DOCUMENT RESUME

ED 344 744 SE 052 442

AUTHOR	Lewis, Eileen Lob
TITLE	The Development of Understanding in Elementary Thermodynamics.
SPONS AGENCY	National Science Foundation, Washington, D.C.
PUB DATE	Apr 91
CONTRACT	MDR-8470514; MDR-8850552
NOTE	62p.; Paper presented at the Annual Meeting of the American Educational Research Association (Chicago, IL, April 3-7, 1991).
PUB TYPE	Reports - Research/Technical (143) -- Speeches/Conference Papers (150)
EDRS PRICE	MF01/PC03 Plus Postage.
DESCRIPTORS	*Cognitive Development; Concept Formation; Grade 8; Interviews; *Intuition; Junior High Schools; *Learning Processes; Middle Schools; Misconceptions; Physical Sciences; Pretests Posttests; Science Education; *Secondary School Science; *Thermodynamics
IDENTIFIERS	Middle School Science

ABSTRACT

This study investigates how students participating in the same curriculum construct understanding in elementary thermodynamics during a semester-long eighth-grade physical science class. Two questions were addressed: (1) How does the learners' understanding change during the study of elementary thermodynamics? and (2) What role do students' intuitive conceptions play in the restructuring and reorganization of their knowledge? Within each, middle school students' (n=180) knowledge restructuring was considered on an individual basis with generalizations made to larger student groups. All students responded to a two part pretest and posttest and 33 participated in all 5 clinical interviews. Three types of students were identified. "Converging" student were quick to recognize that heat flow is a model for thermodynamics. They use this powerful model and continue to add new information to their existing knowledge, finding that new knowledge is consistent with and reinforces the way they think about thermodynamics phenomena. "Progressing" students combine new information at the level of local knowledge, but do not integrate the pieces of that knowledge to build a more robust and cohesive view of thermodynamics. These students are progressing towards the coherent understanding of the students in the previous category. A third group of students can best be described as having an "oscillating" perspective of thermodynamics. These students combine experiences sporadically, change their views without additional evidence, and finish the course with a group of isolated ideas. Unlike the students with a progressing view of thermodynamics, these students do not gain more predictive ideas as time goes on, but simply move from one set of ideas to another. These findings contribute to understanding both the nature of the learner and the nature of the learning process and suggest ways to design science curricula to facilitate robust student understanding. (Author)

The Development of Understanding in Elementary Thermodynamics

Eileen Lob Lewis
Science & Mathematics Education (SESAME)
University of California, Berkeley

This paper was originally presented at the American Educational Research Association's Annual Meeting in Chicago, IL in April, 1991, Symposium 29.51, "The Nature and Development of Scientific Understanding."

Acknowledgements:

This material is based upon research supported by the National Science Foundation under grants No. MDR-8470514 and MDR-8850552. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the National Science Foundation.

We wish to express our gratitude to Doug Kirkpatrick for his spirit and assistance in all aspects of our CLP research. We appreciate contributions of software and equipment from Bob Tinker and Technical Education Research Centers (TERC). We gratefully acknowledge the donation of equipment and software from Apple Computer, Inc.

INTRODUCTION

This study investigates how students participating in the same curriculum construct understanding in elementary thermodynamics during a semester-long eighth-grade physical science class. In particular, it addresses two questions: (1) How does the learners' understanding change during the study of elementary thermodynamics? and (2) What role do students' intuitive conceptions play in the restructuring and reorganization of their knowledge? Within each of the above questions, middle school students' knowledge restructuring was considered on an individual basis with generalizations made to larger student groups.

Three types of students were identified. "Converging" students were quick to recognize that heat flow[1] is a model for thermodynamics. They use this powerful model and continue to add new information to their existing knowledge, finding that new knowledge is consistent with and reinforces the way they think about thermodynamic phenomena. "Progressing" students combine new information at the level of local knowledge, but do not integrate the pieces of that knowledge to build a more robust and cohesive view of thermodynamics. These students are progressing towards the coherent understanding of the students in the previous category. A third group of students can best be described as having an "oscillating" perspective of thermodynamics. These students combine experiences sporadically, change their views without additional evidence, and finish the course with a group of isolated ideas. Unlike the students with a progressing view of thermodynamics, these students do not gain more predictive ideas as time goes on, but simply move from one set of ideas to another. These finding contribute to understanding both the nature of the learner and the nature of the learning process and suggest ways to design science curricula to facilitate robust student understanding.

[1]The heat flow model used in the CLP curriculum was developed and refined over successive semesters. It is similar to the historic caloric model, but stresses that heat lacks mass. Further information can be found in Linn (1988).

Theoretical Framework

The Nature of the Learner

A fundamental premise of this research is a constructivist view of learning (Driver & Bell, 1986; Linn, 1987; Linn, Layman & Nachmias, 1987; Osborne & Wittrock, 1983; Resnick, 1983; Wittrock, 1974). There has been widespread agreement that learning science is considered to be an active, constructive, and cumulative process in which the learner plays a critical role (diSessa, 1983; Glaser, 1990; Linn, 1987; Osborne & Wittrock, 1974, 1983; Shuell, 1986, 1988 ; White and Tisher, 1986). This constructivist perspective builds on the views of Dewey (1902), Piaget (1972), and Schwab (1973) and describes learners as experiencing the world and constructing understanding from those experiences. As shall be seen in this and other studies, learning is indeed cumulative and learning outcomes depend up the learner's prior knowledge as well as the way new information is elaborated and related to the learner's existing knowledge.

The limitations of our perceptions of physical events and the complexity of the processes we daily observe often results in learners constructing fragmentary and not infrequently contradictory explanations of these experiences (Chaiklin, 1984; diSessa, 1983; 1987; Lewis, 1987; Lewis & Linn. 1989, April). An example can be found in Linn (1988) where she notes that observing motion in a friction-filled universe led individuals to reach the same conclusions as Aristotle rather than the accepted principle of "bodies in motion tend to remain in motion." She further notes that since objects usually move in the direction in which they are pushed, observers tend to ignore the speed and direction an object may already bring to the situation; they tend to predict its future motion only considering the new force acting upon it.

Learners acquire a knowledge of "school science" and often are able to apply concepts only to situations that directly mirror their school experiences. However, when varying real-world situations are used, students revert to their pre-instruction explanations. While teachers and researchers may be frustrated by the existence and tenacity of the individual constructions students bring to instruction that are contrary to the accepted principles of science, these constructions emerge as a result of the very methods that should be fostered in science students—namely, the ability to make observations, synthesize the results of these observations, and generalize to other events.

Part of this study, therefore, looks at how students integrate new and existing knowledge. Beginning with the initial conceptions of the learner, the manner in which students revise their knowledge is investigated. This knowledge revision occurs during a 13-week thermodynamics curriculum in which students' understanding changes as a result of empirical evidence that they help create and actively interpret. The focus of this study is on the process of change. This approach is consistent with other studies examining conceptual changes in knowledge (Carey, 1985, 1988; Chi & Ceci, 1987; Ranney, 1987; Shuell, 1982; Strike & Posner, 1985).

Students' Existing Knowledge

Research has demonstrated the role students' existing knowledge plays in constructing generalizations of science instruction to the natural world (diSessa, 1988; Driver, 1981; Gunstone, April, 1988; Lewis & Linn ,1989,April; Linn, 1987; McCloskey, 1983; Resnick, 1987; Songer, 1989; Tiberghien, 1980, 1982; West & Pines, 1985). Ausubel, Novak, and Hanesian (1978) were among the first to recognize the important role prior knowledge played in the learning process. Today there is a body of literature that details these individually constructed knowledge structures, their origins, contextual dependence, cueing conditions, tenacity, and pervasiveness (Caramazza, McCloskey & Green, 1981; diSessa, 1983, 1988; Gunstone, April, 1988; Law, 1988; McCloskey,Caramazza & Green, 1980; Posner, Strike, Hewson & Gertzog, 1982).

Many of these knowledge structures, which will be called "intuitive conceptions" in this study, are remarkably uniform among adolescents and non-scientist adults. This suggested to Eylon and Linn (1988) that there are some well-defined mechanisms for their creation. In a later paper, Linn, Songer, Lewis, & Stern (1990) suggests one such mechanism. When students acquire knowledge as a result of their experience, this knowledge is at first represented as "action" knowledge or simply responses to situations. They cite Baldwin (1894) and Piaget (1952) in suggesting that these actions are constructed in isolation often by imitating the actions of others. As an example, students learn to "turn up the heat," if they are cold or take off a jacket if they are warm.

As a part of making sense of the world, students actively amalgamate their action-oriented knowledge into intuitive conceptions. Thus intuitive conceptions are firmly grounded in observation and personal experience. Linn, et al. (1990) state that intuitive conceptions are constructed by students using a conscious process mediated by language in order to "group actions and observations into meaningful conceptions that they can use to make predictions about the world." Intuitive conceptions represent students' conscious identification of ideas that apply to several actions and related observations. Thus when students say, "metals attract, absorb, or hold cold" they are combining their experiences touching metals in cool or cold environments into a generalization that provides some explanation for their experience. This intuitive conception gives students excellent ability to predict the feel of metals in a variety of cool or cold situations. While this predictive power is limited, intuitive conceptions are useful for daily living. As a first level amalgamation of actions and observations, they provide no level of explanation beyond observation.

A similar view of learners' early efforts to construct meaning is found in diSessa's (1988) phenomenological primitives (p-prims). He describes p-prims as minimal abstractions of common phenomena. As minimal abstractions, they can be used to explain other phenomena and they are not themselves explained within a learner's system of knowledge. Instead they are perceived to be self-explanatory. These ideas are all consistent with research findings on the constructive nature of the learner. It seems quite reasonable that learners should generate their own explanations and mechanisms for observed phenomena since the mechanisms underlying many everyday phenomena are not readily observable. Lewis & Linn (1989, April) gives a list of students' intuitive conceptions in elementary thermodynamics. Table 1 shows these intuitive conceptions. Lewis and Linn additionally discuss how students construct these intuitive conceptions as a result of everyday experiences, the cultures[2] in which they exist, and the use of language within that culture.

This resistance of intuitive conceptions to change may, in fact, be a very useful and important part of the overall learning process. Linn (1983) suggests that "persistence is useful for advancing knowledge and that if reasoners changed all their ideas after each contradiction, they would gain little insight into a problem." It seems reasonable, then, that an effective mechanism for facilitating the development of understanding may be to strengthen those parts of a student's knowledge that are the beginning of good science, using them as anchors for conceptual refinements, reformulations, and ultimately coherent and robust models of scientific processes (Clement, Brown & Zietsman, 1989, March). It would also be desirable to facilitate student experiences that encourage the development of new intuitive conceptions consistent with scientific principles which may be cued more readily in the future. There is evidence that intuitive conceptions rarely disappear, but the development of new, scientifically acceptable conceptions may bolster a student's understanding and sense of success. As a result, the new conceptions might be cued more commonly by external events. As will be show later, intuitive conceptions consistent with scientific principles can be used by a student to construct a principled understanding of thermodynamic phenomena.

[2]Culture here refers to the practices and assumptions of daily activities in student's lives. This includes family practices, peer activities, and advertising that fosters incorrect interpretation of phenomena.

Name	Character of Intuitive Conception	Prototypic Circumstances	Surprising Extensions
Metals as Insulators	Metals absorb, hold, or attract cold in cool environment	Touching a variety of objects, all at room temperature or in a cool/cold environment	Use of aluminum foil for wrapping cold objects in order to keep them cold
	Metals absorb, hold, or attract heat in warm/ hot environment	Touching a variety of objects, all at the same temperature a warm/hot environment	Use of aluminum foil for wrapping hot objects in order to keep them hot
	Conductors conduct heat more slowly than insulators		
Insulators as Conductors	Insulators conduct heat fast and heat leaves so insulators don't feel hot	A wooden spoon/insulator standing in boiling water	Insulator as intermediate to best material to allow sensation of warmth from an object.
	Insulators absorb/trap heat	Touching a variety of objects all at room temperature	
Hot Wool	Wool warms things up	Surround any object in wool	Wool cannot be used as an insulator for cold objects since it warms things up

Table 1. A list of intuitive conceptions, their characteristics, prototypic circumstances, and surprising extensions from which the concept might have evolved and to which it applies

Process of Knowledge Integration

The persistence of intuitive conceptions in spite of a variety of instructional methods is well documented (Clough & Driver, 1985; Erickson, 1980; Gunstone, April, 1988; Lewis, 1987; Posner, et al., 1982; Ranney, 1987; Tiberghien, 1980, 1982). Several studies can give insight into reasons for the persistence of intuitive conceptions. What students consider possible and reasonable overrides tendencies to look at evidence and patterns of evidence (Tschirgi, 1980; Linn & Pulos, 1983; Schauble, 1988). These include the observations made of events, the interpretations offered for such observations, and the strategies students use to acquire new knowledge. Exposure to coherent, even meaningful knowledge may be insufficient if that material is incompatible with existing intuitive conceptions. The result may be rejection of the new information or the creation of new, unintegrated pieces of knowledge.

Schauble (1988a, 1988b) noted that the driving force behind the students' experiments was outcome rather than determining causal relationships. As a result, she found support for Piaget's

(1969) observation that students typically fail to construct experiments in which one variable at a time is changed. The lack of controlled experiments greatly limits discovery of causality. Conversely, successful learners in Schauble's study consciously constructed and coordinated the relations between evidence and their evolving theories.

Experiments and simulations provide the opportunity to experience new situations and expand knowledge. Equally important, they provide a means for testing the ideas students have often acquired as a result of limited experiences which permitted inconsistencies to go unnoticed. One way to increase the likelihood of learners effectively using experimentation is to frame experiments so that single variables are considered, intuitive conceptions are engaged, and mechanisms for facilitating useful notions of causality are present. As will be seen, the Computer As Lab Partner (CLP) Curriculum used in this study promotes experiments and simulations that limit exploration to a single variable in any given experiment or simulation. More information about the CLP curriculum can be found in the methods section of this paper and in Linn & Songer (in press) and Linn, et al. (in press). Additionally, the simulations of real world situations were designed to engage students' intuitive conceptions, to allow them to test their ideas, and to facilitate the construction of scientific principles from their results (Lewis, Stern, & Linn, 1990).

Student Reflection. The role of student reflection in all of these processes must be emphasized. Many students are not accustomed to the level of reflection required for meaningful learning and will, in fact, resist "thinking about things for that long." Embedded in all these considerations must be mechanisms for fostering this reflection. One such mechanism is to require that students make written and graphical predictions before all experiments and simulations. Further reflection occurs when students are required to resolve those predictions with their experimental/simulated outcomes. This process for enhancing student reflection was evolved and successfully used in the Computer As Lab Partner (CLP) Curriculum described by Linn & Songer (in press).

Summary. In summary, the premises of this research are that learners construct their own systems of knowledge and that learning environments can facilitate the construction of robust and coherent knowledge. In order to encourage the construction of such knowledge, the learning environment must provide time and support for active construction. It must allow learners to participate in activities that provide opportunities for discovering the causal nature of the world. Those activities must engage their intuitive conceptions and provide coherent, appealing alternatives that emphasize differentiation and integration. While the focus of all these activities must be conceptual, the contexts must be varied and include real world phenomena in order for learning to be robust and meaningful.

This position is supported by research describing a number of important conditions that facilitate the development of understanding. Posner, et. al. (1982) and Strike and Posner (1985) state that students must be dissatisfied with their current conceptions in order to alter them. Additionally, any new concept must be both understandable and plausible. Finally, the new ideas must be seen as beneficial. The curriculum and experimental treatments proposed here meet each of these requirements and provide additional opportunities for students to extend their experience to real world processes. This provides additional support for the usefulness of their evolving concepts while decontextualizing their application.

Method

Subjects. The subjects in this study were 180 eighth grade students (ages 12-14 years old) in a middle class, ethnically diverse middle school. Each was a student in a semester-long physical science class in which thirteen weeks were spent studying elementary thermodynamics u[illegible] the CLP curriculum. The classroom teacher is a "Mentor Teacher" who has been recognized for his excellence in teaching. A detailed description of the classroom environment can be found in Linn and Songer (1988). All students (N = 180) responded to a two part pretest and posttest and 33 participated in all five clinical interviews.

Curriculum. The CLP curriculum used during this study is a 13 week, microcomputer based study of thermodynamic properties and variables (Kirkpatrick, 1987; Linn, Layman, & Nachmias, 1987; Linn, & Songer, 1988; Mokros, & Tinker, 1987). Using real-time data collection and simulations, "research groups" of students behave as working scientists in an inquiry-based learning environment. They plan experiments, predict outcomes, use computers to display empirical or simulated results, analyze their data, and discuss surprising or contradictory outcomes. A detailed study of the evolution of the CLP curriculum can be found in Linn and Songer (in press) and Linn, et al (1990). The curriculum was designed to encourage the development of integrated understanding of elementary thermodynamic process and the variables that affect those processes. Computer simulations of real world phenomena have been added to engage students' intuitive conceptions and encourage integration of their real-time data experiments with real world experiences. Eight Macintosh computers were used to construct the electronic laboratory notebook and perform simulated experiments described in Lewis, Stern & Linn (1990).

Design

Since the goal of this research was to chart the development of students' understanding in elementary thermodynamics, the research design needed to assess both group and individual change. As a result, pretests, short tests, and posttests were administered to the entire student population. From this sample, 36 students were selected from the middle 50% of students using a stratified random design for individual case studies. There were six students from each of the physical science classes in the case studies. The strata used in this study were sex and class period. This was done to obtain equal numbers of males and females and equal representation from each period in the physical science classes. The limited number of males falling into the 50% criterion in two of the class periods overly constrained choices and resulted in unequal distribution of females and males in half the classes. This unequal class distribution was necessary to allow for equal numbers of males and females in each treatment group.

Class rankings to determine the middle 50% were based on partitioning the first pretest into two parts by type of question (e.g. essay, fill in, multiple choice) and variable considered. The middle 50% from this analysis was then matched with the middle 50% from the second pretest. This was done to ensure internal validity as well as validity between tests. The numerical scores represent the number of total number of correct responses on each pretest. No statistical difference were found between any groups as shown in Table 2.

Table 2: Measurement of Between-Test Validity for Two Pretests: Mean, Standard Deviations, and Range for Interview Group, Middle 50% and Whole Population

Group	Pretest, Part 1 Mean (Std Dev.)	Range	Pretest, Part 2 Mean (Std Dev.)	Range
Interviewed Students	27.8 (2.7)	23—32	34.0 (2.7)	29—39
Middle 50% of Students	27.7 (2.6)	22—32	32.0 (5.7)	20—43
Whole Population (N=180)	26.2 (5.6)	11—39	31.4 (5.4)	15—43

The top 25% of students were omitted from the case studies since they are often able to integrate and generalize knowledge without assistance. The omission of the lower 25% from case studies was made because students' placement in that percentile may be related to language skills (in this particular setting many students are learning English as a second language), motivation, or behavior problems. Additionally, any knowledge reorganization or reformulations promised to be more interesting for this average group of students. If knowledge can be gained on the design of instructional systems that are effective for the average students, they should also meet success with students of greater abilities.

Data Sources. Since the investigation of complex processes like the development of understanding demands a variety of data sources, this study used two different kinds of sources for its data: (1) pretest, short tests, and posttest, and (2) 5 clinical interviews with each of 36 case study students. Over the course of the 13-week curriculum 3 students were lost from the 36 case study students. Two moved from the area and one student did not want to participate, all too late for them to be replaced. Additionally, one student did not take the posttest, so that while the number of students interviewed was 33, posttest data were only available for 32 students.

Instruments

Written Tests. A two-part pretest was devised to assess students' conceptions in the area of thermodynamics. The questions used were refined over several semesters in the CLP curriculum and have been shown to provide reliable information on students' understanding (Linn & Songer, in press). The two parts of the test were given ten days apart to allow test re-test reliability to be established (see figure 1 for sample questions from pretests) for group selection. Several questions on each part of the test focused on the students' understanding of heat energy, temperature, thermal equilibrium, and variables that affect heating and cooling processes such as starting quantity, starting temperature, insulation and conduction, and surface area.

Figure 1: Sample Questions from Fall 1989 Semester Pretest/Posttest[1]

1a) You want to keep a soda cold for your school lunch. What is the best things to wrap it in?
b) What is the **main** reason for your answer?

2a) 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?
Give an example that explains your answer.

3a) Give an example of a good conductor. ____________________
b) What makes the substance you picked a good conductor?

4a) Give an example of a good insulator. ____________________
b) What makes the substance you picked a good insulator?

5a) A metal spoon and a wooden spoon were put into a 65°C oven for 2 hours. What do you predict their temperatures will be after two hours in the oven?
temperature of the metal spoon __________
temperature of the wooden spoon __________
b) What is the **main reason** for your answer.

6. If a metal plate and a Styrofoam plate are in the same room, what will happen?
a) (check one)
_______ the metal plate will be warmer.
_______ the Styrofoam plate will be warmer.
_______ both plates will be equally warm.
b) Give the **main reason** for your answer.

7. You are shoveling snow without wearing gloves. (Picture showing both shovels)

a) Which shovel handle would you rather use? (circle one)
metal-handled shovel wooden-handled shovel either shovel handle would be okay

b) Fill in the blanks to make a principle that applies to these shovels.
If two objects that differ only in material are in the same surrounding, heat energy will flow into and out of the object that is the better ____________________ faster than it will flow into and out of he object
insulator / conductor
that is the poorer ____ __________
insulator / conductor

8. You take a bag of frozen peas from the freezer and place it in a container of hot water. (Picture showing cluster of cold peas and container of hot water then peas in container of water.)

a) What can you say about the heat energy of the **cold peas after** it is placed in the **hot** water?
(check one)
_______ Heat energy from the cold peas will flow into the hot water.
_______ Heat energy from the hot water will flow into the cold peas.
_______ Cold energy will flow from the cold peas into the hot water.
_______ Cannot predict.
b) What is the **main reason** for your answer?
c) If you left and came back several hours later, what would you find?
(check one)
_______ the peas would be colder than the water.
_______ the peas would be warmer than the water.
_______ the peas and the water would be the same temperature.
_______ cannot predict.

---

[1] Print and size have been significantly reduced and pictures are missing due to space limitations.

Questions w re chosen to provide diversity, include both school and real world problems, elicit students' intuitive conceptions, and display inconsistencies in student's knowledge. Many questions were open-ended, allowing students to express their beliefs in their own language. Interrater coding reliability for both the Pretest and Posttest was 98%.

A two-part posttest was given. The posttests were identical to the pretests except that the first posttest contained 5 additional questions on heat flow. This allowed comparisons with pre-test knowledge and the nature of student explanations. The results of the two pretests and posttest were combined to produced single pretest and posttest scores.

Clinical interviews. A series of 5 clinical interviews were conducted with each of the 33 students in the case studies (see Figure 2 for sample questions). The interviews were modeled along the lines of Piaget's "clinical method" (1969, first published in 1929). In keeping with Piaget's method, questions were asked informally and repeated as necessary. In addition, the experimenter often paraphrased responses so that a confirmation or denial of the experimenter's perceptions of subject's response could be made. Open-ended follow-up questions were posed in the language of the subject.

The initial interview focused on clarifying students' responses on the pretest in areas of interest (thermal equilibrium, heat flow, and insulation/ conduction). The final interview focused on the students' responses on the post-test in areas of interest (thermal equilibrium, heat flow, insulation/conduction, heat energy and temperature distinction). Since a goal of this study was to monitoring the learners' development of understanding and factors that affect any restructuring or reorganization that occurs, interviews were conducted at four week intervals throughout the students' 13 week study of thermodynamics. The questions were designed to assess robust knowledge. As a result, questions were framed in familiar contexts to cue intuitive conceptions. The questions were also designed to illustrate conflicts in a subjects' conceptions as well as to demonstrate their ideas of causality in thermodynamics.

As a means of studying the effect of various factors on the development of understanding, students were asked what they were thinking about, which of their ideas they thought had changed and why. All questions required prediction and explanation to elicit the diversity of student beliefs and conceptions and to measure the robustness of their responses. Most questions were set in the real world to test students' ability to generalize their ideas The same questions were posed to all 33 case study students.

Figure 2: SAMPLE INTERVIEW QUESTIONS

1. You and your friend are sharing a milk shake. Because you aren't very hungry, you and your friend divide it up as you see.

What can you say about the heat energy present in each of your glasses of milk shake? Does one glass of milk shake have more heat energy than the other or are they the same? Why do you think that? What is heat energy? Do cold things have heat energy? Were the milk shakes the same temperature when they are poured into the glasses?

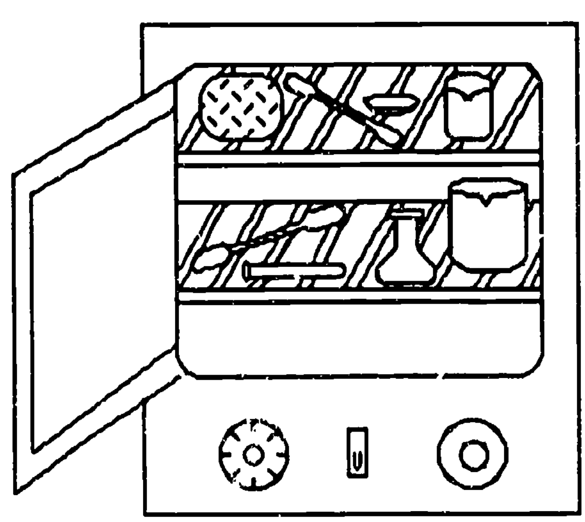
2. Write the names of each of the following materials on the line where you think they belong. Assume all the materials have the same thickness.

1	5	10
good insulator		good conductor

metal Styrofoam wood glass
wool ceramic floor tile paper saran wrap

Why did you place (each material) here on the continuum line? What makes this material a good conductor/insulator? What does it do as an insulator? Does it work for hot/cold things only? How did you come to understand about this material? (Probe student's understanding of conduction and insulation.)

3. In a chemistry lab students were drying equipment in an oven like this one. 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 student's understanding of thermal equilibrium. What is the source of their understanding.) If you could touch them, would they feel the same? Why? (Probe student's understanding of conduction and insulation using the students' terms.)



Data Analysis

This investigation relied on two different sources of data: (1) pretest and posttest from the entire population (N = 180), and (2) clinical interviews for case studies (N =33). The pretest and posttest allowed statistical distribution, parametric, and nonparametric analysis of students' ability to apply thermodynamic concepts and thereby measured the impact of instruction over the 13-week curriculum.

Clinical Interviews. The clinical interviews were evaluated using a method developed by Erickson (1979, 1980). Using this method transcripts are carefully examined for expressions that state or infer the underlying beliefs of the subject. An inventory of ideas held by each subject is be generated and forms the basic unit of analysis. These ideas are defined as follows: "an attempt by the subject to explain a phenomenon or in some way account for a judgment or prediction the subject makes in the course of the interview or thought questions." Attention is also paid to the cueing conditions for these ideas, their systematically, and where their knowledge breaks down (Posner, et al., 1982).

Level of Explanations Analysis. The Level of Explanations Analysis was developed to measure how students' inventory of ideas changed over time. It considered the quality of an explanation from the level of intuitive conceptions to target conceptions using the progression of students' ideas developed by Lewis (1991). The assessment included students' use of examples as well as their ability to interpret complex and ambiguous real world situations. Additionally, the level of explanations scale, shown in Figure 3, measured the consistency and cohesiveness of students' explanations within a given interview. Since each interview was assessed individually and different aspects of the same concept were often considered from interview to interview, there was some fluctuation in student responses. Student responses were charted in the areas of Insulation/ Conduction, Thermal Equilibrium, Heat and Temperature Distinction, and Heat Flow over the sequence of tests and interviews. Figure 4 provides a diagrammatic representation of the target conceptions in this study.

Figure 3: Level of Explanations Used to Analyze Students' Interview Responses

Level of Explanations

1—Intuitive Conceptions—response to questions and explanations consist primarily of intuitive conceptions, e.g. choice of aluminum foil to wrap a cold soda because foil holds the cold in; wool wrapped around a cold object would cause it to warm up faster than an unwrapped object.

2—Encoding New Facts without Explanations—students' responses display the encoding of new factual data without an understanding of that information or the ability to apply it, e.g. after a class experiment, students become convinced that objects in the same environment are the same temperature. However, they cannot explain why they are the same temperature or why they feel different to the touch.

3—Mixed Predictions, Idiosyncratic Explanations—students at this level give some correct and some incorrect predictions which were typically cued by the surface features of a problem. Their explanations appear to result from an attempt to preserve intuitive conceptions, but explain experimental outcomes, e.g. a student might state that metals feel cold in a cold environment because they don't really absorb the cold, it just sits on the surface of the metal. Insulators, on the other hand, were said to absorb cold into them so that they do not feel cold to the touch.

4—Mixed Predictions, Explanations—students make both correct and incorrect predictions and give explanations that are a mixture of both correct and incorrect conceptions. Incorrect explanations are usually tied to initial intuitive conceptions. These mixed explanations exclude any idiosyncratic explanations.

5—Good Predictions, Mixed Explanations—students make excellent predictions and give explanations that are a mixture of target conceptions, intuitive conceptions, and intermediate conceptions

6—Target Conceptions—predictions and explanations are consistent with target conceptions.

A plot of students' level of explanations over the sequence of tests and interviews suggested three categories of student development. These categories are defined as "Converging," " Progressing," and "Oscillating." Converging Students progressed through the level of explanations and were found to use target conceptions in their discussions of insulation/conduction, thermal equilibrium, heat and temperature distinction, and heat flow. but all improved their level of explanations over time. Progressing Students varied greatly in their range of responses and did not construct target conceptions in all desired areas. They did, however, improve their level of explanations over time. Oscillating Students oscillated between levels of explanation or utilized idiosyncratic explanations in the areas measured. To ensure reliability each Level of Explanation analysis was performed twice with a two month interval between analyses. The interview transcripts and pre/posttest alone provided the data sources for each analysis. Results from the use of the Level of Explanations criteria were consistent with qualitative measures used for case studies to characterized the nature of students' reasoning.

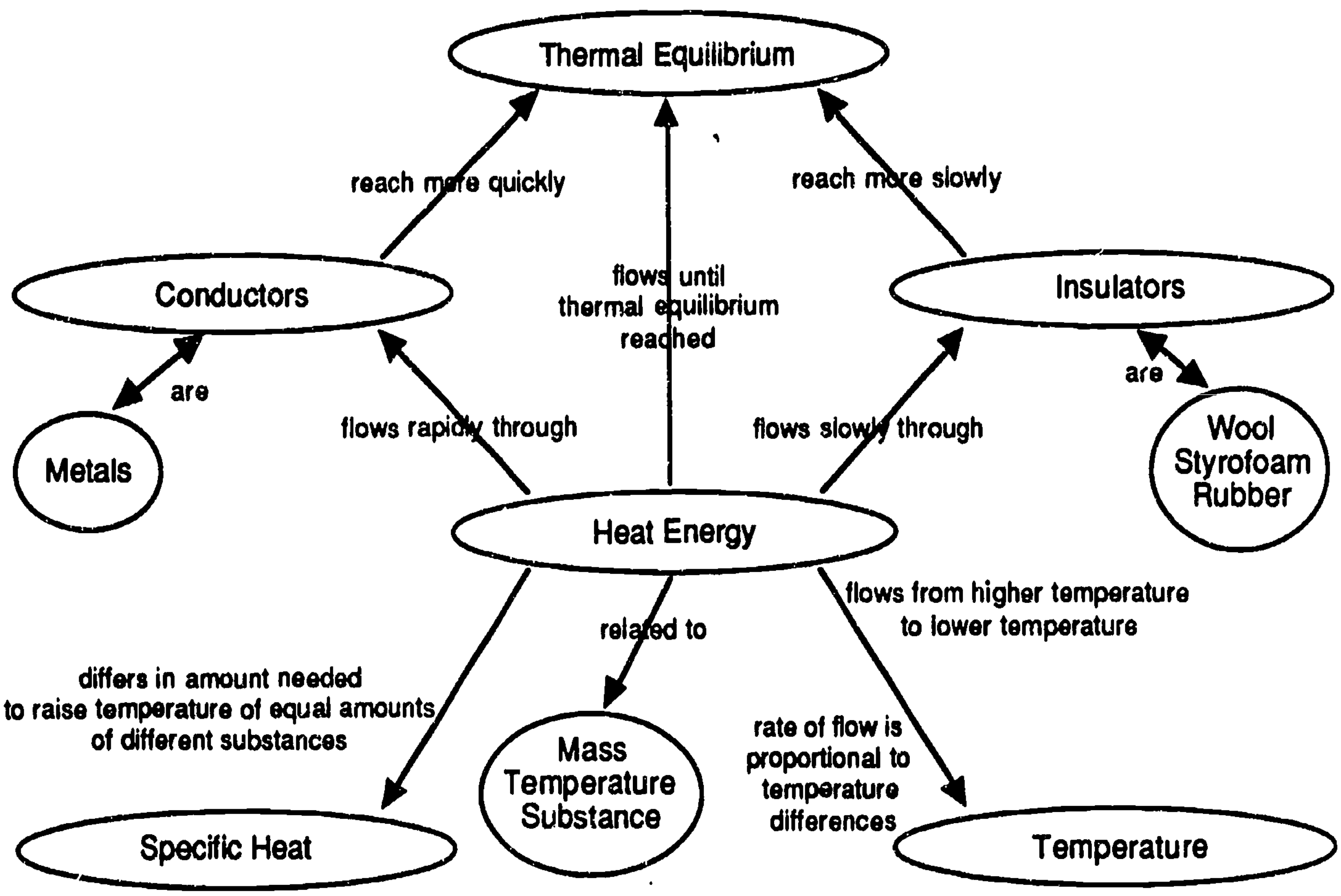


Diagram of Target Concepts in Elementary Thermodynamics

Figure 4: Diagram of Target Concepts in Elementary Thermodynamics

The Level of Explanations Analysis for each of the 33 case studies allows the generation of a within-subject summary of the growth of each individual in the sample over the course of the semester. Subsequently, these within-subject summaries of individual growth become the basis for the between-subject analyses. This allows inferences to be made from individual and group development of understanding that may have broader application in instruction. A Level of Explanations figure for each student is found after the descriptions of their category.

Case Studies. The data from pretests and each series of interviews were used to construct a case study for each student that chronicled their development of understanding over the sequence of tests and interviews. Attention was given to who noted any conflict in a student's responses and how that conflict was resolved. Notation was made of what characterized the learner's responses over the sequence of interviews. Careful attention was paid to determine the coherence of a student's knowledge as well as his or her ability to apply that knowledge in a variety of settings. The case studies were also used to create a level of explanations chart for each student.

RESULTS AND DISCUSSION

The cognitive growth of individuals is presented along with generalizations that can be drawn from observations of that growth. Analysis of student interviews suggests that students fall into three general categories of cognitive growth: Converging, Progressing, and Oscillating. "Converging" students are characterized by a robust and coherent understanding of heat flow as a model for thermodynamics. They continue to add new information to their existing knowledge and find that new knowledge is consistent with and reinforces the way they think about thermodynamic phenomena. Their conceptions of elementary thermodynamics begin to converge with accepted scientific conceptions. Seven out of thirty-three (or 21.2%) students fell into this "converging category."

The second category can be described as "progressing." Students with a progressing understanding of thermodynamics are incorporating new information to build a more robust and cohesive view of thermodynamics based on the heat flow model. These students are progressing towards but have not reached the coherent understanding of the students in the previous category. Eighteen out of thirty-three (or 54.5 %) students fell into the "progressing" category.

The third group of students can best be described as having an oscillating perspective of thermodynamics. These students oscillate between more and less predictive views of thermodynamics and lack any ubstantial integration of their ideas. Unlike the students with a progressing view of thermodynamics, these students simply move from one set of ideas to another without gaining a more predictive view over time. Nine out of thirty-three (or 24.2 %) students fell into the oscillating category.

More detailed descriptions of each of these categories of students are presented below in addition to a case study for each category of student development. An analysis is presented showing the interaction of posttest scores for each of these student categories.

Categories of Learners

Students' pretests, interviews, and posttest were assessed using the six Levels of Explanations presented in the methods section of this paper. These analyses suggested three natural categories in students' development of understanding. These categories resulted in grouping students into "Converging students," "Progressing students," and "Oscillating students." The results of these analyses are presented for 6 of the interviewed students in this study, two from each category (see Figures 5-10) after the discussion of their category. These figures display in tabular and graphical form the Level of Explanations used by students over the sequence of tests and interviews for the concepts of insulation/conduction, thermal equilibrium, heat energy and temperature differentiation, and heat flow. It is easy to distinguish Converging students, Progressing students, and Oscillating students by graphically following their progress over the sequence of tests and interviews.

Converging Students. Converging students were so named because of their robust and coherent use of heat flow as a model for understanding elementary thermodynamics was converging with accepted scientific views. A key characterization of the reasoning of converging students was their ability to resolve contradictions in their responses, reason through their in and out of class experiences and decide which explanations were most consistent with other pieces of their knowledge. Their attention to their own inconsistency and their efforts to resolve conflicting ideas resulted in greater reflection and some form of resolution. The following excepts provide examples of these processes.

Student PE5 entered the curriculum with some explanations at an action level and others representing typical intuitive conceptions. This is demonstrated in his pretest response to the question, "You want to keep a soda cold for your school lunch. What is the best thing to wrap it in? What is the main reason for your answer?" His reply was aluminum foil and his reason was, "lots of people use it to keep their sodas cold." In Interview 1, he added:

PE5: "Every time you see someone with sodas, they always have it wrapped in aluminum foil, never anything else."
E: How does aluminum foil keep them cold?
PE5: Because it's sort of like a little metal, cause metal really keeps the heat in or cold or whatever.
E: So metal works to keep things hot and cold?
PE5: I think so. I guess.

In a later pretest question he was asked to agree or disagree with the statement, "Things that help hot objects stay hot also help keep cold objects cold," and give an example of a situation that illustrated his answer. CE5 agreed and cited aluminum foil as an example of something that keeps things hot and cold. During Interview 1, he agreed with his pretest response. However, on the next interview question, he makes statements that will cause him to reconsider a later question.

E: This question asked for an example of a good conductor and you left it blank.
CE5: I don't know.
E: Do you know what a conductor is?
CE5: Isn't it something that lets the heat in? All the air would come in or out or something like that.
E: So something wrapped in a conductor would stay cold if it was cold to begin with or not?
CE5: Uh, let me think...I think it would probably make it hotter, I guess. If you wrapped it around it.

E: If you wrapped a conductor around something cold, would it warm up faster?
CE5: Yeah, I think so.
E: Why do you think that?
CE5: If it lets in all the air, then it will make it a little hotter cause all the energy goes.

He applies this new understanding in a question at the end of Interview 1. The question asked which dish of lasagna would stay hotter, one with a metal lid or one with a pottery lid.

E: On this lasagne question, you said the one with the metal lid would stay warmer. Can you say a little more about that?
CE5: Oh, wait. I think this is all wrong now. I understand this now. I think this could be hotter (points to the dish with the pottery lid) because the metal, it feels hotter because all the heat went inside that, inside the lid. While all the heat just sort of bounced off the pottery lid so it keeps the lasagna hotter. So then the lasagna loses energy because it goes into the metal lid. That's why this (points to the metal lid) feels really hot and this (points to the pottery lid) doesn't feel as hot.

This is a excellent example of a student combining pieces of knowledge. However, in the next question, the typical separation of heat and cooling process is demonstrated as well as the persistence of belief in aluminum foil for keeping cold objects cold.

E: Here you said aluminum foil was excellent for keeping hot things hot and cold things cold. Is that OK?
CE5: I think it would be between poor and good for hot and be excellent for cold.
E: So it is different for different things?
CE5: Yeah.
E: Why did you change your mind?
CE5: Well, I guess cause that's why the aluminum foil is always hot when you take it off cause it just absorbs all the air, I guess.
E: Absorbs all the air?
CE5: Well, just like the energy of the air, the degrees or something like that.
E: Would the same thing be true if you wrapped some thing cold in aluminum foil?
CE5: Oh yeah, it would be the same. These two would both be between poor and good. Yeah, yeah. I see now. Yeah.

He then applies his new understanding.

E: Here you said Styrofoam was good for keeping things hot and poor for keeping things cold.
CE5: Uh, I think this would be good, too. (points to his previous poor for keeping things cold)
E: So Styrofoam is good for both keeping things hot and keeping things cold?
CE5: Yeah.
E: Better or worse than aluminum foil?
CE5: I think it's better now.
E: If you had an aluminum cup and a Styrofoam cup and you poured the same amount of cold orange juice into them, which orange juice would be colder 5 minutes later?
CE5: The one in the Styrofoam.
E: Why would the juice in the Styrofoam cup be colder?
CE5: Cause, let me think. Whenever you take an ordinary Styrofoam cup, it just feels like normal, not like hot or cold. But then, because the metal absorbs all the things like I said and so you take some, it will take some cold out of the orange juice, so the orange juice will go up a little.

While his explanation about taking some cold out needs refinement, he is exhibiting the testing and comparing processes that are desirable in student reasoning. His understanding of terms and use of language will improve as will his process of comparing new pieces of knowledge to existing ones and constructing a coherent system of knowledge. By Interview 3 he illustrates an excellent understanding of thermal equilibrium in his response to the objects in the laboratory oven question. He stated, "150°C. All of them. The metal will be quicker getting there but then this one (points to glass) will take a little longer but nothing can get higher." He then explained how objects could not get hotter than their surrounding. He explained why they feel differently. A later question about a wrap for a cold candy bar illustrates his increasing understanding of heat flow.

E: You like very cold candy bars and keep them in the freezer. You want to take one to school with you. What would be good to wrap it in to keep it cold?
CE5: Wool.
E: Why?
CE5: It's a good insulator. It will keep all the energy inside, it won't take any energy out or bring it in.
E: Is there cold energy inside the candy bar?
CE5: No, there is heat energy but not much.
E: So what would happen?
CE5: It's not letting any of the energy of the candy go out or any energy from outside go inside the candy.
E: What kind of energy would go out?
CE5: Actually energy can't leave from it, it can't cool down. It will warm up.
E: What is the wool doing?
CE5: Preventing the warm air from coming in.
E: Does that make sense?
CE5: Yeah.
E: What if I wrapped it in aluminum foil?
CE5: It would warm up to the temperature of the room quicker.
E: Why?
CE5: The heat energy from outside can go through the foil easily.

Converging students actively used evidence from classroom experimentation/simulations and discussions to develop new concepts and attempted to link those new ideas with their existing ones. They were more able to subject their intuitive conceptions to examination and comparison with their experimental/simulated outcomes construct new understandings of previous experiences.

An illustration of this is found in excerpts from interviews with Student ME7. On the pretest question about the wooden and metal spoons in a 65°C oven, her written response gave the temperature of the metal spoon as 50°C and the temperature of the wooden spoon as 65°C. Her explanation was, "The wood won't absorb the coldness, the metal spoon will." Like many students she assumed that 65°C was cool. During Interview 1 when was asked if her answer was OK, she replied:

ME7: Yeah, I think so. I forgot about the Celsius. I thought this was Fahrenheit.
E: On the Celsius scale, this would be a warm oven.
ME7: I'd say they'd both be the same temperature, 65°.
E: Why?
ME7: Because with the experiments in class that we've done. Uhm, it showed us that it doesn't matter how they feel, it's like how they conduct the heat and stuff like that.
(skip ahead)

ME7: (Before the experiments) I would have said they were different temperatures.
E: But now you think they are the same?
ME7: Yes.
E: Why does metal feel cooler?
ME7: Because the materials in the metal and the wood is different.
(skip ahead)
E: This question about the metal and the Styrofoam plate in the same room. You said, "metal plate warmer because assuming the room was warm and that metal heat up fast." Is that OK?
ME7: It would feel warmer. I don't know if it would be warmer. (She feels a piece of metal.) Well, this feels colder now. Wait. It probably depends on what the room temperature was and would there be something on the plate.
E: The plates would just be off a shelf.
ME7: You couldn't really tell, because you don't know what the room temperature would be. Cause it could be like a really hot room and the metal plate would be warmer--it would feel warmer. But then if it was a really cold room, then the metal plate would feel colder.

Her experience with the Probing Your Surroundings Experiment[3] enabled her to change her understanding of thermal equilibrium. While she still doesn't understand why objects feel different, she has incorporated her experiences into her new thermal equilibrium and generalized to how materials feel in different surroundings. Later in the interview, she considered the question of whether orange juice would stay colder in an aluminum cup or a Styrofoam cup. She decided the Styrofoam cup would work better to keep orange juice cold and hot chocolate hot. She decided to change her pretest responses which said aluminum foil was excellent for keeping hot objects hot and cold objects cold.

When converging students used analogies in their reasoning processes, they did not rely on surface similarities but reasoned from underlying thermodynamic processes. The explanations for predictions in the interviews also reflected a generalization in that students explanations were increasingly given in general (principled) terms which the student then applyed to specific situations. This is exemplified in the following excerpts from interviews with Student CQ6, a foreign student who had some difficulty expressing himself in English. In the first excerpt from Interview 2, he was explaining how the objects in the laboratory oven would be the same temperature because, "They've been left in there for a long period of time, gradually, they'll get there." He then explained that they would warm up at different rates, "Metal will be faster than glass." He was then asked if the objects would feel the same since they were the same temperature?

CQ6: No, the metal will feel hotter than asbestos.
E: What makes this feel hotter?
CQ6: It maybe a better conductor.
E: What is it conducing?
CQ6: ...Your hand could be conducting, but this is hotter (points to metal object) so it is conducting the heat from that (metal object) to your hand. The asbestos is not as good of a conductor.

[3]This is a powerful experiment in which students predict the temperature of objects in their surroundings then measure their temperature with a thermal probe.

E: Did you always think of things this way?
CQ6: Not really, doing all the experiments and the simulations. Classroom discussion are pretty helpful and people bring different things like real life examples...and the metal is actually the same temperature and it surprised me. The classroom discussion helped but not as much. The principles helped. They are kind of hard.
E: Do you use the principles?
CQ6: Yeah, like, well, so I find out about other things that I...It kind of changes my thinking about things in general.

He had less difficulty expressing himself in writing. This is evidenced by his response to the heat energy and temperature distinction question. The main reason he gave for heat energy and temperature being different was, "heat energy is the amount of heat in an object. Temperature is just how cold or hot it is. If you add the same amount of heat energy to different liquids, the heat energy is still the same but the temperatures are different." His example was, "if you add the same amount of heat energy to a cup of water and a pool. The heat energy contained in both of them are the same, but when you measure the temperatures the cup of water will be higher than the swimming pools (sic) since the cup has less mass." In a later question about the temperature of a hot horseshoe placed in water, he stated, "If an object is placed in a surround,the object and the surround will eventually reach the same temperature." His definitions for insulators and conductors were equally lengthy and generalized. A last example comes from his response to a question about a block of wood and metal on a warm "hot plate." Students were asked to draw a picture of tell how they thought the blocks became hot. His response was, "The heat from the hot plate comes from the generator underneath. It is conducted through the plate into the blocks. Each will heat up at different rates. The metal will heat up faster than the wood since it's a better conductor."

Overall characteristics of Converging students:

- Converging students appeared to add a new piece of knowledge and integrate it with their existing knowledge. This process results in a gradual reorganization and reformulations of their exiting knowledge. A driving force in this process was a need for coherence which induced additional reflection upon their ideas and experiences. This increased reflection and desire for coherence facilitated knowledge reorganization and reformulation.

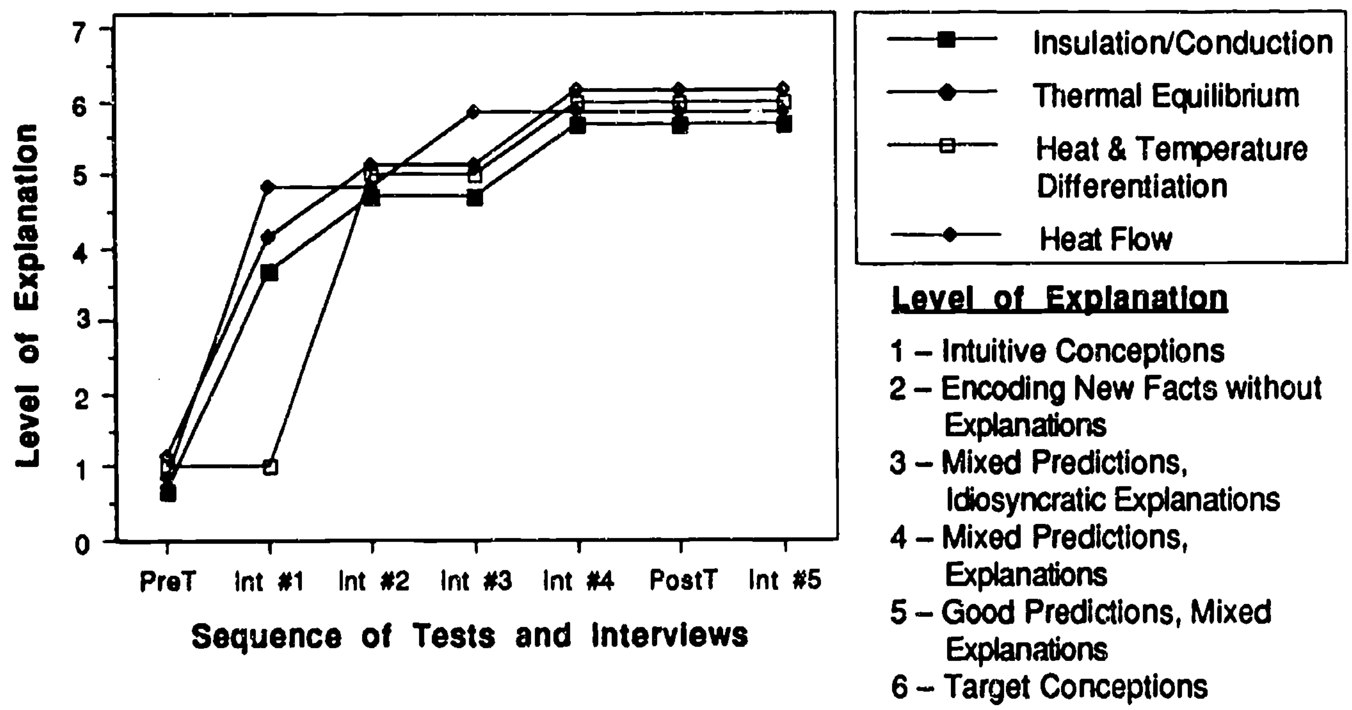
- Converging students relied on evidence to make predictions and as a result were the first to abandon intuitive conceptions which were contrary to scientific findings. Their explanations for predictions were more causal in nature throughout the course of the interviews.

- Converging students developed generalized explanations and increasingly expressed explanations in principled terms. They were, however, quite able to apply those generalizations to specific situations with very different surface features. Seven of thirty-three students (or 21.2%)

fell into the category of converging students. Further analysis of why students fell into these categories will be presented later in this section.

Converging students represent an ideal for the development of understanding. Figures 5 and 6 provide Level of Explanations analyses for two Converging students. A case study of a Converging student MQ5 can be obtained from the author by request.

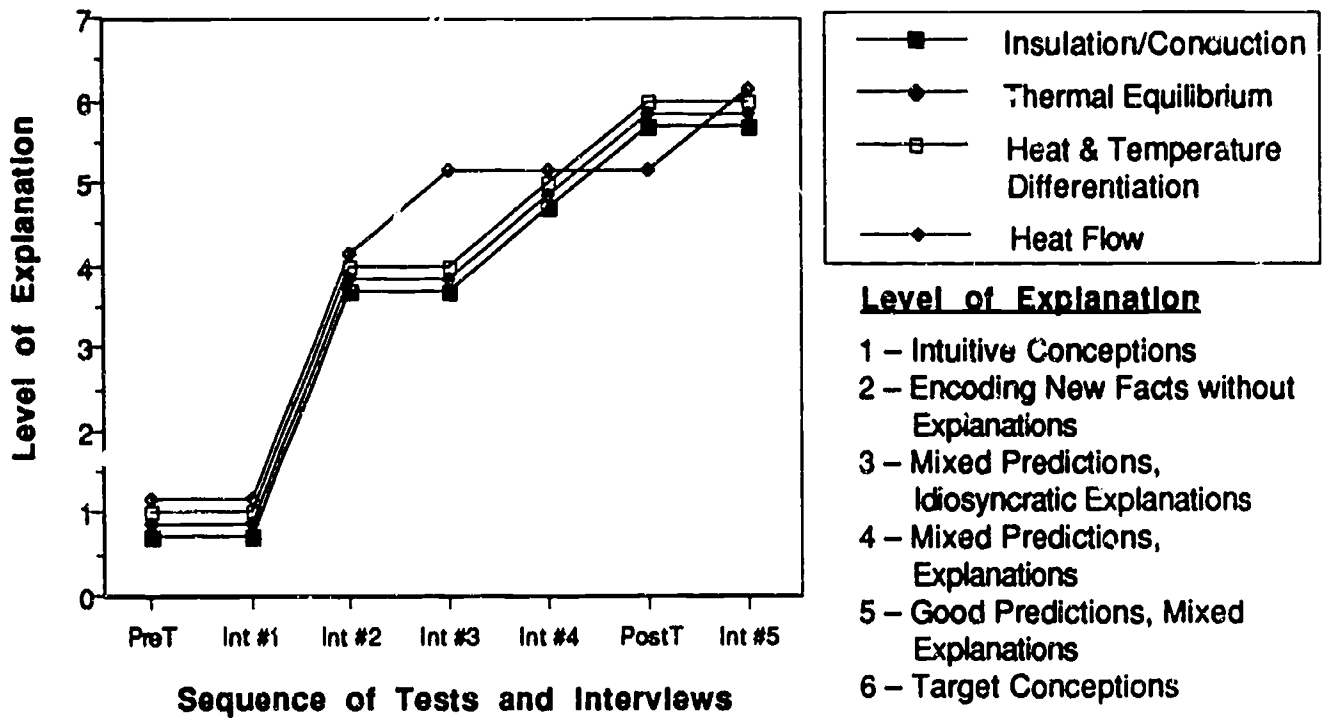
Figure 5: Level of Explanations Over Sequence of Tests and Interviews for Converging Student CE5



Level of Explanations:

Sequence of Tests and Interviews	Insulation/ Conduction	Thermal Equilibrium	Heat & Temperature Distinction	Heat Flow
Pretests	1	1	1	1
Interview #1	4	5	1	4
Interview #2	5	5	5	5
Interview #3	5	6	5	5
Interview #4	6	6	6	6
Posttest	6	6	6	6
Interview #5	6	6	6	6

Figure 6: Level of Explanations Over Sequence of Tests and Interviews for Converging Student MQ5



Level of Explanations:

Sequence of Tests and Interviews	Insulation/ Conduction	Thermal Equilibrium	Heat & Temperature Distinction	Heat Flow
Pretests	1	1	1	1
Interview #1	1	1	1	1
Interview #2	4	4	4	4
Interview #3	4	4	4	5
Interview #4	5	5	5	5
Posttest	6	6	6	5
Interview #5	6	6	6	6

The following categories of students illustrate ways in which the processes displayed by converging students breaks down.

Progressing Students. Students with a progressing understanding of thermodynamics are incorporating new information to build a more robust and cohesive view of thermodynamics based on a heat flow model. These students are progressing towards the coherent understanding of the students in the previous category. The progressing category, quite naturally encompasses great diversity in student understanding. It includes students who have just begun to make sense of their experiences and find general principles underlying a variety of phenomena as well as students who are very close to developing the level of explanations required to fit into the category of converging students. All students in the progressing category did, however, differ in their processes and/or time lines for developing understanding.

The reasoning processes of Progressing students is best characterized by struggles to resolve experimental/simulated outcomes and to develop relationships between those outcomes. They advanced by fits and starts, they often reached plateaus, followed unfruitful paths or have, in some cases, maintained two separate bodies of knowledge (e.g. heating processes are different from cooling processes), but overall continued to progress toward a robust and coherent understanding of thermodynamics. This is illustrated in the following excerpts.

Student MQ8 began the CLP curriculum with common intuitive conceptions about insulators, conductors, aluminum foil, and thermal equilibrium. On her pretest she stated the metal spoon would be hotter than the 65°C oven and the wooden spoon would not be as hot as the oven. During Interview 1, she agreed with her written statements about the temperature of the spoons. Later in the interview she was asked:

E: On this question about the metal and Styrofoam plates in the same room you checked that the Styrofoam plate was warmer and said, "The metal plate will be cooler than the Styrofoam plate because that's what I think." (MQ8 laughs) Is that OK?

MQ8: Well, actually, the experiment (refers to Probing Your Surroundings experiment), now that I think about it, it did change the way I think because, in the experiment, well, before I thought that, that they could be different. Like if they're placed in the same room, they could be different temperature, but that's not necessarily true because they're both at the same temperature. So they both could be the same temperature but just feel different.

E: So the experiment make you think about that.

MQ8: Uh-huh.

In discussing her response to whether a metal or wooden handled shovel would be best for shoveling snow, she was asked whether the shovels would be the same or different temperatures if left out overnight in a snowbank.

MQ8:. . . Uhm, probably different. The wooden handled one would be warmer and the metal one would be colder.

E: So they'd be different temperatures, and would they feel different?
MQ8: Uh huh! (laughs)

In Interview 2 she consistently applies the concept of thermal equilibrium and appears to be developing understanding about the nature of insulators and conductors. She predicted that all the objects in the ski cabin would be the same temperature and explained:

MQ8: Because the furniture were all the things that were in the cabin. Adjust to the room temperature because they can't be hotter or colder because there is nothing that can make them stay... they just go to room temperature because that is the way they are.
E: Do you always think that way?
MQ8: I never really thought about it.
E: What makes you so sure that this is true?
MQ8: All the experiments we did.
E: Any in particular?
MQ8: We are always talking about the table top or the table leg, the table leg feels colder because it is metal and metal is a better conductor to conduct heat away from your body or heat away rapidly but still, it is still room temp., it is just whether it is a conductor or insulator. So it can be the same temperature
E: So did you always think that that is the way it was, or not really?
MQ8: Kind of, yeah.
E: But it wasn't that big of a deal?
MQ8: No, not really.
E: So you think all the objects in that cold cabin is going to be the same temperature
MQ8: Basically, unless some are wrapped or in boxes... then they may be warmer.
E: But all these stuff that was sitting out will be the same temp.?
MQ8: Yeah.
E: What would that temperature be? Warmer cooler?
MQ8: It would be 5°.
E: Would they feel the same?
MQ8: No, the iron will be really cold.
E: What is going on?
MQ8: The way that it can, the metal stove, the way it conducts the heat away from your body very rapidly, so it feels really really cold.
E: So it is conducting the heat away from my body?
MQ8: Yeah.
E: What if I touch the wood pile?
MQ8: It would probably be cold but not as cold, but it wouldn't be so freezing though.
E: So what is happening?
MQ8: The wood is not a very good conductor, so it conducts the heat away from your body to various rates, so like if you just touched it, it wouldn't feel that cold because it is not a very good conductor.

On the next question, which asked for the best cover for a warm object that would allow someone to feel how warm it is, she chose Saran Wrap©, but couldn't explain why. At first she said it was a conductor then changed her mind. She chose aluminum foil to best feel the coolness of cold objects and gave the explanation, "You could feel it with foil because it is a conductor. It's a good conductor so when you feel it, it feels cold because it is conducting the heat away from your body rapidly" Most students can explain heat flow in one direction long before they can explain it in the other, but for most students it is more difficult to explain why objects feel cold. She had the opposite problem as demonstrated in her response to who is right about the temperature of strips of metal and wood in the hot trunk of a car.

MQ8: Neither of us. They are both the same temperature because they've both been in the same surround.
E: Does that make sense?
MQ8: Yeah, it is in the same surroundings so it can't be two different temperatures.
E: Why not?
MQ8: Because they are both in the same surroundings, and they can be insulators and conductors, but they will be the same temperature because... I don't know.
E: But they won't feel the same?
MQ8: No, the wood will feel warm but not as warm as the metal.
E: How do I feel the sensation of heat?
MQ8: If it is a good conductor and you touch it, then... I can always get the cold but not the hot... if it's hot, maybe it absorbs the heat... I don't know.

Her inability to explain why objects feel different appears to affect her understanding of thermal equilibrium. In Interview 3 after being asked about the temperature of objects in a laboratory oven overnight, she stated:

MQ8: They are probably all the same temperature.

E: Why probably?
MQ8: Actually, they might be the same temperature because they are all the same surroundings...You know, they are all in the same oven, they have all the same amount of heat energy added to them.
E: Do they feel the same?
MQ8: No.
E: What might you find when you touch them?
MQ8: The metal would probably feel the warmest, the glass would probably feel hot, the paper or the asbestos stuff would be warm, and I don't know what that is...well, the glass is the same temperature as the beaker since it is still glass.
E: Are you real sure that they'd all be the same temperature?
MQ8: I am real sure.
E: Why is it if they are all the same temperature, they would feel different?
MQ8: The metal is a conductor so when you touch it, it conducts heat away from your body...wait, no...[end of tape]...I am just going to start over, they feel differently because they...actually maybe they couldn't be the same temperature, because some things take more heat energy to heat them than others. So actually, I kind of change what I said.
E: So they are not the same temperature in spite of the fact they they've been there over night?
MQ8: Maybe, yes, it's possible.

She is trying to put pieces of knowledge together and have them be consistent with her own experiences. She has constructed an explanation for why metals feel cold but has been unsuccessful is understanding heat flow from hot objects. Later in the same question she is struggling to explain why the metal objects feel hotter. She finally decides they must have more heat energy.

E: Let's imagine that this (points to metal spatula) has been there over night and I touch it. What happens to make me say it is hot?
MQ8: The heat, it's flowing out of...well, it is conducting the heat and so...when you touch it, the, it'd feel hot.
E: The metal is conducting from where to where?
MQ8: From itself...I don't know what to think...I don't know what to say, except that it's conducting heat maybe from your body into the metal and then...I don't know...
E: So if I touch this and heat is conducted from my body into this, I am going to say that it is hot.

MQ8: Yes.
E: If I touch the glass, it wouldn't feel as hot.(Editors note: she previously stated this.) So what is different about the glass?
MQ8: It is probably not that good of a conductor but the metal is, so...
E: So what happens that it doesn't feel quite as hot?
MQ8: Less heat energy.
E: Where?
MQ8: There is more heat energy in the metal...
E: Does that make sense?
MQ8: Yes.

Progressing students encompass both students who may and may not observe inconsistencies in their prediction or explanation responses. Their similarity comes in their responses to either self-noted or interviewer-noted inconsistencies—resolution is difficult. They may engage in sufficient reflection that knowledge reorganization occurs and new representations develop, but this is a difficult and lengthy process. Additionally, insights are typically limited in scope and students are often not able to apply them in situations where underlying principles are similar but which differ in surface features. Progressing students knowledge reorganization may not persist throughout a single interview or be carried from one interview to another. This is demonstrated in the following excerpts.

CE4 relied on experiences to make predictions throughout the interviews and had difficulty seeing beyond the surface features of a question. He began the CLP curriculum with typical intuitive conceptions. He chose "tin foil" to keep the soda cold for lunch because, "Tin foil keeps things the same temperature." In a later question on the metal and Styrofoam plates at room temperature, he states, "Metal attracts heat." He later states, "wool has a lot of heat energy" and "wool gives out heat energy." In Interview 1 he said the metal spoon would be at a lower temperature than the wooden spoon in the 65°C oven because metal was a good insulator and wood was a good conductor. In a later question he was asked if all the objects in the room were the same temperature. He responded yes and cited the Probing Your Surroundings experiment.

CE4: Well. before the experiment, I didn't really think about it but after it I knew they were the same.
E: Did the experiment make sense?
CE4: Yeah, pretty much if they've been here for a long time.
E: When touch the things in room, don't feel same. Why don't feel the same if they are the same?
CE4: Because of your uhm, body heat when you touch it because you're always warm, because you've only been here a few minutes.
E: OK, so if touch this and I touch this, ...so what do you think?
CE4: Well, this (metal) would feel colder,but it's room temperature.
E: It really is room temperature?
CE4: Yeah, I think so.
E: Why do you think it feels colder?
CE4: Cause metal, well, I think cause the hot air rises and this stuff would kind of be colder, but it's all the same temperature, I guess. I'm confused.
(skip ahead)

E: This question asks about a metal and Styrofoam plate in same room. You said the metal plate would be warmer because, "Metal attracts heat."
CE4: (Reads) OK. I think that the metal plate should be warmer. Uhm, because, let me think this over a minute. OK, the metal plate would absorb the heat and they Styrofoam, wait, I guess. The metal plate would absorb the heat around and the Styrofoam plate would just stay.
E: So the metal plate is warmer?
CE4: Yeah.
E: So if had metal plate and Styrofoam plate in here and had been sitting here since last night, would they be the same or different temperatures?
CE4: Oh, overnight, I think they'd be the same temperatures.
E: But you were saying the metal plate would be warmer?
CE4: I just thought like a couple of hours. I thought that they'd be in a freezer or something like that.
E: OK, so if they had been in freezer and I took the two plates out and put here, the metal plate would be warmer?
CE4: Yeah, cause the Styrofoam would insulate it.
E: Insulate what?
CE4: The cold air that it just came out of.
E: From the freezer?
CE4: Yeah.
E: OK and you said if they'd been here overnight,
CE4: They'd probably be the same. If they had enough time to get (inaudible).
E: OK. If I touched them, feel the same?
CE4: No, but if you got there temperature, they'd be the same.
(skip ahead)
E: This question was about shoveling snow.
CE4: I've shoveled snow before. I'd probably want to use the wooden one.
E: Why?
CE4: Well cause the metal one would get, when I used one before it gets colder real fast and the wooden one seems to be warmer.
E: Were the shovels different temperatures or the same temperature?
CE4: I think they're different when they're out in the snow. Cause when I've done it before the wooden one feels warmer than the metal one.
E: If those two shovels were in a snowbank overnight, would their handles be the same or different temperatures.?
CE4: I think they would be different because of what I've felt before.
E: Which one was warmer or colder?
CE4: I think the metal one would be colder and the wooden one would be warmer.

This student's inability to apply thermal equilibrium across problems is not unusual. Nor is he usual in thinking of aluminum as an insulator. He later states that orange juice would stay colder in an aluminum cup than it would it a Styrofoam cup because aluminum has more insulation on it.

In Interview 2, CE4 makes predictions consistent with the concept of thermal equilibrium, and while he is unable to explain why objects feel differently, evidence of some knowledge construction is present.

E: What kinds of things feel colder?
CE4: Metal does, usually, I think.
E: So if I touch metal, it feels colder, what's happening?
CE4: I guess because it can absorb the heat energy and then. . .
E: The heat energy from what?
CE4: From the room, I guess. I am confused. I can feel this and it feels pretty warm and this feels colder, but it is actually the same.
E: But you are not sure why?
CE4: Yes.

E: Did you do the potato or Coke experiment? Did you remember doing the principle? Do you remember what your principle was?
CE4: No, I don't. I think it was something to do with the temperature. I am not sure.
E: What do you remember about the experiments themselves, when did you discover about the potato experiments?
CE4: We found that the wool was better because it is a better insulator to keep the potato warm and that aluminum foil, when we went on, it got all the heat energy from the potato until it got the the same temp.
E: So what does that tell you? What do insulators and conductors do?
CE4: Well, an insulator will keep something cold or hot, as long as it possibly can, and then a conductor will take the heat from it from another object, and then it will even out to then.
(skip ahead)
E: If we imagine wrapping something in an insulator, the insulator does what?
CE4: It keeps the thing cold or warm. It keeps the temperature.

In the Interview 3 he is still struggling with his knowledge of thermal equilibrium and his intuitive conceptions about metals becoming warmer than their environment. He is asked about the temperature of objects inside a 150°C laboratory oven overnight.

CE4: I think the metal spatulas would be the hottest.
E: You think it'd be about how hot?
CE4: For overnight if you left it? Almost 200, maybe.
E: So it'd be hotter than the oven?
CE4: No, I don't think so, actually. It'll probably only be about 160 or something like that.
E: So it would be hotter than the oven?
CE4: Yeah.
E: But not a lot hotter than the oven? Okay, but it'd be hotter than the oven. What about the other things in there?
CE4: I think all the glass stuff would be almost even with the oven.
E: What about the asbestos pad?
CE4: What's it made out of?
E: Asbestos. [explanation]
CE4: I think it'll be even, too, with the oven.
E: But you think the metal would be hotter than the oven.
CE4: Not too much.
E: But not that much hotter, maybe 10 or 15 degrees, you said.
CE4: Not that hot, actually, like 10.
E: How do you think the metal gets hotter than the oven?
CE4: I think . . . okay . . .
E: What are you thinking?
CE4: I guess I kinda messed up on the metal because I didn't think about how long they would be there.
E: What if they were there two days, would that make a difference?
CE4: Yeah, I think they'd all pretty much all be the same temperature.
E: What if they were there two hours?
CE4: I would think the metal would be hotter.
E: Hotter than the other things?
CE4: Yeah.
E: What about the oven?
CE4: I don't think so, well, yeah, a little bit
E: You were originally saying that you though the metal things were hotter than the oven and then it looked like you had a conflict in your own mind when I asked you how it would get hotter than the oven. So what was going on in your mind at that point?
CE4: I was thinking about time, then I got confused.
E: So you think if the time is right that the metal can get hotter than the oven that it's in?
CE4: Yeah.
E: How would that happen?
CE4: Actually now that I think about it, I don't think it can.
E: Why do you think it can't now?

CE4: Because inside when you close it, that would be the temperature right there. I don't think it could get any hotter than the oven is itself.
E: So why do you think it can't get hotter than the oven?
CE4: (inaudible)
E: What is it that doesn't allow things to get hotter than the oven?
CE4: Because I guess when you put in the metal and all that stuff, it's not even close to 150 degrees so I don't think it could heat up more than the oven itself.
E: Can things ever get hotter than the oven that they're in?
CE4: I don't know. I'm not sure about that.
E: I don't mean things that generate heat but just normal, inanimate objects.
CE4: Not like fire.
E: No, not like fire, but the things you see in front of you. If you put any of them in an oven, could they get hotter than the oven?
CE4: I don't think so.
E: It looked like you were thinking one way and then you kind of changed the way you thought. What made you change your mind?
CE4: After I thought about it for awhile . . .

After his reflection and reconsideration of thermal equilibrium, he overextends the concept to include objects also feeling the same. It is almost as though he needs explicit help in focusing on the important features of the problem. Another possibility is that he doesn't pay much attention to what is being said or what he is saying. A third possibility is that this is very difficulty for him and requires a considerable amount of work. His comments about class discussion may indicate he has a hard time listening and understanding. His discussion of what he perceives as helpful also provides insight. He finds the simulations most useful. These are quite concrete and related to his daily life.

E: If you touched all these things, the minute you opened the oven door, what do you think you'd find then?
CE4: They'd all feel the same, I think.
E: You think they'd feel the same, too?
CE4: Yeah.
E: So if I touched the metal spatula or the asbestos pad, you think they'd feel exactly the same?
CE4: Oh wait, no. The metal one would feel hotter.
E: Why?
CE4: Because they'd be giving out heat to your fingers when you touched it.
E: Better than the asbestos?
CE4: Yeah.
E: What is it about metal that lets it do that?
CE4: Just the material it's made out of.
E: Is there a special name that you give to materials that do that sort of thing?
CE4: I don't know.
E: Like what metals are called? Conductors?
CE4: Yeah.
E: When you were thinking about things, you could tell that you sort of changed the way you were thinking about it. Did you always think this way before you came into the class, or do you remember what you thought before you came into the class?
CE4: Before this year I didn't really do anything with heat energy.
E: So in a case like this, if somebody asked you if all the objects in the oven were the same temperature, what might you have said?
CE4: Probably said no, that some of them would have been hotter than others.
E: Like you said at first? So what in this class worked to help you understand these ideas?
CE4: When we did the computer stuff on the Macs, that helped me a lot.
E: The experiments and the simulations both, or . . .

CE4: I guess the simulations.
E: The simulations were better than the experiments?
CE4: Yeah.
E: What about class discussion?
CE4: No, because I don't really understand Mr. K. a lot of times.
E: You don't understand what he's saying?
CE4: It's just hard for me to key in on what he's trying to talk about because a lot of people tell me stuff like how the class, like my friends tell me what's going to go on and then he says something different, then I get lost.
E: I wonder if your friends misunderstood what he was going to say.
CE4: Yeah.
E: Are they in a different subject?
CE4: No, they have him but a different time, period.
E: So they tell you he's going to say one thing and he says something really different? Or he just talks about different subjects.
CE4: Yeah, they might have different lessons.
E: That happens. How about the principles? Have they been helpful?
CE4: Yeah, I guess so, because I use them in my thinking, I guess.
E: How do you use them in your thinking?
CE4: It's there and then it clicks in my mind, and that's how I use it.
E: Do the principles help you apply ideas to new problems, or not?
CE4: Sometimes.
E: Sometimes but not all the time.
CE4: Yeah.
E: Do the prototypes help. . ., or do they just . . .
CE4: No.
E: So probably the most useful thing to you is the simulations?
CE4: Yeah.
E: Or do a bunch of thing work together?
CE4: I would say the simulations are the best.

Later in the interview when placing materials on the continuum line, he cited experiments and simulations as explanations. He found the question very hard because, "I don't know (mumbles), because some of these things, I wouldn't even think about using." His references for predictions and explanations are usually concrete experiences. Generalizations are difficult for this student. During Interview 4 he a gave good explanation of why conductors in the pizza oven would feel warmer than other materials. When the question was placed in the context of a freezer, his separate ideas about the cooling and warming of insulators became evident.

E: What is it that a conductor does?
CE4: It gives off heat energy, it gives it to whatever is... give it to its surround.
E: What if a conductor was colder than the surround, would it still give off heat energy?
CE4: So if you have it from the freezer?
E: Yes.
CE4: I guess, I don't know... I am confused. It would... I think it will melt... well my first thoughts that it would take in heat energy but that goes against what I really think, I am not sure.
E: What happens if you put a chunk of metal on the counter for a long time?
CE4: It will get warmer.
E: So if you put a cold thing in a warm surround...
CE4: I think the heat will overcome the...
E: How is it going to get warmer?
CE4: By taking in heat energy from the surround.
E: What did you think of that second, what did you think first?

CE4: Well, I thought the metal was a conductor, then when you said you are putting on a cold, then I didn't know, I got mixed up...
E: Can it still be a conductor?
CE4: Yes, I think so.
E: How is it being a conductor if it is colder than it's surroundings?
CE4: Well, I guess, it will take in heat from the surround and putting it in some...
E: Can conductors do that?
CE4: Yes.
E: Would they do that easily?
CE4: No, I don't think so...
E: So they may warm up with more difficulty than they can cool off?
CE4: Yes.

It should be noted that his confusion did not extend to insulators. In the next bit of dialog, he gave good descriptions of the behavior of insulators in warm and cold environments. Later he restated his idea that conductors lose heat more easily than they gain it. This could be related to the powerful intuitive conception about aluminum foil/metals being able to stay cold. It also displays that his knowledge consists of pieces that have not been integrated. When he receives assistance cueing his pieces of knowledge, his understanding seems to improve. But useful knowledge is not cued on a reliable basis. Support for this is found in the next question where he constructs a container to keep hot objects hot and cold objects cold. He chose Styrofoam for the middle and lined the outside with aluminum. His explanation for his choice follows:

CE4: I remember my mom always wrap the cans with that.
E: So the aluminum will help?
CE4: Yes, sort of like the protector.
E: Does the aluminum work better than the Styrofoam?
CE4: I don't think so, I think Styrofoam is better.
E: Is aluminum a metal?
CE4: Oh yeah, I don't know... I think so.
E: What if we put something hot inside?
CE4: Well then, the hot thing will lost its heat energy slowly but... the container would heat up as a whole and the object will also cool down a little bit.
E: Will the object cool down fast or slowly?
CE4: I think it would cool down slow.
E: What about the trap air?
CE4: I think it gets warmer, it goes with the container.
E: So the air will get as warm as the temperature of the container?
CE4: I think it will cool off as much as the container thing gets warm.
E: What happens to the heat energy that passed through the Styrofoam and hits the aluminum on the outside?
CE4: I think since it's a metal, I think I messed up. I shouldn't have done that, it would go out.
E: Would it?
CE4: Yes, I am pretty sure.
E: Maybe it wouldn't make a difference... what would we use in its place?
CE4: Nothing comes to mind.
E: Maybe it's okay to just use Styrofoam?
CE4: I think you should have another outside, but I just can think of anything.
E: What if we put a cold object in there?
CE4: I think that the heat energy from the container will be absorbed by the cold thing, so the cold thing will slowly heat up and then the cold that it had will just like... I don't know... I think slowly the air inside of it will get a little cooler but it would be melting down slowly.
E: What about heat energy from the outside?
CE4: I don't think it could get in... well, I don't know.. I think some of it could get in... well, I don't think so..

E: A little or a lot?
CE4: A little if any...
E: You think this is good then?
CE4: I am not sure...
E: Can you think of a better way to do it?
CE4: [pause] I don't... I don't know... buy one from the store.

His uncertainly was evident in Interview 5 when he discussed his posttest responses. When asked to explain his heat energy and temperature distinction he responded, "OK, I knew, I knew this yesterday. I think I have a block on it." Later when reading one of his correct responses, he made a noise and said, I don't know. It seems wrong." Unfortunately, he could not explain further. He then stated, "Wait. This. I'm not sure. Now I'm confused. But I'm sure of that answer there. I just throw in the first thing I think of." This is probably not a bad representation of his process. He has developed new, useful intuitive conceptions, but his responses are cued by a variety of stimuli and somewhat varied. There is substantial evidence that while he has improved in his understanding of individual pieces of concepts, his knowledge lacks coherence and robustness.

Progressing students develop the ability to make accurate predictions reasonable rapidly, but explanations for those predictions and events develop more slowly. Their explanations typically refer directly to analogous experiences with limited numbers of principled explanations. Eighteen of thirty-three (or 54.7 %) students fell into this category

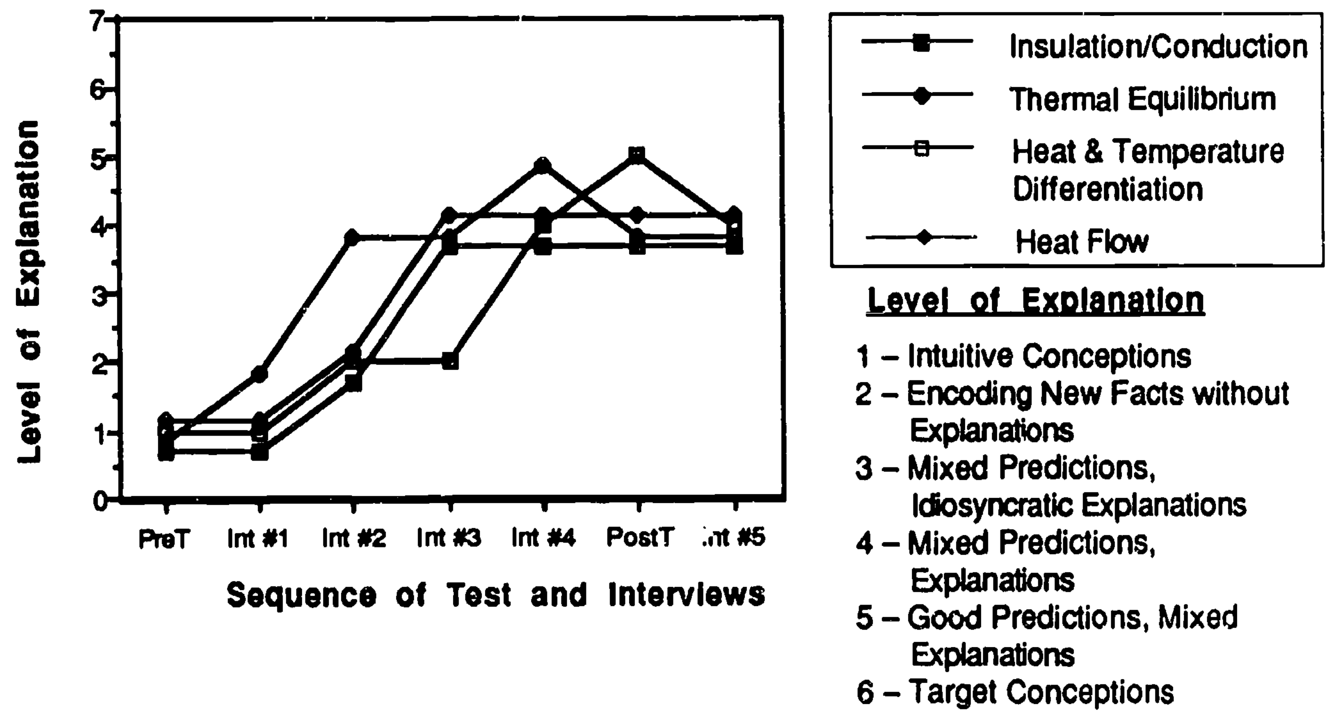
Overall characteristics:

- Consistency in predictions and explanations is less important for Progressing students but more important than it is for Converging Students. While consistency is of some concern, Progressing students have difficulty integrating concepts ideas in spite of a desire to do so.

- The explanations of Progressing students vary in their attentiveness to experimental results and constructed principles but do change over time as a result of their classroom experiments/simulations and discussions.

- Student predictions and explanations rely heavily upon previous everyday and classroom experiences rather than principles. As a result, discussion are specific in nature and there is a tendency to match surface features of problems rather than underlying principles. Figures 7 and 8 provide the Level of Explanations analyses for two Progressing students. A case study of Progressing Student ME 10 can be obtained from the author upon request.

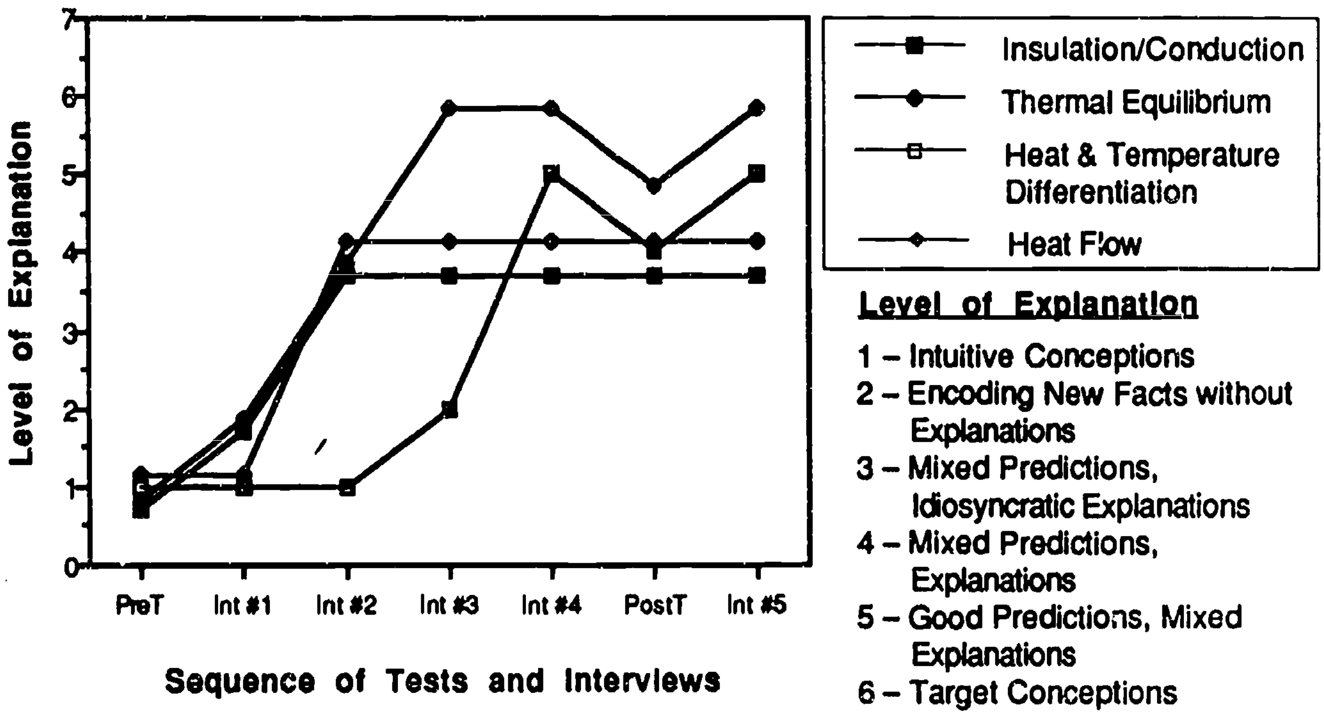
Figure 7: Level of Explanations Over Sequence of Tests and Interviews for Progressing Student CE4



Level of Explanations:

Sequence of Tests and Interviews	Insulation/ Conduction	Thermal Equilibrium	Heat & Temperature Distinction	Heat Flow
Pretests	1	1	1	1
Interview #1	1	2	1	1
Interview #2	2	4	2	2
Interview #3	4	4	2	4
Interview #4	4	5	4	4
Posttest	4	4	5	4
Interview #5	4	4	4	4

Figure 8: Level of Explanations Over Sequence of Tests and Interviews for Progressing Student ME10



Level of Explanation

1 – Intuitive Conceptions
2 – Encoding New Facts without Explanations
3 – Mixed Predictions, Idiosyncratic Explanations
4 – Mixed Predictions, Explanations
5 – Good Predictions, Mixed Explanations
6 – Target Conceptions

Level of Explanation

Sequence of Tests and Interviews	Insulation/ Conduction	Thermal Equilibrium	Heat & Temperature Distinction	Heat Flow
Pretests	1	1	1	1
Interview #1	2	2	1	1
Interview #2	4	4	1	4
Interview #3	4	6	2	4
Interview #4	4	6	5	4
Posttest	4	5	4	4
Interview #5	4	6	5	4

Oscillating Students. The Oscillating student category is used for students who oscillate between more and less predictive views of thermodynamics, who lacks integration of their ideas and makes little overall progress toward target conceptions. At the end of the CLP curriculum these students had incorporated son.. new facts and experienced some reorganization of knowledge. However, their predicuons and explanations were still based based largely on action knowledge and intuitive conceptions. Some were able to incorporate some experimental outcomes into their intuitive conceptions which limitedly enhanced the predictive power of those conceptions. Unlike the students with a progressing view of thermodynamics, these students did not gain more predicti.·e ideas as time goes on but simply moved from one set of ideas to another. They did not develop an understanding of the use and value of principles. As a result, they consider thermodynamic events individually with no need for overall coherence. This resulted in the application of different conceptions to questions with the same underlying principles.

This is demonstrated in excerpts from interviews of oscillating student CQ8. On the pretest question about a wrap for a cold soda she wrote, "foil. Foil will keep it isolated from the heat." During Interview 1 she was asked to say a little more about her answer.

CQ8: It'll keep it like, it;s not free, all the hot air can't get to it. It's surrounded by something, you know.
E: Would anything that surround something work as well as foil? If you put it in a zip-lock bag or something like that.
CQ8: Well, I think that foil, well, yea, I guess it kinda would, but I think foil because it has that stuff, that frost stuff, like you get on your mirror. Then foil kind of protects it and foil is tighter than a zip-lock bag.

She then goes on to explain why foil would work to keep things hot.

CQ8: I think it would because you put stuff in the oven, like if you want to bake lasagna then you have it in your glass thing and it'll bake with foil on top of it.
E: What is the purpose of the foil in a case like that?
CQ8: To keep it isolated at whatever temperature you want, whatever temperature it is.

Later in the interview, after she discussed insulators, she decided that aluminum foil was an insulator. Still later, when discussing whether objects in the same room were the same temperature, she was asked for an example for her "Cannot predict" answer. Her reply was telling, "Let me think of an example, then I can understand it better."

A few minutes later she announced, "Yeah, I think I've come to a conclusion about metal and wood. I think that metals gets either hotter or colder than wood, like quicker." This is an excellent observation. It may be surprising that she has never noticed this before, but clearly reflecting on these questions has cause her to reorganized some of her thoughts.

In Interview 2 she stated that the metal objects would be the coldest in the 5°C ski cabin because they were conductors (note: she did the Probing Your Surroundings Experiment before Interview 1). Her explanation for why they were colder was, "They can't...like uh, they well, they keep, the heat energy goes out of them quicker than insulators. The heat energy just goes, flows out quicker and it can't keep things warm." While this appears to be the beginning of an developing an understanding of conductors, she has a very different response to the question about iron and aluminum.

CQ8: (The iron gets hotter because) it's a better insulator.
E: OK. So if it's a better insulator, what happens that it is able to get hotter.
CQ8: It, uh, it can keep the hot, it can keep the heat in.

It should be noted that most students assume iron must be a better conductor than aluminum if it became hotter. In Interview 3 she explains that all the objects in the laboratory oven would be the same temperature as the oven or hotter. When asked how they could get hotter than the oven, she responded, "The heat energy comes out of something, like let's say it's a hot fridge, then it would get into the objects." Later in the interview when asked the best wrap for a cold candy bar she replied:

CQ8: I am thinking of like the wood and I remember we did all this stuff. I think either wool or aluminum.
E: Wool or aluminum. OK. Would one work better than the other?
CQ8: I am trying to remember our experiment.
E: Let's think about each of them. Why do you think wool would work?
CQ8: Because it's a good insulator and a good conductor. But a really good insulator almost like a good conductor, you know? I was just learning that because--I think we learned that because an insulator keeps things warm and keeps the outside air not to touch it, you know? Well, not to get near it. And it keeps the energy in. And so wool would keep the cold energy in there..., you know.
After a few more interchanges, she was asked:
E: You said something about an insulator also being a conductor. Can you say a little more about that?
CQ8: It's not a conductor, it just kind of does the same things as a conductor.
E: What does a conductor do?
CQ8: It keeps things cool without letting the heat energy and the air come in.
E: Do conductors also keep things warm?
CQ8: No, because the conductor makes it so heat energy can't come it, and that keeps it for cold things, but an insulator is, keeps the cold energy not to come in, just to keep the heat energy in.

After CQ8 gave an explanation of how aluminum would work to keep the candy bar cold, she was asked if she had any idea which would work better.

CQ8: Um...no, I don't.
E: Would they work the same?
CQ8: No, I think one would work better.
E: But you are not really sure which?
CQ8: I can't really remember.
E: So you are inclined to say one, but you can't remember which one?

CQ8: Yeah.
E: Can you reason your way through it and see which one might be better?
CQ8: I think aluminum would because it was a better--it was more of a conductor. Yeah, so like I would guess aluminum. Like, on a test, I would guess aluminum.

Later on a question about the temperature of a cold room in the tropics, she stated that metal would feel cold because it was a better conductor and "could keep in the cold better than the wood can." In the next question on the continuum line, at first she placed metal as a good insulator, then placed it in the middle of the continuum line giving a confused explanation, "I think that the metal would be like...um right here you know? Oh no, not an insulator. I mean conductor. Well, actually I don't because it's not a good insulator--it's not a good conductor because it does keep in the cold and...so I'd say a good insulator." When asked what a good insulator was she stated it was "great at keeping things warm," and conductors "keep the cold inside of it."

In interview 5 she used the same definitions saying insulators keep hot things hot and conductors keep cold things cold. She was integrating some of her classroom experiences into her definitions and stated, "wool is a good insulator and a good conductor." She then explained that it could keep hot food hot and cold food cold. Later in the interview she correctly predicted that the wax on the metal block would melt first. The exchange reveals her conflict between what she thinks should be thermal equilibrium and her own experiences.

CQ8: Metal will melt the quickest because metal always feels the hottest so the wax will melt the quickest.
E: So the metal will feel hotter than the block of wood or would it get hotter?
CQ8: It would feel hotter, but it would not get hotter.
E: If it is the same temperature, wouldn't the wax melt at the same time?
CQ8: Yeah. Except, I still think that the wax on the metal will melt first.

It should be noted that on the post test she selected aluminum foil to wrap the cold soda for school lunch. Her explanation was, "aluminum foil is a good conductor." Her posttest responses represented a development of intuitive conceptions about insulators and conductors that she did not have prior to taking the course. Additionally, she had incorporated experimental outcomes to the extent that she knew that wool was effective at keep things hot and cold. Her explanation was not useful in understanding future problems, but it did allow effective predictions about wool. Her understanding of thermal equilibrium had progressed so that she made good predictions on all thermal equilibrium posttest questions. While her explanations did not represent much in the way of generalization, they were essentially correct. This is demonstrated by her explanation for why the spoons in the 65°C oven were both 65°C: "I think in about that time they will become the temperature of the oven." In spite of what seems like small progress, she effectively incorporated the concept of thermal equilibrium and some additional action level knowledge about wool into her existing knowledge. Her response to the request to, "describe something you learned in science classes which you could use to explain events outside of school" tells of her perceptions. "I could use the stuff I learned about insulators and conductors a lot in my life."

Some oscillating students attempted to develop explanations for their action-level knowledge and intuitive conceptions. However, the explanations were tied to their individual interpretation of experiences in ways that did not allow the integration of new information. Their idiosyncratic explanations were not altered by alternative classroom experiences. In fact, they often made biased interpretations of experiments/simulations and misinterpreted patterns of evidence to preserve intuitive conceptions or some constructed idiosyncratic explanation. This is exemplified by the following selection of excerpts from student MQ7. On the pretest he named aluminum as an example of a good conductor and wrote, "Aluminum can let electricity pass through." When asked if this response was alright in Interview 1, he replied:

MQ6: Not really. I really didn't understand the question. (He mumbles something about Mr. K).... Aluminum. I don't know about electricity. I don't know why I put that.
(editors note: later says aluminum a good conductor)
E: Why would you say aluminum is a good conductor?
MQ6: Cause it's uhm...uhm, it's just good. I don't know.

Students seemed to perceive these explanations as applicable in some cases and not in others. As a result, they were unconcerned with responses that seem contradictory. Contradictions were usually explained away with no apparent need for consistency. This may well be based on some belief that science is not coherent (Songer, 1989). This is exemplified by a response when the interviewer expressed general confusion with contradictory explanations to similar questions. The student responded by patting the interviewer on the hand saying, "Don't worry. I understand it."

Their reasoning was characterized by mapping of real world experiences onto questions and responding to those questions based on those real world experiences. Oscillating students made good predictions when such a match existed. Since their observations and explanations were typically very concrete, it may be that seemingly straightforward thermodynamic explanations were too abstract and unintelligible. As a result, principles had limited appeal and usefulness. Oscillating students clung to alternative, simpler constructions which provided some explanation for some events. As a result, these students appear to reject coherent explanations because they cannot integrate their own intuitive conceptions with principles. Eight out of thirty-three students (or 24.2%) fell into the Oscillating category.

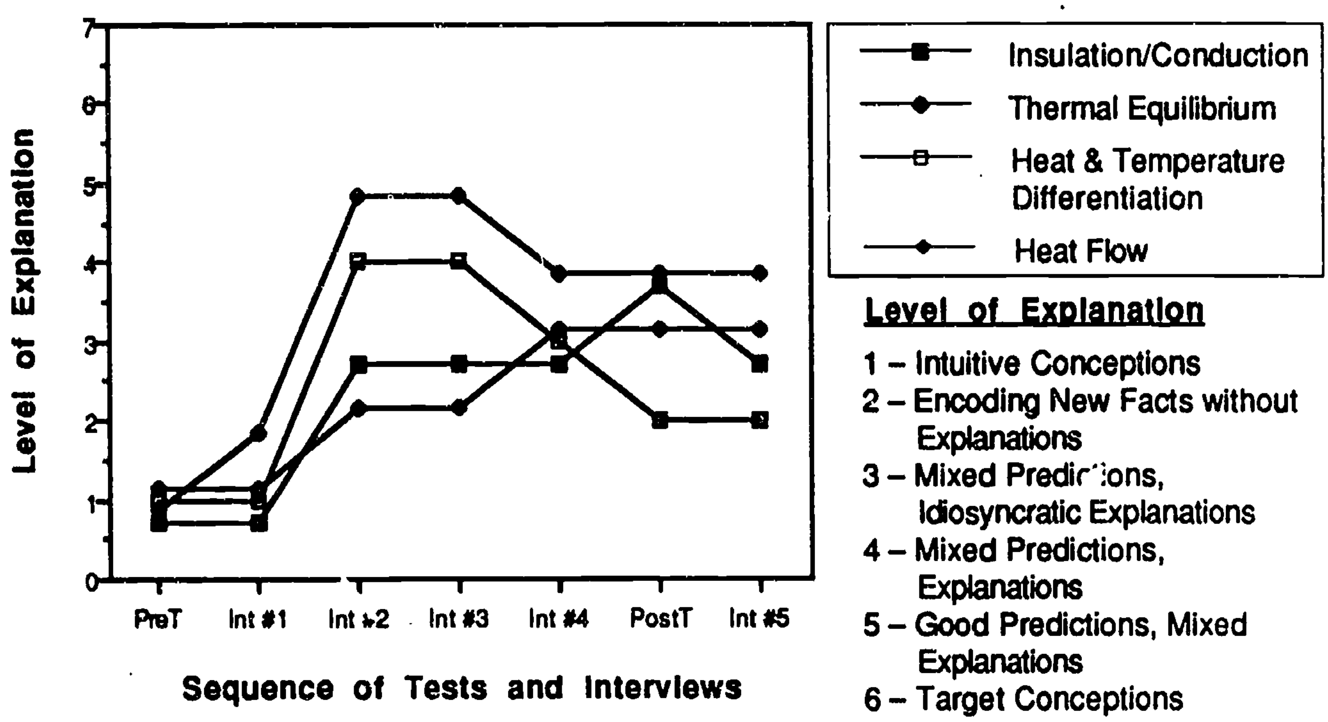
Overall characteristics:

- Consistency was local, not general for Oscillating students. Contradictions were never noted by the students and were not acknowledged when noted by the interviewer. These contradictions are instead seen as different problems requiring different solutions.

- Oscillating students' reasoning was characterized by direct mappings of questions to previous experiences. Explanations were derived from intuitive conceptions or intuitive conceptions that evolved into idiosyncratic explanations that were perceived to apply to that example.

- Oscillating students' recall of experimental/simulated outcomes was often reconstructed to supported their intuitive or idiosyncratic concepts. Figures 9 and 10 provide a Level of Explanations analyses for two Oscillating students. A case study of Oscillating student MQ6 can be obtained from the author on request.

Figure 9: Level of Explanations Over Sequence of Tests and Interviews for Oscillating Student MQ6



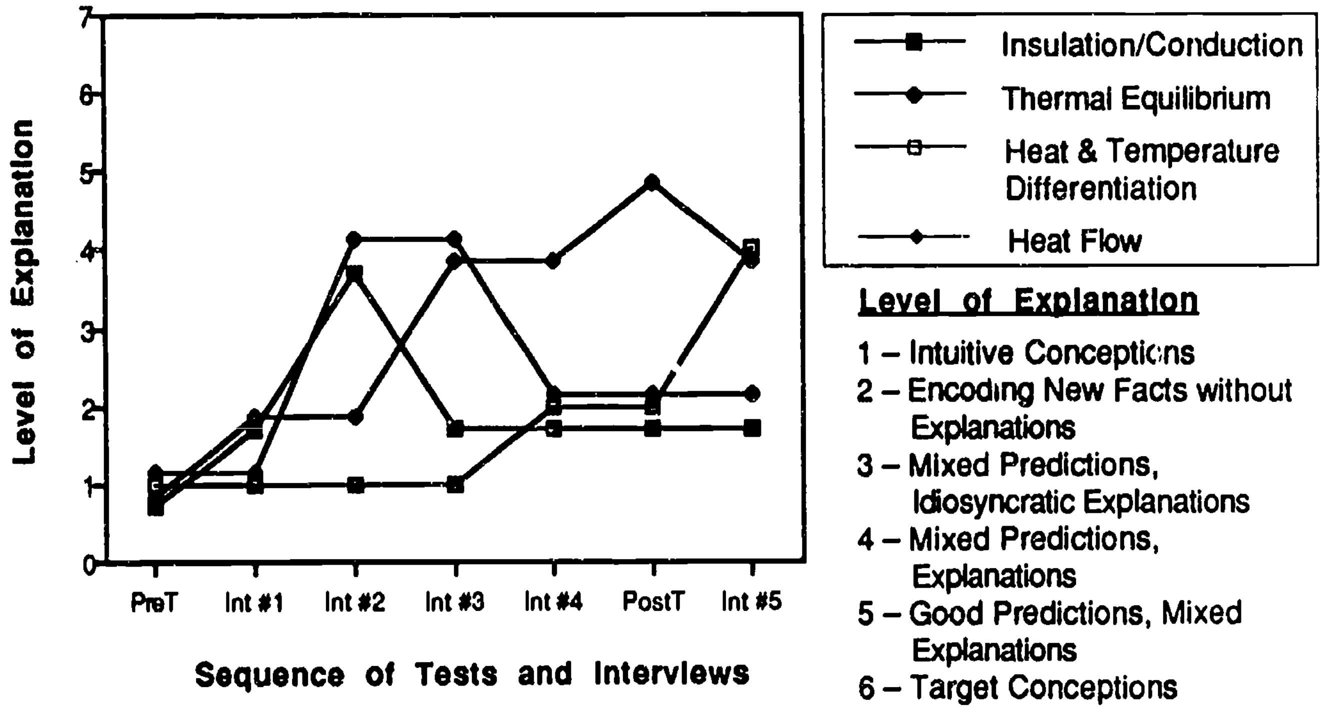
Level of Explanation

1 – Intuitive Conceptions
2 – Encoding New Facts without Explanations
3 – Mixed Predictions, Idiosyncratic Explanations
4 – Mixed Predictions, Explanations
5 – Good Predictions, Mixed Explanations
6 – Target Conceptions

Level of Explanations:

Sequence of Tests and Interviews	Insulation/ Conduction	Thermal Equilibrium	Heat & Temperature Distinction	Heat Flow
Pretests	1	1	1	1
Interview #1	1	2	1	1
Interview #2	3	5	4	2
Interview #3	3	5	4	2
Interview #4	3	4	3	3
Posttest	4	4	2	3
Interview #5	3	4	2	3

Figure 10: Level of Explanations Over Sequence of Tests and Interviews for Oscillating Student CQ8



Level of Explanations:

Sequence of Tests and Interviews	Insulation/ Conduction	Thermal Equilibrium	Heat & Temperature Distinction	Heat Flow
Pretests	1	1	1	1
Interview #1	2	2	1	1
Interview #2	4	2	1	4
Interview #3	2	4	1	4
Interview #4	2	4	2	2
Posttest	2	5	2	2
Interview #5	2	4	4	2

Comparison of Categories Using Posttest. Coding requirements for "correct" posttest responses were not as rigorous as the requirements for achieving target conceptions in the Level of Explanation Analysis. The primary source of this difference relates to what can be assessed from an answer on a test compared to probing a student's response during an interview. For instance, a student's response of "metals" as an example of a good conductor would be coded as correct. In an interview, if that same response were probed and the discovery made that a student thought metal was a conductor because it held cold, this response would not be considered correct. In spite of these differences, a comparison of student categories and posttest means supported student placement in those categories. Table 3, below, shows such a comparison. Since coding processes and coding keys transcend semesters, this gives additional validity to the Levels of Explanation method by which student understanding was assessed as well as to the categories into which students were placed.

Table 3: ANOVA of Pretests and Posttest Means by Student Categories

Student Categories	N	Pretests Mean (Std. Dev.)	Posttest Mean (Std. Dev.)
Converging	7	61.4 (4.9)	98.7 (9.8)*
Progressing	18	61.6 (4.2)	91.2 (6.9)**
Oscillating	8	60.9 (5.9)	77.2 (5.6)

* Converging Students' Posttest Means significantly better than Progressing and Oscillating students at $p<.0001$
**Progressing students' Posttest Means significantly better than Oscillating students at $p<.0001$

The reliability of these student categories is further supported by comparisons of student responses to the heat energy and temperature distinction question. The percentage of students meeting strong criteria[4] on this question has been used as a measure of student success in the CLP curriculum for many semesters. Converging students performed better than Progressing students, $F(1, 31) = 3.9$, $p<.05$. Converging students also performed better than Oscillating students, $F(1, 31) = 8.4$, $p<.005$. Additionally, Progressing students performed better than Oscillating students, $F(1, 31) = 2.1$, $p<.05$.

[4]/Strong Criteria require a good differentiation between heat energy and temperature including one of the following and an example: (a) intensive properties of heat energy and extensive properties of temperature; (b) a discussion of heat flow which includes direction; or (c) a discussion of heat flow until thermal equilibrium is reached. The criteria can also be met by two good examples or two good explanations using a, b, or c.

Intervention Effects

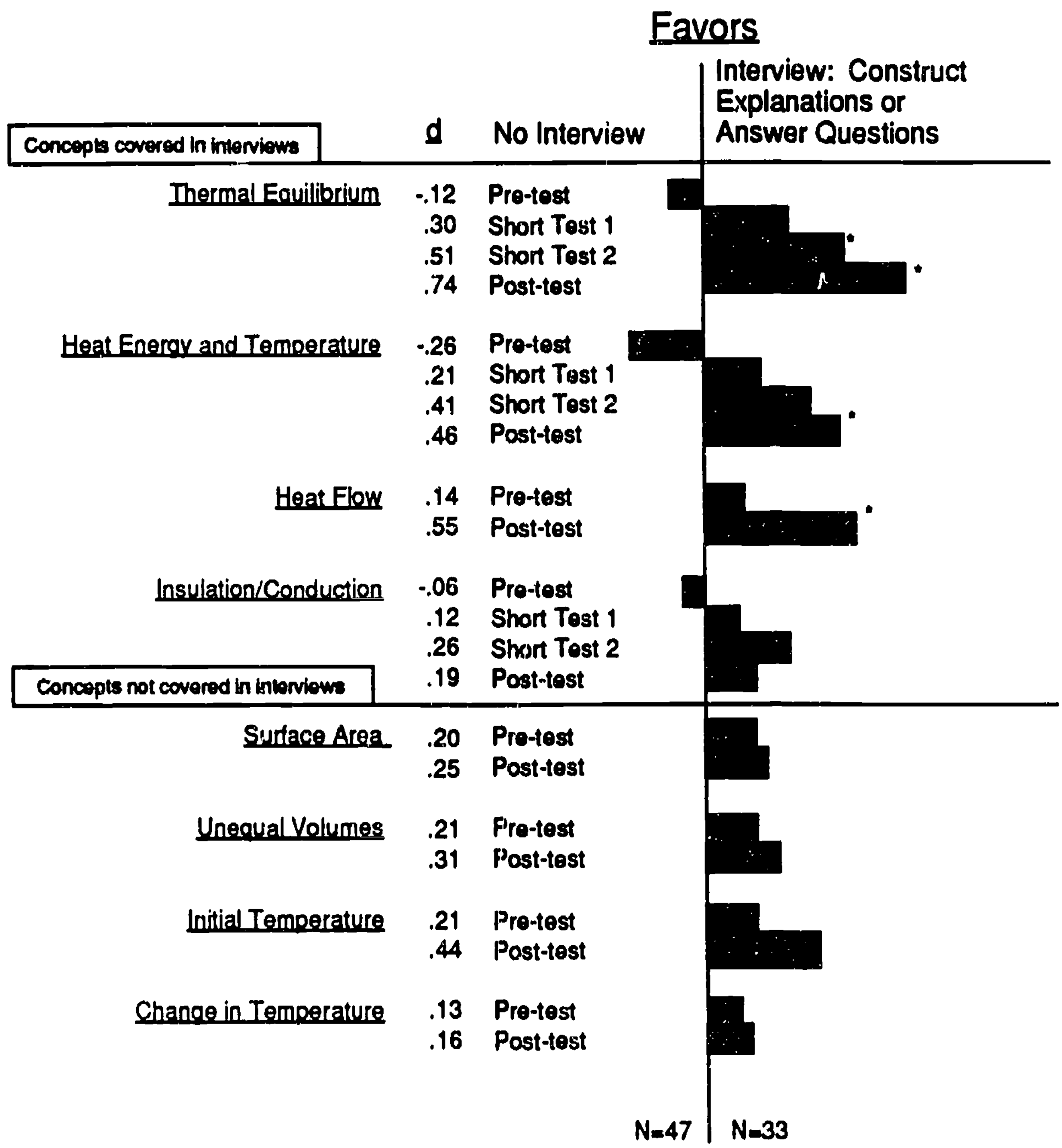
The very act of interviewing students facilitated the development of understanding and produced statistically significant differences in posttest scores. While the interviews were short (approximately 15-20 minutes per interview) and of limited number (4 interviews before the posttest; one after), it is apparent that encouraging students to reflect deeply upon their responses and explanations is beneficial in the development of understanding.

An effect size analysis shown in standard deviation units of test results over the course of the 13-week curriculum demonstrates the improvement in student understanding (see Figure 11). Students began with no significant differences in their pretest scores. Over time, interviewed students progressed steadily in their test responses compared to the non-interviewed students. On the posttest, significant differences were found in the areas of predictions and explanations of thermal equilibrium, distinguishing heat energy and temperature, and heat flow.

Figure 11 shows that the interview produced no differences in the area of insulation/ conduction probably because this already comprised a large part of both the curriculum and students' classroom activities. Since the Spring 1989 semester, a major focus of the curriculum has been insulation and conduction. Pilot studies showed that students' intuitive conceptions in the the area of insulation and conduction were persistent and presented substantial barriers to understanding elementary thermodynamics (Lewis, 1987). This led to curricular reformulations during the Spring 1989 semester: Simulations of everyday experiences related to insulation and conduction were added (Lewis & Linn, 1989). Additionally, great emphasis was placed throughout the curriculum on the concepts of insulation and conduction. As a result, all students attained relatively high understanding in this area in subsequent semesters.

A consequence of the emphasis on insulation and conduction was that thermal equilibrium received less attention and student performance in this area declined in both Spring and Fall of 1989. However, interviewed students again performed significantly better than non-interviewed students in the area of thermal equilibrium. Further Figure 11 shows the progression in their understanding from pretest along the way to posttest. These results are not surprising since each interview contained at least one thermal equilibrium question about everyday situations. Students' responses to these questions were then probed to determine their depth of understanding. As a result, interviewed students spent more time considering thermal equilibrium and their own understanding of that concept.

Figure 11: Effect Size by Comparing Interviewed Students with Non-Interviewed Students (All Students from Middle 50% on Pre-Tests)



*Indicates statistically significant at p = 0.05

It is also not surprising that no statistical differences arose for variables not covered in the interviews, e.g. surface area, unequal volumes, initial temperatures, and temperature differences. Most students entered the curriculum with good intuitive conceptions of these variables and their understanding continued to increase over the course of the curriculum.

While using the CLP curriculum, students engage in the process of reflection. They give explanations for predictions as well as experimental/ simulated outcomes. However, since these predictions and explanations are "research group" constructions, individual students are engaged to varying degrees. The process of interviewing students compels them to engage more deeply in the process of reflection on an individual basis. Students participating in the interview process also knew that their understanding of everyday thermodynamic phenomena would be probed regularly. Students' anticipation of future interviews may have provided additional motivation to reflect further on the questions asked during the interviews and to be pay greater attention to classroom processes.

The interview also provided students the opportunity to compare their responses to related questions within a given interview and check the consistency and coherence of these responses. Since students often give contradictory responses to similar questions, the interview questions were designed to illustrate inconsistencies in a student's knowledge. Students who perceived those contradictions on their own would often engage in illuminating monologues where they would sort out their thoughts (this will be discussed in detail in the section on cognitive growth). As might be expected, these students were typically more successful at integrating their knowledge and applying that knowledge successfully to new problems. Other students who might normally choose to ignore contradictions in their responses were presented with questions about those contradictions. While they were free to say they had no explanation, the interviewer would return to the contradiction in some new question in an attempt to encourage resolution. Alternately, some students constructed ad hoc explanations or engaged in processes of reflection that were not profitable but which were satisfactory to that student.

CONCLUSIONS AND IMPLICATIONS

Students participating in interviews were encouraged to engage in reflection by requiring them to focus on their experimental/simulated outcomes as well as their own descriptions and explanations of thermodynamic processes. In doing so, the interviews did not permit students to give a single piece of information in response to a question. Instead, the interviews encouraged and required students to continually reconsider their classroom and real-world experiences and their own understanding of those experiences. In essence, the interview encouraged students to reflect on their experiences and engage in sense-making processes. As a result of this reflection, over time, most students' verbal representations of their ideas improved. This process, in turn, appeared to encourage further knowledge reformulation.

Furthermore, the interviews, with their persistent requirements for explanations, promoted and encouraged students to engage in more analytical processes. T is, in turn, encouraged students' generalization of their conceptions. The interviews, further, instilled in students a propensity toward giving explanations. Over time, students increasingly incorporated explanations into their predictions without being asked. During the interviews, it was not uncommon for a student to say, "I knew you were going to ask me that!" in response to a "Why?" from the interviewer. Later in the interviews, several students finished giving a prediction and then mimicked the interviewer by adding, "Why?" It was clear they expected to give explanations and began to give them more spontaneously. This elaboration represents an additional step in knowledge construction. Mindful, deliberate abstraction is a difficult process that takes time and requires motivation by students. The interviews appear to have provided extrinsic motivation for students to persist in reflective processes. This outcome is noteworthy because it shows that even a short instructional intervention has the potential of encouraging students to engage in additional reflection and elaboration of their ideas.

How Understanding Changes—Three Categories of Learners

All students proceeded to some extent by fits and starts, gaining some local reorganization of knowledge, overextending new ideas, acquiring new pieces of knowledge, and integrating them into their existing knowledge. These constructive processes proceeded at considerably different rates, and revealed great diversity in students' understanding at the end of the CLP curriculum.

Some students engaged in a small scale reorganization of knowledge, while others showed major restructuring of their concepts. Most students were somewhere between these extremes. This middle group experienced major restructuring in some areas and was in the process of knowledge acquisition and developing coherent understanding in other areas. Analysis of student interviews suggested three general categories of students' development of understanding. These categories are called Converging, Progressing, and Oscillating.

Student Categories of Knowledge Acquisition

The emergence of three categories in the development of students' understanding was determined to some extent by differences in students' perceptions of the nature of the unit of knowledge. Oscillating students perceived the unit to be at the level of actions or events, each requiring different explanations. Thus phenomena, which were governed by the same principles, but with differing surface features, were perceived as different domains (e.g. heating and cooling would be considered different domains). As different domains, they required separate rules to describe their behavior. Progressing students were beginning to combine these domains using some underlying concepts and generalize beyond the surface features of phenomena. As an example, they may have been able to apply the concept of thermal equilibrium to a variety of circumstances, but were unable to explain why materials in those circumstances felt different. Their unit of knowledge was at the level of individual concepts (e.g. thermal equilibrium, insulation, etc), but they had not integrated these concepts into a larger more cohesive view of elementary thermodynamics. Converging students used all of the concepts in the curriculum as a single domain that was expected to have internal coherence.

These very different views of thermodynamic problems yielded very different approaches to their solutions. Oscillating students tried to locate the appropriate piece of knowledge for a given problem. Progressing students tried to locate the individual concept involved and determine how it could be applied. Converging students examined the problem from a more global perspective and were more able to see how individual processes contributed toward an given outcome. Additional discussion of the characteristics of each of three categories of students follow.

Converging Students. Converging students are characterized by a robust and coherent understanding of heat flow as a model for understanding elementary thermodynamics that begins to converge with accepted scientific views. A key characterization of their reasoning processes was their ability to resolve contradictions in their responses, reason through their in-and-out of-class experiences, and decide which explanations were most consistent with other pieces of their knowledge. Converging students continued to add new information to their existing knowledge and find that new knowledge was consistent with and reinforced the way they thought about thermodynamic phenomena.

Converging students were more able to subject their intuitive conceptions to examination and comparison with their experimental and simulated outcomes. In doing so, they constructed new explanations for previous experiences. When Converging students used analogies in their reasoning processes, they did not rely on surface similarities, but reasoned from underlying thermodynamic processes. Their explanations for predictions in the interviews were more causal and principled in nature. Some Converging students' behavior in the first interview suggested a belief that all of their pieces of knowledge should fit together. Other Converging students recognized this knowledge coherence later in the interview process. The emergence of this awareness appears to accelerate students' progress toward knowledge integration. This hypothesis is consistent with the findings of Songer (1989). She found that students' beliefs about the nature of science were a predictor of the level of knowledge integration they would attain.

Progressing Students. Students with a progressing understanding of thermodynamics are incorporating new information to build a more robust and cohesive view of thermodynamics based on the heat flow model. These students are progressing towards the coherent understanding of the students in the previous category. The progressing category, quite naturally encompasses great diversity in student understanding. It includes students who have just begun to make sense of their experiences and find general principles underlying a variety of phenomena as well as students who are very close to developing the level of explanations required to fit into the category of converging students.

The reasoning processes of Progressing students are best characterized by struggles to resolve experimental/simulated outcomes and to develop relationships between those outcomes. They advanced by fits and starts, often reached plateaus, followed unfruitful paths or, in some cases, maintained two separate domains of knowledge (e.g. heating processes are different from cooling processes). Overall they continued to progress toward a robust and coherent understanding of thermodynamics.

An example of this knowledge construction is found in students' understanding of thermal equilibrium. At first, students consider objects in different surroundings as different domains. That is, different "rules" apply to objects in warm environments, cold environments, and at "room temperature." The Probing Your Surrounding experiment is a powerful tool for enabling them to simultaneously experience the identical temperatures and different feel of materials. This results in the incorporation of facts relating to the temperature of objects at room temperature. Since this matches students' intuitive belief that objects in the same environment should be the same temperature, it is more readily accepted and ultimately generalized to thermal equilibrium in different surroundings. Their ability to explain the feel of materials comes later as they combine their evolving facts and concepts of insulators/ conductors, heat flow, and thermal equilibrium. Pieces of knowledge are constructed and integrated within the concepts of thermal equilibrium, heat flow, and insulators/conductors. After integration within these concepts occurs, the concepts must be linked before students can develop explanations for why conductors feel different than insulators to the touch. This process is a difficult and lengthy one for Progressing students. The level of integration that was just demonstrated gives insight into why many Progressing students are never able to explain the feel of a variety of materials in different environments. Since Progressing students' insights into problems are more limited in scope, they are often not able to perceive situations whose underlying principles are similar, but differ in surface features.

Progressing students encompass both students who may and may not observe inconsistencies in their prediction or explanation responses. Their similarity comes in their responses to either self-noted or interviewer-noted inconsistencies—resolution is difficult. Progressing students' knowledge reorganization may not persist throughout a single interview or may not be carried from one interview to another.

Oscillating Student. The Oscillating student category is used for students who oscillate between more and less predictive views of thermodynamics, who lack integration of their ideas and make little overall progress toward target conceptions. At the end of the CLP curriculum, these students had incorporated some new facts and experienced some reorganization of knowledge. At the level of isolated knowledge, these students had made progress. As a result, their predictions and explanations were still based based largely on action knowledge and intuitive conceptions. Some were able to incorporate some experimental outcomes into their intuitive conceptions which limitedly enhanced the predictive power of those conceptions. Unlike the students with a progressing view of thermodynamics, these students did not gain more predictive ideas as time went on, but simply moved from one set of ideas to another. They did not develop an understanding of the use and value of principles. As a result, they considered thermodynamic events individually with no need for overall coherence. Oscillating students were not concerned by a lack of coherence or sense-making in their responses. This resulted in their application of different conceptions to questions with the same underlying principles.

Implications of Student Categories. It is clear that learners develop understanding of scientific principles in very different ways and at very different rates. The emergence of these categories of student development of understanding in elementary thermodynamics has implications for science instruction.

In general, curricula must have components that serve all categories of students. As an example, the construction and use of principles was very difficult for Oscillating students. A common response was, "They're too hard—and they don't make sense." For these students to make progress in understanding, experiments and simulations that relate to their real world knowledge can be used to construct new intuitive conceptions. Since much of the reasoning processes of Oscillating students is experience-based, experiments and simulations can be encouraged as new referents. If explanations can be imbedded in these experiments and simulations there is the possibility of increasing coherence. It is vital that a new way of thinking about science must be made appealing if these students are to ultimately gain skill in detection and application of principles. One way to expand their ideas about the nature of science is to model problem-solving and sense-making processes. The development of simple models and prototypes should appeal to these students. If this development is accompanied by student success in predictions and explanations, Oscillating students may be led to see the usefulness and power of generalizations.

These recommendations are equally valid for students who are beginning to use underlying principles in their assessment of phenomena. While they will progress more rapidly in their understanding, they still need representations to form bridges between their intuitive conceptions that are the beginning of scientific principles and those principles. Furthermore, they need experiences that require comparison of their intuitive conceptions that are not consistent with scientific principles with experimental outcomes in real-world settings. Such experiences should include experiments on and simulations of everyday phenomena so that they can begin the complex and difficult process of knowledge integration. These students are able to construct and apply principles with varying difficulty. Principle construction and integration activities should accompany all experiments and simulations.

If instruction is to serve all students, it must have a variety of components that are appropriate to the level of the learner, that encourage sense-making in exploring concepts and that facilitate knowledge integration. The absence of these components serves to reinforce many students' ideas about the nature of science learning: "In science the best thing to do is just memorize, because it isn't supposed to make sense." Students' fundamental views on the nature of science must also be addressed in curricula. Included in this understanding of science must be what constitutes evidence and the ability to compare evidence in order to reach conclusions.

This study demonstrated that the received view of learning does not describe the ways students acquire knowledge. If the goal of instruction is to produce individuals with coherent and robust knowle lge, telling students about science and science principles is not an effective method for attaining these goals. This raises the question of what are appropriate and desirable levels of stude understanding. Is the goal to have students learn isolated facts that seem to have little relevance in their lives? If so, current methods that provide students with information on a wide breadth of subject matter as well as detailed coverage within those concepts—all in remarkably short periods of time seems a reasonable way of attaining that goal. If the goal is for students to develop an understanding of science and scientific principles, and be able to apply these concepts to daily life, current educational practices will not work.

Students' difficulty in knowledge acquisition and knowledge integration has been demonstrated in this study. These difficulties existed in spite of a 13-week curriculum that explored a few concepts in great depth. These difficulties existed in spite of a curriculum that began with learners' intuitive conceptions and sought to assist them in knowledge construction using real-time experiments and real-world simulations. These difficulties existed in spite of efforts to engage students in deep reflection by having them engage in numerous integration activities.

The implications for science instruction are obvious. Curricular emphasis must be placed on depth rather than breadth and on understanding versus recall of facts. Curricula must provide sufficient time to take into consideration both students' initial understanding of the subject matter and their beliefs about the nature of science. Curricula must also provide sufficient time for a variety of experiences that facilitate knowledge construction. Additionally, instruction that fosters knowledge integration should be embedded in curricula. Two examples of this type of instruction found in this study could be embedded in any curriculum: (1) encourage students to engage in deep reflection and (2) instill in students a propensity to construct explanations. While these processes require time, they should produce students whose knowledge is robust and coherent and who also feel capable of understanding science and its relationship to their world.

Instruction that Fosters Knowledge Integration

Consideration of Intuitive Conceptions. The observation that students have persistent intuitive conceptions is not new. What has been presented here are some insights into the nature and construction of these conceptions and causality for their persistence. Intuitive conceptions are constructed by the very processes that are valuable to individuals and valued by science—making observations of phenomena over a variety of circumstances and attempting to find generalizations for those phenomena. Students' action knowledge and intuitive conceptions are the product of many years of such observation and attempts, however limited, at sense-making of those processes. This study has shown how resistant some intuitive conceptions are to change. This is especially true when students do not understand and cannot apply alternative explanations.

Any instruction that wishes to facilitate the reorganization of students conceptions, in an area where intuitive conceptions exist, would be wise to explicitly take those intuitions into consideration. As this study demonstrated, students have great difficulty with ideas that do not fit their world experience. Instruction must be connected to students' observations of the world and have concerns for students' conceptions and their learning processes. It is, therefore, useful to include real-world knowledge and experiences in instruction for several reasons. First, it encourages the integration of knowledge instead of the isolated "school knowledge" and "real-world" knowledge we find in students, nonscientists, and even a few scientists. Second, it encourages students to develop alternative explanations for those intuitive conceptions that are contrary to scientific principles. Instruction can ground useful notions of causality in students' real world experiences. Additionally, it makes scientific knowledge easier to remember. Real world experiences can serve as prototypes and cueing mechanisms for new intuitive conceptions as well as more principled understanding.

Emphasis on Reflection and Explanations. When students engage in activities that requires sustained reflection, they make greater cognitive gains and are more successful in integrating knowledge. Additionally, instruction that instills a propensity for explanation encourages students to engage in additional reflection that facilitates knowledge integration. The process of sustained reflection is quite difficult for most students. This could be improved if science curricula began to emphasize reflection as an integral part of the daily activities in the early grades.

Students must engage in sense-making in science. Instruction must foster and encourage student reflection on their own notions of science and the coincidence or conflict of those notions with school science. Science curricula should emphasize students' construction of explanations of phenomena on a regular basis. As deeper explanations become a part of a students' discourse in science, they will engage in different learning processes. This changes should motive changes in the way students perceive phenomena—more analytically and with greater emphasis on underlying processes.

Motivation for reflective process can be found by choosing activities for science instruction that seems relevant to students' lives. A part of fostering reflection and construction of explanations includes demonstrations of scientific processes and reasoning about those demonstrations. Since demonstrations that relate to daily life are often most interesting and remembered, one of the goals of science instruction should be to embed students' learning in real-world contexts. This not only creates functional learning environments but encourages students to employ more scientific reasoning in their daily lives.

As shown in this study, mindful, deliberate abstraction of experiences into principles is difficult for students. The process also takes time and requires student motivation. Curricula contents must be appropriate to the cognitive demands for knowledge integration. Extensive coverage of fewer topics is more likely to provide the time required for students to develop coherent and robust knowledge. Fewer topics are not enough. Science curricula must include more than facts, experiments, and prototypes if students are to engage in the difficult process of knowledge integration. Emphasis must be placed on activities that foster students' construction and application of more abstract and general scientific principles.

The question of how integration activities should be defined is worthy of future consideration. Should integration activities been created from students in general or should they be created bases more diagnostically for the individual student or a combination of the two?

REFERENCES

Ausubel, D. P., Novak, J. D. & Hanesian, H. (1978). *Educational psychology: A cognitive view. (2nd. Ed.).* New York: Holt, Reinhart, and Winston.

Baldwin, J. M. (1984). *The development of the child and of the race. (Reprinted by Augustus M. Kelley, 1968 Ed.).* New York: MacMillan.

Caramazza, A., McCloskey, M. & Green, B. (1981). Misconceptions about trajectories of objects. *Cognition, 9,* 117-123.

Carey, S. (1988). Conceptual differences between children and adults, *Mind and Language, 3* (3), 167-181.

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

Chaiklin, S. (1984). *Reasoning with a physical-science concept.* Unpublished dissertation, University of Pittsburgh.

Chi, M. T. H. & Ceci, S. J. (1987). Content knowledge: Its representation and restructuring in memory development. In H. W. Reese, & P. Lipsitt (Ed.), *Advances in child development and behavior* (pp. 91-142). NY: Academic Press.

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

Clement, J., Brown, D. E. & Zietsman, A. (1989, March)*Not all preconceptions are misconceptions: Finding "anchoring conceptions" for grounding instruction on students' intuitions.* Paper presented at the American Educational Research Association, San Francisco, CA.

Clough, E. E. & Driver, R. (1985). Secondary students' conception of the conduction of heat: Bringing together scientific and personal views. *Physics Education.*

Dewey, J. (1902). *The child and the curriculum.* Chicago: The University of Chicago Press.

diSessa, A. A. (1988). *Knowledge in pieces.* Hillsdale, N. J.: Lawrence Erlbaum Associates.

diSessa, A. A. (1983). *Phenomenology and the evolution of intuition*. Hillsdale, N. J.: Lawrence Erlbaum Associates.

Driver, R. (1981). Pupils' alternative frameworks in science. *European Journal of Science Education, 3*, 93-101.

Driver, R. and Bell, B. (1986). Student's thinking and learning of science: a constructivist view. *School Science Review, March*, 443-456.

Erickson, G. L. (1979). Children's conceptions of heat and temperature. *Science Education, 63* (2), 221-230.

Erickson, G. L. (1980). Children's viewpoints of heat: A second look. *Science Education, 64* (3), 323-336.

Eylon, B. & Linn, M. C. (1988). Learning and instruction: An examination of four research perspectives in science education. *Review of Educational Research, 58* (3), 251-301.

Glaser, R. (1990). The reemergence of learning theory within instructional research. *American Psychologist, 45*, 29-39.

Gunstone, R. F. (April, 1988).*Some long-term effects of uninformed conceptual change*. Paper presented at the American Educational Research Association, New Orleans, LA.

Kirkpatrick, D. (1987). Technology in education: A middle school teacher's experience. *Technology and Learning, 1*(3),

Law, N. W. V. (1988).*Knowledge structures: Where can we find them?* Paper presented at the American Educational Research Association, New Orleans, LA.

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

Lewis, E. L. & Linn, M. C. (1989, April). *Heat energy and temperature concepts of adolescents, naive adults, and experts: Implications for curricular improvements*. Paper presented at the Annual Meeting of National Association for Research in Science Teaching, San Francisco, CA.

Lewis, E. L., Stern, J. L. & Linn, M. C. (1990, April). *The effect of simulations on thermodynamics understanding*. Paper presented at the Annual Meeting of the American Educational Research Association, Boston, MA.

Linn, M. C. (1983). Content, context, and process in reasoning during adolescence: Selecting a model. *Journal of Early Adolescence, 3*(1-2), 63-82.

Linn, M.C.& Pulos, S. (1983). Male-female differences in predicting displaced volume: Strategy usage, aptitude relationships and experience influences. *Journal of Educational Psychology, 75*, 86-86.

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

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

Linn, M. C. (1988). *Designing robust science instruction: A model for thermodynamics*. Proposal submitted to the National Science Foundation.

Linn, M. C., Songer, N. B., Lewis, E. L. & Stern, J. (1990). Using technology to teach thermodynamics: Achieving Integrated Understanding. In D. L. Ferguson (Eds.), *Advanced Technologies in the Teaching of Math and Science*. Berlin: Springer-Verlag.

Linn, M. C. & Songer, N. B. (in press). Teaching thermodynamics to middle school students: What are appropriate cognitive demands? *Journal of Research in Science Teaching,*

McCloskey, M., Caramazza, A., & Green, B. (1980). Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. *Science, 210*, 1139-1141.

McCloskey, M. (1983). Naive theories of motion. In D Gentner & A. L. Stevens (Eds.) *Mental models*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Mokros, J. R. & Tinker, R. F. (1987). The impact of microcomputer-based labs on children's ability to interpret graphs. *Journal of Research in Science Teaching, 24*(4), 369-383.

Osborne, R. J. & Wittrock, M. C. (1983). Learning science: A generative process. *Science Education, 67*, 489-508.

Piaget, J. (1972). *Science of education and the psychology of the child.* New York: The Viking Press.

Piaget, J. (1969, first published in 1929). *The child's conception of the world.* Totowa, N. J.: Littlefield, Adams & Co.

Piaget, J. (1952). *The origins of intelligence in children.* New York: National Universities Press.

Pines, A. L. and West, L. (1986). Conceptual understanding and science learning: An interpretation of research within a sources-of knowledge framework. *Science Education, 70,* 583-604.

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

Ranney, M. A. (1987). *Changing naive conceptions of motion.* Ph.D. Dissertation, University of Pittsburgh.

Resnick, L. B. (1987). Learning in school and out. *Educational Researcher, 16*(9), 13-20.

Resnick, L. B. (1983). Mathematics and science learning: A new conception, *Science*, 220, 477-478.

Schauble, L. (1988a). *Processes of constructive learning and interference in children: Understanding the causal structure of a microworld.* Ph.D. Dissertation, Teachers College, Columbia University.

Schauble, L. (1988b). Applying scientific thinking skills in self-directed exploration: A microgenetic study of transfer of learning. *Proceedings of the International Conference of Intelligent Tutoring Systems*, Montreal, Canada.

Schwab, J. (1971). The practical 3: Translation into curriculum. *School Review, 81* (4), 501-22.

Shuell, T. J. (1988). The role of the student in learning from instruction. *Contemporary Educational Psychology, 13*, 276-295.

Shuell, T. J. (1986). Cognitive conceptions of learning. *Review of Educational Research, 56*, 411-436.

Shuell, T. J. (1982). Developing a viable link between scientific psychology and educational practices. *Instructional Science, 11*, 155-167.

Songer, N. B. (1989). *Promoting transfer in thermodynamics: Representing variables on a continuum*. Unpublished doctoral dissertation, University of California, Berkeley.

Strike, K. A. & Posner, G. J. (1985). A conceptual change view of learning and understanding. In L. H. T. West, & A. L. Pines (Ed.), *Cognitive structure and Conceptual Change*. New York: Academic Press.

Tiberghien, A. (1980). *Modes and conditions of learning. An example: The learning of some aspects of the concepts of heat*. Leeds, England: University of Leeds Printing Service.

Tiberghien, A. (1982). *The development of ideas with teaching*. S. F.: Academic Press.

Tschirgi, J. E. (1980). Sensible reasoning: A hypothesis about hypotheses. *Child Development, 51*, 1-10.

West, L. and Pines, A. L. (Eds.). (1985). *Cognitive structure and conceptual change*. Orlando, FL: Academic Press.

White, R. T. & Tisher, R. P. (1988). Research on natural sciences. In M. C. Wittrock (Ed.) *Handbook of research on teaching*. New York: Macmillian.

Wittrock, M. C. (1974). Learning as a generative process. *Educational Psychologist, 11*, 87-95.