Students' Construction of Scientific Explanations in a Collaborative Hyper-Media Learning Environment

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Abstract

This exploratory study examined how elementary school students make use of a collaborative hyper-media learning environment in constructing scientific explanations. The target environment was a computer-networked database system in which students externalize their thoughts in the form of texts or graphics, then elaborate their thoughts by structuring with links or by commenting. Thirty students in a 5th- and 6th-grade combined classroom participated in this study as part of their regular curriculum. The students studied "how heat affects matters." Contents of their discourse in the database were evaluated by two independent raters from the perspective of whether critical conceptual changes happened in the students' explanations, then the students were divided into High Conceptual Change (HCC) learners and Naive learners. Further, the same contents were evaluated by two other independent raters from the perspectives of (1) what types of explanations the students generated, and (2) how they applied their explanations across different problem contexts. Results showed that HCC learners generated more explanations and more frequently used their explanations across multiple contexts, particularly ones which they had studied before CSILE sessions. A further case analysis manifested critical differences in the movement in the problem space between a HCC and a Naive learner after generating a new type of explanations. The HCC learner used the type of explanations across contexts in which they had rich information, whereas the Naive learner did not. Thus, explanation-based exploration and progressive learning in knowledge-rich contexts were found to be crucial to deeper conceptual understanding.

1. Background and Problems

1.1. CSILE: A Collaborative Hyper-Media Learning Environment

This study examined a classroom community supported by CSILE (Computer-Supported Intentional Learning Environments). CSILE is a networked computer environment particularly designed to support progressive discourse (Scardamalia & Bereiter, 1996). In CSILE, students write text or graphic notes to convey their explanations. These notes reside in a communal database where other participants have access to them, and can work collaboratively to compare explanations, find counterexamples, record new information bearing on these explanations, provide constructive commentary, and generally work to construct higher levels of understanding. The system supports students' active engagement with explanations by providing: (1) note types that encourage theory formulation 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 (Fig. 1).

The comparison between students in CSILE classrooms and students in traditional classrooms showed that CSILE students outperformed those in the traditional classrooms in comprehension of difficult texts and acquisition of basic skills (e.g., Scardamalia, Bereiter, Brett, Burtis, Calhoun, & Smith-Lea, 1992). However, mechanisms behind such achievements have not been sufficiently clarified. Oshima, Bereiter, and Scardamalia (1995) attempted to describe differences in learning activities between high-conceptual-progress learners and naive learners in CSILE by applying a framework of information-flow analysis (Perkins, 1993). Results showed that high-conceptual-progress learners were more likely to integrate others' ideas or thoughts with their own ones in the "knowledge-transforming" way. They did not only read and comment on others' thoughts, but also applied their thoughts to solve their peers' problems and attempted to build new explanations. Further, the study showed that such progressive problem-solving would happen more effectively by introducing students a collaborative space called "discussion notes" in which they can explicitly share problems to pursue. Thus, the previous study suggested us that differences in students' dispositions to learning in CSILE have effects on how they proceed their learning.

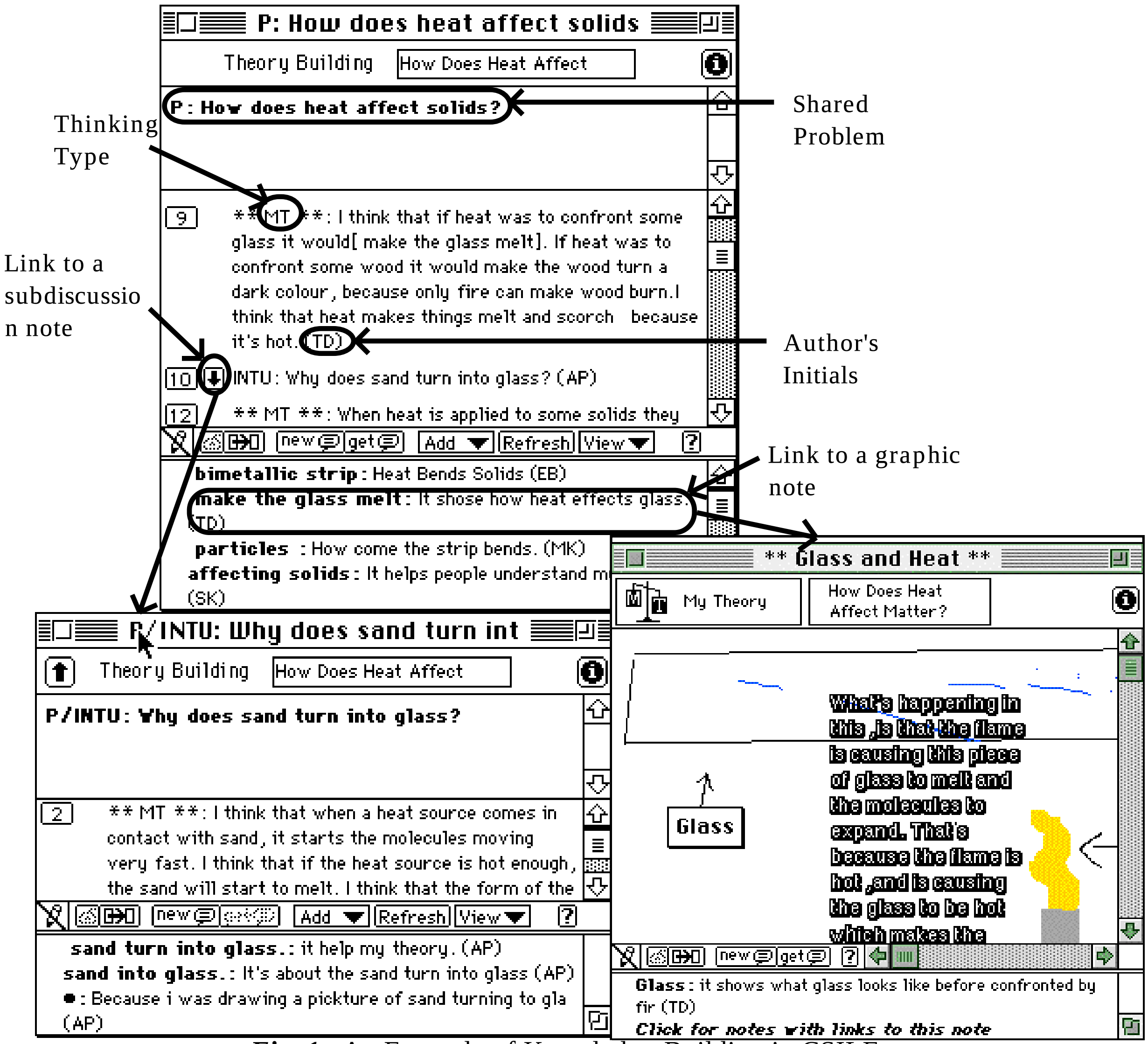

Fig. 1. An Example of Knowledge-Building in CSILE.

Although the previous study provides us with information of how students' recogniiton of a learning environment affects their achievement, the information is not sufficient for us to conclude some curriculum plans using hyper-media learning environments like CSILE. The aim of this study is, therefore, to discuss cognitive processes of learning in CSILE through the comparison of high-achieving (called "High-Conceptual Change" learners) and naive students. Particularly, this study analyzes knowledge students bring in CSILE, and discuss individual differences in manipulation of the knowledge from the perspectives of: (1) problem contexts students cover in constructing their explanations, (2) types of their explanations, (3) how they engage in construction of explanations through problem-solving.

1.2. Methodological Issues

Category test for conceptual change. This study focused on students' conceptual change as their achievement. The study topic focused in this study was "How heat affects matters." Conceptual change in students' written discourse in CSILE notes was evaluated based on Chi et al.'s *category test* (Chi, Slotta, & de Leeuw, 1994). The category test is a new method to assess which ontological tree(s) students attribute concepts to by classifying predicates students used in their explanations. Based on progress in their conceptual understanding of heat, students were divided into High-Conceptual-Change learners and Naive learners.

Classification of students' explanations. Students' explanations were categorized based on components and principles in their explanations. For instance, some students used a component "energy" with a superficial level of causal principle: "Heat is a type of energy, so it can burn a paper." Other students used a component "molecules" with the principle of density: "Some substances are hard to heat since they are dense in their molecules." Eventually, students' explanations were classified into seven different types. The details are described in the study description.

The movement in the problem space. Students' learning in CSILE is self-regulated. They can pursue their own inquiries at their own pace. Since they report their thoughts in a communal database, contents of the database are assumed to be a collaboratively constructed problem space. This study attempted to describe how students move in the communal problem space for the purpose of examining differences in learning processes between HCC and Naive learners. The problem space was created as a matrix of dimensions of: (1) types of explanations and (2) problem contexts. How each student moved in the problem space matrix was delineated by tracing log files stored in the CSILE server.

2. Study Description

2.1. Participants

Thirty students in a fifth- and sixth-grade combined 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 seven-week curriculum unit on heat and matter. Students conducted classroom experiments before they started CSILE sessions. During the CSILE sessions they recorded their explanations 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, and (3) heating bimetallic strips to see them bend.

2.3. How CSILE Sessions Worked

During CSILE sessions, students collaboratively engaged 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.

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. Data

Data used in this study were: (1) Contents of students' written discourse, and (2) log information of the date and time when students used CSILE.

To examine a possibility that high conceptual change might be related to learners' basic skills related to written discourse, the Canadian Tests of Basic Skills (CTBS) conducted at the beginning of the academic year were analyzed. Three students were absent when the CTBS was conducted. A one-way MANOVA on CTBS scores (combined vocabulary, reading, and spelling score) showed no significant differences (Wilk's Lambda (3, 33) = .85, p = .29).

2.5. Study Design

Students were first divided into High-Conceptual-Change (HCC) and Naive learners based on an analysis of conceptual change represented in the notes they wrote over the course of this investigation. Students' activities of using explanations were then analyzed, with emphasis on the comparison of HCC and Naive learners.

2.6. Evaluation of Students' Conceptual Change

Conceptual change in students' written discourse in CSILE notes was evaluated based on Chi et al.'s *category test* (Chi et al., 1994). Two independent raters (inter-rater agreement = .95) 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. Eight students who attained a process-based conceptual understanding of heat were classified as HCC learners, whereas the remaining 22 students were classified as Naive ones.

2.7. Classification of Students' Explanations and Problem Contexts (Appendix A)

Two other raters (different from those who rated conceptual change) independently identified learners' explanations in CSILE notes, then discussed to create a taxonomy of the explanations. Five categories of explanations were finally agreed: (1) vibration, (2) characteristics, (3) density, (4) intention, and (5) heat-as-material. Then they again independently categorized students' explanations in CSILE notes into one of the five categories. The inter-rater agreement was .85. Disagreements were solved through their discussion.

Students in this study generated 59 problems shared in discussion notes. The same two raters independently classified the problems. Seven categories were finally identified: (1) heat conduction, (2) change in modes of substances among solid, liquid, and gas, (3) change in shape, (4) change in color, (5) burning, (6) what heat is, and (7) others. Then they again independently categorized problems students raised in CSILE notes into the seven categories (Appendix B). The inter-rater agreement was .85.

3. Results

3.1. Students' Explanations

Each learner's generation of explanations was summarized in a problem space matrix (see Appendices C & D). Then, (1) frequencies of different types of explanations, and (2) the frequencies of explanations across problem contexts were calculated.

A 2 (Conceptual Change) X 5 (Explanation) ANOVA showed that both main effects and an interaction effect were significant, $F(1, 28) = 27.9$ for Conceptual Change, $F(4, 112) = 3.8$ for Explanation, $F(4, 112) = 3.2$ for the interaction effect, all *p*s $< .05$. *Post hoc* comparisons by Tukey's HSD for unbalanced cells further manifested that HCC learners used "density-based" and "intention-based" explanations more frequently than did Naive learners (Fig. 2).

A 2 (Conceptual Change) X 7 (Problem Context) ANOVA showed that both main effects and an interaction effect were significant, $F(1, 28) = 27.9$ for Conceptual Change, $F(6, 168) = 10.3$ for Problem Context, and $F(6, 168) = 6.1$ for the interaction effect, all *p*s $< .01$. *Post hoc* comparisons further manifested that HCC learners generated explanations more frequently than did Naive learners in problem contexts of "heat conduction," "mode change," "shape change," and "burning." (Fig. 3)

3.2. Further Analysis of Generation of Explanations

The previous analysis showed a global picture of how students generated their explanations in different problem contexts. Here, more detail analyses were conducted for examining how students covered problem contexts by what types of explanations.

Repeated use of the same types of explanations in the same problem contexts. Multiple *t*-tests showed: (1) that HCC learners repeatedly used more types of explanations, 2.1 for HCC learners vs. 0.2 for Naive learners, $t(28) = 6.6$, $p < .01$, (2) that HCC learners repeatedly

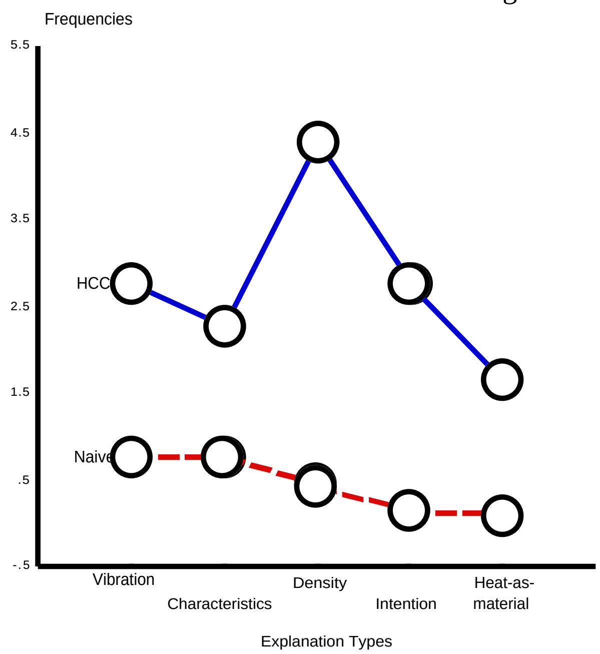

Fig. 2. Frequencies of Explanations in Different Categories.

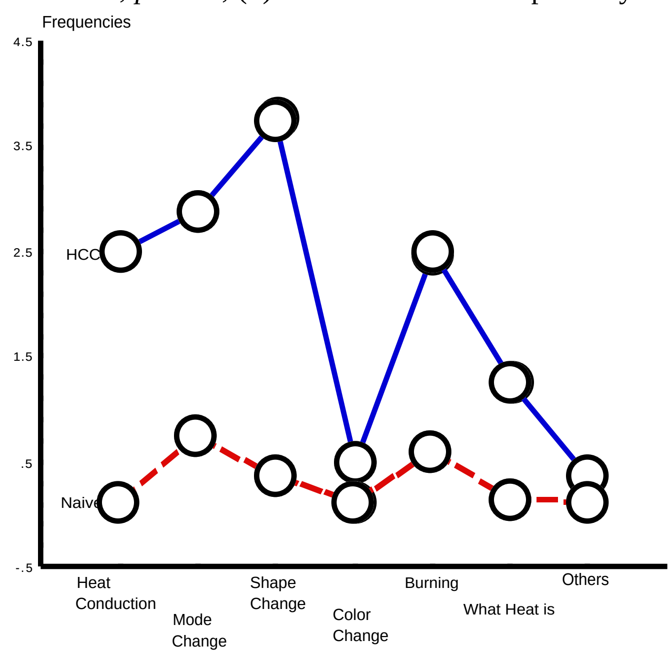

Fig. 3. Frequencies of Explanations in Different Problem Contexts.

use the same types of explanations in more problem contexts, 2.3 for HCC learners vs. 0.2 for Naive learners, t (28) = 5.6, $p < .01$, and (3) that HCC learners more repeatedly used the same types of explanations, 1.4 times (per cell) for HCC learners vs. 0.1 times for Naive learners, t (28) = 6.5, $p < .01$.

Repeated use of the same types of explanations across different contexts. Multiple t-tests showed: (1) that HCC learners used more types of explanations across different problem contexts, 2.5 for HCC learners vs. 0.3 for Naive learners, t (28) = 7.5, $p < .01$, and (2) that HCC learners covered more problem contexts by the same types of explanations, 1.5 for HCC learners vs. 0.4 for Naive learners, t (28) = 3.9, $p < .01$.

Movement in the problem space. In addition to the above quantitative analyses, a case analysis of movement in the problem space by a HCC and a Naive learner was conducted. Each student's movement in a problem space matrix was described by splitting a total process into stages. Boundaries were set between stages when learners had not logged in for more than two days. With this criterion, total processes of CSILE sessions by both learners were divided into seven stages (Appendices C & D).

By comparing the movements in the problem space stage by stage, the following were found. First, in the initial stages of CSILE sessions, the HCC learner moved more frequently within problem contexts which they had studied before CSILE sessions, whereas the Naive learner moved across problem contexts related to classroom experiences and those unrelated to the experiences. Second, as learning went on, both learners shed light on "vibration-based" explanations in the stage 2. The HCC learner further used the type of explanations in the experienced contexts, whereas the Naive learner never attempted to apply the same type of explanations in different contexts.

4. Discussion

4.1. Learners' Use of Explanations and Conceptual Change

Results of the above analyses showed that HCC learners generated more explanations. These findings support previous research on problem-based learning and self-explaining in CSILE (e.g., Scardamalia & Bereiter, 1992). In this study, a few more were found. First, HCC learners generated more explanations in particular problem contexts: (1) heat conduction, (2) mode change, (3) shape change, and (4) burning. The first three contexts were those which they had studied in classroom sessions before CSILE. The fourth context is considered a familiar one for learners in studying how heat affects matters. Second, HCC learners were not necessarily generating more elaborate explanations than those by Naive learners. HCC learners generated two types of explanations more frequently: (1) density-based and (2) intention-based. Intention-based explanations are primitive because students see components in their explanations have intentions (e.g., "Molecules attempted to get away from heat."). Although HCC learners eventually attained deeper conceptual understanding of heat as process, they had not been at more elaborate levels of explanations before starting their study. Thus, these particular results lead us to conclude: (1) that students' attainment of conceptual change does not result from their initial level of scientific knowledge, but (2) that *use of explanations based on their experiences or knowledge* facilitates their deeper comprehension of the scientific concept.

4.2. Learners' Progressive Problem Solving Through Explaining Activities

Learning in CSILE is self-regulated and progressive. Students collaboratively challenge new problems and invent solutions based on their knowledge. Results in this study showed that HCC learners used more types of explanations across more problem contexts. Furthermore, the case analysis provided us with useful information to infer a cognitive mechanism for students to attain higher conceptual understanding of scientific concepts. First, the HCC learner in the case study was more likely to explore within his familiar problem contexts in the initial stages. Second, the HCC learner was more likely to use new types of explanations in familiar problem contexts.

These results suggest us that, for attaining deeper conceptual understanding, learners must not only more frequently generate their explanations, but also have some systematic movements in the problem space. Keys to deeper conceptual understanding are: (1) *the movement in the space for recognition and clarification of own understanding*, and (2) *for integration of new thoughts and ideas into their own understanding*.

4.3. Instructional Methods and CSILE Functionalities to Facilitate Deeper Conceptual Understanding

As results in this study showed, learning environment technologies would play their crucial roles when they are appropriately used by learners. To support learners in using hyper-media learning environments like CSILE, the following aspects of learning were found to be important.

Explanation-based learning. Explaining activities should be a basis in learning. HCC learners repeatedly explain problems. They did not necessarily generate explanations which critically differed from others'. Rather, they wrote down similar explanations to others' *in their own words*. Reporting their knowledge, even though similar ideas to it had already been reported by others, might be important for HCC learners to regulate their learning and elaborating own ideas.

On the other hand, Naive learners might attempt to explore new areas of knowledge rather than to elaborate their ideas by writing down in text then comparing the ideas with others'. Generating explanations on problems which nobody has touched might not be useful for Naive learners to elaborate their ideas.

Thus, externalization of knowledge to share with and to compare with others' might be a key to deeper conceptual understanding. One way to support this externalization process is an instructional intervention. Teachers can support students to report their ideas in their own words then search friends who have similar ideas. However, this instructional intervention may lead students to generate a number of notes including similar ideas so that they can not search useful information in the database.

Another possibility from the system side might be to provide a function for students to refer to others' ideas similar to their own then revise the ideas in their own words. This type of function could be a solution to reduce notes that include similar ideas so that learners can search the database in a more useful way.

Knowledge-based inquiries. HCC learners were generating more explanations on problems in contexts they had studied before CSILE. A possible interpretation for the result that explaining activities in the contexts led HCC learners to deeper conceptual understanding may be that the contexts consist of domain knowledge which requires students of making their explanations more scientific. However, this interpretation is not supported by another result that HCC learners more frequently generated a primitive level of explanations (i.e., intention-based).

Another interpretation may be that the contexts were more information-rich because students had conducted experiments before CSILE sessions. Students' explanations in the contexts could be referred to real data and experiences shared by students. Based on their shared experiences, students could question, criticize, and elaborate their own and others' ideas.

Along with the interpretation, we can further consider instructional support for students who are likely to work in new contexts. One possible support is to provide students with opportunities to conduct further experiments related to the contexts not covered by the initial experiments. Teachers' flexible coping with students' knowledge-based inquiries should be required. Another possible support is to provide information through the database. Classroom schedule is sometimes difficult to manage for emergent problems. Setting up new experiments is hard to do. Instead, teachers can collect useful information for students through the World Wide Web, or other electronic or hard copy resources. For this purpose, a variety of information resources should be prepared in the future.

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Author's Note

CSILE is being developed at the Ontario Institute for Studies in Education, Canada. For information, visit http://csile.oise.utoronto.ca.

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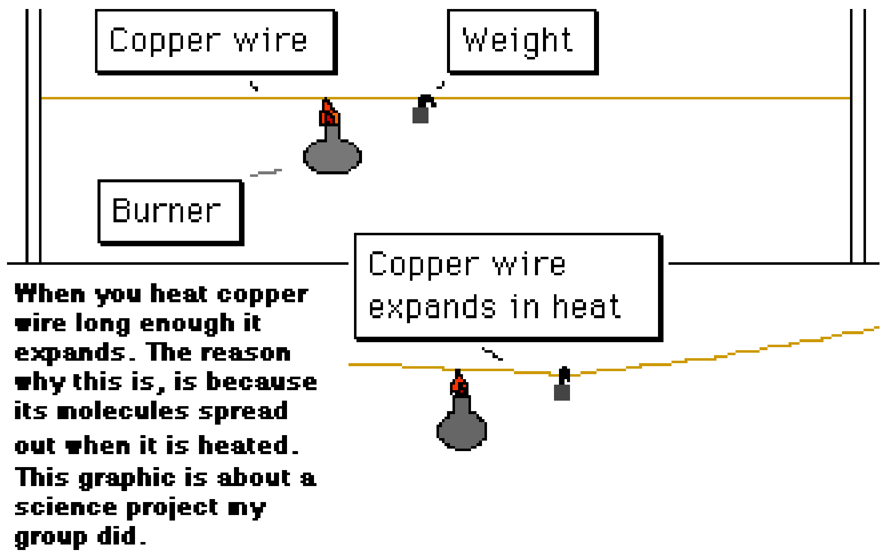
Appendix A. *Examples of Different Types of Explanations in CSILE Notes.*

Types of Explanations	Examples of Discourse in CSILE
Vibration-based	When heat comes in contact with a liquid, the molecules in the liquid start to move faster and faster. The hotter it gets the faster the molecules move. So when you see a liquid boiling, inside the liquid tiny microscopic particles are moving around very fast.
Density-based	
Characteristics-based	I think that different solids are affected by heat in different ways. For example if you had a thick metal bar and you applied it to heat it would begin to expand because the heat excites the molecules and that makes the metal expand. But other solids like wood are a drier substance so the heat would affect it more quickly and it would start to burn.
Intentions-based	My theory is that when heat is applied to some things they will expand. I think that a solid such as metal will expand much faster than another object such as a brick. I think that the particles in the metal will expand very fast. The bimetallic strip bends because the particles get bent away from the flame. They want to move away from the heat.
Heat-as-material-based	Internal heat is the heat inside molecules and atoms. If a very hot rock, and a very cold rock made contact, the internal energy would pass through and change the internal temperature of the rocks. After a while the internal temperature will be evened out, and the rocks will have about the same temperature.

Appendix B. *Examples of Problems Categorized in Seven Problem Contexts.*

Problem Contexts	Examples of Problems
Heat Conduction	• Why are metals better conductors than wood, liquids and gases. • I need to understand which would expand faster if heated at the same temperature, gas, liquids or solids? • How does heat transform in air.
Change in Modes of Substances	• I need to understand how hot does it have to be when the metal melts? I would like to know. • I need to understand why solids melt. • I need to understand what would happen if honey and water were boiled? Would there be any difference in the boiling point of the two? Maybe we can try an experiment. • I need to understand what the molecules in liquids do to make the liquid bubble. • What happens when liquid gets heated or cooled. • I need to understand if the boiling point would change if water was mixed with another liquid such as orange juice? If it would change what would it change to?
Change in Shape	• I need to understand why heat makes solids (like the ball and ring) expand. If you left a solid too long in heat, what would be the effect? • Why do some soilds [sic] bend, shink [shrink] and expand? • I need to understand why when you make when your doing the ball and ring experiment when you make the ball hot and the ring cold they don't go in but when you make them both hot they slip through easily.
Change in Color	• I need to understand why heat changes the colour of solids that it might melt. • What happens to the molecules to make the fabric lose colour
Burning	• What in water makes fire be put out? • Why does lack of oxygen put a fire out? • Why does lightning have different effects from fire? • I need to understand how you can make fire by rubbing two sticks together.
What is Heat?	• WHAT IS HEAT? • How is energy converted into heat? • how is heat made
Others	• Why does sand turn into glass? • I need to understand how light rays travel. How do they get here from the sun. How does light flood the room instantly when we turn a light on? • I need to understand why the mercury in a thermometer is as dangerous as everyone thinks it is. I would like to know what makes it so dangerous.

Appendix C. The Movement in the Problem Space by a HCC Learner.

SKÅHCC

1

	C	M	S	Cl	B	H	O
V							
D	1	1		1			
C							
I		1	1				
Ma							

2

	C	M	S	Cl	B	H	O
V						1	
D	2	1		1			
C					1		
I		1	1				
Ma							

3

	C	M	S	Cl	B	H	O
V						1	
D	2	2		1			
C					1		
I		1	1				
Ma							

4

	C	M	S	Cl	B	H	O
V	2					1	
D	2	2		1			
C					1		
I		1	1				
Ma							

5

	C	M	S	Cl	B	H	O
V	3					1	
D	2	2		1			
C					1		
I		1	1				
Ma							

6

	C	M	S	Cl	B	H	O
V	4	1	2			1	
D	3	2		2			
C					2		
I		1	1		1		
Ma							

7

	C	M	S	Cl	B	H	O
V	4	1	2			1	
D	3	3		2			
C					2		
I		1	1		1		
Ma							

Note. A total process of the movement in the problem space was divided into seven stages. Each stage shows cumulative frequencies of explanations students generated. Rows of the matrix show types of explanations: V = Vibration-based, C = Characteristics-based, D = Density-based, I = Intention-based, and Ma = Heat-as-material-based. Columns show types of problem contexts: C = Heat conduction, M = Mode change, S = Shape change, Cl = Color change, B = Burning, H = What heat is, and O = Others. The area with bold lines was considered as part of the problem space related to the classroom experiences before CSILE sessions.

Appendix D. The Movement in the Problem Space by a Naive Leaner.

JPÅFNaive

1

	C	M	S	Cl	B	H	O
V							
D			1				
C			1				
I							
Ma							

2

	C	M	S	Cl	B	H	O
V					1		
D			1				
C		1	1				
I							
Ma							

3

	C	M	S	Cl	B	H	O
V					2		
D			1				
C		1	1				
I							
Ma							

4

	C	M	S	Cl	B	H	O
V					2		
D			1				
C		2	1				
I							
Ma							

5

	C	M	S	Cl	B	H	O
V					2		
D			1				
C		3	1		2		
I							
Ma							

6

	C	M	S	Cl	B	H	O
V					2		
D			2				
C		3	1		2		
I							
Ma							

7

	C	M	S	Cl	B	H	O
V					2		
D		1	2				
C		3	1	1	2		
I							
Ma							

Note. A total process of the movement in the problem space was divided into seven stages. Each stage shows cumulative frequencies of explanations students generated. Rows of the matrix show types of explanations: V = Vibration-based, C = Characteristics-based, D = Density-based, I = Intention-based, and Ma = Heat-as-material-based. Columns show types of problem contexts: C = Heat conduction, M = Mode change, S = Shape change, Cl = Color change, B = Burning, H = What heat is, and O = Others. The area with bold lines was considered as part of the problem space related to the classroom experiences before CSILE sessions.