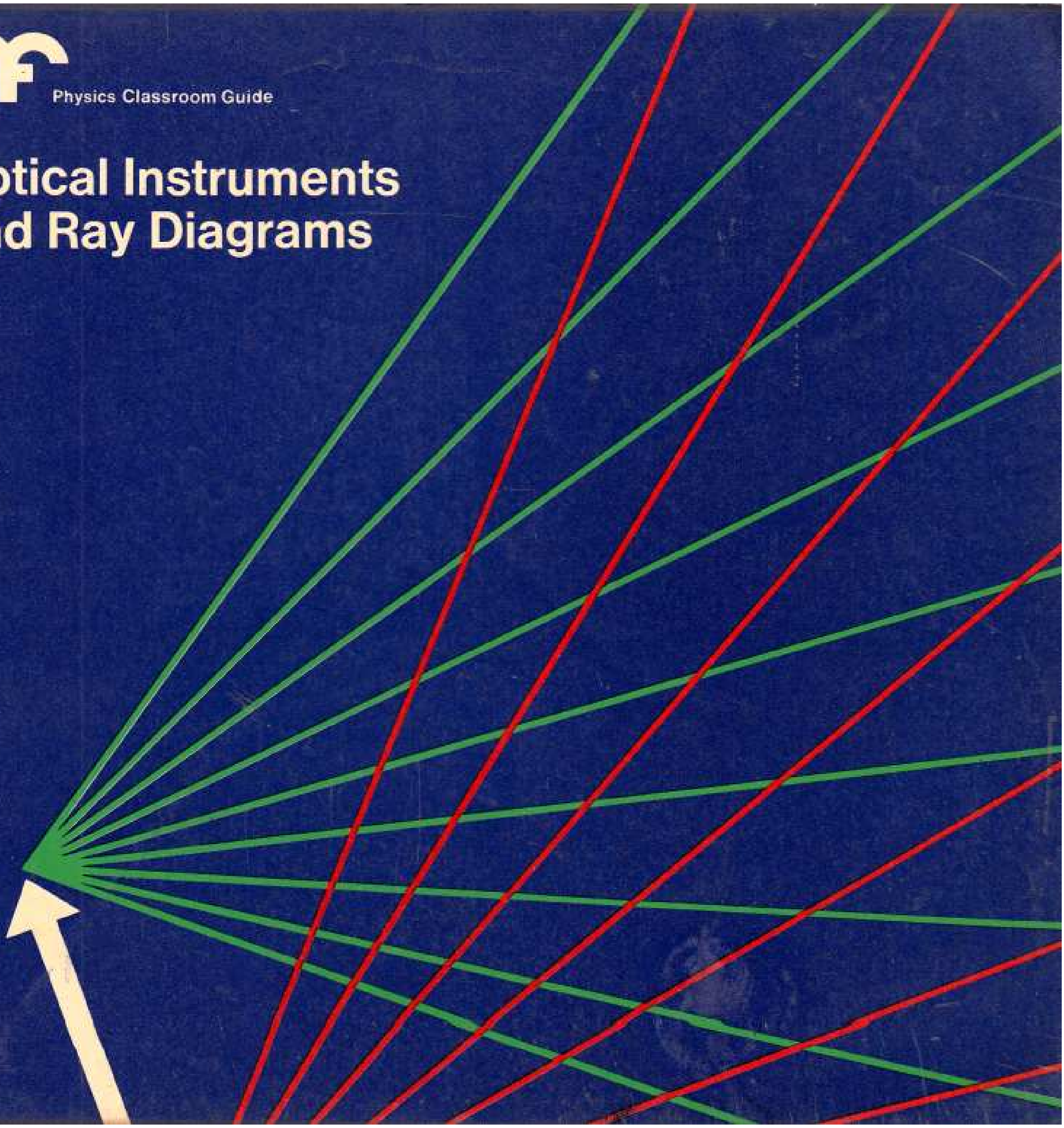
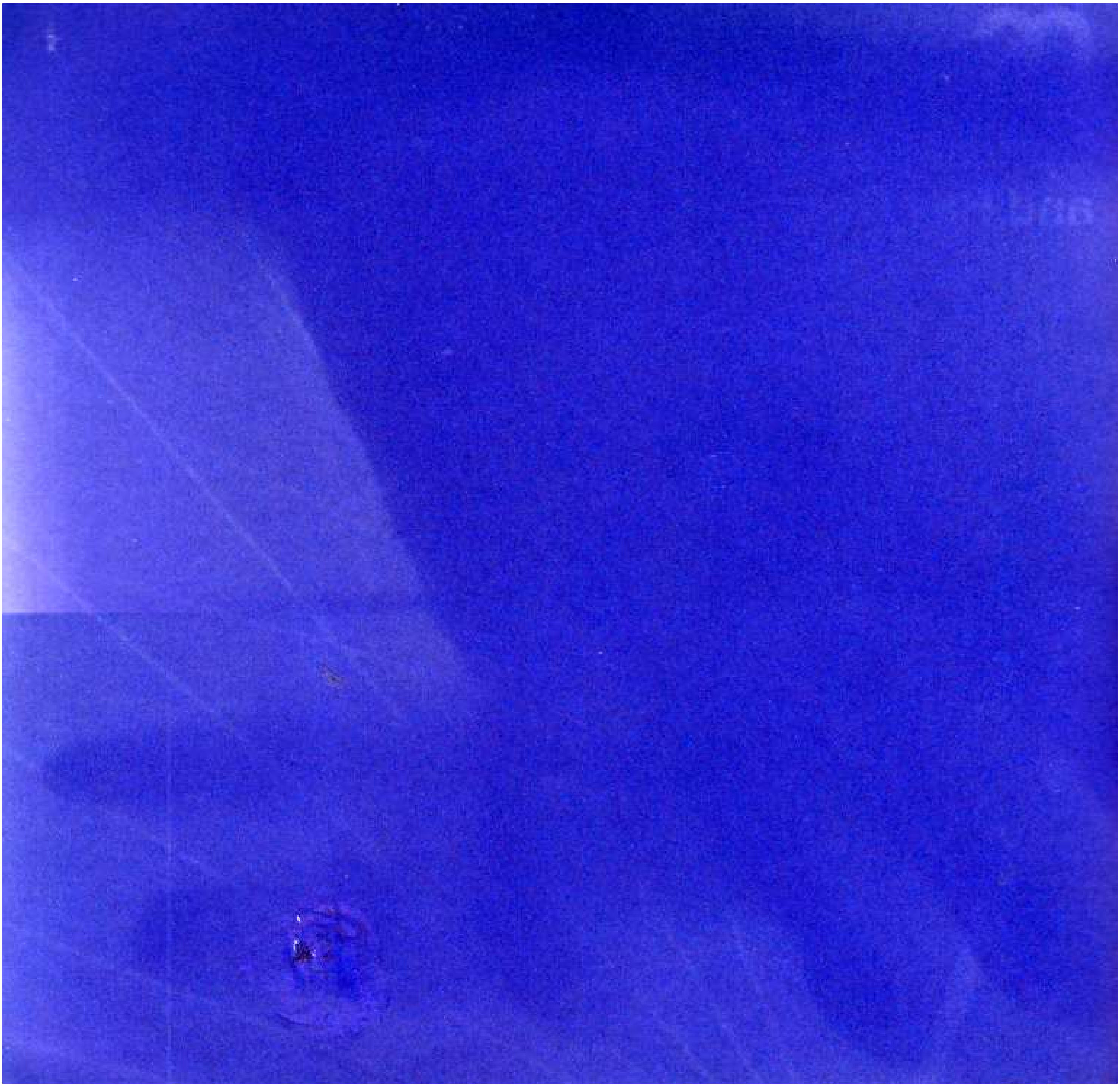
Physics Classroom Guide

# Optical Instruments and Ray Diagrams





# Optical Instruments and Ray Diagrams

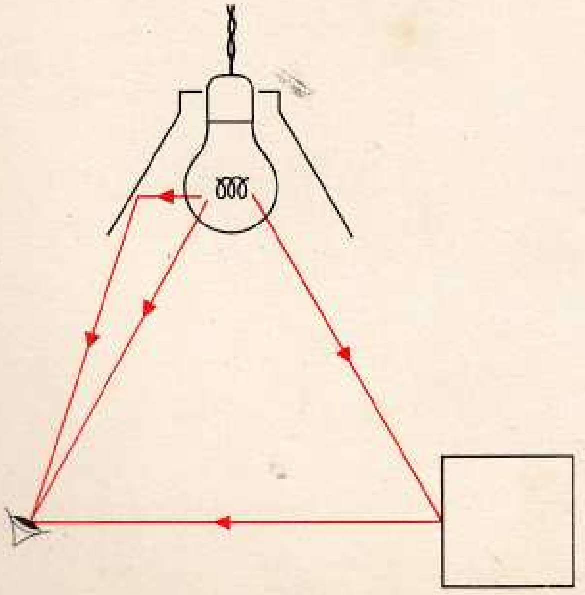
## Preface

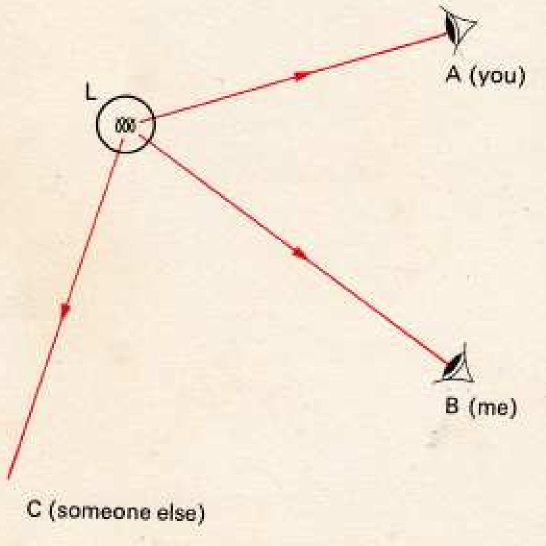
This booklet is intended to accompany the work on Optics in Year III of the Nuffield Physics course and it is not a substitute for it. It is anticipated that the booklet will first prove useful as a companion to the ray-streaks experiments. The first section of the booklet, entitled 'Seeing', covers briefly the work on lenses already discussed in class. The second section suggests a sequence of experiments to be performed using the ray-streaks kit and asks a series of questions. The final section of the booklet is concerned solely with drawing ray diagrams and gives full instructions to those who want to learn how to draw these diagrams.

# Seeing

When you see an object, rays of light from it are going straight into your eyes.
Look into someone else's eyes. You see a white part (which is very tough). What else do you see? A coloured part; a central black part.
Where is the seeing done? It has been found that the seeing is done at the back of the eye. Where does the light get in? Through a window – we call this window the *pupil*. That is the central black part you noticed earlier.
When you look at an object, rays are coming from all the different parts of it. This may be because it emits light, or because light from somewhere else is bouncing off it.
You can see the candle flame because it emits light; you can see its holder because light from the candle is reflected from it.

Rays are also going in all other directions.
Look at the stars at night – they send light to the eye: but they also send light everywhere else – to other stars for example.
If I put a lamp at L, you will see it along the ray LA; I see it by the ray LB; someone else sees it by the ray LC.

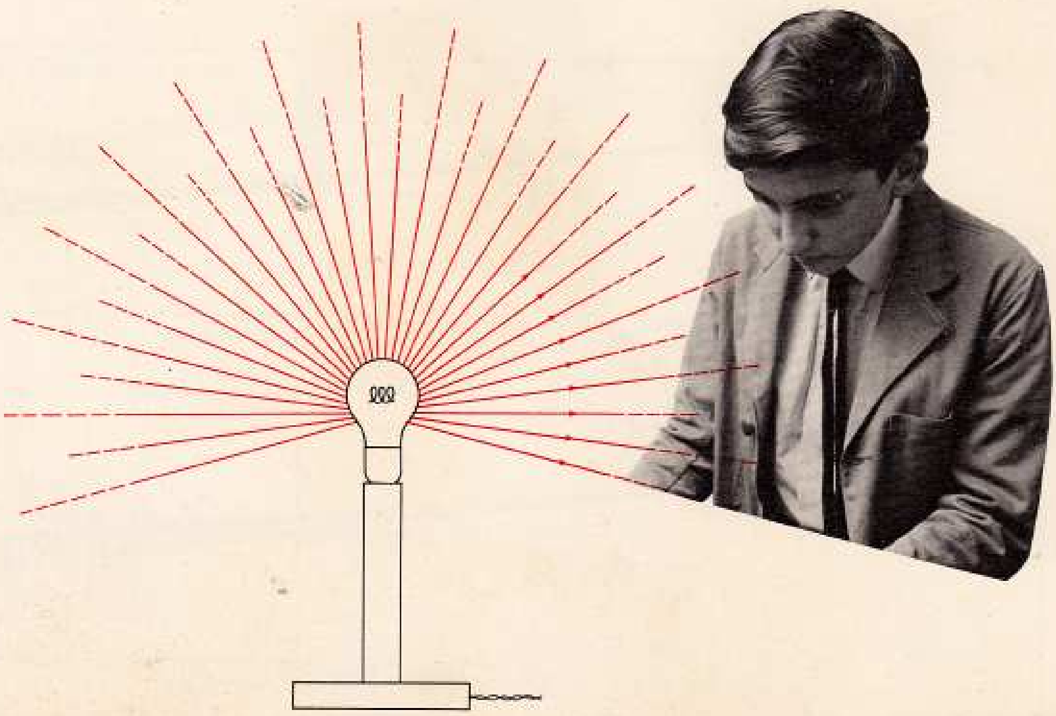




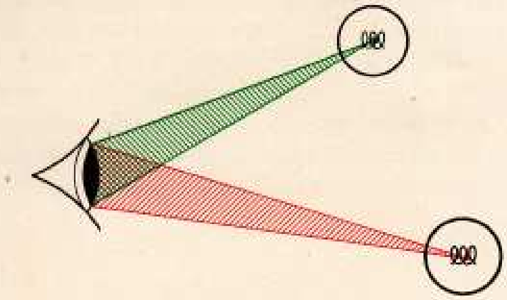
How do you know that the rays go straight out from L to A, B, and C?
Here is a boy looking at a lamp.
Rays from the lamp go in all directions. Some hit the head; some the eye in the head. It is the light that enters his eye that enables him to see the lamp.

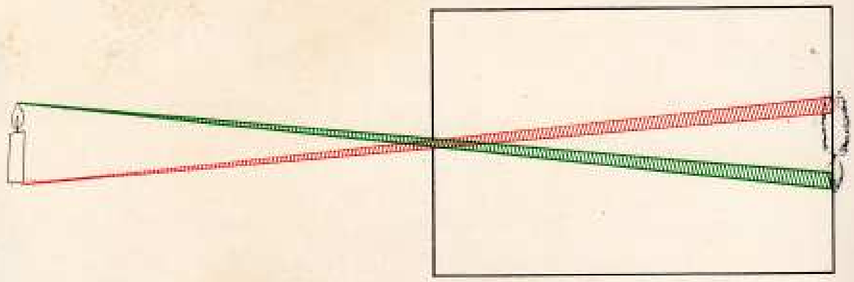
For the eye to look at *two* objects (two lamps, say) *two* lots of rays go into the eye.
But you do not always look directly at something: perhaps you wear spectacles, or you use a telescope, or a microscope. These all make use of lenses, What does a lens do?

The experiments in which you study lenses show you what lenses do: how they help us to see things that are far away (telescopes) or very small (microscopes) or outside the range of clear vision of our own eyes (spectacles). You will set up lenses in the laboratory to make such 'optical instruments'.
Before we use lenses for cameras and other instruments, we should try the simplest type of camera, a pinhole camera, which has no lens. From that we learn some things about rays of light and lenses.

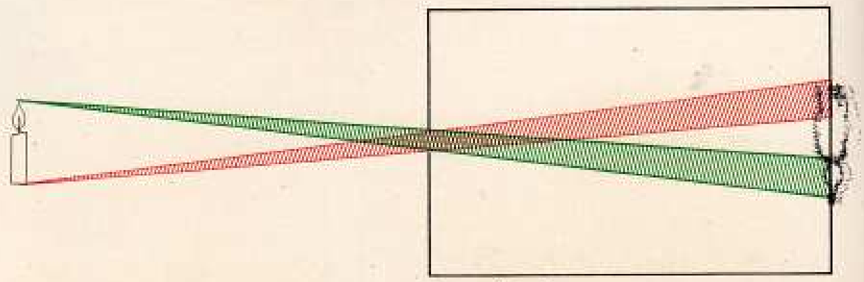


**The pinhole camera and the lens camera.** A pinhole camera forms pictures.
From any point on the object, light travels out in all directions. But we only draw in the cone of rays which pass through the pinhole to form the picture.



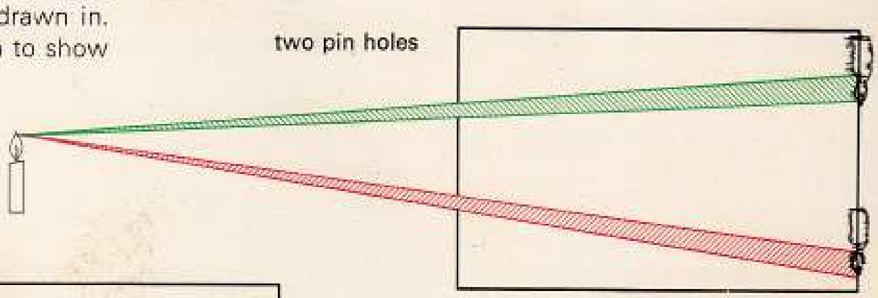


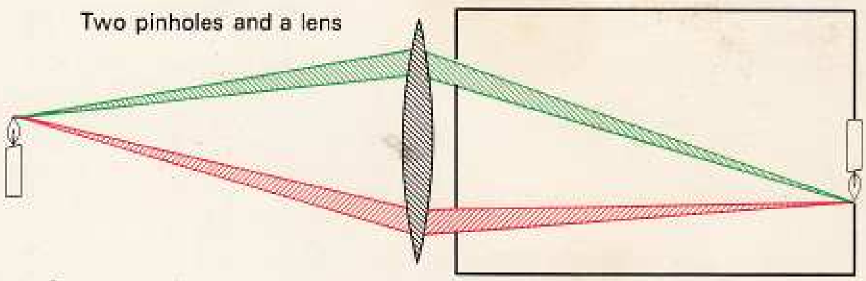
small pinhole

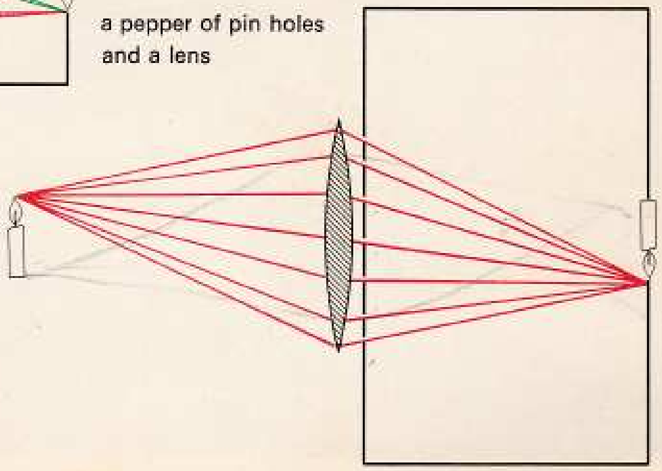


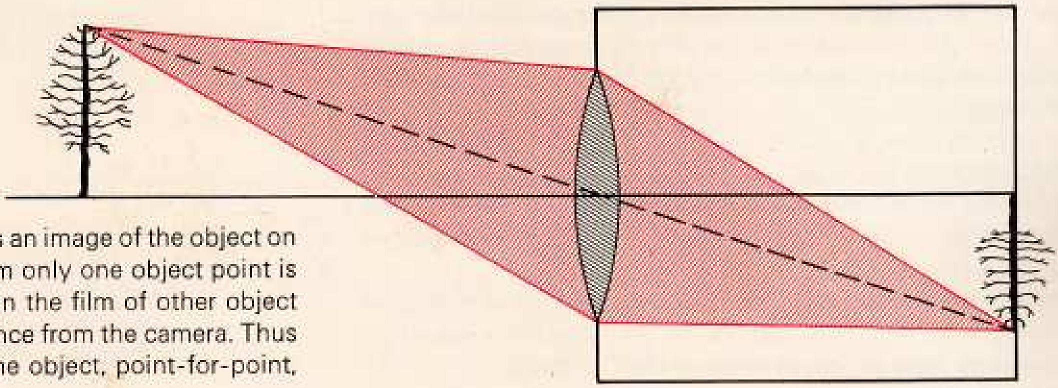
large pinhole

When the right lens is chosen for the 'camera-box' and held at the right distance from the object, one bright image is obtained. The lens somehow collects together all the separate pictures.
If another lens is chosen or the box is held at a different distance from the object, then what is seen is not so simple. The lens must bend the rays as they pass through it so that they all go through one image. If a lens can do that, the pepper of pinholes can be replaced by one large hole.
In the next diagrams, only the extreme rays which pass through the lens from a point on the object are drawn in. The cone between these extreme rays is shaded in to show it is full of rays.



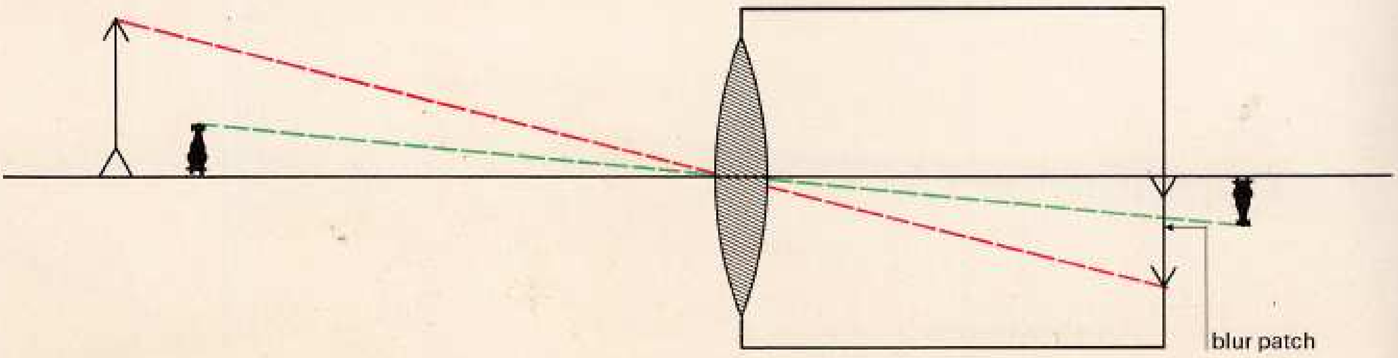





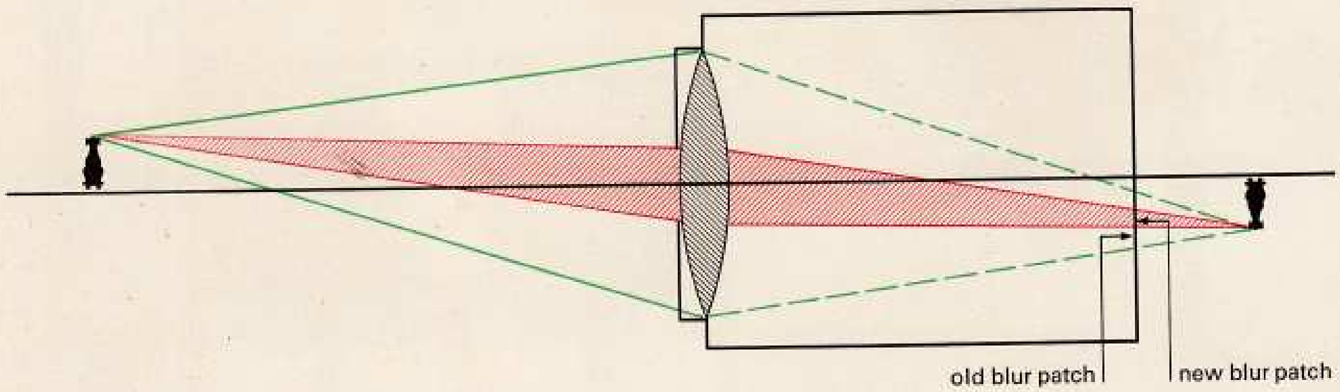
In the diagram above, the lens forms an image of the object on the film. Here, the cone of rays from only one object point is shown. The lens forms an image on the film of other object points, if they are at the same distance from the camera. Thus the lens forms a sharp picture of the object, point-for-point, on the film.

If there are two objects at different distances from the camera, their images cannot both fall on the film. If the tree, in the diagram at the bottom of this page, forms a sharp image on the film, the dog (in front of the tree) forms an image at a different distance from the lens. The cones of light going to the dog's image are intercepted by the film and make a blur patch. The dog's picture is only a *patch-for-point* reproduction. Note that in this diagram the dog is close to the camera at a distance which happens to make his image life-size.



Look at the photograph below. The lens aperture of the camera which took the photograph was made as large as possible, and it was arranged that the middle-distance made a sharp image on the film.

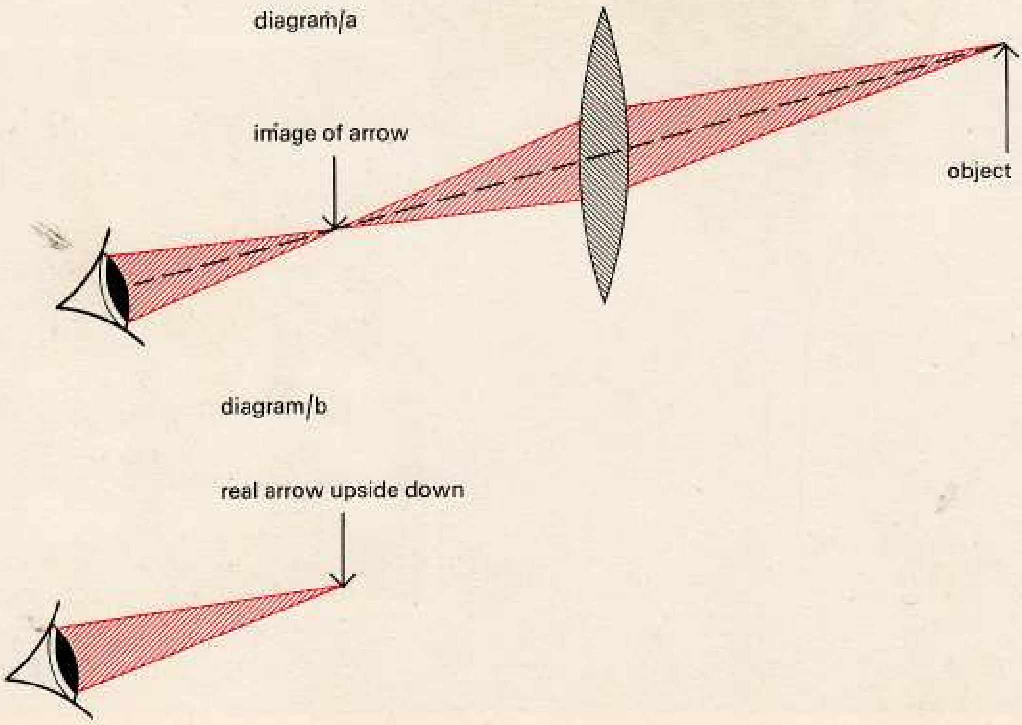
If the aperture of the lens is reduced, the images are in exactly the same position as before. But the cones from lens to image are smaller than before. Therefore the blur patches for objects which do not form a sharp image on the film are smaller and the picture is sharper. This is what happens with cheap cameras: the lens aperture is so small that the images of all objects further away from the camera than about ten feet are fairly sharp. But the small aperture means that the film requires a longer exposure to light.
In the diagram below, the tree and the light cones from it have been omitted so that the diagram is not too confusing.



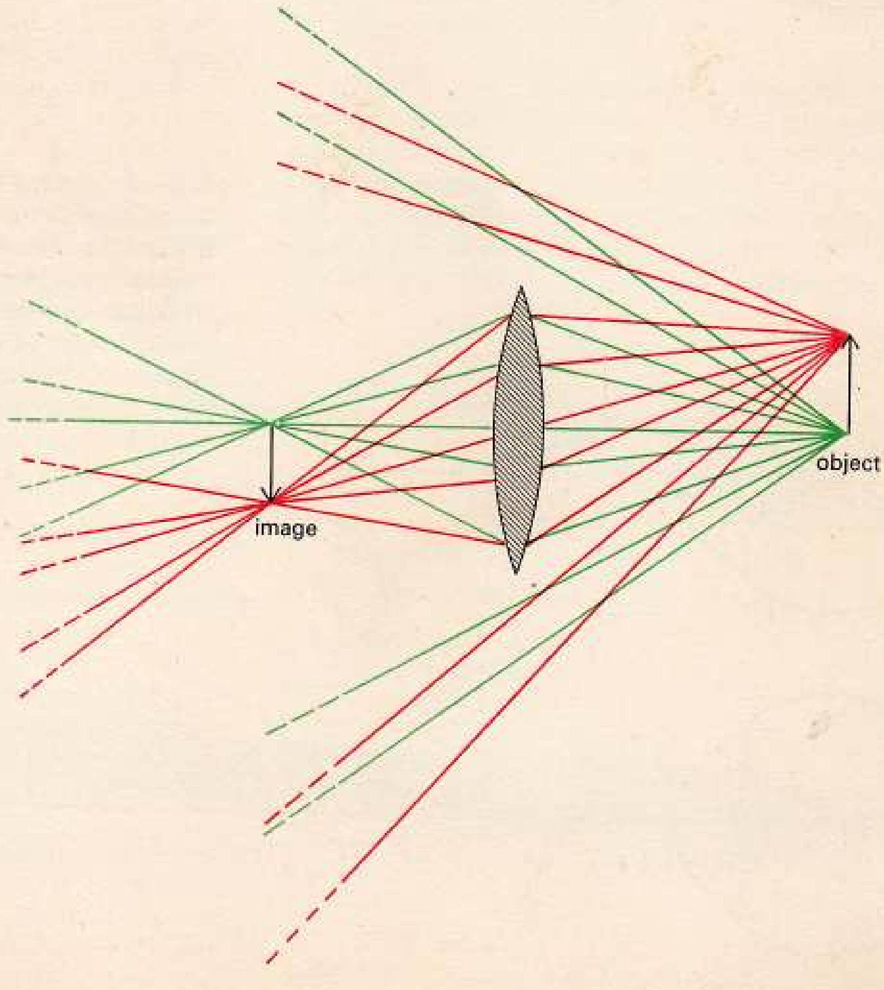
The photograph below was taken with the lens aperture as small as possible.

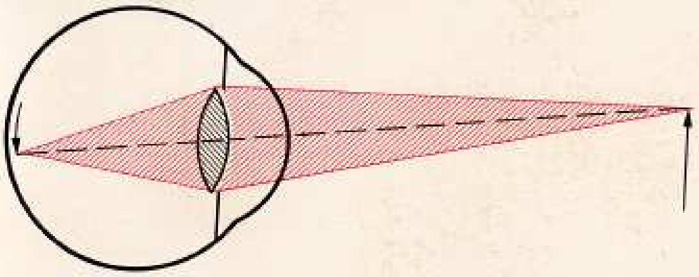
**What is an image?** Here are two things to notice about an image:

1. Look at the diagrams below. From the point of view of the eye, there is no difference between the image it is looking at in diagram (a) and the real object it is looking at in diagram (b).



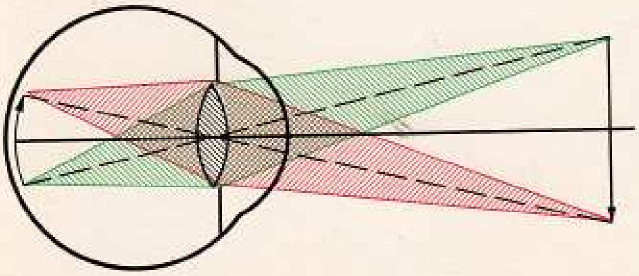
2. The image is formed by a lens taking *all* the rays from a point on the object and bending them so that they all pass through *one* point. This point then becomes the image point of the corresponding object point.
If the light passes on to the eye it is *this* point that the eye sees. The lens forms an image point of each point on the object and so builds up an image of the object.

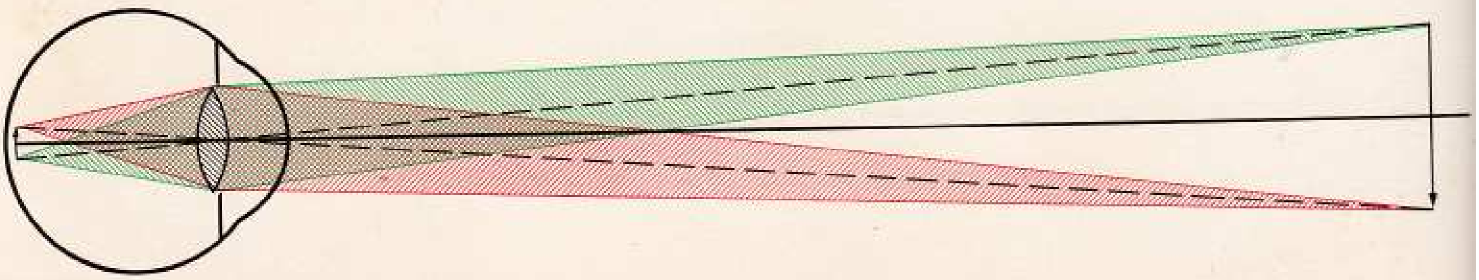




**How do we see?** We see by the eye itself forming an image of anything we look at, on a screen of nerves at the back of the eye. Much of the image-forming action of the eye is done by the front surface but there is also a lens inside the eye that can change its shape, so that objects at different distances from the eye can be focused in turn to make sharp images on the back of the eye.

Look at these two diagrams. In each case the eye is looking at the same size object. But the image formed on the back of the eye by the distant object is much smaller than the image formed by the closer object. Thus the closer object *appears* to be bigger than the distant object.





**Your own eyes: range of comfortable vision.** Try a quick experiment with your eyes, to find your own range. (If you wear spectacles, you should keep them on, because [your spectacles + your eyes] make 'average eyes' with the range of vision that is most useful for ordinary life. Also try the experiment without your spectacles if you like ..Hold your hand (or a book) in front of you and look at it carefully while you move it closer and closer to your face. When it is very near, it will look fuzzy, because the adjustable lens in your eye is not strong enough to make the image fall on your retina. Move your hand away until you can see it sharply in focus. That is your 'near point', at the shortest distance of comfortable vision.

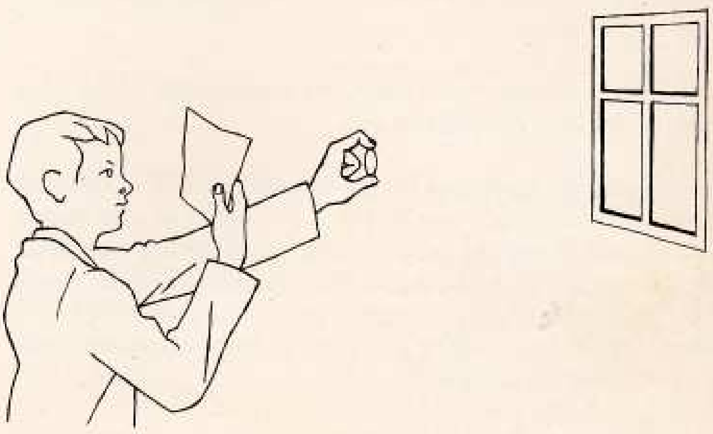
When you move your hand farther and farther away, you can still focus it sharply, because the adjustable lens in your eye changes its power automatically. Where is your 'far point'? How far away can you put the object and still see it clearly? Look out of the window: you can see a distant hill, or an aircraft in the sky—so far off that we call that distance 'infinity'. At your age, your eyes (with spectacles if needed) have an enormous range of focusing – accommodation as it is called – from a few inches in front of your face right out to infinity.

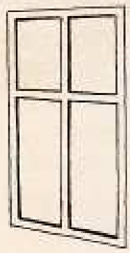
As people grow older that range decreases. At about the age of forty it is something like 10 in. to infinity; and at about the age of sixty it is so small that many old people need several pairs of spectacles.

You should remember your own range of vision (it might be '5 in. to infinity'). But for teaching you about optical instruments we shall imagine you are an older person with an 'average eye' that has a range 10 in ($= \frac{1}{4}$ metre) to infinity.

**Using a lens to make images.** Take a weak magnifying glass, a positive lens, of power about +7 D. Sit or stand some distance from a window, face the window and hold the lens out at arm's length towards it. Look towards the lens and see whether you can see a *real image* of the window. Find out where that image is by catching it on a piece of tissue paper: hold the paper out in front of your face with your other hand and move it towards the lens until you catch the image of the window on it. Now you know where the image is. Concentrate on looking at something just there, and pull the paper away. The image is still there. Look at it, remembering it *is* just there. If you have lost the place, put the paper back to catch the image of half the window, leaving the other half of the image in open air for you to stare at.

If you still do not feel the image is really there in mid-air between the lens and your face, catch it on tissue paper again and ask a neighbour to come and point to that place with his finger and pretend to snatch at the image when you have taken the tissue of paper away. If he keeps on telling you 'The image is just here', as he points to it and snatches at it, you may find that this helps to convince you the image is really there.





Also, try letting the image fall on a piece of white paper, like the picture on a camera film. For that, turn round with your back to the window, hold the white paper at arm's length and move the lens with the other hand until it puts the image on the white paper.

That is an example of a lens forming a *real* image, on the other side of the lens from the object.

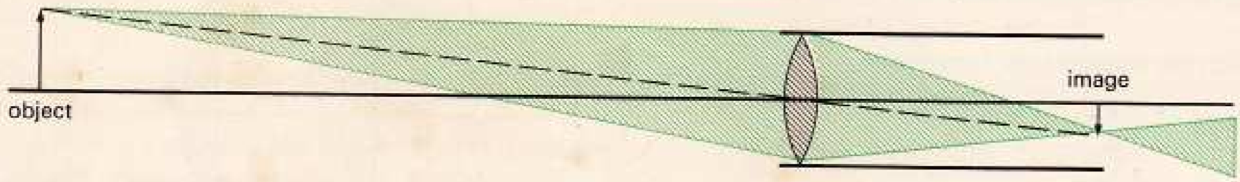
Now make the same lens form a different kind of image. Hold the lens close to your eye and look through it at your thumb. Move your thumb until you can see it very clearly, magnified. Since your thumb looks bigger than life, you cannot be seeing the real thumb directly; you must be looking at an image. And since that image is sharp and clear it must be *somewhere in your own range of vision.*

If you take the lens away, keeping your thumb in the same place, you will see that it is too near; it is not within your range of vision. So now the lens took light from an object which was very near and made it *seem to come from an image that is farther away,* and *magnified, on the same side of the lens as the object.* This is a case of the lens making a *virtual image.*

Magnifying glasses and eyepieces make virtual images for us to look at; and you will find that spectacles also do that.

**Virtual images.** Sometimes, a lens does not bend the rays of light from an object sufficiently to make them meet again at another place. Some lenses even bend rays in the opposite direction, making them fan out more than before.
When received by the eye, these rays look as though they come from a different place from the one where the object is. What is seen at this place is called a *virtual image*.

**What use can we make of optical images?** We have already found one use – in the camera. Look back at pages 6, 7, and 8.




Another use is in the telescope.
When you want to look at a distant object it may be impossible to move the object closer to the eye. The first lens of the telescope forms a real image of the distant object as in the diagram above, and the eye can be placed closer to this image so that it appears to be larger. To make it appear even bigger we usually look at it with a magnifying glass – that is the eyepiece lens at the other end of a telescope.
We shall learn more about telescopes later.
But before that, the following pages contain some experiments which you can do with ray streaks.

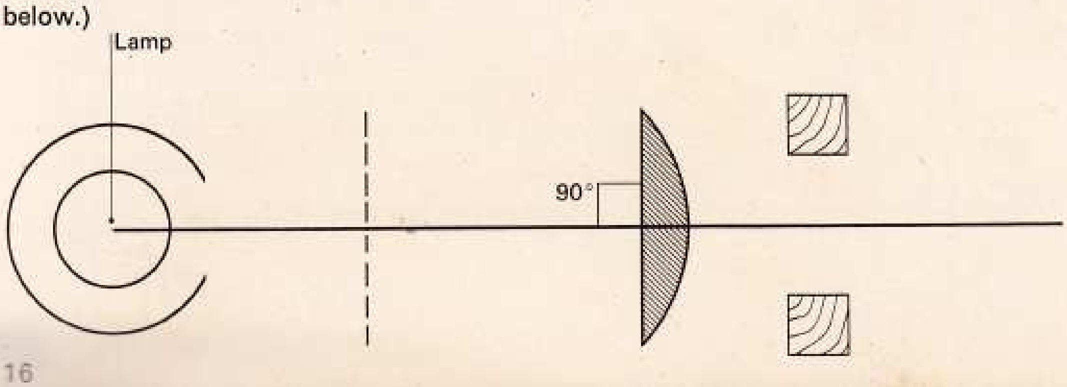
# Experiments with Ray Streaks

To do these experiments, you will use lamps and lenses. Be careful with the lenses as they are easily chipped. In the diagrams which accompany some of the experiments, the lines which are drawn from lamp to lens and which may appear to be rays, are intended only to help alignment of lamp and lens in doing the experiment.

**Experiment 1**
Switch on the lamp, and cut off part of the light with the black cylinder. Then place a 'comb' across the light so that it is divided up into rays.
Raise or lower the lamp until the rays continue right across the paper.
Compare these rays with the diagrams we have drawn earlier in the book.
Where do they come from?

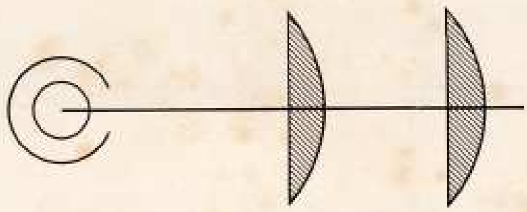
**Experiment 2**
Ask for a weak lens, +7D. Place this across the fan of rays.
What does it do to the rays?
Do the ray streaks look like the diagrams you have seen?
Try some other lenses and see what they do.

**Experiment 3**
Go back to the weak lens and place it about 20 cm from the lamp, after the comb. Make sure that its flat face is at right-angles to the central ray and block off extreme rays until all those that remain pass through one point. (See below.)

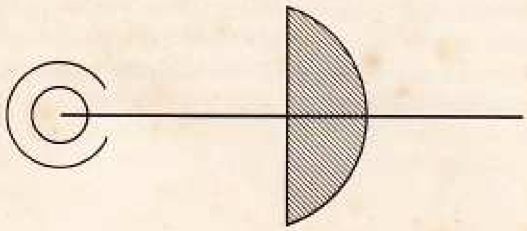



What do we call this point which all the rays pass through after they have been bent by the lens?
Where is the object?

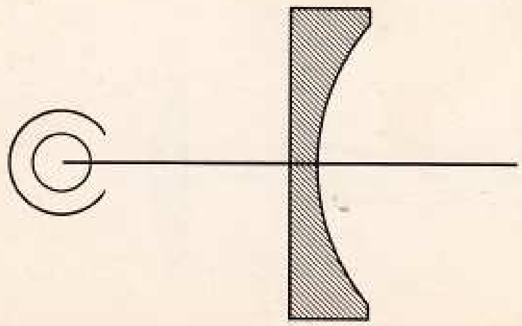
**Experiment 4**
Now get a second lens of the same strength and try using them both together. There are several ways of doing this – the diagram shows only one way. Try them all. Look how far the image is from the lens when you use only *one* lens.
What happens when the *two* lenses are closer than this?
What happens when they are further apart than this?



**Experiment 5**
Exchange your two weak lenses for a stronger lens, +17D. Place it in front of the fan of rays. Compare what happens now with what happened when you had the weak lens. What do you notice?

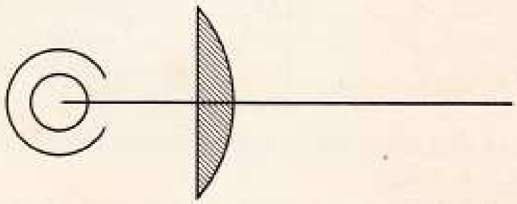


**Experiment 6**
Try putting a *negative* lens in front of your fan of rays instead of the strong positive one. (A negative lens is one which is thinner in the middle. Look at the diagram.)
What effect does it have on the rays?
Can you find an image?
Bend down and look along the ray streaks so that you can see them coming through the lens.
Can you see the lamp and comb as well?
The ray streaks *look as though* they come straight from the lamp.
Now look down from above at the paths the ray streaks really take.



Do the rays really go straight through the lens?
Can you describe what the lens does to the rays, using the word 'image' in a new way?

**Experiment 7**
Change back to the weak positive lens (+7D) and place this close to the lamp. Is the lens bending the rays enough to make a real image?
If it is, move the lens closer to the lamp. The lens does not bend the rays enough to make a real image.
Bend down and look along the ray streaks so that you can see them coming through the lens. What do you notice?



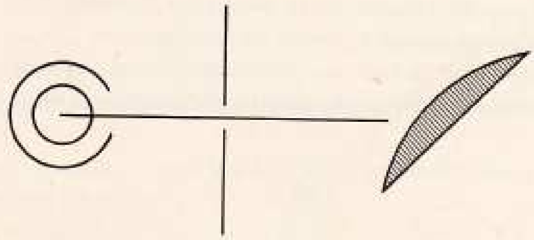
In both of the last experiments, the ray streaks *looked as though* they came straight through the lens when we looked at them through the lens. But you saw, when looking from above, that the ray streaks do not really go straight through the lens. We call the place that the rays seem to come from, the *virtual image*.

**Experiment 8**
Go back to the arrangement of Experiment 3. When the lens bends the rays so that they really pass through a place on the paper, we call that place a *real* image. What happens to the position of the real image as you move your lamp farther away from the lens?
What happens as the lamp is moved closer?
Can you make this lens form a virtual image? (This can be done.)

**Experiment 9**

Replace your 'comb' with a single slit so that you can experiment with a single ray. (This single ray could be made thinner by placing a positive lens just before the slit; but this is not necessary.)

Direct your ray at various places on both a positive and a negative lens, and see what happens.

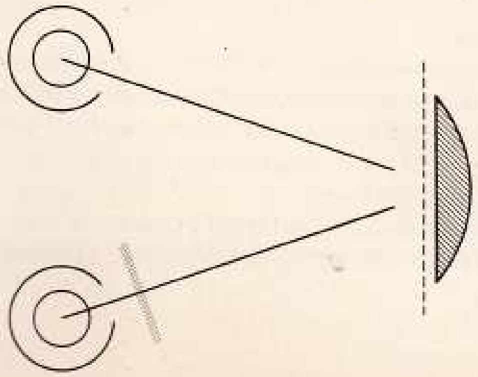


Can you find a place where the ray passes straight through the lens?

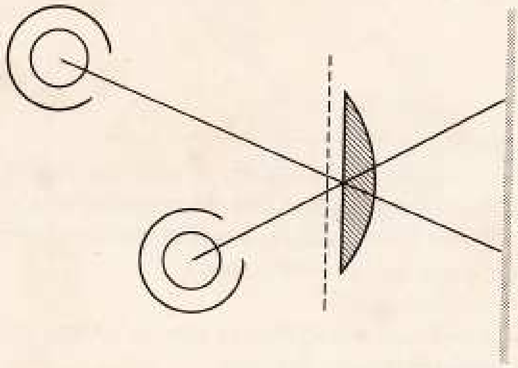
Try twisting the lens so that the ray strikes this part of the lens at different angles. What do you notice?

**Experiment 10**

Get a second lamp and use the weak positive lens to form images of both the lamps. To do this, place both lamps some distance from the comb and place the lens just beyond the comb. To distinguish between the two lots of rays you can put a piece of coloured gelatine in front of one lamp. You should now make with ray streaks several of the diagrams which were drawn earlier in the book. If the lamps are the same distance from the lens, they can represent the top and bottom of a large object.

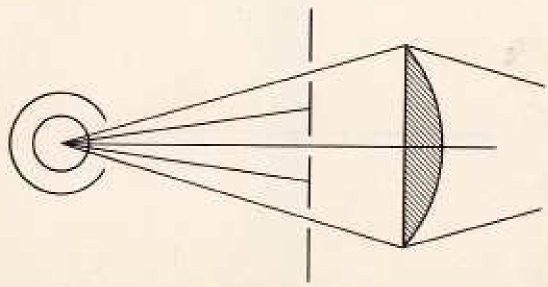


With the lamps at different distances from the lens you can see for yourself what happens in a camera when you take photographs of two objects at different distances. You can use a screen as the film, and two wooden blocks to alter the aperture of the lens.




**Experiment 11**

Go back to one lamp and place a comb in front of it. Now put a strong positive lens a considerable distance in front of the lamp.



Does it form a good image? What is wrong? Move in barriers until a good image *is* formed. You will notice that we are only using a small central region now. (Ray diagrams with only a small part of the lens in use may seem awkward to draw. Try the following way to illustrate the wide diagrams that people often draw. Take the comb and barriers away and place a screen with three slits close to the lens. That will let just three rays go through the lens, so you will get what *looks like* a good image. Of course, the two outer rays do not really agree with all the other rays that are missing in forming a good image. This arrangement is only a trick to make a diagram that is clearer than the real facts!)

(You may prefer not to do the next three experiments until you have read more of this book.)

**Experiment 12 A model of the telescope**

Place a lamp several feet from a weak positive lens (+7D). Put the screen with the three slits in it close to the lens so that three rays pass through the lens. The curved face of the lens should be towards the lamp.

Use a strong positive lens (+17D) as eyepiece and place it so that the rays emerge from it in a parallel beam. Its curved face should be towards the first lens.

Now place a second lamp (covered with a piece of coloured gelatine) close beside the first one (so that the two lamps represents the top and bottom of an object).

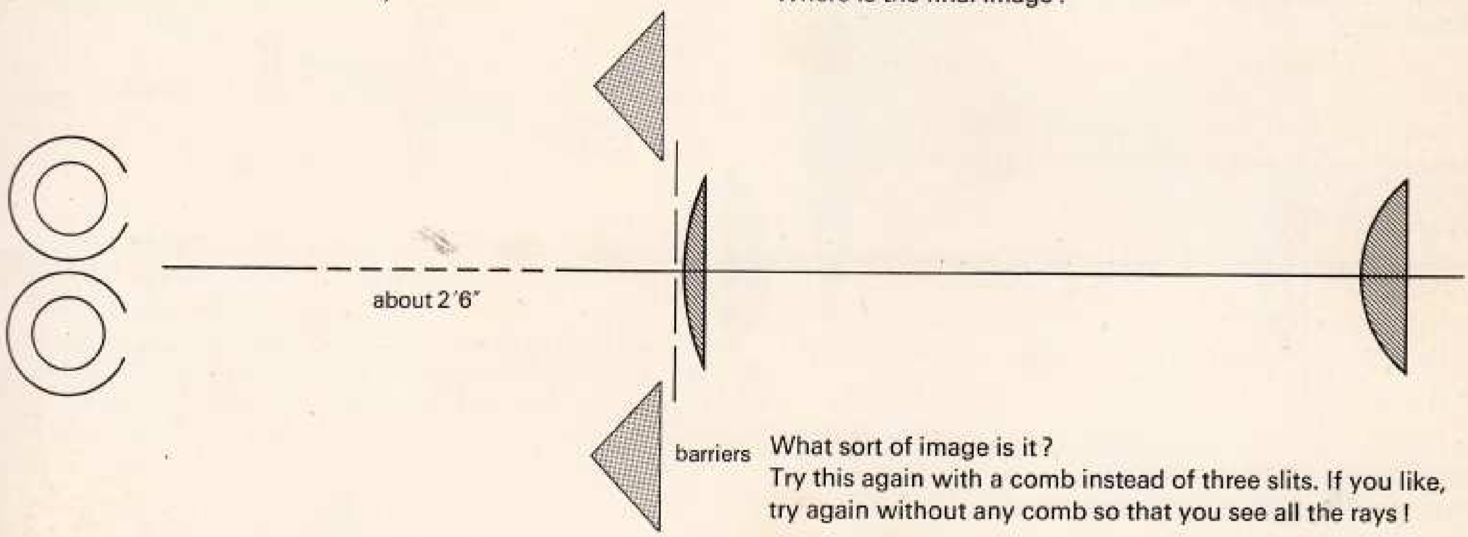
Where is the first (real) image?

Is it bigger or smaller than the object?

Look along the emergent parallel rays.

Does the final image look bigger or smaller than the object?

Where is the final image?




What sort of image is it?

Try this again with a comb instead of three slits. If you like, try again without any comb so that you see all the rays!

**Experiment 13** (This is a difficult extra)

Add an extra positive lens (+7D or +10D) at the real image itself in the model telescope of the last experiment.

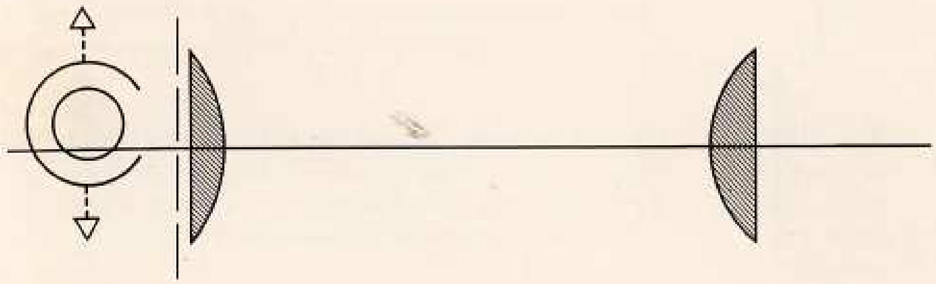
What effect does it have on the rays?

By making the rays hit the central part of the eyepiece, distortion is reduced.

Look along the emergent beam.
Is the final image any bigger?
The lens you have added is called a *field lens;* how does it affect what you see?

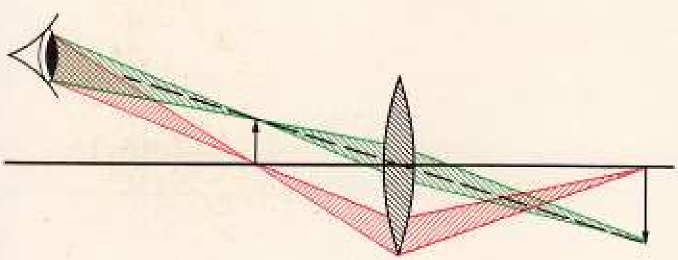
**Experiment 14 A model of the microscope**

To make a model microscope, use a medium positive lens (+10D) and move the first lamp towards the lens until the image distance is two or three times the object distance. Use a strong positive lens (+17D) as an eyepiece.
You will find it impossible to use two lamps as they cannot be placed close enough together. Instead, move one lamp quickly to and fro perpendicular to the axis of the microscope. This will give you some idea of the size of the first (real) image.
Is the final image bigger or smaller than the object?
Where is it?

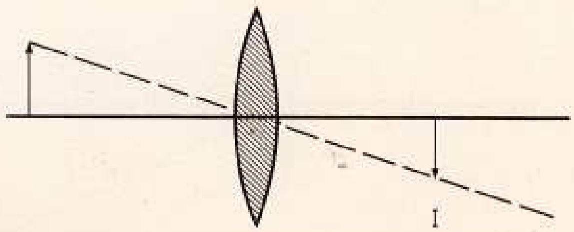


# How to draw ray diagrams

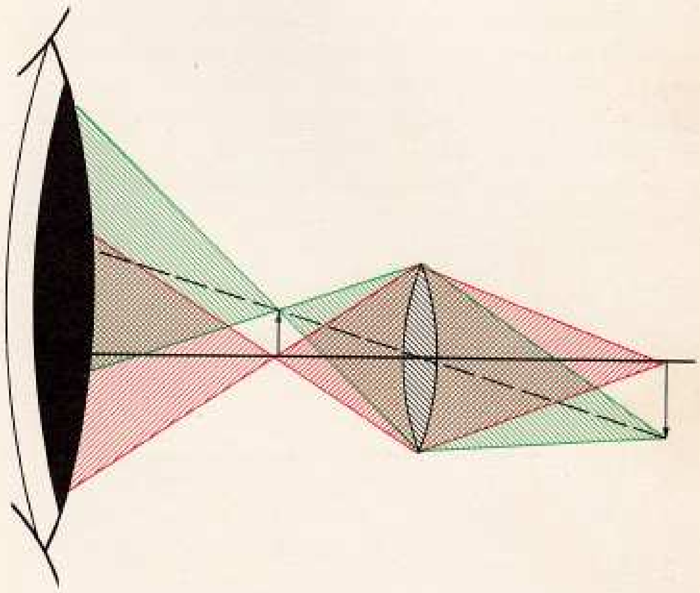
**Small cones of rays to an eye**
Some people like to draw diagrams to show how light goes through optical instruments. If you would like to do this, you should read the next section carefully.
We want to draw a diagram of an eye looking at a real image formed by *any* lens of *any* object. In these diagrams, we should show an eye, at a suitable distance from the image it is viewing, receiving cones of rays which start from *two* original object points, one on the axis and one off the axis. We need not be fussy about the distance of the object and image from our lens drawing. Choose any distances which from your experiments you think look all right.
This is how your completed diagram ought to appear:



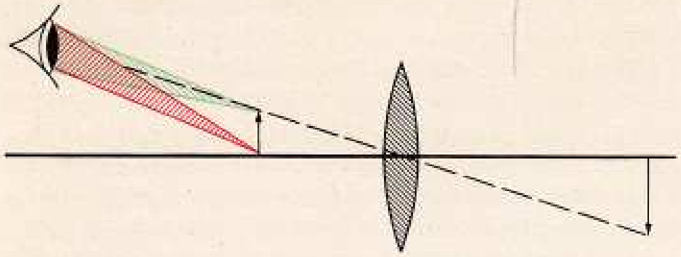
The eye, the lens, the object and image distances are all in about the right proportions. It is easy enough to draw if you adopt the right method.
In order to get the object and image sizes in the correct proportions, choose first a suitable object height (NOT equal to the lens height). Draw the undeviated rays from the top and bottom of the object like this:




Before we can draw the rest of the diagram, we must know how far away the image is. In these diagrams we just choose a place for the image that looks suitable. Suppose we have decided to place the image at 'I'. Then it is easy to put in the correct image height. Now to construct two cones of rays. If we start from the object and draw small cones from points on it, we may end with a very uncouth diagram requiring a huge eye to admit both ones that emerge. For, remember, the eye must be some way behind the image in order to see it clearly.

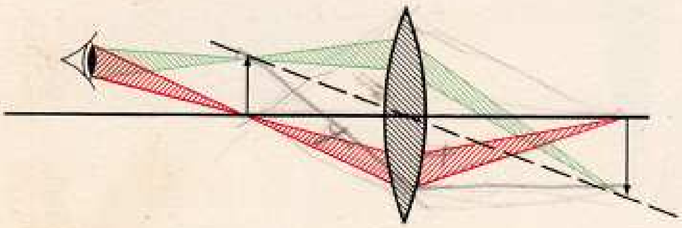


That's no good – and it is also very confusing!
Instead, place a small eye in a suitable position, and show the eye looking at the image, by drawing the extreme rays of small cones *from the image to the eye*. Shade the part of the cone along which light travels to the eye.



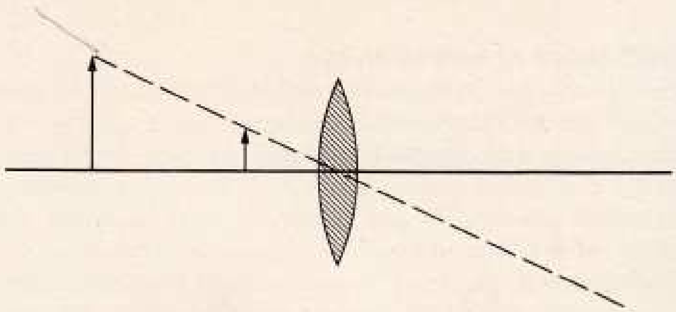
Then remember that, though the rays entering the eye do come from the image, they really start from the object and are bent by the lens. They pass through the image, each of them straight through without bending there.

Continue the rays that you drew backwards from eye to image, back through the image (without bending them there) until they meet the lens. Then you know where those rays came out of the lens. Complete the diagram by drawing rays from the proper object-points to these places on the lens.

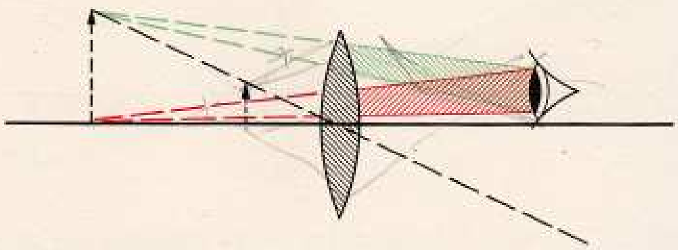


Now you have a diagram which shows an eye looking at the image. You will have noticed that the eye in this case does not make use of the full aperture of the lens.

**Viewing a virtual image.** To show an eye looking at a virtual image, very much the same procedure is adopted. First, we draw in an object and the undeviated rays from the top and bottom of the object:

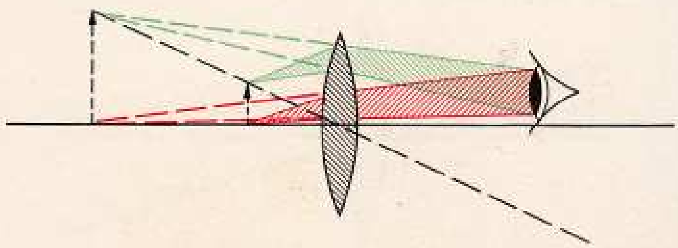


A small eye is placed in a suitable position and the eye is shown looking at the image by drawing the extreme rays of small cones. We use broken lines for virtual rays along which the light does not travel and full lines for real rays. We only shade in the real part of the cone along which light actually travels to the eye:



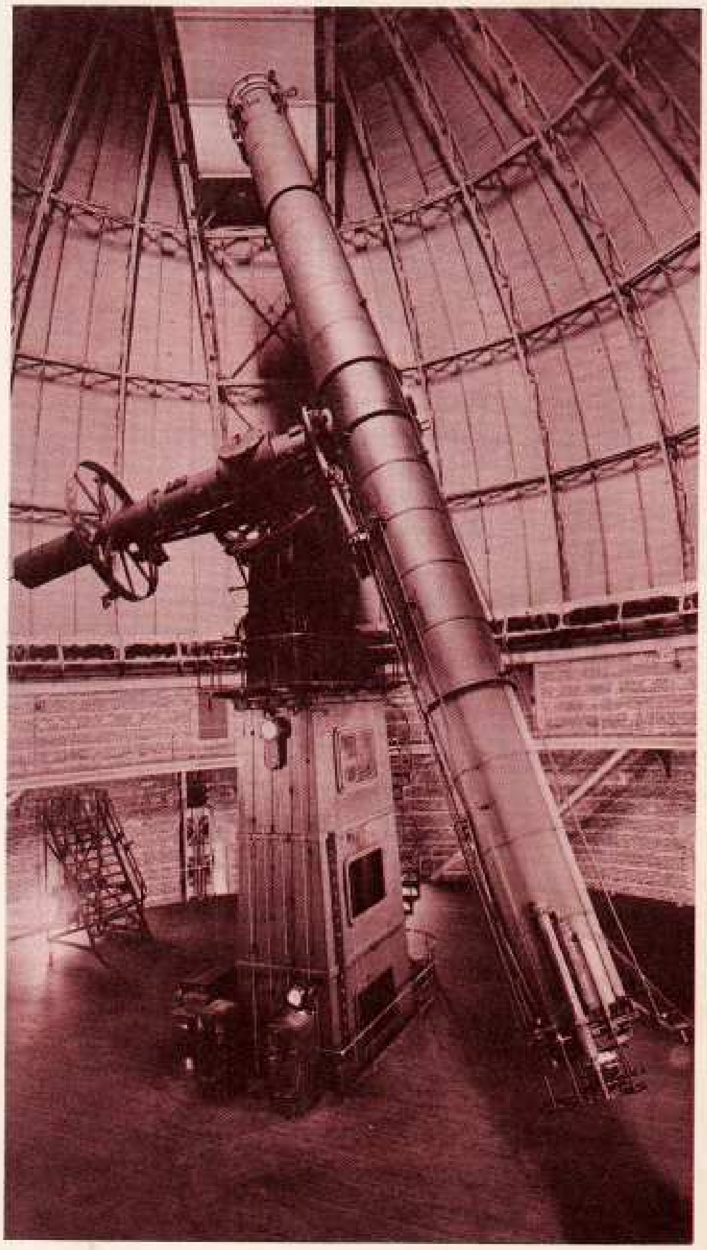
Then finally we can complete the cones by extending them back from the lens to the object, as shown below.

Those cones that extend back to the virtual image do not contain 'real' rays but only 'virtual' rays.



# The astronomical telescope

**The astronomical telescope**
On the right is a photograph of a giant telescope at Yerkes Observatory, which has an object lens 40 inches in diameter.



**Ray diagrams for an astronomical telescope**

A diagram of an astronomical telescope viewing a nearby object gives a better picture of the way a telescope works and its magnifying power.

To draw such a diagram, draw first an object lens, but don't make this too tall. Remember how much taller a man or a tree or something else you are going to look at is than the telescope lens . Also, don't make the object lens very thick. (Remember that the weaker this lens is, the farther behind it the real image will be, and therefore the larger that image will be. So you need a *weak* lens.)

Next,draw in an object some distance from the telescope, and *a little* higher than the top of the lens, with its foot on the axis. Draw in an undeviated ray from the top of the object to the lens, to locate a position for the real image.

Since you are not told how strong a lens to use, you must pretend you have chosen a suitable object-lens which will produce a real image at a suitable distance behind. Of course for a telescope the original object is much farther away from the lens than the real image is; so to make a sensible diagram that you can get on to the paper, you should make the image distance about a quarter of the object distance, or even less.

Decide where the image is for your diagram, and pretend that you have chosen an object lens which will put it there. The undeviated ray will tell you the height of that image.

Choose a position for the eyepiece a short distance behind the real image. Suppose you want the telescope to 'magnify' about six times. Then the distance from eyepiece to real image should be about one-sixth of the distance from object lens to real image.

Draw the path of a new undeviated ray from the real image through the eyepiece. Continue that undeviated ray backwards towards the object, to find the size of the virtual image formed by the eyepiece. Choose a suitable place for the virtual image. It might be as far away as the object or it might be nearer. It is probably clearer to draw it a little nearer than the object as in the sketch here. When you have decided where the virtual image is, its size is settled by the undeviated ray; and that means you have settled what lens you need for the eyepiece. Pretend you have obtained a lens of that power, and draw in the eyepiece.

Then draw a full cone of rays from the top of the object to the *whole* aperture of the object lens. Continue those rays from the object lens to the image and straight on through it to the eyepiece. When those rays emerge from the eyepiece they must seem to come from the virtual image; so you should draw them as *broken lines* (not real rays) from the virtual image to the eyepiece, and then as *full lines* out towards the eye.

You will have to choose the size of the eyepiece to catch all those rays—a simple matter of trial and error. You should make it a strongly curved lens, to show it needs to be a strong one to give some magnification.

To make the diagram simpler, only one cone of rays is drawn. This will suffice, provided you understand what would happen to the cone of light from another object point. When drawing a simplified diagram like this, always choose an object-point *off* the axis so that the diagram will show the magnifying power of the instrument.

The final virtual image may be any convenient distance from the eye, from a quarter of a metre to infinity. For most comfort in looking at distant things with the telescope, the final virtual image should be placed as far away as the object. If the observer wishes to make notes in a nearby book or if he is short-sighted he should place the final virtual image much closer. This makes very little change in the magnifying power of the instrument.

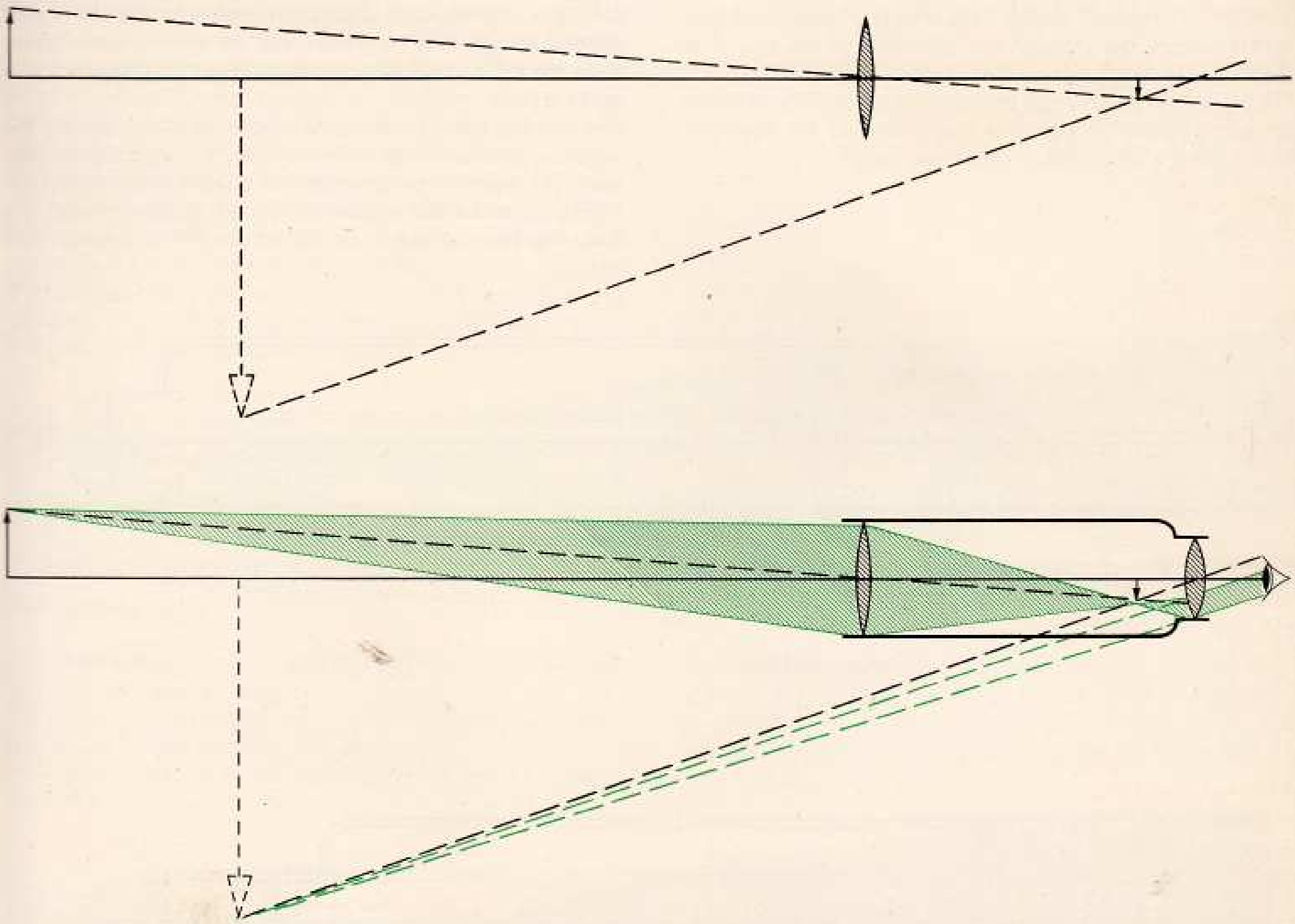


Diagram (1) (below) shows the passage of a beam of light from a distant star through the telescope to the eye of an observer.
The object lens forms a real image of the object. Cones of rays proceed straight through this real image to the eyepiece, which forms a virtual image of the real image.

Notice that the beam has parallel edges – for the star is very distant. In fact, it is so distant that we cannot draw beams from the top and bottom of the star. Even its image is just a point of light.
The eye is placed at the point where the beam leaving the eyepiece crosses the axis. This is called the *eye-ring*. In Diagram (2), beams from two stars have been drawn in. All the light that enters the object lens passes finally through the eye-ring. The eye should be placed there for maximum field of view.

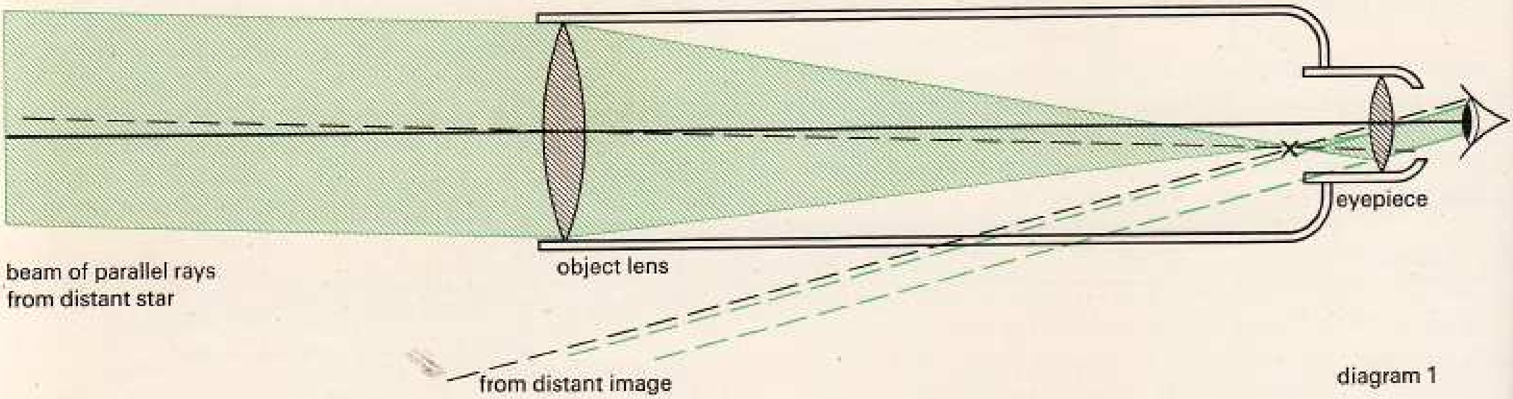



diagram 1

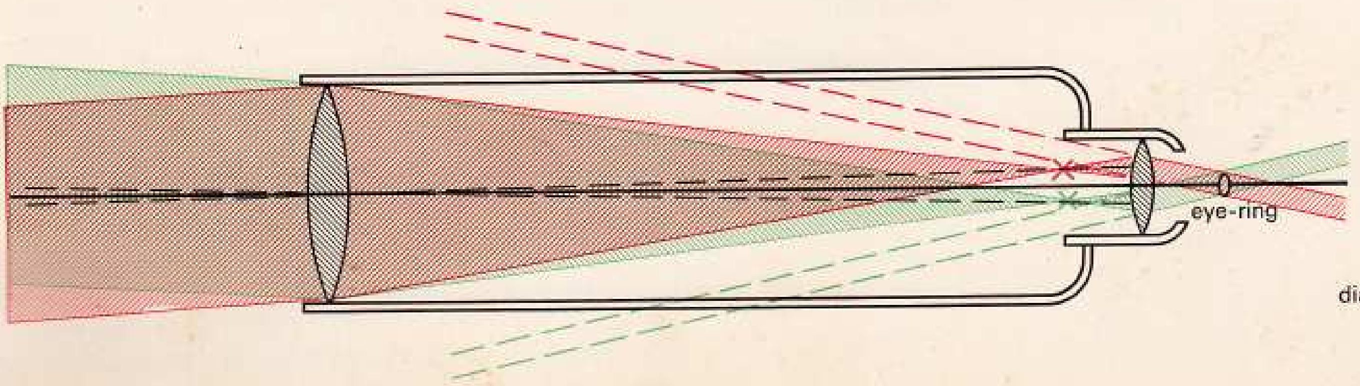


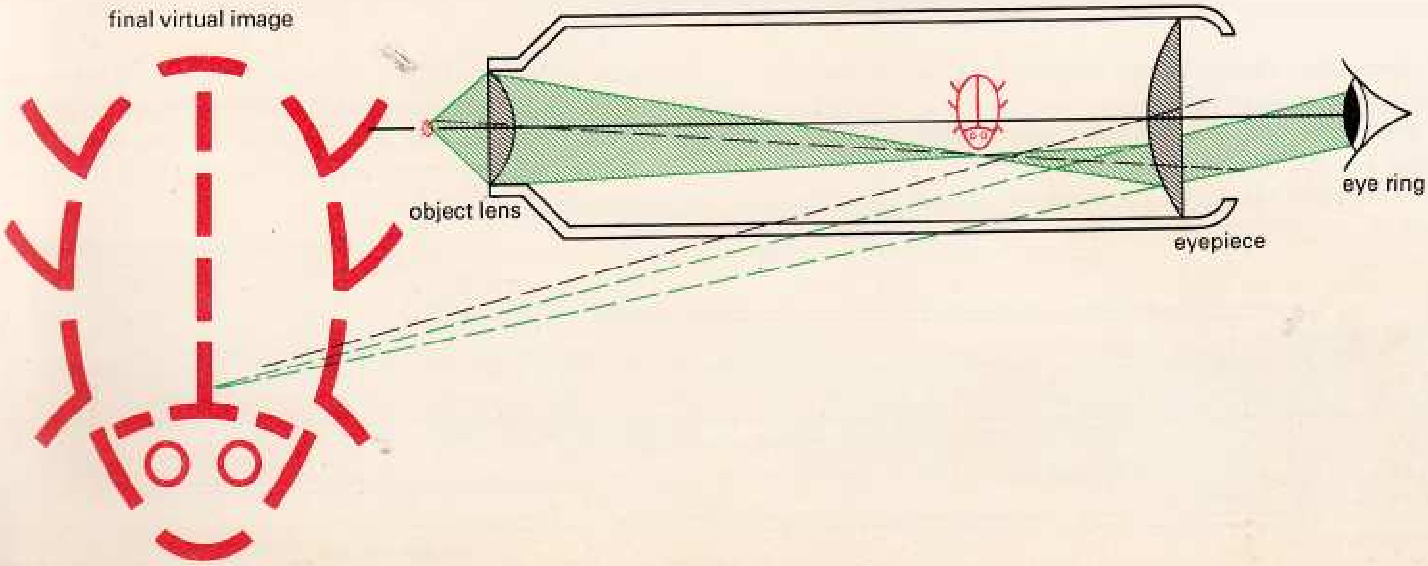

diagram 2

**The simple microscope or magnifying glass**
Let us first look at a simple microscope which *is* just a magnifying glass. This is a single convex lens used to produce a virtual image of an object held close to the lens. For best use the lens should be held *very close* to the eye. Then the virtual image *looks* no larger than the object, but the eye sees that image clearly because it is far enough away. Without the lens, the object held in that close position is much too close for comfortable vision. The ray diagram for this is shown on page 21. Attempts to produce high magnifications this way lead to behaviour that makes a poor image, and small field of view.

**The compound microscope.** A ray diagram for a compound microscope is shown below on this page. To increase the magnifying power, an object lens produces a *magnified* real image of the object. Rays proceed straight through this image to the eyepiece which forms a virtual image of the real image. The final object is inverted, but this does not matter since the observer now has control over the original direction of the object.

**Ray diagram of a compound microscope**
It is easiest to draw the diagram in the same way as the diagram for the telescope – start with a suitable object and object lens, draw in the undeviated ray through the object lens and select a suitable place for the real image. When the position of the eyepiece has been chosen, the virtual image can be located.
In this case, the eyepiece may have a larger aperture than the object lens.
*In drawing these diagrams, it is always important to draw in undeviated rays first of all.*

**Position of the final image.** The wise observer places the final image about a quarter of a metre from his eye.
Now try Experiment 14. (Page 20.)

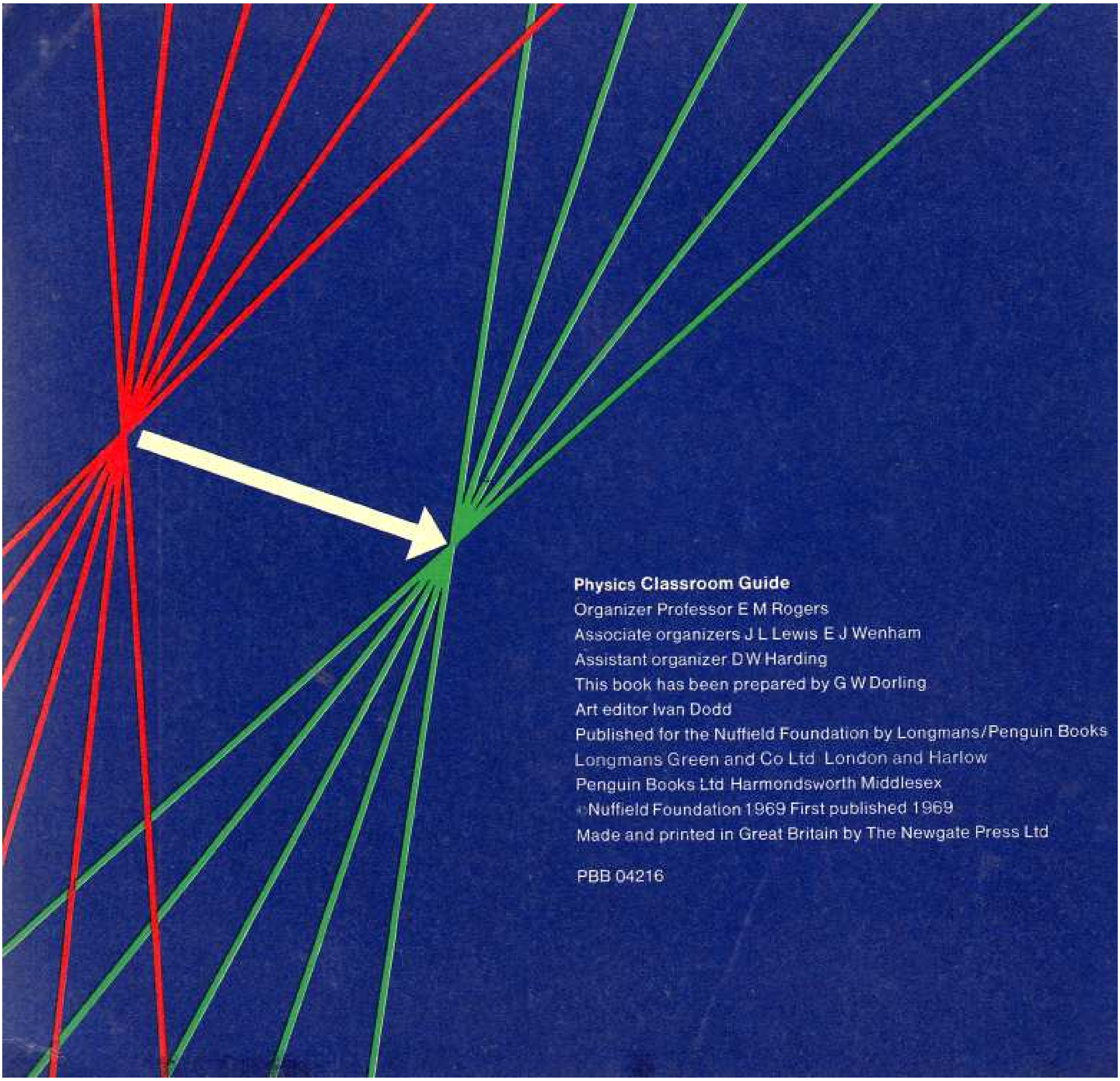


**Further developments.** In many microscopes both the object lens and the eyepiece consist of more than one lens.

**The object lens.** Lenses of different kinds of glass are combined to remove chromatic aberration and their shapes are chosen to lessen spherical aberration.

**The eyepiece.** The eyepiece consists of two (or more) lenses. The first lens is placed near the image to catch all cones of light passing through the image and bend them towards the middle of the second lens. The second lens then sends the cones to the eye, through an eye-ring close to it. This arrangement gives a large field of view with little distortion and little chromatic aberration.

**The need for a large aperture.** Light waves will deceive us and produce unreliable or fuzzy images of *very* small objects unless the object lens has a large aperture, to take in very wide cones of light. This requirement raises serious difficulties when the highest magnifying power is required. Lenses of very special shape and arrangement have to be used for the object lens.



**Physics Classroom Guide**
Organizer Professor E M Rogers
Associate organizers J L Lewis E J Wenham
Assistant organizer D W Harding
This book has been prepared by G W Dorling
Art editor Ivan Dodd
Published for the Nuffield Foundation by Longmans/Penguin Books
Longmans Green and Co Ltd London and Harlow
Penguin Books Ltd Harmondsworth Middlesex
 First published 1969
Made and printed in Great Britain by The Newgate Press Ltd

PBB 04216