

“The coat traps all your body heat”:

Heterogeneity as Fundamental to Learning

Ann S. Rosebery
Chèche Konnen Center
TERC
2067 Massachusetts Ave
Cambridge, MA 02140
617/873-9718

Mark Ogonowski¹
Arizona Game and Fish Department, Region 2
3500 S. Lake Mary Road
Flagstaff, AZ 8600

Mary DiSchino²
Chèche Konnen Center
TERC
2067 Massachusetts Ave
Cambridge, MA 02140

Beth Warren
Chèche Konnen Center
TERC
2067 Massachusetts Ave
Cambridge, MA 02140

In Press

Journal of the Learning Sciences

Abstract

This paper explores heterogeneity as fundamental to learning. Inspired by Bakhtin's notion of heteroglossia, a design team consisting of an experienced classroom teacher and two researchers investigated how a class of 3rd and 4th graders came to understand disciplinary points of view on heat, heat transfer and the particulate nature of matter. Through a series of planned and unplanned encounters, official versions of the Second Law of Thermodynamics and the particulate view of matter were juxtaposed with varied domains of experience of heat transfer and phase change in water. We analyze the children's discourse to examine how they populated these phenomena with meaning and what they learned in the process. We conclude by describing key principles, and a conundrum, that emerged from this research.

Predictions of an increase in the population of students from historically non-dominant communities³ (Hochschild & Scovronick, 2003) often serve, among other functions, to support a narrative of an educational “problem” to be solved (Gutiérrez and Orellana, 2006). This narrative tends to emphasize growth in the number of children who do not speak middle class English or who are seen as not prepared for academic learning, in short, children who differ from a presumed “mainstream” norm. Gutiérrez and Orellana (2006, p. 503) argue that while this kind of descriptive statistic can usefully serve to point out inequities and other critical issues related to structural inequalities, it can, and often does, reinforce “deficit-oriented, uncomplicated, and uneven narratives about students” from non-dominant communities. It does this, first, by locating diversity in “otherness” - - in deviations from a presumed mainstream European American, middle-class norm – and, second, by flattening the complex and varied ecologies of everyday life into an essentialized group trait, often linked with academic deficits or disadvantages (Cole, 2000; Erickson, 2003; Moll, 2000; Nasir, Rosebery, Warren & Lee, 2006; Rogoff, 2003).

Diversity does not have to have these resonances. What if, as a field, we worked to construct a different narrative? One that conceptualizes the heterogeneity of human cultural practices as fundamental to learning, not as a problem to be solved but as foundational in conceptualizing learning and in designing learning environments (Bang, Medin & Atran, 2007; Lee, 2007; Moje, Ciechanowski, Kramer, Ellis, Carrillo, & Collazo, 2004; Moll & González, 2004; Rosebery & Warren, 2008)?

In theory, such a view is consonant with constructivist approaches to work in the learning

sciences (diSessa, Hammer, Sherin, & Kolpakowski, 1991; Sherin, 2006; Smith, diSessa, & Roschelle, 1993; Vygotsky, 1930/1978). At the same time, constructivist approaches to educating students from non-dominant groups have been insightfully critiqued (Delpit, 1986; Heath, 1989; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001). Heath's (1989) critique of schooling, made 20 years ago, still stands. She pointed out that American schools typically recognize only a very narrow range of language and thinking practices as contributing to literacy in the broadest sense, and that these tend to be those of middle class, European American communities. Schools do not see the instructional advantages in what she identified as the "potentially positive interactive and adaptive verbal and interpretive habits learned by Black American children (as well as other nonmainstream groups), rural and urban, within their families" (Heath, 1989, p. 370) and communities. In short, the discourse practices of students from non-dominant groups are not routinely treated as academically fertile ground in most theory or practice relating to education (Gutierrez & Rogoff, 2003; Ladson-Billings & Tate, 1995; Lee, 2007; Moll & Gonzalez, 2004; Warren et al., 2001).

Various interdisciplinary endeavors are attempting to change this landscape. These endeavors theorize learning and development as engagement with and negotiation of specific, situated repertoires of practice that build centrally on the rich diversity of human experience (e.g., Cope and Kalantzis, 1993; Nasir, et al., 2006; Rogoff, 2003). The multi-campus Collective for the Study of Human Learning and Development⁴ (CHiLD, 2005; see also Nasir et al., 2006), for example, aims at understanding the complex ecologies of children and youth, particularly from non-dominant communities, as they

navigate varied forms of culturally organized practices and simultaneously contend with historically structured orders of racial, linguistic, social, economic, and cultural inequality. Taking a slightly different tack, the New London Group (2000) links ideas of local diversity and global connectedness in arguing for a new kind of civic pluralism, in which cultural and linguistic diversity, assumed as the norm, is taken up as a productive resource in learning and teaching. Moje et al. (2004) provide a broad summary of work concerned with theorizing and constructing “third space” designs for learning, including various studies of third space practices in literacy and science (Calabrese Barton & Tan, 2009; Cole, 2000; Gutiérrez, Baquedano-López, & Alvarez, 2001). In all of these endeavors, learning is viewed as an activity in which heterogeneous meaning-making practices come into contact – explicitly and implicitly, intentionally and emergently – to generate new understandings, extend navigational possibilities, and adapt meaning-making practices to new forms and functions.

These interdisciplinary research endeavors analyze in principled ways relationships among the “everyday” experiences, ideas and ways of talking and knowing of students from non-dominant groups and the “everyday” practices of professional disciplines. In both cases, “everyday” indexes routine, mundane, sense-making practices of specific, historically and culturally formed communities. And further, that these relationships can be mobilized productively in learning and teaching.

Cultural modeling, for example, designs instruction based in an analysis of everyday discourse practices in African American communities and literary forms of reasoning to

expand African American students' argumentation and symbolizing repertoires to academic practices of literary interpretation (Lee, 1993, 2000). Research in mathematics education has documented forms and functions of mathematical thinking across multiple communities of practice in which students from non-dominant groups participate e.g., sewing, basketball, dominos, track (Civil, 2005; Moll & González, 2004; Nasir, 2000; 2002). Research in science education has analyzed a variety of discourse practices within the repertoires of students from non-dominant groups that intersect generatively with those in the sciences, e.g., practices of argumentation, narrative and metaphor in developing explanations, embodied imagining to explore the inner workings of phenomena, and analogies from everyday experience to evaluate evidence (Calabrese Barton & Tan, 2009; Gee & Clinton, 2000; Hudicourt-Barnes, 2003; Michaels & Sohmer, 2000; Warren et al., 2001). This body of research emphasizes instructional potential in the inevitable diversity of human experience, ideas, and ways of talking, acting, knowing, and valuing which are continuously developed within historically constituted communities of practice (Gutiérrez & Rogoff, 2003; Nasir et al., 2006).

This view of diversity ties in with Bakhtin's (1981, 1984) conception of *heteroglossia* as a fundamental condition of everyday life. Heteroglossia encompasses varied ways of conceptualizing, representing, evaluating and engaging the world in language (Morson & Emerson, 1990). Bakhtin's view of the way in which any national language is stratified into "languages of social groups, 'professional' and 'generic' languages, languages of generations and so forth" (Bakhtin, 1981, p. 272) is now well recognized (Gee, 1996; Morson & Emerson, 1990; Wertsch, 1985). Further, and importantly for our purposes

here, it is broadly understood that these languages are not distinguished from one another by their vocabularies alone but as “specific points of view on the world, forms for conceptualizing the world in words” and as “specific forms for manifesting intentions” (Bakhtin, 1981, p. 291-292, 289) what Gee (1990) has termed “big D Discourse.”

All languages of heteroglossia...are specific points of view on the world, forms for conceptualizing the world in words, specific world views, each characterized by its own objects, meanings and values. As such they all may be juxtaposed to one another, mutually supplement one another, contradict one another and be interrelated dialogically... (T)hese languages live a real life, they struggle and evolve in an environment of social heteroglossia. (Bakhtin, 1981, pp. 291-92)

Consonant with this view, we posit that deep engagement with heteroglossia is a necessary and generative, although often underdeveloped or unrecognized, aspect of learning and teaching. As students navigate daily life in school and out, they inevitably encounter heteroglossia in the ways different languages, in the Bakhtinian sense, conceptualize, represent, and evaluate the world (cf. Goodwin, 1994; 2000; Latour, 1986; Ueno, 2000), ways that are also powered according to sociohistorically structured orders of inequality rooted in language, culture, race, class and gender.

Let's take an example of how heteroglossia might live in the elementary science classroom. In ordinary usage people use the word *cold* to refer to their sensory experience of an object. To a 3rd grader holding an ice cube, the ice cube is making her hand cold. To a physicist, at 32°F an ice cube has a lower temperature than the child's hand; heat energy is thus transferred from her hand to the ice cube. This represents a fundamentally different way of seeing heat and cold, a fundamentally different point of view. In the sciences, as in other academic disciplines, words like heat take on

specialized, historically-constituted meanings, and function to organize other meanings and practices in ways that can be “difficult to penetrate” (Bakhtin, 1981, p. 276).

Let’s extend this example in order to illustrate more fully in what ways students’ encounters with heteroglossia intersect with their participation in varied communities of practice. Thus far, we have treated 3rd graders as homogeneous with respect to how they have experienced cold in their lives, but this cannot be the case. Homogeneity of experience with phenomena such as cold, and therefore the constellation of meanings and values associated with them, cannot be assumed in any classroom. For example, cold will have different resonances for children who have grown up in Massachusetts and experienced winter in different ways, depending on their life circumstances (e.g., skiing vs. living in a poorly heated home). Likewise, it will have different resonances for children who have moved to Massachusetts from warm climates like southern California, Florida, or Haiti. Thus the meanings and values associated with even simple words like cold cannot be taken for granted. In this sense, words and the discourses in which they live are never neutral; they taste of the complex ecologies of children’s lives (Bakhtin, 1981, p. 293).

Constructing shared meaning in the midst of heteroglossia is challenging because the languages commanded by a given individual may be more or less overlapping, continuous, discontinuous, conflicting or complementary with those used predominantly in school and with those associated with a historically constituted discipline like physics (CHiLD, 2005; Nasir et al., 2006). When the fundamental heterogeneity of languages is

neglected, as it typically is in schools, students are left on their own to sort out – or not – the complex interrelations among the meanings, values, and points of view that “cross, converge, and diverge” (Bakhtin, 1986, p. 93) in the classroom. This can have at least two consequences for learning.

First, as discussed earlier, it can be difficult for students from non-dominant groups who do not command middle class language practices to participate or be understood in the restricted space of school discourse (Calabrese Barton & Tan, 2009; Gee & Clinton, 2000; Lee, 2007; Michaels & Sohmer, 2002; Warren, et al., 2001). Second, and of equal importance, is that the learning of *all* students is limited when heterogeneity is ignored or goes unrecognized in the classroom. If learning fundamentally involves the negotiation of meanings across culturally-saturated boundaries of practice, including those of academic disciplines, it becomes circumscribed when the space of possible meanings is restricted. On this view, intellectual rigor results from multiple, varied opportunities to think broadly and deeply about a phenomenon or idea from many places (Hall & Greeno, 2008; Nasir et al., 2006). To be clear, we are not advocating an “anything goes” approach. To the contrary, this perspective advocates for intentional engagement of the heterogeneity that is ubiquitous in classrooms through the emergent design of curricula that bring into contact students’ diverse meaning-making practices and the big ideas and practices of the discipline under study (Ball & Wilson, 1996; Lee, 2007; Warren, Ogonowski & Pothier, 2005).

In the research reported here, we document a classroom design experiment in which we

explored what it might mean to conceptualize learning as ongoing engagement with heteroglossia and to design instruction accordingly, to allow for both planned and unplanned encounters. Specifically, we investigated how a class of 3rd and 4th graders developed understanding of ideas related to heat, heat transfer and the particulate nature of matter.

Methods

This research took the form of a classroom design experiment (Brown, 1992; Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; The Design-Based Research Collaborative, 2003). As such, the design team had the dual goals of a) designing innovative learning environments and b) contributing to the development of theory. We were active in the educational process at the same time that we studied what was happening, and we documented our work in ways that would allow us to link our design and instructional activity to specific kinds of learning outcomes.

The investigation is part of a larger program of research conducted at the Chèche Konnen Center (CKC). The broad goal of CKC's work is to develop innovative designs for learning and teaching that engage students from non-dominant groups in deep and rigorous learning in the sciences (Hudicourt-Barnes, 2003; Rosebery, 2005; Rosebery & Warren, 2008; Warren, Ogonowski & Pothier, 2005).

Design Team

The design team was composed of the classroom teacher, DiSchino, and two CKC researchers, Ogonowski and Rosebery. In keeping with design research methodology, all three members of the design team were actively involved in planning and implementing the instructional innovation. The classroom teacher, henceforth referred to as Mary according to her preference and the custom of address at her school, participated as a full partner in all phases of the design research. Mary is a highly experienced and knowledgeable teacher and teacher researcher. She has been teaching for over 30 years, and has been a key partner in research at CKC since 1991. (For more information on Mary's teaching practice and her collaboration with CKC, see DiSchino, 1998; Rosebery, 2005; and Rosebery & Warren, 2008.) Except for occasional absences due to illness, all three members of the design team were present for all design and instruction sessions. Mary acted as teacher for all instructional sessions, and Ogonowski and Rosebery documented the sessions through videography and field notes, at times taking part in classroom discussions.

Research Setting

The study took place in a combined third-fourth grade classroom in an urban public school. The twenty-one students ranged in age from 9 to 11 years. The students varied in first language (English, Haitian Creole, and Spanish) and their families varied in cultural, educational, and work histories. Twelve of the children received free/reduced

lunch and nine spoke a language other than English at home. Two of the children lived in homeless shelters during the school year. By including this information we do not mean to reinforce reductive characterizations of individuals or groups, nor do we wish to reinforce assumptions of deterministic relationships between individual learning and group membership (Gutierrez & Rogoff, 2003; Lee, 2002). Rather, we provide it, limited and limiting as it is, to give readers a feel for the varied life experiences of the children, and therefore how heterogeneity in their life experiences might emerge as central to learning in this classroom, as in any classroom.

At the time this study was conducted, although science was tested as part of the Massachusetts Comprehensive Assessment System, student performance on science-related achievement tests did not “count” as part of the state-mandated, NCLB-linked assessment system. As a result, schools felt little pressure to tailor science to “the test.” Thus, the design team had more freedom to experiment with curricular innovations in science than would likely be possible today.

Disciplinary Focus

The disciplinary focus of the study was heat transfer and the particulate nature of matter. We wanted to know what third and fourth graders could learn about these ideas when everyday and scientific perspectives were brought into deliberate contact. We chose these ideas, in part, because of the central, organizing roles they play in the domain of

physics (Feynman, 1995; Hewitt, 2002). Specifically, we focused on fostering understanding of the following five “big” scientific ideas:

- 1) heat flows from objects at higher temperatures to objects at lower temperatures;
- 2) matter is composed of molecules⁵, which are in constant motion;
- 3) changes in the behavior and organization of matter at the molecular level can explain visible/macroscopic states and transformations of materials;
- 4) temperature and heat can be understood in terms of molecular motion; and
- 5) molecules are not *in* stuff; they *are* stuff.

We focused on heat transfer and the particulate nature of matter knowing that they can be difficult for students from elementary school through college to understand (Chi, 2005; Reiner, Slotta, Chi, & Resnick, 2000; Smith, Wiser, Anderson, Krajcik & Coppola, 2004). We were also aware that although our disciplinary focus complemented standards in physical science on phase change and the particulate nature of matter specified in the Massachusetts Frameworks (MA DOE, 1995) and in national standards (AAAS, 1993; NRC, 1996), these topics are typically taught in middle and high school.

Despite the demonstrated challenges associated with learning these ideas, a small but robust body of work suggests that elementary and middle school students can in fact develop understanding of important aspects of them. These studies designed, developed, and implemented new approaches to teaching (Johnson, 1998; Southerland, Kittleson, Settlage & Lanier, 2005; Varelas & Pappas, 2006) and innovative computer-based

curricula (e.g., Computer as Learning Partner, Linn & Hsi, 2000; and Models of Matter, Snir, Smith & Raz, 2003) to scaffold students' understanding of concepts like heat transfer, insulation and conduction, the particulate nature of matter, and the idea that macroscopic properties of a substance are properties of collections of particles. In a related vein, interviews with elementary-age students demonstrated that they can spontaneously generate analogies between visible phenomena and atoms or molecules as they try to explain and further develop their understanding of matter in gas and solid form (Noble, in preparation).

Design Research Practice

The goal of our design research was to see what and how third and fourth graders could learn about heat transfer and the particulate nature of matter when heterogeneity was taken as foundational to learning and teaching. In particular, we were interested in fostering contact among everyday and scientific perspectives. Thus, we designed lessons and activity structures that a) broadened the Discourse space beyond what is ordinarily sanctioned in school science; b) engaged *all* students in articulating their thinking publicly; c) attempted to make aspects of the structure and ideas of physics visible to students; and d) engaged students in probing the meanings of scientific ideas and perspectives, and the relationship of these to their everyday understandings.

To broaden the Discourse space and make students thinking public, we used a participation structure called science talk, which Mary and her students called

“Sherlock,” after the famous, fictional detective. Science talk is intentionally structured to enlarge the Discourse space that typically occurs in school science. The common pattern of school talk has been characterized as teacher initiation-student response-teacher evaluation (IRE, Cazden, 1988). IRE is different from ordinary person-to-person talk in at least two ways. First, the teacher does not actually need the information she has requested; instead, she is checking to see if the student knows it. Second, the teacher controls the interaction, determining the topic, its development, what counts as relevant, and who gets to speak.

By contrast, in science talk, students have some control over the discussion. They determine the range and flow of ideas, exploring their emerging understandings of the scientific question or phenomenon under study. The teacher acts as facilitator, encouraging her students to articulate their thinking for one another and for her. Science talk is a space for listening, understanding, and exploring possible meanings, not for evaluating or correcting students’ ideas. The positive effects of this practice on the science learning and achievement of all students and particularly on that of students from non-dominant groups is well documented (Ballenger, 2009; Gallas, 1995; Rosebery, 2005; Rosebery & Warren, 2008). Science talk, aka Sherlock, has been a regular part of Mary’s science program since 1991, when she began participating in CKC projects.

Like other researchers who have addressed relationships between everyday and scientific modes of thinking (Clark & Linn, 2003; diSessa, 2000; Hammer & Elby, 2003; Krajcik & Blumenfeld, 2006; Lee & Sherin, 2006; Smith, diSessa, & Roschelle, 1993), the design

team made deliberate decisions that would allow us to explore how the children made sense of heat transfer and the particulate nature of matter in the context of familiar, everyday situations at the same time that we attempted to make the structure and meanings of ideas of physics visible. We did this by, for example, presenting the Second Law to students and engaging them in inquiries into its meaning in ways that made contact with their everyday understandings of heat and cold.

To develop lessons, the design team met weekly for approximately two hours to review and discuss the talk and activity that had taken place during that week's Sherlock and to plan the following week's session. Transcripts, made immediately after each Sherlock session, were a key tool in our design practice. We jointly reviewed the transcript and videotape of each session to study the children's thinking. Thus, our process was emergent; our evolving view of the children's understanding was the basis for developing the subsequent lesson.

Developing subsequent lessons entailed a) identifying the core idea(s) on which to center the children's work (e.g., expanding the investigation of heat transfer to include evaporation as well as melting), b) reviewing our own understanding of the core idea(s) and their relationships to heat transfer and the particulate nature of matter, c) considering and selecting appropriate instructional materials (e.g., ideas children had expressed in a previous session, computer simulations of the behavior of atoms), and d) designing focal activities to bring everyday and scientific meanings into contact (e.g., investigating the effect on melting of wrapping an ice cube in a winter coat).

The investigation was conducted from mid-October, 2002 through mid-February, 2003. It consisted of eighteen weekly instructional sessions, each of which lasted approximately 45 minutes. Additional time was set aside as needed for the children to finish up work begun in these sessions. In total, the investigation comprised approximately 22 hours of instructional time.

Data and Analytic Procedures

The principal sources of data for this investigation were videotape records, transcripts made from videotapes, field notes and children's written work for each of the eighteen Sherlock sessions. In addition, for summative assessment purposes, we held two benchmark discussions (a variation of benchmark lessons following diSessa & Minstrell, 1998) and administered an end-of-unit test. We used an interaction analysis approach to analyze videotapes and transcripts (Jordan & Henderson, 1995). Summaries of each Sherlock session were generated and a "map" of the eighteen-week investigation was created. The sessions were then grouped into three thematic phases for the purposes of analysis: 1) inquiry into the Second Law; 2) inquiry into the particulate nature of matter and phase change; and 3) assessment of student learning. These three phases allowed us to develop a picture of the emergent nature of the children's learning during the investigation as well as a summative view of their learning following the investigation.

Three levels of analysis were conducted on the data in each of these three thematic phases. First, the transcripts of all eighteen Sherlock sessions were examined for episodes in which contact between everyday and scientific perspectives was in evidence. Second, sessions that seemed pivotal in the development of the children's learning were further examined. Finally, specific excerpts from those sessions were chosen for analysis, with an emphasis on tracing the microgenesis of children's understanding of concepts of "heat" and "molecule." Interpretations were triangulated with students' written classroom work and their performance on the end-of-unit test. The heart of this paper is an analysis of the two instructional phases. A summary of our assessment findings follows this analysis.

Analysis

Each Fall, Mary makes ice cream with her students to welcome them back to school. In October, 2002, she and her students continued this tradition, but inadvertently made a mistake. Rather than adding salt to the ice in the ice cream maker to harden the cream mixture, they added sugar. As a result, the ice cream did not harden as expected. This turn of events provoked intense curiosity among the children. Although we had planned to begin our design experiment later, the design team – led by Mary – saw opportunity in this event and took up the children's curiosity about ice cream as the "driving question" (Krajcik & Blumenfeld, 2006) for the investigation into the meaning of the Second Law of Thermodynamics and the particulate nature of matter.⁶ After a second, successful venture at making ice cream, the students discussed what they thought might have

happened. They raised many questions: “Why does the salt make the ice cream hard but sugar doesn’t?” “Why does salt melt the ice so fast?” “What would happen if we put pepper on the ice instead of salt?”

The design team’s examination of the class’s initial discussion about their attempts to make ice cream showed that most, if not all, of the children believed that, similar to the human body, substances maintain a constant temperature as an inherent property of the substance itself and independent of the environment. During the first month of the students’ investigation of this question, the design team engaged the children in a series of observational experiments to explore the evidentiary basis of their belief about the temperature of substances. By the middle of November, most of the children thought that the temperatures of salt, sugar, pepper and other substances “change with the weather, kind of like lizards,” as Manuel said. At this point, the design team felt the children were poised to begin exploring the Second Law.

Phase One, Mid-November to Mid-December, 2002:

Inquiry into the Second Law of Thermodynamics

The children engaged in an inquiry into the meaning and implications of the Second Law (i.e., heat flows from objects at higher temperatures to objects at lower temperatures) from mid-November through mid-December. They did this through a series of activities designed to engage them in examining their everyday meanings and experiences of heat and temperature (e.g., melting ice cubes, wearing coats in the winter) in relation to the

scientific meanings organized in the Second Law. In this section, we summarize their activity for the month of November and present an analysis of an excerpt from a Sherlock discussion that occurred in early December.

The design team introduced the children to the Second Law on a poster, which subsequently hung in the classroom. The poster read, “Heat always flows from objects at a higher temperature to objects at a lower temperature.” The design team suggested the Second Law might help the students think about some of their questions about ice cream-making. At the same time, we engaged them in thinking about the meaning of statements related to heat transfer that five of them had made during the previous Sherlock. In this way, the children collectively expanded their understanding of terms such as “hot,” “cold”, and “temperature,” using their classmates’ statements as generative spaces for imagining and exploring situations in which hot and cold were co-present.

The following week, each child was given an ice cube in a ziplock bag and told to hold it in the palm of her hand. As they observed what happened, Mary asked them how the Second Law applied to the ice cube. Some tried to use the language of the Second Law as it appeared on the poster to describe what they thought might be happening. Others said that their hands were hotter than the ice cube, which made the ice cube melt. A few worked on aspects of the idea of heat transfer, although their descriptions were grounded in the sensory experience of their hands getting cold.

Toward the end of Sherlock, Herve said, “I think if you could put this (holding up his ziplock bag which now contained liquid water) in the window for two days it would turn to ice.” This prompted the children to consider what the likely conditions would be for this to happen. Would two days be enough time? Would the water evaporate? In response, Mary invited Herve to put his baggy on the ledge outside the classroom window. When they checked on it two days later, they found it had frozen and discussed what might have happened. As we will see, Herve’s baggy became an important touchstone for the students as the investigation unfolded. By the beginning of December, the design team was convinced that, while most of the children seemed to have little interest in the Second Law/heat transfer, hot and cold had become objects of fascination.

December 11, 2002

The children’s relationship to the Second Law changed profoundly the following week. At the beginning of Sherlock on December 11, Mary asked the students to use the Second Law to explain why they wear coats in the winter. The children didn’t have much to say and those who did made statements such as, “Because it’s cold” and “To stay warm because it’s windy and cold.” The conversation was labored; Mary described it as “pulling teeth.”

About 10 minutes into the session, the fire alarm went off, and the children tumbled out into the chilly winter air *without* their coats. Outside, they talked animatedly about how their “body heat” (as they called it) was going “to the air.” They improvised various

ways of staying warm. Some jumped up and down in place. Others pulled their arms out of the sleeves of their sweaters and wrapped them around their bodies. Others stood closely together in little groups. Alex announced loudly that he could “see the heat” (i.e., steam) leaving the top of Ogonowski’s head!

When they returned to the classroom, the conversation about why they wear coats in the winter took off. Fifteen of twenty-one hands shot up, as children were eager to talk about their fire drill experiences. Excerpt 1 below includes the utterances of all the children who responded to Mary’s reintroduction of the question (line 1). It represents the first five minutes of a twenty-five minute discussion.

Excerpt 1: Why do we wear coats in the winter?⁷

1. Mary: So what just happened when you went outside? Most of you didn’t wear jackets. Now can anyone say why you wear a coat when you go outside in the wintertime based on the Second Law?
2. Arnaud: I think that um all the- the coat traps all your body heat- I think the coat traps all your heat so you can stay warm.
3. Mary: It traps all your heat. Okay, who would like to use other words to explain this?
4. Herve: Because um your blood is warm blooded- because your blood is warm blooded and the warm goes into the coat.
5. Mary: (...) because you’re warm-blooded? Okay. Who can add to that?
Kenthea?

6. Kenthea: When you go outside and it's cold and the sun is out it doesn't mean it's going to be hot. And you're like- when you're- when you're outside your jacket keeps you warm and- and when you're- when you zip it all the way up to the top it traps um the warmness in you.
7. Mary: It traps the warmness in you. Okay, who else?
8. Harriet: Well if it's hot outside- if it's hot outside and you go out without a coat and you're colder than the hotness out- if you're colder than the temperature that's outside the heat will go to you so you don't have to wear a coat. But then if it's cold outside and you're hotter than- than the temperature outside and you wear a coat it traps your body heat so it doesn't go out and you get colder.
9. Donnell: Mary here's what I say (.) I say that since your coat's colder than you your heat goes to the coat and then the- since the- and your coat's colder- I mean hotter than you it switches off.
10. Mary: Okay. Susannah?
11. Susannah: Um I think that when- that you have body heat and when you go outside your body heat fl- flows out of you but when you put a coat on it acts as a stopper for the body heat and it traps it.
12. Helen: I think it's because you- your heat- the heat from your body um flows to the cold air and then (.) um if you put a coat on it traps it just like Harriet said.
13. Steve: And Kenthea. She said it too.
14. Mary: Manuel, what do you think? Why do you wear a coat in the wintertime to keep you warm?

15. Manuel: Um well if you wear a jacket your- um the heat from your body won't like go into the cold air. It like traps it and so you won't get cold.
16. Mary: Okay. Steve? What do you think?
17. Steve: Well wearin' a coat (.) keeps you warm because obviously like 18 degrees at 98 degrees I mean- it- your body heat isn't the only thing that's gonna- that can keep you warm during winter you need like a coat and a sweater because (.) those things trap body heat but (.) they trap body heat from people around you also. I mean body heat doesn't just come from you (.) or like- ah- yourself. Body heat comes from all kinds of people (.) like I could be collecting body heat from anybody in this room and that's probably how I'm (.) how I'm warm right now. Like the Long House.

In this excerpt, we can see that the children's experience during the fire drill brought the Second Law to life in a way that neither the words of the Law alone nor their prior experience with cold had. Here, their experience and the Second Law made contact, each giving shape to the other's potential meaning. The children saw "cold" in a new light, that is, as heat flowing out of their bodies. An important related change was that they also began to see heat as an object itself, in addition to understanding it as a bodily sensation. The Second Law also gave them a way to understand *how* coats work. They raised three central conceptual threads in this discussion: 1) heat flows from one object to another, 2) its more specific instantiation, heat flows from objects of higher temperatures to objects of lower temperatures, and 3) it is possible to stop or greatly

reduce the flow of heat, in this case with a coat. (Table 1 shows which children referred to which ideas during Excerpt 1.)

----- insert Table 1 about here -----

As the transcript and Table 1 show, eight of the nine children who responded to Mary's initial question made reference to heat flowing from one object to another, and six of those eight incorporated the notion that heat flows in a particular direction, from objects at higher temperatures to objects at lower temperatures. Seven of nine mentioned the possibility of stopping or reducing the flow of heat, in this case with a coat.

Harriet (line 8), for example, set up a pair of comparisons to explain the connections she was making. In the first comparison, she described a person who was "colder than the hotness out- if you're colder than the temperature that's outside the heat *will go to you* so you don't have to wear a coat." In the second, if the person was "hotter than than the temperature outside and you wear a coat *it traps your body heat so it doesn't go out* and you get colder."

Donnell (line 9) seemed to "see" a coat in an entirely new way, that is, as an active agent, as he posited a simple model for a body-coat system. He described a dynamic process, reminiscent of thermal equilibrium, in which the direction of heat flow is determined by the relative temperature of two objects. His model suggests that the heat of a body flows to a coat ("since your coat's colder than you your heat goes to the coat") but as the body

loses heat to the coat, the process reverses itself and the heat of the coat then flows to the body (“and then the- since the- and your coat’s colder- I mean hotter than you it switches off.”). Although a physicist would not see Donnell’s statement as correct because he is suggesting that the coat can become warmer than the body, it is easy to imagine how the idea of one’s body and one’s coat taking turns at being the object of higher temperature might occur to an active fourth grader, who regularly puts on and throws off his coat during recess. In his utterance, Donnell seemed to be “trying on” the Second Law, that is how heat flows between objects of different temperatures, exploring if and how it fit with his experience, and if and how his experience with coats might fit with the Second Law.

Steve’s comment (line 17) pulled together several threads of thought. First, he acknowledged the role that clothes play in keeping “you warm during winter” (“You need like a coat and a sweater because those things trap body heat.”). Then he explained that “...body heat doesn’t just come from you or like- ah- yourself. Body heat comes from all kinds of people like I could be collecting body heat from an- anybody in this room and that’s probably how I’m- how I’m warm right now. Like the Long House.” “Like the Long House” refers to a practice of the Wampanoag Indians, an indigenous community the class had studied in social studies earlier that year. Prior to contact with European settlers, Wampanoags lived in nuclear family dwellings in the summer and moved to a community dwelling, called a Long House, in the winter to protect themselves against, among other things, the harsh winter conditions in Massachusetts.

Although Mary and his classmates understood Steve's reference, Rosebery and Ogonowski did not and followed up with him after class. He explained the role the Long House played in the life of the Wampanoag community. He then added that during the fire drill he and a few friends "did something like them like we huddled our heat." Thus, in line 17, Steve was describing a thermodynamic situation in which the distance between objects at higher temperatures (e.g., human bodies) is reduced to minimize contact with objects in the environment at lower temperatures (e.g., cold air) and therefore heat dissipation, and to maximize contact among heat-producing objects (i.e., human bodies). In thinking about Mary's question, Steve created illuminating connections among heteroglossic phenomena that most of us would think of as inhabiting distant worlds: the Second Law, winter coats, his fire drill antics with friends, and housing practices among the Wampanoag.

Summary of Phase One

In this section, we analyzed the children's sense-making as they inquired into the possible meanings of the Second Law. The children were initially introduced to the Second Law and asked to consider potential meanings in the context of familiar situations (e.g., melting ice cubes, Herve's ziplock bag, wearing a coat). In both planned and unplanned ways, scientific and everyday views of heat, temperature, and heat transfer (e.g., the official version of the Second Law, students' explanations of melting ice cubes and changes in temperature) came into contact, and the children were asked to consider these in light of one another. As they studied heretofore unconnected objects and phenomena,

the children began to see familiar phenomena (e.g., frozen water in a ziplock bag, melting ice cubes) in new ways. They began to understand what it might mean for heat to flow from an object at a higher temperature to an object at a lower temperature. They began to see heat itself as an object of interest, and they began to see cold in terms of relative amounts of heat, rather than as qualitatively different from heat. The breadth of the connections they made (e.g., the fire drill, the Wampanoag's Long House) took us by surprise.

The children also populated their perspectives on the everyday world with new meanings. They came to see coats and sweaters and huddling for warmth from the perspective of heat transfer. One child even reinterpreted the story of the Wampanoag's seasonal housing practices through the eyes and language of the Second Law. In these ways, the children were, in effect, creating a transformative space in which boundaries between their lived experience and scientific laws could become coordinated in new understandings.

The Discourse space that Mary and the children co-created and sustained enabled these encounters with heterogeneous worlds. For her part, Mary insisted that all the children participate in Sherlock discussions. She did this by asking each of them to respond to the question at hand (e.g., line 14), and by listening carefully to what each student said.

When she did not understand, she asked the child to elaborate, to "say more". She also routinely invited children to "use other words to explain" something or to "add to" what a child had just said (lines 3 and 5). She took note of who was quiet and when, and was

uncomfortable when she did not know what a given child was thinking. For their part, the children were generally eager to participate and share their thinking. They regularly built meaning together, picking up and elaborating, extending, or probing possible meanings, as evidenced in Excerpt 1.

What role does heterogeneity play in the children's thinking and learning? As stated earlier, we believe that heterogeneity is a fundamental condition of everyday life; it is ubiquitous in daily encounters, including those in classrooms. And these encounters whether or not they are formally engaged can influence what and how we learn. To our mind, Herve's question about how long it would take the melted ice cube in his ziplock baggy to refreeze in the window is a good example of one of the many moments in which heterogeneity was in operation in this investigation. Herve is an immigrant from Haiti; this was his third winter in Massachusetts. His proposal makes the phenomenon of water freezing outdoors strange and wondrous, something to be investigated rather than taken for granted. Thus, the idea of re-freezing a melted ice cube became an object of curiosity for him, and, as it happened, he was in an instructional environment that invited him to put his curiosity into contact with scientific ideas. As a result, Herve's sense that re-freezing an ice cube would reveal something fascinating and important to their inquiry came to be collectively held by the class as a whole.

By pointing this out, we do not mean to stereotype Herve or the other children. We are not saying that all children from tropical environments would have pursued matters in the way that Herve did, nor that Herve's idea might not have occurred to a child raised from

birth in Massachusetts. Instead, our point here is that Herve introduced a different way of seeing something as mundane as a melted ice cube in a baggy and that engaging with this way of seeing brought out multiple resonances for the children. In this sense, Herve's move and the class's encounter with it became instructionally generative.

To conclude this section, we would like to make two points about the language the children used in Excerpt 1, as examples of transformative contact between different points of view and its relation to expanding understanding. First, we would like to note the novelty of terms like "your heat," "the warm," "the hotness," "body heat," and "we huddled our heat." The children created these linguistic innovations as part of their emerging understandings. From a cognitive linguistic point of view (Amin, 2001), they took meanings they had previously understood as descriptors of everyday sensory experience (e.g., both as adjectives – "hot," "warm" – and as verbs "getting hot," "heating up) and nominalized them (e.g., "the warmness," "the hotness"). Why do this kind of language work unless there is some need? In this case, "hotness" was becoming an object or quantity of interest in its own right as the children's understanding grew; it was no longer just a physical sensation. They *needed* to be able to point to, index, discuss, and interrogate it as a phenomenon. And for that, they needed a noun. Halliday & Martin (1993) have noted that it is standard practice in science to transform processes or actions into nouns; for example, refracted becomes refraction and moving becomes motion. This enables scientists to operate on processes as if they were objects. The children transformed language in similar ways as they began to see heat as an object of investigation in its own right.

Second, we would like to note changes in the nature of the explanations the children offered in response to Mary's question, "Why do we wear coats in the winter?" Prior to the fire drill, they said things like, "because it is cold," and "to stay warm because it's windy and cold." These responses were based in their everyday knowledge of ways to respond to the reality of winter in New England. After the fire drill, however, their thinking about coats was infused with the Second Law, aspects of which they used to frame causal explanations, i.e., "Because your blood is warm-blooded and the warm goes into the coat." "... when you zip [your jacket] all the way up to the top it traps um the warmness in you." "...when you go outside your body heat fl-flows out of you, but when you put a coat on it acts as a stopper for the body heat and it traps it."

In an analysis of scientific texts, Gee (2008) showed that when scientists write for different audiences, e.g., popular magazines like National Geographic or Natural History vs. scientific journals, their writing styles change markedly. Among other things, texts written for scientific journals foreground theory and causal connections among natural phenomena because their purpose is to provide evidence for theory-building activity. Popular texts, in contrast, are descriptive in nature, telling stories about organisms or systems rather than making claims about theory. We want to highlight a similar kind of shift we see in the explanations the children constructed before and after the fire drill. While we are certainly not claiming that the children commanded genres as professional scientists do, we believe that this shift reflects the fact that they were beginning to see heat and cold in ways that were becoming coordinated with both scientific (e.g., Second

Law, heat transfer, insulation) and everyday perspectives (e.g., their knowledge of coats). As “hotness” was becoming a distinct quantity for them, they now could – and perhaps needed to – begin to account for its behavior. Thus, re-conceptualizing hotness as a quantity opened up new opportunities for exploring how heat behaves, and enabled the children to work with it as a component of a causal explanation.⁸

A final comment on the fire drill. There is no question that the talk that occurred in Excerpt 1 was motivated – at least in the moment – by the fire drill, which although unplanned was experienced by the children in ways that made heat transfer salient (i.e., they literally felt it). However, the children’s subsequent conversation did not happen by chance. By design, they had engaged for almost two months with aspects of temperature, heat transfer, phase change and their relationships. The fire drill took on significance because of the children’s prior work and because in the moment Mary – based in her knowledge of children, her understanding of the scientific ideas under study, and her previous experiences learning science as an adult (at CKC and in other forums) – saw the possibilities it afforded and capitalized on them. We feel certain that if the fire drill had not happened, some other event would have catalyzed the children’s thinking in a similar, if less dramatic, way. By creating encounters between everyday and scientific meanings over the course of several months, with opportunities to think through relationships between possible meanings, the children were positioned to see their experience and the ideas inherent in the Second Law in light of each other. Thus, the fire drill also represents productive engagement with heterogeneity.

Phase Two, January to Mid-February, 2003:

Inquiry into the Particulate Nature of Matter and Phase Change

In this section, we address the children's sense-making activity into the particulate nature of matter and phase change. We summarize their activity for the month of January and present an analysis of an excerpt from Sherlock that took place in early February. As the children explored the Second Law, they became fascinated with phase change. They had many questions about melting and freezing, events which a few months before had seemed commonplace and not in need of explanation. Not only did the children participate eagerly in the phase change activities we introduced but they initiated some of their own, as illustrated by their ongoing interest in Herve's baggy.

In late January, the children's interest extended to evaporation when they noticed that water left in a paper cup from an earlier experiment had disappeared. When Mary asked them what they thought had happened, they said the water "evaporated." But as each child explained what she or he meant, it became clear that they had many different ways of thinking about this phenomenon. Some said that the water had "disappeared into the air." Herve said he thought it was like clothes hung outside: "the water inside it blows, it dries." Rosalynde thought it might have gone "into the cardboard in the cup." Kenthea wondered whether the water inside Herve's ziplock bag had evaporated and, if so, where had it gone? The children's inquiry into the Second Law had created deep curiosity about processes of phase change.

In the children's curiosity, the design team saw an opportunity to introduce the particulate nature of matter. Our decision was motivated in part by the nature of their questions and in part by our view that learning to "see" through a disciplinary perspective entails grappling with the core ideas that organize a discipline. Specifically, we wanted to know if putting the particulate nature of matter out for interrogation, in much the same way we had done with the Second Law, would help the children understand how processes of heat transfer and phase change are explained in physics.

January 30, 2003

We introduced the children to a molecular simulation, Simple Molecular Dynamics⁹ (SMD). Using a simple model of phase change, the simulation allows users to observe the effects of increasing and decreasing amounts of heat on approximately 200 particles (technically, atoms) of a noble gas (e.g., helium, neon). Although SMD simulates phase change in noble gases, we scaffolded the children's understanding by telling them it was a model of water. We encouraged them to think about the object on the screen as a tiny piece of ice composed of molecules sitting inside a closed container that was itself surrounded by water (i.e., a heat bath). To further support this interpretation, Mary placed a cup containing an ice chip and a cup containing liquid water next to the computer as exemplars of what they were seeing on the screen. (Figure 1 shows five printouts from the simulation showing conditions of increasing heat.)

As SMD begins, individual molecules of “ice” are closely aligned and vibrate in place (see Printout 1, Figure 1). As the molecules are slowly heated, they vibrate with increasing frequency, and gradually, start to move apart as the energy of a given molecule overcomes the attractive bonds holding it in place (Printout 2). As the heating process continues, more and more molecules escape their bonds and the solid becomes a liquid (Printout 3). When more heat is added, individual molecules gain enough energy to break free and become vapor (Printouts 4 and 5).

----- insert Figure 1 about here -----

The students were first shown phase change from solid to liquid, and then after some discussion, phase change from liquid to vapor. They were captivated by what they saw. They watched with mouths agape, describing aloud what they thought they were seeing (e.g., “All the molecules are constantly moving.”; “They’re melting!”; “Whenever they bump into each other they go the opposite way.”). They accurately predicted how the molecules would act when the “water was boiled” (“It’s going to evaporate!”; “I think they’re going to move around more because it’s getting hotter.”; “They’re going to go up farther.”). Among other things, they were fascinated by the behavior of molecules as they sped around the container, bouncing off the lid, the sides, and one another, sometimes being recaptured in the remaining liquid and other times not. As can be seen from these examples, many of the children’s comments suggested that they were engaged in figuring out the “rules” of the simulation and relating these to their everyday knowledge of the behavior of water at the macroscopic level.

At the end of Sherlock, the design team introduced the students to a simplified version of the particulate nature of matter. It read:

The Molecular Hypothesis

EVERYTHING is made of molecules. Molecules are little particles that are always moving. They attract each other when they are a little distance apart. They repel each other when they are squeezed into one another. When heat flows into an object the molecules of that object move faster. When heat flows out of an object the molecules of that object move slower.

A poster of the Molecular Hypothesis was hung on the classroom wall beside the poster of the Second Law. By the end of class, the children had been formally introduced to the ideas that 1) matter is composed of molecules, which are in constant motion; 2) changes in the behavior and organization of matter at the molecular level can explain visible states and transformations of materials, 3) temperature and heat can be understood in terms of molecular motion, and 4) molecules are not in stuff, they are stuff.

February 5, 2003

The following week, Mary started Sherlock by asking: “Does anyone remember the simulation? What did you see?” The children took this up as an opportunity to probe possible relationships among the Second Law, their experience with water at the macroscopic level, and their emerging understanding of the particulate nature of matter. In particular, they wanted to understand how the behavior of the water molecules in the simulation related to evaporation. Excerpt 2 below took place approximately six minutes

after Mary's initial question and lasted for about six minutes. (The entire discussion was about 38 minutes long.) We enter the discussion as Jewel posed what we regard as a thought experiment on evaporation. She was speculating on how molecules of water vapor would behave in a container that has "little holes in the like top of it."

Excerpt 2: "Does anyone remember the simulation? What did you see?"

1. Jewel: Um the molecules- it looks like- I think - I think like once it gets hotter- it keeps on getting hotter so when they separate they kind of- besi-why- besides if you put- if - wait- so if they didn't have a lid on like the top of the container or something- um- what if – what if they- if- well if they went out then how could they come back in? I know there's like air and molecules in the room but how could- like if you put little holes in the- in the cup- like in the like top of it? Then maybe the molecules could come out and some of them could stay in.
2. Mary: If you have a cover some of them could stay in?
3. Jewel: I'm saying- no I'm saying like if you put the cover (on) and you put holes in then maybe the- maybe half of them would stay in and half would stay out.
4. Mary: Okay. Does anyone else want to say anything about this? Rayelle?
5. Rayelle: Well uh mine is almost like Jewel's- mine is almost like Jewel's, it's like if you have a cup and an ice cube in it and //then it gets really hot
6. Mary: //I can't hear you.
7. Rayelle: (1.8) If you- if you have a cup with an ice cube in it and then you- and then you ah- I mean um it's cold and then it gets really hot and then after the

- molecules all spread apart like how do they know to come back? Like why- why do they come back?
8. Mary: Okay. Helen?
 9. Helen: Well to answer Rayelle's question they come back when it's- when it gets colder (.) and they spread apart when it's- when it gets hotter.
 10. Mary: Remember the ice cubes Herve had us put over here? ((knocks on window)) When it was warm what happened to the ice cubes?
 11. Rayelle: (They melted.)
 12. Mary: And then when it got cold what happened?
 13. Rayelle: They freezed. (.) They freezed.
 14. Mary: They froze again. Is that what you mean Helen?
 15. Helen: Yeah.
 16. Mary: Okay why don't you look around and see if someone's hand is up? And you call on the next person who has a remark okay? And let's do that. I'll stay out of it and you guys talk.
 17. Jewel: Um I actually- I want to talk to like Helen. Um I'm actually combining this and it's kind of like a question. Helen, what if you- what if we put- like it's combining- like what if we put holes in the cup and then we put it outside? Would it esc- would you think it would escape?
 18. Helen: Um well (2.0)
 19. Rayelle: I don't think it's gonna escape cuz it's already cold outside ()
 20. Jewel: Yeah but she's saying that- we're- I'm kind of saying- we're kind of saying that it's gonna- that it probably would- that the molecules would probably

- escape if- because they wouldn't bounce off the- because there was holes on the top so the molecules wouldn't bounce off so it would probably go out. Kenthea?
21. Kenthea: Well (.) I actually think if you put it outside just like what happened in those Ziplock bags they would freeze (.) But if you had little holes in them like when- when we hold- held the Ziplock bags in our hands and we let 'em melt? And they turned into water and we put it outside and it froze and if you put water outside a cup I think it would like- not water outside the cup like- when you put it outside and you had holes in it it would freeze.
22. Jewel: So you're saying that if it did fre- if it did freeze it wouldn't be able to be f- like free which- it would just be trapped in the ice cube.

Three of the four children who speak in this excerpt, Jewel, Rayelle and Kenthea, are from non-dominant communities. Jewel, who is European American, and Rayelle, who is African American, are from single-parent, high school-educated households. Although only in fourth grade, Jewel has had a disrupted school experience, moving from school to school within and across years as her place of residence changed. Kenthea is an immigrant from Haiti and learning English as a Second Language. All three girls receive free/reduced lunch. The fourth student, Helen, is European American and from a middle class, college-educated family. Together, these four girls explored evaporation using a view of the particulate nature of matter. (See Table 2 for a summary of the ideas that each child referred to in Excerpt 2.)

Jewel, Rayelle, and Kenthea worked with four of the five big ideas under study. (They did not take up the idea that molecules are not in stuff, they are stuff.) Helen worked with two of the ideas (matter is composed of molecules that are in constant motion; temperature and heat can be understood in terms of molecular motion). In the following analysis, we describe how, in Excerpt 2, these students worked to explain evaporation, coordinating what they knew from a variety of perspectives (i.e., the simulation, their experiences with melting and freezing, Herve's ziplock bag) with four of the five big ideas under study.

----- insert Table 2 about here -----

In her thought experiment, Jewel played with the constraints of the simulation to account for the kind of complexity the class had encountered earlier in their work and she knew existed in the world. She used aspects of the Second Law and the particulate nature of matter to explore where water goes when it is heated. In line 1, she wondered how water molecules that have been heated might behave if someone “didn't have a lid on like the top of the container... if they [the molecules] went out then how could they come back in?” Then in line 3, she speculated that “if you put the cover (on) and you put holes in then maybe the- maybe half of them would stay in and half would stay out.” Jewel complicated the world represented in the simulation, opening it up, so that she could explore her own experiences with water through a view of the particulate nature of matter.

Jewel's language reflects the extent to which the world of the simulation and the real world had fused with one another. At first she talked about a "container" that "didn't have a lid on like the top," language that the class had used the previous week to refer to the simulation. But as she elaborated the specifics of the scenario she imagined the container as a "cup," language the class had used consistently as they experimented with real cups and real ice cubes to explore the Second Law. In fact, aspects of these worlds are so merged in Jewel's utterance that it is hard to tell if she was referring to a real cup, the simulation, or some other entity.

Rayelle (lines 5 and 7) wondered about relationships among evaporation, condensation, the Second Law, and the perspective represented in SMD. The worlds of the simulation, the Second Law, and everyday experience merged as she talked about "a cup with an ice cube in it" that got "really hot... after the molecules all spread apart." Like Jewel, Rayelle worked hard at coordinating molecular-scale and macroscopic perspectives and, in the process, merged scientific and everyday perspectives in analytically generative ways.

In lines 10, 12, and 14, Mary asked a series of questions about Herve's baggy. Her questions pushed Jewel (lines 17 and 20) to expand her thought experiment by "combining" the cup with holes and the class's observations of the effects of cold on Herve's baggy "outside". Although we don't know why, Jewel turned to Helen for an answer (line 17). Then Rayelle (line 19) jumped in to help work through the problem. She rejected the idea that the molecules would escape because "it's already cold outside."

Despite Rayelle's response, Jewel held to her view that the molecules would escape (line 20).

This prompted Kenthea (line 21) to sketch a scenario grounded in their common experience (melted ice cube water in ziplock bags) and analogous to Jewel's thought experiment along several important dimensions (e.g., both the ziplock bag and Jewel's imagined cup contained warm water; both had holes; both were outside where it was cold). By drawing an analogy between the simulation and the ziplock bags, Kenthea helped Jewel see SMD from a different perspective, a macroscopic point of view (line 22): "So you're saying that if it did freeze it wouldn't be able to be f-like free which- it would just be trapped in the ice cube." Here, Jewel articulated for herself and others the idea that molecules that are in the process of freezing or are frozen are not "able to be f-like free" (i.e., to evaporate) but are "trapped in the ice cube."

Jewel's use of language here, in particular her use of "it," is ambiguous. Does "it" refer to a molecule, or to water at a macroscopic level? While these ambiguities of reference could be viewed as troublesome (i.e., imprecise or confused), we would argue that in such cases ambiguity functions generatively, allowing the children to dwell in both molecular-scale and macroscopic worlds simultaneously in intellectually productive ways. Here we see Jewel and the others working at coordinating these different but related ways of seeing. Indeed, the design team encouraged the children to think simultaneously about molecular-scale and macroscopic-scale worlds by presenting SMD as a model of water.

Summary of Phase Two

In this section, we have analyzed the children's sense-making as they explored aspects of the particulate nature of matter across the course of five weeks. We have highlighted their discussion of SMD (Excerpt 2) as an example of the generative ways they navigated a heterogeneous space populated by the particulate view, the simulation, and material phenomena.

In Excerpt 2, the children's thinking was motivated by Jewel's thought experiment, which both expanded and complicated the meanings with which they were working. Her question challenged them to think about a situation they had not seen simulated in SMD (i.e., evaporation in an open container), one that required them to push beyond the boundaries of both their immediate experience and the simulated world. They did this by not only working within the perspective represented in the simulation (e.g., Jewel's formulation of the problem, Helen's response to Rayelle) but also by merging simulated, imagined, and real world meanings into a new formulation, and using this to move analytically between their understandings of SMD and phase change in water at the macroscopic level (e.g., Rayelle's question and subsequent response to Jewel; Kenthea's response to Jewel; Jewel's realization about the relationship between freezing and evaporation). When Kenthea drew an analogy between the world of the cup – itself a contact zone between simulated and real worlds – and the world of the ziplock bag – located in the children's activity – and then suggested manipulating the bag (“if you put it outside and you had holes in it”), she helped Jewel see and articulate aspects of the relationship among changes in temperature, molecular behavior, and phase change at the macroscopic level.

As the children worked to understand the particulate view of matter and evaporation, they flexibly took on roles of both teacher and learner. As they made their thinking public, Jewel and Rayelle created the conceptual space. Helen and Kenthea joined them in populating that space meaningfully. These children asked one another questions (e.g., Jewel's question for Helen), offered one another responses (e.g., Helen, Rayelle, and Kenthea), and listened carefully to those responses (e.g., Rayelle and Jewel) as they co-constructed meaning. The eagerness with which they took up and lived inside aspects of the particulate view reflected their desire to account for not only how heat flows between objects and how phase change happens but also how molecular and macroscopic points of view are related.

The children were able to do this in part because, with Mary, they had expanded the space of communicative activity beyond what is typically permitted in elementary school science. As a result, we see children who might otherwise feel marginalized in school science assuming voices of intellectual agency. For example, in other Discourse spaces in the classroom (e.g., during reading or social studies), Jewel could sometimes be difficult to understand and therefore experienced frustration as she tried to express herself. In many classrooms, she would simply have remained silent. Here, however, she felt free to propose a thought experiment as it was unfolding for her, knowing that if her talk was unclear to her listeners, they would help her unpack and elaborate it, rather than correct or dismiss it. Likewise, we see Kenthea mobilizing a social practice common among many communities of African descent, in which children assume caretaking roles with respect to other children (Burton, Allison & Obeidallah, 1995; Rogoff,

2003; Spencer, 2008). Here her reminder to Jewel that there were conceptual connections between the latter's thought experiment and their common experiences with melting and freezing water served co-constitutive intellectual and social care-taking functions for her friend. It is interesting to note that at other times and in other Discourse spaces in the classroom (i.e., outside of Sherlock) similar moves by Kenthea were sometimes construed as intrusive, rather than helpful, by Mary and the other children. In this moment in Sherlock, social form merged comfortably and naturally with intellectual function.

The various roles the children assumed share some interesting similarities with the pedagogical strategy of revoicing, which has been shown to be an important feature of teacher's discourse in classroom discussion (Forman, Larreamendy-Joerns, Stein, and Brown, 1998; O'Connor & Michaels, 1993), and with intellectual role-taking, an approach that scaffolds all students to ask each other questions and deeply engage with relevant conceptual ideas during classroom discussions (Herrenkohl, 2006; 1998). Notably in this case, it was the children themselves who negotiated which ideas needed additional probing and the roles they would take on as part of that process.

Summary of Assessment of Student Learning

At the end of the unit, we assessed the children's understanding of the five "big" ideas through two benchmark discussions and a written test. We present a summary of our findings here.

Benchmark Discussions

In mid-February, the design team used a variation on benchmark discussions (diSessa & Minstrell, 1998) to see whether and how the students would use the five big ideas to think about phase change in two substances they had heretofore not considered in class: rock and ice cream. We expected the discussion about rock to be challenging because the students' understanding of melting and freezing points (i.e., that ice melts quickly at room temperature but freezes only under "special" conditions in a freezer) did not hold for rock. We expected the discussion about ice cream to be challenging because their understanding of freezing, modeled on water, did not fit neatly with the behavior of cream as it is cooled and whipped into ice cream (a semi-solid or colloid). To mediate the first discussion, the children watched a short video segment of an erupting volcano. To mediate the second and to bring the investigation full circle, Mary and the children made ice cream again, something they had not done since October.

Throughout both discussions, the children explored possible causal connections among heat transfer, temperature, and molecular motion. During their discussion of volcanic eruption, they described differences between the melting points of water and rock, and used the SMD printouts to map "melting" and "freezing" behaviors of rock and water at a macroscopic level to behaviors at a molecular level. During their discussion of ice cream making, they used their developing understandings of the Second Law and the particulate nature of matter, along with the SMD printouts, to explain at a molecular level

differences they knew existed between “frozen” ice cream and frozen water at the macroscopic level (e.g., the difference between “chewing” ice, which is hard, and “chewing” ice cream, which is not), and differences they imagined taking place in molecular behavior as the cream cooled (e.g., molecular behavior corresponding to “hot” cream, “cold” cream, and “ice” cream). Our analysis of the benchmark discussions showed that students marshaled their understandings to think generatively about different, familiar substances (e.g., rock, ice cream) and novel conditions (e.g., different melting and freezing points), which, according to Hall & Greeno (2008), is a hallmark of robust learning.

Written Assessment, May, 2003

In May, the children took a written test consisting of six questions. Three of these were developed by the design team to assess the students’ understanding of the particulate nature of matter and were extensions of activities they had done in class. Three other questions tested their understanding of heat transfer and were taken from standardized science achievement tests. Two of the achievement test items were from 3rd/4th grade tests (TIMSS, IEA, 1997; Massachusetts Comprehensive Assessment System, MA DoE, 2000); the third item was from an 8th grade achievement test (Massachusetts Comprehensive Assessment System, MA DoE, 2002). Inclusion of standardized achievement test items enabled us to compare, in a small way, these children’s performance to that of other students.

Mean percent correct across six questions for all students was 90%. Students scored slightly higher on the three items developed by the design team (92%) than on the three standardized items (88%). That said, 95% of the students answered the 3rd/4th grade TIMSS item correctly (international average for 4th graders is 47%) and 90% answered the 4th grade MCAS item correctly (MA state average is 62%). And, of greater interest, 80% of the students answered the *eighth* grade MCAS item correctly (MA state average for eighth graders is 67%). Thus, students did well on the written test, scoring well above their grade-level peers as well as older students.

Together, the results from the benchmark discussion and the written test demonstrate that the children developed understanding of four of the five big ideas we set out to teach: 1) the Second Law of Thermodynamics; 2) matter is composed of molecules, which are in constant motion; 3) changes in the behavior and organization of matter at the molecular level can explain visible states and transformations of materials; and 4) temperature and heat can be understood in terms of molecular motions. It is important to note that we do not know what they learned about the fifth big idea: molecules are not in stuff, they are stuff. Although comments about molecules as ingredients gradually dropped out of the children's talk, we did not probe it directly in our assessments, and are therefore unable to characterize their end-of-unit understanding of it.

Conclusion

At the beginning of this paper, we wondered what it might mean if, as a field, we were to conceptualize the heterogeneity of human cultural practices and experience as fundamental to everyday life and learning (Erickson, 2003; Moll, 2000; Nasir, et al., 2006; Rogoff, 2003). As discussed earlier, inspired by Bakhtin (1981), we see heteroglossia – varied ways of conceptualizing, representing, evaluating and engaging the world through language – as a core, pervasive manifestation of heterogeneity in lived experience. Consonant with this, we view classrooms as spaces in which whole systems of meaning or ways of seeing the world come into contact with one another, in both planned and unplanned ways. In the case presented here, we designed instructional encounters with the aim of fostering contact among varied languages and points of view in order to generate learning of disciplinary ways of seeing the world. Our design was, inevitably, both intentional and open to unforeseen possibilities. By way of closing, we would like to share some key design principles, some of which we anticipated, and some of which emerged in the course of the study.

First, building on prior work in the learning sciences (Hammer & Elby, 2003; Krajcik & Blumenfeld, 2006; Lee & Sherin, 2006; Linn & Hsi, 2000), we provisioned the classroom with scientific tools, materials, and activities designed to make the structure and big ideas of the domain visible to students (e.g., posters of the Second Law and a particulate nature of matter; the SMD simulation). We explicitly encouraged contact among the varied Discourses (Gee, 1990), or languages (Bakhtin, 1981), circulating in the classroom.

Based in our knowledge of the discipline, the design team created encounters that encouraged the children to bring scientific and everyday perspectives into contact. Of equal instructional importance was the contact that emerged from the children's own activity and insights (e.g., Herve's baggy, fire drill), which they imbued with significance.

Second, we intentionally broadened the Discourse space typically found in elementary science, and in education more generally, to allow every student to use his or her everyday ideas and heterogeneous ways of knowing and talking as resources for understanding scientific ideas (Ballenger, 2009; Hudicourt-Barnes, 2003; Rosebery & Warren, 2008). This included, for example, taking up those ideas and experiences the children marked as important (e.g., Herve's baggy), and encouraging inventive use of language (e.g., "body heat"), including narrative, metaphor and analogy, to construct scientific explanations (e.g., Donnell's explanation of how a coat works). An assumption that underlies the expansion of Discourse spaces is that children are routinely making sense, even when teachers and researchers do not understand them.

Third, new meanings developed through the *analytic* work the children did across boundaries of everyday and scientific worlds (Rosebery, 2005; Warren et al., 2001; Warren, Ognowski & Pothier, 2005). Their ideas and ways of knowing and talking became objects of inquiry in their own right, alongside "official" forms (e.g., the Second Law, a particulate view of matter). They analyzed everyday phenomena such as melting ice cubes and wearing coats through the Second Law; and they animated the Second Law

as they reinterpreted previous learning and experience (e.g., Steve's insights into "huddling heat" and the Wampanoag's Long House). This kind of cross boundary analysis allowed them to begin to see how behavior and organization of matter at the molecular level could explain changes to visible states of substances like water, rocks, and ice cream, and to relate these in meaningful ways.

An unanticipated result of contact among varied languages was the productive role that ambiguity played in the children's learning. By design, we encouraged contact between simulated and real worlds in order to scaffold the children's understanding (i.e., representing SMD as a model of phase change in water and reinforcing this interpretation by putting ice and water in front of the children during the demonstration). Our analyses showed that symbolic and real world referents were sometimes completely blended in the talk of the children, and that this blending allowed them to coordinate and explore objects and meanings in both simulated and real worlds. Nemirovsky, Tierney & Wright (1998) have called the process by which such ambiguity is created "fusion." They have described it as "merging qualities of symbols with qualities of the signified events or situations, that is, talking, gesturing, and envisioning in ways that do not distinguish between symbols and referents" (Nemirovsky et al., 1998, p. 141). A similar kind of fusion has been identified in the work of practicing scientists. Ochs, Gonzales & Jacoby, 1996, for example, showed how a group of solid state physicists, exploring atomic properties and interactions within magnetic solids, projected themselves via language and gesture into the physical system represented in the graph they were trying to understand. According to Ochs et al. (1996, p. 348), this kind of fusion allowed them to

“symbolically participate in events from the perspective of entities in worlds no physicist could otherwise experience.” While some educators may regard fusion as problematic, we regard it as a pedagogical inevitability. From our point of view, this kind of merging has a generative function because it allows learners to explore and coordinate relations among different ways of seeing (Goodwin, 1994; 2000).

Fourth, as designers we were intently attuned to the children’s meaning-making, and to the emergent pedagogical possibilities it afforded. We assumed they would make visible to us and each other what particular relationships or aspects of heat transfer and phase change might be in need of further elaboration, how that might best be done, and what roles should be played by whom in making this happen (e.g., the design team’s introduction of SMD; Kenthea’s strategic coordination of the simulation and the zip lock bag in response to Jewel). As we have tried to make clear through the analyses, the children showed us and one another repeatedly, in local moments of interaction, exactly what needed to be elaborated through the actions they took, the questions they asked, and the meanings they explored.

As we have argued here, whether or not it is officially recognized and taken up in school, heterogeneity is fundamental to life and learning (González, Moll, & Amanti, 2004; Gutiérrez, Baquedano-López, & Alvarez, 2001; Moje et al., 2004; Nasir et al., 2006). By way of closing, we would like to raise two implications for learning theory, practice, and policy that, in our view, are part and parcel of taking heterogeneity seriously.

The first is that when heterogeneity is deeply engaged, the opportunities for learning multiply. As we have tried to show, it can result in deep and rigorous learning for all students, that is, students from non-dominant as well as dominant communities. The second implication is that in the era of NCLB, when standardized performances, especially on high-stakes tests, are so consequential, teachers are under enormous pressure to narrow, rather than expand, what and how they teach. They are both covertly and overtly encouraged to limit the material, conceptual, and linguistic resources available to students, the instructional approaches they use, and what counts as scientific in the classroom. In our experience, this mindset works actively against the kind of deep, engaged learning described here, learning that is grounded in intense curiosity and emergent insight. Such moments, when the familiar becomes strange and wondrous, happen routinely in classrooms. What is in question is whether teachers continue to be prepared – or feel authorized – to capitalize on them as expansive teaching opportunities.

Thus, we close with a conundrum. On the one hand, the current state of educational policy suggests that mounting serious efforts to take up heterogeneity as foundational to learning will be difficult at best. On the other, if our goal is to understand, theorize, and represent learning and development in ways that reflect and mobilize the rich diversity of human experience, ignoring heterogeneity is not an option.

References

- American Association for the Advancement of Science/Project 2061. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.
- Amin, T. (2001). A cognitive linguistics approach to the layperson's understanding of thermal phenomena. Alan Cienki, Barbara Luka, and Michael Smith (Eds.), *Conceptual discourse factors in linguistic structure*. Stanford, CA: CSLI Publications.
- Amin, T. (2000). *Cognitive models, conceptual construals, and language in science learning*. Paper presented at the 30th Annual Meeting of the Jean Piaget Society, Montreal, Canada.
- Bakhtin, M. M. (1986). *Speech genres and other late essays*. Austin, TX: University of Texas Press.
- Bakhtin, M.M. (1984). *Problems of Dostoevsky's poetics*. Minneapolis: University of Minnesota Press.
- Bakhtin, M. M. (1981). *The dialogic imagination: Four essays*. Austin, TX: University of Texas Press.
- Ball, D.L., and Wilson, S. (1996). Integrity in teaching: Recognizing the fusion of the moral and intellectual. *American Educational Research Journal*, 33(1), 155-192.
- Ballenger, C. (2009). *Puzzling moments, teachable moments*. New York: Teachers College Press.
- Bang, M., Medin, D.L., & Atran, S.A. (2007). *Cultural mosaics and mental models of nature*. Proceedings of the National Academy of Sciences.

Brown, A. (1992). "Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings". *Journal of the Learning Sciences*, 2, 141 – 178.

Burton, L., Allison, K., & Obeidallah, D. (1995). Social context and adolescents: Perspectives on development among inner-city African-American teens. In L. Crockett & A. Crouter (Eds.), *Pathways through adolescence: Individual development in social contexts* (pp. 119-138). Mahwah, NJ: Lawrence Erlbaum

Calabrese Barton, A. & Tan, Ed. (2009). Funds of knowledge, discourses and hybrid space. *Journal of Research in Science Teaching*, 46(1), 50-73.

Cazden, C. B. (1988). *Classroom discourse: The language of teaching and learning*. Portsmouth: Heinemann.

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

CHiLD (2005). The Center for the Study of Human Learning and Development: A proposal submitted to the National Science Foundation. C. Lee, B. Warren & K. Gutiérrez, Principal Investigators.

Civil, M. (2005). Building on Community Knowledge: An Avenue to Equity in Mathematics Education.

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

- Cobb, P., Confrey, J. diSessa, A. Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher*, 32(1), 9-13.
- Cole, M. (2000). Struggling with complexity: The Handbook of Child Psychology at the Millennium. Essay Review. *Human Development*, 6, 369-375.
- Cope B. and Kalantzis, M. (1993). *The powers of literacy: A genre approach to teaching writing*. Pittsburgh, PA: University of Pittsburgh Press.
- Delpit, L. (1986). Skills and other dilemmas of a progressive Black educator. *Harvard Educational Review*, 56 (4), 379 – 386.
- Design-Based Research Collective (2003). Design-based research: An emerging paradigm. *Educational Researcher*, 32(1), 9-14.
- diSessa, A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, 10(2 and 3), 105-225.
- DiSchino, M. (1998). "Why do bees sting and why do they die afterward?" In A. Rosebery and B. Warren (Eds.). *Boats, balloons, and classroom video: Science teaching as inquiry*, pp. 109-133. Portsmouth, NH: Heinemann.
- diSessa, A. (2000). *Changing minds: Computers, learning and literacy*. Cambridge, MA: MIT Press.
- diSessa, A., Hammer, D., Sherin, B., and Kolpakowski, T. (1991). Inventing graphing: Meta-representational expertise in children. *Journal of Mathematical Behavior*, 10, 117-160.

- diSessa, A. and Minstrell, J. (1998). Cultivating conceptual change with benchmark lessons. In J.G. Greeno and S.V. Goldman (Eds.), *Thinking practices in mathematics and science learning*, pp. 155-188, Mahwah: Erlbaum.
- Erickson, F. (2003). Culture in society and in educational practice. In J. Banks and C. Banks (Eds.), *Multicultural education: Issues and perspectives*, pp. 31 - 58. 5th Edition. New York: John Wiley.
- Feynman, R. (1995). *Six easy pieces: Essentials of physics explained by its most brilliant teacher*. Reading, MA: Perseus Books.
- Forman, E. A., Larreamendy-Joerns, J., Stein, M. K., & Brown, C. A. (1998). "You're going to want to find out which and prove it": Collective argumentation in a mathematics classroom. *Learning and Instruction*, 8(6), 527-548.
- Gee, J. P. (1990). *Social linguistics and literacies: Ideology in discourses*. London: Falmer.
- Gee, J.P. (1996). Vygotsky and current debates in education: Some dilemmas as afterthoughts to Discourse, Learning, and Schooling. In Hicks, D. (1996). *Discourse, learning, and schooling*, pp. 269-282. Cambridge: Cambridge University Press.
- Gee, J.P. (2008). What is academic language? In A. Rosebery and B. Warren (Eds.). *Teaching science to English language learners*, pp. 57-70. Arlington, VA: National Science Teachers Association Press.

- Gee, J. P. and Clinton, K. (2000). An African-American child's "science talk": Co-construction of meaning from the perspective of multiple Discourses. In M. Gallego and S. Hollingsworth (Eds.), *What Counts as Literacy: Challenging the School Standard*, pp. 118-135. New York: Teachers College Press.
- González, N., Moll, L., and Amanti, C. (2005). *Funds of knowledge: Theorizing practices in households, communities, and classrooms*. Mahwah, NJ: Lawrence Erlbaum Associates.
- Goodwin, C. (2000). Practices of color classification. *Mind, Culture, and Activity*, 7(1 and 2), 19-36.
- Goodwin, C. (1994). Professional vision. *American Anthropologist*, 96(3), 606-633.
- Gutiérrez, K. (2008). Developing a sociocritical literacy in the Third Space. *Reading Research Quarterly*, 43 (2), 148-164.
- Gutiérrez, K., Baquedano-López, P. and Alvarez, H. (2001). Literacy as hybridity. In M. de la Luz Reyes and J.J. Halcón (Eds.), *The Best for our children: Critical perspectives on literacy for Latino students*, pp. 122-141. New York: Teachers College Press, Columbia University.
- Gutiérrez, K. & Orellana, M. (2006). The problem of English Learners: Constructing genres of difference. *Research in the Teaching of English*, 40 (4), 502-507.
- Gutiérrez, K. and Rogoff, B. (2003). Cultural ways of learning: Individual traits or repertoires of practice. *Educational Researcher*, Vol. 32, No. 5, pp. 19 – 25.

- Hall, R. & Greeno, J. G. (2008). Conceptual learning. T. Good (Ed.), *21st Century Education: A Reference Handbook*, pp. 212-221. Thousand Oaks, CA: Sage.
- Halliday, M.A.K. and Martin, J.R. (1993). *Writing science: Literary and discursive power*. Pittsburgh: University of Pittsburgh Press.
- Hammer, D. and Elby, A. (2003). Tapping epistemological resources for learning physics. *Journal of the Learning Sciences*, 12(1), 53-90.
- Heath, S.B. (1989). Oral and literate traditions among Black Americans living in poverty. *American Psychologist*, 44(2), 367-373.
- Herrenkohl, L. (2006). Intellectual role taking: Supporting discussion in heterogeneous elementary science classes. *Theory into Practice*, 45(1), 47-54.
- Herrenkohl, L. (1998). Participant structures, scientific discourse, and student engagement in fourth grade. *Cognition and Instruction*, 16(4), 431-473.
- Hewitt, P. G. (2002). *Conceptual physics*. Reading, MA: Addison-Wesley.
- Hochschild, J. and Scovronick, N. (2003). *The American dream and the public schools*. New York: Oxford University Press.
- Hudicourt-Barnes, J. (2003). The use of argumentation in Haitian Creole science classrooms. *Harvard Educational Review*, 73(1), 73-93.
- International Association for the Evaluation of Educational Achievement (IEA). (1997). IEA's Third international mathematics and science study. TIMSS science items:

Released set for population 1 (third and fourth grades). Chestnut Hill, MA: TIMSS, Boston College.

Johnson, P. (1998). Progression in children's understanding of a 'basic' particle theory: a longitudinal study. *International Journal of Science Education*, 20(4), 393-412.

Jordan, B. and Henderson, A. (1995). Interaction analysis: Foundations and practice. *The Journal of the Learning Sciences*, 4, (1), 39-103.

Krajcik, J. and Blumenfeld, P. (2006) Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences*, pp. 317-334. Cambridge, England: Cambridge University Press.

Latour, B. (1986). Visualization and cognition: Thinking with eyes and hands. In H. Kuclick (Ed.), *Knowledge and society: Studies in the sociology of culture past and present*, 6, 1-40. Greenwich, CT: JAI Press.

Ladson-Billings, G. & Tate, W. (1995). Toward a Critical Race Theory of Education. *Teachers College Record*, 97(1), 47 – 68.

Lee, C.D. (2007). *Culture, literacy and learning*. New York, Teachers College Press.

Lee, C.D. (2002). Interrogating race and ethnicity as constructs in the examination of cultural processes in developmental research. *Human Development*, 45, 282-290.

Lee, C.D. (2000). Signifying in the zone of proximal development. In C.D. Lee and P. Smagorinsky (Eds.), *Vygotskian perspectives on literacy research: Constructing*

meaning through collaborative inquiry, pp. 191-225. Cambridge, England: Cambridge University Press.

Lee, C. D. (1993). *Signifying as a scaffold for literary interpretation: The pedagogical implications of an African American discourse genre*. Urbana, IL: National Council of Teachers of English.

Lee, V. R., & Sherin, B. (2006). Beyond transparency: How students make representations meaningful. *Proceedings of the Seventh International Conference of the Learning Sciences*: 397-403.

Linn, M. C. & Hsi, S. (2000). *Computers, teachers, peers: Science learning partners*. Mahwah, NJ: Lawrence Erlbaum Associates.

Massachusetts Department of Education. (2000). Release of Spring 2000 test items.
Available at: <http://www.doe.mass.edu/mcas/2000/release/>

Massachusetts Department of Education. (2002). Release of Spring 2002 test items.
Available at: <http://www.doe.mass.edu/mcas/2002/release/default.html>

Massachusetts Department of Education. (1995). *Massachusetts curriculum frameworks for science and technology*. Boston, MA: Massachusetts Department of Education.

Michaels, S. and Sohmer, R. (2000). Narratives and inscriptions: Cultural tools, power and powerful sensemaking. In B. Cope & M. Kalantzis (Eds.), *Multiliteracies*, pp. 267-288. London and New York: Routledge.

Moje, E. B., Ciechanowski, K.M, Kramer, K., Ellis, L., Carrillo, R. and Collazo, T. (2004).

Working toward third space in content area literacy: An examination of everyday funds of knowledge and Discourse. *Reading Research Quarterly*, Vol. 39, No. 1, 38 – 70.

Moll, L. (2000). Inspired by Vygotsky: Ethnographic experiments in education. In C.D.

Lee and P. Smagorinsky (Eds.), *Vygotskian perspectives on literacy research:*

Constructing meaning through collaborative inquiry, pp. 256-268. Cambridge:

Cambridge University Press.

Moll, L., and González, N., (2004). Engaging life: a funds of knowledge approach to

multicultural education. In J. Banks & C. McGee Banks (Eds.). *Handbook of research*

on multicultural education (2nd edition), pp. 699-715. New York: Jossey-Bass.

Morson, G. S. and Emerson, C. (1990). *Mikhail Bakhtin: Creation of a Prosaics.*

Stanford, CA: Stanford University Press.

Nasir, N. (2002). Identity, goals, and learning: Mathematics in cultural practice.

Mathematical Thinking and Learning, 4(2&3), 211-245.

Nasir, N. (2000). Points ain't everything: Emergent goals and average and percent

understandings in the play of basketball among African-American students.

Anthropology and Education, 31(3), 283-305.

Nasir, N., Rosebery, A., Warren, B., and Lee. C. (2006). Learning as a cultural process:

Achieving equity through diversity. In R. K. Sawyer (Ed.), *Cambridge Handbook of*

the Learning Sciences, pp. 489-504. Cambridge, England: Cambridge University

Press.

- National Research Council. (1996). *National science education standards*. Washington DC: National Academy Press.
- Nemirovsky, R., Tierney, C. and Wright, T. (1998). Body motion and graphing. *Cognition and Instruction*, 16(2), 119-172.
- New London Group. (2000). A pedagogy of multiliteracies: Designing for social futures. In B. Cope & M. Kalantzis, M. (Eds.), *Multiliteracies: Literacy learning and the design of social futures*. London: Routledge.
- Noble, T. (in preparation). *Atoms, molecules, and models: How do students make sense of the particulate nature of matter?*
- Ochs, E., Gonzales, P. and Jacoby, S. (1996). “When I come down I’m in the domain state”: Grammar and graphic representation in the interpretive activity of physicists. In E. Ochs, E.A. Schegloff and S.A. Thompson (Eds.), *Interaction and grammar*, pp. 328-369. Cambridge, England: Cambridge University Press.
- O’Connor, M. C., & Michaels, S. (1993). Aligning academic task and participation status through revoicing: analysis of a classroom discourse strategy. *Anthropology & Education Quarterly*, 24(4), 318-335.
- Reiner, M., Slotta J. D., Chi T., H., & Resnick L., B. (2000). Naïve physics reasoning: A commitment to substance-based conceptions. *Cognition and Instruction*, 18(1), 1-34.
- Rogoff, B. (2003). *The cultural nature of human development*. New York: Oxford University Press.

- Rosebery, A. (2005). "What are we going to do next?" A case study of lesson planning. In R. Nemirovsky, A. Rosebery, B. Warren, B., and J. Solomon, (Eds.), *Everyday matters in mathematics and science: Studies of complex classroom events*, pp. 299-328. Mahwah, NJ: Erlbaum.
- Rosebery, A. and Warren, B. (Eds.) (2008). *Teaching science to English language learners*. Arlington, VA: National Science Teachers Association Press.
- Sherin, B. (2006). Common sense clarified: The role of intuitive knowledge in physics problem solving. *Journal of Research in Science Teaching*, 43(6), 535-555.
- Smith, J.P., diSessa, A. and Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *The Journal of the Learning Sciences*, 3(2), 115-163.
- Smith, C. L., Wiser, M., Anderson, C. W., Krajcik, J., & Coppola, B. (2004). *Implications of research on children's learning for standards and assessment: Matter and the atomic molecular theory*. Invited paper for the National Research Council committee on Test Design for K-12 Science Achievement. Washington, DC, National Research Council.
- Snir, J., Smith, C., and Raz, G. (2003). Linking phenomena with competing underlying instructional models. *Science Education*, 87(6), 794-830.
- Southerland, S., Kittleson, J., Settlage, J. and Lanier, K. (2005). Individual and group meaning-making in an urban third grade classroom: Red fog, cold cans, and seeping vapor. *Journal of Research in Science Teaching*, 42(9), 1032-1061.

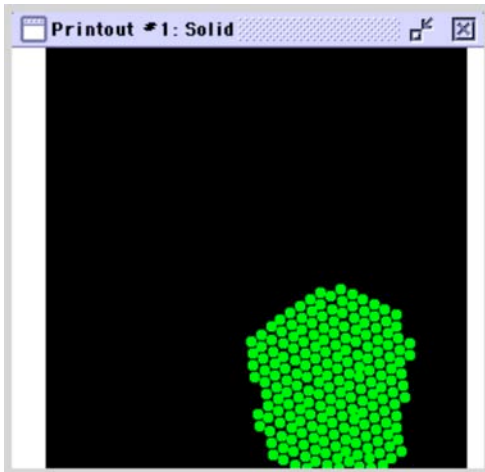
- Spencer, M.B. (2008). Lessons learned and opportunities ignored since Brown V. Board of Education: Youth development and they myth of a color-blind society. *Educational Researcher*, 37(5), 253-266.
- Ueno, N. (2000). Ecologies of inscription: Technologies of making the social organization of work and the mass production of machine parts visible in collaborative activity. *Mind, Culture, and Activity*, 7 (1and2), , 59-80.
- Varelas, M. & Pappas, C. (2006). Intertextuality in read-alouds of integrated science-literacy units in urban primary classrooms: Opportunities for the development of thought and language. *Cognition and Instruction*, 24(2), 211-259.
- Vygotsky, L. (1930/1978). *Mind in society*. Cambridge, MA: Harvard University Press.
- Warren, B., Ballenger, C., Ogonowski, M., Rosebery, A. and Hudicourt-Barnes, J. (2001). Rethinking diversity in learning science: The logic of everyday sensemaking. *Journal of Research in Science Teaching*, 38, 529-552.
- Warren, B., Ogonowski, M. and Pothier, S. (2005). 'Everyday' and 'scientific': Re-thinking dichotomies in modes of thinking in science learning. In R. Nemirovsky, A. Rosebery, J. Solomon, and B. Warren, (Eds.), *Everyday matters in mathematics and science: Studies of complex classroom events*, pp.119-148. Mahwah, NJ: Erlbaum.
- Wertsch, J. (1985) (Ed.). *Culture, communication and cognition*. Cambridge: Cambridge University Press.

Student	refers to heat flowing from one object to another	refers to heat flowing from objects at higher temperatures to objects at lower temperatures	refers to stopping, reducing the flow of heat
Arnaud (line 2)			X
Herve (line 4)	implied		
Kenthea (line 6)	X	X	X
Harriet (line 8)	X	X	X
Donnell (line 9)	X	X	
Susannah	X	X	X
Helen (line 12)	X	X	X
Manuel (line 15)	X	X	X
Steve (line 17)	X		X

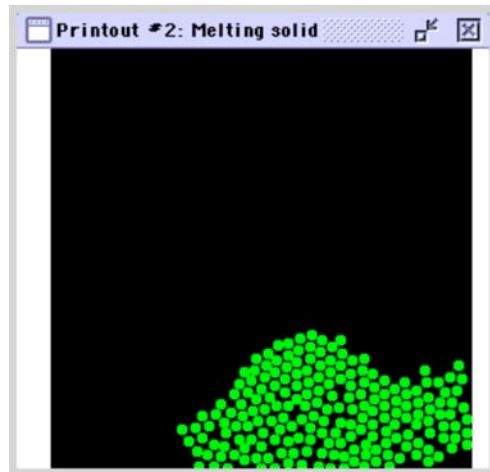
Table 1. Summary of ideas by child in Excerpt 1.

Student	Heat flows from objects at higher temperatures to objects at lower temperatures (2 nd Law)	Matter is composed of molecules that are in constant motion	Changes in matter at molecular level can explain visible states and transformations of materials	Temperature and heat can be understood in terms of molecular motion	Molecules are not in stuff, they are stuff
Jewel (lines 1, 3)		X		X	
Rayelle (lines 5, 7)	X	X	X	X	
Helen (line 9)		X		X	
Rayelle (lines 11, 13)	X		X		
Jewel (line 17)		X		X	
Rayelle (line 19)		X		X	
Jewel (line 20)		X		X	
Kentheia (line 21)	X	X	X	X	
Jewel (line 22)	X		X	X	

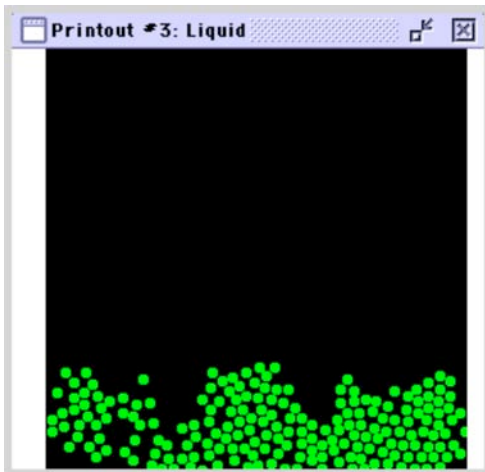
Table 2. Summary of the ideas by child in Excerpt 2



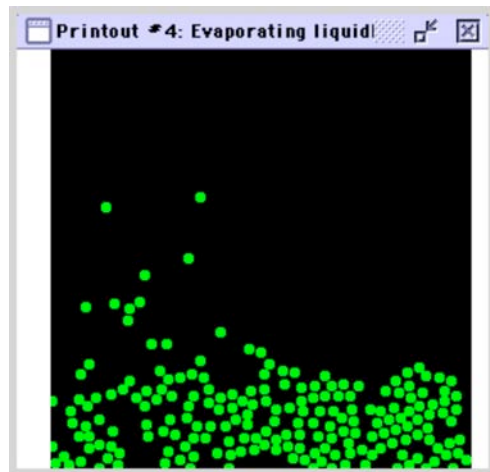
Printout #1



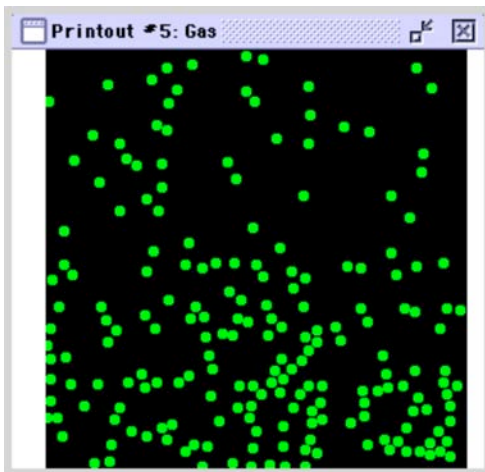
Printout #2



Printout #3



Printout #4



Printout #5

Figure 1. Printouts from SMD showing phase change under conditions of increasing heat

Acknowledgements

The research reported herein was supported by grants from the National Science Foundation (REC-0106194) and the Spencer Foundation. The opinions, findings, and conclusions or recommendations expressed herein are those of the authors, and do not necessarily reflect the views of the National Science Foundation or the Spencer Foundation.

The authors wish to thank Cindy Ballenger, Gary Goldstein, Paula Hooper, Josiane Hudicourt-Barnes, Megan Bang, Tracy Noble, Folashade Cromwell Solomon, and Eli Tucker-Raymond for their insightful comments. We would also like to thank the reviewers and editor of JLS for their on point suggestions. Finally, we wish to acknowledge the children, who have contributed much to our thinking.

Endnotes

¹ Ogonowski was a senior researcher at Chèche Konnen until 2003. He is currently an Urban Wildlife Planner with the Arizona Game and Fish Department, Flagstaff, AZ.

² DiSchino was a 3rd-4th grade teacher at the Graham and Parks Alternative Public School, Cambridge, MA until June, 2006 when she retired.

³ By students from non-dominant communities, we mean African American and African-descent immigrants, Latino/as, American Indians, Asian-Americans, Pacific Islanders, and European American youth who face persistent intergenerational poverty. Their navigation of everyday life is often complicated by asymmetrical relations of power owing to poverty, racism, and other forms of historically structured inequality.

⁴ CHiLD includes scholars and graduate students at Northwestern University; University of California (UC), Los Angeles; TERC; Stanford University; UC, Berkeley; UC, Santa Cruz; UC, San Diego; University of Pennsylvania; University of Arizona; University of Illinois at Chicago Circle; and University of Utah.

⁵ We use the terms molecule/molecular and particle/particulate interchangeably in this paper, much like physicists who often describe the particulate nature of matter as the ‘molecular’ view or hypothesis. While technically not all substances are composed of molecules (e.g., noble gases) this distinction was not important for our analytic purposes, nor did we think it was an important distinction to make for students in 3rd and 4th grade.

⁶ Like most foods produced in a kitchen or factory, ice cream is not a simple compound and does not behave as such. Ice cream is created by dispersing liquid fats and sugars, among other things, in frozen water. When frozen, it is a solid in which liquid droplets are suspended. Thus it is not strictly a solid or a liquid but is a semi-solid, sometimes called a gel or a colloid (Wikipedia, <http://wikipedia.org/w/intex.php?title=colloid>, retrieved 12/2008). Other fat-in-water food colloids include butter, whipped cream, salad dressing, and beer foam.

⁷ We use the following transcription conventions: timed pause (1.8), measured in seconds, indicates interval of silence; (.) indicates a brief pause; ? indicates rising pitch or intonation that may or may not have the grammatical structure of a question; ! indicates the conclusion of an utterance delivered with emphatic and animated tone; - indicates self interruption; > < indicates portion of an utterance delivered at a noticeably quicker pace than surrounding talk; underscore indicates stress on a word or syllable; (word) indicates uncertainty on the transcriber’s part but represents a likely possibility; () indicates that something was said but it can’t be heard; (...) indicates deleted talk; // indicates overlapping speech; (()) indicates researcher annotation.

⁸ We would like to thank an anonymous reviewer for encouraging us to analyze this difference.

⁹ Simple Molecular Dynamics is one of a suite of research-based software tools in the Virtual Molecular Dynamics Laboratory (Center for Polymer Studies, Boston University, 2000-2002,). It is available at <http://polymer.bu.edu/vmdl/>