

COGNITIVE PROCESSES AND THE LEARNING OF PHYSICS PART II: MEDIATED ACTION

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1. Introduction

Socio-cultural theoretical perspectives have been used within the mathematics and science education research communities for over 20 years [1] [2] [3] [4] [5]. These perspectives have helped educational researchers move beyond investigations of what is happening inside the head of the individual and into investigations of learning as it takes place in the broader classroom “context.” One of the fundamental features of the socio-cultural perspective is the notion that cognition is not only impacted by “context” but is also co-constitutive of “context.” The context is dynamically created by all of the elements within the classroom including the students and their conceptual development. The term “context” is defined here as the student, the student interacting with tools and the student interacting with others and with tools. This dynamic definition of context is necessary if the researcher seeks to understand how participation leads to learning.

The *participation metaphor* is used to encompass theoretical perspectives of cognition where learning is viewed as the process of *doing* and *participating in the norms and practices of the discipline* [6]. This can be contrasted with the *acquisition metaphor*, where learning is typically viewed as a more rational process of conceptual growth and growth of reasoning [6] [7]. Perspectives that can be defined by the participation metaphor include socio-cultural perspectives such as situated cognition [8], distributed cognition [9], feminist perspectives [10] and semiotic interaction theory [4]. Much of the work within this tradition has partial foundation in the work of Lev Vygotsky.

Perspectives that can be defined by the acquisition metaphor include cognitive perspectives such as schema theory [11] [12], conceptual change perspectives [13] [14], epistemology studies [15], metacognition [16] and other phenomenological or epistemological resource perspectives [17] [18]. Much of the work within this tradition has some roots in the work of Jean Piaget.

In her article *On Two Metaphors for Learning and the Dangers of Choosing Just One*, [6] Anna Sfard argues that both metaphors for learning have limitations in the types of questions they allow researchers to ask and answer. They also limit the types of answers researchers can generate. Sfard argues that both the participation and the acquisition metaphors are necessary to fully understanding the learning process, but that the metaphors as well as the research and theory they represent, are incommensurate. She concludes that acquisition and participation metaphors are like the wave/particle

duality, where each perspective is very useful and necessary, but the two cannot be considered simultaneously.

Others argue that research guided by the participation and acquisition metaphors *must* be commensurate. Cognitive psychologist Michael Cole [19] argued that the perspectives can be made to be consistent with one another and can work together to form a description of learning. Mathematics educator Paul Cobb argued that the two perspectives actually complement one another. In describing the work of Leont'ev, [20] said, "The teacher's role is to mediate between students' personal meanings and culturally established mathematical meanings of wider society." Cobb went on to point out that constructivist epistemologies, such as the radical constructivism of Glasersfeld [21], implicitly assumes participation in cultural practices, while sociocultural perspectives implicitly assume that the individual is actively constructing knowledge. He argued that these two perspectives actually complement each other but simply emphasize different aspects of the learning process. I argue that knowledge as acquisition and knowledge as participation *must* be considered simultaneously as interacting features that define the process of learning science.

Cognitive scientist Jeremy Roschelle [22] analyzed the collaborative interactions of two students working with a computer visualization tool in their study of kinematics. In his analysis, he argued that a perspective that focused only on the students' development of scientific concepts would be too narrow to fully understand the process and context through which these concepts were developed. He also argued that a perspective that focused only on the knowledge that emerged through the social interactions would be too narrow to resolve the fact that this knowledge was grounded in a particular case and was unstable. He concluded that the students' emergent understanding was composed of many interacting "elements in an extended system that supports knowing, doing and discussing." Rochelle went on to define three different lenses that researchers in science education are currently taking: (1) a focus on the students' knowledge, (2) a focus on conversation and (3) a focus on enculturation or the development of scientific behaviors. He argued that none of the above on its own is sufficient to capture the truth about learning. One reason is that elements of learning that are identified through an analysis that used a particular lens may be identified as something entirely different when another lens is used. He therefore concluded that conceptual development, interactions between students, and classroom materials should be considered as a system of elements over which "encoding" is distributed.

Learning is complex. In order to begin to capture and understand its complexities researchers must draw on theoretical perspectives that can help us weave together the many social, cultural and individual cognitive aspects of the learning process. I draw directly on the work of Lev Vygotsky [23]. The purpose of this paper is to examine Vygotsky's perspective of mediated action and to show that it can provide a useful theoretical mechanism for researchers, teachers and curriculum developers to develop a single diverse yet inclusive understanding of the learning process. The theory of mediation can help physics education researchers understand and manage the contributions of the social and material classroom environment to learning. In this paper, I first outline the socio-cultural theory of mediated action and then I apply this theoretical approach to classroom data. I argue that the individual, the individual's interactions with tools and the individual's interactions with others and with tools comprise a cognitive

system that generates knowledge. I then show that the socio-cultural cognitive system *is* the classroom context, therefore as an individual student learns, the very structure of the social *and* material learning environment changes.

2. An Alternative History of Cognitive Science

Cognitive anthropologist Edwin Hutchins offered an official and an unofficial history of cognitive science in *Cognition in the Wild*. In his official history, he argued that the representation of knowledge as structures that exist in the human brain “is so deeply ingrained in our culture that we can scarcely see how things could be otherwise” ([9] p. 356). He goes on to argue that the information processing view of cognition, widely used within cognitive science for 20 years, led to a paradigm in which the computational, mental-structures metaphor of the mind exerts a compulsive force on the research we do and on the theories we develop.

The computer is a logical manipulator of symbols. According to Hutchins’s unofficial history of cognitive science, because the computer was able to carry out certain problem solving tasks that had previously been attributed only to humans, early cognitive scientists tried to model the human after the computer. He criticized the last 30 years of work in cognitive science, as “attempts to remake the person in the image of the computer” ([9] p. 363). The cognitive process was placed inside the head of the individual and the senses, emotions, relationships, culture, tools and interactions were removed from our theories and models of the cognitive process.

As an individual interacts with symbols, he certainly produces some kind of computation. Hutchins argued that the cognitive properties of the human are different from the cognitive properties of the system made up by the human-symbol system. The computer models not the structure and function of the human mind, but the structure and function of the broader socio-cultural cognitive system. The cognitive work that is necessary to complete a task is distributed among tools, cultural practices, interactions and individuals that make up the socio-cultural cognitive system.

3. Mediated Action

The notion of mediated action is fundamental to understanding how features of the social, cultural and material environment restructure the mental functioning of the individual [24]. Mediated action may be defined broadly as action in which individuals make opportunistic use, consciously or unconsciously, of features of the environment to transform symbols into meanings. In blurring the boundaries between the internal and external worlds of the individual, we can discuss how humans capitalize on features of the environment to offload some of the cognitive work associated with a task. Symbols, representations and language play a part in cognitive functioning to the extent that they facilitate communication and free up space in the mind for operations on those symbols. These cultural tools act as an intermediate agency between the mental processing of the individual and the object of the mental processing.

Napkin computations are a case in point. Most readers of this paper have done a napkin computation at one time or another. The scenario is as follows: two physicists are discussing a problem while they are having lunch. As they talk, one of them grabs a

napkin and a pen and begins to draw pictures and possibly write equations. The physicist has offloaded some of the cognitive work involving representation, analysis of concepts and communication onto the napkin. The napkin was a tool of thought as well as a tool for communication. Most of the time, the napkin is not used solely as a means for sharing internal thought with another person, it is also used to facilitate thought. It participates in and shapes the thought process.

Another example can be found in classic research done by Luria and Vygotsky. Luria and Vygotsky worked with a patient that had Parkinson's disease [25]. The disease was so severe that the patient could not walk across the floor. Strangely, the patient could climb stairs. Luria and Vygotsky hypothesized that the patient made opportunistic use of the discrete design of the stairs so that each leg-lifting motion was conceptually coupled with the appearance of each individual stair step. To test this hypothesis, Luria and Vygotsky placed sheets of paper on the floor in a straight line, each separated by a given distance. When asked to try to walk, the patient was able to walk across the floor unaided. This suggests that the patient made opportunistic use of the discrete features of the stairs for the cognitive functions that led to the successive lifting of the leg. Luria and Vygotsky conducted many studies of this type with similar results.

In *Being There: Putting the Brain, Body and World Together Again*, computer scientist Andy Clark [26] reflected on the role of the external world in shaping thought. He said, "We manage our physical and spatial surroundings in ways that fundamentally alter the information-processing tasks our brains confront" ([26] p. 63). The following excerpt elaborates on this perspective.

Where, then, is the mind? Is it indeed "in the head," or has mind now spread itself, somewhat profligately, out into the world? The question is a strange one at first sight. After all, individual brains remain the seats of consciousness and experience. But what about reason? Every thought is had by a brain. But the *flow* of thoughts and the adaptive success of reason are now seen to depend on repeated and crucial interactions with external resources. The role of such interactions, in the cases I have highlighted, is clearly computational and informal: it is to transform inputs, to simplify search, to aid recognition, to prompt associative recall, to offload memory, and so on. In a sense, then, human reasoners are truly *distributed* cognitive engines: we call on external resources to perform specific computational tasks, much as a networked computer may call on other networked computers to perform specific jobs. One implication of Kirsh and Maglio's demonstration of the role of epistemic action is thus, I suggest, a commensurate spreading of *epistemic credit*. Individual brains should not take all the credit for the flow of thoughts or the generation of reasoned responses. Brain and world collaborate in ways that are richer and more clearly driven by computational and informational needs than was previously suspected ([26] p. 68).

In the excerpt above, Clark talks about giving epistemic credit to features of the environment and he uses the word "collaborate" to describe the relationship between the brain and the world. If epistemic credit is to be given to something other than the individual, then we need a theoretical means for relating the internal mental functions of

the human being to the external cognitive functions of a broader socio-cultural cognitive system.

The Unit of Analysis

I have used the term *cognitive* theory broadly to encompass theoretical perspectives for which cognitive activity is considered to take place entirely in the head of an individual. Research in this tradition considers the structure and function of the individual's mental processes as the unit of cognitive analysis. In cognitive theory the unit of analysis is sometimes thought of as neurological processes, concepts, mental models, p-prims, schemata, etc. and the connections between them. The term *socio-cultural theory* has been used here to encompass theoretical perspectives for which the mind is thought to exist inside and outside the head of the individual and cognitive processes are thought to be shared between the mental functioning of the individual brain and the external features of the environment. In socio-cultural theory, the unit of analysis is the irreducible mediated action consisting of the individual as he creates the context, the cultural and historical artifacts internal and external to the individual and the individual interacting with others and with these artifacts. A central difference between a cognitive perspective and a socio-cultural perspective is the central claim of the socio-cultural perspective that things outside of the head of the individual fundamentally shape and transform the mental functioning.

A useful analogy is provided by Andy Clark:

The simple sponge, which feeds by filtering water, exploits the structure of its natural physical environment to reduce the amount of actual pumping it must perform: It orients itself so as to make use of ambient currents to aid its feeding. The trick is an obvious one, yet not until quite recently did biologists recognize it. The reason for this is revealing: Biologists have tended to focus solely on the individual organism as the locus of adaptive structure. They have treated the organism as if it could be understood *independent of its physical world*. In this respect, biologists have resembled those cognitive scientists who have sought only inner-cause explanations of cognitive phenomena ([26] p.46).

This analogy is not only useful for illustrating the error that can come out of analyses that consider only the individual as the unit of analysis, but also the error that can come out of an analysis that fails to consider the individual. When biology researchers looked only at the sponge with the assumption that the water was a stable, unwavering "context" they learned very little about the breathing of the sponge. They failed to consider the interaction between the sponge and the water as a larger system. It was not until they realized that the breathing of the sponge was an interaction between the active internal process of the sponge and the active external features of the environment that they were able to understand those things that were originally attributed to the sponge itself. The process of breathing could not be inferred from analyses of the water current alone and it could not be inferred from analyses of the sponge outside its environment. Similarly, the process of learning can not be inferred from an analysis of the social interactions alone nor can it be inferred from analysis of the individual as the sole unit of analysis.

4. Tools, Artifacts, Culture and Language

Cultural artifacts (often referred to as tools) such as language, equations, maps, schemes, representations and graphs transform cognitive activity. Cole and Wertsch quote Vygotsky [27]:

The inclusion of a tool in the process of behavior (a) introduces several new functions connected with the use of the given tool and with its control; (b) abolishes and makes unnecessary several natural processes, whose work is accomplished by the tool; and alters the course and individual features (the intensity, duration, sequence, etc.) of all the mental processes that enter into the composition of the instrumental act, replacing some functions with others (i.e. it re-creates and reorganizes the whole structure of behavior just as a technical tool re-creates the whole structure of labor operations) ([27] p. 2).

The phrase *piggy-backing on the environment* can be used to illustrate the notion that individuals make opportunistic use of tools such as language and other features of the environment to share the cognitive responsibility for completing a task. The way the tool is used may or may not resemble its intended use; this is why it is important to speak of the mediated action rather than the tool alone or the way the tool is used.

A central theme of Vygotsky's theoretical approach is the idea that higher mental processes have their origins in social processes. In science, the origin of the knowledge that the student must develop is the historical practices and products of the scientific community. It is in appropriating the language, the agreed upon usage of language, and the processes for developing scientific knowledge that the student gains scientific understanding. These ideas are included in Vygotsky's theory of concept formation. In differentiating between *spontaneous* (intuitive) and *scientific* (academic or canonical) concepts, Vygotsky's theory includes the tools, symbols, practices, and norms of the culture of the academic discipline in the definition of the scientific concept. This is part of what differentiates a scientific concept from a spontaneous concept. Scientific concepts are concepts that have been agreed upon by a community. These concepts by their very nature can be shared, articulated and evaluated as products of a broader culture. Spontaneous concepts exist in the private, unarticulated world of the individual. Spontaneous concepts are experience-based complexes of information that have not been abstracted nor do they necessarily exist in the awareness of the individual.

Scientific knowledge includes tools, practices and norms including mathematical symbols, schematic diagrams, shared understandings of what counts as evidence, criteria for determining the explanatory power of a conceptual model, the process of making inferences from observations, and an understanding of knowledge as a shared, communicated and agreed upon cultural product. These processes facilitate the necessary sharing of scientific knowledge. When learning science in an inquiry-based learning environment the student must appropriate these norms and practices of the scientific community in order to achieve conceptual understanding.

The remainder of this paper is devoted to research in an inquiry-based physics classroom where knowledge of the tools, practices and norms of the scientific community were appropriated by a group of students through participation in scientific activity.

The unit of analysis is the mediated action of the students. Following the perspective of distributed cognition, I defined the individuals, the individuals interacting with tools (such as computer simulators and their representations, activity documents, and laboratory apparatus), individuals interacting with each other and individuals interacting with each other and with tools as a socio-cultural cognitive system. The research described in this paper shows how changes in the individuals' conceptual frameworks had a major impact on the structure and function of the social and material learning environment. Resulting changes in the learning environment then had a major impact on the learning of the individuals. This research shows that the social and material learning environment is not a fixed set of surroundings in which the individual is embedded. Instead, it is a dynamic player in the cognitive process.

5. Research Method and Data Sources

Classroom Setting and Data Sources

This study took place in a physics course for prospective elementary teachers that used the collaborative inquiry-based Constructing Physics Understanding¹ (CPU) course materials and simulator software [28]. The research took place during the static electricity unit which required eleven 140-minute class periods to complete. The CPU pedagogy does not use a textbook. Instead students are expected to construct their own ideas through the process of consensus, drawing on the ideas that were generated in small group discussions and experimentation.

Thirty students were enrolled in the course, mostly juniors and seniors with little or no prior formal instruction in current electricity or static electricity. Two groups of three students were video taped as they worked in small groups and the entire class was videotaped during whole class discussions. The six students who participated in the study were interviewed independently once or twice a week outside of class. Over 100 hours of classroom data was video recorded, transcribed and time-stamped. Much of the class time was spent in small group discussions where groups of three students worked on computer-based activity documents using laboratory experiments and computer simulations. Students' written work such as daily journals, homework, tests and diagrams constructed during interviews also served as data sources. Two interrelated analyses were performed: one focusing on the evolution and development of the two groups' scientific behavior and the reciprocal development of the classroom social and material environment (this paper) and one focusing on the evolution and development of the six students' conceptual models (*Cognitive processes and the learning of physics I: The evolution of knowledge from a Vygotskian perspective*, this volume).

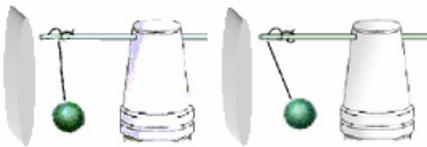
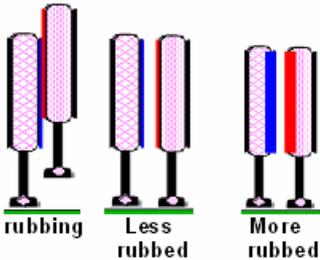
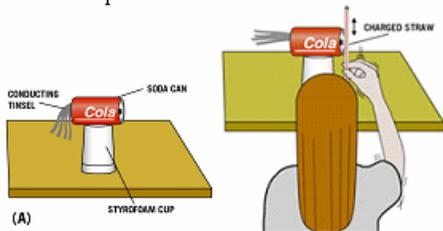
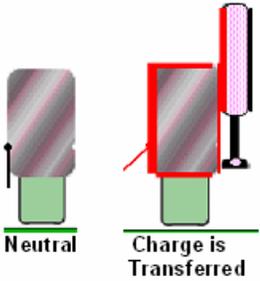
The Activity Documents and the Computer Simulator

The CPU activities are electronic documents that focus on one or two scientific concepts such as attraction and repulsion between insulators, distance effects of forces between charged objects, quantity of charge, models for charging insulators by rubbing, charge polarization within conductors and charging a conductor by induction. The activities are designed such that students are asked to make predictions, perform

¹ The CPU Project was supported in part by National Science Foundation grant #ESI-9454341.

experiments and interpret results of laboratory experiments using common objects such as soda cans, Styrofoam plates and plastic straws. At a certain point in the unit, the computer simulator was introduced as a new tool that could be used to make predictions, observations and interpretations of the simulated phenomena. The CPU static electricity computer simulator has a dual representation. It represents what one would observe using laboratory apparatus (such as attraction and repulsion) and it overlays a simple red and blue coloring scheme that provides “model-like” results. The red and blue coloring scheme is a simple macroscopic model of charge. Charged surfaces of conductors and insulators are represented by a red or blue line of varied thickness. As the quantity of excess charge increases on the surface of the object, the red or blue line gets thicker. Charge transfer from an insulator is represented by a decrease in the thickness of the blue line on the insulator and an appearance of a thin blue line on the surface of the conductor, as shown in table 1. Table 1 shows corresponding laboratory and simulator experiments that appear in the CPU activity documents.

Table 1. Corresponding laboratory and simulator experiments in CPU.

Laboratory Experiment	Simulator Experiment representation.	Scientific (expert-like) inference
<p>Rub two insulators together and observe that the more vigorously they are rubbed together the greater the attraction between objects.</p> 	<p>Rub two simulated insulators together and notice that the more the object is rubbed, the thicker the color generated on the surface becomes.</p> 	<p>More charge is transferred between objects the more the objects are rubbed together.</p>
<p>A charged insulator is rubbed up and down against a neutral soda can electroscopes.</p> 	 <p>Neutral</p> <p>Charge is Transferred</p>	<p>Charge is transferred from the insulator to the soda can. Since the soda can is a conductor and so is the tinsel, charge is transferred into the tinsel. The tinsel is the same charge as the left end of the soda can, so it repels from it.</p>

The CPU static electricity unit consists of three cycles. In cycle I, students do several simple experiments rubbing insulators and they become familiar with attraction, repulsion and distance effects. In cycle II, students construct an explanatory model for the process of charging insulators by rubbing. In cycle III, students do experiments with conductors and insulators and construct explanations for charge polarization and charging by induction. Within each cycle there is an elicitation phase (designed to elicit students initial ideas about phenomena to be studied in that cycle), a development phase (when

students conduct laboratory and simulator experiments in small groups), and a consensus phase (when the whole class is expected to come to a consensus on a few theoretical models that can explain all of the evidence collected). An application phase should follow, but the teacher in this study rarely assigned application assignments. Each activity is labeled according to the cycle and phase. For example, the elicitation activity for cycle II is labeled “Activity II-E” and the third development activity for cycle III is labeled “Activity III-D3.” Students worked on most activities at the computer with laboratory apparatus nearby. Each activity document was presented on the computer and each group was expected to type in one answer for each question that represented the consensus of the group. This collaborative process is demonstrated through the data and analysis later in this paper.

Method

The analysis described in this paper focused on groups’ scientific behavior. Time-stamped transcripts were analyzed and each statement or set of statements was initially coded according to the type of behavior that it represented, such as experiment, data-logging, etc. Further analysis of the same data led to a coding scheme into which all comments made by students fit. The codes of interest here are the *scientific inquiry codes* consisting of behaviors observed during the prediction/reasoning phase or observation/interpretation phase of both laboratory and simulator portions of activities. *Model-based reasoning*, *peer instruction* and *unresolved issues* were the three codes that were considered to comprise *sense-making behavior*. Other events that were coded *data logging* and *computer/apparatus manipulation* were not considered sense-making behavior. The time spent in sense-making behavior was determined by marking the beginning and end points of each sense-making episode and calculating the time. The data were graphed and trends were noted. Trends were explained by combining the data from the two studies in this project.

6. Research Results and Analysis

Sense-Making Profiles

Two groups of three students were studied. The group, the activity documents, the laboratory apparatus, and computer simulator were considered the cognitive system and served as the unit of analysis. MJH was the name given to the group that consisted of Mark, Jenny, and Heidie. PRT was the name given to the group that consisted of Pedro, Rosa, and Tara. After the data were coded, the events coded as sense-making behavior were used to determine the percentage of time each group of students spent sense-making during each activity. The percentage of time spent in sense-making discussions for each activity was determined by dividing the amount of time spent sense-making during a particular activity by the total amount of time spent on the activity. The sense-making profiles for each group are shown in fig. 1.

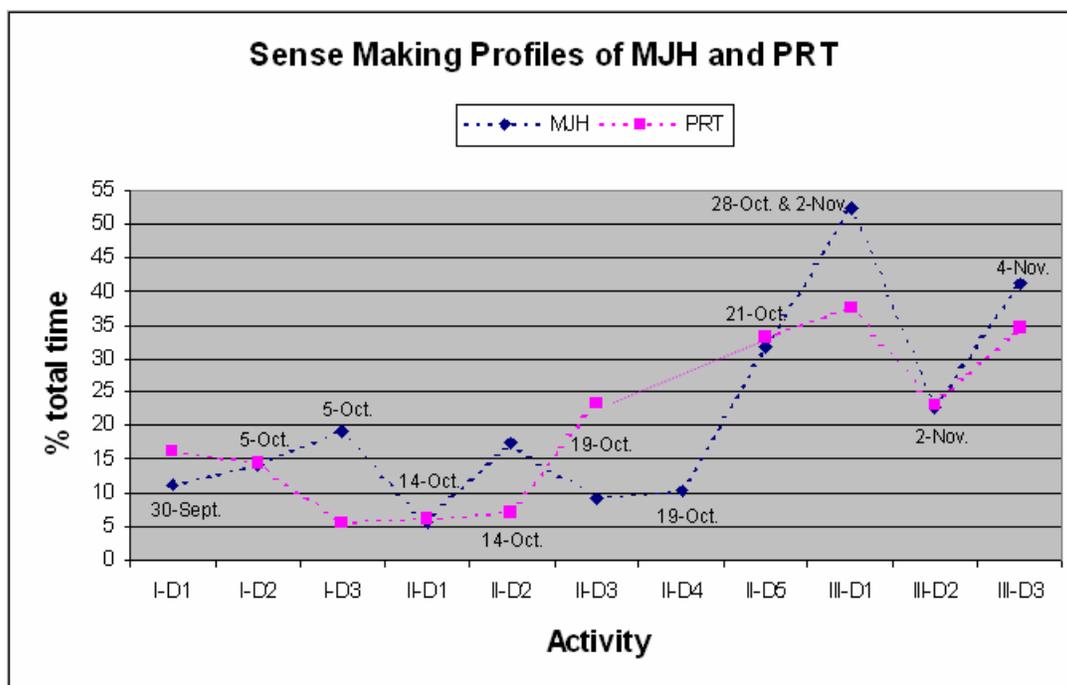


Figure 1. Sense-making profiles for groups MJH (diamonds) and PRT (squares).

Each data point in the graph in fig. 1 represents the percentage of time spent sense-making for each activity. The activity name is plotted along the x-axis and the percentage of time spent sense-making is plotted along the y-axis. The dates on which the activities took place are shown near the data point. MJH's sense-making profile is represented by the diamond symbols in fig. 1 and PRT's sense-making profile is represented by square symbols. A noteworthy similarity in the sense-making profiles of the MJH and the PRT groups can be observed. According to the graph, both groups worked through the first five activities spending from 5-20 % of their time in sense-making discussions with an average of 13% for MJH and 10% for PRT. After activity II-D3, MJH averaged 28% of class time in sense-making discussions and PRT averaged 30% of class time in sense-making discussions. The average amount of time groups engaged in sense-making increased by 15% for MJH and 20% for PRT after activity II-D3.

Activity II-D3 was the first activity in which the computer simulator and coloring scheme was introduced. Before Activity II-D3 on 19-Oct., each group used laboratory apparatus only, as directed by the activities, so all of the events coded as sense-making events before 19-Oct. involved no use of the computer simulator.

The fact that both sense-making profiles show a notable increase shortly after the computer simulator and coloring scheme was introduced suggests that the coloring scheme and computer simulator had something to do with this increase in sense-making for both groups. To test the hypothesis that students were able to engage in more model-based discussions for longer periods of time with the assistance of the computer simulator, each sense-making curve was separated into laboratory and simulator components.

The percentage of activity time spent sense-making in laboratory and simulator portions of activities are represented in figs. 2 and 3. The date and activity that took

place on that date are plotted on the x-axis and the percentage of time spent sense-making in either laboratory or simulator portions of activities are plotted on the y-axis. Because the simulator was not introduced until 19-Oct., the laboratory and simulator components shown in figs. 2 and 3 begin on Activity II-D3.

Again we see similarities in the sense-making profiles for MJH and PRT. Both profiles show an increasing trend in the laboratory components of the sense-making profiles. The simulator component on both graphs increases between Activities II-D3 and II-D5, flattens out between Activities II-D5 and III-D1 and then decreases between III-D1 and III-D2. The curriculum was not designed to decrease the use of the simulator over time. In fact, new features of the simulator were written into the last three activities of the unit. The curriculum developers anticipated that the computer simulator would be helpful through the end of the semester. Nevertheless, the amount of time spent in simulator-based sense-making discussions by both groups decreased near the end of the semester and I wanted to know why.

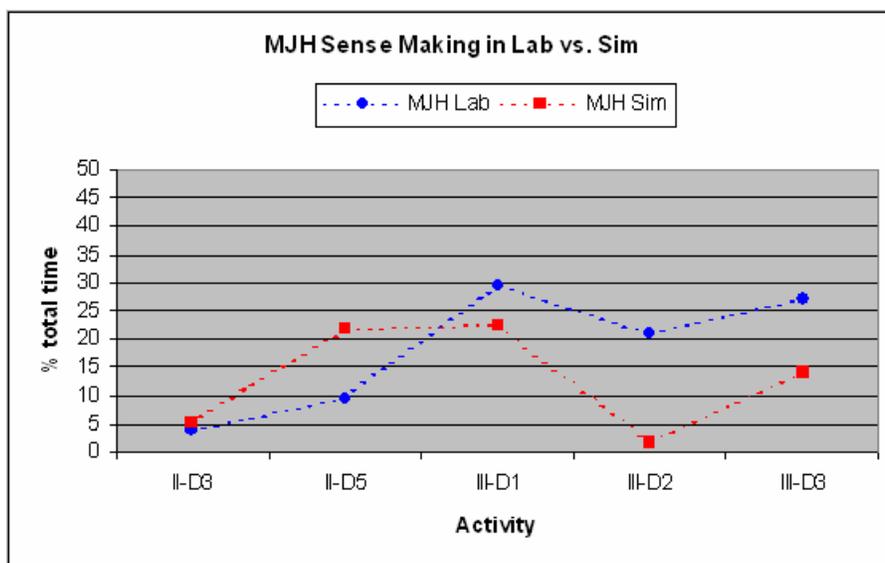


Figure 2. Laboratory & Simulator sense-making profile for MJH.

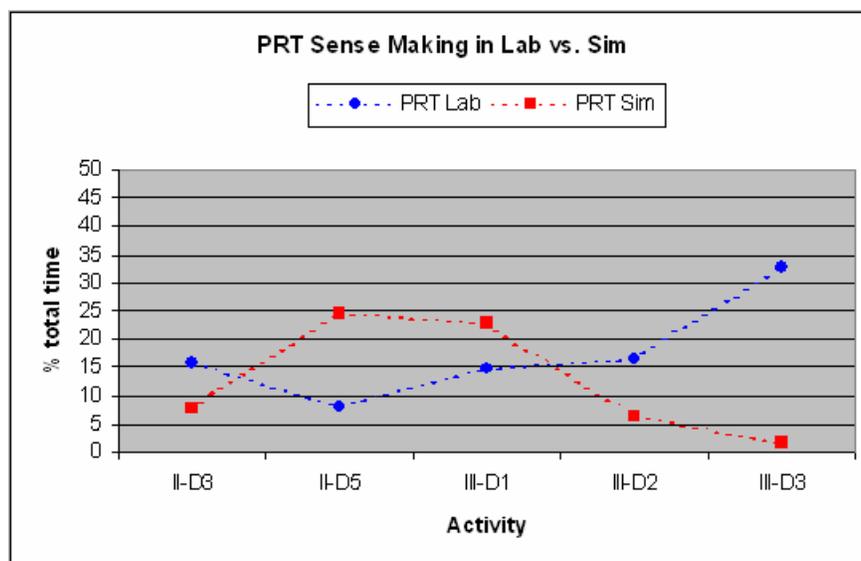


Figure 3. Laboratory & Simulator sense-making profile for PRT.

In attempts to explain the increasing trends in laboratory sense-making and the decreasing trends in simulator sense-making, I used data from another part of the study where explanatory models were inferred for each student at various points throughout the unit. Each of these models was empirically determined through analysis of the student interviews, pictures, homework, journals, and in-class discussions. Twelve models were inferred for the six students throughout the entire unit. For a detailed explanation of the process for inferring models, please see the companion paper *Cognitive processes and the learning of physics part I: The evolution of knowledge from a Vygotskian perspective* (this volume).

Students' model profiles are represented in figs. 4 and 5. The CPU activity is plotted along the x-axis. The twelve models inferred for students in the study are hierarchical organized along the y-axis in terms of the date on which they appeared in the data and on the basis of the explanatory power of the model. All models were generated and articulated by the students and the *one-way transfer* model was the target for instruction.

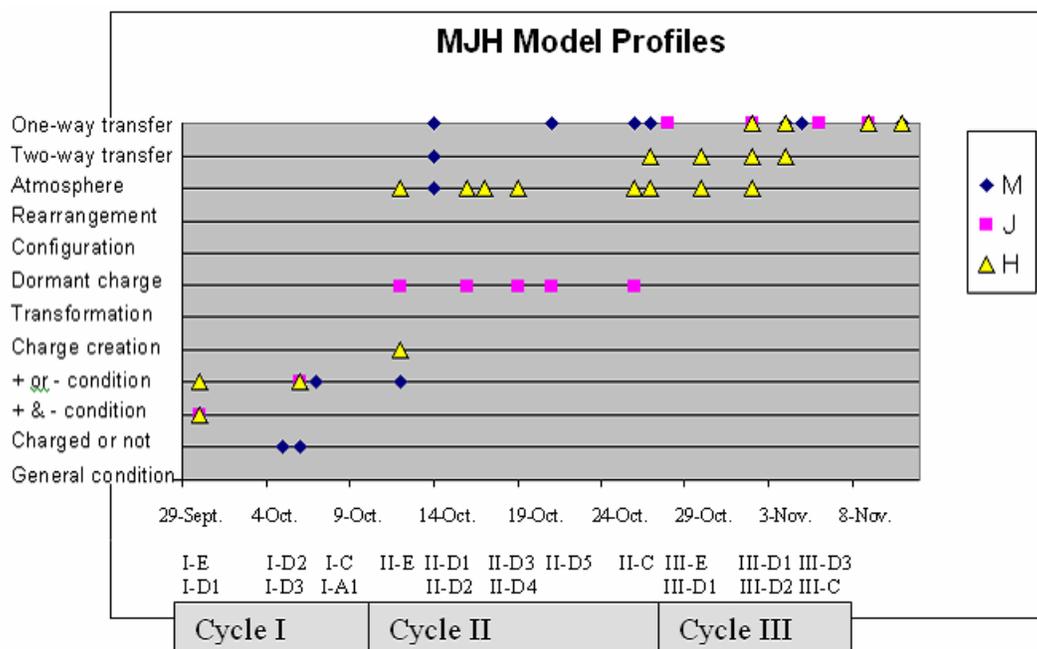


Figure 4. Model profiles for Mark, Jenny, and Heidie

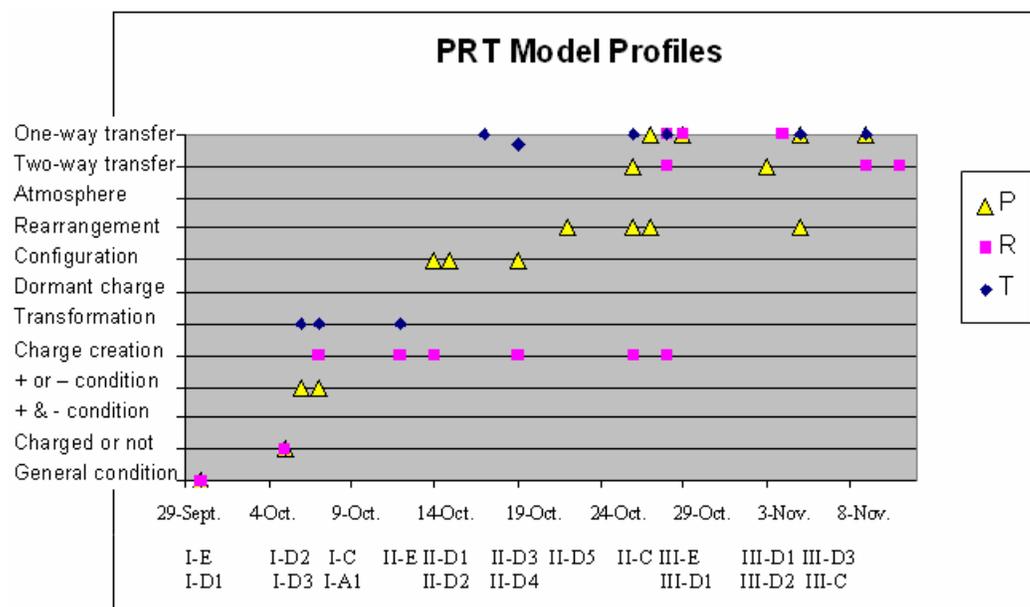


Figure 5. Model profiles for Pedro, Rosa, and Tara

According to the data shown in figs. 4 and 5, throughout much of the unit the three students in each group were using different models from one another. Around 2-Nov. student models for both groups began to converge to a one-way or two-way transfer model. Even though students were working together, answering questions from the activity documents and doing computer and laboratory experiments, they were still conceptualizing of the process of charging insulators by rubbing differently. It was often the case that students used words such as “lose charge” “transfer,” and “create” in their discussions but each student had a different, unarticulated meaning for the terms. The

task at hand is to explain the similarities between the PRT and MJH laboratory and simulator sense-making profiles and to explain the trends in laboratory and simulator sense-making shown in figs. 2 and 3.

Figures 6 and 7 show each group's laboratory and simulator sense-making profile superimposed on their group's model evolution profiles. The laboratory and simulator components of the sense-making profiles differ slightly from figs. 2 and 3 because in figs. 6 and 7 they are plotted by date rather than activity so that they would correspond with the data in the model evolution profiles. Some activities took place over two class periods and in some cases two activities were completed in the same class period. The activity(s) that each data point represents is shown near the data point. Square and round symbols coincident with the sense making curves represent the percentage of time spent sense-making on the activity(s) that took place on a given day. The symbols that lie along the sense-making curves do not represent student models.

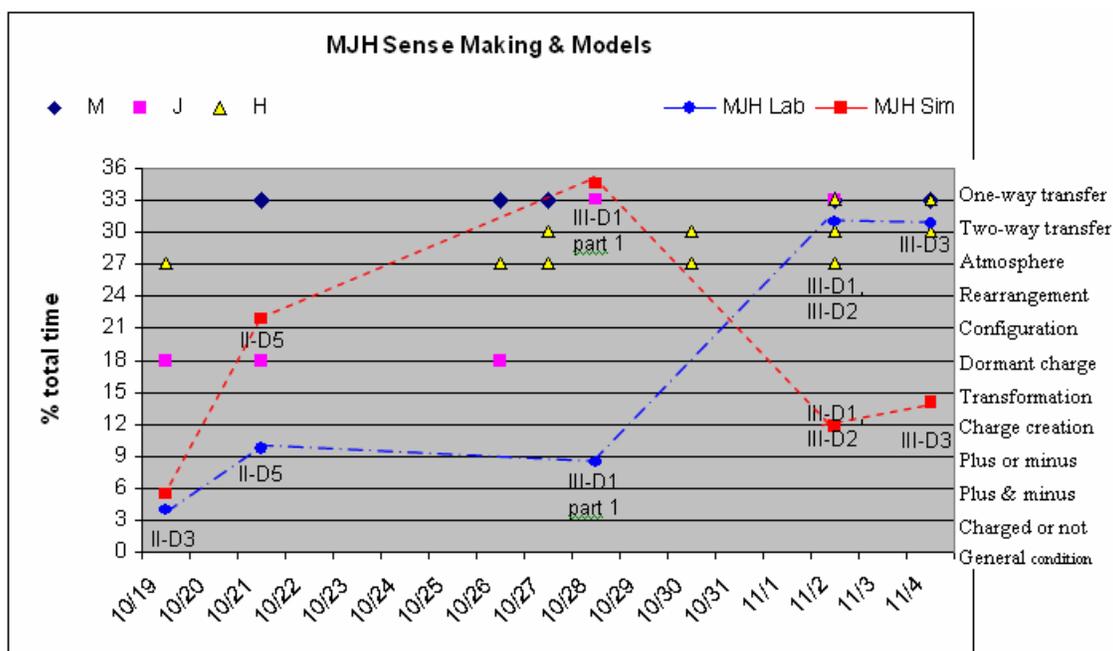


Figure 6. Superimposed model and SM for MJH

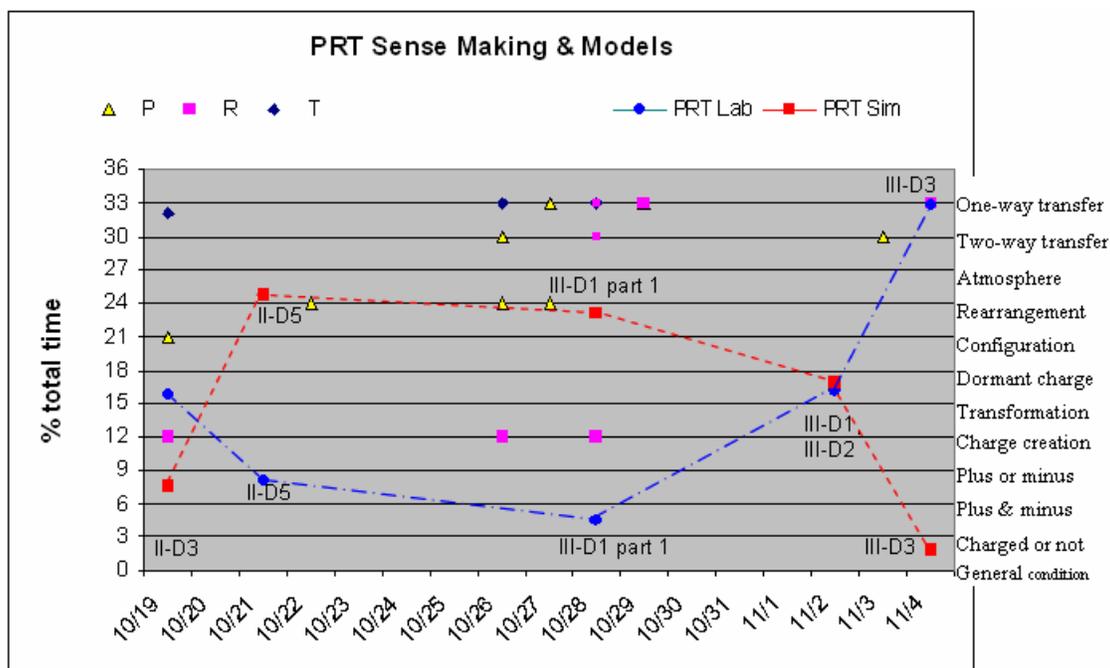


Figure 7. Superimposed model and SM profiles-PRT

Figures 6 and 7 suggest that simulator sense-making began to decrease around the time that students' models for each group began to converge to a one-way transfer model. For MJH, a one-way transfer model was inferred for all students around 2-Nov.. For PRT, one-way transfer models were inferred for all students around 28-Oct..

The increase in laboratory sense-making and the corresponding decrease in simulator sense-making can be explained by examining the role of the coloring scheme in the groups' communication of scientific ideas. The simulator coloring scheme provided a *shared model* that mediated sense-making discussions when students' models were very different from one another. They did not have concepts of "charge," "neutral" and "charge transfer" that were shared by all members of the group. In PRT, the students were not even aware that they all had different models. When they constructed explanations to both laboratory and simulator problems as a group the terms "charge," "charged," "red" and "blue" had different meanings for each of the students in the group. For much of the time, Rosa was explaining the charging process as an actual creation of charge. Pedro was explaining the charging process as a rearrangement of charges within the insulator. Tara had constructed a one-way transfer model but she was not entirely convinced that it was the best model and she realized that there were alternative possibilities.

The presence of multiple models is evident in the transcript below. The discussion took place on 19-Oct. during activity II-D3, the first activity in which the simulator was introduced. Students had just performed a simulator experiment where they rubbed two insulators together once or twice and noticed that a thin red line appeared on one insulator and a thin blue line appeared on the other. They then rubbed the two simulated insulators together many times and noticed that the red and blue lines got thicker and thicker. The question posed in the activity document asked students to compare the thickness of the red and blue lines when objects were rubbed once to the thickness of the

red and blue lines when the objects were rubbed together many times. It also asked them to compare the thickness of the lines on two objects that were rubbed together.

- 42:22:05 Rosa Okay, so how do you want to put this? With the simulator um, both
- 42:33:16 Rosa (typing) Both charges are evenly
- 42:42:11 Rosa Are created evenly? Is that what we want to say?
- 42:47:17 Tara The charges are-
- 42:49:22 Rosa Both or are we, with the rubbing both charges are evenly created? Is that what we're trying to say or do you want to say something else? Go ahead and tell me what you want me to write.
- 42:58:13 Tara I'm just wondering whether both of them already contain both of them, both charges in the beginning and then one eventually gets more of the negative and one gets more of the positive. I'm just trying to understand this cause I'm like-
- 43:11:14 Rosa So you're saying that one has more than the other?
- 43:14:22 Tara No is that what the two lines represent there if one's blue and one's red it's like one, like more of the negative and one more of the positive?
- 43:28:16 Rosa So say that again, you're saying that-
- 43:32:14 Tara No, I'm saying what do they both start off with? Are they both starting off with both negatives and positives?
- 43:38:06 Rosa No, they're both starting off with nothing.
- 43:40:09 Tara Oh okay, and then one's just getting more negative and one's getting more positive?
- 43:44:11 Rosa Um hum. As the more you rub. What we said is that at first they don't have anything, there's nothing in them or- and then we rub them once and we have a thin line on each of them and as the more you rub the thicker it got.
- 43:57:06 Tara So then they're gaining charges, they're both gaining opposite charges evenly?
- ...
- 44:34:11 Pedro Oh, cause they said they
- 44:34:21 Rosa Different materials
- 44:36:05 Pedro They couldn't- right- plus and minus, cause that's how described so they just said that it would use color.
- 44:41:10 Rosa But still aren't they representing one as negative and the other as-
- 44:45:11 T&P No
- 44:46:07 Pedro Cause they said, when we drew our models or whatever, it said that there were a bunch of plus and minuses but they couldn't- for the purposes of this they didn't want to put a whole bunch of plus and minuses so they just did (red and blue lines)

44:58:06 Rosa Okay, I understood it the other way around. I thought one had one type, I thought red was one type and blue was another type. I didn't think they were mixed.

In the transcript above, it is evident that Rosa thinks that before rubbing, there are no charges in the insulators and these charges are created during rubbing. The concept that the neutral state of the insulator is an absence of charge is evident in Rosa's statements at times 43:38:06 and 43:44:11. Rosa's concepts that the process of charging involves the creation of charge are evident in statements 42:33:16 and 42:49:22. Other evidence from interviews, homework, and diagrams confirm that Rosa was using a charge creation model. Tara's statements in the transcript above indicate that she conceived of the neutral state of the object as having an equal distribution of positive and negative charges. Other data suggest that Tara was conceiving of the charged condition as an excess of positive charges in one insulator and an excess of negative charges in the other and she was conceiving of the charging process in terms of the transfer of charges. Other data suggest that for Pedro, only the distribution of charges within the insulator changed, where positive and negative charges within each insulator came to the surface of the insulator during rubbing. The charges were configured or ordered as plus, minus, plus, minus for one insulator and minus, plus, minus, plus for the other. Since the configurations on the surface were equal and opposite, the insulators attracted each other.

The transcript above is an example of a model-based discussion mediated by the simulator coloring scheme. The red and blue coloring scheme and computer simulator mediated the process of students' transforming their personal concepts into words that could be shared with other individuals. Before the coloring scheme was introduced, the students used terms such as "charge" and "charged" but had yet to articulate their own personal meanings of these terms. The coloring scheme helped them do this. These types of discussions continued for Pedro, Rosa and Tara until 26-Oct. when they became fully aware of the differences in the models that each was using. At that point they worked through the difficulties with each model and co-constructed a one-way transfer model. Although Tara had been using the one-way transfer model for two weeks, she did not simply describe her model to the group; she re-constructed it with them.

For MJH, the group discussions were similar to the one shown in the PRT above. Students used different models to explain phenomena and to discuss the coloring scheme images. As was the case with PRT, the red and blue coloring scheme led to rich discussions where differences in Mark, Jenny and Heidie's models were articulated when they attempted to predict and make sense of simulator coloring scheme results. The coloring scheme and computer simulator impacted discussions in two ways. First, in making predictions about the colors that would appear on insulators and conductors after the simulator experiment was performed, subtle aspects of students' models were brought not only to their own awareness but they were also shared with their group. Their previously unarticulated ideas were articulated and became subject to evaluation by themselves and by others. Second, the coloring scheme provided a shared model that students could use to mediate discussions about real and simulated phenomena when their models were very different from one another. In many cases students were unaware of some of the abstract implications of their own models. It would have been difficult to engage in model-based discussions using their own personal models when they were not

even aware of the features and the implications of the features of their own models. The coloring scheme was a generalized shared model that facilitated these model-based discussions, allowing students to make predictions and claims that were implicitly based on their own personal models and concepts, even when they had not yet abstracted the features and implications of their models.

By the time students' models converged, they had already engaged in many mediated model-based discussions about real and simulated phenomena. These coloring-scheme mediated discussions helped students become aware of their own models and the models of others. This led to the evaluation of critical features of an abstract model that could be supported by real and simulated evidence. After students' models converged, all students in each group had articulated and shared the important features of the one-way transfer model. They had discussed the concept that only negative charges moved, that the charged condition was defined by an excess of charge, and that the process of charging an insulator required the transfer of charge from one insulator to the other. Since these concepts had been articulated and shared, each student now knew what the other students in his or her group knew and he or she also knew that the others knew what he or she knew. Anthropologist Roy D'Andrade [29] refers to this process of shared knowledge in terms of *intersubjectivity*. He describes intersubjective sharing using the following example.

You and I may both know the money is hidden in the teapot and I may know that you know (I saw you hide the money there), and you may know that I know (you caught a glimpse of me when I was spying on you as you hid the money), yet because I do not know that you know that I know, I cannot assume that your seeing me look at the teapot would tell you that I was thinking about the money. However, when everybody knows that everybody knows that everybody knows, then anyone's glance toward the teapot is understood by all, including the one giving the glance, as a potential reference to money ([29] p.113).

A model is intersubjectively shared when I know that you know that I know. It is necessary that I know that you know that I know because this allows us to engage in discussions using agreed upon understandings of the meanings of terms and symbols. Because both groups did not have a shared model for charging insulators by rubbing that was intersubjectively shared until 2-Nov., they relied heavily on the coloring scheme as a shared representation with which to clarify and articulate their scientific ideas.

After the convergence of models, sense-making discussions that focused on the coloring scheme or simulator images began to take place less frequently and/or for less time and discussions that focused on the laboratory apparatus began to occur more frequently and/or for longer periods of time. The emergence of a more detailed and refined intersubjectively shared one-way transfer model made it possible for groups to reason about observed phenomena with less guidance from the coloring scheme and computer simulator.

Model-based reasoning about a phenomenon was now taking place with the laboratory apparatus *before* the group got to the simulator portion of the activities. In fact, when the documents asked students to open the simulator, they made comments such as, "We already know we did it right, right? We just have to take pictures," and "We

already know what's gonna happen.” “Oh, this just proves our theory” before they opened the simulator in Activities III-D2 and III-D3. The computer simulator now served only as a *confirmation* of the explanations the groups had already constructed using laboratory apparatus alone. And when they were asked to make coloring predictions, the nature of discussion was different than it had been in the past. For example, PRT spent approximately 17 minutes discussing the process of charging an object by induction during the laboratory portion of the activity. They worked out an explanation and typed it into the computer. The explanation they worked out and typed into the computer is given below.

In our experiments we noticed that when we put a red charge close to the can, the tinsel carried the red charge too because the can contains both red and blue, so the red from the acrylic attracts with the blue in the can. The red charge in the can is left. When our body takes the red charge, therefore leaving the blue. When we put the acrylic next to the can the red charge from the acrylic attracts the blue charge left in the can so the tinsels are down. When we move the acrylic away the can still has blue charge so the tinsels raise (time stamp 44:01:04).

The group moved on to the next question, which asked them to perform the simulator experiment and to modify their explanation if necessary. Their discussion was approximately 3 minutes and they used the computer simulator simply to confirm their explanation. An excerpt from their discussion is given below.

55:19:10	Tara (reading) Using the set of pictures from the simulator, modify if necessary your explanation for why the soda can acquires an opposite charge to the charged insulator.
55:29:27	Tara Why don't we just close this first. (closing the simulator)
55:42:12	Tara (reading) Okay, using the set of pictures...
55:50:07	Tara So we said before it attracts.
55:56:05	Tara This is after you touch it?
55:57:27	Rosa Yea, um hum. It's because they're opposites and then, when it-
56:04:15	Tara So that's what we've been saying.
56:06:28	Rosa Yea.
56:07:27	Tara (typing) The simulator represented the model that we explained for number 8 and 9.
56:36:19	Rosa So we didn't make any changes right?
56:44:20	Rosa Should we save it?
56:46:28	Tara Yea, I saved it.

For MJH the simulator results also had mostly a confirmatory role in Activities III-D1 part 2, III-D2 and III-D3. The laboratory portion of the activity had the role of generating model based discussions. Instead of making quick interpretations of phenomena and then moving on to the simulator as they had done before, they were now spending much more time trying to construct explanations before they opened the simulator. An example of MJH engaging in sense-making discussions during the

laboratory portion of the activity is given below. Anne is a student from another group who was sitting near MJH.

- 32:50:22 Mark Wait, Styrofoam's negative right?
- 32:52:28 Anne Yea. Positives right here, negatives right here. When you touch the can with your finger you're absorbing the negatives right? Why?
- 32:55:26 Heidie Okay, so when the Styrofoam, the Styrofoam which is negative, um, is moved towards, towards the can, the positives are left at the front and the negatives break away and go to the back. To the back of the can. When you touch your finger to the can, you absorb the negatives, you absorb the excess negatives at the back of the can into your body. Um, and then um, when you pull your finger away you leave the can with a net positive because um, you absorbed all those extra negatives that were at the back of the can.
- 34:09:17 Mark Good.

The excerpt above is the conclusion of a 25 minute discussion that occurred prior to the simulator portion of the activity. After the group worked out an explanation for charging by induction, they went on to the next question in the activity document which asked them to open the computer simulator. An example of their dialog is given below. The group spent less than three minutes making predictions about the colors that would appear on the simulated objects and performing the simulator experiment.

- 35:12:07 Mark (reading) The simulator can help provide feedback on your ideas. Use your model of static electricity to explain what's happening in each picture.
- 35:19:14 Mark Dude, we already know what's gonna happen. Oh, this just proves my theory.
- ... (several minutes are spent manipulating the computer simulator.)
- 37:54:05 Mark Good, okay that makes sense.
- 37:57:10 Heidie That's right. That makes sense, isn't that what we said.
- 38:02:25 Mark Okay let's, let's keep going. So we can get this done, so we can put in ideas.
- 38:07:20 Heidie Do we need to take pictures of this stuff.
- 38:08:26 Mark Yea, (reading) explain what is happening in each picture.
- 38:11:07 Mark But you know what, we already described everything right?
- 38:13:16 Jenny Yea.
- 38:14:12 Mark So (type) "see above."
- 38:15:20 Heidie Let's take the pictures then.

The simulator results confirmed the model-based explanation that was generated during the laboratory portion of the activity.

Analysis

Prior to the convergence of models, the coloring scheme and computer simulator played a special role of mediating model-based discussion before students understood each other's thinking. The simple red and blue coloring scheme was general enough to allow for interpretation. As a result, it fit nicely into each student's model even though the models for the students in each group were very different from one another.

Transcripts from videotaped small group discussions confirm that discussions that centered on laboratory experiments were generally limited to confirmation and data logging before students' models converged. Discussions that centered on simulator experiments and coloring-scheme images tended to be conceptual in nature, where students articulated more aspects of their thinking as they were trying to predict and interpret simulator results. After students' models converged, around 2-Nov., model-based discussions took place more frequently in the laboratory portion of activities, before students opened the computer simulator. They started to use the simulator only to confirm the theoretical model they generated and articulated prior to opening the simulator.

Sense-making behavior increased after the simulator and coloring scheme was introduced for two main reasons: (1) The simulator and coloring scheme provided assistance that mediated model-based discussions by helping students transform, articulate and discuss their models (2) experience using model-based reasoning to predict and interpret simulator results scaffolded the process of constructing explanatory models based on observable phenomena. Constructing explanatory models based on observable phenomena is central in the norms and practices of science. This is what scientists do. Early in the unit, the students did not know how to do this as is evidenced by the prevalence of experience-based discussions. A smoothed, averaged sense-making curve is shown in fig. 8.

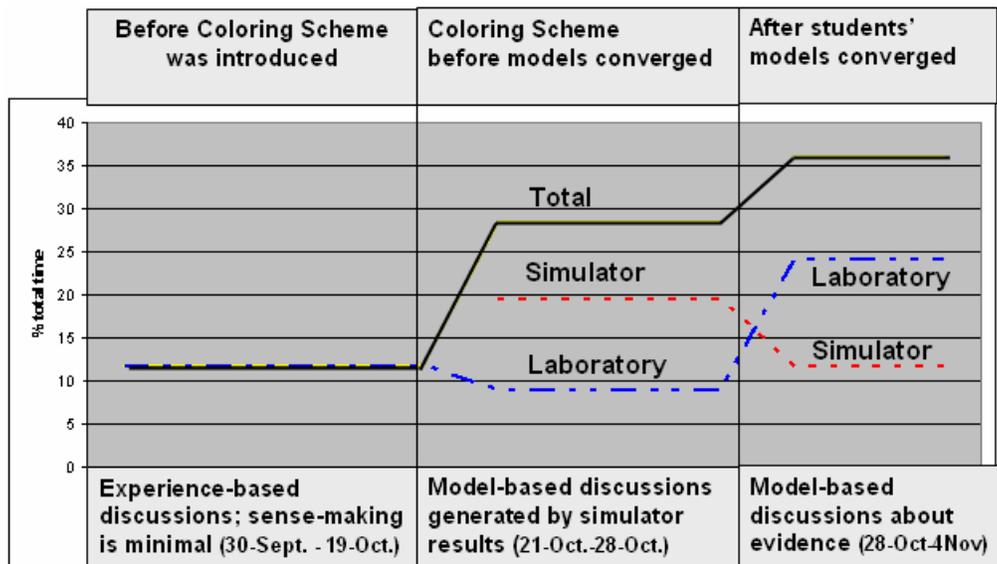


Figure 8. Smoothed, averaged sense-making curve representing MJH and PRT.

Figure 8 shows the data for both groups averaged over three different segments of the unit: (1) before the coloring scheme was introduced, (2) after the coloring scheme was introduced but before students' models converged and (3) after students' models converged. The average percentage of activity time spent in sense-making discussions is plotted along the y-axis and the segment of the unit is plotted on the x-axis. The laboratory and simulator components of the sense-making curve are labeled. This curve shows that the average time spent sense-making during simulator activities was higher than it was for laboratory activities just after the simulator was introduced but before the students' models converged. The average sense-making time during laboratory activities was higher after the students' models converged. Before the simulator was introduced, total sense-making was lowest and data indicate that these discussions centered on the students' experiences rather than on the conceptual or explanatory models. The shift in the amount of time spent sense-making during simulator and laboratory experiments indicates a difference in the use of tools that were available in the learning environment. Students' reliance on the simulator for articulating and sharing ideas disappeared after their models converged. Groups' patterns of sense-making behavior and the tools associated with it changed along with students' conceptual development.

6. Discussion

The scientific practice of constructing explanatory models based on evidence was developed among both groups through participation in the process of constructing and discussing explanatory models. The participation was made possible by a mediating artifact, the red and blue coloring scheme and computer simulator. Sense-making discussions increased by the end of the unit and they were transformed from reliance on the computer simulator and coloring scheme to reliance on a shared, scientific, transfer model. By the last part of the electrostatics unit, the way in which the computer simulator and coloring scheme were used was different from the way it was used in the middle of the unit. Just after the coloring scheme was introduced and before students' models converged, the computer simulator and coloring had a *generative* role. It generated and facilitated discussions. After the students' models converged, computer simulator had a *confirmatory* role and the laboratory experiments had a generative role. The process by which this shift was possible is related directly to the evolution and development of each student's concepts. As they developed an abstract understanding of the concepts related to the one-way transfer model, the group developed a shared language for discussing real laboratory phenomena. At the same time, the simulator tools made the individual students' awareness of their own ideas, and the sharing of their ideas, possible. This led to the growth and development of the conceptual models of the students. The use of the simulator tool and related discussions directly impacted students' conceptual development. Students' conceptual development directly impacted the way the tool was used and the resulting shift in the focus of discussions.

This reflexive, co-constitutive relationship between individual cognition and the social and material learning environment is predicted by the Vygotskian perspective of mediated action. In the situation described in this paper, the norms and practices of science were communicated to the students through the activity documents. Questions in the documents asked students to make predictions, perform experiments and interpret

results in the form of an explanatory model. Students did not know how to do this at first and they needed to appropriate this knowledge as a means for making further development in their conceptual understanding. An understanding of how to construct explanatory models of phenomena was mediated by the generalized red and blue coloring scheme that appeared in simulator results. After 19-Oct., students were asked to make predictions about how objects would be colored after simulator experiments were performed. Students removed the reliance on the computer simulator themselves. This is a form of *self-scaffolding*, where participation itself led to the gradual removal of conceptual guidance offered by the simulator tools.

The theoretical utility of the term *socio-cultural cognitive system* is illustrated in this analysis. The students, the students interacting with tools and the students interacting with others and with tools were a system that generated two kinds of knowledge. The first type was knowledge of the scientific practice of making inferences based on evidence. The second type was in the form of the development of spontaneous and scientific concepts that took place within each individual.

The transformations in the socio-cultural cognitive system, such as the transition in the roles of the computer and laboratory experiments, *were as dependent* upon the evolution of individual students' concepts as the evolution of students' concepts were on transformations in the socio-cultural cognitive system. The separation between the individual and the cognitive system is artificial. The relationship between the two is reflexive and co-constitutive.

A single theoretical perspective that could manage the evolution of the social and material learning environment *vis a vis* the conceptual evolution of the students is the notion of mediation. The notion of mediation is present in Vygotsky's theory of concept formation and in his theory of mediated action. For Vygotsky, concept formation and mediated action are not separate activities. The students in this study appropriated knowledge of the norms and practices of science as they participated in the process of science. The appropriation of this knowledge was only made possible by the evolution and development of students' spontaneous and scientific concepts. Scientific practices and scientific concepts developed simultaneously for the students and, as illustrated in the research and analysis presented here, the development of each depended on the development of the other. This is the process of mediated action.

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