Tutorial Instructor's Guide

A model for light

Equipment:

- A dark room, the darker the better. Disable any security lighting and cover any windows with blackout shades. TAs can do this at the prep meeting.
- Optional flashlights or dim lamps for students to read with, one or two per table. Alternatively, students can use their cell phones.
- A power outlet near each table (or appropriate extension cords) with a power strip for plugging in multiple items at once.
- Butcher paper or 11x17 paper. One clean sheet per table.
- Single-bulb circuits consisting of one flashlight bulb in a socket connected to two C or D batteries in a battery holder, with a switch to easily turn the bulb on and off. The circuit can be already hooked up for the students. It doesn't matter what type of socket or wire is used. One per table.
- A white screen, at least 8x10 inches. It's helpful to have the screen be inside the bottom of a box, so that the sides shield the screen from ambient light. A small white board is an alternative. One per table.
- An opaque mask with a choice of hole shapes and sizes including a small circle (hole-punch size), larger circle (about 1 cm), small right triangle, larger right triangle, pinhole, and optional other shapes (star shape or whatever is convenient). The shapes need to have clean edges, not be raggedy or have torn corners. One per table.
- A second flashlight bulb, socket, and connecting wire so that this bulb can be added in parallel to the first bulb. The second bulb need not be identical to the first but it's nice if it's about the same brightness when connected in parallel. One per table.
- A long-filament bulb in a socket – straight bulb with clear glass. Two per table.
- A thickly frosted bulb in a socket. The frosting needs to be thick in order for the bulb to be uniformly lit all over its outer surface; with thin frosting, the lit region is much brighter at the center of the bulb, which is not desirable. Bug lights often work well. Test your particular bulbs in part II.D to make sure they give a bright bulb shape and not a bright triangle within a dim bulb shape. One per table.
- A heavy black marker for optionally marking a dark spot on the frosted bulb. One for the room.
- *Supplementary equipment* (shadows): Thread, scotch tape, and clay or large beads, one per table. Green and red colored acetates, roughly large enough to cover one of the long-filament bulbs, one each per table.

I. In this part the students apply ideas which they are probably able to state but not reliably use – *i.e.*, that light travels in straight lines and that light from a point source travels out in all directions.

Start with clean scratch paper, mask, screen, and small-bulb circuits at the tables (no large bulbs). It's fine if the circuits are hooked up already. Make sure there's a switch in the circuit so they don't use up batteries unnecessarily.

TAs should start by impressing upon students that the value of this tutorial is in *making predictions.* That's where you test your own thinking. Students are going to be asked for a bunch of different situations what they will see on the screen. They should actually draw what they will see, in a sketch. TAs should request to see the sketches when they interact with students. Otherwise it's easy for things to get vague (as in, "We'll see a lit spot").

A-C. Students are usually able to be pretty independent this page, although if you listen, you might be surprised at how much discussion they're having over just these simple experiments. For example, some think that if the bulb moves up the image should move up too. There should be no need to correct them – they should be able to correct themselves as they do the experiment. Eavesdrop for your own interest, and to make sure that they're figuring out how light works, rather than memorizing rules.

TAs sometimes have more trouble than students because they think there will be diffraction effects. Don't correct them, just ask them about it after they correct themselves.

D. The answer is meant to be simply, "It goes in a straight line." Especially alert students might add that light goes out in all directions from the small bulb and is blocked wherever it hits the mask. This is something the students could surely have said coming in, yet most of them will have had a lot to think about while working on this page. It can be nice to point this out to them – how the supposedly obvious is sometimes hard to apply.

II. In this part the students develop a model for extended light sources. Don't let students have any big bulb before they talk to a TA about their prediction for that particular bulb.

A. Make sure students draw what they predict before you give them the long-filament bulb. Students are usually able to make a correct prediction about the string of closely-spaced bulbs. (We don't have one of those; they are usually content to imagine it.) However, for the long filament bulb, there are a variety of interesting incorrect predictions by students **and TAs.** Many say that they will see a vertically-stretched image of the hole in the mask – for a circular hole, a hot-dog shape, or for a triangular hole, a tall triangle. Note that the prediction is actually correct for a circular hole even though the model is incorrect – ask about a triangular hole to distinguish the two ways of thinking. Don't correct them – they are about to do the experiment – just make sure they include the triangle. Different students in a group may have different opinions and that is fine. They don't have to agree, but they do each have to commit to a prediction.

Others say that the image will be the same shape as the hole, perhaps brighter than before. Ask these students to show you what they're thinking. Some will draw light as emerging only perpendicular to the filament. Again, don't correct them, just get them to articulate their thinking.

B. This exercise is intended to give students practice with the inversions they need to master to make accurate predictions. Many students **and TAs** have trouble interpreting the diagram – they hold the small bulb behind the long-filament bulb (so it doesn't appear on the screen), things like that. The intention is for it to be *beside* the long-filament bulb and *level with the top* of it. Left and right matters. Try to make sure students draw precisely what they expect to see before they do the experiment. Keep in mind that for some students this will be the first prediction of a triangular hole with a long-filament bulb.

C. More practice similar to part B. Some students make incorrect predictions about what they would see if the mask were removed – they think that the inversion would be eliminated but the image would be otherwise the same (that the "job" of the hole is to invert), or that they would see images of the filaments.

D. This is the most instructionally brilliant (ha) and conceptually intense exercise in the tutorial. Students **and TAs** make rampant incorrect predictions. Guard the frosted bulbs carefully so that students don't do the experiment before talking to someone. Most predict that you will see "a big triangle," sometimes blurry, or bright, or dim. When asked how they know, many say it's because the frosted bulb is a "big point source" (which is sort of an amazing thing to say, when you think about it). As always, don't correct them. Just make sure they draw a clear sketch of their prediction and let them do the experiment. Again, different students in a group may have different opinions and that is fine. Don't make them reach consensus; just make sure they each commit to a prediction.

   The result of the experiment can be a little tricky to observe, especially if the bulbs are not very heavily frosted or the room is not very dark. Questions 2 and 3 are intended to help students recognize what they're seeing. Without these questions, some students see what they wanted to see, or just see a big blurry blob. Check up on their observation.

   Question 4 can help students reconcile their observation with the triangle prediction.

   Question 5 can help students toward developing a way to account for the bulb shape. Ideally, they can black out a spot on their frosted bulb and observe that there is then a dark *triangle* on the image.

III. This part tries to insure that students aren't just memorizing rules for image formation, but are actually developing a model for geometric optics. Many of these questions would also be perfectly appropriate to bring up in earlier parts of the tutorial, depending on the group.

A. Many students are able to say that the long filament bulb is like a string of small bulbs. One particularly poetic student said to me once that it was like a "string of pearls." They should be able to draw the image formed by the long-filament bulb as a composite image made up of overlapping small triangles (or whatever the shape of their hole is), one for each point along the filament. Students can test this idea by blocking one spot on the long-filament bulb with a finger and observing a missing triangle, or chunk of triangles, on the image. (There may already be such a spot where the filament is interrupted by a holder within the bulb.) Even cooler is to have them make a kind of a claw out of one hand (fingers curled and held apart) and hold that in front of the bulb; then they will see just a few triangles in between the dark parts caused by their fingers.

B. Students should be able to say that the frosted bulb is like a bunch of small bulbs arranged in a frosted-bulb shape. My poetic student said it was like a "pearl broach." **This is really hard,** much harder than the long-filament model for some reason. Prompt them strongly using the long-filament bulb if necessary: "If the long-filament bulb is like a string of pearls, then what is a frosted bulb like?" Some students have trouble recognizing that this model of a frosted bulb is not so much an answer as a thinking tool with which to generate predictions. Ask them, "How could thinking of a bulb in that way have led you to predict a bulb shape for the frosted-bulb triangular-hole combination?"

C. By now, students are usually well equipped to account for this phenomenon, and it's still very cool because few students will have observed this on their own. They should be able to show with a sketch that where the supposed individual triangles from different points on the filament overlap a lot, the image on the screen is brighter. They might be able to use a similar analysis to account for any brightness variations in the frosted-bulb image.

D. TAs can make suggestions if the students aren't feeling creative. Good shapes include triangles, gammas, exclamation points, L's, F's, etc.

A good supplementary section for those who finish early is to explore shadows. For this, students can set aside their mask with holes in it, and instead hang a bead from a thread several inches in front of their screen. If their screen is in the bottom of a box they can tape the hanging bead to the front of the box.

Predict what you will see if you have two small bulbs and this bead here. What if you wiggle one bulb?

Predict what you will see with a long-filament bulb.

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Predict what you will see if you use two small bulbs and cover one of them with a green acetate and the other with a red acetate. Sketch your prediction including the color of each shadow and the color of the background.

Repeat the above but use two long-filament bulbs instead of two small bulbs.