COGNITIVE PROCESSES AND THE LEARNING OF PHYSICS PART I: THE EVOLUTION OF KNOWLEDGE FROM A VYGOTSKIAN PERSPECTIVE

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1. Introduction

The intent of this paper is to outline the Vygotskian approach to concept formation and to argue that this approach can be useful in physics education research. Vygotsky's work is largely missing from the literature in physics education, especially in the United States. As we increasingly consider contextual dependence of students' problem solutions [1] [2] [3] [4] [5]. Vygotsky's theoretical approach becomes increasingly relevant. Also, Vygotsky's approach can help interested researchers move beyond explanations of what is going on inside the head of the individual and into the domain of the processes of learning that take place in the broader social and cultural milieu.

Theoretical perspectives widely used in science education typically fall under the larger umbrellas of either cognitive theory or socio-cultural theory. I define cognitive theory as consisting of theoretical perspectives that seek to describe what is happening in the head of the individual. Examples of such theoretical perspectives include schema theory, neural networks and information processing perspectives [6] [7] [8]. Cognitive perspectives typically involve activations, connections and reorganizations of conceptual elements within the head of the individual. Cognitive theory is often used to support macroscopic views of learning such as classical conceptual change [9]. Consistent with the work of Piaget, these perspectives typically involve the individual's interactions with the world. However, the world is typically considered passive and the brain of the individual is considered the active agent in the structure and function of cognition. Cognitive theories often differ in their emphasis on the role of the external world in influencing the internal mental processes [10] [11].

Socio-cultural theory places a greater active agency on the external world. These perspectives take into account how socialization and culture impact the structure and function of the thinking of the individual. Like cognitive theory, there is a spectrum of socio-cultural perspectives in terms of their attributions to external interactions and processes internal to the individual. Some deemphasize the role of internal mental processes while others take cognitive processing into account [12] [13] [14].

The theoretical perspectives of Piaget and Vygotsky may be thought of as representative of cognitive and socio-cultural theoretical perspectives, respectively [15]. Both theoretical perspectives are widely used in research in the constructivist tradition. It has been argued that both Piagetian and Vygotskian theory are limited in their emphasis on the "limits, rather than the strengths, of intuitive knowledge (naïve conceptions, prior knowledge etc.)" [16, p. 254]. I argue that this is not the case for Vygotsky. In fact, Vygotsky saw intuitive knowledge as that which mediates the development of schooled knowledge. This is one of the places where Vygotsky and Piaget differed in their theoretical approach. Vygotsky's theory of concept formation accounts for the development of intuitive knowledge *and* canonical knowledge as separate processes that interact and mediate one another. Piaget accounted only for the development of intuitive knowledge through the process of disequilibration, assimilation and accommodation. For Piaget, intuitive knowledge is abstracted into, or is replaced by, canonical knowledge. For Vygotsky, the intuitive knowledge and canonical knowledge are separate entities and each is critical for the development of the other. Vygotsky's theoretical approach is developed in detail in the following section. The distinction between knowledge of content and knowledge about content is not clear in the Piagetian approach. The norms and practices of the community that produced the knowledge are rarely considered. Vygotsky's approach, on the other hand, sees higher mental functioning as social in nature.

In their revision to the classical conceptual change model [17], Strike and Posner define the term concept in the following way:

> Concepts are also seen not only as objects of thought but as the tools of thought. Scientific method is not specified solely by formal logic. Instead, the approach to the investigation of scientific phenomena is generated by paradigms. They determine what questions are appropriate to ask and what is to count as evidence" ([17] p. 153).

Posner et al.'s [9] conceptual change model was built not only on the foundations of Piagetian theory, but also on the foundations of the history and philosophy of science, especially on Thomas Kuhn's 1962 [18] account of how knowledge is developed within a scientific community. Kuhn's work is partially based on the socio-cultural approach of Ludwig Fleck [19]. The critical error of the classical conceptual change model is Strike and Posner's de-emphasis of "those aspects of the sociology of scientific communities that have figured in the philosophical theories of conceptual change" ([17] p. 152). This de-emphasis is evident in the following statement:

> Novice learners have not been initiated into a scientific community with its current conceptions and commitments. Nor do the politics or social behavior of such communities figure in learning. Notwithstanding, novice learners do not approach learning as blank slates. They approach new ideas with prior conceptions that govern their interactions with them ([17] p. 152).

They have chosen to focus only on the students' interactions with evidence and not with the students' interactions with the broader social and cultural features of science. These norms and practices provide motivation and criteria for determining, for example, the explanatory power of a conceptual model. They state, "Our theory of conceptual change is first and foremost an attempt to describe the kinds of evidence that are relevant to generating a major conceptual revision" (p. 155). The preceding statement implies that only observational evidence is necessary for bringing about conceptual change in students.

Many researchers in science education have attempted to construct models of cognition and learning that include more than observational evidence as factors that influence learning. Multi-perspective frameworks have been developed to understand, describe, and communicate the social and individual aspects of the learning process [20] [21] [22]. These multi-perspective frameworks include individual aspects of learning such as conceptual change, metacognition, and epistemology as well as social aspects of learning such as interactions of students with each other and with tools. Niedderer [23] brought together several perspectives such as schema theory, phenomenological primitives, reasoning primitives and other “cognitive tools” in his model of the student’s “cognitive system” that interacts with the learning environment. Within the cognitive system are current constructions such as observations, descriptions, expectations, explanations and meanings as well as their frames of thinking, preconceptions, interests, goals and elements of language. For Niedderer, all of these things exist within the individual, who is then acted upon by features of the learning environment. Exactly how the “cognitive system” is re-structured and acted upon by the external environment is not clear. Other multi-dimensional frameworks [20] [22] provide an account of how external and internal factors influence learning but they have yet to incorporate them into a comprehensive theory of conceptual change. Furthermore, most multi-dimensional frameworks fail to account for how the conceptual development of the individual(s) fundamentally re-structures the external social and material learning environment.

diSessa and Sherin [24] have also taken multiple factors of learning into account in their theory of coordination class, which defines knowledge in terms of a complex system. This system is made up of strategies for “seeing” relevant information in the world as well as causal nets of intuitive and canonical inferences that both impact and are impacted by the strategies for observing the world. As the coordination class evolves, students become consciously aware of certain knowledge associated with the norms and practices of the scientific community (such as integration and invariance criteria). Coordination class theory is quite useful for analyzing classroom data (a coordination class analysis of the data presented in this paper is reported elsewhere). However, because of its generality, an analysis of this sort makes it difficult to distinguish the *causes* of a student’s modifications of a coordination class. And, like other multi-perspective frameworks it provides little account of how the conceptual development of the individual re-structures the social and material learning environment. If one argues that student knowledge is “context” dependent, it becomes increasingly important to utilize a theory of cognition that can not only account for what is happening in the head of the individual but also for what is happening outside the head of the individual.

Although the learning environment is not the subject of this paper, a theory of cognition should be consistent with, and embedded within, a theory that can explain learning in the broader classroom context. This is the subject of the companion paper, *Cognitive processes and the learning of physics: Mediated Action* (this volume).

The field of educational research in general does not necessarily seek coalescence to one theoretical superstructure [25]. This may or may not be the sentiment of the physics education research community [26]. Nevertheless, I propose the Vygotskian perspective of concept formation and mediation for the analysis of the individual student’s learning and her interactions within the larger social and cultural system. In the remainder of this paper, the Vygotskian perspective of concept formation is described and then applied to classroom and interview data.

2. Socio-Cultural Theory

The Vygotskian Approach to Concept Formation

Much of the educational literature based on contemporary socio-cultural theory is grounded in the work of Russian psychologist Lev Vygotsky [15] [27] [28] [29]. Vygotsky [30] differentiated between elementary mental functioning and higher mental functioning and he viewed higher mental functioning as social in nature. Vygotskian scholar James Wertsch [31] described three general, interrelated themes in Vygotsky's theoretical approach: (1) reliance on a genetic or developmental method, (2) the claim that higher mental processes in the individual have their origins in social processes, and (3) the claim that mental processes can be understood only if we understand the tools and signs that mediate them.

Vygotsky's genetic approach holds that a single set of explanatory principles cannot be applied to explain mental processes as a human being transitions from one age to another. He argued that as humans grow there is a change in the *type* of development that takes place. For very young children, development can be explained largely in terms of biological principles, but as children grow, the central forces that shape cognitive development are governed by social and cultural principles.

According to Vygotsky [30] there are three phases in concept formation: conglomerates, complexes and concepts. The first phase consists of conglomerates that develop within a child's mind.

> At that state, word meaning denotes nothing more to the child than a *vague syncretic conglomeration of individual objects* that have somehow or other coalesced into an image in his mind. Because of its syncretic origin, that image is highly unstable ([30] p. 110).

In the preceding statement, the term "syncretic" is used to define the trait of the child's thought that characterizes the merging of diverse elements into the unarticulated image in the child's mind that operates under the chance that it is useful. The second phase of concept formation involves the organization of *complexes* which are collections of representations of objects that are, in actuality, related to one another. These complexes however, are factual and concrete, based on experience and are not logical nor are they abstracted from experience. Complexes may be grouped together according to shape, size, color, function etc. The third phase of concept formation is the development of the higher-order *concept*. The concept differs from the complex in that it entails abstracting and singling out elements apart from the totality of concrete experience. For Vygotsky there is a difference between the inner speech directed at oneself and the inner speech that is being prepared for communication with others. The difference between experience-based complexes and abstracted concepts resides in framing the abstracted concept in a formalized, culturally agreed-upon way.

Vygotsky differentiated between *spontaneous concepts* and *scientific concepts*. A difference between a spontaneous concept (intuitive knowledge or complexes) and a scientific (academic or canonical) concept is in the level of conscious comprehension of the substance of the concept. Verbal definitions and abstractions are associated with scientific concepts whereas no such verbal definitions or abstractions are associated with spontaneous concepts. Vygotsky showed that students were more confused when asked to define the spontaneous concept of "brother" than when asked to define the scientific concept of Archimedes' Law. The concept of brother was developed through experience and has not been subject to definition through language. Archimedes' Law on the other hand, was introduced and developed through language. According to Vygotsky, the full set of spontaneous concepts is not developed prior to the beginning of the development of related scientific concepts. Instead, they often develop simultaneously but in different ways; that is, a scientific concept is not necessarily an abstraction of a spontaneous concept. In *Thought and Language* [30] Vygotsky describes the development and use of concepts in the following way.

> The adolescent will form and use a concept quite correctly in a concrete situation, but will find it strangely difficult to express that concept in words, and the verbal definition will, in most cases, be much narrower than might have been expected from the way he used the concept. The same discrepancy occurs also in adult thinking, even at very advanced levels. This confirms the assumption that concepts evolve in ways differing from deliberate conscious elaboration of experience in logical terms. *Analysis of reality with the help of concepts precedes analysis of the concepts themselves* (emphasis added; [30] p. 141).

The final statement in the excerpt above proposes that the child (or learner) practices using scientific concepts (e.g. in speech, in problem solving) before he has developed them as a coherent abstraction from experience. This view of the development of spontaneous concepts versus scientific concepts may be useful in understanding physics students' naïve conceptions and the "resistance to change" phenomenon that has reoccurred in the physics education research literature [32] [33]. It may be useful to think of the student's naïve "conception" as a spontaneous concept grounded in experience and the canonical concept as the scientific conception which entails both abstraction and an articulated shared-language. This perspective provides an explanation of why students can express canonical concepts but not believe them and why students have such a difficult time applying their new physics knowledge to real-world situations.

A case in point is Newton's Third Law. In the physics classroom, students are often shown demonstrations and computer generated graphical representations of collisions. Carts of different masses are used and students see that even when one cart is pushed and the other is stationary, the graphical representations on the computer screen shows that the magnitude of the force acting on each cart is identical and the directions of the forces are opposite in all cases. Students are then able to *say* that this must mean that the two carts are exerting an equal and opposite force on each other. If, immediately following this analysis, the teacher asks the isomorphic question of whether a small car or a large truck in a collision will exert a greater force on the other, students often respond that the large truck exerts a greater force on the car. According to a Vygotskian perspective, in the former situation, the student was utilizing a scientific concept, one generated through the practices and tools used within the scientific community (such as graphical representations and controlled observations). In the latter situation, the student was using a spontaneous concept drawn from experience which may not have the same root as the scientific concept; they are different concepts. The scientific concept is developed as a shared structure by definition and the spontaneous concept exists in the private, experiential, unarticulated world of the individual. According to this perspective, spontaneous concepts and scientific concepts are two different things developing simultaneously and mediating the development of the other. This is quite different from a resource perspective, where different elementary abstractions from experience (or combinations thereof) are applied in different situations. Instead, this perspective argues that the student is utilizing terminology associated with a scientific concept that she does not yet understand.

The Vygotskian theoretical approach holds that spontaneous concepts develop "upward" (bottom-up) while scientific concepts develop "downward" (top-down), each assisting in the development of the other. Top-down development implies that the language and abstract idea is articulated first and the meaning of this idea is developed later. Bottom-up development implies that the experience-based meaning of the idea is developed first and is defined, organized, and abstracted later. Conceptual understanding occurs when these two concepts meet in their development.

It was of great interest to Vygotsky to determine how scientific concepts develop through schooling. He concluded that when a child learns a formal concept, the development of that operation or concept has only begun. That is, school instruction and conceptual development do not coincide. Instruction precedes development. Viewing conceptual understanding as a dynamic process, Vygotsky concluded that an adequate measurement of a child's conceptual level was in what the child could do with assistance, not in what the child already knew. He refers to the distance between what the child is able to articulate at a given time and what the child can articulate with the assistance of a more knowledgeable other as the zone of proximal development. The utility of the notion of the zone of proximal development is that the zone of proximal development is the space or time in which the expert can help the student bring her spontaneous concepts into coordination with scientific concepts.

An example of how the teacher can play a role in helping learners develop scientific concepts on the basis of their awareness of spontaneous concepts can be found in the work of [33] [34] [35] where "bridging analogies" were used to help students create incremental links between the knowledge they had developed through experience and the canonical knowledge of the discipline (scientific concepts). In fact, many of the research-based instructional approaches that have been developed within the past 20 years in physics education [36] [37] [38] [39]) are consistent with Vygotskian theory.

The research presented in this paper is a case study of a single student, Heidie, interacting with a member of her group of three students, with the whole class, and with Constructing Physics Understanding (CPU)[1] pedagogy, activity documents, laboratory apparatus and simulator software. Over a five week period, Heidie constructed an understanding of the charge transfer model of charging an insulator by rubbing. Her understanding was evidenced by her ability to use this model in further investigations involving charging conductors by induction. Vygotsky's theoretical approach is used to analyze the data and other approaches are used wherever relevant. The data set is presented in a story-like fashion because this is story of Heidie's conceptual development. Segments of transcripts from classroom discussions and interviews are provided as evidence to support claims. The letter "I" is used to represent the interviewer's comments and "H" is used to represent Heidie's comments. In all transcript segments an ellipsis is used to mark segments that have been omitted due to space constraints. A time-stamp is also included in transcripts from videotaped small group discussions.

3. Research Method and Data Sources

Classroom Setting and Data Sources

This study took place in a collaborative, guided-inquiry physics course for prospective elementary teachers at a state university. The course structure was based on the CPU pedagogy, activity documents, and simulator software [39]. The research described here took place during the static electricity unit which required eleven 140-minute class periods to complete. The static electricity unit consisted of three cycles: Cycle I-Familiarity and Experience with Electrostatic

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

Phenomena (attraction, repulsion, and distance effects), Cycle II-Building an Initial Model for Static Electricity (charging insulators by rubbing and charging conductors by contact), and Cycle III-Building a More Sophisticated Model for Static Electricity (charge polarization and induction effects in conductors).

There was no textbook used for the course; students were expected to construct their own ideas through the process of consensus, drawing on the ideas that were generated in small group discussions and experimentation. The instructor, Mr. P, had 10 years of experience teaching in a traditional, lecture-style classroom but had never taught in a small, inquiry-based classroom. The main role of a CPU teacher is to guide whole class discussions and to make sure the groups make appropriate observations. Mr. P. provided very little direct information involving the content of physics during the experimentation phase of each cycle. However, he provided more information during whole class consensus discussions which took place at the end of each cycle. The purpose of consensus discussions was for each group to present their final explanations or conclusions to the class, and for the class to come to a consensus on the explanations or conclusions that best fit experimental data. Students were familiar with the CPU format when they began the electrostatics unit because they had just completed a short CPU unit on light.

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. Approximately 100 hours of video and audio-taped data were transcribed, time-stamped, and analyzed. Students' written work such as homework, daily journals, 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 six students' conceptual models (this paper) and one focusing on the evolution and development of the two groups' scientific behavior and the reciprocal development of the classroom social and material environment (*Cognitive processes and the learning of physics: Mediated Action,* this volume).

Method

I inferred conceptual models for students at different points of time throughout the five-week unit on static electricity. All data sources were triangulated for inferences involving individual students' conceptual models. The models that were identified for each student were my own constructs, inferred from several sources of data. By checking with students about my inferences and through homework assignments that specifically asked them to "express their models" of charging two insulators by rubbing, I have confidence that my inferences accurately represented students' explanations of charging two insulators by rubbing them together. A model was inferred for a student only if he or she used it consistently such that it appeared in several different data sources or was used to explain several isomorphic real or hypothetical situations during interviews. I define the term *model* as a frequently used explanation for how two different insulators are affected when they are rubbed together. More generally, a model is a collection of spontaneous and/or scientific concepts. There are two types of concepts considered in this study: spontaneous concepts and scientific concepts. Spontaneous concepts are inferred from students' articulations and pictures, and they are explanatory features of a model. Scientific concepts are explanatory chunks of information contained in the canonical knowledge of physics. Not included in these definitions are strategies for distinguishing a good model from a bad model, knowledge of what counts as evidence, criteria for evaluating a good explanation and other characteristics of scientific rationality. These norms and practices of science are included in the analysis and interact with conceptual development; however they are considered separately for the purpose of elucidating their function in the development of scientific understanding.

4. Research Results and Analysis

Models for Charging Insulators By Rubbing

Twelve models for charging insulators by rubbing were inferred from the data of all six students who participated in the study. Only those models used by the Heidie are elaborated in this paper the full set of models is described elsewhere [40]. The *one-way transfer model* was one of the primary objectives of instruction. In this model, there are an equal number of positive and negative charges in each insulator before rubbing. During rubbing, one type of charge is transferred from the surface of one insulator to the surface of the other. This leaves the surface of one insulator with a deficit of negative charges, or an excess of positive charges (it is positively charged) and the surface of the other insulator with an excess of negative charges (it is negatively charged). In the student generated *two-way transfer model* there are an equal number of positive and negative charges in each insulator before rubbing. During rubbing, positive charges from the surface of insulator B are transferred to the surface of insulator A; negative charges from insulator A are transferred to insulator B. After rubbing, the surface of insulator A has an excess of positive charges, or a net positive charge, and the surface of insulator B has an excess of negative charges, or a net negative charge. Experiments that could support the one-way transfer model over the two-way transfer model were beyond the scope of this course and therefore were not included as a part of the laboratory or computer activities. This leads to the question of how students constructed an understanding and belief that a one-way transfer model was better than a two-way transfer model without evidence, a textbook, or a teacher that would tell them the answer. This is the subject of the remainder of this paper.

Students' Model Profiles

To understand the process of learning by individuals, I tracked the evolution of student models throughout the static electricity unit. I defined learning as transitions between models and looked for explanations for why these transitions occurred. The evolutions of each student's models throughout the unit are summarized in fig. 1. The graph in fig. 1 represents the three students, Mark, Jenny, and Heidie (MJH) in one group that was studied. The date and the activities that took place on that date are plotted along the x-axis. All of the models inferred from the study are hierarchically organized along the y-axis. The hierarchical organization was based on two things: (1) for each student, the models are organized chronologically on the basis of the dates at which they appeared in the data, (2) models for all students are represented hierarchically on the basis of explanatory power, for example the transfer models are higher on the y-axis and models that show only end-state conditions are the lowest. It is not the case that each student progressed through each of the models shown on the y-axis. There are some models, for example, the *charge rearrangement model*, that were used by only one student in the study. There are many differences between the students' model evolutions and different events turned out to be critical for each student's transitions. Heidie's case is presented and analyzed below.

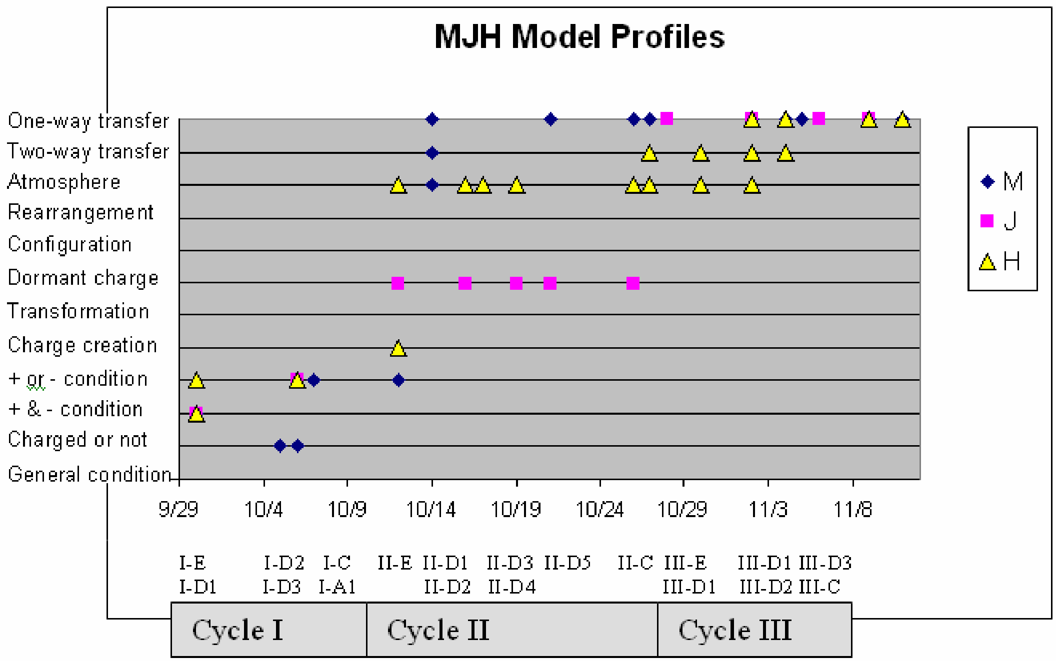


Figure 1. Model profiles for Mark, Jenny, and Heidie in group MJH.

Heidie's Model Evolution (MJH Group)

Heidie's model evolution profile is shown by the triangular symbols in fig. 1. This model profile illustrates that Heidie made five major transitions. The analysis presented here focuses mostly on the three final transitions because they illustrate her struggle to make meaning of scientific concepts. A timeline of activities and the dates on which they took place is provided for reference in table I.

Table I. Timeline of activity (row 1) and the days they took place (row 1).

Date	**30-Sept.**	**5-Oct.**	**7-Oct.**	**12-Oct.**	**14-Oct.**	**19-Oct.**	**21-Oct.**	**26-Oct.**	**28-Oct.**	**2-Nov.**	**4-Nov.**
Activity	I-E I-D1	I-D2 I-D3	I-C I-A1	II-E	II-D1 II-D2	II-D3 II-D4	II-D5	II-C	III-E III-D1 (p. 1)	III-D1(p. 2) III-D2	III-D3
	Cycle I			**Cycle II**					**Cycle III**		

The course materials were designed so that there was an elicitation discussion at the beginning of each cycle. The purpose of the elicitation discussion was for students to articulate their initial ideas about the phenomenon to be studied during that cycle. Activities are labeled according to the cycle in which they took place (e.g. I represents cycle I) and whether they were elicitation activities, development activities (experimentation), application activities or consensus discussions (e.g. II-D2 is the second development activity in cycle II, I-E is the elicitation activity for cycle I). In activity I-E students were asked to explain what they thought caused clothes to stick together when they are removed from the clothes dryer (the phenomenon known as static cling). Activity II-E asked students to draw an initial model for charging insulators by rubbing them together. Activity III-E presented a complicated demonstration involving charge polarization and students were asked to construct an initial explanation of the physical processes that led to the result.

Introduction to Heidie's Atmosphere Model

The *atmosphere model* was used consistently by Heidie for two weeks (from 12-Oct. to 26-Oct.). Heidie first mentioned the idea of involving charges going off into the atmosphere during rubbing during activity II-E, a whole class elicitation discussion that took place on 12-Oct., the first day of Cycle II. In an interview on 12-Oct., Heidie said that she was considering the idea of charges going out into the atmosphere during rubbing, leaving one object entirely negatively charged and the other entirely positively charged. She said that this made sense to her because it explained why objects were attracted to each other after rubbing; they were seeking what they had lost. Heidie described her atmosphere model to the interviewer. She said that different materials were predestined to retain (and therefore give off) either positives or negatives. This is expressed in the transcript below.

I: We're looking at the picture on Activity II-E and I'm just wondering how you're thinking about it now…
H: I'm a little confused kind of, on kind of what we're doing so I'm kind of clinging to that model because it's the only thing that I really feel like I can kind of explain and I don't get too flubbed up and it kind of covers all the bases but, you know, maybe 8 out of 10 times it does.
I: Okay.
H: So I just kind of, I still think that you have to rub and you have to create the friction and the heat to get any kind of a reaction whether it's an attraction or a repulsion and um, and I, I really am, I'm really buying into the, the, the reason they're attracting is that they're looking for something that they're missing, that one article (object) is missing something and the other article is missing what the other one has so that's why they're sticking or that when they're repulsing they have too much, like they have the same thing, they don't need anything from the other object that you're trying to put it together with and that's why, that just kind of seems to make sense to me…
I: What are they like before being rubbed? Where do the charges come from?
H: But so, I don't know if they have, if they actually have, I mean it would make sense that they probably both have, I don't know maybe an equal amount meaning that they're just not moving.
I: Equal amount of what?
H: Of like positives and negative charges…Before rubbing and then maybe the rubbing, if the material is you know to be like a positive and the rubbing is giving off the negatives and that's why they're attracting because it originally had enough of what it needed to be stable, maybe, and then with the introduction of the friction and the heat, it gave off something that it was needing that it was okay with before and that's why it attracts to something else because it was trying to get what it lost, I guess.

Heidie's explanation (model) in the excerpt above has four conceptual elements outlined in table II. In interviews, homework, and small group discussions, Heidie consistently used this atmosphere model exclusively. Her representations were basically the same throughout the time period between 12-Oct. and 26-Oct.. She depicted rubbed objects as having retained either positive or negative charge. The charge given off to the atmosphere was represented by plus or minus symbols in the space surrounding the object as shown in fig. 2. The picture in fig. 2 appeared in a homework turned in on 14-Oct. and a very similar picture appeared in homework turned in on 21-Oct..

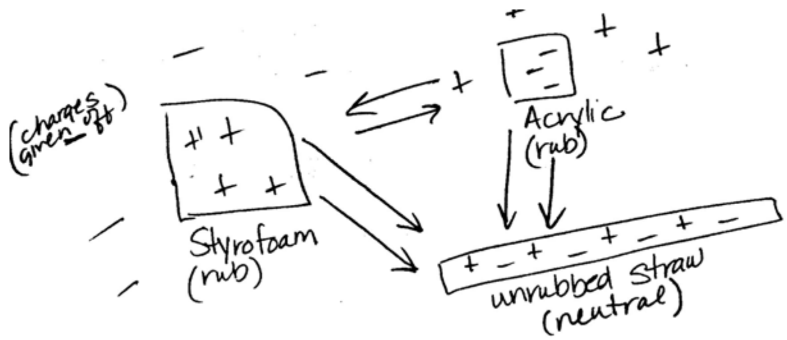


Figure 2. Heidie's atmosphere model. Charges were given off to the atmosphere from foam and acrylic when they were rubbed together. No charge has been given off from the unrubbed straw.

Figure 2 depicts a foam plate that has been rubbed with acrylic (acrylic-rubbed foam), an acrylic sheet that has been rubbed with foam (foam-rubbed acrylic), and an unrubbed plastic straw. According to the model, the acrylic-rubbed foam was predestined to retain positive charges, so its negative charges have been given off to the atmosphere. The foam-rubbed acrylic was predestined to retain its negatives, so its positive charges have been given off to the atmosphere. The unrubbed or neutral plastic straw has not lost any charges, so there is a balance of positive and negative charges. Notice also that the charged objects in fig. 2 contain only one type of charge within them, the objects have given off *all* of the opposite type of charge. This feature will cause some difficulty for Heidie when she seeks to understand the concept of charging by charge transfer which requires a conception of imbalance or excess of charge within one object.

Analysis

The concepts that were present in Heidie's initial model are mapped to the associated scientific concepts that make up the one-way transfer model in table II. Spontaneous concepts that were inferred for Heidie are given in column 2 and the associated scientific concept is given in column 3.

Table II. Conceptual elements of Heidie's atmosphere model and of the scientific model

Elements of the model	**Heidie's Spontaneous Concepts**	**Scientific Concept**
1. Definition of Neutral	A neutral object has an equal distribution of positive and negative charges.	A neutral object has an equal distribution of positive and negative charges.
2. Definition of the Charged Condition	A charged object contains only positive or only negative charges. Implication: the object is charged on all surfaces.	A charged object contains an excess of either positive or negative charge.
3. Process by which objects become charged	Friction: releases all of one type of charge to the atmosphere for each material.	Friction: transfer of negative charges from one object to the other. Implication: the object is only charged on the rubbed surface.
4. Why one object gets charged negative	The material is predestined to give off a certain type of charge	The molecular structure of the material in relation to the

and the other positive	and retain the other.	molecular structure of the other material.

A model including scientific concepts 1, 2, and 3 in table II was the learning objective for Cycle II and concept 4 was not written into the unit. The curriculum at this time did not anticipate that this question would become critical to the conceptual development of the students. The expert might reason that, at minimum, the concept of transfer as the process of charging (#3) and the concept of excess as a definition for charged conditions (#2) must develop together (one implies the other) but this is not clear to Heidie. At this time, Heidie has not consciously distinguished between the charging process and charged conditions. Somehow, Heidie must get from her current spontaneous concepts to the scientific concepts represented in column 3 and a cognitive theory should be able to predict how this will happen.

According to Piagetian theories this will happen through the process of disequilibration and dissatisfaction with her existing concepts in the face of conflicting evidence. According to the Piagetian perspective, we should be able to observe instances of contradiction between Heidie’s concepts and her observations. This should lead to dissatisfaction with these concepts, and we should be able to observe this. We should observe the ultimate *displacement* of these concepts by concepts that help Heidie resolve the contradiction.

A Vygotskian theoretical perspective would predict that Heidie’s spontaneous concepts will *mediate* the development of scientific concepts and vice versa. We should be able to observe Heidie’s use of scientific concepts even before she understands them. They will not be abstractions from her spontaneous concepts. Ultimately, we should observe a point in time where Heidie’s spontaneous concepts meet the scientific concepts. We should also observe the appropriation of certain criteria for selecting one concept over another. In the following sections, I use classroom, homework and interview data to illustrate that both displacement and mediation occurred. There is displacement of the atmosphere model but this happens through the process of mediation and social motivation.

Introduction of the Scientific Concepts

In the two weeks following the elicitation discussion described above, students experimented with acrylic, foam, wool cloths, plastic straws and the computer simulator and answered questions about their observations and their “models” (a term introduced in the written documents) for charging insulators by rubbing. At the end of the experimentation phase, a whole class consensus discussion was held (on 26-Oct.). Each small group was to represent their model for charging two insulators by rubbing on a 1m by ¾ m dry-erase board (whiteboard) and present it to the class. The course materials anticipated that the group would have come to a consensus by now, but it is evident in the models inferred by each student in fig. 1 that this was not the case.

While the MJH group was constructing their whiteboard representation, group member Mark proudly presented his one-way transfer model to his group[2]. According to Mark’s model, both objects lost electrons (a term he introduced) to the space between the objects during rubbing. When the objects were pulled apart after rubbing, one object grabbed all of the electrons that had been lost to the space between. He reasoned that this resulted in one object

[2] Mark’s development of the one-way transfer model is also interesting and is discussed elsewhere [40]. The focus here is on how Heidie developed the scientific concepts associated with one-way transfer of charge.

being positively charged because it now has a lack of negative charges and the other being negatively charged because it now has extra negative charges. A small part of this discussion is given in the transcript below.

03:40:28	Mark	Look at, look at, when you're rubbing two things, when you're rubbing two things-okay no matter what they are, they're both insulators, let's say. Okay, when you're rubbing um, the rubbing, the more vigorously it rubs the more electrons you're breaking apart and they're free to run around right?
03:58:16	Heidie	In the atmosphere somewhere. (this was not a question)
04:00:01	Mark	No like in between here or something, they're like electrons. And then, when you pull them apart, one of the objects, depending on its make-up, is going to be more likely to attract the negatives on the surface of the object.
04:14:22	Mark	For instance, when you rub, in the homework, when you rub Styrofoam with the straw (he means when you rub the straw with the wool), it made it one charge. But then when you made it with the acrylic, no not acrylic, I mean cellophane, the cellophane took the electrons. I think, I forget which way it went, you had different materials.
04:34:28	Mark	Okay, so, you guys agree with that? Okay, and then to explain the more rubbing, how it's rubbing more: is the more you rub the more electrons are broken off and the stronger the charges can be.
04:50:25	Heidie	So you will never give off a positive charge you will always give off the electrons?

Heidie had a very difficult time understanding both the notion of the transfer of charges and the idea that only electrons (or negative charges) could move. Mark added more details to support the idea that only negative charges could move by introducing the electron orbit model for an atom. He had looked this up in his biology book a few days before. Mark explained that this atomic model supported the idea that only electrons could be knocked off the atom because the farther away they were from the positive center, the weaker the force between the two charges would be (macroscopic distance effects were studied earlier in Cycle I). He reasoned that this was why only negative charges could move during rubbing and therefore only the negatives could transfer from one material to another. At this point Heidie expressed frustration and confusion. She tried to make sense of the idea of one-way transfer by using her atmosphere model. In doing so, she discovered a contradiction with experimental results (during the development phase, students observed that when two objects are charged by rubbing, they attract to each other). She said that the idea of only negative charges moving did not make sense because if only negative charges were given off (for Heidie, this meant to the atmosphere) then both objects would lose negative charges during rubbing, leaving both positively charged so they would repel, not attract. This is evident in the transcript below.

23:39:00	Heidie	But if you rub, then everything would lose a negative charge, do you see what I mean? If I'm rubbing these equally together, this is gonna lose electrons and this is gonna lose electrons so then they're

gonna repel, they're not gonna attract to each other because they both lost electrons so-

Heidie was viewing Mark's explanation through the lens of her own model, the atmosphere model. When Mark talked about "losing" electrons, he was talking about the objects losing electrons to the small space between the objects during rubbing. When Heidie heard the word "lose" she was conceiving of both objects losing negatives to the surrounding area or atmosphere. Her comment above makes sense according to the atmosphere model. She used the conceptual framework that associates rubbing with the *loss* of charges, in her attempts to understand the new model. For Heidie, *transfer* meant *loss.* The new model required that *loss* meant *transfer.*

Heidie also evaluated the implications of transfer in terms of her own model. Earlier in the discussion, Mark claimed that charge movement was taking place only on the rubbed surfaces so only the rubbed surfaces became charged (the group came to this conclusion in an earlier experiment where they tested all the surfaces of a thick foam block.) In Heidie's atmosphere model, charges were given off from all sides of the object. Although she did not refer to the foam block experiment, she did say that the idea that only the rubbed surfaces became charged made sense. She said:

15:57:19	Heidie	It makes more sense to lose electrons here then it does to lose them all the way out here, cause nothing's happening on these surfaces here, it's just happening here.

In the excerpt above, Heidie made sense of one of the implications of the one-way transfer model although she did not understand the model itself. Near the end of the discussion, Heidie had concluded that one aspect of Mark's model made sense. However, according to Heidie's analysis, the model itself was inconsistent with observations (the rubbed objects should attract one another, but Heidie's analysis led to the conclusion that they would repel according to Mark's model). As Mark continued to try to justify his model for why only negative charges moved, Heidie finally gave up, saying, "What? Oh just forget it! I will look this up on the Internet. I have no idea."

Mark and Jenny then presented a *one-way transfer model* to the class and Mark described his atomic model. Most other groups presented a two-way transfer model where positive objects from object A are transferred to object B and negative charges from object B are transferred to object A, leaving both charged differently. After all groups presented their whiteboards, the teacher began to describe similarities and differences in the models the groups had presented. The class spent over an hour discussing whether the charging process was one-way (only one type of charge being transferred from one object to the other) or two-way (both objects transfer a different type of charge to the other). The teacher showed subtle support for the one-way transfer model by commenting on its simplicity and that it achieved the same results as the two-way transfer model. At the end of the discussion the teacher typed the following text as the Class Consensus Idea for charging insulators by rubbing into a computer document projected on the wall:

> **Charging an insulator by rubbing idea:** Rubbing two insulators together brings about a charge on the surface of each. The charging results from a transfer of charge from one of the objects to the other during rubbing. (We don't know yet whether the transfer of

charge is one-way or two-way). The excess charge on each object after rubbing are opposite and equal. Different pairs of materials may produce different types of charges. (Plastic straws rubbed with cellophane end up charged oppositely to plastic straws rubbed with wool).

After class, a document with this and other consensus ideas was distributed to the students.

Analysis

The classical conceptual change approach [41] can be used to analyze Heidie's attempts to understand the one-way transfer model. According to this approach, an alternative model has been made available to Heidie by a peer. In the episode described above, Heidie tried to make sense of the one-way transfer model but it was not intelligible to her at this time. While Heidie did not understand the concept of *transfer* as it applied to charging insulators, she did express that she thought its implications were believable by stating that it made sense that objects were only charged at the surface. This indicates that the plausibility of the model was increasing even though the model itself was not fully understood. This issue of plausibility becomes increasingly relevant to Heidie's conceptual change. The one-way transfer model was not fruitful at all because Heidie's interpretation of it could not even explain the basic observation that two objects that are charged by rubbing them together attract.

From a Vygotskian approach we see that Heidie's own spontaneous atmosphere model mediated the development of her understanding of the scientific one-way transfer model, and the scientific model mediated Heidie's conscious comprehension of her own atmosphere model. According to the theory, the learner does not have conscious comprehension of the substance of a spontaneous concept. The bottom-up development of the spontaneous concept is the increased awareness of the concept, its parts, and their implications. Mark mentioned that the objects were only charged on the surface only once in the 30 minute discussion (transcript time 04:00:01 above). In addition to this information, by looking at the picture that Mark drew on the whiteboard, Heidie concluded that the objects were only charged on the surfaces. The picture showed each object with only plus symbols or only minus symbols on the surface that was rubbed. Both plus and minus symbols were drawn on the inside and unrubbed surfaces of both objects. The picture mediated further development of Heidie's understanding of *her own model* by acting as tool that allowed her to mentally visualize the implications of the atmosphere model. Although her model was not drawn on the whiteboard, she compared a mental image of her model to the diagram on the whiteboard. She then compared the implications of her model to the implications of Mars model. She realized that her model implied that all surfaces of the objects would be charged. In Mark's model, only the rubbed surfaces were charged. This made sense to Heidie. In this way, the scientific concept of charge transfer (still not completely formed) together with the representational tool (the whiteboard image of the model) mediated Heidie's awareness of the surface-charge implications of the atmosphere model. This is the development of a spontaneous concept—the learners' increased awareness and conscious control of the spontaneous concepts themselves.

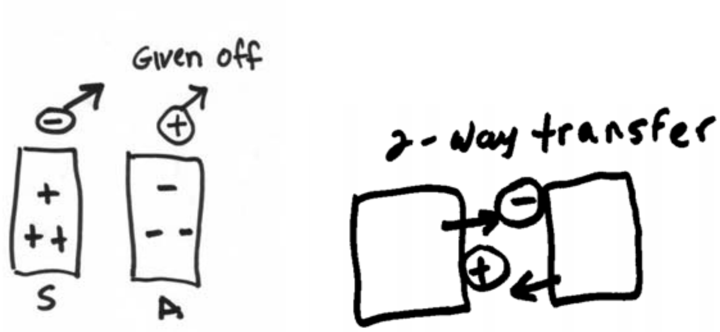
Although the idea that only the rubbed surfaces became charged made sense to Heidie, the mechanism by which those surfaces became charged according to this model did not. This is evident in transcript time 23:30:00, when Heidie tried to use the idea that only negative charges moved and ran into a contradiction. In Heidie's attempt to use the one-way transfer model, she tried out the concept that only the negative charges moved by using her stable understanding of the atmosphere model to mediate her evaluation of the consequences. She incorporated the idea of only negative charges moving into the spontaneous concept of charges getting lost to the atmosphere. She reasoned that the consequence was that both objects would become positively charged and therefore repel. In this episode, Heidie's spontaneous concept mediated her attempts to develop the scientific concept.

Beginnings of the formation of the concept of charging by transfer

Heidie did not develop an understanding of the one-way transfer model all at once. Instead, she developed the concepts shown in table II a little at a time. Heidie's explanations during an interview on 27-Oct., the day following the episode discussed above, did not initially involve the atmosphere model that she had been using consistently in interviews, homework, and class discussions for two weeks. At the beginning of the interview, Heidie was hesitant to commit to the idea of charges being "given off," using vague statements such as "Well, because if they stayed inside the plastic stirrer then it would still be neutral so something has to change in, I guess maybe the makeup or whatever, the charge of the plastic stirrer, to cause it to, um, not be the same." When the interviewer asked her what happened during rubbing she said that the charges were either "transferred to the other object that it's been rubbing against or they're given off in the atmosphere somehow." When the interviewer asked her to describe how each of those processes might occur, Heidie said,

> I: Okay. So that would explain, so if, let's, can you draw a picture of either or both of those situations (she has drawn the two pictures in fig. 3)
> H: Okay, well I guess maybe their negative charges are given off or they're transferred.
> I: Now, let's say they're given off as shown in your picture. And then what happens to the other object like the acrylic according to either or both models.
> H: Well I guess it would, I guess maybe one is giving off the negatives and one is giving off the positives. See I don't know, because they were talking about one-way, two-way transfer and I'm blown out of the water, I have no idea what's going on with that. So I mean it's gotta have some kind of transfer, I guess, or else I guess they wouldn't be talking about it.

Two of the diagrams she constructed during the interview to explain interactions involving foam and acrylic are shown in fig. 3. Throughout this interview, she tried to use the two-way transfer model for interactions involving foam and acrylic (although she also used the atmosphere model as shown in fig. 3(a)). In the picture in fig. 3(b), Styrofoam is transferring negative charge to acrylic and acrylic is transferring positive charge to the Styrofoam. The picture indicates that Heidie was beginning to use the scientific concept of transfer as the process by which objects become charged but she did not draw any plus or minus symbols inside the objects in fig. 3(b). She tried to use the concept of transfer but she had yet to consciously consider the concept of excess charge.



(a) (b)

Figure 3. Heidie's pictures of (a) the atmosphere model and (b) the two-way transfer model constructed during an interview on 27-Oct..

Piagetian theory would predict that Heidie's dissatisfaction was derived from either conflicting evidence or from the awareness of two equally plausible, yet contradictory models. Heidie's decision to use the two-way transfer model was not derived from dissatisfaction with her atmosphere model due to a discrepancy between her model and her observations nor was it derived from an awareness of an equally plausible model. Instead, Heidie's decision to try out the two-way transfer model was driven by the social content of the course: the whole class was "talking about it," as stated in the last line of the interview above. This provided motivation for Heidie to try to understand the new model. The fact that Heidie drew no symbols within the object as well as statements such as the one presented below provide evidence to support the claim that Heidie did not fully understand the two-way transfer model. She began to use the two-way transfer model even though she did not fully understand it.

> H: Well the transfer model, I mean I guess with the rubbing, when they're rubbed together, I mean there has to be a negative that this one is picking up. I guess and this one is picking up the positive from this one. So when they're rubbing, I guess if maybe you can go from the theory that because of the material, or the make-up of the material, something is gonna be more likely to hang on to a positive or more likely to hang on to a negative charge, or seek out that other one. Then the transfer model is going to, I guess maybe, explain the reaction.

Analysis

Heidie is not sure how objects actually get charged through transfer. I inferred that this is due to the fact that the meaning of charged conditions in her atmosphere model required both that (1) the objects are predestined to retain either a positive or negative charge and (2) the charged condition is defined as a total lack of the other type of charge. Heidie may not know that being able to explain the charged condition is necessary and she may not have yet developed an abstract distinction between the process and the product of rubbing. The absence of symbols in her diagrams involving transfer, leads to the inference that Heidie, at this time, had some conscious or unconscious comprehension that the two-way transfer model had different implications for charged conditions than the atmosphere model. In all of her diagrams of the atmosphere model, Heidie drew the charged condition of the object during and after rubbing. On

4-Nov. Heidie actually articulated that she did not know what was happening to the objects during rubbing using the two-way transfer model:

> I: Okay. Draw the during picture, cross out that after, where it says after and then draw a during picture. Start with your before picture and show what happens during rubbing.
> H: But that's what I'm confused on, that's what I don't understand.

It was not until after she began using the two-way transfer model that Heidie expressed awareness that she did not understand the implications that it had for the charged condition of the object.

Attempts to use the one-way transfer model

During the interview on 27-Oct., Heidie did not attempt to use a two-way transfer model for a situation involving a wool cloth and a plastic straw. Instead, she attempted to use a one-way transfer model, which once again, was mediated by her atmosphere model. As shown in fig. 4, Heidie used a hybrid model when she tried to explain the charging process involved when a plastic straw is rubbed with a wool cloth. Hybrid models of this sort have been noted in the physics education research literature in other content areas [42]. In Heidie's hybrid model, positive charges are transferred from the wool to the straw during rubbing and the straw gives off negative charges to the atmosphere.

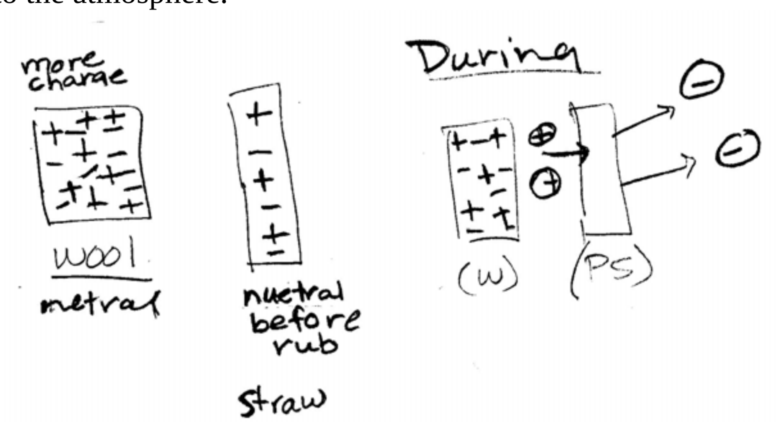


Figure 4. Atmosphere/transfer hybrid model. Positives are transferred from the wool to the straw and negatives are given off from the straw to the atmosphere.

Figure 4 shows charges only moving *one way*—both positive and negative charges are moving toward the right. In addition, only one type of charge (positive charge) is transferred from the wool cloth to the plastic straw but negative charges from the plastic straw are given off to the atmosphere. In fig. 4, we see that Heidie has left out the charged condition on the plastic straw once again. Notice also that Heidie has added the words "more charge" above the picture of the neutral wool in fig. 4. It turns out that Heidie did not believe that wool was the same as other objects. She figured that the wool cloth was "special" because it did not get charged during rubbing (which is not a bad inference since wool loses charge easily). In order to explain this, she added a large quantity of both plus and minus charges to the picture of the unrubbed wool. She said that she needed this so that, "in the wool that when it loses some, it doesn't even make a dent**”** in the neutral state of the wool. In an interview that took place two days later, Heidie used the same hybrid model for situations involving wool.

Analysis

Heidie’s hybrid model captures the characteristics of the one-way transfer model that she saw as relevant: (1) charges only move one way, (2) only one type of charge is transferred from one object to the other and (3) only negative charges are given off or lost. These inferences are parts of scientific concepts that Heidie was trying to learn. The first two inferences above are consistent with the one-way transfer model but the third is founded in the spontaneous concepts associated with Heidie’s atmosphere model. This is an excellent example of a time in Heidie’s conceptual development where we can see the scientific concepts developing downward and the spontaneous concepts developing upward. Heidie has developed some scientific terminology in her discussions with Mark and in whole class discussions. She has interpreted these terms through the lens of the atmosphere model, as was discussed earlier. Heidie’s spontaneous concept of the charged condition (see table II) has also developed more fully, through her awareness of its implications. I argued earlier that this awareness was mediated by the transfer model Mark presented and the image that appeared on the whiteboard. She began to gain conscious control of the surface-charge implications of her own model as a result of trying to understand the scientific concept of transfer. The scientific transfer model mediated Heidie’s conscious awareness and evaluation of her own model. The spontaneous concept was growing upward from simple meaning to an awareness of that meaning.

In the case of the hybrid model, we see the spontaneous concept mediating the development of the scientific concept where the scientific concept was growing downward from abstracted terminology to meaning. From the hybrid model we can see that Heidie tried to make sense of the three features of the one-way transfer model that she saw as relevant. The terms “transfer” and “one-way” were given meaning by embedding them within the atmosphere model which already had meaning for Heidie. When the development of *meaning* of the scientific terms is analyzed *vis a vis* the development of abstract analyses of Heidie’s own model, the conclusion may be drawn that scientific concepts and spontaneous concepts are growing toward one another and are growing together.

Notice that Heidie was able to deal with the charged condition of the wool during the transfer process (she had been unable to do this when she tried using two-way transfer). According to Heidie, the wool did not get charged. Therefore, by loading up the wool with “more charge,” losing just a few would not, according to Heidie, affect the final charged condition of the wool. Here she was consciously considering the charged condition of the wool. In all other cases, fig. 3(b) and the plastic straw in the “during” picture in fig. 4 (and several others constructed during the interview), Heidie did not deal with the implications of transfer on the charged condition. She only did so for wool where she needed a way to keep the object neutral before, during and after rubbing. Acrylic, foam, cellophane and plastic were different according to Heidie because she could feel both (non-wool) objects getting hot when they were rubbed together, therefore they were both being affected.

> H: Well it’s gotta be two way, because they react together, you’re not just doing something to one, if you’re rubbing they’re both being rubbed they’re both having the same thing happening to them so I would think it’s gotta go two ways. Because like when you rub something, like when we were rubbing the plastic stirrer with the

> cellophane, both the materials got hot when we did that. So it wasn't just that one thing wasn't being affected. It was both being affected.

For Heidie, both objects being affected meant that both objects had to be *doing something active*, like transferring charge to the other object or giving off charge to the atmosphere. It may be that Heidie was conceiving of one-way transfer as the process by which one object "actively" gives charge and the other "passively" receives charge. If so, Heidie was only able to reconcile this source/receiver model with her understanding in the case of wool, where according to her observations, all things were not equal—the wool did not get charged in the interaction. Heidie was not yet consciously aware of the concept of the charged condition as a excess of charge. Therefore, the idea that one object was the source and the other was the receiver worked in the case of the wool. It was not simply a change of "context" that elicited a different explanation for Heidie. The change in context did elicit a different explanation but for good reason. The change in context for Heidie, entailed a different set of outcomes and therefore required a different set of conditions and a different explanation. Heidie was beginning to show conscious consideration of the implications of the one-way transfer model. She showed awareness of the idea that if the wool had lost too many of one type of charge, it would become charged. This concept of the charged condition as an excess of charge is an idea that she had previously been unable to express, articulate or represent.

Bringing together models and evidence

Heidie continued to use an atmosphere model, a two-way transfer model, and a hybrid model until 2-Nov., the second to the last day of the unit. Furthermore, she was aware that she was undecided between different models. Near the end of an hour-long interview on 30-Oct., after Heidie had used the three models several times, the interviewer asked Heidie how she was viewing the process of charging two insulators by rubbing. Again, Heidie expressed that she was not sure whether charges were transferred or going out to the atmosphere, however she provided observational evidence that could support a transfer model. She told the interviewer,

> I: I just wanted to know if in one instance you feel as though they're going to each other, and in another instance you feel as though they're going to the atmosphere, or if in all instances, you're not exactly sure whether they go to the atmosphere or to each other.
> H: Well in all of them, I'm not sure.
> I: Okay.
> H: But I guess you could create a pretty, I don't know maybe not pretty, but maybe a semi-convincing argument that they go to each other. In the case of the cellophane and the wool.
> I: Why?
> H: Because we observed that the cellophane and the wool can rub the same object and create a different effect. So, if they're creating a different effect and the only change is this one right here, it has to be, and they're giving it off to the atmosphere, I guess you could say that it's the material you're rubbing it against, in opposing, I don't know how I want to say that. Um, humm.
> I: They're both pretty explanatory right? They both actually explain what's happening, it seems like.

H: I mean it can’t be a coincidence that the cellophane changes the charge on the straw when it rubs it and the wool changes it the opposite way that the cellophane does. Like that can’t be an arbitrary coincidence.

In the excerpt above, Heidie was referring to a previous experiment where a plastic straw was rubbed with wool and was found to repel another wool-rubbed straw. Then, when an identical plastic straw was rubbed with cellophane, it was found to attract a wool-rubbed straw. This was an activity the groups had done over a week before and Mark had mentioned this evidence in his initial attempts to support his one-way transfer model during the consensus discussion on 26-Oct.. In addition, these experimental results were typed into the Class Consensus Idea by the teacher. Until now, Heidie had not paid attention to these results and the implications of this experiment. She was aware of the experiment, she had participated in the experiment, and she had written about the results of the experiment. She had even completed a homework assignment (turned in on 26-Oct.) that asked her to draw her model for each situation (wool-rubbed plastic and cellophane-rubbed plastic). In this homework, she depicted both plastic objects as positively charged after rubbing. Until the interview on 30-Oct., she had not connected the actual results of the experiment with the implications of her own (or any other) model. She had not realized that the implications of her atmosphere model (that objects were predestined to retain a certain charge) were contradicted by the experimental results.

Adoption of the scientific concept of the charged condition as excess

The data suggest that it was not until small group Activity III-D1 on 2-Nov. that Heidie became consciously aware of the concept of the charged condition as an excess of charge. During a discussion with her group, Heidie articulated the idea that a charged object might consists of an imbalance of positive and negative charges rather than consisting entirely of one type of charge. This was mediated by investigations involving conductors and the computer simulator. The computer simulator used a simple coloring scheme to represent the charged condition as a red or blue line of varied thickness depending upon the relative amount of charge on the surface of a conductor or insulator. When simulated insulators of different types are rubbed together, a red line appears on the surface of one insulator and a blue line appears on the surface of the other. The more the objects are rubbed together, the thicker the red and blue lines get. When a “blue charged” insulator is rubbed against a neutral conductor, a blue line appears on the surface of the conductor and the blue line on the insulator gets thinner. A blue-charged simulated insulator with a polarized conductor is shown in fig. 5.

The computer simulator was introduced on 19-Oct., but up until 2-Nov. all computer simulator experiments involved only insulators. As such, all charged objects were depicted with either a solid red line or a solid blue line of varied thickness depending upon how many times the simulated insulator was rubbed. In activity III-D1, which students started on 28-Oct. and finished on 2-Nov., conductors were introduced for the first time in both laboratory and simulator experiments. Heidie was absent on 28-Oct., the date on which the group began working on the activity. The purpose of the activity was for groups to construct an explanation of charge polarization within a conductor. In this activity students conducted laboratory experiments with charged insulators and a conducting “soda-can electroscope” [43].

A soda-can electroscope is an aluminum soda can with aluminum foil strips taped to the back end of the soda can, as shown in fig. 5c. In the laboratory part of the experiment, students observed that the conducting strips stuck out away from the soda can when a charged insulator was brought near the front end of the soda can. The computer simulator has a dual representation. It represents laboratory results similar to those observed using apparatus but it overlays a red and blue coloring scheme that represents a simple, macroscopic model of charge within conductors and simulators. Figure 5(a) and 5(b) show the simulated soda-can electroscope with the coloring scheme. In fig. 5a, a simulated blue-charged insulator is far away from the simulated soda can electroscope, the simulated aluminum strip is hanging down. There are no red or blue lines shown on the electroscope. In fig. 5b, the simulated blue-charged insulator is brought near but not touching the simulated electroscope and the aluminum strips are now sticking out away from the electroscope. A blue line appears on the end of the simulated electroscope farthest from the blue-charged insulator and the simulated aluminum strips are also colored blue. A red line appears on the end of the electroscope closest to the blue-charged insulator. The thickness of the blue line on the surface of the insulator has not changed. Neither the computer simulator nor the activity documents provide any information about what the red and blue actually represent.

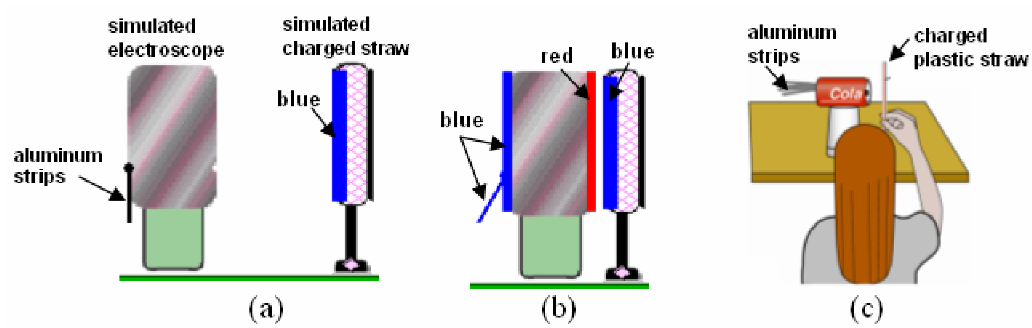


Figure 5. (a) a simulated soda can electroscope with a blue-charged insulator far away, (b) a simulated, blue-charged straw is brought near a soda can electroscope, (c) corresponding laboratory experiment.

In the class discussion that preceded this activity the teacher tried to clarify student questions about whether the red lines in the simulator represented positive charge or negative charge. The teacher responded that, for the remainder of the unit, the class should consider the blue line to represent an excess of negative charge and the red line to represent an excess of positive charge. This was not the first time he had used the word excess. In fact, he used it during the elicitation discussion over two weeks earlier. It also appeared in the Consensus Ideas document that was handed out at the end of cycle II. Heidie did not pay attention to the term “excess charge” until she saw the simulator image described above. When the MJH group began the computer-based activity, Heidie began to question the meaning of the simulator image that appeared on the computer screen. She asked whether the red and blue colors represented total charge or excess charge and whether the process of charge polarization also applied to insulators. An excerpt from this discussion is given below.

28:18:20	Heidie	So on these, wait go back up for just a minute. So from what, from what he was saying when we were sitting in the other room, this only has a net charged but it's not solely negative, it's um, because the blue is negative right?
28:35:15	Jenny	Right.
28:36:18	Heidie	so there are red in there it’s just is so small of an amount that um,

		that um it's not represented anyway because it doesn't matter anyway cause it doesn't shift it either way.
28:47:28	Jenny	I think it's kind of like, like this, where you know where all of one charge is going towards the other.
28:53:24	Heidie	So it's not that something is created or given off given off it's that one thing moves, to the, it's one charge or the other moves depending upon what you're rubbing it with?
29:02:28	Jenny	Right.
29:04:01	Heidie	Oh, okay. Is that right? Yes?
29:09:26	Mark	Well, are you guys explaining this or what?
29:12:12	Heidie	No, I was asking according to what he was saying in class that, that these, when it shows oh, either blue or red charge it's not that's all negative or all positive, it's just that the positives from the, from the material, either the insulator or conductor, whatever, it's just that all the charges have moved to that surface? So nothing is really given off to the atmosphere or transferred?
29:37:25	Mark	It's just a net negative or net positive.

At times 28:18:20 and 29:12:12, Heidie was consciously considering the idea that the charged condition might have to do with an excess of one type of charge rather than with only one type of charge in the object. Heidie did not invent the concept of excess charge. It was a term that was mentioned by the teacher in answer to an entirely different question. In order to make meaning of the term, “excess charge” Heidie had to associate it with the abstracted notion of *charged condition*. As was the case with other scientific concepts discussed in this analysis, Heidie had to transform the words into meanings. The red and blue coloring scheme together with the simulator image presented on the computer screen mediated this process. This was another case of concept formation mediated by a visualization tool. In this case it was the computer screen and simulator image.

Heidie was also questioning the validity of both the atmosphere model and the transfer model at times 28:53:24 and 29:12:12. The ensuing discussion took the form of peer instruction, where Mark carefully described the process of transferring charge between two insulators by rubbing. He began by explaining that the idea of rearrangement of charges within an object is applicable to conductors not insulators (a process he and Jenny had worked out the previous class period). He went on to explain his one-way transfer model of charging two insulators by rubbing. It was the same model he had explained a week before, but this time he used laboratory apparatus as explanatory tools, he involved Heidie in the explanation by asking for her explanations, and he used anthropomorphisms.

29:44:04	Mark	But like in an insulator though, like an insulator like this, like it's not taking charges from over here to over here, because we know that insulators you can't move it through it, you know what I mean?
29:57:18	Heidie	It just goes ov-
29:58:30	Mark	It's just on this outside, cause there's all kinds of little whatevers right here, and it's just when you rub these guys together, right,

30:08:02	Mark	When you rub them together and what's this? Styrofoam's positive?
30:11:20	H&J	Um hum.
30:12:24	Res	Negative.
30:13:26	Mark	Okay so what's happening is that when you rub them together you're breaking off the, the negatives. Like, on, just on the outside of it cause it's an insulator right?
30:23:00	Heidie	Um hum
30:23:14	Mark	Okay, when you pull it apart, now this thing is net what?
30:26:21	Jenny	Negative.
30:27:06	Mark	Negative, so what happens is it took some of the negatives that were floating on this guy, and now it's on this guy.
30:32:25	Heidie	Oh okay.
30:33:20	Mark	So now this guy's minus those, he does't have those negatives, so he's net positive.
30:39:03	Heidie	So, so then they are, they are transferred between, they're not given off.
30:44:08	Mark	Yea, yea, they're just, it's going from one to there other.
30:46:18	Heidie	So then there's always a two way transfer between these two?
30:50:06	Mark	It's actually a one-way, because, because really this guy's just taking his negatives. He's not giving positives. So when you rub this the acrylic is just saying, alright I'm I want some- I mean this guys saying alright, you have these little electrons or little negative charges running around there and I'm stronger so I take some, that's why it has that little whatever you know what I mean? And this guy doesn't have it so it, he has, he's minus those guys so he's like also charged up, because he has a more positive.
31:24:00	Heidie	He's out of balance

In the transcript above, Heidie and Mark's interaction was very different than it was a week and a half earlier. On 26-Oct. Heidie was frustrated and unable to understand Mark's explanation of the one-way transfer model. Heidie has experienced conceptual development since then. She has become aware of various abstract features of her own model and made personal meaning of some of the abstract features of the transfer models. Additionally, the new concept of excess of charge had been recognized as relevant by Heidie. We have reached the zone of proximal development for Heidie. Heidie is for the first time consciously considering all of the concepts involved in her atmosphere model and all of the concepts involved in the one-way transfer model (see below) and she is now ready to put them all together.

Pulling it all together with a model of the atom

The group went on to discuss charge polarization, and Mark noticed that Heidie was explaining the process with both negative and positive charge being mobile. At this point Mark explained the electron orbit model of the atom to justify his claim that only the negative charges moved. Evidence that Heidie had at least a fragile understanding of electron orbit model of the atom at this time can be found in her statement, "It's like an onion, it's easier to peel the edges than it is to get to the middle." In her daily journal at the end of the class that day, Heidie wrote:

> Today we experimented on the computer with the transfer of charges between conductors and insulators. We found that when two cans are put end to end, the charges are able to flow freely between the two. In the activities, I seem to have resolved my questions as to the ideas of two-way vs. one-way transfer and whether or not charges are "shared"/transferred between insulators/conductors or given off to the atmosphere (2-Nov.).

Interview data from 4-Nov. indicate that Heidie was now struggling only with the idea of one-way versus two-way transfer and was no longer considering the atmosphere model. When asked what happened when acrylic and foam were rubbed together, Heidie described a *two-way transfer model*. Her diagrams on 4-Nov. were very similar to the diagrams she constructed during the interview on 30-Oct., where there were no charges depicted in the objects during or after two-way transfer (fig. 5). The interviewer asked her to explain her diagrams and Heidie became very frustrated, throwing her pencil down. A two-way transfer model made more sense to her but she understood the electron orbit model of the atom (this is evidenced in the transcript below). Mark's introduction of the model of the atom, and Heidie's understanding of it, brought a new requirement to the situation. A sensible model for charging insulators by rubbing must be consistent with this other scientific information (the atomic model). Up until now, Heidie had little or no other relevant canonical information that she understood. Her model needed only to be consistent with laboratory observations. Heidie began to align the atomic model with a model for charging insulators by rubbing during an interview on 4-Nov.:

I: Um, okay, so um there's one way, one of the problems you started having over here in (the pictures just constructed) was that um, that you thought something might need to be transferred.

H: Yea.

I: Why?

H: Because with what we were doing today with the holding the (simulated) acrylic, the rubbed acrylic up to the (soda) can, we didn't touch the can and that explained the movement within the can, within the surface of the can. But when we touched it, that was the actual transfer (describing the simulated blue-charged insulator touching a simulated neutral aluminum soda can. The blue line on the insulator got thinner and a blue line appeared on the soda can).

H: …on the surfaces I mean, cause we just said that insulators, it's not the movement in, it's the movement on the surface being rubbed…So if we're gonna go with this (atomic) model, where everything starts off where it's made up of the atom that's got the proton in the middle and then each outer ring is an electron and it's easier to break off the electrons than it is to actually move a positive, so we're gonna go with the one-way transfer idea. Then you have to be able to explain how this idea of the movement of only the negatives gels with the whole rubbing thing. So that's what threw me off, is I was not understanding what I was, how I was gonna fit that in. But the only way it does fit in is if, when you rub them together, it's the, because you know that acrylic retains the positive charge so the um, Styrofoam, it must be because of the Styrofoam pulling, it must be breaking the bond between the positives and the negatives in the acrylic. Therefore explaining, I guess the one-way transfer between

> how the acrylic can retain a net positive and the Styrofoam a net negative making them attract to each other. Does that make sense?

There are two points to be made from the transcript above. First, in Heidie's second comment, she refers to a simulator experiment which strongly suggested transfer. This is the first piece of visual evidence that she had that promoted the concept of transfer. Second, Heidie is struggling to bring known scientific knowledge (the electron orbit model of the atom) into alignment with a sensible model for charging insulators by rubbing them together. She had already accepted the possibility of two-way transfer and this was driven in part by early discussions within the whole class, accumulating evidence that the atmosphere model was ineffective in explaining all of the observations made in the class, and now the transfer idea was promoted by the computer simulator.

Heidie continued to use a one-way transfer model throughout the remainder of the unit. This is evidenced in a final assessment called a learning commentary, where students were asked to explain how they came to understand one or more of the class ideas. An excerpt from Heidie's learning commentary is given below.

> My finished model builds on the concept that like-charged objects repel from each other and oppositely charged objects attract. This attraction or repulsion is due to the one-way transfer of negative charges during the rubbing process in which the negative charges from one object are transferred to another object, leaving one with a lack of negative charges or net positive charge and the other with an excess of negative charges or net negative charge. Knowing that all objects, before rubbing, begin with an equal amount of positive and negative charges (neutral), my model assumes that after rubbing these same objects are all searching for a way to get back to their original state of neutrality. Attraction and repulsion occur between objects because each is seeking to acquire the opposite charge that it needs, while repelling the ones that it does not need. Transfer of charges happens only when two objects come into direct contact with one another. These objects, depending on their make up, can be either conductors or insulators. Conductors transfer charges within itself (from the front of an object to the back of an object) and insulators absorb charges into itself (16-Nov.).

Analysis

During the last few segments of the analysis, we have seen Heidie gain access to two different scientific concepts: the charged condition as an excess of charge and the electron orbit model of the atom. These very concepts were articulated by Mark on 26-Oct., a week an a half prior to this. At that time, these concepts were available, but not accessible, to Heidie. On 12-Oct., these scientific concepts were introduced for the first time to Heidie and the top-down concept formation had not yet taken place. In addition, the bottom-up development of Heidie's spontaneous model was just beginning. In the small group discussion on 2-Nov. and the interview on 4-Nov., Heidie's spontaneous concepts and the scientific concepts had grown together. Heidie had made meaning of the terms that were introduced on 12-Oct. and this meaning was mostly mediated through her stable atmosphere model. Similarly, Heidie had abstracted the elements of her atmosphere model and had begun to consciously consider and articulate the implications of each of these concepts. This awareness was brought about in Heidie's attempts to use the scientific ideas of transfer, electrons, etc. So just as the atmosphere model mediated the meaning making of the scientific terms, attempts to use the scientific concepts mediated the awareness and evaluation of Heidie's own model.

Vygotsky uses the example of learning a foreign language to illustrate how spontaneous and scientific concepts mediate one another as described above. When one learns a foreign language, maturity in one's native language allows one to associate the new language with terms in the native language. In learning the new language deliberately and consciously (in contrast to the unconscious learning of the native language), the learner becomes aware of the abstract structure of his own native language and is able to develop further in his native language. This is what happened to Heidie. The use of concepts that she did not yet understand yielded a better understanding of her own model. This was the same model that allowed her to use these concepts in the first place. I would argue that Heidie began to have a "conceptual understanding" of the one-way transfer process when her awareness of the abstract-able, articulate-able features of her spontaneous concepts coincided with the meaning she had formed for the terms and symbols used in the one-way transfer model.

4. Summary and Discussion

The data and analyses presented in section 3 illustrate the process of conceptual change. Heidie initially developed the spontaneous concepts that: (a) charged object contains only positive or only negative charges, (b) releases all of one type of charge to the atmosphere for each material, and (c) the material is predestined to give off a certain type of charge and retain the other. Although Heidie did not understand the one-way transfer model when it was first presented to her, the whiteboard representation of the model served as a visualization tool that mediated the evaluation of the implications of her own model (that the object became charged on all surfaces).

Social motivation led Heidie to try to understand one and two-way transfer models. In doing so, Heidie began to use them even when she did not understand them. According to Vygotskian theory, the "analysis of reality with the help of concepts precedes analysis of the concepts themselves" ([30] p. 141). This was evident in two ways. First, in her diagrams that showed two-way transfer, she did not depict the charged condition. Several times in interviews she stated that she was not sure what was happening within the objects. Second, she applied the one-way transfer model only to a single situation that involved a special set of circumstances. Because Heidie thought that the wool did not get charged during rubbing, she figured that it was okay to use an "unbalanced" model (such as a one-way transfer model) to account for the source-receiver effect. In addition, Heidie's hybrid model was clearly an interpretation of the one-way transfer model through the lens of the atmosphere model. This is also evidence of concept mediation occurring between the spontaneous and scientific concepts.

The hybrid model is an excellent example of the process by which spontaneous concepts (forming from bottom-up) and scientific concepts (forming from top-down) come together. The fact that Heidie was trying to use a scientific model that she did not understand, coupled with the fact that she fully understood, and was able to use, her atmosphere model is evidence that scientific concepts and spontaneous concepts have different roots. It was not until Heidie was exposed to the idea that a charged condition can result from an excess of charge that she began to actually evaluate critical concepts within all of the models.

The simulator mediated the formation of the transfer models in two ways. First, it provided an image on which Heidie's conceptual functioning "piggy-backed" to transform the *words* used by the teacher into the *concept* of excess charge. The red and blue coloring scheme gave no evidence of excess. It was general enough to elicit multiple interpretations. All of the pictures Heidie drew previously showed charged conditions as consisting of entirely negative or positive charges. In Heidie's diagrams, the *charged condition* meant the existence of only one type of charge throughout the entire object. This was depicted with plus or minus symbols and it is consistent with her *plus and minus condition model* that she had in the beginning of the unit (see fig. 1). Her own images actually impeded the development of the concept of excess as charged conditions because they provided no room for interpretation. The red and blue coloring scheme offered a whole range of possibilities. Second, when Heidie observed the process of charging a conductor by contact on the simulator, she observed that the blue line on the insulator got thinner while a blue line appeared on the conductor. This provided evidence and a simple explanation for transfer: something moves from one object to the other. It showed that after the transfer took place, there was more of something on one object and less of that thing on the other. This may have helped Heidie transform the vague terminology of "transfer" (which she had previously only associated with arrow symbols in her drawings) to the idea of something going from one thing to another thing, leaving the original object with less of that thing.

By the time Heidie was able to consider the electron orbit model of the atom she had already developed a shared language for talking about transfer, charge, insulators, conductors and excess. This shared language was necessary for Heidie to make sense of the atomic model, which she finally did during her discussion with Mark on 2-Nov.. It was not until an interview on 4-Nov. that Heidie first used the one-way transfer model successfully. During this interview, Heidie showed clear understanding of the atomic model, the concept of transfer, the concept of excess charge and the implications that each had on the others. Through the bottom-up development of the atmosphere model and the simultaneous top-down development of the one-way transfer model, Heidie developed conceptual understanding of the process and products of charging insulators by rubbing them together.

An important feature of the Vygotskian perspective is the concept of mediation. This is a mechanism by which decisions are made and cognitive actions are transformed and carried out. There were two types of mediation in the analysis presented in this paper. First, there was mediation of one concept by another. Heidie used her own understanding of the world to transform the words used by the scientific community into meaning. Second, there was mediation by cultural artifacts such as the red and blue coloring scheme, laboratory apparatus, and shared representations on the whiteboard. Heidie "piggy-backed" on these physical features of the environment to transform a vaguely articulated atmosphere model into an abstract entity subject to scrutiny. When students develop school knowledge these two things have to happen. First, the intuitive concepts that exist in the unarticulated world of the individual need to be brought to the fore and students must become objectively aware of them and use them as the subject of evaluation. Students must learn to step back from their own vaguely formed concepts and evaluate these concepts that are not yet fully articulated in their minds. Further articulation of the concept occurs through the very process of stepping back and evaluating it. Some refer to this process as *bootstrapping*. This is a good metaphor but it does not have as much explanatory power as Vygotsky's theory of concept formation through mediation.

Second, students must develop a meaningful understanding of the terms used in textbooks, the symbols used by the community, and the way in which such symbols are used.

They must connect what is being presented in the class to their own stable understanding of the world. This happens through application and re-application of concepts and terms that the student does not yet understand. It is in applying these concepts that students come to understand them. Again we can use the bootstrapping metaphor, but Vygotsky's theory explains it through the process of concept mediation and the notion that spontaneous and scientific concepts develop independently, are dependent on each other, and ultimately grow together. For a student, the application and re-application of the scientific concept must happen through the students' own resources. It should come as no surprise that students often fail to apply the same scientific concept to isomorphic problems. They have yet to fully develop that concept. They are *developing* it. Educators should understand that when students are applying terms and symbols used in the discipline they are developing the associated concepts. The last 30 years of research in "misconceptions" is evidence of this. These misconceptions have been recognized as partially schooled knowledge and partially intuitive knowledge.

So what does "construct their own knowledge" mean? According to the theory and research outlined in this paper, it means mediation. If the teacher wants students to "construct their own knowledge" he must provide assistance in bringing spontaneous knowledge to the fore through mediating artifacts that leave some room for interpretation. These mediating artifacts should have some foundation in the culture, practices and canonical knowledge of the discipline. In science, we have traditionally done this in the laboratory where students are to make observations and inferences. As we saw with Heidie, this is not enough to mediate the development of the appropriate models because in many cases, spontaneous models work fine for the macroscopic observations we are able to make in the lab. The computer becomes an increasingly powerful tool for providing representations, serving as a shared space for discussion, and allowing students to try out ideas. Vygotsky's perspective can help us understand how to use this tool—as a mediating artifact.

With the Vygotskian perspective, we can evaluate both how spontaneous concepts developed through interaction with the classroom content and evidence and how scientific concepts developed through the mediation of spontaneous concepts. The idea that spontaneous and scientific concepts do not develop from the same "root" is extremely useful for understanding the contextual dependence of student representations and their hybrid representations. In order for students to fully understand and be able to use a scientific concept she must be not only intelligible, plausible, and fruitful but the student must understand how and when to apply the concept. The knowledge of how and when to apply a scientific concept is associated with norms and practices within the scientific community, such as in what counts as evidence, criteria for determining the explanatory power of a model, that an acceptable model must be consistent with sanctioned knowledge within the field etc. Knowledge of science content and knowledge about science content are two different but closely related elements that comprise scientific understanding. When Vygotsky refers to the *formation* of scientific concepts he includes the appropriation of the norms and practices that exist within the scientific community, this is part of what he means by higher mental processes having their origins in social processes.

Norms and practices within the scientific community are only marginally related to a student's everyday experience and in many ways, must develop in a top-down way (which in this theory means that it must be mediated by the intuitive knowledge of the individual). In the case study presented in this paper, we saw Heidie appropriate the practice by which an explanatory model must be consistent with *all* available evidence when she became increasingly uncomfortable with the fact that the atmosphere model could not explain the results of the cellophane/wool experiment. We also saw her appropriate the norm that an explanatory model must be consistent with accepted scientific knowledge when she began to require that her model for charging insulators by rubbing be aligned with the electron orbit model of the atom. In addition, Heidie's motivation for understanding the concept of transfer in the first place came from social, not empirical forces. The process of appropriating the norms and practices of the scientific community also occurs through mediation. To understand this process one must look at the broader social and cultural milieu. To understand how Heidie appropriated the norms described above, we must look more closely at her interactions with others, her interactions with tools, and her interactions with others and with tools. We must look at the broader socio-cultural cognitive system. This is the subject of the companion paper, *Cognitive processes and the learning of physics: Mediated Action* (this volume).

REFERENCES

[1] SMITH, J. P., DISESSA, A., ROCHELLE, J., *Journal of Learning Science*, **3**(2) (1993) 115.
[2] HAMMER, D., *American Journal of Physics,* **68**(S1) (2000) S52.
[3] ELBY, A., *Journal of Mathematical Behavior,* (to appear).
[4] ELBY, A. and HAMMER, D., *Science Education*, **85**(5) (2001) 554.
[5] THADEN-KOCH, T., *A coordination class analysis of college students' judgments about animated action.* (Unpublished doctoral dissertation, Lincoln, Nebraska) 2003.
[6] RUMELHART, D. E., "Schemata: The building blocks of cognition", in *Theoretical issues in reading comprehension,* R.J. SPIRO, B.C. BRUCE and W.C. BREWER, Editors, (Erlbaum, 1980); CAREY, S., *American Psychologist*, **41** (1986) 1123.
[7] CLARK, A., *Being There: putting brain, body, and world together again.* (MIT press, Cambridge, MA) 1997.
[8] NEWELL, A. and SIMON, H., *Human Problem Solving.* (Prentice-Hall) 1972.
[9] POSNER, G., STRIKE, K. HEWSON, P. and GERTZOG, W., *Science Education* **66**(2) (1982) 211.
[10] ANDERSON, REDER, and SIMON, , *Educational Researcher,* (1996) 5.
[11] COBB, P., *Educational Researcher ,* **23**(7) (1994) 13.
[12] LAVE, J. and ROGOFF, B., *Everyday Cognition: Its Development in Social Context, (*Harvard Univ. Press, Cambridge, MA) 1984.
[13] HUTCHINS, E., *Cognition in the Wild*, (MIT press, Cambridge MA) 1995.
[14] COLE, M., *Cultural Psychology: a once and future discipline,* (Harvard University Press, Cambridge, MA) 1996.
[15] FOSNOT, C.T., "Constructivism: A Psychological Theory of Learning", in *Constructivism: Theory, Perspectives, and Practice*, C.T. FOSNOT, Editor, (New York: Teachers College Press, New York 1997).
[16] DISESSA, A., *Changing Minds.* (MIT Press, Cambridge, MA) 2001.
[17] STRIKE, K. and POSNER, G., "A Revisionist Theory of Conceptual Change", in *Philosophy of Science, Cognitive Psychology, and Educational Theory and Practice* R. DUSCHL and R. HAMILTON, Editors (State University of New York Press, Albany, NY, 1992).
[18] KUHN, T., *The Structure of Scientific Revolutions*, (University of Chicago Press, Chicago, IL) 1962, 1970.

[19] FLECK, L., *Genesis and Development of a Scientific Fact*, (The University of Chicago Press, Chicago, IL) 1935, 1979.
[20] DUIT, R. and TREAGUST, D., "Learning in science—from behaviourism towards social constructivism and beyond", in *International Handbook of Science Education*, B. FRASER and K. TOBIN, Editors (Kluwer, Netherlands, 1998).
[21] ROCHELLE, J., *International Journal of Science Education*, **20**(9) (1998) 1025.
[22] PINTRICH, P., MARX, R. and BOYLE, R., *Review of Educational Research*, **63**(2) (1993) 167.
[23] NIEDDERER, H., in *Bridging Research Methodology and Research Aims, Proceedings of the 5th European Science Education Research Association Summer School*, edited by R.H. EVANS, A.M ANDERSEN and H. SORENSEN (The Danish University of Education, Denmark) 2001, pp. 397-414.
[24] DISESSA, A. and SHERIN, B., *International Journal of Science Education*, **20**(10) (1998) 1155.
[25] GREENO, J.G., COLLINS, A.M. and RESNICK, L.B. "Cognition and Learning", in *Handbook of Educational Psychology*, D.C. BERLINER and RC. CALFEE, editors (Simon & Schuster Machmillan, 1997).
[26] REDISH, J., *Teaching Physics with the Physics Suite*, (John Wiley and Sons, Inc.) 2003.
[27] MOLL, L., *Vygotsky and Education*, (Cambridge University Press, Cambridge) 1990.
[28] LEMKE, J.L., *Journal of Research in Science Teaching*, **38**(3) (2001) 296.
[29] FINKELSTEIN, N., *Journal of College Science Teaching*, Sept./Oct. (2003) 37.
[30] VYGOTSKY, L. *Thought and Language.* (MIT Press, Cambridge, MA) 1934, 1986.
[31] WERTSCH, J., *Voices of the Mind: A Socio-cultural approach to Mediated Action.* (Harvard University Press, Cambridge, MA) 1991.
[32] MCDERMOTT, L., *American. Journal of Physics* **59** (1991) 301.
[33] BROWN, D. and CLEMENT, J., *Instructional Science* **18** (1989) 237.
[34] CLEMENT, J., BROWN, D. E. and ZEITMAN, A., *International Journal of Science Education*, **11** (1989) 554.
[35] BROWN, D., *International Journal of Science Education.* **16**(2) (1994) 201.
[36] HESTENES, D., in *The Changing Role of Physics Departments in Modern Universities, Proceedings of the International Conference of Undergraduate Physics Education*, edited by E.F. REDISH and J. S. RIGDEN, (American Institute of Physics, College Park, MD) 1997, pp. 935-957
[37] MINSTRELL, J. in *Research in Physics Learning: Theoretical Issues and Empirical Studies, Proceedings of an International Workshop at University of Bremen* edited by R. DUIT, F. GOLDBERG and H. NIEDDERER, (IPN - Kiel, Germany) 1991, pp. 110-128; DISESSA, A. and MINSTRELL, J. "Cultivating Conceptual Change with Benchmark Lessons", in *Thinking Practices in Mathematics and Science Learning,* J. GREENO and S. GOLDMAN, Editors, (Lawrence Erlbaum Associates, Mahwah, NJ., 1998).
[38] MCDERMOTT, L.C. and THE PHYSICS EDUCATION GROUP, *Physics by Inquiry, Volumes I & II*, (John Wiley & Sons, Inc., New York) 1996.
[39] GOLDBERG, F., in *The Changing Role of Physics Departments in Modern Universities, Proceedings of the International Conference of Undergraduate Physics Education*, edited by E.F. REDISH and J. S. RIGDEN, (American Institute of Physics, College Park, MD) 1997, pp. 375-392.

[40] OTERO, V., *The process of learning about static electricity and the role of the computer simulator*, (Unpublished dissertation, San Diego, CA) 2001.
[41] HEWSON, P. W. and THORLEY, N. R., *International Journal of Science Education,* **11**(5) (1989) 541.
[42] GALILI, I., BENDALL, S. and GOLDBERG, F., *Journal of Research in Science Teaching* **30**(3) (1993) 271.
[43] MORSE, R., *Teaching about Electrostatics*, (American Association of Physics Teachers, College Park, MD) 1993.