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Learning by Collaborating: Convergent Conceptual Change

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The goal of this article is to construct an integrated approach to collaboration and conceptual change. To this end, a case of conceptual change is analyzed from the point of view of conversational interaction. It is proposed that the crux of collaboration is the problem of *convergence:* How can two (or more) people construct shared meanings for conversations, concepts, and experiences? Collaboration is analyzed as a process that gradually can lead to convergence of meaning.

The epistemological basis of the framework of analysis is a relational, situated view of meaning: Meanings are taken to be relations among situations and verbal or gestural actions. The central claim is that a process described by four primary features can account for students' incremental achievement of convergent conceptual change. The process is characterized by (a) the production of a deep-featured situation, in relation to (b) the interplay of physical metaphors, through the constructive use of (c) interactive cycles of conversational turn-taking, constrained by (d) the application of progressively higher standards of evidence for convergence.

> Mind as a concrete thing is precisely the power to understand things in terms of the use made of them; a socialized mind is the power to understand them in terms of the use to which they are turned in joint or shared situations. (Dewey, 1916, p. 34)

> The knower is not simply a mirror floating with no foot-hold anywhere, and passively reflecting an order that he comes upon and finds simply existing. The knower is an actor, and a co-efficient of the truth on one side, whilst on the other he registers the truth which he helps to create. (James, cited in Cremin, 1988, p. 400)

The goal of this article is to construct an integrated approach to collaboration and conceptual change. To do so, I examine a case of concep-

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tual change from the point of view of collaborative conversational interaction.

I propose that the crux of collaboration is the problem of *convergence:* How can two (or more) people construct shared meanings for conversations, concepts, and experiences? Few theories account for the achievement of convergence in the face of tendencies for meanings to diverge. This potential for divergence is particularly acute in science education; misconceptions research (see reviews in Confrey, 1990; Eylon & Linn, 1988; McDermott, 1984) documents the unusually strong tendencies of students to construct nonstandard meanings for scientific concepts. A serious account of science learning must provide an analysis of how convergence is achieved despite these tendencies.

In order to understand students' collaborative learning, it is helpful to reflect on scientists' collaborative work. To converge on meaningful new theories, scientists collaborate. Ethnographic and sociological analyses (e.g., Knorr-Cetina, 1981; Latour, 1986; Mulkay, Potter, & Yearly, 1983) of scientific theory construction argue that scientific collaboration shares most of the features of everyday, informal interaction, including the use of conversational turn-taking structures to negotiate meaning. Investigators of scientific conceptual change emphasize two differences that distinguish scientific work: (a) the production of visible displays that represent features of the world at an intermediate level of abstraction (e.g., Latour, 1986; Lynch, 1985; Miller, 1986) and (b) the interplay and recombination of metaphors drawn from experience to construct explanations (e.g., Boyd, 1979; Einstein, 1950; Lightman, 1989; Nercessian, 1988). Similar findings have emerged in studies of science learning. Conceptual change is seen as a process of learning to register "deep features" of situations (Anzai & Yokohama, 1984; Chi, Feltovich, & Glaser, 1980; Larkin, 1983) and restructuring systems of physical metaphors (Clement, Brown, & Zietsman, 1989; diSessa, 1983, 1987; Ogborn, 1985).

This article takes the negotiation of meanings of relations between such deep-featured situations and theory-constitutive metaphors to be the focus of students' collaboration in conceptual change. It builds on social constructivist (e.g., Newman, Griffin, & Cole, 1989; Vygotsky, 1978) and situated action (e.g., Suchman, 1987) perspectives in order to account for students' achievement of convergent conceptual change. Sufficient information for constructing shared knowledge is not contained by the social actions themselves, nor is it contained in the embedding situation. Only when the actions are considered in relation to the situation is sufficient information available to construct intelligible interpretations of what is taking place. Thus, the relations of actions and situations—"situated actions"—are the essential units to which participants orient themselves in their efforts to succeed in convergent conceptual change. This view is called a relation theory of meaning (Barwise & Perry, 1983).

The central claim is that conversational interaction can enable students to construct such relational meanings incrementally. Specifically, it is argued that conversational interaction provides a means for students to construct increasingly sophisticated approximations to scientific concepts collaboratively, through gradual refinement of ambiguous, figurative, partial meanings. The basis for this claim is research in conversational analysis (CA) and pragmatics (e.g., Goodwin & Heritage, 1990; Levinson, 1983). This research has identified conventional structures of face-to-face interaction that enable participants to construct, monitor, and repair shared knowledge (Sacks, Schegloff, & Jefferson, 1974). Moreover, CA research shows that meanings can accumulate incrementally, subject to ongoing repairs (Schegloff, 1991). In addition, it has identified standards of evidence that enable participants to gauge the degree to which knowledge is shared (Clark & Schaefer, 1989). CA has shown how convergent meanings can be achieved gradually through collaborative interaction.

A process is proposed that integrates prior research about scientific collaboration and convergence of meaning in everyday conversation in order to analyze students' convergent conceptual change. The four primary features of the proposed process are:

1. The construction of a "deep-featured" situation at an intermediate level of abstraction from the literal features of the world.
2. The interplay of metaphors in relation to each other and to the constructed situation.
3. An iterative cycle of displaying, confirming, and repairing situated actions.
4. The application of progressively higher standards of evidence for convergence.

The first two features describe the nature of the conceptual change that students achieve: The essence of the change occurs in the relation of deep-featured situations and theory-constitutive metaphors. The latter two features describe the mechanism of convergence that enables incremental, social construction of concepts. Convergence is achieved through cycles of displaying, confirming, and repairing shared meanings. A greater degree of sharing is gradually produced by joint use of meanings in situations that require progressively more constrained actions in order for attributions of shared knowledge to be warranted.

This analysis of conceptual change shares some features with prior analyses, but advances a particular stance on the role of collaboration. It shares with contemporary cognitive theory the emphasis on students' construction of deep-featured situations and their restructuring of commonsense metaphors. It differs by taking the view that meanings are relational, and that collaboration provides a mechanism for achieving convergent relational meanings. Specifically, the analysis argues that convergent conceptual change is achieved incrementally, interactively, and socially through collaborative participation in joint activity.

A PUZZLING ACCOMPLISHMENT

This article seeks progress on the issue of *convergent conceptual change* through the microscopic analysis of a single case. The case involves two students, Carol and Dana, who engaged in discovery learning with the Envisioning Machine (Roschelle, 1991), a computer simulation of velocity and acceleration (i.e., a Newtonian microworld; diSessa, 1982; White, 1984). The analysis will show that Carol and Dana cooperatively constructed an understanding of acceleration that constituted (a) a large conceptual change from their previous concept, (b) a qualitative approximation to the scientific meaning of acceleration, and (c) a closely shared meaning between one another. On the basis of these accomplishments, I argue that Carol and Dana achieved convergent conceptual change.

Within this accomplishment lies a puzzle. The puzzle becomes obvious when examining the protocol of the students' interaction with each other and the computer. It would be expected that convergence on a new shared understanding would require clear articulations of meanings, in the manner of scientific presentations of the concept of acceleration. For instance, the scientific definition of acceleration is "the derivative of velocity with respect to time." Whereas scientific language is precise and literal in its meaning, Carol and Dana's is only weakly suggestive of any particular meaning. For example, the protocol under analysis begins as follows:

1. D: But what I don't understand is how the lengthening, the positioning of arrow . . .
2. C: Ooh, you know what I think it is? It's like the line. Fat arrow is the line of where it pulls that down. Like see how that makes this dotted line. That was the black arrow. It pulls it.

Carol and Dana's use of language in this excerpt is typical of their language throughout the duration of their conceptual change process: There are large gulfs between the ambiguous expressions the students use and the precise meanings those expressions come to have. For example, later analysis will show that the key phrase in this dialog is "it pulls it." In this phrase, the verb "pull" is a metaphor with many possible interpretations. Likewise, the pronouns that "pull" relates are highly ambiguous. Throughout their process of convergent conceptual change, Carol and Dana's language continues to have this character – their actual utterances, taken in isolation, are virtually meaningless.

Thus Carol and Dana's language is not much like written scientific language. It is also hard to detect in the students' behavior any patterns that are as strong as the hypothetico-deductive method. Moreover, Carol and Dana received no prior instruction on scientific descriptions or conceptions of motion. Nor can one attribute their learning directly to the structure of the computer simulation, as students who experience the same simulation construct widely divergent ideas (Roschelle, 1991). As a result, the means for convergent conceptual change therefore appear incommensurate with the outcome: How could Carol and Dana converge on a deep new conception with only figurative, ambiguous, and imprecise language and physical interactions at their disposal? This is the specific question the case study seeks to answer.

THE TASK

The computer software involved in this case is called the Envisioning Machine (EM). The EM is a direct-manipulation graphical simulation of the concepts of velocity and acceleration. A brief summary of relevant features of the simulation follows. Roschelle (1990) provided a detailed discussion of the design of the EM, focussing on the symbolic mediation perspective that informed the design.

The EM window (Figure 1) displays two objects, a ball and a particle. The EM displays the ball as a black circle, and the particle as a white circle with two arrows attached. The thin arrow with its base at the particle's center represents the particle's velocity vector. The thick arrow with its base at the velocity's tip represents the particle's acceleration vector. The computer displays an animation of both the particle and the ball moving across the screen. In the case of the particle, the computer simulation updates the velocity and acceleration arrows to reflect the correct velocity and acceleration of the particle's motion. During the computer simulation, both the particle and the ball leave a series of trace dots behind them, placing the dots at a uniform rate. These dots therefore present information about each object's speed, as well as its path.

The students' task is to manipulate the position, velocity, and accelera-

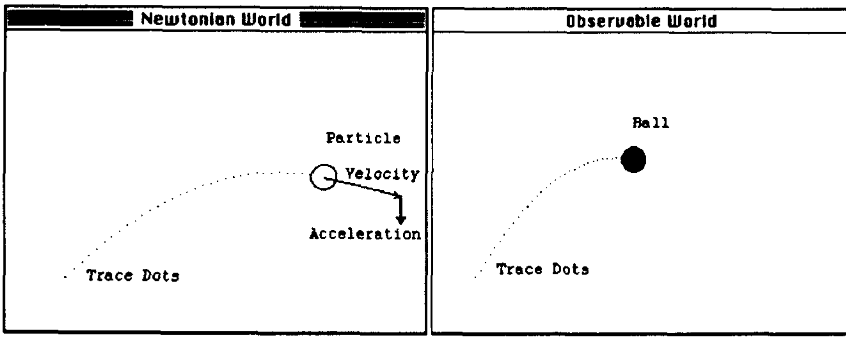

FIGURE 1 The Envisioning Machine (labels added).

tion of the particle so that it makes the same motion as the ball does. Students control the simulation of the Newtonian particles by using menus and a mouse. Students are not told the scientific names of the arrows, velocity and acceleration. Instead, the arrows are called the "thin" and "thick" arrows, respectively. In the specific case considered here, the correct initial position and velocity were set for the students, so they only manipulated acceleration. In this version of the EM activity, acceleration occurs in bursts that change velocity for exactly 1 sec. Constant velocity motion occurs before and after bursts of constant acceleration.

The simulation also has an additional "velocity space" display (Figure 2). The velocity space display shows the velocity and acceleration arrows of the particle. In the course of a 1-sec burst of acceleration, the tip of the velocity moves from the base of the acceleration to the tip of the acceleration (see Figure 2). As the tip of the velocity moves, it leaves a trail of dots behind. The velocity space therefore animates the process of vector addition.

Roschelle (1991) investigated what students learn as a consequence of engaging in collaborative problem-solving tasks with the EM. Some results are particularly pertinent to the framing of this case as a study of successful

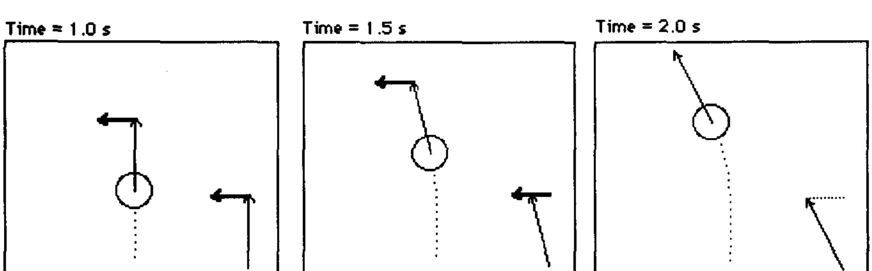

FIGURE 2 Velocity space display (lower right) at three time instants.

convergent conceptual change. A critical observation is that no single literal registration of the deep features of the EM display was consistent across students; students constructed a wide variety of incompatible sets of features for use in problem solving and explanation. Moreover, only 6 of 14 students converged on explanations that were like scientists' explanations. The other 8 students either never converged on a stable explanation, or converged on an explanation that was incompatible with conventional science. In addition, although all the students worked in pairs, the individuals in each pair did not always end up with isomorphic conceptions (as measured in separate interviews). These observations show a strong tendency to form diverse interpretations of the physical setting, and to construct divergent concepts. Convergent conceptual change is a real problem for students in the EM setting.

Roschelle (1991) also examined potential factors in the different outcomes between the 6 more successful students and their less successful peers. The outcomes were connected to students' use of physical metaphors (e.g., "p-prims," diSessa, 1983, 1987) in theory construction. Successful students almost uniformly used a pulling metaphor to construct their explanation of acceleration; the core explanation was "acceleration pulls the tip of the velocity vector." This use of pulling contrasts with the common misconception "force as a mover," which specifies force as directly related to change of position. The key transformation of conceptual structure for successful students was the redirection of pulling from "acceleration pulls the particle" to "acceleration pulls the tip of velocity"—a transformation of a "misconception" into an explanation that is more compatible with the interpretation of acceleration in scientific practice. This is the transformation that occurs herein.

THE CASE STUDY

Introduction

Carol and Dana (not their actual names) were students in a private, urban high school. Carol and Dana had not yet studied physics, but had studied vector addition in their Algebra II class. Their chemistry teacher described them as average students who were "having a hard time in science." Carol and Dana were close friends and often worked on school assignments together. They volunteered to participate. Their participation consisted of attending two after-school sessions in which they worked with two versions of the EM. Each session lasted about an hour.

This analysis focuses on episodes that occurred about 15 min into their second session. By this time, Carol and Dana had solved 2 problems, in addition to the 10 problems they solved in their first session. Yet they had not developed explanations that correspond to a scientific understanding of acceleration. This is not unusual: The median point at which students develop appropriate explanations is after solving 10 problems (Roschelle, 1991).

The analysis provides evidence for cognitive and social outcomes. The cognitive outcome is that a conceptual change occurred. The social outcome is that Carol and Dana shared the new conceptual structure.

With respect to the cognitive outcome, it will be argued that Carol and Dana achieved a conceptual change consisting of two related constructions, a geometric figure containing the appropriate deep features of the situation, and an interaction of metaphors comprising an explanation of accelerated motion. In particular, the geometric figure is the vector addition triangle, and the explanation involves the interplay of metaphors of pulling, adding, traveling, and hinging. Appropriate placement of these metaphors in relation to the deep features of the vector addition diagram can articulate a concept analogous to the scientist's concept of a derivative.

In addition, evidence will be examined for the claim that the students achieved shared knowledge, a social outcome. This analysis of this case will show that Carol and Dana use conversational turn-taking to cooperatively construct situations and concepts. Through iterative turn-taking structures, the students are able to build on each other's ideas and intentions, draw new ideas into a common conceptual frame, and repair divergences. This occurs despite the high degree of ambiguity in each individual utterance that the students produce. The multiplicity of meanings allowed by the utterances is constrained by the sequence and situation in which they are related. Thus the use of turn-taking enables Carol and Dana to monitor the degree of shared understanding, and to repair divergences when they become apparent. The efficacy of such conversational structures for achieving convergent meanings has been thoroughly documented in the fields of CA and pragmatics (e.g., Clark & Schaefer, 1985; Goodwin & Heritage, 1990).

The achievement of shared knowledge will occur incrementally throughout the episodes, through the students' application of progressively higher standards of evidence. By the application of *progressively higher standards of evidence* for convergence, I mean that students follow confirmation of shared meaning at low standards of evidence with confirmation at high enough standards that the attribution of shared knowledge is warranted. CA research has identified a variety of means for confirming the mutual acceptability of a display of shared knowledge, with attendant degrees of evidence for attribution of shared knowledge (Clark & Schaefer, 1989). For example, a mutually acceptable elaboration or collaborative completion of a concept is stronger evidence than a verbatim recitation of a concept or inference rule. A verbatim recitation is stronger evidence than a simple affirmative acknowledgment. A simple affirmative acknowledgement is stronger evidence than a smooth continuation of the activity sequence into the next relevant topic or activity goal. By employing standards of evidence, coparticipants can determine that a concept is shared up to a mutually acceptable level.

In summary, I propose that convergent conceptual change is achieved by using conversational interaction in the service of conceptual change. In particular, the process of conversational interaction affords opportunities for coparticipants to negotiate the meanings of metaphors-in-situation. In a case of scientific conceptual change, these meaning are in the relationship between deep-featured situations and theory-constitutive metaphors. Socially-coordinated situated action provides a basis for such meanings to be negotiated, confirmed, and repaired at a suitably high standard of evidence. The case study that follows is a plausibility argument for this proposal. The discussion that follows addresses its potential generality.

From this point forward, the analysis proceeds in episodes that correspond to durations of coherent activity demarcated by students' own behavior. In each episode, transcripts and pictorial data are presented, followed by analyses of: (a) conversational action, (b) conceptual change, and (c) shared knowledge. In each episode, the discussion of conversational action gives a brief account of what happened. The discussions of conceptual change and shared knowledge explore each of those two aspects in more depth.

Episode 1: Ooh, You Know What I Think It Is?

The analysis begins with the first two turns of a longer conversation. The full episode is presented later, after considering the first two turns. The notation is described in the Appendix. This episode shows the initiation of convergent conceptual change.

Data (first two utterances).

1. D: But what I don't understand is how the lengthening, the positioning of the arrow . . .
2. C: Ooh, you know what I think it is? It's like the line. Fat arrow is the line of where it pulls that down. Like see how that makes this dotted line. That was the black arrow. It pulls it.

Conversational action. Taken out of context, Carol's utterance is ambiguous and indecipherable. It is clearly a relevant response to Dana's public announcement about her lack of understanding, but based on the utterance only it is hard to make the case that Carol produced a significant insight. Yet if one hears these words as they were uttered in relation to Carol's gestures to the computer display, a strong case can be made that Carol produced a proposal for a new conception of acceleration. Unlike the students' previous conceptions, her new insight was compatible with a scientific conception of acceleration.

Figure 3 presents Carol's statements in relation to her simultaneous gestures to the computer screen. As she spoke, Carol was gesturing to the velocity space display. Note that this display was in the state following the simulation run. Therefore, only the final (resultant) velocity and the dot trace representing the previous burst of acceleration were visible (i.e., in the upper left of Figure 3). Carol began her presentation by recalling the objects necessary for her explanation. She did this by slowly and deliberately tracing her finger over the display. First she traced her finger over space previously occupied by the initial velocity, and then over the previous acceleration, effectively creating a focus of attention on these invisible objects. When she said "fat arrow is the line of where it pulls that down," she grasped the tip of the (invisible) initial velocity, and made a gesture

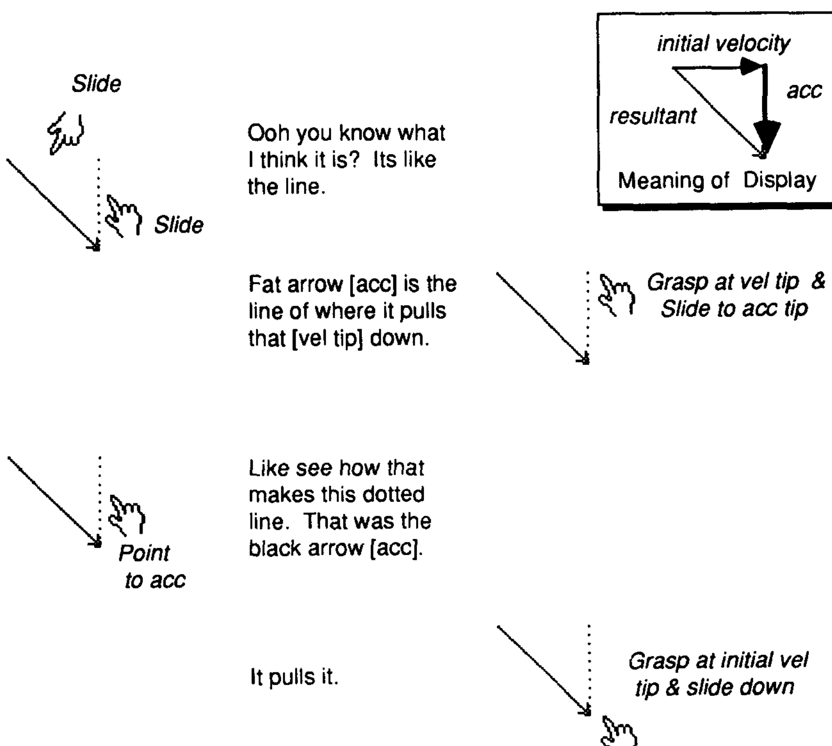

FIGURE 3 Explanation using gestures to relate metaphors to the situation.

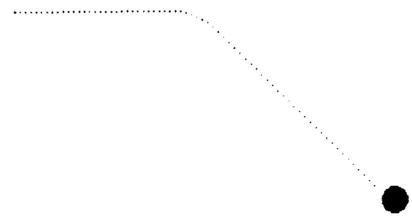

FIGURE 4 The desired trajectory, a 45° bend.

expressed the idea of pulling the tip of the vector to its new location. She then interpreted the dotted line as the previous acceleration (the students had not interpreted this trace previously). Finally, she summarized her conception, "It pulls it," and again synchronized this utterance with a grasp-and-drag gesture. To summarize, Carol brought the three lines to the foreground and gave them abstract interpretations as deep features—initial velocity, final velocity, and acceleration. She developed an explanation of the configuration by reference to the metaphor of pulling.

Conceptual change. This combination of utterances and gestures articulates a concept analogous to a physicist's concept of acceleration. In the physicist's conception, acceleration describes a change of velocity. Carol's presentation also describes acceleration as changing velocity via the pulling metaphor (i.e., "It pulls it"). Her grasp-and-drag gesture captures the process of vector addition that would occur over the course of 1 sec. Moreover, Carol's discussion of the initial and final states of velocity agree with a scientific understanding of the vectors that occupied the spatial positions that she indicated.

To see Carol's combination of utterances and gestures as a conceptual change, it is necessary to recount the students' behaviors leading up to this moment. At the time of this episode, Carol and Dana had just managed to solve a challenge in which a particle "veered" at a 45° angle from its original, straight-line trajectory (Figure 4, solution is Figure 5). Before solving this challenge they proposed and tested a series of settings for the acceleration vector (Figure 6). This progression of settings has two interesting properties. First, in each setting the 1 sec burst of acceleration is

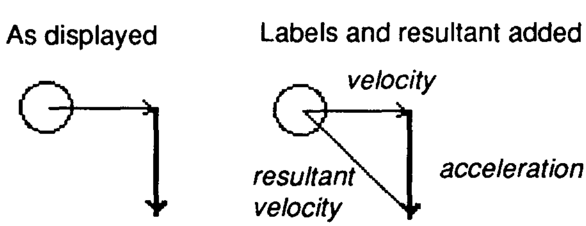

FIGURE 5 The correct solution.

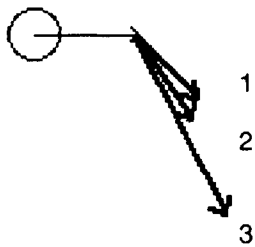

FIGURE 6 Three solution attempts.

pointed roughly in the direction that the students want the particle to travel. Second, when Carol and Dana observed that the "veering" effect they had produced was insufficient, they responded by making the acceleration longer.

These properties, along with the students' protocol, show that they initially did not conceive of velocity and acceleration as a physicist would. Instead, Carol and Dana viewed the velocity and the acceleration as controlling the first and second parts of the motion, respectively. This is consistent with the notion that acceleration directly pulls the particle in a new direction, with effort proportional to the length of the arrow. This prior conception is a well-documented misconception (diSessa, 1982; Roschelle, 1991; White, 1983).

Given this misconception, this solution to the challenge presents an anomaly: When acceleration is 90° from velocity, a 90° bend in the trajectory would be predicted by their theory, but a 45° bend occurs. As Dana said just before the first turn in this conversation (No. 1), "But it doesn't go at a 90° angle. I don't understand."

Carol's response to Dana (No. 2) therefore marks the first appearance of a new conceptual structure. In the previous conception, acceleration directly pulls the particle during the second part of the motion. In the new conception, acceleration changes the direction of velocity. This new conception potentially can account for the anomaly that Dana noted. Moreover, the new conception is closer to the scientific ideal. But as later data show, it was unlikely that the theory was complete at this time. In particular, there is no mention of change of speed, just change of direction.

Shared knowledge. Does this combination of language and gesture in relation to the computer display constitute a viable explanation? Fortunately, there is no need to debate the issue. Dana's response indicated clearly that Carol's metaphor-in-situation could be meaningfully interpreted by another student. Indeed, Carol's explanation became the initiating act in the students' convergent conceptual change. The next section examines the construction process by presenting the data for the entire episode.

Data (full episode).

1. D: But what I don't understand is how the lengthening, the positioning of arrow . . .
2. C: Ooh, you know what I think it is? It's like the line. Fat arrow is the line of where it pulls that down. Like see how that makes this dotted line. That was the black arrow. It pulls it.
3. D: You're saying this [dotted line] is the black arrow?
4. C: Yeah.
5. D: And it pulls it the other arrow [points to vel with mouse cursor] like . . .
   [
6. C: Like on its hinge. It pulls the other arrow on the hinge down to the tip of the black arrow.
7. D: Making the line that you see here [gestures to the trajectory after the 45° bend].
8. C: Right.

Conversational action. The episode is framed by Dana's request for an explanation (No. 1). The explanation itself is collaboratively completed over the course of the next seven conversational turns, ending with Carol's positive evaluation, "Right" (No. 8). Interpreting this explanation requires a situated action perspective because the explanation emerged and became a mutually-satisfactory understanding through the coordinated action of the participants, placed in space and time, and in relation to a deep-featured situation. The discussion below proceeds through the episode chronologically.

Following Dana's request (No. 1), Carol produced the description of the pulling process that has already been analyzed (No. 2). It is important to note that Carol's utterances describe a process, but do not directly account for the 45° bend. Yet because of next-turn-relevancy conventions, these utterances can be seen as proposing a new explanation of the acceleration arrow.

After Carol's process description, Dana and Carol coordinated a series of two clarifications. The fact that the next turns were clarifications indicates that Carol's proposal was accepted as a potential source of explanation. The first clarification, "You're saying this is the black arrow" (No. 3), negotiated a specific deep feature. What Dana indicated as "this" was literally a series of dots. The "black arrow" was a figurative reference to the EM acceleration arrow, which is thicker, and thus blacker than the velocity arrow. With Carol's acknowledgment, "Yeah" (No. 4), this exchange resulted in shared knowledge of the fact that in the situation under consideration, the acceleration arrow was a deep feature, available by visualizing the dots as forming a line.

The second clarification, "And it pulls the other arrow" (No. 5), accomplished two additional negotiations. First, it identified the recipient of pulling to be the initial velocity. This was accomplished by Dana's use of the mouse cursor to point to the spatial position that the velocity arrow had occupied initially, thus identifying another deep feature. Second, it clarified the meaning of the pulling metaphor. Indeed, Carol responded with two clarifications (No. 6). By "on the hinge," Carol implied that the velocity arrow pivots about its base (evidence for this interpretation is the consistent use of "hinge" in this manner in later episodes). By "to the tip of the black arrow," Carol clarified that the outcome of the pulling process is that the tip of the velocity arrow moves to the place originally indicated by the tip of the acceleration arrow.

In these two clarifications, the students linked the initial state of the velocity arrow to the diagram and linked the acceleration arrow to the velocity change process. Furthermore, they delineated the end state of the process. These relations were organized into an integral whole through the geometric, dynamic metaphor that Carol had introduced, "pulling."

Following the clarifications, Dana (No. 7) employed a gesture and utterance to connect the end state of the pulling process (the new direction of the velocity) to the goal, thus explaining the 45° bend. This act completed the explanation of the anomaly, pending a display of evidence that it was mutually satisfactory. Carol's acknowledgment (No. 8) provided that evidence.

Conceptual change. This explanation demonstrates that a conceptual change had been initiated. Through situated action comprising spatially and temporally placed utterances and gestures, Carol introduced a new metaphoric explanation in relation to a new set of deep features: The explanation "acceleration pulls the tip of velocity" was related to the newly interpreted velocity space display. Then both students collaboratively used this set of meanings to account for an observation that had been anomalous under their prior theory. In their prior theory, the direction of acceleration corresponds to the direction of the latter part of the trajectory. But in the current solution, an acceleration at a 90° angle resulted in a 45° bend in the trajectory. Carol and Dana's use of the pulling metaphor accounted for this anomaly, and introduced a new theory about the simulation.

Shared knowledge. Carol's utterances and gestures to the display were anything but precise, unambiguous, and literal. Indeed, two of the objects of her explanation, initial velocity and acceleration, were not literally visible in the marks on the display. They were possible to visualize by connecting the dots (in the case of acceleration) and imagining a line segment between the base of velocity and the top dot (in the case of initial velocity). Using these physical affordances, Dana and Carol negotiated a consistent set of references to a set of deep features that they superimposed on the physical space they shared. Because it is simple to trace or envision the lines that connect these dots, both students could share access to the deep features invoked in Carol's explanation.

Likewise, Carol's key phrase, "it pulls it," is neither precise nor unambiguous. Yet through coordinated action, Carol and Dana were able to negotiate a shared interpretation of what "pulling" could mean in this context. Again, this use of pulling cannot be literal: Groups of black pixels don't exert contact forces on each other. Nonetheless, pulling could provide an integrating abstraction to link the deep features in the abstract situation into a coherent whole. Thus the social interaction that followed the introduction of the pulling metaphor rendered a particular meaningful interpretation to pulling in this situation.

Despite the abstractness of the situation and the figurativeness of their language, Carol and Dana collaboratively articulated a coherent new explanation of the behavior of the computer simulation. This explanation satisfactorily resolved the anomaly that Dana noted. However, given the sparseness of Carol and Dana's action, it is hardly certain that the students have shared knowledge. Thus it is entirely appropriate that in the next episode, the students generalize the explanation and explicitly test the degree to which it is shared.

Episode 2: So If You Were to Have ...

This episode shows how Carol and Dana tested shared understanding at a higher standard of evidence.

Data.

9. D: So if you were to have, like, this (drags velocity-space)
10. D: Wow.
    [
11. C: Wow. Put that [vel-space] back.
12. D: I, can't I move that or, like, am I not allowed?
13. C: [cough, cough] I wouldn't mess with it.
14. D: Damn. OK so I guess. OK so if you have this arrow =
15. C: =The, the black arrow, was like, was like, right, I'm totally making this up, but, see the black arrow was right there : : : [traces out

a new acceleration with the mouse] But I'm assuming it would pull the other arrow like right out to there.

[

16. D: Like, like [traces out resultant with finger].
17. C: But this is completely made up no way so don't . . .

Conversational action. Following the explanation produced in the last episode, Dana tried to manipulate the velocity space display into a new state. Simultaneously, she began to discuss a hypothetical situation, "So if you were to have, like, this. . . ." It is plausible that her intention was to manipulate the velocity space display into a new state that would serve as a hypothetical test case for comparing the students' individual interpretations. Certainly, this would be a highly relevant next thing to do. Moreover, Carol appeared to have picked up this intention, because she later (No. 15) completed Dana's second bid (No. 14) to produce a new situation. In the intervening turns (No. 10–13), Carol and Dana discovered that the computer software would not support their intended manipulation; instead of dragging the acceleration with the mouse, Dana ended up dragging the whole display to a new location. The students agreed to abort this proposal.

In the conversation that followed (No. 14–17), Carol accomplished Dana's intent, producing a novel and somewhat more abstract context for a test of their degree of sharing (No. 15). She set up the new context by producing gestures on the screen with the mouse, but without pressing the mouse button to manipulate the objects on the screen. The left side of Figure 7 shows the new acceleration that Carol traced out with the mouse. The right side of Figure 7 shows the new resultant velocity that Dana traced with her finger in response. The thick gray lines in these figures were added to show the path traced by Carol's mouse cursor and Dana's finger; these did not actually appear on the computer screen.

Conceptual change. From a scientific standpoint, Dana's projected resultant velocity is the correct prediction for the accelerated motion situation posed by Carol. The production of these gestures in successive

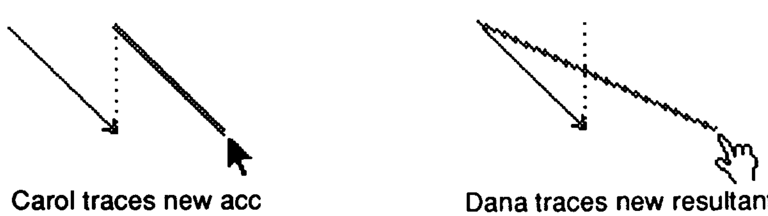

FIGURE 7 Constructing a situation to compare predictions.

turns suggests a correct question-answer pair. Carol in effect said, "So what would the new velocity be if this were the acceleration?" Dana gave the appropriate response. This question-answer pair agrees with the new conception of pulling, and disagrees with the old conception, again suggesting that a conceptual change had occurred.

Shared knowledge. The first two episodes are particularly important because they illustrate how the students build shared knowledge. In these two episodes, the students constructed a geometric situation that drew from the literal features of the display, but was not literally visible in the surface features of the display. In the first episode, acceleration was represented by dots, whereas in the second episode the surface features were gestures. Thus, the two representations of acceleration were similar only at the level of deep features.

With respect to this set of deep features, Carol and Dana negotiated the meaning of metaphors to explain the anomaly they observed, and to predict velocity changes. The negotiation occurred through situated action—their actions gain meaning through exacting placement in space and sequence with respect to the deep features of the situation. The turn-taking structure of language provided a means for displaying and confirming knowledge.

Upon confirmation of shared meaning at a low standard of evidence in Episode 1, the students jointly constructed an opportunity to confirm meaning at a higher standard of evidence in Episode 2. Their conversation in Episode 2 is stronger evidence because, instead of merely parroting Carol's insight, Dana now applied it correctly to a new context. In this episode, Carol's new acceleration was represented gesturally by the line from the tip of the imagined initial velocity to the mouse cursor. Dana's new velocity was represented gesturally by the line from the base of velocity to the mouse cursor. The response that Dana produced was a highly specific choice, given that she could have traced a variety of lines, or none at all. Indeed, we know that prior to Episode 1, Dana probably would have traced a different line—a line that points in the direction of the acceleration. In addition, the sequence of action is a highly explicit form of confirmation; Dana completed an independent prediction which agreed with Carol's own prediction. Thus, this episode provides stronger evidence for shared knowledge.

Episode 3: I Got It!

This episode provides a look at the processes by which students incrementally elaborate their concepts through collaboration.

Data.

18. C: Oh.
19. D: Umm. That was great.
20. C: Hhh.
21. D: It [particle] speeded up. Did you see that?
22. C: Hhh. Ours [particle] speeded up. Uhh. Let's reset. [Resets]
23. D: Wow.
24. C: And play for three seconds. [Runs]
25. D: Now watch the bottom arrow [vel in vel-space]. Look it, it gets lengthened. But how : : : ?
26. C: It gets speeded up.
    [
27. D: It [vel] gets lengthened until, oh [2 loud table slaps] *I got it!*
28. C: What?
29. D: When you add on this arrow [acc], it's the length of the total [resultant] . . .
30. C: That's what I was saying.
    [
31. D: That it [vel] assumes [comes to have] . . .
32. C: Is that the black arrow [acc] pulls out this arrow [vel], that's just what I was saying, to its tip.
    [
33. D: Oh, I . . .
34. C: But you were doing it, saying it in a different way.

Conversational action. The analytic interest in this episode is in lines 25–34. In the preceding lines, the students began the next EM challenge. As it turned out, the initial setting of the acceleration of the Newtonian particle (which was random) was colinear with velocity, producing an increase in speed. The students (Nos. 21–22) negotiated a focus of attention on this increase in speed, and Dana further emphasized the depiction of the velocity arrow in the velocity space display (No. 25).

In her next statement, Dana asked another question, which can be paraphrased as "How does the velocity arrow get lengthened?" (No. 25). Interestingly, Carol responded by stating an observation that related the change in length of velocity to the change in speed, "It gets speeded up" (No. 26). This could either be an independent observation that the particle's speed increases, or a statement that the lengthening should be interpreted as increase in speed. At any rate, Dana responded with an exclamation that can only mark a dramatic insight, which she accentuated by slapping the table twice (No. 27).

After Dana's display of a personal insight, Carol sought a clarification of the content of the insight (No. 28). In response, Dana articulated a process using the metaphor of addition (No. 29): Acceleration adds length to the initial velocity; therefore the addition of the initial velocity and acceleration indicates the length the velocity will have after the one second burst of acceleration.

Carol's response is particularly interesting. Carol claimed (Nos. 30 & 34) that Dana's idea was identical to hers. To substantiate this point, she repeated Dana's gestures, but superimposed her vocabulary of explanation (bottom of Figure 8). Thus, by grounding their conversation to the gestures to their deep features, Carol produced a translation between their metaphoric vocabularies (pulling versus addition over time). Moreover, she displayed clearly her preference that Dana's insight be taken as an elaboration of the same underlying process (No. 34). In tracing through Carol's actions, there is a pattern that suggests a deliberate attempt to bring Dana's insight into students' shared knowledge, rather than accepting it as a divergent, conflicting view.

Conceptual change. The explanation in the previous episodes covered change of direction, but not necessarily change of speed. A physicist would use the concept of acceleration to explain both speed and direction changes simultaneously. Yet students often do not make both connections (Roschelle, 1991). In this section, Dana introduced the metaphor of addition to describe the speed increase. For the linear case, addition complements the pulling metaphor, as Carol ably argued.

One cannot know whether Carol already had change of speed integrated

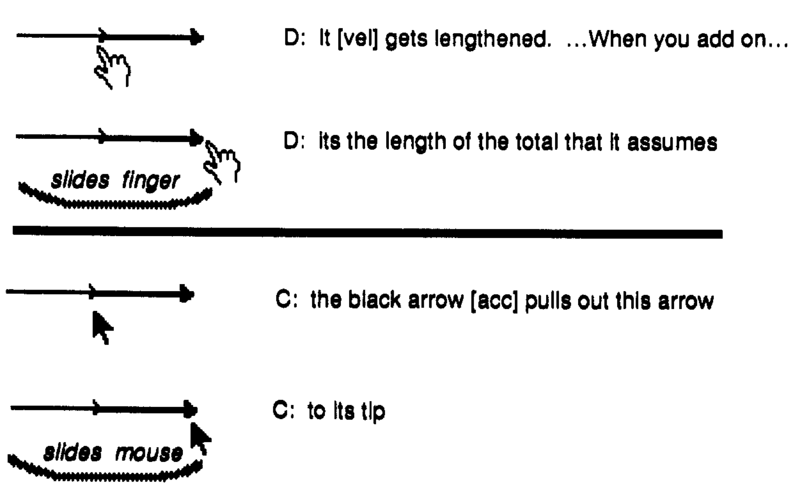

FIGURE 8 Translating between vocabularies using the situation.

into her explanation of the EM. Dana's case is more certain. While the simulation began to run, Dana focused attention specifically on the velocity space display, and on the fact that the length of the velocity increased (No. 25) in the circumstances of the new challenge. This was apparently a puzzle to her, indicating that she did not yet connect vector change to speed change. When she watched the simulation, her puzzlement turned to an outburst of excitement as she generated an insight about change of speed (No. 27). Thus, in Dana's case one can conclude that an additional conceptual change occurred in this episode, amounting to the integration of change of speed into her conceptual structure.

Shared knowledge. This episode should make it clear that the "sharing" of an explanation or an abstract situation only approximates complete overlap in meaning, and even then only converges toward more complete overlap through continued effort to display, monitor, and repair interpretations. Thus, although it looked like Carol and Dana shared the same interpretation of acceleration in Episodes 1 and 2, it turned out that Dana was not yet attending to change of speed. (Carol may or may not have been thinking about change of speed earlier; there is no evidence on this point.) Through the continuation of their collaboration in this episode, this difference became apparent and the students took action to integrate change of speed into their mutual understanding. The action once again took the form of relations of metaphors to the constructed, deep-featured situation. In particular, the students used a conjunction of metaphors (adding and pulling) and gestures to the deep features to translate between their personal vocabularies, and thereby make public their common commitment to the same underlying meaning regardless of the surface form of the explanation. Thus the "it" in Carol's statement, "But you were doing it, saying it in a different way," can only refer to Carol and Dana's shared understanding.

The next episode provides a closer look at the processes by which students display, monitor, and repair their knowledge, and thereby counteract the tendencies for their interpretations to diverge.

Episode 4: It's All So Much Clearer Now

This episode shows the repair of a divergence.

Data.

35. C: So if we wanted to pull this [vel] down to there [a vertical line]. We'd have to have this [acc] all the way around or something like that [begins to set acceleration, but doesn't release mouse button].

36. D: No, 'cause that wouldn't that make this [vel] tip swing around to that [acc] tip and make that angle? [ambiguous gesture]
37. C: What angle? [Aborts setting acceleration]
38. D: So I'm saying, OK=
39. C: =I bet if I leave it [acc] like that [releases acceleration as in Figure 10] it's going to make this [resultant] angle =
40. D: =right that's what I'm saying.
41. C: So we're going to have to swing all the way down here.
[
42. D: Oh my God! It's all so much clearer now.

Conversational action. In Episode 4, Carol started work on solving the new challenge (No. 35). She proposed a particular new setting of acceleration, and dragged the current acceleration into the proposed setting (Figure 9). However, Carol did not release the mouse button, which would complete the action. Instead, she paused with the acceleration hovering over the proposed setting. By postponing the release of the setting, Carol provided an opportunity for Dana to confirm or disconfirm her display of knowledge.

As it turned out, Dana rejected and then questioned Carol's setting of acceleration (No. 36), arguing that the chosen setting of acceleration would make a wrong angle. This rejection and questioning explicitly marked a possible divergence in interpretations, and led to repair cycle in successive turns (Nos. 37–42). Carol started the repair cycle by seeking clarification of the "angle" Dana was talking about (No. 37). But before Dana could give the clarification, Carol dragged the acceleration to a new setting (Figure 10), which she marked as a hypothetical (No. 39, "I bet"). In this hypothetical situation, Carol carefully traced the resultant velocity with the mouse, and explicitly marked this new velocity as the relevant "angle." Dana pronounced her agreement, thus concluding the repair in a mutually satisfactory resolution (Nos. 40 and 42).

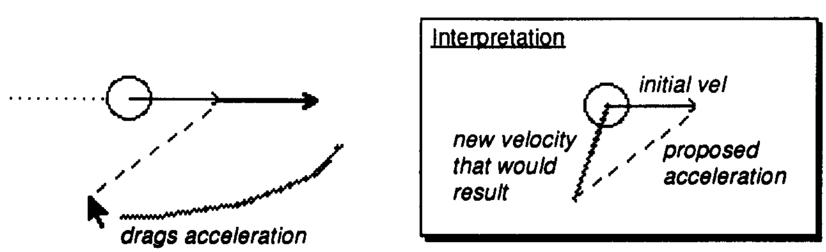

FIGURE 9 Carol's mistaken setting of acceleration.

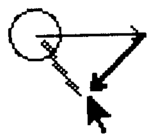

FIGURE 10 The situation constructed for repairing meaning.

Conceptual change. At the beginning of this episode, Carol proposed a new setting of acceleration. From a scientific point of view, the setting she proposed was obviously wrong: The desired resultant velocity should point straight down, whereas her proposed acceleration would indicate a resultant velocity that pointed down and to the left. This wrong proposal is an indication that Carol's conceptual structure was not yet complete. Indeed, it has been commonly observed across students (Roschelle, 1991) that students who give vector addition explanations do not immediately see how to use that knowledge to infer useful problem solving moves. Knowledge of the pulling, or vector addition explanation does not necessarily result in knowledge of vector subtraction as a problem solving inference rule.

Dana inferred that the proposed acceleration would not result in the desired resultant velocity, because the direction ("angle") of the resultant would be wrong. This is the reason for her objection.

As a result of Dana's objection, Carol backed off from the goal of problem solving and used the computer to construct another situation for the students to display, monitor, and repair their mutual state of understanding. Within this setting, Carol produced an inference about the exact direction and length of the resultant velocity. This inference agreed with the students' conception of acceleration articulated in Episodes 1-3, as Dana confirmed.

Shared knowledge. The students' collaborative production of the repair was critically dependent on the precise placement of actions in the situation and sequence of activity. Dana said, "So I'm saying, OK [long pause] right that's what I'm saying." Taken out of situation and sequence, this phrase is void of content. Yet when it was actually uttered, the phrase was pregnant with meaning precisely because at Dana's pause, Carol produced a hypothetical acceleration and traced the predicted resultant velocity, "I bet if I leave it [acc] like that [hypothetical situation] it's going to make this [resultant vel] angle." Moreover, once Carol started, Dana did not complete what she started to say. Instead, she produced an acknowledgment of Carol's utterance ("Right") that bound it to her own understanding and intentions ("that's what I'm saying"). The time placement of Carol's utterance and the spatial placement of her manipulations and gestures cannot be altered without stealing all meaning from Dana's phrase. Nor would the repair have been completed if Dana had not altered what she was about to say to adapt it to Carol's action. But given the precise spatial and temporal placement of both student's utterances in adaptation to each other's intentions and in relation to the constructed situation, we can recognize a successful repair of the apparent divergence in meaning.

It is also notable that the surface features of this new context were different than the surface features of previous contexts. In Episodes 1 and 2, the resultant velocity was literally present in the display, and the acceleration and initial velocity were only present by connecting the dots. In Episode 4, the circumstances were reversed: The resultant velocity was only made present by gestures, but the initial velocity and acceleration were literally visible. Furthermore, in previous episodes the students had produced these deep features with respect to the velocity space display. In this episode, the students produced the deep features with respect to the particle display. This difference was unremarkable to the students and posed no difficulty for their reasoning. This shows the students' ability to re-engage with the same abstract situation despite changes in underlying surface features. The commonality in the literal features was at the level of the affordances for seeing a triangle. This data warrants describing the constructed situation as having deep features.

This interaction is notable because Carol and Dana resolved the potential divergence by producing a sequence of actions in relation to a new situation that represented the same triangle. By making predictions in reference to same deep features in a new, hypothetical situation, the students determined that no breakdown in their mutual understanding had occurred. Notice that the language used was still ambiguous and error prone. Convergence was achieved only through the coordinated placement of actions in relation to the constructed situation to display, confirm, and repair relational meanings.

Episode 5: Oh That's Perfect

This episode demonstrates Carol and Dana's mutual contributions to their shared conceptual change.

Data.

[Some dialog between 42 and 43 was omitted. The topic was running the simulation.]

43. C: Yeah, see that's right.

[

44. D: Oh, that's perfect.

45. C: It does, it [vel] travels right along that edge [acc]. So we want it to travel that edge until there [sets acceleration]. 'Cause that

will make it [vel] come down straight. See it [vel] will travel along that edge =

46. D: = Yeah =
47. C: = Until it's straight down =
48. D: = So, but what we didn't realize before.
49. C: Might have to make it a little shorter though.

Conversational action. Following the previous episode, Carol went back to the goal of solving the challenge. When she did so, she set the acceleration back to the position she had proposed earlier (No. 41). While she did this, Carol commented on the likely incorrectness of this setting, saying, "I think it will probably go back too far, but let's just see." Thus Carol cast her apparent mistake as an intentional setting of acceleration that would test their conception. Thus, again the students produced a situation specifically to test their joint understanding.

When Carol and Dana said "that's right" (No. 43) and "that's perfect" (No. 44) they were not referring to the current setting of acceleration, but to their joint conception. There are two pieces of evidence to support this assertion. First, both students had predicted that acceleration would result in too much turning (i.e., a resultant velocity pointed down and to the left, rather than just down). Thus their statements confirm their prediction, and not that they had made a good choice of acceleration. Second, immediately after saying "that's right" Carol referred to the tip of velocity "traveling" along the edge formed by the acceleration vector, a new metaphoric expression of the same conceptual structure.

Carol changed the setting of acceleration next so that the travel of the velocity tip would result in the motion going straight down, which was their goal in this challenge (No. 45). Notice that in this case Carol used the display to make her reasoning publicly available and thus confirmable. She did this by demonstrating the process ("traveling") that would transpire and result in the desired new state. In contrast to previous occasions on which Carol proposed settings of acceleration, this time Dana agreed (No. 46).

Conceptual change. Recall that in the last episode, Carol apparently could not use her knowledge to infer a correct setting of acceleration. In contrast, in this episode, Carol used her model of velocity change to infer an acceleration that would lead directly to the problem solution. Moreover, as Carol stated (No. 49), this resultant velocity was too long (too fast), even though it was in the right direction. On their next move, the Carol reduced the length of the resultant while maintaining the correct direction. These moves demonstrate a further change in Carol's conception—she now could use the new conception to infer problem-solving moves, in addition to giving explanations.

Dana's conceptual change is similar. In the prior episode, Dana was able to recognize an incorrect problem-solving move. Moreover, by the end of Episode 5, both students could explain change of direction and change of speed, and use their knowledge to infer correct problem-solving moves. Before Episode 1, they did not have these capabilities.

It is also noteworthy that Carol now described their understanding in terms of an additional metaphor, "traveling." This metaphor captures the fact that the tip of velocity moves along the edge specified by the acceleration, until it reaches the tip of the acceleration, completing the one second burst of acceleration. Traveling adds a geometric constraint to the pulling metaphor, analogous to incremental vector addition.

Shared knowledge. This episode illustrates the mutuality of the students' construction of knowledge. In Episode 1, Carol had an insight about acceleration, which she shared with Carol. In Episode 3, Dana had an insight about change of speed, which Carol may not have had. The students collaborated to make change of speed a part of their shared knowledge. In Episodes 4 and 5, Dana exhibited an understanding of the problem-solving implications of their new conception that Carol clearly did not have. Through their collaboration, both students came to share the knowledge of problem-solving implications. Thus, the set of knowledge elements that comprised the students' new conception emerged out of collective effort of the students to build shared meanings incrementally and interactively.

Indeed, the agreement between the students in this episode suggests that Carol and Dana were beginning to feel confident about the convergence of their conceptual change. For example, Dana uttered the first joint attribution of ownership of the conceptual change (No. 48, "what we didn't realize before"). Moreover, while Carol finished the solution of the challenge, Dana reflected on their conceptual progress, not just their progress toward a solution. Between bits of conversation about problem solving, Carol and Dana interspersed reflections on their learning:

D: Can't believe we didn't like think of this at all, yesterday.
C: I know. Makes me feel quite stupid.
[Later]
D: Well, before we didn't have this little picture of what the arrow is doing.
C: Yeah.

The Interview: It Instantly Made Sense

This section presents the initial portion of Carol and Dana's interview with the experimenter. This interview occurred about 20 min after the episodes already presented. In the intervening time, Carol and Dana solved two more challenges, including one quite difficult problem that involved multiple bursts of acceleration. In the course of these solutions, the students continued to explain and solve problems by constructing the same deep features for each situation and using pulling (and related metaphors) to reason.

The following interview transcript makes three points. First, Carol and Dana's individual explanations during this interview expressed the same underlying conception of the simulation. Moreover, their confirmations were tightly interwoven, highly abstract, explicit, and specific. This demonstrates the degree to which Carol and Dana participated in a shared conception. Second, in this interview, Carol and Dana analyzed their shared conceptual change—they recalled their old conception, explained why it was wrong, and discussed their new conception. This shows that they shared an account of their mutual conceptual change. Third, the interview demonstrates the generality of Carol and Dana's deep-featured situation. They were able to construct the same abstraction in a visual field with quite different surface features (their bodies).

Carol and Dana opened the interview by talking about the conceptual breakthrough they had made. Notice the use of "we," one of many indicators of a shared state of knowledge.

Data.

50. X: What did you figure out?
51. C: We finally figured out what the black arrow [acc] was . . .
                    [[
52. D: Well . . .   yeah.
53. D: The black arrow [acc], like, instantly made sense. I don't know why we didn't get it yesterday. I guess it showed on here [velocity space], that helps you see, like, where your black arrow [acc] was. And it showed your other arrow moving to the tip of that. So it, like, showed you what it wasn't showing you yesterday.
54. C: Yeah.
55. X: So could you explain to me how it works?
56. C: Yeah, I think so. [Sets up index fingers to represent vectors. See Figure 11.] If you have the light arrow [vel] and the black arrow [acc]. The light arrow's [vel] tip moves along the line of the black arrow [acc] and stops at the end [tip] of the black arrow [Slides index finger representing vel to tip of acc].
57. D: And then . . .
58. C: Like it moves from the ball—if that was, like, an axis, if that was a hinge or something, it moves along the line of the black arrow and stops, at the tip.

59. D: And then continues . . .
[
60. C: Goes that way [gestures in the path of the resultant].
61. D: As its path.
[
62. C: The thin arrow [velocity].
63. D: It, like, changes the path [Sets up arms to represent vectors]. If this, like, the black arrow [right arm] and this is the light one [left arm] it like goes up and when you change it—when you put the [acc] arrow down—it, like, goes along that.
64. C: But it stays hinged to the ball, wherever the ball [touches at Dana's left elbow, the base of the vector].
65. D: Yeah, it stays hinged and then it starts going like that.
66. D: So, if you wanted to change it to a 90 degree angle, you'd have to put the black arrow [acc] so that it was, like, at the right angle.
67. C: So that when it moves along . . .
[
68. D: To get it to go down, like that. So even though you put the black arrow straight down, it's not really always a 90 degree angle.
69. C: 'Cause that's what we thought before, was that you put the black arrow at a 90 degree angle and it would make it go and take a 90 degree angle bend.
70. D: But that's wrong because you have to, like, overcompensate.
[
71. C: If it's like that, and that, you have to make it like [demonstrates vector addition that would result in a 90 direction change with hands] . . .

Conversational action. When the interviewer asked for an explanation, Carol volunteered the first account (No. 56). In giving her explanation, Carol used her index fingers to represent velocity and acceleration (Figure 11). During the explanation, Carol demonstrated the process by

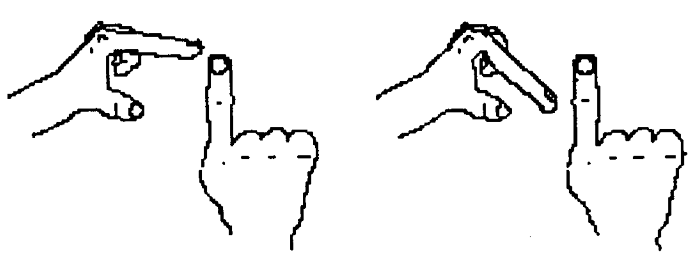

FIGURE 11 The vector addition triangle, constructed on Carol's hands.

which the velocity vector changed in the course of 1 sec. (The direction her finger points is actually opposite to the direction the acceleration vector points. This is probably a matter of convenience in carrying out the gesture; there is no evidence that the students misunderstood the directedness of acceleration.) This explanation and Dana's later explanation (No. 63) demonstrate the mobility of the students' representation to quite different sets of literal features.

Carol and Dana then collaboratively completed the explanation, discussing both the new path direction and the new velocity direction (Nos. 59–62). Notice that though the students gave different simultaneous completions, the completions were complementary and mutually confirmatory – both the new direction of velocity and direction of the path of motion point along the resultant, and necessarily so.

Dana then gave a similar explanation, but used her left and right arms to represent the vectors, instead of index fingers, another example of the generality of the representation (No. 63). Carol added that the base of the velocity vector stays fixed (No. 64, pivots as if it were a hinge).

Dana then (No. 66) introduced the topic of producing a 90° bend in the path, which was the context in which the convergence of their conceptual change had been achieved. Dana stated that putting the acceleration at 90° would not work. Carol explained that this is what they had thought before their conceptual change. Then Carol and Dana both expressed the correct acceleration for producing a 90° bend. Carol demonstrated the correct solution with her hands (No. 70). Dana used the idea of overcompensating, probably because the acceleration needs to be set at more than a 90° angle to produce a 90° bend (No. 71).

Conceptual change. Carol and Dana's own account of their learning is in terms of shared conceptual change. They discussed what "we thought," why it was wrong, and what their new conception was. Their own account agrees with this analysis. Before these episodes, the students thought that acceleration points in the final direction of motion, and that a longer acceleration would result in greater speed of turning. As the students admitted, this conception was wrong.

Their new conception was based on constructed deep features that the students could refer to by combinations of talk and gesture in front of the computer display and their own bodies. In either case, the key deep features were readily available, though not literally visible. To refer to these entities, the students constructed a shared convention of "reading between the lines," which enabled them to orient to the aspects of the display that were significant for their shared conceptual structure. Throughout the episodes, their knowledge was continually produced by placing actions in relation to this set of deep features.

Their new conception was not phrased in language that had the surface features of a scientific discussion of velocity and acceleration, yet it did express an analogous concept. They related three entities: initial velocity, final velocity, and acceleration. The initial velocity and final velocity were correctly related to the initial and final speed and direction of motion. The acceleration was correctly related to the difference between the initial and final velocity, and their various metaphors—pulling, hinging, traveling—expressed the fact that velocity change is a dynamic process, constrained by the vector addition triangle. Their conceptual change was a significant one.

It is worth stating that their conceptual change did not amount to a complete convergence on everything that scientists know about velocity and acceleration. This became apparent in a later interview, when the students were asked to describe the velocity and acceleration of a ball tossed vertically in the air. As it turned out, the students described the ascent of the ball as occurring at a constant speed, whereas a physicist would describe a constantly decreasing speed. As a consequence of this wrong description, the students could not satisfactorily apply their conception of acceleration to a discussion of tossing a ball into the air. They were aware of this problem, but were not sure whether (a) their description of the ball toss was wrong or (b) their conception of velocity and acceleration did not apply to ball tosses.

In the debriefing session, the experimenter discussed this dilemma with the students. That discussion is too long to present here, but its basic character was analogous to the preceding episodes; the students and experimenter engaged in a negotiation using the processes of situated action as a means to converge on an understanding of the ball toss. This understanding integrally involved and extended the conceptual structure the students had built during these episodes.

Shared knowledge. This interview presents considerable evidence that the students' new conception was shared. This is not to say that the two students' knowledge was completely isomorphic. But based on the evidence in the interview, we can conclude that a considerably large extent of the important aspects of velocity and acceleration were shared: change of speed, change of direction, and problem-solving implications. The students demonstrated independent ability to construct the necessary deep features on top of varied surface features (like fingers, or arms). Moreover, they demonstrated the ability to collaboratively complete, elaborate and paraphrase the same basic explanation. Furthermore, they themselves described the ownership of the conceptual change in the plural.

EVALUATION OF THE CLAIMS

The preceding sections summarized the evidence for the two outcome claims. The comparison of the students' problem-solving inferences and explanations before, during, and after these episodes shows that a conceptual change occurred. Indeed, the students' conception changed in ways that made it more compatible with a scientific interpretation of velocity and acceleration. Moreover, the interview provides sound evidence that the students arrived at a common, shared new conceptualization of the acceleration arrow. The analysis of the sequence of episodes shows that this conceptual change occurred through a gradual convergence toward a shared understanding. Thus, the data support the outcome claims that (a) conceptual change occurred and (b) individual interpretations converged toward shared knowledge.

The remaining claim addresses the nature of the process through which convergent conceptual change occurred. After reviewing the reasons for employing a relational epistemology, the four features of the proposed process are considered.

The necessity of seeing Carol and Dana's actions as being placed in relation to specific spatial and temporal characteristics of the constructed situation suggests the need for a relational epistemology. For example, Carol's first explanation "it pulls it" is barely interpretable without its synchronous links to gestures produced in the space occupied by the newly constructed situation. Likewise, the repair in Episode 4 was produced by precise temporal and spatial placement of situated actions, not merely by the ambiguous phrase "So I'm saying, OK [long pause] right, that's what I'm saying." Indeed, throughout the episodes, removing the sequence and situation of students' actions from consideration would lead to serious deterioration of an observer's ability to produce an explicit analysis of meaning. Taking account of the relations between actions and situations in order to determine their meaning is therefore warranted.

Substantial evidence also supports taking a collaborative view of Carol and Dana's learning. Throughout the episodes, one finds constant evidence of the design of utterances as social acts. The students responded to utterances with mutual concern for shared knowledge, exerting deliberate effort to create convergence and avoid divergence. For example, consider the initial explanation in Episode 1. This explanation was constructed as a collaborative act by both partners: Dana requested the explanation, Carol presented a metaphor, Carol and Dana together clarified the relations between the metaphor and the simulation, and Dana connected the metaphoric description to the simulation behavior. After this explanation, in Episode 2, Carol and Dana collaborated in creating a new abstract situation that would enable them to test the degree to which their interpretations were shared. In Episode 3, when Dana had an individual insight, Carol produced conversational actions clearly designed to bring Dana's individual interpretation into the students' shared knowledge as a display of the same underlying idea in different words. In Episode 4, Dana detected an apparent divergence in the students' knowledge, and produced an utterance that explicitly marked this divergence. Carol responded by initiating a conversational repair cycle in which the students could align their interpretation. In Episode 5 and in the interview, Carol and Dana began to treat the new conception as shared knowledge, as marked by both the use of "we" and the smooth production of collaborative completions of explanations.

Evidence for the Proposed Process

The utility of an integrated account of Carol and Dana's collaboration and conceptual change is now considered. Recall that the four elements of the proposed process are:

1. The construction of a "deep-featured" situation at an intermediate level of abstraction from the literal features of the world.
2. The interplay of metaphors in relation to each other and in reference to the constructed situation.
3. An iterative cycle of displaying, confirming, and repairing situated actions.
4. The application of progressively higher standards of evidence for convergence.

Each of the four proposed features will be discussed in turn.

Throughout the episodes, Carol and Dana demonstrated considerable ability to engage with the same deep-featured situation despite significant changes in the literal features on the computer screen. To a casual observer, the features of the successive circumstances have little in common. For example, Carol and Dana re-engaged with deep features on the basis of surface features present in the velocity space display (Episode 1), surface features gesturally traced on the screen over blank space (Episode 2), surface features in the particle display (Episode 4), features of their fingers (interview), and surface features of their arms (interview). It is unlikely that anyone would include "representations of velocity and acceleration vectors" in an a priori description of students arms when the two students sat down for their interview. Yet, despite the wide variation in surface features in each of these contexts, Carol and Dana repeatedly engaged with those features that could articulate the vector addition triangle.

The consistency of their pattern of reference to the same set of deep features despite the variation in literal features supports the contention that the students constructed and utilized a shared deep-featured situation. This constructed situation, however, was not literally "given" to the students or easily recognizable by them. Indeed, Carol and Dana's first reading of the computer simulation was not compatible with the deep features they later constructed. Moreover, although every pair of students had the same literal features of the EM available, only a few constructed a situation similar to Carol and Dana's (Roschelle, 1991).

Moreover, Carol and Dana used physical metaphors (p-prims) to constitute their new conception of acceleration. The pulling metaphor was used throughout to describe the relationship between acceleration and velocity change. However, pulling does not unambiguously describe a single possible process. Indeed, students who use the EM generate many uses of pulling that are not compatible with scientific understandings of velocity and acceleration (Roschelle, 1991). A particular version of pulling was selected partially by the gestures that accompanied its application (Episodes 1 and 2). But, in addition, students used the interaction of supplementary metaphors to suggest and constrain their emerging concept. For example, the idea of the hinge adds the constraint that in this version of pulling, the base of velocity stays fixed. The introduction of addition (Episode 3) suggests that change of length, and thus speed, is implied in this version of pulling (whereas objects generally do not change length when pulled). The introduction of traveling further constrained the type of pull to be a pull along a line, rather than a pull along an arc (Episode 5). Though none of these metaphors alone constitutes a valid explanation of the relation of acceleration to velocity change, the interaction of the metaphors in concert does suggest an analogous concept. This concept captures many of the essential properties of acceleration at the level of qualitative reasoning.

Carol and Dana's collaborative effort to coordinate acts that displayed, monitored, and repaired shared knowledge also provides strong evidence for the proposed process. In Episode 1, their coordination took the form of a collaboratively completed explanation, as discussed earlier. In Episode 2, coordination was evident in the students' similar efforts to construct a new hypothetical situation in which to test the degree to which their knowledge was shared. When Dana's first attempt to construct a hypothetical situation was obstructed by the behavior of the EM, Carol provided a suitable hypothetical situation through gestures. In Episode 4, coordination was invited by Carol's delayed mouse click in specifying a setting of acceleration. Moreover, when Dana objected, both students responded to the implied divergence by engaging in a cycle of repair. Similar coordination was evident in the interview, in the smooth display of a shared explanation. Throughout the episodes, Carol and Dana intentionally employed their ability to coordinate conversational acts that display, monitor, and repair knowledge so as to bring their understanding into convergence.

The progression to higher standards of evidence throughout the episodes also supports the contention that the students deliberately acted to construct shared knowledge. For example, although the students collaboratively completed a mutually satisfactory explanation in Episode 1, this was not sufficient evidence (neither for us or them) that they shared an understanding. Thus, it was entirely appropriate that in Episode 2, the students collaboratively produced a new test case in which they could compare their predictions. Similarly, one can see recourse to more explicit standards of evidence in Episode 4, when Dana detected an apparent divergence in the students' understandings. The highest standards of evidence occur in the interview, when the students continually complete each other's partial utterances, provide appropriate paraphrases, and elaborate each other's emerging thoughts. Moreover, they do so in reference to highly abstract situations, yet with very specific actions.

In conclusion, the data presented in these episodes provides powerful evidence for the outcome claim that conceptual change occurred, and for the outcome claim that a convergence in the conceptual change was achieved by the students. Furthermore, considerable evidence supports the process claim that these outcomes occurred through a process integrating conversational convergence and conceptual change.

DISCUSSION

This article has focused on the problem of convergent conceptual change: How can two (or more) people coordinate their construction of concepts so that they can be increasingly certain that they share a common understanding of a particular subject matter?

The problem is important and difficult, both theoretically and practically. It is difficult theoretically because it raises a form of the learning paradox (Bereiter, 1985): If new learning is constructed from transformations of existing knowledge, and individuals start with idiosyncratic bases of existing knowledge, how can they ever achieve the same meaning for a particular conversation, symbol, or experience? This question takes on great practical importance in science education, because students enter science classes with a commonsense understanding of the physical world that is not directly compatible with scientific theory (Halhoun & Hestenes, 1985a, 1985b; McDermott, 1984; Resnick, 1983). Moreover, science educators and researchers widely hold the view that students must construct their own understandings of scientific concepts (Confrey, 1990; Resnick, 1983). Thus, students of science face the task of reconstructing their idiosyncratic common-sense notions of the physical world to converge on the meanings shared by the scientific community. A large research literature documents the failure of students to adopt scientific meanings (e.g., Carramazza, McCloskey, & Green, 1981; Clement, 1983; Viennot, 1979).

To seek progress, researchers have turned to cognitive science for theories of conceptual change. Almost all cognitive science theories entail some form of constructivism; learning is explained as the construction of representations. Few theories, however, account for the achievement of convergent constructions in the face of tendencies to diverge. Moreover, students' tendencies to diverge from desired meanings are exceptionally strong in science education.

The problem of convergent conceptual change is made especially difficult by the recognition that the literal features both of the world and of spoken language dramatically underdetermine their meaning. In Norman's (1988) lucid phrases, there is a "gulf of interpretation" between the literal features of the world and the meaningful situations we experience, and, likewise, a "gulf of evaluation" between human intention and actions in the world. How can students who are building new concepts overcome the gulfs of interpretation and evaluation?

This article has demonstrated one process that can accomplish convergent conceptual change, involving:

1. The construction of situations at an intermediate level of abstraction from the literal features of the physical world.
2. The interplay of metaphors in relation to each other and in reference to the constructed situation.
3. The iterative cycle of displaying, confirming, and repairing meanings.
4. The application of progressively stringent standards of evidence.

The first two features capture the main thrust of conceptual change as involving the construction of metaphoric explanations in relation to appropriate deep-featured situations. The second two features draw in the analysis of conversational interaction emerging from ethnomethodology. Linking conceptual change with the more recent research on convergence in conversation analysis suggests a pragmatic process by which convergent conceptual change can occur incrementally, interactively, and socially.

A case study cannot prove or disprove a theory, but it can clarify the meaning and import of a set of ideas. Moreover, it can attract attention to problems that have been overlooked, and create awareness of powerful theories that have not been fully tapped. The remainder of this discussion argues that mainstream conceptual change research on science learning should focus attention on convergence. To do so, cognitive science should incorporate additional methodological and theoretical approaches emerging from the situated learning perspective.

Learning as Situated Action

As it has been used herein, situated action is a further specification of the theoretical position usually called social constructivism (e.g., Vygotsky, 1978), and the general approach to social constructivism described as situated learning (e.g., Brown, Collins, & Duguid, 1989; Greeno, 1989; Lave & Wenger, 1989). A situated action perspective provides a plausible solution to a fundamental theoretical problem within social constructivism, the problem of convergence.

A social constructivist theory must provide for convergence without assigning a literal reading to the world. If one assumes that social constructivism works by presenting an ideal experience for the mind to read, the underlying theory reduces to naive empiricism. For example, a computer simulation might be viewed as presenting an unambiguous mental model; in this case the underlying theory reduces to an internalization of appearances in the world, essentially a naive empiricist account. Alternatively, if one assumes that social constructivism works by the teacher telling constraints to the student, the underlying theory reduces to a disguised transmission model. In a true social constructivist account, convergence must work without assuming literal readings of either individual speech acts or of the world.

By emphasizing relational meanings, a situated perspective can avoid the pitfalls of both naive empiricism and idealized linguistic models of learning and knowing. A situated approach accepts the ambiguity of language and the underdetermination of meaning in situations as fundamental premises (Barwise & Perry, 1983). Research in CA shows how people can achieve convergence of relational meanings despite the inevitable ambiguity of individual utterances and multiplicity of possible interpretations of the world. The CA account is fundamentally situated: Utterances are recognized as displays, confirmations, and repairs of knowledge because of their exacting placement in the sequence and situation of activity. Moreover, the CA account is social and incremental: Common meaning accumulates (Clark & Schaefer, 1989) and is retroactively repaired (Fox, 1987) as the activity progresses. Meaningful concepts are seen as collective accomplishments, achieved through participation in collaborative social activity (Schegloff, 1991).

The roots of convergence accounts can be traced to pioneering theoretical work by John Dewey (1938) and G. H. Mead (1934). Dewey and Mead were among the first to develop a relational theory of meaning, while simultaneously developing a pragmatic view of social interaction. Dewey's view of shared knowledge is congruent with the more detailed account of convergence later developed in CA. Moreover, the view of conceptual change used herein substantially agrees with Dewey's view of inquiry. Dewey (1938) argued that inquiry was a cultural and biological process in which people collaboratively construct new meanings through participation in transforming problematic situations.

In addition to resolving a theoretical dilemma within social constructivism, a convergence-oriented situated action perspective can contribute to methodology for analyzing learning events. Traditional protocol analysis is concerned with utterances that "read out" the mental state of the speaker (Ericsson & Simon, 1984). In contrast, this study focused on conversational actions produced deliberately to change the relationship of the speaker and hearer, utterances designed to enable speaker and hearer to become partners in the construction of shared knowledge. Because such acts are designed specifically to create an effect between speaker and listener, rather than being passive self-reports, the social intent of such acts is not captured by protocol analysis.

CA and related fields are developing rigorous methods for analyzing the kinds of social interaction displayed in this case study, supplementing the methods of protocol analysis. Moreover, CA is building systematic methods for determining the referents of ambiguous utterances and the meaning of gestures, areas in which ad hoc assumptions prevail in protocol analysis. However, CA research has tended to focus on rather shallow domains of knowledge and mundane activities, rather than such areas as scientific reasoning and collaborative problem solving. A key implication arising from this case is that continued effort is needed to develop rigorous methods for data analysis that extend those of protocol analysis to deal with social and relational data, and that provide tools to analyze convergence.

Conceptual Change as Social and Cognitive

Within research on science learning, there is a growing interest in collaboration in general and social constructivism in particular. This article has sought to construct a theory that integrates collaboration and conceptual change. To do so, traditional aspects of the analysis of individual conceptual change have been reinterpreted as simultaneously cognitive and social. In particular, the analysis of the construction of deep features and metaphoric explanations both connects to prior analyses of conceptual change, and expands them into the social and relational realm.

For example, Larkin and Simon (1987) analyzed the efficacy of diagrams as supports for individual cognitive functioning. Others (e.g., Anzai & Yokohama, 1984; Chi et al., 1980) have demonstrated the importance of deep features in individual experts' use of diagrams empirically. Along with Pea, Sipusic, & Allen (in press), this article added an emphasis on the role of diagrams and computer displays as social tools for achieving common meaning in discourse (see also Pea, in press; Teasley & Roschelle, in press). Diagrams, such as provided by the EM, simultaneously support individual reasoning and facilitate negotiation of meaning.

Likewise, diSessa (1983, 1987) developed an analysis of conceptual change as a process of restructuring prior pieces of knowledge. DiSessa postulated that abstractions of everyday phenomenological experience provide the conceptual primitives for the construction of scientific knowledge. These building block abstractions are called *p-prims*. Although this case study has used the more general term "metaphors" in place of p-prims, this case study has built on diSessa's view, analyzing students' learning as a restructuring of p-prims such as pulling, adding, and hinging.

The case study also expanded on diSessa (1987) by adding a social, communicative role for such metaphors. In particular, it has taken a socially interactive view of p-prims as metaphors (Black, 1979; Boyd, 1979). Boyd (1979, p. 381) similarly described a class of "theory constitutive metaphors" that "play a vital role in the socially coordinated discovery and communication of knowledge; indeed, the employment of terms of this sort appears to be essential to scientific inquiry (and rational inquiry generally)." In Boyd's view, metaphors play a social role by generating an orientation to the world that allows for coordinated, socially distributed inquiry to progress, despite the fact that the theories to be discovered cannot yet be known or defined. This view was essential to the case study, in which it was argued that the interplay of metaphors enabled students to construct a new concept socially and incrementally, through the interaction of ambiguous, fuzzy constituent meanings.

A focus on these two aspects of conceptual change is supported by research on scientists' conceptual change and theory construction. For example, Einstein (1950) described his own theory construction process as arising from playful interaction between simple situations (i.e., thought experiments) and everyday physical abstractions (i.e., rigidity and simultaneity). Historians, philosophers, and sociologists of science (Kuhn, 1970; Mulkay et al., 1983; Nercessian, 1988) attribute equally strong roles to a figurative use of commonsense abstractions to constitute new theories. Furthermore, sociologists and anthropologists (e.g., Knorr-Cetina, 1981; Latour, 1986; Lynch, 1985) have drawn attention to the critical role of figurative discourse about deep-featured situations in the practice of working scientists.

In particular, Latour (1986) argued that the scientific practice can be characterized as a discourse over written inscriptions that provide a means of mutual orientation to intermediate abstractions from actual experience. Latour's analysis of "immutable mobiles" couples nicely with the analysis of students' learning here. Carol and Dana, like collaborating scientists, coconstruct an invariant spatial display, the vector addition triangle, which they transport to each new discourse situation in order to reproduce shared meaning.

COLLABORATION AS CONVERGENCE

This article has argued that the crux of learning by collaborating is convergence. This view is just one of several available accounts. Followers of Vygotsky who investigate collaboration have tended to see collaboration as scaffolding and appropriation—scaffolding by a more expert peer, and appropriation by a less expert peer (Forman & Cazden, 1985; Newman et al., 1989). Piaget and his followers tended to see collaboration as producing productive individual cognitive conflict—disequilibrium drives conceptual change (Doise & Mugny, 1978; Perret-Clermont, 1980; Piaget, 1932). The Vygotskian account tends to portray asymmetric roles, whereas the Piagetian account emphasizes the benefits of conflict. Each focuses attention away from the process of mutually contributing to shared knowledge. In contrast, the convergence point of view emphasizes mutual construction of understanding.

In this case study, mutual construction of knowledge was a more apparent feature of students' interaction than was cognitive conflict or scaffolding. Other researchers investigating collaboration and conceptual change have argued likewise (Lemke, 1990; Light, 1991; Pea, in press). Moreover, complementary frameworks for the careful analyses of convergence of relational meanings in specific subject areas are starting to appear (see Greeno, 1989; Hall, 1990; Meira, 1991; Schoenfeld, Smith, & Arcavi, in press).

One compelling reason for exploring a convergence account as a complement to Piagetian and Vygotskian accounts follows from a fundamental commitment to collaborative inquiry, and the relation of collaborative inquiry to scientific conceptual change. Democratic participation, intellectual progress, and gradual convergence are base attributes of social inquiry practices that enable scientists to undergo conceptual change. In contrast, Vygotskian theory lends itself to accounts of the reproduction of existing scientific knowledge, whereas Piaget suggests development through static, maturational levels. A convergence account alone suggests the attractive possibility that students develop their concepts in the course of learning to participate in the practices of inquiry that scientists themselves use to develop scientific concepts.

The domain of collaboration is diverse, and each perspective can offer valuable insights and tools for analysis. As research about learning as cognitive and social progresses, it is imperative that differing accounts of relationships among conceptual change and collaboration are actively questioned, elaborated, and investigated. The quest for convergence in what we mean by "learning by collaborating" is an essential goal for the learning sciences.

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APPENDIX

Notation

[Bracket indicates a point at which a current speaker's talk is overlapped by the talk of another, with overlapping talk directly beneath.

?	Question intonation.
.	Full stop with falling intonation.
=	Equals sign indicates no interval between the end of a prior and the start of a next piece of talk.
: : :	Preceding sound elongated.
.hh	Audible breath. Dot before indicates in breath. No dot indicates outbreath.
( )	Words enclosed in parentheses indicate either nonlinguistic action, or transcriber's uncertain over verbatim.
[vel]	The Envisioning Machine velocity arrow.
[acc]	The Envisioning Machine acceleration arrow.

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