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Learning as Social and Neural

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Abstract.

Representations are created and given meaning in a shared perceptual space, where they are spoken, written, and drawn in the context of social activity. Consequently, problems in science education cross the boundaries of traditional modularization of the mind into separate perceptual, representation, and communication components that act at distinct times, in distinct domains. We illustrate these issues with a case study of physics learning using a simulation program. The learners are initially uncertain about what aspects of motion to see, where the representations are on the screen, and how to express the relationship between vector notation and motion. At a local level, the students jointly coordinate conversational and perception-action processes to maintain a *mutually intelligible stream of activity*. At a slightly broader level, they use perception, language, and gesture to construct *a shared understanding of what the notation on the computer screen means*. Even more broadly, the students use their understanding of the notation to relate their activity to *ways in which scientists address similar situations*. We conclude that learning to make sharp distinctions from a repertoire of fuzzy, everyday descriptions requires *simultaneous, coordination* of perception, gesture, and language; one cannot assume competence in two areas and analyze only the third.

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Research in fields surrounding cognitive science is providing increasing evidence that *understanding of representations is formed in a dialectic between the social and the neural*. Such research opposes the stratification of neural, cognitive, and social layers in the manner of the stratification of transistors, machine languages, and software applications in computer engineering. For example, researchers in conversation analysis (Garfinkel & Sacks, 1970; Goodwin & Heritage, 1990) have shown that the creation of meaning is changed in social interaction by split-second variations in conversational turn-taking. This argues for a rather direct relation between social interaction and neural organizations. Similarly, neurobiologists have recently undermined the plausibility of explaining perception by storage and retrieval of sense impressions; rather "memory" is a production of perceptual activity and motor activity that coordinates the present interaction by recomposing previously activated neural processes (Edelman, 1987; Freeman, 1991; Maturana, 1983). Crucially, the internal, neural processes that control perception are themselves organized by the ongoing social and physical activity (Bartlett, 1932; Dewey, 1896; Rosenfeld, 1988).

This research raises theoretical, methodological and practical issues for educators and psychologists who are concerned with how students learn scientific concepts. We illustrate these issues with a case study of science learning. The learners begin with a doubly uncertain experience: They are uncertain about what aspects of motion to see and about how to express the relationship that links vector notation to motion. Through shared activity, students are able to construct a way of meaningfully seeing, notating, and communicating about motion. We show that social and neural processes mutually constrain student's learning.

Science Learning as Shared Activity

Educators and psychologists need a rapprochement of social and neural perspectives to account for how explanations and representations are created in shared activity. Scientific explanation is always a social activity; it requires a community that shares practices of seeing, representing, and communicating. "Scientific explanation is a particular kind of coordination of actions in a community of observers" (Maturana, 1983, p. 255). Scientific ways of seeing, doing, and talking are often tacit within the scientific community; they cannot be defined in precise terms for the layperson. From the coordination of interactions among the community in the context of shared observation and action, meaning emerges.

For example, consider this statement, which was seen on a postcard : "Gravity: It's not just a good idea, it's the law." This humorous slogan overlays two meanings of "law," legislative and scientific. These two different meanings are ordinarily not in contradiction because these meanings are localized in different communities of practice. However, when both practices are simultaneously invoked, interpretation is uncertain (and perhaps funny).

As in the case with the lawyer and the scientist, a deep contradiction of perspectives occurs when students learn physics: Everyday understanding of motion often contradicts scientific understanding. Research on student's understanding of scientific concepts finds significant differences between students' and scientists' interpretations of concepts like "acceleration," "energy," and "force" (Confrey, 1990; Halhoun & Hestenes, 1985; McDermott, 1984). But the differences between students and scientists are not necessarily localized at the level of concepts. To continue the analogy, an attorney cannot become a scientist simply by changing her definition of law; neither should we expect a student to become a scientist simply by changing her definition of "acceleration." Differences in perspectives extend throughout the fabric of thinking, including perception, focus of attention, descriptions of the world, and practices of interaction with the world. Thus, learning science (or any other discipline) requires crossing a large gap in perspective and practice; it requires becoming a member of a community of observers that sees and acts in ways that are at first incomprehensible or imperceptible to a newcomer. Put succinctly, learning science is a process of *enculturation*.

Investigating Learning as Shared Activity: A Three-Level Framework

We focus on the consequences this view of scientific explanation has for what it means to learn scientific concepts. In particular, analyses of learning cannot assume that perception, representation, and social interaction are three separate modules operating at different times. Instead, we argue that appropriate units for analyzing the learning of scientific concepts cross these functions, and occur at three levels: *mutual intelligibility*, *shared activity structures*, and *communities of practice*. At each of these, basic research on representation will need to build an account of social and neural organizations of function.

The case study that follows exemplifies each level within our framework. We provide excerpts from two students' behavior over the course of one hour. We do so to make two points. First, we call attention to the fact that basic impasses and learning events which occur in science education, even those occurring within a single hour of instruction, require analyses at each of these levels. Second, we argue that basic research on learning at these levels must examine social and neural organizations in an integrated fashion.

Our case study illustrates these levels as follows: We start with the issue of constructing mutual intelligibility of social action in a very local context. This involves acting on and re-perceiving materials (Bamberger & Schön, 1983) as well as displaying, confirming and repairing social meanings of these actions (Clark & Schaefer, 1989). We next move to the issue of building shared ways of interpreting a notation. The issue is generating a shared understanding of the relationship between the configuration (form) of the notation and consequent activity. Students acheive this understanding by negotiating a relationship of communicative metaphors to experience (Roschelle, in press; Schön, 1987). Finally, we suggest that the goal of learning is not just to make experience meaningful in a personal way. People learn to become a member of a community (Lave & Wenger, 1989). This requires simultaneous, coordinated changes to one's ways of seeing, talking, and acting.

Case Study: The Envisioning Machine

We consider two students using Roschelle's Envisioning Machine (Roschelle, 1991) to learn about velocity and acceleration. Figure 1 illustrates the screen of the Envisioning Machine (EM). There are two windows, the "Observable World" and the "Newtonian World." The Observable World displays a simulation of a ball moving across the screen. This presents the goal motion. The Newtonian World displays a particle with velocity and acceleration arrows (the thin and thick arrows, respectively). Using the mouse, the user can manipulate the settings of these . When the simulation is run, the particle in Newtonian World moves with the initial velocity indicated by the velocity arrow and the acceleration indicated by the acceleration arrow. In both worlds, the moving objects leave a trace of dots behind as they move. Because the dots are dropped at a uniform time interval, the dot spacing represents speed. All the EM motions are constant velocity or constant acceleration motions.

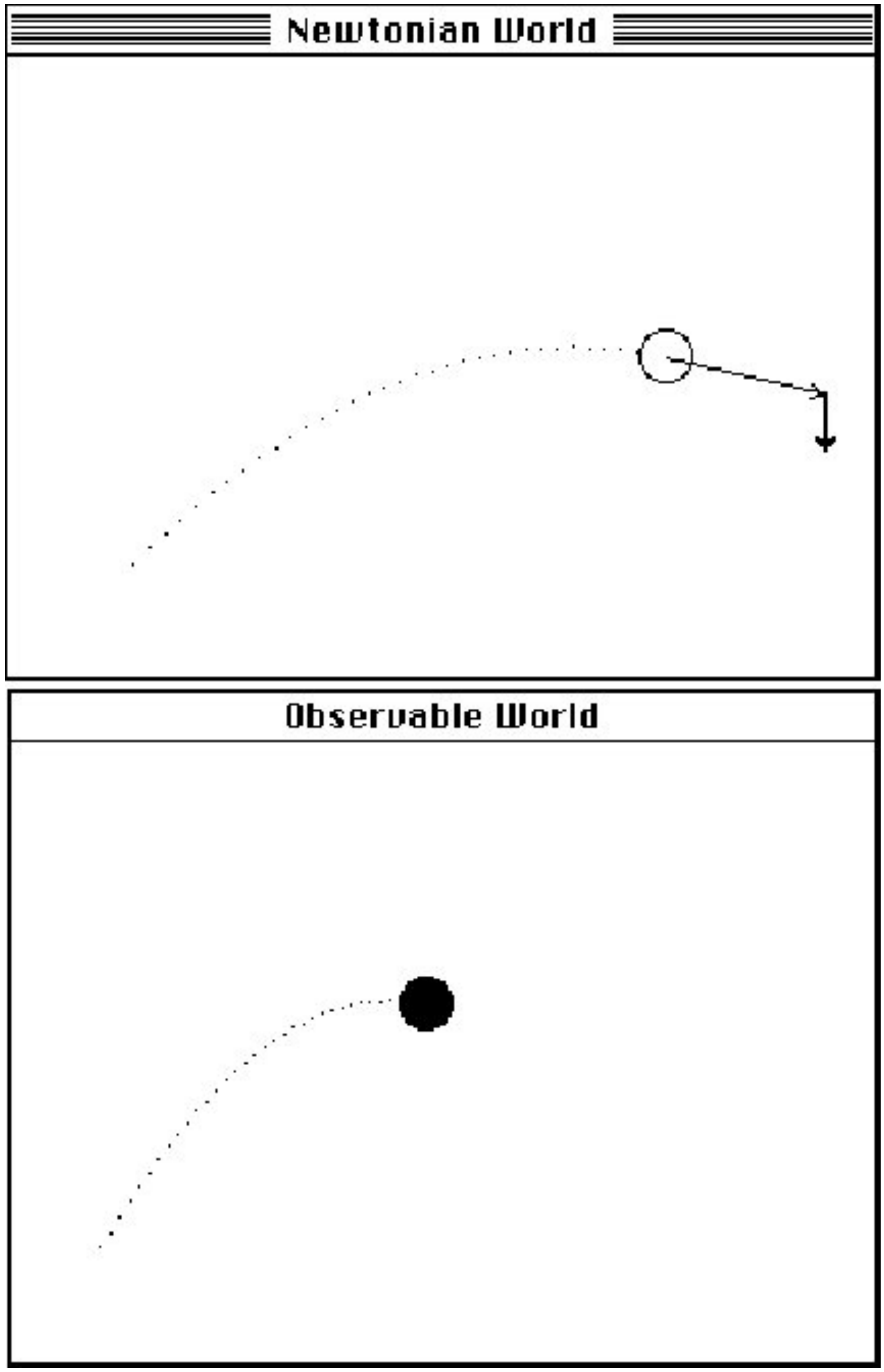
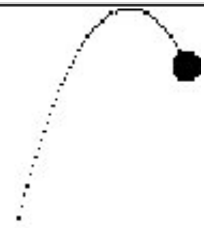
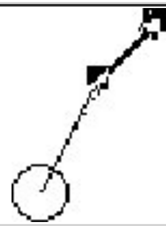
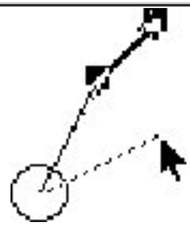


Figure 1: The Envisioning Machine

The specific EM activity used in this study involved matching the goal motion displayed by the ball in the Observable World by adjusting velocity and acceleration arrows on the particle displayed in the Newtonian World. This activity is called a "challenge." Typically, solving a challenge requires a series of trials in which the students watch the motions in the Observable and Newtonian Worlds, adjust the arrow of a particle in the Newtonian World, run the simulation, and evaluate whether the two motions are the same. Since the students had not previously studied velocity and acceleration, they needed to experiment with the simulation to learn how to adjust the arrow to produce motions that matched motions in the Observable World. Moreover, since the computer did not give explicit feedback on the correctness of a solution, students develop their own criteria for determining whether two motions are "the same."

Mutual Intelligibility: What should we do now?

The transcription provide in Figure 2 illustrates a situation in which interpretation of language and action by co-participants has become problematic. Such situations can lead to a breakdown in meaning. We note that the resources deployed to repair mutual intelligibility depend on the simultaneous activation of neural processes and socially-structured conversation.

Talk	Gestures and Screen	Interpretation
		Gerry and Hal are trying to replicate this motion, which appears in the Observable World window.
G: And I think the angle should be pointing downwards, or else		To produce the motion, Gerry suggests changing the direction of one of the arrows. The thin arrow is velocity. The thick arrow is acceleration.
H: Down? G: Yeah, or else **H: Like this?**	 **H drags velocity down.**	**Hal indicates uncertainty, and asks for confirmation. Then apparently unsatisfied with the confirmation, Hal initiates a clarification, using the mouse to demonstrate his current interpretation.**
G: No. Um, that angle I think is OK,	 G touches velocity.	Gerry initiates a repair, first by indicating that he was not talking about velocity. He touches the velocity to make this clear.
G: But the fat an-, the fat arrow should be pointing downwards	 G touches acceleration.	Gerry continues the repair by presenting the correct interpretation, he wanted the acceleration arrow pointed downwards. Again he touches the arrow.
H: Like this? G: Yeah.	 **H returns velocity to its original position and then drags acceleration down.**	**Hal uses the mouse to ask for clarification, this time dragging the acceleration vector down.** Gerry confirms.

	 **H releases acceleration in the new position**	**Hal completes the transaction by releasing the acceleration.**

Figure 2: Negotiating the Meaning of Terms

What is going on in the behavior recorded in Figure 2? It is important to note that the problem is not literally a mishearing of Gerry's words, but rather Hal's inability to coordinate the intention of Gerry's phrase with his own active processes of speaking, hearing, and moving. The students start a hand-eye coordination *process* of moving the velocity arrow until the directions of velocity and the start of the trajectory *are perceived to match*. This is not a representational process internally, but rather a neural coordination of action and perception, much like a frog capturing a fly. The representation occurs on the screen and in their talk.

Hal's actions with the mouse show that he intends to move the velocity in the upwards direction, while Gerry is talking about the acceleration. Therefore, Hal cannot coordinate the meaning of Gerry's utterance with the meaning of the action he is in the process of undertaking. As a consequence, a breakdown occurs, signalled by Hal's identification of one of the incoherent elements in the on-going activity ("down?"). Importantly, the form this breakdown takes is an invitation for Gerry to enter into the eye-hand coordination loop. That is, Hal adjusts his active motion with the mouse to coordinate with Gerry's verbal description of down, and asks Gerry, "Like this?"

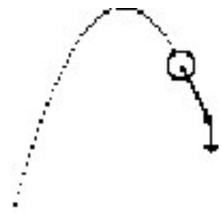
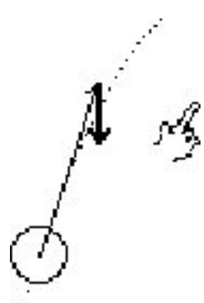
Gerry accepts the invitation by simultaneously producing a verbal repair ("No, not this, but that") and an example of the movements he wishes Hal to undertake. Gerry's gestures, even without the talk, project a suggestion to "Put that back. Pick up this and make it point downward." This combination of verbal repair and gestural suggestion is apparently effective, for Hal returns the velocity arrow to its original location, and begins a new hand-eye coordination that pulls the acceleration arrow into perceptual conformity with the students' sense of "down." Again, this coordination is opened up for social negotiation between Gerry and Hal ("Like this?" "Yeah.") This time Gerry and Hal agree.

This example suggests that mutual intelligibility succeeds in the EM situation because the tool offers opportunities for social negotiation to become a part of perception-action feedback loops. Mutual intelligibility is a consequence of the tight coupling of social and neural processes, such that the action-reaction loop between the people and the physical materials is coherent and unified.

Notational Significance: What does this mean?

The previous example showed how the local coherence of an activity is maintained by interwoven social and neural coordinations. The next section of transcript, taken from slightly later in Gerry and Hal's activity, shows them striving to achieve a broader level of coherence; they seek a sensible relationship between the means for problem solving (controlling the arrows) and the goals (shapes of trajectories). In Figure 3, social and neural coordination enables Gerry and Hal to achieve a shared understanding of the relations of means (arrows) and ends (trajectories).

In the episode reproduced in Figure 3, the students have succeeded in reproducing the goal parabola exactly, but only through trial and error. Preceding this conversation, neither student has explained the relationship between the setting of the arrows and the resulting motion. During the interaction shown here, Gerry and Hal use a combination of talk, gesture, and activity to come to a better understanding of the notation. They point to objects to make references clear, gesture and act out concepts, and synchronize their talk to events on the computer screen. The students collaboratively construct an understanding of what the particle notation is and how it works. Roschelle & Behrend (in press) have described this process as the construction and maintenance of a "joint problem space."

Talk	Gestures and Screen	Interpretation
G: It [acc] stays the same, but it influences the long arrow [vel] **H: I still- I don't understand what it's doing.** [bracketted nouns inserted based on gestures and display]	 The simulation is running	Gerry now sees acceleration as a change ("influence") on velocity. **Hal is watching the same display, but apparently does not see this relationship.** The discourse problem for this episode is for Gerry to communicate his understanding to Hal.
G: OK, I think. See, it [acc] pulls it [vel] down **H: mm,hmm.**	 G resets simulation and runs it forward one second. Then he points to acceleration and gestures down.	Gerry re-iterates his view of acceleration as change in velocity, this time using the metaphor of acceleration as a pull on velocity. He uses gestures to act out the pulling he is describing, integrating the idea in his talk with the same idea expressed in gesture. **Hal indicates his attention.**
G: so it [acc] makes this [vel] shorter **H: Oh:::right** G: cause that'll slow it down.	 G points to the velocity.	Gerry applies this view to the present circumstances: acceleration makes the velocity shorter, explaining why the motion gets slower. He points to the velocity as he talks to clarify which arrow gets shorter. **Hal indicates a partial understanding.**
G: And also **H: as it pulls it** G: the long arrow's [velocity is] pointing this wayG: so this one's [acc] pulling it [vel] down **H: so it's [acc] pulling it [vel] downward** G: so it [acc] will pull the angle [direction of vel] down **H: right.**	 G uses his finger to act out the change in velocity	Gerry continues applying his view, explaining the change of direction of velocity. As he does so, he moves his finger analogously to the change in velocity. **By completing the consequent sentence jointly with Gerry, Hal shows that he has understood the explanation.**

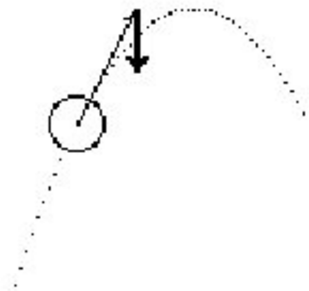
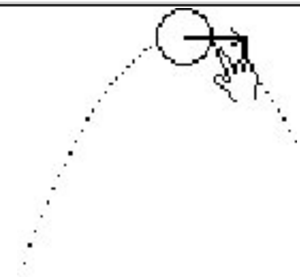
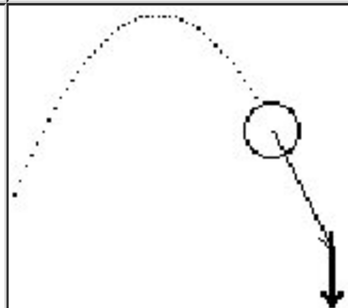
G: so then **H: there you go right there**	 The simulation is running	Gerry now starts the simulation running, and starts to talk over the simulation. **Hal interrupts to indicate that he now sees the processes Gerry described above.**
G: it [vel] crosses [the horizontal]	 G touches velocity on the running simulation	Gerry continues the story, synchronizing it to the running simulation; the change in velocity eventually results in the direction of velocity becoming horizontal.
G: and then it [acc] pulls it [vel] down.H: yeahG: and makes the angleH: Its kind of like a weight or something.	 The simulation is running	�and finally pointing downwards, completing the parabola. His final sentence is timed to correspond to the downwards motion of the particle. **Hal indicates his understanding of the explanation by paraphrasing it in his own words.**

Figure 3: Constructing a Shared Understanding of Velocity Change

During the interaction shown in Figure 3, Hal moves from "not understanding what it is doing" to interpreting the bold line as "kind of like a weight or something." That is, the bold line becomes a representation for Hal; it is a form that stands for something else.

To understand the significance of this episode, it is necessary to understand some general aspects of the problems that students encounter while trying to interpret the EM notation. First, students often do not notice important attributes of the display, or misinterpret their significance. In particular, many students do not notice that the velocity arrow changes over time. Hal had not noticed this before the conversation in Figure 3. Similarly, students often misinterpret the significance of properties. For example, students sometime decide that where the velocity arrow points is significant; they expect the velocity to point to the apex of the parabola, and ignore the significance of velocity as initial speed and direction. The list of unusual ways that students perceive the screen is very long (Roschelle, 1991).

Second, students build explanations by applying metaphors to the situation (Roschelle, 1991). In this example, as in many successful explanations, the "pulling" metaphor is used. Pulling is a good metaphor because it approximately captures the relation between acceleration and change of velocity. But many other metaphors occur to students: guiding, stretching, attracting, and balancing (Roschelle, 1991). Thus, the situation is doubly indeterminate for students; they are not sure what they should be noticing, and they are not sure what metaphors might be useful in structuring their experience.

Consider Gerry and Hal's conversation apart from the display. Read as a separate text, the conversation appears as meaningless gibberish. Where does the significance of this discussion arise? A close look at the data suggests that it arises through the exacting coordination of the students' perceptions of the running simulation, their gestures in front of the display, and their conversational interaction. In this dialog, Gerry invited Hal into his active process of perceiving-describing-and-looking � Gerry produced descriptions and gestures that primed Hal's attention for those features he should look for next in the changing display. Thus, Gerry's social actions oriented Hal's perceptual processes. Through this coupling, Hal came to re-perceive the simulation as Gerry does; that is, Hal notices the change in velocity over time and its relation to the speed and direction of motion.

At the same time, Gerry and Hal used the "pulling" metaphor to express relationships between the notation and the resulting motion. In particular, Gerry used "pulling" three times in a row: First he connected the present state of the simulation to the past state, then to the next state, and eventually to the final direction of motion as the particle left the display. As he did so, Hal slowly came to use the metaphor as Gerry did. He started by indicating his attention, then a partial understanding, then he articulated the basic mechanism ("it pulls it") and then the mechanism and its consequence ("so it's pulling it downwards"). As additional data (presented in Roschelle, 1991) shows, Hal's explanation eventually came to be quite close to a physicist's qualitative description of acceleration. Thus, the sharing of the significance of the notation occurred through close coupling of social and perceptual levels of organization in the students' collaborative activity.

Communities of Practice: How do scientists do this?

At the broadest level, learning enables an individual to become a member of a community of knowledge and practice, thereby reproducing the community. At this level, the goal of physics instruction, for example, is to enable students to participate in what scientists do, and ultimately to become the living embodiment of scientific knowledge in the next generation. Lave and Wenger (1989) have characterized the process of learning at this level as "Legitimate Peripheral Participation" (LPP). LPP involves learning-by-doing, with increasing participation, ownership, and membership in the authentic work of the community. Although Gerry and Hal made significant progress in advancing their understanding of the EM simulation in the episode in Figure 3, aspects of their understanding were still in conflict with the conventions of the physics community. Consider Hal's description of acceleration as a weight pulling down on the velocity vector: "It's kind of like a weight or something that's stuck onto the end of the arrow, and it's sort of pulling, the arrow pulls it down." Although this is an intuitive mechanical analogy, a physicist would balk at describing acceleration as a weight, because (1) weight has a different technical meaning in the scientific community, and (2) the analogy to a physical lever arm conflicts with actual properties of velocity in that the vector stretches (gains length) as well as turns.

In the interview following the session, Hal explicitly mentioned his difficulty in mapping his (rudimentary) knowledge of physics to the EM:

H: I'm trying to understand, um, exactly

E: What's that?

H: Nothing, I'm just trying to understand what this has to do with, uh, I mean if there's anything I can- not- I know it has a lot to do with physics but, I'm just trying to understand um- Trying to see if I can think of any um- doesn't matter

E: No, it does matter. What?

H: No just, you know, you know I'm trying t- I mean I don't know anything about physics but you know I've heard about it

E: mm, hmm.

H: Heard about certain things and I'm just trying to sort of see what law of physics- what anything I've heard, anything that has anything to do with this.

Neither Hal nor Gerry were successful in making meaningful connections to physics concepts on their own.

The de-briefing interview following the Gerry and Hal's session can provide a glimpse into the process of adopting the scientific community's perspective and conventions (Figure 4). In this interview, the experimenter explained the mapping of the scientific terms "velocity" and "acceleration" onto the two arrows of the EM display, and how this mapping differs from everyday usage of these terms. In response, the students spontaneously applied these terms to describing the behavior of an automobile. Interestingly, the students correctly applied the concept of acceleration to situations other than "speeding up." This marks significant progress in moving from an everyday perspective to a scientific one. Whereas an everyday perspective sees speeding up, braking, and turning as three characteristically different events, a scientific perspective sees these events as different manifestations of the same underlying description. The students' uniform explanation of all three events is a significant step towards participation in the scientific perspective.

Talk	Interpretation
E: Now in physics, what these arrows would be called is the thin arrow would be called velocity **H: Uh, huh**. E: and velocity means both speed and direction **H: Yeah** E: And the thick arrow would be called acceleration, and acceleration in physics means change in velocity. **H: Ohhh.** E: So the thick arrow tells you how the thin arrow changes	Experimenter explains the mapping of the scientific terms "velocity" and "acceleration" onto the thin and thick arrows respectively.
H: Oh so like you're in a car, and you slap on the gas petal E: Mm, hmm. **H: And you're going at a certain speed, but you slap on the gas pedal, and you start to go faster.** G: It would be like an arrow, a thick arrow [acc] going out in front of your car	**Hal introduces topic of a car accelerating.** Gerry makes the mapping to the EM simulation, that the acceleration vector would be directed forward.
E: And what about when you put on the brakes? **H: When you put on the brakes its like the arrow [acc] coming back in towards the car and slowing it down.**	**Hal correctly describes braking as acceleration in the opposite direction as the car's motion.**
E: Hmm, mm. Now I'll ask you a tricky one. What happens when you go around a curve? **H: Ho:::::.** G: That's like your steering has changed, so its like the thick arrow [acc] is pointing around the curve and it sort of drags your car hhhh. ((laughter by all))	Both correctly describe the acceleration vector for the car going around a curve as pointed in the direction of the turn (in this case, toward the right).

E: Suppose you're turning to the right, is the thick arrow to the right or left? G: Thick arrow would be to the right. **H: If you're going to the right. Yeah.**	

Figure 4: Applying the Scientific Perspective to an Automobile

Although the students did not use the EM display directly during this conversation, the objects of the display still served as important common ground between the students and the experimenter. In particular, the available shared understanding of the meaning of "thick arrow" and "thin arrow" enabled the students and the experimenter to discuss the students' knowledge. In general, it will take many small episodes like this to guide students into the scientific community's way of solving problems and talking about them. Without a rich, perceptual common ground (provided in this case by the computer display), it is difficult for students and scientists to recognize and repair their differences in belief, language, and perspective.

Discussion: Creating Forms and Meaning in Shared Activity

The case study illustrated the processes involved in learning science within the scope of three nested units of analysis. At a local level, students jointly coordinated conversational and perception-action processes to maintain a mutually intelligible stream of activity. At a slightly broader level, Hal and Gerry used perception, language, and gesture to construct a shared understanding of the significance of the EM notation. Viewed even more broadly, Hal and Gerry used their understanding of the notation to negotiate the relation of their activity to the ways in which scientists address similar situations.

We believe that the problems addressed at each unit of analysis are fundamental to science education. Students need to be able to track the local progress in a learning activity. They need to grasp the significance of scientific notations. They need to learn to use scientific notations the way that the scientific community does. Thus the specific process of learning scientific concepts, at each level, must be accountable to the overall demands of shared activity. This in turn, requires an analysis of scientific concept learning which is compatible with a view of science learning as enculturation.

Enculturation poses basic theoretical issues about representation and meaning: How can one learn to perceive aspects of the world that are invisible within one's current world view? For example, a physicist sees deformation and resilience in every real object (even a glass marble), whereas everyday folks see the world as composed of rigid entities (diSessa, 1987). How can one learn meanings that are both more complex and dramatically at odds with one's current meanings? For example, Maxwell's laws require that electricity communicates information at the speed of light while the electrical particles which carry information move only at a slow drift; to many students this is incomprehensible, and it is certainly more complex than familiar physical behaviors (Haertel, 1987). Considering science learning as enculturation immediately brings the reflective educator face to face with these questions, as well as any number of related forms of the learning paradox (Bereiter, 1985).

From a cognitive standpoint, the learning paradox rapidly degenerates into a *reductio ad absurdum*. The only apparent cognitive way to treat enculturation from one world view to another is to define a universal perception of microfeatures, or microcategories. Similarly, one must define universal atomic meanings. From these microfeatures and atomic meanings, one can attempt to construct a translation of one paradigm to another. For example, most schema-based theories of learning claim that representations come from other representations, by a process of refinement, generalization, and composition (Chi, Glaser & Farr, 1988;

Norman, 1982). Data to be represented is expressed as programmer-supplied primitive categories and measurable features. Schema-based models assume that the world comes pre-represented, already parameterized into objects and features. Since the world can be modeled as objective fact, building in primitive features into the model is viewed as just bootstrapping the program. Researchers may ask, "What is the raw material of reasoning?" (Koedinger and Anderson, 1990), but they tend to give one choice �varieties of representations. Schema models of learning involve perceptible features, but deal only with a priori representations of experience (Schank and Abelson, 1977).

To do so is to commit what Dewey (1926) termed "The Philosophical Fallacy." This fallacy occurs when one assumes the necessity of a more detailed and complex underpinning for an earlier developmental stage to explain the emergence of later stage (Tiles, 1988). In schema theories of science learning, this occurs because detailed and complex categories and microfeatures must be built into the initial state of the system for learning to occur. Moreover, rather than merely supporting everyday qualitative, inaccurate reasoning about physical world, the categories and microfeatures must be compatible with more stringent demands of precise scientific reasoning.

Accepting that science learning is enculturation forces the opposite assumption, that little if anything is sensible to students as they begin to learn science. Students neither see the same phenomena, nor have meanings for the fundamental concepts that scientists use. Indeed, students start out with very few distinctions in areas that are richly textured for the experienced physicist�for example, the description of motion. Moreover, their theoretical vocabulary has concepts that are less specific and less general. Thus, there is no universal set of microcategories upon which scientific explanation can be bootstrapped (Gregory, 1988).

However, if one moves from a pure cognitive standpoint to a socio-neural standpoint, the learning paradox need not occur. As Iran-Nejad (1990) points out, a social-neural standpoint overturns the basic assumptions in the pure cognitive story that give rise to the learning paradox. Neural research emphasizes viewing memory as dynamic, transient structures that are continually reproduced (Bickhard and Richie, 1983). At the level of neural architecture, the formation of new categories looks more like chaotic settling into a new activation state, rather than incremental modification of existing structures (Freeman, 1991; Edelman, 1987; Iran-Nejad, 1990). Thus the emergence of new categories is a matter of re-using transient organizations of neural maps; structured cues from the physical and social world gradually can stabilize new relations of features and world. Crucially, these maps coordinate perception and action�they do not *represent* how behavior or the world appears to an observer (Clancey, 1991). In addition, neural research emphasizes diverse sources of relational coordination, rather than just a strong central executive (Rosenfield, 1988). Through these sources, interaction can serve as a source of control for organizing new complexes of experience.

Social structures are critical for understanding how reproduction of existing scientific concepts can occur (Vygotsky, 1978). Considerable research has been done on the social processes by which conversational partners locally manage the uncertainty of meaning in a conversation (Clark & Schaefer, 1989; Goodwin & Heritage, 1990; Levinson, 1983). These processes enable conversational partners to seek convergence in meaning and repair divergences. Similarly, students construct the meaning of tasks, goals, and means in social activity, creating a "construction zone" (Newman, Cole & Griffin, 1989) or a "Joint Problem Space" (Roschelle & Behrend, in press).

Learning how a community uses certain notations and meanings generally involves a process in which members of the community can participate with learners in joint activity (Lave & Wenger, 1989). The use of particular notations and their meaning can thereby be negotiated relative to (1) the conventions of the community and (2) the shared experience at hand. Thus, we have argued that basic problems at the levels of mutual intelligibility, activity structures, and communities of practice can only be resolved by simultaneously drawing on stable relations of social and neural organization. Put simply, a learner participates in the creation of what is to be represented and what constitutes a representation by simultaneously perceiving, acting, and communicating. Coherence, composition, and coordination among neural and social processes are the fundamental forces at work.

Implications for instructional design

The three units of analysis we have used suggest specific ways of thinking about instructional design. At the level of mutual intelligibility, the pertinent question is "What would students have to see and talk about to use this concept?" We have argued that new relations of concepts emerge through the coherence-making processes available to the students in neural and social experience. Thus, it is important that the relation of acceleration to change of velocity is available to the students in a form that has a perceptual coherence as a "pull." The ability to negotiate meaning using concrete, manipulable objects is particularly important for beginning physics students, because they do not come prepared with a shared technical vocabulary for talking about motion. Without some help in establishing common vocabulary, provided by the shared visual and manipulative space of the simulation tool, the language would repeatedly fail to be mutually intelligible.

At the level of the significance of notations in activity, we draw attention to the richness of modalities available to students for perceiving and talking about meaning. In the specific examples we considered, one key aspect that students sought to understand was the relation between the arrow notation and changes of direction. To do so, they used gestures, metaphors, and experimentation with the simulation. As we pointed out earlier, these resources are essential�without them, Gerry and Hal's talk is gibberish. Indeed in actual scientific practice and in everyday talk, simultaneous use of multiple modalities of experience in close synchrony is a prominent fact. Yet, classroom science most often falls back on the manipulation of a single representational formalism, namely mathematics, as the basis for all learning. Thus designers should ask themselves, "How can I support a diverse ways of constraining meaning, both through experiential and social interaction?"

Finally, at the level of communities of practice, computer simulations and other instructional displays can play a significant role in learning because often there is no periphery in which newcomers can directly begin to participate in the work of the community. This is the case with air traffic controllers�there is no periphery in which common folk can practice the skills of guiding aircraft. A solution to this problem is the construction of animated microworlds, which provide activities in which newcomers can participate without danger or excessive expense. Of course, the validity of a microworld depends on getting the appropriate abstraction and simplification of the full-scale practice, especially the social interaction, which is often left out. For example, a paper and pencil simulation of air-traffic control may be so distant from the reality of the workplace that it is virtually useless in enabling newcomers to enter the professional community.

Conclusion

Representations have been viewed as the essential concern of cognitive science, yet few studies have examined how people create and attribute meaning to representations. Using a case study, we have drawn attention to how two students were able to construct meaningful interpretations of scientific concepts through coordination of social interaction and perception-action processes. For example, in Figure 3, Hal expresses uncertainty about what the notation means. What follows is a complex coordination of direct perceptual experience and social negotiation of meaning. As the simulation runs, Gerry attracts Hal's attention to the change in the thin arrow (Table 2), and shows Hal via the simulation and gestures how the thick and thin arrows relate. Gerry literally points at the changes in other forms, and Hal repeats what he sees ("it's pulling it downward"). At the same time, Hal and Gerry gradually converge on a metaphoric use of the notions of pulling and weight to express the significance of what they both now perceive. Their achievement is not an "application" of a cognitive structure to social circumstance nor to perceptual experience � that is putting the cart before the horse. Representation and meaning are not prior to social and physical interaction, but constructed in activity.

Our viewpoint differs from the usual stance of cognitive science. Cognitive science has most frequently taken a correspondence view of representation, a retrieval view of memory, and an individualistic view of meaning. These views minimize the need to consider social and neurological processes jointly. For example, in his recent proposal for a unified theory of mind, Newell (1990) places social and neural considerations outside the bounds of what he termed "The Knowledge Level"�the place of representation and knowledge in cognitive architecture. Newell places the "social band" on a time scale of hours and minutes, claiming it was not relevant to understanding the millisecond-based processing of the brain. Newell also places the neural-perceptual mechanism outside the scope of cognition, claiming perception to form a generic encoding substrata for the physical symbol system. Thus Newell relegates neural and social levels to the implementation and application of reasoning.

This model of learning misses much of the phenomenology of how representations are created, given meaning, and used. Science learning requires simultaneously perceiving new forms, generating new actions, and communicating new meanings. By requiring representation of categories and microfeatures prior to physical and social interaction, cognitive science has produced a view of learning that is incompatible with enculturation. Representing is, in essence, coordinating perception with action; this coordination takes place in a dialectic between the social and neural processes.

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