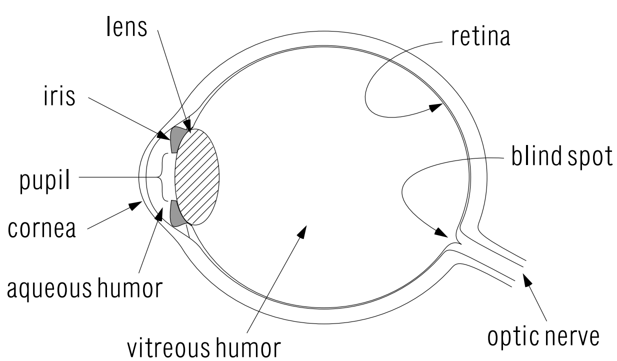
PHYSNET

MISN-0-263

THE CAMERA, THE EYE, THE MAGNIFYING GLASS, AND THE MICROSCOPE



Project PHYSNET Physics Bldg. Michigan State University East Lansing, MI

THE CAMERA, THE EYE, THE MAGNIFYING GLASS,
AND THE MICROSCOPE

by

Peter Signell

Title: **The Camera, the Eye, the Magnifying Glass, and the Microscope**

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Input Skills:

1. Vocabulary: converging lens, diverging lens, focal length, focal point (MISN-0-262) or (MISN-0-223).
2. Calculate the image position and image height of a given object viewed through a single thin lens of given focal length (MISN-0-262) or (MISN-0-223).
3. Relate focal length to radius and index of refraction for a symmetric double-convex lens (MISN-0-262) or (MISN-0-223).

Output Skills (Knowledge):

K1. Vocabulary: eyepiece, eyepiece image, far point, fixed-focus camera, hypermetropia, magnification factor, magnifying glass, myopia, near point, objective, objective image, optic nerve, pin-hole camera, retina, variable-focus camera.

K2. Explain how a pin-hole camera works: include a sketch and a discussion of how "focusing" is achieved in it.

K3. Explain how fixed- and variable-focus cameras work: include sketches and a discussion of "focusing."

K4. Explain focusing in the human eye: include a sketch and a discussion of focusing, myopia, hypermetropia, image inversion in the eye, and image up-righting in the brain.

K5. Explain how a magnifying glass works: include a sketch and show all steps in deriving its magnification factor for the optimal case.

K6. Explain how a microscope works: include a sketch and explain the compound microscope's advantages over a magnifying glass. Give reasons, not merely statements describing the microscope and glass.

THE CAMERA, THE EYE, THE MAGNIFYING GLASS, AND THE MICROSCOPE

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1. The Camera

1a. The Pin-Hole Camera. The simplest optical instrument is probably the pin-hole camera, consisting of a box with a tiny hole in one side and a square piece of sheet film on the opposite side (Fig. 1). Such a camera, made of thick cardboard, was actually marketed by Kodak early in this century. It had no lens or shutter, just a flap that could cover and uncover the tiny hole where the light entered. As long as an object was not too close to the camera, it would be in reasonably good focus in the resulting picture. The main problem was that the tiny hole let in very little light, so exposure times of 20 minutes were not unusual. Of course what was being photographed must not move during that period of time!

As a hobby project, one can make a pin-hole camera of cardboard, cutting a larger-than-needed hole for the incoming light and covering that hole with a piece of ordinary kitchen foil in which one has made a tiny hole with a pin. Sheet film can be purchased in photography stores, where it can also be sent for processing after exposure.

To see how the pin-hole camera works, study Fig. 2. Note that a point on the object being photographed becomes a spot on the film with the same shape as the pin hole (approximately circular). An adjacent point on the object produces an adjacent, overlapping, spot on the film. If the pin

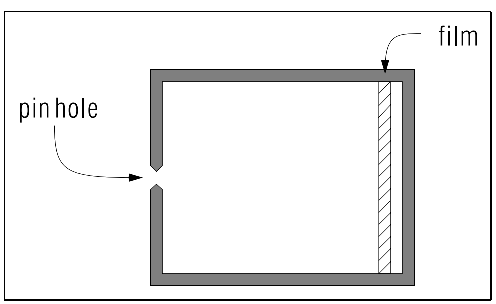

Figure 1. The parts of a pin-hole camera.

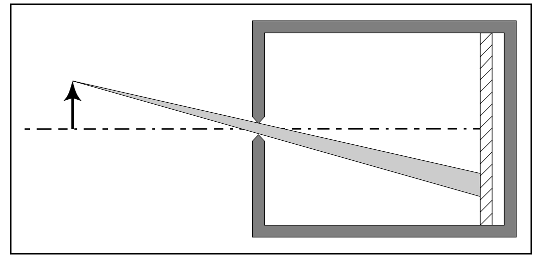

Figure 2. Pin-hole camera image of a point.

hole is small enough, each spot will be so small that the overlapping will not be noticable to the human eye and the picture will appear "sharp." It would seem prudent to make the pin hole as small as possible, but if the hole is made too small diffraction effects will fuzz the image.

▷ Demonstrate the pin-hole effect by using it to focus on a horizontal line that is close enough to your eye (less than 10 inches) so the line is just out of focus. Make your thumb and index finger parallel to each other near their ends and brace them a little further back with your bent next finger. Bring the fingers up next to your eye so that you are looking at the horizontal line through the horizontal gap between your fingers. If you make the gap small enough, the line will look sharper than without the fingers, showing that (with the fingers) your eye is acting like a pin-hole camera (more on this later when discussing the eye). Persons who have defective eyes and cannot normally focus on a nearby object such as, say, a bedroom clock, can often make out the time by squinting and thus making their eyes into pin-hole cameras.

1b. The Fixed-Focus Camera. Putting a lens in place of the pin hole in a pin-hole camera allows one to let in large amounts of light, making exposure times more reasonable. The larger the lens, the shorter the exposure time needs be. In such "focus free" cameras, the focal length of the lens is set so objects at about 15 feet from the camera lens are in focus on the film. If the user wants to have objects at other distances be in focus, the lens opening must be made smaller ("stopped down") so as to take advantage of pin-hole focusing. Of course this means one must take non-15-foot pictures only in strong light and with longer exposure times, or just not worry about how sharp the pictures look.

1c. The Variable-Focus Camera. In variable-focus cameras the lens can move toward and away from the film, thus varying the distance of the objects that will be in focus. In many modern cameras this is accomplished automatically by a device that uses an infra-red light beam to

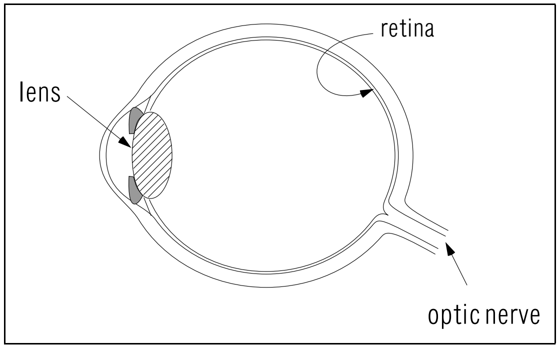

Figure 3. Some parts of the human eye.

determine the distance to the object the camera is aimed at and thereupon activates a motor to move the lens. If one wants to have objects at several distances be in focus in the same picture, one must stop down the lens to take advantage of pin-hole focusing and hence use brighter light and/or longer exposure times.

2. The Eye

2a. The Eye as a Camera. To a first approximation, the human eye can be thought of as a small spherical camera. Like a camera, light enters it through a lens and is absorbed on an internal surface (Fig. 3). In the camera, the light-sensitive surface is the film: in the eye it is the "retina," a surface composed of nerve endings (Fig. 4). Light absorbed at a spot on the camera's film causes a local chemical reaction that permanently alters the film at the point of absorption. In contrast, light absorbed on a retinal nerve ending causes a chemical reaction that starts a signal down that particular nerve, heading toward the brain, whereupon the nerve "resets" and is ready to fire again.

2b. The Focusing Mechanism. The camera and eye use different mechanisms in order to change focus from objects at one distance to objects at a different distance. To make this change, the camera moves a fixed-focal-length lens to a different distance from its internal light-sensitive surface (the film), while the eye keeps the position of its flexible lens fixed and changes the lens's focal length by varying the lens's radius of curvature. Thus to focus on a more distant object the camera lens is moved closer to the film, while in the eye the muscles attached to the lens relax more and the lens becomes thinner, increasing the lens's radius of curvature and hence its focal length. To focus on a closer object the

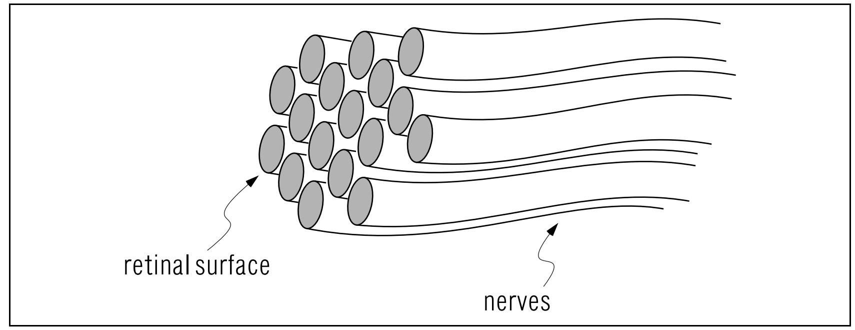

Figure 4. A representation of nerve connections to the retinal surface.

camera lens is moved farther away from the film while the eye's lens muscles force its lens to be fatter, producing a smaller radius of curvature and thus a shorter focal length.

2c. Near Point, Far Point. The nearest and furthest objects on which an eye can comfortably focus are called, respectively, that eye's "near point" and "far point." These are determined by the condition of both the lens and the muscles that control the shape of the lens. The camera also has such points, but these are determined by the amount of travel allowed the lens.

For a normal young person the eye's near point is at about 25 cm (10 inches) while its far point is at infinity, but there is a good deal of variation between individuals. Moderately priced cameras generally have a near point of about 3 ft and a far point at infinity.

▷ Determine your own near point by relaxing your eye while moving small print toward and away from the eye until you find the nearest position of sharp focus. If you wear corrective lenses, try this with and without the correction.

2d. Myopia and Hypermetropia. Two common eye defects, related to focusing, are: (1) myopia, where an eye's far point is closer than infinity (the person is said to be "near sighted"); and (2) hypermetropia, where an eye's near point is so much farther than 25 cm that reading print becomes difficult.[1] For such "far sighted" people, positive focal length corrective glasses supply the extra focusing power they need, while for near sighted

[1] For example, so far away that one's arms are not long enough to hold reading material at that distance.

people negative focal length glasses undo some of the too-large focusing they have.

As people age, their eyes' lens system becomes ever more resistant to being focused, so the near point gradually recedes and "reading glasses" become a necessity. When the near point recedes far enough, people whose work still requires them to focus throughout the normal young person's range must resort to carrying several pairs of glasses of varying powers, or to glasses with different parts having different powers ("bi-focals" or "tri-focals" or glasses with focusing power that varies continuously from the top to the bottom of the lens).

2e. An Inverted Image. Both the camera and the eye produce inverted images, since they are both single-lens devices. Even the pin-hole camera produces an inverted image (Fig. 2). To right a printed picture from a camera one need only turn the picture around. In the brain, the picture arriving from the eyes is automatically inverted so as to be presented proper-side up in the "mind's eye." Experiments have been performed in which subjects are asked to wear special glasses that invert the light rays so the image inside the eye is now *upright*. To the person who starts wearing those glasses, the world at first looks upside down. However, within several days the brain accommodates to the new situation and the scenes switch to being upright in the "mind's eye"!

3. The Magnifying Glass

3a. Description. A magnifying glass is a single double-convex lens, attached to a handle, used by itself alone to produce a larger image in the eye (Fig. 5). The magnifying glass may be a large "reading glass" used by an elderly person or a small pocket magnifier used by a biologist or geologist in the field. All magnifiers have this in common: the object is placed between the lens and its focal point (see Fig. 5) so the image is virtual and upright. The distances are such that the image produced by the magnifying glass is at the eye's near point. Thus the magnifying glass enables one to put the object itself much closer to the eye, while maintaining a focused image in the eye, than would be possible without the glass.

3b. The Magnification. The magnification factor for a magnifying glass can be defined as:

$$M = \frac{h'}{h} \tag{1}$$

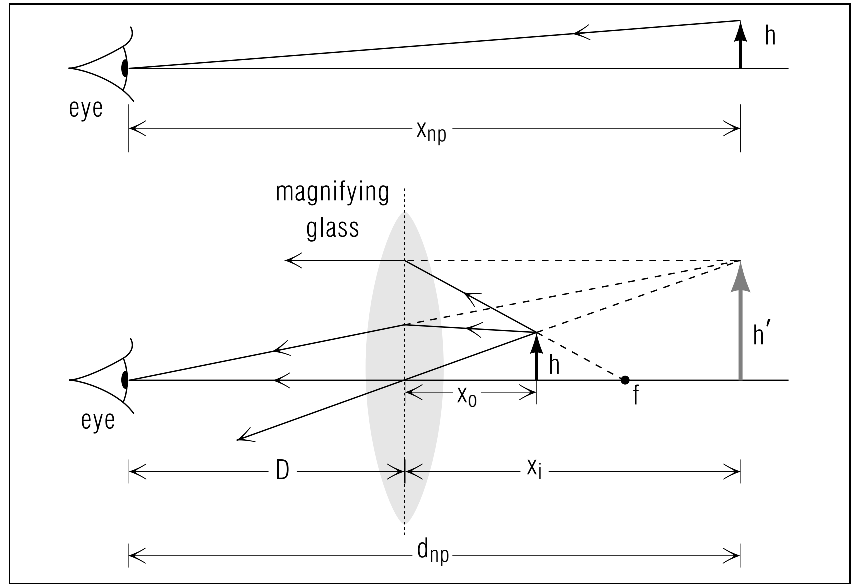

Figure 5. Viewing an object unaided (upper figure) and aided by a magnifying glass (lower figure). The eye's near point is x_{np} distant.

where h' is the size that the eye sees in the "aided" case (with the magnifying glass) while h is the size the eye sees in the "unaided" case (without the glass). Thus h' is the size of the image produced by the glass at the eye's near point, while h is the size of the object itself. Of course in the unaided case the object is placed at the eye's near point while in the aided case the object itself is much closer to the eye even though the image the eye sees is at the eye's near point.

We now find the magnification factor by referring to Fig. 5:[2]

$$x_i + D = d_{np} \tag{2}$$

$$\frac{1}{f} = \frac{1}{x_o} - \frac{1}{x_i} = \frac{1}{x_o} - \frac{1}{d_{np} - D} \qquad \textit{Help: [S-1]} \tag{3}$$

We solve Eq. (2) for x_i and Eq. (3) for x_o and put them into Eq. (1) to obtain:

$$M = \frac{h'}{h} = \frac{x_i}{x_o} = 1 + \frac{d_{np} - D}{f} \qquad \textit{Help: [S-2]} \tag{4}$$

[2]In the following equation the notation [S-1] indicates help can be obtained in sequence [S-1] in this module's *Special Assistance Supplement*.

where d_{np} is the distance from the eye to its near point ($\approx$ 10 inches).

We see from Eq. (4) that the maximum magnification occurs when $D = 0$, meaning the magnifying glass is held right up to the eye. In that case:

$$M = 1 + \frac{d_{np}}{f}. \qquad (5)$$

Thus if $f = 5$ in, the magnification factor will be 3. For normal glass, where the index of refraction is about 1.5, the radius of curvature of the lens is:

$$R = 2(n-1)f \approx f, \qquad \textit{Help: [S-3]} \qquad (6)$$

▷ From Eqs. (5) and (6) show: if $M = 3$ in, then $R = 5$ in.

Note that if we let the magnifying power go away by letting $R \to \infty$, so the glass becomes a pane, then the magnification factor goes to one, as it should.

To get a magnification factor of 100 we must make f about 0.1 in and the resulting radius of the lens is also 0.1 in! Furthermore, for such a large magnification factor:

$$x_o \approx f \qquad \textit{Help: [S-4]} \qquad (7)$$

so what we have is a *tiny* glass sphere that must be held next to the eye, and the object must be just a tiny distance beyond that glass bead. These are the problems (1) tiny distances; (2) precise manufacture of the bead; and (3) the miniscule amount of light gathered by the lens to go into producing the image. Perhaps it is obvious why a magnifying glass is used only for modest amounts of magnification.

4. The Microscope

The microscope is basically a two-lens magnifier, where the first lens has a small radius, small focal length, and small distance to the object. In contrast to the magnifying glass, the object is placed *outside* the focal point, producing a real, inverted, highly magnified image near the second lens. The second lens, called the "eyepiece," then acts as a simple magnifier (magnifying glass) acting on that real image (Fig. 6). The eyepiece produces an inverted image in the eye since magnifiers do not invert images. The magnification factor of the microscope is (approximately) the product of the magnification factors of the two lenses, so two lenses with $M = 10$ can together produce a magnification factor of approximately a

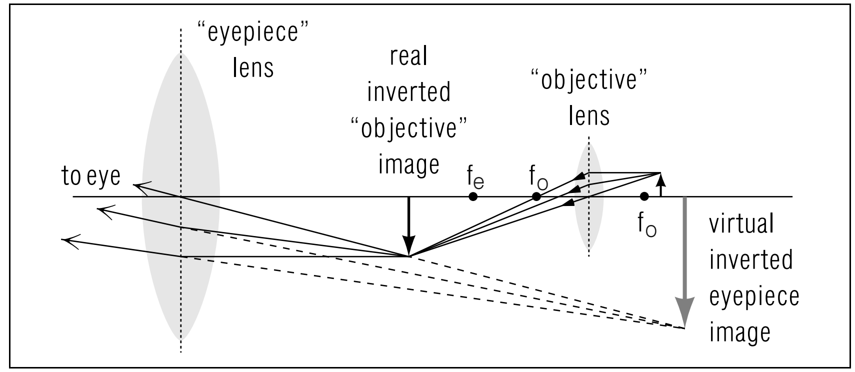

Figure 6. Image formation in a two-lens ("compound") microscope. The focal length for the objective lens is f_0; for the eyepiece lens, f_e.

hundred. Even ten-power lenses must have fairly small radii so one must use strong illumination on the object to get a reasonably bright image. This checks with the fact that the amount of light leaving the very small object (or part of an object) is all the light that is available to form the much larger final image in the eye.

Acknowledgments

The author wishes to thank Paul Parker for assistance in the construction of this module. Preparation of this module was supported in part by the National Science Foundation, Division of Science Education Development and Research, through Grant #SED 74-20088 to Michigan State University.

Glossary

- **eyepiece**: in a multi-lens microscope, telescope, or binocular, the lens nearest the eye. It acts as a simple magnifier (magnifying glass) acting on the real image produced by the lenses nearer the object being viewed. It produces an inverted image in the eye.
- **eyepiece image**: the image produced by the eyepiece without the aid of the eye.

- **far point**: the distance of the farthest objects on which an eye can comfortably focus. It is determined by the condition of both the lens and the muscles that control the shape of the lens. For a normal person the far point is at infinity. For the abnormal condition, see "myopia."
- **fixed-focus camera**: a camera in which the focal length is fixed, usually set such that objects about 15 feet away are in sharpest focus on the film. If the user wants to have objects at other distances be in focus, the lens opening must be made smaller ("stopped down") so as to take advantage of pin-hole focusing. This requires longer exposure times, which may not be available on these inexpensive cameras, or stronger light. Such cameras are often referred to as "focus free" by their manufacturers.
- **hypermetropia**: an eye defect in which an eye's near point is so much farther than 25 cm that reading print becomes difficult. For such "far sighted" people, positive focal length corrective lenses supply the extra focusing power they need. Hypermetropia advances inexorably as people age.
- **magnification factor (magnifying glass)**: the ratio of image size seen by the aided eye to that seen by the unaided eye. For a magnifying glass with focal length f and an eye with near point d_{np}, the magnification is: $M = 1 + (d_{np}/f)$.
- **magnifying glass**: a single double-convex lens, attached to a handle, used by itself alone to produce a larger image in the eye. It may be a large "reading glass" used by an elderly person or a small pocket magnifier used by a biologist or geologist in the field. It enables one to put the object itself much closer to the eye, while maintaining a focused image in the eye, than would be possible without the glass.
- **myopia**: an eye defect wherein an eye's far point is closer than infinity. For such "near sighted" people, negative focal length corrective lenses supply the defocusing power they need.
- **near point**: the shortest distance at which objects can be comfortably brought into focus by the eye. It is determined by the condition of both the eye's lens and the muscles that control the shape of the lens. For a normal young person the eye's near point is at about 25 cm (10 inches), but there is a good deal of variation between individuals. For the abnormal condition, see "hypermetropia."

- **objective (microscope)**: the lens nearest the object being viewed. It has a small radius, small focal length, and small distance to the object. It produces a real, inverted, highly magnified image.
- **objective image**: the image produced by the objective lens in a microscope.
- **optic nerve**: the bundle of nerve cells leaving the retina of the eye, heading toward the brain. These cells carry the visual information received at the retina.
- **pin-hole camera**: a camera consisting of a box with a tiny hole in one side and a piece of sheet film on the opposite side. It has a flap that is used to cover and uncover the tiny hole where the light enters. As the pin-hole is made smaller the focus improves. However, if the hole is made so small that it is no longer large compared to the wavelengths of visible light, diffraction effects begin to blur the image.
- **retina**: a surface in the back of the eye, composed of nerve endings. Light absorbed on a retinal nerve ending causes a chemical reaction that starts a signal down that particular nerve, heading toward the brain, whereupon the nerve "resets" and is ready to fire again.
- **variable-focus camera**: a camera in which the lens can move toward and away from the film, thus varying the distance of the objects that will be in focus. In many modern cameras this is accomplished automatically by a device that determines the distance to the object the camera is aimed at and thereupon activates a motor to move the lens.

SPECIAL ASSISTANCE SUPPLEMENT

S-1 *(from TX-3b, Text Eq. (3))*

If you have trouble with this, review Input Skill #2 (use its reference).

S-2 *(from TX-3b, Text Eq. (4))*

If you have trouble with this, review Input Skill #2 (use its reference).

S-3 *(from TX-3b, Text Eq. (6))*

If you have trouble with this, review Input Skill #3 (use its reference).

S-4 *(from TX-3b)*

From Text Eq. (3), with $D = 0$, we have:

$$\frac{1}{f} = \frac{1}{x_o} - \frac{1}{d_{np}}$$

Here f is small compared to d_{np} so x_o must be correspondingly small. *Help: [S-5]*

S-5 *(from [S-4])*

Solving for $1/x_o$:

$$\frac{1}{x_o} = \frac{f + d_{np}}{f d_{np}}.$$

Solving for x_o:

$$x_o = \frac{f d_{np}}{f + d_{np}},$$

so with f small compared to d_{np}:

$$x_o \approx \frac{f d_{np}}{d_{np}} = f.$$

MODEL EXAM

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_2} - \frac{1}{R_1}\right)$$

1. See Output Skills K1-K6 in this module's *ID Sheet*. A selection of these skills will be on the actual exam.

Brief Answers:

1. For answers to this exam's Knowledge items, work through this module's *text*.