriculum. Students' greatest difficulty came in labeling the curves in their graphs. The microcomputer-based laboratory software does not allow students to label curves. After the experiment, students save their graphs on a disk, take the disk to another computer, and print the graph. Students often forget to label their graphs. An improvement would be to have the labels stored on the disk.

Students in the CLP curriculum come to understand change over time, as it is represented in a graph, because they directly experience how it occurs. For example, students in these classes frequently talk about when the graph changes quickly and when it changes slowly. These students represent their understanding of graphs in terms of rate of change. In contrast, when students collect data in tables and convert it into graphs, they rarely pay attention to dynamic changes represented in the graph. Thus, the CLP curriculum materials effectively teach graphing skill.

Reliability and validity of computer-presented information. To benefit from the CLP curriculum, students must understand the nature of computer-presented information. Some students believe that everything a computer prints out is completely valid, while others distrust anything presented by computers. Students in the CLP project tended to accept computer-presented information, even when it was invalid. For example, when the data they collected exceeded the range available on their graph, and therefore, presented a straight line at the top or bottom of the screen, students frequently believed that the temperature of their experiment had stabilized. We identified a series of potential misunderstandings about computer-presented data and evaluated student progress.

The CLP curriculum dramatically reduced misunderstanding about computer-presented information. Students were far less likely to accept incorrect graphs after the CLP curriculum. After instruction, only 3% of the students persisted in interpreting incorrectly scaled graphs as reflecting the physical phenomenon. Only 7% of the students misinterpreted the graphs that resulted from incorrect set-up of their experiments, after instruction. In contrast, 31% of the students persisted in interpreting incorrectly calibrated experiments as being meaningful. These students frequently remarked, "Look, water boils at 100°; it boils at 212°; why can't it boil at 310°?" These students understood that temperature scales are relative. On balance, they did not recognize that their probes were poorly calibrated.

In light of these findings, the curriculum was reformulated to include more instruction concerning calibration. Subsequent investigations revealed that students became more proficient at interpreting experimental results from uncalibrated probes. For further information, see Nachmias and Linn (1987).

Learning environment. The CLP project takes place in a realistic classroom setting. One project goal was to take advantage of the learning context and capitalize on opportunities for cooperative problem solving.

Many postulated that introducing computers along with laboratory experimentation would lead to chaos and confusion. In fact, students were observed to be off-task less than 2% of the time (see Stein, 1986, for further discussion). Close observation of student interaction during problem solving revealed that students quickly devised methods for cooperatively approaching the laboratory. One student booted up the computer and set up the experiment on the screen, while another gathered the apparatus needed and set up the physical experiment.

Initial observations revealed that some students controlled the computer while others watched. As a result, the curriculum was reformulated to require students to switch roles regularly. Whereas students cooperated immediately and effectively to set up their experiments, they were less prone to negotiate their understanding of the results of their experiments. The first observations revealed that students split up the work of writing the experiment report, with one student answering one question and the other answering a subsequent question. As a result, little discussion about the results of their experiments occurred.

To capitalize on student interaction, the curriculum was reformulated to emphasize joint problem solving. Word processing software allowed students to write joint laboratory reports. This intervention resulted in considerable discussion of the results of experiments and substantial negotiation of scientific understanding. Observations revealed that some questions are far better than others in eliciting student discussion. Subsequent reformulation of the curriculum added questions that specifically encouraged students to contrast opposing views.

Theoretical Concerns

The theoretical concerns included (a) whether students were acquiring effective models of the distinction between heat energy and temperature (b) whether students could apply their models to naturally occurring problems and (c) whether the apprenticeship model of instruction was being implemented effectively.

Models of heat energy and temperature. Initially, most students had isolated ideas about heat energy and temperature. Over half thought heat energy and temperature were the same thing. In addition, they had inconsistent and even contradictory ideas about how heat or temperature would change in experimental situations. For example, many students expected water collected in a pail by the sea shore to maintain the same temperature as the ocean on a hot day while at the same time indicating that if they had a big cup of hot chocolate it would have a higher temperature than a small cup of the same hot chocolate. Only 3% of the students had what we considered sophisticated ideas about heat energy and temperature as indicated on the heat energy and temperature assessment (see Figure 2).

- - - Figure 2 about here - - -

Our first goal was to ensure that students correctly interpreted the results of the experiments they conducted in class. We assessed understanding of the role of insulation, surface area, starting temperature, and volume on either heating or cooling. Since some of these variables were only introduced in the third semester, we present data for this semester. However, results were similar for other semesters. To measure correct interpretation we asked students to predict the results from an experiment similar to one conducted in class and to interpret the results. We provided the outcome from one trial and asked them to predict the outcome from another trial and explain what it meant. See the sample question in Figure 3.

- - - Figure 3 about here - - -

We found that initially 30 to 60% of the students could predict the outcome of these experiments and that after the program, 60 to 80% could make accurate predictions (see Figure 3). The greatest difficulty arose for the effect of volume, consistent with the beliefs about hot chocolate described above. Overall, students made large gains in understanding these variables and most students acquired understanding of most of the variables. Thus, the program was reasonably successful in teaching students about the variables that influence temperature change.

Naturally, students could add information about the variables to their knowledge of heat energy and temperature and still not have robust or cohesive understanding. To assess improvements in cohesive understanding we used the heat energy and temperature assessment. As shown in Figure 2, the first two versions of the curriculum were not very successful in imparting either cohesive or robust understanding.

We found that many students gained new understandings but not more integrated understandings. Many students who initially stated that heat energy and temperature were the same changed to the response that heat is calories and temperature is degrees centigrade. This "measurement" response reflected no increase in cohesive or robust understanding. Students giving these responses sometimes gave examples that made sense and sometimes gave examples unrelated to their general answer. For example, students m[illegible] say in an example that a cup of water could be 22° centigrade and lose 50 c[illegible]ies of heat. Typically, no indication of the relationship between these two measurements would be given. Clearly, this is not a robust or cohesive model of the distinction but it seemed to appeal to students and did indicate that they had recognized that heat energy and temperature were different in at least one way. We described students who accepted this answer as "cognitive economists," happy to have an answer that seemed to fit the question and unwilling to assess whether their answer was consistent with or contradictory to other information they had gained.

Another common change was for students to initially say that heat energy and temperature were the same thing and then later to say that heat was "kinetic energy." These students knew no more about kinetic energy than the name, but found it a scientific-sounding explanation that seemed more appropriate than their initial answer. We described these students as "aspiring scientists" who had a poor model of the nature of the scientific enterprise.

The results of the heat energy and temperature assessment combined with classroom observations convinced us that students were not acquiring the model of this distinction we intended. Our first response was to analyze the information we were providing to see if students could get a sensible model from it. We concluded that our attempt to teach the multiple explanations of heat energy and temperature was construed by the students as a multiple choice test and that they were selecting the explanation that appealed to them rather than trying to integrate the information.

As a result, the project team sought a more appropriate model for the distinction between heat energy and temperature. Rather than using the textbook for inspiration, we analyzed our own models of these concepts. We selected the notion of "heat flow" as a technique for unifying the ideas presented in the curriculum. We described heat as flowing from things that were warm to things that were cold. We essentially adopted the historical notion of heat as something contained in a substance, but stressed that heat did not have a mass. We explained that heat was conserved and passed from warm to colder objects, liquids, or gases. We stressed that objects in a system reached thermal equilibrium.

Understanding the controlling variables strategy. The CLP curriculum set out to help students understand the controlling variable strategy. The controlling variables strategy refers to the approach of changing one variable while holding all the others constant in order to investigate the effect of that one variable.

During the first and second semester of the program, we found that students made limited progress on understanding how to control variables in heat and temperature experiments. During the third semester the prediction and observation treatments emphasized the nature of experimentation. Students were directed to compare experiments about one variable with experiments about another. In each case, the need to hold all other variables constant while investigating a single variable was discussed. Thus, students encountered multiple representations of an abstract scientific principle. Furthermore, students were familiar with the variables affecting heat energy and temperature.

Results showed that students could apply this instruction to problems such as designing an experiment to determine which variables would influence the heating cost for a swimming pool (see Friedler, Nachmias & Linn, in press, for further discussion).

Apprenticeship instruction. Observations in the classroom convinced us that the instruction came close to the apprenticeship model we desired in a number of ways but fell short in other ways. In particular, the teacher was successful in reducing the complexity of the experimental situation and students gained good understanding of their investigations. This was reflected in the performance on the assessment of the effects of individual variables in the experiments shown in Figure 3. In addition, all observers greed that the teacher was effective in modeling explicit problem-solving strategies and in providing support for students as they attempted to use these strategies. Both the classroom discussions and the student sheets engaged students in the experiments. Furthermore, students cooperated to solve problems although, as discussed above, this cooperation centered more on logistic issues than on conceptual issues.

In spite of all these successes, students did not gain cohesive or robust understanding from the curriculum offered during the first two semesters. What were the problems? Several elements of the apprenticeship approach to learning were missing. First, as discussed above, students did not acquire powerful models of thermodynamics. Second, students did not reflect on their experiments, but rather rushed to complete them and go on to the next activity. Third, information was not integrated by the students. Fourth, students did not become a community of scholars as hoped.

To encourage students to reflect and to integrate information, we implemented two conditions during the third semester and combined them during the fourth semester (see Friedler, Nachmias, & Linn, in press, for details). We insisted that students make predictions for each experiment, based on prior knowledge. Then we asked the two students working together to jointly develop an explanation when the predictions were incorrect. Finally, we asked students to record detailed observations while the experiment was running and to relate these observations to their predictions. For some laboratories we also specified roles for the cooperating students to encourage more discussion.

As a result of these reformulations to the curriculum, the percent of students with robust understanding of the distinction between heat energy and temperature doubled (see Figure 2). Observations in the classroom suggested that students made serious efforts to integrate their ideas. The desired reflection was more common with the new materials. Analysis of the predictions made by students revealed that students quickly learned to make more accurate predictions, but that as soon as the situation changed from, for example, heating to cooling, the success of predictions fell off dramatically (e.g., Linn & Songer, 1988). After a series of these experiences, students became more adept at making predictions in unfamiliar situations and, probably as a result, gained more cohesive understanding of the distinction between heat energy and temperature.

Analysis of student responses to the heat energy and temperature assessment revealed that many students had used the heat flow model to integrate their ideas about heat energy and temperature and that, as a result, there were many fewer "measurement" models and somewhat fewer "kinetic energy" models.

Even in the final version of the curriculum many students failed to exhibit sophisticated reasoning. The accomplishments of students in the program are, nevertheless, substantial. First, almost all of the students learned to interpret graphs and to generalize their skills to graphs of phenomena they had not studied. Second, almost all of the students learned to use a new technology to help them accomplish an important task and to interpret the data collected with the computer. Third, most of the students learned the role of the variables that influence changes in heat energy and temperature. And fourth, most students came to realize that heat energy and temperature are different.

SUMMARY AND CONCLUSIONS

In summary, the CLP curriculum was dramatically improved as the result of reformulations. These reformulations were motivated by the poor performance of students and were inspired by research on learning and instruction in controlled settings. Several pragmatic considerations led to changes in the curriculum. For example, the difficulties students had with calibration of the temperature probes led the team to devise additional activities for teaching this important idea.

Furthermore, a group of cognitive principles governed changes in the curriculum and resulted in improved understanding of heat energy and temperature. By analyzing the models of this complex scientific idea that resulted from the instruction, we were able to devise a more appropriate model. In addition, using the principles of apprenticeship teaching helped the development team come up with a way to encourage students to reflect on their ideas and experiments and, ultimately, to gain more robust, cohesive understanding.

Taken together these results lend support to the curriculum reformulation approach to devising technology-based materials. The results illustrate the difficulty of implementing principles from current controlled studies of learning and instruction in real settings. Curriculum reformulation allowed us to refine these principles rather than abandoning them and to create far more effective materials that were initially used.

In conclusion, principles for science curriculum design gained from cognitive research aid developers but do not provide complete answers. Much trial and refinement is required to create effective curriculum materials. As illustrated for the CLP project, evaluation revealed weaknesses in the program. Reformulations of the curriculum consistent with cognitive theory improved student learning.

Much remains to be done before effective curricula for the information age become available. Advances in understanding the nature of the learner and the process of instruction, combined with new technological tools, fuel effective trial and refinement. Researchers, developers, and classroom teachers working together have the expertise required to mold these advances into powerful instruction.

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