# Laws of lenses and optical instruments

Physics | Light & Optics | Optical devices & lenses

| Difficulty level | Group size | Preparation time | Execution time |
|---|---|---|---|
| - | - | - | - |

This content can also be found online at:

http://localhost:1337/c/65f04edac6bdac0002d1ed36

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# General information

## Application

A photo of a refracting telescope

Since human eyes have limited size and frequency response, our vision is hence limited to certain distances and size of the objects. However, microscopes let us to peer within microscopic world, telescopes take us far beyond the Earth to the universe and endoscopes allow us to examine the inside of the body. All these things are possible because of lenses.

A lens focuses or refracts light rays as they pass through it, that means the rays seem to come from a point that's closer or further away from where they actually originate and that's what makes objects seen through a lens seem either bigger or smaller than they really are. It can be used as a single lens or as a compound lens, which consists of more than one element.



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## Other information (1/3)

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**Prior knowledge**

Since the index of refraction of the lens is greater than that of air, in accordance with the law of refraction, the light rays move towards the perpendicular as it enters and away from the perpendicular as it leaves, depending on the lens's shape. The point at which the rays cross is defined to be the focal point *F* of the lens. The distance from the center of the lens to its focal point is defined to be the focal length *f* of the lens.

**Scientific principle**

1. If light passes through a convex lens, it is converged to a spot (a focus) in front of the lens to form a real image of the object. The focal length of a converging lens is defined to be positive.
2. If light passes through a concave lens, it is diverged and appears to emanate from a particular point on the axis behind the lens, which is called the virtual image. The focal length of a diverging lens is defined to be negative.

## Other information (2/3)

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**Learning objective**

The focal lengths of unknown lenses are determined by measuring the distances of image and object and by Bessel's method. Simple optical instruments are then constructed with these lenses.

**Tasks**

1. To determine the focal length of two unknown convex lenses by measuring the distances of image and object.
2. To determine the focal length of a convex lens and of a combination of a convex and a concave lens using Bessel's method.



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## Other information (3/3)

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### Tasks

3. To construct the following optical instruments:

- Slide projector; image scale to be determined.
- Microscope; magnification to be determined.
- Kepler-type telescope.
- Galileo’s telescope (opera glasses).

## Safety instructions

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- The common rules of safe experimentation in scientific education apply in this experiment.



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## Theory (1/8)

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The relationship between the focal length $f$ of a lens, the object distance and the image distance is obtained from geometrical optics. Three particular rays, the focal ray, the parallel ray and the central ray, are used to construct the image. From the laws of similar triangles,

$$\frac{B}{G} = \frac{b}{g} \quad \text{and} \quad \frac{G}{B} = \frac{f}{b-f}$$

where $B$ is the image size and $G$ is the object size. By transforming, we obtain the lens formula

$$\frac{1}{f} = \frac{1}{b} + \frac{1}{g} \quad \text{or} \quad f = \frac{bg}{b+g}$$

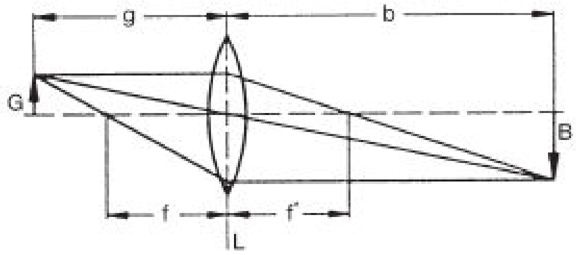


Image construction with three principal rays

## Theory (2/8)

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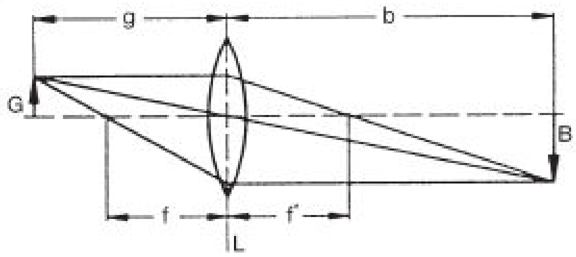
The magnification is obtained from the relationship between object size $G$ and image size $B$

$$V = \frac{B}{G} = \frac{b-f}{f}$$

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# Theory (3/8)

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**Combination of two lenses**

Since $g_I = b_{II}$ (the object distance in case I = image distance in case II) and since $b_I = g_{II}$ .

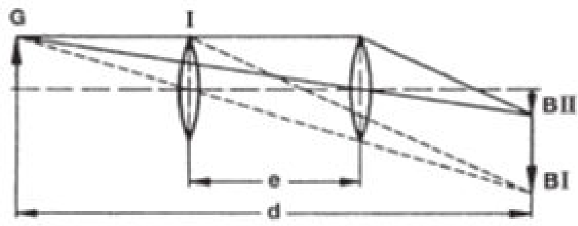
$$g_I + b_I = d$$

$$g_I + b_I = e\ .$$

If we solve the equations for $g_I$ and $b_I$ we obtain

$$g_I = \frac{1}{2}(d+e)$$

$$b_I = \frac{1}{2}(d-e)$$




Determination of focal length after Bessel

# Theory (4/8)

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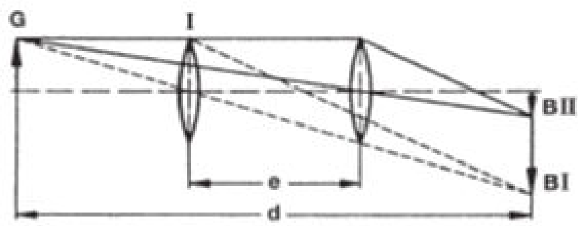
Substituting into the lens formula gives

$$f = \frac{d^2-e^2}{4d}$$

The focal length of the convex lens can therefore be determined from the measured values of *d* and *e*.




Determination of focal length after Bessel



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# Theory (5/8)

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If the combined focal length $f_{comb}$ of a lens system consisting of a convex lens with measured focal length $f_s$ and a concave lens, and the measurement is carried out in the same way, the focal length of the concave lens $f_z$ can be defined as:

$$\frac{1}{f_z} = \frac{1}{f_{comb}} - \frac{1}{f_s} \quad \text{or} \quad f_z = \frac{f_{comb} \cdot f_s}{f_s - f_{comb}}$$

Here it is assumed that

$$\frac{1}{|f_s|} > \frac{1}{|f_z|}$$

as otherwise no real images would be produced.

# Theory (6/8)

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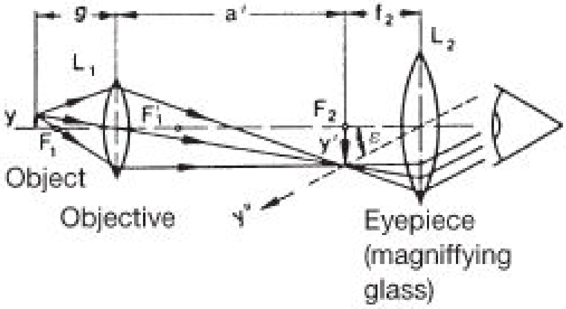
**Microscope**

The overall magnification is obtained by multiplying the magnification due to the objective

$$\beta_{objective} = \frac{Y'}{Y} = \frac{a'}{g} = \frac{a'}{f_1} - 1$$

by the angular magnification of the eyepiece

$$\Gamma_L = \frac{250\,\mathrm{mm}}{f_2}$$




Path of a ray in the microscope



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## Theory (7/8)

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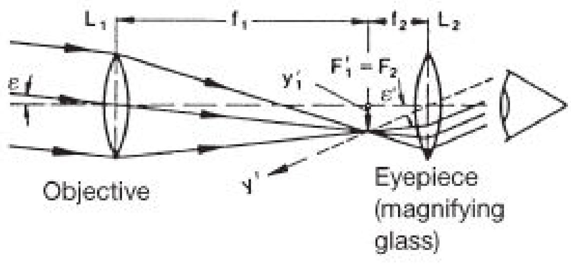
### Telescope after Kepler

The objective $L_1$ provides a real, inverted image of size $Y_1'$ of a very distant object, and this image is observed through the eyepiece $L_2$ . The angular magnification (for small angles) is

$$\Gamma_L = \frac{\epsilon'}{\epsilon} = \frac{Y_1'/f_2}{Y_1'/f_1} = \frac{f_1}{f_2}$$




Path of a ray in a Kepler telescope

## Theory (8/8)

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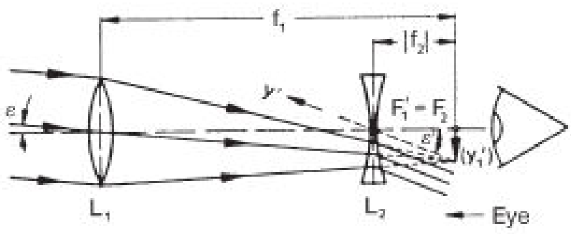
### Galileo Telescope

A concave lens is placed in the path of the ray in front of the real first image produced by objective $L_1$ so that the focal points $F_1'$ and $F_2$ coincide. The eye then sees a virtual, upright image. The magnification is once again

$$\Gamma_L = \frac{f_1}{|f_2|}$$




Path of a ray in Galileo telescope



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# Equipment

| Position | Material | Item No. | Quantity |
|---|---|---|---|
| 1 | Experimental lamp LED HEX 1 | 08130-99 | 1 |
| 2 | Lens made of glass, biconvex, f = + 20 mm | 08059-00 | 1 |
| 3 | Lens made of glass, biconvex, f = + 50 mm | 08050-00 | 1 |
| 4 | Lens made of glass, biconvex, f = + 100 mm | 08051-00 | 1 |
| 5 | Lens made of glass, biconvex, f = + 300 mm | 08054-00 | 1 |
| 6 | Lens made of glass, biconcave, f = - 50 mm | 08055-00 | 1 |
| 7 | Lens made of glass, biconcave, f = - 200 mm | 08057-00 | 1 |
| 8 | Screen, translucent, 250x250 mm | 08064-00 | 1 |
| 9 | Screen, with arrow slit | 08133-01 | 1 |
| 10 | Ground glass screen,50x50x2 mm | 08136-01 | 1 |
| 11 | PHYWE Object micrometer on glass plate, 1 mm in 100 parts | 62171-19 | 1 |
| 12 | Dog flea, microscopic slide in slide box | 87337-55 | 1 |
| 13 | Slide -Emperor Maximilian- | 82140-00 | 1 |
| 14 | Optical bench expert, l = 1000 mm | 08282-00 | 1 |
| 15 | Base for optical bench expert, adjustable | 08284-00 | 2 |
| 16 | Slide mount for optical bench expert, h = 80 mm | 08286-02 | 6 |
| 17 | Universal Holder, rotational | 08040-02 | 2 |
| 18 | Component holder | 08043-00 | 2 |
| 19 | Swinging arm | 08256-00 | 1 |
| 20 | Ruler, plastic, 200 mm | 09937-01 | 1 |
| 21 | Ring for component holder | 08044-00 | 6 |



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# Setup and procedure

## Setup


Experimental set-up (microscope)

The experiment is set up as shown in the figure. A parallel light beam is produced with the lamp and the double condenser. The screen is clamped at the end of the optical bench.



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# Procedure (1/6)

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**Determination of focal length of a lens**

The object (screen with arrow slit) is placed directly behind the condenser, and a clear image is projected on to the screen with a lens. The distances of image and object from the lens are measured (assume that the lenses are thin).

The measurement of distances of image and object is repeated, using both lenses and with the lens and the screen in different positions

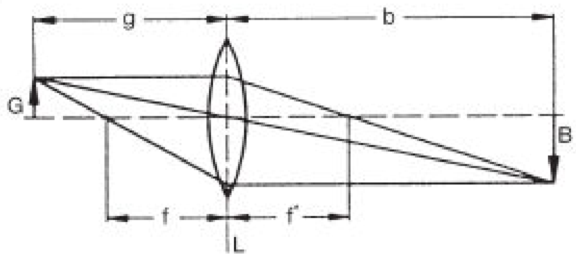



Image construction with three principal rays

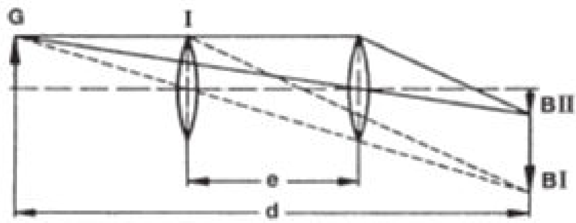
# Procedure (2/6)

PHYWE

**Determination of focal length of two lens**

If, at a fixed distance *d* between object and image (case I), the position of the lens is altered so that the image and object distances are transposed (case II), we still obtain a clear image of the object. In case II the image is magnified, in case II it is reduced.

Using a convex lens of focal length +100 mm, for instance, measure the distance *e* at which a sharp image is obtained for both possible lens positions. Repeat the measurement and calculate the average value of $\overline{e}$. Then take a measurement in the same way but using the convex lens from the first measurement and a concave lens (-200 mm for example). Make the distance *d* as large as possible, and measure at least four times the combined focal length.




Determination of focal length after Bessel.



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# Procedure (3/6)

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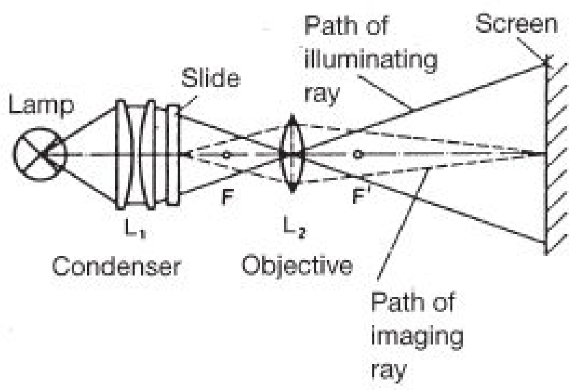
**Slide Projector**

1. Place the slide Emperor Maximilian directly behind the condenser and project an image on the screen with the lens $L_2( f_2 = +100mm)$.
2. To obtain the best image illumination, set the condenser so that the image of the lamp coil is in the plane of objective lens $L_2$.
3. Determine the magnification $V$ of the image.




Path of a ray in a slide projector.

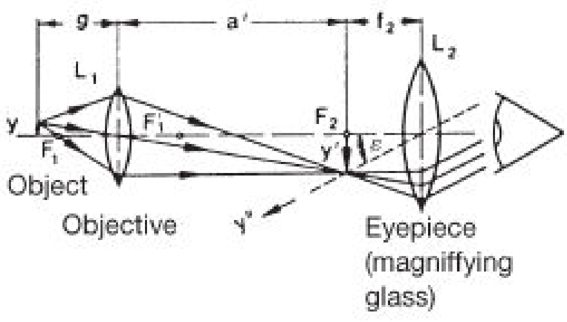
# Procedure (4/6)

PHYWE

**Microscope**

A magnified image of a small object (stage micrometer and micro-slide of a dog flea) is produced with a lens $L_1$ of short focal length $f_1 = 20mm$. The real intermediate image is observed through an eyepiece $L_2(f_2 = +50mm)$. The ground glass and the object holder with the object are fixed in the swinging arm. $L_1$ is brought as close to the object as possible. The object is illuminated through a ground glass screen.

The size of the image and thence the overall magnification are roughly determined by comparing it with a scale at the least distance of distinct vision (approximately 25 cm). To do this one looks through the microscope with the right eye and at the scale with the left.




Path of a ray in the microscope.



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## Procedure (5/6)

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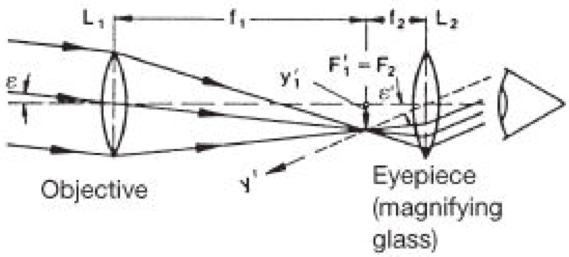
**Telescope after Kepler**

A convex lens of long focal length $f_1 + 300mm$, for example), and one of short focal length $f_2$ (e.g. +50 mm) are secured to the optical bench at a distance of $f_1 + f_2$.

If one looks through the lens of short focal length, one can see an inverted, magnified image of a distant object.




Path of a ray in a Kepler telescope.

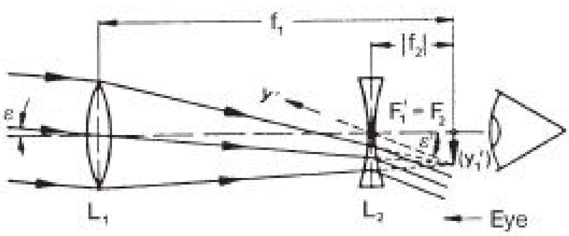
## Procedure (6/6)

PHYWE

**Galileo Telescope**

A convex lens of long focal length $f_1$ (+300 mm, for example) and a concave lens of short focal length $f_2$ (e. g. -50 mm) are set up at a distance of $f_1 - |f_{2-}|$.

Through the concave lens one can see distant object magnified and the right way up.




Path of a ray in Galileo telescope.



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## Evaluation (1/3)

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The determination of the focal length of a lens for single lens system (left) and two lens system (right) can be computed as below.

| $g/mm$ | $b/mm$ | $\frac{1}{g}/mm^{-1}$ | $\frac{1}{b}/mm^{-1}$ | $f/mm$ |
|---|---|---|---|---|
| 20 | | | | |
| 40 | | | | |
| 60 | | | | |

$\overline{f}$ = ____________

| No. | *e* / mm |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| 4 | |

$f_s$ = ____________

$d$ = ____________

$\overline{e}$ = ____________

$f_{comb}$ = ____________

$f_z$ = ____________

## Evaluation (2/3)

PHYWE

Fill in the statements best describes the image produced by a concave and a convex lens

A convex lens produces a ________, inverted and ________ image, meanwhile a concave lens produces a ________, upright, and ________ image. Besides, the sign convention of magnification is relative to the orientation of the object. A positive magnification corresponds to an ________ image, while a negative magnification corresponds to an ________ image.

- reduced
- virtual
- inverted
- enlarged
- real
- upright

Check



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# Evaluation (3/3)

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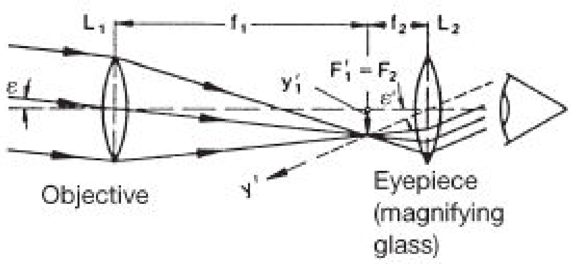
Which of the following statements best describes the schematic of the Kepler telescope below?

- [ ] The telescope forms an inverted image
- [ ] The objective must have a shorter focal length than that of eyepiece for a greater magnification.
- [ ] The eyepiece magnifies the first projected image.

Check




Schematic of Kepler telescope

| Slide | Score / Total |
|---|---|
| Slide 25: Lenses and their images | 0/6 |
| Slide 26: Kepler's telescope | 0/2 |

**Total Score** 0 / 8

Show solutions Retry



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