Seeing the light on optics[1]: Classroom-based research and development of a learning environment for conceptual chan(

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Introduction

How do we construct learning environments that are effective in changing the knowledge and practices available to people? Considerable research on the learning of complex subject matter in mathematics, science, and technology indicates that traditional formal instruction has serious deficiencies in establishing desired conceptual understanding and problem-solving practices by students. These are all subject areas in which expertise is very rarely developed by learners "spontaneously", without benefit of cultural interventions.

There has been considerable optimism about the likely impact of cognitive science research on educational practice. For example, the largely curriculum-centered focus of education reform in the 1960's and 1970's has yielded to a largely learner-centered focus influenced by the cognitive research of the 1980's (Linn, 1987; Pea & Soloway, 1987; Resnick, 1983). But while talk of higher-order thinking skills, problem-solving, and

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teaching for understanding resounds through the halls of education conferences and school boards, little evidence of progress toward learner-centered change in the design of learning environments is apparent. Educational practitioners and researchers experience considerable frustrations about the lack of impact of cognitive research on educational practices across a variety of settings. Particularly under-utilized are information technologies, in spite of their pioneering role in the development of intelligent tutoring systems, microworlds, and tools for problem-solving.

It has also become increasingly apparent to researchers concerned with affecting conceptual change in classroom contexts that an analytic paradigm for assessing the effects of educational programs may be effectively supplemented by a systemic paradigm (Salomon, this workshop). In the systemic paradigm, one focuses both in research and design on the whole learning environment, the transactions between learners and teachers, and the learners' interactions with representations of subject matter.

Also at issue is the prevalent wishfulness of a pipeline model of the impact of research on practice, which presumes a fairly linear translation of published research and theory on learning into educational practices (Pea, 1985). Nearly all research on creating effective learning environments with a learner-centered orientation has been laboratory-based and has not dealt with the complexities of crafting a viable alternative to the learning environments now in existence in real classroom settings (for a few notable exceptions, see Driver, Guesne, and Tiberghien, 1985; Newman, Goldman, Brienne, Jackson, & Magzamen, 1989; Osborne and Freyberg, 1985). The project reported here develops a classroom-based research and development methodology that is aimed at working toward implementable learner-centered environments for complex learning that could supersede the pipeline model - by engaging in research and development in the very contexts of learning in which those environments must function.

The Science Dynagrams Project

The Science Dynagrams Project is devoted to integrating research on and development of learning environments in real situations. In the short-term, our objective is to understand the nature of diagrams and other external representations (such as algebraic equations) in learning geometrical optics. We are examining the cognitive and social roles of diagrams, and exploring the use of computer technologies to enhance these roles. Our broader aims are to deepen understanding of the role of dynamic diagrams ("dynagrams") for facilitating learning of scientific subject matter and the development of domain-specific scientific reasoning skills, and to contribute effective designs of associated activities for enhancing science learning outcomes.

Our project methodology first explores the current state of classroom use of diagrams and the understandings of subject matter that result for individual students. This focus allows us to investigate the ways in which existing learning activities using diagrams do (or do not) enable students to reason within our area of interest, in this case, geometrical optics (see below). On the basis of this analysis, we then explore the use of new features of learning activities to help students establish sound conceptual and procedural knowledge in the time available in the classroom. We thus face a major challenge: to invent new means for diagram "enculturation." In particular, we need to design new kinds of *activity structures*, the shaping features of both the physical and social environments which guide and support students' actions. Using activity structures to combine the affordances of new media (e.g., dynamics) and of new kinds of conversational structures (scientific discourse rather than didactic interactions), we hope to support a variety of student actions on symbolic representations and conversations about them and their meanings. Such activities, which involve computer technologies in part, are designed, engineered and tested for efficacy and usability. A project team representing physics education, cognitive science, developmental psychology, anthropology, computer science, and animated graphics design contributes to this work. We believe that our project methodology and interdisciplinary activities may more directly contribute to the goal of linking advances in science learning research with materials and classroom activities development, and have applicability to other arenas of complex learning beyond that of geometrical optics.

The aim of this chapter is to describe the student learning that results from the existing diagram "ecology" in two exemplary classrooms. We report on an analysis of student problem-solving activities observed during individual demonstration interviews, to be described later, which were carried out immediately following instruction. Students used words, diagrams and equations to solve optics word problems involving 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.

Subsequent reports will provide analyses of: (1) the teacher's uses of diagrams during instruction, (2) diagram use by both teachers and students in a different school with a "conceptual physics" orientation, and (3) research and development on the new classroom activities, including interaction with computer microworlds and animations, and group discussions.

Toward understanding diagrams for learning

Diagrams are complex and important external representations which are little understood as cognitive and social artefacts. They serve as markings in the world that have semantic content. They are symbols with semantic content which mediate cognitive activities that, if done mentally, are error-prone and less efficient. Diagrams are also significantly different from pictures, as they commonly correspond to *types* of things in the world rather than individual things. Diagrams play critical roles in the practices of virtually all scientific disciplines, and serve fundamentally in thought experiments, qualitative reasoning, and as objects of conversation among scientists analyzing situations and debating theory.

But compared to text processing and understanding, which has been thoroughly studied at various levels of analysis (word, sentence, paragraph, text), very little is known about the invention, use, or comprehension of diagrams.

It is in the context of formal learning settings that our lack of understanding of the ecology of diagrams - their use, exchange, relationship to activity - is troublesome. It is noteworthy that little explicit instruction takes place in the interpretation and use of diagrams, certainly nothing comparable to what we find for reading texts. How do diagrams come to have meaning for students? How are they used appropriately for reasoning about situations? Like the child acquiring language - in use and without instruction - the student must generate the meaning of scientific diagrams as they are talked about and used in activities with the accessible expert practitioner, the teacher. For this reason, we consider the situated study of diagram use and understanding in classroom contexts to be essential, and the role of language in making sense of diagrams and negotiating their meanings as primary.

Scope of the chapter

Our curriculum topic is *introductory geometrical optics*, with emphasis on image formation by mirrors and lenses. The project is organized in three phases:

Phase 1. We study the "ecology of diagram use and understanding" for geometrical optics in exemplary schools. This includes videotaping expert teachers' use of diagrams for science education and individual students' use of diagrams as they think-aloud and solve optics problems at a chalkboard.

Phase 2. We design and implement *Optics Dynagrams*, a set of technology-enhanced teaching and learning activities. Central to these is an optics simulator which includes a dynamic diagram ("dynagram") construction kit, a videodisc with optical situations and related explanatory animations, and an activities manager for using these materials for learning and teaching.

Phase 3: We will examine how the use of *Optics Dynagrams* affects the nature of instructional practices and resulting student learning outcomes in a classroom whose previous practice and learning outcomes have been documented during the first phase.

This chapter highlights findings from Phase 1 and provides an introduction to how this work is guiding the development of the *Optics Dynagrams* learning environments during our current Phase 2. We will present the results of analysis of student video protocols from one classroom, and discuss the development plans for *Optics Dynagrams* materials and software to be implemented and tested in Phase 3.

Geometrical optics

An understanding of the nature of light has been a major preoccupation of physical science for centuries, and many of the fundamental breakthroughs of physics in the twentieth century emerged from deep investigations of its electromagnetic properties. The special case of geometrical optics - in which light is treated as traveling in straight lines called rays - is a standard part of introductory physical science.

Geometrical optics is a particularly graphics-dense subject. Texts are replete with diagrams of physical situations: light sources emit "pencils" of light; rays are reflected off plane or spherical mirrors; light is refracted as it passes from air into water or glass. Iconic/schematic diagrams made up of line drawings representing light sources, prisms, light "rays," and reflective surfaces are widely used, particularly since such conceptual relations as the ratio of image size to object size are common graphical illustrations.[2]

Previous research on students' understanding of light

These topics typically represent targets of student difficulty in understanding, and a few reports have documented in a preliminary way

[2] In our work to date, we have not examined learning about light propagation by transverse electromagnetic waves because of its much greater complexity. Such learning involves treatment of topics as diverse as Grimaldi's discovery of diffraction, Newton's work on the color spectrum, Young's experiments on interference of light waves, polarization of light, and such devices as the grating spectrometer and Michelson's interferometer. Of course explaining not only the propagation of light but its emission and absorption by matter leads into the intricacies of quantum physics.)

students' preconceptions about light before formal physical science instruction (Anderson & Smith, 1984; Guesne, 1985; Jung, 1981). They have found, using interviews with children about phenomena which for the physicist involve light (such as shadows, vision, mirror reflections, or use of a magnifying glass), that students of age 10-11 tend to represent light as its source, its effects, or as a state. By age 13-14, many students conceive of light as an entity distinct from its perceptible effects, something which propagates outward from a source and interacts with objects it encounters in its path. However, the physicist's notion of conservation of light seems a difficult one for the older children to grasp. They confound light with its visible effects; they may feel that light "gives out" over long distances even though there is no interaction with a material medium, or that light can be "multiplied" by a magnifying glass, or that there is no light when they look at objects or pieces of paper which do not reflect intense light (Guesne, 1985). Many of them recognize light as necessary for vision but do not see the light as reflected by the objects seen (cf. Anderson & Smith, 1984 with fifth graders). They thus do not appreciate that light travels from an object to the eye, which will cause problems during instruction:

"Often a teaching course will start by establishing the propagation of light in a straight line. To accomplish this, it will show pupils that they cannot see a candle's flame through a series of holes punched in a card unless the holes are aligned. Children cannot appreciate this demonstration; they cannot interpret the experiment in terms of the path of the light from the object to the eye, when they do not link the vision of the flame to a reception of light by the eye" (Guesne, 1985, p. 29).

This older group also has a very difficult time with the concept of a virtual image of an object seen in a mirror. Guesne attributes this to the typical explanatory model offered, which rests on the idea that an object is seen because light coming from it penetrates our eyes after propagating in a straight line through the intermediate space.

We are not aware of any cognitive research on the nature of students' understanding of light and geometrical optics at the age level of our interest, 10th-11th grade (15-17 years), at which time students receive their first systematic and extended introduction to the physics of light.

Research studies

The research project thus far consists of two major studies. Each is an investigation of teaching practices in optics, and an in-depth examination of student learning which we conducted immediately following students' exposure to these teaching practices.

Our methodological approach was to select classes for study that are taught by highly experienced physics teachers in high schools widely-recognized as producing an unusually high number of scientifically-oriented student graduates. We expected to learn a great deal from the expertise that these physics teachers had developed in teaching this subject over a significant period of time. We expected that even in these schools, however, we would find substantial variation in student comprehension and use of diagrams in geometrical optics.

The first of these studies entailed collecting videorecordings of optics lessons in an introductory physics classroom in an outstanding science-oriented high school in New York City (henceforth "NY school"), and the video protocols of that classroom's students as they attempted to represent and solve optics problems at a chalkboard using diagrams, equations, and words. The high school in which the study took place has a large physics department, with over a dozen faculty and a department chairperson. These physics faculty have been integrally involved in the reform of the NY State Regents Physics syllabus and examination, and the school is widely considered to be one of the best science high schools in the country. Westinghouse Science Project competition winners from the student body are routine, and it counts among its alumnae a large number of Nobel laureates. Most students in the school will take five years of science before graduating, and half of the students will go on to careers in science, engineering, or medicine.

The second major study required the cooperation of the physics faculty of one school for the duration of the project. At our "CA school", we have videotaped all optics lessons given by an award-winning high school physics teacher, as well as interviews with students from his classroom as they attempted to represent and solve optics problems at a chalkboard using diagrams, equations, and words. In contrast with the NY study, these interviews also incorporated the use of a simple laboratory apparatus (including light source, converging lens, screen, ruler). By including a physical apparatus, we were able to conduct interviews with three principal episodes. First, 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 will continue working with this teacher for our observations of the impacts of Optics Dynagrams on teaching and learning activities, and learning outcomes.

The NY School provided the initial motivation for our study of optics diagram use and understanding by students in the introductory physics class. Here geometrical optics was learned during the second semester of a compulsory first year introductory course on physical science. We began by videotaping each lesson given by the teacher on optics over the approximately three-week period. Our classroom observations and follow-up conversations with the teacher led to identification of the topic of image formation as a particularly challenging and difficult one within geometrical optics, in which the use and understanding of diagrams is essential. Having analyzed student difficulties in tests held during the period of instruction, we then developed an interview guideline to be administered to students immediately following instruction. During the interview, each student was asked to draw diagrams at a chalkboard in order to solve basic geometrical optics problems involving a single lens or mirror.

The class of 30 students we studied was largely composed of juniors (16 to 17 years-old), many of whom planned to continue as science majors. By passing the highly competitive entry examination to get into this school, they had fulfilled minimal state requirements in mathematics and English proficiency. Student participation in the study was encouraged by the teacher. Of the 30 students in the class, we were able to schedule sessions with 24. Optics instruction took place from May 3 to May 26, 1988;

students took their optics final on May 30; their Physics Achievement Test was held between June 6 and June 15; and the interviews took place between June 6 and June 15, just before the June 19 New York State Regents Physics Examination which also covered geometrical optics.

Procedure

Our methodology involved having students think aloud while working on questions within an "individual demonstration interview." Individual demonstration interviews are now widely used as a methodology for revealing students' conceptual models in science, as well as their reasoning patterns and strategies while they learn and solve problems. This method, an elaboration of the Piagetian clinical interview, involves asking students to keep saying what they are thinking as they make predictions and offer explanations during various scientific reasoning tasks. Such tasks may involve real apparatus, pictured or diagrammed situations, or textually-described situations. This technique has been used by Clement (1982), diSessa (1982), Driver et al. (1985), and many others in science education. The method is useful for evaluating specific difficulties students are having, and for characterizing "bugs," "misconceptions," "alternative theories," and so forth that represent students' non-canonical explanations of scientifically explainable events.

The first part of each problem the student attempted was just like those which had served as worked examples in the teacher's lectures, which students had worked in homework assignments, and which had appeared on a test shortly before our interviews. For example, in presenting a concave mirror problem we asked the student to explain using diagrams and words where an image of an object would form, and what size it would be, given a specified distance of the object from the mirror and focal length for the mirror. The student was then asked a non-standard question: what changes will take place in the image as the object is moved closer and closer to the mirror? A similar sequence of queries was carried out for a converging lens problem. The researcher carefully followed the substance of talk so that the student's occasional prompting could maintain his or her thinking-aloud. These prompts were designed to be as non-directive as possible to the student's thinking. The session with each student took approximately one class period of 45 minutes.

Optics diagrams used in the classroom

Before our assessment, the major focus by both the teacher and the students during instruction was a series of diagrams that provided cases where image properties vary in significant ways as a function of object location. One page of diagrams displays six cases of object location for a single concave mirror; another page displays six cases of object location for a single converging lens. These diagrams are reproduced as Figures 1 and 2:

(Insert Figures 1 and 2 here)

There are some noteworthy features in these diagrams, which help make comprehensible what we will come to see are problematic aspects of student problem-solving activities during these sessions:

(1) A side view of optical apparatus setups is presented, with the default assumption that the viewer is looking from the side.
(2) A principal axis divides the mirror (or lens).
(3) The object depicted is an upright arrow.
(4) The object depicted is perpendicular to the principal axis.
(5) The object depicted has its base touching the axis.
(6) Light rays are only depicted as originating from a single point on the object.
(7) Only two rays are depicted as originating from that object point, and they are sufficient to locate the corresponding image point, but not the remainder of the image. One who has the appropriate conceptual model of point-by-point mapping between object and image "assumes" that rays could be drawn which would locate each of the image points that together make up the image that is shown in the diagrams (and hence define its location, orientation and size).

It is characteristic of ray diagrams in introductory physics textbooks to present either arrows or lit candles as the objects whose ray paths are depicted to image formation. The reason is that these are simple graphical objects whose two "ends" can be readily distinguished.

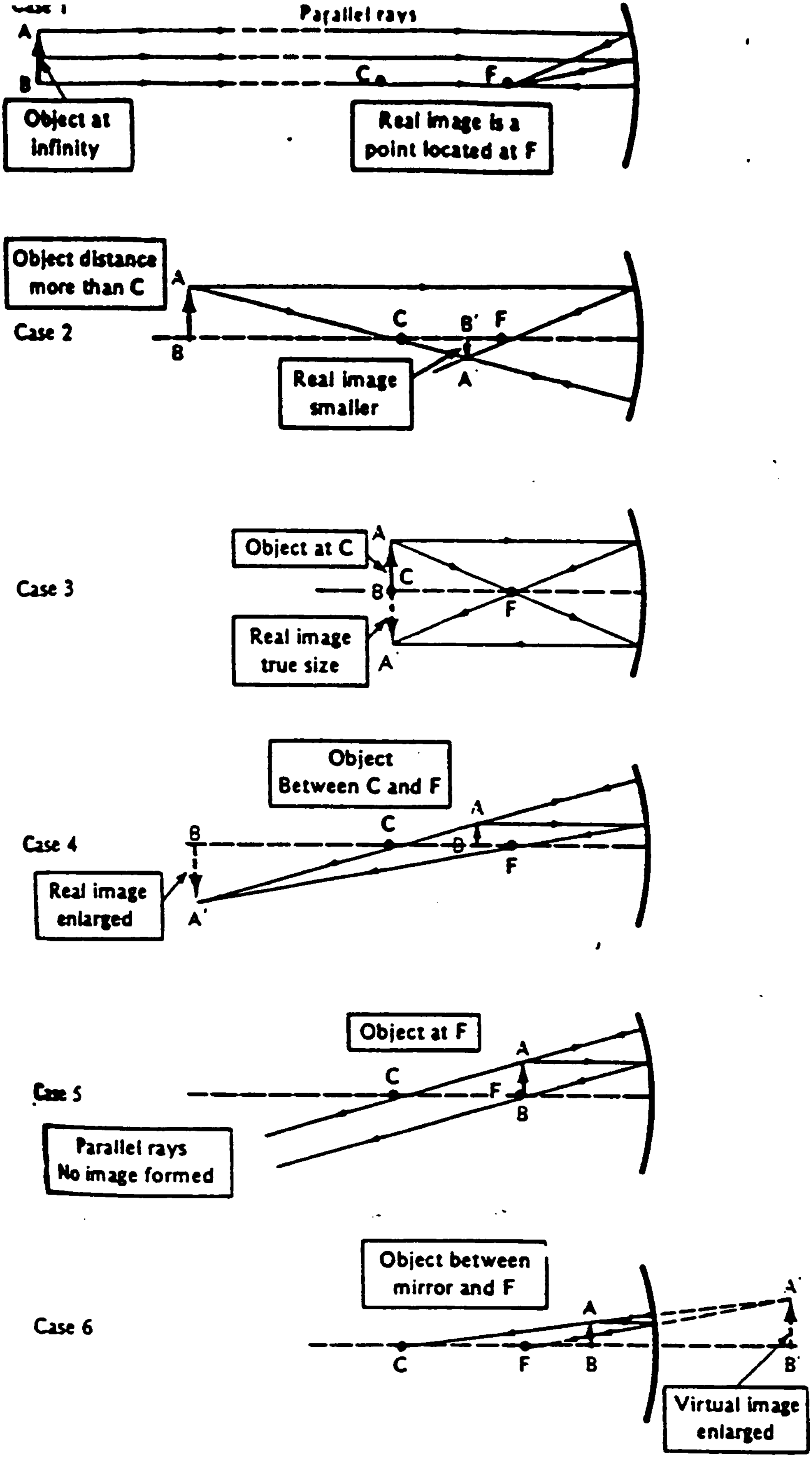

Figure 1. Ray diagrams showing how images are formed by a Concave mirror as the object distance changes.
(From Taffel A. Physics: Its Methods and Meanings. 5th ed. Allyn & Bacon, Co., 1986).

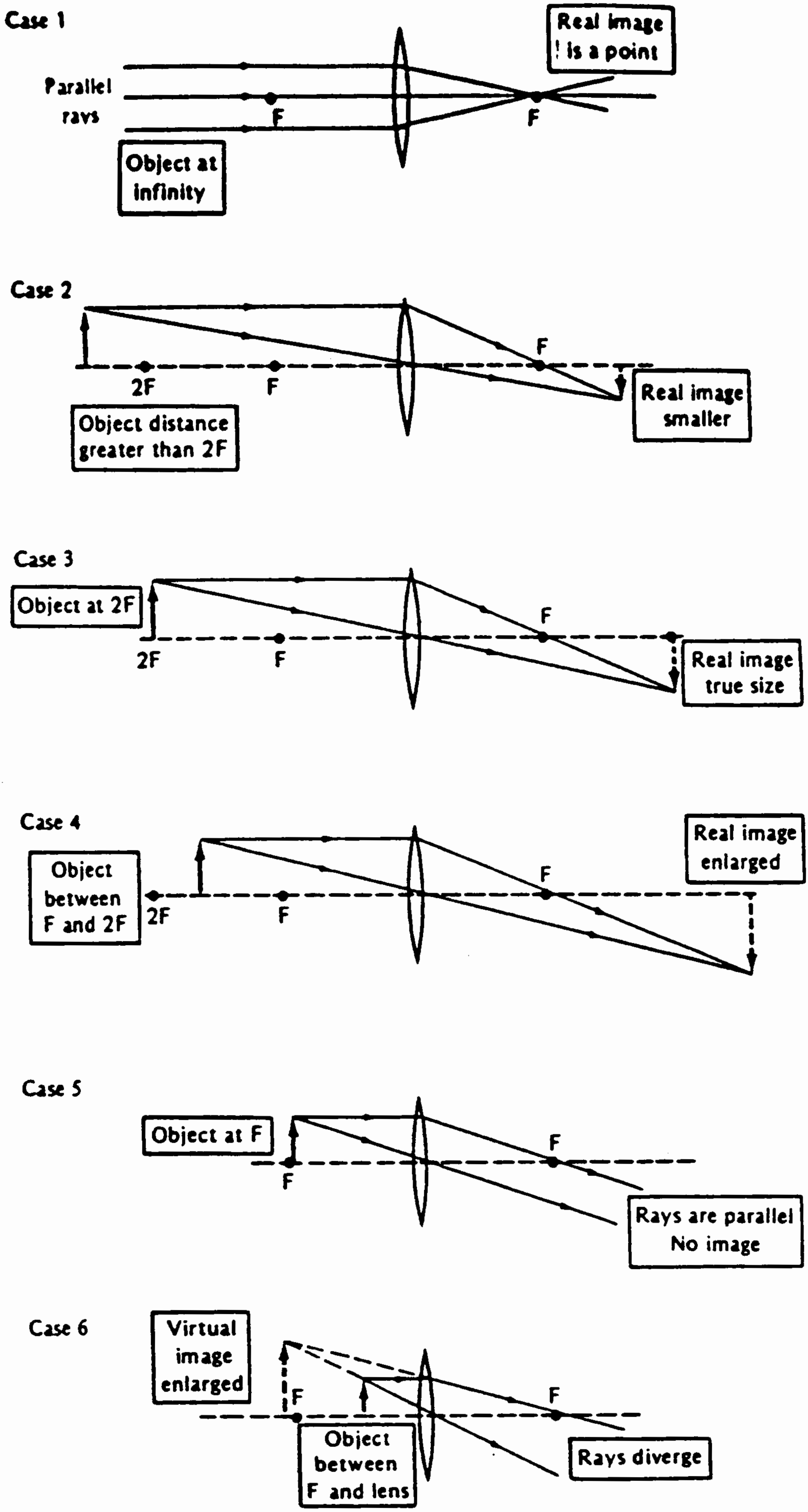

Figure 2. Ray diagrams showing how images are formed by a converging lens as the object distance changes.
(From Taffel A. Physics: Its Methods and Meanings. 5th ed. Allyn & Bacon, Co., 1986)

Research findings

Our resulting video protocols have proven to be revealing of students' difficulties with both diagrammatic representations and the conceptual substance of geometrical optics. We have found that students, even in these exceptional science education settings, had striking difficulties in appropriately using diagrams as symbolic vehicles for thought. We have been examining processes of diagram (and equation) construction and use, in order to diagnose student knowledge of geometrical optics and specific difficulties encountered in learning to reason about this subject matter. Results of this study have influenced the design of *Optics Dynagrams* software and activities for use in our forthcoming classroom intervention, in ways described later in the chapter.

Problems in creating situational and behavioral models for qualitative reasoning

We may distinguish two parts of students' work with respect to the optics diagrams, and characterize problems they had with each.[3] First, a student needs to build a *situational model* from the verbal description. This involves the preliminary work of depicting appropriate optical devices, distances between entities, and unmentioned but required diagram components (such as a principal axis) from the verbal problem description. Then, he or she needs to build a *behavioral model* of the situation using the diagram. This is the process whereby the student graphically characterizes how light will behave as it propagates through the optical system depicted in the diagram. (such as light bending, bouncing, passing through, forming images). This characterization of course assumes that ray diagrams represent the behavior of light for students, which as we shall see, is a problematic assumption. Each part of the modeling process affords many opportunities for error.

Situational model difficulties

In creating a *situational model*, approximately half of the students had difficulties identifying and recreating in the diagram the relevant elements of

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3 These observations are from analyses of the NY data; we have comparable work underway on the CA data.

the optical situation from the verbal description. Often they confused lenses with mirrors, and converging with diverging lens or mirror types. For the mirror problem, roughly two-thirds of the students had problems in translating the radius of the concave mirror into the diagram entities **C** (Center of curvature), **F** (Focal point), and placement of the object relative to **C**. In addition, key components of the optical diagram were often mislocated or left out of the diagram altogether, causing great difficulties when the students attempted to create a behavioral model of the situation. For example, the principal axis was often omitted entirely from diagrams, or located under the lens rather than through its center.

Behavioral model difficulties

Students had a host of problems that together led to very rare success in attaining correct diagram image projections, for either the mirror (7/24 students correct) or lens problems (5/24 students correct). In building a *behavioral* model of light, students particularly lacked a semantics of diagrams to relate their diagrams to real world situations. For example:

- Students generally tended to treat rays as graphic objects (often called "lines") whose rules of transformation and relationships were hard to remember or construct, rather than as conceptual entities in a scientific model of light.
- Instead of using diagrams to reason flexibly about the given problem, most students primarily remembered “cases” of diagrams which related image properties to particular object positions (e.g., "an image is inverted if the object is farther from the converging lens than the focal length, f."), such as those represented in Figures 1 and 2. We assessed students' reasoning about these cases in probes during our sessions with them if they did not mention image properties at these object locations spontaneously. Even then their case memory was imprecise: depending on the object's location, only 30-60% of students were able to remember or construct the two rays from an object point sufficient to determine the corresponding image point.
- On the rare occasions that students did try to use their experiences with magnifying (converging) lenses, telescopes, or plane mirrors to help them answer questions, they usually became confused and unable to complete

the mapping of their experience onto the spatial representation of the diagram. We believe that one factor contributing to this problem may be the lack of viewer perspective in diagrams students ordinarily see and study, making it especially difficult for them to use the "you-are-here" navigational aspect implicitly afforded by such diagrams.

- Applying standard ray diagram procedures to an ideal lens or mirror, one needs any two rays from a given point on an object in order to determine the location of the image of that point. However, two-thirds of the students did not correctly remember the behavior of more than one of the three "special rays"[4] introduced by the teacher for image location.
- Students showed little, if any, evidence of a conceptual model of image formation as a point-by-point mapping from object to image (Pea, Sipusic, and Allen, 1989). Thus many students did not know how to determine the image orientation from the diagram, even though they often knew that an image point is located "where light rays intersect." All students who were able to construct an image did so as follows: they first found the image point that corresponds to the top of the object. They then completed the image by "dropping the perpendicular" to the principal axis, a phrase used by the teacher to specify the technique. No student used any other object point beside the top for ray tracing, even though the technique of "dropping a perpendicular" from a single object point would be insufficient to locate an image of the object if: (1) it were not perpendicular to the principal axis; (2) its base was not touching the principal axis; or (3) the object had sufficient width and/or asymmetry of shape so that its left-right sides needed to be traced. Similar conceptual difficulties were noted by Goldberg & McDermott (1987) in their empirical studies with university students in introductory physics courses.

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4 "Special rays" are those rays that one can use without protractor to roughly define an image location. One special ray runs parallel to the principal axis of the lens (or mirror), which, by definition, refracts (or reflects) through the focal point. A second special ray, for the concave mirror, is one through its center of curvature, which reflects back directly on itself. Since the special rays that are useful vary across object location cases even within a given type of lens and mirror (see Figure 3, next page), it is not surprising that students find their attributes hard to remember. And only a very few students have an understanding of the conceptual model of light sufficient to generate the special rays.

Figure 3

Variations in the Construction of the Second Ray for the Ray Diagram Procedure Across Cases

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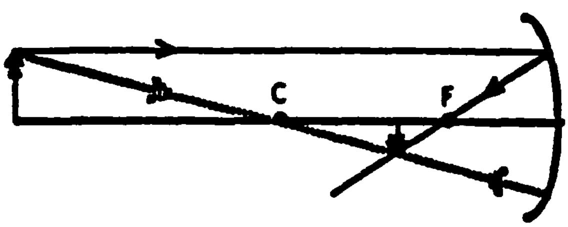

In case 2, the second ray leaves the object, passes through C, the radius of curvature of the mirror, which insures that the ray will strike the mirror surface at a 90 degree angle of incidence. By the Law of Reflection, the ray will reflect at the same angle, returning along the same path, back through C, to the top of the arrow.

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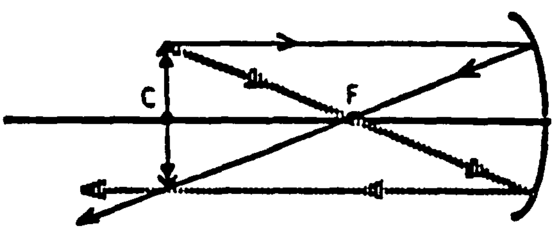

In case 3, by virtue of the objects position at C, the 2nd ray can no longer leave the top of the object and pass through C. To patch our first procedure for the 2nd ray, we must use another privileged ray, through the focal point, which upon stiking the mirror, reflects in a line parallel to the Principal Axis.

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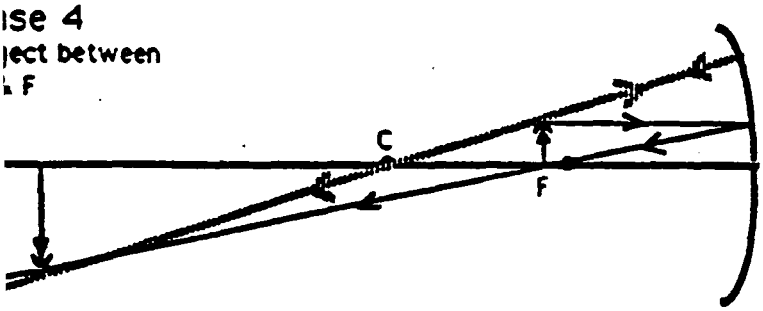

In case 4, a variation of the ray leaving the top of the object and passing through C is required. In the previous drawings, the ray leaves the top of the object, goes through a "privileged point", reflects off the mirror, and returns in a predictable manner. In this case, the drawing sequence is altered so that the light ray first reflects off the mirror and then "seeks" the point C to pass through.

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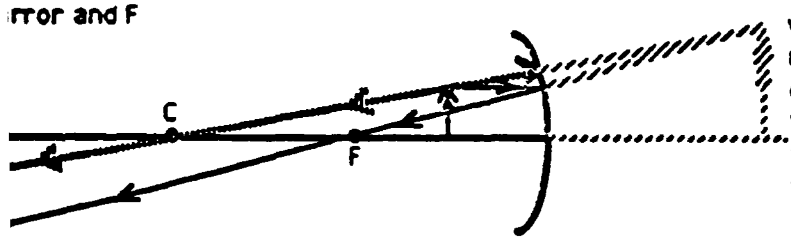

The second ray in case 6 is similar to the ray drawing procedure used in case 4. In addition, one has to extend the virtual equivalent of the ray behind the mirror till it intersects with the extension of the first ray. The cue for this drawing move is the graphic fact that the rays are diverging after reflecting from the mirror. Since an image forms at the intersection of the two rays, the only way that goal can be achieved is to break the light barrier of the mirror, extending a special light to form an image where no light actually exists.

- Some of the students seemed to have the belief, also documented in some ongoing studies by Goldberg and colleagues (unpublished data), that an object's image travels holistically through space. For example, one of our students noted that "it goes through and flips over."

Problems in quantitative reasoning

Students needed to remember two different equations to find the numerical values for the location and size of the image. The location equation, known as the "Thin Lens Equation," (with a corresponding formula of the same form for mirrors) specifies that the reciprocal of the focal length is equal to the sum of the reciprocal of the distance of the object from the lens and the reciprocal of the distance of the image from the lens:

$$1/f = 1/d_o + 1/d_i$$

The equation for determining image size as a fraction of object size, takes the form:

$$size_i/size_o = d_i/d_o$$

Most students had great difficulty remembering these equations, in spite of their recent need to know them in the New York Regents examinations. Only about a third of the students remembered the Gaussian lens (or mirror) equation which relates image distance, object distance, and focal length. Many of those who could had difficulties mapping its numerical results onto the mathematical parameters of their diagrams.

How to account for these findings?

We believe that adequate scientific explanations of student activities in our interview sessions have many layers of complexity beyond those dominating the research literature on student "preconceptions" and "misconceptions" in science learning. Based on our analyses of both classroom activities and student interviews, we have identified five major classes of problems which are reflected by our students' difficulties:

(1) Impoverished discourse contexts of diagram use in the classroom for meeting the objectives of having students use diagrams as conceptual reasoning tools.

We have conjectured that there is a social construction of diagrams as meaningful objects of conversation and tools for reasoning. Unfortunately there are few opportunities in the classroom for students to have *accountability* for being able to use diagrams and relate them to real situations - even those in the lab, much less in other non-technical optical situations. Diagramming is treated as an activity remote from lab work, used for problem-solving only, as part of homework assignments. Thus, students do not make explicit for the teacher their understandings of the relations of diagram components and their correspondences to world situations. Students do not learn how to get connected to a diagram as a device to see through to the world, as subject matter experts in optics do.

We describe below as "missing" from our classroom of study many of the pragmatic functions of diagram discourse that *could* enculturate students to the appropriate use of these representations:

(a) *Diagrams are rarely used as predictive devices which support the making of conjectures and their experimental testing in the lab.* Students' intuitive expectations about where images will be formed in a particular system are not solicited or expressed in the classroom.

(b) *Diagrams are not used to convince, persuade, or argue about these conjectures.* The French sociologist of science Bruno Latour (1986) has written a provocative paper on "Thinking with the eyes and hands" which has influenced our conception of diagrams as representations. His analysis originates from his studies of the creation and uses of diagrams, figures, charts, and other "inscriptions" in the laboratories and at conferences of scientists. He is particularly concerned with understanding what gives such representations their obvious powers. His argument is that:

> "A new visual culture redefines both what it is to see, and what there is to see....People before science and outside laboratories certainly use their eyes, but not in this way. They look at the spectacle of the world, but not at this new type of image designed to transport the objects of the world... to label them with captions and legends, to combine them at will." (p.10)

> "What is so important in the images and in the inscriptions scientists and engineers are busy obtaining, drawing, inspecting, calculating, and discussing? It is, first of all, the unique advantage they give in the rhetorical or polemical situation. "You doubt of what I say? I'll show you." And, without moving more than a few inches, I unfold in front of your eyes figures, diagrams, plates, texts, silhouettes, and then and there present things that are far away and with which some sort of two-way connection has now been

established. I do not think the import of this simple mechanism can be overestimated. Eisenstein has shown it for the past of science, but ethnography of present laboratories shows the same mechanism....One simple way to make the importance of inscriptions clearer is to consider how little we are able to convince when deprived of these graphisms through which mobility and immutability are increased." (p. 14)

(c) *Meta-discourse about diagrams is missing.* What it means for something to be a useful diagram for the purposes of inquiry or design at hand is not discussed. Yet the limits of diagrams need to be understood. This discourse more generally connects to what Susan Carey has called "metaconceptual understanding" in science; it includes talk about model-building and the inadequacies of models when extended beyond the limits of their assumptions.

(2) Lack of connection between real optical situations and diagrammatic activities in classroom discourse.

There is a well-intentioned use of world situations to introduce optics topics as mandated by the NY state physics curriculum syllabus guide, but student's preconceptions about light are not addressed in the instruction, and the testing procedures used by the school and state do not identify these difficulties.

Students do not build graphical depictions of physical optical situations by constructing diagrams. There is very little mapping activity in which the translation from situation to diagram and back to situation is travelled. Diagrams are used predominantly in lectures and textbook problem-solving activities, but diagramming is not used in labs or required in testing. It is not surprising that students have difficulty in recognizing or remembering how diagrams refer to real-world phenomena, because students' experiences with image formation have not served in the constructions of these memories through mapping activities. Diagrams are thus used to tell a self-referential story about conventions for their construction. This focus on the syntax rather than the meaning of diagrams leads to a stranding of students' conceptualization and use of diagrams from their experience with the behavior of light either in the laboratory or in the outside world.

(3) Insufficient concept formation work on properties of lenses, mirrors, light sources, images

During the social construction of meaning for science concepts and representations (such as diagrams), there is a classic tension between "meaning" (considered as archival "dictionary" meaning) and "use" (considered as live "cultural practices" of meaning-in-context) of science concepts. Many of our students were facile at memorizing dictionary meanings of scientific terms for later recall on a multiple-choice test; the class test scores averaged in the mid-80's for both the physics final and the NY State Regent's Exam. But applying these concepts to a series of situations in which they play a causal role is more problematic. Procedures for concept use are rarely given in the definition of a technical term, so that students have understandable difficulty in using concepts as building blocks for reasoning.

(4) Use of deficient or misleading static ray diagrams

Sometimes the eye-view *on* a diagram and *in* a diagram are not distinguished, leading to particular student difficulties with understanding the nature of virtual images. Understanding of optics diagrams is intimately bound up with perception and perspective. One's whole experience of visual reality is grounded in object perception of the material world. This, in turn, is governed by how light forms images, and the role of the placement of eyes as information processors of patterns of light. Yet perception is rarely taught in physics (including the classrooms of our study) beyond placing eyes in some diagrams and noting that the angle of incidence is somehow important to the eye's processing of light.

(5) Peculiarities of assessment procedures that come to influence what students view as significant for them to learn through the instruction

For example, in the NY school, students' formal assessment activities include a NY State Regents Examination, which is in a multiple-choice format *not* requiring student construction of diagrams. This is the means by which accountability of instruction to norms is established. Naturally, students' (and teachers') concerns about the subject matter and their study strategies are directed largely toward success with that evaluation performance. Since mappings between world situations and diagram components are not required by tests, memorizing cases and equations is an alternative path to "success" in the school system's terms.

Activity structures for sense-making in optics

A major way in which students come to what optics diagrams "mean" on this view is through their use for various but specific purposes in the discourse of the classroom. But without their uses for explanation, prediction, and justification, they cease to function as tools for scientific thinking and discourse.

In this regard, one unusual aspect of our work is the treatment of diagrams as *social* objects, as well as *cognitive* objects. Current work on roles for diagrams in scientific thinking highlight their information processing properties, examining how problem-solvers substitute perceptual actions on diagrams for logical actions on mental representations of text propositions (e.g., Larkin & Simon, 1987). We recognize the importance of these features of diagrams. However, we believe that for enhancing the practices of science education, it will be as or more important to articulate the ways in which such diagrams serve (and could serve better) as "conversational artifacts," i.e., designed objects that mediate conversations that can lead to new conceptual understanding. Diagrams as social objects may 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 could reflect the behavior of a system under various perturbations.

For such goals to be achieved, new kinds of activity structures will need to be designed. These activity structures should provide the shaping features of both the physical and social environments which guide and support students' actions. What are some of the needed features of activity structures?

Two fundamental concepts for analyzing learner-teacher communications contribute to the design of our activity structures: *co-registration*, and *discourse accountability*. Students and teachers need to become aligned in their attentional states - to *see* situations *as* ray-diagrammable - in order for students to reason with diagram representations according to the conventions that have determined their usefulness. This "co-registration problem" is fundamentally *social* in nature, requiring the alignment of the student's attentional state/linguistic state mappings for an optics diagram (or situation to be represented for purposes of investigating its optical properties) with that of one (such as the teacher) who is facile with optics representations.[5] Members of a community using ray-diagrams *see through* such representations to the conceptual entities to which they refer, since they are connected similarly to them. The classroom discourse practices we observed were insufficient for picking out the structural features of the world for aligning student attentional and linguistic states to the purposes of the scientific community using ray diagrams as representations for optical situations.

Students and teachers need to become similarly connected to action in situations (i.e., reasoning about optics) by means of diagram representations. Conversations can promote a re-registration for a learner of situations and diagram-situations correspondences, through the pointed-to and the talked-about, and their alignment between the learner (L) and science practitioner/teacher (T). Coming to co-registration of diagrams and situations involves a kind of "ontological attunement" of L registrations of what-there-is in the diagram and situation, and the T's registrations. What may get "connected" by a diagram (in use) is L's and T's registration or parsing of the world that it is about. By T's crafting a diagram and talking/pointing to it (or its parts) in a conversation with L, T is trying to get L to become similarly connected to the situation it is about, or to relations among its parts as a representation. Being "similarly connected" involves L and T "registering" the same things in that referential space. This is often a complex matter, since L and T may believe that they are referring to the same thing, and come to discover only through conversation the need to repair their alignment of registrations of that situation.

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[5] Our discussion on registration and attentional states is indebted to some ongoing unpublished work by Stucky and Greeno at IRL on uses of number words to count.

Thus, the objectives of co-registration (shared attention) and discourse accountability are fundamental constructs of these new conversations. Empirically determining whether two individuals are co-registering an event or diagram may be underdetermined by the data available in their talk and other activities, but repairs of registration which work to do alignment between the conversationalists is one indication. It may often be the case that two persons are not co-registering a situation, and do not know this, since their registration deviations have not been conveyed in the evidence of joint activity, and no repair has been necessary. What these registration problems make evident is that the ray diagram representational system serves to create objects and relations for conversation, and to allow for negotiation of meaning in problematic situations, not as "pictures of reality." The diagram serves as a social memory mediator.

"Discourse accountability" is an insight about diagrams we have borrowed from ethnomethodology. Two speakers may believe that they have the same understanding of a term, such as "virtual image," and proceed for a very long time without coming to a situation in which their uses/interpretations of the term become clearly out of joint. The "repairs" that take place between speakers in doing the alignment of meanings - that they had earlier presupposed *were* aligned - are very important phenomena that give us insights into the mutual sense-making that underlies discourse. The problem for the co-registration of diagrams as subject-matter representations between student and teacher (as representative of the community of physics) is that there is too little discourse, and thus too little opportunity for students to encounter the accountability to conventions for diagram meaning and use that they should. In the absence of repairs, it is easy for the teacher to believe that the students have "mastered" the ray diagram representation for reasoning about image location and image properties.

Now we will briefly detail how we have taken our classroom research findings and our orientation to establishing a culture of sense-making for optics through activity structures into the task of designing a learning environment.

Developing the Optics Dynagrams learning environment

Having identified the broad range of problems that students have in using diagrams to reason about geometrical optics - even in "excellent" instructional environments - we have embarked on Phase 2 of the project, to develop an interactive learning environment aimed at overcoming many of these difficulties. While this phase is still underway, we can give an overview of plans and progress to date.

We are directed in our research toward the provision of *classroom-realistic learning activities.* We conjecture that research should work to understand existing teaching practices and learning outcomes, and the realities that influence actual classroom activities. We argue that seeking to engineer change *in situ*, based on a deeper understanding of constraints on teaching-learning practices and outcomes, is a more productive research transfer methodology. Our vehicle for such engineering is a software program for interactive optics diagrams, along with a set of activities designed to foster the kinds of interactions we think characterize learning-effective discourse in the classroom.

Our learning activities establish discourse contexts for predicting, explaining, and testing predictions about optical system behaviors. These activities utilize a computer simulation of geometrical optics for diagram construction, and overlay computer animations that gradually "fade" into diagram representations.

The Dynagrams simulator is the centerpiece of the software environment. We have chosen "direct manipulation" as the interface paradigm most suited for our purpose[6]. This paradigm is readily supported using object-oriented programming techniques and Allegro Lisp has been selected as the

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[6] Unlike direct command language communication with the computer, a "direct manipulation" paradigm for human-computer interaction builds on users' intuitive physical knowledge about how to interact with objects represented on the computer screen (Hutchins, Hollan, & Norman, 1985). For example, in our case, one can 'grab' and 'move' objects, 'stretch' rays, 'open up' objects to see or change their properties, and so on.

implementation environment. Among the key features of Optics Dynagrams will be:

(1) Support of situational model-building, given a problem presented in a format of video imagery, natural language, or mathematical description.
(2) Support of behavioral model-building, given a situational model already constructed or one constructed by students.
(3) Support of the social activities of explaining, predicting, and justifying optical predictions.

The core notion of an optical dynagram is that it should serve as a conversational artifact during the teacher's and students' constructions of predictive and explanatory causal narratives. As such, it is oriented toward supporting co-registration and discourse accountability as described earlier. Conversational support is provided by the following system properties of dynagrams: they are to be configurable, interactive, inspectable, arguable, and replayable. Each of these properties is explained below.

An Optics Dynagram is *configurable* in the sense that it captures (reifies) features of a student's understanding which may then be referred to in subsequent discourse. Unlike the temporal succession of spoken utterances in classroom talk that are soon lost beyond recall, the diagram remains unaltered. Nuances of meaning are discoverable in the dialectic of social discourse around the diagram. This reification should make it possible to arrive at shared meanings for the technical vocabulary used in making sense of an optical phenomenon. Differences in teacher-student discourse with and without indexical support from a configurable dynagram will be a subject of our classroom research investigations.

Dynagrams are also highly *interactive*. Students model the physical situation by constructing a situational model, configuring a diagram of objects and their spatial relations. They then create a behavioral model of light propagating through the diagrammed optical system. The connecting of the objects in the diagram by rays or cones[7] constitutes a simple form of visual programming, which can be interpreted or "run" by the machine. The key

[7] A cone is a "solid" bundle of diverging or converging light rays that form a cone shape.

aim of the simulator is to encourage students to make public conjectures by reifying the process of construction and displaying diagrams. Feedback on the executability of a particular diagram configuration should be rapid. One possibility is a two-stage interaction process. In the first stage, students request the simulator to run their model. If the model is unrunnable, the system asks the student in the second stage to select a part of the model that the student would like to get feedback on. By making it easy for students to record their diagram conjectures for public display, we hope to encourage active participation by students and to provide context-based support for refining their conjectures.

Dynagrams are *inspectable*. A feature of the simulator that we hope to evaluate is the facility to query an object in the simulator about the knowledge that pertains to that object. "Poking" on an object would elicit a hypertext menu of topics ranging from its properties, to its technical definition (in text), to multiple examples on videodisc of its real world exemplification. Providing access to excerpts from the technical literature in the activity context of solving a challenge presents conceptual knowledge as a useful tool for problem-solving. This feature is like an "on-line help" system for a software application. By contrast, the traditional approach to textbooks is to provide all the necessary conceptual information preliminary to solving problems with those concepts. Continuing with the "textbook as documentation" metaphor, it is significant that human-computer interaction research (e.g., Carroll, 1988) reveals how rarely users read documentation as background to understanding the software they want to use. Instead, users read the minimum necessary to embark on an authentic task, and then obtain information out of the documentation as a means to repair troubles encountered during the task. Concepts learned in context by this information-on-request feature may thus prove to be more understandable and memorable than traditional textual presentations.

Dynagrams are *arguable*. Upon completing the exploration entailed in constructing a qualitative behavioral model, the student (or student group) will be asked to construct an explanation of the model that includes justifications for the diagrammatic configuration. The primitive elements of justifications will include the scientific principles of geometrical optics (e.g., Law of Reflection), and technical definitions of the domain (e.g., focal point; convex lens). Building an explanation involves selecting entries from the information-on-request facility, annotating the model with these selections, and creating sequences of such explanations. Since a student's model is now justified by a structured argument, the focus of discussion when a model is falsified by "running" the dynagram simulator appropriately becomes the elements of this structure.

Dynagrams are also *replayable*. It will be possible to play back a series of model configuration and justification actions in *Dynagrams*, thereby linking the conceptual content that justifies a model to the model. Prior challenges may be replayed and configurations which occur at impasses saved. The utility of these "thinking process replays" as materials for student learning and instructor use (for teaching-relevant assessment) will be examined in our subsequent research.

New dynamic animations of ray diagrams are incorporated not so much as a support for solitary reasoning by students, but to facilitate negotiation of meaning in conversations about physical situations, and the use of dynamic diagrams to predict and explain, test predictions, and revise beliefs given such cycles of activity.

The classroom situation for initiating use of the *Dynagrams* learning environment will primarily be small groups working at a table with a set of physical objects for producing light phenomena, and a videodisc machine controlled by a computer. The students will be asked to model or explain an optical system constructed with the physical apparatus. Exploration of the physical situation will be encouraged. Since some conceptual entities (such as light rays) are not directly visible in the physical situation, a critical step in constructing a situational model with the Dynagrams simulator involves representing the conceptual entities and their relationships with the physical objects which are directly observable.

We are also exploring the use of computer animation tools to create non-interactive representations of simple optical systems. We call these representations "conceptual fades," and conjecture that they will help establish semantic mappings between real optical situations and diagrammatic representations. In one such representation, physical objects and their spatial configurations are preserved, while visible light representations, such as rays or cones, are superimposed. Animations of these prototypical light systems (such as a light source, converging lens, and screen) selectively dissolve elements of a video picture of the physical apparatus, while simultaneously overlaying the corresponding diagrammatic entities in their proper geometric configuration. This will be the dynamic equivalent of the construction of a diagram to model an actual situation depicted by the video image. The conceptual fade thus serves as an intermediate representational "bridge" between the physical apparatus, or natural event, and the interactive optical simulator.

Conclusions

Creating learning environments informed by classroom-based research on student conceptions and the effects of existing instructional practices is a new challenge for education. In this chapter, we have outlined our progress on the Optics Dynagrams Project, which has these aims. While new technologies may offer great potential for enhancing learning outcomes, it will be essential to incorporate them in activity structures that both provide the kinds of authentic scientific practices that are conducive to understanding, and that allow for their realistic assimilation into instructional practices.

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