The Telescope and the Microscope

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 conditions, the Thin Lens Formula can be used:

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

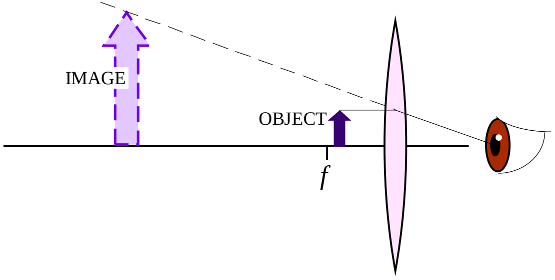
[Eq. 1 — The thin lens formula.]

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:

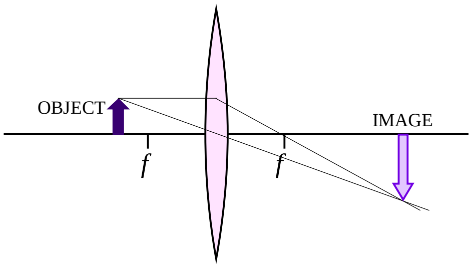
$$m=\frac{-d_i}{d_o}$$

[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, it m is positive; the image is upright. It 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 on 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:

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

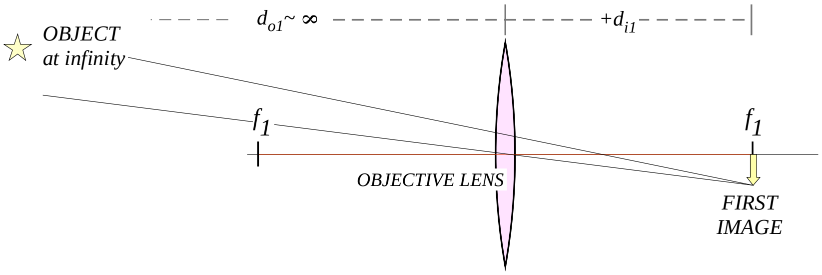
[Eq. 3 — The total magnification of a two-lens system.]

The Refractive Astronomical Telescope:

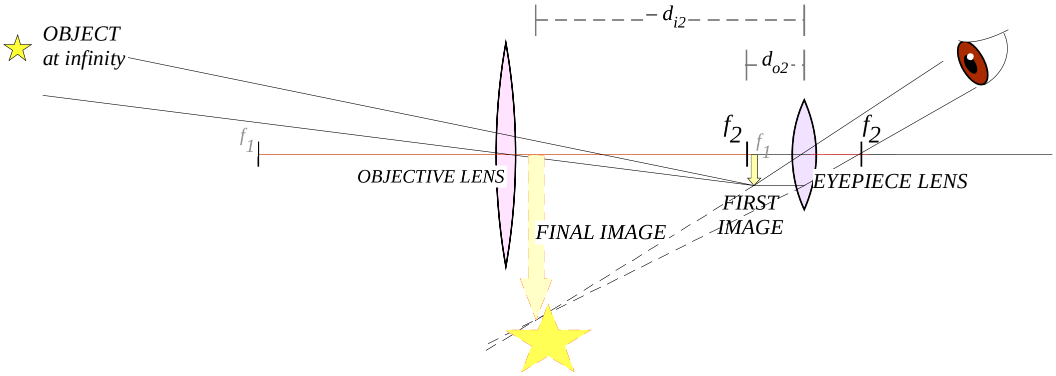
An astronomical telescope is used to view large objects that are at large distances from the lenses. A *refractive telescope* uses lenses, and the principle is very simple: the objective lens produces a first real image of a very far away object. From the thin lens equation, notice that if the distance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

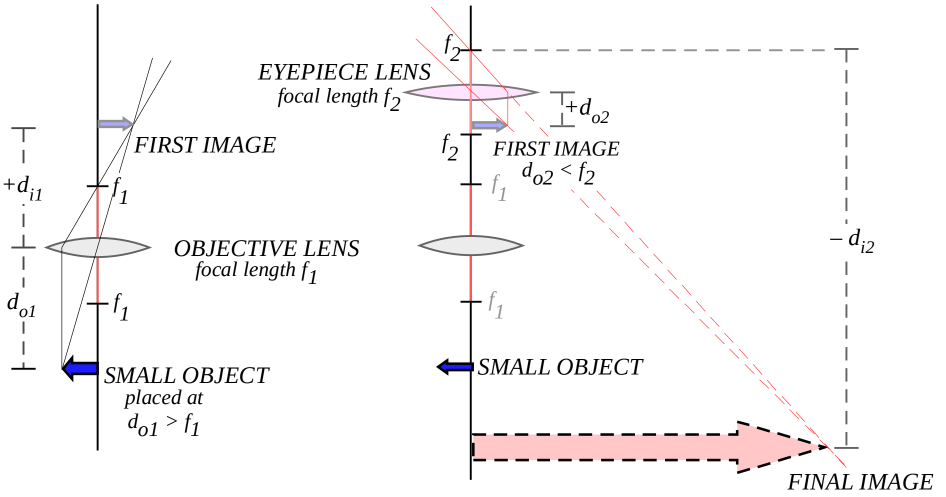
The magnification of an astronomical telescope with the object at infinity, and with f_1 and f_2 both coincident with the first image, is defined as the ratio of the focal length of the objective to that of the eyepiece:

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

[Eq. 4 — The magnification of a telescope with an 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. Go to the wall near the rear door of the laboratory. Bring with you the mounted converging lens (the one with +100 and +200 nm on it) and a ruler. Your TA will raise the blinds of the window directly across from the wall. The light coming from the wall will be your object.
2. Focus an image of the trees or buildings outside of the window on the wall. You may ask your lab partner to stand in front of the window so that you can see how this situation related to the movie theatre.
3. When you have a focused image, use the ruler to measure the distance from the wall to the lens. The distance you measured is the image distance d_{i1} and d_{i2}.

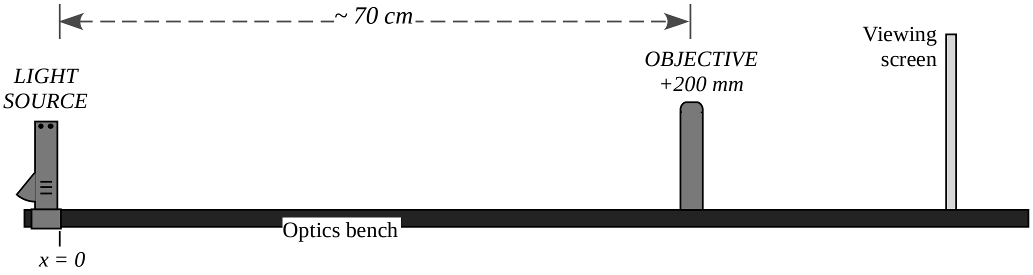
Analysis A
The Astronomical Telescope: Looking at a Far Away Object

1. Why is the image distance approximately equal to the focal length ?
2. Is the image real or virtual?

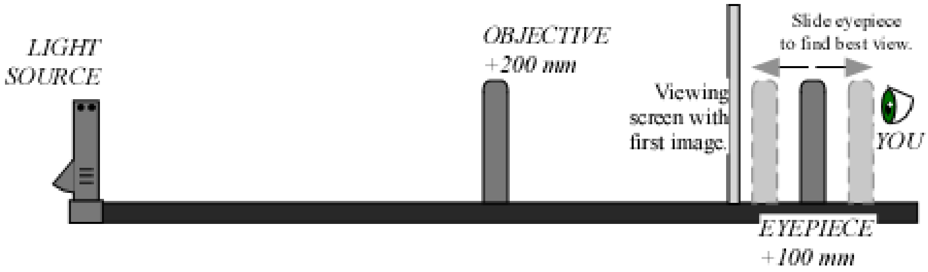
Procedure B: The Astronomical Telescope: Looking at a Nearby Object

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.
4. 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.
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. Install the +100 mm lens (the eyepiece) directly behind the viewing screen.
7. 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 comfortably see 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.)



Analysis B
The Astronomical Telescope: Looking at a Nearby Object

1. Use the recorded positions to determine the following distances:
    - Distance from object to the objective lens d_{o1}.
    - Distance from an objective lens to the first image d_{i1}.

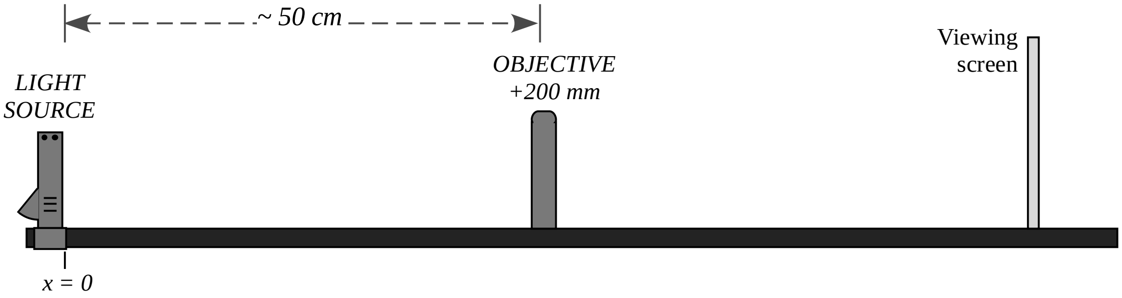
- Distance from the first image to the eyepiece lens d_{o2}.

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.

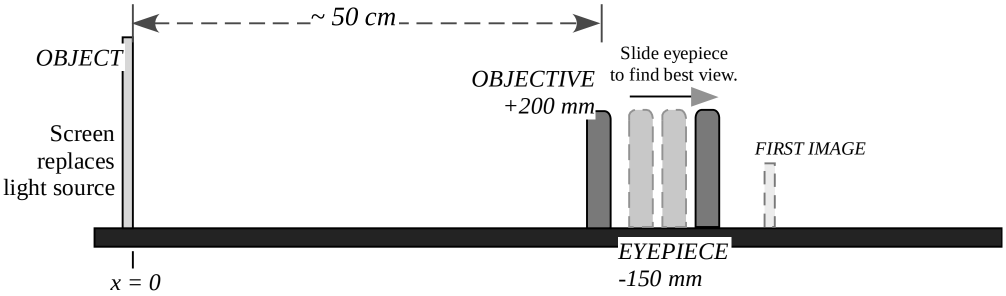
Procedure C
The Galilean Telescope: Using a Negative Eyepiece

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.)

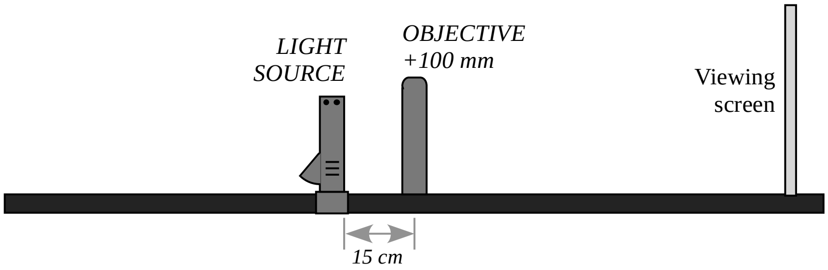


Analysis C
The Galilean Telescope: Using a Negative Eyepiece

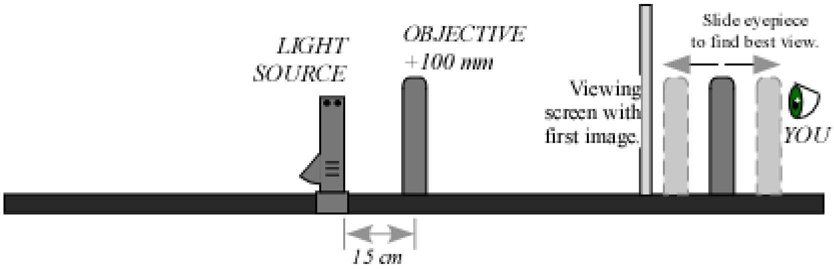
1. Use the recorded positions to determine the following distances:
   - Distance from object to the objective lens d_{o1}.
   - Distance from an objective lens to the first image d_{i1}.
   - Distance from the first image to the eyepiece lens d_{o2}.
2. The convention for using the thin lens equation 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 comfortably see 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.)



Analysis D

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

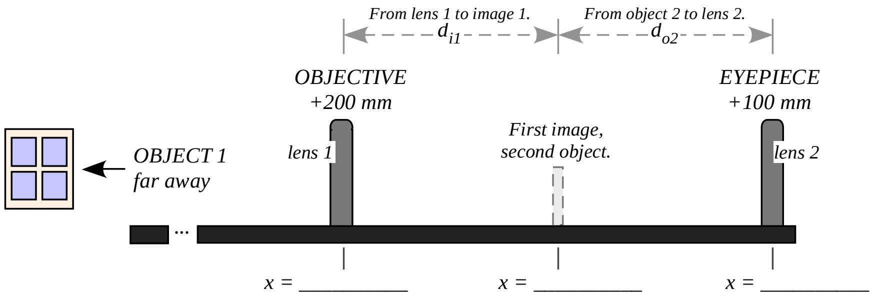
1. Use the recorded positions to determine the following distances:
   - Distance from object to the objective lens d_{o1}.
   - Distance from an objective lens to the first image d_{i1}.
   - Distance from the first image to the eyepiece lens d_{o2}.
2. Use the thin-lens formula (Eq. 1) to calculate 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: $d_{o1} \to \infty$

$d_{i1} =$ ________ cm

FINAL IMAGE:

$d_{o2} =$ ________ cm

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

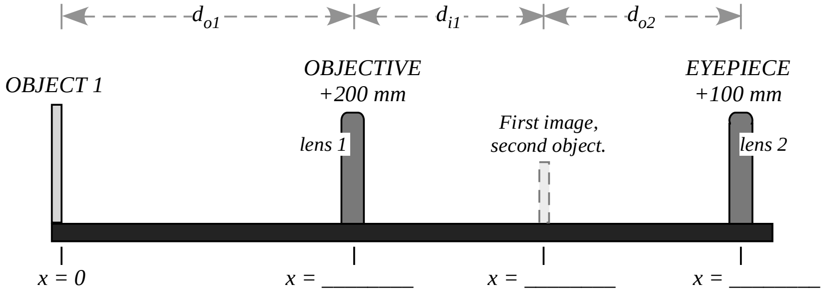
$$\left.\begin{aligned} d_{o2} &= \_\_\_\_\_\_\_\_ \text{ cm} \\ d_{i2} &= \_\_\_\_\_\_\_\_ \text{ cm} \end{aligned}\right\} \to m_2 = \frac{-d_{o2}}{d_{i2}} =$$

Theoretical Total Magnification:

$$\left.\begin{aligned} \text{Objective focal length} \quad f_1 &= \_\_\_\_\_\_\_\_ \\ \text{Eyepiece focal length} \quad f_2 &= \_\_\_\_\_\_\_\_ \end{aligned}\right\} \quad M = \frac{-f_1}{f_2} =$$

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:

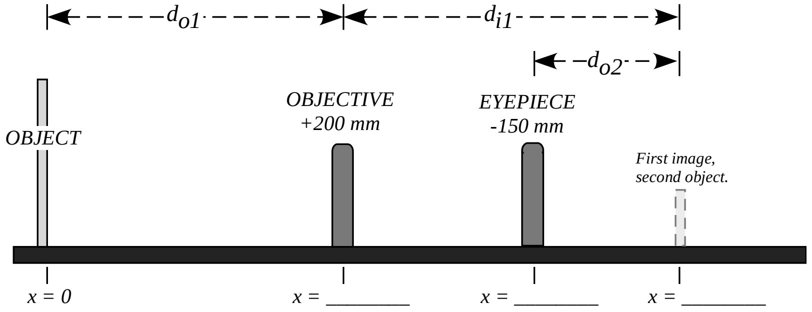
$$\left.\begin{array}{l} d_{o2} = \_\_\_\_\_\_\_\_ \text{ cm} \\ d_{i2} = \_\_\_\_\_\_\_\_ \text{ cm} \\ \text{(calculated)} \end{array}\right\} \rightarrow m_2 = \frac{-d_{o2}}{d_{i2}} =$$

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:

$d_{o1} =$ ________ cm

$d_{i1} =$ ________ cm

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

FINAL IMAGE:

$d_{o2} =$ ________ cm

$d_{i2} =$ ________ cm

(calculated)

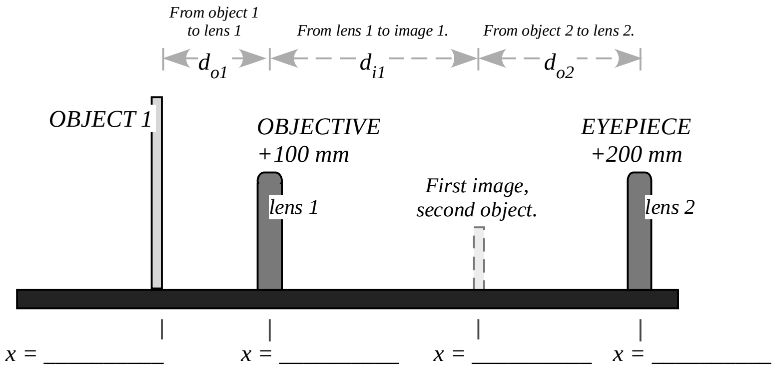
$$\rightarrow \quad m_2 = \frac{-d_{o2}}{d_{i2}} =$$

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:

$$\text{FIRST IMAGE:}\quad \left.\begin{array}{l} d_{o1} = \underline{\hspace{2cm}}\ \text{cm} \\ \\ d_{i1} = \underline{\hspace{2cm}}\ \text{cm} \end{array}\right\} \quad \rightarrow \quad m_1 = \frac{-d_{i1}}{d_{o1}} =$$

$$\text{FINAL IMAGE:}\quad \left.\begin{array}{l} d_{o2} = \underline{\hspace{2cm}}\ \text{cm} \\ \\ d_{i2} = \underline{\hspace{2cm}}\ \text{cm} \\ \text{(calculated)} \end{array}\right\} \quad \rightarrow \quad m_2 = \frac{-d_{o2}}{d_{i2}} =$$

Total Magnification:

$$M = m_1 m_2 =$$

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

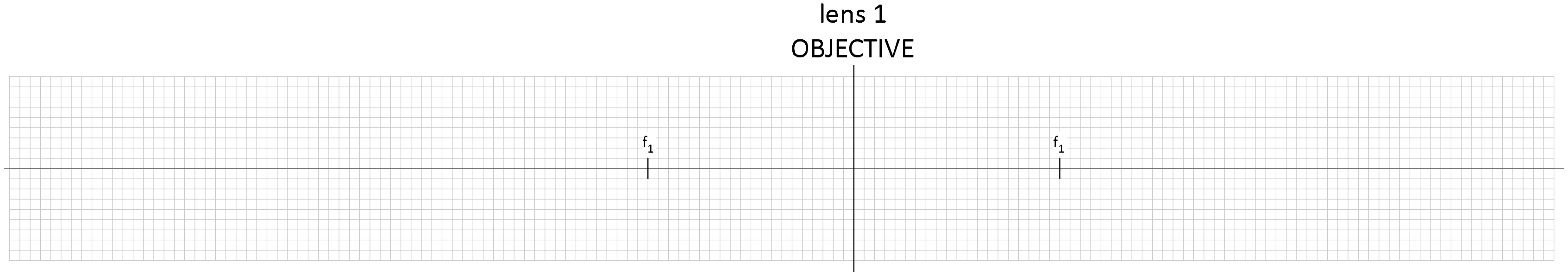
QUESTIONS for PROCEDURE D: The Compound Microscope

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?

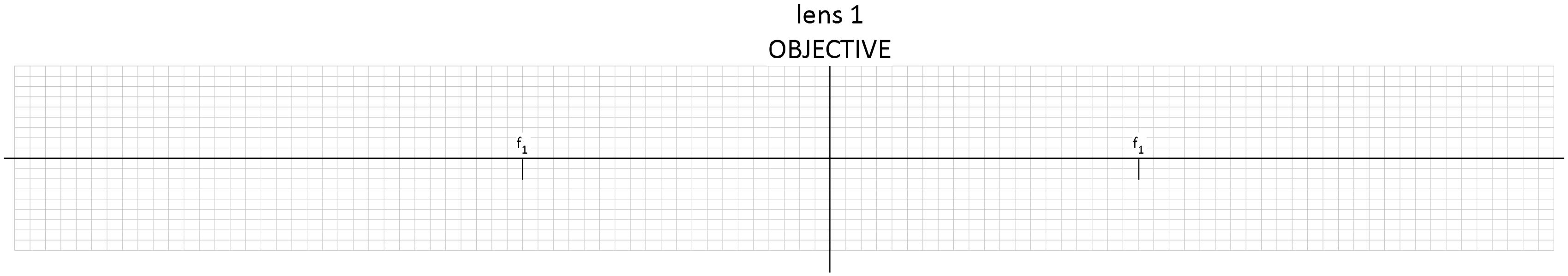
RAY DIAGRAMS

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

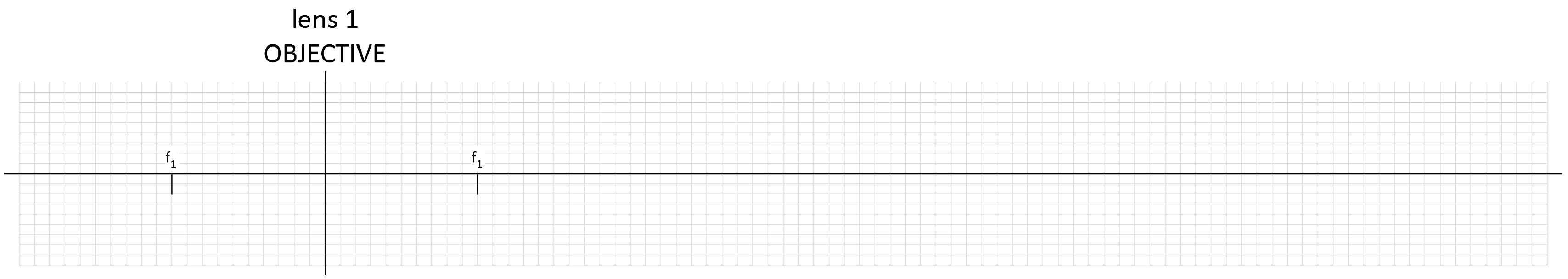
PROCEDURE B: The Astronomical Telescope: Looking at a Nearby Object



PROCEDURE C: The Galilean Telescope: Using a Negative Eyepiece



PROCEDURE D: The Compound Microscope



GRID PATTERN
Copy and attach to the Viewing Screen