The Telescope and the Microscope

Applications:

Lens combinations, the description of images, the magnifier, the compound microscope and telescopes.

Equipment List

1	Geometric Lens Set	1	Viewing Screen	1	Metric Ruler
1	Basic Optics Light Source	1	1.2-m Optics Bench	1	Rubber band or tape
2	Adjustable Holders				

Introduction

The telescope and the microscope are two important optical devices that use two lenses. In each device a primary lens (the *objective*) forms a real image and a secondary lens (the *eyepiece*) is used as a magnifier to make an enlarged virtual image. The purpose of this activity is to construct a simple telescope and a simple microscope and to measure their magnifications. Biconvex (convergent) thin lenses of focal lengths +100 mm and +200 mm will be used as the primary and eyepiece lenses. A viewing screen covered with a reference grid on an optics bench will be used to make measurements.

THEORY

The Images Formed by Thin Lenses

All the lenses used in this activity are thin compared to the other distances involved. Under these condition, the Thin Lens Formula can be used:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

[Eq. 1 — The thin lens formula.]

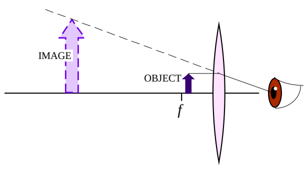
Here f is focal length, d_o is the distance between the object and the lens, and d_i is the distance between the image and the lens. The image formed by a thin lens can be described by its orientation (upright or inverted) and by its magnification (enlarged or reduced, compared to the original object). Both descriptors can be determined by taking the ratio of d_i to d_o:

$$m = \frac{-d_i}{d_o}$$

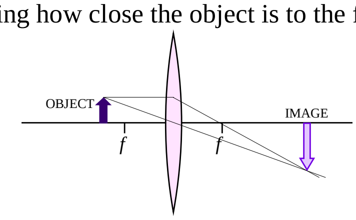
[Eq. 2 — The magnification.]

The distance d_i is taken as negative if the image appears on the same side of the lens as the object (virtual image). Then, if m is positive, the image is upright. If m is negative, the image is inverted.

When an object is placed closer to a biconvex (convergent) lens than the focal length, the lens works as a magnifier and produces an enlarged virtual image.



When an object is placed farther from a biconvex (convergent) lens than the focal length, the lens produces an inverted, real image. (The image could be reduced or enlarged, depending how close the object is to the focal point.)



When two thin lenses are used, we analyze the distances by taking the image from one lens as the object for the second. The observer views an image that is "an image of an image." The overall magnification, *M*, of the two-lens system is the product of the individual magnifications of each lens:

$$M = m_1 m_2 = \left(\frac{-d_{i1}}{d_{o1}}\right)\left(\frac{-d_{i2}}{d_{o2}}\right)$$

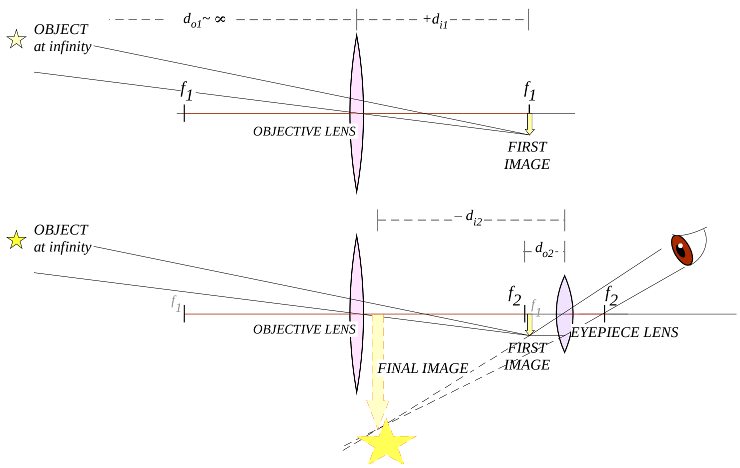
[Eq. 3 — The total magnification of a two-lens system.]

The Refractive Astronomical Telescope

An astronomical telescope is used to view large objects that are at large distances from the lenses. A *refractive telescope* uses lenses and the principle is very simple: the objective lens produces a first real image of a very far away object. From the thin lens equation, notice that if the distance to the object is very large ($d_o \to \infty$), then,

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \approx \frac{1}{d_i},$$

and the image forms coincident with the objective's focal point. The eyepiece then is placed close to that first image, so that the first image falls within the eyepiece's focal length and is thus magnified. The closer the first image is to the eyepiece's focal point, the longer the distance to the final image. Astronomical telescopes are usually built so that the first image forms exactly at the focal point of the eyepiece lens. In this case, the separation between the lenses is exactly $d = f_1 + f_2$, which is the length of the telescope tube.



(a) The OBJECTIVE lens forms the first image.

(b) The EYEPICE lens greatly magnifies the first image.

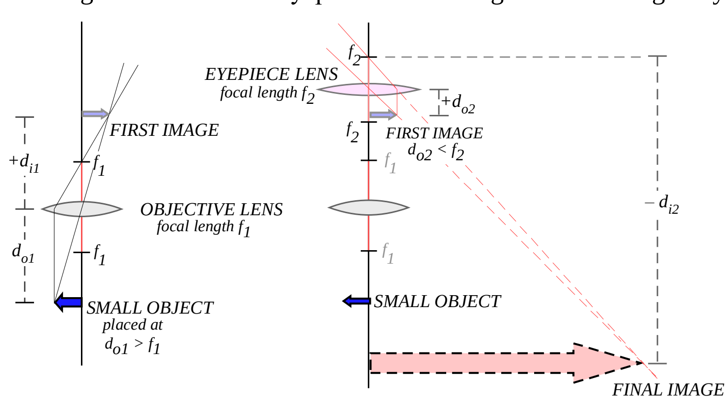
The magnification of an astronomica telescope with the object at infinity, and with f_1 and f_2 both coincident with the first image, is defined as the ratio of the focal length of the objective to that of the eyepiece:

$$M = \frac{-f_1}{f_2}$$

[Eq. 4 — The magnification of a telescope with object at infinity.]

The Compound Microscope

A compound microscope is used to view small objects that are very close to the lenses. A microscope is useful when the magnification required is more than what can be obtained with a single magnifier lens. The principle is very simple: the objective lens produces a first real image of the object, by having the object be just beyond its focal length. The eyepiece will then be placed very close to that first image, so that the first image falls within the eyepiece's focal length and is thus greatly enlarged.

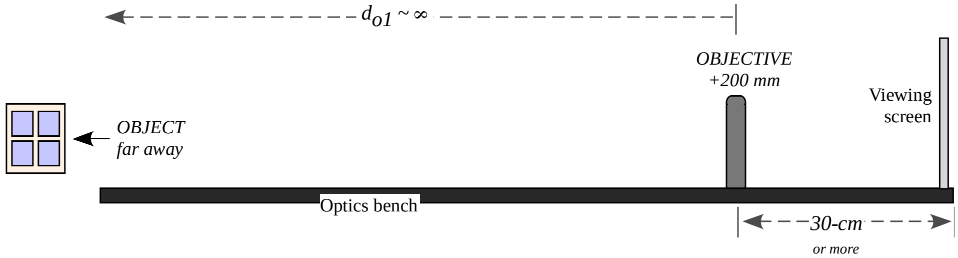


(a) The *OBJECTIVE* lens forms the first image. This image is real, inverted and reduced.

(b) The *EYEPIECE* lens forms the final image using the first image as its object. This final image is virtual and greatly enlarged.

PROCEDURE A
The Astronomical Telescope: Looking at a Far Away Object

1. Set the optics bench on a table so that one end points to an open window or open door or a lamp at the opposite end of the classroom. Dim the lights inside the classroom.
2. Mount the +200 mm lens on the opposite side of the bench, at least 30-cm away from the end. (This space is needed to install the eyepiece later.) Install the viewing screen at the end of the track.



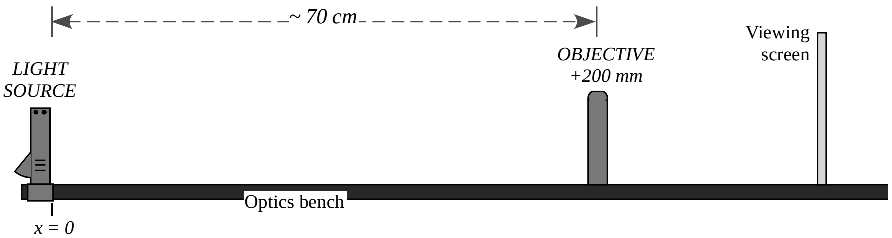
3. Move the viewing screen towards the lens until a sharp image of the object is seen. According to the theory, if the object is infinitely far away, then the first image forms at the focal point of the objective lens. (Does this hold true? Is the image forming about 20-cm from the lens?) Make fine adjustments around the focal point until the image is very sharp.
4. Make a note of the exact positions along the track of the objective lens and the first image in the Data Table.
5. Write a description of this first image in the Data Table: Is it inverted or upright? Is it enlarged or reduced? Is it real or virtual?
6. Mount the +100 mm eyepiece 10 centimeters behind the first image. This should make the separation between the lenses 30-cm (that's the telescope's lengths: $f_1 + f_2$), plus or minus any small adjustment made in step 3.
7. Remove the viewing screen, but keep track of the position of the first image. It is useful to mark the position with a piece of tape on the side of the track.
8. With only one eye open, look through the eyepiece directly toward the object. Move the eyepiece forward or backwards a little bit, as needed, until you comfortably see a very sharp, enlarged image of the object. You should not be squinting or forcing your eye into focus. Move the eyepiece until the image comes into focus without any strain on your eyes.
9. Record the position of the eyepiece in the Data Table.
10. Visually estimate the magnification of this telescope: position yourself where you can see both the image and the object comfortably. Hold a ruler a fixed distance near your eyes and measure the apparent height of both the image and the object. You may need to open and close your eyes in turns, and focus on the ruler to do this, but as best as you can keep your eyes and the ruler in the same position. Record the estimates in the data table.

ANALYSIS PROCEDURE A
The Astronomical Telescope: Looking at a Far Away Object
1. Use the recorded positions to determine the following distances:
- Distance from the objective lens to the first image, d_{i1} .
- Distance from the first image to the eyepiece lens, d_{o2} .

2. Use the thin-lens formula (Eq. 1) to calculate the distance from the eyepiece to the final image, d_{i2} .
3. Calculate the magnification of the second image, $m_2 = -d_{i2}/d_{o2}$.
4. Calculate the theoretical magnification, M .

PROCEDURE B: The Astronomical Telescope: Looking at a Nearby Object
In this part of the experiment the telescope arrangement will be used to examine an object that is a finite distance from the lenses. It will no longer be assumed that $d_{o1} \to \infty$.

1. Install the Light Source so that its front edge (the side with the crossed-arrows) is at the $x = 0$ mark on the track. Turn the light source on.
2. Place the +200-mm lens about 70 cm away from the light source and place the viewing screen behind the lens, as illustrated.

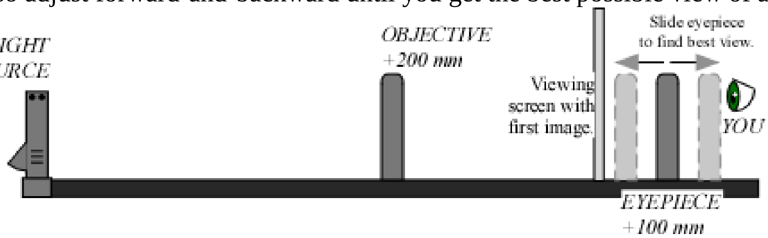


3. Move the viewing screen forward or backward until a sharp image of the crossed-arrows is seen. This is the first image. Record the position of the objective and the first image in the Data Table.

4. Write a description of this first image in the Data Table: Is it inverted or upright? Is it enlarged or reduced? Is it real or virtual?

5. Install the +100 mm lens (the eyepiece) directly behind the viewing screen.

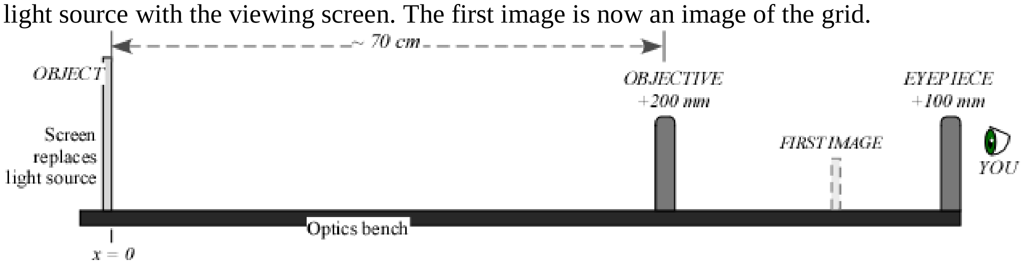
6. With your eye close to the +100-mm eyepiece, look through the lens as you move it back away from the viewing screen. Stop when you are comfortably seeing a sharp and enlarged image of the back of the viewing screen. (You are using this lens as you would a magnifier glass, so adjust forward-and-backward until you get the best possible view of a magnified screen holder.)



7. Remove the viewing screen, but remember the location of the first image. It helps to mark the location with a piece of tape on the side of the track.

8. Tape a copy of the grid (see the last page) onto the viewing screen.

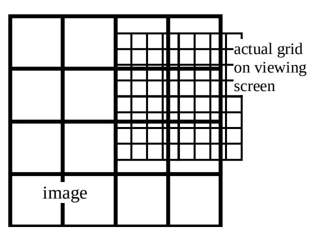
9. Replace the light source with the viewing screen. The first image is now an image of the grid.



10. ***Check for and Eliminate the Parallax.*** *Parallax* is an apparent shifting of the image with respect to the background due to the motion of the observer. It happens when the image is not in same plane as the object (grid pattern).

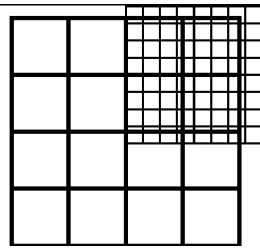
Check to see if your image shows parallax:

- Open both eyes and look through the lens at the image with one eye while looking 'around the edge' of the lens at the grid pattern with the other eye. You should see the image-grid on top on a dimmer, smaller grid, as illustrated.
- You may also see that the lines tend to curve near the edges of the lens, which is not shown in the illustrations.
- Move your head up and down or side to side and observe how (or if) the image moves with respect to the grid.

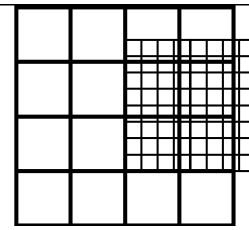


***Parallax* —** the image appears to freely float in all directions above the actual grid.

If there is parallax, the image-grid will change position with respect to the smaller grid as you move your head.



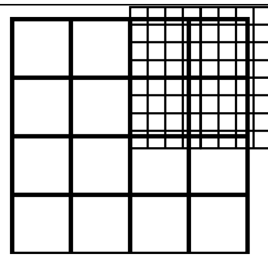
(a) The view with both eyes open.



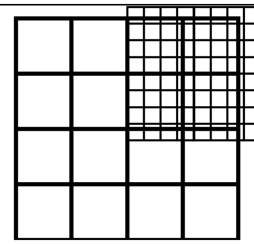
(b) Move your head and the image displaces with respect to the grid.

NO parallax — the relative position of the image and the grid stay fixed for any position of the observer.

If there is NO parallax, then as you move your head the position of the image with respect to the background will not change. They will appear to be stuck together.



(a) The view with both eyes open.

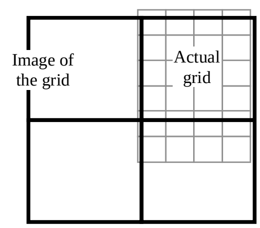


(b) The view from any position of your head is the same.

11. If you found that your image shows parallax, move the eyepiece lens until the image lines do not shift relative to the object lines when you move your head.

12. At this point record the position of the eyepiece in the Data Table.

13. Visually estimate the total magnification of this telescope by counting the number of squares in the grid pattern that lie inside of one square of the image. Record the estimate in the data page.



In this example there are about 4 grid squares inside 1 image square.

ANALYSIS PROCEDURE B: The Astronomical Telescope: Looking at a Nearby Object

1. Use the recorded positions to determine the following distances:

- Distance from object to objective lens, d_{o1}.
- Distance from objective lens to the first image, d_{i1}.
- Distance from the first image to the eyepiece lens, d_{o2}.

2. Use the thin-lens formula (Eq. 1) to calculate the distance from the eyepiece to the final image, d_{i2}.

3. Calculate the magnification of the images, m_1 and m_2.

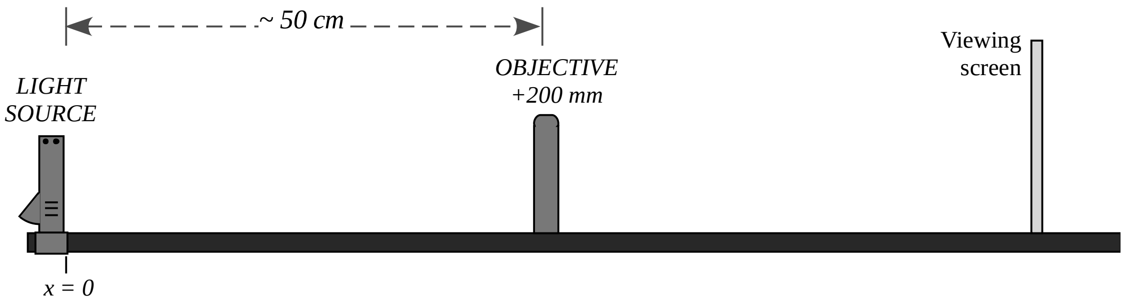
4. Calculate the total magnification of the telescope, M.

PROCEDURE C: The Galilean Telescope: Using a Negative Eyepiece

The famous telescope built by Galileo near 1609 used a diverging convex lens as the eyepiece. In this part of the experiment this design will be compared to the astronomical telescope built in the previous activities, in which a convergent lens was used as the eyepiece.

1. Install the Light Source so that its front edge (the side with the crossed-arrows) is at the $x = 0$ mark on the track. Turn the light source on.

2. Place the +200-mm lens about 50 cm away from the light source and place the viewing screen behind the lens, as illustrated.



3. Move the viewing screen forward or backward until a sharp image of the crossed-arrows is seen. This is the first image. Record the position of the object (the light source), the objective lens and the first image in the Data Table.

4. Write a description of this first image in the Data Table: Is it inverted or upright? Is it enlarged or reduced? Is it real or virtual?

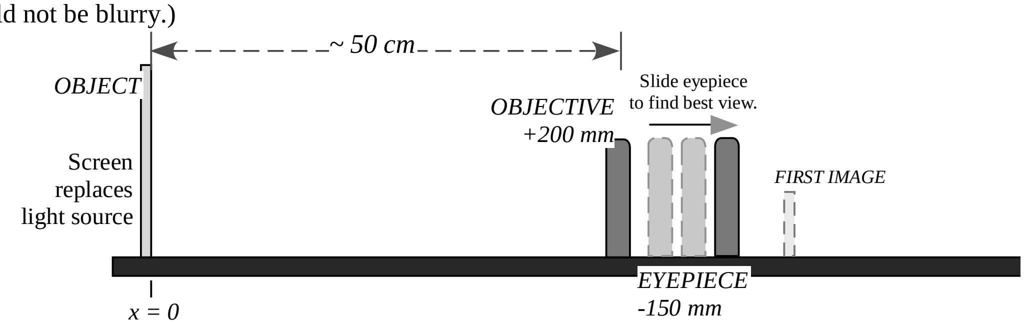
5. Remove the viewing screen, but remember the location of the first image. It helps to mark the location with a piece of tape on the side of the track.

6. Tape a copy of the grid (see the last page) onto the viewing screen.

7. Replace the light source with the viewing screen. The first image is now an image of the grid.

8. Install the divergent -150-mm lens directly behind the objective lens. This will be the eyepiece.

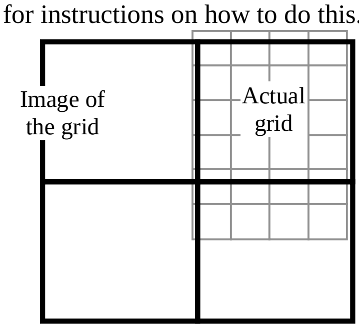
9. Look through the eyepiece at the grid. Slide the eyepiece back (away from the objective) to find the best enlarged image of the grid. (Should not be blurry.)



10. ***Check for and eliminate the parallax.*** Go to **Procedure B, step 10**, for instructions on how to do this.

11. After removing the parallax (if any), record the position of the eyepiece in the Data Table. Notice that the eyepiece is between the objective and the first image. This is different from what happened when using a converging (positive) eyepiece.

12. Visually estimate the total magnification of this telescope by counting the number of squares in the grid pattern that lie inside of one square of the image. Record the estimate in the data page.



In this example there are about 4 grid squares inside 1 image square.

ANALYSIS PROCEDURE C: The Galilean Telescope: Using a Negative Eyepiece

1. Use the recorded positions to determine the following distances:

- Distance from object to objective lens, d_{o1}.
- Distance from objective lens to the first image, d_{i1}.
- Distance from the first image to the eyepiece lens, d_{o2}.

2. The convention for using the thin lens equation requires that when both lenses end up on the same side of the first image, the "second object distance" be taken as negative. Add a negative sign to the distance d_{o2} and use it as such in any calculation.

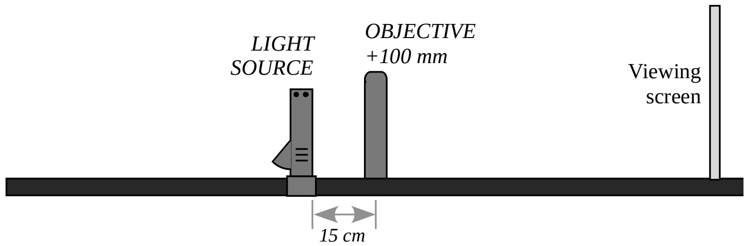
3. Use the thin-lens formula (Eq. 1) to calculate the distance from the eyepiece to the final image, d_{i2}.

4. Calculate the magnification of the images, m_1 and m_2.

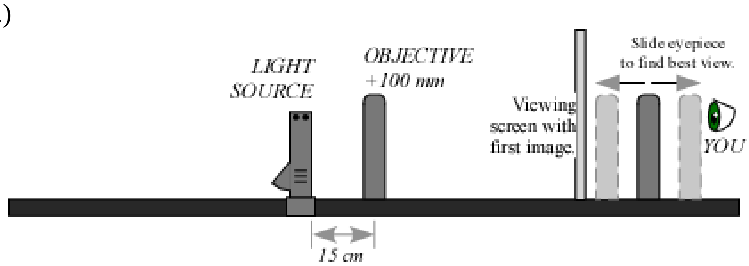
5. Calculate the total magnification of this telescope, M.

PROCEDURE D: The Compound Microscope: Looking at a Nearby but Very Small Object

1. Mount the +100-mm lens about the middle of the track. In this part of the experiment, the +100-mm lens will be the objective.
2. Install the Light Source 15-cm behind the +100-mm lens, with the crossed-arrows facing the lens. Install the viewing screen on the other side of the lens, as illustrated.



3. Move the viewing screen towards the lens until a sharp image of the crossed-arrows is seen. This is the location of the first image.
4. Make a note of the exact positions along the track of the object (the light source), the objective lens and the first image in the Data Table.
5. Write a description of this first image in the Data Table: Is it inverted or upright? Is it enlarged or reduced? Is it real or virtual?
6. Mount the +200-mm lens directly behind the viewing screen. In this experiment, the +200-mm lens will be the eyepiece.
7. With your eye very close to the +200-mm lens, look through the +200-mm lens as you move it back away from the viewing screen. Stop when you are comfortably seeing a sharp and enlarged image of the back of the viewing screen. (You are just using this lens as you would a magnifier glass, so adjust forward-and-backward until you get the best possible view of a magnified screen holder.)



8. Remove the viewing screen, but remember the location of the first image. It is useful to mark this location with a piece of tape on the side of the track.
9. Remove the light source. It is no longer needed.
10. Use a rubber band to hold a copy of the grid (see last page) against the viewing screen. The rubber band is used instead of tape so that you can still move the grid and adjust its position later on.
11. Place the screen with the grid in the exact same position where the light source used to be. The grid has a very small message written in the middle of it. This will be the very small object we want to see through the microscope.
12. Look through the +200-mm lens (the eyepiece) and move your head around to find the image of the small message. You may need to move this lens just slightly to focus it. Move the grid, if needed, to center the message in your field of view. Can you read the message?
13. Record the position of the eyepiece lens (the +200-mm) in the Data Table.

ANALYSIS PROCEDURE D: The Compound Microscope: Looking at a Nearby but Very Small Object

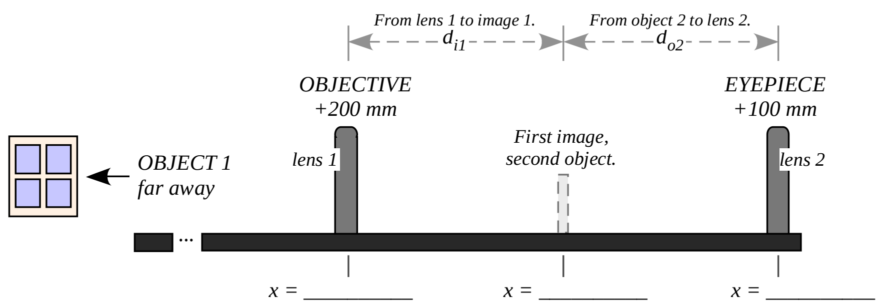
1. Use the recorded positions to determine the following distances:
   - Distance from object to objective lens, d_{o1}.
   - Distance from objective lens to the first image, d_{i1}.
   - Distance from the first image to the eyepiece lens, d_{o2}.
2. Use the thin-lens formula (Eq. 1) to calculate the distance from the eyepiece to the final image, d_{i2}.
3. Calculate the magnification of the images, m_1 and m_2.
4. Calculate the total magnification of the microscope, M.

Lab Report: The Telescope and the Microscope

Name: ____

DATA TABLE PROCEDURE A: The Astronomical Telescope: Looking at a Far Away Object

Summary of Positions:



Visual Description of the First Image:

Orientation: ____________________

Magnification: __________________

Type: __________________

Summary of Distances:

FIRST IMAGE:

$$d_{o1} \to \infty$$

$$d_{i1} = \_\_\_\_\_\_\_\_\text{ cm}$$

FINAL IMAGE:

$$d_{o2} = \_\_\_\_\_\_\_\_\text{ cm}$$

$$d_{i2} = \_\_\_\_\_\_\_\_\text{ cm}$$

(calculated)

$$\to \quad m_2 = \frac{-d_{o2}}{d_{i2}} =$$

Visual Estimate of the Total Magnification:

Apparent height of image $h_i = \_\_\_\_\_\_\_\_$

Apparent height of object $h_o = \_\_\_\_\_\_\_\_$

$$M_{\text{visual}} = \frac{-h_i}{h_o} =$$

Theoretical Total Magnification:

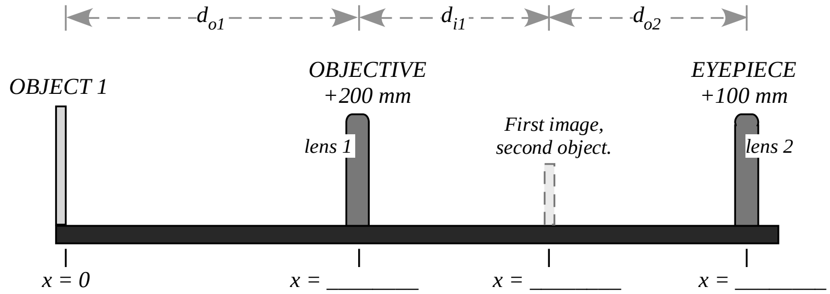
Objective focal length $f_1 = \_\_\_\_\_\_\_\_$

Eyepiece focal length $f_2 = \_\_\_\_\_\_\_\_$

$$M = \frac{-f_1}{f_2} =$$

DATA TABLE PROCEDURE B: The Astronomical Telescope: Looking at a Nearby Object

Summary of Positions:



Visual Description of the First Image:

Orientation: ____________________

Magnification: __________________

Type: __________________

Summary of Distances:

FIRST IMAGE:

$$\left.\begin{array}{l} d_{o1} = \_\_\_\_\_\_\_\_\ \text{cm} \\ d_{i1} = \_\_\_\_\_\_\_\_\ \text{cm} \end{array}\right\} \rightarrow m_1 = \frac{-d_{i1}}{d_{o1}} =$$

FINAL IMAGE:

$$\left.\begin{array}{l} d_{o2} = \_\_\_\_\_\_\_\_\ \text{cm} \\ d_{i2} = \_\_\_\_\_\_\_\_\ \text{cm} \\ \text{(calculated)} \end{array}\right\} \rightarrow m_2 = \frac{-d_{o2}}{d_{i2}} =$$

Visual Estimate of the Total Magnification:

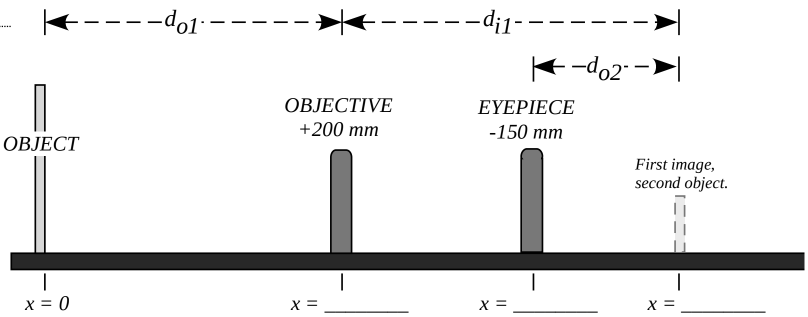
$$\left.\begin{array}{l} \text{There are } n_o = \_\_\_\_\_\_\_\_ \text{ squares of the object,} \\ \text{inside } n_i = \_\_\_\_\_\_\_\_ \text{ squares of the image.} \end{array}\right\} \quad M_{\text{visual}} = \frac{-n_o}{n_i} =$$

Theoretical Total Magnification:

$$M = m_1 m_2 =$$

DATA TABLE PROCEDURE C: The Galilean Telescope: Using a Negative Eyepiece

Summary of Positions:



Visual Description of the First Image:

Orientation: ____________________

Magnification: __________________

Type: __________________

Summary of Distances:

FIRST IMAGE:

$$\left.\begin{aligned} d_{o1} &= \_\_\_\_\_\_\_\_\ \text{cm} \\ d_{i1} &= \_\_\_\_\_\_\_\_\ \text{cm} \end{aligned}\right\} \rightarrow m_1 = \frac{-d_{i1}}{d_{o1}} =$$

FINAL IMAGE:

$$\left.\begin{aligned} d_{o2} &= \_\_\_\_\_\_\_\_\ \text{cm} \\ d_{i2} &= \_\_\_\_\_\_\_\_\ \text{cm} \\ &\text{(calculated)} \end{aligned}\right\} \rightarrow m_2 = \frac{-d_{o2}}{d_{i2}} =$$

Visual Estimate of the Total Magnification:

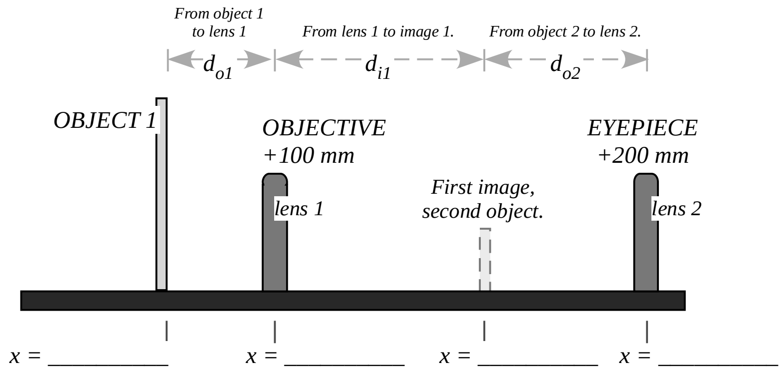
$$\left.\begin{aligned} &\text{There are } n_o = \_\_\_\_\_\_\_\_\ \text{squares of the object,} \\ &\text{inside } n_i = \_\_\_\_\_\_\_\_\ \text{squares of the image.} \end{aligned}\right\} \quad M_{\text{visual}} = \frac{n_o}{n_i} =$$

Theoretical Total Magnification:

$$M = m_1 m_2 =$$

DATA TABLE PROCEDURE D: The Compound Microscope: Looking at a Nearby but Very Small Object

Summary of Positions:



Visual Description of the First Image:

Orientation: ____________________

Magnification: __________________

Type: __________________

Summary of Distances:

FIRST IMAGE:

$d_{o1} =$ ________ cm

$d_{i1} =$ ________ cm

$\rightarrow \quad m_1 = \dfrac{-d_{i1}}{d_{o1}} =$

FINAL IMAGE:

$d_{o2} =$ ________ cm

$d_{i2} =$ ________ cm (calculated)

$\rightarrow \quad m_2 = \dfrac{-d_{o2}}{d_{i2}} =$

Total Magnification:

$$M = m_1 m_2 =$$

What is the message?

QUESTIONS for PROCEDURES A, B and C: Telescopes

1. It should have been immediately obvious that when you look through the astronomical telescope (procedures A and B) the image is upside down. Discuss: Is this a big problem when making astronomical observations?

2. In contrast: What is the orientation of the final image in the Galilean telescope?

3. Is the final image from a telescope real or virtual? How can you tell?

4. How good were your visual estimates of the total magnification of the telescopes, as compared to the theoretically expected values? Discuss what makes the visual estimates hard to measure in each case.

5. According to Eq. 3, the total magnification of a two lens system is $M = m_1 m_2$. Go to Procedure A: use the theoretical magnification and the calculated value for m_2, to calculate what must have been the magnification of the first image, m_1. Does the value of matches your visual observations? Discuss.

6. Use your calculation of m_1 (question 4) and Eq. 2 to determine the distance from the objective to the object, d_{o1} (the one we assumed was infinite). Discuss: does the calculated distance seem realistic, given the actual object you were looking at? Why yes or why not? Was it reasonable, then, to assume that $d_{o1} \rightarrow \infty$?

7. In general, which type of telescope would require a longer tube-length, an astronomical telescope or a Galilean telescope? Why?

QUESTIONS for PROCEDURE D: The Compound Microscope

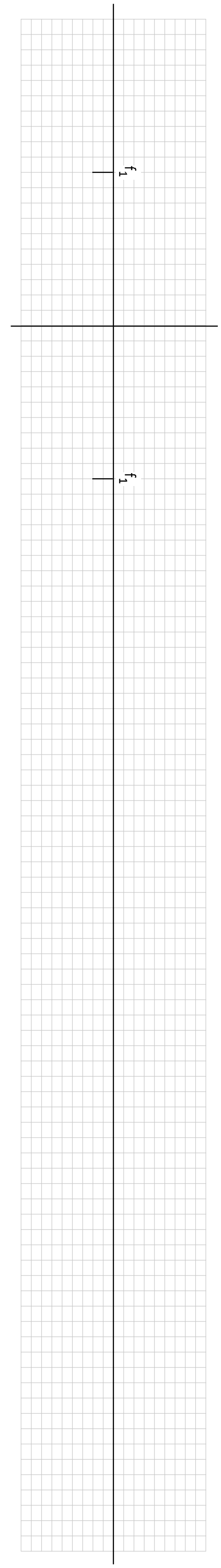
1. Is the final image of the microscope upright or upside down?

2. Is the final image of the microscope real or virtual? How can you tell?

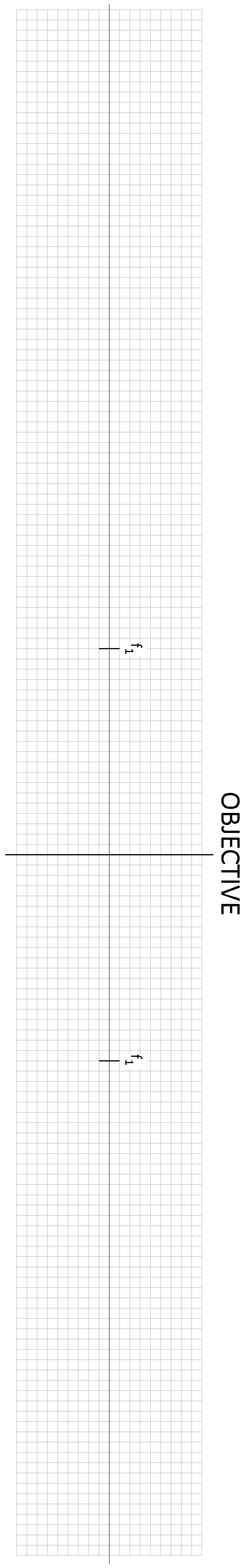
RAY DIAGRAMS

Use the grids provided in the next pages to trace principal ray diagrams for Procedures B, C and D.

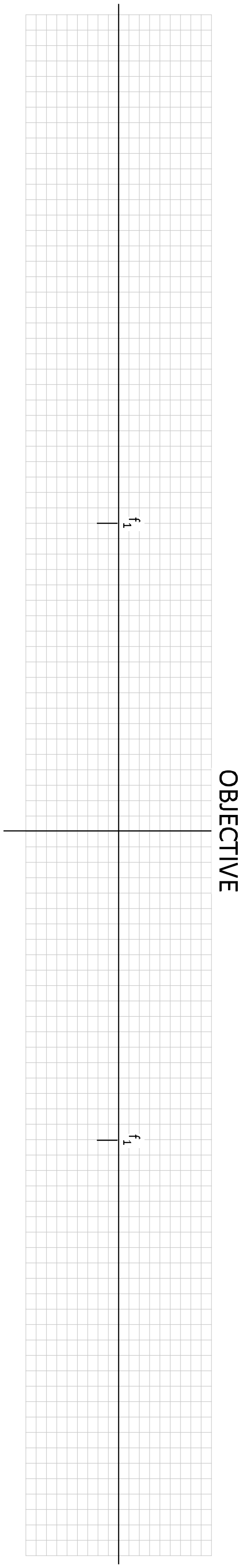
PROCEDURE D: The Compound Microscope



PROCEDURE B: The Astronomical Telescope: Looking at a Nearby Object



PROCEDURE C: The Galilean Telescope: Using a Negative Eyepiece



GRID PATTERN

Copy and attach to the Viewing Screen