Knowledge-Building and Conceptual Change: An Inquiry into Student-Directed Construction of Scientific Explanations

Jun Oshima
Faculty of Education, Shizuoka Univ., Japan
joshima@oise.on.ca
&
Marlene Scardamalia
Centre for Applied Cognitive Science, OISE, Canada
Marlene_Scardamalia@cacsmail.oise.on.ca

Abstract: The aim of this study was to examine conceptual change from a knowledge-building perspective. Knowledge-building is a process by which learners collaboratively improve their understanding by recording their current ideas as knowledge objects in a communal database. These ideas are then available for discussion and continual improvement. The target environment for our investigations was the CSILE (Computer-Supported Intentional Learning Environments) networked environment in which students report their thoughts as text or graphic notes, then collaboratively work to construct higher levels of understanding. A fifth- and sixth-grade combined classroom participated in this study by constructing a database on the topic of how heat affects matter. Based on computer-tracking files, students' written discourses were evaluated by two independent criteria: (1) conceptual change, and (2) knowledge-building activities. The results suggested that students who maintained knowledge-building goals and evaluated their ideas in the context of the writings of the scientific community beyond their classroom succeeded in attaining critical conceptual change.

1. Background and Problems

Recent studies of conceptual change [e.g., Vosniadou 1994] suggest that students' belief system acquired through everyday experiences prevents them from integrating new scientific principles into their existing knowledge. [Chi, Slotta, & de Leeuw 1994b; Slotta, Chi, & Joram 1995] have shown that conceptual change phenomena can be divided into two types: (1) difficult conceptual change that requires students to reject their current belief system, and (2) relatively easy conceptual change that can be attained through accumulation of new scientific knowledge. To explain the difference in difficulties of conceptual change, Chi et al. proposed an ontological perspective on scientific concepts. They assume that a concept belongs to one or more of three ontological trees in our knowledge structure: material, process, and mental state. Difficulty of conceptual change happens if an ontological tree in which students place a concept is different from a scientifically correct ontological tree (e.g., heat as material vs. heat as process).

Although studies have provided us with the theoretical mechanisms of conceptual change and methods to evaluate students' knowledge [e.g., Slotta et al. 1995], we need to clarify how conceptual change happens in classroom learning. Studies in cognitive science suggest the following: Self-explanation facilitates students' reflection on their knowledge and new principles, allowing them to integrate more mature scientific concepts with their existing ideas [e.g., Chi, de Leeuw, Chiu, & Lavancher 1994a]. Further, studies suggest the importance of a learning environment where students engage in knowledge-building activities through distribution of their expertise [e.g., Brown & Campione 1994; Scardamalia & Bereiter 1993]. Knowledge-building is a process by which learners collaboratively improve their understanding by manipulating their existing knowledge and new information through progressive discourse [Bereiter & Scardamalia 1993]. From this perspective, misconceptions are resources for improving conceptual understanding [Smith, diSessa, & Roschelle 1993]. The issue is how to create an explanatory-discourse-based community in the classroom.

In this paper, we examined a knowledge-building classroom community supported by CSILE (Computer-Supported Intentional Learning Environments). CSILE is a networked computer environment designed to support knowledge building. In CSILE, students write text or graphic notes to convey their theories. These notes reside in a communal database where other participants have access to them, and can work collaboratively to compare theories, find counterexamples, record new information bearing on these theories, provide constructive commentary, and generally work to construct higher levels of understanding [Scardamalia & Bereiter 1993; Scardamalia, Bereiter, & Lamon 1994]. The system supports students' active engagement with theories by providing: (1) note types that encourage theory formulation and analysis and sustained inquiry regarding problems of understanding, and (2) database search mechanisms that support students in the creation of a collaborative community in which they read each others' notes and work to advance the ideas contained in them.

We analyzed students' written CSILE discourse along two dimensions: (1) conceptual change and (2) knowledge-building. Based on the conceptual change in students' written discourse, we categorized students into high- or low-conceptual-change learners, then compared knowledge-building activities between the high- and low-change groups.

2. Study Description

2.1 Participants

Thirty students (21 males and 9 females) in a combined fifth- and sixth-grade classroom in a Toronto public school participated in this study. The school has an ethnically diverse, largely middle-class population.

2.2 Study Topic

The unit studied was a curriculum unit on heat and matter. Students conducted classroom experiments before they started CSILE sessions. During the seven-week CSILE sessions, they recorded their theories about how heat affects matter and worked to provide explanations of the phenomena they viewed as part of the following experiments: (1) thermal expansion by using a ring and a ball, (2) heat conduction in different objects, (3) heating bimetallic strips to see them bend, (4) heating different types of liquids, and (5) heating or cooling air captured in a container to see how the air affects water levels in another container.

2.3 How CSILE Sessions Worked

During CSILE sessions, students collaboratively engage in explanatory discourse on a shared problem. Students used discussion notes which require that they identify a problem of understanding and then enter the following note types: My Theory (MT), I Need To Understand (INTU), New Information (NI), and Comment (C). Students could then search the database by these entry types or by a variety of other attributes that CSILE records automatically (e.g., author) or that students assign to notes when they store them (e.g., topic or keywords). If they wanted to discuss a new problem that emerged in the course of pursuing the main shared problem, they created a sub-branch of the discussion note, and a subset of students pursued this line of inquiry while others continued with the central problem that they had identified. Students also generated graphic notes and created links between notes so that they could trace dialogical processes across different discussion notes, comment notes, and graphic notes [see Appendix A for an example of a CSILE-based knowledge-building episode].

The teacher had students focus on three main discussion notes, each of which dealt with a different form of matter, i.e., "How heat affects solids," "How heat affects liquids," and "How heat affects gases."

2.4 Study Design

Students were first divided into high-conceptual-change (HCC) and low-conceptual-change (LCC) learners based on an analysis of conceptual change represented in the notes they wrote over the course of this investigation. Students' knowledge-building activities were then analyzed, with emphasis on the comparison of high- and low-conceptual-change.

2.5 Assessment of Conceptual Change

Conceptual change in students' written discourse in CSILE notes was evaluated based on Chi et al.'s *category test* [1994b; Slotta et al. 1995]. The category test is a new method to assess which ontological tree(s) students attribute concepts to by classifying predicates the students used in their explanations. Two independent raters (inter-rater agreement = .93) classified concepts used in students' explanatory discourse as (1) material-based (e.g., heat as substance *having volume*), (2) process-based (e.g., heat as dynamic movement of molecules in objects), and/or (3) mental-state-based (e.g., molecules as substance *trying to avoid* heat).

On the basis of the category test of concepts used by students, two different types of learners were identified. As we described in the procedure, students were engaged in their knowledge-building with the three main problems such as: (1) how heat affects solids, (2) how heat affects liquids, and (3) how heat affects gases. Students who attained a process-based conceptual understanding of heat in at least two of the three problems were classified as HCC learners, whereas the remaining ones were classified as LCC learners. The notes that were used to make this judgment were eliminated from subsequent analyses so that the activities surrounding conceptual advances could be analyzed independently of the conceptual advance itself.

2.6 Evaluation of Knowledge-Building Activities

Knowledge-building is a process by which learners collaboratively use their current understanding as a knowledge object -- a written account of their ideas that they can return to in an effort to construct a higher level of understanding. In CSILE, such activity is reflected in how students report their theories, add new information, state what they need to understand, and help to improve each other's knowledge objects. Each note is labeled by its "thinking type" (my theory, new information, I need to understand, and comment). Two independent raters evaluated the students' knowledge-building activities by analyzing the following aspects of students' notes.

2.6.1. Pedagogical orientation (inter-rater agreement = .95)

We categorized each entry as either task-oriented or knowledge-building oriented [Bereiter & Scardamalia 1993]. A *task-oriented* goal means that students are completing assigned tasks or directly reporting results of experiments (e.g., reporting melting points of different objects as determined in the course of their experimental investigation). A *knowledge-building* goal is indicated when students interpret or analyze ideas, using new information to rework or advance an idea (e.g., a student reasons "Heat is formed by atoms moving, so there for kinetic energy and heat are directly related"). [Ng & Bereiter 1991] found that learners with knowledge-building goals demonstrate superior learning.

2.6.2. Subject-matter level (inter-rater agreement = .90)

This aspect involves the level of scientific information students aimed to understand. Based on graded curriculum guidelines that specify concepts students are expected to comprehend at different grade levels, we categorized the level of statements in their entries into: (1) lower than expected grade level, (2) expected grade level, or (3) higher than expected grade level.

2.6.3. Context of knowledge advancement (inter-rater agreement = .86)

Recent educational studies suggest that students develop their understanding most effectively through distributed knowledge processes in the classroom, as opposed to working alone or having all students engaged in the same activity, with no effort to share findings or to help one another [e.g., Brown & Campione 1994; Scardamalia, Bereiter, & Lamon 1994]. We evaluated what context students tried to work in, then categorized each entry according to: (1) *subjective* knowledge advancement and *objective* knowledge advancement. The distinction between subjective and objective knowledge is from Popper's notion of the difference between knowledge in World 2 and World 3 [Bereiter, 1994; Scardamalia, Bereiter, & Lamon 1994]. According to [Popper 1972], knowledge in World 2 represents knowledge as represented in each human mind. If people are primarily working on improving their own understanding of matters, they are advancing their World 2 knowledge. Researchers and scientists are more likely to treat their ideas as objects to be shared among people in their community, with the goal of improving knowledge itself, as well as their own understanding. Scientific communities tend to serve as models for treating ideas as World 3 objects. We categorized students' written discourse in each entry, determining whether they presented their ideas as concepts or principles to be reviewed and debated by others in the classroom or whether they presented them as personal opinion.

2.7 Measures for the Analysis

Besides frequencies and proportions of note entries with different thinking-types, we analyzed the students' scores of the Canadian Tests of Basic Skills (CTBS) conducted at the beginning of the academic year. Our goal was to explore difference between groups of learners that might be related to the basic skills tapped by these tests.

3. Results

3.1 Differences in Quality of Initial Theories

Students' initial explanations of how heat affects matters varied considerably when viewed from the perspective of the conceptual category test. Sixteen of the 30 students had explanations at the molecular level, but no one showed evidence of understanding heat as process. Through application of the same category test to their later explanations, eight students were identified as HCC learners who attained explanations of heat as process in at least two sub-domains. Six of them had their initial explanations at the molecular level. However, there was not a significant difference in proportions in 2 (Conceptual Change) X 2 (Initial Theories) table, $\chi^2(1, N = 30) = 2.06, p = .15$.

3.2 Differences in Basic Skills

Three students (one HCC and two LCCs) were absent when the CTBS was conducted. A one-way MANOVA on CTBS scores (combined vocabulary, reading, and spelling score) showed no significant differences, Wilks' Lambda (3, 33) = .85, $p = .29$. Therefore, we concluded that there were no differences in basic skills related to the usage of CSILE between High-Conceptual-Change and Low-Conceptual-Change learners in this study.

3.3 Differences in Knowledge-Building Activities

3.3.1. Entry frequencies

We analyzed frequencies of note entries with different thinking-types. A 2 (Conceptual Change) X 4 (Thinking Types) ANOVA showed two significant main effects, $F(1, 28) = 4.95$ for Conceptual Change, and $F(3, 84) = 23.8$ for Thinking Types, both $ps < .05$, and an almost significant interaction effect, $F(3, 84) = 1.45$,

$p < .07$. Two main effects showed: (1) that HCC learners were more likely to produce note entries than LCC learners, and (2) that both groups of learners were more likely to produce MT (My Theory) entries than the three other types of entries. Post-hoc comparisons[1] for the interaction effect revealed that HCC learners were more likely to produce MT (My Theory) entries than LCC learners [Table 1]. Because of the significant differences in entry frequencies, we conducted analyses of students' knowledge-building activities based on proportions of different categories in each scale.

	Thinking Types			
	MT	NI	INTU	C
HCC Learners	13.8 (10.7)	5.1 (3.6)	8.5 (9.6)	3.5 (4.6)
LCC Learners	7.1 (5.3)	3.0 (2.5)	4.1 (4.1)	1.6 (2.2)

Table 1: Mean Frequencies of Note Entries with Different Thinking Types.
Note. Values in parentheses show SDs.

In the following analyses, 2 (Conceptual Change) X 4 (Thinking Types) ANOVAs were conducted on proportions of entries identified in each aspect of knowledge-building activities.

3.3.2. Pedagogical orientation

The analysis of proportions of entries with knowledge-building goals showed two significant main effects, $F(1, 26) = 25.34$ for Conceptual Change, and $F(3, 78) = 4.95$ for Thinking Types, both $ps < .05$ [Figure 1]. Post-hoc comparisons following the main analysis revealed: (1) that HCC learners were more likely to focus on knowledge-building goals in their activities than LCC learners, and (2) that both groups of learners were more directed to knowledge-building goals in "My Theory" and "In Need To Understand" entries than in "New Information" and "Comments" entries. The analysis of proportions of entries with task goals showed two significant main effects, $F(1, 26) = 16.36$ for Conceptual Change, and $F(3, 78) = 3.30$ for Thinking Types, both $ps < .05$. Post-hoc comparisons revealed: (1) that LCC were more likely than HCC learners to focus on task goals, and (2) that both groups of learners were more likely to show task-oriented activities in "New Information" entries than in "I Need To Understand" and "Comments" entries.

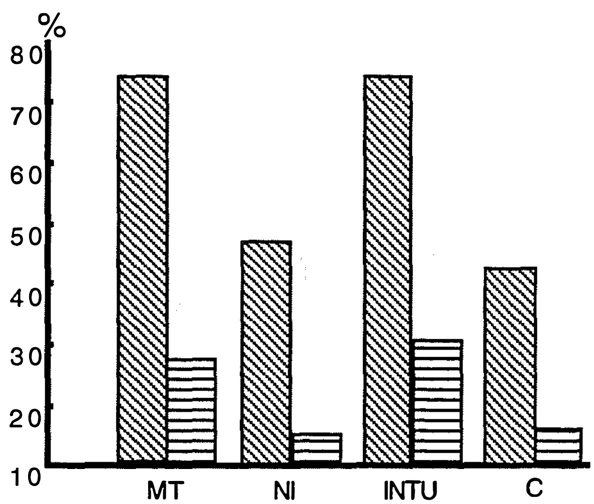

Figure 1: Proportions of Entries with Knowledge-Building Goals.

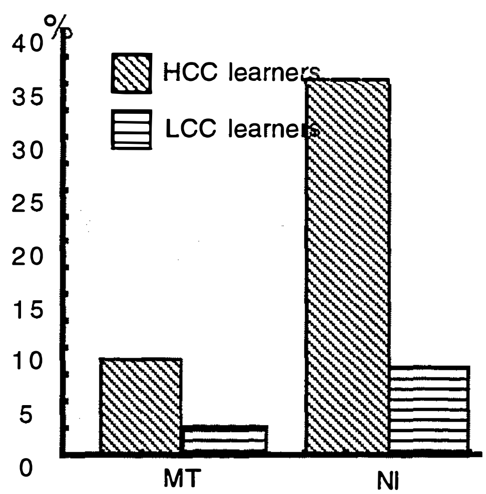

Figure 2: Entry Proportions with High Level of Expertise.

[1] We used Tukey's HSD test for unequal size samples for post-hoc comparisons across analyses in this study.

3.3.3. *Subject-matter expertise*

The analysis of proportions of entries at a high level of subject-matter expertise showed two significant main effects, $F(1, 26) = 10.85$ for Conceptual Change, and $F(1, 26) = 15.34$ for Thinking Types, and an interaction effect, $F(1, 26) = 6.64$, all $ps < .05$ [Figure 2). Post-hoc comparisons revealed that, compared to LCC learners, HCC learners conveyed significantly higher levels of subject-matter expertise in "New Information" entries. Both groups of learners reported equally high levels of subject-matter expertise in "My Theory" entries. The analysis of proportions of entries at an average level of subject-matter expertise showed a significant interaction effect of Conceptual Change X Thinking Types, $F(1, 26) = 8.80$, $p < .05$ [Figure 3]. Post-hoc comparisons revealed that compared to LCC learners, HCC learners reported average levels of subject-matter expertise significantly more frequently in "My Theory" entries. Both groups of learners reported equal levels of expertise in "New Information" entries. The analysis of proportions of entries at a low level of subject-matter expertise showed two significant main effects, $F(1, 26) = 8.13$ for Conceptual Change and $F(1, 26) = 5.49$, both $ps < .05$ [Figure 4]. The results revealed: (1) that LCC learners, in comparison to HCC learners, reported low levels of subject-matter expertise in both "My Theory" and "New Information" entries, and (2) that both groups of learners conveyed significantly more subject-matter expertise in "My Theory" entries than in "New Information" entries.

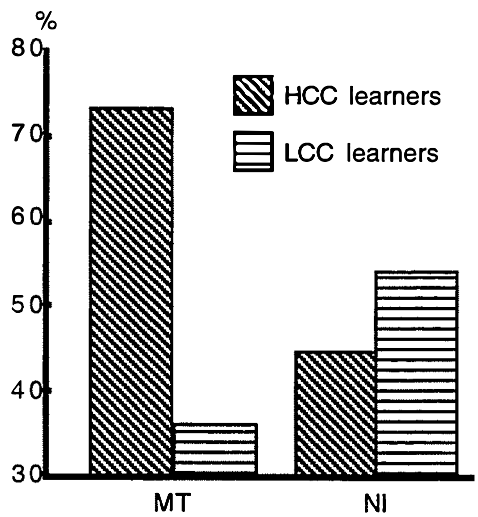

Figure 3: Entry Proportions with Average Level of Expertise.

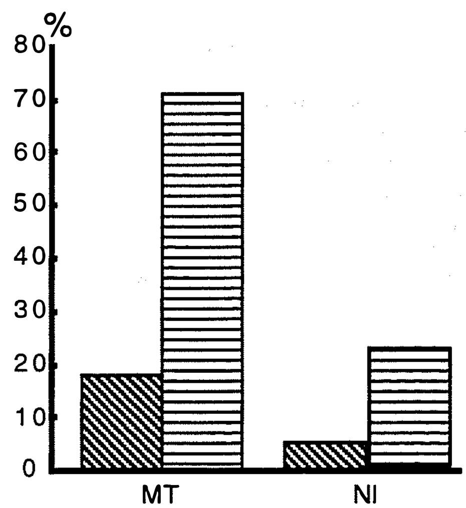

Figure 4: Entry Proportions with Low Level of Expertise.

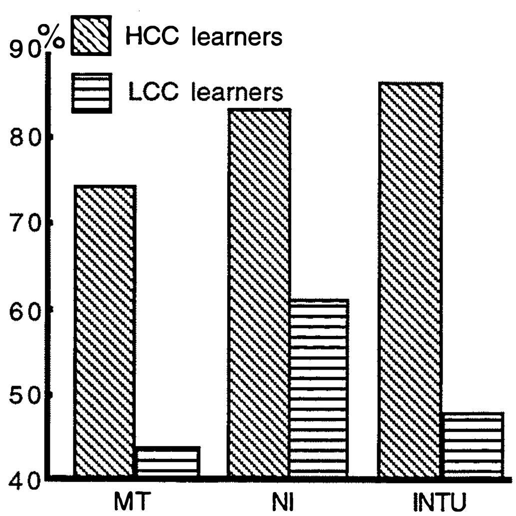

Figure 5: Entry Proportions of Objective Knowledge Advancement.

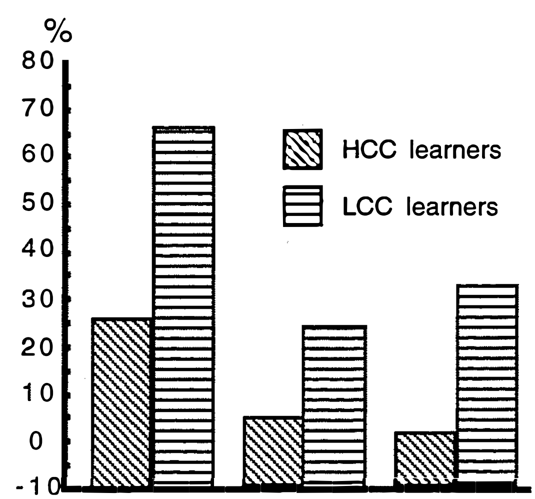

Figure 6: Entry Proportions of Subjective Knowledge Advancement.

3.3.4. Context of knowledge advancement

The analysis of proportions of entries identified as objective knowledge advancement showed a significant effect of Conceptual Change, $F(1, 26) = 9.63$, $p < .05$ [Figure 5]. The results revealed that HCC learners showed significantly higher proportions of entries identified as objective knowledge advancement than LCC learners. The analysis of proportions of entries identified as subjective knowledge advancement showed two significant main effects, $F(1, 26) = 12.18$ for Conceptual Change and $F(2, 52) = 4.38$ for Thinking Types, both $ps < .05$ [Figure 6]. Post-hoc comparisons revealed: (1) that LCC learners conveyed significantly more subjective knowledge advancement across three different thinking types than HCC learners, and (2) that both groups of learners reported significantly more subjective knowledge advancement in "My Theory" entries than in other entry types.

4. Discussion

As might be predicted from research on mental models, more HCC learners started with a molecular level of explanation than did LCC learners (although differences were not found to be significant). Because HCC learners had more appropriate mental models to understand scientifically correct conception of heat, they were more likely to attain critical conceptual change. The comparison of frequencies showed that HCC learners generated more entries with "My Theory" thinking type than did the other two groups. This result suggests that learners' engagement with the system was related to their success in conceptual change. When the students were given and made use of new media to externalize their knowledge, particularly in the problem-based way (i.e., "My Theory" entries), their quality of learning improved. One of reasons HCC learners were more likely to generate entries may be that they had more appropriate mental models, thus allowing them to more readily write about their ideas, and subsequently search and integrate new information. Thus, initial level of knowledge might affect their knowledge-building activities.

The comparisons of proportions in the three aspects of knowledge-building activities suggest the following: HCC learners consistently set knowledge-building as opposed to task goals for themselves. Three activities were found to be critical to success in conceptual change: HCC learners attempted to improve their theories through integration of scientific ideas they found in the course of their research , using books that brought them into contact with ideas beyond those found in the database. Further, they were more inclined to challenge new problems (INTUs) with knowledge-building goals. Finally, they were also directed to knowledge-building goals in improving others' knowledge. Thus, progressive problem-solving [Bereiter & Scardamalia 1993] often appeared in HCC learners.

Another noticeable finding in the pedagogical analysis of students' knowledge-building activities was that both groups of learners were significantly more directed to knowledge-building goals in "My Theory" and "I Need To Understand" entries than in "New Information" and "Comments" entries. In the "New Information" entries, they were more likely to copy information from reference sources, and comments were more likely to focus on task goals than on knowledge-building goals.

The subject-matter expertise analysis, as we expected, showed that HCC learners reported their theories and information at higher levels of expertise than did LCC learners. An interesting finding here was that both groups of learners, even though engaged in different levels of subject-matter expertise, reported significantly higher levels of information in their theory entries. It is not clear from the analysis in this study: (1) if students had difficulty integrating "New Information" into their theories or (2) if they used the "New Information" entries to record information not directly related to their theories. We are currently analyzing "New Information" entries to explore these different possibilities.

5. Educational Implications

Within a knowledge-building framework naive conceptions can be an asset, but only if naive ideas are brought out in the open, as the objects of discussion. For this to succeed, teachers must create classroom cultures in which students feel free to discuss naive conceptions. The CSILE environment helps by encouraging students to write about their current understandings, and to use these as stepping stones for more mature understandings.

Making current understandings the objects of discussion is a first step in knowledge-building. The present study provided us with an account of knowledge-building activities that facilitate conceptual change beyond this point. High-conceptual-change students set knowledge-building goals for themselves -- goals that engage them in efforts to understand ideas beyond the tasks as presented by teachers or by the school curriculum. They do not simply interpret the results of tests, they actively work to determine how those results fit with their current explanations. They additionally juxtapose their ideas with more mature ideas as represented in the scientific literature they read, and in this way extend their ideas beyond the ideas discussed by the immediate community.

Thus, intentional reflective activities should be emphasized for the purpose of increasing efficiency of learning. [Chi et al. 1994a] discuss three characteristics of information-processing in self-explanations: (1) constructive, (2) facilitating integration of self knowledge with new information, and (3) having learners engage in continuous revision of ideas. In the student-CSILE interaction, these three characteristics are also emphasized and extended to asynchronous communication and collaborative learning. As Chi et al. point out, intentional reflective activities such as self-explanations manifest maximum effects when learners are continuously (i.e., minute-by-minute) engaged in such constructive activities. When learners do not have ways to integrate knowledge fraagments, educationally preferable results cannot be expected. The computer-support for asynchronous communication provided by CSILE allows students to engage in distributed cognitive processes over lengthy periods of time and across diverse communities [Oshima, Bereiter, & Scardamalia 1995]. The results in this study suggest that CSILE has educational effects for students to engage in continuous and progressive problem solving in their curriculum.

Six of the eight students in the high-conceptual change category started their inquiry with a molecular explanation of how heat affects matter. The molecular account represented a more mature account than demonstrated by the remaining students. It is important to note, however, that two HCC students did not have this advantage, yet shifted within the same time span to the more sophisticated process account evidence by all HCC students. Data suggest that the HCC students without molecular levels of explanations accomplished this through execution of the same knowledge-building strategies as the HCC students who started the activity with more mature mental models. While the design of the present study does not allow us to determine if knowledge-building activities are more facilitative than other classroom activities might be, the progress students made in seven weeks was substantial. In the aggregate, the fifth and sixth graders involved in this study set goals for understanding beyond that typical of their grade level and made substantial progress toward achieving those goals.

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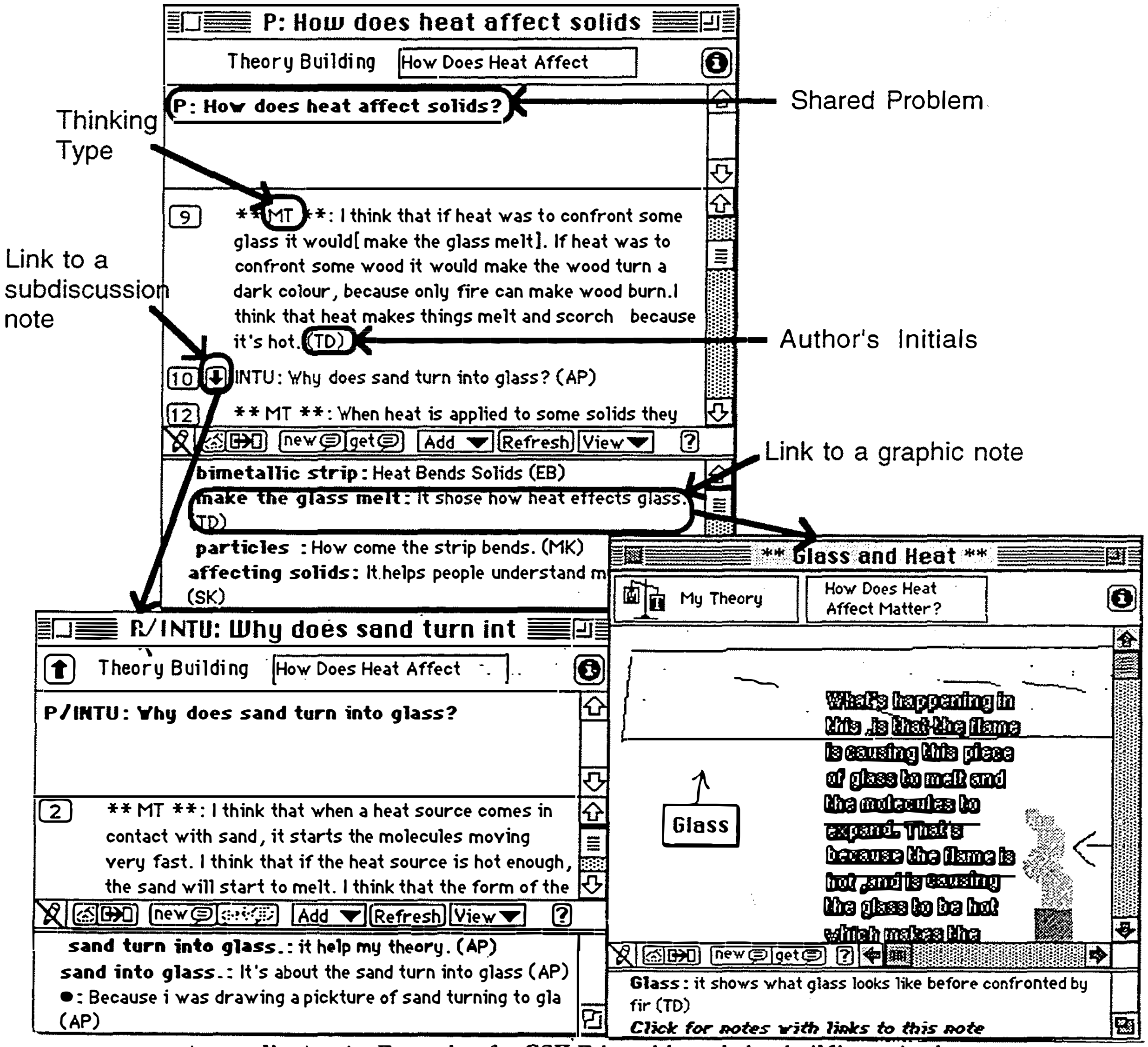

Appendix A: An Example of a CSILE-based knowledge-building episode.