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Learning Scientific Concepts Through Material and Social Activities: Conversational Analysis Meets Conceptual Change

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The number of analyses of cognitive activity situated in a material and social world has increased. It has been particularly challenging to the theoretician and researcher to make the bridge from macrosocial theories of cultural learning to microanalytic details of situated human activities for learning in specific subject domains. The ontogenesis of conceptual change in scientific thinking provides a central case for examining this problem. A sociocultural framework informed by studies of conversation analysis is described, in which meaning negotiation and appropriation are identified as mechanisms for achieving such conceptual change. Key implications of this perspective for the design and study of learning environments are outlined.

THE ENIGMA OF CONCEPTUAL CHANGE

Although individual cognitive activity has been the subject of most investigations of learning and education, its situated nature in a material and social world has garnered substantial recent attention. Inquiries comparing learning in and out of school, cross-cultural investigations of cognitive development and apprenticeships, and studies of small-group learning all contribute to this direction. Calls for cognitive apprenticeships in school have become common (Brown, Collins, & Duguid, 1989; Collins, Brown, & Newman, 1989; Pea, in press-a). These efforts have expanded the units of analysis beyond the individual mind so highlighted in cognitive science to

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include peer groups, local communities, and culture in broader terms. Yet, actually making the bridge from macrosocial theories to microanalytic details of situated human activities on specific subject matter has provided substantial challenges to the theoretician and researcher.

This relationship between individuals and society and its consequences for learning was at the heart of writings by Dewey (1915) and Mead (1967) early in this century and of empirical investigations of learning and development by Vygotsky (1978) between World War I and World War II.

The special version of this problem I examine is the ontogenesis of conceptual change. The gaps between sociocultural theory and cognitive theory are strikingly evident in the area of conceptual change in scientific thinking. Conceptual change is somewhat of a mysterious process if you come at learning from either current cognitive or social perspectives.

From a cognitive perspective, it is typically described as building up mental representations of knowledge, largely through solitary activity. In the past 2 decades, a rich body of empirical research and theory has grown around documenting patterns of reasoning and problem solving in science among children, students, and nonscientists that deviate from expected norms in the subject areas. Variously described as "misconceptions," "preconceptions," "intuitive theories," and the like, these findings have fostered the creation of a variety of constructivist theories of learning. What these perspectives share is a conviction that learners approach the task of learning formal science in educational settings with conceptual structures and strategies that, when solving problems, may lead to solutions discrepant from those of formal science. Findings that conceptual schemes compete with those presented in traditional science instruction lead to very different pedagogical recommendations from a more traditional science education that treats the student as *tabula rasa* (inexperienced with science), with the goal of clearly transmitting scientific method and concepts to be remembered and used by the learner. From the constructivist orientation, the aims of science education are often formulated as ones of "overcoming misconceptions" through instructional strategies such as exposing how students are currently thinking by means of group discussions or think-aloud reasoning during problem solving, then illustrating the contradictions and problem-solving cul-de-sacs to which such approaches lead, and finally presenting as viable alternatives the more advanced conceptual schemes of the formal science. Conceptual change is thus viewed as theory revision faced with rational choice.

Although the constructivist agenda constitutes an advance on the ideology of learning through the clear transmission of knowledge found in traditional science education, it is still beset with problems. The approach to alternative conceptions, which views triumph over them as the goal of education, does not put a very positive light on using the existing intuitions and creative, generalizing competencies of the learner as an instructional resource (i.e., as one side in a learning conversation). And the approach does not treat as reasonable whatever learners currently think, unlike important works in anthropology that take for granted the reasonableness of human beliefs and thinking about topics as diverse as witchcraft and ethnobotany and then seek to identify the premises and problem environments in which these beliefs function effectively. Also, many have argued that learners' beliefs appear more piecemeal than cohesive theories poised for reformulation through persuasive options.

On the social side, in the Westernized version of Vygotsky's (1978) appearing as social constructivism, the general belief is that one comes to internalize in a language of thought what first takes place externally in social relations mediated by a more knowledgeable other (thus, progressing from interpsychological to intrapsychological functioning). The problem with this view is the implausibility of as simple a mechanism as internalization. It cannot be as simple as that because the mind of the learner, in the midst of the cultural richness of social interaction, is not simply a sponge veridically soaking up social process into mental life. What could *internalization* mean? How does organization arise? Surely something is transformed; there must be more of a generative process involved.

A LEARNING SETTING AND WHAT IS THERE

Let us move from problem to context. Imagine a classroom. But instead of having a teacher in front of 30 students, imagine small groups using artefacts, such as optical devices including mirrors, light sources, lenses, and a computer tool kit that lets one build dynamic models of different optics situations. Imagine the students talking animatedly with one another, comparing predictions and arguing about how to frame and solve problems by creating simulations of optical situations established with these hands-on materials. And they are interacting with other groups. The teacher is an additional resource and interpreter who comes around and who the students may request information from when they feel blocked in their inquiries.

What are the visible aspects of learning here? We can see they are engaging in conversation and activity using objects and software with one another, with other groups, and with the teacher. We can see them pointing and seeking to map between objects and computer representations. We can see them looking through activity sheets for guidance and information. We can see them building alternative models of an optical situation with the technologies. These models appear on the computer screen.

What is the invisible background and the underlying process here? There is the disciplinary structure of geometrical optics and the history of its formation—including problems posed and concepts developed. There are the beliefs that the students and the teacher have coming into the classroom about such matters as light, image formation, and vision. These may relate quite obliquely to the details of the developed discipline. And maybe most critically, the participants are each in their own way caretakers of the symbol systems they are using, which have been constructed over a sociohistorical past, and they keep them alive and refine their possibilities by using these symbol systems in activities such as these. There is the history of technologies that brings them to where they are, including the book, the lens, and the computer. And we can see them pausing and probably thinking on their own.

How do the visible and the invisible come together? Their coupling appears in a visible and temporally extended process that is girded by conversational turn taking, actions on objects, the use of ways to attract attention, and achieving joint reference, and other nonverbal interactions for making sense.

Now, with this scene as our backdrop, we must ask how is it possible for conceptual change to take place in the structure and process of that activity?

DEVELOPING MEANING THROUGH USE: MEANING NEGOTIATION AND APPROPRIATION AS MECHANISMS FOR CONCEPTUAL CHANGE

Earlier I (Pea, 1992) presented a social framework that proposes that crucial aspects of learning are fundamentally built up through conversations among persons, involving the creation of communications and efforts to interpret communications. Creation and interpretation are the reciprocal processes of human conversational action through which the meaning of symbolic action involving talk, deixis, and such representations as diagrams and formulas get negotiated (Goodwin & Heritage, 1990; Heritage, 1984; Schegloff & Sacks, 1973). Communication is thus not viewed in terms of one-way meaning transmission and reception of communicative intentions, as if these intentions were fully specified as mental representations and then expressed, but as two-way transformative communications (Pea, in press-b) in which meanings emerge in the space between two interlocutors. Two mechanisms, *meaning negotiation* and *appropriation,* are proposed as integral to this conversational learning process.

The meaning of one's production of symbolic actions is progressively constructed through successive turns of talk and action. Every turn at once provides a possible response to what went before and prepares a stage for what could come next. Thus, persons collaboratively construct the common ground of beliefs, meanings, and understandings that they share in activity, as well as specify their differences. By means of the resources for interpretation made public in this conversational space, rich opportunities exist for speakers to determine how they were understood, often but not invariably leading to meaning negotiation and conceptual change. Meaning negotiation takes place using interactional procedures such as gestural indications of misapprehension, requests for clarification or elaboration, commentaries, repairs, paraphrases, and other linguistic devices for signaling and fixing troubles in shared understanding (Schegloff, 1992; Suchman, 1987).

The second generative mechanism is appropriation. From a quite different literature than conversational analysis, Leont'ev, Vygotsky's colleague, characterized learning in terms of the sociohistorical process of the appropriation of cultural tools. Newman, Griffin, and Cole (1989) noted:

> For Leont'ev, the objects in the learner's world have a social history and functions that are not discovered through the learner's unaided explorations. The usual function of a hammer, for example, is not understood by exploring the hammer itself. . . .The learner's appropriation of culturally devised "tools" comes about through involvement in culturally organized activities in which the tool plays a role. . . .The learner has only to come to an understanding that is adequate for using the culturally elaborated object in the novel life circumstances he encounters. (pp. 62–63)

Newman et al. suggested that this concept of appropriation applies to schooling:

> Just as the children do not have to know the full cultural analysis of a tool to begin using it, the teacher does not have to have a complete analysis of the child's understanding of the situation to start using their actions within the larger system. (p. 63)

This observation is crucial and a likely precipitator of conceptual change. Because a given activity by the child (or any other speaker) can have diverse interpretations, more conceptually advanced interpretations can emerge as the teacher takes the next turn to talk. Newman et al. gave this possibility a Vygotskian reading: "While in the ZPD [zone of proximal development] of the activity, the child's actions get interpreted within the system being constructed by the teacher" (p. 64).

It is crucial that appropriation has two sides. The tool itself may be transformed as it comes to be used by someone new. We may translate these two sides in terms of symbolic action and conversation. The first is appropriation of what one takes another to mean by his or her productions (the interpretation). The second is appropriation from observed practice to one's own use (which other theorists have narrowly conceived as imitation). Considered in broader terms, such appropriation is the fundamental, reciprocal, sense-making activity of conversational interaction and a major pathway for learning to mean.

Teachers and peers can go about appropriating the learner's symbolic action to their own activity frameworks. Through interpretations by others (those appropriations of your conversational action), you may come to mean more than you thought you did. You create some message or take some action, and I interpret it in some manner. My taking-you-to-mean helps shape the next possible response. You also seek to interpret me. You may affirm my interpretation, disconfirm it, refine and elaborate it, or engage in meaning alignment through processes of repair.

You do not learn, however, only through such breakdown and repair, because these processes primarily work to establish a ritual process of affirmation, an alignment of speakers. There is also an important innovative generativity in these conversational processes. You learn how your productions can mean by acquiescing in others' interpretations of what you have said (because they advance the activity in some activity framework), even if you did not mean to use them in your production. As listener, I act as if you meant Y by saying/doing X. Learning thus takes advantage of the common phenomenon of production ahead of comprehension. And, taken in that way, in the future you may thereby come to mean by your production how you were taken: You may come to mean Y by saying/doing X. The listener's appropriation may pull your production into a new activity frame of interpretation and treat it as indicative of a more mature form of practice than you, the producer of that message, would claim it to be. You may well not deny it, because it is an assimilation—of you, into a community to which you may wish to belong or, more locally, into an activity—participation in which you may want to continue. (The reverse is also true; you may have your activity pulled down and made primitive by an appropriation, thus limiting your learning potential if you so acquiesce.)

What is involved in these processes of meaning negotiation and appropriation that may lead to conceptual change? The signaling of troubles by the listener may focus the speaker's attention on the need to either reformulate the belief they were heard to be expressing or to clarify their expression if they feel misheard. Signaling agreement to an appropriation may come through the alignment of a reformulated message toward the heard message or a silent acquiescence in the other's interpretation.

Although the outcomes of conversation often are cooperatively structured common ends, meaning negotiation and appropriation are fundamentally agonistic processes, with the resulting discourse reflecting triumphs of appropriation. One comes to accept the content of an appropriation of one's talk/activity by another's interpretation, or successfully prevail in challenging that appropriation as a mishearing, or as mistaken in its own expression, or in contrast, by reformulating one's talk/activity to align with the expectations of one's listener. These change processes are rarely precipitous but take place over many conversational turns, sessions of talk, and action.

By focusing on meaning as use, and turning this Wittgensteinian insight to the learning sciences, we may see that *expertise* is defined dynamically through continuing participation in the discourse of a community, not primarily through the possession of a set of problem-solving skills and conceptual structures. Achieving expertise is becoming indistinguishable in your actions and uses of representations in the language games at play from other members of a community of practice. These other members are tacitly involved in evaluating your belonging every time you are involved in a conversation with them—you reveal a communicative competency through your actions and words. Conceptual change becomes manifest in performances during activities resembling authentic ones in the community of interest. Learning is thus viewed as attunement to canonical practices.

IMPLICATIONS FOR EDUCATION

This perspective has a variety of important implications for education, including special roles for technologies (Pea & Gomez, 1992), and a reformulated agenda for learning activities, classroom design, and teacher roles. I can only briefly allude to them here. Using the 2-D Dynagrams simulator, a classroom-based research and development project was developed to document substantial conceptual change for high school students in an introductory course in geometrical optics (see Pea, 1991; Reiner, Pea, & Shulman, 1993).

IMPLICATIONS FOR TECHNOLOGY

Technologies may play special roles in augmenting learning conversations by representing dynamic concepts (e.g., light rays) that enable the establishment of common attention to referents or coreference among participants in these conversations. In our own work, this orientation led us to create a 2-D Optics Dynagrams simulator (Pea, 1992; Pea, Sipusic, & Allen, in press). This simulator allowed users to easily create and manipulate one or more scenes made up of optical entities such as spherical, triangular, and rectangular objects (whose materials and properties—reflecting, absorbing, refracting—could be assigned). One could also emit single light rays or ray sprays over an angle range from one or more point light sources. Users could create geometrical entities such as tangent lines, grids, and angles and measure distances and angles. Simple "eyes" could be set up as ray detectors. *Dynagrams* was our shorthand for *dynamic diagrams,* a central kind of symbolic representation that provided a rapidly constructable and highly interactive communication medium about geometrical optics. Users could create conversational artefacts for coordinating their activity, talk about the conceptual content of their work, and negotiate differences in their beliefs.

Student groups observed real-world optical situations (or video depictions), used our dynagramming tools to build "scenes" that made predictions about the behavior of light in these situations and provided arguments to justify these predictions based on scientific principles, definitions, or prior experiences. The dynagrams by-passed many difficulties students have in constructing paper-and-pencil or chalkboard diagrams. By composing such representations, students in a group could each graphically express predictions and then use these representations as indexical support for narrative explanations of light behavior in the situations they modeled. Because the simulator "knew" how light rays depicted would propagate in the situation that students had modeled, students could run their simulation models and discuss how well each of their graphical conjectures fit the actual results. Through their creation and interpretation of these representations in sense-making activities, the dynamic diagrams became symbolic vehicles for expressing students' conjectures about light behavior and the topic for negotiating group and individual understanding of technical language, concepts, procedures, and skills.

IMPLICATIONS FOR LEARNING ACTIVITIES, CLASSROOM DESIGN, AND TEACHER ROLES

Researchers believe these processes of appropriation and meaning negotiation need to take place by participating in a community of science practice. Physics practice is comprised of ways of talking and acting, shared beliefs about what a problem is, how to work on it, and which tools and representations are useful for what conditions of inquiry.

For the novice science learner, the classroom context often radically underestimates the conventions of meaning for uses of technical terms and symbols and their mapping to the physical world. In the didactic mode typical of science instruction, few opportunities emerge for resolving the problems that either students or teachers may have interpreting the meaning of their respective talk about science.

It is striking that during activities in which children participate, adults play language games such as question–answer and naming and elaboration through which children learn how to mean (Bruner, 1976; Halliday, 1975). Studies of lexical development reveal that through communicative exchanges toddlers engage in what Miller (1977) called a "spontaneous apprenticeship" with mature practitioners in communities of linguistic practice. Children observe words used by others in contexts and then try out the use of words in other contexts, with conversational repair among participants providing opportunities to establish a working alignment of saying and perceived meaning.

Influenced by these considerations, Hawkins and Pea (1987), among others such as Lemke (1990), argued for the need to reorganize science learning environments so that students come to be able to "talk" science and to produce and interpret speech acts involved in participating in scientific activities, rather than just "hear" science. A crucial facet of the practice of science is its rhetoric—how the discourse of the field is organized, how viewpoints are presented, what counts as an argument and its support, and so on. Science education should result in capabilities to participate in scientific discourse—to converse about scientific ideas and the scientific aspects of issues and systems generally.

The discourse forms of a discipline can be considered as an example of *language games,* the image developed by Wittgenstein (1967) in *Philosophical Investigations* for processes by which meaning is communicated and developed. In Wittgenstein's terms, many human activities may be productively viewed as language games, participation in which can lead to appropriate use of language for the activities involved in those games through refinement of meaning in contexts of use.

My pedagogical goal in the Dynagrams Project (Pea, 1991, 1992; Pea et al., in press) was to have students become better able to engage in appropriate conversations about the conceptual content they were investigating through their collective activity and symbolic action—to achieve expertise through participation. I felt that their work should be focused on inquiry and sense-making conversations involving authentic tasks in science practice such as making predictions, designing experiments to test them, careful observations, explanations, and revising conjectures in light of their observations. These activities involve use of the technical concepts and procedures of science in optics. I thus created a learning environment and activities so that students might achieve competency in the language games of geometric optics.

For this to happen, I provided activity structures that encouraged continual participation and conversation in the classroom in small groups. I thought we could arrange for more learning:

- If students actively engaged in problem-solving and exploratory activities during which they got to manipulate optics materials and phenomena.
- If there were opportunities for students to talk and communicate with each other during these activities.

- If the activities arranged for students to use diagrams to explore optical phenomena.
- If the students were organized to use the diagrams to explore and communicate about optics in ways that were similar to the practices of real scientists.

During their inquiries, the meanings of representations for learners, such as words for technical concepts, optical devices, and diagram components, were continually remade through their use and interpretation by others in the discourse community.

I had to design and refine activities involving curricula that were responsive to the details of conceptual change in the specific areas of optics discourse. This was a hard empirical problem. In my work, I largely focused on promoting qualitative understanding of relations in geometrical optics (e.g., to define shadows, find image location, and fine lines of sight for mirrors), rather than formal quantitative principles and formulas. Working with the teacher, I used the Dynagrams simulator to create a set of challenge activity structures of increasing complexity (e.g., single to multiple light sources for making shadows, single mirrors to multiple mirrors, and simple lens refraction to a coin-in-pool situation) for small-group classroom work.

Some activities were better at laying bare learners' current ways of conceptualizing content and situations, and they provided opportunities for more progressive conceptual learning conversations to occur. For example, I found that some fundamental conceptual objects needed to be part of the expressive medium of Dynagrams, such as an "eye" as a detector and rays of light instead of single rays or parallel beams, to enable the most productive learning conversations to take place (Pea, 1992). These entities inclined students toward different ways of thinking about the subject matter in optical situations that served to anchor conceptual change and to serve students in achieving more adequate predictions and explanations of optical phenomena.

Broadly considered, the conversational mechanisms of meaning negotiation and appropriation provide continual opportunities for learning. But exploiting these resources for education is a more complex design task. Not just any conversations will do well in this respect. One can bias the kinds of conversations likely to occur by the arrangement of the classroom situation—including problems, challenge activities, tools, materials—that launch inquiries that invite learners to use the concepts and strategies the educator wants to bring into the conceptual change process of meaning refinement and appropriation. Making the best situations for fostering crucial learning conversations that enable significant conceptual change to transpire is at present an ill-understood art. Furthermore, I have not in this analysis been concerned with developmental constraints on such conversational learning practices or on the belief systems engaged in them. These influences on the shape of learning conversations for specific subject domains will require substantial empirical investigation across a broad age range.

In the Dynagrams Project, the teacher's roles in these classroom activities were diverse. He served as collaborator in identifying and designing productive activities for establishing learning conversations by modeling inquiry, provoking students' inquiry oriented to conceptual change from their preexisting alternative conceptions of the subject domain, and providing guidance during these inquiries toward domain norms of established scientific practice and theory. He also acted to represent a community of scientific practice and reduced his reliance on presenting other peoples' physics.

Although teachers can rarely literally reproduce all the details of authentic science activity in their classrooms, they can model authentic practice by engagement and reflection on real exploration of topics occasioned by inquiry activities. We hope that one consequence of the teacher professionalism movement will be to make science teacher participation in communities of practice for science among colleagues outside school more common than it is today (see Ruopp, Gal, Dayton, & Pfister, 1993, for an impressive example of such progress). All the same, the community of practice of science learning in classrooms has critically distinctive features from actual scientific work practice, as in university or industrial research laboratories. For example, such scientists have a very different socioeconomic context to their work that creates distinctive incentive structures for influencing the planning, progress, and critical communities for their scientific work practices.

SUMMARY

I outlined a perspective for examining conceptual change in science through learning conversations. Competency in the language games of science is co-produced by the participants' actions of meaning negotiation and appropriation in authentic tasks. The concept of appropriation is central to providing this process not only with the engine of enculturation or ritual establishment of canonical practice, but with generativity as well. The openness of interpretation of symbolic action ensures an ongoing dynamic between what is said and what is heard.

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The general concept of "community of practice" was developed by Lave and Wenger (1991).

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