Designing for Knowledge Integration: The Impact of Instructional Time

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Science educators face constant tradeoffs between allocating time to important topics and including more topics in the curriculum. We study 3,000 students experiencing 4 increasingly streamlined versions of a computer-enhanced middle school thermodynamics curriculum to investigate the impact of instructional time on knowledge integration. Knowledge integration refers to the process of adding new ideas and sorting through connections to develop a cohesive account of scientific phenomena. Our analyses contrast performance on inquiry assessments that require knowledge integration with performance on multiple-choice items. The results show that decreasing instructional time is strongly and significantly related to diminishing student knowledge integration around complex concepts. Whereas the inquiry assessments capture the impact of decreasing instructional time on knowledge integration, the multiple-choice assessments are relatively insensitive to these decreases. To explore further the process of knowledge integration, we follow 50 students through the full curriculum. We then analyze the performance of 1 representative student from middle school through high school. These case studies show why packing the curriculum with many science topics results in superficial understanding for many students. We show why deep understanding of science requires sustained study of carefully designed materials.

Learning science involves connecting disparate ideas and making sense of complex phenomena such as heat and temperature. This process takes instructional time, yet curricula in the United States generally involve fleeting coverage of many topics. We compare four increasingly streamlined versions of a computer-enhanced thermodynamics curriculum to assess the impact of instructional time. To understand the benefits of instructional time, we analyze the progress of 50 students at five points as they study the full curriculum. To clarify the mechanisms governing knowledge integration, we examine the progress of one representative student in detail. Our work reveals not only that the streamlined curriculum leaves many students behind but also that standard multiple-choice assessments are often insensitive to decreased student understanding.

SCIENCE KNOWLEDGE INTEGRATION

Knowledge integration describes the process students follow as they make sense of science. Students come to science class with a vast array of disparate, contradictory, and confused ideas about scientific phenomena like heat and temperature. To become lifelong science learners, students must add new ideas from instruction or experience, sort out these ideas, learn how to combine them, develop a sense of coherence among ideas, and recognize new situations where these ideas apply (Linn & Hsi, 2000).

Knowledge integration involves a dynamic process of linking, connecting, distinguishing, organizing, and structuring ideas about scientific phenomena. These ideas include facts, patterns, templates, views, theories, models, and visualizations. Students develop new ideas in varied contexts and generate a repertoire of perspectives (D. B. Clark, 2000, 2003; diSessa & Sherin, 1998; Linn & Hsi, 2000). Effective instruction should enable students to expand, revise, restructure, reconnect, and reprioritize their ideas. When students hold one scientific idea up to another and analyze similarities and differences they engage in knowledge integration. Students who apply classroom science principles to everyday problems engage in knowledge integration. Students who develop integrated understandings of science topics can add new ideas using the knowledge integration process. In contrast, students with disconnected ideas tend to isolate new ideas and readily forget the ideas they learn. Students who build on and expand their ideas are prepared for science inquiry assessments that require connecting classroom, personal, and everyday ideas to reach conclusions. Promoting the process of knowledge integration is the first step toward providing a firm foundation for lifelong learning, enabling students to revisit and refine their ideas after completing their science classes.

SCIENCE TOPIC COVERAGE AND KNOWLEDGE INTEGRATION

Many groups call on curriculum designers to focus on a few topics to promote knowledge integration, but local and state frameworks and standards make this difficult (F. A. Cotton, 1980; Meier, 1995; Sizer, 1996). The full version of the Computer as Learning Partner (CLP) curriculum, the focus of this analysis, devoted 12 weeks to thermodynamics, exceeding the 1 to 2 weeks typical in U.S. schools but consistent with the small number of topics covered per year in the highest scoring countries in the Third International Mathematics and Science Study (TIMSS, 1996; Schmidt, McKnight, & Raizen, 1997). According to the TIMSS study, U.S. curricula listed the most topics per year (65 in eighth grade), whereas the most successful countries like Japan and the Czech

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Republic listed as few as 5. Observations in Japanese science classes show benefits from covering fewer topics in greater depth, consistent with our knowledge integration perspective (C. Lewis, 1995; C. Lewis & Tsuchida, 1998; Linn, Lewis, Tsuchida, & Songer, 2000).

Examining the impact of the curriculum in typical U.S. schools suggests the limitations of covering numerous topics. The National Assessment of Educational Progress (NAEP) test results for thermodynamics show minimal gains between 4th and 12th grades in students' understanding of thermodynamics (O'Sullivan, Reese, & Mazzeo, 1997). The same holds for other science topics as shown by the NAEP (O'Sullivan et al., 1997) and TIMSS data (Schmidt et al., 1997).

In contrast, longitudinal study of the CLP curriculum shows that students make substantial gains in 8th grade and actually perform even better in 12th grade, whereas students following the typical curriculum perform in 12th grade at the same level they did prior to studying thermodynamics in 8th grade (Linn & Hsi, 2000).

Instructional time, of course, is not the only factor in the success of the CLP curriculum. Intuitively, one expects more success from greater engagement in a topic. Some research studies show that increasing the attention devoted to a topic can increase understanding (McMullen, 1996; Newmann & Wehlage, 1995; Wasley, Hampel, & Clark, 1997). Studies of time-on-task, however, show mixed results for increased instructional time (J. Aronson, Zimmerman, & Carlos, 1998; Berliner, 1992; K. Cotton & Wikelund, 1990; Hossler, Stage, & Gallagher, 1988). Quality and design of instruction have a major impact on outcomes (J. Aronson et al., 1998; Berliner, 1992; Berliner & Casanova, 1989; Hannafin & Sullivan, 1995; Melmed, 1994). In addition, studies show that spending more time on fewer topics or on hands-on curricula does not diminish outcomes on standardized tests (Gallagher & Stepien, 1996; Kyle & Shymansky, 1982; Shymansky & Kyle, 1982, 1983).

These findings underscore the importance of alignment between instructional goals, curricular activities, and assessments. For example, if courses emphasize collections of facts rather than coherent connections between ideas, problems, and possible solutions, students may not make progress on knowledge integration tests that assess construction of a convincing argument. In contrast, many standardized tests primarily assess recall of independent pieces of information and may fail to detect the impact of courses like CLP that focus on knowledge integration. In addition, courses might devote additional time to a topic without emphasizing coherent, connected understanding. Our study clarifies the relations between curriculum design, use of instructional time, and assessment.

THE CLP KNOWLEDGE INTEGRATION CURRICULUM

The CLP thermodynamics curriculum was designed and refined to promote knowledge integration by a partnership of stakeholders including experts in natural science, classroom teaching, pedagogy, and technology (Linn, 2000; Linn & Hsi, 2000). From this research we abstracted design principles (see Table 1) to promote knowledge integration. These principles help designers create instruction that enables science learners to integrate ideas from school, personal experience, and experiments (Linn & Hsi, 2000; Linn & Muilenburg, 1996). The principles describe activity structures that make science accessible, make thinking visible, help students learn from each other, and encourage lifelong learning (Linn & Hsi, 2000). These design principles guided the streamlining of

Table 1. Pragmatic Principles Driving the Design of Computer as Learning Partner.

Pragmatic principles to make science accessible

- Encourage students to build on their scientific ideas as they develop more and more powerful and useful pragmatic scientific principles.
- Encourage students to investigate personally relevant problems and revisit their science ideas regularly. Scaffold science activities so students participate in the inquiry process.

Pragmatic principles to make thinking visible

- Model the scientific process of considering alternative explanations and diagnosing mistakes.
- Scaffold students to explain their ideas.
- Provide multiple, visual representations from varied media.

Pragmatic principles to help students learn from others

- Encourage students to listen and learn from each other.
- Design social activities to promote productive and respectful interactions.
- Scaffold groups to design shared criteria and standards.
- Employ multiple social activity structures.

Pragmatic principles to support lifelong learning

- Engage students in reflecting on their own scientific ideas and on their own progress in understanding science.
- Engage students as critics of diverse scientific information.
- Engage students in varied, sustained science projects to illustrate the broad range of science activities and meet the needs of diverse learners.activities and meet the needs of diverse learners.
- Establish a generalizable inquiry process useful for diverse science projects.

the curriculum, the design of our research methodologies, the design of our assessments, and the interpretation of our findings.

The CLP partnership developed the thermodynamics curriculum and conducted iterative design studies to increase its effectiveness (Linn & Hsi, 2000). Design studies, focusing on increasing knowledge integration, were conducted in science classrooms guided by the multidisciplinary partnership. Working with a shared knowledge integration framework, agreed-upon vocabulary, and egalitarian patterns of interaction (see Dunbar, 1995, 1996; Latour & Woolgar, 1986), the partnership codesigned the curriculum along with two types of assessments.

The CLP thermodynamics curriculum includes four main topics: (a) heat flow, (b) insulation and conduction, (c) heat energy and temperature, and (d) thermal equilibrium. The curriculum makes science accessible by selecting scientific models, such as the heat flow model, consistent with student's knowledge and experiences (Linn & Muilenburg, 1996); CLP features many everyday topics such as comparing materials to keep soft drinks cold for lunch, investigating how ovens work, analyzing methods for survival in the wilderness, and designing picnic containers that keep food safe. To make thinking visible, CLP features heat flow simulations as well as opportunities for teachers and students to describe their ideas (E. L. Lewis, 1996). The curriculum helps students learn from each other by featuring small group work as well as asynchronous online discussions (D. B. Clark, in press; Cuthbert, Clark, & Linn, 2002; Hoadley & Linn, 2000). To encourage lifelong autonomous knowledge integration, the curriculum features prompts designed to support reflection (Davis & Linn, 2000), opportunities to critique student ideas (Linn & Songer, 1991), and complex projects (Songer & Linn, 1991).

In CLP, eighth-grade students work in pairs on computers using microcomputer based labs, simulations, an electronic laboratory notebook, Internet software, and other custom software. Technology amplifies the impact of the science teacher by guiding students and freeing the instructor to tutor small groups. Students use this software to design experiments, collect real-time data, predict outcomes, design simulations, display results, record observations, and make reports (see activities in Appendix A).

The full CLP curriculum resulted from an eight-semester design and iterative refinement study conducted with one teacher in a California public middle school. During this initial design and refinement process the curriculum involved 12 to 13 weeks of instructional time. Through eight semesters of iterative refinement, the CLP partnership raised student posttest scores on knowledge integration items like the heat energy–temperature distinction question by 400% (Linn & Hsi, 2000). These results demonstrate that design of the curriculum can substantially impact instruction. This study builds on these findings, to investigate the impact of reducing instructional time on student learning.

STREAMLINING THE CURRICULUM

All four versions of the CLP curriculum that we studied include the same topics and knowledge integration supports. The tools in the streamlined versions were iteratively refined from the tools originally designed through the eight-semester study. Even the most

Table 2. Weeks Allocated to Each Activity in the Four Versions of the Computer as Learning Partner Curriculum

Activities	Primary Topic	Full Version	Streamlined 1	Streamlined 2	Streamlined 3
Probing your surroundings (and related real-time labs)	Thermal equilibrium	1.25	0.75	0.50	0.50
Heat pulsing (and related real-time labs)	Heat and temperature	2.00	1.50	1.50	0.75
Potatoes and Cokes (and related simulation labs)	Insulation and conduction	2.25	2.00	1.25	1.25
Heat bars (and related simulations)	Rate of heat flow	1.00	0.75	0.75	0.50
Equilibrium (and related real-time labs)	Thermal equilibrium	2.25	2.25	1.50	1.25
Thermal model kit (and related simulations)	Practical problems	1.25	1.00	1.00	0.50
Integration projects	Personal relevance	2.25	2.00	1.75	1.75
Total weeks of curriculum focused on thermodynamics		12.25	10.25	8.25	6.50

Note. See Appendix A for more details about the Computer as Learning Partner curriculum activities.

streamlined version took about 6 weeks of class time (see Table 2 and Figure 1), which contrasts sharply with the minimal 1 or 2 weeks that would be devoted to these topics in most U.S. curricula.

To streamline the curriculum, we condensed and increased the efficiency of some activities and shortened the final projects. In addition we increased emphasis on students' learning from each other to promote knowledge integration using a jigsaw approach (E. Aronson, 1978). The jigsaw involved dividing the class in half and asking some students to perform one experiment while others performed a different experiment before having the students share results. We therefore retained all of the project types across versions of the curriculum and retained our focus on the design principles described in Table 1. In summary, the streamlined curriculum retained all the knowledge integration mechanisms, principles, and project topics but reduced the time spent on each of them.

This study contrasts the full version of the CLP curriculum, developed through the initial eight-semester iterative design process (Linn & Hsi, 2000), with more streamlined versions. The full version devotes approximately 12 weeks to thermodynamics, with little time devoted to other topics. The first streamlined version reduces thermodynamics by 3 weeks and adds weeks on the scientific method. The second streamlined version reduces thermodynamics by another 2 weeks and adds other energy topics including light. The third streamlined version reduces thermodynamics to half its original length and includes additional energy topics. (Table 3 provides a timeline of how the four versions of the curriculum relate to the initial design of CLP and to the longitudinal interview studies discussed later in this article.)

Figure 1. Curricular topics in the four versions of the curriculum.

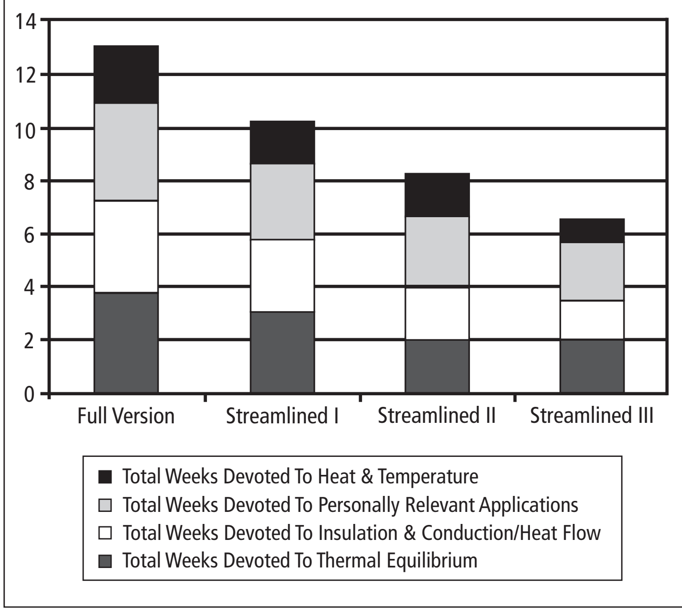


Table 3. Timeline of Studies and Data Discussed

Semesters	Studies Conducted
1–8	Initial 8-semester iterative study of design culminating in creation of full version of the curriculum.
9–12	Data on full version of curriculum collected. Eighth grade longitudinal interviews conducted
13–17	Data on first streamlined version collected. Longitudinal interviews continued with original students prior to their 10th-grade year.
18–22	Data on second streamlined version collected. Longitudinal interviews continued with original students prior to their 12th-grade year.
23–28	Data on third streamlined version collected.

Note. Semesters are listed rather than dates to protect identities of students participating in longitudinal interviews. All studies took place in the same classroom overseen by the same master teacher over the 28 semesters.

METHOD

To understand the impact of streamlining the CLP curriculum we connect three levels of analysis. First, we study 3,000 students learning from the four versions of the CLP curriculum, contrasting inquiry and multiple-choice assessments. Second, we analyze student knowledge development longitudinally for 50 students to clarify the nature of knowledge integration in the full version of the curriculum. Third, we examine the knowledge integration of 1 representative student from the longitudinal cohort to illustrate the impact of the CLP instruction on students as they continue through high school.

Participants

The same teacher taught all versions of the CLP curriculum in a diverse middle school. During each of the 20 semesters of the study, he taught 150 to 180 eighth-grade students in either five or six classes, yielding a total of 3,000 students who took pretests and posttests. The 50-student sample was randomly selected from 300 students in 1 academic year and studied intensively (E. L. Lewis, 1996). The detailed case study focuses on one representative student from this 50-student group to illuminate the findings from the other two analyses (D. B. Clark, 2000, 2003).

CLP Knowledge Integration Assessments

Each semester, all students respond to a set of common items on pretests and posttests. These tests include inquiry items (H. C. Clark, 1996; Linn & Hsi, 2000) and multiple-choice items. The CLP partnership designed inquiry assessments to measure knowledge integration. For instance, we ask students to distinguish between heat energy and temperature and give several reasons and examples for their answers, to write a principle explaining their views of everyday situations, and to explain what happens to a cold Coke and a hot potato when both are left on the table in the dining room. We also ask students to explain complex everyday phenomena such as why metal objects feel hotter than wood objects when left in a hot car trunk.

In the multiple-choice items, students select the best insulator, predict the temperature of objects around them, or select the best principles to explain various phenomena. Often, after selecting their multiple-choice answers, the inquiry questions ask students to give examples, justify, or explain their answers. The tests include a subset of common items to allow comparisons between semesters.

Knowledge integration items are scored on a 4-point scale based on the level of accuracy and cohesion in the responses: (1) non-normative, (2) transitional or mixed, (3) normative, or (4) nuanced and normative (Interview statements from the 50-student analysis and case study analysis were coded using the same scale—see representative responses in Appendix B.) Non-normative responses might include connections such as "metals keep drinks cold but not hot." Answers scored as transitional or mixed have both normative and non-normative ideas or ideas that involve normative elements. Answers scored as normative include normative ideas without many connections to other normative ideas or evidence. Answers scored as nuanced and normative involve not only the normative ideas but also important connections to other normative ideas or evidence.

This study focuses on four sets of common items, each involving both multiple-choice and inquiry questions (see Figures 2 and 3). The first set asks students to distinguish heat energy and temperature (see Figure 2), a concept central to understanding thermodynamics (Erickson & Tiberghien, 1985; Wiser, 1988, 1995; Wiser & Carey, 1983). This set appears in all four versions of the curriculum. The second set, also about the heat energy–temperature distinction, asks students to compare the amount of heat energy in a bucket of water to the amount of heat energy in the ocean (see Figure 2). This set appears in the first three versions of the curriculum. The third set asks students to explain what makes something a good insulator or conductor and to give examples. This set occurs in the first three versions of the curriculum (see Figure 2).

The fourth set involves three questions about thermal equilibrium and heat flow (see Figure 3). These questions occur in the first and second streamlined versions of the curriculum. The first question asks students to estimate the temperature of wooden and metal spoons after 4 hr in an 80 °C oven and to explain their answers. The second question focuses on the connections between heat flow, thermal equilibrium, insulation and conduction, and why objects feel the way they do. This question asks students to imagine holding the end of a metal nail and putting the other end on a piece of ice. Students are asked how the end of the nail will feel after 5 min and to explain their reasoning. The third question focuses on

Figure 2. Heat–temperature and insulation–conduction test items consistent across semesters.

HEAT/TEMPERATURE MEASURES

Distinguish Heat & Temperature item

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.

Ocean/Bucket item

A student went to the ocean and filled a bucket with ocean water. He measured the temperature of the water in the bucket and found it was 16 degrees Celsius. He also stuck a thermometer into the ocean directly and measured the temperature of the water to be 16 degrees Celcius. He concluded that since these two water sources have the same temperature, they contained the same amount of heat energy. What do you think?

a. (circle one)
   the ocean has more heat energy
   the water in the bucket has more heat energy
   they both have the same heat energy

b. What is the main reason for your answer?

INSULATION & CONDUCTION ITEMS

Good Conductors item:

a. Give an example of a good conductor. ____________________

b. What makes the substance you picked a good conductor?

Good Insulators item:

a. Give an example of a good insulator. ____________________

b. What makes the substance you picked a good insulator?

Figure 3. Thermal equilibrium and heat flow items consistent across semesters.

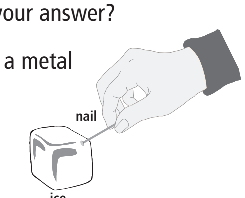
Oven item: A metal spoon and a wooden spoon were put into a 40 degree Celsius (warm) oven for 12 hours.

a. What do you predict their temperatures will be after 12 hours in the oven?
   Temperature of metal spoon ________________
   Temperature of wood spoon ________________

b. What is the main reason for your answer?

c. What evidence do you have to support your answer?

Nail & Ice item: Suppose you hold one end of a metal nail and put the other end on a piece of ice.



a. After five minutes how will the end of the nail in your hand feel? (check one)
   __________warmer __________colder _________the same

b. What is the main reason for your answer?

c. What evidence do you have to support your answer?

Hot & Cold item: Do containers or wraps that help keep hot objects hot also help keep cold objects cold?

a. (circle one) Yes No Cannot predict

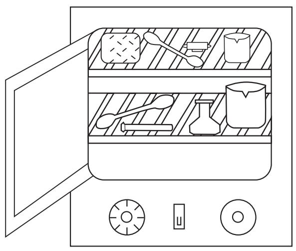
b. What is the main reason for your answer?

insulation and conduction and thermal equilibrium. It asks students to predict whether a container that keeps cold objects cold will also keep hot objects hot and to explain their answers.

Interviews for the 50-Student Sample

The randomly selected 50-student sample participated in five 30-min. interviews during eighth grade. Interviews were tape-recorded and transcribed. Tests and written class assignments were also collected. The interview questions address students' understanding of thermodynamics using everyday situations (see Figure 4). The interviewer probed contradictions, connections, differentiations, and reasoning patterns.

Figure 4. Sample interview questions for the longitudinal cohort.



Chemistry Drying Oven Question: In a chemistry lab students were drying equipment in an oven. The temperature of the oven was 150°C. In the oven were metal spatulas, glass beakers, and asbestos pads that had been there overnight. What do you predict the temperature of each is? Why? [Probe for their understanding.] If you could touch them, would they feel the same? Why? [Probe for their understanding of conduction and insulation using the students' terms. Also ask them to consider the small and large beaker. Most students will say they are the same temperature even if they do not have thermal equilibrium as a concept. Then ask them to compare the heat energy of the two beakers — is it the same or different and why?]

Hot Car Trunk Question: You are running an errand for your parents to buy several long strips of metal and several long strips of wood at a hardware store. You place the strips in the trunk of the car. It is a hot day and you and your friend stopped at another friend's house on the way home since you are not in a hurry. You left the strips of metal and wood sitting in the trunk of the car. When you returned several house later, you and your friend have different predictions about the temperature of the strips of metal and wood in the trunk. Your friend thinks the wooden strips would be hotter than the metal strips. Yo say the metal strips would be hotter than the wooden strips. Who is right? Why? [Probe for their understanding of the process of conduction and insulation as using the students' terms.]

Ski Cabin Question: You arrive at a ski cabin during the winter and no heat was left on. The room thermometer reads 5°C. What can you predict about the temperature of the objects in the cabin? Why? Did you always think about the objects in a room this way? [Probe for their understanding of thermal equilibrium.] What happens when you touch some of the objects in the room, e.g., the cast iron stove and wood on a small pile of wood next to it? If student says they feel different, ask why. [Probe for their understanding of conduction and insulation using the students' terms. If students are confused about why metals warm up, place a metal weight in their hands and ask them how it feels. Ask them to hold it tightly for a short while, then ask them how it feels again. Do the same with a wooden block and have them compare their feelings and try to explain what is happening.]

Interviews were coded for the sophistication of the students' understanding of (a) thermal equilibrium, (b) insulation and conduction, (c) heat energy and temperature, and (d) heat flow using coding methods designed by E. L. Lewis (1996) for an earlier longitudinal cohort. We collapsed this scoring to make it comparable to the non-normative, transitional, normative, and nuanced categories used for the knowledge integration items on the pretest and posttest.

Case Study

The representative case study student was selected from students demonstrating average performance in the 50-student longitudinal interview sample. This student, whom we call Cedar, brings many ideas from his outside experience into the classroom and struggles to reconcile these ideas with normative instructed ideas.

By watching Cedar's progress, we get a sense of the process through which many students make sense of science. This case study clarifies the results from the 3,000-student and 50-student samples in terms of why it takes so much time for students truly to learn core science concepts.

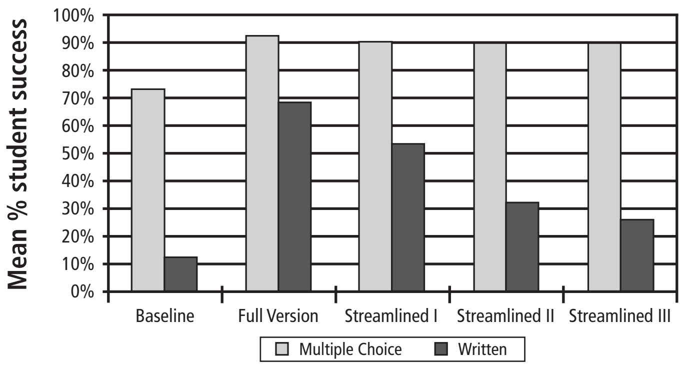
In the case study, we follow the knowledge integration process focusing on five areas: (a) the main ideas and models employed by Cedar in his explanations at each interview; (b) connections between ideas made at each interview; (c) warrants used in interviews; (d) apparent integration and coherence strategies employed in the interviews; and (e) overall progression, regression, and digression across Cedar's longitudinal career. We report analyses for three aspects of thermal equilibrium, including the temperature of objects in the same environment, sensory experience when touching objects in the same environment, and the role of insulation and conduction in thermal equilibrium.

RESULTS

To compare the 12-week CLP curriculum with the streamlined versions, we examine performance on multiple-choice and inquiry measures. For the most demanding inquiry item, the essay distinguishing the difference between heat and temperature, results shown in Figure 5 demonstrate substantially reduced student understanding as the curriculum is streamlined, $F(3, 2875) = 115$, $p < .001$. More students (about 69% vs. 25%) achieve the most complete understanding of the distinction between heat and temperature in the full version of the curriculum than in the more streamlined versions of the curriculum. This heat energy–temperature differentiation question also involves a multiple-choice component in which students indicate whether heat energy and temperature are the same or different. For this recall item, students perform equally in the full curriculum and all of the streamlined versions of the curriculum.

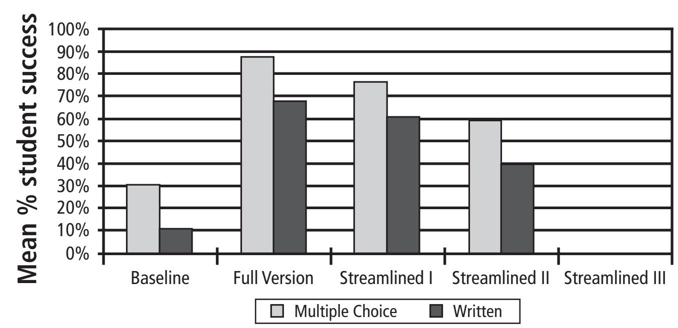
The second heat energy–temperature differentiation question asks students to compare the impact of heat energy in a bucket of water and in the ocean (see Figure 6). This question was administered across the first three versions of the curriculum. More students (about 68% vs. 39%) give complete explanations of the distinction between heat and temperature in the full version

Figure 5. Performance by curricular version on the heat–temperature item.



Inquiry: (F(3, 2875) = 115, p < 0.001)
Multiple-choice: no significant difference

Figure 6. Performance by curricular version on the ocean–bucket item.



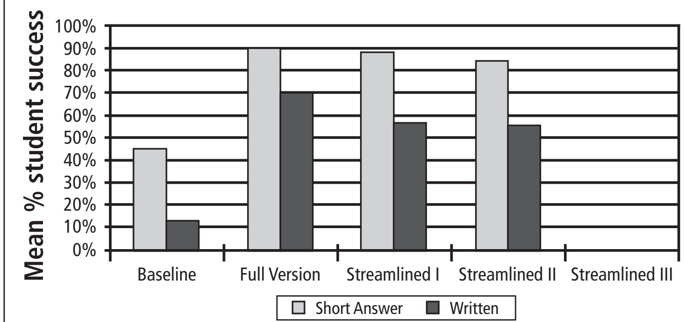
Inquiry: F(3, 1354) = 33, p < 0.001
Multiple-choice: F(3, 1364) = 39, p<0.001

compared to the streamlined versions of the curriculum, $F(3, 1354) = 33$, $p < .001$. The multiple-choice portion of this question is also sensitive to streamlining of the curriculum, $F(3, 1364) = 39$, $p < .001$.

Questions on insulation and conduction are consistent across the full version of the curriculum and the first two streamlined versions. These questions ask students to give examples of good insulators and good conductors and to justify and explain their answers. Consistent with results for heat and temperature, students in the full version have greater success on the knowledge integration question (about 70% vs. 55%) than do students in the streamlined versions, $F(3, 1755) = 4.5$, $p < .005$ (see Figure 7). Students from all three curriculum versions perform more similarly on items where the students are required to give examples of good conductors and insulators, but students in the full version show somewhat stronger performance, $F(3, 1755) = 3.8$, $p < .01$.

Three questions on thermal equilibrium and its connection to insulation and conduction appear on the first and second streamlined versions of the curriculum. The first question asks about

Figure 7. Performance by curricular version on the insulation–conduction items.

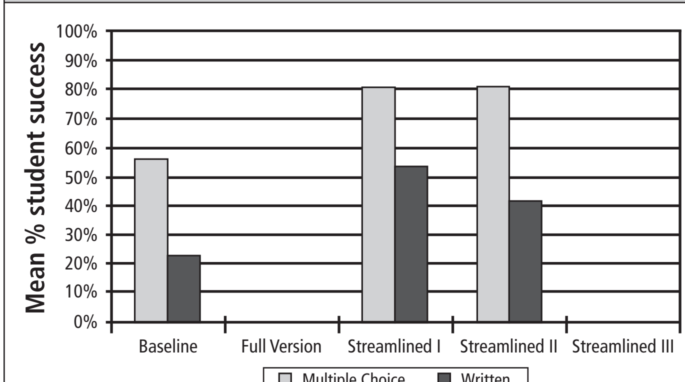


Inquiry: F(3, 1755) = 4.5, p < 0.005
Short Answer: F(3, 1755) = 3.8, p<0.01

thermal equilibrium and the role of insulation and conduction by having students estimate the temperature of a wood spoon and a metal spoon after 4 hr in an 80 °C oven and explain their answers. The second question addresses the direction of heat flow, thermal equilibrium, insulation and conduction, and why objects feel the way they do. This question asks students to imagine holding the end of a metal nail and putting the other end on a piece of ice. Students explain how the end of the nail in their hands will feel after 5 min and describe their reasoning. The third question focuses on insulation, conduction, and thermal equilibrium. Students predict whether a container that keeps cold objects cold will also keep hot objects hot and explain their answers. Scores for these questions show that students in the full version of the curriculum have greater success (about 54% vs. 40%) on the essay items than do students in the streamlined versions, $F(3, 1266) = 18$, $p < .001$. The multiple-choice questions are insensitive to curriculum version (see Figure 8).

These results demonstrate that streamlining the full version of the curriculum to make room for other topics reduces overall knowledge integration. About three quarters of the students

Figure 8. Performance by curricular version on the thermal equilibrium and heat flow items.



Inquiry: F(3, 1266) = 18, p < 0.001
Multiple-choice: No significant difference

succeed on knowledge integration for the full version, whereas between one quarter and one half of the students succeed with the streamlined versions. In particular, students have less ability to reason and warrant ideas in essays. These declines in student knowledge integration as the curriculum is streamlined mean that well over half the students are left behind. By streamlining the full version of the curriculum to make room for other topics such as light, we substantially impact the knowledge integration process. In the most streamlined version, only 25% of the students develop understanding generative and rich enough to write essays that make connections to other concepts, warrant assertions, and explain perspectives for the most challenging questions.

Aligning knowledge integration inquiry items with the curriculum reveals the impact of streamlining. The knowledge integration inquiry items depart from the typical assessment practices by requiring coherent arguments including examples. In contrast, success on many types of multiple-choice items requires less sophisticated understanding of the material and hence less substantive instruction.

It is possible to construct multiple-choice questions that require knowledge integration and application as opposed to memorization, as shown by the second heat and temperature question about the ocean and the bucket. Many multiple-choice questions currently in use, however, are not as sensitive to knowledge integration as we would like. The ocean–bucket question demonstrates features of effective questions. This question asks students to distinguish temperature, mass, and heat energy. The normative answer, that the ocean holds more heat energy because of the greater mass of water in the ocean, clashes for students with the idea that the water in the bucket and ocean are the same temperature. This item demands that students untangle and apply the relation of heat energy and temperature. This multiple-choice question therefore requires more than a rote answer and prompts some of the non-normative ideas that signal a lack of knowledge integration.

Threats to Validity

Potential threats to the validity of this type of longitudinal study might include (a) varying the teachers or the settings of the trials, (b) conflating the longer versions of the curriculum and versions of the curriculum receiving the most iterative refinement, and (c) conflating the presence of fewer researchers in the classroom and lower student performance. In terms of setting and teacher, we conducted the research in the same classroom with the same master teacher for the 28 semesters, and he currently continues to work with our research group. Therefore the setting remained as constant as possible, and if anything, the teacher became more experienced in dealing with students' alternative conceptions of thermodynamics, inquiry teaching, and use of technology. In terms of the second concern, the shortest versions of the curriculum were the final versions and benefitted from several more years of refinement. The quality of the software remained the same or improved over the course of those years. With regard to the third concern, the number of graduate students involved in research on the experimental classroom varied during each phase of the curriculum. The number of graduate students observing and interviewing students was higher in the first streamlined version than in the full version of the curriculum and slightly lower in the second and third streamlined versions, but several graduate students observed and gathered data in the classroom across all versions of the curriculum. The fact that the first streamlined version of the curriculum resulted in lowered student outcomes in comparison to the full version suggests the possibility that active graduate students could interfere with student learning. However, the outcomes from the second and third streamlined versions of the curriculum demonstrate the opposite relation, diminishing concern about this variable.

Comparison to the National Science Standards and Other Frameworks

The CLP curriculum aligns with the National Science Standards (National Research Council, 1996) by focusing on inquiry and the suggested physical science energy topics for Grades 5 through 8. CLP uses accessible macroscopic models as opposed to molecular models for Grades 5 through 8, also consistent with these standards. Finally, although the National Science Standards do not explicitly assign a number of topics per year, there is philosophical agreement between the CLP curriculum and the National Science Standards with respect to recommending conceptual in-depth learning goals. Neither the CLP curriculum nor the National Science Standards align with the average rate of 65 topics per year in U.S. schools found in state frameworks as determined by the TIMSS study (Schmidt et al., 1997).

In one semester the full version of the CLP curriculum covers 4 thermodynamics topics that equate to a rate of 8 topics covered per year. This rate of topic coverage is on par with the rate of 5 to 7 topics covered per year in the countries scoring highest in science in the TIMSS findings. The results for the four versions clearly demonstrate the strong relation between the full curriculum and knowledge integration. Streamlining the curriculum results in significantly diminished student learning. Even the most streamlined version took about 6 weeks of class time, contrasting sharply with the 1 or 2 weeks recommended for these topics in most U.S. textbooks. If the rate of topic coverage in the 6-week (most streamlined) version were adopted, schools would cover about 16 topics each year or about one quarter of the topics recommended in state frameworks. Indeed, the recent California Science Framework advocates about 48 topics in eighth grade organized under main themes.

A critical issue besides time per topic, however, is the integrated nature of the curriculum. In CLP, students regularly revisit the topics they have covered during the course. This coordinated coverage of interrelated topics is a central component of the CLP curriculum and requires teachers to draw connections across the curriculum. Drawing connections across the curriculum is also central to the National Science Standards. To understand how the CLP curriculum impacts student learning, we analyze progress of a 50-student sample following the full version of the curriculum.

Longitudinal Analysis

To clarify the nature and process of knowledge integration, we summarize performance for 50 students who were interviewed approximately every 3 weeks during the full version of the CLP curriculum. We examine the course of their knowledge integration for the four main topics and characterize their progress in knowledge integration during and after instruction. We note that most students continue to build understanding of every topic throughout the curriculum, attesting to the success of the supports for knowledge integration.

Figures 9 through 12 represent the performance of all 50 students for each of 4 topics including heat energy and temperature (see Figure 9), thermal equilibrium (see Figure 10), insulation and conduction (see Figure 11), and heat flow (see Figure 12). These figures show the percentage of students at each interview exhibiting non-normative, transitional, normative, and nuanced understandings of each thermodynamics topic.

By the second interview (after 3 weeks of instruction), less than 50% of the students have a normative understanding of the heat and temperature distinction, and only 5% of the students have a nuanced or normative understanding of this topic that allows them to make connections to other important normative ideas (see Figure 9). In contrast, a typical course would have covered all thermodynamics topics by Interview 2. At this point, the students would move on to another aspect of physical science such as mechanics. Across the subsequent interviews in the CLP curriculum, however, we see a steady increase in the percentage of students having normative and nuanced understanding of this first topic. By the final interview, 87% of the students have at least a normative understanding of heat and temperature, and 68% of the students have a nuanced understanding of heat and temperature that they can connect to other important normative ideas, consistent with the overall posttest level of 70% success on heat and temperature inquiry items (see Figure 5).

For thermal equilibrium, prior to instruction only 3% of students express primarily normative ideas and no students can make nuanced connections to other normative ideas (see Figure 10). By the second interview (3 weeks into instruction) only 12% continue to express primarily non-normative ideas (a decrease from 68% before instruction), but only 17% of the students have achieved nuanced understandings. Progress continues, and by the end of instruction 70% can express at least normative understandings of thermal equilibrium and 60% can express nuanced understandings. This interview performance is consistent with the posttest performance of the full curriculum groups on inquiry items (see Figure 8).

For insulation and conduction, students come to the CLP class with a larger collection of transitional insulation and conduction ideas than they do for the other topic areas (see Figure 11). In spite of this information, less than 2% of the students express normative ideas about insulation and conduction at the first interview. On the second interview, after 3 weeks of instruction, 40% of the students achieve primarily normative ideas, and 82% express primarily normative ideas by the final interview. Even more impressive, by the final interview, 42% of the students consistently make nuanced connections to other important normative ideas.

For heat flow, the first topic in the curriculum, students make more rapid initial progress than on the other thermodynamics topics (see Figure 12). For heat flow, 65% of the students achieve normative or nuanced understanding by the second interview (after 3

Figure 9. Performance on heat and temperature questions by the longitudinal interview students.

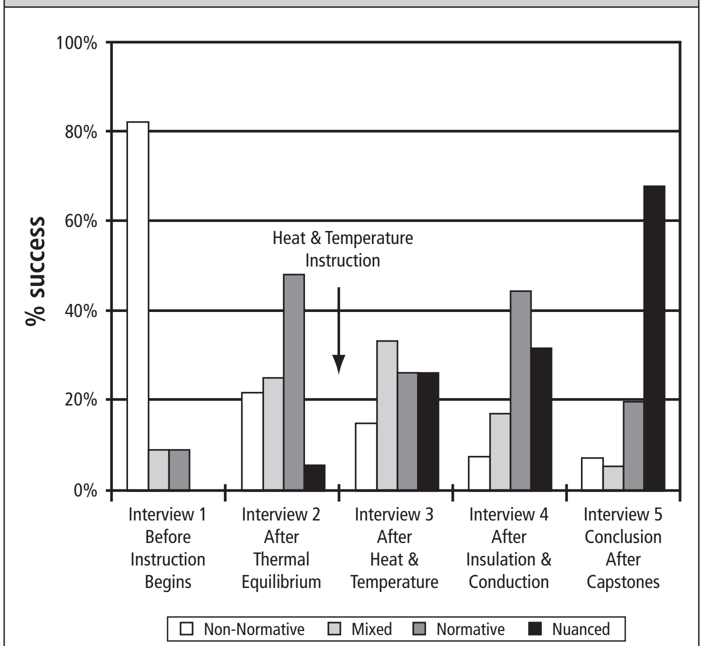


Figure 10. Performance on thermal equilibrium questions by the longitudinal interview students.

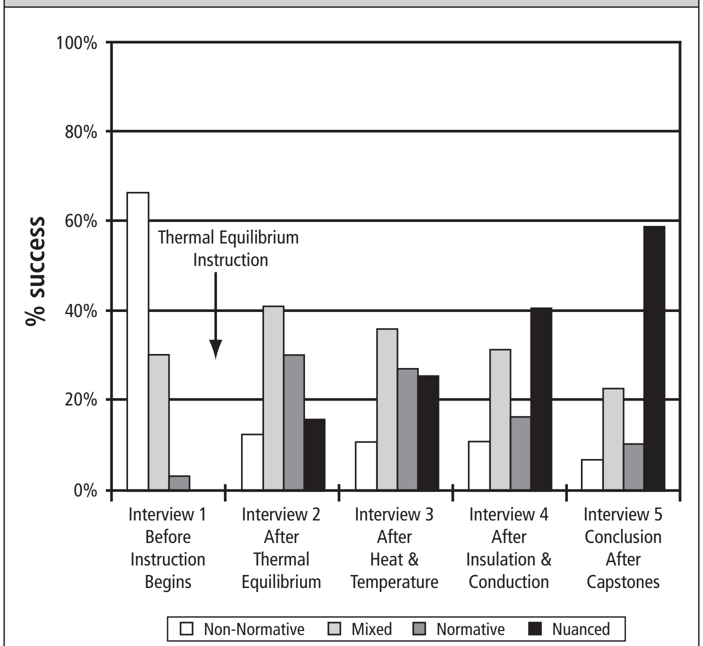


Figure 11. Performance on insulation and conduction questions by the longitudinal interview students.

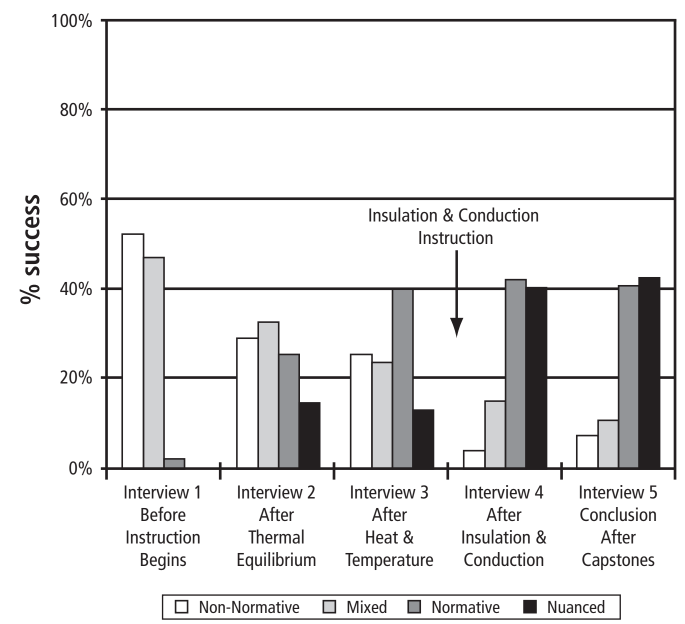
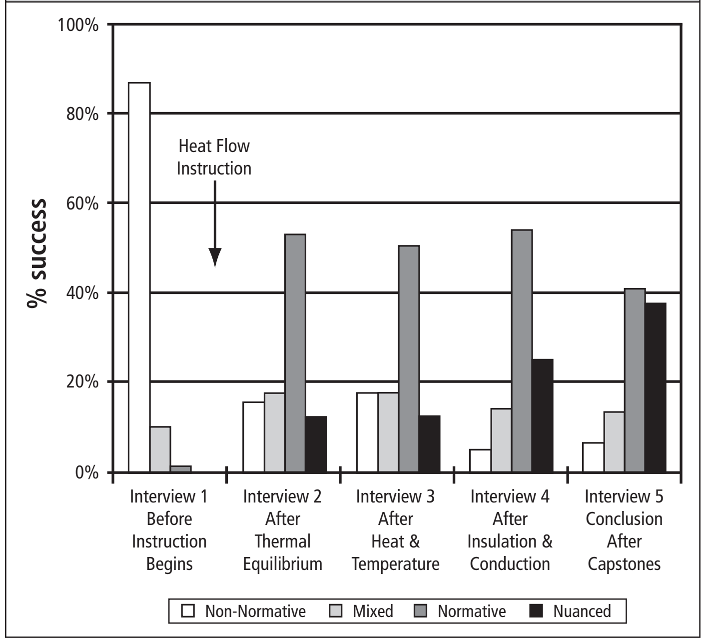


Figure 12. Performance on heat flow questions by the longitudinal interview students.



weeks of instruction). By the end of the curriculum 79% achieve this level of sophistication, with 38% expressing nuanced connections to other important normative ideas.

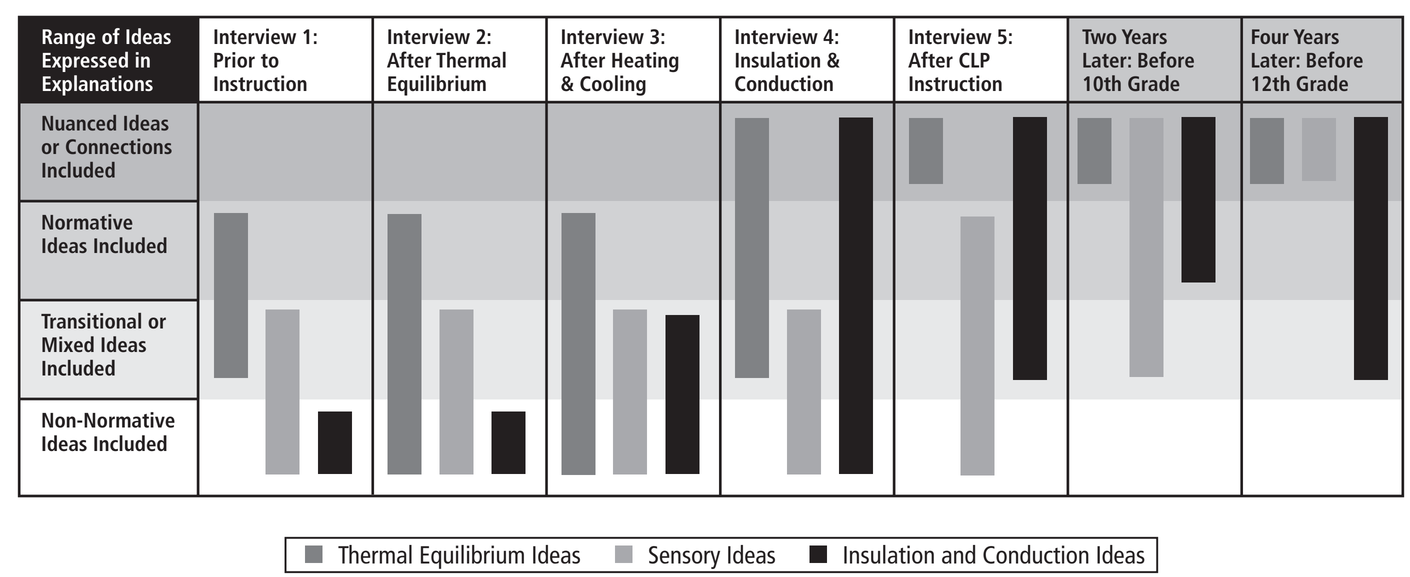
These results illustrate the advantage of instructional depth for achieving knowledge integration. For example, at the beginning of the semester, most students start with predominately non-normative repertoires of ideas regarding thermal equilibrium. By the second interview, many of the students add ideas and maintain mixed repertoires including non-normative and normative ideas regarding thermal equilibrium. Although adding ideas signifies progress, these ideas are not integrated or cohesive. Some ideas are connected normatively, but non-normative ideas and connections remain prominent. The typical curriculum would stop coverage at the second interview, leaving the students with a weak foundation for future learning. At this point, less than 47% of the students express primarily normative or nuanced under standings and only about 17% of the students make nuanced connections to other important normative ideas. These levels increase dramatically by the final interview and approach the levels reported for the posttest items.

These results also demonstrate that the CLP curriculum enables students to make progress on all of the major thermodynamic topics simultaneously. The CLP emphasis on knowledge integration supports students so they can connect their ideas from all the major topic areas starting in the 1st week and continuing to the 12th week. The CLP curriculum emphasizes building connections between all of the major topics and personal experiences throughout the curriculum, rather than focusing narrowly on each topic separately and independently of the other topics and personal experiences. This approach takes time in the curriculum but appears from these results to be successful. For example, thermal equilibrium is the focus of the first portion of the curriculum, but students continue to make significant progress in thermal equilibrium during the subsequent time in the curriculum. In fact, if students were to stop making progress in thermal equilibrium after it was no longer the primary focus of the curriculum, the majority of the students would be left with non-normative, brittle understandings of thermal equilibrium. Similarly, although insulation and conduction is not the primary focus until later in the curriculum, students are already building a foundation for insulation and conduction from the beginning. As the results from streamlining reinforce, these additional opportunities to revisit ideas dramatically enhance knowledge integration.

These results from the 50-student analysis also suggest an explanation for why performance on the complex inquiry questions is so sensitive to changes in instructional time, whereas many of the multiple-choice questions are less sensitive. These figures show that students are able to add new ideas by the time of the second interview, but that at the time of the second interview they have not yet sorted and integrated these new ideas into a nuanced repertoire. This level of understanding may be sufficient for many multiple-choice questions where the students are not required to draw connections or to warrant their assertions. To respond successfully to inquiry questions, however, students need generative and rich connections to other concepts, as well as the ability to select from among the normative and non-normative ideas. The figures show that, for many students, this higher level of understanding is not achieved until the fifth interview.

The results showing that students add ideas quickly but that sorting takes more time begin to explain the deleterious impact of the curricular streamlining. To understand the adding and sorting process more clearly, we now look at an in-depth case study of an

Figure 13. Range of ideas expressed in Cedar's explanations across all interviews.



individual student to see how students actually integrate their understandings over time.

CASE STUDY: CEDAR

This student, whom we call Cedar, is representative of CLP students in terms of the process through which he makes sense of thermal equilibrium over the course of his eighth grade semester and on into high school. Cedar was selected from the students demonstrating average performance within the longitudinal cohort. Cedar brings many ideas from his outside experience into the classroom and struggles to reconcile these ideas with normative instructed ideas. This case study clarifies the results from the 3,000-student and 50-student samples with respect to why it takes so much time for students really to learn core science concepts.

Cedar's case study is particularly illustrative and representative in the way that he grapples with multiple contradictory ideas as he makes sense of thermal equilibrium. Thermal equilibrium is a science concept explaining aspects of heat energy transfer between objects of different temperatures. Essentially, objects in the same environment (e.g., in a refrigerator) will eventually become the same temperature unless they produce their own heat energy (e.g., a wooden bowl and a metal spoon become the same temperature as the refrigerator, but a living person does not become the same temperature as her surroundings). This is because there is a net heat energy flow from objects of higher temperatures into objects of lower temperatures until equilibrium is established. Thermal equilibrium is a difficult concept for students because it seemingly contradicts their personal experiences. Some materials often feel hotter or colder than other materials. For example, a metal spoon in the refrigerator will feel colder than a wooden bowl even though after several hours in the refrigerator they are the same temperature. Certain materials (e.g., metal and glass) tend to feel hotter or colder because they conduct heat energy better than other materials (e.g., wood); when you touch a metal object, heat energy flows more quickly into or out of your hand. For example, heat energy flows more quickly out of your warm hand when you touch a metal spoon in the refrigerator than when you touch a wooden bowl. Students, however, interpret this experience to mean that the metal spoon is actually a lower temperature than the wooden bowl (i.e., if it feels different it must be a different temperature). Students are so committed to this interpretation of their experience that they are extremely resistant to the idea that the objects actually become the same temperature. Cedar's case study illustrates the difficulties students have integrating their experiential knowledge with school instructed ideas like thermal equilibrium.

In analyzing Cedar's understanding of thermal equilibrium, we focus on issues of temperature change, time, sensory perception of temperature, and the role of insulation and conduction in thermal equilibrium. Figure 13 provides an overall view of Cedar's progress in these topics. A list of the primary ideas Cedar expresses in each interview is included in Appendix B, and an extensive analysis of each interview is also available (Clark, 2000, 2003). During the first two interviews, Cedar expresses non-normative thermal equilibrium, sensory, and insulation and conduction ideas in his explanations, although he also expresses some transitional and normative thermal equilibrium and sensory ideas. During these early interviews, Cedar makes few connections between ideas unless prompted. By the third interview (9 weeks of instruction), Cedar has added new normative and nuanced ideas and is making connections between ideas. At the end of CLP, in the last interview, Cedar relies primarily on normative and nuanced ideas and is able to make significant connections between core instructed concepts. Cedar has integrated a robust framework of ideas into which he connects new ideas from high school as he continues to make progress in his understanding of sensory ideas and insulation and conduction.

Interview Analysis

Interview 1: Prior to instruction. Following the pretest, Cedar expresses multiple contradictory ideas about thermal equilibrium in his explanations. In particular, we see Cedar switch between normative and non-normative thermal equilibrium explanations based on his experiences and the interviewer's questions. Cedar has apparently not drawn connections between these ideas before.

- Cedar initially asserts that metal and wood objects "both would be the same [temperature as the oven] . . . if [the oven] was same temperature how could they get hotter or colder?"
- This explanation, however, is overruled when Cedar is asked if two objects can be the same temperature but feel different. He initially says "yes" because "one could be metal and one could be wood." As he explains, "metal is usually cool, and wood you can't really tell what temperature wood is."
- When asked why objects feel different if they are the same temperature, he revises his position and says that the objects actually are different temperatures.

Consistent with our other case studies (D. B. Clark, 2000, 2003; Linn & Hsi, 2000), Cedar's ideas vary by context such as a hot car or a cold ski cabin. Contexts apparently cue students' sensory experiences about how objects feel and, as shown by Cedar's case, often elicit a contradictory mix of normative and non-normative ideas. Also consistent with many other students, Cedar makes few unprompted connections between ideas.

Interview 2: After thermal equilibrium instruction. Three weeks later, when a typical curriculum would end, Cedar has added multiple class ideas to his explanations. His explanations, however, are often in conflict with one another. Cedar is becoming aware of these conflicts. Cedar attempts to create explanations for the apparent contradictions by discounting or weakening the instructed thermal equilibrium concepts. Early in the interview, Cedar expresses (a) the accurate idea that "objects in the same room should be the same temperature," (b) a disruptive idea that "objects that are the same temperature should feel the same," and (c) an accurate idea apparently from experience that "some objects feel colder than others in the same room." Cedar creates a series of explanations trying to make these ideas fit with one another. Example explanations include the following:

- When asked why in some situations objects of different materials would be the same temperature, and in other situations objects of the same material would be different temperatures Cedar says, "Um they, they're in like something that's warming up and something that's staying the same temperature."
- When asked why objects might be the same temperature but feel different Cedar says, "Because it's like, it's made of a different thing. It's wood and it doesn't feel as cold as metal."
- Later, Cedar explains that metal feels the way it does because "it's like smoother, and it's . . . solid, more solid."

Throughout the second interview, we see sensory information conflicting with school-instructed ideas. Cedar expends significant effort developing idiosyncratic explanations that connect sensory and school-instructed ideas. Overall, Cedar has added class vocabulary and class ideas to his repertoire of ideas, but he has not managed to sort and connect them into more normative and integrated explanations. If the curriculum ended here, as it would in a traditional arrangement, Cedar would be left with a fractured set of ideas that might be sufficient for a multiple choice test but not for an essay test probing his understanding. Cedar lacks an integrated, core understanding robust enough to support lifelong learning.

Interview 3: After heat and temperature instruction. After 6 weeks of instruction, Cedar evidences significant progress in his understanding of thermal equilibrium. His thermal equilibrium explanations are often normative. As in the earlier interviews, however, Cedar's sensory experiences remain disruptive. In addition to his normative thermal equilibrium explanations, Cedar expresses several non-normative thermal equilibrium explanations that are interesting alternatives to the normative concepts. Some of these have obvious appeal in light of the apparent contradictions facing Cedar.

- In a new non-normative explanation, objects come "within a degree or two" of equilibrium, and therefore Cedar's experiential sense that "objects that feel different must be different temperatures" is left intact while his thermal equilibrium explanations seem "close enough."
- Cedar attributes temperature differences to materials in some of his explanations, saying for example that asbestos may never become the same temperature as the oven because it is a different material.
- Cedar uses conductivity non-normatively in some explanations.
- Cedar uses the properties of "surface," "solidness," or "coolness" to explain how objects of different materials might be the same temperature but feel different.

Essentially, Cedar is continuing to sort through the contradictions and ideas. Although he has made significant progress in his understanding of thermal equilibrium and seems committed to the instructed thermal equilibrium concepts, his sensory experience continues to provide dissonance. Amongst his vast array of ideas, Cedar has all of the necessary concepts and ideas to build a strong normative understanding of thermal equilibrium. He now needs to sort and reorganize these ideas and connections into an integrated framework.

Interview 4: After insulation and conduction instruction. After 9 weeks of instruction, Cedar begins the fourth interview with the general notion that materials can conduct heat so that objects come close to the same temperature but do not quite reach it. These new ideas about conductivity disrupt his progress on thermal equilibrium explanations, and Cedar expresses fewer normative thermal equilibrium explanations than in the third interview. His thermal equilibrium explanations tend to emphasize and apply experiential sensory ideas and instructed conductivity ideas inaccurately. Examples include the following:

- Cedar explains that a "metal bowl would be warmer [in the oven] than the wood [bowl] because metal is a good conductor and wood is not. And wood is a, is a poor insulator."
- Interestingly, Cedar at times denies his own experiential sense to reduce conflict with the instructed concepts. When Cedar asserts normative thermal equilibrium ideas about all objects reaching the same temperature, Cedar is again faced with conflict. In these situations, Cedar revises his idea that metal and wooden objects feel different, saying that "If they are the same temperature, then they must feel the same."
- Through further discussion with the interviewer, Cedar eventually decides that "they're probably the same temperature but they don't feel the same." When asked to explain, Cedar uses non-normative versions of classroom ideas about insulation and conduction creatively to link ideas, saying, "Well um metal feels colder than wood and it's a, it's a better conductor so the heat from the outside um, uh would get in but it's a poor insulator so it would escape."
- After some struggle, Cedar returns to his idiosyncratic "surface" ideas: "I'm not sure. It might be because of the surface . . . It's smooth and hard and wood is kind of like rough." (There is an unexplainable change in format in the original text, re: indentation, but I hope we can keep a consistent format throughout the text on interview results.)

This attempt to interpret instructed ideas suggests that Cedar is actively trying to connect newly introduced classroom ideas about conductivity into his explanations along with his experiences. These new school ideas prompt Cedar to reassert his experiential view that the objects remain different temperatures and to support his observation that the objects feel different. Although his thermal equilibrium explanations tend to be less normative in this interview, Cedar has now begun connecting conductivity, albeit non-normatively. With further reorganization and sorting of his ideas, Cedar stands poised to make a significant breakthrough in his understanding of thermal equilibrium (and of thermodynamics in general).

Interview 5: After eighth-grade posttest. In the fifth and final eighth-grade interview, Cedar embraces several normative thermal equilibrium ideas and sets aside several prior non-normative ideas. Cedar enters the fifth interview with normative explanations of thermal equilibrium that correctly incorporate change over time.

- When asked about the temperatures of a metal and wooden spoon after 12 hr in an oven, Cedar answers that after "12 hours, they'd probably both reach the same temperature of the oven, because after a long time, the objects will adjust to the surroundings." He connects insulation and conduction by saying, "The metal spoon will adjust more quickly because ''it is a better conductor."
- He continues, however, to have trouble explaining how two objects could be the same temperature but feel different. When asked, he explains that "maybe they have um the like maybe they're different surfaces, and one can be like smooth and the other one can be rough or soft or hard," which is important because "the smooth one would probably feel a little warmer cause when you touch it, there's more that you feel, cause rough is like you don't feel the whole thing."

Overall, Cedar makes significant progress unifying and integrating his repertoire of ideas for the fifth and final interview of his CLP semester. He connects the important instructed ideas of insulation and conduction, heat energy flow, and thermal equilibrium. This ability to draw connections between major instructed concepts represents a significant achievement in comparison to the isolated ideas Cedar expresses in his early interviews. His final remaining challenge involves connecting insulation and conduction and thermal equilibrium to why things feel hot or cold. One interesting aspect of his "surface" explanations is the manner in which they become more intricate and reasoned in each interview. We first see the germination of these explanations in the second interview with the relatively inchoate "it's like smoother, and it's . . . solid, more solid" and over the course of the interviews we see him build a much more rich and articulate explanation that, because wood is rougher, you feel less of the surface when you touch it so that it does not feel as cold. This evolving explanation is further evidence that Cedar has been actively working over the semester to resolve the conflict between his experiential knowledge and the instructed ideas.

Interview 6: Before 10th grade. Two years later, after taking biology in the interim, Cedar maintains a repertoire of ideas and explanations resonant with a fundamental understanding of thermal equilibrium. He still, however, has difficulty explaining why things feel the way they do.

- When asked about the temperature of various objects in a ski cabin that has had the furnace turned off for several months, he answers: "Well, no one's been there for a long time, right? . . . Room temperature." When asked how the metal objects would feel, Cedar accurately predicts that the metal will feel colder, but lacks an explanation for why objects feel the way they do: "The metal—the stove would probably . . . feel colder . . . I don't know [why]."
- In the context of metal and wood objects in a hot car trunk, Cedar also connects and integrates a nuanced set of insulation and conduction, thermal equilibrium, and temporal ideas. As Cedar explains: "The metal would have warmed up faster so it would probably be the room temperature—the temperature of the trunk, so it would probably be pretty hot. But the wood, it's not as good of a conductor so it wouldn't have warmed up as fast, it wouldn't be hot . . . [But after a few hours] maybe both would probably be the same temperature."
- A few of Cedar's explanations verge on inappropriately applying insulation and conduction ideas to the thermal equilibrium

- process, but these conflicting ideas are no longer as strongly connected to his current explanations as they were during the fourth interview of his CLP semester.
- Cedar is very accurate in connecting the correct properties to various materials.

Cedar has taken high school biology preceding this interview, and although he does not seem to have added many new ideas, he definitely retains the understanding of thermal equilibrium he built during eighth grade. Rather than collecting a set of brittle forgettable facts, Cedar has apparently built a framework that remains robust.

Interview 7: Before 12th grade. In the final longitudinal interview before 12th grade, after taking chemistry in the interim, Cedar demonstrates progress in expanding his framework of ideas and understanding.

- Cedar demonstrates how his CLP foundation connects to his high school study of chemistry and the molecular kinetic model, saying: "The faster the molecules move around the hotter it gets."
- His understanding of thermal equilibrium remains strong, as in the context of two different sized blocks of ice in the freezer where he explains: "They'd be the same temperature because um, the freezer is set at zero degrees centigrade. Celsius whatever. They can't get colder than that, because they need something to get colder, and they can't get any warmer."
- The major breakthrough for Cedar is a connection of the flow of heat energy and insulation and conduction ideas with how objects feel. When asked how different objects in an oven would feel, Cedar says, "Uh, I think the metal spatula would feel hotter or more hot, [laughs] because the, it's a better conductor, and the heat energy it can escape and go through the object faster than wood. So it would go to your fingers faster than the wooden object."

We see very coherent and integrated explanations involving all of the instructed thermodynamics topics. Cedar has moved from integrating only a few ideas together in the early interviews to competently integrating multiple ideas. Although Cedar has not yet taken physics, he seems well prepared to continue building and expanding his understanding of thermodynamics in the future.

CASE STUDY SUMMARY AND CONCLUSIONS

Cedar brings many ideas from his outside experience into the classroom and struggles to reconcile these ideas with normative instructed ideas. During the first two interviews, Cedar expresses non-normative thermal equilibrium, sensory, and insulation and conduction ideas in his explanations, although he also expresses some transitional and normative thermal equilibrium and sensory ideas. During these early interviews, Cedar makes few connections between ideas unless prompted. By the third interview (9 weeks of instruction) Cedar has added new normative and nuanced ideas and is making connections between ideas. At the end of CLP, on the last interview, Cedar relies primarily on normative and nuanced ideas and is able to make significant connections between core instructed concepts. Cedar has integrated a robust framework of ideas into which he connects new ideas from high school as he continues to make progress in his understanding of sensory ideas, insulation, and conduction.

Cedar was selected from the students demonstrating average performance within the longitudinal cohort. Cedar, like many other students, grapples throughout with multiple contradictory ideas as he makes sense of thermal equilibrium. Consistent with our other case studies (D. B. Clark, 2000, 2003; Linn & Hsi, 2000), Cedar's ideas are often connected to a context such as a hot car or a cold ski cabin. Contexts cue sensory experiences about how objects feel and, as shown by Cedar's case, often elicit a contradictory mix of normative and non-normative ideas. Cedar's sensory information conflicts with school-instructed ideas. He expends significant effort developing idiosyncratic explanations that connect sensory and school-instructed ideas. Cedar's ultimate success therefore involves more than the addition of normative ideas. Cedar must sort, reorganize, and integrate his ideas and knowledge from outside the classroom with these new instructed concepts. Cedar successfully adds normative ideas from class by the second interview (3 weeks). It takes the rest of the semester to integrate successfully these normative ideas with one another and with his experiential knowledge. Had instruction stopped after 3 weeks, Cedar would develop only easily forgotten fragmented ideas. The ideas Cedar develops help him continue to add ideas in high school.

Cedar's case study helps explain results from the 3,000-student and 50-student samples. The case shows why it takes so much time for students really to learn core science concepts. This case study also clarifies the mechanics behind the impact of the CLP curriculum. CLP prompts students to revisit ideas in multiple contexts and to engage in crucial sorting and refining of explanations. CLP also provides scaffolding to build critical connections and explanations. Furthermore, CLP identifies pivotal cases that help students focus on these critical connections (Linn, in press; Linn & Hsi, 2000).

The early weeks of CLP primarily enable Cedar to add ideas even though prompts encourage making connections. The CLP curriculum supports students in revisiting ideas multiple times and building connections across contexts but cannot speed up that process. With sufficient time, the curriculum enables students like Cedar to lay the groundwork for lifelong learning.

DISCUSSION

Teachers, curriculum designers, state framework committees, and groups setting national standards all face a tradeoff between including every important topic in science and devoting more instructional time to fewer topics. Some groups argue that students need an introduction to all of the varied topics central to science, whereas teachers and students themselves often complain that fleeting coverage of myriad topics stands in the way of understanding. These investigations showcase this tradeoff. They raise three important issues focusing on (a) the impact of instructional time, (b) the ability of assessments to detect the impact of instruction, and (c) the processes individuals follow to engage in knowledge integration during the available time. To address these issues, we looked at four versions of the curriculum, two kinds of assessments, and three levels of analysis.

Our research shows that well-designed opportunities for knowledge integration yield greater student understanding. The comparison of four versions of the curriculum demonstrates that decreasing the time spent on CLP strongly and significantly diminishes student understanding of complex thermodynamics concepts. For thermodynamics, a 12-week curriculum results in 70% to 90% of students gaining normative ideas about the four thermodynamics topic areas. Shortening this curriculum to half its length reduces the proportion of students who gain a normative understanding in all four areas by roughly one half and reduces the proportion of students who gain an understanding nuanced enough to make normative connections to other core concepts by roughly two thirds.

These results complement and reinforce the results from the eight-semester initial design and iterative refinement of the CLP curriculum. Through eight semesters of iterative refinement, the CLP partnership raised student posttest scores on knowledge integration items like the heat energy–temperature distinction question by 400% while maintaining 12 to 13 weeks of instruction (Linn & Hsi, 2000). These results demonstrate the importance of effective instructional design. This study builds on these findings, showing that streamlining a well-designed curriculum reduces student knowledge integration.

Our partnership concurrently designs instruction and assessments, making the knowledge integration instructional framework the basis for both. This approach results in good alignment between instruction and assessment and takes advantage of the instructional framework. These investigations demonstrate that assessments vary in their sensitivity to instruction. In particular, inquiry questions requiring students to connect their answers to classroom evidence and experiments detect the impact of instruction more successfully than do multiple-choice questions that primarily ask students to distinguish among potentially plausible responses. To assess a knowledge integration curriculum one needs instruction-sensitive knowledge integration inquiry items because they tap students' ability to link and connect ideas.

In the current debate about topic coverage, multiple-choice results may reinforce the view that fleeting coverage makes sense for an instructional framework emphasizing recall. Our findings suggest that for many multiple-choice questions, shortening the instruction does not impact immediate recall. If we measure knowledge integration, however, shortening the curriculum diminishes immediate success and probably provides a more shaky foundation for future instruction.

To capture the process of knowledge integration we followed 50 students. At the beginning of the semester, most students have a predominately non-normative repertoire of ideas regarding thermal equilibrium. By the second interview, many of the students add ideas and maintain mixed repertoires including non-normative and normative ideas regarding thermal equilibrium. Adding ideas is necessary for knowledge integration but not sufficient. Some ideas are connected in a normative fashion, but non-normative ideas and connections remain. For most students, at least 6 or 8 more weeks of knowledge integration are necessary to establish a firm foundation.

Cedar's case study further clarifies the importance of instructional time. Cedar's success involves more than simply adding normative ideas. Knowledge integration and learning also include (a) sorting and promoting promising, normative ideas; (b) productively integrating new normative ideas with experiential ideas; and (c) productively integrating new normative ideas across topic areas, thereby allowing the reinforcement of school-instructed ideas with one another.

The case study and longitudinal investigation in this research illustrate not only the process of knowledge integration but also the proportion of students who integrate their ideas to reach normative perspectives as they participate in the curriculum. Clearly, engaging in knowledge integration takes instructional time and some students integrate their ideas more rapidly than others. Furthermore, the curricular elements that contribute to knowledge integration may disparately impact different learners. Looking specifically at how students engage in and proceed with knowledge integration reveals that students come to science class with a broad range of diverse ideas that they sort out iteratively over a period of time. Information that is pivotal for one student may not be pivotal for another, making the design of instruction that enhances knowledge integration challenging. Supporting teachers as they customize their instruction to incorporate ideas that might have local relevance or ensure connections back to prior instruction could greatly facilitate the knowledge integration process and the understandings that students and their teachers achieve. The Japanese curriculum, for example, emphasizes these connections (e.g., Linn et al., 2000).

Although students progress at different rates in the process of knowledge integration, the longitudinal study suggests that once students are started on this path, many will continue to engage in knowledge integration after science class is completed. This is perhaps the most important argument for a knowledge integration curriculum and for devoting more, rather than less, instructional time to complex scientific concepts. It appears that unless one invests sufficient opportunity to enable students to become autonomous guides of their own knowledge integration, one cannot expect effective outcomes from the knowledge integration process.

Taken together, these results demonstrate that knowledge integration takes time, energy, varied activities, and many opportunities to make connections from one topic to another. In streamlining the curriculum, we inevitably reduce opportunities for students to reflect on the connections between one topic and another. As students race through the topics, they have less opportunity to engage in the process of sorting out, comparing, prioritizing, organizing, and critiquing their science ideas. These processes, essential for life-long learning, are less practiced in the streamlined curriculum. A difficult challenge lies in how teachers and curriculum designers might streamline instruction to balance the many topics of importance in the curriculum with the availability of instructional time.

Our detailed design studies suggest several strategies to increase the effectiveness of additional instructional time. Visualizations properly constructed to present an appropriate target model lead to significant learning gains (Foley, 2000; Lewis, Stern, & Linn, 1993). Pivotal cases can improve knowledge integration (Linn, in press). Creating appropriate prompts for reflection enhances knowledge integration independent of the length of the curriculum (Davis & Linn, 2000). Embedding reexplanation strategies within projects can harness pivotal cases to help students reexplain disruptive experientially supported ideas (D. B. Clark & Jorde, in press). Connecting science to contemporary issues and controversies can potentially improve knowledge integration and extend classroom instruction, because these issues will appear in the media and nudge students to continue to think about their ideas (Bell & Linn, 2000). Increasing social relevance and scaffolding facilitate students' reorganization of their ideas (Cuthbert, Clark, & Linn, 2002; Hoadley & Linn, 2000). These strategies are represented in the pragmatic design principles developed by the Computer as Learning Partner group (Linn, Davis, & Bell, in press; Linn & Hsi, 2000).

This research raises a broad range of instructional and curricular issues that deserve further investigation. In particular, questions about how thermodynamics instruction generalizes to other topics, questions about aspects of the curriculum that promote knowledge integration, and questions about the general impact of knowledge integration experiences deserve further scrutiny.

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Appendix A: Activities in the Computer as Learning Partner Thermodynamics Curriculum

Heat Pulsing Labs (Real-Time Lab)

Description: The students add pulses of heat to different amounts of liquids and measure the increase in temperature. In Pulsing 1 the students add different amounts of heat to the same volume of water. In Pulsing 2 the students add the same amount of heat to different volumes of water and alcohol. This is the first lab of the semester where the students work with heat and temperature.

Cognitive Goals: One of the goals of the Computer as Learning Partner curriculum is to get the students to differentiate "heat" and "temperature." Coming into the semester most of the students indicate that heat and temperature are the same. Temperature is an intensive property of an object, "heat energy" is an extensive property, and it depends on the extent or mass of the object. Thus adding the same amount of heat to different objects will have different results which depend on the heat capacity of the objects. One of the analogies that we use is that temperature is a measure of the concentration of the heat.

Heat Bars (Simulation)

Description: Heat Bars is used to help students develop a model for the flow of heat energy. All materials conduct heat energy, but the rate the heat flows will vary greatly for different materials. Each material may be placed along the continuum line from good to bad conductor. Those that are placed near the poor conducting end of the continuum are referred to as insulators.

Cognitive Goals: Heat bars help students understand that heat flows at different rates, depending on the material. Students develop a model of conduction by observing that different materials conduct heat differently.

Probing Your Surroundings (Real-Time Lab)

Description: The students measure and compare the temperature of objects in the room.

Cognitive Goals: This lab appears at the end of the heat and temperature unit to elaborate the heat–flow model. The heat–flow model allows a causal explanation of the objects at different temperatures coming into equilibrium. This lab extends the discussion to include why the temperatures of all objects (that are not heat sources) in the room are the same temperature even though they feel as if they are at different temperatures when you touch them. This explanation draws on all of the facets of the heat–flow unit: heat sources, heat flow, heat conduction, and equilibrium.

Coke and Potatoes Lab (Simulated Labs)

Description: The students investigate how different wrapping materials affect the rate at which a hot potato cools and the rate at which a cold Coke warms up.

Cognitive Goals: In this lab, students learn that (a) heat energy flows more or less easily through different materials, (b) the rate that heat energy flows affects the rate at which objects heat up or cool down, (c) any given material may be placed along a continuum from poor conductor to good conductor, (d) insulation and conduction are related to each other and related to the rate that heat flows through a material, and (e) objects tend to heat up or cool down to room temperature.

Equilibrium Lab (Real-Time Lab)

Description: The students investigate two objects in thermal contact coming into thermal equilibrium. In this specific lab we use a test tube of hot (~80 °C) water placed in a beaker full of room temperature water.

Cognitive Goals: The heat–flow model allows a causal explanation of the objects at different temperatures coming into equilibrium. The principles in this lab reinforce the basic dynamics of heat flow: (a) heat flows depending on temperature differences between objects and (b) the heat flow causes the temperatures of the objects to change. Combining these principles leads to a causal model of equilibrium. Students can also see that the rate of heat flow is related to temperature differences.

Thermal Model Kit (Simulated Lab)

Description: Thermal Model Kit is a simulation program that allows the students to design experiments around a heat–flow model. Students are able to set and control a variety of variables, exploring oven designs and other topics. Students begin to gain an understanding of models and their use in science.

Cognitive Goals: This activity is designed to help students understand how scientists use models in their research. A scientific model allows scientists to make and test predictions over a range of conditions. Using this model helps students to a better understand heat flow and thermal equilibrium.

Greenhouse Effect (Integration Project)

Description: The students model the greenhouse effect and determine how an increased level of carbon dioxide gas in the air affects the temperature of the atmosphere.

Cognitive Goals: This lab is intended to help students integrate the principles constructed in previous labs related to heat and light energy. Ideas about transmission and conversion of heat and light energy, heat flow, and thermal equilibrium need to be linked to understand the mechanism behind the greenhouse effect. The lab emphasizes that although light energy passes through all clear, transparent materials equally, heat energy does not. This lab also provides a context for discussing scientific modeling and global warming.

Appendix B: Sample Ideas Expressed by Case Study Student at Each Interview

Interview 1: Before Instruction (0 Weeks*)*

Nuanced Ideas:

- Metal and wood objects would be same temperature as oven because there is no way for them to get hotter or colder.

Normative Ideas:

- Two objects can be the same temperature and feel different.
- Paper towel would be good for keeping a soda can cold because it insulates well.

Transitional and Mixed Ideas:

- Metal usually feels cool, and wood you can't really tell what temperature it is.
- Metal and wood feel different but are probably the same temperature.

Non-normative Ideas:

- An insulator is compact and so it would keep the heat or cold in.
- Paper towel insulates because it has fibers that are really close so it keeps the cold in.

Interview 2: After Thermal Equilibrium Instruction (3 Weeks*)*

Nuanced Ideas:

- When metal is cold it feels cooler than wood of the same temperature.

Normative Ideas:

- Metal and wood will be same temperature in a hot car trunk after several hours.

Transitional and Mixed Ideas:

- Metal feels hotter than wood because it changes temperature more quickly and it is actually hotter.
- Wood doesn't feel as cold as metal, and so would be room temperature in the cabin.
- In an area that is warming up, metal will be hotter, but in area where the temperature is staying the same, both objects will be the same temperature.
- No explanation for why metal feels colder and warms up easily.
- Wood and metal are around the same temperature.
- You could feel the temperature of a hot object through cloth easier than glass, because heat energy would go through the cloth faster than glass.

Non-normative Ideas:

- Metal and glass objects in cold cabin will be below room temperature because they feel colder.
- "Coldness" flows as well as heat.
- Metal feels cooler "cause it's, it's made of a, it's like smoother, and it's . . . solid, more solid."
- Specific object feels cold because it is made of something that makes it colder.

Interview 3: After Heat Energy and Temperature Instruction (6 Weeks)

Nuanced Ideas:

- Objects can't get hotter than the oven they are in because there is nothing to make them hotter.
- Size doesn't matter—Glass objects reach the same temperature in the oven after a while.

Normative Ideas:

- When you hold metal your heat warms it up by flowing into it.
- "Metal is a good conductor . . . It conducts heat energy."
- Styrofoam or Saran wrap would keep an object cold better and aluminum foil common the outside temperature . . . it would "trap like the cold or heat energy in."

Transitional and Mixed Ideas:

- At room temperature, wood and metal are the same temperature but feel different because "it's more solid I guess."
- In an air conditioned room, all objects are within a few degrees of the same temperature, with metal objects being cooler.
- A good insulator keeps a frozen candy bar cold by keeping the cold in or heat in. Specific object feels cold because the coolness from the object touches your hand and your hand is warm so it will cool down your hand and makes it feel cold.
- Same temperature metal and wood objects will probably feel the same.
- Asbestos doesn't reach the same temperature because it's made of the difference substance—"I'm really not sure."

Interview 4: After Insulation and Conduction Instruction (9 Weeks*)*

Nuanced Ideas:

- Specific objects of same material in freezer are the same temperature even though they have different sizes and amounts of heat energy.
- Integration of heating and cooling.
- Metal is a good conductor that would make it get hot faster than the wood, but it couldn't get warmer than the oven because there's nothing to make it get warmer.
- Metal is a good conductor and poor insulator so I wouldn't use that to make a container to keep hot things hot and cold things cold. Styrofoam is a poor conductor and good insulator so I would use that.

Normative Ideas:

- Metal object might just feel hotter than wood object in oven rather than be hotter.
- Thick Styrofoam is better than thin Styrofoam for the container.

Transitional and Mixed Ideas:

- Metal object would be slightly warmer than the oven and wood object would be cooler than the oven because metal is a good conductor and wood is not.
- Conductors heat up quickly and cool down slowly—Insulators keep in heat energy.
- They put metal on the outside of Coleman ice chests because it is a good conductor so if you put it in a freezer to keep it cold and then take it out, it would cool off really quickly and keep the objects inside cool.
- Aluminum cools down really fast and aluminum on outside of cooler will help the Styrofoam insulate.

Non-normative Ideas:

- Metal feels cooler because of its surface, which is smooth and hard, whereas wood is kind of rough.
- Specific metal and wood objects in oven feel the same and are the same temperature.

Interview 5: After Synthesis Activities and Posttest (13 Weeks)

Nuanced Ideas:

- Metal object will adjust more quickly to the oven temperature than the wood object because it is a better conductor that lets the heat travel through it very fast.
- Styrofoam wrapped around something cold lets heat energy into the cold objects more slowly than having nothing wrapped around it. It's a good insulator.
- Objects can't get hotter than the oven they are in because there is nothing to make them hotter.
- Heat goes more slowly through insulators than through conductors because good conductors are poor insulators and good insulators are poor conductors.

Normative Ideas:

- Wood and metal objects in oven will be same temperature after time because objects become temperature of surroundings.
- Aluminum will not slow down the flow of heat energy into a cold object or out of a warm object in a room because it is a conductor.

Transitional and Mixed Ideas:

- Styrofoam is a good insulator, and so keeps the soda can cold by keeping the coldness in.
- Touching an ice cube with a metal nail feels cold because metal is a good conductor and so the coldness travels quickly through it to your hand.

Non-normative Ideas:

- Objects feel different because they have different surfaces—One can be smooth and the other ones rough or soft or hard. Smooth objects feel a little warmer because when you touch it, there's more that you feel, because with rough ones you don't feel the whole thing.

Interview 6: Before 10th Grade (2 Years Later After Biology)

Nuanced Ideas:

- Metal object in trunk would heat up faster and be the temperature of the trunk, but the wood is not as good a conductor and so it wouldn't have warmed up as fast, and wouldn't be as hot right away but eventually should be same temperature.
- Metal object with one end in the fire feels hot "cause the heat from the fire travels through the wire."
- Heat energy flows from the surrounding area into cold objects to warm them up to the temperature of the surrounding area.
- Styrofoam is better to keep a soda can cold because it's a better insulator.

Normative Ideas:

- Aluminum foil doesn't help keep the soda can cold because we did an experiment and it didn't do anything.
- An insulator keeps the heat energy from going into the soda can, whereas aluminum would allow the heat energy to go right through.
- Metals are better conductors and so they will heat up or cool down faster.
- All objects will become room temperature after a long time.
- Metal in cabin would feel colder than the wood, but no explanation for why.

Transitional and Mixed Ideas:

- Metal is a good conductor, and so gets colder quickly, and so will feel cold because the cold travels through the nail to your hand. A wood stick would be a worse conductor and so it would take longer for the cold to reach your hand.

Non-normative Ideas:

- Same temperature metal might feel hotter in hot trunk than wood but probably not. No explanation for why.

Interview 7: Before 12th Grade (4 Years Later After Chemistry)

Nuanced Ideas:

- All objects eventually reach room temperature, but good conductors reach it more quickly, while objects wrapped in Styrofoam will take more time.
- Metal object feels hotter because it's a better conductor and the heat energy can escape into your fingers faster than through the wood.
- Objects in the freezer will be same temperature as the freezer because there's nothing to make them be colder or warmer.
- Objects like bodies don't reach room temperature because we produce our own heat energy.
- Molecular Kinetic model connected to thermal equilibrium.
- Cold objects that are conductors take heat energy away from an object very quickly making them feel cold.

Normative Ideas:

- Styrofoam is not a very good conductor so it would keep the cold away—It would be a very slow conductor.
- Surface area and volume affect rate at which objects cool down.

Transitional and Mixed Ideas:

- Aluminum foil is not good to keep a soda can cold—Styrofoam is better because it insulates well keeping the heat energy in or out depending on which one you want it to do.