Augmenting the Discourse of Learning with Computer-Based Learning Environments

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Augmenting the Discourse of Learning with Computer-Based Learning Environments[1]

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Abstract: Computer tools for learning are often thought of as providing practice in working with symbolic representations. We exemplify a different perspective in which the technology augments the kinds of learning conversations that can take place. Research from the Optics Dynagrams Project illustrates contributions from this perspective. I will describe pre-intervention learning environment characteristics and student learning, our design strategy for new activities and technologies to address problems we observed, and results with a classroom field test of our redesigned learning environment. In the Dynagrams learning environment, small groups of students work with a software simulation of phenomena of geometrical optics. They observe optical situations in the world or laboratory, use dynamic diagramming tools to make predictions and arguments to justify them based on scientific principles, definitions, or prior experiences, and test these predictions in runs of their simulation models. The dynamic diagrams become symbolic vehicles for externalizing student cognitions for peers and teacher, as well as the topic for negotiating group and individual understanding toward physics norms. The pedagogical goal is to have students become better able to engage in appropriate conversations about the conceptual content they are investigating. Such inquiry-focused discourse is a fundamental part of learning environments in authentic practices outside schools; our aim is to examine ways for augmenting such learning conversations in schools.

Keywords: learning theory, science education, classroom discourse.

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Introduction

The learning problems our cognitive science research community has studied for several decades center on the use of concepts and on conceptual change, especially in science and mathematics. We have also focused on the acquisition of problem-solving skills and procedures involving representational systems (e.g., graphs, algebraic equations, programming languages) that are the currency of thought for specific content domains. Several responses are common by those concerned with these educational problems. One is to seek out through knowledge diagnosis during problem-solving tasks the conceptions students have which deviate from current scientific understanding. Students are then confronted with problem situations in which these conceptions can be shown to be inadequate, with hopes that such conflict may precipitate conceptual change [e.g., 17, 43, 50, 64, 69]. Another response has been to identify the skills and procedures utilized by competent problem solvers in the domain and to then establish means for training students to use those skills [e.g., 3, 31, 44, 61, 63].

Work with these objectives has made valuable contributions to understanding conditions sufficient for promoting learning. But now we must go on to ask yet harder questions. Do the results of such training carry beyond the school walls? Can experiments establishing transfer of learning results on near-variants of training tasks lead to spontaneous and successful use of such educational innovations after the researcher fades from the scene? These hard indicators have rarely been sought, at the level of social uptake of "solutions" to learning problems that emerge from the research community.

There are foundational issues beyond the common responses of our field which might provide the radical reconstruction of the epistemological eyeglasses with which we view the significant categories of meaning, learning, and knowledge involved in education. What are the characteristics of learning environments that initiate and sustain the learning and use of new concepts and procedures? Our thesis is that these characteristics may be identified by seeking out the properties of *successful* learning environments beyond those provided in current classroom settings.[2] And we are interested in experts, but not so as to just identify their achievements and practices, but to characterize the communities of practice that *give rise* to "experts" and *in terms of which* their achievements have meaning and their disciplines keep dynamically evolving their knowledge claims [e.g., 35, 39]. We believe that current progress in the cognitive sciences of learning may be reformulated and

2 This emphasis on the study of successful learning is a central theme of research work at the Institute for Research on Learning in Palo Alto, California. Among its central predecessors are [8, 40, 50, 55, 62]. Gelman and Brown [21] describe a similar emphasis in studying cognitive competence in the young.

extended by attending to and better understanding this deeper social and situated fabric of cognitive activity.

My method will be to outline aspects of a broader social framework for understanding learning and for investigating how competent problem-solving is established, and to point to alternative characterizations of learning, knowledge, and instructional processes that arise from these considerations. Finally, I will highlight the implications of this social framework for the design of computer-based learning environments, alluding to our Optics Dynagrams Project.

Key concepts of a theory of learning as situated in communities of practice

Lave and Wenger [41], in generalizing the theory of learning as "cognitive apprenticeship" developed by J. S. Brown and colleagues [5, 15], have formulated a situated learning perspective that sees learning as an ongoing and integral part of membership in "communities of practice." Such membership is conceived of as an activity system about which participants share understanding regarding what they are doing and what this means in their lives and for the different communities of practice in which they participate. Learning is conceptualized as a lifelong process integral to *becoming* a member of different communities of practice, and *sustaining* such membership. The construction of personal identities largely involves defining participatory roles in different communities of practice. Persons always are members of multiple communities of practice, which may emerge, change, or disappear during their lifetimes. Allen [1] develops this perspective in her characterizations of the ways in which learning environment design can be conceptualized as providing conditions for the "growing" of communities of practice.

On this view, as in cognitive science, the acquisition of expertise is still viewed as important. But rather than construing expertise primarily as the acquisition of domain facts, problem-solving procedures, heuristics, and metacognition for formal problem-solving, expertise is viewed as a practice of a community. Learning is viewed not only as a relation to problem-solving activities, but in terms of participation as member in the practice of different social communities. For science, such a practice consists of ways of talking and acting (which include many shared goals, concepts, procedures), belief systems about what is interesting or promising about problems, shared views of when it is appropriate to use particular tools, and evolving kinds of sense-making activities that seek to evolve scientific concepts to fit the world (e.g., modelling, theory building, simulations). A community of practice for science includes at its frontiers diverse claims to knowledge, and disputatious means for advancing and resolving such claims, as the success of concepts as resources for resolving new problems is tested [e.g., 36, 67]. Learning then is not perceived as information transfer from teacher to learner, but as a process of participating in the activities of a community, by means of collaborative sense-making in which knowledge functions as a tool to resolve emergent dilemmas [4, 41, 51]. Learning conversations are central to these participations, in the sense I will now describe.

This emphasis on learning through conversations is not intended to *replace* that of learning by other means, such as remembering past experiences when alone and reflecting on the usefulness of one's current knowledge in the face of new problem conditions, or learning by reading and engaging in self-explanations [9]. But conversations *are* a major source of learning resources which have been unreasonably neglected by the cognitive science community in its studies of learning, and yet which, given the pervasiveness of learning through conversations outside schooling institutions, is bound to be critical to achieving successful learning in school settings.

What is a learning conversation?

Learning is fundamentally built up through conversations between persons, involving the *creation* of communications and efforts to *interpret* communications. Creation and interpretation are the reciprocal processes of human conversational action, through which meaning gets established and negotiated [e.g., 24, 32, 51, 60]. Communication is thus not viewed (as it is commonly in educational practice) in terms of one-way transmission and reception of meanings, but as two-way transformational, enabling the progressive construction of meaning through successive turns of action and talk. And conversations are the means by which people collaboratively construct the common ground of beliefs, meanings, and understandings that they share, and also articulate their differences. These conversations also provide the publicly available resources and thus the opportunities for speakers to determine how they were understood, often leading to meaning negotiation and cognitive change. Meaning negotiation takes place using interactional procedures such as commentaries, repairs, paraphrases, and other linguistic devices for signalling and fixing troubles in shared understanding [59].

Learning by participating in the language games and activities of science

In science, as in any communicative exchange, the problems of interpreting speaker meaning are deep. For the novice science learner, the classroom context often radically underdetermines the meaning of technical terms and symbols, and their mapping to the physical world that they are about. 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. When science educators write that "it has become a commonplace belief that learning is the result of the interaction between what the student is taught and his current ideas or concepts" [54, p. 211], it is too rarely acknowledged that it is through learning conversations that these differences are most commonly observable and resolvable.

The problem of learning to do scientific conversations is analogous to learning a natural language. During activities in which children participate, adults play language games such as question-answer, of naming and elaboration, through which children "learn how to mean" [6, 27]. Studies of lexical development reveal that through communicative exchanges toddlers engage in what George Miller [47] has 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 contexts, with conversational repair among participants providing opportunities for establishing a working alignment of saying and perceived meaning.

Influenced by these considerations, Hawkins and Pea [30], among others such as Lemke [42], have argued for the need to re-organize science learning environments so that students come to be able to *talk* science, 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 in *Philosophical Investigations* [71] 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. Fluency in these practices comes with recognition of membership in a given community of practice [18, 41].

In our work we generalize these observations about *language* to *symbolic forms* more generally, including such representations as diagrams, pictures, mathematical symbols and equations. Just as speakers make speech acts with natural language, they make diagram acts that have analogous interpretive demands in a discourse to those of speech. Such discourse also often involves the use of complex symbolic representational systems in a discourse "workspace" between participants (e.g., diagrams, graphs on a whiteboard, lines of programming code on a computer screen). These representations come to serve as resources that enable speakers to engage in conversations about complex conceptual entities, such as slopes on a graph, or rays of light. They can point to these entities, talk about them to clarify what is meant, and describe how they are connected to other things.

A major part of enculturation in these games of scientific practice is coming to be able to engage in sense-making conversations that use and talk appropriately about how such external representations relate to situations in the physical world and to each other. For science, the key authentic tasks of sense-making in science -- those tasks that are the ordinary activity of the practitioners of a scientific community -- include producing causal accounts including technical concepts, symbols, and models to explain observations of a physical situation, forecasting a future state of a situation given some variation in its properties, and dealing with emergent problems in the course of an inquiry.

This view of learning science relates closely with Hanson's [28] idea about "seeing-as" in his discussion of the philosophy of science. For example, the Copernican revolution taught us to see the sun as a very large stationary object that the earth revolves around rather than a smaller object rotating around the earth. Learning to interpret and use scientific ideas involves learning of ways of "seeing-as" in two important senses. Students learn to see scientific notations such as diagrams and equations as symbols that represent aspects of the conceptual entities of science. They also learn to see systems and events as instances of scientific structures and principles. We emphasize that "seeing-as" is a central part of what communities of practice do, and that the process of learning to see and talk about things in the ways that one's pertinent community sees them is a major aspect of community socialization.

The meaning of representations such as words and diagrams in a community becomes evident through their use and the reshapings of their meanings through commentary by other participants of learning conversations. As such, meaning is dynamic and in continual flux because its use is coupled to the particularities of each new situation, not a static proposition mentally represented in a truth-functional calculus.

Learning through processes of appropriation and interpretation

We now believe that two central mechanisms underlie these processes of enculturation in scientific practice, or what Lave and Wenger [41] would call increasing participation in the "community of practice" affiliated with talking science.

One mechanism is *appropriation*. Appropriation has two sides--appropriation for use and appropriation of what one takes another to mean. Leont'ev (a colleague of Vygotsky whose work [68] established a pioneering theory of the social construction of knowledge), characterized learning as the "appropriation" of cultural tools. For Leont'ev, the biological language of Piaget's interactionism is replaced with the sociohistorical language of "appropriation." Newman, Griffin and Cole [49] apply this concept of appropriation to cognitive change from schooling. They note how:

> 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 (although the learner may discover some facts about weight and balance). The learner's appropriation of culturally devised "tools" comes about through involvement in culturally organized activities in which the tool plays a role....He emphasizes the fact that they [children] cannot and need not reinvent the artifacts that have taken millennia to evolve in order to appropriate such objects into their own system of activity. 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. The appropriation process is always a two-way one. The tool may also be transformed, as it is used by a new member of the culture; some of these changes may be encoded in the culturally elaborated tool [p. 62-63].

Newman et al. apply Leont'ev's concept of appropriation to problems of cognitive change in schools. They observe: "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]. They see the fact that a given activity by the child can have multiple interpretations (for example, those of the child and of the teacher) as what makes cognitive change possible, through the negotiations of meaning about that situation that arise out of conversations: "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]."[3]

Several features of the processes of appropriation should be evident from the description already: (1) One must come to acquire appropriate moves in the context of the activity itself (including its social and material environments); (2) in the context of the

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3 In the language acquisition literature, this attribution process is described as one in which adults do "rich interpretations" of the talk young children produce. These interpretations may be viewed as *creating* richer meanings in the interaction through the processes of meaning attribution [6]. In the science learning conversations with teacher and student, the teacher may appropriate the student's talk as arising from understandings that the student does not have, but which such appropriation may help create, in the sense that the joint meaning they have constructed in the space between them is then viewable as an appropriate move in the game to which the learner has contributed.

interactive activity, there are different interpretations possible of the actions - a learner or teacher's self-interpretation (how what I am doing means to me), and a learner or teacher's appropriation of other-action to mean what it is taken to mean (which may diverge from the self-interpretation); and (3) with growing participation, one comes to anticipate and produce possible next moves in the game.

Meaning negotiation is the other central mechanism for the social construction of the meaning of what was expressed, and of events that are the target of sense-making activities among conversationalists. Its structure consists of reciprocal acts of *interpretation* between speakers. The resources for meaning negotiation are quite diverse, and include: requests for clarification or elaboration, gestural indications of misapprehension, explicit paraphrasings of what-may-have-been-meant to test for understanding, and explicit commentaries.

Ethnomethodologists such as Garfinkel [19], Garfinkel and Sacks [20], Schegloff and Sacks [60], and Mehan and Wood [45] have highlighted the importance of *indexical support* for such meaning negotiation. With indexical support, speakers opportunistically use the resources of the physical world to clarify what they mean, given the ephemeral nature of spoken language. Their words are "indexed" to referents in a situation, such as words or symbols on a whiteboard or computer screen. Such indexing is critical for establishing a shared semantics of representations, referential mappings between situations and formal symbols depicting world entities. Herbert Clark and colleagues [10, 11] have referred to this achievement as establishing a "common ground". Roschelle and Behrend [57] have emphasized the fundamental indexing roles of action on and gesture towards computer screen representations in constructing shared knowledge in collaborative problem-solving with the "Envisioning Machine," a computer microworld for exploring concepts of velocity and acceleration.

These processes of appropriation and meaning negotiation need to take place in the context of authentic activities that arise from *participating in a community of practice* for science learning. This means engaging in inquiries that require sense-making conversations using the technical concepts and procedures of science, and tasks such as prediction, observation, and explanation. During such inquiries, the meanings of representations for learners such as words for technical concepts and diagram components are continually remade through their *use* and *commentary* on their use, through creation and interpretation.

In summary, competency in the language games of science is co-produced by the participants' actions of appropriation and interpretation in authentic tasks for a community of practice. The teacher's role is to model inquiry, provoke inquiry oriented to students' conceptual change from pre-existing alternative conceptions of the subject domain, and serve to *represent* a community of scientific practice.[4] In the case of our physics students from "expert classrooms," we saw achievement of competency, but it was in a community of practice focused on training for test performance, not oriented to physics inquiry and understanding [53]. How might we change this with the design of the Dynagrams learning environment?

Tools for augmenting learning conversations

J. S. Brown [4] has characterized the epistemological shifts that emerge from a focus on successful learning, including the importance of implicit (tacit) knowledge in understanding[5], the significant process of developing rather than merely acquiring formal concepts, and the central nature for successful learning of the social context, activity[6], features of the material environment, and learner improvisation and exploration. He argues that learning technologies must become capable of drawing on these social, collaborative, constructive, and situated elements of human learning.

By contrast, computer tools for learning are often thought of as especially well-suited to providing solitary practice in the skills of working with externalized knowledge representations (e.g., geometric proof statements; algebraic equations; physics formulae) that it is the student's task to master. Given the need for appropriation activity to make meaning in human discourse, it seems unlikely that computers can be effective agents for directly teaching the language games of science (or any subject, for that matter). Appropriation requires taking a student's utterance, providing it with an interpretation, and engaging with the student in a negotiation that results in a closer approximation to norms of scientific meaning. The intentionality and membership in communities of practice required for this interaction is unavailable in computers in principle. This strengthens the motivation for designing computational resources that can provide things for teachers and students to

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4 While 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. Lampert [37] and Schoenfeld [61] have experienced success with such practice in mathematics education. 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.

5 See [70] for related theory on computers and cognition.

6 A focus on learning by doing was central in Dewey's [16] seminal work on education, and in Bruner's [7] influential formulations of an activity-centered, inquiry approach to learning. The perspective on situated learning under development by Brown, Greeno, Pea and others at IRL [4, 5, 15, 25, 52] places greater emphasis that those earlier works on both the *social theory* in terms of which learning-by-doing is framed [41] and the *fine structure of human interactions* through which the collaborative construction of meaning for specific subject matter learning takes place [this chapter, 56, 57].

talk about, and for students to talk about with each other, rather than providing instruction through computers directly.

Here I develop the stance on learning technologies that conceptualizes computer tools as enabling *augmentation* of learning conversations that can take place either between learners, or between learners and more proficient users of the targeted knowledge or skills. In related work at IRL, Roschelle [56] calls this "designing for conversations."

The Optics Dynagrams Project

Science learning research from the Optics Dynagram Project exemplifies our approach for designing tools to augment learning conversations. "Dynagram" is our shorthand for "dynamic diagram," a central kind of symbolic representation in the software we have created as a communication medium for learning conversations about geometrical optics. Visual representations such as diagrams play a far more important role in the reasoning and problem representation processes of scientists than educational practices and learning theories now acknowledge [46]. Diagrams are important symbolic forms for representing concepts and conceptual relations, and provide, in the arguments of many researchers, a "language of thought" that exploits the visual processing capabilities of the human mind [38]. From our perspective, diagrammatic representations also provide conversational artefacts that better enable learners and teachers to become similarly connected to the conceptual content of these representations, and to negotiate differences in beliefs about how such diagrams representing world states will behave under various changes in the world they are about.

The pedagogical objective is to have students become better able to engage in appropriate conversations about the conceptual content they are investigating. These inquiry-focused conversations include such activities as making conjectures, designing experiments to test them, revising conjectures in light of observations of experiments, and so on. Before characterizing how we recrafted the learning environment and technologies to support these aims, let us review what we found upon examining the teaching and learning practice of several "exemplary" physics classrooms.

The shape of conversations in "expert classrooms" before Dynagrams

With the aim of identifying successful learning practices, we selected two classes for study that were taught by highly experienced physics teachers in high schools widely-recognized as producing an unusually high number of scientifically-oriented student graduates (one in New York, one in California).

In one study, we analyzed videorecordings of a teacher's optics lessons in an introductory physics classroom in a science-oriented high school in New York City (henceforth "NY school"), and videos of individual students as they attempted to represent and solve optics problems at a chalkboard using diagrams, equations, and words. Widely considered one of the best U.S. science high schools, it has over a dozen physics faculty and a department chairperson. Geometrical optics was taught for three weeks during the second semester of a required first year introductory course on physical science. Classroom observations and teacher conversations led us to image formation[7] as a particularly challenging and difficult topic, one in which the use and understanding of diagrams is essential. An interview guideline was administered to students immediately following instruction. Each student was asked to draw diagrams at a chalkboard in order to solve basic geometrical optics problems involving image formation with a single lens or mirror. Our goal was to examine student use and comprehension of diagrams as representations for reasoning about optical phenomena, and to document types and likely sources of difficulties during these activities.

For the second study we enlisted the cooperation of the physics faculty of our "CA school", where we have videotaped all optics lessons given by an award-winning physics teacher, and interviews with his students while individually attempting to represent and solve optics problems at a chalkboard using diagrams, equations, and words. These interviews also incorporated use of a simple hands-on laboratory apparatus (light source, converging lens, screen, ruler). We had the student represent and solve optics problems at the chalkboard with diagrams (and equations, when remembered). Then the student was asked to predict what would happen, and why, when the physical apparatus was used to create various optical phenomena. Finally, we asked the student to reconsider the design of the diagram used to justify a prediction if it was disproven by the physical apparatus. (We are now working with this teacher for our observations of the impacts of Optics Dynagrams on teaching and learning activities and outcomes.)

The teachers each predominantly worked by introducing key concepts with definitions, and offering demonstrations of these concepts perhaps common to the students' everyday experiences. Expositions of these situations were then presented using the various technical demonstration apparatuses and the symbolic representations of optics, such as ray

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7 Research by Goldberg and McDermott also indicated severe problems in understanding image formation from a plane mirror [23], and of real images formed by a converging lens or concave mirror [22] among college-age introductory physics students both before and after instruction.

diagrams. Preeminent in these discussions was the highlighting by the teacher, and questions by the students, about what they would be held accountable to in quizzes and tests. These tests placed great emphasis on facts and definitions of geometrical optics, rather than their use for prediction and explanation. Labs took place but did not involve students in using these representations for prediction and explanation, or negotiation of their meanings.

Given the learning resources provided by the teacher, we asked whether students could appropriate for their own flexible use the various representations used by the teacher to reason about and explain optical phenomena. Were they able to participate in the language games of geometrical optics? These included technical concepts such as "refraction," ray diagrams, direct or pictorial experience with optical events from everyday situations, and algebraic equations (in NY) used to reason about the quantitative relations among the focal length of a mirror or lens, the size and distance of the object, and the size and distance of the image of the object.

We found that the dominant role of teacher's lectures and demonstrations as the students' resources for learning led to the following results [53]:

- fragile use of symbolic representations including diagrams, equations, and technical terms for reasoning about simple optical situations, both in using the representations to model a situation, and for reasoning about how light would behave in that modelled situation;
- learning was viewed by students as the memorization of definitions of technical terms and states of the diagrams that could be expected to appear on assessment tests;
- students lacked a scientific model of image formation as a point-by-point mapping from object to image governed by laws of reflection and refraction;
- in terms of learning conversations, we see there were few opportunities for students to map the meaning of diagrams or technical terms onto physical situations and apparatus, for making predictions, or modelling the physical situations to explain optical phenomena; and
- virtually no activities involving student groups and the teacher allowing for meaning negotiation for either the linguistic, diagrammatic, or equation representations central to reasoning in the domain.

Students had achieved some competency in a community of practice, but it was in test-taking and surface memory for physics facts, not a flexible capacity to engage in reasoning with the representational resources and techniques we expect as part of scientific practice.

Key aspects of the Optics Dynagrams learning environment

Our thesis is that we can foster learning by augmenting the learning conversations that take place with the Dynagrams learning environment. To do so, we sought to create *powerful affordances* for students to acquire competency in the language games of geometric optics.

Our design involved both technological and social dimensions. To augment learning conversations, we designed new kinds of *activity structures*, with careful attention to the supporting features of the physical and social environments for students' actions and conversations. These activity structures seek to combine: The affordances of new media (e.g., easy creation of diagram graphics and their direct manipulation with a mouse input device; ability to make diagrams dynamic; accompanying video of optical situations for precipitating inquiry), new kinds of conversational structures (scientific discourse in collaborative groups with teacher guidance rather than didactic interactions), and specific opportunities for developing conceptual understanding and techniques for the domain. We largely focused on promoting qualitative understanding of relations in geometrical optics, rather than formal quantitative principles and formulas.

In terms of conceptual understanding, based on problems we found students to have in our prior research, we sought to develop through these activity structures the following notions:

(1) Objects can absorb, refract, reflect, or diffusely reflect light;
(2) A point source emits light rays in all directions;
(3) An extended source is a sum of many point sources, and an object diffusely reflecting light can be viewed as such an extended source;
(4) An extended image is a point-by-point mapping of the object;
(5) Light travels in straight lines infinitely far but decreasing in intensity;
(6) Ray sprays may diverse, converge, or go parallel;
(7) The local mechanisms by which light rays are propagated at surfaces - Snell's Law and the Law of Reflection;
(8) The properties of how a lens bends light depend on its shape and refractive index;
(9) Structure and function of the eye in image formation;
(10) Image properties are often dependent on the position of observer (eye);
(11) Determination of focal point of lens.

Later we provide an example of a Dynagrams learning conversation in which a student group is working on the challenges involved in (1), (6), (7), (9), and (10).

In terms of techniques, we worked to provide activities that would:

- Encourage sense-making with a simulation model through actions of explanation, prediction, modelling, design, and troubleshooting;
- Foster diagram interpretation, diagram use as a qualitative reasoning tool (e.g., to define shadows, find image location, find lines-of-sight for mirrors), and diagram use as indexical support for sense-making arguments and narratives;
- Require continual mapping across diagram representations and physical situations with hands-on materials; and
- Establish collaborative inquiry, including competing conjectures, meaning negotiation, troubleshooting and repair, and refinement of language of description and explanation.

Furthermore, as we have considered science learning by analogy to language learning, we have seen that learning conversations with diagrams need to have three basic properties:

- They need to allow for the *production* of speech acts by learners that incorporate uses of technical concepts, diagrams, and other representations. This called for technology design of a readily-accessible expressive medium for students to use for frequently composing meanings in reasoning during sense-making activities about optical situations (see below). Dynagrams provides an "intelligent" graphical design language for learners to construct ray diagram models of optical situations.
- They need to take place so that learners do their own *interpretations* of the situation. Students need regular opportunities for the social construction of meaning through negotiation around the terms, models, conceptual entities, and causal narratives which they are using to express their beliefs and conjectures with Dynagrams activities. This may mean accepting what has been said, challenging other students' productions with their own, questioning the meaning of terms and actions in such productions, or seeking to account for discrepancies between predictions and experimental results.
- The conversations need to be *sense-making*. The social goal of a learning group is to try to make reasonable causal narratives, attempting to use their ideas and those introduced by the teacher's challenges to provide accounts of observed and predicted phenomena in authentic contexts of problem formation and problem-solving. Note that such sense-making conversations are predominantly synthetic/design tasks seeking congruence/fit between world experience and causal model, rather than analytic tasks seeking verification of hypotheses through problem-solving.

In the Optics Dynagrams Project, small groups of students work with a software simulation, or microworld, that supports the construction and running of graphical models of simple optical situations related to interaction of light and matter. Dynagrams treats the phenomena of reflection and refraction, and deals with absorbance (allowing exploration of topics involving shadows) without any relation to temperature. Learners engage in inquiry cycles of prediction, testing, observation, and explanation.

The 2-D optics simulator we designed and created at IRL [34] allows users to easily create and manipulate one or more scenes made up of optical entities such as spherical, triangular, and rectangular objects (that have assignable properties--materials; reflecting, absorbing, refracting). One may also emit single light rays, or ray sprays over an angle range, from one or more point light sources. Users may also create geometrical entities such as tangent lines, grids, and angles, and measure distances and angles.

We have 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 periscopes; simple lens refraction to a coin-in-pool situation) for small group, sense-making activities.

Students observe real-world optical situations (or their video depictions), use our dynagramming tools to build "scenes" that make predictions and arguments to justify them based on scientific principles, definitions, or prior experiences. The dynagrams bypass many difficulties students have in constructing paper and pencil or chalkboard diagrams. By composing dynagrams representations, students in a group can each graphically express predictions and then use these representations as indexical support for narrative explanations of light behavior in the situations they have modelled. Since the simulator knows how light rays depicted will propagate in the situation students have modelled, they can then run their simulation models and discuss how well each of their graphical conjectures fit the actual results. Through learners' creation and interpretation of these representations in sense-making activities, the dynamic diagrams become 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.

Building on prior work [29, 33, 48], Clement [13] distinguishes between four major types of knowledge used in science: observations, empirical laws summarizing observed regularities, explanatory model hypotheses that introduce theoretical visual models (such as molecules, waves, light rays), and formal quantitative principles. He argues that science educators have overassociated "real" scientific thinking with only empirical laws and formal quantitative principles. Our aim for the students' work with our Dynagram challenges -

which include hands-on work and simulation model building of the physically-observable optical situations - is to have students engaged in building an explanatory model of diverse optical situations using the ray model of light provided by the optics simulator. Clement [13] has argued for the importance to such model construction of having students attempt to give explanations and argue about them in large or small group discussions:

> The complex, tacit, nonobservable, and sometimes counterintuitive nature of scientific models means that misconceptions or "bugs" will be the rule rather than the exception during instruction, requiring critical feedback and correction processes. This means that the learning of complex, unfamiliar, or counterintuitive models in science requires a kind of learning by doing and by construction and criticism than by listening alone [p. 377].

The kinds of critical feedback, correction, and criticism he describes here are integral discourse practices of a scientific community, and build upon the conversational resources students bring with them to the science classroom, but which they rarely have opportunity to utilize in typical didactic instruction.

The shape of learning conversations with Dynagrams use

We have only now just completed a four-week field-test of the Dynagrams environment in a physics classroom in California. The teacher has been regularly involved in the co-planning with our research team of activities using Dynagrams in his classroom.

From pilot teaching experiments with three small groups of physics-naive high school students that took place in Summer 1990, we have begun to see that the kinds of learning conversations we had hoped for with Dynagrams are occurring. Through inquiry activities and "social gedanken experiments," students in their small groups are using, questioning, and refining the meaning of terms in optics such as point source, extended source, reflecting, refracting, absorbing, ray paths, object materials, intersecting rays, object point, image point, image location, real and virtual image, index of refraction. Students are exploring new relations among concepts - such as that a point source emits light in *all directions* not only for a few "special rays," that lenses *bend* light - and new properties of entities (e.g., rays of light propagate in straight lines). There is an excited and enthusiastic use of the dynamic diagramming tools, and mapping activities back and forth between modelling with Dynagrams and hands-on experimenting with optical equipment and light sources. The students engaged in extensive predictions and explorations, far beyond those we have anticipated in the setup of our activities. And after only a few days, groups had achieved a better grasp of the mechanisms of image formation than our pre-Dynagram classroom students had achieved, one girl coming to recognize and teach to others in her group the meaning of a virtual image as including the perspective of the eye. In our previous work, we have found this concept problematic for teachers, not only students.

Studying bids and outcomes of meaning negotiation activities

It may be clarifying to briefly describe some of the ways in which we will be looking at our data from our Dynagrams classroom experiment. We have videotaped for close analysis two groups of three students for each day of optics activities, and the teacher's work setting up and consolidating classroom inquiry activities for the duration of the field-test. Additional outcome evaluations were provided by other data from the classroom as a whole, including frequent homework results, and results from an extensive pre/post test involving paper and pencil reasoning about a broad range of optical situations that tap reasoning processes and concepts described in previous literature on students' pre-instructional alternative conceptions of optics [e.g., 2, 22, 23, 26].

For purposes of analyzing the small group process data, we will be identifying the kinds of meaning negotiation that are central to competent participation in a community of practice for reasoning about geometrical optics. What specific aspects of practice do we find have their meaning negotiated? What are the terms and actions whose meaning is offered up by learners during use that make them available for commentary by others and subsequent cycles of meaning negotiation? And what results emerge in the uptake of repairs by learners who are making moves in these learning conversations?

An Example of Dynagrams Learning Conversations

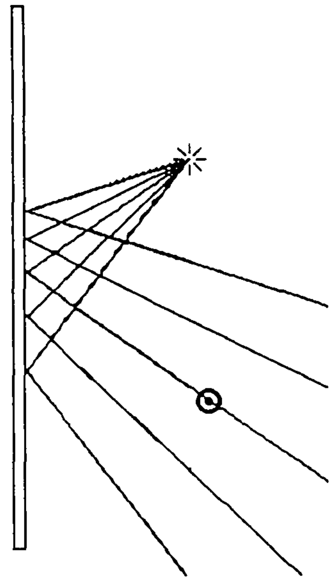
In this section, I will provide an example that illustrates the critical kinds of meaning negotiation processes we see taking place in the discourse of the Dynagrams classroom, and the kinds of learning that can take place as a result of such discourse. I will focus on a major case of meaning alignment that occurred during the second of four weeks in the Dynagrams classroom where introductory physics students were studying geometrical optics.[8] The group is grappling with the concepts involved in understanding image position for a plane mirror. While they start out a class period with a diversity of views for what "image position" means, at the close of the period they share a very different perspective, which appears robust in the individual reasoning profiles of the students in the group a month later[9].

Some background is required to present the example. During the previous day, the teacher had provided one of his favorite full-class demonstrations. At the front of the classroom is a long plane mirror, with an object in front of it. A number of students each gets a long string. Each student then hands one end of the string to the teacher who is standing behind the mirror. Each student then sits down at his or her chair, and the teacher asks them, one at a time, to follow their line of sight to the image they see in the mirror, and then say where the teacher should hold the string above the mirror such that it is aligned with the image they see. What the class determines with this demonstration is that the various strings, one from each student, intersect at a point that is directly behind the mirror and the same distance behind the mirror as the object in front of it. This hands-on collective demonstration provides an important reference experience for the group as they embark during the next day on their inquiry activity with the Dynagrams simulator.

At the start of the session, the three students (*A, *B, and *C; *T refers to the teacher) are engaged in a collaborative sense-making activity where they construct this diagram with the Dynagrams simulator. In this Dynagram screen display, the target represents the observer's eye in the situation, the twinkle-like object is a point light source that is "on," a ray spray of five rays has been directed at the plane mirror, with the diverging ray spray reflecting off of the mirror surface:

[8] I would like to thank Sue Allen and Michael Sipusic of the Dynagrams Project team for their identification and analyses of these sequences of learning discourse from the Dynagrams fieldtest work. For simpler reading of the transcript for our purposes here, I have followed the transcription convention of using // in successive lines to demarcate overlapping speech junctures in the participants' talk. Pertinent contextual actions such as pointing or referent identification are enclosed in parentheses.

[9] Reports on individual student performance are in preparation, and not described in this chapter.



• In this first conversational sequence, we see the students offering multiple interpretations -- all plausible -- of the meaning of the teacher's question: "Where is the image formed by the plane mirror?"

(1) *T: Now, how does this help you find... or what does it help you find out about the image?

(2) *B: About the image?

(3) *T: Yeh. Where is the image according to what you've got here? (the simulator screen).

(4) *C: It's all around//.

(5) *A: The //image according to what we have *here* is on the mirror (points to paper diagram like one they have built on their simulator screen). Yeah, but it is really behind // the mirror.

(6) *B: //Yeah, with the //image.

(7) *T: //OK, but hold it, it can't be on and behind at the same time.

(8) *B: Well, I don't understand this behind thing//

(9) *C: //Well, neither did I

(10) *A: Well, like you said that it appears to be behind the mirror. But, like according to like, these (points to screen - rays bouncing off surface of the mirror), it gets *on* the mirror. Now you see, none of these rays go behind the mirror (points to screen - rays at surface of mirror).

We thus see three interpretations: In (4), *C sees the image as "all around" (as the rays are), in (5), *A sees the image to be "on the mirror" (at the reflective turn of the rays in the diagram) and yet "really behind the mirror" (as they saw yesterday in the string demonstration), while in (8), *B doesn't understand this "behind thing." And in (10), *A notes the hard topological constraint that "none of these rays go behind the mirror." The teacher's role will be to give them a clearer sense of what it means for the image "to be" in some location -- note he is already indicating an unacceptable contradiction between these different interpretations. And the students' collaborative work to negotiate the meaning of these terms will contribute importantly to this objective.

• In a second sequence, we find that this conundrum of "behind the mirror" contradicts *B's beliefs about image formation:

(11) *B: Yeah, like see, like I, I don't really understand this behind the mirror thing.

(12) *B: It's, it's like you look in a mirror, and the only reason that you see anything is because the light reflects off the mirror and you can see an image. Right? (*T nods)

(13) *B: But if there wasn't any light does that mean that the image wouldn't be there? Or would you just not be able to see it?

Her deep philosophical question reveals serious work to figure out what an image "is," to determine the relationship between the rays reaching an observer from an object and the existence of the image.

• In the next sequence, the teacher work through a number of cycles trying to bring the students to see what *he* means by image position. He repeatedly returns to the fundamental idea, conveyed in causal narrative, that our eyes trace back the reflected rays and infer that at the end of those light rays' intersection, behind the mirror, is the location of the image of the light source. The students' diverse contributions to this interchange, including sentence completions with the teacher and noddings, begin to reveal signs of alignment with the teacher:

(14) *T: Alright, now let's go back and pretend that this is a light bulb (points to light source).

(15) *B: OK.

(16) *T: OK. Like the little flashlights.

(17) *B: Right.

(18) *T: Now//

(19) *B: So --

(20) *T: The light is going to be shooting out of that (points to the light source) in all directions, just like we saw here.

(21) *B: Uh huh.

(22) *T: And it is going to be coming towards your eye, right?

(23) *B: Right.

(24) *C: Yeah.

(25) *T: What do our eyes tend to do with the light that they get? They tend to say, "Hey, they started some, someplace."

(26) *B: Uh huh.

(27) *T: OK, so they sort of trace back (triangulating convergent gesture) to say "Oh! at the other end of that light ray --

(28) *B: //Uh huh (nodding).

(29) *C: //Uh huh (nodding).

(30) *T: -- is -- the source." OK? //

(31) *B: //-- is the source. So --//

(32) *T: // Now, I'm standing out here (points to target in diagram representing observer's eye) and seeing these light rays (points to rays diverging from reflection off of the mirror).

(33) *A: Uh huh.

(34) *T: What are my eyes gonna do with them?

(35) *A: They will think //that they came from --

(36) *B: //-- they came from here (points to surface of the mirror).

(37) *C: //Trace back from here (points to the target-eye icon in diagram) to the mirror.

(38) *T: From there? (*T looks at *C, 'there' marked by skeptical intonation, *A,*B, *C then all turn to his gaze)

(39) *B: Well, they are gonna, you don't see them here, do you? (points behind mirror, which has no rays behind it) and //you are going to think that they came from the mirror. You're not going to look to *here* (points behind the mirror).

(40) *C: //Cause they can't come in back of the mirror (*T starts to physically withdraw from the circle, shaking head)

(41) *A: Well no (*T bends back into group). You are going to think that they are all going to meet....they are all going to meet up back *here* somewhere (points behind the mirror).

(42) *B: Right.

(43) *T: They are?

(44) *B: //That's what you are going to *think* .

(45) *A: //That's what you are going to *think* .

(46) *T: That's what I *think* they are going to come from, huh?

(47) *B: Right.

(48) *T: And, and that's what we are talking about with this *image*, see.

(49) *B: OK.

(50) *T: We are thinking "Where did these light rays appear to come from?" They appeared to come from -- //

(51) *B: //-- somewhere *here* (*T points behind mirror after 'here')

(52) *A: Back *here//*

(53) *T: //back *here.*

(54) *C: //Yeah. Hold it .//

(55) *T: //They *didn't* (shaking his head) We *know* they didn't --//

(56) *B: //Right.

(57) *C: //Yeh, OK.

(58) *T: -- but that is where they *look like* //they came from.

(59) *C: //Yeah, because you would think that they just go straight (pointing gesture with hand "through" the mirror on diagram, as if a ray).

(60) *T: Does that help clarify?

(61) *B: Yeah, that totally... I understand (nods her head).//

(62) *T: I know that you have been fighting that.

(63) *B: Uh huh.

(64) *B: Now I understand.

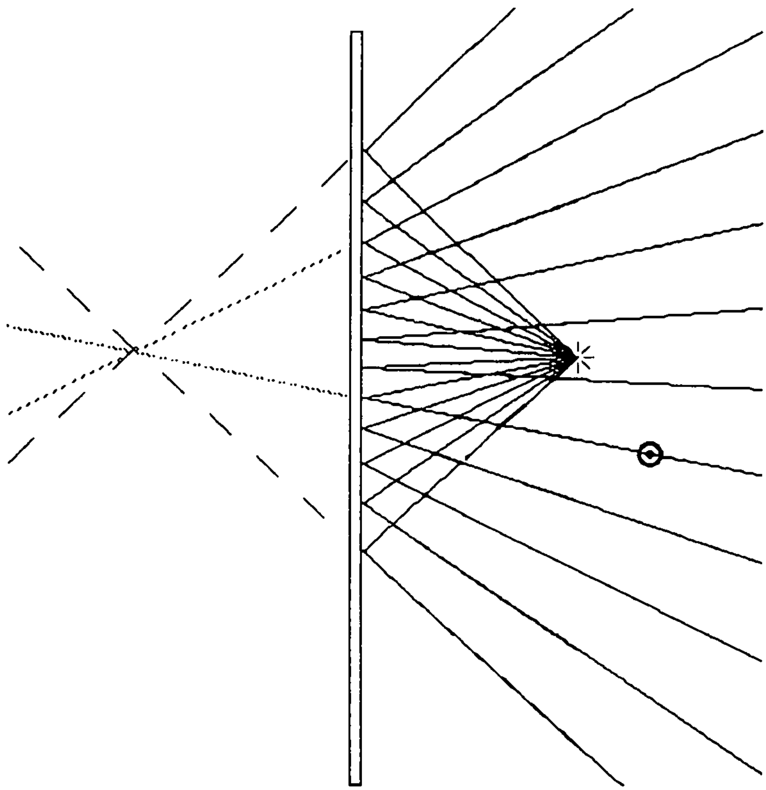
(65) *T: I've got a whole classroom of people in third period that is fighting it too (shaking his head).

(66) *B: I can see *now* what you mean (*T withdraws from group).

(67) *T: OK (nodding).

Note here that, interestingly, it is *A in (41) who attempts to bring the conceptual work of the group into alignment, but *T must still refine *A's claim that "they (the rays) are all going to meet up back *here* somewhere" (pointing behind the mirror), by questioning his phrasing in (43), and getting the better response in (44-45) from *A and *B, sung out in unison, of "that's what you are going to *think*".

• But the meaning negotiation work is by no means complete. There are suggestions that the teacher is aware of this because in (55) and following, *T is still working on the distinction between how we *think* the light rays appeared to come from behind the mirror, but "they *didn't*, we *know* they didn't." At this point, the teacher uses the simulator as a resource for them to use to disambiguate "trace back" -- he constructs a version of the diagram they have been working with but with fewer rays:



The rays reflect automatically and then the teacher and students add the "dumb lines" included in the diagram, which can then be seen to meet at a point (i.e., those traced back behind the mirror, not dynamic rays sprayed from the source). Here are their observations:

(68) *A: That's the intersection. All the lines meet there... (points to image point)

(69) *C: And it's like even across from the other one (noting symmetry with source on other side of mirror)

The students thus notice the two important features of the geometry of the situation: that the lines all meet at a point, and that the point is symmetrically placed behind the mirror with respect to the object.

• In the next sequence, we see that while *A and *B now are using "behind" in the teacher's sense, *C realizes that she is having troubles (which is true, since she is conflating the source and the image). Now let's see what happens after the teacher leaves:

(70) *C: You guys. I can see why like, we said that they look like they would be coming from back there (gestures ray paths from in front to behind mirror), but what does that have to...are we saying that they *are* coming from back here?

(71) *B: No, we are saying that that is what you *think* when you look in the mirror.

(72) *C: Oh man! You mean like when you look in a mirror, you think like//

(73) *B: //Like, if you//

(74) *C: //like you were behind the mirror (nervous laugh) or something?

(75) *A: Well, we know that, so we don't think that. But remember, like...remember when he, yesterday, like in the classroom when he had the mirror, and then he put the image behind the mirror and you had the line, and the string, remember? And then they intersected behind the mirror.

(76) *C: Yeah, that is true.

(77) *B: So.

(78) *A: And that is where the image is supposed to be.

....

(79) *A: So basically...No, if you see... It (activity sheet) says, "Demonstrate how the light can get from the source to the target." Well then it just goes and bounces off... then the target....If you are looking from the target, you can see that it comes from back here. So you just *think* that it is coming like that. So that is like where the light would come from that you would see, I guess (pointing along path from eye target icon to mirror and behind mirror). (8 second pause without any talk as they look at their papers).

(80) *C: That is not like, if you're saying that the source is *there*, right? (points behind mirror, *A is distracted, looking away as she speaks)

(81) *A: What? (*A then orients to her point to the screen behind the mirror). Yeah. You would be *seeing* the source as there.

Note that in (71), *B is now using the crucial characterization (earlier modelled by the teacher) of *thinking* that the rays are coming from behind the mirror, to help *C out in her confusion expressed in (70), as *C seeks to pin down the meaning of the rays "coming from" somewhere. *C seems to interpret *B's (71) use of "think" in the sense of as-in-an-illusion, which one only thinks to be the case. In (72) and (74), *C checks her comprehension by trying out this interpretation with *B, clearly showing us that she sees this check of "You'd *think* you were behind the mirror?" in (74) as patently absurd.

What happens next? In (75), *A, by saying: "Well, we know that, so we don't think that. Remember the intersecting strings...", does the crucial work of first acknowledging the correctness of *C's viewpoint on the absurdity of thinking one is behind the mirror, thus aligning to *C's meaning. Then he continues to offer her an importantly different interpretation of "think," based on their shared experience with the strings demonstration the day before. *C seems to align to *A's meaning in (76) -- "yeah, that is true," and accepts it. Also note one final clarification check by *C to *A in (80), since he is still not crisply describing the difference between where the light *would* come from, and where an observer *would think* it is coming from. *C says: "that is not like, if you're saying that the source is there, right?" (points behind mirror), which *A affirms.

• Finally, in the last sequence, *C resolves her dilemma, and *B summarizes what she has learned. They are reading together the final question from their activity sheet, and drawing their final conclusions:

(82) *B: Why //

(83) *C: "Draw a conclusion why//

(84) *B: //you would think that the image was coming from behind the mirror." And you would *think* that because you would assume that all the light would converge to that point there behind the mirror.

(85) *B: I mean if you were completely stupid and didn't know, didn't know how mirrors worked. You know what I am saying?

(86) *C: Uh huh

(87) *C: Just because you would think it was like a window, or something.

(88) *B: Right.

These concluding sections of discourse are fascinating for several reasons. Note in (79), how *A is now very much aligned with the teacher, both in words and in form of explanation:

- "it bounces" (mechanism)
- "if you were looking from the target" (observer viewpoint)
- "you'd think it was back here" (points to convergence point of rays)
- "you'd just see these rays" (localness of detector)

The second observation is that *B, who earlier was massively confused about "behind," has in (84-85) joined in on the concepts and language used by the teacher, and earlier in the session, by *A. At the conclusion of this session, *B has basically aligned to the same viewpoint as *A. She has managed to transcend the commonsense perspective she had before this learning. She describes the belief that the light is coming from behind the mirror as something one would think (certainly not her!): "if you were completely stupid and didn't know how mirrors worked". Finally, *C makes a very deep metaphoric comment in summing up her understanding in (87), that "it's like a window." *A, *B, and *C seem through this discourse to have become aligned with the teacher and each other.

Summary of the example

We may capture some important general features of learning conversations by way of this example: Students began a classroom session making different plausible interpretations of the things they were seeing, hearing, and remembering (the diagram; the string demonstration the day before; uses of technical terms such as "think,""behind," and "trace back"). We saw important meaning-making activities in the students' talk and action, as they tried to construct the same meaning as the teacher (evidenced by their active listening, nods, agreement, and eventually by their use of the same phrases and explanatory accounts). They raised their own alternative interpretations and questions, clarifying and repairing their understanding during the use of these concepts and terms for inquiry activities. And when he is available to the group, the teacher tries to understand the student meanings and lead them through the use of these terms to new and appropriate understandings more closely aligned to physics norms.

One can imagine that students *could* generate a variety of idiosyncratic meanings for the scientific terms involved - in this case, involving what it means for the virtual image to be behind the mirror. Similarly, one could imagine that students' work in a group would produce discourse at such a vague level that the different meanings individuals hold would not be manifested or resolved in the discourse. But we can see from this example that the teacher's role is critical in serving as a guide to establishing productive inquiry situations, and in providing the kinds of integrative questions that will lead students toward scientific norms and practice. It is significant, we believe, that the students do a major share of the collaborative sense-making themselves. Given the right activities and encouragement, as well as appropriate resources that allow for establishment of co-reference and the building of a common ground of understanding, students will spontaneously do a great deal of impressive collaborative sense-making and meaning alignment, and facilitate conceptual change for each other.

Looking ahead to analyses of Dynagrams learning conversations

While we are just beginning these analyses, we can say with some confidence that analyses of the following aspects of the data will prove fruitful, and provide other critical loci of *appropriation* and *meaning negotiation* activity (see earlier discussion). Such categories highlight important "bids" for meaning presentation in a student's talk, which may then get accepted, rejected, revised, repaired, and so on by others in subsequent turns of talk, and be ignored, or acknowledged, and so on, in that student's subsequent talk:

- Statements of goals and objectives of an activity (e.g., predict a result, explain an observation)
- Selection of means as appropriate fit for achieving a goal in an activity (e.g., Which representational systems are used - lab apparatus, diagram, words, equation?)
- Details of the use of means (e.g., Are the moves in constructing the situation and ray diagram appropriate? Are the moves in using the terms to describe the situation appropriate? Are appropriate moves used to account for the lack of fit of a prediction and observations of its experimental testing?)
- Conclusions that a goal has been achieved (e.g., How do students resolve what counts as "enough" of a fit between their predictions and evidence coming from testing these predictions by running the simulator or observing lab outcomes?)

We will also be analyzing the discourse outcomes of learners' production of these activities, asking how other members of the group or the teacher interpret previous turns of talk, with a special focus on objections, alternative expressions, and other forms of repair that make up the moves of meaning negotiation. Finally, we will look at how and whether students take up these acts of meaning interpretation in repairing their expressions or not.

While we realize that repair and meaning negotiation may have non-local effects (i.e., occurring significantly after their immediate context in time), we will be able to identify what are likely to be locally significant impacts of repair and meaning negotiation during student's collaborative work on Dynagrams challenges.

Results from these analyses will provide a careful longitudinal picture of the ways in which groups of inquiring students, guided by challenge activities and with some teacher coaching, develop through sense-making activities a deeper understanding of concepts, representations, and procedures for scientific conversations about geometrical optics.

Caveats

While we are quite encouraged by learners' sense-making conversations about geometrical optics we have seen in our teaching experiments this summer, and in the recent field test, we can already see some of the challenges that will remain in truly establishing a classroom community of practice that does sense-making in geometrical optics using Dynagrams. As enthusiastic as our teacher has been about the innovations we have designed and to which he has helped contribute, in the familiar context of the classroom, he regularly lapses into his previous routines of demonstrations (using Dynagrams as a new form of lab apparatus) with explanations, and asking and answering his own questions to the students after such demonstrations. It will require an extended effort, focusing more on supporting the revision of the teacher's roles in the school institution, to evolve communities of practice of the kind we hope to establish for science learning. Lampert [37], in her recent work to establish authentic mathematical discourse in the elementary classroom, has characterized the diverse challenges that such a fundamental shift requires.

General Implications for Learning Environment Design

The construction of learning environments is a challenging task that when examined from a social framework becomes all the more demanding. The issue for science learning from this perspective is not so much one of coming to master the component skills of manipulating scientific symbol systems, and the problem-solving skills associated with their use in working on problems. What is most *centrally* "constructed" through experience in scientific activity is the disposition to engage in appropriate scientific conversations, not a set of mental representational structures. Science learning consists of entering into the web of social relations and actions that are constituted by various practices, accountabilities, and duties that make up the discourse of scientific knowing.

I have laid out some of the specific implications for designers of this perspective, and of the charge that computer tools should serve to augment students' sense-making capabilities and their learning conversations. There are both technological and social design goals that must go together to contribute to effective learning that has some chance of surviving beyond experimental treatments in the ecology of communities of practice and institutions. Among these goals are: authentic activity from a community of practice; in-situ role modelling of appropriate activity for a practitioner in the community of practice, and learners' legitimate peripheral participation in that community; opportunities for use of concepts and skills that allow for social meaning repair and negotiation; and the keystone activity of collaborative sense-making through narration -- to provide reasonable causal stories that account for some event with a set of explanatory constructs. While we expect many challenges to establishing conditions for "growth" of such communities of practice in school institutions, we are optimistic that a focus on augmenting learning conversations with computer tools will go a long way toward taking the insights gleaned from successful learning outside school into the classroom.

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