# Studying the Foundations of Optics with the Master

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Physics teaching can and should help address pressing social issues. We need to improve the discussion of science in the public sphere by emphasizing the importance of evaluating the evidence behind claims. We need to address systematic racial discrimination, starting in our own discipline. And of course, we also need to teach physics. Doing all three at once is a challenge, but there are ways that it can be done. One thing I have done in my conceptual optics course is to explicitly connect our study of the foundational ideas of optics to the break-through work of the great and largely forgotten non-European founder of modern geometric optics through hands-on activities replicating some of his innovative experiments.

Ibn al-Haythem (a.k.a. Alhazen) was a medieval Arab polymath whose greatest impact was in optics. Born around 965 in what is now Basra, Iraq, he presumably studied at the great center of scholarship that then existed in Baghdad before spending most of his professional life in Cairo, Egypt. There is an interesting story about how he wound up in Cairo: after hearing about al-Haythem's boast that he could control the Nile River's flooding, the Egyptian Caliph (ruler) sent for al-Haythem who with a sinking feeling realized that the task was beyond his ability upon arriving and actually seeing the Nile. To avoid the wrath of the mercurial ruler, al-Haythem feigned having gone insane and as a result was confined to his house for two decades until the Mad Caliph's death.[1] While the story should be taken with a grain of salt as it was first written down two centuries after the reported events, it is not inconsistent with the glimpse of al-Haythem that comes through in his masterpiece, *The Book of Optics*. He clearly appears to be someone with great confidence in his own abilities who had a lot of time to spend hanging around white-washed adobe buildings.

*The Book of Optics* begins lamenting the confused state with incompatible theories of light and vision inherited from the Greeks; Plato, Aristotle, Galen and the atomist school all had proposed wildly different, speculative theories about the process of vision, while the geometric analysis of perspective by Euclid and Ptolemy involved mathematical (not physical) rays emanating from the eye. [2] Ibn al-Haythem continues the introduction by declaring that he will "recommence the inquiry into its principles and premises" in order to "gather by induction" empirical evidence before starting to build theory "gradually and orderly, criticizing premises and exercising caution in regard to conclusions."[1] Not only is this a clear description of an empirical approach to natural science written many centuries before it was clearly articulated in Europe,[3] al-Haythem put it into practice. He provides detailed descriptions of his experimental procedures which includes construction of his equipment. He starts by testing every type of light he can identify (e.g. that from the sun, moon, stars, fire, reflections off surfaces) to verify it does in fact travel in straight lines. He then empirically establishes -other key principles that light:

- is emitted in all directions from every point on the surface of a light source,
- reflects off mirrors with angle-in equaling angle-out,
- reflects in all directions from non-mirror surface,
- carries color with it, and
- enters the eye which forms an image by combing rays coming from all points in the visual field.

Ibn al-Haythem's theory of light and vision seems obvious to us today because it has been integrated into western thought since the 13th century. Translated into Latin around 1200 AD, it became the basis for the optical theory of three influential works produced later that century, all connected to the papal court. The first was Roger Bacon's *Opus Majas* (which also contains the first European advocacy for "Experimental Science"). The second was a massive (10 volume!) mathematically rigorous textbook on the science of vision by a cannon (church) lawyer named Witleo. The third was a shorter, more accessible textbook by the theologian and future Archbishop of Canterbury, John Pecham. Both of the latter works merely reformulated al-Haythem's theory into a long series of theorems and proofs, a standard medieval scholarly format[4] which also served to make them more practical reference works. However, neither Witelo nor Pecham identified al-Haythem by name, but merely referred to him as "the Perspectivist," "the Master" or "the Author." This obscured his racial identity[5–8] in this period at the tail end of the era of Catholic crusades against Muslims in the Holy Land. In fact, Pope Gregory X, who was probably the pope when Witelo finished his text, had actually been crusading in Palestine when elected pope.[9] Perhaps facilitated by obscuring the Arab origins of the theory, Witleo's and Pecham's works became standard medieval European university texts.[2] This turned al-Haythem's revolutionary theory into "what everybody knew" without his name attached. Ibn al-Haythem's theory also had a significant impact on the development of Renaissance art—again without due credit.[10] The next significant development in optics did not occur until the seventeenth century when Johannes Kepler published his *Additions to Witleo* (not al-Haythem!). In it he systematically analyzed image formation with lenses and improved on al-Haythem's model of how the eye works.[2] Thus, while Ibn al-Haythem was a pioneer of inductive experimental science and laid the foundations for modern geometric optics, his name was deliberately obscured and has largely been lost from memory.

Every semester I seek to bring a degree of recognition to this non-European pioneering scientist and understanding of how science works through having my students engage in hands-on activities similar to what al-Haythem described. The topics investigated in these activities include straight-line travel of light, reflections off of colored surfaces, and the formation of images by pinholes.

On the first day, I have the students do a think/pair/share activity in which they are asked to predict the ability of a person to see different objects in a room illuminated by a single light bulb, including one around a corner from the light. They will identify the later to be less illuminated, and upon being questioned they will state that is because light travels in straight lines. After pointing out this shows that they already knew one of the basic concepts of the course, I challenge them to prove that claim. In science, it is not enough to make a claim; we must be able to back it up with evidence. To do this, they are asked to come up with an experiment/demonstration to support the claim of straight-line travel of light using a provided set of equipment that includes a flashlight, a section of a ½" PVC tube and various other objects (Figure 1). The most common demonstration my students come up with is to observe that light passes through the PVC tube only if there is a straight-line path from the flashlight through the far end. This replicates one of Ibn al-Haythem's experiments with light, although his tube was made out of brass and he attached a straight edge along the side to ensure that it was straight.[1]

After students have successfully demonstrated evidence for straight-line travel of light, I ask them to shine the flashlight on the surface of all the different objects in the box. They observe reflection, refraction, absorption, blocking, scattering, and the light taking on a particular color when reflected off a colored surface or passing through a colored object (Figure 2). These are key observations described in *The Book of Optics*—that sunlight reflected from a green cloth casts greenish light on white walls and light passing through colored glass takes on that color.[1] While the connection of light and color may seem obvious to us, that was not always the case; in Aristotle's theory of vision light played only an indirect role in the observation of a colored object.

Later in the semester we replicate Ibn an-Haythem's work exploring pinhole images. *The Book of Optics* contains the earliest description of an investigation and explanation of the formation of pinhole images. Ibn al-Haythem set up three candles side-by-side such that their light passed through a small hole in a door. This produced three points of light on the far wall in the dark room on the other side of the door, or *camera obscura*. By selectively blocking light from each candle, he showed that each candle gave rise to one illuminated spot and no evidence that light from one candle was interfering with light from the others when passing through the hole.[1] When I do this activity with students, I provide them with a set of three different color LEDs, though in the past I have used multiple mini-mag lights or an image on a screen. Our *cameras obscuras* are made from a clean, empty food can with a small nail hole punched in the bottom, the top removed and covered with a piece of a white plastic shopping bag held in place by a rubber band (Figure 3). After observing the image of the LEDs on the plastic sheet, students are asked to work in groups to draw a ray diagram to show how the light travels from the lights, into the can, and forms the image. Having made ray diagrams before with shadows, most of my students will draw a diagram showing a ray from each LED entering into the can at the hole (and therefore crossing) and then striking the plastic screen to form the inverted image (Figure 4). After a little discussion of their diagrams, I then ask if they notice any geometric shapes in their diagrams. Primed by a previous discussion of proportionality in shadow formation, they quickly recognize similar triangles, meaning that the sides and altitudes are proportional, which can be written down as:

$$\frac{height\ (width)\ of\ image}{height\ (width)\ of\ object} = -\frac{distance\ of\ image\ from\ pinhole}{distance\ of\ object\ from\ pinhole} \tag{1}$$

where the negative sign indicates that the image orientation is flipped. Next, I challenge them to test our "just developed" theory of pinhole image formation by experimentally measuring the distances and widths of the set of lights and the images they form and see if those values agree with equation 1. Most proceed to confirm the equation. This leads to a discussion of how we made a series of observations, came up with a model (theory) to explain those observations, derived a specific prediction, and then verified that our prediction was correct. This is, of course, how science works and what Ibn al-Haythem did a thousand years ago. He first made a whole series of careful observations, built an empirically rooted theory of light and visual perception, and then tested that theory in a mathematically rigorous manner to a whole series of phenomena such as shadows, perceived sizes of objects in the visual field, and images in a wide range of flat and curved mirrors.

The need of Ibn al-Haythem to employ empirical methods to cut through the conflicting claims about light and vision is a good reminder of the importance of educating our students on both the "truths" of science and the process by which those truths are established. I have found these three simple hands-on classroom activities that re-create some of Ibn al-Haythem's experiments to be useful to introduce foundational topics in optics, illustrate the process of science, and to give due credit to a great yet largely forgotten non-European scientist.

## References

[1] I. Al-Haytham and P.A.I. Sabra, *The Optics of Ibn Al-Haytham: On Direct Vision Books 1-3*, First Edition (Warburg Institute, London, 1989).
[2] D.C. Lindberg, *Theories of Vision from Al-Kindi to Kepler*, Revised ed. edition (University of Chicago Press, Chicago, Ill., 1996).
[3] F. Bacon, *Novum Organum* (1620).
[4] E. Grant, *The Foundations of Modern Science in the Middle Ages: Their Religious, Institutional and Intellectual Contexts* (Cambridge University Press, Cambridge ; New York, 1997).
[5] Witelo, *Witelonis Perspectivae Liber Primus / Book I of Witelo's Perspectiva : An English Translation, with Introduction and Commentary and Latin Edition of ... of Witelo's Perspectiva* (Ossolineum, 1977).
[6] Witelo, *Witelonis Perspectivae Liber Secundus et Liber Tertius / Books II and III of Witelo's Perspectiva: A Critical Latin Edition and English Translation with Introduction, Notes, and Commentaries* (Ossolineum, Wrocław, 1991).
[7] Witelo, *Witelonis Perspectivae Liber Quintus / Book V of Witelo's Perspectiva: An English Translation with Introduction and Commentary, and Latin Edition of ... Copernicana)* (Polish Academy of Sciences Press, Wrocław : Warszawa, 1983).
[8] J. Peckham, *John Pecham and the Science of Optics: Perspectiva Communis*, 1st edition (University of Wisconsin Press, Madison, 1970).
[9] The Editors of Encyclopaedia Britannica, Encyclopedia Britannica (n.d.).
[10] H. Belting, *Florence and Baghdad: Renaissance Art and Arab Science*, 1st English language ed. (Belknap Press of Harvard University Press, Cambridge, Mass, 2011).

## Figures


Figure 1: Box with simple equipment provided to students for exploration of the general behavior of light and demonstrating light travels in straight lines.  Photo credit: Raquel Bonham

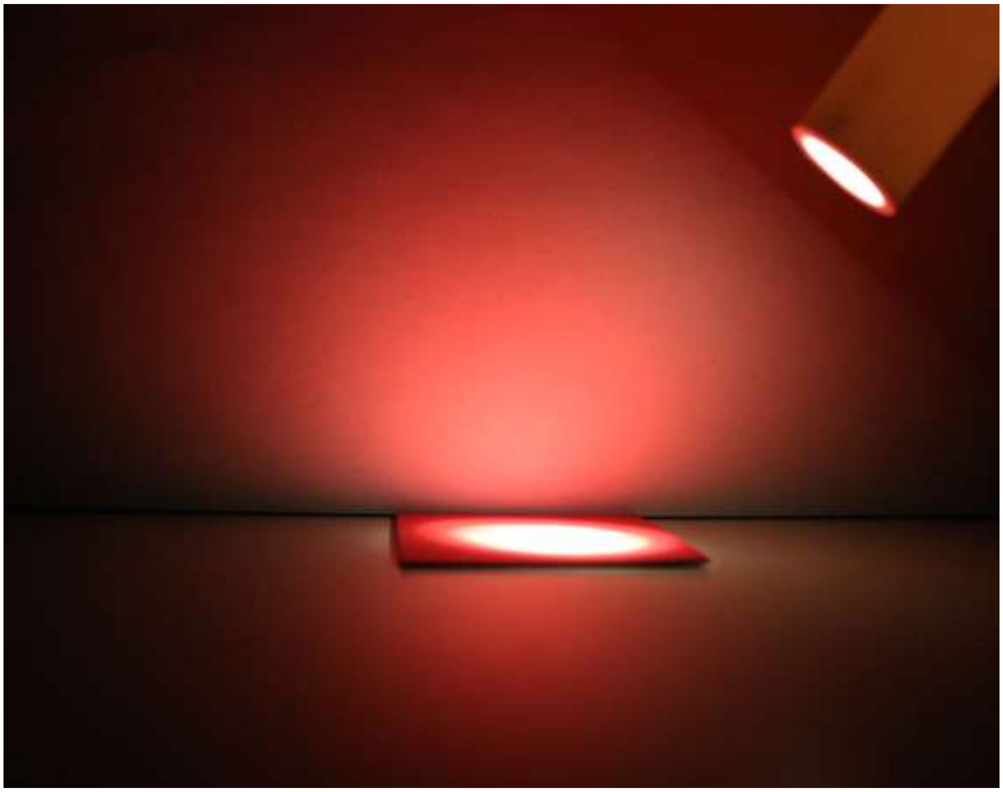

Figure 2: Reflection of white light off a red square turns the light red.  Photo credit: Raquel Bonham

Figure 3: Light from red, green and blue LEDs passing through a pinhole in a tin can to form an inverted image on the screen.  Photo credit: Raquel Bonham

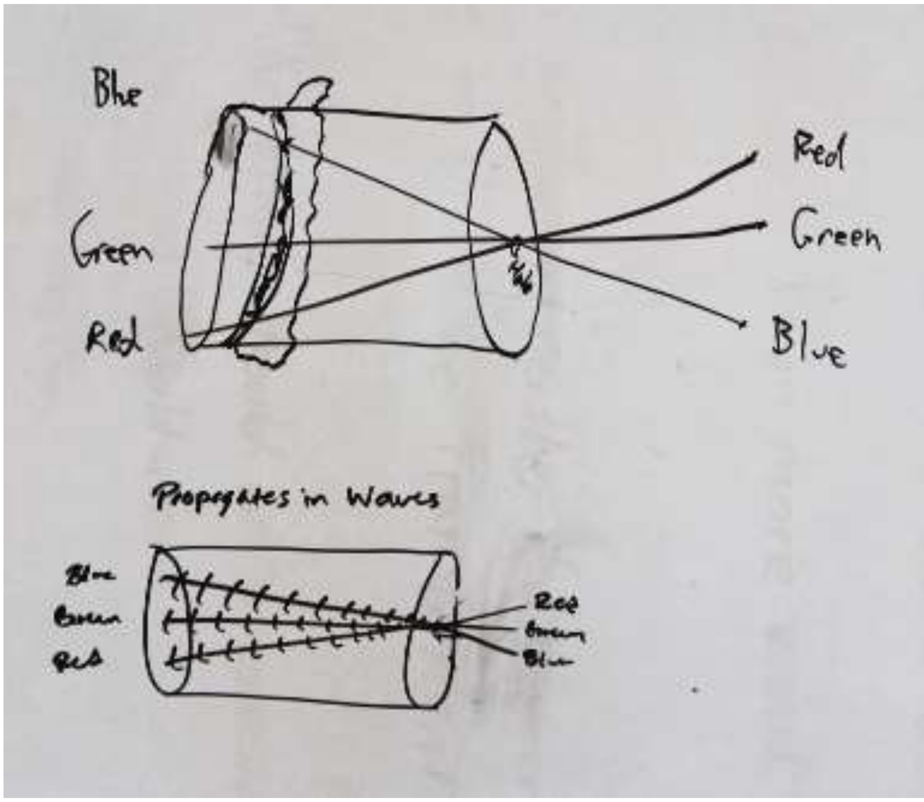


Figure 4: Examples of student ray diagrams showing how light passes through pinhole to form the inverted image. Photo credit: Raquel Bonham