Designing classroom discourse resources for conceptual change in science: Dynagrams

Principal Investigator: Roy Pea

Research Group: Sue Allen, Shelley Goldman, Susanne Jul, Miriam Reiner, Dan Shulman, Michael Sipusic, Erik Slavin

Institute for Research on Learning, Palo Alto, California

Final Project Report for NSF Grant #MDR-88-55582*, August 1991

Abstract

The Optics Dynagrams Project is a classroom-based research and development project that is investigating the use of diagrams in science learning, and how computer technologies might enhance the roles of diagrammatic representations. Our curriculum topic is introductory geometrical optics, in particular, image formation with mirrors and lenses.

The project was organized in three phases. In the first, we studied the ecology of diagram use and understanding for geometrical optics in two exemplary high school classrooms. This included videotaping expert teachers' use of diagrams for science education and individual students' use of diagram problem representation and topic understanding as they thought-aloud and solved optics problems with diagrams at a chalkboard. In the second phase, we used these results to influence the design and implementation of *Optics Dynagrams - technology-enhan* teaching and learning activities. Central to these is a set of challenge activities integrating learning with an optics simulator we created, which includes a dynamic diagram ("Dynagram") construction kit, hands-on optical tools, and videotape with optical situations and related explanatory animations for scientific visualization. These small-group activities involve continual mapping between real-world experience of optical situations and formal representations of optics concepts and relations (ray diagrams). In the third phase, from Fall 1990 through Summer 1991, we examined how the use of *Optics Dynagrams* changed the nature of instructional practices and resultant student learning outcomes in a classroom whose previous practice and learning outcomes have been documented for this science topic during the first phase. Significant learning outcomes were apparent for conceptual change measures and in students' diagram use and understanding, although some aspects of students' conceptions of light-matter interactions and classroom activity design implementations were resilient to change in this iteration of the new learning environment.

The scientific importance of this work resides in its potential for deepening our understanding of the role of dynamic, visual representations (dynagrams) for building understanding of scientific subject matter, and of effective designs of learning environments for enhancing science learning outcomes. We have been developing a different approach to learning-teaching technologies as *augmenting* learning conversations by providing a communicative medium for collaborative sense-making.

---

* The title of the original grant was "Cognitive Processes in Understanding and Using Scientific Diagrams."

Introduction

In this report we provide a case study of a classroom-based research and development program that begins with an investigation of existing teaching-learning practices for a well-circumscribed piece of curriculum, then designs and develops a new learning environment intended to redress a variety of shortcomings of those practices for students' achievement of subject matter understanding. We conclude with an analysis of changes in teaching-learning practices that resulted from uses of this research-guided learning environment. We consider such research and development in the midst of situations of learning and teaching essential to advance basic research that is useful for the improvement of educational practices.

Our target curriculum is introductory geometrical optics in a first year physics course, and particularly topics in image formation with lenses and mirrors. Understanding the nature of light has been a major preoccupation of physical science for centuries. Fundamental physics breakthroughs during the 20th century have emerged from deep investigations of light's electromagnetic properties. The special case of geometrical optics - in which light is treated as traveling in straight lines called rays - is a standard unit in introductory physical science. For our project interests, geometrical optics is a particularly diagram-dense subject. Texts are replete with diagrams of physical situations: point light sources emit rays of light; rays are reflected off plane or spherical mirrors; light is refracted as it passes from air into water or glass. Iconic diagrams comprised of line drawings representing light sources, lenses, 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.

We begin by providing an account of what learning problems students had that made a new learning environment design appropriate. Previous research on science learning, teaching practices in classrooms, and assumed roles for technologies in teaching-learning practices will be introduced in the context of these discussions. A principle objective of our presentation of this project is to provide a well-articulated model of the component parts of our activity, and its consequences for teaching-learning processes that would recommend that other researchers utilize such a classroom-based research and development strategy. We make the case that the classroom level research, and the methods we use in analyzing learning-teaching processes and design of new learning environments to remediate identified problems, are likely to be applicable far beyond our specific content domain of optics.

Our methods involve characterizing the learning problems and their proposed solutions in terms of teaching-learning processes, including activities with talk and representations. We were led in our investigations to a focus on the interpersonal construction of the referents and meanings of technical terms and other symbols such as diagram components used for specific scientific reasoning activity. How are the symbols used by teacher and students related to other concepts? How do learners come to change their perceptions of appropriate concepts and causal language for accounting for optical events?

We contrast this approach with much of the research literature on preconceptions, alternative conceptions, and misconceptions, which primarily consists of "snapshots" of student beliefs about empirical phenomena at a given point in their conceptual developmental history. Such an approach neglects empirical study of the teaching-learning processes that may have contributed to those findings, and the kinds of learning conversations that may contribute, positively, to conceptual change in the desired direction of science pedagogy.

We also find that a critical aspect of our approach involves the articulation of design tradeoffs in learning environment design. Inevitably, and whether through conscious attention to the tradeoffs or not, a planned learning environment and an enacted one (which can easily deviate from the "plans") embody specific choices, with attendant consequences in terms of resources required, student learning outcomes observed, teacher education required, and the like. Whenever possible we will work to make explicit the tradeoffs we have identified, and the rationale for the choices we have made. One example is the *access/understanding* tradeoff: By providing high-level primitives such as lenses in an optics microworld, many students are provided access to reasoning tasks involving them. But by providing these lenses as primitives, the students' learning has bypassed the understanding that could have resulted if the students were to have built up the lenses from a more basic programming language (they would have come to recognize the idealizations and assumptions underlying the creation of the lens primitive by the software designer). This debate emerges often in relation to Logo, Boxer, and microworld-based learning.

A second example is the *results maximization /feasibility/* tradeoff. It is not uncommon for research activities involving technological innovations in education and curriculum materials development to have a member of the research team carrying out the "instructional treatment." The assumption is that that researcher understands the intentionality of the designed-for teaching-learning objectives so well that the learning results that may be observed will be maximized (as compared with the normal teacher for the class). But this researcher-intensive instruction runs the common risk of making for an unfeasible, "hothouse" research environment in which the likelihood of replicating the effects observed with the regular teachers is in question.

Another example is the *coverage/depth* tradeoff: one can choose to pursue learning for understanding in depth, but this may cost weeks of curriculum coverage time then not spent on other subject matter topics. We feel that talk about such tradeoffs, and the design space they represent, is critical for advancing the scientific understanding of learning, and for improving educational practices.

Methods

In this section, we briefly explain our overall set of methods and theoretical commitments intrinsic to the methods. We include details where appropriate in terms of research questions, methods, findings for each section.

Research sites

Our methodological approach was to select in New York and California 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. Even in these schools, we expected to find considerable diversity in student comprehension and use of representations, concepts, and strategies in geometrical optics.

General methods

Our methodology for the 1988-1990 clinical studies involved having individual students think aloud while working on questions within an "individual demonstration interview." Individual demonstration interviews are 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.

In 1989 and 1990, we added Modelling Tasks to this clinical interview, and reduced the Word Problem Task for a given student to only a lens (all 1989 students), or a mirror (half the 1990 students were in a Lens group, half in a Mirror group). For these Modelling tasks, we 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 (see *Appendix B*). 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.

New York 1988

The first of the 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"), 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. This high school had a large physics department, with over a dozen faculty, some of them integrally involved in reforming the NY State Regents Physics syllabus and examination. The school is widely considered to be one of the best U.S. science high schools, routinely yielding Westinghouse Science Project competition winners, and counting among its alumnae many Nobel laureates. Most students in the school take five years of science before graduating, and half of the students go on to careers in science, engineering, or medicine.

The NY School provided the first site 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 teaching lesson on optics over the approximately three-week period. Classroom observations and follow-up conversations with the teacher led us to identify the topic of image formation[1] as a particularly challenging and difficult one within geometrical optics, in which the use and understanding of diagrams is essential. Having analyzed student difficulties expressed in the instructor's tests held during the period of instruction, we then developed an interview guideline to be used with students right after instruction (see *Appendix A*). Each student was asked to draw diagrams at a chalkboard in order to solve basic geometrical optics problems involving a single lens or mirror. Results of these investigations are reviewed below.

Our class of 30 students was mainly composed of juniors (16 to 17 years-old), many of whom planned to continue as science majors. By passing the school's highly competitive entry exam, they had fulfilled minimal state requirements in mathematics and English proficiency. The teacher encouraged student participation in the study. We were able to schedule sessions with 24 of 30 students. Optics instruction took place from May 3-26, 1988; students took their optics final on May 30; their Physics Achievement Test was held between June 6-15; and the interviews took place between June 6-15, just before the June 19 New York State Regents Physics Examination, which covered geometrical optics.

California 1989

The second major study required the cooperation of the physics faculty of one school for the duration of our project. At our "CA school", we videotaped all optics lessons given by an award-winning high school physics teacher with approximately 20 years experience, as

---

[1] Research by Goldberg and McDermott (1986) also indicated severe problems in understanding image formation from a plane mirror, and of real images formed by a converging lens or concave mirror (Goldberg & McDermott, 1987) among college-age introductory physics students both before and after instruction.

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. Results of these investigations are reviewed below.

The physics course taught is a general introductory course, with a non-quantitative emphasis on conceptual physics, or as the teacher described it:

"most of the kids are what we call B-line math students. They are less comfortable solving math problems, less successful at it, and yet we've convinced them, somehow or another,that physics is an important thing for them to learn either for college or for life....They are not the gung ho type of learners who just jump in and want to learn all of the time. When you get their curiosity piqued they do fine....the term I've coined is math-reluctant. They tend to shy away from it whenever they can."

In contrast to the NY school, the CA teacher felt few of the students would take up careers in science, although all of them would go on to complete a third or fourth year of science before graduating high school.

California 1990

We continued working with this CA teacher for our observations of the impacts of Optics Dynagrams on teaching and learning activities, and learning outcomes. He was involved as a consultant in co-designing the new learning environment activities, since we wanted him to be able to build upon what he considered his most effective practices.

In the course of our planning for the Fall 1990 field test implementation of the new Dynagrams learning environment, an extensive set of materials, including 8 experiments and homework activities was developed (see *Appendix C*).

We carried out a set of four studies during this field test:

Study 1: Clinical interviews with CA 1990 students (compared to CA 1989 baseline performance)

Study 2: 1990 Pre-posttest comparisons of individual student performance on everyday optics reasoning situations (paper and pencil)

Study 3: Longitudinal studies of small group learning and conceptual change

Study 4: The CA 1990 physics taught (compared to CA 1989 baseline performance)

Results of these four studies are reviewed below.

Problems in Existing Teaching-Learning Processes

Our project has led to many surprising findings. In the first instance, we had planned to investigate how expert teachers in well-recognized science-oriented high schools successfully taught our target domain in introductory physics. We would then seek to replicate these "best practices," and work to enhance them by means of dynamic diagramming tools and other technology augmentations for portraying the dynamic interrelationships of conceptual relations in the content domain. But we found "success" in very different terms then we had anticipated. Specifically, the teachers at our sites were superb in preparing students to do well on physics exams, less so in attaining physics understanding. We now present details of what we found as the existing set of teaching - learning processes, and learning outcomes. We will summarize the physics learned and the physics taught for our two classroom sites, one in a NY school (collected in 1988), one in a CA school (collected in 1989).

Optics teaching and learning in NY 1988

The '88 physics learned. Our video protocols revealed NY students' difficulties with diagrammatic and verbal representations concerning the conceptual substance of geometrical optics. Even in these exceptional science education settings, learners had striking difficulties appropriately using diagrams for reasoning and inference. We looked at the students' processes of diagram (and equation) construction and use, to observe their understanding of geometrical optics and their specific difficulties.

We distinguished two phases of students' work with respect to the optics diagrams, and then characterized their problems and partial learnings. First, a student needed to build a *situational model* from the verbal description. This involved 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 needed to build a *behavioral model* of the situation using the diagram. This is the process of graphically characterizing how light will behave as it propagates through the optical system depicted in the diagram (e.g., light bending, forming images). Each part of the modeling process affords many opportunities for error.

In creating a *situational model*, approximately half of the students had difficulties identifying and recreating in the diagram the relevant elements of 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**. Key components of the optical diagram were often mislocated or left out of it altogether, causing difficulties when 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.

Students had a host of problems that together contributed to very rare success in attaining correct diagram image projections, for either the mirror (7/24 students) or lens problems (5/24 students). 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 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. Depending on the object's location, only 30-60% of students remembered or constructed the two rays from an object point sufficient to determine the corresponding image point.

• On rare occasions when learners tried to use their experiences with magnifying (converging) lenses, telescopes, or plane mirrors to help them answer questions, they usually became confused and did not complete the mapping of their experience onto the spatial representation of the diagram.

• 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"[2] introduced by the teacher for image location.

---

[2] "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

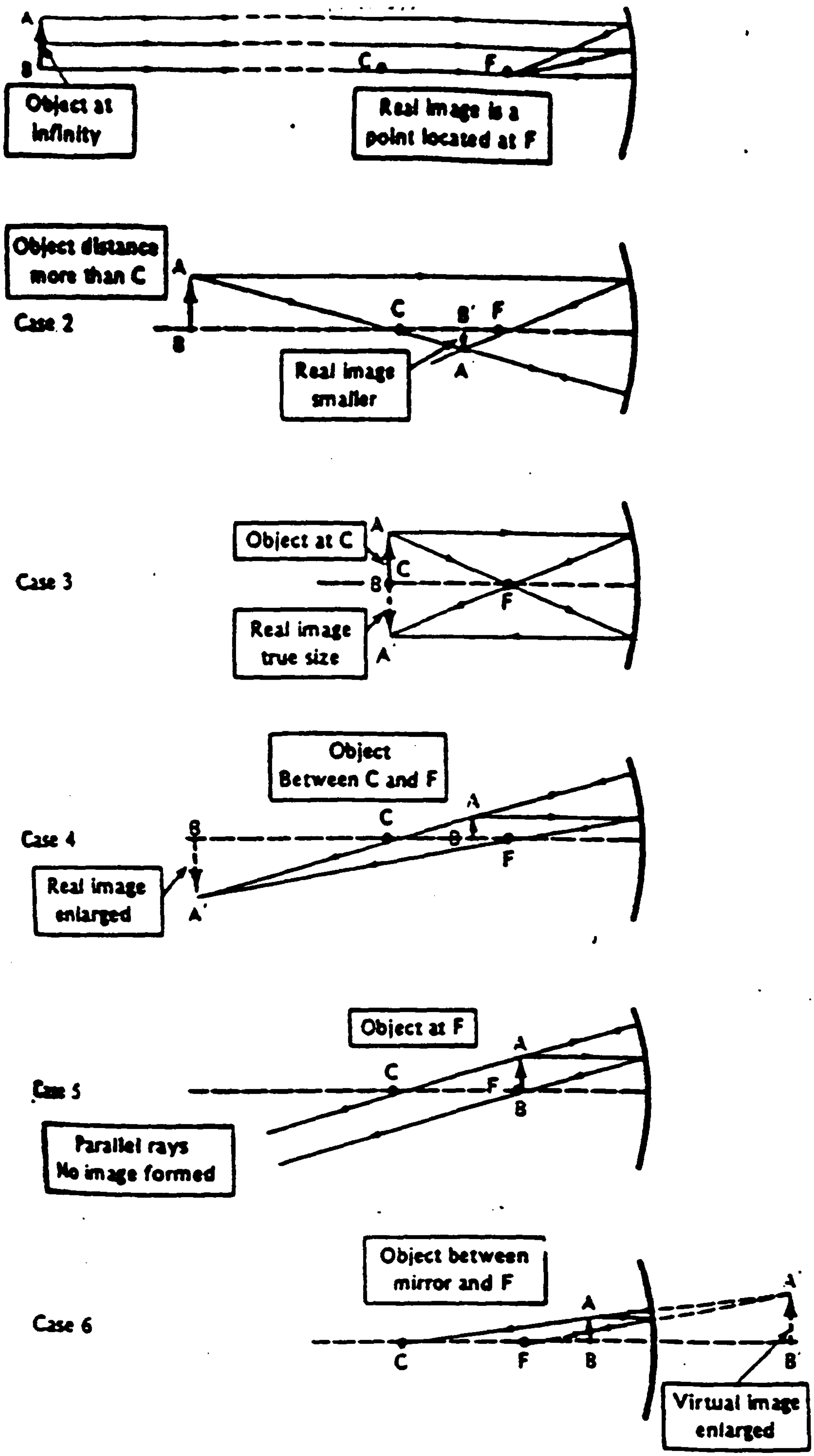


Figure 1. Ray diagrams showing how images are formed by a Concave mirror as the object distance changes.
(From Taffel A. Physics: Its Methods and Meanings. 5th ed. Allyn & Bacon, Co., 1986)

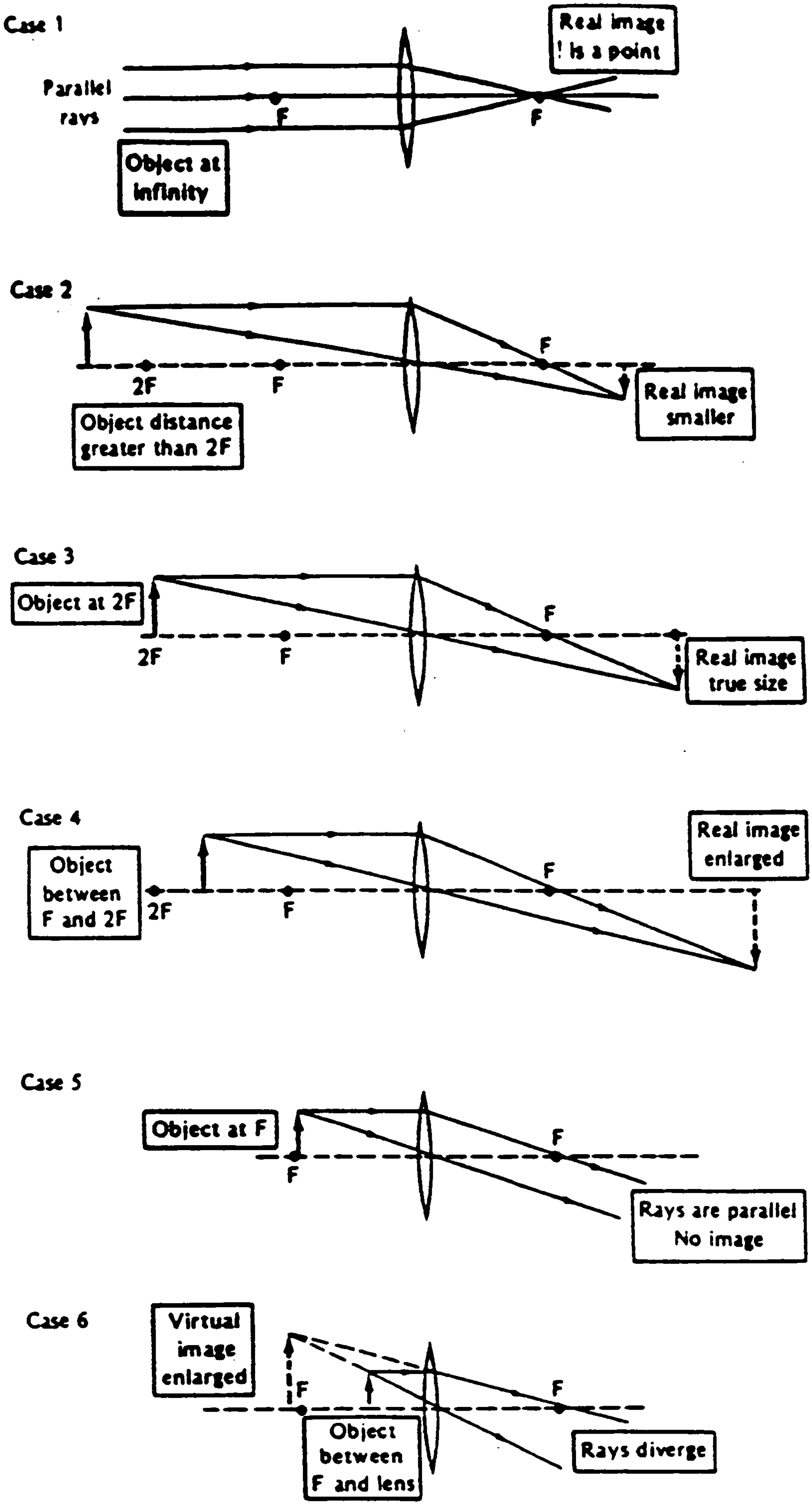


Figure 2. Ray diagrams showing how images are formed by a converging lens as the object distance changes.
(From Taffel A. Physics: Its Methods and Meanings. 5th ed.

• 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, & Allen 1989, in press). 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 corresponded to the top of the object. They then completed the image by "dropping the perpendicular" to the principal axis - a phrase often 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.

• 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." (See 1989 and 1990 data below for additional support for this claim.)

With respect to 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 immediately previous need to know them for the New York Regents examinations. Only

---

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, 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.

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.

The '88 physics taught. The NY teacher spent the highest proportion of his time giving explanations and demonstrations of phenomena in a traditional lecture format. Particular emphasis was placed on clearly presenting definitions of technical terms such as "virtual image" and "index of refraction," and demonstrating such concepts in situations involving an optical bench and other laboratory equipment. Diagrams played an expository role in these lectures and definitions, since many optical concepts are best conveyed in diagrammatic form. This teacher would repeatedly during lessons stop and tell students to take note of particular definitions of technical terms, and diagrams, explaining that they would appear on the classroom test or NY State Regent's Exam. During these sequences, he would give definitions slowly, repeating phrases and pausing between them, surveying the class in order to determine whether students were keeping up or not.

When we examined the structure of question and answer sequences in the classroom we found that students rarely initiated questions, and when they did, they often went unanswered. The teacher would ask questions, mainly using them as rhetorical devices for punctuating their lectures. In fact, most questions asked were answered by the teacher, disregarding student responses and treating them as guesses or as partial responses. Student questions often were about whether something just presented was to be remembered for their tests, or to clarify what they would be accountable for in what had been presented.

When students were tested, short answer and multiple choice items were presented, much like those they would encounter on the NY State Regents Examination and their Physics Achievement Test. Diagrams were included in these tests, but as a setup for the questions asked. Students did not construct diagrams either in the laboratory activities, or for their tests. They did use ray tracing diagrams for homework problems that accompanied the instruction in geometrical optics.

Students spent little or no classroom time engaged in discussions about science concepts. Most of their classroom time was spent discussing procedural and definitional matter related to their goal of completing the assignments. We saw no evidence that students used diagrams in their classroom conversations with each other, although students were presented with diagrams daily during lectures and demonstrations.

Furthermore, the discourse contexts of diagram use in instruction were impoverished for meeting the objectives of having students use diagrams as tools for making predictions, or explaining observed behaviors of light in an actual world or lab situation.

Optics teaching and learning in CA 1989

The physics learned in CA 1989. When we examined the 1989 CA school learning outcomes apparent from students' clinical interview protocols reasoning about lenses with diagrams and words, we found many of the same problems that we had identified in the 1988 NY study. What the students learned and could do with representations in problems was far more limited than we expected. We present a detailed account of these data in comparisons with what happened in the same teacher's classroom in 1990 after students worked with the Dynagrams learning environment (see *Studies 1A* and *1B* below). But in short, rather than drawing ray sprays from an object point to determine the location of the image point, they incorrectly drew parallel beams, in which single rays are traced from two or more locations on the object. And although 55% of the students drew in at least one special ray to locate the image in the word problem, only 40% used any special rays for the modelling tasks, and just 15% used a special ray through *f*, refracting through the lens and coming out parallel to the axis.

The physics taught in CA 1989. As the teacher described his approach, it has been influenced considerably by the PSSE approach used in the 1960's, with lab activities and many lecture demonstrations of concepts, although during the 1989 course, he used a conceptual physics text by Hewitt for the students.

Several patterns in his teaching were particularly noteworthy for our concerns:

Attitudes about diagrams. The CA teacher was asked about what roles diagrams played in his teaching and students' understanding of the topics after teaching his optics lesson sequence:

> "I think it was crucial. There was no way that I could say, "Oh, I have a light here, and the image shows up over there." Without figuring out how I got from there to there. Something must have happened here when it got through the lens that really changed the path of the light. And, I just don't see how you can explain anything without diagrams. One of the tricks is trying to get the kids to use diagrams themselves."

The teacher saw clearly the importance of reasoning with diagrams, and he recognized the need for more student access to diagram use.

Roles for technology in optics teaching-learning. One of the most fascinating aspects of his use of diagrams in instruction was his construction and use during lectures of a Hypercard stack (essentially like push-button, sequentially-linked, electronic overhead transparencies) which he projected on a screen and then used to support his expositions. Students also had access to this animated textbook during lunches and after school periods. Here is what he said about his rationale for this instructional aide:

> "Well, I think if the diagrams were clear and if they didn't understand it, they would go back and do it again....I can repeat the same thing two or three different times just to make sure they really understand the concept...I mean you can essentially put a text book in there but you can really, really order their thinking so it goes in one direction".

Use of beams in his ray diagrams. The teacher commonly used a beam of light in his expository diagrams concerning how light interacts forms images. A beam representation of light is one in which one light ray from each of two points at the extremity of a light source are traced through an optical system. The problematic nature of his use of this technique became apparent when we looked at student learning outcomes from this instruction, and found many of them relying far too broadly on one of several beam models to (inaccurately) reason about image formation.

Question and answer patterns in instructional discourse. We completed an analysis of question and answer sequences on the CA 1989 data at the classroom level. The overall pattern was remarkably *different* from discourse patterns that characterized elementary classroom lessons (Cazden, 1988; Mehan, 1979), where the discourse of question and answer sequences was characterized overall by the Initiation–Response-Evaluation (IRE) model, in which the teacher initiates, the student responds, and the teacher evaluates the student response. The sequence is a familiar one to anyone who has spent time in a classroom:

> Teacher: How much is two plus two?
>
> Student: Four.
>
> Teacher: Very good.

In the CA high school, the pattern was different: the teacher still controlled turns to talk, but he also responded to his own initiations over 70% of the time. We concluded that the teacher used questions as rhetorical devices for continuing the lesson (getting to the next point, setting the stage for the next demonstration, and controlling the science path being taken), rather than as inquiry or discovery tools. A question and answer sequence could be characterized as having long teacher turns and short student turns, as illustrated in the following examples taken from transcripts of classroom lessons:[3]

Teacher: I've got a shadow coming from one source, but I've got light coming from the other one to help it light up. To make it gray. Sort of in between.

Not quite as dark.

Okay?

So now I've got light, gray, and dark. **How does that relate to fuzzy shadows? Well, what's the difference between having two sources, and a lightbulb's all full of sources, isn't it? Places all over the lightbulb giving off light. Okay?**

Whoops.

And so, what we've got is we have a source here, which is giving off light at one end, the other end, in between, all over. So we've got one shadow from one side, we've got another shadow from the other side, we've got a shadow from the middle, we've got a shadow from close to the end, a shadow from close to the other end.

Shadows coming from every place on the source. And they overlap. And they overlap, and they overlap, and they overlap. And the place where every single shadow overlaps, is totally dark.

Okay?

Now here, there's going to be not too much light, a little bit more, a little bit more, a little bit more, until I get to the edge of this area, and then out here I get light from all over the source.

Does that make sense?

So, we're going to have gradations of grey, going from fairly dark, to fairly light. And then it becomes light again So I think what we call fuzziness, or what you and I would interpret as being fuzzy shadows, is really, comes about because we have lots of different places, each one casting a shadow, and those overlapping one another.

Okay?

Now what happens when...

Here is an example of a "question and answer" sequence during his demonstration of the concept of virtual image:

Teacher: (re: an image in a mirror at the front of the room)...**he's the same size as he was when we were up close, but he looks smaller to me, why?**

Student: 'Cause of distance.

Teacher: Distance, perspective, right? Perspective. When we're up close, he was occupying a great big angle of my...I say, "wow, you're big." Now he's

---

[3] Questions are in bold type.

occupying a small angle, okay, so he looks smaller. Now you guys are telling me this, but that still hasn't answered my question. **How big is the image?** Okay. You want the cheap answer, the free answer, without thinking anymore?

Sure. Okay, how big is the image. Well, it turns out, that the image is, in fact, the same size as the object and part of that object is, and this is where I really like geometry, okay, I really like the geometry. Here's my object, here's my image....

A student-initiated question concerning an observation made while the teacher was demonstrating the path of a laser beam through water:

Student: Mr. Cabban: When you held it underneath the table, it looked like it was bouncing off the top of the water and going back down.

Teacher: That's quite possible. Actually, we can get that to happen in here. Just so you can see that it does work. By the way, one of the things that you don't want to do with lasers, guys, is you don't want to be in a position where you're looking straight into it...

.......(setting up laser to replicate what the student saw)...Is that what you were seeing?

Student: Yeah.

Teacher: **How about that?** Light comes down at the bottom, comes roaring up to the top, when it gets to the top, it bounces and comes back down. When that happens, notice the interesting thing, there's no light up here at the top.

Student: **Why is that?**

Teacher: It's all bounced underneath, okay? Now this is a concept which we Physics people call "total internal reflection."

And it's something that we hope to take up with you tomorrow. But we need to get through the refraction stuff real fast, okay?

So. Lots of demos today. Or tomorrow. Okay.

As different as these lengthy sequences are from those in the elementary school, they are equally recognizable to anyone who has ever tried to teach or learn science in a classroom. In each instance, the teacher takes most of the turns and answers or redirects student answers in order to give explanations concerning the topic under discussion. In the third sequence where the student makes an observation and initiates an inquiry, the teacher sets up the equipment to replicate the conditions under question, and then proceeds to explain what has happened and provides a term that names it. These three sequences are very representative of the shape that most talk took in the CA 1989 classroom.

In summary, there were few turns for student talk during lectures, demonstrations and question and answer sequences. Students were *audience* for the most part, and the teacher's questions were more like rhetorical devices to allow the teacher to construct the next point rather than invitations for student turns to talk. The discourse pattern did open for student participation during lab sessions when students worked in small groups and had almost exclusive rights to turns at talk (except when their group was visited by the teacher).

These current classroom attitudes and practices present special obstacles for learning physics, and we wondered if life inside a collaborative classroom group might be more conducive to learning. We looked closely at what the students did during one laboratory sequence and found that their talk was a very different kind of classroom talk than what we observed during lectures and demos.[4] Without the teacher as maestro, students talked about themselves, such things as their friends, their grades, their parties, and the assignment at hand. There was a strong contrast between the kind of science talk students created during lab sessions and science talk generated by the teacher during whole class lessons. While the teacher talked science to the class (Lemke, 1989), the students talked around and about science. Their talk was "meta" in nature and helped them attend to the task, at least in the sense of identifying the vocabulary and terms needed to accomplish the task and assignment. While students organized with each other to complete the assigned work on focal points and distance to the object, no instances were identified during which students discussed a pattern, idea or hypothesis about what they were manipulating. They did accomplish some definitional work with each other, asking "what's the D_O?" (distance to the object), but these were requests for complying with lab assignment directions that requested them to measure the D_O, a term they had heard defined in the lecture preceding the lab activity. There was no mention by the students of the pattern that resulted from the manipulations and measurements of the "distance to the object" and the "distance to the image" during the lab, and these were not taken up until the teacher pulled them together during a subsequent classroom presentation.

Use of science vocabulary and terms. In a complementary data review, we identified the teacher's introduction and explanation of new words and terms and then tracked on how students used of the same terms during subsequent classroom activities. We found that students did not begin to use the science vocabulary after the teacher's introduction and rarely used technical terms except when parroting the teacher or worksheet. Our conclusion was that the student conversations during laboratory activity fell short of engaging the students with talk about the optics ideas and concepts being covered. At best, and not to be down played as an important science learning activity, the students' behavior and talk practiced them at laboratory and experimental procedures. The Dynagrams staff desired

4 Ray McDermott, Marjorie and Charles Goodwin, Susan Irwin and Francois and I were part of a group that met at IRL and studied the pre-Dynagrams laboratory group tape. I'd like to thank them all for bringing their skills, talents and insights to the analysis.

students to become involved in science learning conversations, but realized that putting students into collaborative groups would not be enough. The stage would need to be set with resources and props in order to reshape and support conversational moments enough for students to gain access to learning.

Similarities between '88 NY and '89 CA school results

Although there are interesting differences across the school sites in the conceptual and reasoning difficulties students expressed in their clinical interview protocols involving optics diagrams, and in the teaching practices we observed, the similarities were profound.

In terms of teaching practice, both teachers are constrained to 3-4 weeks for curriculum coverage for geometrical optics. This time constraint emerges in relation to state-mandated curriculum topics for high school physics. So many complex topics are rapidly introduced and "covered," in lecture-centered expositions of concepts and demonstrations involving technical optics equipment students with which students have had little experience. And the nature of the instructional discourse is teacher-dominated and teacher-centered. Student questions rarely play the role of clarifying a concept relative to a difficulty with the use of the concept for the student, but are instead often oriented to testing issues (more so in '88 NY). While labs are part of the teaching-learning process in each site, students' work largely consists of working through a set procedure for determining some optical behavior and obtaining some pre-known results.

Patterns of learning results are also remarkably convergent across the two sites, even given the very different orientation to science of the two classrooms: one mathematical (NY) and science-career path pitched, and one qualitative (CA) in nature.

How might we account for these findings on qualitative and quantitative reasoning patterns? Our central observation is that adequate scientific explanations of student activities in our interview sessions require layers of complexity beyond those dominating the science learning research literature on student "preconceptions" and "misconceptions." In particular, they must look at the nature of teaching-learning processes, and broader social frameworks than the classroom, including the scientific community, and the levels of accountability in the educational system. Based on our analyses of both classroom activities and student interviews, we identified five major classes of problems 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 propose that there is a social construction of diagrams as meaningful objects of conversation and tools for reasoning. What this means is that students, not only the teacher through lectures, must have ample opportunities to display what they take these symbols and the concept/things they represent to mean and be useful for. Otherwise, how can these student beliefs be refined toward the desired norms of instruction?

Few opportunities appeared in the classrooms for students to be *accountable* 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 was treated as an activity remote from lab work, used for problem-solving only, as part of homework. So students did not make explicit for the teacher their understandings of the relations of diagram components and their correspondences to world situations. Students did not learn how to get connected to a diagram as a device to see through to the world.

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.* Yet in science, the creation and uses of diagrams, figures, charts, and other "inscriptions" is integral to the activities of scientists in their laboratories and at conferences (Latour, 1986).

(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 (e.g., 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 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. 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" (as static dictionary entry) and "use" (considered as dynamic cultural practice) of science concepts. Many NY students were adept in memorizing dictionary meanings of scientific terms for a multiple-choice test. The scores of their class averaged mid-80's for both physics final and NY State Regent's Exam. Applying these concepts causally to a series of situations was a problem, however. Since procedures for concept use were rarely packed in a term's definition, students had understandable difficulty using these concepts in reasoning.

(4) ***Use of deficient or misleading static ray diagrams.*** Sometimes the eye-view *on* a diagram and *in* a diagram were not distinguished. This contributes, it seems, to student difficulties in understanding the nature of virtual images. Understanding optics diagrams is bound up with perceptual perspective. Perceptual perspective 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 beyond placing eyes in a few diagrams, with a note 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.*** In the NY school, students' formal assessment activities include a State Regents Examination, in a multiple-choice format *not* requiring student construction of diagrams. By this means the

accountability of instruction to norms is established. 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.

Rationale for Dynagrams Learning Environment Design

"Dynagrams" is our shorthand for "dynamic diagrams," a central kind of symbolic representation in the software we have created as a rapid and highly interactive communication medium for students' *conceptual 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 (Miller, 1986). Diagrams can represent concepts and conceptual relations, and provide a "language of thought" that exploits the visual processing capabilities of the human mind (Larkin & Simon, 1987). From our perspective, diagrams also provide conversational artefacts better enabling learners and teachers to become coordinated in activity, including talk, regarding their conceptual content, and to negotiate differences in their beliefs.

Pea (in press-a) presented a social framework on learning that highlights the role of *conceptual learning conversations* as a major source of learning resources which have been unreasonably neglected in cognitive science. 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 of talk, diagrams, formulas, and actions gets established and negotiated (Goodwin & Heritage, 1990; Heritage, 1984; Pea, 1988; Schegloff & Sacks, 1973). Communication is thus not viewed in terms of one-way meaning transmission and reception, but as two-way transformational.

Meaning is progressively constructed through successive turns of symbolic action and talk. Such conversational interactions allow persons to collaboratively construct the common ground of beliefs, meanings, and understandings that they share, as well as articulate their differences. In this publicly available space, rich opportunities exist 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 (Schegloff, in press).

Our global pedagogical objective is to have students become better able to engage in appropriate conversations about the conceptual content they are investigating through their collective activity and symbolic action. We reasoned that their conversations should be inquiry-focused, sense-making conversations including authentic tasks in science practice such as making conjectures, designing experiments to test them, and revising conjectures in light of their observations. To pursue these objectives, we worked to create a learning environment, so that students might achieve competency in the language games of geometric optics. This design involved complex choices involving both technological and social dimensions.

The 2-D Optics Dynagrams simulator we created (for details, see Jul, 1991; Pea, in press-a) allowed 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 could also emit single light rays, or ray sprays over an angle range, from one or more point light sources. Users may create geometrical entities such as tangent lines, grids, and angles, and measure distances and angles. We largely focused on promoting *qualitative* understanding of relations in geometrical optics (e.g., to define shadows, find image location, find lines-of-sight for mirrors), rather than formal quantitative principles and formulas.

We 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; simple lens refraction to a coin-in-pool situation) for small group work in the classroom.

Student groups observed real-world optical situations (or video depictions), used 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.

Let us now briefly review some of the central technical, social, and curriculum design choices we made before presenting analyses of results of learning and teaching processes with the Dynagrams environment.

Technical design choices

In the deliberations of an interdisciplinary design team, complex and interacting decisions are made that together culminate in a completed design for learning environment technologies and curriculum activities. This is true for technical, social, and curriculum design choices for a learning environment. We were concerned to track these various commitments, and some of the theoretical debate that generated a design space prior to a solution, and we report on some of the key outcomes of this design process in this section. Details will be laid out in a forthcoming report.

With respect to major technical design choices, we selected a Macintosh II platform, determined the 2-dimensionality of the Dynagrams simulator, rejected color and picked black on white graphic background, designed an active "eye" in the simulator world, opted to support student inquiry, and provided some measurement tools.

Computer choice. We chose the Apple Macintosh II as a classroom technology of the near-future, and as allowing for pilot work with computer animations of preliminary interface designs written in Macromind Director, a Mac application.

Dimensionality of Dynagrams simulator. We initially hoped for 3-dimensions to support extensive visualization (hence, our choice of affine geometry); we later decided to use 2-d as our prototype. This was also justified in terms of a vastly easier interface, plus easier mapping for students to traditional 2-d diagrams. (Instead, we put emphasis into teaching students the mapping skills from a 2-d diagram to a 3-d physical situation - e.g. the exact shadow setups in Experiments 1.00, 1.50; see *Appendix C*).

Use of Color: We decided against color. Two arguments were strong for color: 1) With the huge number of generateable rays, students had difficulty with diagrammatic overwhelm, and in particular with deciding when two rays crossed to form an image. Attributing different colors to different point sources might have helped to alleviate this confusion; and 2) Giving students free choice of color might provide fascinating data on diagram development during learning (i.e. what do they use the colors to represent, and how does this evolve?). But two arguments were stronger against it: 1) Color might confuse students, since it could be used to represent different things (e.g. observable color of a ray, property of a ray's point of origin, direction of a ray, etc.), and (2) Color monitors too expensive and/or unavailable.

Graphics as black on white or white on black. We considered an argument for white on black, because black more intuitively represents darkness, the absence of light, while white more intuitively represents light. But in opposition, we realized that whenever students drew diagrams on their papers, they would then have to black-white reverse them. Furthermore, lens outlines would become white halos, which might confuse students. We decided to keep black on white. (While students did report being somewhat confused by this at first (especially since the curriculum began with shadows), they soon became comfortable with the convention).

Major technical design decisions

Finding the right "eye" for Dynagrams

We weighed arguments carefully in terms of adding an "eye" to the simulator, which could represent the presence of a detector of light in the modelled scenes students created with their Dynagrams tools. We opted to include an eye, and it was used throughout the curriculum, and in the Dynagrams software.

Arguments in favor of an eye: 1) Facilitates mapping from diagram to real world, by including explicit observer. 2) Helps to focus attention on particular diagrammatic features which are critical for reasoning about image formation - e.g. divergence of a spray of rays. 3) Provides operational definition of "image" as optical illusion for a given observer. (Note: most texts never explicitly define *image* at all. In particular, they give meaning to "virtual image", which many students believe is either a distorted image or invisible to them. Also enables definition of "image size" in terms of observer perceptions (another term not usually given any explicit definition in texts)). Our argument against an eye was weak: Students could get confused by too many eyes - one or more in a diagram, as well as their own "God's eye view" as they look at the diagram.

Having decided in favor of an eye, we then determined *which type of eye*, considering: (1) a simple non-functional target that could represent an eye, (2) an interpretive eye, and (3) a realistic optical eye. We opted for beginning the curriculum with a non-functional eye, and the teacher would help students interpret what such an eye would see. Later, after students have studied refraction (experiment 3.50 and beyond), we introduced the full optical eye.

(1) A simple ***non-functional target "eye"*** would be easy to program; its non-functionality would make it easy for students to transfer it to activities where computer simulation is unavailable; and the use of target-icon and activities such as "shoot rays from this point source to strike the target" would facilitate students' appreciation of the goal state for image perception: that light from the source must eventually enter a person's eye.

But the lack of functionality could make it difficult for students to understand its significance, unless the teacher is particularly careful to make this clear. Furthermore, the target-icon might make it difficult for students to relate it to their own eyes and to what they see.

(2) An ***interpretive eye*** is one which would be activated when two or more rays from a point source strike it, after which it would flash synchronously with the point in space where the image of that point source lies. We ruled against an "interpretive eye," more for shortage of programming effort than for weight of negative argument. Positively, we considered that: (a) This eye would give students direct feedback on where the eye sees an image of the source, thus reducing the burden of interpretation on the teacher; and (b) The built-in functionality of the eye would then support inquiry activities in which students search for a lawful description of the way the eye behaves (thus articulating for themselves the notion of an eye triangulating to a perceived source).

We reasoned that some negatives of the interpretive eye might be that: (a) The flashing (or other means of perceptual linkage between eye and image point on the computer screen) might seem artificial or implausible to students; (b) The physical mechanism by which the eye locates an image is mysterious; and (c) This is the most computationally demanding of the eye models: The eye must calculate image positions even when no rays have passed through the image points (viz. locate virtual images); also, it must know whether rays striking it are from the same or different sources (viz. decide when it has enough information to calculate image position), and it must be able to handle the difficulties arising from three or more rays from a single point source which have a non-unique intersection point (viz. to deal with spherical aberration).

(3) We then considered a computational, ***realistic "optical eye"*** consisting of a spherical ball of fluid with absorbent back surface, and containing a lens of an adjustable shape. The arguments in its behalf were: (a) The physical mechanism by which the eye

locates an image is accessible (though requiring some additional interpretation); (b) Light within the eye behaves according to the same physical laws as light elsewhere in the system; (c) Students can easily see that near and far point sources produce ray sprays which focus at different distances from the "retina". (The internal eye lens can then be adjusted to focus on any particular point source.); (d) Far-sighted and near-sighted eyes could be constructed in Dynagrams, and appropriate correcting lenses could then be added on and adjusted for perfect focus; (e) This kind of eye looks much more like students' eyes, and links up with whatever knowledge they have about eye structure and function; and (f) This kind of eye can provide a means to answer the question "Why is it that devices such as mirrors and lenses can fool us into seeing things that aren't really there?" (covered in Experiment 5, see *Appendix C*).

The arguments against the "optical eye" were these: (a) Interpretation of what this eye would see is indirect and not obvious; (b) Even a fuller explanation is difficult, because depth vision really draws heavily on the information from two eyes. This leaves us with two possibilities: either put two eyes in explicitly (we felt this was really too complex) or explain depth-perception as attainable by a single eye, using the shape of the adjustable internal lens as calibrating device (not quite true, except for a simple camera, but we chose this option); (c) The eye is complex, with two separate refractions happening (at eye surface and at internal lens) so that predictions are more difficult; and (d) The bootstrapping problem: in order to understand the basics of image formation, one must understand vision, and hence the eye, which is *itself* a very complex optical device.

Supports for student inquiry in optics

We continually asked how we could provide more than a canned optical simulation? The arguments *in favor of support* for student inquiry were that: (1) Students are active learners and should be given scope to ask and answer their own questions as they arise; (2) Processes of scientific inquiry (e.g., activities of prediction, explanation, model generation and evaluation) constitute an essential part of professional science, as well as underlying what we would characterize as basic scientific literacy for the layperson. Yet, they are rarely addressed explicitly or supported in school science curricula; (3) If students make a public and recordable prediction of the outcome of a simulatable optical event, they are likely to be much more highly motivated to understand any result which contradicts that prediction.

Arguments *against supporting* student inquiry were: (1) It is difficult to anticipate student questions sufficiently well to provide exactly the right tools, with the right precision and intuitive interface, to enable students to answer their questions; (2) There was already enough to learn, and worries arose about students feeling overwhelmed by curriculum; and (3) Any learning environment which supports inquiry learning puts a higher responsibility on the teacher to monitor student progress and guide the learning in the new arenas.

We agreed on the need to support student inquiry, and then entered into intricate planning on which tools and activities would do so most appropriately. Four major inquiry supports were considered: (1) splitting the simulator functionality into "smart" ray-simulations and "dumb" drawing features; (2) providing both a run mode and a step-by-step mode of simulation; (3) measuring tools; and (4) an iconic system of justifications for predictions. The first three were implemented, while the fourth was too demanding on project time. These decisions are discussed in turn.

(1) Splitting the simulator functionality into **"smart"[5] ray-simulations and "dumb" drawing features**

Arguments in favor were:

(a) The ray simulation supports student exploration and induction (e.g., in Exp 3.00, students are asked: "Send a light ray from the source downwards towards the surface between the two substances. Does it travel in a straight line? If it bends, which way does it bend? Send other rays downwards, checking to see if any general patterns are operating..." Thus, students search for a qualitative version of Snell's Law of Refraction, rather than being presented it as a formula and having to interpret its meaning in different situations [actually, this pattern-induction task proved quite difficult for students, until the teacher introduced the notion of a surface normal as a reference line for angle measurement]; e.g., Students may set the refractive index of a lens to a very large number, and discover that this hypothetical device behaves almost like a black box.)

(b) The "dumb" drawing features allow students to draw their predictions about the paths of rays before trying them out. This could help students identify the detailed decisions that need to be made in the construction of a ray diagram (e.g. they must predict which way a certain ray will bend at each lens surface). Also, their commitment to a prediction is left as

---

[5] "Smart" in the sense that when a ray is sent from a light source, it "knows" what to do when it hits any surface, i.e., to reflect, refract, or absorb depending on the material nature of the surface boundary, and in a direction determined by optical laws. "Dumb" drawing features when used have no alignment with what rays "should" do in that optical system.

a permanent record on the screen, thus facilitating clear comparison with the real ray behavior, after the prediction has been made.

(c) The careful splitting of these two types of simulator functionality, using quite different menu's for ray-drawing and line-drawing features, should facilitate students distinguishing between *prediction* and *simulation.*

The main argument against was the potential for confusion by students, given the increased complexity of the system.[6]

(2) Providing both a **run mode and a step-by-step mode of simulation**

The use of a step mode is one in which the computer generates only the next segment of a ray path and then pauses at each next reflective or refractive surface until the user commands it to continue to the next surface. The argument for the step-by-step mode, in addition to the normal run mode which traces ray paths according to optical laws, was that it might facilitate short cycles of predict, simulate, compare, and reflect by the students, and support interesting conceptual learning conversations.

The argument against two modes of simulation was only the increased potential for interface confusion. We implemented two modes, but in the '90 field-test, students very rarely used this feature.

(3) Providing **measuring tools**

The arguments in favor of a tool emphasis was that providing such features as a grid, and an angle and length measure, would support inquiry learning by students, who could then use these tools to observe consequences of changing such variables as lens shape, refractive index of materials, and reflective and/or refractive surfaces.

Arguments against were that the tools were somewhat at odds with the qualitative emphasis of the teacher and Dynagrams curriculum, and that providing data recording tools to report results of such measurements for specific queries would be too complex an implementation for the project. We implemented simple measurement tools, and they were infrequently used.

---

[6] In practice, students did not show obvious confusion about these two modes. However, they rarely made predictions about ray behavior at all, apparently because of the ready availability of the ray simulation features. We did not have a way to temporarily disable the ray-drawing features of the simulator, which would have forced students to make explicit predictions.

(4) An **iconic system of justifications for ray-tracing predictions**

We considered developing an innovative iconic system of justifications to make it easy for students to provide their reasons for making a ray-tracing prediction. Arguments in favor were that: (a) Students might become more adept at giving correct causal accounts if they had to offer *justifications* for their assertions; (b) While the using well-grounded justifications is a vital part of any scientific argument, it is rarely an explicit part of any science curriculum; (c) Use of icons to label constructions or interpretations on the computer screen would be less time-consuming than requiring the student to produce a text response, and (d) would allow other students or the teacher to make rapid evaluation of a particular student's arguments as an integral part of diagram construction, since an "audit trail" of that student's reasoning would be graphically available. Any disagreements could be easily located for subsequent discussion.

Arguments against the iconic system of justifications were: (a) The variety of justifications required for flexible reasoning is actually very large (e.g., "A beam of rays parallel to the axis will pass through the focal point" is different from "A single ray parallel to the axis will pass through the focal point", and different again from "A ray parallel to the axis will bend at this surface, and again at this one, and will finally pass through the focal point"); (b) Such a set of iconic justifications would need to be accompanied by a system of incremental building, so that more of them would become available as students learn; (c) Students' own wording of a justification might vary in many subtle ways from that of the official "key" to an iconic justification, both in substance and in level of detail, making the system potentially cumbersome and confusing; and (d) The use of iconic justifications would require considerable resources in programming and curriculum-redesign.

We decided we could not afford to implement such an inquiry support for the project.

How should rays be generated?

One of the more important decisions concerned how to generate rays in simulator screens. We looked closely at both single rays and ray "cones," and settled on providing both single ray "shooting" functionality from a point source, and a minimal ray cone -- basically a ray spray from a point source, whose angle of extent and number of rays could be simply defined by the user.

Arguments *for* single activity structures to encourage participation and conversation in the classroom. We thought we could arrange for more learning:

- if students actively engaged in problem–solving and exploratory activities during which they got to manipulate optics materials and phenomena;
- if there were opportunities for students to talk and communicate with each other during these activities;
- if the activities arranged for students to use diagrams to explore optical phenomena;
- if the students were organized to use the diagrams to explore and communicate about optics in ways that were similar to the practices of real scientists.

Lave and Wenger (1989) had developed a perspective of situated learning that viewed learning as on–going participation in "communities of practice". Membership in a community of practice is considered to be comprised of shared understandings of what participants are doing and what it means in their lives and for other communities of practice within which they participate. This view had implications for how we thought about expertise and the role of the school in initiating students into a community of science practice. Learning on this view is thought to be engaged by participation in the practice of a community. In the physics community, for example, practice is comprised of ways of talking and acting, shared beliefs about what a problem is, how to work on it, and which tools and representations are useful for what conditions of inquiry. A community of practice for science includes quests for certain kinds of knowledge and understanding, and certain kinds of processes and symbolic forms for legitimating and establishing new understandings and ways of knowing. The notion of learning as the incremental joining of a community of physics practice, was directly relevant to the design of the Dynagrams classroom. Learning science would mean opportunities to participate in the practices of the community of science, during which participants collaboratively make sense and organize their knowledge and other concerted activities to resolve emergent dilemmas (also see Hawkins & Pea, 1987).

If the notion that participation in the talk and actions of a community constitutes learning, then being part of the conversation is essential for most students. Being a listener or onlooker to a community is rarely enough. Participation in activities and conversations is the vehicle for sense-making in the concerns and ways of science as well as the way learning is accomplished. Learning is generated by communication, and it is the interactions among persons and materials in the world that gives them the opportunity to generate a phenomenon for observation, reflection, and interpretation. The community of practice is negotiated and reproduced as the interactions proceed and are acted on and talked about before, during and after by their participants.

By these standards, our physics classroom would have to become an environment where students would have opportunities to engage collaboratively in inquiries that required and challenged them to have conversations about "what was happening" while pacing themselves through the procedures of the science (hypothesizing, observing, experimentation, explanation). The tasks would have to be structured to encourage the students to seek out and use the terms, tools and representations of the physics community to accomplish their work. It also required an altered role for the teacher who would move from dispenser of other peoples' physics to facilitator and consulting physics expert.

Curriculum design choices

Many decisions emerged from debates on curriculum scope and sequence in the inquiry activities planned for student groups during the four-week optics field test with Dynagrams. Only several are highlighted in this final project report. Allen's UCBerkeley doctoral dissertaion (forthcoming) deals with some of these conceptual development issues in optics curriculum design.

Introductory multimedia collage of optics phenomena

Local outdoor video footage of reflection, refraction, shadows, and other optics phenomena was collected, and along with many brief clips of similar phenomena from a shoot at the Exploratorium, and from feature films, was edited into a five-minute introduction to the Dynagrams optics course, with Peter Gabriel's *In Your Eyes* as the soundtrack.

Students found this an exciting way to begin their introduction to geometrical optics, and a large number of students in the post-Dynagrams interviews described different events outside school that they had thought about in terms of geometrical optics concepts (in contrast to the 1988 NY students, who only repeated the several real-world examples the teacher had listed for them during his lectures). Whether this video contributed to this shift or it was primarily due to the other learning environment activities was not a research focus of the project.

Conceptual dissolves

We designed and developed a set of high-quality Macromind Director interactive animations in 3-D color. They had the sole intention of providing a smooth gradient of obviously-connected mappings between abstract geometrical optics diagrams and real-world situations involving optics events and artefacts. Basically, these animations started with a 3-D video-like depiction of a familiar optical situation, and "dissolved" gradually into a 2-D geometrical optics diagram in which the various entities were depicted, including rays and ray sprays. The animations included such topics as: Fuzzy shadows; Periscope; Optics Bench; Inside the Eye. They were interwoven as appropriate into the different experimental activities during the Dynagrams curriculum.

Mapping experience: The "cycle" design of hands-on lab, Dynagrams software activities, discussions

The general issue pointed to here was teaching the student mapping relations across representational domains. We wished students to be able to map conceptual categories of geometric optics between the observable phenomena of a lab set-up, paper and pencil explanation-oriented activity sheets, or the simulator modelling. We intended to achieve this objective through well-integrated hands-on activities, simulator modelling, writing and diagramming with pencil and paper as an outcome of the small group work.

1990 Results from the Dynagrams Learning Environment

During September-October 1990, the Dynagrams learning environment was field-tested in the CA classroom with the teacher whose classroom we had studied in 1989, and who had collaborated in the design of technologies and activities for this new effort. In this section, we describe results from four different studies that were carried out during this period. An important consideration for us was to understand what would happen when a real teacher with 20 years physics teaching experience, under everyday classroom conditions in a real school, worked to make the Dynagrams learning environment work for supporting the development of conceptual understanding of optics by students. In carrying out both the field test, and the comparisons between his students' performance in 1989 and 1990, we are fully aware of the complexities of research in real classroom environments, and the contingencies that arise, making interpretations of results problematic. We explain these provisos in characterizing the results for the various studies.

Study 1: Clinical interviews with CA 1990 students (compared to CA 1989 baseline performance)

In our most elaborate analyses to date of the comparative impacts of Dynagrams instruction on the learning of geometrical optics for understanding, we undertook a variety of studies of results from clinical interview protocols obtained from students working alone at the blackboard after instruction. Our main questions concerned how the 1990 students (N=21) reasoned differently than the 1989 students (N=20), especially in terms of the aspects of conceptual understanding of optics that our activities targeted as problems in the 1989 learning outcomes. First, we present the description of task and methods, then methodological issues and provisos in these comparisons, then the results of *Study 1A: Diagram and Model Use Analysis*, and finally the results of *Study 1B: Diagram Components Analysis*. Study 1A focused on how various icons were *used* in diagrams, while Study 1B focused on the presence/absence of various icons in students' diagrams.

(1) Description of tasks and method. *Appendix B* presents the guideline we used for the 1989 CA clinical interviews, and *Appendix C* presents the guideline we used for the two different student groups in 1990: the Lens Group, and the Mirror Group. Students who signed up for interviews were randomly assigned to condition by coin tossing technique. In each year, the guideline included a Word Problem Task, and a set of Modelling Tasks involving real world artefacts. The session with each student took approximately one class period of 45 minutes. We present analyses separately for each task.

In the Word Problem part of the session, the student attempted to draw a diagram to depict the problem situation. For example, in presenting a converging lens 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 what changes will take place in the image as the object is moved closer and closer to the lens. 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.

In the Modelling Tasks part of this clinical interview, we 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 (see *Appendix B,* and questions below). 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.

(2) Comparative methodological issues and provisos. There are several general methodological problems intrinsic to such comparisons, and some problems with these assumptions specific to our two classroom groups.

In 1990, we utilized Word Problem and Modelling Problems only for *lenses*. The positive aspect of this feature was that it allowed comparisons of student performance data on the Word Problem task in 1989 CA with 1988 NY (no modelling problems were used in 1988). The negative aspect of this design feature is that we did not learn about students reasoning in such tasks with mirrors in 1989, because the tasks would have taken too long. We reconciled this in 1990 by splitting our CA 1990 class into equal size groups: half receiving a lens version of the clinical interview guideline, half receiving a mirror version.

Furthermore, the 1989 and 1990 classroom comparisons utilized the same teacher, but a different learning environment, and a different set of students. The teacher was not a neutral "implementer" of the learning environment, but was involved with our research team as a design collaborator in the Dynagrams environment and activities.

(a) Differences in coverage in 1989 and 1990.

Mirrors and lenses. In 1989, as noted earlier, our clinical interview guideline concerned only problems involving lenses. Yet as the teacher notes below, lenses were covered rather quickly compared to mirrors. So students' performances need to be seen against an instructional background where more time was spent on concave mirrors than on concave lenses, even though their clinical interview assessments were limited to lens problems. One consequence of this fact is that roughly a quarter of the students in 1989 substituted a concave mirror for a lens in their diagram for the problem! Nonetheless, many students did well reasoning with representations of lenses even though they were not covered so much in class.

In 1990, we had a different problem. Since the simulator did not support concave mirrors, more instructional time was devoted to concave lenses. So the lens group did very well at correctly reasoning with diagrams of lenses, but no one in mirror group remembered what a concave mirror was, substituting something else, like a plane mirror.

For example, the teacher was interviewed after the 1989 course and some of his remarks highlight the problem of interpreting '89-'90 student comparisons:

> We did the lenses very, very fast. So, so..in are asking them to try to link what we spent a little more time on with concave mirrors, to something which we spent a little bit of time on but which has the same sort of patterns. And, the success rate with them doing that would not be particularly high. Uh...we did go through all that..in fact the...uh..they ought to have some relationship thing that works like this; it says as the object distance gets bigger, the image distance gets smaller. Now, whether they are able to move this way or not, I am not sure. So, but as you get closer the image gets farther away. Um..but they are transitioning that from the mirror to the lens, I don't know.... You would be asking them to extrapolate knowledge and to link to things which they may not have caught the link on. And that might have been pretty difficult for them....yeah, if I had my way to say differently we would have more time with lenses, in fact, what's really nice is to do a mirror, a mirror lab, and then a couple weeks later come back and do a lens lab and have similar results and then, oh my goodness, the same thing applied. We didn't have that "ah ha" experience. Um...I think if you... the one thing you should have found, I hope, is that when they got inside the focal length that you suddenly went from having images over here to having images...to going to virtual ones. I trust about 60 to 70 percent of them should have been able to deal with the virtual image beginning to happen. That was something we spent some time on.

Special rays to spatial zones. In addition, the emphasis of the 1990 taught curriculum shifted, in the teacher's emphases, away from the 1989 focus on special ray behavior toward the behavior of ray spray patterns as a function of the location of a light source in one of three zones: outside the focal point, at the focal point, and inside the focal point. In 1989, special ray diagrams for the converging lens and the converging mirror were each presented on two separate days as the main point of a standard classroom lecture. As part of subsequent lectures on mirrors and lenses, all the teacher's ray diagrams drawn for expository purposes contained special rays. This was not the case in 1990, when special ray diagrams for a converging lens were covered only in one lecture/review session for the unit exam. Special ray diagrams for converging mirrors were covered after the unit exam, and prior to the start of the next unit.

Summary of implications of instructional coverage differences from 1989-1990. Interpreting comparative differences between 1989 and 1990 differences is thus a subtle affair. While 1989 students, assessed only on lenses, did study lenses, they studied mirrors far more. And while 1990 students, half assessed in a Lens Group, half assessed in a Mirror Group, did study mirrors, they studied lenses more. And the teacher's emphasis on ray behavior shifted from special rays in 1989 to spatial zones for ray spray behavior in 1990.

We wished to turn this difference to advantage, in the following sense. Our rationale for forming two groups in 1990 was this: Whatever content was most prevalent in the classroom would form the content for directly measuring what was learned from instruction (e.g., converging mirrors or converging lenses). Since the causal story for explaining optical phenomena with converging mirrors and lenses contains many of the same components, the content area with the least coverage could then serve as a "near transfer" test for the content students learned. Since our '89 clinical interview covered only lenses, which received less classroom coverage than mirrors, then to balance the effect of classroom coverage across school years, our 1990 clinical interviews should be on mirrors, since the class received less coverage on converging mirrors than lenses. Because we desired some direct comparability on tasks across years, we needed a '90 Lens Group. So we split our '90 interview sample into a Lens and a Mirror Group.

(b) Differences in student profiles in 1989 and 1990. Although we do not have achievement data or preinstructional assessments to back up this intuition, our CA teacher noted at the outset of the school year and during the field test that this group of students was overall less able and "sharp" than in 1989. Furthermore, in 1990-1991 school year, the high school reorganized its science curriculum, by collapsing a three-tiered offering of science classes into a two-tiered model. In the opinion of our on-site teacher and his colleague who worked with Dynagrams in her class, the ability level of the students went downward from our baseline condition in 1989. So it is likely that any difference we find that constitutes an improvement from 1989 to 1990 has had to overcome a starting point deficit for the 1990 student group.

Study 1A: Diagram and Model Use Analysis for 1989-1990 Clinical Interviews

Goal performance: The Physicist's Model. First, we define expert solutions in diagram and model use for the clinical interview problems, in order to provide normative benchmarks for evaluating student performance. We may narrowly characterize expertise in the use of elementary ray diagrams as having three major areas: construction, interpretation and semantic mapping:

- *Construction* refers to the creation (on paper or using a computer tool) of a ray diagram that will support inferencing.
- *Interpretation* is the viewing of a diagram to decide where (if at all) images exist and what their properties are.
- *Semantic mapping* is the extent to which a person can translate from a diagram to a real optical situation, and vice versa.

These skills are not altogether orthogonal. For example, a person may incorrectly locate the position of an image either because of poor interpretation skills, or because he or she constructed a diagram which did not support the kinds of inferences he wishes to make.

However, successful performance in our individual clinical interviews requires expertise in all areas: a physical situation must be modelled, diagrams constructed, and inferences made from those diagrams. These inferences must then be tested with the real apparatus, and the diagrams appropriately modified. Let us look at the physicist's model for image formation.

Physicists model image formation (by a lens, for example) in terms of point sources of light. A point source is a fictitious but highly useful abstraction, a tiny luminous speck from which light emerges as rays that travel outward in all directions.

Ordinary objects can be considered as having large numbers of point sources all over their surfaces. (A more subtle version of this is that non-luminous ordinary objects emit "diffusely reflected" light that originally came from a luminous source, but which now leaves the object as if it were a collection of point sources.)

The utility of this model lies in its ability to predict the location of an image: if rays from a single point source are redirected so as to meet each other (extended either forwards or backwards), then there will be a clear image of the point source at that meeting point.

Apart from image location, the model enables one to predict the size, orientation and type of an image. It also supports dynamic reasoning about how the size or intensity of an image might change, and what an observer would see from different positions.

Actual student performance

We will review student performance comparisons between 1989 and 1990 CA classrooms [N =20/N=21] in terms of the following sequence of analyses:

Review of diagrams drawn during Word Problem only

Review of diagrams drawn during Modelling Problems only:

- Initial model of a real optical situation
- Modelling: Covering top half of the lens
- Modelling: Lifting the object an inch
- Modelling: Removing the lens/mirror completely
- Modelling: Showing interviewer a virtual image
- Modelling: Looking at an aerial real image

Review of all diagrams drawn throughout interview

Overall observations from these comparisons

Review of diagrams drawn during Word Problem only

Students received the following problem:

> "An object is 12 cm from a converging lens (mirror) of focal length 3 cm. Using diagrams and words, could you explain:
>
> • where and at what distance from the lens an image will form?
>
> • what will be the size of the image?
>
> • what kind of image will it be, and why?
>
> • What would a person see if they put their eye on the axis, far away from the lens?
>
> Now imagine moving the object closer and closer to the lens. Describe to me the changes that take place in the image, and why. Could you show me how the diagram would look for that?"

A new diagram was defined as starting whenever a new object was drawn, or a new pattern of rays was extended from an existing object. Diagrams containing incomplete rays (i.e. rays from an explicit source that emerge after interacting with a lens/mirror) were *not* counted, nor were diagrams in which objects did not seem to be the generators of rays. Benefit of the doubt was given in the few cases where it was difficult to tell a beam from a spray (i.e., where the source spray began at an area somewhat larger than a single point).

The total number of counted diagramming events that were coded is was 65 for 1989 and 69 for 1990. In answering the following questions of these data, we represent the 1989/1990 quantitative results as [1989 value/1990 value].

(1) *Appropriate construction of real image*: How many cases were there of diverging sprays (i.e., two or more rays from an object point) from an object *beyond* f becoming converging sprays after interaction with the lens/mirror? [26/30]

> 1a) Of these, how many were correctly interpreted (i.e. the crossing point identified as the image location)? [24/27]
>
> 1b) Of these, how many were incorrectly interpreted or not interpreted at all? [2/3]

2) *Inappropriate construction of real image*: How many cases were there of diverging sprays (i.e. two or more rays from an object point) from an object *not beyond* f becoming converging sprays after interaction with the lens/mirror? [6/5]

> 2a) Of these, how many were correctly interpreted (i.e. the crossing point identified as the image location)? [4/3]
>
> 2b) Of these, how many were incorrectly interpreted or not interpreted at all? [2/2]

3) *Appropriate construction of virtual image*: How many cases were there of diverging sprays (i.e. two or more rays from an object point) from an object *within* f becoming converging sprays after interaction with the lens/mirror? [2/16]

> 3a) Of these, how many were correctly interpreted (i.e. the crossing point identified as the image location)? [1/6]
>
> 3b) Of these, how many were incorrectly interpreted or not interpreted at all? [1/10]

4) *Inappropriate construction of virtual image*: How many cases were there of diverging sprays (i.e. two or more rays from an object point) from an object *not within* f becoming converging sprays after interaction with the lens/mirror? [0/1]

> 4a) Of these, how many were correctly interpreted (i.e. the crossing point identified as the image location)? [0/1]
>
> 4b) Of these, how many were incorrectly interpreted or not interpreted at all? [0/0]

5) *Appropriate construction of no-image*: How many cases were there of diverging sprays (i.e. two or more rays from an object point) from an object at f becoming parallel sprays after interaction with the lens/mirror? [0/6]

> 5a) Of these, how many were correctly interpreted (i.e. there is no image formed)? [0/2]
>
> 5b) Of these, how many were incorrectly interpreted or not interpreted at all? [0/4]

6) *Inappropriate construction of no-image*: How many cases were there of diverging sprays (i.e. two or more rays from an object point) from an object *not at f* becoming parallel sprays after interaction with the lens/mirror? [0/1]

> 6a) Of these, how many were correctly interpreted (i.e. there is no image formed)? [0/0]
>
> 6b) Of these, how many were incorrectly interpreted or not interpreted at all? [0/1]

7) *Insurmountable problem with second special ray for within-f case*: How many cases were there of failure to locate image for object within f because of inability to draw the difficult backward-extended ray that emerges parallel to the axis? [4/0]

8) *Parallel beams*: How many cases were there of a beam from the object, rather than sprays from any one point source? [17/5]

> 8a) Of these, how many were parallel beams? [15/2]
>
> 8b) Of these, how many were diverging beams? [0/2]
>
> 8c) Of these, how many were converging beams? [2/1]

9) *Single rays*: How many cases were there of a single ray from a point on the object? [9/5]

10) *Mixed rays*: How many cases were there of a diverging spray being incomplete, so that only one ray was completed? [1/0]

Conclusions from review of diagrams drawn during Word Problem only:

(from #1): Both '89 and '90 groups can successfully construct and interpret [real] images as located at the crossing points of converging sprays.

(from #2): However, the '90 group shows a marked improvement in their ability to deal with virtual images. The notion of a diverging spray that remains diverging after it leaves the lens/mirror was almost entirely unfamiliar to the pre-students, and is now being used frequently and appropriately. (from #3) Although more than half of these cases were not correctly interpreted, six of them were, which indicates that those students have become adept at one of the most difficult aspects of optics diagramming: the virtual image.

(from #8): From '89 to '90, there has been a spectacular drop in students' use of parallel beams from objects - from 17 to 2 cases. This underlies the increased extent to which students after Dynagrams rely on point sources to locate images.

(from #5): In addition, we see that '90 students successfully used parallel *sprays* on six occasions (versus zero in '89). A parallel spray is significantly different from a parallel beam; it also looks like a group of parallel lines but these leave a mirror/lens after originating from a single point source, and are thus useful reasoning tools in optics.

(from #7 and #9 and sundry additions): Clearly, the '90 students used diverging sprays of light from point sources as their most common depiction of light from an object. This is highly desirable and notoriously difficult to achieve in optics instruction. We found that '89 students used diverging sprays in 54% (45/65) of their diagrammatic constructions, while the '90 students used diverging sprays in 86% (59/69) of theirs. That the '90 students are using diverging sprays more consistently as reasoning tools can also be seen by the reduction in their drawing of other, less useful ray patterns. The number of single rays they draw is approximately half of the '89 students, and they never get into problems of the tricky second special ray for objects within f, because they use ray sprays, rather than special rays, in order to reason.

Review of diagrams drawn during Modelling Tasks only

In the first of six Modelling problems, students received these instructions: "Here I have a lamp with a smiling face painted on it, a converging lens, and a screen. The lens is a different shape to the ones you worked with in class, but it works the same way. All the things can be moved." (We started with the lens quite far from the lamp, and an image on the screen but blurry.)

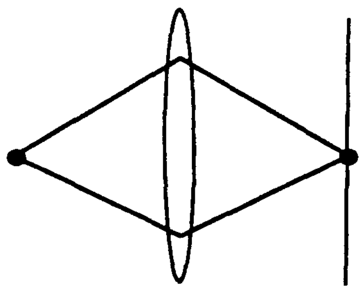
In answering these questions, students could draw on any resources they like, and could represent whichever entities in whichever ways they choose. Thus, it was of central interest to know how they choose to represent and reason about the situation, within the broad constraints of the problem. We first look at their diagrams for this initial model of a real optical situation.

(1) *Initial model of a real optical situation.* Students worked through the following sequence of activities during our procedure:

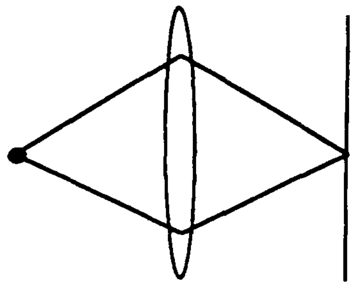
> "I'd like you to create a focused image of the smiling face on the screen."
>
> "Can you explain to me what is happening there? Why is the image forming as it is?"
>
> "Please draw a ray diagram on the board to represent that situation."

In judging their responses to these queries, we show only the last interpretation given by the student. Sometimes there were several earlier attempts before the student was satisfied; for the sake of simplicity, these revised versions have been omitted:

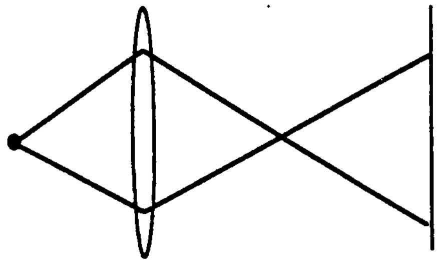
1) "Correct" model: Diverging spray to converging spray, with image identified at crossing point. [3/5]



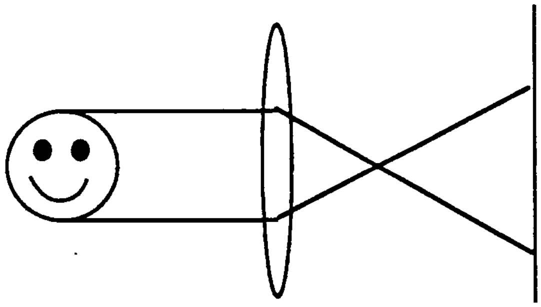
2) Diverging spray to diverging spray, with image position not identified. [1/0]



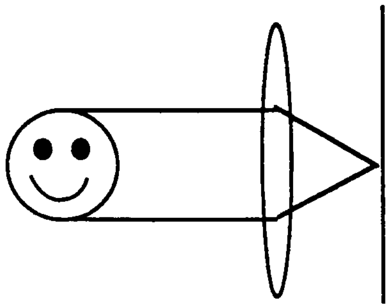
3) Diverging spray to converging spray, with image identified beyond crossing point, within spray boundaries. [1/4]



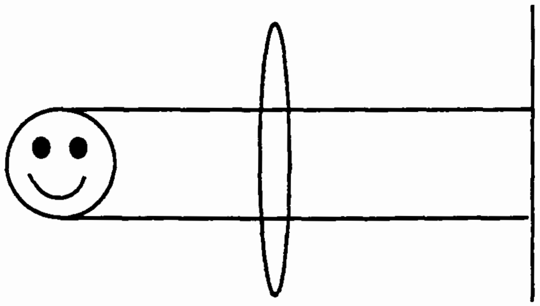
4) Parallel beam to converging beam, with image identified beyond crossing point, within beam boundaries. [7/1]



5) Parallel beam to converging beam, with image identified at crossing point. [2/0]

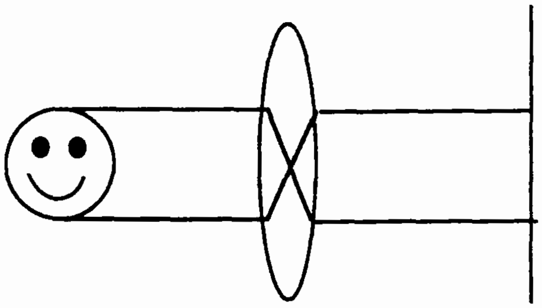


6) Parallel beam to parallel beam, with no crossing. [2/0]



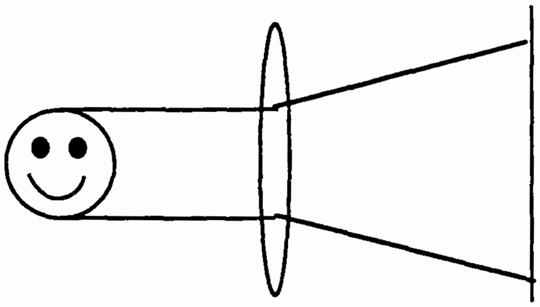
---

7) Parallel beam to parallel beam, with crossing inside lens [1/0]



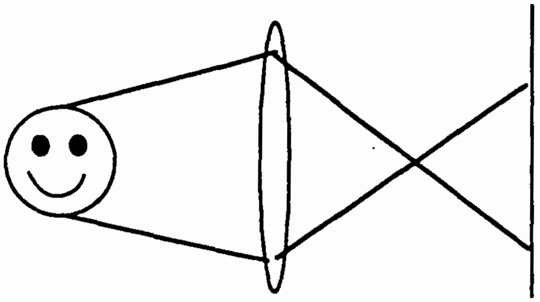
---

8) Parallel beam to diverging beam, no crossing. [1/1]



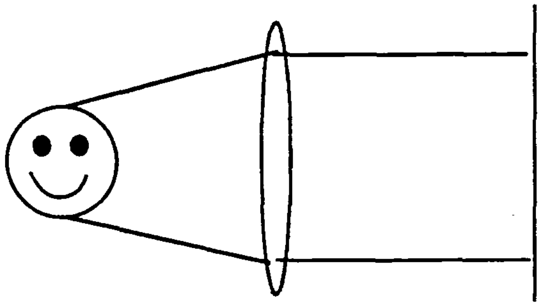
---

9) Diverging beam to converging beam. Image identified behind crossing point.
[0/6]

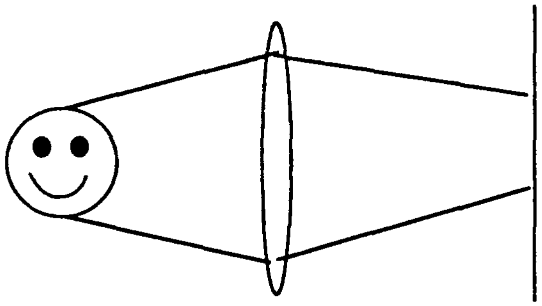


---

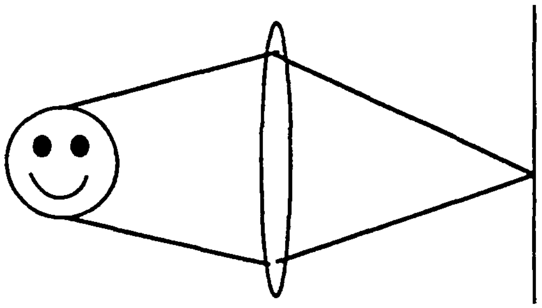
10) Diverging beam to parallel beam. [0/1]



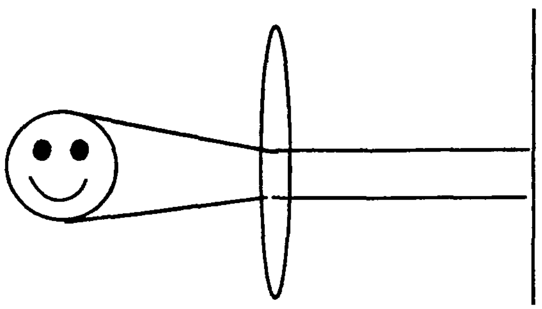
11) Diverging beam to converging beam. Image before crossing point. [0/1]



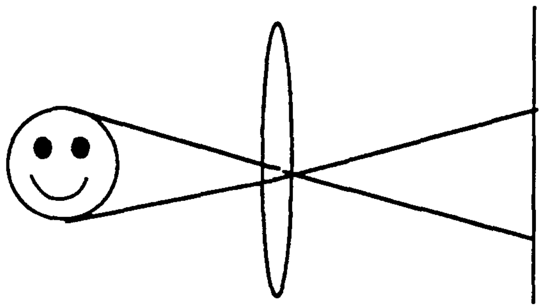
12) Diverging beam to converging beam. Image identified at crossing point.
[1/0]



13) Converging beam to parallel beam. [0/1]



14) Converging beam to diverging beam. Image at crossing point. [0/1]



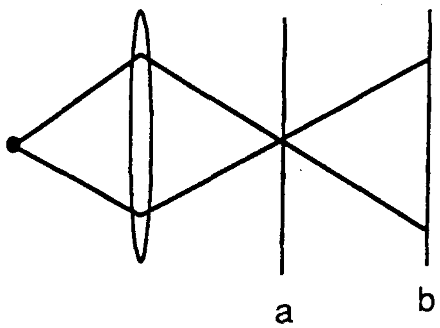
---

15) Single ray. [1/0]

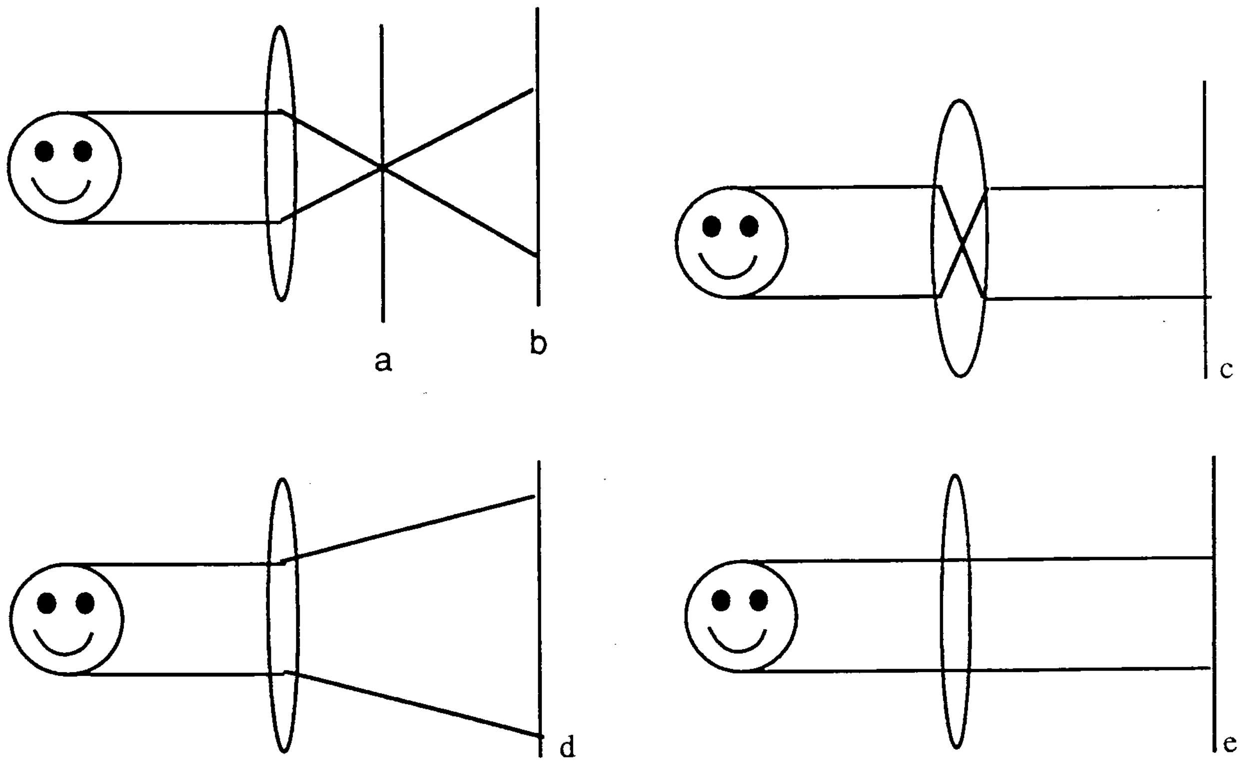
Summary of these student diagram "model" types

We find five different models, categorized by source ray pattern, not unique or even optimal. They are depicted below by example, and by #'89/#90 students presenting diagrams of these types in this part of the clinical interview.

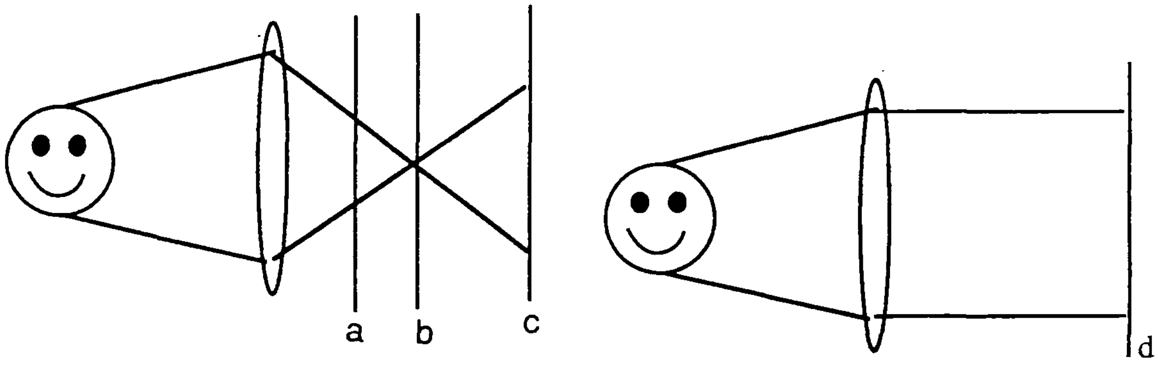
Category 1: Point source models: [5/9]



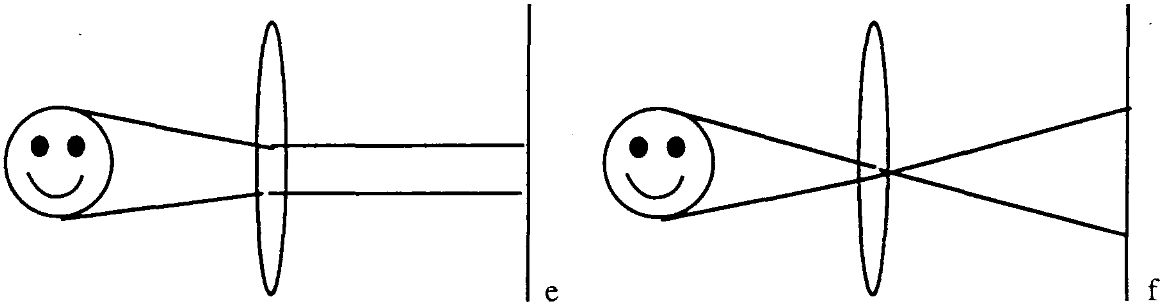
Category 2: Parallel beam models: [13/2]



Category 3: Diverging beam models: [1/8]



Category 4: Converging beam models: [0/2]



Category 5: Single ray models: [1/0]

Conclusions re: diagrams drawn during Modelling Problems only. There is a wide range of individual diagrams which students draw, even for this simple, classic optical situation.

As in the theoretical, Word Problem part of the interview, the '90 students draw diverging sprays from object point sources more frequently than the '89 students [5/9], while '89 students draw parallel beams far more frequently than '90 students [13/2]. Thus we see that students' most common characterization of the situation changed from object as generator of parallel beam, to object as generator of diverging beam or multiple diverging sprays. There was a significant shift from parallelism to divergence in the rays leaving the object, as we had hoped to see. In addition, nearly twice as many '90 as '89 students [5/9] characterize the situation in terms of a diverging and reconverging ray spray from a point source.

However, we should not rejoice too loudly. Instead of parallel beams (which '90 students have only rarely seen during their curriculum), many of the '90 students use diverging beams of light! With a subtle variation on the "beam-theme", they manage to combine the advantages of the beam (listed below, under final comments), while keeping the notion that light expands out from an object in all directions. These diverging beam models are very similar to the parallel beam models in terms of the predictions they support, as we shall now see.

(2) *Modelling: Covering top half of the lens.*

We examine the half-lens problem in detail, since it provides students with a very surprising result, and an opportunity to critically examine their models.

The instructions for students in this part of the task were as follows: "I have a black card here. What do you think will happen to the image (if anything) when I use it to cover the top half of the lens, like this? (cover top half of lens) Why? Could you draw me a ray diagram to show me why you think that will happen?"

Strikingly, no student in either group correctly predicted the result.

It should be noted that, while students' diagrammatic models are reasonably stable, there are occasional shifts. For example, of the 41 students in both groups, 6 changed their models from their initial characterization in order to answer this question.

The five model categories discussed above are based on the pattern of rays shown leaving the object. However, for this particular question, it turns out that a different grouping of the same models provides more insight into students' responses.

Results are described below in terms of which model type students manifested in their initial diagrammatic model of the real optical situation, as depicted in the previous section. Recall that there were five model types (1-5), and subtypes within several of the types as labelled (a-e).

Point-to-point models: (1a)

Students in this category reasoned in one of three ways, leading to one of two predictions. All of the students had the same (faulty) underlying assumptions, namely that blocking half of the image-generator would result in a disappearance of half of the image. (Note that, for these students, *all* rays come from a single point on the object.):

(i) They focused on the blocked part of the lens/mirror, reasoning that the part of the face from which the newly-blocked rays came, must disappear from the image. Typically this resulted in a prediction of seeing only the chin of the face. [1/2]

(ii) They focused on the unblocked part of the lens/mirror, reasoning that the part of the face from which these rays came would still appear, while the other half would not. Typically this resulted in a prediction of seeing only the forehead of the face. [2/0]

(iii) They reasoned, perhaps with a sort of shadow idea, that blocking the top half of the lens would result in the disappearance of the top half of the image. This resulted in a prediction of seeing only the forehead, since the image is inverted. [1/1]

Beam-to-beam models, with inversion: (2b, 2c, 3c)

These models are very easy to reason with on this problem. Almost without exception, students predict (based on either the origin or end point of a blocked ray) that only the chin will appear on the screen. This reasoning, though leading to the wrong prediction, is entirely consistent with their model. [6/3]

Models which violate ray-as-local-carrier-of-information: (1b, 2a, 2d, 2e, 3b, 3d, 4e)

These models, since they already violate the notion of rays as going from an object point to the corresponding image point, provide a variety of lines of reasoning.

(i) Two students traced the end point of the blocked ray, and predicted that that part of the image would disappear. [0/2]

(ii) One student reasoned in terms of a shadow cast horizontally in space, and thus predicted that the chin would disappear. [1/0]

(iii) One student became confused and was unable to decide which half would disappear. [0/1]

(iv) Two students reasoned that there would be no change in the image, because (by analogy with a plane mirror) "you only need half of it to see yourself". [0/2]

v) Two students felt that the image would become blurry or non-existent because of the need for the whole lens to create an image. [1/1]

Conclusions for the half-lens modelling problem results: Students in both '89 and '90 experienced difficulty explaining this problem, particularly once they had seen the surprising result. Of the 41 students across the two years, only 2 were able to successfully and fully explain the dimming of the image using ray sprays. Most others were not able to construct an explanation at all [11/13], or decided (reinforced by their experiences with plane mirrors) that only half of the lens/mirror was necessary for the image to form. Several others seemed to jump easily to a different underlying assumption, namely that blocking half the lens will halve the light intensity, still without a convincing ray diagram.

(3) *Modelling: Lifting the object an inch.*

In this part of the modelling task, students were asked: "If I lift the lamp up about an inch, like this, what do you think will happen to the image, if anything?" What we found was four different predictions.

Prediction #1: *The image will move upward on the screen.* [3/1]

These were students who did not use the constraints on the special ray that strikes the lens/mirror parallel to the axis and emerges to pass through f. Instead, they did a "simple lifting" of the rays in relation to the lens. This type of reasoning could apply equally well to all models of the situation.

(i) Three of the students (all pre-OD) drew parallel beams.

(ii) One student (post-OD) drew a diverging ray spray.

Prediction #2: *The image will move lower on the screen.* [11/14]

(i) Intuition of oppositeness [3/2]: Students reported "just having a feeling" that the image would behave in the opposite fashion to the object. Some said this was because it was inverted.

(ii) Embroidered intuition [4/5]: Many students made a prediction before beginning a diagram, and then drew diagrams to support those predictions, without any obvious diagrammatic constraints.

(iii) Examination of critical ray [2/3]: Several students considered the changing behavior of a particular ray, and apparently used this to infer that the image would move downward on the screen.

(iv) Tilting parallel beams [2/0]: These students drew parallel beams tilted at an angle to the lens axis.

(v) Reflection [0/4]: Students who were given mirrors rather than lenses reasoned that the reflection process ensured (by equal angles of incidence and reflection) that raising the object would lower the image.

Prediction #3: *There will be some other change in the image.* [2/3]

These were varied. Students variously predicted the image would become:

(i) "chopped off" as it moved above the level of the lens/mirror.

(ii) fuzzy, since its position with respect to the lens was changing.

(iii) larger and higher

(iv) blurry and lower.

Prediction #4: *There will be no change in the image.* [3/3]

These students exhibited a variety of reasoning, including:

(i) a focus on constant features of the situation, such as the light dispersing from the bulb, or the observation that rays continue to strike the mirror.

(ii) use of parallel beam with image as crossing point. This model predicts no change to the image, since the higher parallel rays are still brought to the same convergence point.

Conclusions from results from lifting the object by an inch. It was clear that this was a task which elicited the correct intuitive prediction for the majority of students in both '89 and '90 groups. Five students [3/2] expressed these intuitions as predictions, without using ray reasoning ("The image moves downward"). Several more [4/5] apparently contrived to have their diagrams support their predictions. However, four students (all of whom drew beams) were convinced by their faulty diagrams to revise their originally correct predictions. Overall, there was little difference between the groups on this prediction task.

(4) *Modelling: Removing the lens/mirror completely.*

Students were asked: "What do you predict will happen to the image (if anything) when I remove the lens? Why? Could you draw me a ray diagram to show me why you think that will happen?"

It turned out that this question was not very revealing of students' diagrammatic models, since most students draw an expanding beam of rays with no further structure and little reasoning.

Prediction #1: *You will see nothing at all on the screen.* [5/6]

Students who made this correct prediction argued that, without something to converge the rays, they would diverge in all directions.

Prediction #2: *There will be something on the screen, but not a face.* [4/2]

These students predicted a shadow or blur on the screen, but said there would be no recognizable face.

Prediction #3: *There will be a blurry, upright image of the face.* [2/4]

Prediction #4: There will be a place (or condition) for which the image will be clearly in focus. [6/3]

Typically, this condition was that the object be very close to the screen. One student said it could only be seen if the room was very dark.

Prediction #5: *There will be a clear, upright image of the face.* [3/6]

Most of these students added that the image would be larger than the object; one said it would be the same size.

Conclusions from results on removing the lens/mirror completely. Other studies (ref Goldberg) have critically examined the dependence of students' responses to this question on the exact nature of the object used. We originally chose the painted face on a bulb because we felt that candles were unnatural and impractical, and we were concerned about the way students would respond to a source surrounded by a globe of glass. However, the smiling-face bulb clearly had its drawbacks; the face was some distance in front of the bulb filament (which some students correctly identified as the true light source), and it was a "negative" object, being painted on the bulb with black marker pen. Thus many students, with good reason, invoked notions of shadows instead of treating the face as a single object.

There was little difference between the two groups. The most noticeable change is that more post than pre -students thought the image would be clear, while more pre than post-students thought the image could be made clear under certain circumstances.

(5) *Modelling: Showing interviewer a virtual image.*

Students were then asked: "If it's possible with this system, can you show me in some way a virtual image of the smiling face?" Here is what we found.

1) Correct identification of virtual image: [2/3]

2) Near-correct identification: [0/1]

This student knows all the features of a virtual image, but what he finds is actually an unfocussed real image viewed too closely.

3) "The image is already virtual" [1/8]

> (i) No reason given. [1/3]
>
> (ii) Students focus on the aerial image and identify it as virtual. [0/3] (Note: Two of the three believe the image is located behind the lens, which would tend to support this identification.)
>
> (iii) Students reason that the screen is not really producing light rays itself, so the image on the screen is virtual by definition.

4) The image should be right-side up on the screen. [6/2]

These students know that a virtual image is erect, but fail to find it because it cannot be formed on a screen.

5) The image should be on the screen when the object is within f. [6/0]

Again, these students have remembered one property of a virtual image, but not its definition.

6) It is an impossible task. [3/1]

7) No memory of what a virtual image is. [2/4]

Conclusions from results of showing interviewer a virtual image. The '89 students remember the properties (orientation, object-distance) of a virtual image much more frequently than the '90 students [12/2]. However, more of the '90 students know the definition of virtual image (as one which light rays do not actually pass through) or its operational form as incapable of appearing on a screen [4/8].

(6) *Modelling: Looking at an aerial real image.*

The 1990 students only were asked to look at an aerial image of the smiling face, and asked what they were seeing. Specifically, they had a setup in which they had just created a focused image of a smiling face on the screen, using the lamp with a smiling face painted on it, a converging lens, and a screen. They were then read this description and question:

> "Now if I take away the screen, like this, and move further back and look towards the lens, I can see the smiling face. Why don't you try it? Can you see a smiling face? Tell me about what you are seeing? Can you show me how that works on your diagram? Where are you in the diagram? Where is the smiling face you are seeing?"

1) 5 students correctly identified it as an image in front of the lens/mirror, and drew the appropriate rays from image to eye.

2) 2 students misidentified it as an image behind the lens/mirror, but correctly constructed diagrams in support of their view, and drew appropriate rays from image to eye.

3) 2 students misidentified it as an image on the mirror, and drew appropriate rays from image to eye.

4) 2 students misidentified it as behind the mirror, but drew no rays to the eye.

5) 3 students drew an image but had their eye see something other than that image.

One such student, after constructing an image correctly, drew in an eye and treated it as a new light source - identifying the aerial image with the image of the eye in his diagram!

6) 6 students gave no clear explanation of what they were seeing.

Conclusions from results on looking at an aerial real image. Unfortunately, we do not have comparative data on this question. It is very clear that students have difficulty judging the position of a real, aerial image, and that these misjudgements can lead students to draw faulty diagrams or make faulty predictions. At least we find that approximately half of the students (9/21) explicitly draw light entering their eyes when they see the image.

As a final piece of data on this subject, 6 students answered the question by replacing the screen in their diagrams with an eye at the same location. This is incorrect because the eye only "sees" with diverging ray sprays, and must thus be some distance behind the image; whereas a screen must be placed exactly at the image location for best viewing. Of the six students, one made incorrect inferences due to this mistake, one already had severe difficulties with her diagram, and four experienced no penalty because they were using beam models in which a screen is also positioned in a diverging spray of rays. This provides yet another clue to the resilience of beam models of light.

Review of all diagrams drawn throughout clinical interviews in 1989-90

In our presentation of these results, [a/b] represents the numbers of students (or diagrams, depending on the analysis) for the 1989 (pre-Dynagrams) and 1990 (post-Dynagrams) groups, respectively.

A) *Awareness of point sources versus beams*

1) How many students reasoned exclusively with point sources in their diagrams? Answer: [2/2]

2) How many students reasoned exclusively with beams in their diagrams? [2/0]

3) How many students reasoned with both point sources and beams, but always keeping the two clearly distinct from each other (suggesting that they had at least differentiated point sources from beams)? [9/5]

4) How many students reasoning with sources that were difficult to distinguish (suggesting that they were not aware of the significance of the difference between points and beams)? [6/14]

5) Remaining category: "other" [1/0]

Conclusions. Nothing much worth noting.

B) *Violation of ray-as-local-carrier-of-information*

We looked only at those diagrams containing rays. A diagram used for two separate questions was counted as a single diagram.

1) Complete triangulation: In how many diagrams did students draw two (or more rays) from a single object point which met at the corresponding image point? [35/36]

2) Minimal consistency: In how many diagrams did students draw only one ray from a single object point which passed through the corresponding image point? [19/14]

3) Neutral rays: In how many diagrams was the relationship between the object and image point not specified? [73/113]

4) Incomplete rays: In how many diagrams did students draw disembodied or incomplete rays - i.e., rays with no explicit source, or no completion after they strike the mirror/lens? [38/46]

5) Violation: In how many diagrams did students draw one or more rays from a single object point which passed through a contrary image point? [28/26]

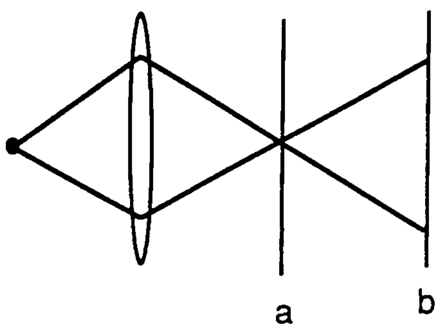
Conclusions from review of all diagrams drawn throughout interview. Nothing much, except that the post-students drew a lot more neutral rays. (Probably they were more used to seeing lots of rays on the simulator.)

Overall observations from these comparisons

Prevalence of non-standard models of light in students' diagrams

The most important observations from these 1989 and 1990 comparisons [#89/#90] concern the prevalence of student models for thinking about light behavior that deviate from the Physicist's Model of light as point-to-point mapping described earlier. Recall that in describing the students' diagrams of the initial geometric optics physical situation, we characterized five different categories of models expressed by students' diagrams. These were (1) point source models [5/9], (2) parallel beam models [13/2], (3) diverging beam models [1/8], (4) converging beam models [0/2], and (5) single ray models [1/0]. Given the prevalence of the first three categories of models in students' diagrams, we will briefly articulate the strengths/utilities of each, the weaknesses/problems with each, and then speculate as to their likely origins, at least in part, in the classroom practice involving diagram construction and use.

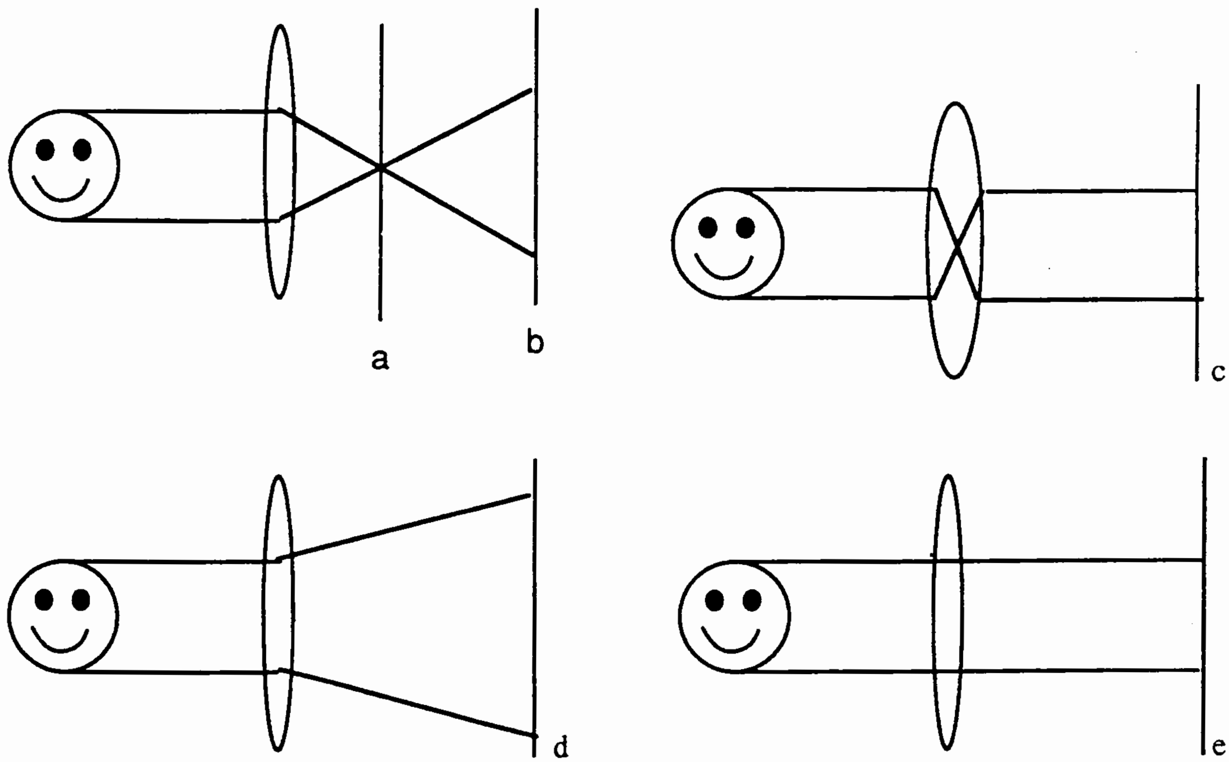
Category 1: Point source models: [5/9]



The strengths of point source models are that they represent the object as made up of multiple point sources, represent the point source as producing a diverging spray, and the lens then converges the spray to a point. The flaws are that some students (those who drew 1b diagrams) identified the image at the wrong place, viz. after the convergence point.

We can identify possible origins for this category of model in classroom practice. Firstly, the whole notion of point sources which produce diverging sprays was emphasized throughout curriculum. Secondly, the teacher made extensive use of realistic point sources of light: flashlights with their lenses removed. The students spent a whole lab period determining that the light from such a source would diverge, converge or go parallel, depending on its distance from the lens. This helped students visualize the geometry of a diverging spray brought to a convergence point. However, it is quite possible that some students did not see a single image (blurred on each side), but instead saw images at every distance, varying only in size. This would account for the model shown in Category 1b above.

Category 2: Parallel beam models: [13/2]



The strengths of parallel beam models are that they predict image orientation (with the exception of (2a)), and in the most frequently drawn model (2b), the predicted image orientation is correct, and the crossing point represents the focal point of the lens, as many students note. The flaws are that the image location is either incorrect (2a), or underdetermined (for 2b-e), so that one may plausibly reason that the image would be visible at many positions of the screen.

We can identify several possible origins for this widespread and robust category of beam model in classroom practice:

(1) Many everyday light sources do emit approximately parallel beams of rays (e.g., flashlights, headlights, searchlights). They are *made* parallel by a lens or mirror within the device, but the students may not know this); and

(2) The optics courses (e.g., first year CA school) may well have entrenched this model, because:

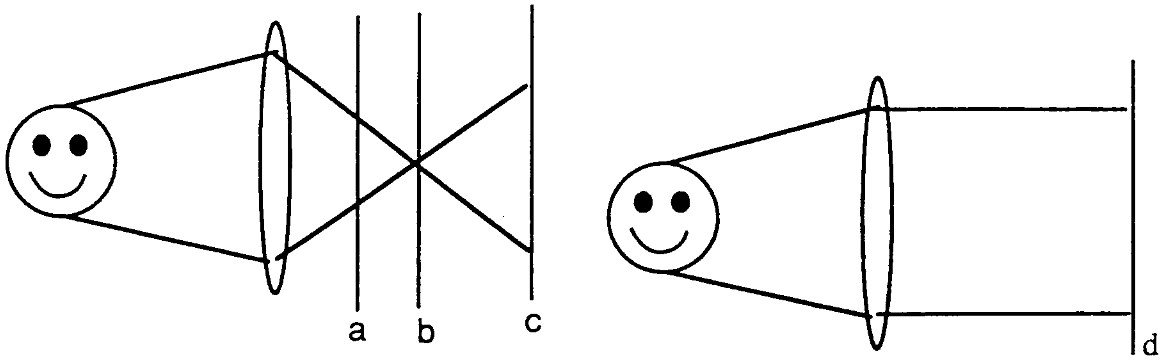
(a) it was not emphasized that ordinary, non-luminous objects act as collections of point sources, so that "source of light" for students was much more likely to cue one of the "parallel beam" devices listed above;

(b) students were given many, many diagrams of parallel rays to define the focal point of a lens or other optical device. The source of these rays was never articulated. Thus, when the students were given our optical situation, it was quite a reasonable extension for them to draw the smiling face (extended object) as the source of the parallel beam whose image was strongly in their minds; and

(c) the sun was often referred to as "a source of parallel rays" because of its great distance. In fact, the sun's great distance makes rays *coming from any point on the sun* essentially parallel, but this point was not mentioned, so the same kind of error (addition of a large sun as the source of parallel rays) would have been easy for students to make.

We made intensive attempts to overcome the Beam Model held by students in the 1990 CA Dynagrams learning environment. Specifically, we eliminated the possibility of drawing "disembodied parallel rays" on the simulator, by insisting that rays always begin at a point source; and we used diverging ray sprays throughout the curriculum. These were not altogether successful; although the number of students using parallel beam models dropped from 13 (1989) to 2 (1990), the number of students using Diverging Beam models climbed from 1 to 8, as we describe below.

Category 3: Diverging beam models: [1/8]



The strengths of diverging beam models rare that they correctly predict image orientation (with the exception of 3b), and in the most frequently drawn model (3c), the prediction of orientation is correct. The weaknesses are that the image location is either incorrect (3b), or underdetermined (3a, c, d), so that one may plausibly reason that the image would be visible at many positions of the screen.

Again, we can identify possible origins for this category of model in classroom practice. These diverging beam models suggest a strong interaction between students' naive beam-like models (as also documented by other researchers) and the Dynagrams curriculum we developed, with its emphasis on diverging light rays from an object. These models seem to be closely related to the point-source models of Category 1 above, in that they show diverging rays from the object, but they are closely related to the parallel beam models of category 2 in that they *are* beam models, and thus do not provide sufficient information for unambiguous image location.

Flipping of an image by a lens

Very widespread was the notion of "flipping" of an image by a lens. Clearly the orientation of the image is very salient to students, as is its size. The multitude of beam models probably owe their resilience, at least in part, to the fact that they allow students to account for both of these properties through the drawing of only two rays. Beam models can be adjusted in a variety of interesting ways so as not to violate ray-as-local-carrier-of-information.

The notion of holistic image travel remains very strong, in both pre and post groups. Indeed, 3 students from each group explicitly described the outward propagation of the image to "hit" the lens, and one of them even attempted find the orientation of this propagating image at different distances from the lens, by using a screen.

Roles for special rays

While it was heartening to see students using patterns of diverging, converging and parallel rays, it was also clear that the role of the "special rays" is an important complement. In both the pre and post groups, students did not seem to appreciate the diagrammatic constraints which the special rays provide, when making predictions. For example, knowing that any ray parallel to the lens axis must pass through its focal point, might help students avoid the kind of "simple lifting" of the rays when predicting the result of lifting an object (as 4 students did).

The "eye" introduces other problems

The inclusion of the eye, while it seemed to aid student understanding of virtual images, introduced some new problems. In particular, we underestimated the difficulty of judging where an aerial image is located. One consequence of this: students who judged (incorrectly) that the inverted image they were looking at was back on the lens/mirror found themselves reinforced in the belief that the "flipping" of the image happens at a certain point in its propagation through the system.

Even worse, the human eye is such an accommodating detector that some students thought they were seeing images when, in fact, they were in the yet-to-converge spray of rays from the lens/mirror. This introduced a new set of problems, since such an out-of-focus image is seen to change orientation as one moves backwards, apparently being transformed from a real to virtual image just by an observer's shift in position!

Diagrams used for bolstering, not making predictions

More often than we would like to see, students make their predictions and then draw a ray diagram to confirm those predictions. Thus, for example, we see a profusion of diagrams that support (without being predictive in themselves) the notion that if an object is lifted, its real image will move downward. This was somewhat exacerbated by the teacher, for example, when drawing virtual images in a plane mirror. Having once proven that the image and object are equidistant from the mirror, he tended to draw the image first and the rays afterwards, in subsequent diagrams.

Study 1B: 1989-1990 Diagram Components Analysis

Reliability. We established reliability of our coding categories for the the 1989/90 Clinical Interview comparison according to a set procedure. Definitions for the categories were written by one member of the research team to be self-explanatory, with example diagrams drawn for each one (see *Appendix E*). A "principle of charity" was used, such that each student's best (rather than final) answer within a protocol session was used for coding purposes. This was important because students would often produce multiple diagrams in developing their answer to a problem. A second member of the research team then coded half of the subjects from each of the two years in order to determine percentage agreement in the coding assignments of the student protocols.

There was approximately an 92% reliability in our answers (for the Word/Model 1990 and the Word 1989) and an 82% reliability in the 1989 Model Task. After the two coders discussed the differences resulting from this independent coding, they agreed on every answer except one that had to do with a type of special ray. These coding difference problems were primarily to do with interpretation of the kinds of rays depicted in students' diagrams.. Sometimes a student would draw an icon with rays being emitted out of it. This could either represent a diverging beam or a diverging spray, and sometimes it could even look like a parallel beam. Differentiating between these is a complicated perceptual task, and most of the time involves some inference on the part of the person coding the interview. After these discussions, reliability was close to 100%.

Rationale for the statistical tests. To compare the performances of our CA classes in 1989 and 1990, we used Pearson's Chi-Squared Statistic as a large-sample approximation of the Irwin-Fisher procedure for two-sample dichotomous variables (Marascuilo and McSweeney, 1977). Statistical values for p are reported for comparisons significant at p = .05 or greater (e.g., "$X^2(1) = 4.43$, $p = .0353$" depicts chi-square results with df=1). To compare within-individual pre and post-test performance for the Dynagrams students (1990 CA), we used the McNemar test of symmetry for two dichotomous variables (Marascuilo and McSweeney, 1977).

1989-1990 Comparisons

Summary from analyses of Word Problem results

Students received the following word problem:

> "An object is 12 cm from a converging lens (mirror) of focal length 3 cm. Using diagrams and words, could you explain:
>
> • Where and at what distance from the lens an image will form?
> • What will be the size of the image?
> • What kind of image will it be, and why?
> • What would a person see if they put their eye on the axis, far away from the lens?
>
> Now imagine moving the object closer and closer to the lens. Describe to me the changes that take place in the image, and why. Could you show me how the diagram would look for that?"

The 89-90 comparisons for diagram components in our analysis are based on unequal sample sizes in two ways. In 1989, all 20 students had the lens task (above); in 1990, 12 students had the lens task and 9 had the same task but with a converging mirror. First we will present significant trends in '89-90 comparisons for the lens task performance, followed by the '90 overall performance for mirrors. Due to unequal sample size, we will present percentages of students expressing the diagram components in question in the following form [X%/Y%] for the 1989/1990 groups.

Two main themes emerge from this analysis of the Word Problem part of the clinical interview:

1) *Declining use of traditional ray diagrams:* Across the various object locations, the 1989 students were most competent at drawing traditional ray diagrams (including special rays) for the case of an object beyond *f*. But 1990 students, although instruction did not highlight special rays, were better at correctly explaining that this situation would result in a diverging spray originating from the object, turning into a converging spray after it went through the lens (92% vs. 50% in '89: $X^2(1) = 5.77$, $p = .0163$). Furthermore, the '89ers' ray drawing techniques were fragile with respect to object position; they were largely unable to correctly draw the corresponding ray spray diagrams for an object either at *f* (0%) or within *f* (10%). Nor were they able to circumvent the problems they faced (difficulties drawing a particular special ray) by relaxing the constraints of a classic ray diagram in favour of the less precise geometries of converging and diverging ray patterns.

In contrast, the 1990 students made much less frequent use of the full standard ray diagram. For example, 42% did not draw a lens axis at all, as compared to 5% in 1989 ($X^2(1) = 4.89$, $p = .0271$). Of those who did draw an axis, 42% drew it correctly through the lens center, as compared to 65% in 1989 (n.s.). Clearly, the lens axis was no longer a critical feature of their ray diagrams; ray patterns could be constructed without one. The use of special rays also declined from 1989 (55%) to 1990 (33%), but not significantly.

2) *Increasing use of correct geometrical ray patterns:* As a complementary trend to that noted above, students in 1990 were *much* more likely to draw correct converging, diverging and parallel ray sprays for identifying image location than the 1989 students. For example, significantly more 1990 students drew diverging ray sprays from the object [45%/92%: $X^2(1) = 6.97$, $p = .0083$]. More of them also correctly drew the lens as bending these rays into a converging spray, for the case of the object beyond *f* [35%/92%: $X^2(1) = 9.79$, $p = .0018$]. And none of the '90 students at all drew (unhelpful) converging beams from the lens, as 50% had done in '89 ($X^2(1) = 8.73$, $p = .0031$).

Furthermore, the 1990 students' geometrical ray patterns were extraordinarily robust with respect to identifying object position. When asked how the image would change if the object were moved to *f*, 50% correctly drew a diverging spray of rays emerging from the lens parallel to each other, as compared to 0% in 1989 ($X^2(1) = 12.31$, $p = .0005$). When asked to draw the object inside *f*, 83% correctly drew a diverging spray which emerged from the lens still diverging, as compared to 10% in 1989 ($X^2(1) = 17.21$, $p = .0001$).

Interpretation: These complementary trends reflect the shift in emphasis from the more traditional 1989 curriculum to that using Dynagrams. In 1990, special rays and lens axes were given much less significance than the bending of arbitrary (and thus selectable) rays as they pass through a lens, and the resulting patterns of changing ray geometries. Presumably because this kind of reasoning does not rely on the intricacies of applying special rays to at-*f* or within-*f* cases, this kind of reasoning seemed easier for students to remember or reconstruct up to several weeks after the course.

Preservation of the major trends for the modelling tasks

Similar trends as those just depicted for the word problem appeared for the modelling part of the interview, when students were asked to draw a diagram of a real optical situation. From 1989 to 1990 we saw a declining use of traditional ray diagrams, and an increasing use of correct geometrical ray patterns. The 1990 students were much more likely to draw diverging sprays of light from a single point on the object than were the 1989 students [35%/75%: $X^2(1) = 4.8$, $p = .0285$]. And they were much *less* likely to make the mistake of drawing parallel beams from the object [65%/17%: $X^2(1) = 7.04$, $p = .008$]. They were also somewhat less likely to draw the special rays [40%/17%].

Erosion of performance from word problems to modelling tasks: 1989 and 1990 repeated-measures comparisons

However, there was a subtle shift in performance from the word problem to the modelling part of the interview. Students generally used more concrete and naive representations of the physical situation than in the word problem; there was a trend toward more students drawing no special rays for the modelling task than in the word problem ('89: 45% to 60%; '90: 67% vs 83%) and more beams ('89 only: 35% vs 65%), and they used more photo-realistic depictions of the object than the symbolic arrows appearing in their earlier diagrams. Perhaps of most interest is that the '90-'89 advantage in correctly using a converging spray from the lens for the word problem (92%/35%) fades away for the modelling task (58%/45%). It is as if the presence of a real lamp in the modelling task re-awakens an developmentally more-primitive beam model of representation, in that some 1/4 of the students regress from using a converging spray to a converging beam as they move from word problem ('90: 0%) to modelling task ('90: 25%). There is not such a corresponding drop across tasks for the '89ers: on the word problem 50% of them use a parallel beam representation of light, on the modelling task, 45% do.

Summary: Comparing learning outcomes with '89 and '90 CA curricula

Following the '89 curriculum, students were more likely to draw beams of light from objects. After Dynagrams, students were more likely to draw diverging sprays of light from objects.

Using the '89 curriculum, students had difficulty adapting their standard ray diagrams to deal with the tricky cases of an object at or within the focal point (respectively forming no image, and a virtual image). After Dynagrams, students were more successful at diagramming these cases, using parallel or diverging ray sprays that emerge from the lens.

While the number of students using point sources is greater with Dynagrams, there is still a large number of students who use beams to explain a real optical phenomenon; typically, these beams shift from parallel (without Dynagrams) to diverging (with Dynagrams).

Study 2: Pre/post comparisons on everyday optics reasoning situations

How did teaching-learning processes lead students to "see" world situations differently, in terms of their paper and pencil diagrammatic depictions of various optical situations and the inferences they make with them in answering questions about predicted optical phenomena? These are the questions we ask in this study, which compares pre-instructional and post-instructional answers to the same questions in the 1990 CA classroom (see *Appendix F* for questionnaire details). None of these specific questions were directly used as topics of instruction during the course, so changes in students' patterns of response are of interest as indices of learning from the Dynagrams environment.

Analysis of conceptual development. We describe results from multiple perspectives on learning and conceptual shifts after Dynagrams learning. These will include, in separate sections below, the development of conceptual understanding of the interaction of light and matter, development of verbal and diagrammatic tools that represent related scientific ideas, changes in the nature of explanations involving scientific central concepts, and changes in the consistency of students scientific ideas.

Conceptual understanding of the interaction of light and matter. The pretest reflected some major conceptual difficulties in students' understanding of light-matter interaction. Formation of shadows, especially fuzzy shadows, formation of images by optical devices such as mirrors, lenses, glass and water, and vision as related to the role of the eye, are all identified as major difficulties. In the following sections, we describe the changes in the understanding of each of these ideas. We analyze the conceptual responses from three points of view: (1) the changes in the content of the concept, (2) the changes in the conceptualization of light as an integrative mechanism which relates the components of the system to each other to create a causal story, and (3) the role of the eye (See table 10, *Appendix H*).

Formation of Shadows. In the pretest, only 13% of our students explained correctly how a shadow is formed. 79% explained formation of shadows in terms of one of three physical properties of the system, rather than by the interaction of light with this properties (%s are broken out below). Thus, in the pretest responses, shadows are fuzzy because of the:

1) *Relative distances of source-object-shadow* (43%), e.g.: "As the distance increases between an object and its shadow, the clarity decreases. The closer a shadow gets to the exact size of an object, the shadow will become more detailed. This is caused by gases of the atmosphere which scatter the light..." (S-13)

or: "the farther away from the object the light is, the less fuzzy it (the shadow) is" (S-2)

The diagrams support the written explanation, e.g.: the diagram following S-13's explanation shows a far-away and nearby shadow of an object situated between a wall and the sun. The first shadow is fuzzy, and the latter is sharp.

2) *Intensity of light source* (29%) e.g.: "It depends on how strong the sun or light is shining" (S-12). The student's diagram describes a fuzzy shadow when the sun is blocked by clouds, and a sharp shadow when the sky is clear.

3) *Physical properties of the object such as "sharpness" of the object's shape, "smoothness" of the wall, and motion of the objects or sources.* (21%), e.g.,: "perhaps the surface that the shadow is lying on is not a smooth surface" (S-20)

This distribution changes significantly in the post-test: 92% of the students now account for the fuzziness of shadows with explanations in terms of multiple light sources. The diagrams in the post-test, though not always correct, explicitly describe the role of light in the formation of a shadow. Only 17% of students still explain fuzziness in terms of relative distances. None of the students now explains fuzziness in terms of light source intensity or objects' properties. An answer which has not been given before, and is now reflected in 7% of the responses, accounts for fuzziness in terms of the *size* of the light source. Physics treats an extended light source equivalently to multiple light sources. There is no indication that students equate extended light sources with multiple light sources.

Light is recognized by students in the pretest as playing a necessary role in shadow formation. All students revealed some representation of light -- either a light source or some representation for rays. Yet, none of our students, even those who answered correctly, explained *how* light accounts for shadow formation.

In contrast, students in the post-test commonly use relational reasoning, describing the central role of light rays in the formation of the various boundaries of fuzzy shadows. All 75% of the students who answered this question correctly describe the relations between light sources, objects, and shadows by using light sprays to project the boundaries of the shadows. And the boundaries of the various levels of "darkness" of shadow are now explained in terms of the overlapping illuminated areas by each light source interacting with the object casting the shadow.

In summary, while in the pretest, students treat light sources, objects and shadows as isolated fragments, in the post-test these are treated as an integral system linked by the light rays. Some of the post-test students' answers (21%), though correctly stating that multiple light sources cause fuzzy shadows, are unable to support their answer by a diagram which includes the causal relations between the multiple light sources and the structure of the shadow. Light sprays are correctly drawn, and so are the locations of the object, wall and shadow, yet the light sprays do not link these together into an integral causal relation). It seems that the strategy of the diagram is learned, the actual correct answer - multiple sources cast a fuzzy shadow - is also learned, yet the relations between the two are still weak.

The nature of the shadow as the surface of a material object which reflects less light or no light, is hardly addressed by students either in the pretest or the post-test. It is sometimes addressed in the diagrams by including an eye that looks at the shadow (14% on the post-test). This response reflects a deep understanding of the shadow as a reflectance phenomenon. For the shadow to be seen, there must be a surface to reflect the decreasing flux of light, and an eye to detect it. This is probably the deepest understanding of shadow formation represented by geometrical optics.

Formation of images: Real and virtual.. Students' conceptions of the formation of *real* images are revealed in their answers to Questions #10 (burning paper), #11 (goggles when swimming in a pool) and #16 (patterns of light in a wavy pool). Their conceptions of the formation of *virtual* images is revealed in answers to Questions #3 (looking at a mirror), #4 (coin in the water), #6 (window as a mirror), #13 (brightening a room by mirrors or white walls) and #14 (dark room with one mirror). We present first results concerning the development in students' concepts of real images, and then move on to the development of the concept of virtual image.

Real images. The situations described in the questionnaire are not necessarily associated to the "classical" lens and real images introduced in a typical physics class. Neither the questions nor the responses included the phrase "real image," although the situations required reasoning about real image phenomena. This presentation of questions increases the degree of difficulty. One needs to recognize this question as associated to refraction, and then demands application of concepts learned in different situations.

Question #10 (burning paper). None of our students explained the burning paper situation as an image of the sun, which falls on the paper, placed at the focal distance from the lens, either in the pretest or post-test. A majority (53%) explained it correctly in the pretest, as the result of the focused rays, which increase the heat of a specific small area on the paper.

The percentage of correct answers increased to 73% in the post-test. The remaining 27%, as some of those who responded correctly, mention intensity of light yet do not explain it as resulting from refraction of light through the lens in a converging manner. Only 7% of students in the pretest and 25% in the post-test mention the focal point. It appears that students acquire a phenomenological understanding of burning a piece of paper with a lens, which is refined by learning, yet encounter difficulties explaining it as the image of an infinitely far object, formulated at the focal point of the lens.

Question #11 (goggles when swimming in a pool). The role of the goggles while swimming under the water is somewhat tricky. It relates to a real image formation on the retina, by the lens of the eye. It presupposes understanding of the index of refraction as a normative rather than an absolute concept. Therefore, to answer this question one needs to understand that each transparent substance has multiple indices of refraction, determined by the materials of the surrounding environment. For the eye to create an image, it needs to refract the rays of light. The closer the relative index of refraction is to 1 (lowest possible is 1), the less refraction occurs, and the more blurry the sight becomes. The role of the goggles is to create an "air lens" which diverges the rays before convergence by the lens of the eye.

We found only minor differences in the distribution of correct responses to this problem from pretest to post-test (0% in the pretest and 17% in the post-test). The content of the answers distribute differently: 50% of the responses in the pretest, and 11% in post-test were based on the properties of the water/goggles/eyes:

- "water takes up part of the light" (S-6)
- "water pressure on the eye" (S-18)

Another 50% of students for the pretest (67% in the post-test) based their answer on phenomenological accounts:

- because... "there is air between you and the water" (S-2)
- "eyes are irritated by chlorine" (S-16)
- "there is friction between eyes and the water" (S-17, S-14)

Only one student mentioned that goggles have the role of a lens, but went no deeper in explaining the phenomenon.

Though no major changes appear in the frequency of correct responses, more post-test students (67 % vs. 0% in the pretest) explained the need for goggles as a tool to create a layer of air. The precise role of the air layer for the image formation on the retina is still missing in their explanations.

Question #16 (pattern of light in a wavy pool). The wavy pool question deals with images of the sun created by the wavy surface of the water. Correct explanations went up from 20% pretest to 58% post-test. A major difference between the two groups is in the post-test groups' ability to not only write a correct explanation relating the interaction of light and water, but to construct a causal explanation in the diagram: 92% of the students constructed a diagram after instruction, while only approximately 60% had constructed a diagram.

An overwhelming majority of the students in all these questions related to real images show an important conceptual shift in their understanding of what an image is. In the pretest, real images are not described as light-related phenomena, but as something which is there when light is there. In all (100%) the post-test responses to the coin, wavy pool and burning paper situations, the phenomena are related to light refraction, rather than presented as a phenomenological assertion. This occurs only partly (22%) and in a more shallow layer of understanding in the goggle question.

Virtual images. The understanding of a virtual image presupposes the understanding of the role of the eye in the formation of the virtual image. The eye sees the virtual image because it is deceived to interpret the rays of light as originating from the direction from which they hit the eye. The eye cannot sense the changes of direction of the light rays prior to their hitting the eye. As a result, the eye creates an image in the direction sensed by the eye, which in the case of reflection from a mirror is not the actual original direction. Rays of light do not cross each other at the virtual image, as happens in the case of a real image. Therefore the image is considered to be virtual and it does not actually occur unless there is an eye to "see" it. Obviously then, the role of the eye is central to the understanding of the formation of a virtual image.

Therefore, we analyzed students' responses from three perspectives -- (1) the location of the virtual image on/out of the surface of the reflecting/refracting surface, (2) interaction between light and reflecting/refracting surface, and (3) the essential role of the eye in monitoring the virtual image. Consistency of the responses for each student varies. Therefore we analyzed separately their responses to each question. A unified view is presented in the concluding discussion.

Questions #3 (looking at a mirror). The responses to the classical mirror situation show that the changes in the conceptualization of the location of the virtual image after instruction are massive. While in the pretest all (100%) of the students who draw the image (80% of all students) also position the image on the mirror's surface, in the post-test none (0%) did so. Instead, 83% of post-test students position the image *behind* the surface of the mirror.

Only a few pretest students (7%) used a ray spray to justify the image formation, but 42% use a ray spray in the post-test. 50% of the total post-test students successfully traceback the ray spray to justify the image location; 69% of the total students make an attempt to do so.

As to the role of the eye, it was not mentioned at all in the pretest. And only a few post-test students mention it (30%), either in the diagram or in their written explanations.

Thus, in conclusion, it seems that the principle change from Dynagrams instruction is in the students' conceptualization of the position of the image relative to the surface of the mirror. Only a small change was found in the understanding of the light rays as the causal mechanism accounting for the image formation, or of the role of the eye as an essential factor in the system.

Question #14 (dark room with one mirror). The main pre-post change for responses to this question is not in the correctness of the answer (73% to 83%), but rather in the increasing application of a mirror diagram (18% to 55%)with single rays.Yet only 27% of the post-test students actually positioned the image behind the mirror. 64% of the students still positioned it at the mirror, and others did not mention it at all. No student indicated either in the written explanation or the diagram an understanding of the fact that the door is positioned at half the distance between the flashlight and its image. And the role of the eye was totally ignored by all students.

Question #6 (window as a mirror). From the physics point of view, an explanation of the window serving as a mirror is identical to the previous two situations. Yet the responses seem to be completely different. The dominant response was that the glass changes its properties and behaves differently during the night (71% in the pretest vs 55% in the post-test). Around 14% of students in both pretest and post-test groups conceptualize darkness outside the lighted room as a dark materialistic background, e.g.

- "dark does not absorb light while light colors do" (S-14)

We found a non significant change in the response that the image is hard to see during the day, and that "it is easier to see bright against dark." More diagrams in the post-test present the image behind the window (0% vs 80% of those who draw the image at all). Almost no responses included the role of the eye in the formation of the virtual image.

In summary, overall responses to the three mirror questions show a strong reconceptualization after instruction of the position of the image. Less dominant is the idea of light as an integrating link between the object, source, virtual image, and eye. The role of the eye is almost totally ignored, except in the basic case of looking in a plane mirror.

Question #4 (coin in the water). The coin becomes visible to the observer only when immersed in water because of a virtual image due to light refraction. Only 7% of students answered correctly in the pretest, but 67% provided a correct answer on the post-test. However, the number of students who verbally explained the ability to see the coin as a result of refraction in the water increased from 7% to 89%. The 89% to 67% difference is accounted for by those students who responded correctly in the written explanation, yet could not describe the process of light refraction in their diagram. As in the earlier results for explaining shadows, the causal linkage was missing in their accounts between the coin, its image in the water, and the "deceived" eye, as explained by the interaction of light-water-eye. A major change is in the relative number of students who traced rays backwards to show the location of the virtual image created by the eye: 11% in the pretest vs 40% in the post-test. Yet the eye (drawn by the researchers as part of the question) was linked to the light rays and water in all the diagrams drawn by students, either by a direct ray, or by an attempt to describe the field of vision. These rays originated mostly in the eye in the pretest (56%) and mostly originate from the coin to the eye (60%) in the post-test. After instruction, some common responses on the pretest, e.g., "water carries the light" as one among 40% of the pretest group), which are based on some magical properties of the bucket/water/coin system, completely disappeared.

Dark room with a mirror: (#13). Students are asked in this question to identify a door in a dark room which is hidden behind a mirror by using a flashlight. In order to correctly and fully answer this question, they need to answer its two parts:

1) identify the wall with the mirror; and
2) identify the precise location of the door from the position of the image.

Since the position of the door is twice the distance from the student that the mirror is, they need to roughly divide the distance into two to exactly locate the door.

Students' responses, interestingly, assumed that locating the mirror is sufficient in order to locate the door. The image distance at twice the door distance was not considered at all as a factor. It seems that the students assumed that once you know on which wall the mirror is, you also know the distance from you. The underlying assumption which allows such an act is that the image is located at the mirror, which is actually supported by their diagrams.

73% of the students on both the pretest and the post-test answered correctly on the first part of the question. Their diagrams, though, changed significantly. They use *rays* in the post-test, when they did not use them before (18% vs. 55%), the image is located behind the mirror in the post-test by 27% of students (vs. 0% pretest). A surprising result is that more post-test students (64%) put the image at the mirror (vs. 18% in the pretest). This is consistent with the fact that all students ignored the image distance as a factor for determining the exact location of the door. It can be explained by the fact that more students are aware of the fact an image is there, yet they do not apply the correct distance, although 83% they did so in the post-test in mirror question.

Vision and the nature of light. Consider Question #2 (dark room lit by a candle). A correct answer to the candle question, which deals with vision, includes recognition of multiple steps: Light is emitted by the candle in all directions, hits objects, is reflected off objects and hits the observer's eye. More students in the post-test than in the pretest (33 %vs 83% realize that light hits the objects and that objects need to be reflective as a necessary condition for vision. (7% in the pretest vs 75% in the post-test) However, only 13% realize in the pretest that light needs to hit the observer's eye for vision, while 67% mention the eye, and the whole process in the post-test. This is a major understanding of the role of the eye in the process of vision. These changes with instruction are very strong - prior to learning most students had an idea of reflectance as a necessary condition for visibility, but the causal link between light source and rays, the eye and the objects in the room was missing. Over 2/3rds of the students acquired this missing link through learning. Overall, 85% of them developed a some sort of model, sometimes a partial model of visibility and vision based on reflectance.

Development of representational tools

This section focuses on the development of dual representational tools: both verbal and diagrammatic. We look at pre-post changes in students' representations of objects, light sources, light, and physical phenomena such as shadow or images. Then we analyze the development revealed in their representations of *relations* between the light source, physical objects and the natural phenomenon. Finally, we compare the amount and type of information students represent through each of these tools so as to identify the structure of the representational tools which students acquired with instruction.

Students were asked to draw diagrams both in the pretest and in the post-test. There is no significant difference between the number of diagrams drawn prior to and post the learning process. In these terms, students seemed equally confident that they had the tools for diagram construction both before and after instruction.

Representation of light sources, objects, and physical phenomena. Most of the diagrams created by students in the pretest across all questions are of a *photographic nature* (96%). By photographic, we mean that the students draw the situation in the same way that it would appear in a picture taken by a camera. The objects are represented by their shape, the light source is represented by traditional symbols of light such as a glowing candle, glowing sun or bulb, which for our purposes is also considered to be a photographic representation of a light source (see examples in *Appendix G*). A lens is represented by its contour (sometimes with a handle), and the shadow is a darkened area. The image is represented also by its shape.

Light creates a special problem: it can hardly be represented by its shape, in the same way as other components of the system. Students chose to represent light through four different representational tools: rays, beams, sprays, and fully painted regions. Table 1 in appendix H shows a comparison between the distribution of the representation of light across all questions. For both groups, the most commonly used tool is a single ray or a bunch of single rays (73% pretest, 50% post-test). Yet the percentage of students who chose to represent light by means of a spray-of-rays increased remarkably, from 17% pretest to 45% post-test. The use of single rays decreased correspondingly, from 73% to 50%. The pre-post difference are even bigger in specific questions: The representation changes more drastically in the shadow and mirror questions (Questions 1 and 3) The use of divergent rays increases from 15% to 60% while the application of a ray decreases from 60% to 25% (see Table 2, *Appendix H*).

A *halo* is often drawn around a glowing candle, though most of the time (98% of the light sources drawn), it is constructed of small lines which are not related to light rays, beams or sprays. A ray drawn is not a continuation of the halo around the light source, but is drawn separately as emerging directly from the light source, not from the halo. Thus the halo is depicted as a symbol of the state of the source -- active, rather than the function of the source -- emitting light. The function of the source as the origin of light rays is not present. It is more frequently represented in the post-test through the ray spray tool (17% in the pretest vs 45% in the post-test) which, by its very definition, has to emerge from the light source. A *fully painted area* is rarely used to represent light (10% pretest, 5% post-test). In these cases the rays are superimposed on the fully painted area, separating the ray of light form the fully lighted space.

Shadow is represented as a darkened area on the surface of a plain object, by all students in the two groups. This depiction corresponds to their verbal representation: e.g., "no light is reflected", "no light hits the wall," and "no light gets there". Some representations of a shadow are a darkened space, not just a two-dimensional piece on the surface, but rather all the space behind the object, on the far side of the light source (20% pretest, 5% post-test). This difference suggests an increasing representation of the idea that a shadow is not a dark space, but is a surface that reflects less light. Reflection is impossible when the shadow is a dark space.

We first present students' *representations of an image* in the pretest, and then characterize the restructuring of their image representations after learning.

An overwhelming 87% of the students' pretest responses presented an image in its photographic form by drawing the shape of the image (e.g., in *Appendix G*, S-13's pretest, reading question; S-3's pretest, mirror question). Only a few students related image formation to light behavior (fewer than 5%). The concept of image was limited to its existence and shape, and was not related by students to the behavior of light. Parallel lines drawn between the image and the object were not explicitly referred to as light. These have the role of corresponding lines that relate each feature of the object to its symmetric feature in the image (e.g., S-13, pretest, mirror question).

The concept of the location of an image develops beginning from the image on the surface of the mirror (80% pretest, 0% post-test), towards the recognition of the image as an imaginary construct formalized by continuing the reflected rays behind the mirror (0% pretest, 83% post-test).

A further development in the concept of the image is relating it to the light behavior. The main recognition of an image in the pretest is based on the recognition of its shape. Sometimes light is characterized as a carrier of the image: "light passes around your face, bounces off the mirror and back to your face, illuminates your features. These light particles bounce back to the mirror where they display an image of you".

In the post-test, students recognized the position of the image by locating the point at which the continuations of light rays cross each other. Students developed a recognition of the image as a phenomenon which exists at the point where all the rays cross each other, rather than as a mere photographic representation. 80% of the pretest students draw an image without relating it to the interaction of light and the mirror in reflection. None of them realized that the image was related to imaginary lines constructed by the eye, which go beyond the surface of the mirror until they cross each other. This is supported by the literature which points at the virtual image as one of the most complex in Geometrical Optics (Galili & Goldberg, 1990). In the post-test, only 17% of the students draw an image *without* justifying its formation by tracing light rays, and 66% of total post-test students constructed an imaginary traceback either of rays or spray, correctly in order to locate the image. This effect is strongest in the mirror image question (Question #3), somewhat weaker in responses to questions that did not relate directly to formation of an image, such as the lighted window (Question #6) and the mirror in a dark room -- 0% in the pretest vs 9% in the posttest. (Question #14). Results are presented in Table 3, *Appendix H*.)

The relation between the light and the image described in the verbal component of students' responses was fragmented in the pretest, but becomes more coherent in the post-test responses. The concept of the image as a reflected instance is reconstructed into the concept of the image as associated to reflected light rays. Specifically, in the pretest, the commonly used expressions are: "you see your reflected image," and "the image of the flashlight is reflected" (70% average across all image questions). In contrast, the association "reflected image" is rarely used in the post-test (20%). Instead, combined phrases of the type "light is reflected and you see the image of ..." are more frequent (68% post-test). Position of image is mostly on the mirror before instruction and behind the mirror after (Table 4, Appendix H). Interestingly, the mirror in the dark room does not reveal the same change. Students keep on describing the image on the mirror. Probably because more students are now aware of the necessity to draw the image, and they do not correlate it to the traditional mirror situation.

Finally, we found an interesting inconsistency in verbal terminology and diagrams for the differentiation of reflection and refraction. This appeared mainly for the post-test question. In some situations, students write that light is reflected by the water ,and the diagram shows a refracted pattern of light, for instance, in the wavy pool question (#16), some students explain the patterns of light by reflection of water. The diagrams show a change in the direction of the rays from the sun, after they hit the water.

Situational considerations in the use of light representations. Though a general increase occurs in the tendency for students to use ray sprays for image formation, this change is more dramatic in response to the shadow (Q#1) and mirror (Q#3) questions than for other questions. These questions are more explicit in their demand to construct an image, while other questions are non-directly related to image formation. Let us consider the percentage of students, aggregated as an average percentage across the shadow and mirror questions (weighted according the the number of students responding to each question). After instruction, considering their answers to the two questions together, the application of ray-sprays increased considerably: from 15% to 60% of students, while the use of single rays decreased significantly, from 60% to 25% of students (see Table 2, Appendix H)

A similar tendency occurs in the learning we observe in the constructing of the virtual image by using a traceback of reflected rays. The more dramatic change is in the direct mirror question and is less dramatic in the questions about the window as mirror (Q#6) and dark room with one mirror (Q#14). The least dramatic change occurs for the coin question (#4). Though dealing also with a virtual image formation, an additional level of complexity occurs for #4, due to the added complexity of the refraction of light in water.

Rays and ray sprays as causal linkages integrating the various components of the image formation and shadow casting situations. The previous section reviewed evidence on the development of the concept of the image from a representation of the shape on the surface of the mirror, towards a representation which includes light rays as justification facilities. Light rays also integrate through a causal linkage, the light source, the optical device, any objects, and finally the image formed or shadow cast. In contrast, the photographic representation common on the pretest does *not* represent the causal relations among these situational components.

The major difference between the pretest and post-test responses was in the increasing tendency of students to use the ray spray or single ray to construct a causal linkage among the various components of the system. For instance, the formation of the shadow in the pretest is represented as a dark area on the ground, shaped similarly to the object. The pretest diagram typically does not explicate what mechanism is responsible for the size and shape of the shadow. Nor does it explain how the shadow is related to the light source (e.g., s-14, pretest, shadow question). In the pretest, light rays are *not* used as an explanatory tool which could help in efficiently representing the relations between the number of light sources and the number of intensities of the "darkness" of the shadow (fuzziness). The relative number of the overall situations where light rays are used to construct causal links in the pretest is negligible - fewer than 5%. That is not to say that light rays are not drawn. They do appear as entities in the diagram, but they are not constructed in a manner accounting for the shadow cast or for the image formed.

The presence of both the image and the traceback of reflected rays reflects an understanding of light rays as strategy for construction of a causal link between the rays and images. Table 5 in the appendix shows that none of the students constructed a n image by using traceback of rays sprays. 50% in the responses to the mirror question, included the image and the traceback strategy. This process was minor in other questions.

The frequency of diagrams, which present both the physical entities and the light rays as tools for constructing the relations between the light source, object, shadow and sometimes the eye, is increased in the post-test to 50% in the mirror question. The linkage across questions is sometimes partial, since visibility is not always related to reflectance; thus for 20% of students in the post-test, rays hit the object, the eye is present, but the rays are *not* reflected to the eye. Around 10% of the post-test students show the rays as reflected in all directions (correctly), but not hitting the eye they have drawn.

We have identified three representational models for rays and ray sprays as causal linkages integrating the various components of the image formation and shadow casting situations. The most advanced representational model includes all three of the following causal components:

(1) Light originates at the source, hits the object, which reflects, refracts or absorbs the light.

(2) As a result, a shadow or an image is formed, depending on the situation.

(3) Reflected rays hit the eye and an image, shadow or an object is detected by the eye.

We will look at students' pretest and post-test attainment of different levels of the three-component representational model in terms of their responses to three questions: the shadow, candle, and mirror questions (Q #1, 2, 3).

For the shadow question, 50% of the post-test students had acquired the full model versus 14% in the pretest. 75% of the post-test students acquired a model which included the first two components, but not the eye. (The eye was less crucial as a component for explaining the shadow situation than for the candle and mirror situations.)

Responses to the candle question (#2) revealed 58% of post-test students using full models versus 7% in the pretest. For the same question, 67% of post-test students versus 13% in the pretest, had a partial model which did not include the eye.

As to the mirror question, 50% of the post-test students, versus 20% in the pretest, who responded to the mirror question (Q#3) had a full model. %8% of the post-test students had acquired a model lacking only the eye component (see Table 6, *Appendix H*).

We must note for ray sprays that the ray spray representational "game" has its own rules. A ray spray is supposed to originate at the light source, hit objects, then reflect or refract according to Snell's laws. At a broader glance, aggregating across these questions on shadow, candle, and mirror, not all light rays represented in the students' diagrams originated at a light source, or were reflected from an object (10% of post-test students). Rays in these cases are lines coming from the eye (5% of post-test students), or from some other, apparently arbitrary, direction (another 5%) . A whole class of diagrams is based on correct drawing of the rays, but in which the rays are not related to the objects, or to the natural phenomenon discussed. For instance, in some cases, rays don't hit an object but pass *through it* as if it was not there (e.g., S-10 shadow question). For SA-10, the light rays hit the object correctly, the fuzzy shadow is correctly drawn, but the projection is a right-angle projection, drawn by parallel lines, instead of a diverging angle projection.

Types of explanations

In this section, we look at a metalevel of learning. We examine changes in what counts as an explanation from pretest to post-test, and at what the developmental differences are in students' construction of justifications.

The perspective taken here is that verbal tools are not sufficient to construct a causal explanatory argument in the case of geometrical optics. We base this claim on the historical necessity which drove the construction of diagrammatic tools for reasoning and communication in physics (e.g., Miller, 1986). Therefore, the following analysis is based on an integrative view of explanations, which are represented *both* by verbal means and by diagrammatic tools.

We look at the development of argumentation and justification from two points of view: (1) presuppositional vs. causal explanations , and (2) the presence of single layered vs. multi-layered accounts (i.e., in which single vs multiple elements of knowledge are used to justify the same phenomenon).

Presuppositional vs. causal explanations. We define *presuppositional explanations* as based on an assumption that the observed or predicted state-of-affairs is how things happen naturally, and thus there is no need for justifications. In contrast, *causal explanations* account for the event by using a rational, causal linkage between the components of the system observed. Thus all accounts of image formation based on representation of interactions of light with optical devices are considered to be causal in nature, not presuppositional. The following cases are examples of presuppositional explanations:

- On the formation of fuzzy shadows: "the shadow grows clearer as the flashlight moves towards the wall" (S-2 pretest, shadow question)
- On the observation of an image in a lighted room window: "Dark outside does not absorb any light" (S-14 pretest, window as mirror question)
- On the formation of images: "When looking into a mirror, you observe a reflection of yourself....light makes the image visible"(S-3 pretest, mirror question)

These examples share a presuppositional belief that what is observed is just how nature behaves, and so an explanatory account is not needed. We observed a strong restructuring of the types of explanations offered from pretest to post-test : most explanations offered on the pretest are of a presuppositonal type (61%). The frequency of students offering presuppositional explanations decreased after the learning experience to about 30%, and the causal explanations increased to 67% from 37% on pretest). Some of the questions yielded bigger pre-post increases in the frequency of causal explanations than others - shadow formation (21% to 92%), vision with a candle (13% to 58%), image formation in a mirror (7% to 83%), reading process (45% to 82%), and the wavy pool (56% to 82%). This result is consistent with the result we found before on the adoption of causal models represented by the ray sprays. After Dynagrams instruction, students adopted the ray tools they learned to use in order to construct causal relations among the system components, even with a paper and pencil medium. It also allowed them to construct causal explanations.

Single vs. multiple-elements of knowledge used for explanations. In most pretest explanations, students provided a single element of knowledge to justify their responses. This is sufficient to construct a legitimate justification.75% of the justifications in the pretest are based on such a single element of knowledge. Only 24% explicate more then one element of knowledge: this is sometimes logically layered, meaning that one statement is justified by another one, which again can be justified by a third statement. A justification can be wrong and yet layered: e.g., "As the distance increases between an object and its shadow, the clarity decreases. The closer a shadow gets to the exact size of an object, the shadow will become more detailed. This is caused by gases of the atmosphere which scatter the light..." (S-13). This account consists of three layers: a phenomenological observation - shadows are fuzzy, a physical property which explains the reason why shadows are fuzzy (distance), and a possible abstract explanation to account for the reason that the distance is a factor in the sharpness of the shadow. Conceptually, it seems to be structured through three logical relations accounting for each other.

We find that fragmentedness, considered to be one of the characteristics of naive knowledge, decreases. A layered justification reflects logical linkages that the student constructs between different elements of knowledge. Therefore, a We find an increase in the number of students who conducted layered justifications - 24% of the justifications in the beginning are layered, while 53% are layered after instruction. The single element justification is a predominant justification strategy in the pretest (75% of students), and much less frequent in the post-test (47% of students).

Changes in consistency in use of concepts across situations

In this section we test changes from pretest to post-test in students' consistency of application of the following ideas and strategies across problem situations in the questionnaire:

1) Position of image
2) Conditions for visibility
3) Use of diagrammatic tools for formation of images and shadows: rays, ray spray, reflection and refraction.

We calculated the relative number of responses in which each student applied a similar idea. For instance, 50% reflects that the student applied an idea over only half of the relevant situations. The aggregated numbers, over all students, appear in Table 19 (*Appendix H*).

(1) Position of image. The consistency of application of the position of the image is less than 0.6 The inconsistency lies in the fact that the image is not always drawn in the diagram. Yet whenever they draw it, it is located on the surface of the mirror. Therefore, if the consistency is judged relatively to the number of drawn images only, the consistency is close to 1. This means students are very consistent in the tendency to draw the image on top of the mirror. Both the consistency of application of image behind and on at the mirror decreases after the learning period to 0.5 and0 .6. Students who draw the image on the surface tend more often to draw the image on the mirror. Those who learnt that the image is behind the mirror still apply it only sometimes: most cases of inconsistency are due to the mirror in the dark room. The flashlight in this diagram is almost always drawn on the surface of the mirror.

2) *Conditions for visibility.* Analysis of the conditions across which students apply to different situations as necessary for visibility is based on the candle and reading mirror, window and dark room with a mirror. To be completely consistent on this issue means to always apply the following causal link: light that originates at a light source, hits an object which reflects light that can hit the eye and thus see or hit a reflector and then be reflected again to hit the eye and create a virtual image. Table 9 describes the number of situations to which this full logical chain was applied. The consistency of applying the logical chain necessary for visibility increases after instruction. So does the consistency of using similar tools for image construction.

3) ***Use of diagrammatic tools for formation of images and shadows***: rays, ray spray, reflection and refraction. Being consistent within this group of questions means that students needed to apply the following steps (not necessarily correctly): rays are emitted from a source; hit the object; reflect, refract, or create a shadow; and finally present a traceback when necessary.

In the post-test, students draw rays in 40% of the relevant situations (vs 20% pretest). This finding is consistent with our observations that the pretest diagrams are most commonly *photographic*, representing primarily what the eye can see. The rays hitting the object are represented by 60% of post-test students (vs. 30% pretest) for the relevant situations within the image and shadow questions. 80% (vs. 40% pretest) of the situations included reflection, refraction, or shadow formation, and 60% (vs. 0% pretest) of the cases included some attempt for traceback. The overall consistency as evident in application of both new acquired ideas and ideas already expressed in the pretest is overall bigger.

Integrative discussion of conceptual development after Dynagrams learning

These analyses have presented an integrative view of learning -- looking at conceptual development, developments in representations used, and at epistemological development in terms of explanation structures. Across these perspectives, we found that student performance after the instruction reflected various developmental stages.

Conceptual development. A few examples are reviewed below, from various perspectives of our analysis of conceptual development, and we then unify the various examples to suggest a possible pattern of learning in this project.

Example 1. Various levels appear in the understanding of *shadow formation*

> *Level 1*: Students use verbal representation of multiple sources to account for fuzzy shadows. Yet they still can't support their answer by a diagram which includes the causal relations between light sources and level of darkness of a shadow.

Level 2: Students' verbal representations are full and correct. Light ray-sprays are drawn, and so are the locations of the other components of the system -- the light sources, the object, and the wall. Yet the light rays do not link these together into a causal explanation.

Level 3: A full account is constructed by linking the components in the system, and the verbal and diagrammatic representations into a causal chain that explains how these components interact to create a shadow.

Example 2. Various levels appear in the understanding of ***virtual images***

Level 1: The virtual image is located behind the mirror. The image distance is equal to the source distance.

Level 2: Light rays illuminate the object, reflected light reflects from the object, hits the mirror, and reflects back to hit the eye. The eye creates a virtual image of the object.

Level 3: Level 1 is verbal, and the Level 2 uses a different representation -- through diagrams. The deeper understanding includes both.

The first level for each example could have been judged as correct in a sense. It is only the necessity to construct multiple representations that unfolds the weakness of the shadow and virtual image conceptualization. Therefore it seems that conceptual understanding needs to be tested through multiple representational tools. Based on the same argument, we see that understanding has to be developed through multiple representational tools.

Students developed models of light behavior in various levels of complexity and representation. The diagrammatic tool allows a deeper understanding of the phenomena. We have shown that a complete understanding of light behavior is impossible without multiple representational tools. Therefore, the process of acquisition of the representational tools is crucial for students to attain a full understanding of the optical phenomena. Furthermore, lack of multiple representational tools limits students' ability to represent their ideas to others, either in a paper and pencil test or for discussion with others. The ability to communicate about physics ideas, especially in optics, is determined by the student's reserve of representational tools.

We have seem how the initial stage of the development of representations for students in our study was a very concrete one -- a *photographic* form of representing a physical optical system. The only entities that needed to be represented, according to this initial stage, are the observed objects. Students described in a diagram what they saw quite literally, not in terms of processes and causal relations. Therefore, the mapping function between the diagrammatic representation and the observed physical entities is based on the shape of the objects. This raises a major difficulty for students in the construction of a representation for abstract entities such as *light.* Therefore, a new diagrammatic "language" is necessary to allow students to represent ideas which cannot be represented otherwise. Such representations are also crucial to the construction of explanations of more complex optical phenomena, as we have seen.

Changes in representations. Intuitively, the most frequently used representation is a ray. The more powerful representation, a diverging ray-spray, is partly developed by most students, and fully by some. Students construct a mapping function in both the pretest and post-test. The mapping function changes: it becomes less photographic, which means the shape of objects is not the function students use continuously. They expand the mapping function to represent the abstract concept of light, and its relations not only to light sources but to the eye as a detector of images and shadows. This representational tool is a new convention they developed during Dynagrams learning, and it brings them closer to the communicational tools accepted in the scientific community.

Construction of explanations. Students developed an important methodology of causal explanations. This result is consistent with the result we found before: students adopted the ray tools to construct causal relations among the system components. It also allowed them to construct causal explanations.

A corresponding result is that fragmentedness of explanations decreases in the post-test: The response given by (S-13) consisted of three layers: a phenomenological observation - shadows are fuzzy, a physical property which explains the reason why shadows are fuzzy, (distance) and a possible abstract explanation to account for the reason the distance is a factor in the sharpness of the shadow. Conceptually, it seemed to be structured through three logical relations accounting for each other. Thus it could hardly be a "fragmented" isolated type answer, frequently mentioned in the literature as one of the characteristics of students' naive knowledge.

Implication for teaching: Most of these changes from pre-post were larger for a few identifiable questions, and smaller for others. Specifically, the restructuring process resulting from students' learning was stronger for situations analogous to those covered in the Dynagrams activities, and not as strong in others.

Study 3: Classroom sessions from small groups

We devoted substantial energies to carefully collecting videotape data, worksheets, and homework from several classroom groups for all 21 classroom sessions during the Dynagrams field test. To date, we have used these records for several major empirical analyses. In several papers, we have illustrated the microgenetic changes in conceptual learning that occur for one group during a ten-minute period of intensive conceptual learning conversations (Pea, in press-a; Sipusic, in preparation). This was a major case of meaning alignment that occurred during the second of four weeks in the Dynagrams classroom. The group was grappling with the concepts involved in understanding image position for a plane mirror. While they started out a class period with a diversity of views for what "image position" meant, at the close of the period they shared a very different perspective, which appeared robust in the individual reasoning profiles of the students in the group a month later.

In another complementary analysis, Goldman (submitted) has characterized the ways in which students interweave conversations concerning science learning, social relations, and classroom procedures into their work together. She demonstrates that 1990 students' interactions with the resource-rich Dynagrams learning environment enabled them to increase their participation in classroom conversations about science concepts. We anticipate using these videorecords for a variety of future microgenetic studies of conceptual change which will complement the quantitative comparisons of conceptual development during Dynagrams instruction which we have characterized in Studies 1a, 1b, and 2 above.

Study 4: The 1990 CA physics taught

We videotaped four groups of students in two classrooms working in groups for 16 out of 21 days spent on the optics unit. (The other classroom was with a teacher who had not been studied in 1989, and so for our comparative analyses, results from the two groups from that classroom using Dynagrams are not included in this report.) On these 16 days, the students collaborated in the accomplishment of laboratory table activities with optics manipulatable, the Dynagrams simulator and interactive demo tools. This amount of small group laboratory work was an increase over the number of laboratory days of the pre–Dynagrams year when the students visited the lab only 5 times during the 15 day unit.

Additionally, we made videotapes of all whole–class activities and kept a remote microphone with the teacher at all times so we could have records of all small group and dyadic conversations he engaged in with students during laboratory sequences. Two researchers took paper and pencil notes describing classroom events and moments of interest during each classroom period.

Let's look at what the teaching practice was like to try to understand the nature of our post-test learning results, their pattern of strengths, and also their limitations.

The physics classroom had some regularized sequential patterns. Class began with all students taking their assigned seats. Each class started with an attendance check and the teacher's introduction to the topic and activities for the day. Occasionally, assignments were collected during this time, and the introduction was often supplemented with announcements (e.g., a state–wide physics contest, the soccer team victory, a new student to be introduced, science in the news). The segment was teacher directed. This introductory segment was followed by "the lesson or activities" segment of the class. This particular segment could take different forms, depending upon the goals for the day. The usual possibilities were: teacher directed activities such as lecture, demo or class discussion or small group work at the lab tables. The lesson segment of the activity usually lasted the most time during the 48 minute period, lasting anywhere from 12–40 minutes. The third and final sequence was the "wrap up," in which main points were restated, assignments and due dates confirmed, the next day's lesson introduced, and "things to think about" mentioned. This final segment included formal dismissal of the class. It is in the middle segment, main lesson activities, where we found our students collaborating and conversing at the lab table.

We identified many changes in what the teacher did with his diagrammatic representations, demonstrations, labs, tests, and patterns of discourse, as well as some similarities with past practice in the 1989 study. In terms of his uses of diagrams, the teacher drew fewer beams, more ray sprays, included more eyes in his diagrams to indicate the fundamental role of the detector of images and shadows. He also proposed as an improvement and carried through on the use of a "spatial zones" topology, rather than a special ray methodology for explaining variations in ray behavior to students, which seems from our analyses of student learning to have had effects on what students did after instruction.

Students worked in groups more often and had many more conversational opportunities than they had in the pre-dynagrams classroom. Students used diagrams regularly as the basis from which they were asked to observe and describe optical phenomena. Rather than just know the definition of terms and properties, students were asked repeatedly to use and experiment with them in their modelling activities (e.g., light sources, rays, focal points, virtual and real images, normals,etc). They made reference to terms and/or their properties in more varieties of ways and in more instances. The simulator provided an exploratory environment where students were asked to reason about optics. Our early analyses (Goldman, in preparation) indicated that student activities and conversations became focussed on making projections and conjectures, and then testing out their ideas of how light would react.

The Dynagrams classroom activities provided students with more opportunities to ask questions of each other and an environment within which to test their answers. When questions emerged out of a group's activities, the teacher used the simulator with students for exploring questions before giving answers and explanations. Interactions surrounding classroom activities became more discovery oriented.

Most importantly, the teacher saw this organization of the optics learning environment as leading to many more “teachable moments” with Dynagrams than in his previous methods. He would routinely move between student groups as they worked together on activities through the four-week period, identify where they were in their progress, and work to move them forward in their conceptual growth. A major difference was that the teacher reduced the amount of time lecturing in front of his class by about 60%. In his own terms, he decided it was time to "Get the sage off the stage" and "Put the guide on the side".

Several provisos are important to make. Under the time pressure of covering the diverse topics in geometric optics that had been co-planned with the Dynagrams research team, later sessions involving mirrors and lenses did not allow for as much integrative discussion at the end of class periods as the teacher had planned, and he felt he sometimes slipped into the pre-Dynagrams practice of "handing-over" conclusions to student groups that should have emerged from their own inquiries. Also, there was less within-period integration of hands-on activities, simulator modelling work, and paper and pencil contributions to challenge activities on worksheets; this was stretched across periods rather than integrated within periods as the latter sessions of the four-week period drew near (with uncertain consequences).

Discussion: Connections between Results and Learning Environment Design

The major insights from the Dynagrams research project have to do with the connections we have been able to establish between observing learning and teaching practices and their attendant results, and learning environment design. In an ideal situation, we would continue iterating our cycle of tightly coupling our observations of such practice, and redesigning the learning environment, until we had achieved dramatic improvements. As it is, we have engaged in two rounds of inquiry concerning practice, and one round of design, which has led to significant gains in student learning, but left certain issues outstanding. What have we learned so far about both teaching-learning relations, and about methods for such classroom-based research and development?

Effects of minute details of teaching on student reasoning

One of the most striking aspects of our findings has been how small changes in instructional practice with diagrams seem to co-vary with patterns of student reasoning with diagrams, in ways suggesting significant causal relations. Of course, our quasi-naturalistic study design does not allow such strong inferences to be made. But there is a strong surface plausibility to the claim that the use of *ray sprays* rather than ray beams, by students in the Dynagrams activities and in the teacher's diagramming practices, contributed to the virtual eradication of the simple parallel beam model evidenced by 8 of the students in 1989, and the students' emergent widespread use of diverging sprays of light from objects in their diagrams.

Similarly, using the '89 curriculum, very few students were able to represent and interpret *virtual images*. After Dynagrams, a larger number of students knew what a virtual image is and can represent one on a diagram, although the number was still small. This is what we expected based on our emphasis on *eyes*, and on the virtual image behind the mirror in specific experiments students conducted.

Effects of large details of teaching on student reasoning

For contrast, it is important to highlight the major '89-'90 difference in the teacher's role in the classroom. Not only minute details of the material features of the learning environment differed in this transition. Whereas in '89, the teacher served primarily as an agent for clear knowledge delivery, in '90 , he saw his role much more as facilitator and cultural interpreter for the language and authentic tasks of science that it was the students' task to come to appropriately use. And '90 students worked in small lab groups three times more often than they had in '89.

"What Dynagrams design features made the difference?"

In a classroom-based research and design study such as Dynagrams, it is tempting to ask which Dynagrams design features accounted for whatever student performance differences across years we have observed. We have speculated about several of these contributions already, but not in any way in a statistical manner, such as "what percent of the variance observed between groups was accounted for by which features?" The reasons for this neglect are simple: we would require more carefully controlled experimental comparisons, but more basically, even with respect to features, such experimental comparisons might be difficult to implement, since it is never technology or social design features *per se* have effects anyway. It is their interpretation and use in the activities of a social community that come to give them meaning.

Nonetheless we may risk the plausible inference from our Dynagrams field-test results that making the theory-and-results motivated changes we did in the learning environment for the students contributed to differences in learning outcomes that we may observe. But for those cases in which we *do not* determine advantages for students in our intervention, we will find it hard to know why (e.g., insufficient amount of learner experience with events likely to lead to overcoming the difficulty in question; inappropriate design for overcoming that difficulty, etc.).

Dynagrams 2.0?

Both the teacher and research team completed the project eager for a new iteration, and aware of many of the ways in which a new cycle of design and research could improve on the existing learning environment. Some of the most salient are mentioned in these closing notes; we expect to elaborate these observations in Pea, Sipusic, Allen, Reiner and Goldman (in preparation).

1. Beyond the point source alone, we identified an important need to do diffuse reflector work so that students might come to "see" world events in the terms provided by the geometrical optics concepts. Students did not come to see objects as collections of point sources as we had hoped; it was beyond our implementation time to get the simulator to support it, and the teacher did not emphasize it.

2. Concave and convex mirrors are needed in the simulator, since they are commonly covered in comparison to concave and convex lenses.

3. Special rays for the simulator would be helpful -- the teacher wants them, and they are an integral part of off-computer reasoning in optics

4. More scaffolding is needed for kids in activities when working in groups, more teacher time needed as they work on the difficult points in conceptual learning conversations

6. We would like to consider more structured activities in which student engage in optics argumentation with teacher guidance, analogous to Lampert's work in elementary mathematics learning

General Implications for Learning Environment Design

The construction of learning environments is a challenging task that becomes all the more demandingwhen examined from a social framework. 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.

We 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 technological, social and curriculum 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 that community, 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 concepts and processes. While we expect many challenges to establishing conditions for "growth" of such communities of practice in school institutions, we are optimistic that an increasing focus on augmenting conceptual learning conversations with computer tools could go a long way toward improving science learning.

Bibliography

Allen, S. (in press). The Gaussian formula and the elusive fourth principal ray. *American Journal of Physics.*

Allen, S. et al. Student mental models of light-matter interactions and their classroom origins. *American Journal of Physics.*

Anderson, C. W., & Smith, E. L. (1984). Children's preconceptions and content-area textbooks. In G. G. Duffy, L. R. Roehler, & J. Mason (Eds.), *Comprehension instruction: Perspectives and suggestions* (pp. 187-201). New York: Longman.

Andersson, B., & Karrqvist, C. (1983). How Swedish pupils, aged 12-15 years, understand light and its properties. *European Journal of Science Education*, 5(4), 387-402.

Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics*, 50, 66-71.

DiSessa, A. (1982). Unlearning Aristotelian physics: A study of knowledge-based learning. *Cognitive Science*, 6, 37-75.

Driver, R., Guesne, E., & Tiberghien, A. (1985). (Eds.). *Children's ideas in science.* Philadelphia: Open University Press.

Goldberg, F. M., & McDermott, L. C. (1986). Student difficulties in understanding image formation by a plane mirror. *The Physics Teacher*, *24*, 472-480.

Goldberg, F. M., & McDermott, L. C. (1987). An investigation of student understanding of the real image formed by a converging lens or concave mirror. *American. Journal of Physics, 55*, 108-119.

Goldman, S. (submitted). Mediating micro-worlds: Collaboration on high school science activities. *J. Learning Sciences.*

Goodwin, C., & Heritage, J. (1990). Conversation analysis. *Annual Review of Anthropology, 19*, 283-307.

Guesne, E. (1985). Light. In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science* (pp. 10-32). Milton Keynes: Open University Press.

Hawkins, J., & Pea, R.D. (1987). Tools for bridging the cultures of everyday and scientific thinking. *Journal for Research in Science Teaching*, *24*, 291-307.

Heritage, J. (1984). *Garfinkel and ethnomethodology*. Cambridge, England: Polity Press.

Jul, S. (1991). Dynagrams™: The software. *IRL Technical Report*, Institute for Research on Learning, Palo Alto, CA.

Jung, W. (1981). Conceptual frameworks in elementary optics. In *Proceedings of the international workshop on problems concerning students' representations of physics and chemistry knowledge*. Ludwigsburg, West Germany.

Larkin, J. L., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, *11*, 65-100.

Lave, J., & Wenger, E. (in press). *Situated learning: Legitimate peripheral participation.* New York: Cambridge University Press.

Lemke, J. L. (1990). *Talking science: Language, learning, and values*. Norwood, NJ: Ablex

Miller, A. I. (1986). *Imagery in scientific thought*. Cambridge, MA: MIT Press.

Pea, R. D. (November, 1988). Dialogism and mathematical discourse. *Invited address at the Tenth Annual Meeting of the North American Chapter, International Group for the Psychology of Mathematics Education.* DeKalb, IL.

Pea, R. D. (in press-a). Augmenting the discourse of learning with computer-based learning environments. In E. de Corte, M. Linn, H. Mandl, & L. Verschaffel (Eds.), *Computer-Based Learning Environments and Problem-Solving.* New York: Springer-Verlag.

Pea, R. D. (in press-b). Distributed intelligence and education. In D. Perkins & B. Simmons (Eds.), *Teaching for understanding in an age of technology.* Cambridge, MA: Harvard University Press.

Pea, R. D., Allen, S., Sipusic, M., Goldman, S., Reiner, M., and Jul, S. (submitted). Designing classroom discourse resources for conceptual change in science. *Interactive Learning Environments.*

Pea, R.D., Sipusic, M., & Allen, S. (1989, July). *Conceptual difficulties in reasoning with geometrical optics diagrams.* Invited Session on Research on Conceptual Difficulties and Strategies of Intervention, American Association of Physics Teachers, San Luis Obispo, California.

Pea, R. D., Sipusic, M., Allen, S., Reiner, M., Goldman, S., and Jul, S. Theoretical and empirical foundations for the Optics Dynagrams learning environment for the social construction of physics understanding. To be submitted to *J. Research in Science Teaching.*

Pea, R.D., Sipusic, M., & Allen, S. (in press). Seeing the light on optics: Classroom-based research and development of a learning environment for conceptual change. In S. Strauss (Ed.), *Development and Learning Environments: Seventh Annual Workshop on Human Development.* Norwood, NJ: Ablex.

Reiner, M., Pea, R. D., & Shulman, D. (submitted). The impact of simulator-based instruction on the diagramming of the interaction of light and matter by introductory physics students. *J. Learning Sciences.*

Roschelle, J., & Goldman, S. (1991). VideoNoter: A productivity tool for video data analysis. *Behavior Research Methods, Instruments, and Computers, 23,* 219-224.

Roschelle, J., Pea, R. D., & Trigg, R. (1990, March). VideoNoter: A tool for exploratory video analysis. *IRL Technical Report* IRL90-0021, Institute for Research on Learning, Palo Alto CA.

Schegloff, E.A. (in press). Conversation analysis and socially shared cognition. In L. Resnick, J. Levine & S. D. Behrend (Eds.), *Socially shared cognition.* Washington DC: APA Press.

Schegloff, E.A., & Sacks, H. (1973). Opening up closings. *Semiotica, 7,* 289-327.

Directory of Appendices

Appendix A:
1988 New York School Clinical Interview Guideline

Appendix B:
1989 California School Clinical Interview Guideline

Appendix C:
1990 Dynagrams Learning Environment: Experiments and Activities

Appendix D:
1990 California School Clinical Interview Guideline (For lens/mirror groups)

Appendix E:
Categories of analysis for the 1989-1990 Clinical Interview Diagram Components Analysis

Appendix F:
1990 Pre-Post Test Instrument for Assessing Conceptual Change

Appendix G:
Coding Scheme for 1990 Pre-and Posttest Diagrams and Verbal Explanations, Organized by Question

Appendix H:
Distribution Data Tables for 1990 Pre-Posttest Performance Comparisons on the Conceptual Change Instrument

Appendix A.

1988 New York School Clinical Interview Guideline

PART 1:

An object is 12 cm from a converging lens of focal length 3 cm.

Using diagrams and words, could you explain where and at what distance from the lens the image will from? What will be the size of the image? What kind of Image will it be? Why is this?

PART 2:

Imagine moving the object closer and closer to the lens. Describe to me the changes that take place in the image, and why.

(If not mentioned, prompt:

- Is there always an image? Does it ever invert?
- Is the image always real, or always virtual? What does that mean?)

(Finally, if not all changes mentioned... What happens at the following locations?

- Past C
- At C
- Between C and F
- At F
- Between F and lens)

Can you describe two types of images that CANNOT be formed by either a mirror or lens? Use ray diagrams to explain why.

- Could you describe and sketch a real world situation where knowing about these concepts and techniques would be useful. Why?

Appendix A.

1988 New York School Clinical Interview Guideline

In this experiment, I am interested in what you think about when you find answers to some questions that I will ask you to answer.

In order to do this I am going to ask you to THINK ALOUD as you work on the problem.

What I mean by THINK ALOUD is that I want you to tell me **everything** you are thinking from the time you first see the question until you give an answer.

I would like you to talk aloud CONSTANTLY from the time I present each problem until you have given your final answer to the question. I don't want you to try to plan out what you say or try to explain to me what you are saying. Just act as if you are alone in the room speaking to yourself. It is most important that you keep talking. If you are silent for any long period, I will ask you to talk.

Do you understand what I want you to do.

A practice problem. First, multiply two numbers in your head and tell me what you are thinking as you get an answer. What is the result of multiplying 24 times 36?

Now I am going to describe a problem situation involving a **mirror and an object**. What I would like you to do is think–aloud, speaking your thoughts as you work on these problems.

PART 1: An object is 24 cm in front of a concave mirror of radius 12 cm.

Using diagrams and words, could you explain where and at what distance from the mirror the image will form? What will be the size of the image? What kind of image will it be? Why is this?

PART 2: Imagine moving the object closer and closer to the mirror. Describe to me the changes that take place in the image, and why.

(If not mentioned, prompt:

- Is there always an image? Does it ever invert?
- Is the image always real, or always virtual? What does that mean?)

(Finally, if not all changes mentioned... What happens at the following locations?

- Past C
- At C
- Between C and F
- At F
- Between F and mirror)

Now I am going to describe a problem situation involving a lens and an object. What I would like you to do is think–aloud, speaking your thoughts as you work on these problems.

Appendix B.

1989 California School Clinical Interview Guideline

Appendix B.

1989 California School Clinical Interview Guideline

Instructions

In this experiment, I am interested in what you think about when you find answers to some questions that I will ask you to answer.

In order to do this I am going to ask you to THINK ALOUD as you work on the problem.

What I mean by THINK ALOUD is that I want you to tell me **everything** you are thinking from the time you first see the question until you give an answer.

I would like you to talk aloud CONSTANTLY from the time I present each problem until you have given your final answer to the question. I don't want you to try to plan out what you say or try to explain to me what you are saying. Just act as if you are alone in the room speaking to yourself. It is most important that you keep talking. If you are silent for any long period, I will ask you to talk.

Do you understand what I want you to do.

A practice problem. First, multiply two numbers in your head and tell me what you are thinking as you get an answer. What is the result of multiplying 24 times 36?

CALIFORNIA LENS PROBLEMS (nor Mirror Group)

Now I am going to describe a problem situation involving a **lens** and an **object.** What I would like you to do is **think-aloud**, speaking your thoughts as you work on these problems.

Word Problems (same as NY Problems)

PROBLEM 1: AN OBJECT IS 12 CM FROM A CONVERGING LENS OF FOCAL LENGTH 3 CM. USING DIAGRAMS AND WORDS, COULD YOU EXPLAIN WHERE AND AT WHAT DISTANCE FROM THE LENS THE IMAGE WILL FORM? WHAT WILL BE THE SIZE OF THE IMAGE? WHAT KIND OF IMAGE WILL IT BE? WHY IS THIS?

PROBLEM 2: IMAGINE MOVING THE OBJECT CLOSER AND CLOSER TO THE LENS. DESCRIBE TO ME THE CHANGES THAT TAKE PLACE IN THE IMAGE, AND WHY.

Anywhere else?

Prompts for PROBLEM 2:

(If not mentioned, prompt:

- Is there always an image? Does it ever flip over?
- Is the image always real, or always virtual? What does that mean?)

(Finally, if not all changes mentioned...What happens at the following locations?

  - Past C
  - At C
  - Between C and F
  - At F
  - Between F and lens)

PROBLEM 3: Here I have a light source, a converging lens (that works like the one in your classroom but is a different shape), and a screen.

(1) Can you construct a situation in which the converging lens is used to create a FOCUSED image? How will you do that?

(2) (After action on objects)...Can you explain to me what is happening there? Why is the image forming as it is?

(NOTE to Experimenter: WATCH OUT! Won't work if screen is too close to object—no image; or 4–5" range with the same clear image—OK but lens is symmetrically between lens and object so you are getting both the solutions close to one another.)

PROBLEM 4: Please construct a ray diagram at the board to represent that lens solution.

PROBLEM 5: If it is possible with this system, can you show me in some way a *virtual image* of the smiling face on the light?

(NOTE: S would have to place bulb inside of 25 cm focal length. Thus they need to FIND the focal length. Expect that lens to image distance may be conceived of as the focal length. If too much measurement, say to do approximately)

(PROCEDURAL NOTE: For Problems 6–8, ask for all predictions before allowing any experimentation. Then cycle back with experimentation and explanation of conflicts with prediction as they arise.)

PROBLEM 6: I have a little black card here.

(1) What do you predict will happen to the image (if anything) when I use it to cover the top half of the lens?

(2) Why?

(3) Could you draw me a ray diagram to show me why you think that will happen?

PROBLEM 7:

(1) What do you predict will happen to the image (if anything) when I remove the lens?

(2) Why?

(3) Could you draw me a ray diagram to show me why you think that will happen?

PROBLEM 8:

(1) When I lift the light up about an inch—do you predict that anything will happen to the image? (e.g., get blurry, move, flip...)

(2) Why?

(3) Could you draw me a ray diagram to show me why you think that will happen?

(SET UP NOTE: Still keep light level with the lens, keep image in center screen)

Now have student make their predictions, and explain the results for each of Problems 6–8.

PROBLEM 9:

(1) Can you tell me what I should do if I want to make the focused image bigger?

(PROCEDURAL NOTE: Be sure to NOT allow hands–on guessing at this point.)

(2) Why is that?

(3) Please explain this on a ray diagram.

(4) Now try out doing what you suggested.

(After arrangement made, and results observed...)

(5) Is the image like you predicted it would be?

(6) (IF NOT...) Why is it different? What should you do to fix it to make it bigger?

(7) Cycle back to questions (2)–(7) until complete

Appendix C.

1990 Dynagrams Learning Environment: Experiments and Activities

DETAIL SHEET - Showing even more Detail - 8/23/90

Date	Topic	Activity	Demo	Lab Sheet	DG Lab Sheet	Homework
9/4	Intro to Course	Discussion			Video Releases	
9/5	Fuzzy Shadows	Discussion, Lab		Shadows Lab	Exp. 1.00	Places they see shadows
9/6	Shadows cont.	DG Lab Wrap-up of Shadows			Exp. 1.50	
9/7	How We See Things Plane Mirrors	Lect./Demo	Use DG, Yarn			Size of Mirror to see Self

****

Date	Topic	Activity	Demo	Lab Sheet	DG Lab Sheet	Homework
9/10	Corner Mirrors	Lab			Exp. 2.00	Kaleidoscope, Dressing M's
9/11	Mirror Follow-up Refraction Intro	Lab Demo	Aquarium	Worksheet	Exp. 2.50	Periscope
9/12	Refraction	Lab			Exp. 3.00	Location of Fishes
9/13	Prisms, T.I.R.	Lab			Exp. 3.50	
9/14	Catch-up Day Dispersion, Rainbows	Demo		Worksheet		Examples of Color Effects

Date	Topic	Activity	Demo	Lab Sheet	DG Lab Sheet	Homework
9/17	Prisms-to-Lenses	Using Stack	Fresnel Lenses		Exp. 4.00 ?	Examples of Fresnels
9/18	Convex Lenses	Lab		Lens Lab	Exp. 4.50	
9/19	Convex Lenses	Lab				Camera, Eye
9/20	The EYE Focal Points	Lect./Demo	Various Objects		Exp. 5.00	Examples
9/21	Concave Lenses	Lab			Exp. 6.00	Uses of CCL
******						
9/24	Concave Lenses Concave Mirrors?	Lab Lect./Demo				Examples of CC Mirror
9/25	Review for Test	Stack Work ***				
9/26	**TEST** ***	Self-Explanatory!				

*** Need ideas and suggestions from IRL re: Practice Test Stack and Test. Would like to have stack on-line by 9/20 at latest.

Compiled by Clarence Bakken, starting 8/23/90

Experiment 1.00

Physics 1

Names:√________________

Period________ Computer___________

____

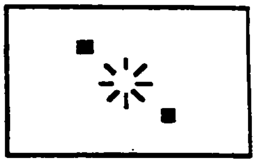
____

PURPOSE: The major goal of this lab will be to experiment further with shadows, searching for the cause of fuzzy shadows. The secondary goal of this lab will be to become acquainted with Dynagrams™ and how the simulator system works.

PROCEDURE:

1. Turn on the Macintosh II by pressing the key with the "<" symbol in the upper right-hand side of the keyboard. Once the computer is on and ready, launch "Dynagrams™" by double-clicking on the icon with that name. When the program is loaded, drag down the menu under "File" to "Open." When presented with file choices, double-click on the file called "Experiment 1.00".

2. When this file is loaded, you should see a diagram on your screen containing a light source, an object, a screen and several "targets." The various items are labeled on the screen. The "object" and screen are made of absorbing material. The "targets" represent several places in the light pattern that a person might stand or look.



Selected Light Sourc

3. Make a **spray of light rays** from the point source towards the screen.
   a) Select the light source by clicking on it. You will know it is selected when there are two square dots next to the source (see diagram).
   b) Now drag the menu item "Source" down to "Ray Spray."
   c) You will be presented with a box asking you how many rays to use. Type 25.
   d) Now click the "Okay" button to get a spray with 25 light rays.

ACTIVITIES AND QUESTIONS:

4. SIMULATOR: If you were located at pt A:

   a) Could light coming from the light source reach you? What evidence do you have for your answer?

   b) Would you be able to see the source? Explain your reasoning.

5. Answer these same two questions, imagining you were at B, C, D, E and F. Be sure to discuss your answers with your group.

6. If you were to stand somewhere near the source and look toward the screen, what would you see as the pattern of light on the screen? (Use a sketch in your answer.)

7. <u>**REAL:**</u> You have been provided with a printout of the computer diagram for this simulation. Put a wood block on the object and place a cardboard screen on the "screen" shown on the printout. Use a flashlight which has had its lens removed as the light source, holding it at the same location as the "source" in the printout.

   Compare what you now see on the real screen with what you predicted would be there based on the simulator pattern. Note any similarities and any differences. Use this space to sketch what you saw on the real screen.

8. Put your eye close to the paper and near points A, B,....F. See if you can see the flashlight source. Record your observations here.

[Note: Be sure to put the lens assembly back on the flashlight and turn it off when not in actual use. Thank you.]

9. **SIMULATOR:** Erase the light rays by dragging down "Scene" in the menu to "Erase all Rays." **Move the object** closer to the source.
   a) Click on the object to select it.
   b) Then "click and drag" the object to its new position.
   c) Click on the light source to re-select it in order to produce light rays.

   Predict what will happen to the overall pattern of light on the simulator when you use a new Ray Spray.

10. Use a new spray of 25 rays. What affect did your change make at points A, B,....F?

11. **REAL:** Set up the flashlight, object and screen as you did previously. Now move the object closer to the source and verify your predictions about what would happen.

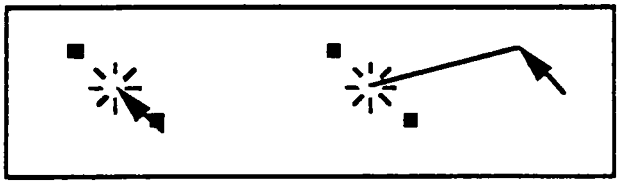
12. What would happen if the object were returned to its original position and then the screen were moved? Predict. Try it on the simulator. Then try it using the flashlight, object and screen.

13. **Explore.** In each case, predict any differences in the light pattern on the screen due to making the change. Then try it out. Use the space below to record your attempts, observations, conclusions, results.

a) Try varying the number of rays in the ray spray.

b) Try varying the width or size of the ray spray.
  1) Erase any rays coming from the source using "Erase all rays" under "Scene" on the menu.
  2) Select one of the two lines that is to the right of the source. Dark boxes will appear at both ends of the line when it is selected.
  3) Click on the end away from the source and move that end up or down, making the spray wider or narrower.
  4) Repeat this process for the other line.
  5) Select the source; choose "Ray Spray" under "Source" on the menu.

c) Try drawing single rays from the point source.
  1) Erase any rays coming from the source using "Erase all rays" under "Scene" on the menu.
  2) Select the source if it isn't already selected.
  3) Click the arrow at the center of the source and hold the button down.
  4) Drag the arrow away from the source, creating a line or "ray." (see diagram)
  5) When the line is pointing the direction you wish it to go, release the button and a ray will be created.



Generating a single light ray

13. **Explore, cont.**

d) How many ways can you think of to get light from the source to reach D? Demonstrate as many of these ways as time allows. Describe your attempts and results here:

HOMEWORK: State the 3 most important ideas that you have learned about the shadows produced by a single point source of light.

1.

2.

3.

11. When **FINISHED**, drag down "File" on the menu to "Quit." After a few seconds you will be returned to the desktop, and from there drag down "Special" on the menu to "Shut Down." We hope your first encounter with Dynagrams™ has been successful!

Experiment 1.00

Physics 1

Names:√________________

____

____

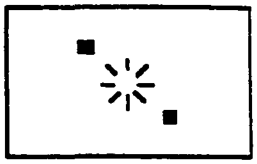
Period________ Computer__________

PURPOSE: The major goal of this lab will be to experiment further with shadows, searching for the cause of fuzzy shadows. The secondary goal of this lab will be to become acquainted with Dynagrams™ and how the simulator system works.

PROCEDURE:

1. Turn on the Macintosh II by pressing the key with the "<" symbol in the upper right-hand side of the keyboard. Once the computer is on and ready, launch "Dynagrams™" by double-clicking on the icon with that name. When the program is loaded, drag down the menu under "File" to "Open." When presented with file choices, double-click on the file called "Experiment 1.00".

2. When this file is loaded, you should see a diagram on your screen containing a light source, an object, a screen and several "targets." The various items are labeled on the screen. The "object" and screen are made of absorbing material. The "targets" represent several places in the light pattern that a person might stand or look.



Selected Light Sourc

3. Make a **spray of light rays** from the point source towards the screen.
   a) Select the light source by clicking on it. You will know it is selected when there are two square dots next to the source (see diagram).
   b) Now drag the menu item "Source" down to "Ray Spray."
   c) You will be presented with a box asking you how many rays to use. Type 25.
   d) Now click the "Okay" button to get a spray with 25 light rays.

ACTIVITIES AND QUESTIONS:

4. SIMULATOR: If you were located at pt A:

   a) Could light coming from the light source reach you? What evidence do you have for your answer?

   b) Would you be able to see the source? Explain your reasoning.

5. Answer these same two questions, imagining you were at B, C, D, E and F. Be sure to discuss your answers with your group.

6. If you were to stand somewhere near the source and look toward the screen, what would you see as the pattern of light on the screen? (Use a sketch in your answer.)

7. **REAL:** You have been provided with a printout of the computer diagram for this simulation. Put a wood block on the object and place a cardboard screen on the "screen" shown on the printout. Use a flashlight which has had its lens removed as the light source, holding it at the same location as the "source" in the printout.

   Compare what you now see on the real screen with what you predicted would be there based on the simulator pattern. Note any similarities and any differences. Use this space to sketch what you saw on the real screen.

8. Put your eye close to the paper and near points A, B,....F. See if you can see the flashlight source. Record your observations here.

[Note: Be sure to put the lens assembly back on the flashlight and turn it off when not in actual use. Thank you.]

9. SIMULATOR: Erase the light rays by dragging down "Scene" in the menu to "Erase all Rays." Move the object closer to the source.
   a) Click on the object to select it.
   b) Then "click and drag" the object to its new position.
   c) Click on the light source to re-select it in order to produce light rays.

   Predict what will happen to the overall pattern of light on the simulator when you use a new Ray Spray.

10. Use a new spray of 25 rays. What affect did your change make at points A, B,....F?

11. REAL: Set up the flashlight, object and screen as you did previously. Now move the object closer to the source and verify your predictions about what would happen.

12. What would happen if the object were returned to its original position and then the screen were moved? Predict. Try it on the simulator. Then try it using the flashlight, object and screen.

13. **Explore.** In each case, predict any differences in the light pattern on the screen due to making the change. Then try it out. Use the space below to record your attempts, observations, conclusions, results.

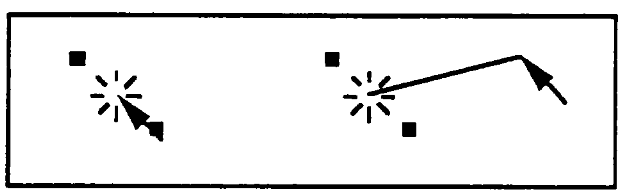
a) Try varying the number of rays in the ray spray.

b) Try varying the width or **size of the ray spray.**

1) Erase any rays coming from the source using "Erase all rays" under "Scene" on the menu.
2) Select one of the two lines that is to the right of the source. Dark boxes will appear at both ends of the line when it is selected.
3) Click on the end away from the source and move that end up or down, making the spray wider or narrower.
4) Repeat this process for the other line.
5) Select the source; choose "Ray Spray" under "Source" on the menu.

c) Try **drawing single rays** from the point source.

1) Erase any rays coming from the source using "Erase all rays" under "Scene" on the menu.
2) Select the source if it isn't already selected.
3) Click the arrow at the center of the source and hold the button down.
4) Drag the arrow away from the source, creating a line or "ray." (see diagram)
5) When the line is pointing the direction you wish it to go, release the button and a ray will be created.



Generating a single light ray

13. **Explore, cont.**

d) How many ways can you think of to get light from the source to reach D? Demonstrate as many of these ways as time allows. Describe your attempts and results here:

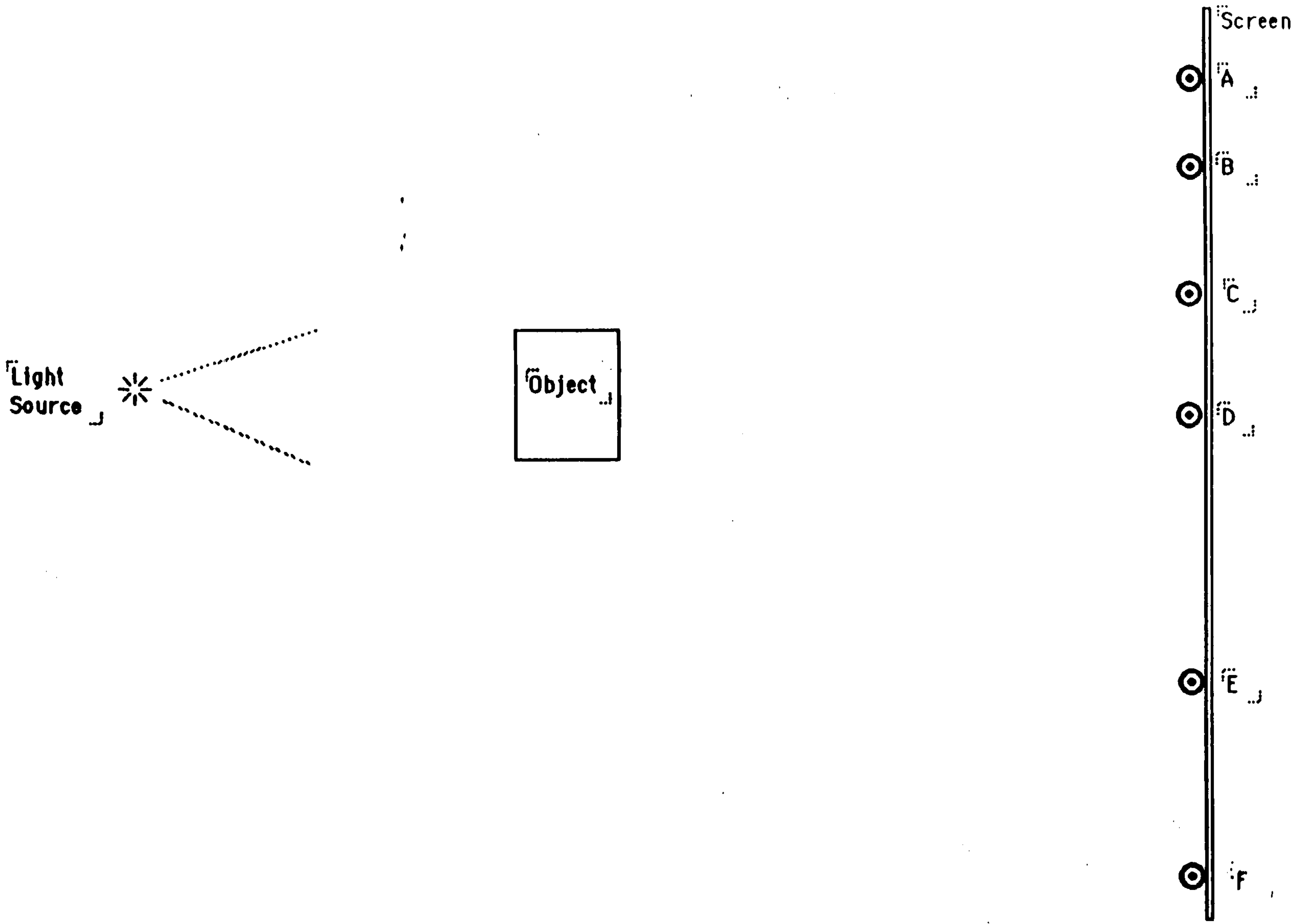
<u>**HOMEWORK:**</u> State the 3 most important ideas that you have learned about the shadows produced by a single point source of light.

1.

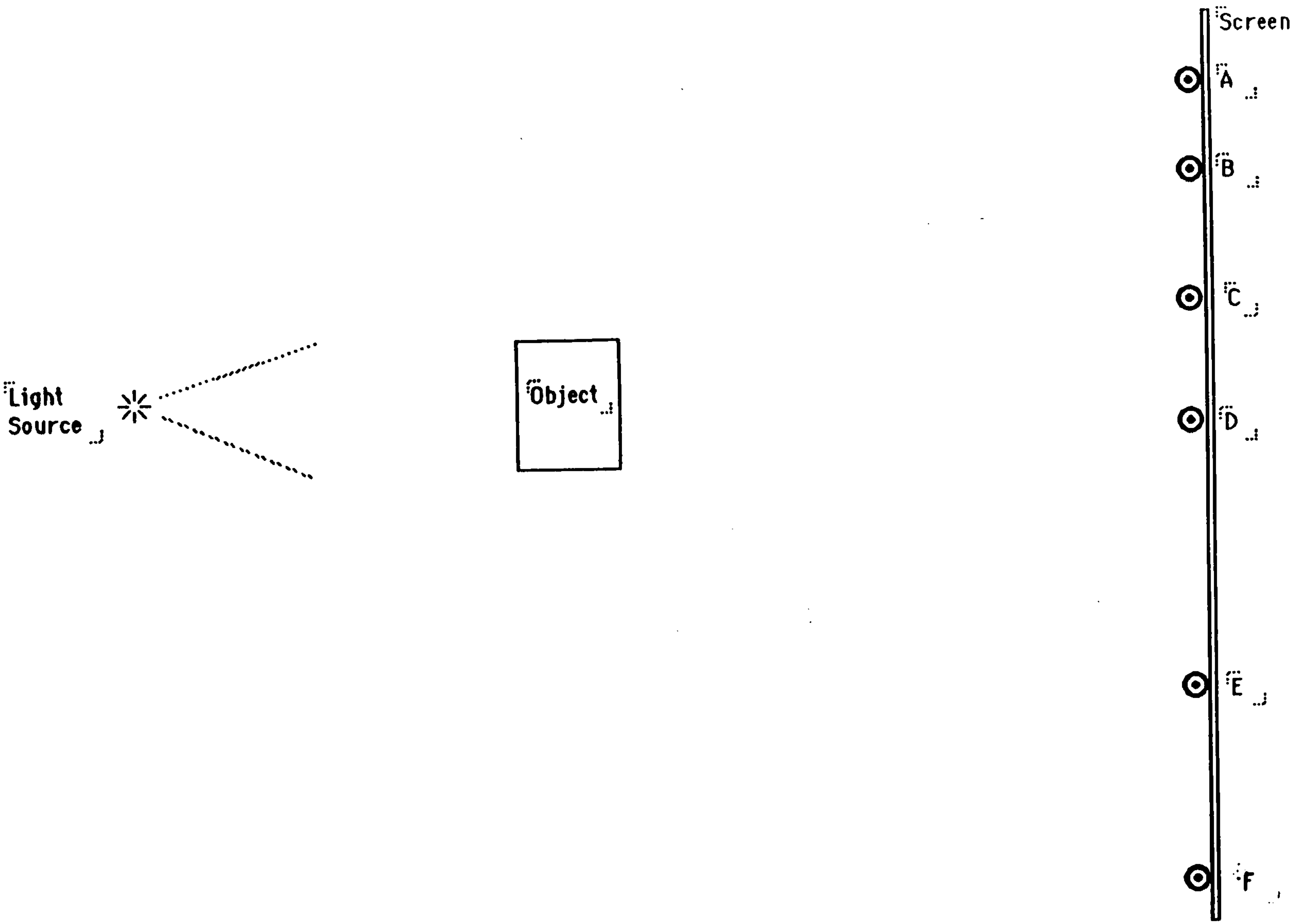
2.

3.

11. When **FINISHED**, drag down "File" on the menu to "Quit." After a few seconds you will be returned to the desktop, and from there drag down "Special" on the menu to "Shut Down." We hope your first encounter with Dynagrams™ has been successful!



Experiment 1.00



Experiment 1.00

Experiment 1.50

Physics 1

Names:√________________

____

____

Period________ Computer_________

PURPOSE: The purpose of this lab will be to experiment further with shadows, searching for the cause of fuzzy shadows. You will also be learning more of the Dynagrams functions.

PROCEDURE:

1. Turn on the computer and launch "Dynagrams™" by double-clicking on the icon. When the program is loaded, drag down the menu under "File" to "Open." When presented with file choices, double-click on the file called "Experiment 1.50". On your screen you should have a diagram with an object, a screen and two light sources.

ACTIVITIES AND QUESTIONS:

2. **SIMULATOR:** Sketch what the pattern on the simulator will look like if you were to do Ray Sprays from both light sources.

3. Select the light sources, one at a time and produce a 25-ray spray for each. (If you have questions about procedure, refer to Experiment 1.00.)

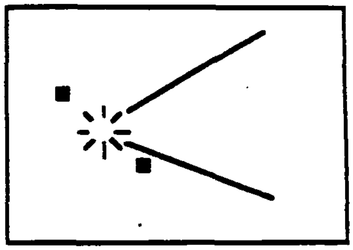
4. Could you see either or both of the light sources if you were standing at A? B? C? D? E? F? Put Y's or N's in the grid below to record your prediction. Explain your reasoning briefly.

Source	A	B	C	D	E	F
#1						
#2						

5. What would the pattern of light on the "screen" look like as seen by an observer standing near the sources? (Draw it)

10. SIMULATOR: What would happen if you added a third light source between the other two? What changes in the pattern on the screen would occur?

11. Return the screen and object to their original locations. **Add a third light source** midway between the original light sources.


Setup for Ray Spray

a) Under "Scene" on the menu, select "Add a Source."
b) Drag the source to a location midway between the two existing sources.
c) With the source selected, choose "On" under "Source" on the menu.
d) Under "Scene" on the menu, select "Add a line."
e) Click and drag a line about 3 cm long. End the line by double-clicking.
f) Repeat step (d).
g) Click on one line to select it. Drag one end of the line to a point at about the +45° point on the new source. Drag the other end of the same line until it makes roughly a 45° angle upwards.
g) Repeat step (f), only position the line pointing 45° downwards. (Use the existing sources as models for your construction.)

12. Use "Ray Spray" for all three sources. If you were located at each of the target points, could you see the sources? Use the table below to summarize your results.

Source	A	B	C	D	E	F
#1						
#2						
#3						

13. Sketch the pattern of light that you would expect to show up on the screen behind the object. How many different areas of brightness would there be on the screen now?

Experiment 1.50

Physics 1

Names:√ ____________________

____

____

Period________ Computer__________

PURPOSE: The purpose of this lab will be to experiment further with shadows, searching for the cause of fuzzy shadows. You will also be learning more of the Dynagrams functions.

PROCEDURE:

1. Turn on the computer and launch "Dynagrams™" by double-clicking on the icon. When the program is loaded, drag down the menu under "File" to "Open." When presented with file choices, double-click on the file called "Experiment 1.50". On your screen you should have a diagram with an object, a screen and two light sources.

ACTIVITIES AND QUESTIONS:

2. **SIMULATOR:** Sketch what the pattern on the simulator will look like if you were to do Ray Sprays from both light sources.

3. Select the light sources, one at a time and produce a 25-ray spray for each. (If you have questions about procedure, refer to Experiment 1.00.)

4. Could you see either or both of the light sources if you were standing at A? B? C? D? E? F? Put Y's or N's in the grid below to record your prediction. Explain your reasoning briefly.

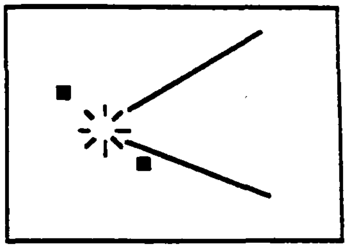
Source	A	B	C	D	E	F
#1						
#2						

5. What would the pattern of light on the "screen" look like as seen by an observer standing near the sources? (Draw it)

10. SIMULATOR: What would happen if you added a third light source between the other two? What changes in the pattern on the screen would occur?

11. Return the screen and object to their original locations. **Add a third light source** midway between the original light sources.

a) Under "Scene" on the menu, select "Add a Source."
b) Drag the source to a location midway between the two existing sources.
c) With the source selected, choose "On" under "Source" on the menu.
d) Under "Scene" on the menu, select "Add a line."
e) Click and drag a line about 3 cm long. End the line by double-clicking.
f) Repeat step (d).
g) Click on one line to select it. Drag one end of the line to a point at about the +45° point on the new source. Drag the other end of the same line until it makes roughly a 45° angle upwards.
g) Repeat step (f), only position the line pointing 45° downwards. (Use the existing sources as models for your construction.)

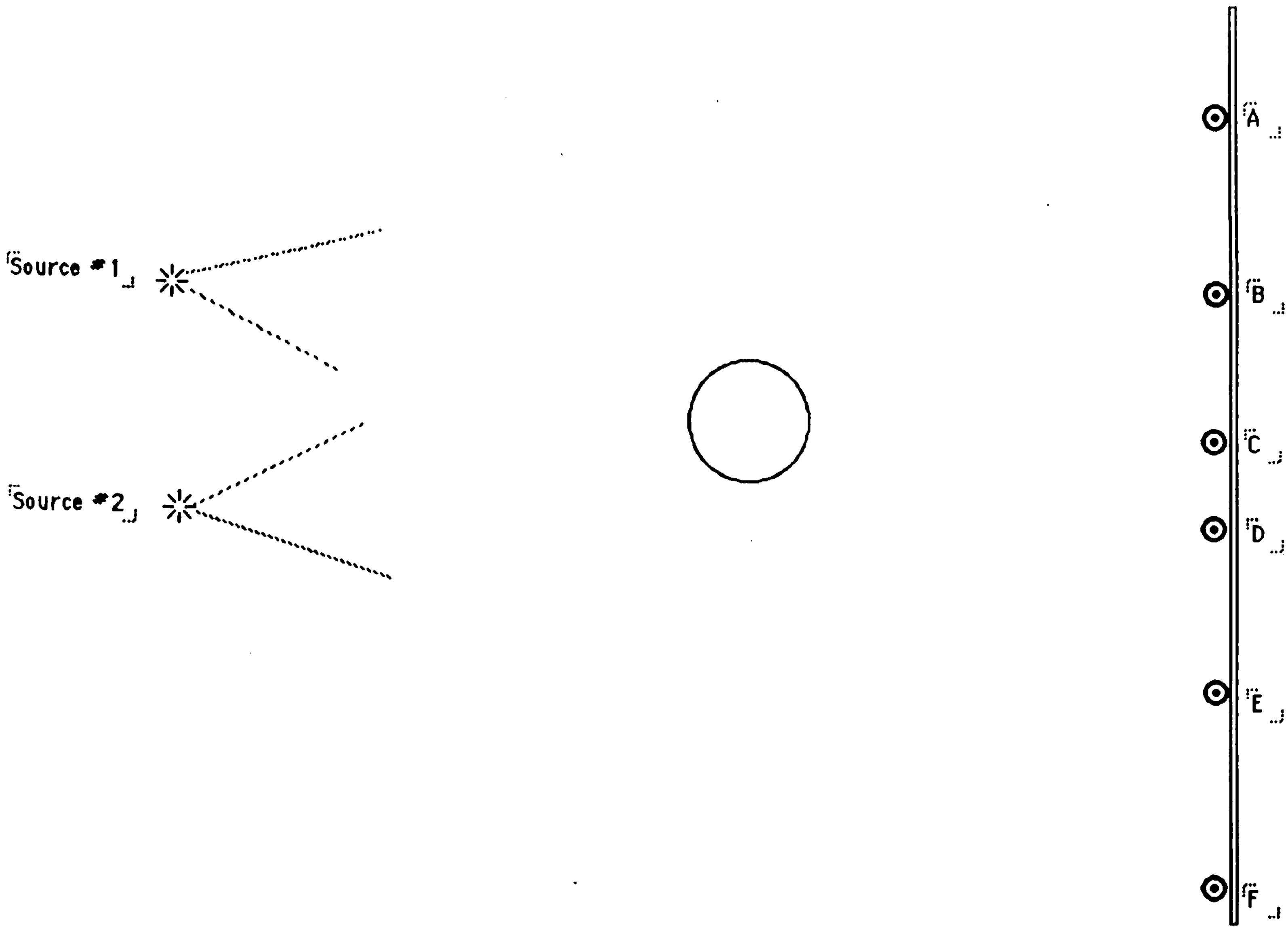


Setup for Ray Spray

12. Use "Ray Spray" for all three sources. If you were located at each of the target points, could you see the sources? Use the table below to summarize your results.

Source	A	B	C	D	E	F
#1						
#2						
#3						

13. Sketch the pattern of light that you would expect to show up on the screen behind the object. How many different areas of brightness would there be on the screen now?



Experiment 1.50

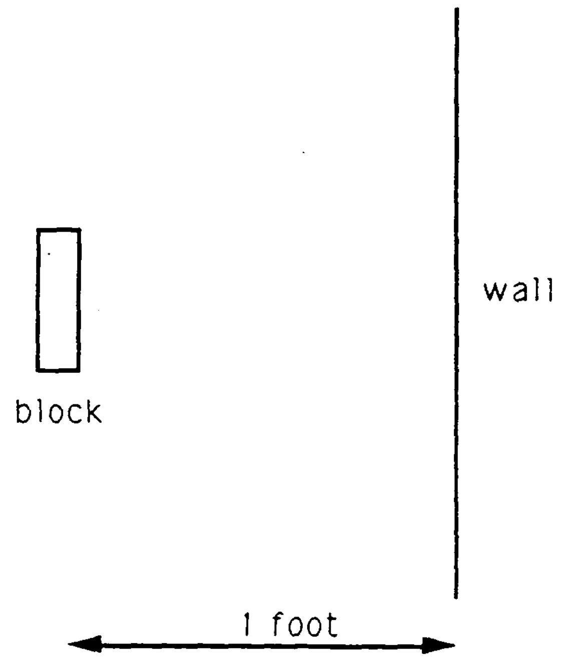
HOMEWORK 9/5/90
PHYSICS I

NAME______________________________

PERIOD____________________________

To get full credit, hand this question in tomorrow:

a) The diagram below shows a block of wood which is one foot away from a wall. Where must a point source of light (such as a naked flashlight) be placed so as to throw a shadow on the wall that is exactly twice as large as the block? Explain your reasoning.



b) If the block were to be moved steadily away from the wall, what changes would take place in the shadow, and why?

HOMEWORK 9/6/90
PHYSICS I

NAME________________________________

PERIOD______________________________

To get full credit, hand this sheet in tomorrow:

a) A solar eclipse happens when the moon blocks the sun as seen from the earth. Using the diagram below (not drawn to scale) explain why the eclipse takes place.

b) Where would a person have to stand to see the total eclipse? Where would a person have to stand to see a partial eclipse?

c) If the earth and moon were farther apart, would there be total eclipses? Would there be partial eclipses? Explain.

Write down a question of your own about an everday optical situation you think is interesting and/or important. There are no right or wrong questions, so feel free to ask something that matters to you.

HOMEWORK 9/6/90
PHYSICS 1

NAME____________________

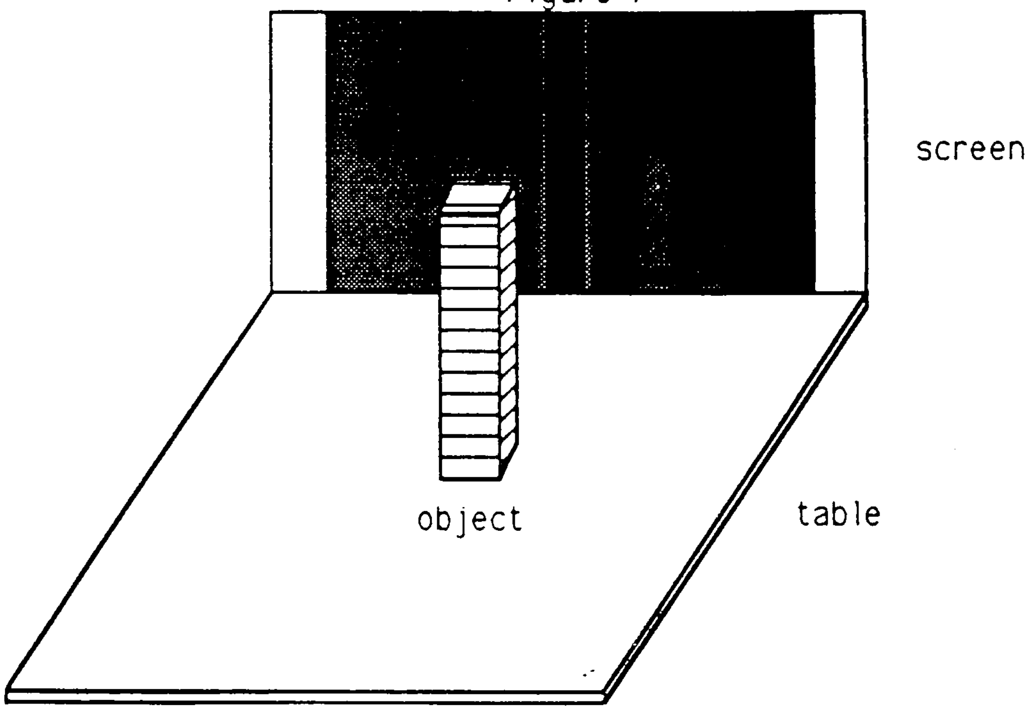
PERIOD__________________

e) In figure 1, you can see a pattern of light and shadow formed on a screen. How many point sources of light would it take to produce pattern, given that the object in front of the screen absorbs light?

______

f) Given the position of the object on the table in front of the screen, can you locate the position of the point sources that would produce this pattern of light and shadow? Mark the locations with small stars. Using different colors, shade in the total area that light from each point source will travel towards.

Figure 1



Hint: Do so by drawing light rays along the surface of the table in figure 1. If you get confused, try simulating the pattern using real lights and objects to duplicate the pattern on the screen, then draw in your conclusions.

g) Predict the number of point sources necessary to produce this pattern of light and shadow on the screen in figure 2? ________
Determine the location of the point sources by drawing them into figure 2.

Figure 2

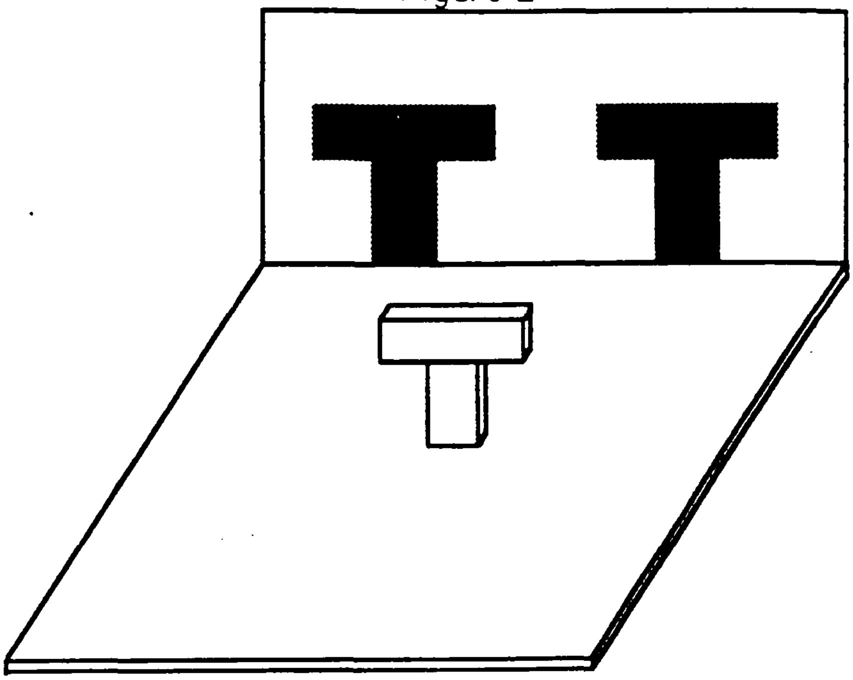
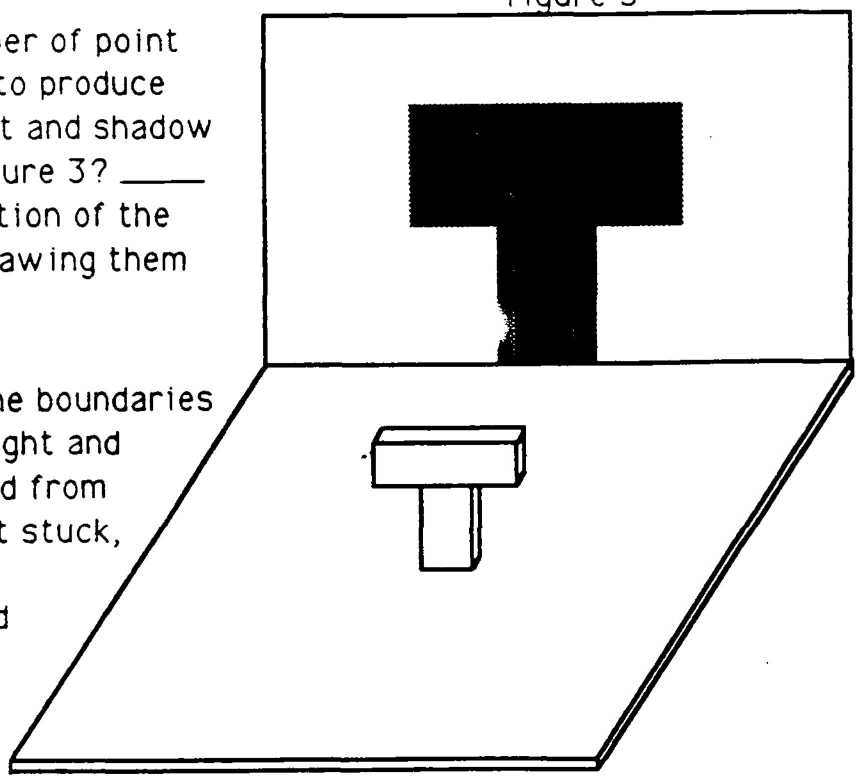


figure 3



h) Predict the number of point sources necessary to produce this pattern of light and shadow on the screen in figure 3? _____
Determine the location of the point sources by drawing them into figure 3.

Hint: Notice that the boundaries of the pattern of light and shadow has changed from figure 1. If you get stuck, try simulating the situation described in figure 3.

HOMEWORK 9/6/90
PHYSICS I

NAME________________________________

PERIOD______________________________

To get full credit, hand this sheet in tomorrow:

a) A solar eclipse happens when the moon blocks the sun as seen from the earth. Using the diagram below (not drawn to scale) explain why the eclipse takes place.

b) Where would a person have to stand to see the total eclipse? Where would a person have to stand to see a partial eclipse?

c) If the earth and moon were farther apart, would there be total eclipses? Would there be partial eclipses? Explain.

Write down a question of your own about an everday optical situation you think is interesting and/or important. There are no right or wrong questions, so feel free to ask something that matters to you.

HOMEWORK 9/6/90
PHYSICS 1

NAME________________________

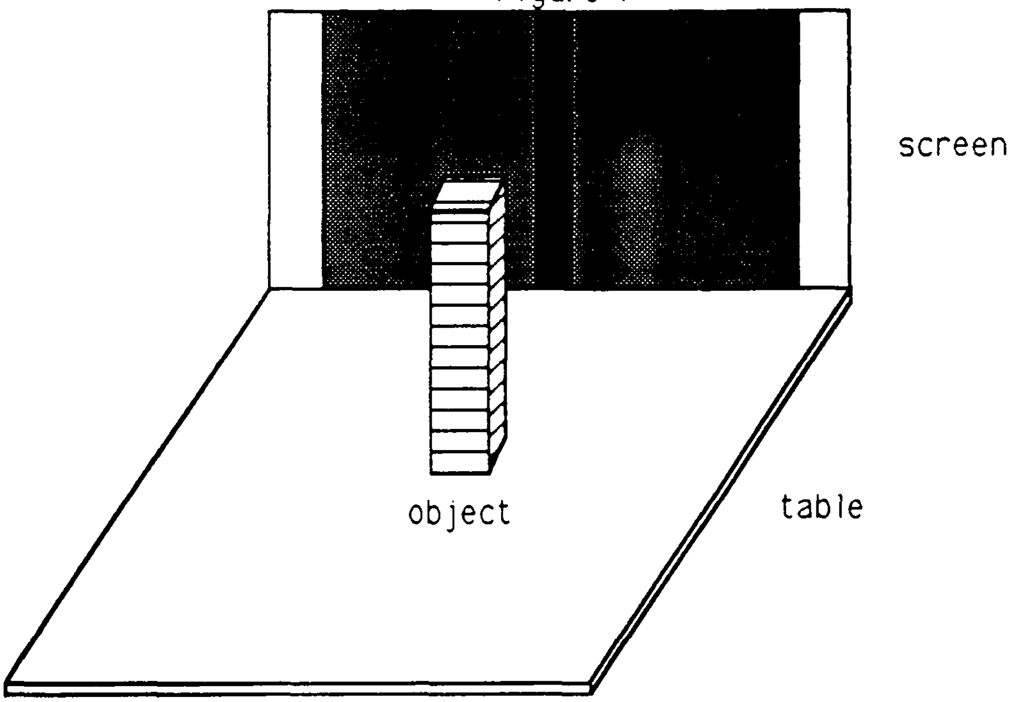
PERIOD________________________

e) In figure 1, you can see a pattern of light and shadow formed on a screen. How many point sources of light would it take to produce pattern, given that the object in front of the screen absorbs light?

______

f) Given the position of the object on the table in front of the screen, can you locate the position of the point sources that would produce this pattern of light and shadow? Mark the locations with small stars. Using different colors, shade in the total area that light from each point source will travel towards.

Figure 1



Hint: Do so by drawing light rays along the surface of the table in figure 1. If you get confused, try simulating the pattern using real lights and objects to duplicate the pattern on the screen, then draw in your conclusions.

g) Predict the number of point sources necessary to produce this pattern of light and shadow on the screen in figure 2? ________
Determine the location of the point sources by drawing them into figure 2.

Figure 2

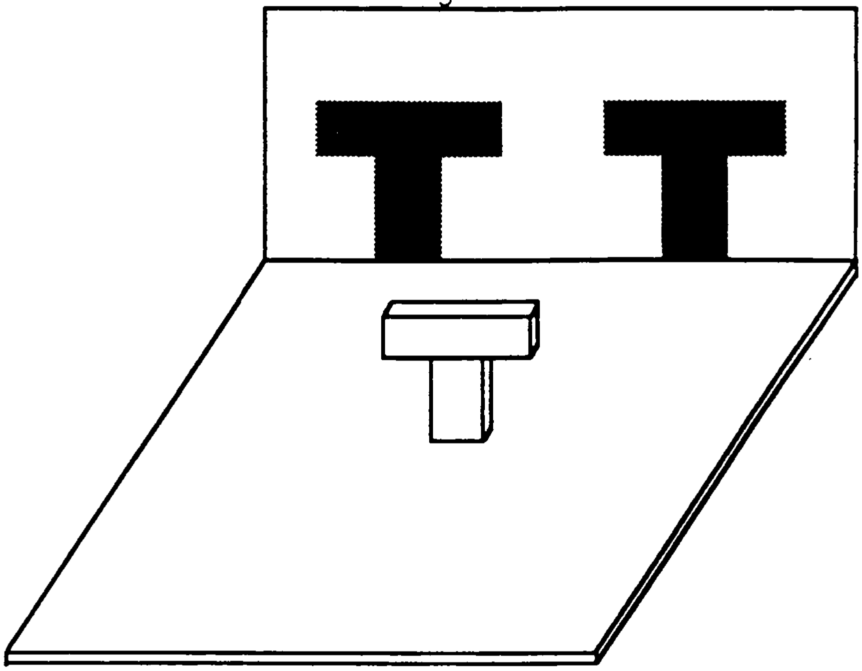
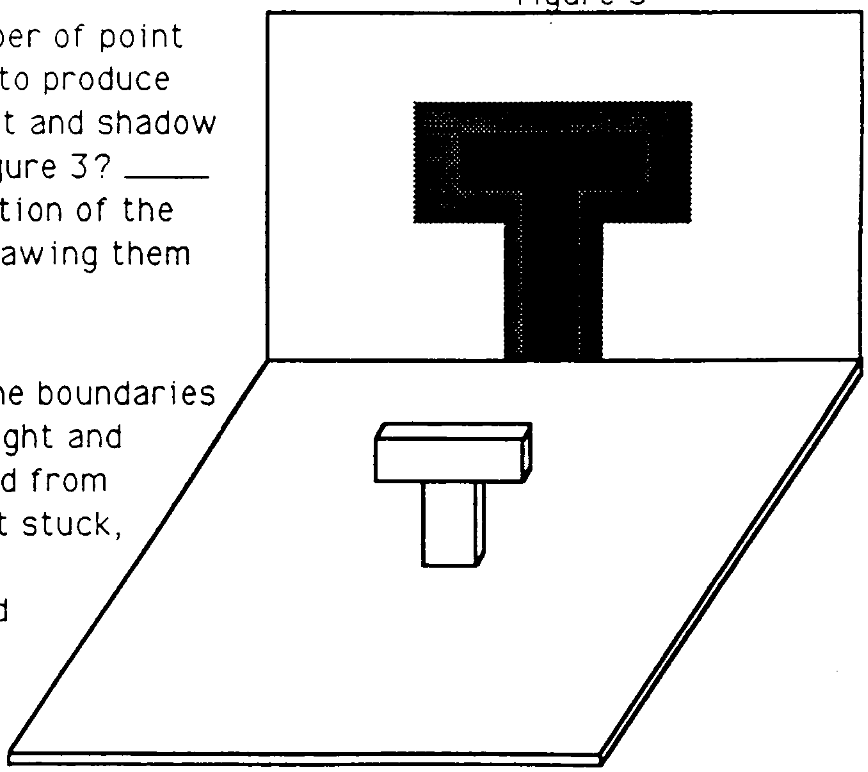


figure 3



h) Predict the number of point sources necessary to produce this pattern of light and shadow on the screen in figure 3? _____
Determine the location of the point sources by drawing them into figure 3.

Hint: Notice that the boundaries of the pattern of light and shadow has changed from figure 1. If you get stuck, try simulating the situation described in figure 3.

PLANE MIRROR LAB
Physics 1

PURPOSE: How long must a mirror be to see your entire image in it? How does this length change as you move further and further from the mirror?

MATERIALS:

"Full-Length" Mirror	Masking Tape
Measuring Device	Assistant

PROCEDURE: Stand so your toes are 3 feet (1 meter) from a full-length mirror.** Have your "assistant" place a piece of masking tape at the lowest point on the mirror where you just see your toe. Have them also place a piece of tape at the highest point where you just see the top of your head. Measure the distance between the two pieces of tape.

Move until you are 6 feet (2 meters) from the mirror and repeat the procedure. Move until you are 9 feet (3 meters) from the mirror and repeat.

Finally, measure your height as accurately as you can.

ANALYSIS: (1) Answer the two questions asked in the PURPOSE. Cite evidence from your data to support your conclusions. (2) What sources of error could have affected your results, keeping them from being ideal?

WHAT IS DUE: A 1-page report consisting of Purpose, Data and Discussion

is due in class _______________ .

** Sources of full-length mirrors include Saks Fifth Avenue, Nordstrom, Macy's, etc. should you not have one in your home or your assistant's home.

Experiment 2.00

Physics 1

Names:√____________________

____

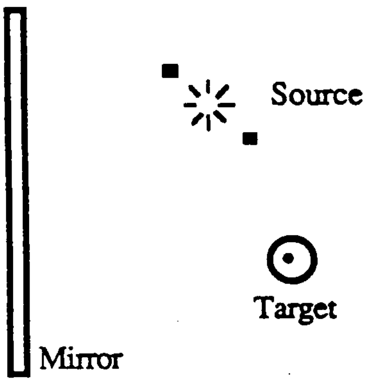
____

Period_________

PURPOSE: The purpose of this lab will be to experiment with one and two plane mirrors, and to explore the images that they form.

ACTIVITIES AND QUESTIONS:

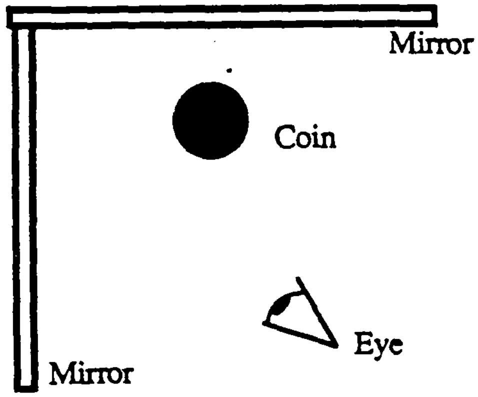
1. **SIMULATOR:** Turn on the computer and launch "Dynagrams™."
2. Use the menu choices under "Scene" to construct the situation diagrammed below.



3. **Set the material** for the Mirror to be reflective:
   a) Double-click on the mirror. This will get you a material dialog box.
   b) The program automatically chooses Zinium as the material. Note that there is a check-mark next to Zinium under the "selected" column.
   c) Click next to Zinium under the Reflect column to the right. A check mark should appear, making the Zinium reflect light.
   d) Click next to Zinium under the Refract column. The check mark should disappear.
   e) Click on the "Okay" button when finished.

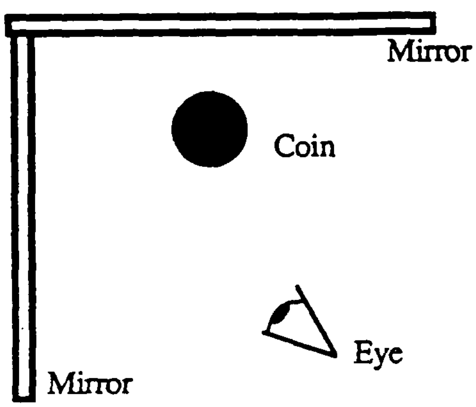
4. Use a Ray Spray and/or individual light rays to demonstrate how light could get from the source to the target via reflection from the mirror. Use this setup to demonstrate where and how an image is formed. Use this space to sketch your Dynagrams diagram:

5. REAL: Set up two plane mirrors carefully so that they are at a 90° angle to each other. Place an object (we suggest a coin) in the space between the mirrors as shown below. If your eye is placed where the eye in the diagram is located, how many images do you see? Where do they appear to be located?

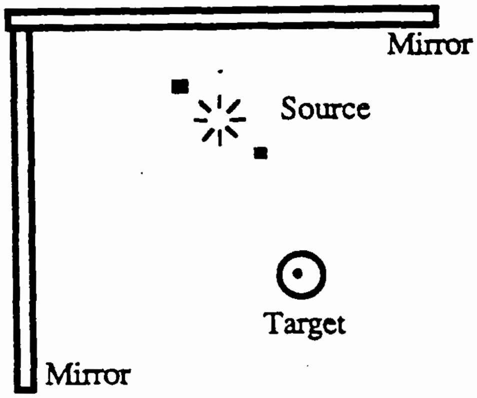


6. Look carefully at all of the images that appear. Compare them to your object. Write down any observations you have about these images.

7. Based on your experience with mirrors to this point, suggest what paths light took in going from the object to the mirrors and finally to your eye.



8. **SIMULATOR:** Add a new mirror which is oriented at right angles to the original mirror you had in step 2 above. Your final result should resemble the diagram below. (Note that we use the Target to represent the location of your eye in the REAL experiment.



9. Use a Ray Spray or individual rays to demonstrate the paths that light rays take going from the source to the mirrors and reflecting. Sketch the paths that light rays successfully take in going from the source to the mirrors to the target on the diagram above.

What conclusions do you reach about the images formed in two mirrors placed at 90° to one another?

10. **REAL:** Change the angle between the two mirrors. Some suggested angles might be 60° and 45°. How does the number of images change as the angle decreases? Is there a mathematical pattern? Can you determine the paths that light took going from object to mirror to your eye?

11. **SIMULATOR:** **Change the angle** between the two mirrors:
    a) Select one of the mirrors by clicking on it.
    b) Choose "Rotate" under "Object" on the menu.
    c) Type 30 to rotate it 30°, making the angle effectively 60°.
    d) Move the mirror so the two are touching each another at one end, with the source and target in the space between the two.

    Examine the patterns of light as you reflect rays off of the two mirrors. How many different directions can you send rays and still hit the target? Sketch your results below.

12. Change the angle to 45° and repeat your work in step 13.

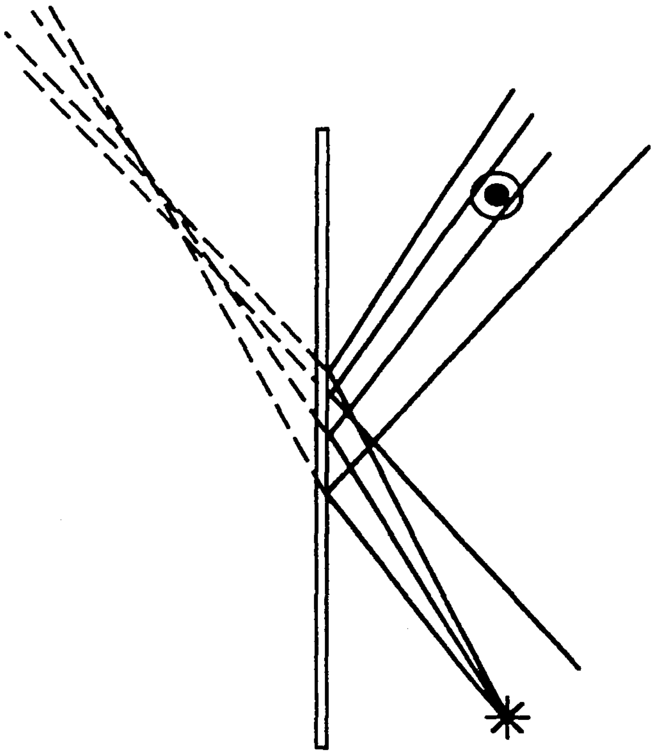
What application uses mirrors angled to one another in the manner you investigated here? What do we see when we use one of these devices?

Plane Mirrors Homework

Name ____________________________ Period __________

Date __________

Below is an incorrectly drawn diagram of an image formed by light reflecting off a plane mirror into a "target" eye. Label the flaws (1, 2, 3, etc.) and explain why they are wrong? Make the necessary corrections to the diagram.



plane mirror

Plane Mirror Worksheet - 1

Physics I - Backen

Name ____________________

Period ________

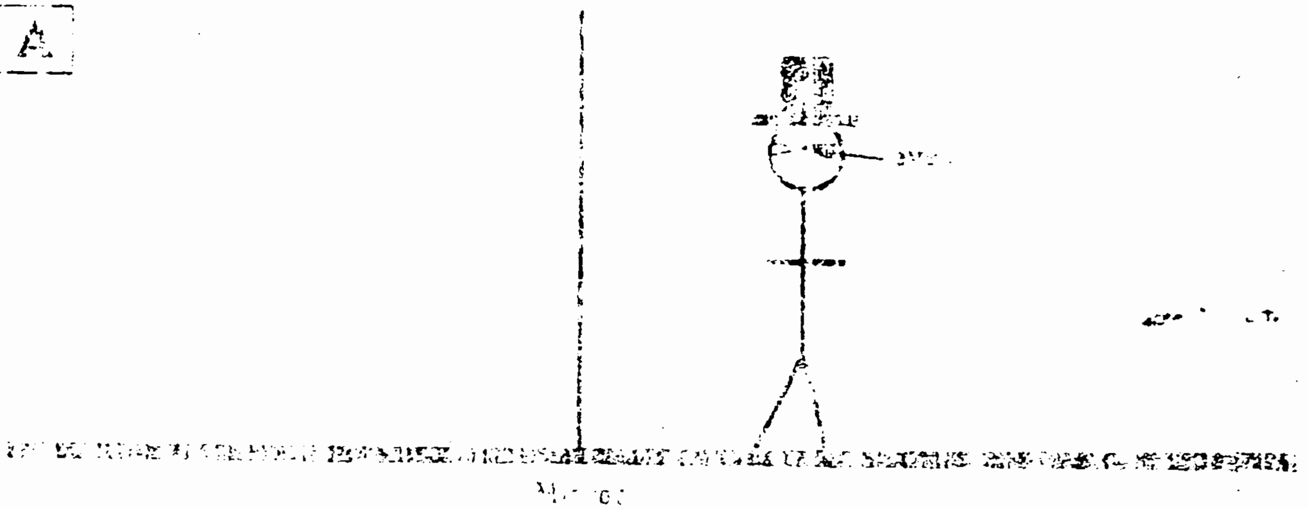
In the diagrams below, a person wearing a hat is illustrated standing at two different distances from a vertical plane mirror. His/her eye is clearly shown.

1. Sketch the image that is formed by the mirror in each case.

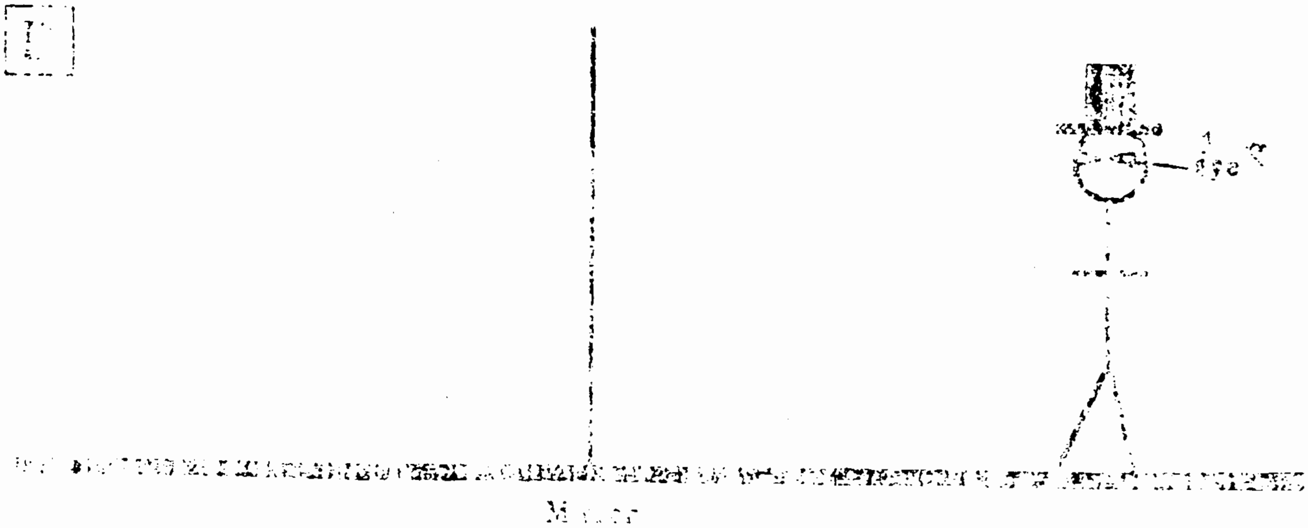
2. Show the paths that light takes going from the toe to the mirror to the person's eye and from the top of the hat to the mirror to the person's eye in each case.

3. In each case, show the part of the mirror needed for the person to see him/herself completely based on your drawing of the light rays.

A



B



Plane-Mirror Worksheet - 1

[illegible]

Name ____________________

Period ________

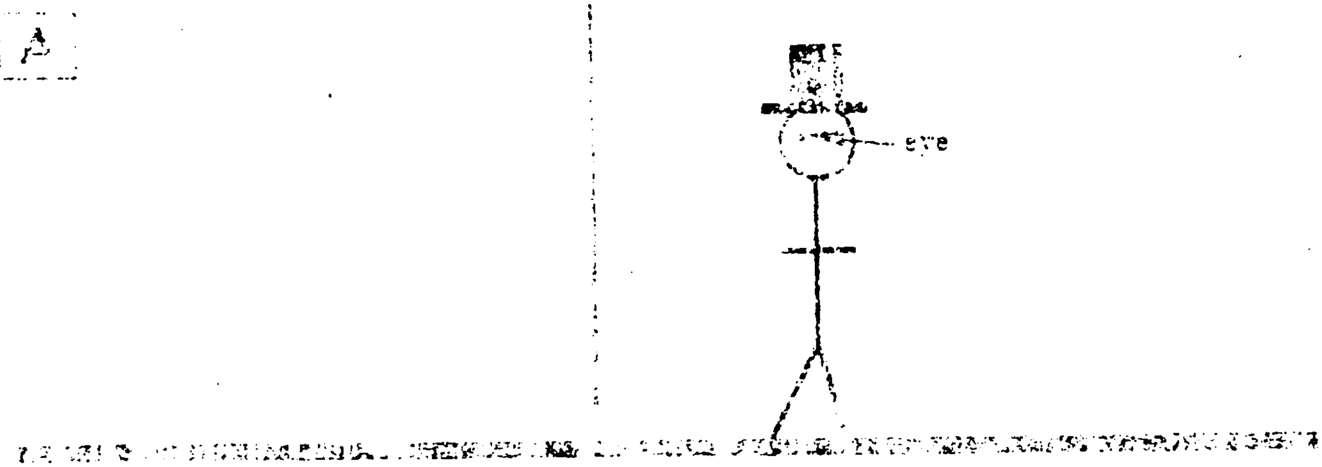
The diagrams below show a person wearing a hat illustrated standing at two different distances from a vertical plane mirror. His/her eye is clearly shown.

1. Sketch the image that is formed by the mirror in each case.

2. Show the path that light takes going from the toe to the mirror to the person's eye and from the top of the hat to the mirror to the person's eye in each case.

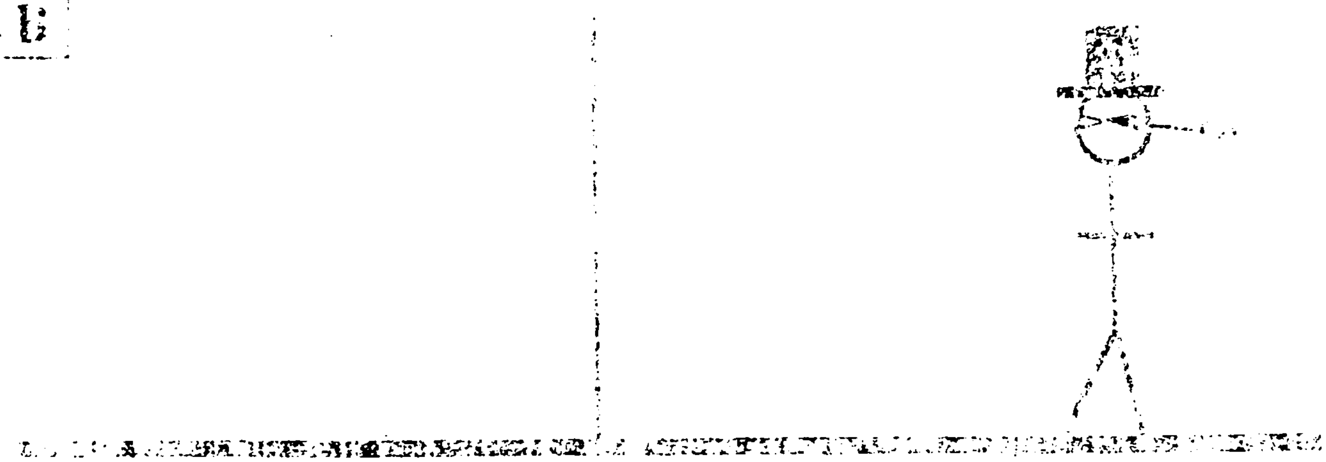
3. In each case show the part of the mirror needed for the person to see him/herself completely based on your drawing of the light rays.

A



Mirror

B



Mirror

PLANE MIRROR WORKSHEET

Physics 1 - Bakken

Name____________________________

Period_______

Directions: Answer the following questions. Explain your answers using complete sentences in your own words. Include diagrams when they are called for in the question.

1. Is a good, clean mirror visible or invisible? Explain your answer.

2. When you stand 3 meters in front of a plane mirror, at what distance must you focus your camera in order to take a clearly focussed picture of your image? Explain in words and diagram.

3. Why is the lettering on the front of some vehicles "backwards"? Example:

[illegible]

4. Compare the reflections from a rough road and from the smooth surface of a wet road to explain why it is difficult for a motorist to see the roadway ahead when driving on a wet, rainy night.

Experiment 3.00
Physics 1

Names:√________________

____

____

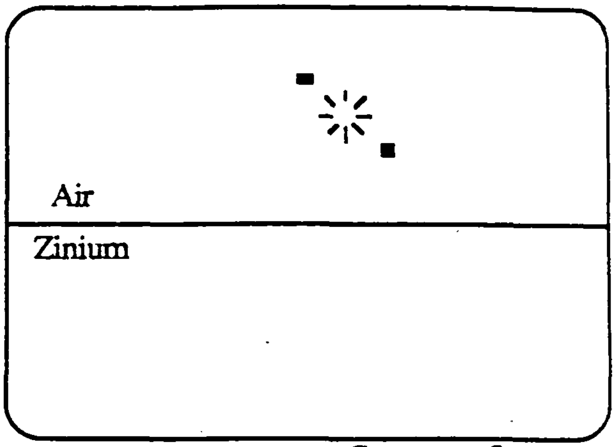
Period________

PURPOSE: The purpose of this lab will be to experiment with a behavior of light called refraction. You will use the simulator to help determine the general and specific patterns that light follows.

ACTIVITIES AND QUESTIONS:

1. **SIMULATOR:** Turn on the computer and launch "Dynagrams™."

2. Set up the situation to the right.
   a) Add a rectangular object using the menu.
   b) Expand it until it is the full width of the screen and approximately half the height of the screen.
   c) Move the rectangle until it occupies the bottom half of the screen.
   d) Set the material of the rectangle so that it refracts but doesn't reflect or absorb.
   e) Add a light source and locate it about 1/4 the distance down the screen as shown.
   f) Turn the source On using the menu.

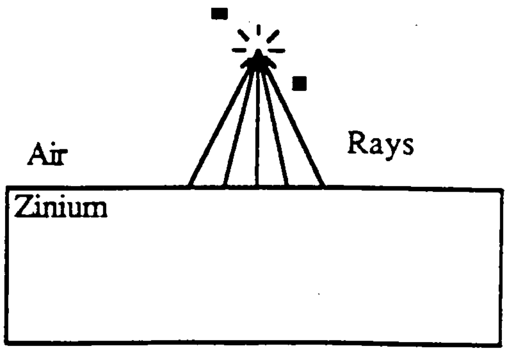


Computer Screen

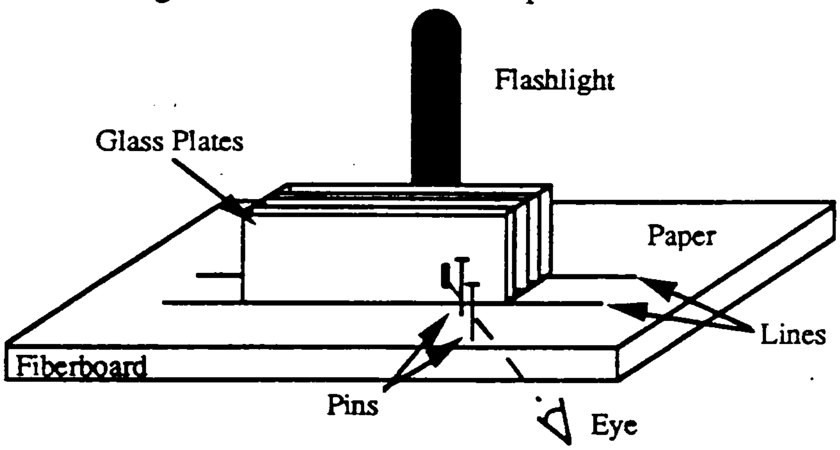
3. Send a light ray from the source downwards towards the surface between the two substances. Does it travel in a straight line? If it bends, which way does it bend? Send other rays downwards, checking to see if any general patterns are operating. Sketch what you observe and state what you conclude about the behavior of light as it goes from air into Zinium.

4. Erase the rays. Add a light source in the lower portion of the screen, inside the Zinium. After turning it On, send a light ray from the source upwards towards the surface. Does it travel in a straight line? Send several rays at different angles. Sketch what you observe and state what you conclude about the behavior of light as it goes from Zinium into air.

9. Erase all of the light rays. Send five rays at different angles from the source through the block of Zinium. (See diagram to right.) Add lines to trace the emerging rays back to their apparent origin, thus locating the "image" of the original light source. Use the distance measuring tool to determine the distances of both the source and the "image" from the top of the Zinium block. Sketch your results here, labeling the distances you measure:



10. **REAL:** On a piece of paper, mark carefully the edges of a stack of glass plates or a glass block. Place a flashlight on one side of the glass at a location that you mark. Look through the glass towards the light source, and use two pins to point towards the apparent location of the light as shown in the diagram below. Use two more pins to locate a second line of sight.



11. After you have set up two lines of sight using pins, remove the glass plates and extend the two lines until they meet. Measure the distances to the real source and the apparent source. Sketch your results below, labeling the distances. Compare your results with what you saw on the simulator.

15. Now put yourself in the place of the fish. How do things above water look to him/her? Use the source in the air above the Zinium to model this situation. Will the source appear to be the same distance, closer or farther as seen from inside the Zinium (water)? Sketch your results and state your conclusions.

State the key ideas that you have gained thus far from your investigations of refraction:

1.

2.

3.

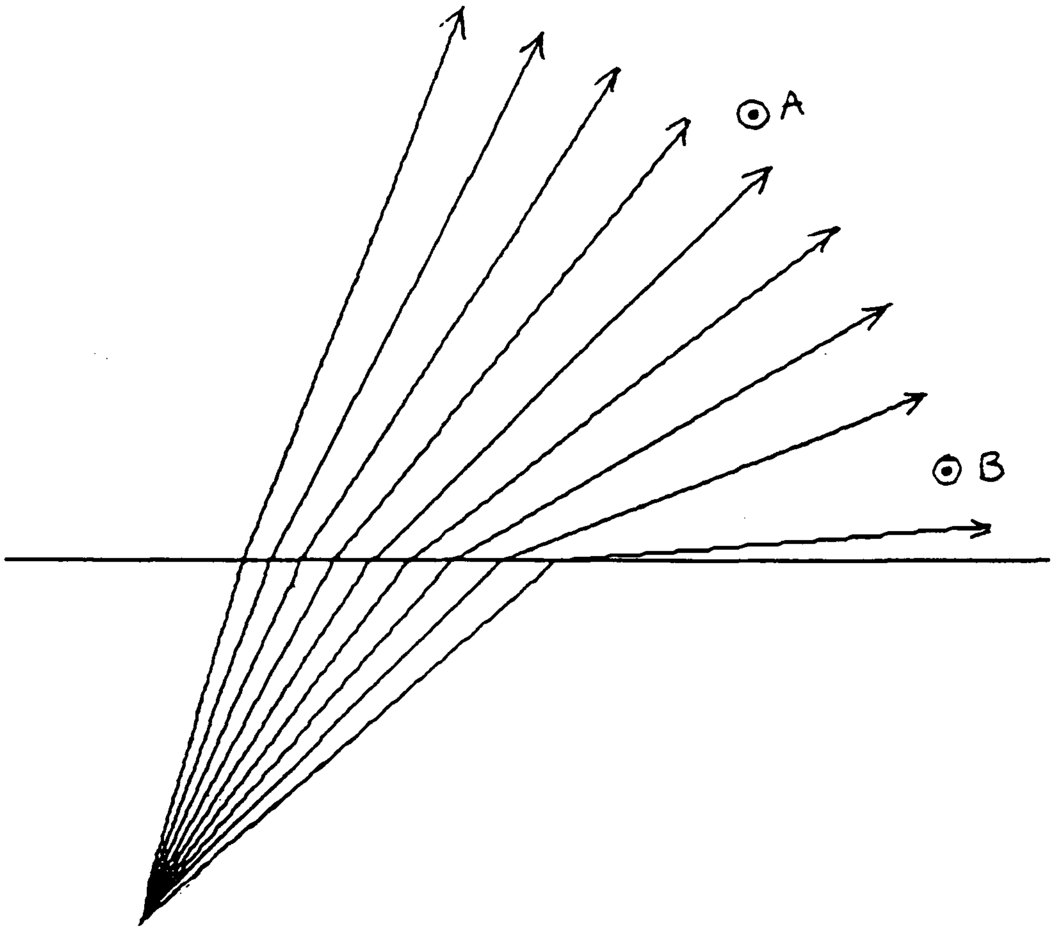
HOMEWORK 9/13/90 NAME____________________

PHYSICS I

PERIOD____________________

To get full credit, hand this sheet in tomorrow:

The ray diagram below shows refraction at a single surface.



a) Suppose the diagram represents you sitting in the bathtub, looking at your submerged big toe. On the diagram, draw where your toe would be. Also label the water and the air.

b) Suppose your eye is at A. Where would your toe seem to be? Use the diagram to find the exact location of the image of your toe.

c) If you were to get down low in the bath, so that your eye was much closer to the surface of the water, at B, would your toe still seem to be in the same place? Explain, using the diagram.

Experiment 3.50

Physics 1

Names:√________________

____

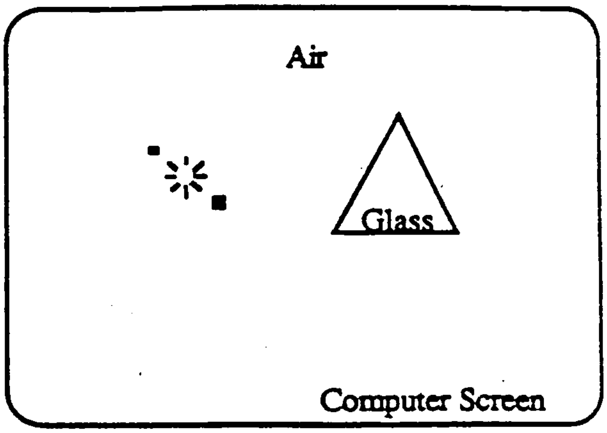
____

Period________ Computer__________

PURPOSE: The purpose of this lab will be to continue experimenting with the behavior of light called refraction. You will use the simulator to help determine the general and specific patterns that light follows.

ACTIVITIES AND QUESTIONS:

1. **SIMULATOR:** Turn on the computer and launch "Dynagrams™."



2. Use the menu under "Environment" to put a prism on the screen. Use the box in the lower right-hand corner to enlarge the prism somewhat so that it is relatively large. Make the prism material be **glass** that only refracts. Add a light source to resemble the diagram to the right.

3. Send a light ray toward the prism. Sketch the path that the light takes as it passes through the prism. Use words and your diagram to describe the manner in which light is affected by the prism.

   Is this behavior a general one, that is, does it happen for other light rays, too? Try it and then explain why the light bends the way it does passing through the prism. Is light obeying the patterns you saw earlier with refraction?

4. **PREDICTION:** What pattern would light follow going through a prism if it were "fatter" or "thinner," wider or narrower at the base? Sketch your prediction below.

5. **SIMULATOR:** Change the prism to make it "fatter" or "thinner." Send light rays through the prism to observe their behavior. Sketch the pattern below. How does the pattern compare with your prediction?

6. **PREDICTION:** What pattern would light follow going through a prism of air if it were surrounded by glass? Sketch your prediction below.

7. **SIMULATOR:** Change the materials in your situation so the prism is air and the surroundings in glass. Send light rays through the prism to observe their behavior. Sketch the pattern below. How does the pattern compare with your prediction?

If you were to describe the general direction that a prism bends light, what would you say?

Experiment 3.50

Physics 1

Names:√ ____________________

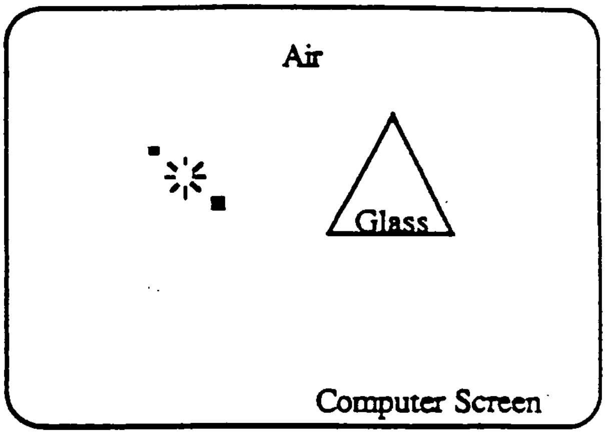
____

____

Period________ Computer__________

PURPOSE: The purpose of this lab will be to continue experimenting with the behavior of light called refraction. You will use the simulator to help determine the general and specific patterns that light follows.

ACTIVITIES AND QUESTIONS:



1. **SIMULATOR:** Turn on the computer and launch "Dynagrams™."

2. Use the menu under "Environment" to put a prism on the screen. Use the box in the lower right-hand corner to enlarge the prism somewhat so that it is relatively large. Make the prism material be glass that only refracts. Add a light source to resemble the diagram to the right.

3. Send a light ray toward the prism. Sketch the path that the light takes as it passes through the prism. Use words and your diagram to describe the manner in which light is affected by the prism.

Is this behavior a general one, that is, does it happen for other light rays, too? Try it and then explain why the light bends the way it does passing through the prism. Is light obeying the patterns you saw earlier with refraction?

4. **PREDICTION:** What pattern would light follow going through a prism if it were "fatter" or "thinner," wider or narrower at the base? Sketch your prediction below.

5. **SIMULATOR:** Change the prism to make it "fatter" or "thinner." Send light rays through the prism to observe their behavior. Sketch the pattern below. How does the pattern compare with your prediction?

6. **PREDICTION:** What pattern would light follow going through a prism of air if it were surrounded by glass? Sketch your prediction below.

7. **SIMULATOR:** Change the materials in your situation so the prism is air and the surroundings in glass. Send light rays through the prism to observe their behavior. Sketch the pattern below. How does the pattern compare with your prediction?

If you were to describe the general direction that a prism bends light, what would you say?

Experiment 4.00
Physics 1

Names:√________________

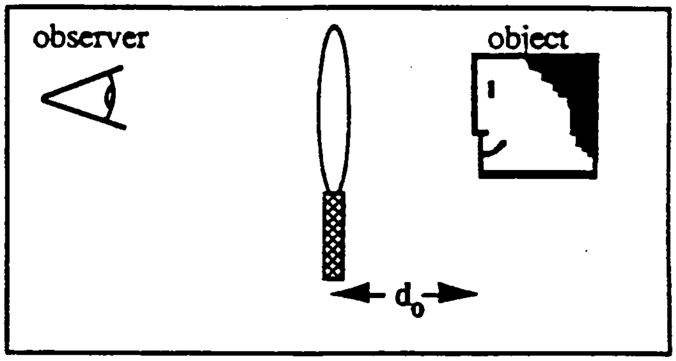
____

____

Period________

PURPOSE: The major goal of this lab will be to understand the major patterns which are produced by the interaction of light with convex lenses during the formation of images.

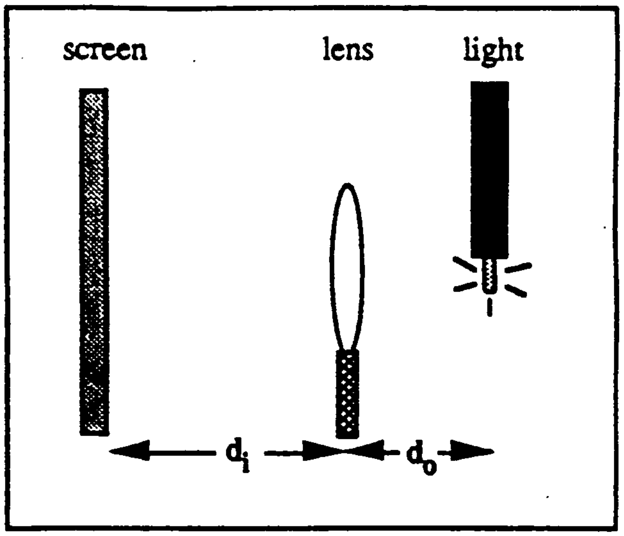
ACTIVITIES AND QUESTIONS:



1. **REAL:** You will be furnished with a convex lens, otherwise called a magnifying glass. As indicated in the diagram to the right, look through the lens at a handy object - one of your lab partners. Try to keep the distance between the object and the lens (called the **object distance - d_0**) constant. Move your head (eye) back and forth to see if your observation point has any affect on the image you see. Use this space to write down your observations:

2. Now change the object distance (d_0) but keep your eye-to-lens distance constant, and note any changes in the image you see. Are there any patterns to the changes? Are there any surprises?

3. REAL: Set up the situation diagrammed to the right. Use one of the flashlights, your lens, and a fiberboard "screen." Set the lens on the table so that it rests stably in a vertical direction. Use a ring stand to hold the light. With the object distance set to the values below, move the screen back and forth, changing d_i. Write down your observations of the light which falls on the screen after passing through the lens for each of the situations.



(a) d_o = 10.0 cm

"As we move the screen further and further from the lens, the light pattern on the screen becomes...

(b) d_o = 30.0 cm

4. If you were successful in step 3, you found one distance gave you a diverging light pattern, while the other had a pattern where the light converged behind the lens. Now change d_o until you find a distance which gives you a light pattern which doesn't change its size as you move the screen away from the lens. How far is the lens from the light when this happens?

5. REAL: Take your lens outside, letting light from the sun pass through the lens. Move your screen back and forth until the place where the light strikes the screen is at its smallest size. Measure the distance from the lens to this point. How does this distance compare with the distance that you saw in Step 4?

Summarize your observations of light from a point source travelling through a convex lens. Use another sheet of paper if needed to construct diagrams of how the light rays were probably going in each situation (diverging, converging and same size).

Experiment 4.50
Physics 1

Names: ______________________

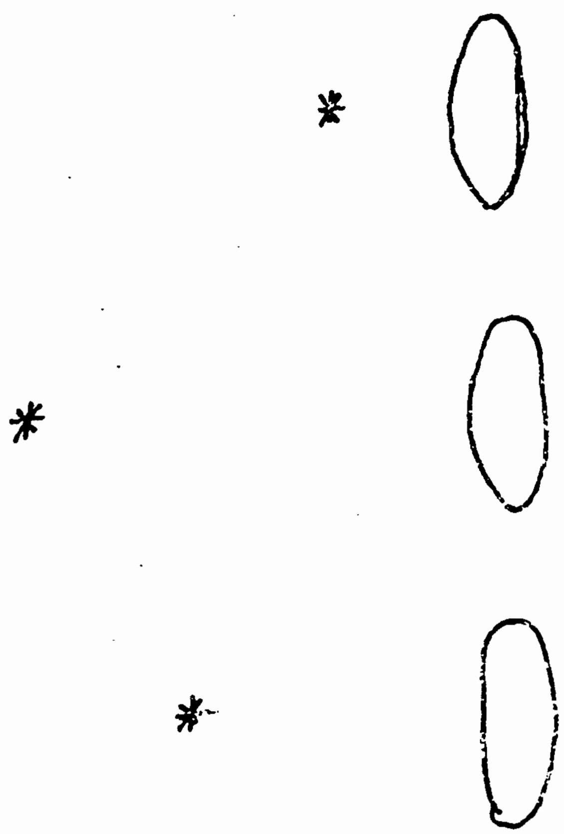
____

____

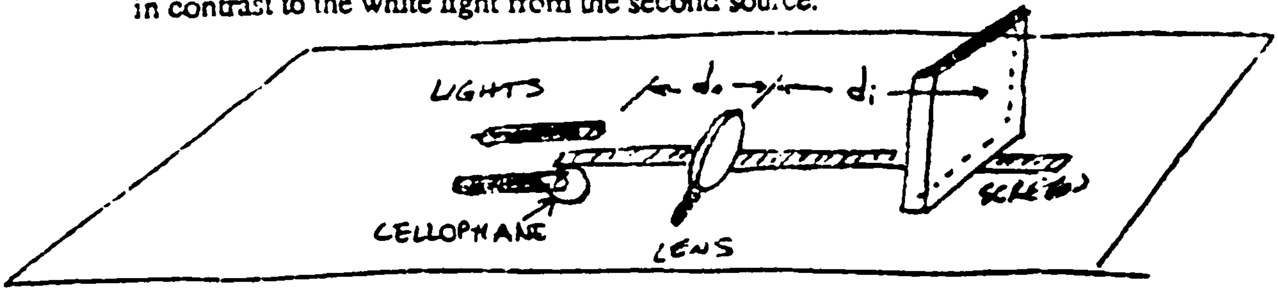
PROCEDURE:

1. **SIMULATOR:** Boot up Dynagrams. When it is launched, OPEN Experiment 4.50.

   The screen should show a light source, two "aiming" lines, and a lens-like oval object. Work to create situations by using ray sprays, individual rays, moving the source, etc., in order to create the same types of light behavior that you saw in lab 4.00 yesterday. When you have successfully re-created the three situations, sketch the resulting ray diagrams (as seen on your computer screen) in the space below.



2. REAL: Now set up two light sources as pictured in the diagram below. Note that on one of the lights we are going to wrap a piece of colored cellophane around the light, giving it a color in contrast to the white light from the second source.



Set the distance between the lights and the lens to 30 cm. Move the screen back and forth until you have clearly focussed images of the two lights on the screen. Measure the distance to the screen and record it in the column under d_i, the image distance. (Note that 30 cm is the object distance, d_o.

Now move the lens until you have the remaining object distances listed, each time getting the clearest focus possible, measuring and recording your values of d_i.

Object Distance, do	Image Distance, di
30 cm	
40 cm	
50 cm	
60 cm	
70 cm	

What general patterns do you observe about the image distance as the object distance gets larger and larger? Is there any pattern to the spacing between the two images as the object gets further and further from the lens? Are there any interesting observations that you make about the images of the light sources? Use this space to record your observations.

3. Now modify the screen on Dynagrams to include two light sources. Try to create a situation similar to the one you just worked with in step 2. When you get it finished, sketch the ray pattern below.

4. Now use a light bulb with size, not your point sources, and place it various distances from the lens. Find and observe the clearly focused images in each case. Write down any observations that you make of those images.

Based on your work with the simulator and your work with real light sources, etc., try to summarize how a convex lens operates on light to form the images you saw in step 4.

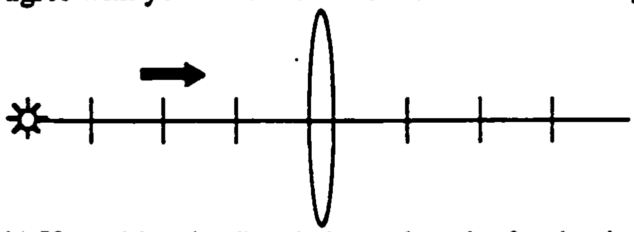
Physics 1

Period________ Computer__________ _______________

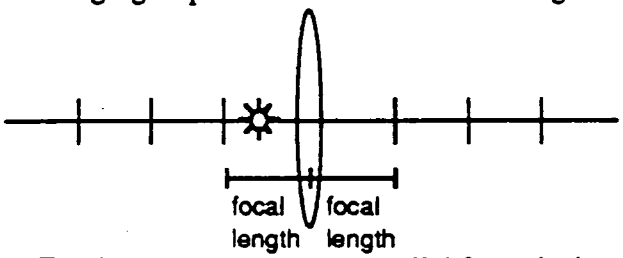
____

5. **ANIMATION:** Do not start Dynagrams, but instead double-click on "Lens Animation", which is an animation about the optical properties of a simple convex lens (magnifying glass). Explore the animation by mouse clicking on the arrows to see how the location of an image depends on the location of the object (ie. light source).

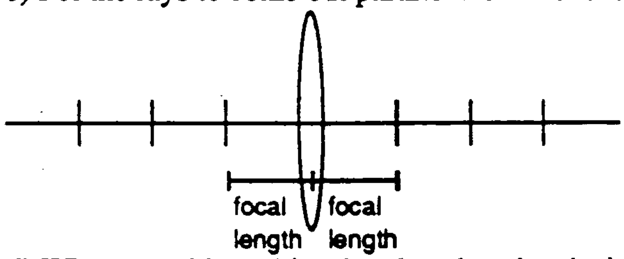
a) As the object (light source) is moved closer to the lens, which way does the image move? Does this agree with your data from the lab with two flashlights? Illustrate in the diagram below.



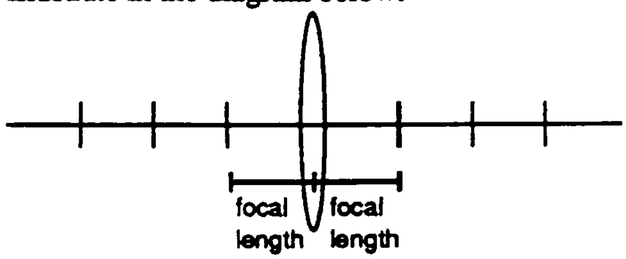
b) If an object is placed closer than the focal point of the lens, do the rays come out diverging, converging or parallel? Illustrate in the diagram below.



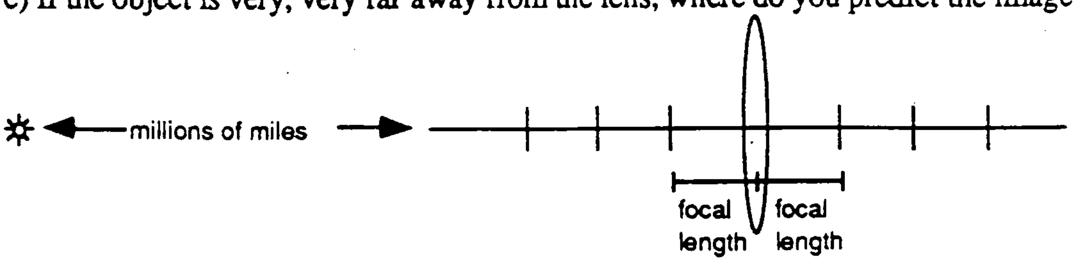
c) For the rays to come out parallel from the lens, where must the object be placed? Illustrate below.



d) Where would an object be placed so that the image and object are equally far from the lens? Illustrate in the diagram below.



e) If the object is very, very far away from the lens, where do you predict the image will be? Illustrate.



Experiment 4.50
Physics 1

Names:√______________________

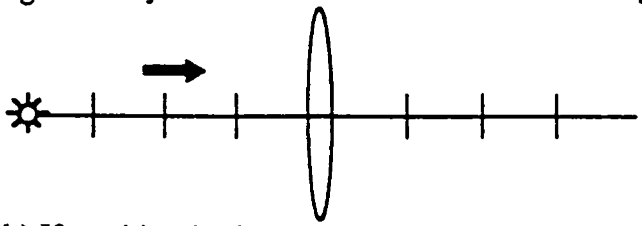
____

____

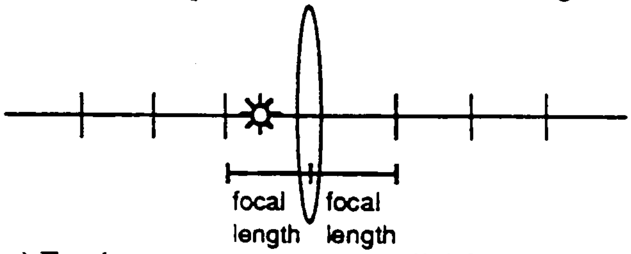
Period________ Computer___________

5. ANIMATION: Do not start Dynagrams, but instead double-click on "Lens Animation", which is an animation about the optical properties of a simple convex lens (magnifying glass). Explore the animation by mouse clicking on the arrows to see how the location of an image depends on the location of the object (ie. light source).

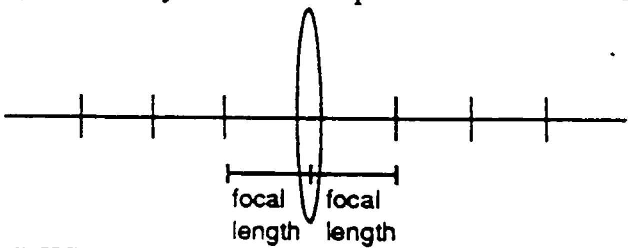
a) As the object (light source) is moved closer to the lens, which way does the image move? Does this agree with your data from the lab with two flashlights? Illustrate in the diagram below.



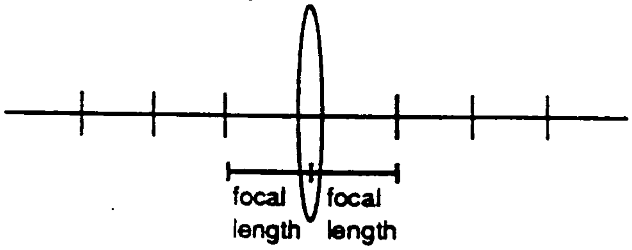
b) If an object is placed closer than the focal point of the lens, do the rays come out diverging, converging or parallel? Illustrate in the diagram below.



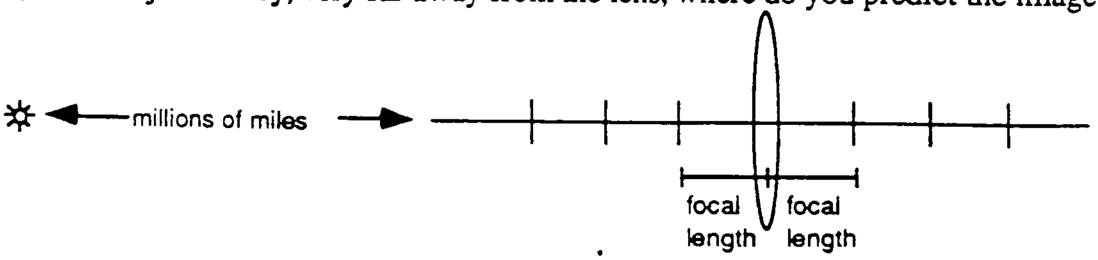
c) For the rays to come out parallel from the lens, where must the object be placed? Illustrate below.



d) Where would an object be placed so that the image and object are equally far from the lens? Illustrate in the diagram below.



e) If the object is very, very far away from the lens, where do you predict the image will be? Illustrate.



HOMEWORK
PHYSICS I

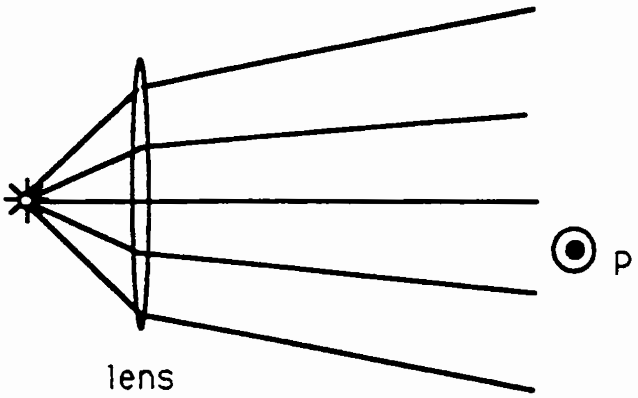
NAME_______________________________

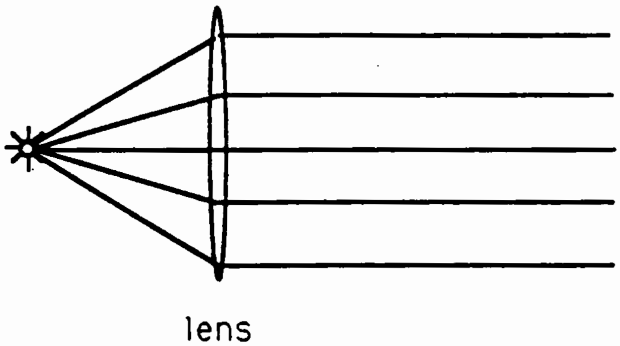
PERIOD_____________________________

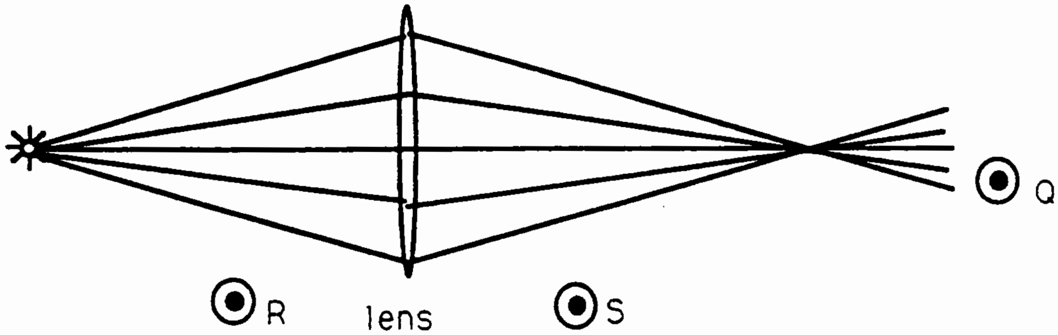
DATE ___________________

To get full credit, hand this sheet in tomorrow:

The three diagrams below show the behaviour of light from a point source at three different distances from a convex lens.







a) Draw the approximate location of the focal points of the lens on each diagram. As best you can, explain your reasoning.

b) Consider observers at P,Q, R and S in the diagram above.

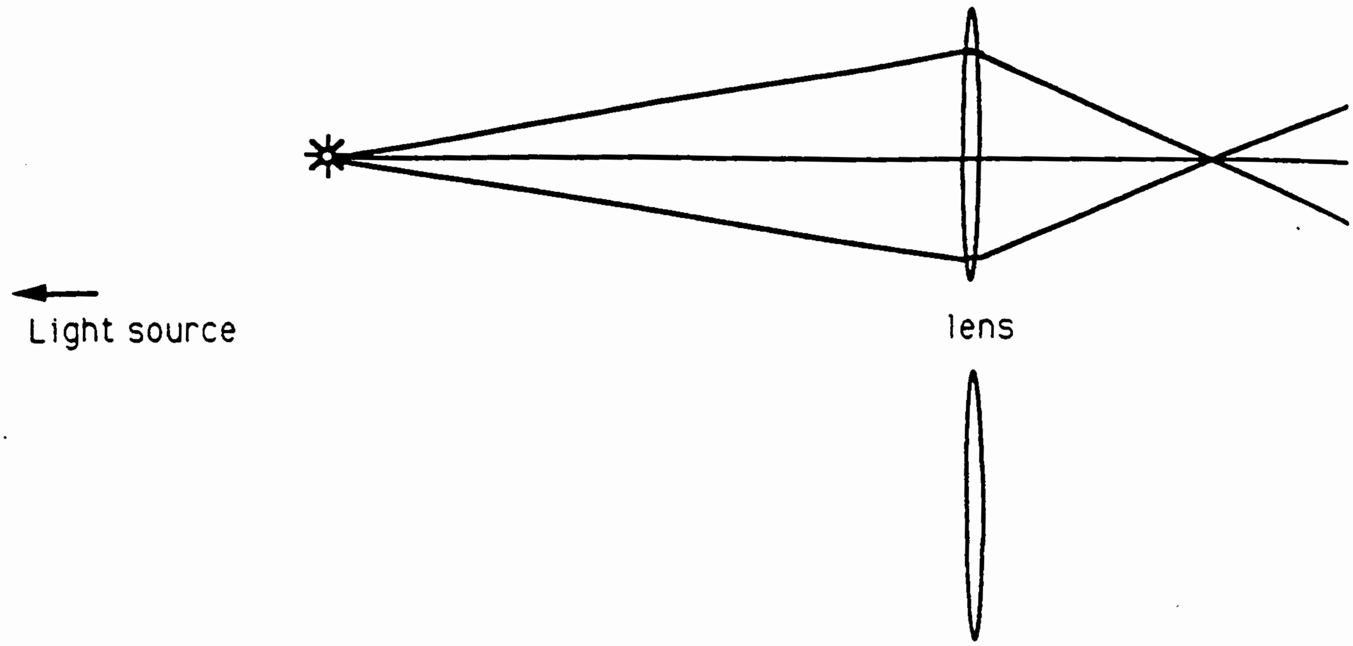
What, if anything, would an eye at P would see? (Show on the diagram)

What, if anything, would an eye at Q would see? (Show on the diagram)

What, if anything, would an eye at R would see? (Show on the diagram)

What, if anything, would an eye at S would see? (Show on the diagram)

c) On the diagram below, draw what you think the ray diagram would look like if the point source was moved very far away, off the left-hand side of this page.



2) Write down a question of your own about an everday optical situation you think is interesting and/or important. There are no right or wrong questions, so feel free to ask something that matters to you.

Experiment 5.00: Eyes

Physics 1

Names:√________________

____

____

Period________ Computer__________

PURPOSE: The major goal of this lab will be to explore the eye as an optical system, and to understand why image locations can be found by drawing the backward extensions of rays in a diverging spray.

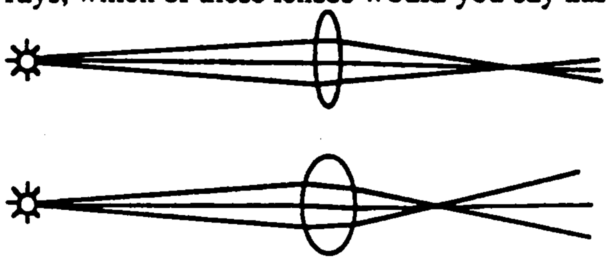
ACTIVITIES AND QUESTIONS:

1. **ANIMATION:** On the computer, **do not start up Dynagrams**, but instead double-click on "Eye Animation", which is an animation about the structure and function of the human eye. Run the animation (several times if you like). Explore the effects of tightening or loosening the muscles which control the shape of the lens, by mouse clicking on the arrows. Use the animation to answer the following questions:

a) If someone can see an object (such as a hand) clearly, what must be happening to light from any point on that object?

b) Under what circumstances does the image become blurry, and why? (Use a sketch to explain.)

c) If we think of a lens's "power" as a measure of how much it can converge a diverging spray of rays, which of these lenses would you say has a greater power?



d) Does the lens in the eye have greater power when it is very curved or when it is stretched almost flat?

e) If the hand was to move farther away, where would the image form: in front of the retina, on the retina or behind the retina?

f) In order to see this distant hand clearly, would the lens in the eye need to be more or less powerful? Should it become more rounded or flatter?

g) Far-sighted people can see distant objects easily, but not close ones. Would you expect far-sighted people to have lenses that are too rounded, or too flat? Explain.

2. **SIMULATOR:** **Now start up Dynagrams**, and open Experiment 5.00.

a) In Setup 1, adjust the shape of the lens in the eye so that the eye clearly sees the source. How do you know when you have achieved this? Sketch the diagram:

b) Duplicate this eye (select it and press command-d) and put the copy in Setup2 directly underneath the original eye. Does light from the source come to a clear focus on the retina?

c) Where does the observer (eye) in Setup 2 perceive the source as being? ie. Where is the image of the source? Sketch the diagram below.

d) Duplicate the eye again, and put the copy in Setup 3 directly underneath the other eyes. Does light from the source come to a clear focus on the retina?

f) Where does the observer (eye) in Setup 3 perceive the source as being? ie. Where is the image of the source? Sketch the diagram below.

g) The image you found in Setup 2 was a virtual image. In Setup 3 you found a real image. What do you think is the difference?

h) Can the eye distinguish between objects, real images and virtual images? If so, how?

SUMMARY: State the 3 most important ideas that you have learned about the way the eye works.

1.

2.

3.

HOMEWORK
PHYSICS I

NAME________________________

PERIOD________________________

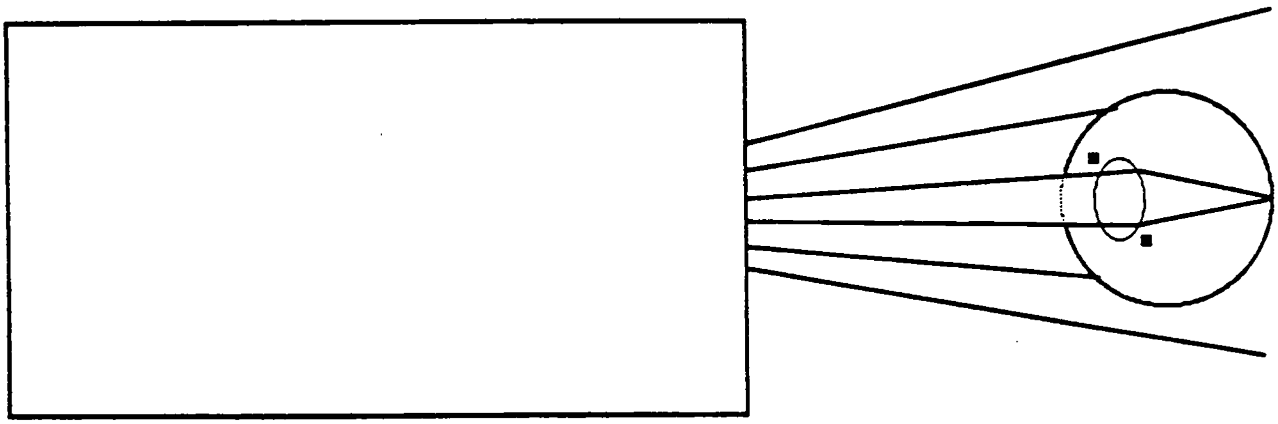
DATE ________________________

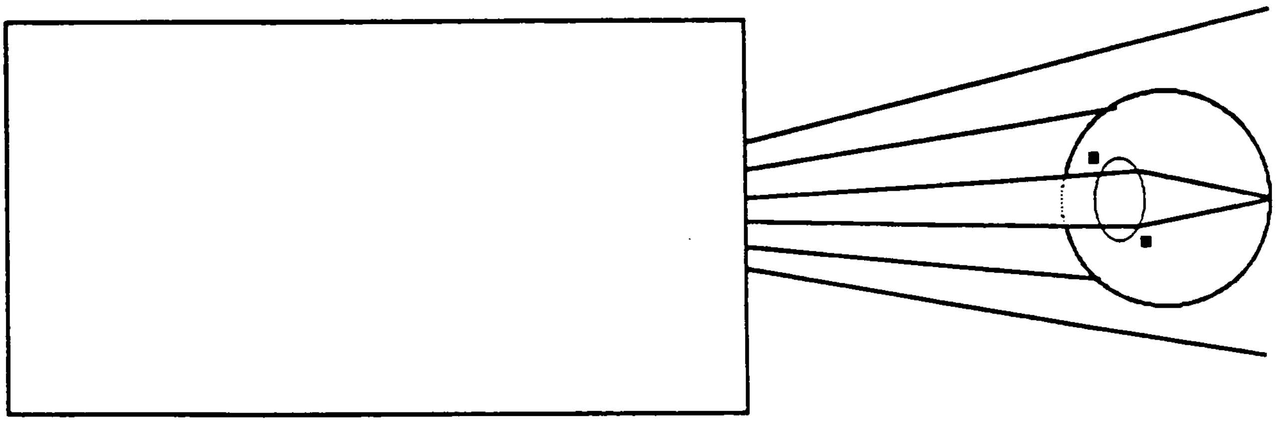
To get full credit, hand this sheet in tomorrow:

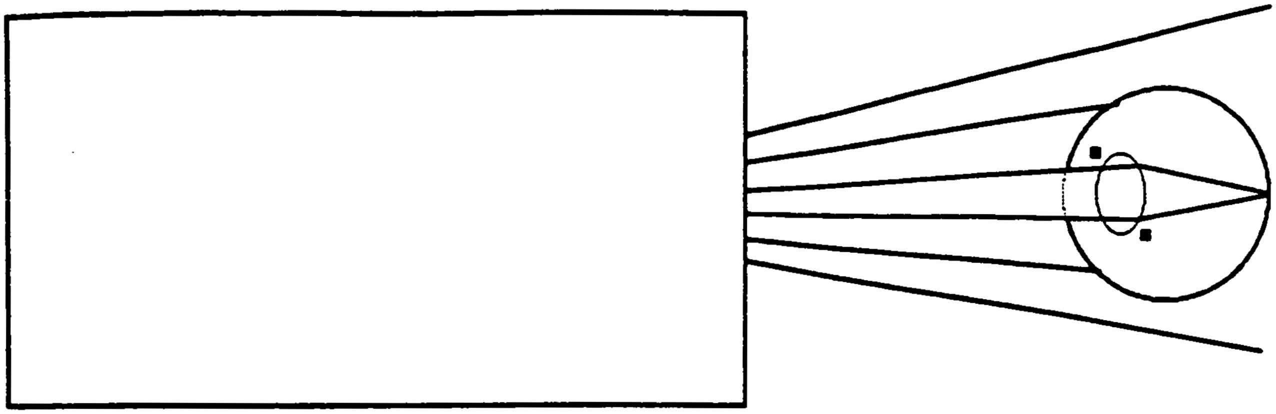
1) The diagrams below shows an optical setup which is partly hidden behind a "black box".

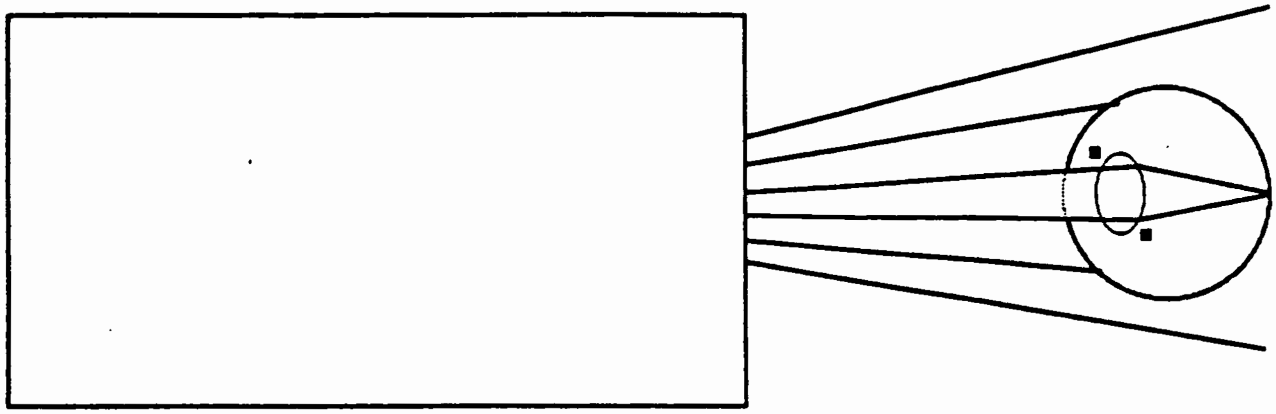
a) Using mirrors, lenses and light sources, draw 4 different configurations inside the black box that could produce this pattern of rays. In each case, your ray diagram should connect to the rays shown leaving the box.

b) On each diagram, indicate where the observer (indicated by the eye) would think the light source was located.









Appendix D.

1990 California School Clinical Interview Guideline (For lens/mirror groups)

Appendix D.

1990 California School Clinical Interview Guideline (For lens/mirror groups)

This is not a test - no grades.

For the next part of the interview, I'm going to ask you to answer some questions about optics. We are interested in two things: how you answer those questions, and what you're thinking while you work on them. If your answers are correct, that's icing on the cake. During this interview, I won't be able to answer your questions or assist you. At the end, I'll answer any questions you have about the interview or our research.

I'm going to ask you to think aloud as you work on the problems. I want you to try and tell me what you're thinking as you work on a problem. It's ok to say things you aren't sure of. Because we prize your thought processes, we might remind you to think aloud during the interview.

Does that make sense?

PROBLEM 1

An object is 12 cm from a converging lens (mirror) of focal length 3 cm.

a) Using diagrams and words, could you explain:

- where and at what distance from the lens an image will form?

- what will be the size of the image?

- what kind of image will it be, and why?

b) What would a person see if they put their eye on the axis, far away from the lens (mirror)?

c) Now imagine moving the object closer and closer to the lens (mirror). Describe to me the changes that take place in the image, and why.

- Could you show me how the diagram would look for that?

(Wrap-up and prompts:

- Is there always an image?

- Is the image always right-side up,

or always upside down,

or sometimes right-side up and sometimes upside down?

- Is the image always real,

or always virtual,

or sometimes real and sometimes virtual?

- What does that mean, real and virtual?

- What happens beyond the focal point?

- What happens at the focal point?

- What happens between the focal point and the lens (mirror)?)

(How does it feel? You're doing really well.)

PROBLEM 2

Here I have a lamp with a smiling face painted on it, a converging lens (mirror), and a screen. The lens (mirror) is a different shape to the ones you worked with in class, but it works the same. All the things can be moved.

(Start with the lens (mirror) quite far from the lamp, and an image on the screen but blurry.)

a) I'd like you to create a focused image of the smiling face on the screen.

- Can you explain to me what is happening there? Why is the image forming as it is?

- Please draw a ray diagram on the board to represent that situation.

b) LENS VERSION: Now if I take away the screen, like this, and move further back and look towards the lens, *(be sure to look from a sufficient distance away)* I can see the smiling face. Why don't you try it. Can you see a smiling face? Tell me about what you are seeing? Can you show me how that works on your diagram? *(Legitimate prompts, if not shown: "Where are you in the diagram?" and "Where is the smiling face on the light?" / "Where is the smiling face you could see?".)*

MIRROR VERSION: Now I'm going to turn the mirror slightly, so that the image is still on the screen, like this. *(Twist mirror and get image back on screen.)* Now if I take away the screen, like this, and move <u>way</u> back and look towards the mirror, *(be sure to look from WAY BACK)* I can see the smiling face. Why don't you try it. Can you see a smiling face? Tell me about what you are seeing? Can you show me how that works on your diagram? *(Legitimate prompts, if not shown: "Where are you in the diagram?" and "Where is the smiling face on the light?" / "Where is the smiling face you could see?".)*

c) If it's possible with this system, can you show me in some way a virtual image of the smiling face?

(<u>Don't</u> tell them they're going to have to draw diagrams for all the following:)

(For each of the following, ask for predictions, then drawings. Only after all predictions are done, ask subjects to test and explain their observations.)

d) I have a black card here. What do you think will happen to the image (if anything) when I use it to cover the top half of the lens (mirror), like this? *(Use exact wording here.)* Why? Could you draw me a ray diagram to show me why you think that will happen? *(NB. make sure subject specifies appearance of image unambiguously - eg. NOT top/bottom of face. If necessary, prompt: chin or hat.)*

e) If I lift the lamp up about an inch, like this, what do you think will happen to the image, if anything?

(Be sure not to lift lamp above level of lens)

f) What do you predict will happen to the image (if anything) when I remove the lens (mirror)? Why? Could you draw me a ray diagram to show me why you think that will happen?

Now I'd like you to test your predictions, and explain the results of each one.

Appendix E.

Categories of analysis for the 1989-1990 Clinical Interview Diagram Components Analysis

Operational Definitions of the Diagram Coding Scheme

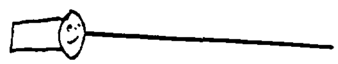
This document is divided into two sections. The first lists the Diagram elements and spatial zones in ray diagrams that are scored. The second section attempts to describe the scoring procedure given a subject's summary.

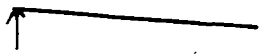
Section 1:

Object:

point source - a dot with at least one ray line attached.

light source - any polygon with at least one ray line attached.





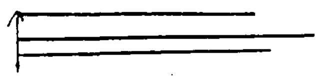
Ray:

Single Ray - A line drawn from an object or a light source.

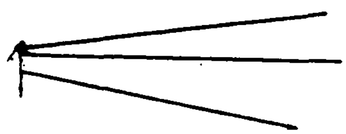
All diagrams that have multiple lines from a source can be subdivided into two categories: beams and sprays. The distinquishing feature of a beam is that a single ray originates from each of multiple locations on the surface of the object. In the case of a spray, multiple rays leave from a single point on the surface of the object.

Beams:

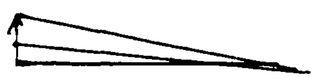
Parallel beam - A beam whose rays are parallel with each other.

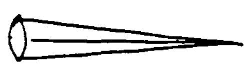


Diverging beam - A beam in which the spaces between rays increase as the distance from the object increases.



Converging beam - A beam in which the spaces between rays decrease as the distance from the object increases.



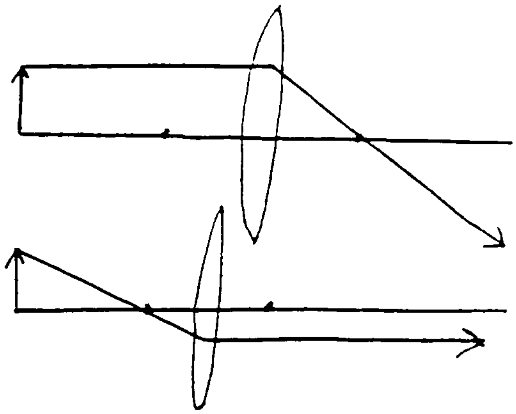


Sprays:

Diverging spray - A beam in which the spaces between rays increase as the distance from the object increases.

Converging spray - A beam in which the spaces between rays decrease as the distance from the object increases.

Special rays - A particular spray pattern in which the rays drawn travel through the appropriate focal points or segments of the optical element to have known behavior. Special rays are divided into two categories:



Parallel: The rays initial tragectory from the source is parallel to the principal axis.

Focal point: The rays initial trajectory passes through the nearest focal point to the source.

Optical Elements:

Lenses:

Converging 

Diverging 

Mirrors:

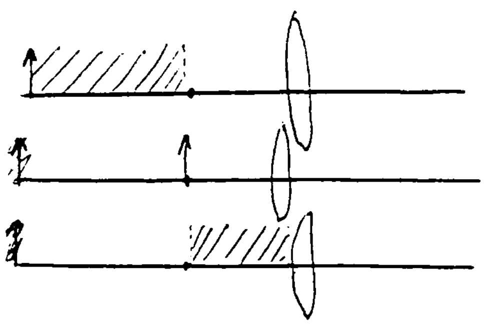
Plane

Converging 

Diverging 

Zones:

There are three spatial zones of interest for simple light systems consisting of a light source, a converging lens or mirror, and an image. A zone is assigned based on the spatial relationship between the light source and the optical element. The marking of F in the diagram is a prerequisite for this judgement.



Outside F:

At F:

Inside F:

All simple optical set-ups are scored for two regions. The first region is the space between the light source and the first region is the space between the light source and the optical element. The second region is the space between the optical element and the image. The pattern of light drawn through each region is assigned the apprcpriate ray, beam, or spray designation.

Section 2: Scoring Procedures

What makes scoring the summary sheets difficult is that for any given question, there may be multiple attempts to solve the problem. With each attempt, the student may learn or reconstruct from memory a more refined knowledge element. In this case, the judge has both incorrect and correct versions of a knowledge element in the summary. Using the principle of charity, I used the problem solving attempt that had the most correct knowledge elements.

A particular difficult scoring situation occurs when the student substitutes the wrong optical element. It is possible to see correct knowledge elements being employed in a problem attempt that is flawed by the inital incorrect substitution. A particular vexing variant of this occurs when the interviewer (e.g. Mike!!!!) gives the student permission to make the optical element substitution, in effect treating the unknown optical element as a known but incorrect knowledge element. In all these cases, the students have initially attempted to solve the problem as stated, and have reached a terminal impasse. In addition, the students have mentioned that if "x" where a "y" they would know what to do. It is only if these two conditions are meet, that they are encouraged by the interviewer to make the "as if" move. In many of these "as if" optical element substitutions, the resulting diagrams are quite good. The original scoring sheet has a column for substitutions. This allows for the marking of the special case in which the subject draws the correctly the wrong diagram. With this marker in place, one can then make an analytic choice as to score these as incorrect at the problem level, and/or to score the diagram knowledge elements correct. This involves another application of the principle of charity.

There are a number of other categories on the original scoring sheet. Some of them turned out to be impossible to score. Others were redundant with other categories. Still others revealed at first glance, no interesting relationships. I know that Sue is interested in eyes. What the correlational relationship between the eye knowledge element and any particular ray patterned has not been explored.

Appendix F.

1990 Pre-Post Test Instrument for Assessing Conceptual Change

Appendix F.

1990 Pre-Post Test Instrument for Assessing Conceptual Change

Here are some questions about everyday phenomena involving light. We will be asking you a similar set of questions at the end of your optics course, to see how your thinking has changed. The purpose of the exercise is to place on paper, your own "natural" thoughts on light. Don't worry if you have trouble with some of the questions - we don't expect you to be able to answer them all correctly. We don't want you to go off to a physics book to research the "correct" answer. If you spend more than 10 minutes on a question, you are working too hard!

Because the questions will take up to an hour to complete, we have divided them into 2 sections. Each section is worth the same number of points towards your unit grade. Full credit will be given for any serious effort to answer a question. Completing both sections will earn you twice as many points. It is important for our research that you complete and hand in your homework by tomorrow's (Wednesday's) class, before you start to use the simulator. Homework received after Wednesday will receive half credit.

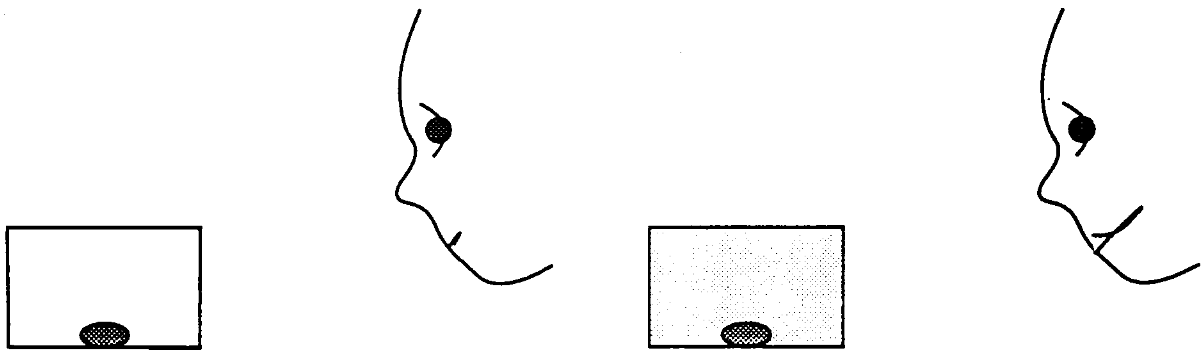
Use words and a diagram to answer each question.

1) Sometimes shadows seem clear and sometimes they seem fuzzy. Why? Show with a sketch what causes this to happen.

2) Imagine yourself in a dark room lit by a candle. Why is it that you can see not only the candle but also other objects in the room? Show with a sketch what causes this to happen.

3) Explain what happens when you see yourself in a mirror. Show with a sketch what causes this to happen.

4) In diagram (a) below, a bucket contains a coin which is just hidden from your view by the bucket walls. In (b), the bucket has been filled with water, and suddenly, though you did not change your position, you can see the coin. Why? Use the diagrams to explain, or draw a diagram of your own.



(a) (b)

5) Draw a diagram of yourself looking at this page. Explain how it is that you can read these words.

6) If you stand in a lighted room and look through the window to a dark street outside, you can see your own image. Why can't you see your image if you stand at the same place during the day? Show with a sketch what causes this to happen.

7) Explain how it is that something looks bigger when you look at it through a magnifying glass. Show with a sketch what causes this to happen.

8) Make a short list of the most important things that you know about light.

9) What are three things you'd like to know about light?

10) Why is it that you can use a magnifying glass to burn a piece of paper on a sunny day? Show with a sketch what causes this to happen.

11) Assume that you are comfortable swimming under water with your eyes open. If you wear goggles or a mask, you can see much more clearly. Why? Show with a sketch what causes this to happen.

12) Does light from a TV travel the same distance at night and during the day? How far does it travel in each case, and how do you know? Show with a sketch what causes this to happen.

13) Which would be a better approach to brightening a room, putting up mirrors or painting the walls white? Why? Show with a sketch what causes this to happen.

14) You are locked in a room which has identical white walls, except for a mirror which covers the door. The room is completely dark. Using a flashlight, how would you recognize the mirror? Show with a sketch what causes this to happen.

15) Descartes (a philosopher who lived in the 17th century) claimed that light has an infinite speed. He based his claim on the following reasoning: if you go outside at night with your eyes closed, and then open them, you immediately see the stars. The fact that it is immediate proves that light has infinite speed. Was he right? What do you think about his explanation?

16) If you watch the bottom of a clear wavy pool on a sunny day, you can see changing patterns of light. What creates them? Show with a sketch what causes this to happen.

Appendix G.

Coding Scheme for 1990 Pre-and Post-test Diagrams and Verbal Explanations, Organized by Question

Definitions for Coding Scheme on Pre/Post Tests

The coding on the pre/post test data was split up in to three categories: General Characteristics, Written Characteristics and Diagram Characteristics. The General Characteristics take into account the whole answer while the Written and Diagram Characteristics only take into account their respective sections.

General Characteristics

no answer:	whether or not the student attempted to solve the problem
written explanation:	whether or not the student attempted a written explanation
correct explanation:	whether or not the student was able to show that he/she could correctly answer the question at a level expected by high school physics teachers
diagram:	whether or not the student attempted to draw a diagram
diagram follows explanation:	whether or not the diagram followed the explanation (no contradictions) whether it was correct or not

Written Characteristics

The answers in the written explanation are self explanatory according to each question.

Diagram Characteristics

Light is represented by:

Note: If a ray originates as a spray, it is called a spray for the remainder of the diagram. If a ray originates as a beam, it is called a beam for the remainder of the diagram.

ray:	represented by a single line emitted from a light source
diverging beam:	represented by more than one ray emitted outward from a light source in different directions
converging beam:	represented by a beam converging to a point (usually after it refracts through a lens)
parallel beam:	represented by more than one beam emitted parallel to each other from different points on a light source
diverging spray:	represented by more than one ray emitted outward from *one* point on a light source (i.e., the tip of an arrow)
converging spray:	represented by a spray converging to a point (usually after it refracts through a lens)
colored area:	represented either by lines dense arbitrary lines or a "fully painted" area (i.e., random lines filling a page to signify a room lit by a candle)

The next few pages contain the coding scheme for each question.

Question #1
Shadow Question
General Characteristics
no answer
written explanation
correct explanation
diagram
digram follows explanation
Written Explanation
fuzzy because:
  less intensity
  one light source, different dist.
  many light sources
Diagram Characteristics
light is represented by:
  ray
  diverging spray
  colored area
more than one light source
rays hit object & define shadow
define sharp shadow
define fuzzy shadow
rays enter eye
perfect explanation & diagram

Question #2
Candle question
General Characteristics
no answer
written explanation
correct explanation
diagram
diagram follows explanation
Written Characteristics
you can see because objects are:
  reflective
  light hits objects
  reflective thus bright
  rays hit the eye
Diagram Characteristics
light is represented by:
  ray (single or parallel)
  diverging spray
  colored area
light originates from source
show eye
bounce off objects
bounce off objects into eye
perfect explanation & diagram

Question #3
Mirror Question
General Characteristics
no answer
written explanation
correct explanation
diagram
digram follows explanation
Written Characteristics
you can see yourself because:
  light reflects off your face
  light is reflected off mirror
  image is reflected off mirror
  reflected light hits eye
  you see the reverse
Diagram Characteristics
light is represented by:
  single/parallel ray
  beam (≥1)
  spray from one object point
  sprays from 2 or more points
  colored area
rays originate from eye
image at mirror
image behind mirror
correct angle ray reflection
correct image distance
Image Distance Justification:
  no beams or sprays
  traceback single ray
  traceback ray spray
  traceback multiple sprays
perfect explanation & diagram

Question #4
Coin Question
General Characteristics
no answer
written explanation
correct explanation
diagram
diagram follows explanation
Written Characteristics
coin reflected at top of/by water
light rays refracted by water
coin seems higher up
Diagram Characteristics
light is represented by:
  (a): rays from eye
(Question #4 continued)
  (a): rays from object
  (a): ray direction unknown
  (b): rays drawn
  (b): rays refract
correct direction of traceback rays
perfect explanation & diagram

Question #5
Window/Mirror Question
General Characteristics
no answer
written explanation
correct explanation
diagram
diagram follows explanation
Written Characteristics
see image in dark because:
  dark outside does not absorb light
  light reflected only when dark
  hard to see image in day
  always reflects.see at night only
Diagram Characteristics
light is represented by:
  ray (single or parallel)
  diverging spray
  colored area
show object
show window
two separate cases
dark:
  don't treat window like mirror
  treat window like mirror
  no image shown
  image at window
  image behind window
  justification for image dist.
light:
  treat as though no window
perfect explanation & diagram

Question #6
Reading Question
General Characteristics
no answer
written explanation
correct explanation
diagram
diagram follows explanation

(Question #6 continued)
Written Characteristics
you can read because:
images of words enter eyes
light illuminates words
see contrast of light and dark
reflected light hits eyes
light reflected from paper
see inverse
Diagram Characteristics
light is represented by:
ray (single or parallel)
diverging spray
colored area
show paper
show eye
show light source
rays from eye->object
show rays from light->paper
show rays from paper->eye
perfect explanation & diagram

Question #7
Burning Paper Question
General Characteristics
no answer
written explanation
correct explanation
diagram
diagram follows explanation
Written Characteristics
the paper burns because:
light focused on one point->hot
focused light hits paper
mention intensity of rays
mention focal point
Diagram Characteristics
light is represented by:
ray (single or parallel)
diverging spray
colored area/ random lines
show sun
show converging lens
diverging spray to lens
converging spray to lens
parallel beam to lens
after lens ray converge to point
show focal point
perfect explanation & diagram

Question #8
Goggles In Water
General Characteristics
no answer
written explanation
correct explanation
diagram
diagram follows explanation
Written Characteristics
you can see better because:
no friction between eye/water
mask lets in more light
eyes are irritated by chlorine
index of refraction bigger
goggles act as a lens/focuses light
there is air between you an water
water pressure
perfect explanation

Question #9
Light From TV
General Characteristics
no answer
written explanation
correct explanation
Written Characteristics
same speed
larger distance at night
larger distance during day
perfect explanation

Question #10
Room Brightening
General Characteristics
no answer
written explanation
correct explanation
diagram
diagram follows explanation
Written Characteristics
mirrors because:
reflects continuosly
reflect more light
more images of light source
white walls because:
reflect more light
mirrors
white walls
perfect explanation and diag

Question #11
Dark Room With Mirror
General Characteristics
no answer
written explanation
correct explanation
diagram
diagram follows explanation
Written Characteristics
can tell which is door because:
see reflection of self
see reflection of flashlight
reflect light beam on other wall
Diagram Characteristics
light is represented by:
ray (single or parallel)
diverging spray
colored area
diagram like that for mirror
image at mirror
image behind mirror
justification for image dist.
perfect explanation and diag

Question #12
Wavy Pool
General Characteristics
no answer
written explanation
correct explanation
diagram
diagram follows explanation
Written Characteristics
water reflects light on bottom
water refracts light
focuses light -> patterns
Diagram Charaecteristics
light is represented by:
multiple rays from sun
parallel beam from sun
show sun
rays refract at different angles
show patterns of light on floor
perfect explanation & diag

Appendix H.

Distribution Data Tables for 1990 Pre-Posttest Performance Comparisons on the Conceptual Change Instrument

Table 1
Pre-Posttest Comparisons of Relative Distribution of Representations of Light Across All Diagrams for All Questions

	Pre #	Pre %	Post #	Post %
rays	44	73%	42	50%
divergent rays	10	17%	38	45%
colored area	6	10%	5	5%
total diagrams	60	100%	85	100%

Table 2
Pre-Posttest Comparisons of Relative Distribution of Respresentations of Light Used Across Shadow (Q#1) and Mirror (Q#3) Questions

	Pre #	Pre %	Post #	Post %
rays	12	60%	7	25%
divergent rays	3	15%	10	60%
colored area	5	25%	4	15%
total diagrams	20	100%	21	100%

Table 3
Pre-Posttest Comparisons of Percentage of Students Using Traceback of Rays Across Questions Involving a Virtual Image

	Pre	Post
mirror	0%	66%
coin	11%	44%
window	0%	10%
dark room	0%	9%

Table 4
Pre-Posttest Comparisons of Distribution of Image Location Across All Virtual Image Questions

	Pre		Post	
	on mirror	behind mirror	on mirror	behind mirror
mirror	80%	0%	0%	83%
window	38%	0%	10%	20%
dark room	18%	0%	64%	27%

Table 5
Pre-Posttest Comparisons of Percentage of Students Recognizing Image Position to be where Virtual Rays Cross Each Other

	Pre		Post	
	image/no traceback	image/ traceback	image/no traceback	image/ traceback
mirror	80%	0%	17%	50%
window	38%	0%	20%	10%
dark room with mirror	18%	0%	64%	9%

Table 6
Pre-Posttest Comparisons of Percentage of Students Demonstrating Different Causal Relations between the Components of the System

	originated light source		hits optical device		reflected/refracted/ refined shadow		hits eye	
	pre	post	pre	post	pre	post	pre	post
shadow	0%	0%	14%	75%	0%	75%	14%	50%
candle	47%	75%	53%	67%	53%	67%	13%	58%
mirror	20%	42%	47%	58%	47%	58%	13%	50%
reading	31%	36%	38%	55%	38%	55%	38%	55%

Table 7
Pre-Posttest Comparisons of Percentage of Subjects using Presuppositional and Causal Justifications in Diagrams for Different Questions

	presuppositional		causal	
	Pre	Post	Pre	Post
shadow	79%	8%	21%	92%
candle	87%	42%	13%	58%
mirror	80%	0%	7%	83%
coin	89%	56%	11%	44%
window/mirror	71%	55%	7%	36%
reading	55%	18%	45%	82%
burning paper	17%	17%	83%	83%
goggles	100%	78%	0%	22%
room brightening	58%	50%	58%	45%
dark room	21%	27%	73%	73%
Descartes	30%	0%	70%	100%
wavy pool	40%	18%	56%	82%
average	61%	31%	37%	67%

Table 8
Pre-Posttest Comparisons of Students Justifications-
Single Layered or Multiple Layered

	single	multiple
Pre (N = 99)	75%	24%
Post (N=90)	47%	53%

Table 9
Pre-Posttest Comparisons of Percentage of Students using
Different Categories of Response for Concepts Applied Across Situations

Idea Applied		Pre	Post
Position of Image:			
	on mirror	100%	60%
	behind mirror	0%	50%
Conditions for Visibility:			
	light hits objects	30%	50%
	reflects	40%	70%
	light hits the eye	30%	40%
Image and Shadow Formation:			
	rays from source	20%	40%
	hit object	30%	60%
	reflect/refract-create shadow	40%	80%
	traceback	0%	60%

Table 10
Major Concepts Covered in Pre-Posttest Questions

		image			nature of
shadow	shadow	real	virtual	vision	light
candle	√				
mirror				√	
coin			√		
mirror/window			√		
reading			√		
burning paper				√	
goggles		√			
light from TV				√	
room brighten					√
dark room			√		
Descartes			√		
Wavy Pool					√
		√			