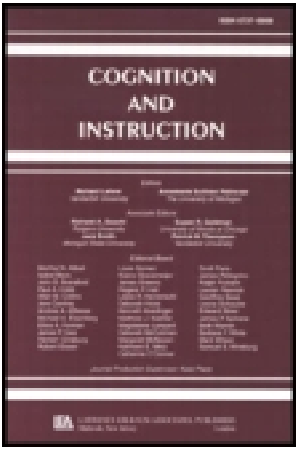

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Longitudinal Conceptual Change in Students' Understanding of Thermal Equilibrium: An Examination of the Process of Conceptual Restructuring

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Longitudinal Conceptual Change in Students' Understanding of Thermal Equilibrium: An Examination of the Process of Conceptual Restructuring

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This research analyzes students' conceptual change across a semester in an 8th-grade thermodynamics curriculum. Fifty students were interviewed 5 times during their 8th-grade semester and then again preceding their 10th- and 12th-grade years to follow their subsequent progress. The interview questions probed students' understanding of thermodynamics in everyday situations. The analysis of the transcripts first focuses on the full cohort. The analysis then focuses on 2 fairly successful and 2 less successful students in greater detail. Direct quotations provide the primary warrants in the analysis of the 4 case-study students, but the analysis also incorporates 2 new analytical–representational forms to map students' conceptual change trajectories. Ultimately, the results clarify the conceptual change processes through which students' understandings of thermal equilibrium evolve from disjointed sets of context-dependent ideas toward, if not achieving, integrated cohesive perspectives.

Thermal equilibrium and, more broadly, thermodynamics are concepts and systems of thought that students traditionally find challenging and difficult to learn (Erickson & Tiberghien, 1985; Kesidou & Duit, 1993; Wiser & Carey, 1983). For example, students hold many intuitive ideas about heat and temperature, but these intuitions are often tuned to common yet comparatively narrow ranges of everyday experience (Clough & Driver, 1985; Jones, Carter, & Rua, 2000; Lubben,

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Netshisaulu, & Campbell, 1999; Tiberghien, 1980). Integrating these everyday experiences with scientific concepts poses significant challenges for students (Harrison, Grayson, & Treagust, 1999; Linn & Hsi, 2000; Wiser & Amin, 2001). This research examines students' conceptual change across a semester as they learned about thermodynamics through a curriculum designed explicitly to foster knowledge integration.

This study builds on the work of a prior study that analyzed data from 3,000 students experiencing four increasingly streamlined versions of a computer-enhanced middle school thermodynamics curriculum (Clark & Linn, 2003). That study focused on the impact of instructional time on students' conceptual progress toward coherent normative understandings. The current study investigates the processes through which four students moved toward these coherent normative understandings. This analysis is contextualized through broader analyses of the 50-student cohort to which they belonged. The goal of the current study involves (a) mapping the paths and processes through which students moved toward integrated normative understandings of thermodynamics and (b) considering the implications of these findings for curriculum design and refinement. In particular, this study focuses on the processes through which instructed ideas were added to students' conceptual ecologies and how these new ideas became interconnected with other ideas (normative and nonnormative) within these ecologies.

Direct quotations provide the primary warrants in the analysis of the four case-study students, but the analysis also incorporates two new analytical–representational forms to map students' conceptual change trajectories. *Explanation maps* enumerate the relative sophistication of students' explanations, displaying trends in sophistication and connections within explanations, clarifying contradictions, and identifying the appearance of new ideas. *Element maps* show connections and levels of integration in further detail, clarifying the paths through which the students reorganized and connected ideas, while highlighting areas of strength and weakness. Although direct quotations from the students provide the primary warrants for the case study analysis, these two representational forms help to triangulate the analysis.

Ultimately, the results clarify the conceptual change processes through which students' understandings of thermal equilibrium evolve from disjointed sets of context-dependent ideas toward, if not achieving, integration, normativity, and cohesiveness. The implications of these results for curriculum design focus on the following: depth of coverage; support for normative connection of ideas, rather than simple addition; increased opportunities to compare nonnormative and normative ideas in contexts that cue the nonnormative ideas; support for multiple conceptual paths through the curriculum; consideration of the pedagogical trade-offs in choosing specific accessible intermediate models; and reexplanation of disruptive experientially supported ideas to support school-instructed ideas. Implications for the conceptual change literature underscore the importance of accounting for extended complex periods of evolutionary change[1] and fragmentation, as well as systematicity within the structure of students' understandings.

STUDENTS' IDEAS AND LEARNING IN THERMODYNAMICS

Thermal equilibrium and, more broadly, thermodynamics are topic areas that the research literature considers challenging and age appropriate for the eighth-grade students in this study. Students hold many intuitive ideas about heat and temperature (Clough & Driver, 1985; Erickson, 1979; Erickson & Tiberghien, 1985; Rogan, 1988; Tiberghien, 1980), and everyday experiences form the basis for many of them. These ideas predominantly involve the substance-based conceptions discussed in Chi's work (Chi, 1992, 2005; Chi & Roscoe, 2002) analyzing students' misapplication of ontological categories. Familial and cultural experiences appear to influence aspects of students' understanding of thermodynamics (Hewson & Hamlyn, 1984; Jones et al., 2000; Lubben et al., 1999), but domain-specific knowledge is also involved in understanding these concepts (Slone, Tredoux, & Bokhorst, 1996). Everyday, children are exposed to the colloquial term *heat* as a noun, verb, adverb, and adjective, and these multiple uses may lead to confusion (Erickson & Tiberghien, 1985; Tiberghien, 1980). In high school, students have great difficulty with energy concepts, the particle model, and the distinction between heat and temperature (Kesidou & Duit, 1993). Long after high school, these concepts remain challenging for scientists, who make more accurate predictions than students do but still have difficulty explaining everyday phenomena (Lewis, 1996; Lewis & Linn, 1994) and present divergent representations from one another in their writings (Tarsitani & Vicentini, 1996).

Fewer studies have examined the actual processes of conceptual change and conceptual development within the domain of thermodynamics. Early conceptual change work in thermodynamics proposed Piagetian (Albert, 1978) and Ausubelian (Shayer & Wylam, 1981) views of heat concepts through which students develop sequentially as a function of age. Other early work about conceptual change in thermodynamics claimed that students' conceptual development parallels historical development of the same concepts (Wiser, 1988; Wiser & Carey, 1983). At the heart of Wiser and Carey's work is the idea that, although early scien-

[1]The terms *evolutionary* and *revolutionary* in the conceptual change literature refer to opposing perspectives on the processes of conceptual change (e.g., Wiser & Amin, 2001). The term *revolutionary* refers to a process of change in which students shift over time between distinct incommensurable theorylike understandings. Essentially, an initial account is replaced by a subsequent coherent but incommensurable account. The term *evolutionary* refers to a gradual, progressive process of refinement wherein students simultaneously hold, juggle, and revise multiple potentially conflicting ideas.

tists and students have similar theories about thermal phenomena, their theories are coherent but incommensurable with the current-day normative theories that differentiate heat and temperature. This proposed "coherent but incommensurable" perspective of Wiser and Carey about heat and temperature resonates with other studies in different domains, suggesting that students maintain coherent, internally consistent models about specific ideas or concepts (e.g., McCloskey, 1983). Carey's current work (2000), although focused less on thermodynamics and more on younger children, continues this focus on revolutionary change and coherent but incommensurable perspectives. Wiser's recent work (Wiser & Amin, 2001) focuses on ontological differences between students' and scientists' terminology but claims that students' conceptual change in science is evolutionary and revolutionary, involving theory change (as discussed by Carey, 1999, 2000) and gradual accretion of information and ideas (e.g., Gunstone & Mitchell, 1997).

Although some recent work on conceptual change in thermodynamics continues to draw analogies to the historical development of theories (e.g., Cotignola, Bordogna, Punte, & Cappannini, 2002), other recent work, such as that by Wiser and Amin, considers the possibility that students' conceptual development in thermodynamics follows a cumulative and gradual evolutionary, rather than revolutionary, trajectory perspective (e.g., Harrison et al., 1999; Laburu & Niaz, 2002; Linn & Hsi, 2000). Harrison et al.'s investigation of students' differentiation of heat and temperature suggests that conceptual change is (a) "cumulative and piecemeal," rather than revolutionary, as the students struggle "to accommodate new, and for them, counterintuitive ideas" (p. 84) and (b) the result of a gradual conceptual-exchange process (per Hewson & Hewson, 1992). Harrison et al. found that students keep many of their original ideas alongside instructed ideas and that learning involves the revision of connections and high-level organization and names. These findings resonate with the findings of others in thermodynamics (Laburu & Niaz, 2002; Linn, Eylon, & Davis, 2004; Linn & Hsi, 2000). DiSessa, Gillespie, and Esterly (2004) and Hunt and Minstrell (1994) have also suggested that conceptual change is gradual and that students hold intuitive ideas alongside instructed ideas.

THEORETICAL FRAMEWORK FOR THE CURRENT STUDY: CONCEPTUAL RESTRUCTURING

The analysis and discussion in this article are conducted primarily from what this study will define as a *conceptual restructuring* viewpoint, but the study considers and discusses the data from additional perspectives. Clearly, some form of knowledge restructuring is assumed by all accounts of conceptual change, but for the purposes of this article, the term *conceptual restructuring* refers to the account of knowledge restructuring outlined in this section. These perspectives on conceptual restructuring relate most directly to perspectives based on knowledge in pieces (diSessa, 1988, 1993; diSessa et al., 2004) and knowledge integration (Linn et al., 2004). More distantly, however, the perspectives outlined here on conceptual restructuring have their roots in early work about conceptual ecologies (Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1992). Strike and Posner (1992) proposed that students maintain conceptual ecologies, including "anomalies, analogies, metaphors, epistemological beliefs, metaphysical beliefs, knowledge from other areas of inquiry, and knowledge of competing conceptions" (p. 150). This conceptual ecology perspective is especially relevant to perspectives that view a student's knowledge as a repertoire of independent elements (Clark, 2000, 2003; diSessa, 1988, 1993; Hunt & Minstrell, 1994; Linn et al., 2004). Anderson (1993) and Thagard (1992) provide relatively mechanical–mathematical examples, whereas Hunt and Minstrell (1994), diSessa et al. (2004), and Linn, Eylon, and Davis (2004) maintain organic perspectives that focus on a collection of elements, including, but not limited to, subconceptual p-prims,[2] facts, facets, and mental models. In their perspectives, diSessa focuses on the nature of the elements; Minstrell on the facets that student use in the classroom; and Linn on the process through which students reorganize, revise, and connect these elements.

For the purposes of the current study, conceptual restructuring assumes that students potentially hold multiple conceptual elements and ideas at various levels of connection, contradiction, and organization. These conceptual elements and ideas are generally considered to include but not be limited to nominal and committed facts, experiences, intuitive conceptions such as p-prims (diSessa, 1993), narratives, and (ideally) some mental models and concepts (Carey, 2000) at various stages of development and sophistication (Clark, 2000; diSessa, 1993; Linn et al., 2004). Learning occurs through a process of restructuring and reorganizing these ideas.

The current study identifies these elements through the explanations and causal descriptions (e.g., "Metals conduct" or "Metals attract heat") that students expressed in their interviews and tests. These explanations and causal descriptions point to the underlying, often unarticulated elements on which the students based their reasoning. For the purposes of this study, explanations include the ideas that students were able to associate, or connect, in answering interview questions. Ideas that a student expressed in one segment of an explanation are considered to be connected so long as the student was able to produce those ideas as part of the explanation with only nondirective probing by the interviewer (see Methods section).

Students use these multiple conceptual elements to understand the phenomena that they encounter in their lives. The particular ideas that students cue and connect

[2]P-prims, or phenomenological primitives, are explanatorily primitive elements that people unconsciously apply to explain how physical events happen (diSessa, 1988, 1993). From this perspective, people explain physical phenomena in everyday life by coordinating many loosely organized p-prims based on context.

may depend on context. Some connections arise from experience; some connections are highly situation specific and not broadly useful; some are established from another domain, such as electricity, and may or may not be useful or accurate in the new domain; and some arise through instruction in the target domain. Some of the connections that students make are spontaneous and ephemeral, whereas some are much more durable. Those that are spontaneous are often created in a given context for specific situation and rarely outlast their invention. Some connections, however, become established and strengthened over time, resulting in significant systematicities in the students' understandings, predictions, and explanations.

As students learn and develop an integrated understanding of a topic, they reorganize these ideas and connections in productive ways. As part of this process, some ideas become central and pivotal as the student uses them as focal points around which to integrate other ideas, whereas others are demoted to occasional use. *Promoting* is defined as increasing the activation strength and centrality of an idea in its connections to other ideas and cueing contexts. Conversely, *demoting* involves decreasing the activation strength and centrality of an idea in its connections to other ideas and cueing contexts. Thus, promoting and demoting involve creating and destroying connections, as well as changing the activation strengths of those connections. Promoting and demoting are similar to increases or decreases in cueing and reliability priority (diSessa, 1993).

Students also modify the ideas and elements themselves. *Integration* is defined as the process through which the connection between two ideas is created or reinforced. *Coalescence* is a related process through which two ideas are merged (e.g., combining heating and cooling models into one thermal equilibrium model). *Differentiation* is the reverse process, whereby one idea is decomposed into distinct components (e.g., differentiating heat energy from temperature). Ideas can also be reassessed and their basic structure reanalyzed, as suggested by Carey (2000) in the example of Newton's realization that weight is a relation between objects rather than simply the property of a single object. Not all integrations, coalescences, differentiations, and reassessments are necessarily productive or normative.

In addition to the terminology defined and discussed here, additional terminology is employed in this study in discussing the case studies. A *warrant* is evidence that a student provides as support for a claim within an explanation. Common warrants in these interviews include labs, the teacher, and home experience. *Local conflict* involves conflict in the student's repertoire within a given local context or explanation. Local conflicts may or may not be recognized by the student. *Global conflict* involves conflict between two or more ideas in a student's repertoire that are not connected within a local context and are therefore generally less likely to be recognized by the student. A *disruptive idea* is a nonnormative idea that conflicts with a normative idea and causes the student to reject the normative idea or alter the normative idea into a nonnormative idea. Related to this process is when students *inappropriately apply* an idea; that is, they give an idea significant priority in determining an outcome or prediction, to the point of ignoring the priority of a normative idea or experience that should inform part of that outcome or prediction (e.g., after several hours, metal objects in a hot car trunk are hotter than wood objects because metal is a good conductor). Finally, this study refers to *blurring* when students use terms like *around* and *approximately* to muddy the distinction between different outcomes or materials. Blurring provides an excuse to ignore a principled difference or skirt an issue (e.g., saying that materials are "around" the same temperature allows students to minimize conflict between class experiments showing that objects are the same temperature and the students' experiential sense that the metal objects feel hotter or colder). The application of these terms is clarified in the Methods section as well as in the case studies.

COMPUTER AS LEARNING PARTNER CURRICULUM

The Computer as Learning Partner (CLP) curriculum, at the heart of this study, emphasizes thermodynamics topics, including thermal equilibrium, thermal conductivity (referred to in the curriculum as *insulation and conduction*), heat flow, and the differentiation of heat and temperature. The curriculum is intended for eighth-grade students. Although segments of the curriculum focus on specific topics, the curriculum attempts to support connections between all of the topics so that students continue to make connections within their understanding (see Results and Discussion: Analysis of the 50-Student Cohort). Students work in pairs on computers using microcomputer-based labs, simulations, an electronic laboratory notebook, Internet software, and other custom software. Students use this software to design experiments, collect real-time data, predict outcomes, design simulations, display results, record observations, and create reports (Linn & Hsi, 2000).

In line with the National Science Standards (National Research Council, 1996), the CLP curriculum focuses on accessible intermediate models, such as *heat flow* models rather than *molecular–kinetic* models, to help middle school students make sense of thermodynamic phenomena that they encounter in their lives. These intermediate models are acceptable because they are accessible to students and because scientists often use these same models to solve appropriate problems (Lewis, 1996). For example, the CLP curriculum explains thermal equilibrium in terms of net heat energy flow from higher temperature objects to lower temperature objects until equilibrium is established. The current study discusses student understanding in terms of these instructed intermediate models such as heat flow because they form the context in which the students studied the concepts. Similarly, the terminology used in the curriculum is the terminology used in the writing of this manuscript (e.g., *insulation and conduction* rather than *thermal conductivity*).

A chronological list of the CLP curricular segments, along with the key activities from each segment, is outlined in Table 1 to provide a detailed overview of the curriculum. Table 1 also includes the timing of the interviews within the curriculum for the current study. The thermodynamics portion of the curriculum spanned 13 weeks. The pretest and first interview were conducted before instruction. In general, the curriculum focused on thermal equilibrium leading up to the second interview, heat and temperature leading up to the third interview, insulation and conduction leading up to the fourth interview, and the integration projects leading up the fifth and final interview, at the end of the eighth-grade semester.

METHODS

This study was built on the claim that information about a student's conceptions can be inferred from the student's test and interview explanations about the interview topics. The analyses present sets of ideas and conceptual elements that the students associate, or connect, in their answers and explanations. The ideas that a student expressed in an explanation are considered to be connected so long as the student was able to produce those ideas as part of the explanation with only nondirective probing by the interviewer. Clearly, students may have held ideas that were not cued by the context of a specific question. By addressing multiple contexts at each interview, however, the study attempts to identify the most prominent ideas of each student's repertoire.

Students

The study first analyzes a group of 50 students who participated in seven interviews. The interviewed students were randomly selected from approximately 300 students participating in the CLP curriculum during that academic year. Detailed analyses of four case-study students selected from this 50-student cohort illuminate the paths and processes of conceptual change through which these students learned within the curriculum. Student gender was masked to avoid stereotyping. Two of the four case-study students were selected from students considered to be representative of fairly successful students, and two students were selected from students considered to be representative of less successful students. These ranges were chosen to investigate strategies for supporting less successful students.

All of the data in this study were collected in the classroom of one master eighth-grade teacher who worked with the CLP research group for the entire span of the CLP project. Every semester, he taught approximately 150–180 eighth-grade students in his classes using the CLP curriculum. The school is diverse and the students represent a range of academic performances.

TABLE 1
Chronological List of the Computer as Learning Curricular Segments Including Sample Activities and Timing of the Interviews for This Study

Pretest and Interview 1 (conducted prior to instruction)
Curricular focus on thermal equilibrium *Probing your surroundings (real-time lab).* The students measure and compare the temperature of objects in the classroom using probeware connected to their computers. The lab and discussion focus on thermal equilibrium, heat sources, heat flow, and heat conduction. *Equilibrium lab (real-time lab).* The students investigate two objects in thermal contact coming into thermal equilibrium. In this lab, we use a test tube of hot water placed in a beaker full of room temperature water. The principles in this lab reinforce the basic dynamics of heat flow: Heat flow depends on temperature differences between objects, and heat flow causes the temperatures of the objects to change. Combining these principles leads to a causal model of equilibrium.
Interview 2 (conducted 3 weeks into curriculum)
Curricular focus on heat and temperature *Thermal model kit (simulated lab).* The thermal model kit is a simulation program that allows students to design experiments around a heat flow model. Students are able to set and control a variety of variables. Using this model leads students to an understanding of heat flow and thermal equilibrium. *Heat pulsing labs (real-time lab).* The students add pulses of heat to liquids and measure the resulting temperature increases. In Pulsing 1, the students add different amounts of heat to the same volume of water. In Pulsing 2, the students add the same amount of heat to different volumes of water and alcohol.
Interview 3 (conducted 6 weeks into curriculum)
Curricular focus on insulation/conduction (thermal conductivity) *Coke and potatoes lab (simulated labs).* The students investigate how different wrapping materials affect the rate at which a hot potato cools and the rate at which a cold Coke warms up. In this lab, students learn that (a) heat energy flows more or less easily through different materials, (b) the rate that heat energy flows affects the rate at which objects heat up or cool down, (c) any given material may be placed along a continuum from poor conductor to good conductor, (d) insulation and conduction are related to each other and to the rate that heat flows through a material, and (e) objects tend to heat up or cool down to room temperature. *Heat bars (simulation).* All materials conduct heat energy, but the rate that the heat flows will vary greatly for different materials. Students choose two materials and run the simulation showing the rate at which heat energy moves along bars of those two materials. Students place each material along a continuum line from good to bad conductor.
Interview 4 (conducted 9 weeks into curriculum)
Curricular focus on integration projects *Greenhouse effect (real-time lab).* Students model the greenhouse effect and determine how an increased level of carbon dioxide gas in the air affects the temperature of the atmosphere. This lab is intended to help students integrate the principles constructed in previous labs related to heat and light energy. Ideas about transmission and conversion of heat and light energy, heat flow, and thermal equilibrium need to be linked in order to understand the mechanism behind the greenhouse effect. This lab also provides a context for discussing scientific modeling and global warming.
Posttest and Interview 5 (conducted 13 weeks into curriculum)

Longitudinal Interview Process

The 50 students participated in five interviews conducted by the CLP research group, lasting 30 min each, during their 8th-grade CLP semester. In the summers preceding their 10th and 12th grades, the 50 students participated in two more interviews conducted by the CLP research group. Interviews were tape-recorded and transcribed. Tests and written class assignments were also collected. The interview questions addressed students' understanding of thermodynamics using everyday situations (see Appendix A). The interviewers probed contradictions, connections, differentiations, and reasoning patterns. The resulting subject matter transcripts totaled approximately 120 pages for each student.

Levels of Analysis

This study involves three levels of analysis: a topic analysis of students within the 50-student cohort, and an analysis of the explanations of a subgroup of four case-study students, an analysis of the elements within these explanations given by the case-study students. In other words, each analysis focuses on one of three increasingly fine grains: topics, explanations, and elements within explanations. The first analysis focuses on the 50-student cohort. The second and third analyses focus on the four case-study students. After providing an overview of each level of analysis in the following paragraphs, the subsequent sections provide detail on each level.

Topic analysis of the 50-student group. The first level of analysis investigates the 50 students' understanding at each interview time of four topics: thermal equilibrium, insulation and conduction, heat energy and temperature, and heat flow.

Case-study analyses of the four-student subgroup. The case studies focus on four students from within this 50-student cohort. The second level of analysis focuses on the explanations that these students gave in their interviews, and the third level of analysis focuses on the elements within these explanations. The case studies focus specifically on the thermal equilibrium topic but include insulation and conduction and thermal sensation ideas in the analysis because pilot work demonstrated the intimate connection among students' understanding of thermal equilibrium, conductivity, and sensation. Direct quotations from students' transcript segments provide the primary warrants for the case studies, but two new analytical forms (explanation maps and element maps) are included to support the case studies. *Explanation maps* present the major distinct explanations employed by the student during an interview as part of the second level of analysis. *Element maps* break the explanations presented in the explanation maps into their component ideas as part of the third level of analysis.

Core Coding Scheme

At the most basic level, each of the three analyses uses a four-tiered coding scheme for students' explanations:

1. *Nuanced* explanations are fully functional, involve important thermodynamic nuances, and productively connect multiple normative ideas.
2. *Normative* explanations contain no misinformation but may involve weak or specific application of a normative idea (e.g., the student may have been speaking about a specific instance without making a strong generalizable statement).
3. *Transitional* explanations involve a combination of normative and nonnormative ideas.
4. *Nonnormative* explanations include significantly nonnormative ideas, often diametrically opposed to target normative models.

Grain-size differences across analyses result in slightly different applications of the core coding scheme for each analysis, but the core hierarchy is consistent across analyses. The specifics of the coding scheme are described in detail in the methodology and results sections for each analysis. Table 2 includes examples from each category. Note that a code of *nuanced* requires the connection of multiple normative ideas; maps and lists that rank specific ideas can therefore only rank those individual ideas on the scale from *nonnormative* to *normative*.

Topic Analysis of the 50-Student Cohort

The interviews of the 50 students were conducted to determine the sophistication of students' understanding of thermal equilibrium, insulation and conduction, heat energy and temperature, and heat flow. The coding methodology used by the CLP research group was identical to that used by Lewis (1996) to compare individual students from an earlier cohort. Under this methodology, each student received a single score on a 6-point scale for each of the four topics at each interview time. The coding scheme was collapsed for this study into the four categories described here. For the topic analysis of the 50-student cohort, this score is a holistic score to represent the primary character of each student's understanding of each topic at each interview time (for more information about this coding process and reliability, see Lewis, 1996). The data are combined for the entire group into graphical representations to compare the sophistication of the group's understanding of each of the topics at each interview time, as shown in the Results section. The data for the first five interviews for the 50 students were analyzed for depth-of-coverage issues (Clark & Linn, 2003) in terms of the students' eighth-grade performance only.

TABLE 2
Representative Student Responses From Each Scoring Category

Nuanced explanations—Two or more distinct normative ideas cohesively connected
The metal spoon feels hotter because it's a better conductor and the heat energy can escape into your fingers faster than through the wood spoon.
Heat energy flows from the surrounding area into cold objects to warm them up to the temperature of the surrounding area.
Metal is a good conductor and poor insulator so I wouldn't use that to make a container to keep hot things hot and cold things cold. Styrofoam is a poor conductor and good insulator so I would use that.
Normative explanations—Single valid ideas in an explanation, whether elaborated or not
Metal is a good conductor. … It conducts heat energy.
Two objects can be the same temperature and feel different.
Metal and wood will be same temperature in a hot car trunk after several hours.
Transitional explanations—Normative elements combined with nonnormative elements
The metal spoon would be slightly warmer than the oven, and the wood spoon would be cooler, because metal's a good conductor and wood's not.
Touching an ice cube with a metal nail feels cold because metal is a good conductor, and so the coldness travels quickly through it to your hand.
Styrofoam's a good insulator, and so it keeps the soda can cold by keeping the coldness in.
Nonnormative explanations—Nonnormative, confused, or uncompleted ideas within an explanation
Paper towel insulates because it has fibers that are really close, so it keeps the cold in.
Asbestos doesn't reach the same temperature because it's made of a difference substance—I'm really not sure.
The metal stove and glass plates in the cold cabin will be below room temperature because they feel colder.

The current study analyzes the data for conceptual change in light of all seven interviews across eighth grade and into high school.

Analysis of the Four Case-Study Students

Whereas the analysis of the 50 students focuses on four broad topic areas, the case-study analyses of the subgroup of four students focus specifically on the thermal equilibrium topic. This decision grew out of related planned research (e.g., Clark & Jorde, 2004), as well as a desire to expand the understanding of a thermodynamic topic less often studied than the typical heat–temperature differentiation.

To study each student's understanding of thermal equilibrium, the transcripts were analyzed to locate all of the segments illuminating the student's understanding of thermal equilibrium, as well as insulation and conduction and thermal sensation. Conductivity and thermal sensation were included because pilot studies demonstrated that these topics are often highly intertwined with students' beliefs about thermal equilibrium. Thermal sensation was not one of the four officially designated core topics for the CLP curriculum and so was not measured for the 50-student topic analysis.

Within each interview, the case-study analyses consider the following: the main ideas and models employed by the student in his or her explanations at each interview, connections between the ideas that the student was able to make at each interview, warrants used in interviews to support explanations, apparent integration and coherence strategies employed by the student in the interviews, and overall progression and digression during the student's sequence of interviews. To support the analysis, all interviews were coded and cataloged for excerpts illustrating students' ideas about thermal equilibrium using NUD*IST qualitative research cataloging and coding software (now known as NVivo). The explanation maps present the major distinct explanations employed by the student during a single interview, whereas the element maps break the explanations presented in the explanation maps into their component ideas.

Explanation Maps

The explanation maps were developed as part of this study to facilitate the analysis of the four case-study students. The explanation maps facilitate the process of organizing and tracking the explanations that a student uses across his or her interviews. These explanation maps thus track the students' explanations held at each level of sophistication (from nonnormative to nuanced), display trends in sophistication and integration of ideas expressed in explanations, clarify contradictions, and identify the appearance of new ideas. In addition to facilitating the organization of the case studies, the explanation maps provide an overview for the reader of a student's explanations at each interview time. Whereas the topic analysis of the 50-student cohort focuses on frequency and mean normativity of students' explanations, the explanation maps (and the element maps derived from them) focus specifically on the range of explanations rather than frequencies.

An explanation map is divided into columns, and each column contains the major distinct explanations (and the ideas contained therein) employed by the student during a single interview. Within each column, an explanation map separates the explanations used by the student in the interviews into four levels of sophistication, using the *nuanced*, *normative*, *transitional*, and *nonnormative* scale described earlier. Each explanation is condensed from the cataloged student explanation excerpts, coded according to the aforementioned classifications to facilitate analysis, and placed in the table column with the other major distinct explanations expressed in that interview (for further clarification and examples of the coding process, see Appendix B; for the process of creating an explanation map, see Figure 1; and for the actual explanation maps, see Tables 4–7).[3]

[3]Although the format of *Cognition and Instruction* does not support color-coding and shading, color-coded versions of these maps are available at http://www.leaonline.com to facilitate visual analysis.

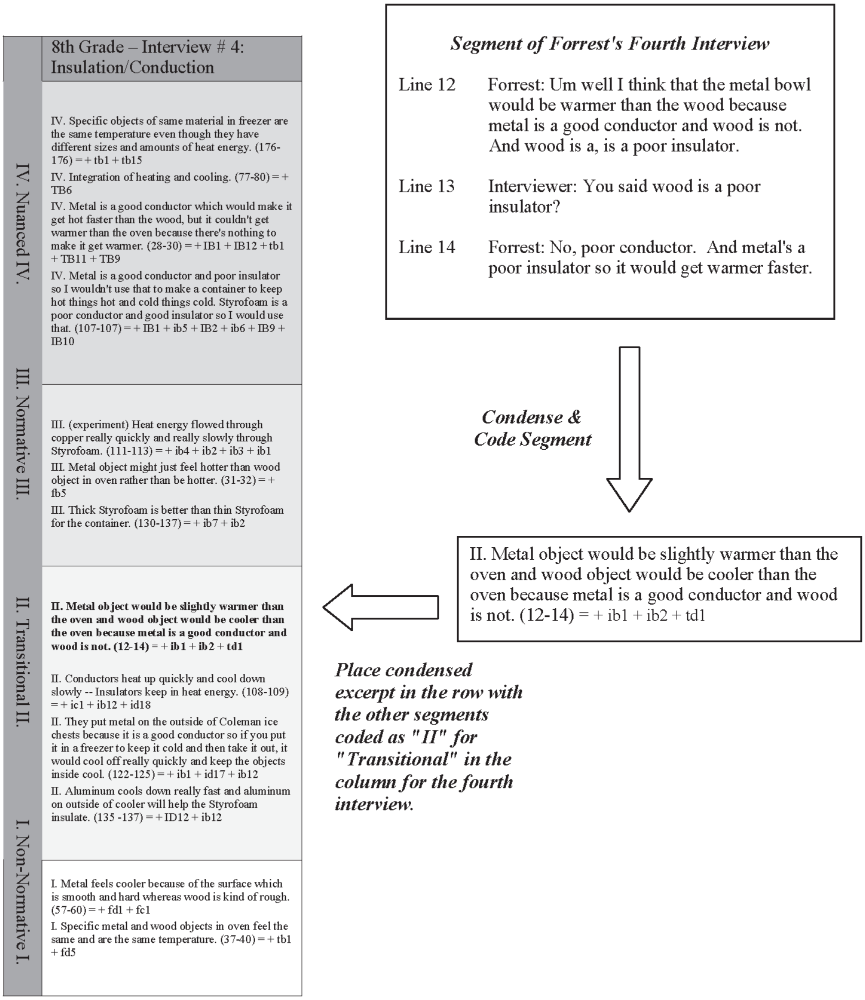

FIGURE 1 Condensing and placing an interview segment into an explanation map.

Element Maps

The element maps show connections and levels of integration in further detail, clarifying paths through which students reorganize and connect ideas, while highlighting areas of strength and weakness. The element maps help in the identification of appropriate targeted curricular interventions by highlighting and clarifying potential students' paths of conceptual restructuring.

Element maps break each explanation included in the explanation maps into the elements representing its main ideas. Each code represents one conceptual element of the student's explanation. The first letter in the code signifies topic area (T =

TABLE 3
Examples of Element Map Coding System

Example 1	"The wood and the metal become the same temperature as the oven."
Code	tb1 = Objects in same room become same temperature/Objects eventually become same temperature/Objects in same surround become same temperature
Explanation	T = thermal equilibrium related B = normative idea 1 = the first code on the TB list Lowercase = weak or specific application of that element in the student's explanations. The student is speaking about a specific instance and not making a general strong statement, such as "The metal and wood will be the same temperature as the oven because after enough time objects become the same temperature as their surroundings."
Example 2	"Wool is an insulator, and insulators store heat energy."
Code	ID8 = Insulators store heat energy/release it slowly/store cold.
Explanation	I = insulation/conduction related D = nonnormative idea 8 = the eighth code on the ID list Uppercase = Student has made strong general statement about insulators.

Note. See Tables 8 through 10 for full code lists.

thermal equilibrium; I = insulation and conduction; F = feel, or thermal sensation). The second letter signifies sophistication (B = normative, C = transitional, D = nonnormative). These elements are placed within columns by sophistication in the top, middle, and bottom regions in a manner similar to that used in the explanation maps. A solid black line then connects all elements coded from a condensed explanation to indicate that they are part of one explanation (for clarification and examples of the coding process, see Table 3 and Appendix B; for an example of the map creation process, see Figure 2; and for the complete coding keys, see Tables 8–10).[4]

Interrater Coding Reliability of Explanation Maps and Element Maps

As discussed, direct quotations provide the primary warrants for the analysis of the four case-study students. The explanation maps and element maps are included, however, to facilitate the analysis, as well as to introduce the methods for future potential refinement. Issues of interrater reliability loom large when discussing new methods. To check for interrater reliability, a second researcher applied the coding schemes described here to a cross-sectional subset of the in-

[4]As with the explanation maps, color-coded versions of the element maps are available at http://www.leaonline.com to facilitate visual analysis.

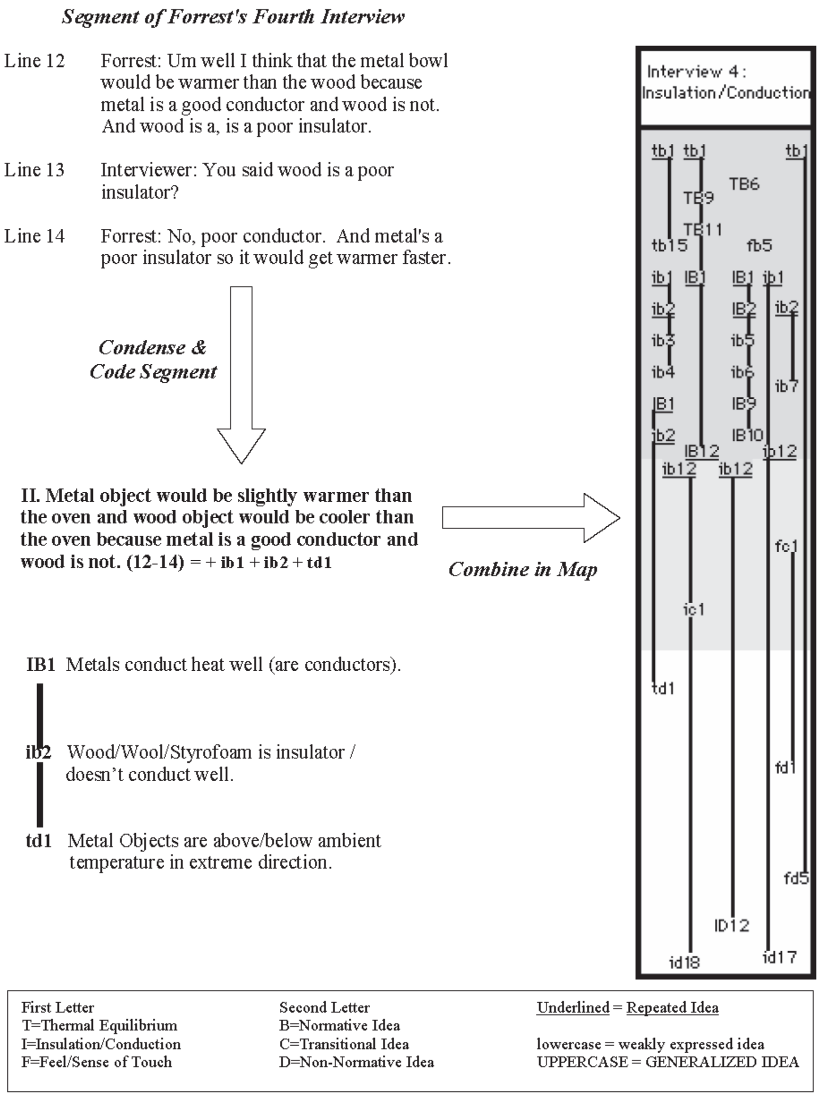

FIGURE 2 Coding and placing an interview segment into an element map.

terview episodes for the explanation maps and element maps. The mean difference between the author's scoring and the second researcher's scoring of a subset of explanations (i.e., the author's score for an episode minus the second researcher's score for the episode equaled the difference) on the 4-point scale described here was only 5.5%, suggesting that the coding scheme for those tables was indeed reliable. For the element maps, each episode can be assigned multiple codes from the lists of 111 codes discussed and presented in the Results and Discussion section. The second researcher and I differed in 22.6% of the coding choices for the element maps, but this variance resulted predominantly from choices that varied slightly within the same topic areas, thus resulting in similar overall characterizations. In light of the complexity of the coding scheme for the element maps, this variation seems inevitable and acceptable. The element maps should therefore be considered qualitative but useful analytical representations for characterizing trends within the substantial longitudinal transcripts involved in this type of study.

RESULTS AND DISCUSSION: ANALYSIS OF THE 50-STUDENT COHORT

By mapping the progress of the 50-student longitudinal group across one semester and into high school, one can better understand the conceptual change process. Figures 3–6 combine the data for the entire group of 50 students into graphical representations comparing the sophistication of the group's understanding at each interview time. These representations allow one to depict the percentage of students at each interview time rated primarily as having a nonnormative, transitional, normative, or nuanced understanding for each topic. These topics include thermal equilibrium (Figure 3), heat energy and temperature (Figure 4), insulation and conduction (Figure 5), and heat flow (Figure 6). The analysis begins with thermal equilibrium, the focus of this article, and then considers the other topics for additional insights.

As discussed in the overview of the CLP curriculum, the curriculum focused on thermal equilibrium leading up to the second interview (Week 3), heat and temperature leading up to the third interview (Week 6), insulation and conduction leading up to the fourth interview (Week 9), and the integration projects leading up the fifth and final interview (Week 13), at the end of the eighth-grade semester (see Table 1). Although segments of the curriculum focus on specific topics, the curriculum attempts to support connections among all of the topics so that students continue to make connections within their understanding.

At the time of the first interview (before instruction began), students expressed primarily nonnormative ideas about thermal equilibrium. Most students added transitional or normative ideas by the time of the second interview (3 weeks into the curriculum). However, only 13% of students continued to express primarily nonnormative ideas, and only 16% of the students could make nuanced connections between normative ideas in the second interview. Over the remainder of the semester, an increasing percentage of students made nuanced connections between normative ideas. By the end of the semester, in Interview 5 (13 weeks into the cur-

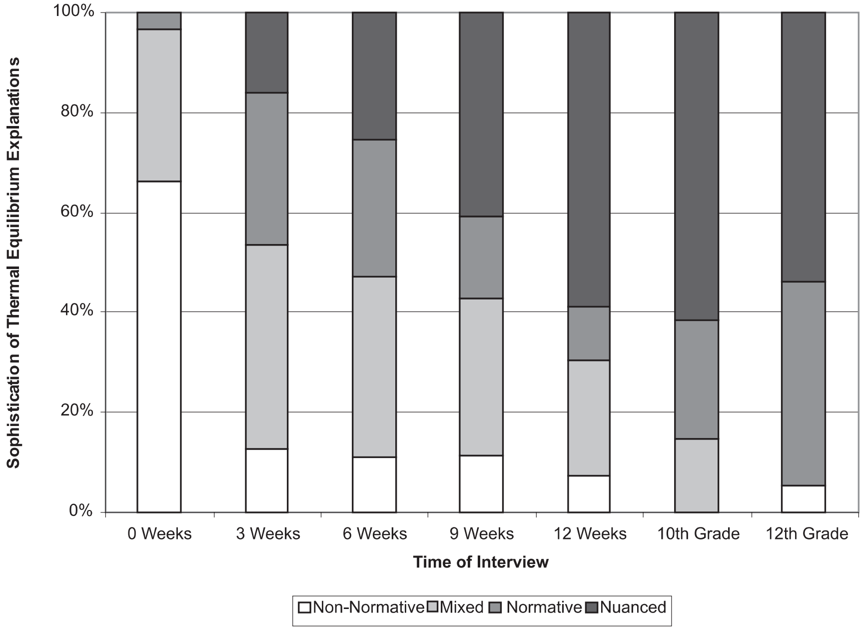

FIGURE 3 Analysis of the 50 students' understanding of thermal equilibrium (percentage of students at each level of sophistication at each interview).

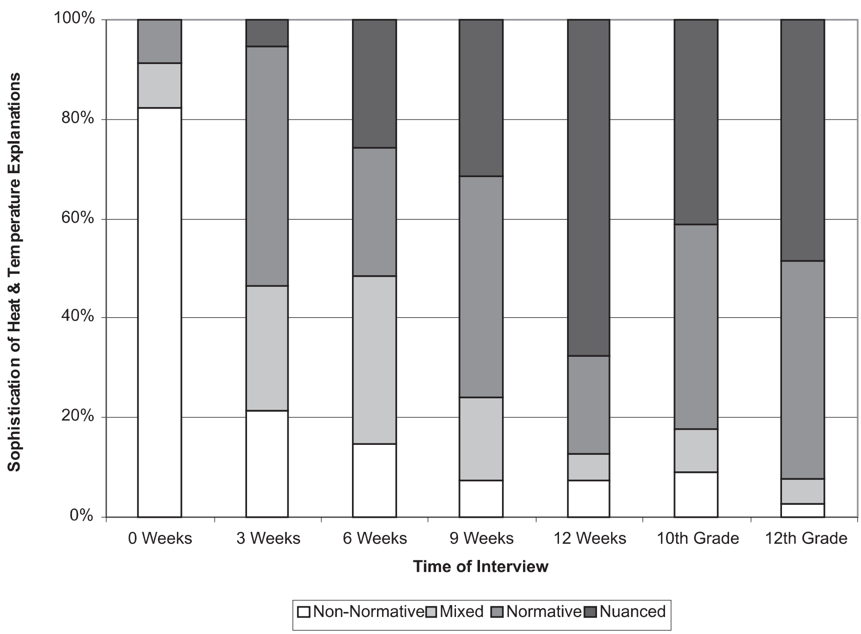

FIGURE 4 Analysis of the 50 students' understanding of heat and temperature (percentage of students at each level of sophistication at each interview).

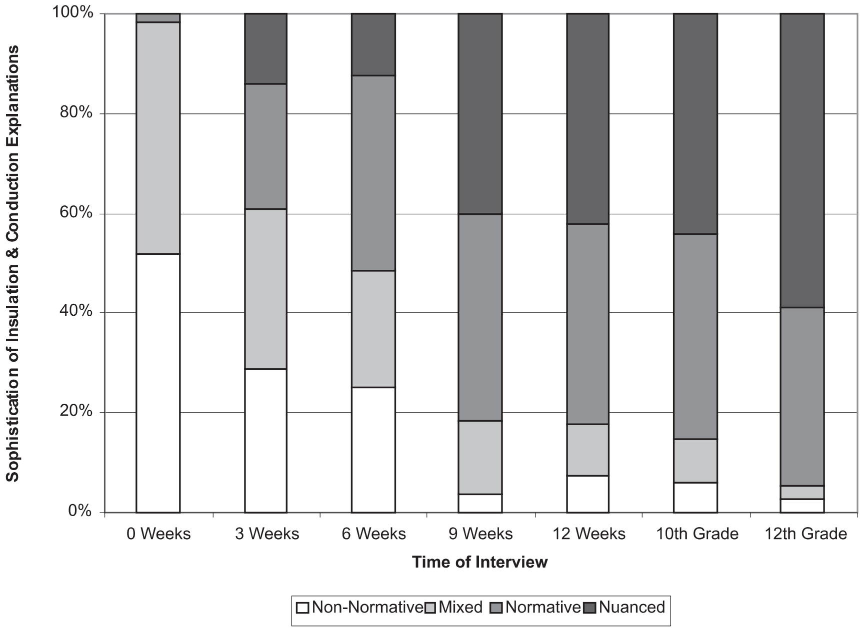

FIGURE 5 Analysis of the 50 students' understanding of insulation and conduction (percentage of students at each level of sophistication at each interview).

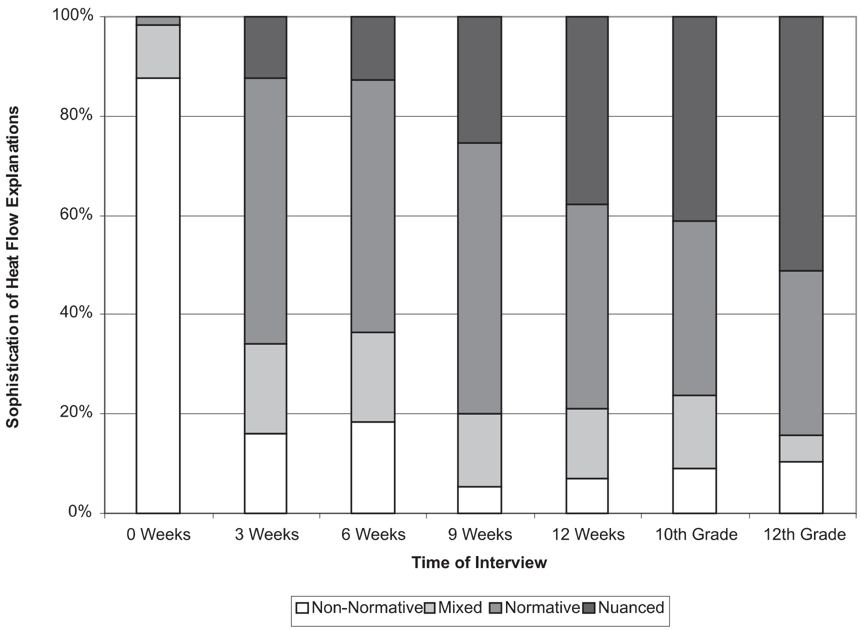

FIGURE 6 Analysis of the 50 students' understanding of heat flow (percentage of students at each level of sophistication at each interview).

riculum), 70% expressed primarily normative ideas, and 59% could make nuanced connections between normative ideas, which is quite impressive for eighth-grade students.

Clearly, conceptual change toward normative understanding occurred for these students between the first and fifth interviews. Furthermore, these changes were fairly robust. Two years later, before 10th grade, 88% of the students expressed primarily normative ideas, and 62% largely made nuanced connections between normative ideas. In the interview before 12th grade, 95% of the students expressed primarily normative ideas, and 54% made nuanced connections between their normative ideas. These results are impressive in light of the minimal differences in thermodynamics understanding for 4th- and 12-grade U.S. students in NAEP (O'Sullivan, Reese, & Mazzeo, 1997) and TIMSS data (Schmidt, McKnight, & Raizen, 1997). Students in the CLP curriculum apparently built an integrated understanding in eighth grade that they maintained and built on in high school.

The 50 students' understanding of heat and temperature (ht), insulation and conduction (ic), and heat flow (hf) followed similar trajectories (Figures 4, 5, and 6). Most students entered the curriculum expressing primarily nonnormative ideas about each topic. By the second interview, although few students continued to express primarily nonnormative ideas (ht = 21%, ic = 29%, hf = 16%), only a small proportion made nuanced connections between normative ideas (ht = 5%, ic = 14%, hf = 13%). By the end of the semester, the majority of students expressed primarily normative ideas (ht = 88%, ic = 82%, hf = 78%), and a large percentage made nuanced connections between normative ideas (ht = 68%, ic = 42%, hf = 38%).

Two years later, before 10th grade, most of the students expressed primarily normative ideas on each topic (ht = 82%, ic = 85%, hf = 76%), and a high percentage continued to make nuanced connections between normative ideas (ht = 41%, ic = 44%, hf = 41%). In the interview preceding 12th grade, the majority of the students continued to express primarily normative ideas for each topic (ht = 93%, ic = 95%, hf = 84%), and a high percentage made nuanced connections between their normative ideas (ht = 49%, ic = 59%, hf = 51%). As with thermal equilibrium, students made dramatic progress over their eighth-grade semester, and this progress remained robust through high school.

One interesting difference among the topics involves students' initial understandings of insulation and conduction. Many students (42%) entered the curriculum with a mix of normative and nonnormative ideas about insulation and conduction. This early mix may have been due to students' many experiences with insulation and conduction in the contexts of their homes and media advertisements. The analysis of the four case-study students in the next section further underscores the importance of students' experiences outside of the classroom.

Summary and Discussion of 50-Student Cohort

Conceptual change toward normative understandings occured. Significant conceptual change toward normative understandings clearly occurred during the semester in which the students participated in the CLP curriculum. For each individual topic, an average of 72% of the students expressed primarily nonnormative ideas about thermodynamics during the first interview (before instruction began), and none of the students expressed primarily nuanced connections between normative ideas in this interview. An average of 82% of students expressed primarily normative ideas for each topic in Interview 5, at the end of the semester, and 47% of students made nuanced connections between normative ideas.

The process was challenging and not binary. The percentages of students rated as transitional or normative at each interview time for each topic in Figures 3–6 make clear that the shifts from students' initial understandings to nuanced normative accounts were neither quick nor clean. The process seems better characterized as incremental and evolutionary.

Figure 7 illustrates these issues from a slightly different perspective and uses a different shading format to represent a different type of analysis. Rather than looking within each topic, Figure 7 essentially looks across the topics. Figure 7 presents the percentages of students achieving (a) a normative or nuanced understanding for one, two, three, and four of the interview topics at each interview and (b) a nuanced understanding for one, two, three, and four of the interview topics at each interview. There are four interview topics for the 50-student analysis: thermal equilibrium, heat and temperature, insulation and conduction, and heat flow. Hence, a student could theoretically be assessed as having a nuanced understanding for all four topics. This condition would represent a fairly coherent and accurate understanding of thermodynamics theory. Although few students achieved a nuanced understanding of all four topics, most achieved at least a normative understanding of all four topics by the end of the semester and maintained this level of understanding across high school. Figure 7 therefore accentuates the challenges that students faced in building an integrated, nuanced, theory-like understanding of thermodynamics. Figure 7 also further demonstrates that the process was not binary, with students understanding all thermodynamics topics or none at all. Instead, many students at each interview time understood one, two, or three of the topics rather than zero or all four.

Students mastered the topics in different sequences. Combining the patterns represented in Figures 3–6 with the patterns in Figure 7 demonstrates that

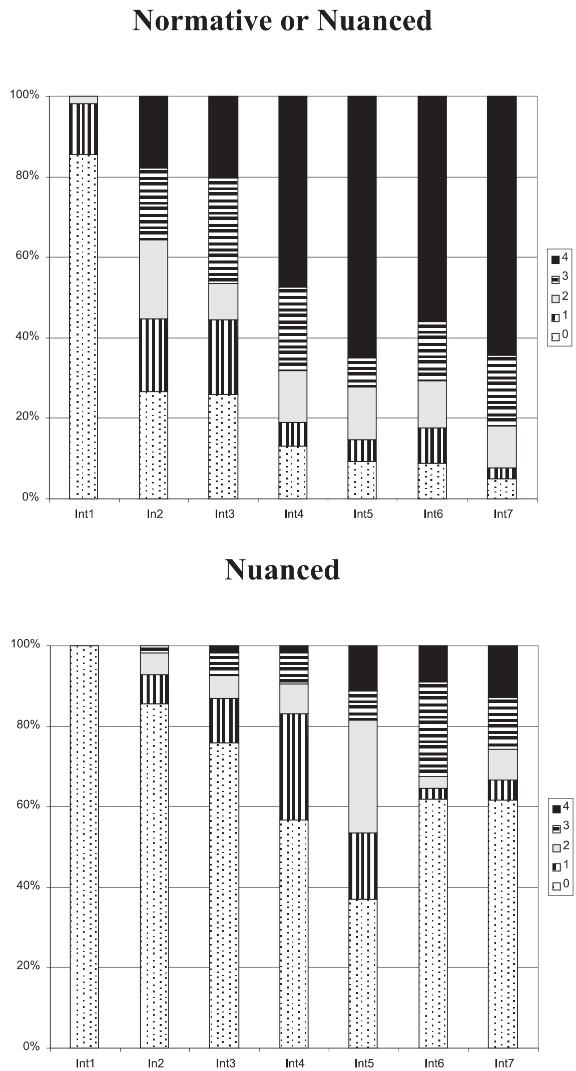

FIGURE 7 Percentages of students achieving (a) a normative or nuanced understanding for one, two, three, and four of the interview topics at each interview time and (b) a nuanced understanding for one, two, three, and four of the interview topics.

individual students were mastering the four topics in different sequences, for two reasons: One, Figures 3–6 show that the overall trends are similar to one another, which suggests a similar distribution of student understandings within each topic; two, Figure 7 shows that students at any given time mastered only a subset of the topics. In other words, most students had mastered some subset of the topics at each interview, but because they mastered different subsets, the patterns of understanding outlined in Figures 3–6 are parallel. This finding further suggests that students progress in their understanding of thermodynamics through different sequences or conceptual paths. The case studies illustrate this implication further.

It is important to note that this analysis only tracks conceptual change toward a normative understanding. Although substantial conceptual change clearly occurred in this direction, the analysis does not capture changes between distinct nonnormative or transitional understandings. In other words, significant conceptual change may have also occurred between distinct nonnormative or transitional understandings, change that would not be captured in this data. One must look to the case-study analyses for an understanding regarding the breadth of forms of conceptual change that was occurring. At the very least, the CLP curriculum clearly resulted in significant conceptual change toward a normative understanding for a large percentage of the students.

Integrating a normative understanding was time-intensive. During Interview 2, three weeks into the curriculum, when traditional curricula would stop covering thermodynamics and switch to another topic, an average of only 12% of students demonstrated a nuanced understanding that allowed them to make connections between their normative ideas for any given topic. Figure 7 shows that no students at this time demonstrated nuanced understandings of all four topics. By the end of the semester, however, more and more students were able to demonstrate this nuanced understanding.

Why did this process require more time for some students than others? What is happening with the 7% of students who continued to express primarily nonnormative ideas and the 13% who continued to express a mix of normative and nonnormative ideas in their final eighth-grade interview for any given topic? By understanding the trajectories of individual students, one can begin to address these questions about the processes through which students restructure their understandings. To examine these questions, the analysis focuses on four case-study students from the 50-student cohort.

RESULTS AND DISCUSSION: ANALYSIS OF THE FOUR CASE-STUDY STUDENTS

Analysis of four students from the 50-student cohort further illuminates student conceptual restructuring within the curriculum. The analysis focuses primarily on the students' understanding of thermal equilibrium. Pilot studies demonstrated that students' understanding of thermal equilibrium is dependent not only on their understanding of the classroom-instructed principles for thermal equilibrium but also on their understanding of insulation and conduction and thermal sensation (i.e., why different materials may feel different even if they are the same temperature). Although focusing primarily on students' understanding of thermal equilibrium, the analysis therefore includes insulation and conduction and thermal sensation (even though thermal sensation was not one of the four officially designated core topics within the curriculum).

Thermal Equilibrium Within the Curriculum

Thermal equilibrium is a challenging thermodynamics concept within the National Science Standards for middle school students (National Research Council, 1996). Thermal equilibrium explains aspects of heat energy transfer between objects of different temperatures. Essentially, objects in the same environment eventually become the same temperature as the environment unless they produce heat energy. For example, a wooden bowl and a metal spoon become the same temperature as the refrigerator, but a living person does not become the same temperature as a cold environment. According to the intermediate models employed by the CLP curriculum, this phenomenon occurs because there is a net heat energy flow from objects of higher temperatures to objects of lower temperatures until an equilibrium temperature is established. The four case-study students are analyzed from the perspective of this heat flow model because it was the context in which the students studied the thermodynamics concepts. Similarly, the other thermodynamics terminology and models used in these analyses are drawn from the curriculum (e.g., insulation and conduction).

Personal experience is at odds with some of the predictions of thermal equilibrium. Some materials feel hotter or colder than other materials. For example, a metal spoon in the refrigerator will feel colder than a wooden bowl even though, after several hours in the refrigerator, they are both the same temperature. From a heat flow perspective, materials such as metal and glass tend to feel hotter or colder because they conduct heat energy better than materials such as wool or wood. When you touch a metal object, heat energy flows quickly into or out of your hand. For example, heat energy flows more quickly out of your warm hand when you touch a metal spoon in the refrigerator than when you touch a wooden bowl. Students, however, interpret this experience to mean that the metal spoon is actually a lower temperature than the wooden bowl (i.e., if it feels different, it must be a different temperature). Students are so committed to this interpretation of their experience that they are resistant to the idea that the wooden bowl and the metal spoon have become the same temperature. Their interpretation is further distanced from fact because they seldom have access to thermometers for measuring the temperature inside solid objects. They must therefore rely on touching objects. Beyond their personal experiences, students' ontological commitments may also impede their understanding of thermal equilibrium. If students are committed to "heat energy" and "cold energy" as distinct entities with independent sources, the processes of heat flow–transfer involved in thermal equilibrium become even more confusing.

Overview of the Students

Two fairly successful and two less successful students were chosen from the cohort for the case studies. The most successful students were not the focus of the analysis because their progress was so rapid that, by the third interview, most of them expressed nuanced connections among normative ideas. Although they continued to refine their ideas in the fourth and fifth interviews, the steepest portions of their conceptual change trajectories spanned fewer interviews (see Figures 3–6 in the analysis of the 50-student cohort). Also, from the perspective of improving the CLP curriculum, these most successful students were apparently already well served. The decision was made for this study to focus extra attention on fairly successful and less successful students in hopes of insights that would facilitate enhancement of the curriculum. The two fairly successful students are referred to in this study as Forrest and Felipe, the two less successful students as Luis and Leo. Student gender was masked to avoid stereotyping. The case-study students' individual scores from the 50-student analysis are included by topic and interview in Figure 8 to provide context with respect to the 50-student cohort.

Forrest. Forrest ranked, on average, at the 58th percentile at each interview time. From Figure 8, one can see that he entered his eighth-grade semester with some sophisticated ideas about insulation and conduction and thermal equilibrium but that connecting these ideas with the ideas introduced in the classroom required significant reorganization. His explanations were less normative during some of the middle interviews.

Felipe. Felipe ranked, on average, at the 72nd percentile at each interview time. His explanations were considered largely nonnormative for all topics on the preinterview, but he made solid progress across the interviews, ranking at the 88th percentile on his fifth and final eighth-grade interview. He made his most rapid progress on heat and temperature and on insulation and conduction.

Luis. Luis experienced low success in the curriculum. His average percentile ranking was 16th on each interview. He made progress on all topics, but he made the most progress distinguishing heat and temperature. Although his explanations incorporated relevant terminology, this terminology was applied in a nonnormative fashion and seemed to be memorized rather than understood.

Felipe	Int #1	Int #2	Int #3	Int #4	Int #5	Int #6	Int #7
Heat Flow	■	■■■	■■■	■■■	■■■■	■■■■	■■■■
Heat/Temperature	■	■■■	■■■■	■■■	■■■■	■■■■	■■■■
Insulation/Conduction	■	■■■	■■■■	■■■	■■■■	■■■■	■■■■
Thermal Equilibrium	■	■■■	■■■	■■■	■■■■	■■■■	■■■■
percentile rank (avg=72)	1	78	91	67	88	94	89

Forrest	Int #1	Int #2	Int #3	Int #4	Int #5	Int #6	Int #7
Heat Flow	■	■■■	■■■	■■■	■■■	■■■	■■■■
Heat/Temperature	■	■■■	■■■	■■■	■■■■	■■■	■■■■
Insulation/Conduction	■■■	■	■■■	■■■	■■■	■■■	■■■■
Thermal Equilibrium	■■■	■■■	■■	■■	■■	■■■	■■■■
percentile rank (avg=58)	99	51	53	44	35	36	89

Leo	Int #1	Int #2	Int #3	Int #4	Int #5	Int #6	Int #7
Heat Flow	■	■	■	■	■	■	■
Heat/Temperature	■	■	■	■	■	■	■
Insulation/Conduction	■	■	■	■	■	■	■
Thermal Equilibrium	■	■	■	■	■■	■■	■
percentile rank (avg=1)	1	1	1	1	1	1	1

Luis	Int #1	Int #2	Int #3	Int #4	Int #5	Int #6	Int #7
Heat Flow	■	■	■■	■■	■■■	■■	■■■
Heat/Temperature	■	■■	■	■■	■■■	■■■■	■■■
Insulation/Conduction	■	■	■	■■	■■■	■■	■■■
Thermal Equilibrium	■	■■	■■	■■	■	■■	■■■
percentile rank (avg=16)	1	13	5	7	26	21	42

■ = non-normative ■■ = transitional ■■■ = normative ■■■■ = nuanced

FIGURE 8 Case-study students' interview scores within the 50-student cohort analysis by interview and topic (including percentile rank within the cohort overall and by interview).

Leo. Leo ranked in the lowest percentile for each interview. Because of his extremely low ranking within the class, Leo might not be considered representative, but in the interest of understanding the less successful students, Leo was chosen because of his willingness to participate in the interviews. Furthermore, although Leo expressed nonnormative ideas in his explanations, for every topic in every interview he also expressed transitional and occasionally normative ideas. Apparently, Leo managed to learn from his CLP experience, but he did not undergo a process of conceptual reorganization and refinement.

Analysis of the Four Case-Study Students' Explanations

The analysis of the case-study students first identifies the students' explanations at each interview time relevant to their understanding of thermal equilibrium and the interrelated topics of insulation and conduction and thermal sensation. The explanation maps provide a framework to facilitate the sorting, analysis, and organization of these explanations and the ideas they contained. They focus on the range of explanations rather than on the frequency, as discussed earlier. Throughout, quotation marks demark the students' direct quotations; italics emphasize key ideas in these quotations, as well as generalities in the students' thinking. The analysis identify four primary commonalities among the students.

1. *Multiple contradictory ideas*. The students simultaneously maintained multiple, sometimes contradictory, ideas in their repertoires. Context apparently played a significant role in fostering and cueing these multiple contradictory ideas.
2. *Disruptive experientially supported ideas*. Specific, experientially supported ideas played persistent and strong roles in students' explanations, disrupting school-instructed ideas that locally conflicted with these experientially supported ideas.
3. *Difficulties productively connecting normative ideas*. Students readily added ideas from the curriculum to their repertoires, but these ideas remained isolated and disconnected from students' other ideas. When students did make connections, these connections were nonnormative, at least initially.
4. *Pursuing idiosyncratic explanations*. Students sometimes expended significant time and effort refining idiosyncratic explanations and ideas to facilitate the integration of experientially supported ideas and school-instructed ideas.

These four commonalities have important potential ramifications for conceptual change research and curriculum design. The following analysis organizes the ideas expressed by each of the four case-study students in terms of each of these commonalities.

It is important to reiterate that the students were asked the same interview questions and that these interview questions were often repeated in different interviews. For example, the spoons question, diagrammed in Appendix B, was asked in Interviews 1, 3, 5, 6, and 7. The students often answered this question differently at different interview times and even within the same interview. The analysis therefore often refers to the spoons question in Interview X in support of one assertion and to the spoons question in Interview Y in support of another. Appendix A presents sample interview questions with an emphasis on questions relevant to this case-study analysis of students' understanding of thermal equilibrium (see Tables 4 through 7).

Commonality 1: Multiple Contradictory Ideas

The first of these conclusions—that students maintained multiple contradictory ideas rather than one coherent theory-like perspective—is supported by all four case-study students. Luis and Leo maintained multiple contradictory ideas throughout their CLP experience. Forrest and Felipe also maintained multiple con-

TABLE 4
Explanation Map for Forrest (Fairly Successful)

Key	*8th Grade—Interview 1: Prior to Instruction*
Horizontally: Each column represents all of ideas expressed in one interview.	IV. Metal and wood objects would be same temperature as oven because no way for them to get hotter or colder. (111–114) = tb1 + tb11
Vertically: Within each column, the student's ideas are coded in terms of sophistication and normativeness using the following codes:	
IV. Nuanced: Explanation that are both normative and nuanced in their connections of elements.	III. Two objects can be the same temperature and feel different. (169–172) = FB5 III. Paper towel would be good for keeping a soda can cold because it insulates well. (14–17) = ib2 + IB9
III. Normative: Explanations that are essentially correct, but not evidencing sophisticated normative connections between elements.	III. Paper towel would be good for keeping a soda can cold because it insulates well. (14–17) = ib2 + IB9 III. Paper towel would be good for keeping a soda can cold because it insulates well. (14–17) = ib2 + IB9
II. Transitional: Explanations that contain both normative and non-normative elements.	
I. Non-Normative: Explanations that are strongly non-normative.	
The interview transcript line numbers are included for each explanation in parentheses, followed by the Element Map codes.	
	II. Metal and wood feel different but are probably the same temperature. (180–182) = FB5 + fd4
	I. An insulator is compact and so it would keep the heat or cold in. (156–159) = ic1 + ID3 I. Paper towel insulates because it has fibers that are really close so it keeps the cold in. (14–17) = IC1 + ID7 + id3

TABLE 4 (*Continued*)

8th Grade—Interview 2: Following Thermal Equilibrium	*8th Grade—Interview 3: Following Heating/Cooling*
IV. When metal is cold it feels cooler than wood of the same temperature. (188) = fb5 + fc1 + fc3	IV. Objects can't get hotter than the oven they are in because nothing to make them hotter. (15–22) = TB9 + TB11 + tb1 IV. Size doesn't matter—Glass objects reach the same temperature in the oven after a while. (47–48) = tb15 + tb1
III. Metal and wood will be same temperature in a hot car trunk after several hours. (175–176) = tb1	III. When you hold metal your heat warms it up by flowing into it. (112–119) = tb3 + tb2 III. "Metal is a good conductor … It conducts heat energy." (203–205) = ib1 + ib3 III. Styrofoam or saran wrap would keep an object cold better and aluminum foil conducts the outside temperature … it would "trap like the cold or heat energy in." (221–224) = ib1 + ib2 + ic1 III. Styrofoam or saran wrap would keep an object cold better and aluminum foil conducts the outside temperature … it would "trap like the cold or heat energy in." (221–224) = ib1 + ib2 + ic1 III. Styrofoam or saran wrap would keep an object cold better and aluminum foil conducts the outside temperature … it would "trap like the cold or heat energy in." (221–224) = ib1 + ib2 + ic1
II. Metal feels hotter than wood because it changes temperature more quickly and it is actually hotter. (179–188) = ib1 + id1 + fc1 + fd4 + td1 II. Wood doesn't feel as cold as metal, and so would be room temperature in the cabin. (96–99) = FC3 + tb1 II. In an area that is warming up, metal will be hotter, but in area where the temperature is staying the same, both objects will be the same temperature. (197–198) = td1 II. No explanation for why metal feels colder and warms up easily. (114–115) = ic2 + fc1 II. Wood and metal are around the same temperature. (96–101) = tc1 II. You could feel the temperature of a hot object through cloth easier than glass, because heat energy would go through the cloth faster than glass. (138–143) = fb1 + tb3 + id15	II. In an air conditioned room, all objects are within a few degrees of the same temperature, with metal objects being cooler. (163–167) = tc1 + td1 II. A good insulator keeps a frozen candy bar cold by keeping the cold in or heat in. (95–99) = ic1 + IB9 II. Specific object feels cold because the coolness from the object touches your hand and your hand is warm so it will cool down your hand and makes it feel cold. (179) = fd2 + td4
I. Metal and glass objects in cold cabin will be below room temperature because they feel colder. (75–79) = td1 + fd4 I. "Coldness" flows as well as heat. (149) = td4 I. Metal feels cooler "cause it's, it's made of a, it's like smoother, and it's … solid, more solid." (160–161) = fd1 + fd10	I. Same temperature metal and wood objects will probably feel the same. (170–173) = tb1 + fd5 I. Asbestos doesn't reach the same temperature because it's made of the difference substance—"I'm really not sure." (23–24) = td11

(*continued*)

TABLE 4 (*Continued*)

8th Grade—Interview 4: Insulation/Conduction	*8th Grade—Interview 5: After Instruction*
IV. Specific objects of same material in freezer are the same temperature even though they have different sizes and amounts of heat energy. (176) = tb1 + tb15 IV. Integration of heating and cooling. (77–80) = TB6 IV. Metal is a good conductor which would make it get hot faster than the wood, but it couldn't get warmer than the oven because there's nothing to make it get warmer. (28–30) = IB1 + IB12 + tb1 + TB11 + TB9 IV. Metal is a good conductor and poor insulator so I wouldn't use that to make a container to keep hot things hot and cold things cold. Styrofoam is a poor conductor and good insulator so I would use that. (107) = IB1 + ib5 + IB2 + ib6 + IB9 + IB10	IV. Metal object will adjust more quickly to the oven temperature than the wood object because it is a better conductor which lets the heat travel through it very fast. (129–137) = IB1 + IB8 + ib12 + IB2 + tb1 IV. Styrofoam wrapped around something cold lets heat energy into the cold objects more slowly than having nothing wrapped around it… It's a good insulator.. (28–31) = IB2 + IB9 + ib4 + tb3 + tb6 IV. Objects can't get hotter than the oven they are in because nothing to make them hotter. (159) = TB9 + TB11 + tb1 IV. Heat goes more slowly through insulators than through conductors because good conductors are poor insulators and good insulators are poor conductors. (135–136) = IB3 + IB4 + IB5
III. (experiment) Heat energy flowed through copper really quickly and really slowly through Styrofoam. (111–113) = ib4 + ib2 + ib3 + ib1 III. Metal object might just feel hotter than wood object in oven rather than be hotter. (31–32) = fb5 III. Thick Styrofoam is better than thin Styrofoam for the container. (130–137) = ib7 + ib2	III. Wood and metal objects in oven will be same temperature after time because objects become temperature of surroundings. (124–128) (normative) = tb1 III. Aluminum will not slow down the flow of heat energy into a cold object or out of a warm object in a room because it is a conductor. (27–32) = IB1 + ib3 + tb2 + tb3
II. Metal object would be slightly warmer than the oven and wood object would be cooler than the oven because metal is a good conductor and wood is not. (12–14) = ib1 + td1 + ib2 II. Conductors heat up quickly and cool down slowly—Insulators keep in heat energy. (108–109) = ic1 + ib12 + id18 II. They put metal on the outside of Coleman ice chests because it is a good conductor so if you put it in a freezer to keep it cold and then take it out, it would cool off really quickly and keep the objects inside cool. (122–125) = ib1 + id17 + ib12 II. Aluminum cools down really fast and aluminum on outside of cooler will help the Styrofoam insulate. (135–137) = ID12 + ib12	II. Styrofoam is a good insulator, and so keeps the soda can cold by keeping the coldness in. (15–19) = ic1 + ib9 + td4 II. Touching an ice cube with a metal nail feels cold because metal is a good conductor and so the coldness travels quickly through it to your hand. (102–106) = td4 + FD12
I. Metal feels cooler because of the surface which is smooth and hard whereas wood is kind of rough. (57–60) = fd1 + fc1 I. Specific metal and wood objects in oven feel the same and are the same temperature. (37–40) = tb1 + fd5	I. Objects feel different because they have different surfaces—one can be smooth and the other ones rough or soft or hard. Smooth objects feel a little warmer because when you touch it, there's more that you feel, because with rough ones you don't feel the whole thing. (150–155) = FD1

TABLE 4 (*Continued*)

10th Grade—Interview 6: Longitudinal Follow-Up	*12th Grade—Interview 7: Longitudinal Follow-Up*
IV. Metal object in trunk would heat up faster and be the temperature of the trunk, but the wood is not as good a conductor and so it wouldn't have warmed up as fast, and wouldn't be as hot right away but eventually should be same temperature. (185) = IB1 + IB12 + tb1 + tb11 + IB2 + IB4 + ib8 IV. Metal object with one end in the fire feels hot "cause the heat from the fire travels through the wire." (192–195) = tb3 + ib1 + fb1 IV. Heat energy flows from the surrounding area into cold objects to warm them up to the temperature of the surrounding area. (13–14) = tb1 + TB3 IV. Styrofoam is better to keep a soda can cold because it's a better insulator. (17–20) = ib2 + ib9	IV. All objects eventually reach room temperature, but good conductors reach it more quickly, while objects wrapped in Styrofoam will take more time. (210–216) = tb1 + IB8 + IB12 + ib2 IV. Metal object feels hotter because it's a better conductor and the heat energy can escape into your fingers faster than through the wood. (97–99) = IB1 + FB1 + ib3 + ib2 + tb3 + tb6 IV. Objects in the freezer will be same temperature as the freezer because there's nothing to make them be colder or warmer. (37) = tb1 + TB11 IV. Objects like bodies don't reach room temperature because we produce our own heat energy. (220) = tb1 + tb11 IV. Molecular Kinetic model connected to thermal equilibrium. (11–17, 58–61) = TB12 + tb1 IV. Cold objects that are conductors take heat energy away from an object very quickly making them feel cold. (109–112) = Fb4 + ib3 + tb6
III. (experiment) Aluminum foil doesn't help keep the soda can cold because we did an experiment and it didn't do anything. (10–12) = ib10 + ib1 III. An insulator keeps the heat energy from going into the soda can, whereas aluminum would allow the heat energy to go right through. (23–30) = IC1 + ib1 + ib3 III. Metals are better conductors and so they will heat up or cool down faster. (127–130) = IB12 III. All objects will become room temperature after a long time. (118–122) = tb1	III. Styrofoam is not a very good conductor so it would keep the cold away—it would be a very slow conductor. (133) = ib2 + ic1 + ib4 III. Surface area and volume affect rate at which objects cool down. (47) = IB7 + tb3
II. Metal in cabin would feel colder than the wood, but no explanation why for why. (123–126) = fb5 + FD3 II. Metal is a good conductor, and so gets colder quickly, and so will feel cold because the cold travels through the nail to your hand. A wood stick would be a worse conductor and so it would take longer for the cold to reach your hand. (170–178) = IB12 + fd12 + IB1 + td4 + IB2	II. Aluminum foil is not good to keep a soda can cold—Styrofoam is better because it insulates well keeping the heat energy in or out depending on which one you want it to do. (3–9) = ib1 + ib10 + ib2 + IB9 + IC1 + ib6 + tb6
I. Same temperature metal might feel hotter in hot trunk than wood but probably not. No explanation for why. (189–191) = fc1 + FD3 + tb1 + fd5	I.

TABLE 5
Explanation Map for Interviews 1 to 3 for Felipe (Fairly Successful)

Key	*8th Grade—Interview 1: Prior to Instruction*
Horizontally: Each column represents all of ideas expressed in one interview.	IV.
Vertically: Within each column, the student's ideas are coded in terms of sophistication and normativeness using the following codes:	
IV. Nuanced: Explanations are both normative and nuanced in their connections of elements.	
III. Normative: Explanations are essentially correct but not evidencing sophisticated normative connections between elements.	
II. Transitional: Explanations contain both normative and nonnormative elements.	III.
I. Nonnormative: Explanations that are strongly nonnormative.	
The interview transcript line numbers are included for each explanation in parentheses, followed by the element map codes.	
	II. Wood object does not reach temperature of oven. (109–113) = td11 II. Some specific materials can keep hot things hot and cold things cold because there are foam manufactured objects to keep hot things hot and foam objects to keep cold things cold, but Coleman-type coolers can only keep cold things cold. (52–54) = ib6 + id15 II. Metal is good conductor of heat and so gets hotter than oven. (105–107) = IB1 + TD13 II. Foam is good for keeping cold things cold because "they're like really solid, thick, and they wouldn't sell them if it didn't work." (18) = ic4 + id5 II. Aluminum foil and rubber foam holders are good for keeping cold sodas cold. (15) = id12 + we + ic12 + we
	I. Metal objects are below room temperature. (141) = td1 I. Aluminum foil is probably better than wool for keeping things cold – We use wool to keep things warm. (30–32) = id12 + id9 + we I. Aluminum foil insulates coldness keeping it in. (25–26) = td4 + ic1 + id12 I. Aluminum foil doesn't let air through so would work better as a block for heat or cold. (32–34) = id3 + id12 I. "Coldness" moves from ice into metal, and you can feel the "coldness" because it is in it. (173) = td4 + fd4

TABLE 5 (*Continued*)

8th Grade—Interview 2: Following Thermal Equilibrium	*8th Grade—Interview 3: Following Heating/Cooling*
IV. The metal and wood objects in the trunk are the same temperature, but the metal is a good conductor, so the heat goes from the metal into your hand, which doesn't happen with the wood, so you can't feel it as much. (169) = tb1 + fb1 + fb3 + ib1 + ib2 IV. Metal conducts heat really well, and so when you touch it, heat goes out of your hand into the cold block, making your hand feel cold. Wood isn't a good conductor, so it doesn't feel cold. (74–75) = IB1 + TB3 + FB4 + IB2 IV. All objects reach room temperature, but they feel different. (across temperature contexts) (69) = TB1 + FB5	IV. Room and oven are related—same process happens in both environments (21) = tb1 + tb7 IV. Metal conducts heat into your hand so you can feel it, but wood isn't a very good conductor so would not conduct heat into your hand so fast so you wouldn't feel it. (53) = tb1 + fb1 + fb3 + ib1 + ib2 IV. Metal and wood are same temperature, but the metal feels cold or because metal is a better conductor and so heat flows out of your hand faster from it. (129–133) = tb1 + tb3 + fb5 + IB1 + IB2 + FB1 + FB3 IV. Aluminum foil would not keep a frozen object cold because the heat from outside would go into the aluminum and into the object. (76) = ib1 + ib10 + tb3
III. You can feel a hot object through aluminum foil because it conducts the heat from inside the object into your hand. (99–102) = fb1 + IB1 + tb3 III. Wool must not be a good conductor because people wear wool to keep warm and if it was a good conductor, it wouldn't keep you warm. (116–120) = IB2 + IB5 + WE III. Wool is more of an insulator. (122) = ib2 III. Specific object feels cold because heat is going out of hand into object. (139–140) = fb4	III. Wool would probably be pretty good for keeping the frozen object cold because it's a good insulator of heat. (79–80) = IB2 + IB9 III. Glass objects of different sizes will reach same temperature in the oven. (95–98) = tb15 III. Glass is a better conductor than the wood but not as good conductor as metal. (59) ib11 III. Conductors conduct heat well – "heat energy flows through it very fast." (226–228) = IB3
II. Metal objects in hot trunk feel hotter because metal conducts the heat more easily, so there would be more heat in it than in wood. (167) = IB1 + ib2 + id1 + fd6	II. Wool will work better if it is the knit kind rather than the porous kind. (79–80) = id3 + ic4 II. Glass is not a good conductor and so will not reach the temperature of the oven. (21) = ib11 + td17 II. An insulator is something that keeps things in or isolates it. (87–92) = IC1
I. Metal objects in hot trunk get hotter than wood objects. (157) = tb1 + td1 I. Aluminum foil conducts only a little bit of heat energy from cold object into my hand and so it feels cold –If not heat energy, then something else is going in. (133–136) = ib1 + fd9 + fd2 + td10 + we	I. Glass doesn't get to temperature of oven because like a potato has a lot of water in it and so it doesn't get to too high a temperature—cites teacher. (15) td11 + wt

(*continued*)

TABLE 5 (*Continued*)

8th Grade—Interview 4: Insulation/Conduction	*8th Grade—Interview 5: After Instruction*
IV. Objects in room are same temperature, but the metal ones conduct heat out your hand faster, leaving your hand feeling cold, but the wood doesn't so it feels warm. (37) = TB1 + IB1 + IB2 + tb6 + Fb1 + FB3 IV. All objects become the temperature of the surroundings, but since they're different materials, they might conduct heat differently, so it happens at different rates. (115) = TB1 + IB8	IV. Metal feels cold because metal conducts the heat out of your hand to the ice or through it, so it leaves your hand feeling cold. (146–148) = tb1 + tb3 + fb4 + fb5 + IB1 IV. Metal and wood object would get to temperature of oven but metal would get there first because it conducts heat the fastest. (79–86) = tb1 + IB8 + IB12 IV. Metal and wood are same temperature in oven but feel different because metal is a better conductor and so heat flows into your hand faster from it. = tb1 + fb5 + IB1 + IB2 + FB1 + FB3 + tb3
III. Wool is good to build a container to keep hot things hot or cold things cold because it insulates heat—it keeps heat in, or if the object is cold, it keeps heat out. (65–68) = ib6 + IB2 + ib9 + IC1 III. Wood and metal don't get hotter than oven—maybe reach same temperature as oven. (25–26) = tb1 + tb9 III. Blocks of ice of different sizes in freezer reach same temperature. (101) = tb1 + tb15	III. Wool is good to keep a cold object cold because it is a good insulator, which keeps heat from going in or out. (16–18) = IB2 + ib9 + IC1 III. Specific objects and room eventually become temperature of room. (107) = tb1 III. Objects reach temperature of surrounds after time. (86–91) = TB1 III. Heat energy travels fast through conductors like copper. (124–126) = ib1 + ib3
II. Wood doesn't absorb as much heat in the oven – metal gets hotter because metal conducts heat energy better. (17–25) = IB1 + td13 + Ib2 + td17 II. Metal in freezer might be colder than the ice because a better conductor. (105–110) = IB1 + td13	II. Heat energy travels only a little bit or not at all through an insulator. (127–128) = ib4 + ic1 II. Containers that keep hot things hot keep cold things cold because it keeps the heat energy in or out. (43–44) = IB6 + ic1
I.	I.

TABLE 5 (*Continued*)

10th Grade—Interview 6: Longitudinal Follow-Up	*12th Grade—Interview 7: Longitudinal Follow-Up*
IV. Objects in room are same temperature, but the metal ones conduct heat out your hand faster leaving your hand feeling cold but the wood doesn't so it feels warm. (71–77) = tb1 + fb5 + IB1 + IB2 + FB4 + FB3 + tb3 IV. Objects in a hot trunk are the same temperature, but "the metal one's going to feel hotter … Because that the heat would go into your finger from the metal." (79–83) = tb1 + fb1 IV. Heat energy comes into a cold object until it reaches temperature of surrounding. (23–23) = TB3 + TB4 + tb1 IV. After a while of touching a nail to an ice cube, the nail would get cold and conduct heat from your fingers through to the ice. (121–123) = tb6 + fb4 + ib1	IV. Objects in room are same temperature, but the metal ones conduct heat quickly out your hand faster leaving your hand feeling cold but the Styrofoam doesn't so it feels warm. (100–109) = tb1 + fb5 + IB1 + IB2 + FB4 + FB3 + tb3 IV. Heat energy flows from higher temperature object to lower temperature object until they eventually become the same temperature. (41) = TB3 + tb2 + TB4 + tb1 IV. All objects reach same temperature in any environment. (61) = TB1 + TB7 IV. All objects eventually become temperature of oven, but because of conductivity some take longer to heat than others. (83–85) = TB1 + IB8
III. Styrofoam would be good to keep a cold soda cold, and so would wool. They aren't conductors so heat energy wouldn't go in as fast. (25) = ib2 + ib9 + IB4 + tb3 III. Covering a hot object with aluminum foil would allow you to feel the heat because "it wouldn't keep out the heat of the oven … it will come out, conduct." (95–97) = fb1 + ib1 III. Aluminum foil is not good to keep a cold soda cold because it is a conductor of heat energy so heat energy goes in until the soda is room temperature. (19–21) = ib1 + ib10 + IB3 + tb3 + tb1 + TB4	III. Wood is not a good conductor because when you walk on it it's not that cold. We would not use wood to build our houses if it were a good conductor. (121–122) = fb4 + IB2 III. Styrofoam and wool are not good conductors of heat and so they would keep the heat out. (5–9) = IB2 + ib9 + IC1 III. Smaller objects of same material change temperature faster on way to same temperature. (63–65) = IB7 + TB15 III. Heat flow is more like a diffusion model of movement than it is like a sponge absorbing something. (54–57) = TB10 III. "Wool is definitely a good insulator. I mean, we wear it for sweaters right?" (145) = IB2
II.	II. Wood is a "blocker" of heat. (160–164) = fb4 + ic1 II. Good insulators keep hot things hot and cold things cold – they keep heat from entering—"It's like a blocker. You know, like stop." (146–147) = ib7 + ic1
I.	I.

TABLE 6
Explanation Map for Interviews 1 to 3 for Luis (Less Successful)

Key	*8th Grade—Interview 1: Prior to Instruction*
Horizontally: Each column represents all of ideas expressed in one interview. Vertically: Within each column, the student's ideas are coded in terms of sophistication and normativeness using the following codes: IV. Nuanced: Explanations that are both normative and nuanced in their connections of elements. III. Normative: Explanations that are essentially correct, but not evidencing sophisticated normative connections between elements. II. Transitional: Explanations that contain both normative and nonnormative elements. I. Nonnormative: Explanations that are strongly nonnormative. The interview transcript line numbers are included for each explanation in parentheses, followed by the Element Map codes.	IV. III. Very cold and very hot objects "would definitely be room temperature" after a month. (293–295) = tb1 III. Several specific objects will come to room temperature after several hours including metal objects. (180–182) = tb1 II. Whether a container that keeps cold things cold will also keep hot things hot "depends on room temperature." (73) = id22 II. Things heat up because atoms vibrate if below room temperature, otherwise they don't. (44) = tc7 II. Objects become room temperature after several hours because of the vibrating atoms in the air. (202–202) = tb1 + -tb12 II. Metal is a good conductor for "heat or cold" (254–256) = td18 + IB1 I. Wooden object gets hotter than metal object which gets hotter than the oven because it would be "on fire … because I tried that out once." (129–131) = td8 + td14 I. Water is a good conductor because "electricity travels through water," and plastic is a good insulator because "electricity can't traveled through it." (218–235) = id23 I. To keep a cold soda cold, wrap it in chilled aluminum foil or in plastic. (16–24) = ic4 + id17 + we I. The metal spoon would not be hotter than oven "because just like in metal shop it takes a long time until you can finally melt the metal." (143–145) = TD21 + we I. The "atoms of the ice" are "sending cold to the nail and making [the nail's atoms] move slower" which makes the nail feel cold. (260–272) = tc7 + fd4 I. Aluminum foil will keep a cold soda cold better than wool because wool will heat it up—it's thick and made of cloth. (45–48) = id9 + id7 + id5 I. A thick piece of aluminum foil would heat up the soda in the same way that wool would. (59–62) = id5 I. A cup of hot chocolate ends up below room temperature because after eight hours it will get cold. (189–190) = td8 + we I. A cold soda can ends up at a temperature above room temperature because it gets hot when you leave it out. (184–186) = td8 + we

8th Grade—Interview 2: Following Thermal Equilibrium	*8th Grade—Interview 3: Following Heating/Cooling*
IV.	IV.
III. Metal is a good conductor of heat energy and cold energy which means that it can go through and spread around. (167–168) = IB1 + ib3	III. Metal objects would be same temperature as the oven, not hotter. (49–51) = tb9 + tb1 III. Frozen candy bar becomes room temperature after time. (159–163) = tb1
II. Wood will be the same temperature as the trunk, and metal will be hotter. (282) = tb1 + td1 II. Wood and similar things are good insulators which “means they’ll just stay. No matter how hot it is, it will um-not unless you burn it, it would, wood would still be the same.” (170–172) = ib2 + td11 II. Metal is a good conductor of cold energy. (164–165) = IB1 + TD18 II. Metal gets warmer than wood because it heats easier—it’s a good conductor—But both get hotter than trunk. (250–272) = td13 + ic2 + IB1 + td8	II. The wooden spoon would be okay to touch because it “wouldn’t really heat up … [the heat energy] is not, um traveling through, it’s not a good conductor or an insulator.” (317–319) = fd4 + ib2 + ic4 + id16 II. The metal spoon would feel hotter than the wooden spoon in a hot pot of soup because it is hotter “Cause metal’s a good conductor for heat. The heat would go up it.” (313–315) = td1 + fd4 + ib1 II. Some objects in air-conditioned room would be same temperature as the room, but metal objects would be cooler. (210–213) = tb1 + td1 + td5 II. A conductor is “something that can travel, can travel like heat, cold, electricity. (243) = ib3 + ID23
I. The inside of metal stove and furniture remain warmer in the cabin because it is not exposed to the outside where the atoms are vibrating. (127–128) = td9 + tb12 I. Objects in a cold cabin remain different temperatures after several months. (122–124) = td5 I. Metal objects in cabin feel different and are different temperatures. (156–160) = fc1 + fd4 + td5 I. Cold energy goes from specific cold object into cloth and then you feel the cold energy in the cloth. (232) = fd12 + TD18 I. A thin piece of cloth would let you feel a warm object through it because cloth is a heat insulator—gets heat energy from the hot object and then the cloth gives it to your fingers easily. (186–192) = IB2 + id16 + fb1	I. Small beaker would be hotter than large beaker in a freezer even after a long time and would have different amount of heat energy. (58–64) = td20 I. Metal objects in oven would be hotter than the oven because metal is a good insulator which means it takes heat up easier, and cools down slower. (41–43) = td1 + ID12 + id19 + ib4 + td16 I. Metal objects get hotter than glass objects and asbestos and even the oven. (36–39) = td5 + td1 I. An insulator is “something that can store … it would get hotter and hotter” if you put it in something hot. (245–249) = ID8 I. Aluminum foil wrapped around a frozen candy bar will slow down the rate at which it heats up because metal is a good insulator for cold energy. (101–105) = ID12 + td18 I. Aluminum foil will only help keep the frozen candy bar cold if foil is itself cold—nothing will keep frozen candy bar cold unless it is itself cold. (144–159) = ID17

(*continued*)

TABLE 6 (*Continued*)

8th Grade—Interview 4: Insulation/Conduction	*8th Grade—Interview 5: After Instruction*
IV. Atoms in ice cream move faster when they come in contact with atoms in the air which makes the ice cream warm up. (143–145) = tb2 + TB12	IV. Styrofoam is good to keep a soda can cold because it is a poor conductor which means that it is a good insulator. (14–15) = ib2 + IB5 + ib9
III. Metal is a good conductor and so heat travels through it easily. (265) = IB1 + IB3 III. Big block of ice is same temperature as small block of ice in freezer. (168) = tb1 + tb15 III. A class experiment shows that Styrofoam is better than aluminum foil for keeping hot objects hot, and for keeping cold objects cold. (97–99) = ib6 + ic4 + ic5	III. Objects in room probably become same temperature. (170) = tb1 III. Heat energy goes into conductors and makes their temperature go up, but with insulators it just touches it and doesn't go through it. (scaffolded) (36–39) = ib3 + TB2 + IC1 III. Copper is a good conductor because "hot things wrapped in it will lose heat fast" because heat flows out from hot object because it is a conductor. (215–219) = tb3 + ib1 + ib3
II. Metal objects would be the temperature of the oven, and wooden objects would be colder. (16–17) = tb1 + td11 II. Metal objects would be a little bit warmer than the oven because they are good conductors and so gather up heat energy faster. (36–41) = IB1 + tc6 + ID2 II. Metal is a good conductor and so has an advantage to get really hot or cold. (55) = IB1 + td1 II. A warm object will cool down if left in a Styrofoam container but not as fast if it was left out—it gets colder because the air can still go in, but if you made it airtight it would probably be much better. (119–121) = ic4 + td7 + ic1	II. Wool is a good insulator "because it keeps you warm" but it does not help to keep cold things cold. (232–237) = ib2 + ib9 + id22 II. Metal feels cold because there is less heat energy because it is a good conductor and it goes through. (178–180) = IB1 + 1d20 + fd4 II. Insulators keep a hot casserole warm because they don't "let the heat energy escape … to the air." (54–58) = ic1 II. Heat energy will come from the air to try to heat up the soda can, but Styrofoam will store it and heat up a little bit. (17–25) = tb2 + tb6 + ib2 + id8
I. Thick Styrofoam would be better than thin Styrofoam because it could gather and store more heat and cold from the air inside and outside the container. (104–113) = ib7 + id8 I. Metal and wood objects in room are different temperatures, and feel different with the wood feeling warm and the metal feeling hot. (62–65) = td5 + fd4 I. Ice keeps cold things cold, and will keep hot things hot because hot things will melt ice into hot water which will keep them warm. (87) = id17 + td19 I. Big blocks of ice can actually get colder than the freezer after a long time because they are good insulators. (189–196) = id8 + td8 I. Big block of ice is colder than the small block of ice in freezer. (172) = td20 + td5	I. Wood feels warmer because it is storing heat energy from the air. (182–187) = fd4 + id8 + ib2 I. Metal object is below room temperature, "because I have found it before." (159–160) = td1 + we I. Metal can take heat energy easier than wood and so it gets hotter than oven—wood would just take some and then stop when it fills up and so isn't as warm. (119–130) = ID2 + TD1 + td11 I. Metal can get hotter than the oven because it keeps on taking heat from the oven. (133–138) = td1 + td12 + id2 I. Hot chocolate becomes cooler than the room temperature because heat flows out of it, and "it has happened to me." (203–204) = td8 + tb2 + we I. A cold can of soda becomes warmer than the room temperature because the light and the air make heat energy that would flow easily through the cold soda. (200–202) = td8 + TB2 + we

TABLE 6 (*Continued*)

10th Grade—Interview 6: Longitudinal Follow-Up	*12th Grade—Interview 7: Longitudinal Follow-Up*
IV.	IV.
III. Wood and metal objects in hot trunk "probably would be the same temperature. Maybe the metal one's slightly higher. [They become the same temperature] because they're in the same temperature area." (378–380) = tb1 + tc6 III. Styrofoam would be good to keep a soda can cold because it is an insulator, not a conductor, and restaurants use it as an insulator. (10–28) = IB2 + ib5 + WE III. Styrofoam doesn't let heat energy come in from the outside environment—it can come in, but very slowly. (scaffolded) (24–28) = ib2 + ib4	III. Styrofoam would be good to keep a soda can cold because of a simulation on those Macs. (3–9) = IC4 + WL III. Specific materials besides metal are good insulators. (305–306) = IB2 III. Cold soda can would warm up to room temperature. (34–37) = tb1 III. Big and small block of ice in freezer would "probably be the same [temperature]" (57) = tb1 + tb15 III. A conductor is something that can transfer heat or energy. (14–17) = IB3 III. "There's no such thing as cold. Heat goes out." (251–253) = TB6
II. You can feel a hot object through aluminum foil because it is a conductor and it will conduct the heat energy from the metal into the foil and you will feel it. (330–332) = tb6 + ib1 + fd4 II. Wood feels cool but not cold in cabin. (312–313) = fc3 II. Styrofoam keeps a soda can cold because it keeps all the heat energy in the soda can and doesn't raise or lower it—it just let's it stay there. (19–23) = ib2 + ib9 + ic1 II. Metal would be "a lot hotter" than the trunk, and wood might be the same temperature as the inside of the hot trunk. (394) = tb1 + td1 II. Conductors take energy from the environment and spread it around. (47–55) = ib3 + id1	II. Wrapping of soda can in aluminum foil might make it heat up faster, or might not make a difference because it would just be the same as the aluminum on the can, but "just thicker."= ib1 + id1 II. When removed from oven, most objects go to room temperature, except for the metal spatula which gets much colder. (156–163) = tb1 + td5 II. Metal is a conductor so heat goes in from the air into the soda so it can get a little bit warmer than room temperature. (47–51) = IB1 + tb6 + tc6 II. How objects feel reflects their actual temperature—Ceramics are insulators because "usually the floors are made out of ceramic so if it gets real hot, if it was a conductor, the house would be steaming." (193–195) = fd4 + ib2 + we II. Ceramic platter will remain hotter than a metal platter when removed from an oven "because it insulates heat. It stores it … [Good insulators] hold the heat longer." (199–205) = ib2 + id8 II. "The heat energy would conduct into the metal spoon and then burn my hand … it diffuses into the metal because the metal will probably be … cool [with] a lot of empty space for heat energy. The heat energy conducts into the thing and burns your hand." (221–225) = tb6 + fd4 + ib1 + id3
I. Wood will be warm but not as warm as the oven because it only takes in a little heat. (80–85) = ID21 + td11 I. The pot-bellied stove would be "really cold … because it's a … conductor … it's const-um conducting um … the little amount of heat energy." (305–307) = td1 + td10 + ib1 I. Specific objects in cabin are different temperatures. Wood is warm, furniture is room temperature, metal is ice cold. (293–315) = td5 + td1 + td11 + fd4 I. Metal gets hotter than the oven because energy keeps coming in and out of it. (87–92) = ib3 + td1 I. Cold objects give off just a little heat energy, and so feel slightly warm initially, but eventually start being cold. (360–363) = td10 + ib1 + fd4 I. An insulator stores heat energy and doesn't release any. (16) = ID8	I. Metal object holds and gets rid of heat at a constant rate, but wood table gets cold because it just holds a little heat and keeps it—eventually though the heat would be gone because something else takes it. (290–299) = ic6 + id8 + id1 I. Metal object gets slightly warmer than oven, glass objects gets slightly cooler than oven, and ceramic objects gets significantly cooler than oven. (145–149) = tc2 + tc6 + td11 I. Metal object feels cold and so must be colder than room temperature. (277–279) = fd4 + td1 I. Metal feels cold and so is cold—The metal "would probably go a little below room temperature, you know like the cool metal feel." (203–207) = td1 + fd4 I. Maybe the bigger [block of ice] would be a little hotter [than the little block of ice]. Would be a little higher temperature." (59) = td5 + td20 I. Cold soda can might get warmer than room temperature by a little bit. (43) = tc6 + we

TABLE 7
Explanation Map for Leo (Less Successful)

Key	*8th Grade—Interview 1: Prior to Instruction*
Horizontally: Each column represents all of ideas expressed in one interview.	IV.
Vertically: Within each column, the student's ideas are coded in terms of sophistication and normativeness using the following codes:	III.
IV. Nuanced: Explanations are both normative and nuanced in their connections of elements.	II. Styrofoam can keep hot things hot and cold things cold because "it can adapt to different kinds of weather." (263) = ib6 + id6
III. Normative: Explanations are essentially correct but not evidencing sophisticated normative connections between elements.	II. Non-metal objects left out on table reach room temperature after a long time. (141–149) = tb1 + td1
II. Transitional: Explanations contain both normative and nonnormative elements.	
I. Nonnormative: Explanations are strongly non-normative.	I. Wool makes things warm because it is thick and makes heat. (33–35) = ID9
The interview transcript line numbers are included for each explanation in parentheses, followed by the element map codes.	I. When asked for an example and explanation of a good insulator, Leo says he doesn't know what an insulator is. (165) = ID24
	I. Things that keep things warm don't necessarily keep things cold because if you want to keep something warm you put wool around it. (40–42) = ID22 + ID9
	I. Nail touching block of ice feels a "little bit warmer" because your hand is covering it up and protecting it from the air and thus making it hotter. (208–212) = fd4 + id6
	I. Metal plate left out on table is warmer than room temperature because metal absorbs more heat, and so it will keep just getting hotter. (133–134) = td1 + td22 + id2
	I. Metal objects feel colder than wood objects and are colder. (233–241) = td1 + fc1 + fd4
	I. Metal object get warmer than wood object in oven because metal can absorb more heat, and both are warmer than the oven they're in. (93) = td1 + td2 + td5 + id2
	I. Metal is a good conductor because "it absorbs a lot of heat." (161) = IB1 + ID2
	I. Metal and wood spoons are hotter than the oven they are in, and the longer it they are left in the oven, the hotter they become. (104–108) = td2 + td22
	I. Cold air makes hot chocolate continue to get colder past room temperature, and hot air in rooms makes objects get hotter past room temperature. (151) = td23 + id6
	I. Aluminum foil is good for keeping sodas cold because "I see a lot of people that have their sodas in tin foil." (15) = id12 + we3
	I. Aluminum foil absorbs cold from soda can and keeps soda can cold. (18) = td19 + id12 + id17

TABLE 7 (*Continued*)

8th Grade—Interview 2: Following Thermal Equilibrium	*8th Grade—Interview 3: Following Heating/Cooling*
IV.	IV.
III. Objects in room are the same temperature even though they don’t feel like it… the teachers said so. (83) = tb1 + fb5 + wt III. Metal and wood objects in room are the same temperature but feel differently. (99–101) = tb1 + fb5	III. Several specific objects in air-conditioned room will be the same temperature as the room. (139) = tb1
II. Specific objects in room are the same temperature, and so must feel the same. (95) = tb1 + fd5 II. It seems like the metal is colder than the wood, but the teachers said it was room temperature. (196–198) = tb1 + fd4 + wt	II. Objects that are the same temperature feel the same. (58–63) = tb1 + fd5 II. Metal and wooden objects are the same temperature in an air-conditioned room and so should feel the same, “except if you touched a bed sheet. It would probably be a little hotter.” (140–143) = tb1 + td11 + fd4 + fd5 II. Glass, ceramic, and metal objects would be the same temperature as the oven, but asbestos would not be as hot as the others. (13–19) = tb1 + td11
I. You can’t feel warm through aluminum foil is easily as through saran wrap because aluminum foil is thicker. (164–165) = fd10 + id5 + fd13 I. You can feel warmth through saran wrap easily because it is not thick. (147) = fd10 + id5 I. You can easily feel cold objects under aluminum foil because it absorbs cold from the object and so feels cold. (174–175) = fc4 + fd4 + id2 I. Wood doesn’t get as hot as metal in the car trunk because metal absorbs more heat. (184) = td1 + id2 I. When you hold something you block the cold weather from getting to it so it can’t get colder so it gets warmer. (119–121) = td24 + ID6 I. No explanation for why things feel warm or cold. (162–163) = FD3 I. Metal object in cabin feels different and is a different temperature because metal can absorb more cold. (107–109) = td1 + fd4 + id2	I. Wrapping frozen candy bar in wool would make it melt because wool is so thick—It would have a lot more heat in the wool. (77–78) = id9 + id5 I. Wrapping a frozen candy bar in aluminum foil will keep it cold by keeping in the cold air and because candy bar would make the aluminum foil cold which would then keep the candy cold, too. (70–72) = td19 + id6 + id12 + id17 I. When asked directly, Leo denies any understanding of what an insulator or conductor might to or be. (170–175) = ID24 I. The top half of a metal spoon gets hot because steam comes up from the boiling water, not because of any heat traveling through the spoon. (192–205) = id6 I. Metal spoon in boiling water is hotter than a wooden spoon because “metal would absorb more heat.” (185–187) = td1 + id2 I. Coldness travels up metal spoon from ice water to make top part of spoon cold. (229) = td18 I. Asbestos wouldn’t be as hot as the oven or the other things because “I can’t just picture that.” (50–53) = td11 + we

(*continued*)

IV.	IV.
III. Objects feel different, and seem like different temperatures, but they could be the same temperature but feel different "because of what Mr. K said." (41) = fb5 + wt III. Big and small blocks of ice are the same temperature in a freezer. (174) = tb1 + tb15 III. Styrofoam would keep the ice cream the same temperature, but no explanation for why. (150–151) = ic4	III. Objects stay the temperature of the room because there's nothing to make them colder or hotter. (167–168) = tb1 + tb11 III. Objects in a room reach the temperature of the room even though they seem different because the teacher explained it that way. (66) = tb1 + fb5 + wt
II. No explanation for why things that are the same temperature feel different. (56–57) = tb1 + FD3 II. Metal becomes the same temperature as ice in freezer because "metal can absorb coldness pretty good, too." (178) = tb1 + td18 + id2	II. Styrofoam is best to keep soda can cold "because um well, I can only remember that when the experiment we did…"—suggests that maybe Styrofoam keeps soda can cold by keeping the cold energy in it. (13–18) = td18 + ic1 + ic4 + wl II. Aluminum foil is poor for keeping things hot because "the heat from the object would go right… through the aluminum foil" but the aluminum foil is good for keeping things cold because "it would absorb… the coldness and keep the cold thing cold." (186) = td18 + td19 + ic5 + id17 + id22 II. A good insulator "probably keeps cold things cold, something like that… would absorb the cold energy from the object and keep it cold"—A good insulator "wouldn't keep [a hot object] that hot." (99–107) = td18 + td19 + ib9 + id17 + id22
I. Styrofoam would not keep casserole as warm because there are little holes that the heat could escape through. (128–129) = id3 + id6 + id15 I. Student gets conductors and insulators "mixed up"—doesn't really know what they are. (120–123) = id24 I. Since metal has no air holes there is no way for hot air to get out and so objects inside the metal would stay hot. (90–91) = ID3 + id6 + id12 I. Metal pan gets hotter in oven than metal rack because metal rack has spaces in it. (16–23) = td5 + id3 I. Metal is good for keeping hot things hot because it can absorb the heat and keep them hot, and metal is good keep cold things cold causes the can absorbs the coldness and keep them cold. (79–83) = td18 + td19 + ID2 + ID12 + id17 I. Metal gets hotter than wood in an oven. (13) = td1 I. Metal bowl continues to get hotter than the oven because it keeps "getting more heat and more heat and it gets hotter and hotter." (30–33) = td22 + id2 I. "Wood would not be as cold as the rest of the things because whenever you touch the wood, it doesn't seem as cold as the other things that you would touch." (180) = td11 + fd4 + we	I. Wool is good for keeping things hot because "wool is sort of thick… so it would keep the hot things hot, it would absorb the… heat energy from the hot object and keep it warm." Wool is poor for keeping things cold because "it's so thick… it's like if you put a blanket over you when you're cold, and you… start to feel warmer after a while." (194–196) = td19 + ic3 + id5 + id9 + id17 + id22 + we I. Styrofoam is a good conductor because "it absorbs more heat." (85) = ID1 + id15 I. Styrofoam "would probably keep… things hot" because "it seems kind of hot right now." Styrofoam would not be good to keep things cold because "the coldness would go right through the little cracks of the Styrofoam." (202–204) = fd4 + ic4 + id3 + id15 + id17 + we I. Objects continue to get hotter than the oven they are in the longer they are there. (45–49) = + td2 I. No distinction made between objects feeling hotter or colder and actually being hotter or colder. (throughout) = fd4 I. Nail is colder because "the coldness of… the ice will have gone through the nail… and it would keep going up and tell it reached [the top]." (154–156) = td18 + fd4 I. Metal gets hotter than wood and both get hotter than the oven because metal absorbs more heat—"I don't know but metal can get hot… and I can't picture wood is getting that hot." (46–47) = + td1 + td11 + ID2 I. Aluminum can be used to keep cold things cold because "it holds the cold energy in… the soda" and it would keep hot things hot because "it keeps the hot energy in the [soda]." (34) = td18 + id12 I. "I… initially thought that aluminum was a good… conductor, but then we did an experiment and it wasn't that good of an um conductor so… I don't know [what a good insulator is]." (95–97) = id16 + id24 + wl

TABLE 7 (*Continued*)

10th Grade—Interview 6: Longitudinal Follow-Up	*12th Grade—Interview 7: Longitudinal Follow-Up*
IV.	IV.
III. Teacher says that objects in same room are the same temperature, but feel different. (57) = tb1 + fb5 + wt III. Objects in ski cabin are "the same temperature, [even though] this one feels hotter than the other… I'd say it's always going to be the same." (118–122) = tb1 + fb5	III. Wool is a "good insulator" because "jackets and stuff are made out of wool and they are used to like keep you warm." (163–165) = ib2 + we
II. Leo says that you can feel the warmth of a hot object through aluminum foil, but doesn't have an explanation because "I've never done it so I'm not sure." (77–82) = fc4 + fd3 + we II. Metal and wood feel different when they are the same temperature because they are different materials—wood absorbs heat or temperature in a different way than metal does. (62–63) = fb5 + fd11	II. Leo is unclear about insulators and conductors, but thinks that an insulator "keeps heat in better." (149) = id3 II. Metal objects are the temperature of the oven, and other objects are a little lower than that even after days. (119–123) = tb1 + td11 II. If you don't wrap an object in something to keep it from emitting cold air or taking cold air in, it becomes the temperature of the room. (47–51) = tb1 + id3 + id6 II. Big block of ice in a freezer is the same temperature as the freezer, but the smaller block is warmer "because since [the big block is] bigger it's got more… cold energy or cold air." (65–73) = tb1 + td5 + td18 + td20 + id6
I. Wrapping a soda can in aluminum foil is the best way to keep it cold. (13) = id12 I. Leo never uses terminology such as "conductor" or "insulator" throughout the interview. (throughout) = id24 I. Metal objects would be hotter than wooden objects, but has no explanation (116) = td1 I. If you touch an ice cube with a metal nail, the end that's touching the ice might be um just a little colder than the top of the nail, since it's touching the ice" but the end near your hand would "probably just be the same temperature that it started out with." (138–142) = fd5 + id25 I. Aluminum foil will allow some heat energy to escape from a hot object, "but maybe not as much as with other materials that you could use." (100–102) = id12 I. Aluminum foil "absorbs the heat from the object… and so it keeps it, and so it's able to keep it hot because of the energy" because of the energy it has absorbed. (84–88) = td19 + id12 + id17 I. A sealed plastic bag will let less heat escape than a sealed paper bag "because there might be… real tiny holes in the paper bag that um that the heat could go though." (104) = id3	I. Wool would keep hot bread warm because it would "keep it like humid inside the wool… just like when you put a sheet over your head and it starts getting hot under there… nothing could get into it and nothing could get out of it." (21–27) = id3 + id6 + id9 + we I. Metal objects get colder than other objects at room temperature. (199) = td1 I. If you wrap a soda can in wool it will get hotter because "nothing would be able to get into it, no like cold air would be able to go out, nothing would be able to come in, so would probably be… really warm." (12–15) = id3 + id6 + id9 I. If you wrap a soda can in Styrofoam the coldness "would probably like leak through, there's like little holes… in the Styrofoam and it with the through the holes in the Styrofoam. So it wouldn't keep it as cold." (13) = td18 + id3 + id15 I. I know that the metal is hotter in the oven than the glass "from experience… I find just from like touching… I'd be able to tell which one was colder." (143–147) = td5 + fd4 + we I. Aluminum foil is good for keeping things cold because "the cold or the molecules… will stay in the can… [and] the cold that… the soda gives off will like stay in the aluminum foil and keep it cold." (5–7) = tc7 + td19 + id12 + id13

text-dependent contradictory ideas through the early interviews, but unlike Luis and Leo, they later refined unorganized concepts to achieve normative, integrated understandings. Even the highly successful students, though not the focus here, expressed multiple contradictory ideas in the first few interviews before achieving the nuanced and integrated understandings shown in Figures 3–6. For all students, during these periods of multiple contradictory ideas, not only were multiple ideas present in a given interview, but this pattern of multiple ideas persisted for several interviews, showing that these competing ideas were coexisting or oscillating in terms of relative prominence.

Luis. Students expressed multiple contradictory ideas in explanations involving thermal equilibrium connected to how objects feel. For example, at one point in his third interview, Luis declared that *metal objects in the oven will be the same temperature as the oven*. At another point in the interview he decided that the *metal objects will be "hotter than the other things [glass beakers and asbestos]" and "hotter than the oven … because metal's a good insulator. … That means it could heat up easier and it would … be slower to cool*." Luis continued throughout his interviews to maintain that metal and wood objects become the same temperature in an environment and that metal objects become a more extreme temperature.

The different contexts provided by different interview questions seemed to influence Luis's assertions. In the sixth interview, Luis said that *wood and metal objects in a hot trunk "probably would be the same temperature. Maybe the metal one's slightly higher. [They become the same temperature] because they're in the same temperature area*." In the same interview, however, in the context of objects in a warm oven, Luis predicted that *wood will be warm but not as warm as the oven because "it only takes in a little heat." The metal in the same oven "would definitely be way hotter than maybe even the oven sometimes* … because energy keeps on coming in and out of it." Further support for the role of context in cueing ideas is demonstrated when Luis was asked how the wood and metal objects will feel in a hot car trunk. Luis changed his earlier prediction and stated that "the metal would be hotter. Maybe way hotter than um, maybe a lot hotter than the inside of the trunk and the wood" whereas the "wood would probably be, probably be, probably the same temperature as the trunk, if it's not very hot."

Luis apparently added several ideas from school to his experiential knowledge but did not resolve the contradictions among all of these ideas. Instead, the ideas that he expressed seemed dependent on the interview question's context. Throughout Luis's interviews were ideas suggesting that objects should become the same temperature in the same environment, as well as many statements suggesting that objects will actually be different temperatures. The former, based on similarities in syntax between his explanations and the class-taught principles, were apparently from school instruction, and the latter from experiential knowledge, as supported by Luis's statement in the seventh interview that metal objects in a ski cabin *"would probably go a little below room temperature, you know like the cool metal feel."*

Felipe. Similarly to Luis, Felipe declared in the second interview that *a metal object in a hot car trunk will actually become hotter than a wood object*. The metal object will therefore feel hotter "because it conducts the heat more easily so there would be like more heat, like in it, kinda." In the same interview, however, Felipe also said that *metal and wood objects in the trunk are "probably both the same temperature* but when you touch the metal it's a good conductor so the heat goes from the metal into your hand, but it doesn't happen with the wood so you can't feel it as much."

Felipe apparently recognized the conflict between his ideas. He tried to verbally reconcile the two positions, and he did not express satisfaction with any of the solutions that he proposed when pressed by the interviewer in terms of this conflict. He continued, however, to express both ideas over the next two interviews. In the third interview, Felipe said that *glass doesn't get to the temperature of the oven,* "because it doesn't conduct heat well. I mean it conducts it—or, it'd feel, um I don't know like a potato has a lot of water in it and so it doesn't get to too high a temperature." But in the same third interview, Felipe said that two different-sized glass beakers

> have different heat energy levels, different amounts of heat energy but I think *they'd be the same temperature* because they're like close to the same surroundings. … [The bigger one] has more, I mean it has more space to have more. Like a big tub of hot water would have more heat energy than a cup of hot water.

In the fourth interview, in the context of objects in a freezer, Felipe said that *"everything in there would come to the same temperatures as the surroundings*, but since they are different materials, it might conduct heat through differently, so it happens at different rates." He also stated the reverse, saying that *"wood doesn't absorb as much heat in the oven—metal gets hotter* because metal conducts heat energy better." Felipe at the time of the third interview appeared to be in transition. Context appears to drive the inconsistency in the ideas expressed.

By the fifth interview, Felipe's explanations became consistent in suggesting that objects in the same environment become the same temperature over time unless the objects produce their own heat energy. From this interview forward, Felipe arguably achieved a theory-like understanding because of his ability to consistently predict the behavior of the objects in multiple contexts. Nonetheless, Felipe maintained and expressed multiple contradictory ideas about thermal equilibrium during the four preceding interviews.

Leo. In the second interview, Leo began with contradictions in his thermal equilibrium explanations similar to Felipe's. He said at one point that *objects in a room would*

> probably be the same [temperature] because, well this one thing that we did in class where we touched the leg of our table and Mr. K said that it's the room temperature, and it didn't seem like it was, but if he said it was, then I guess it was, so then I think that it'd be the same temperature as the room. All the pots and pans and stuff.

Leo later pursued a contradictory line of thinking in the context of wood and metal objects left in a hot car trunk. He explained that "the *wood wouldn't be as hot [a temperature] as the metal* because the metal would, would absorb more heat, I don't know why, but it just makes sense." In the fourth interview, he said that the teacher "said it was room temperature. It seemed colder than room temperature, but I guess *it was room temperature* even though it felt colder." Later in the fourth interview, Leo said that "*wood would not be as cold as the rest of the things* because whenever you touch the wood, it doesn't seem as cold as the other things that you would touch." Even 2 years later, during the sixth interview, Leo continued the contradictions. At one point he said that the teacher said that *"they're all the same temperature in there*, but they just don't feel like they're the same. Um … like if you touch it it feels different than another." Later in the same interview he said that *metal objects would be hotter than wood objects* in a hot car trunk.

Forrest. As with the other three students, Forrest showed a pattern of multiple contradictory ideas in terms of the relationship between thermal equilibrium and how objects feel. Forrest most closely resembled Felipe, displaying these contradictions during his second, third, and fourth interviews before moving to an integrated and coherent set of explanations. In the second interview, Forrest said that *metal and glass objects in a cold cabin will be below room temperature* "'cause some objects like feel colder than others." Later in the same interview Forrest said that *metal and wood objects in a hot car trunk will "probably be the same" temperature*. But when confronted with explaining why the metal feels hotter, Forrest said that *the metal actually is hotter* "'cause it like changes temperature quickly, or more quicker and it's just um … it can, it changes temperature and it's just hotter."

Forrest maintained similar contradictory positions during the third interview, and these positions became even more intricate during the fourth interview. Forrest stated at one point that a *"metal bowl would be warmer [in the oven] than the wood [bowl]* because metal is good conductor and wood is not. And wood is a, is a poor insulator." In fact, the *metal object will be "probably like a little above" the temperature of the oven while the wood object would be "cooler than [the oven]."* Later in the same context Forrest stated that because metal is

> a good um conductor that would make it get really hot fast, faster than the wood but um … I see cause it wouldn't get warmer than 40° because it couldn't … the light in the oven wouldn't make it warmer than 40° because that's hot as it gets and there's no other thing in the oven that'll make it get warmer.

When asked to clarify why he thought that the metal will get hotter, Forrest said, "Well cause um, cause I just thought that metal might feel hotter than the uh wood."

As with Felipe, Forrest proceeded in the fifth interview to express a refined and integrated understanding of thermal equilibrium and related ideas; but the fact remains, through the second, third, and fourth interviews, Forrest continued to express a set of mutually contradictory ideas depending on the interview question context—that is, sometimes objects will become the same temperature and sometimes not. As suggested by Forrest's final quotation in the last paragraph, the ideas that Forrest expressed during the early interviews seemed particularly dependent on what experiential knowledge was cued by the context framed by the question in terms of how he thought the objects should feel.

Summary: Multiple contradictory ideas. For all of the case-study students, one can see extended periods during which the students expressed multiple contradictory ideas in their explanations depending on interview question context. The examples here focused on whether objects will become the same temperature or remain different. The expression of these multiple contradictory ideas across several interviews suggests that the students maintained a collection of independent ideas rather than one cohesive, theory-like perspective. This situation persisted for some students throughout their CLP experiences, whereas for others it eventually progressed to an integrated, cohesive, theory-like understanding. Context apparently played a significant role in cueing these multiple contradictory ideas. Asking students about "placing two items of different material in a warm 40° Celsius environment" cued different ideas and explanations than did asking them about "placing a wood and a metal spoon in a warm 40° Celsius oven," perhaps because the latter example cued specific experiential knowledge related to the objects, materials, and location. Furthermore, students may have considered two contexts as totally different and therefore considered information from one context irrelevant or inapplicable to the other context (e.g., students may have considered a warm oven and a hot car trunk of the same temperature as entirely unrelated thermal contexts). For all of the students and examples given here, it appears that contexts that cued students' experiential knowledge about how objects feel were particularly likely to elicit a contradictory mix of ideas related to the temperatures of the objects. Note that it was possible for students to express coherent, consistent nonnormative understandings across contexts but that none of the four students demonstrated this type of understanding in their transcripts. This issue is considered further in the implications and conclusions section.

Commonality 2: Disruptive Experientially Supported Ideas

Related to the discussion of multiple contradictory ideas is the fact that students maintained certain ideas supported by experience that disrupted conflicting school-instructed ideas. “Objects that feel different are different temperatures” is one such idea that is involved in the aforementioned examples. Some of these ideas are common across several or all of the students, but others are idiosyncratic. Sometimes the students could express these ideas explicitly, but these ideas were often implied by their predictions in a manner similar to diSessa’s p-prims (1993). Some of these ideas applied to specific contexts, whereas others applied generally. Examples of these common disruptive ideas include the following:

1. Wrapping a cold soda in aluminum foil is the best way to keep it cold. (The parents of many students wrap their sodas in aluminum foil to keep them cold, and therefore many students believe that this is the best way to keep a soda cold.)
2. Wool actively warms things up. (Because students have the experience of getting warmer when they wear wool clothing, they believe that wool will actively make other things warmer.)
3. Insulators are barriers, or they need to be airtight to be effective.
4. Coleman coolers only keep things cold, not hot.
5. If something feels hotter or colder, then it actually must be hotter or colder.
6. Insulators do not ever reach equilibrium temperature (because they do not ever feel hot or cold).
7. Better conductors conduct more cold and so get colder (because they feel colder).
8. Metals attract heat (because they feel hotter).

All of these ideas seem related to students’ experientially supported knowledge, sometimes with school ideas or terminology mixed in. The first four ideas involve properties of insulators with which students have had frequent direct experience. Students have probably never wrapped a cold soda in wool, but students have worn wool clothing. Whenever the students wear wool, it keeps them warm. Initially, all of the students in this study explained that “wool warms things up” rather than “wool is an insulator and slows down the flow of heat energy in or out of an object.” This seems to be a direct result of their experientially supported knowledge about wool. The students’ ideas about “wool warming things up” eventually became connected to the label “insulator” in their explanations. This set of ideas actively conflicted with the school-instructed ideas about insulators. An interesting question for future work involves the issue of whether ideas such as "warm wool" are part of a larger theory-like understanding or are simply an independent causal element similar to a p-prim.

Leo. Leo began the first interview by saying that if you wrapped a cold soda in wool, "it would probably … warm up … because um, because … *wool is so thick that it would … make heat and it would make the soda hot.*" These "warm wool" explanations appeared throughout Leo's interviews.

Similarly, the students have seen aluminum foil wrapped around cold sodas. Students inappropriately connected ideas about conductivity and metal to this personal experience in their explanations about conductors. In the same vein, Coleman coolers, thermoses, and foam soda sleeves supported students' ideas that insulators are barriers and need to be airtight. These ideas about insulators stood in the way of students correctly connecting *insulation* and *conduction* as terms describing a continuum of thermal conductivity. Rather, *insulation* and *conduction* remained overly differentiated nonoverlapping categories with distinct properties.

Felipe. Felipe provided examples of the connection between barrier ideas and personal experience in the first interview. He said that aluminum foil is good to keep a soda cold because "it insulates the coldness. … It keeps it in. Yeah, like keep it in." He also explained that foam sleeves are good because "they're like really solid, thick, and they wouldn't sell them if it didn't work." He explained that wool "might [not work] 'cause we wear wool to keep warm, but I just never thought of that … I don't … maybe … I tend to think that aluminum might work better, but I'm not sure." When asked why the aluminum foil is more useful, Felipe said that *"wool is like some like thick and some, you know, it's thinner, and like air can get through it more easily, you know, and that aluminum is more like a block."* Expressing these strongly held experientially supported ideas, Felipe proved resistant to progressing in his understanding of insulation and conduction and in fact expressed related barrier ideas all the way through his final interview, despite all of the progress that he made in other areas of his understanding.

Luis. As with their explanations involving insulators, students' explanations also often referred to experiences suggesting that metal feels warmer or cooler than wood. As a result, students' explanations about thermal equilibrium were apparently compromised because the students inappropriately applied their experientially supported knowledge to mean that something that feels hotter or colder must actually be hotter or colder. As Luis explained, he knew that *a metal object is below room temperature "because I have found it before."* Similarly, in another interview, Luis explained that *metal "would probably go a little below room temperature, you know, like the cool metal feel."* Luis also asserted that a cold soda left out on the table ends up “above room temperature … because um it’s cold and then it gets hotter after eight hours, and it should be hot.” He also asserted that *a cup of hot chocolate would be “below room temperature ’cause it’s hot and after eight hours it will get cold.”*

Forrest. Whereas Leo explained that he knows that metal is hotter in an oven than glass from experience (“I find just from like touching … I’d be able to tell which one was colder”), Forrest initially took the reverse position in the third and fourth interviews, saying that metal and wood objects in an oven should be the same temperature and that they should therefore “feel the same.” When asked about specific experiences, however, Forrest decided that the metal will feel different and that, therefore, the objects are actually different temperatures.

Summary: Disruptive experientially supported ideas. The idea of “feels hotter, is hotter” is an example of an experientially supported disruptive idea. This idea is apparently connected to several other disruptive ideas, such as the final three ideas in the list of common disruptive ideas cited earlier (Ideas 6, 7, and 8). Because a wooden spoon does not feel warm in an oven and wood is an insulator, insulators must never reach the same temperature as that of metal objects in the oven. As Leo explained in his third interview, asbestos would not be as hot as the other things in the oven, because “I can’t just picture that.” In a similar manner, because the metal feels so much hotter and metals are conductors, conductors must “attract” heat energy. Felipe, Forrest, and Luis all expressed such ideas in their fourth interview, following instruction about insulation and conduction. In all of these cases, students’ experiential knowledge conflicted with school-instructed ideas, and students’ explanations inappropriately emphasized the experiential knowledge. This disruptive experiential knowledge exacerbated the other two problematic commonalities observed, as described in the following section.

Commonality 3: Difficulties in Productively Connecting Added Normative Ideas

Students acquired normative school-instructed ideas during the curriculum but had difficulty connecting these ideas normatively within their existing set of ideas. They did not forget these newly added normative ideas, but rather than make connections, they separated these ideas and contexts.

Leo. One example is Leo’s clearly stated memory of the teacher-led demonstration showing that objects in the room are the same temperature even though they feel different. Starting in the second interview, Leo referred to this demonstration, saying that objects in a cold ski cabin would probably be the same [temperature] because, well this one thing that we did in class where we touched the leg of our table and *Mr. K said that it's the room temperature, and it didn't seem like it was, but if he said it was, then I guess it was, so then I think that it'd be the same temperature as the room.* All the pots and pans and stuff.

Unfortunately, Leo never managed to connect this newly added idea normatively to his other ideas, even though he clearly kept it in his repertoire. He did not reconcile this new idea with his personal experience that objects of certain materials always feel warmer or colder in a given environment. Instead, throughout the rest of his interviews, Leo occasionally referred to this teacher demonstration as a warrant for the idea that objects should be the same temperature, whereas in most other contexts he claimed that objects end up being different temperatures. For example, in his fifth interview Leo predicted that objects

> would all be room temperature because this one time like Mr. K said to touch the leg of our table and it seemed colder than the room temperature but he said it was room temperature and so I, so that's why I think it would be.

Leo added an important idea from class, but simply adding ideas was not sufficient. Students need to reexplain and reconnect their experiential knowledge in a way that allows them to connect their newly added school-instructed ideas normatively to their experiences and other school-instructed ideas. The role of context needs to be considered even more carefully in scaffolding the connections between the added school-instructed ideas and existing experiential knowledge.

Forrest. Forrest was representative in the way that he added school-instructed ideas and generally managed to build connections, albeit sometimes in a disruptive manner. For all four case-study students, adding school-instructed ideas initially resulted in new, idiosyncratic nonnormative explanations. Forrest's explanations in the second and third interviews demonstrated this pattern. In his first interview, Forrest expressed the experiential knowledge that *metal and wood objects in a given environment feel different* from each other. After initial instruction in thermal equilibrium, Forrest's explanations stated that *metal and wood objects in the same environment should become the same temperature*, but then Forrest stated in some explanations that the *metal and wood objects should therefore feel the same*. In reducing local conflict, he temporarily contradicted his experiential knowledge that the metal and wood objects feel different. Forrest's explanations during the next three interviews involved multiple recombinations of these ideas, apparently in an attempt to reduce the conflict created by the addition of school-instructed ideas. By the fifth interview, he finally achieved an understanding that allowed him to consistently express a normative understanding.

Forrest, Felipe, Luis. In the fourth interview, Forrest, Felipe, and Luis all added ideas about insulation and conduction from the instruction that preceded the interview, but all three students made nonnormative connections that disrupted previously normative explanations about thermal equilibrium. Forrest decided that a "metal bowl would be warmer [in the oven] than the wood [bowl] because metal is good conductor and wood is not. And wood is a, is a poor insulator." In fact, Forrest decided that the metal object would be "probably like a little above" the temperature of the oven, whereas the wood object would be "cooler than [the oven]."

In the oven context, Luis said that the temperature of the objects would be "probably different. The metal would be the same and the wood wouldn't [be as hot as the oven]." He went on to explain that after several hours "the metal would be a little hotter than the outside and the wood would probably stay the same." When asked how the metal could get warmer than its surroundings, he said, *"Because they are good conductors … [and so] they gather up heat energy faster."*

In the oven context, Felipe said that "the metal would be hot, and the wood would not. It would be warm. … The wood wouldn't like absorb the heat." When asked if time would make a difference, Felipe replied, "I don't think so. I still think the *metal would be hot … [because] metal conducts heat energy."*

All of these students, particularly Felipe, showed progress in the third interview in terms of thermal equilibrium, but after instruction in insulation and conduction, the students connected their new, school-instructed ideas into their repertoires in a way that supported a nonnormative explanation of thermal equilibrium in the fourth interview. Forrest and Felipe did manage to refine, reorganize, and resolve these new problems by the fifth interview, and there was no inappropriate application of conductivity in the fifth interview, but both students required more instruction and time to achieve this progress.

Summary: Difficulties productively connecting normative ideas. In all of these examples, the students added important ideas from class, but in cases such as these, simply adding ideas was not sufficient. Leo clearly added important ideas from class but did not manage to connect these ideas correctly into his explanations. Forrest, Luis, and Felipe added conductivity ideas before the fourth interview that disrupted previous progress in thermal equilibrium and continued to apply their experiential knowledge in ways that disrupted these newly added school-instructed ideas. These results suggest that when students add school-instructed ideas, they require further support in normatively integrating these ideas with their existing understanding. One possible explanation is that students need more opportunities and active scaffolding to make normative connections between their newly added ideas and their experiences and other school-instructed ideas.

Commonality 4: Pursuing Idiosyncratic Explanations

In some instances, the case-study students developed idiosyncratic ideas and explanations. These efforts reduced the local conflicts caused by the introduction of the school-instructed ideas but did not lead directly to a normative understanding of the subject matter.

Forrest. As discussed, Forrest struggled through his early interview explanations reconciling his school-instructed ideas about thermal equilibrium with his experiential knowledge that metal objects always feel warmer or cooler. Forrest normatively said that the objects should be the same temperature in a given environment, but without sophisticated thermal sensation ideas he oscillated between two nonnormative ideas: the objects are the same temperature and therefore should feel the same, and the objects feel different and must consequently be different temperatures. Rather than using conductivity ideas to normatively connect the ideas that "objects become the same temperature" and that "objects feel different," Forrest gradually developed an idiosyncratic surface explanation.

Forrest expanded and refined this surface explanation over the second, third, fourth, and fifth interviews. This ongoing emphasis suggested that Forrest maintained an interest in (a) reducing the local conflicts that existed between his experiential knowledge and his school-instructed thermal equilibrium ideas and (b) finding an explanation for why objects can be the same temperature but feel different. In the second interview, the surface explanation seemed rather unspecified: Forrest explained that a metal object feels colder *"cause it's, it's made of a, it's like smoother, and it's … solid, more solid."* The emphasis in this explanation was specified only to the level of saying that some property of the material makes it feel hotter or colder even though it is the same temperature. Over the third and fourth interviews, Forrest refined and expanded this idea to the point that his explanation was intricate in the fifth interview. When asked if two objects can be the same temperature and feel different, Forrest said yes because "maybe they're different surfaces, and one can be like smooth and the other one can be rough or soft or hard." When asked to elaborate, Forrest answered, "Um, the smooth one would probably feel a little warmer … 'cause when you touch it, there's more that you feel, 'cause rough is like you don't feel the whole thing." This explanation contains definite normative elements in terms of contact area. Even though Forrest worked to build mechanisms to reduce conflict between his personal experience and school-instructed ideas, he pursued a tangent (surface texture) with less explanatory power in terms of normatively integrating his school-instructed ideas with his experientially supported ideas. Furthermore, his personal surface theory did not explain the most important causes of the phenomenon that he was trying to reconcile with his other ideas.

Felipe. In spite of his respectable progress, Felipe pursued an idiosyncratic tangent about insulation. In the third interview, Felipe began to express a barrier idea for insulation, suggesting that wool will work better if it is tightly knit rather than loosely knit. When asked how well wool works to keep things warm, Felipe asks,

> Is it like the knit kind, so it covers or is it like porous? … 'Cause I mean I think if it was porous and stuff … heat, and or like heat energy could go through. But if it was like tightly knit, you know, so then I think it would be better.

Felipe continued to express similar explanations throughout his remaining interviews. In his final interview before his 12th-grade year, Felipe explained that insulators are *"like a blocker. You know, like stop."* This explanation is relatively functional in terms of the performance of insulating materials but is certainly not optimal. The blocker element of this explanation invites comparisons to materials like aluminum foil or plastic wrap, that are relatively airtight but not efficient insulators.

Leo. Leo followed a similar idiosyncratic tangent about insulators as blockers. In the fourth interview, Leo explained that objects will stay warm when wrapped in metal because "there's no air holes or anything, then there is no way the hot air could get out and it would stay hot." In the same interview, when Leo was asked if Styrofoam would work to keep a casserole warm, Leo said no because "there could be little holes in the Styrofoam that the heat could escape through." Leo continued to pursue and develop this explanation throughout the rest of his remaining interviews. In his final interview, Leo chose aluminum foil to keep a cold soda cold because

> the cold or the molecules or whatever will stay in the can, or like the cold that they um, that the um soda gives off will like stay in the aluminum foil and keep it cold, like when it's in the fridge or whatever. So um, I don't know … probably because um, just keeps it, the coldness of the drink in the confines of the soda can.

When asked about Styrofoam, he explained that "the cold air" would "probably like leak through, there's like little holes in the, in the Styrofoam and it would leak through the holes in the Styrofoam. So it wouldn't keep it as cold."

Luis. Luis pursued an unintended tangent across his interviews, focusing primarily on insulators "storing" heat energy. Luis explained in the third interview that *an insulator is "something that can store. … It would get hotter and hotter"* if you put it in something hot. Luis continued to refer to this idea of insulators storing heat energy throughout the rest of his interviews, and some of the explanations became much more elaborate. For example, in the fifth interview, Luis explained that metal objects are warmer than the oven and that wood objects are cooler because "metal can take heat energy easier than the wood. Wood would just take some and then stop … when the heat energy is completely stored in there, like when you fill up a car." Through this process, Luis actively developed an idiosyncratic explanation for insulation that became increasingly elaborate and apparently disruptive to his school-instructed ideas.

Summary: Pursuing idiosyncratic explanations. All of these examples illustrate how the case-study students developed idiosyncratic explanations that connected their experiential knowledge to their school-instructed ideas in nonnormative ways. These efforts reduced the local conflicts caused by the introduction of the school-instructed ideas but did not lead directly to a normative understanding of the subject matter. Without guidance, students might have indefinitely continued to make idiosyncratic connections. In addition to helping students reexplain their experiential knowledge so that they normatively connect it to their school-instructed ideas, educators need to support students in building critical connections and explanations by helping them focus on the connections that are actually critical. Once they have these critical connections and ideas integrated into their understanding, they will be able to connect other experiences and instructed ideas into their frameworks in more productive and meaningful ways.

Summary of Conclusions From the Analysis of the Case-Study Students' Explanations

In summary, the analysis of the four case-study students' explanations suggests that the four students share several commonalities in their explanations across the interviews.

Multiple contradictory ideas. There were extended periods during which all of the case-study students expressed multiple contradictory ideas in their explanations depending on interview question context. The expression of these multiple contradictory ideas across several interviews suggests that the students were maintaining sets of independent ideas rather than cohesive, theory-like perspectives. This situation persisted for some students throughout high school, whereas other students eventually progressed to an integrated normative understanding. Note that students might theoretically express coherent, nonnormative, theory-like understanding across contexts, but this was not evident for these case-study students. There was consistency over time in specific contexts, but these contexts seemed too narrow to represent the domain of theory-like understandings. Context apparently played a significant role in fostering and cueing these multiple contradictory ideas. Students may have considered two contexts as being totally different or incommensurate and therefore considered information from one context irrelevant or inapplicable to the other context. For many of the examples discussed, it appeared that contexts that cued students' experiential knowledge about how objects feel were particularly likely to elicit a contradictory mix of normative and nonnormative ideas.

Disruptive experientially supported ideas. In most of these cases, students' experiential knowledge conflicted with school-instructed ideas, and students' explanations inappropriately emphasized their experiential knowledge. Apparently, students' disruptive experientially based ideas were often the source of the multiple contradictory ideas. Furthermore, this disruptive experiential knowledge exacerbated the other two problematic commonalities observed, as elaborated in the discussion of the third commonality (difficulties productively connecting normative ideas) and the fourth commonality (pursuing idiosyncratic explanations).

Difficulties productively connecting normative ideas. As demonstrated by the third commonality, although important ideas from class were added by all of the case-study students, students applied their experiential knowledge in ways that disrupted these newly added school-instructed ideas. Some students, as exemplified by Leo, clearly added important ideas from class but did not manage to connect some of these ideas into their explanations at all. These findings have ramifications for conceptual change research and refinements to the curriculum.

Pursuing idiosyncratic explanations. Finally, as demonstrated in the discussion of the fourth conclusion, all of case-study students expend significant effort over time developing idiosyncratic explanations that connect their experiential knowledge to their school-instructed ideas in a way that allows them to hold on to their often nonnormative interpretations. Therefore, in addition to helping students re-explain their experiential knowledge so that they might normatively connect it to support the school-instructed ideas, we need to support students in focusing on the connections that are actually critical.

ANALYSIS OF INDIVIDUAL ELEMENTS WITHIN THE CASE-STUDY STUDENTS' EXPLANATIONS

This level of analysis considers the case-study students in light of the individual elements within their explanations. The analysis focuses on element maps, which code the explanations included in the explanation maps directly into the elements that represent main ideas within those explanations. In other words, the element maps look at the same explanations included in the explanation maps but break the explanations into their constituent ideas. The purpose of the element maps is to identify the specific connections that each student made over time (see Figures 9–12). The first letter of each code signifies a topic area (T = thermal equilibrium; I = insulation and conduction; F = "feel," or thermal sensation). The second letter signifies sophistication (B = normative, C = transitional, D = nonnormative). Lowercase letters indicate weak or specific application in student's explanation; uppercase letters indicate a strong or general statement. These elements are placed within columns by sophistication into the top, middle, and bottom regions in a manner similar to that used in the explanation maps. A solid black line connects all elements coded from a single condensed explanation to show that they are part of one explanation (for keys to these ideas and codes, see Figure 2, Table 3, and Tables 8–10; for more details and examples of the coding from the interviews, see Appendix B). Note that the regions of the element map represent the normativity of the individual component ideas rather than the normativity of the explanation as a whole. Therefore, no separate *nuanced* region appears in the element maps, because *nuanced* in this study is defined as the connection of multiple normative ideas.

Fundamental Trends for Each Case-Study Student

The analysis first looks for fundamental trends within each student's interviews. The analysis next considers the specific ideas consistently expressed by the students. These fundamental trends reveal patterns in students' conceptual restructuring paths. It is important to remember that the explanation maps (from which the element maps are derived) represent the range of explanations expressed by students and not necessarily the frequency of those explanations. The element maps therefore also represent range rather than frequency. Tables 11 and 12 provide compiled statistics from Figures 9–12 for each student in terms of the number of distinct topics and elements involved in the explanations at each interview.

Forrest. In terms of Table 11, one can see that, over time, Forrest incorporated an increasing number of distinct normative elements at each interview. Interestingly, the number of distinct nonnormative elements also increased for Interviews 2–4 before dropping again to Interview 1 levels in Interviews 5 and 6. One can also see in Table 11 that he added a large number of normative thermal equilibrium and insulation conduction elements in Interviews 3 and 4 (symbols "T" and "I" in the explanation maps). Finally, the thermal sensation topic remained challenging for him through the final interviews (symbol "F" in the element maps).

From Forrest's element map (Figure 9) and Table 12, one can see that in the first interview, he initially connected only a few ideas together in each explanation and that these ideas tended to be of the same topic area (i.e., thermal equilibrium ideas with thermal equilibrium ideas, sensation ideas with sensation ideas, or insulation and conduction ideas with insulation and conduction ideas). As described earlier

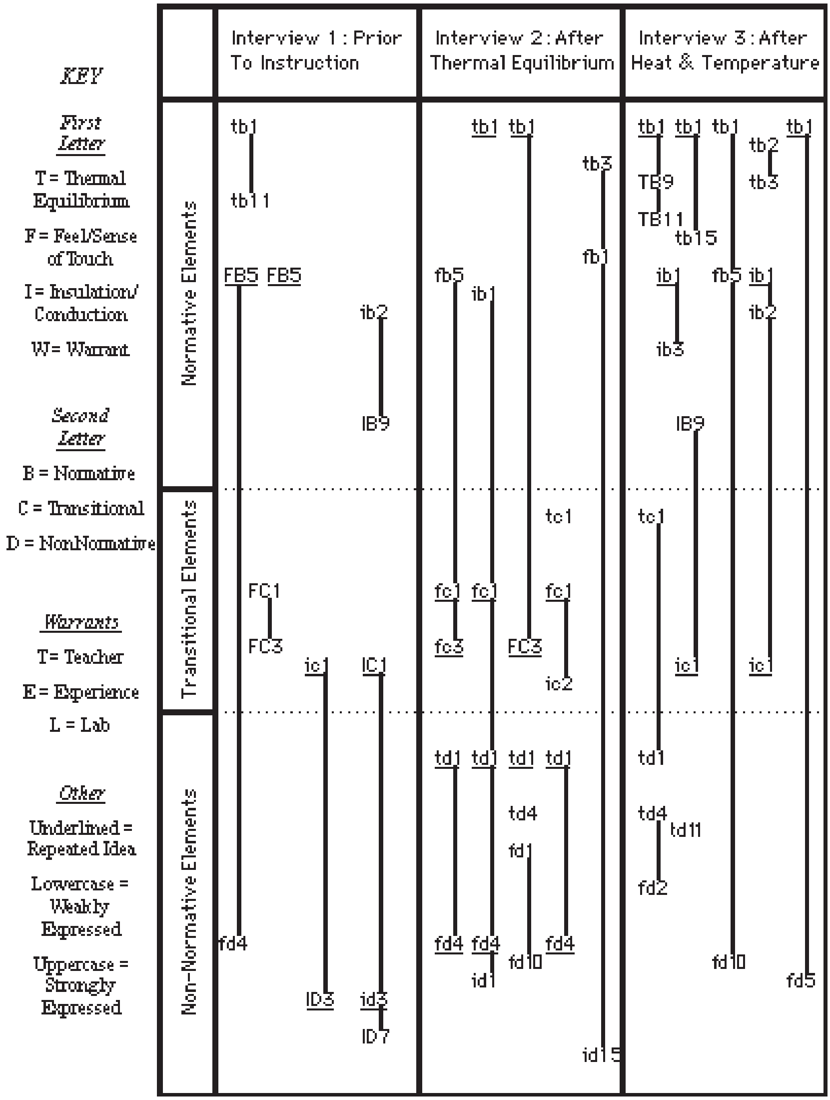

FIGURE 9 Element map for Forrest (fairly successful).

and in the appendixes, *connecting* means connecting multiple ideas within a single explanation. The element maps represent this graphically by connecting codes for multiple elements with black lines.

By the second interview, Forrest started connecting ideas across topics (i.e., thermal equilibrium ideas with insulation and conduction ideas) in his explanations, but

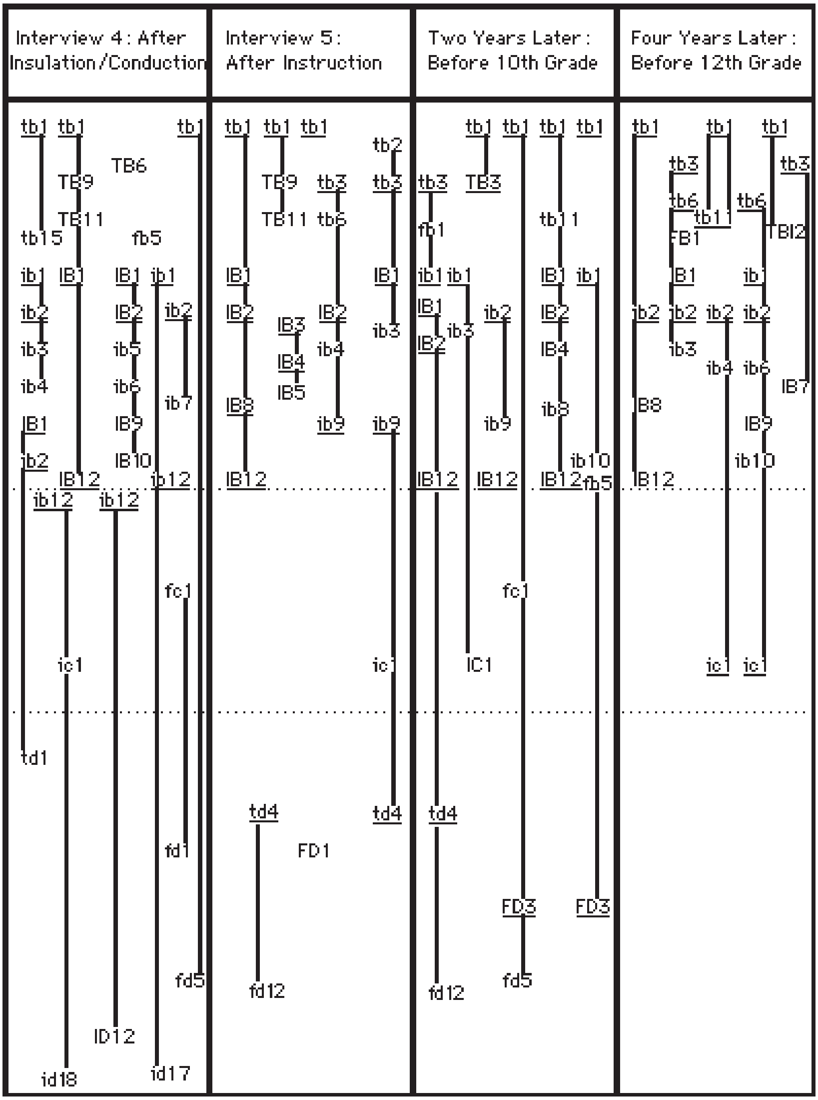

FIGURE 9 *Continued.*

these explanations predominantly involved nonnormative ideas and connections. Graphically, connecting ideas across topics involves the connection of codes beginning with different letters (i.e., thermal equilibrium = T, insulation/conduction = I, and sensation/feel = F). The second letter in an element's code represents its normativity (i.e., normative = B, transitional = C, and non-normative = D). By the

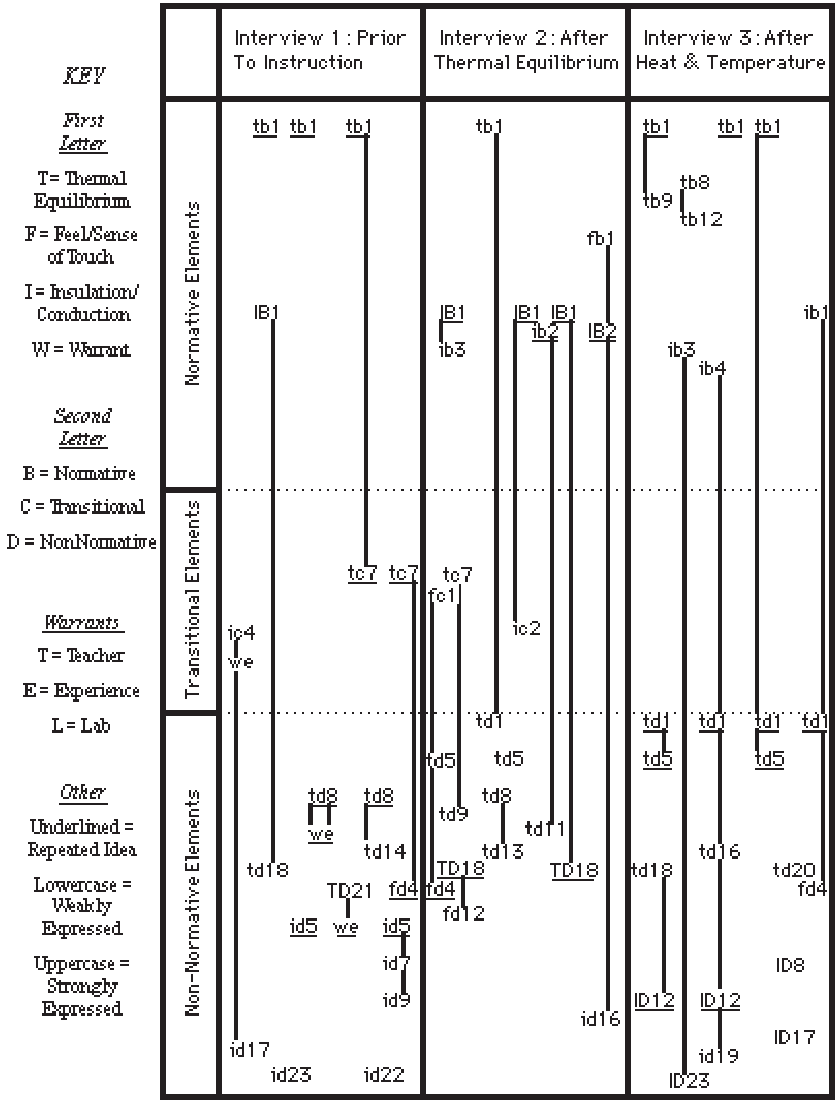

FIGURE 10 Element map for Luis (less successful).

third interview, Forrest could connect multiple normative insulation and conduction ideas or multiple normative thermal equilibrium ideas, but he still did not connect normative ideas from two different topic areas. In Interview 5, Forrest began to connect larger normative chains of ideas with a mix of insulation and conduction and thermal equilibrium ideas. These explanations involving the connection of multiple

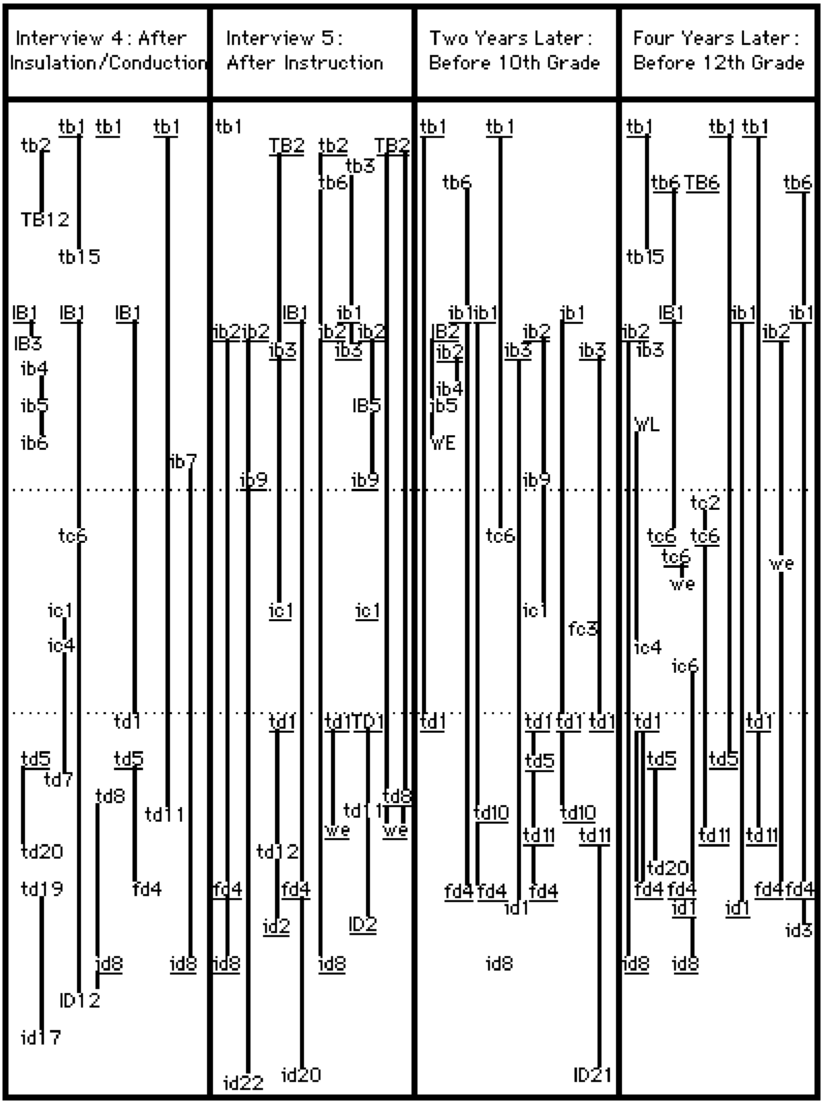

FIGURE 10 *Continued.*

normative ideas from multiple topic areas represent the nuanced explanations in the explanation maps. However, Forrest never really connected insulation and conduction ideas to thermal sensation ideas until Interview 6, except one time in the second interview. When Forrest did connect thermal sensation ideas in his explanations, he connected nonnormative thermal sensation ideas to normative thermal equilibrium

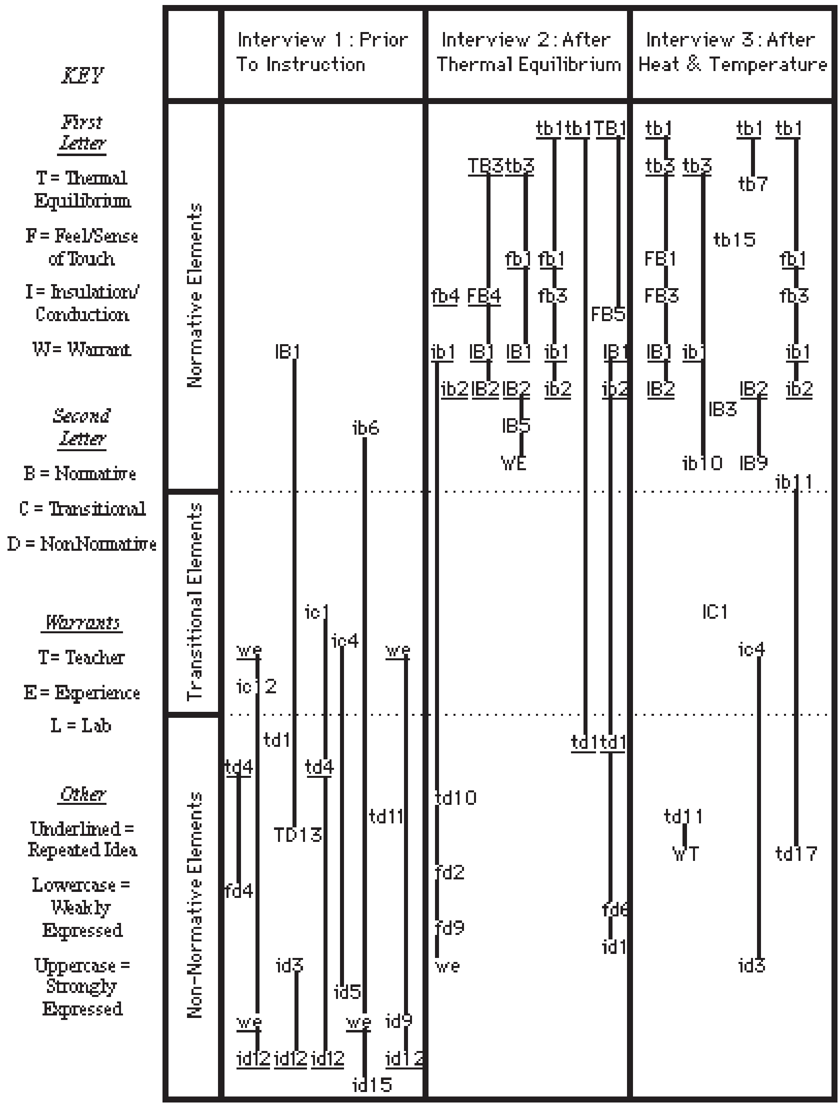

FIGURE 11 Element map for Felipe (fairly successful).

ideas, or normative thermal sensation ideas to nonnormative thermal equilibrium ideas.

It was not until Interview 7 that Forrest was able to integrate thermal sensation ideas normatively with his insulation and conduction and thermal equilibrium ideas. In this seventh interview, there were the beginnings of an integrated under-

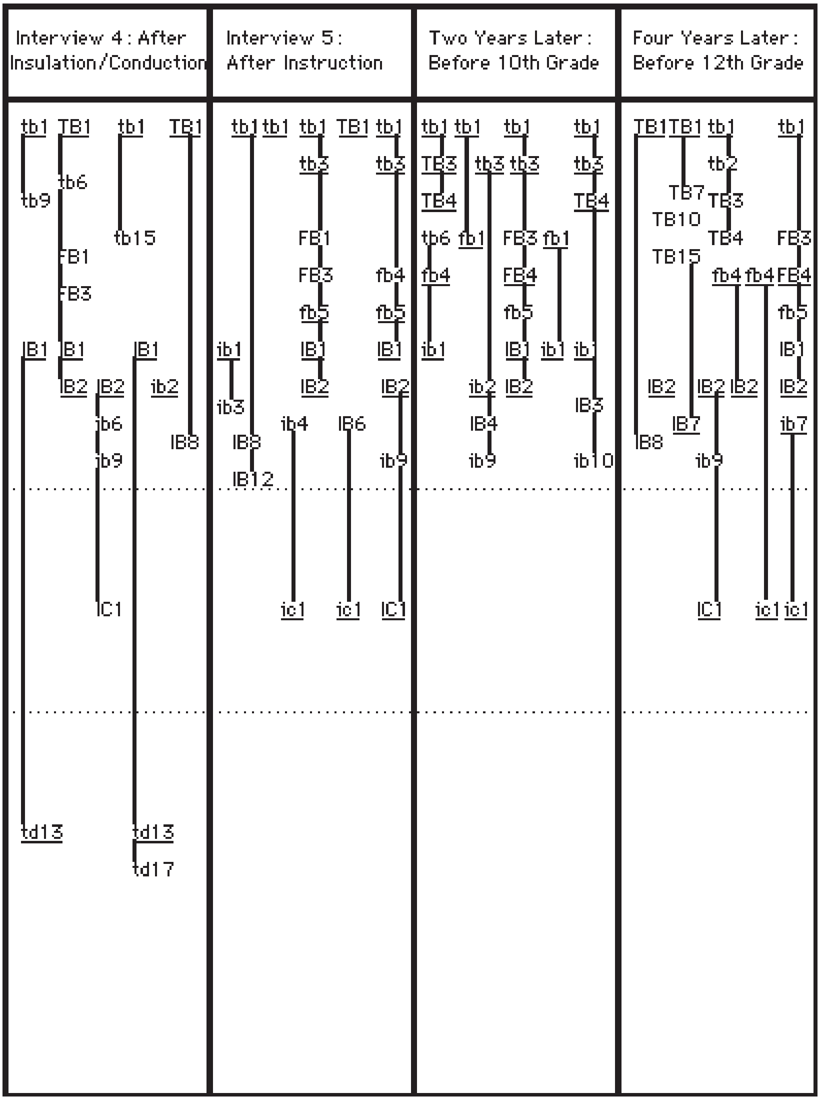

FIGURE 11 *Continued.*

standing of the three thermodynamics topics, as evidenced by his ability to integrate multiple normative ideas from all three topic areas into one explanation. For example, tb3 + tb6 + FB1 + IB1 + ib2 + ib3 represents the three topic areas, all of which are inside the normative region of the far right column that represents the seventh interview. In the explanation map, this code represents the following: "IV.

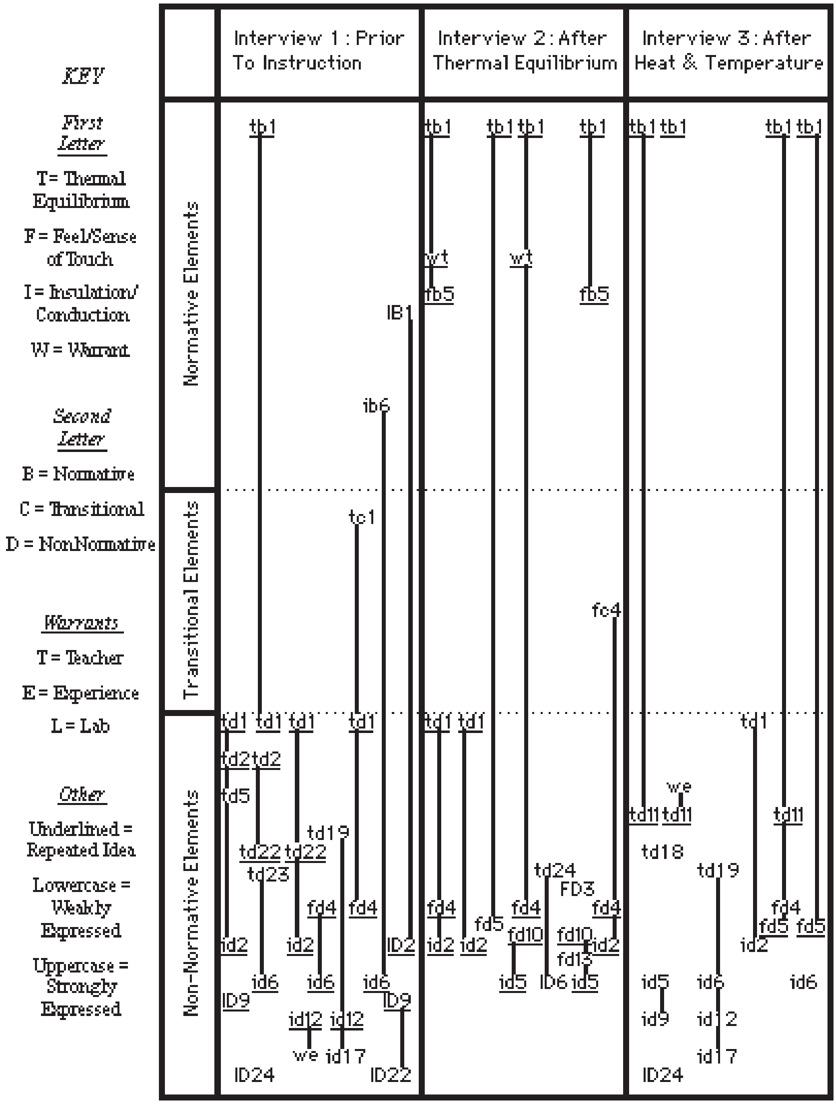

FIGURE 12 Element map for Leo (less successful).

Metal object feels hotter because it's a better conductor and the heat energy can escape into your fingers faster than through the wood."

Luis. Luis, like Forrest, began the first interview by connecting no more than two ideas in one explanation (Figure 10 and Tables 11 and 12). As with

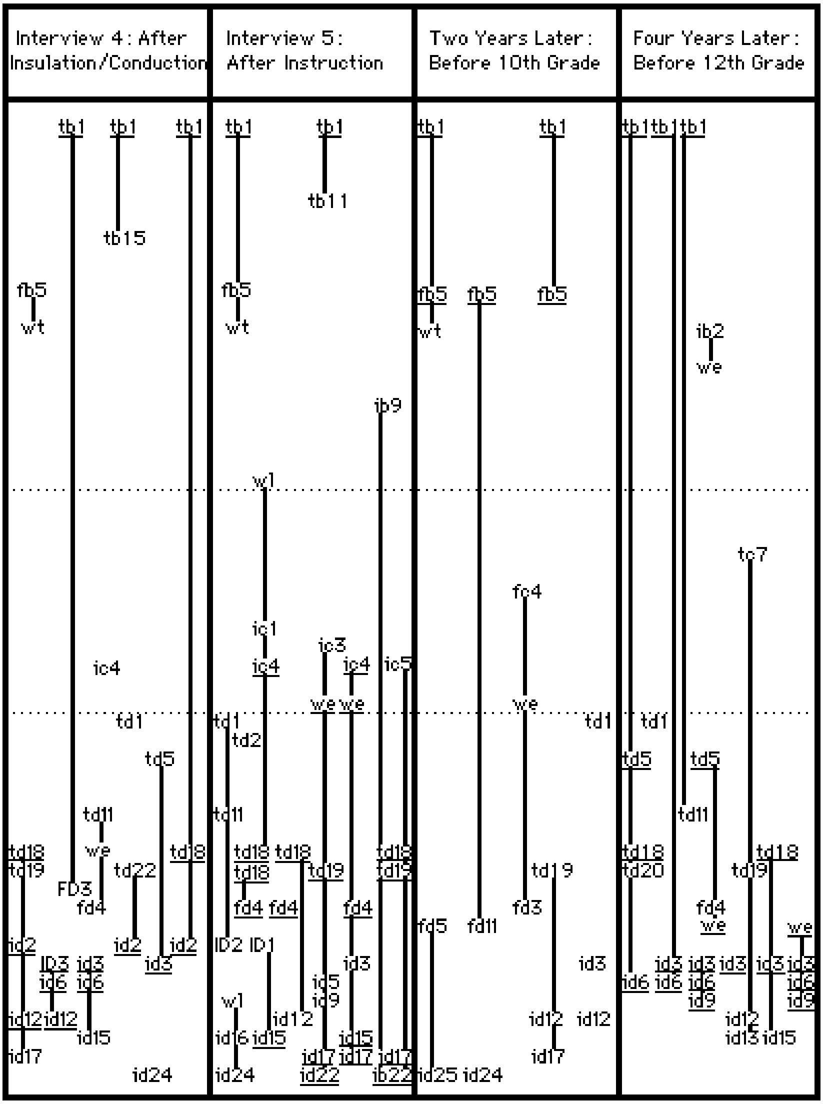

FIGURE 12 *Continued.*

Forrest, each explanation usually consisted of ideas from only one topic area. In the second interview, new normative ideas appeared in Luis's explanations, and Luis was beginning to connect insulation and conduction ideas to thermal equilibrium ideas, albeit nonnormatively—(e.g., IB1 + ic2 + td8 + td13, which represents the following explanation map entry: "II. Metal gets warmer than wood be-

TABLE 8
Coding Key for Element Maps—Thermal Equilibrium

Thermal equilibrium normative ideas	
TB1	Objects in same room become same temperature/Objects eventually become same temperature/Objects in same surround become same temperature
TB2	If more heat flows into an object than out of it, its temperature rises (or reverse)
TB3	Heat energy flows from hot to cold object to warm object up
TB4	Heat energy flows until same temperature
TB5	Heat energy flows faster for bigger temperature differences
TB6	Heat energy flows in or out (correct direction)
TB7	Thermal equilibrium the same at all temperatures and locations
TB8	Heat energy leaves hot objects to the room as they cool down.
TB9	Objects don't go beyond equilibrium temperature
TB10	Relates and differentiates diffusion and thermal equilibrium.
TB11	(Same room/same temperature) unless another heat source/produces own heat
TB12	Molecular kinetic model
TB13	Wood/wool/Styrofoam/asbestos object reaches temperature of surrounding
TB14	Metal object reaches temperature of surrounding
TB15	Size/thickness doesn't affect final temperature
Thermal equilibrium transitional ideas	
TC1	All objects in same room reach close temperatures
TC2	Wood or wool or related material not quite to ambient temperature because of time
TC3	Wood/wool/Styrofoam/asbestos object not quite temperature of surrounding ever
TC4	Metal object not quite temperature of surrounding
TC5	Wood/wool/Styrofoam/asbestos object slightly beyond temperature of surrounding
TC6	Metal object slightly beyond temperature of surrounding
TC7	Garbled molecular kinetic model explanation.
Thermal equilibrium nonnormative ideas	
TD1	Metal objects are above/below ambient temperature in extreme direction
TD2	All objects are (end up) above or below ambient temperature in extreme direction
TD3	Wool makes things warm
TD4	Cold energy travels from cold objects to warm objects to cool them down
TD5	Same room different temperatures
TD6	Thermal equilibrium is differentiated process (at different temperatures/locations)
TD7	Circulating air within an object moves heat through the medium
TD8	Objects can go beyond equilibrium
TD9	Objects hold heat differentially inside and on surface
TD11	Wood, ceramics, or wool or related material never reach ambient temperature/Take heat until they fill up and stop/are not as extreme a temperature as the surroundings
TD12	Some objects get more heat in them.
TD10	Cold objects only give off a little heat energy
TD13	Better conductor ultimately gets hotter/colder (more extreme)
TD14	Wood object/(other insulator) gets hotter than metal.
TD15	Wood/Wool go beyond equilibrium temperature in extreme direction while metals don't.
TD16	Differentiates heating and cooling process.
TD17	Poor conductors don't get as much heat energy.
TD18	Cold energy flows out.
TD19	Hot things can give up heat energy without cooling (or reverse).
TD20	Size/thickness affect final temperature.

TABLE 8 (*Continued*)

TD21	Confuses melting/burning with temperature change.
TD22	Objects keep getting hotter past equilibrium temperature the longer they are in a hot place.
TD23	Objects "overshoot" equilibrium temperature slightly as they cool/warm at room temperature.
TD24	Unless something actively keeps an object cold, it will warm up

TABLE 9
Coding Key for Element Maps—Insulation/Conduction

Insulation/conduction normative ideas	
IB1	Metals conduct heat well (are conductors)
IB2	Wood/Wool/Styrofoam is insulator/doesn't conduct well
IB3	Conductors conduct heat energy quickly
IB4	Insulators conduct heat energy slowly
IB5	Good conductor is poor insulator – connects insulation and conduction as related
IB6	Objects that keep cold things cold keep warm things warm (and reverse)
IB7	Appropriate connection of thickness/size to rate of heating/cooling.
IB8	Rate of reaching equilibrium dependent on conductivity/speed at which objects become temperature of surrounding depends on conductivity
IB9	Good insulators keep hot/cold objects hot/cold
IB10	Good conductors don't keep hot/cold objects hot/cold
IB11	Glass is better conductor than wood/wool but not as good as metal
IB12	Conductors heat up faster/insulators heat up slower
Insulation/conduction transitional ideas	
IC1	Insulators "block" or "trap" heat or cold (they are a barrier)
IC2	Metals adjust temperature more quickly (no connection to IC)
IC3	Wood/Wool changes temperature more slowly than metal (no connection to IC)
IC4	Styrofoam/Wool good to keep cold object cold (no connection to IC)
IC5	Aluminum/Metal not good to keep cold object cold (no connection to IC)
IC6	Heat comes in and out of metal quickly at a constant rate.
Insulation/conduction nonnormative ideas	
ID1	Conductors attract heat/take in a lot of heat/keep taking heat
ID2	Metal attracts/absorbs heat better/keeps taking heat. (or cold)
ID3	Materials with holes (porous/density) allow heat/cold to pass through/barrier model for insulation.
ID4	Good conductors/insulators keep heat on surface vs. insulators/conductors keep inside
ID5	Thickness of material alone determines insulating/conducting properties
ID6	Air transmits heat and cold. (or weather/steam)
ID7	Wood/Wool/Paper insulates because of fibers
ID8	Insulators store heat energy/release it slowly/store cold
ID9	Wool warms things up
ID10	Metals insulate because they reflect heat away
ID11	Metals keep things cold because they feel cold
ID12	Aluminum foil (Metal) good to keep object cold/hot (Insulator model)
ID13	Metal gets cold from object and keeps object cold
ID14	Metal conducts heat away from cold object to keep it cold

(*continued*)

TABLE 9 (*Continued*)

ID15	Styrofoam not good to keep cold object cold/hot object hot/is a conductor.
ID16	Switches terminology for insulators/conductors or definitions
ID17	Only cold things can keep cold things cold/hot keeps hot.
ID18	Conductors cool slowly/heat slowly
ID19	Insulators heat quickly/cool quickly
ID20	Conductors lose heat energy.
ID21	Wood/wool/Styrofoam only take in a little heat.
ID22	Materials that keep cold things cold don't keep hot things hot (and reverse).
ID23	Thermal conductivity confused with electrical conductivity.
ID24	Denies knowing anything about insulators or conductors/explanations incoherent.
ID25	Heat (cold) doesn't travel through metal.

TABLE 10
Coding Key for Element Maps—Thermal Sensation/Feel

Thermal sensation/feel normative ideas	
FB1	Heat entering hand makes it feel hot
FB2	Slow flow means doesn't feel strongly
FB3	Faster heat flow feels more strongly
FB4	Heat energy leaving hand feels cold
FB5	Same temperature objects can feel different
Thermal sensation/feel transitional ideas	
FC1	Metals feel cold/hot (more intense than environment)
FC2	Accurate insulators/conductors feel cold/warm but no connection to heat flow
FC3	Wool and wood feel warm or cool (less intense than environment)
FC4	You can feel heat through appropriate material/can't through inappropriate material
Thermal sensation/feel nonnormative ideas	
FD1	Surface characteristics determine feel
FD2	Coolness property of object touches hand
FD3	No mechanism for feeling hot/cold
FD4	Objects feel different because they are different temperatures
FD5	Objects are the same temperature so they must feel the same.
FD6	Object feels hotter because it has more heat energy in it (at point that would be equilibrium – independent of temperature)
FD7	Feels hotter because heat moves through it faster
FD8	Feels hotter because heat is on surface/feels colder because heat is inside
FD9	Only a little heat energy flowing into hand feels cold
FD10	Solidness/density/thickness determine feel.
FD11	Other unified characteristics determine feel
FD12	Cold energy flowing into hand feels cold.
FD13	You can feel heat/cold through inappropriate material/can't through appropriate.

TABLE 11
Number of Distinct Explanation Elements Expressed by Each Case-Study Student in Each Interview in Terms of Total Distinct Elements and Total Distinct Elements by Topic Area

Student	*Element Quality*	*Int 1*	*Int 2*	*Int 3*	*Int 4*	*Int 5*	*Int 6*	*Int 7*
Total Distinct Elements								
Forrest	Normative	5	5	11	16	14	13	16
	Transitional	3	4	2	2	1	2	1
	NonNormative	3	7	6	6	3	4	0
Felipe	Normative	2	9	12	11	14	14	15
	Transitional	3	0	2	1	1	0	1
	NonNormative	10	6	3	2	0	0	0
Luis	Normative	2	5	7	10	9	8	6
	Transitional	2	3	0	3	1	3	4
	NonNormative	11	10	11	12	9	8	8
Leo	Normative	3	2	1	3	4	2	2
	Transitional	1	1	0	1	4	1	1
	NonNormative	14	10	13	15	17	10	13
Distinct Elements By Topic Area (T/I/F)								
Forrest	Normative	2/2/1	2/1/2	6/4/1	5/10/1	6/8/0	3/8/2	5/10/1
	Transitional	0/1/2	1/1/2	1/1/0	0/1/1	0/1/0	0/1/1	0/1/0
	NonNormative	0/2/1	2/2/3	3/0/3	1/3/2	1/0/2	1/0/3	0/0/0
Felipe	Normative	0/2/0	2/3/4	4/6/2	4/5/2	2/8/4	4/6/4	7/5/3
	Transitional	0/3/0	0/0/0	0/2/0	0/1/0	0/1/0	0/0/0	0/1/0
	NonNormative	4/5/1	2/1/3	2/1/0	2/0/0	0/0/0	0/0/0	0/0/0
Luis	Normative	1/1/0	1/3/1	4/3/0	4/6/0	4/5/0	2/6/0	3/3/0
	Transitional	1/1/0	1/1/1	0/0/0	1/2/0	0/1/0	1/1/1	2/2/0
	NonNormative	4/6/1	7/1/2	5/5/1	7/4/1	4/4/1	4/3/1	4/3/1
Leo	Normative	1/2/0	1/0/1	1/0/0	2/0/1	2/1/1	1/0/1	1/1/0
	Transitional	1/0/0	0/0/1	0/0/0	0/1/0	0/4/0	0/0/1	1/0/0
	NonNormative	6/7/1	2/3/5	4/7/2	6/2/7	5/11/1	2/5/3	6/6/1

cause it heats easier—it's a good conductor—but both get hotter than trunk"). Luis was connecting normative insulation and conduction ideas to nonnormative thermal equilibrium ideas. By the third interview, Luis was beginning to connect ideas together in explanations, but his explanations still tended to contain a significant proportion of nonnormative ideas and elements. He did, however, have some normative explanations involving only thermal equilibrium elements. Luis rarely expressed thermal sensation ideas in his explanations, and when he did, these explanations almost always involved the idea that objects that feel different are actually different temperatures (fd4). His explicit warrants (codes beginning with W) also tended to be experiential, but four of these (out of five) during the first five interviews were nonnormative. Only in high school did Luis begin to provide normative warrants from experiences, either from everyday life or from classroom activities.

TABLE 12
Size of the Single Largest Explanation at Each Interview in Terms of the Number of Elements Connected Within the Explanation and Number of Topic Areas Connected Within the Explanation

Student	*Element Quality*	*Int 1*	*Int 2*	*Int 3*	*Int 4*	*Int 5*	*Int 6*	*Int 7*
Explanation with most elements								
Forrest	Normative only	2	1	3	6	5	7	6
	Any elements	3	5	3	6	5	7	7
Felipe	Normative only	0	5	6	6	7	7	6
	Any elements	3	5	6	6	7	7	6
Luis	Normative only	1	2	2	3	3	2	2
	Any elements	3	3	5	3	3	4	4
Leo	Normative only	0	2	1	2	2	2	1
	Any elements	4	3	4	5	6	3	5
Explanation with most topics								
Forrest	Normative only	1	0	1	2	2	3	3
	Any elements	1	3	2	2	2	3	3
Felipe	Normative only	0	3	3	3	3	3	3
	Any elements	2	3	3	3	3	3	3
Luis	Normative only	0	1	1	1	2	1	1
	Any elements	2	2	3	2	2	3	3
Leo	Normative only	0	2	0	1	2	2	0
	Any elements	2	3	2	2	2	2	2

Note. Sizes for explanations composed entirely of normative elements are reported, as well as sizes for explanations composed of any combination of elements.

Luis did manage to add a large number of normative ideas to his explanations, as is made clear by comparing the number of normative ideas included in his first two interviews' explanations to the number of normative ideas included in his last three interviews' explanations (Table 11). However, Luis continued to express the same number of nonnormative ideas in his explanations across interviews, and these ideas remained remarkably similar from the third interview all the way through the seventh interview. This pattern suggests that Luis was able to add normative ideas from classroom instruction but that he did not reorganize and refine his repertoire of ideas. As a result, although Luis continually added new ideas, he did not resolve the extensive conflicts that existed throughout his repertoire of ideas.

Felipe. Felipe (Figure 11) began his first interview expressing fewer fully normative explanations (none) either Forrest or Luis (Table 12). In fact, all of the thermal equilibrium ideas that he expressed in this interview were nonnormative, and the only two normative ideas in his explanations concerned insulation and conduction. One can see the first of the transitional barrier ideas about insulation (ic1) that extended across his interviews. One can also see that Felipe connected ideas across topics (e.g., insulation and conduction ideas to thermal equilibrium ideas), albeit nonnormatively. Felipe was also willing to warrant his ideas, as shown by his frequent use of experiential warrants in the first interview.

In his second interview, Felipe demonstrated significant progress. The overall number or distinct normative ideas climbed dramatically, and the overall number of nonnormative ideas plummeted (Table 11). This trend continued in subsequent interviews. He normatively connected multiple ideas from all three topics in his explanations (Table 12). He did express some explanations that connected nonnormative thermal sensation and thermal equilibrium ideas, but overall he showed significant positive integration in this interview. By the third interview, the majority of his explanations were fully normative. He expressed only a few explanations that were nonnormative, and these generally involved a few ideas each. Most notably, Felipe no longer expressed nonnormative thermal sensation ideas, and he seemed to understand why objects feel the way they do. This process of refinement continued through the fourth interview. By the fifth interview, with the exception of his barrier ideas for insulation (ic1), Felipe's explanations consisted entirely of normative ideas, and these explanations tended to involve several ideas from all three topics.

Felipe achieved a successful level of integration of his ideas and understanding of thermal equilibrium. Note that in comparison to Luis, Felipe's success involved not only adding normative ideas, which Luis was able to do, but more importantly also included (a) reinterpreting, reorganizing, revising, and reconnecting his nonnormative ideas; (b) productively integrating these new normative ideas with experientially supported ideas; and (c) productively integrating these new ideas across topic areas, thereby allowing him to connect and reinforce the school-instructed normative ideas with one another.

Leo. Leo (Figure 12) began the first interview by connecting a larger number of ideas in his explanations than the other students, but almost all of these ideas and connections were nonnormative (Table 11). Leo also differed from the other students in that he made connections, albeit nonnormative connections, between all three topic areas in the first interview (Table 12). Leo continued this pattern of connecting several nonnormative ideas from across all three topic areas throughout all of the interviews. Unfortunately, other than adding a few new ideas, Leo changed relatively little across his interviews, as shown in Table 11. Table 12 provides a slightly more optimistic perspective, showing that he was connecting a few ideas and a few topics into fully normative explanations in Interviews 4, 5, and 6.

In the first interview, Leo expressed the idea that objects become the same temperature in a room (tb1). Throughout his following interviews, Leo did normatively connect this thermal equilibrium idea to a demonstration by the teacher (wt), as well as to the idea that objects can feel different even though they are the same temperature (fb5). However, Leo never managed to normatively utilize these ideas (that objects become the same temperature even though they feel different) as a locus around which to integrate other normative ideas from class or his experience.

Instead, he added terminology from class to support his nonnormative ideas that objects that feel different must actually be different temperatures (fd4). For example, after instruction on insulation and conduction, Leo, in his fifth interview said that metal and wood objects become different temperatures and feel different because metal is a good conductor and as a result gets hotter. When Leo did add terminology or ideas from class, he essentially added them in a nonnormative way so that they supported his existing nonnormative experientially supported ideas. Leo therefore never engaged in a process of revising, reorganizing, or refining his initial existing ideas, nor did he connect the normative ideas that he added from class in a normative way into his repertoire.

Prevalent Elements in Each Student's Explanations

The analysis now examines the element maps to identify patterns in terms of specific ideas consistently expressed by each student during the interviews.

Forrest. In the first interview, Forrest began expressing that objects should eventually become the same temperature in the same environment (tb1), which he expressed frequently throughout every interview thereafter. Right from the beginning, Forrest asserted that metal objects feel cooler or warmer than wood objects (fc1 and fc3). During the second, third, and fourth interviews, Forrest asserted that metal objects become a more extreme temperature in an environment (td1), a conclusion apparently related to his experiential knowledge about how objects feel. He frequently connected this idea (td1) in the second interview to the idea that objects that feel different are actually different temperatures (fd4). During the third, fourth, and sixth interviews, there was an interesting suppression of previously expressed experiential knowledge when Forrest claimed that metal and wood objects become the same temperature (tb1) and that, therefore, the metal and wood objects should feel the same (fd5). Throughout the second, third, fourth, and fifth interviews, there was a sprinkling of ideas suggesting that metal and wood objects feel different because of surface characteristics (fd1), solidness, or density (fd10). In the seventh interview, Forrest eventually managed to connect thermal sensation ideas normatively with thermal equilibrium ideas.

Beginning in the second interview, Forrest frequently expressed explanations involving normative ideas about heat flow, wherein heat energy flows from a warmer object into a cooler object, resulting in the cooler object becoming warmer (tb3). These explanations continued throughout his interviews, but Forrest often expressed related ideas about “cold energy” flowing (td4). In terms of insulation and conduction, Forrest quickly began to assert that metal conducts well (ib1) and that wood, wool, and Styrofoam do not (ib2). He continued to express these insulation and conduction ideas normatively throughout all of his interviews, as well as add several other normative insulation and conduction ideas. Other than a few nonnormative insulation and conduction ideas expressed in the fourth interview, Forrest quickly progressed to expressing only normative insulation and conduction ideas, with the exception of transitional explanations suggesting the ubiquitous barrier ideas (ic1).

Luis. Luis said that objects become the same temperature in an environment (tb1) beginning in the first interview and continuing throughout all of his interviews. He also quickly said that metal objects will be warmer or cooler than other objects (td1); that objects in the same environment remain different temperatures (td5); that objects can go beyond the equilibrium temperature (td8); and that wood, ceramics, and wool never reach the ambient temperature (td11). He continued to express these nonnormative ideas throughout the rest of his interviews, often connected to the idea that objects that feel different are actually different temperatures (fd4). Luis never really expressed normative thermal sensation ideas, which may explain the ongoing contradiction between his normative thermal equilibrium ideas warranted by teacher statements and his nonnormative thermal equilibrium ideas supported by nonnormative thermal sensation ideas. Luis did manage to add other normative thermal equilibrium ideas over the course of his interviews, including ideas about heat flowing from hot objects to cold objects and thereby warming up the cold objects (tb6 and tb2).

In terms of insulation and conduction, Luis expressed in the first interview the idea that metals are good conductors and conduct heat energy well (ib1). In the second interview, he expressed the idea that conductors conduct heat energy quickly (ib3) and that wood, wool, and Styrofoam are insulators (ib2). These normative insulation and conduction ideas were present across the rest of Luis's interviews, often in fully normative explanations. Beginning in Interview 3 and continuing through Interview 7, however, were the nonnormative ideas that insulators store heat energy or release it slowly (id8) and that conductors attract or absorb heat better (id1 and id2). Although Luis added some important insulation and conduction ideas over the course of instruction (e.g., ib1, ib2, and ib3), he did not fully refine these ideas and their connections, and so they remained connected in his explanations to nonnormative ideas (e.g., td1, td10, fd4, and id8). Without engaging in a reorganization process whereby he might have demoted nonnormative ideas and reorganized the connections that he was making in his explanations, Luis made little progress in integrating his understanding about the topic areas.

Felipe. In the second interview, Felipe began to express his ideas that objects should eventually become the same temperature in the same environment (tb1), to which he consistently connected other normative ideas throughout all of his interviews. He also consistently added and incorporated normative ideas about heat flow (tb3) into his explanations. One critical feature of Felipe's element map distinguishing him from the other students involves his rich interconnection of normative thermal sensation ideas (primarily fb1, fb3, fb4, and fb5) into his explanations. In fact, the majority of his successful explanations connecting thermal equilibrium and insulation and conduction ideas included these normative thermal sensation ideas. From the first interview, Felipe consistently said that metal conducts heat well (ib1), and in the second interview he added the idea that wool, Styrofoam, and wood are not good conductors of heat energy (ib2). Although Felipe did initially entertain the ideas that better conductors will reach a higher temperature (td13) and that poor conductors do not get as much heat energy (td17), by the fifth interview, Felipe reorganized and refined his explanations to the point that he no longer expressed these ideas. In fact the only problematic issues remaining in Felipe's final interviews were his barrier ideas about insulation (ic1), which persisted across all of his interviews.

Leo. As mentioned, Leo expressed ideas throughout the interviews suggesting that objects in the same area become the same temperature (tb1). He managed to connect these ideas normatively to a class demonstration by the teacher (wt), as well as to the idea that objects can feel different even though they are the same temperature (fb5). Leo also used experiential warrants (e.g., we) in a problematic manner in 9 out of 10 instances in his interviews. When he used warrants based on the teacher or class labs (e.g., wt or w1), he used them normatively. These latter school-based warrants suggest that Leo was adding ideas from class. Throughout the interviews, there was a steady stream of nonnormative thermal sensation ideas where objects that feel different are actually different temperatures (e.g., fd4). He generally connected these nonnormative thermal sensation ideas to nonnormative thermal equilibrium ideas suggesting that metal objects will be a more extreme temperature than other objects (e.g., td1 or td5). Leo also connected these nonnormative thermal sensation ideas to insulation and conduction ideas suggesting that metals attract heat (id2) or that materials with holes allow heat to pass through easily (id3). Related to this is the idea that air is a medium responsible for transmitting heat or cold (id6).

Conclusions About Individual Elements Within Students' Explanations

The element maps suggest six primary conclusions regarding the students' conceptual change across the interviews.

Adding is easy; normatively connecting is hard. By the second interview, all of the students were able to express in some contexts the idea that objects should become the same temperature over time (tb1). Similarly, almost all of the students were quickly able to assert in certain contexts that metals are good conductors (ib1) and that Styrofoam, wool, and wood are not (ib2). The students did not use these ideas consistently across all contexts, but this rapid appearance in students' explanations of these core school-instructed ideas suggests that the students readily added core ideas for thermal equilibrium and insulation and conduction to their repertoires. The challenge lies in building normative connections between ideas.

Appearance and disappearance of ideas. The addition of normative ideas in one context (as shown by the appearance of these normative ideas in a student's interviews) did not necessarily coincide with the disappearance in that interview of nonnormative ideas expressed by the student in prior interviews that would conflict with the newly added normative ideas. As exemplified by Luis and Leo, students could add several normative ideas across their interviews without refining and reorganizing their nonnormative ideas. Even successful students like Felipe and Forrest required time after adding ideas to reorganize and refine their explanations.

Multiple contradictory ideas. As seen in the case-study analyses, all of the case-study students expressed multiple contradictory ideas during at least a subset of their interviews, if not across all of the interviews. Luis and Leo expressed multiple contradictory ideas across all of their interviews. Felipe and Forrest primarily expressed these multiple contradictory ideas during their second, third, and fourth interviews. This is discussed in the case-study analyses but is made more apparent here.

Single- to multiple-topic areas. Over time, students generally increased the number of topic areas that they were able to connect normatively in a single explanation (Table 12). Generally, when students first attempted to connect ideas from multiple topics, they did so in a nonnormative way. Over time, the successful students were able to connect multiple normative ideas from several topic areas into a single explanation (i.e., thermal equilibrium, insulation and conduction, and thermal sensation and feel). It is important to note that all of the interviews employed relatively isomorphic sets of questions, and so this outcome was not the artifact of question format evolution over the interviews. Rather, students were better able to connect more ideas across topic areas in their explanations as their understanding of the topic areas became more integrated.

Disruptive experientially supported ideas. Many students expressed the idea that objects that feel different must be different temperatures (fd5). This nonnormative thermal sensation idea was often connected to nonnormative thermal equilibrium ideas (e.g., td1 or td5), even if in the same interview the student was also expressing the contradictory normative idea that objects should become the same temperature in the same environment (tb1). This "feels different, different temperature" idea actively disrupted the students' construction of a normative understanding of thermal equilibrium. Similarly, students' experience with wool (i.e., it makes one feel warm) disrupted ideas about insulation.

Multiple student paths. Even though there were similarities between the students, there were also substantial differences in the patterns and paths of progress that they displayed. This involved not only rate of progress but also the ideas that the students found challenging, as well as the ideas around which they tended to integrate their other ideas. One can first see evidence of this in Figures 3–7, which shows that the 50 students in the cohort mastered the topics in different sequences. One also sees evidence in Figure 8, which presents the data from the 50-student topic analysis for the individual case-study students. Luis made the most progress on the heat and temperature topic. What progress Leo made involved thermal equilibrium. Forrest actually lost ground in his understanding of insulation and conduction and thermal equilibrium before raising it up again. The element maps showed these differences in paths in detail. Felipe fixated on the transitional insulation and conduction barrier idea (IC1) in spite of his rapid progress otherwise. Forrest struggled with the relationship between the temperature of objects and how they feel. Leo never really understood insulation and conduction. Luis added ideas but did not naturally consider his ideas critically. Felipe did sort his ideas critically.

Overall, these conclusions reinforce and expand on the conclusions from the analysis of the explanations in the previous sections. Simply adding normative ideas was not sufficient. The success of Felipe and Forrest involved more than the addition of normative ideas, which Luis and Leo were able to do. Conceptual restructuring and learning also included (a) reinterpreting, reorganizing, revising, and reconnecting preexisting ideas; (b) productively integrating new instructed ideas with experientially supported ideas; and (c) productively integrating normative ideas across topic areas, thereby allowing normative ideas to reinforce one another, as well as expand the explanatory power of one another. This conceptual restructuring process was complex, and the students engaged in it through multiple paths and trajectories.

IMPLICATIONS AND CONCLUSIONS

This study has important implications for the conceptual change literature and curriculum design. Table 13 presents a summary of the assertions from each of the three primary analyses.

Implications for Broader Conceptual Change Literature

In terms of the conceptual change literature, the results of this study clarify understanding of longitudinal conceptual change and the structure of students' under-

TABLE 13
Summary of Assertions From Each of the Three Primary Analyses

Topic analysis for the 50-student cohort	
	Conceptual change toward more normative understandings occurs. Significant conceptual change toward more normative understandings takes place during the students' CLP semester.
	The process is challenging and is not binary. The process is not binary, with students either understanding all thermodynamics topics or none at all. Instead, many students at each interview time understand one, two, or three of the topics rather zero or all four.
	Students master the topics in different sequences. Most students have mastered some subset of the topics at each interview, but they have mastered different subsets.
	Integrating a normative understanding is time-intensive. During Interview 2, three weeks into the curriculum, when traditional curricula would stop covering thermodynamics and switch to another topic, only 12% of students on average for any given topic demonstrate a nuanced understanding allowing them to make connections between their normative ideas for that topic. As the semester progresses, however, more and more students display this nuanced understanding, which they build on into high school.
Analysis of the four case-study students' explanations	
	Multiple Contradictory Ideas. The students simultaneously maintain multiple, sometimes contradictory, ideas in their repertoires. Context apparently plays a significant role in fostering and cueing these multiple contradictory ideas.
	Disruptive Experientially-Supported Ideas. Some specific experientially-supported ideas play very persistent and strong roles in students' explanations, disrupting school-instructed ideas that would locally conflict with these experientially-supported ideas.
	Difficulties Productively Connecting Normative Ideas. Students readily add ideas from the curriculum to their repertoires, but these ideas often remain isolated and disconnected from students' other ideas. When students do make connections, these connections are often non-normative, at least initially.
	Pursuing Idiosyncratic Explanations. Students sometimes expend significant time and effort refining idiosyncratic explanations and ideas to facilitate the integration of experientially-supported ideas and school-instructed ideas.
Analysis of individual elements within the case-study students' explanations	
	Adding is Easy, Normatively Connecting is Hard. The rapid appearance in students' explanations of certain core school-instructed ideas suggests that the students are readily adding the core ideas to their repertoires. The challenge lies in building normative connections between ideas.
	Appearance and Disappearance of Ideas. The addition of normative ideas in one context does not necessarily coincide with the disappearance in that interview of non-normative ideas expressed by the student in prior interviews that would conflict with the newly added normative ideas.
	Multiple Contradictory Ideas. As seen in the case-study analyses, the case-study students express multiple contradictory ideas during at least a subset of their interviews. This analysis provides further detail.
	Single to Multiple Topic Areas. Over time, students increase the number of topic areas that they are able to connect normatively in a single explanation.
	Disruptive Experientially-Supported Ideas. As seen in the case-study analyses, specific experientially-supported ideas play very persistent and strong roles in students' explanations, disrupting school-instructed ideas that would locally conflict with these ideas. This analysis provides further detail.
	Multiple Student Paths. Even though there are similarities between the students, there are also substantial differences in the patterns and paths of progress that they display. This involves progress, the ideas that the students find challenging, and the ideas around which they tend to integrate their other ideas.

standing. Current debate within the conceptual change literature focuses on the structure of students' knowledge: Is a student's knowledge most accurately represented as a coherent, unified framework of theorylike character (e.g., Carey, 1999; Chi, 2005; Ioannides & Vosniadou, 2002; Wellman & Gelman, 1992)? Or is a student's knowledge more aptly considered an ecology of quasi-independent elements (e.g., diSessa et al., 2004; Harrison et al., 1999; Linn et al., 2004)?

Description of the theoretical perspectives and the debate. The statements here are simplifications of the actual theoretical perspectives, which are considerably more nuanced as a result of substantial research and ongoing debate among their respective proponents. Proponents of theory-like perspectives, for example, not argue that students' knowledge is theory-like in the same fashion as the knowledge of scientists (e.g., including metaconceptual awareness or availability to hypothesis testing). These proponents argue, however, for an overarching hierarchical conceptual structure with theory-like properties that constrains a student's interpretation of subordinate models and ideas. Similarly, the elemental perspectives should not be incorrectly caricatured as the random interaction of independent elements. Rather, elements interact with each other in an emergent manner where the combinatorial complexity of the system constrains students' interpretations of phenomena.

Caveats about the current study in relationship to the debate. The design of this study focuses heavily on students' processes of conceptual change toward more normative theory-like understandings. The study focuses less on the existence of nonnormative theory-like structures before instruction. To thoroughly test whether a student's initial understanding involves theory-like nonnormative organization, one needs to (a) hypothesize about the specifics of that nonnormative theory, (b) take into account the fact that the domain of the alternative nonnormative theory does not overlap perfectly with the domain specified by the normative theory, and (c) test for the nonnormative theory across the hypothesized nonnormative domain. This study instead focuses on the domain specified by the normative theory and students' progress from their initial understanding toward a normative understanding within that domain. Although this study is not a strong test of the theory-like nature of students' initial understandings, it does clarify aspects of the debate, as discussed later. The current study's real contribution to the debate focuses on (a) the nature and scope of the observed systematicities with regard to the two theoretical perspectives and (b) the nature of the change process.

Relevant aspects of the current study to the debate. In terms of structural considerations, elemental and theory-like perspectives assume certain levels of systematicity. One certainly sees the systematic application of causal mechanisms within a given student's understandings within a given interview. For example, a student may apply the idea that "metals are good conductors and therefore attract more heat energy and therefore get hotter than the surrounding materials and environment" across multiple contexts. This consistent application of a causal mechanism is not sufficient, however, to distinguish between the two theoretical perspectives, because this type of systematicity might result from (a) an overarching hierarchical conceptual structure with theory-like properties that constrains a student's interpretation of subordinate models and ideas, as per a theory-like perspective, or (b) the emergent interaction of elements where the combinatorial complexity of the system constrains students' interpretations of phenomenon, as per an elemental perspective. In the latter case, the systematicity indicates that the contexts in question cue the same subset of elements, resulting in the same interpretation by the student. This point is important because elemental perspectives are often caricatured as involving random interactions and no consistency. In fact, cuing the same set of elements should result in consistent interpretation and explanation by the student. The question becomes one of scope in terms of these causal systematicities.

There are also systematic ontological differences between a student's meaning for a term, such as *insulator*, and a scientist's meaning for that same term. This soft form of ontological difference relates closely to Wiser and Amin's recent work (2001). Students exhibit strong forms of ontological divergence from normative theory, as discussed by Chi (2005), with regard to the core ontological categories they employ in their interpretation of phenomena. In the current study, for example, students often employed the common "substance" metaphor in their understanding of heat, rather than the scientists' "process" metaphor.

Even taking these causal and ontological systematicities into account in the interpretation of students' explanations, one can still see multiple contradictory normative and nonnormative ideas displayed across at least a subset of the interviews for each student. For example, students thought that metal and wood would be the same temperature in one context but different in another. Sometimes the contradictions were the result of the students' interpreting the phenomena differently as the contexts changed. Sometimes students changed back and forth in their interpretation of phenomena within the same context. Sometimes these changes resulted from the introduction of prompts or physical props by the interviewer. Other times the changes of interpretation arose autonomously from the student, without any external stimulus.

With regard to these contradictions, all of the case-study students exhibited some motivation toward minimizing contradictions within their explanations. This drive was evidenced in the effort that they invested in developing idiosyncratic explanations to reconcile their experientially supported ideas with school-instructed ideas. The case-study students displayed varying ranges of vision and interest in this process of identifying and reconciling contradictions. Luis generally noticed contradictions within an immediately local context. Felipe noticed contradictions between his answers in different contexts. Leo seemed the least concerned with contradictions. He often seemed unperturbed when confronted by the interviewer about contradictions, because he thought that the situations were "just different" from one another. Because every context is different and independent, no contradictions arose for him.

It is important to note that two predictions could be made in two contexts that would be contradictory according to the normative theory but harmonious according to an alternative nonnormative theory. In the latter case, there would indeed be no contradiction in logic for the student. Often, however, a case-study student noted the contradictions autonomously, which suggests that these contradictory answers are not part of an overarching monolithic theory in which the student was embedded and committed. Rather, the student was thinking about the issues with a new set of ideas from class, alongside previous ideas, and was encountering contradictions. In the interviews, for example, Forrest said that the wood and metal objects must be different temperatures because they feel different. Later, Forrest decided from a lab or from listening to the teacher that the objects must be the same temperature. When asked how the metal and wood objects will feel, Forrest now said that the metal and wood objects will feel the same. When asked to touch a metal and wood object, Forrest reverted to his original stance that the objects must be different temperatures. This process seems analogical to installing and smoothing a large carpet: When you smooth or move one area, it perturbs another.

The current study examines the complexity of this reorganization process. The process involved the addition and integration of instructed ideas as well as the coalescence, differentiation, reassessment and reorganization of preexisting ideas. All of these processes were observed in the case studies with regard to individual ideas. The processes were not quick and clean. Instead, the processes involved extended periods where the student struggled to reconcile multiple conflicting ideas and connections, during which time the student's interpretation of the ideas and connections remained fluid and unstable. Context—and the other ideas cued prominently by that context—heavily influenced the interpretation of ideas and their relationships. This process was made more challenging by disruptive experientially supported ideas that played prominent roles in students' understandings.

This is not to say that the process was impossible for students. Conceptual change in thermodynamics was time-intensive but was achieved by most students through significant amounts of time and concerted curricular effort. With this time and support, students negotiated the process along multiple paths, as shown by the 50-student data as well as the case studies. Clearly, the process was neither quick nor clean. Students in the 50-student data did not shift instantly from nonnormative ratings for the four thermodynamics topics in one interview to normative or nuanced ratings for the four topics in the next interview. In fact, even on a single topic, the percentages of students at each interview rated as transitional or normative, rather than nonnormative or nuanced, demonstrated that the transition to a nuanced level of normative systematicity was not instantaneous. Instead, the process spanned across the semester and into high school. In the terminology of the literature, conceptual change appeared much more evolutionary than revolutionary for these students studying thermodynamics (although these analyses cannot rule out the possibility of occasional revolutionary events). These findings align with findings of other research (e.g., Gunstone & Mitchell, 1997; Harrison et al., 1999; Linn et al., 2004; Wiser & Amin, 2001), suggesting a heavy evolutionary component within the conceptual change process.

Implications for elemental perspectives. Clearly, there were significant causal and ontological systematicities in students' explanations, along with significant fragmentation and contradiction during this phase as students moved to integrate new instructed ideas with preexisting ideas into normative understandings. Elemental perspectives can account for this state of being in the students' understanding. Elemental perspectives allow for a range of element types within students' conceptual ecologies, including but not limited to subconceptual p-prims, beliefs, facts, and mental models, among others. Because elemental perspectives assume that the elements interact with one another in a network of positive and negative connections, the elemental perspectives can account for the conflicts between ideas, sensitivity to contexts, differential weighting of ideas, and the systematicities created by the interaction of prominent elements. Ultimately, through a process of reorganization, students can eventually create a level of parsimony and coherence within their understanding of normative theory-like character. Elemental perspectives are therefore well suited for explaining transitional as well as static periods in students' understanding.

Implications for theory-like perspectives. In terms of theory-like perspectives, this study is not able to make strong claims about the structure of students' initial understanding before instruction, for the reasons outlined in the Caveats section. Therefore, for the purposes of this section, assume for the moment that students' understanding before instruction was of a nonnormative but theory-like character. Certainly, the change from this initial state to whatever final state that a student reaches is evolutionary and not revolutionary, as discussed earlier. Almost all of the students made some progress, according to Figures 3–7 from the 50-student analysis, but few students shifted suddenly to a completely normative theory-like understanding. This progress spanned the entire semester and continued into high school. In fact, it seems quite possible that many of the students will remain in a state of flux rather than achieve a parsimonious, coherent, theory-like understanding of thermodynamics throughout adulthood.

This possibility underscores the importance of providing detailed accounts of how the transition between proposed theory-like stages progresses. For example, Ioannides and Vosniadou (2002) suggest that students held *synthetic models* as interim stages between various nonnormative and normative models and claim that a large percentage of their students showed dramatic coherence in the application of a single synthetic model across contexts. The findings from the current study, which focuses on thermodynamics rather than mechanics, suggests that this coherence is not the case, at least for thermodynamics. This discrepancy does not rule out the possibility of nonnormative theory-like understandings, but it does suggest that more emphasis in theory-like perspectives needs to consider the extended stretches of time between these theory-like periods. Carey (2000) outlines processes of differentiation, coalescence, and reassessment through which individual ideas transform, but although many theory-like accounts acknowledge evolutionary components, many do not provide much detail about the interim structures and mechanisms involved.

Issues of domain and scope. Issues surrounding domain and scope remain the trickiest aspect of the debate over knowledge structure. Ultimately, it may depend on the vantage point of the observer and the grain size and scope of the conceptual territory being observed. As an analogy from the physical world, gravity appears to be an up–down hierarchical frame to an observer standing on a basketball court, whereas gravity is more clearly the interaction of all objects with one another from the perspective of an observer in space. Similarly, the debate between proponents of theory-like and elemental perspectives may describe phenomena from different distances and scopes. What appears to be the influence of a framework theory when viewed from one distance may in fact just be a heavily weighted element in an elemental perspective if viewed from a greater distance. Similarly, vantage point and scope may determine one's judgment as to whether a shift in a student's thinking is just the revision of a large element in the student's repertoire affecting the connected elements or the revision of a framework theory resulting in sweeping changes in the students thinking.

Across how large a domain must a student be ontologically and causally consistent for a researcher to rate the student's understanding as being theory-like? At one narrow extreme, all of the case-study students demonstrated consistency in their understanding across some narrow domain for some idea. At the other extreme, not even scientists are fully coherent and consistent in their understanding across the entire overarching domain of science. Unfortunately, "big enough" is hard to define in an objective manner for reliable application by multiple researchers.

Implications for Curriculum Design

Conceptual change and misconceptions research has provided insights into improving curricular design (e.g., Clement, 1993; diSessa & Minstrell, 1998; Driver, Squires, Duck, & Wood-Robinson, 1994; Gunstone, 1987; Hestenes, Wells, & Swackhammer, 1992; Wandersee, Mintzes, & Novak, 1993). The current study provides specific suggestions in this regard. The current study was conducted within a curriculum that focused specifically on depth of coverage and connections. The curriculum supported significant progress by the most successful students (as shown in the analysis of the 50-student cohort) and the fairly successful students (as shown in the analyses of the 50-student cohort and the case studies). The less successful students, however, did not achieve the level of coherence in their understanding that one might have hoped for. Based on this study's findings about students' conceptual change processes, the curriculum (and curricula in general) can be optimized to better support students through further focus on the following: depth of coverage; support for normative connection of ideas rather than simple addition; opportunities to compare nonnormative and normative ideas in contexts that cue the nonnormative ideas; support for multiple conceptual paths through the curriculum; consideration of pedagogical trade-offs in choosing specific accessible intermediate models; and reexplanation of disruptive experientially supported ideas to support school-instructed ideas. As with the conceptual change discussion earlier, see Table 13 for a summary of the major relevant findings from each analysis.

Depth of coverage. The results of this study clarify the results of the study that preceded it (Clark & Linn, 2003) in terms of the role of depth of coverage in the curriculum. The 50-student data demonstrates that conceptual change occurred within the CLP curriculum and that such conceptual change takes time. At the beginning of the semester, most students maintained predominately nonnormative repertoires of ideas regarding thermal equilibrium. By the second interview (3 weeks later), many of the students added ideas and maintained mixed repertoires, including nonnormative and normative ideas regarding thermal equilibrium. Although adding ideas signified progress, these ideas were not integrated with one another in a normative cohesive fashion. Furthermore, many nonnormative ideas and connections remained prominent. Traditional curricula would stop coverage at this point, leaving the students without having made any significant progress on which to build in the future. Given the opportunity and support to continue the integration process, however, most students in the 50-student cohort made significant progress in integrating their frameworks and building nuanced understandings of thermal equilibrium. These data clarify calls from the TIMSS study (Schmidt et al., 1997) to increase depth over breadth within curricula. These results from the CLP curriculum are more encouraging than the minimal improvement in thermodynamics understanding between age groups on the NAEP (O'Sullivan et al., 1997). These results demonstrate that, given proper curricular depth and support, students can make substantial progress on which they continue to build in high school.

Support for normative connection of ideas rather than simple addition. Building on the findings from the 50-student data, the findings from the four case studies demonstrate that simply helping students add normative ideas is not sufficient. The success of Felipe and Forrest involved more than adding normative ideas, which Luis and Leo were also able to do. Successful learning also involves the following: reinterpreting, reorganizing, revising, and reconnecting preexisting ideas; productively integrating new instructed ideas with experientially supported ideas; and productively integrating normative ideas across topic areas, thereby allowing normative ideas to reinforce on one another, as well as expand the explanatory power of one another. Curriculum design should therefore focus on supporting connections between topics and ideas rather than on compartmentalizing topics. Curriculum design should also focus on specific supports for building these connections. The CLP curriculum focused on building connections between instructed ideas but would probably benefit from more emphasis on the connections between experientially supported ideas and instructed ideas, as discussed later in this section.

Increased opportunities to compare nonnormative and normative ideas in contexts that cue the nonnormative ideas. The addition of normative ideas in specific contexts did not mean that the students abandoned earlier contradictory ideas in other contexts. This is related to students' difficulties in making normative connections. Not only do students need help in making these normative connections, but they also need help in revisiting and reconsidering the nonnormative ideas that they have entertained in other contexts.

Support for multiple conceptual paths through the curriculum. The 50-student data show individual differences in trajectories of mastery. Much current interest exists in identifying developmental learning sequences and hypothetical learning trajectories for students studying various topics in mathematics and science education. The 50-student data suggest that these research efforts should assume multiple paths through the conceptual terrain under study. The four case-study students reinforce this idea. The students followed different paths through the material, focusing on different core ideas around which to organize their other ideas. This is made evident in their pursuits of idiosyncratic explanations as well as in the analysis of the individual elements in their explanations. For some students, insulation and conduction may seem intuitive and provide a core around which to integrate other ideas. For other students, thermal equilibrium may provide traction in this regard. Similarly, some students may be more naturally disposed to search for contradictions in the ideas that they are expressing, whereas others may need more support. Similarly, the case studies suggest that individual students may be more autonomous in some domains than in others because of a variety of factors, including personal relevance, motivation, and the social supports that they receive in that domain.

Scaffolding within curricula should therefore provide flexible, adaptable supports to meet a variety of student paths and needs. Teacher professional development to increase awareness of the diversity of student cognitive paths is important. Further research into the variety of cognitive learning trajectories followed by students through the conceptual territory will afford the opportunity to build curricula that provides support for these multiple paths. In terms of curricular tools, rich curricula providing multiple modes and formats for conceptual interaction may prove the most useful tools in large public classrooms where teachers' ability to respond to individual students proves logistically challenging. Technology-based curricula may prove especially useful in this regard by providing different materials to different students in the classroom. For this to be possible, however, further development of computer-based diagnosis of students' conceptions will be necessary.

Consideration of pedagogical trade-offs in choosing specific accessible intermediate models. The CLP curriculum organizes instruction around the accessible intermediate model of heat flow. This decision was based on research showing that heat flow is more accessible to eighth-grade students than molecular kinetic theory. This study suggests that students often enter the curriculum interpreting heat as belonging to the ontological category of substance rather than process (Chi, 2005). The intermediate model of heat flow is indeed highly accessible to students, but it does not support their reconsideration of the ontological categorization of heat. The language of the current study, which consciously incorporates the language from the curriculum in discussing students' understandings, highlights potential issues in this regard in terms of *heat flow* rather than *molecular kinetic theory* and other related terminology, such as *insulation and conduction* rather than *thermal conductivity*. This pedagogical choice by the CLP curriculum therefore provides advantages in terms of accessibility and disadvantages in terms of reinforcing students' incorrect ontological metaphor. The trade-off is arguably beneficial in this particular case, given the extreme accessibility of the models, but curriculum developers need to consider such trade-offs and their goals when incorporating accessible intermediate models into the curriculum.

Reexplanation of disruptive experientially supported ideas to support school-instructed ideas. The current study suggests the importance of helping students reorganize the connections that they make to their experientially supported ideas. This reorganization could dramatically help students address their multiple contradictory ideas and redirect the effort that students are pouring into the pursuit of idiosyncratic explanations as they attempt to reconcile their disruptive experientially supported ideas with the ideas that they are adding from instruction. The case studies highlight multiple examples where experientially supported ideas were tangential but disruptive to instructed ideas because of the way that the students connected the experientially supported ideas to their other related ideas, both instructed and experientially supported. "Warm wool" and the idea that "if it feels colder, it must be colder" exemplify this issue. Students know that they feel warm when they wear a wool coat. If students interpret and connect this experience such that they believe that wool makes things warm and later learn that wool is an insulator, those students might easily assume that insulators make things warm. Instead, instruction should help students reexplain the connections so that experientially supported ideas support rather than disrupt the instructed ideas.

Clark and Jorde (2004) investigated this approach. They synthesized the findings and ideas from preliminary versions of the current analyses to target students' experientially supported ideas that were tangential but disruptive to instructed ideas about thermal equilibrium. The specific goal involved helping students reexplain and reconnect their experientially supported conception that certain materials, such as metal and glass, tend to feel hotter or colder than other materials, such as wood. Students assumed that "if something feels hotter or colder, it must be a higher or lower temperature." This connection of how something feels to students' prediction of temperature resulted in students' dismissing or distorting instructed ideas about thermal equilibrium. From a student's perspective, thermal equilibrium apparently never happens in the real world because metal objects never feel the same as other objects. Students need help revising their connections to understand that, in addition to differences in temperature, differences in thermal conductivity can make things feel hotter or colder by affecting the net rate at which heat energy enters or leaves the body. Thus, the goal of Clark and Jorde involved helping students reexplain the connection between their experientially supported disruptive ideas and instructed ideas about thermal equilibrium. Using computer simulations targeting these connections, Clark and Jorde significantly increased students' understanding of thermal equilibrium on posttests, delayed posttests, and interviews.

Final Thoughts

These results clarify student learning from a conceptual restructuring perspective and, in the process, provide new research tools and insights into curriculum design.

Conceptual change as an evolutionary process. Ultimately, the results clarify the conceptual change processes through which students' understandings of thermal equilibrium evolve from disjointed sets of context-dependent, sometimes contradictory, ideas toward, if not achieving, integrated cohesive perspectives. The results also clarify that these processes progress through multiple paths and trajectories in terms of the core ideas around which students organize their other ideas, the experiences that they consider salient, and their awareness and concern about conflicts between their ideas. The analyses further suggest that the processes appear heavily evolutionary but do not preclude the possibility of some revolutionary changes. Many people recall having *Eureka!* moments of clarity. This study certainly does not deny the possibility of these revolutionary moments. However, these moments of lasting clarity, where a learner transitions cleanly and swiftly from one understanding to another, seem more the exception than the rule in the case studies. For this reason, it seems important for theories of conceptual change to account for the extended complex periods of evolutionary change as well as for clean shifts of revolutionary change.

Similarly, although students exhibit some ontological and causal systematicities, they also exhibit significant contradictions and fragmentation in their understandings over time. Theoretical perspectives on conceptual change therefore need to account for fragmentations as well as systematicities in discussions of knowledge structure. Toward this end, the conceptual restructuring perspective outlined as the lens for the current study appears useful for accounting for longitudinal changes in students' understanding. That does not mean that there are not other equally useful lenses but that this perspective can provide a useful account of longitudinal change at a microgenetic grain size.

Explanation maps and element maps provide useful supplementary analytical–representational tools for case-study analyses. In terms of new tools for research, the explanation maps and element maps introduced here show promise as evolving methods for analyzing and representing conceptual change in longitudinal settings. Clearly, direct quotations from the students' transcripts provided the primary warrants for the case studies in the current analyses, but other researchers and future research can continue the evolution of these tools and methods to create solid new analytical tools for conceptual change research in longitudinal settings.

Curricular design to support conceptual change. Finally, this study has important implications for curriculum design. This study was conducted in a curriculum that specifically focused on depth of coverage and connections. The curriculum supported significant progress in the understanding of thermodynamics by the most successful students and the fairly successful students, but the less successful students did not achieve the level of coherence in their understanding that one might have hoped for. Based on this study's findings about students' conceptual change processes, the curriculum (and curricula in general) can be optimized to better support all students through further focus on the following: depth of coverage; support for normative connection of ideas, rather than simple addition; opportunities to compare nonnormative and normative ideas in contexts that cue the nonnormative ideas; support for multiple conceptual paths through the curriculum; consideration of pedagogical trade-offs in choosing specific accessible intermediate models; and reexplanation of disruptive experientially supported ideas to support school-instructed ideas. Traditional curricula often fail students, as demonstrated by the TIMSS and NAEP data (O'Sullivan et al., 1997; Schmidt et al., 1997). Increasing understanding of students' conceptual change processes in longitudinal settings will provide crucial insights into better serving the needs of all students in the future.

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REFERENCES

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

Anderson, J. R. (1993). *Rules of the mind*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Carey, S. (1999). Sources of conceptual change. In E. K. Scholnick, K. Nelson, & P. Miller (Eds.), *Conceptual development: Piaget's legacy* (pp. 293–326). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Carey, S. (2000). Science education as conceptual change. *Journal of Applied Developmental Psychology, 21*(1), 13–19.

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Implications for learning and discovery in science. In R. N. Giere (Ed.), *Cognitive models of science: Minnesota studies in the philosophy of science* (Vol. 15, pp. 129–187). Minneapolis: University of Minnesota Press.

Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences, 14*(2), 161–199.

Chi, M. T. H., & Roscoe, R. D. (2002). The processes and challenges of conceptual change. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 3–27). Dordrecht, Netherlands: Kluwer Academic.

Clark, D. B. (2000). *Scaffolding knowledge integration through curricular depth.* Unpublished doctoral dissertation, University of California, Berkeley.

Clark, D. B. (2003, March). *Analyzing student knowledge integration: Theories or pieces?* Paper presented at the National Association of Research in Science Teaching Conference, Philadelphia.

Clark, D. B., & Jorde, D. (2004). Helping students revise disruptive experientially-supported ideas about thermodynamics: Computer visualizations and tactile models. *Journal of Research in Science Teaching, 41*(1), 1–23.

Clark, D. B., & Linn, M. C. (2003). Scaffolding knowledge integration through curricular depth. *Journal of Learning Sciences, 12*(4), 451–494.

Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching, 30*(10), 1241–1257.

Clough, E. E., & Driver, R. (1985). Secondary students' conceptions of the conduction of heat: Bringing together scientific and personal views. *Physical Educator, 20*, 176–182.

Cotignola, M. I., Bordogna, C., Punte, G., & Cappannini, O. M. (2002). Difficulties in learning thermodynamic concepts: Are they linked to the historical development of this field? *Science and Education, 11*, 279–291.

diSessa, A. A. (1988). Knowledge in pieces. In G. Forman & P. B. Pufall (Eds.), *Constructivism in the computer age* (pp. 49–70). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2–3), 105–225.

diSessa, A. A., Gillespie, N., & Esterly, J. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science, 28*, 843–900.

diSessa, A. A., & Minstrell, J. (1998). Cultivating conceptual change with benchmark lessons. In J. G. Greeno & S. V. Goldman (Eds.), *Thinking practices in mathematics and science learning* (pp. 155–188). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Driver, R., Squires, A., Duck, P., & Wood-Robinson, V. (1994). *Making sense of secondary sciences: Research into children's ideas*. London: Routledge.

Erickson, G., & Tiberghien, A. (1985). Heat and temperature. In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science* (pp. 52–83). Philadelphia: Open University Press.

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

Gunstone, R. F. (1987). Student understanding in mechanics: A large population survey. *American Journal of Physics, 55*, 691–696.

Gunstone, R. F., & Mitchell, I. J. (1997). Metacognition and conceptual change. In J. J. Mintzes, J. H. Wandersee, & J. D. Novak (Eds.), *Teaching science for understanding* (pp. 133–163). San Diego, CA: Academic.

Harrison, A. G., Grayson, D. J., & Treagust, D. F. (1999). Investigating a Grade 11 student's evolving conceptions of heat and temperature. *Journal of Research in Science Teaching, 36*(1), 55–87.

Hestenes, D., Wells, M., & Swackhammer, G. (1992). Force concept inventory. *Physics Teacher, 30*, 141–158.

Hewson, M. G., & Hamlyn, J. (1984). The influence of intellectual environment on conceptions of heat. *European Journal of Science Education, 6*, 245–262.

Hewson, P. W., & Hewson, M. G. A. (1992). The status of students' conceptions. In R. Duit, F. Goldberg, & H. Niedderer (Eds.), *Research in physics learning: Theoretical issues and empirical studies*. Kiel, Germany: Institute for Science Education.

Hunt, E., & Minstrell, J. (1994). A cognitive approach to the teaching of physics. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 51–74). Cambridge, MA: MIT Press.

Ioannides, C., & Vosniadou, S. (2002). The changing meanings of force. *Cognitive Science Quarterly, 2*(1), 5–62.

Jones, M. G., Carter, G., & Rua, M. J. (2000). Exploring the development of conceptual ecologies: Communities of concepts related to convection and heat. *Journal of Research in Science Teaching, 37*(2), 139–159.

Kesidou, S., & Duit, R. (1993). Students' conceptions of the second law of thermodynamics: An interpretive study. *Journal of Research in Science Teaching, 30*(1), 85–106.
Laburu, C. E., & Niaz, M. (2002). A Lakatosian framework to analyze situations of cognitive conflict and controversy in student's understanding of heat energy and temperature. *Journal of Science Education and Technology, 11*(3), 211–219.
Lewis, E. L. (1996). Conceptual change among middle school students studying elementary thermodynamics. *Journal of Science Education and Technology, 5*(1), 3–31.
Lewis, E. L., & Linn, M. C. (1994). Heat energy and temperature concepts of adolescents, adults, and experts: Implications for curricular improvements. *Journal of Research in Science Teaching, 31*(6), 657–677.
Linn, M. C., Eylon, B., & Davis, E. A. (2004). The knowledge integration perspective on learning. In M. C. Linn, E. A. Davis, & P. Bell (Eds.), *Internet environments for science education* (pp. 29–46). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.
Linn, M. C., & Hsi, S. (2000). *Computers, teachers, peers: Science learning partners*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.
Lubben, F., Netshisaulu, T., & Campbell, B. (1999). Student's use of cultural metaphors and their scientific understandings related to heating. *Science Education, 83*, 761–774.
McCloskey, M. (1983). Naive theories in motion. In D. Gentner & A. Stevens (Eds.), *Mental models* (pp. 299–324). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
National Research Council. (1996). *National Science Education Standards*. Washington, DC: National Academy.
O'Sullivan, C. Y., Reese, C. M., & Mazzeo, J. (1997). *NAEP 1996 science report card for the nation and the states*. Washington, DC: National Center for Education Statistics.
Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Towards a theory of conceptual change. *Science Education, 66*, 211–227.
Rogan, J. H. (1988). The development of a conceptual framework of heat. *Science Education, 72*(1), 103–113.
Schmidt, W. H., McKnight, C. C., & Raizen, S. A. (1997). *A splintered vision: An investigation of U.S. science and mathematics education*. Dordrecht, Netherlands: Kluwer.
Shayer, M., & Wylam, H. (1981). The development of the concept of heat and temperature in 10–13-year-olds. *Journal of Research in Science Teaching, 18*(5), 419–434.
Slone, M., Tredoux, C., & Bokhorst, F. (1996). Decalage effects for heating and cooling: A cross-cultural study. *Journal of Cross-Cultural Psychology, 27*(1), 51–66.
Strike, K. A., & Posner, G. J. (1992). A revisionist theory of conceptual change. In R. Duschl & R. Hamilton (Eds.), *Philosophy of science, cognitive psychology and educational theory and practice* (pp. 147–176). Albany: State University of New York Press.
Tarsitani, C., & Vicentini, M. (1996). Scientific mental representations of thermodynamics. *Science and Education, 5*, 51–68.
Thagard, P. (1992). *Conceptual revolutions*. Princeton, NJ: Princeton University Press.
Tiberghien, A. (1980). Modes and conditions of learning. An example: The learning of some aspects of the concepts of heat. In W. F. Archenhold, R. H. Driver, A. Orton, & C. Wood-Robinson (Eds.), *Cognitive development research in science and mathematics* (pp. 288–309). Leeds, England: University of Leeds.
Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1993). Research on alternative conceptions in science. In D. L. Gabel (Ed.), *NSTA handbook: Research in science teaching* (pp. 177–210). New York: Macmillan.
Wellman, H. M., & Gelman, S. (1992). Cognitive development: Foundational theories of core domains. *Annual Review of Psychology, 43*, 337–375.
Wiser, M. (1988). The differentiation of heat and temperature: History of science and novice–expert shift. In S. Strauss (Ed.), *Ontogeny, phylogeny, and historical development* (pp. 22–48). Norwood, NJ: Ablex.

Wiser, M., & Amin, T. (2001). "Is heat hot?" Inducing conceptual change by integrating everyday and scientific perspectives on thermal phenomena. *Learning and Instruction, 11*, 331–353.
Wiser, M., & Carey, S. (1983). When heat and temperature were one. In D. Gentner & A. Stevens (Eds.), *Mental models* (pp. 267–298). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

APPENDIX A
Sample Interview Questions

Interviewers attempted to probe for students' intuitive conceptions, as well as discover any emerging conceptions in the area of heat energy/temperature, insulation/conduction, thermal equilibrium, and heat flow. Interviewers were instructed to follow up on students' statements in probing their understanding. If students' responses changed from previous interviews, the students were asked what had changed their minds and why. Pictures or physical objects were used for some of the questions. Sample interview questions are included here. The ratio of thermal equilibrium questions is higher than the ratio included in the overall set of interview questions in order to highlight the thermal equilibrium questions to which the case-study quotations most often refer. Students' ideas and explanations expressed for all of the interview questions are considered, however, in the analysis of all of the topics—that is, even if a question seems targeted specifically toward insulation/conduction, any ideas relevant to heat flow or thermal equilibrium expressed in response to that question are considered in analysis of that student's understanding for all of the topics.

Drying Oven Question

In a chemistry lab students were drying equipment in an oven. The temperature of the oven was 150°C. In the oven were metal spatulas, glass beakers, and asbestos pads that had been there overnight. What do you predict the temperature of each is? Why? (Probe for their understanding of thermal equilibrium. What is the source of their understanding?) If you could touch them, would they feel the same? Why? (Probe for their understanding of conduction and insulation using the student's terms.)

Different-Sized Beakers Question

Also ask the students to consider the small and large beakers. Get them to predict the temperature of the two beakers. Most students will say that they are the same temperature, even if they do not have thermal equilibrium as a concept. Then ask them to compare the heat energy of the two beakers—is it the same or different and why?

Wrapping Candy Bars Question

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 for brunch? Why? (Probe their understanding of insulation and conduction.)

Winter Cabin Question

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

Hot Car Trunk Question

You are running an errand for your parents to buy several long strips of metal and several long strips of wood at a hardware store. You place the strips in the trunk of the car. It is a hot day, and you and your friend stop at another friend's house on the way home since you are not in a hurry. You leave the strips of metal and wood sitting in the trunk of their car. When you return several hours later, you and your friend have different predictions about the temperature of the strips of metal and wood in the trunk. Your friend thinks that the wooden strips will be hotter than the metal strips. You say that the metal strips will be hotter than the wooden strips. Who is right? Why? (Probe their understanding of, and conditions for, thermal equilibrium.) What would happen if you touched the metal strips? What would happen if you touched the wooden strips? Why? (Probe for their understanding of the process of conduction and insulation using the student's terms.)

Thermal Conductivity Continuum Question

Write the names of each of the following materials on the line where you think they belong. (Show student a continuum line from *good insulator* to *good conductor.*) Assume that all the materials have the same thickness. (Materials include metal, Styrofoam, wood, glass, wool, ceramic floor tile, paper, saran wrap.) Why did you place [name of 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 for their understanding of conduction and insulation.)

Nail and Ice Question

Suppose that you hold one end of a metal nail and put the other end on a piece of ice. After 5 min how will the end of the nail in your hand feel? What is the main reason for your answer? What evidence do you have to support your answer?

APPENDIX B
Process of Coding the Explanation Maps and Element Maps

The Methods section provides an overview of the coding process for the explanation maps and element maps. This appendix provides further detail and an example of the process for Felipe's Spoons question in the fifth interview.

Demarking Explanation Segments

The explanation maps (and the element maps derived from them) consider one segment of a student's explanations to include the following: the introduction of a new line of questioning by the interviewer, the student's initial answer, and the subsequent interchange between the interviewer and the student as the student's answer is elaborated and probed. New segments of the student's explanations therefore begin at the start of each interview question and as soon as a new tangent or line of questioning that has not been alluded to by the student is introduced by the interviewer.

Students' Ideas About Thermal Equilibrium

In coding ideas from an explanation segment, the following are considered the student's ideas: the student's direct statements within that segment about thermal equilibrium and the related concepts of thermal conductivity (*insulation/conduction* in the curriculum) and thermal sensation, or feel; direct quotations from the student's answers on a subject matter test administered at the same time as the interview; and the student's ideas from a previous segment that are referred to or are the basis of the discussion in the current segment. This last component is important because the coding of each segment must capture all of the assumptions and ideas that can be identified as part of the student's explanations for each segment so that the explanation can be understood in a stand-alone context in the explanation maps and element maps. If the explanations omitted these "alluded to" and "inferred" ideas, the true nature of student's explanations would not be faithfully represented in the maps because important context would be lost.

Segments of student's explanations are not coded as representing the student's ideas when the interviewer was asking leading questions and it seems likely that the student was simply agreeing without adding significant new ideas. In general, answers of only yes or no to directive interviewer questions are ignored. In the relatively uncommon cases where the interviewer asked leading questions but the student added significant amounts of material and built on the probes, the distillations are marked as *scaffolded* and are eligible to be placed in the explanation maps with the marker *scaffolded* because they involve the student's thinking and understanding.

Condensing Explanation Excerpts for the Explanation Maps

Students' ideas about thermal equilibrium from the explanation segments are represented as condensed excerpts in the explanation maps. The process of condensing these explanation segments focuses on avoiding the attribution of new information not represented in the segment. These condensed excerpts are sorted in terms of their sophistication (e.g., nonnormative, mixed, normative, or nuanced, as described earlier). Duplicates from within an interview are removed, and the remaining condensed excerpts are placed in the explanation map.

Refinement for the Element Maps

The element maps code the explanation segments from the explanation maps into the elements representing the explanation's main models and ideas, better showing the connections that the student was making over time. The first letter of each code signifies the topic area (T = thermal equilibrium; I = insulation/conduction; F = thermal sensation, or feel). The second letter of the code signifies the sophistication of the conceptual element. This letter determines region of an interview column in which the code is placed (B = normative, placed in top region; C = transitional or mixed, placed in middle region; D = nonnormative, placed in bottom region). Note that there is no separate *nuanced* region for individual ideas, because *nuanced* is defined in this study as the connection of multiple normative ideas. Following the second letter code is a number differentiating conceptual elements within the same major concept area and degree of sophistication. Finally, codes in uppercase represent strong or generalized examples of this code, whereas codes in lowercase represent less strong or narrow usages by the student.

These elements are grouped and vertically placed within columns by sophistication as normative, transitional, or nonnormative. A solid black line then connects all elements coded from a condensed explanation to show that they are part of one explanation (for examples of the coding process, see Table 3; for an example of the element map creation process, see Figure 2; for the actual element maps, see Figures 9 through 12; and for the complete coding keys, see Tables 8 through 10).

Coding Example: Felipe's Spoons Question, Interview 5

To capture the most prominent ideas of the student's repertoire, the analyses address questions from multiple contexts. The spoons question, presented in this appendix, is one such context that is consistent across several interviews. The spoons question probes the relationship among thermal equilibrium, thermal sensation, and insulation/conduction ideas. The text of the question is as follows:

> A metal spoon and a wooden spoon were put into an 80°C (very warm) oven for 4 hr.
> a. What do you predict their temperatures will be after 4 hours in the oven?
> b. What is the main reason for your answer?
> c. What evidence do you have to support your answer?

The following example presents Felipe's transcript for the spoons question in the fifth interview.

> New Segment FE5079

> Discussion: This identification number signifies Felipe as the student (FE), Interview 5, explanation segment beginning with Line 79 (this segment happens to run through Line 85).

79 S: Metal spoon would be 80 and the wooden spoon might not be 80.
80 I: Why?
81 S: Because metal I think would conduct the heat fastest … [mumble] … would be 80 and I think the wooden spoon would get to 80 but just not as fast.
82 I: So, what if we put them in there for 8 hours?
83 S: I don't know. I mean, it might be, I just don't know how long it would take.
84 I: Right. But you think eventually what would be the temperatures of each of those?
85 S: 80.

Discussion: Lines 79–85 are considered one explanation because the interviewer statements in Lines 80, 82, and 84 are probing the student's initial statement in Line 79. Line 82, for example, followed up on a temporal allusion by the student in Line 81. The student is clear on the role of time but not clear on the amount of time required.

Explanation map excerpt: Metal and wood object would get to temperature of oven, but metal would get there first because it conducts heat the fastest. (79–86) (nuanced)

Element map coding:

tb1 Objects in same room become same temperature./Objects eventually become same temperature./Objects in same surround become same temperature.

IB8 Rate of reaching equilibrium dependent on conductivity./Speed at which objects become temperature of surrounding depends on conductivity.

IB12 Conductors heat up faster./Insulators heat up slower.

New Explanation Segment FE5086

86 I: Could they get hotter?
87 S: No.
88 I: Do you have any evidence?
89 S: You mean that fact that they'll both get to 80 or the fact that it will take longer?
90 I: The fact that they'll both get to 80
91 S: Just because when you put an object in the surround it will reach … get there.
92 I: It will actually get there.

Discussion: Line 86 starts a new explanation segment because the interviewer is pursuing a new tangent not alluded to in the student's previous statements. Lines 86–91 are considered one explanation because the interviewer's statements in Lines 88 and 90 just probe into the student's statements in this section, as opposed to opening new lines of probing.

Explanation map excerpt: Objects reach temperature of surrounds after time. (86–91) (normative)

Element map coding:

TB1 Objects in same room become same temperature./Objects eventually become same temperature./Objects in same surround become same temperature.

Discussion: This explanation segment appears to contain a recitation of a principal taught in the class in Line 91, used to warrant the student's understanding that the objects will not get hotter than the oven.

End of spoons question transcript from Interview 5 for Felipe.