

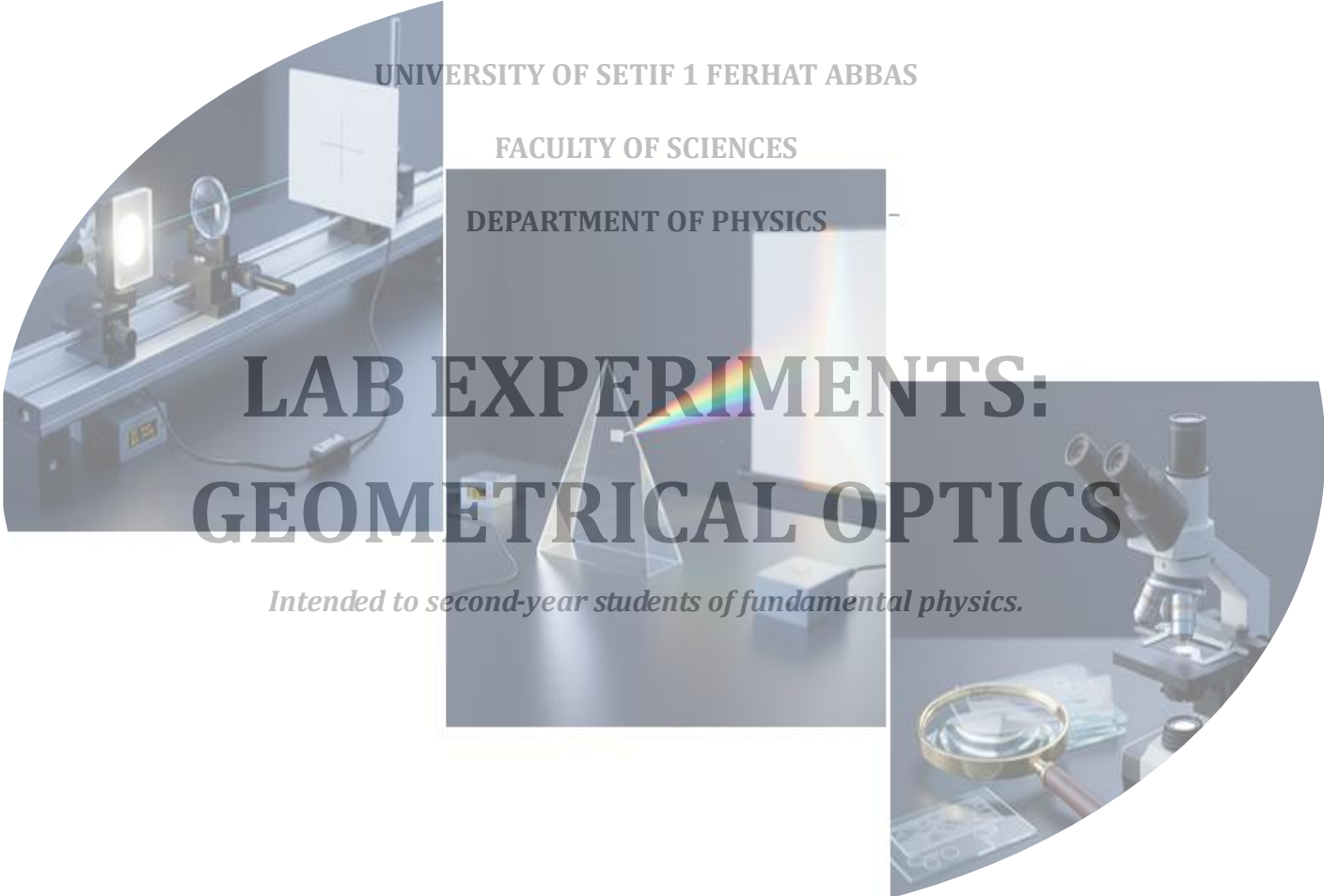
PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

UNIVERSITY OF SETIF 1 FERHAT ABBAS

FACULTY OF SCIENCES

DEPARTMENT OF PHYSICS



LAB EXPERIMENTS: GEOMETRICAL OPTICS

Intended to second-year students of fundamental physics.

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Experiment N°1:

Reflection and refraction of light

Objectives

- Experimentally validate Snell-Descartes laws for reflection and refraction.
- Determine the refractive index of a transparent medium (Plexiglas).
- Observe the phenomenon of total internal reflection.
- Study the path of light rays through prisms and converging lenses.

1. Introduction

Geometrical optics is a branch of physics that models the propagation of light using rays. These rays travel in straight lines within a homogeneous and isotropic medium.

When a light ray encounters the interface between two different transparent media (such as air and glass, or air and water), two phenomena generally occur:

1. Reflection: Part of the light is returned to the original medium.
2. Refraction: Another part of the light enters the second medium, and its direction of propagation is changed.

These fundamental principles are the basis of many optical instruments such as eyeglass lenses, microscopes, endoscopes, and cameras.

2. Materials

- Light source (laser or lamp with condenser)
- Optical disk (graduated circle)
- Plexiglas® plates and prisms (semi-disk, rectangle, prism)
- Converging lens (+100 mm)
- Optical bench
- Sheets of white paper
- Pencil, ruler, protractor

3. Procedure

3.1. Reflection and Refraction on a Plane Surface

3.1.1. Preliminary Experiment:

1. Place the Plexiglas semi-disk at the center of the optical disk, with the flat side facing the light source (air $\rightarrow$ Plexiglas configuration).
2. Turn on the source and ensure that a single incident ray strikes the center of the semi-disk (point I).
3. Observation: Draw a labeled diagram of the situation, showing the incident ray, reflected ray, refracted ray, the normal, the angle of incidence i , and the angle of refraction r .

3.1.2. Verification of Snell-Descartes Law

Snell-Descartes law for refraction is written as:

$$n_1 \sin i = n_2 \sin r$$

With n_1 the refractive index of the incident medium (here, air, $n_{\text{air}} = 1$).

1. Vary the angle of incidence i from 0° to 70° in steps of 10° and measure the corresponding angle of refraction r .
2. Complete the table :

i (in $^\circ$)	0	10	20	30	40	50	60	70
r (in $^\circ$)								

3.1.3. Analysis

Plot the graph $\sin i = f(\sin r)$.

3.1.4. Questions

Q1. What can you say about the obtained curve? Does it justify the proportionality between $\sin i$ and $\sin r$?

Q2. Graphically determine the refractive index n of Plexiglas. Remember that for air, $n_{\text{air}} = 1.00$.

Q3. Compare your value with the theoretical value $n_{\text{theoretical}} = 1.49$. Calculate the relative error.

3.2. Study of the Phenomenon of Total Internal Reflection

1. Turn the Plexiglas semi-disk so that its curved side faces the light source (Plexiglas $\rightarrow$ air configuration).
2. Vary the angle of incidence i from 0° to a larger value.
3. Observation:
 - What happens to the intensity of the refracted ray as i increases?
 - What happens to the intensity of the reflected ray?
 - Is there a value of i for which the refracted ray disappears? Note this limiting value i_{lim} .

3.2.1. Questions

Q4. Define the phenomenon of total internal reflection. In which case is this phenomenon observed?

Q5. Using Snell-Descartes law, calculate the theoretical critical angle i_{lim} for the transition from Plexiglas ($n_{\text{plex}} = 1.49$) to air ($n_{\text{air}} = 1.00$). Compare with your measurement.

Q6. Suggest a practical application of total internal reflection, using the provided documents as a guide.

4. Path of Rays Through a Thin Converging Lens

4.1. Demonstration of Convergence

1. Reset the setup with the optical disk and the parallel light source (using the +100 mm lens and the 5-slit diaphragm).
2. Place the provided converging lens in the path of the parallel rays.
3. Observation: Draw a diagram showing what happens to the 5 rays after passing through the lens.

4.2. Determination of the Focal Length

1. Use only the central slit of the diaphragm.
2. Position the lens so that the central ray (optical axis) is not deviated.
3. Using the graduations on the optical disk, estimate the distance between the optical center of the lens and the point where the rays converge (the image focus F').
4. Measure this distance f' with a ruler.

4.3. Questions

Q7. What is the point where rays parallel to the optical axis converge called?

Q8. What is the value of the focal length f' that you measured? Compare it with the value indicated on the lens (+100 mm).

Q9. What happens if you use the diaphragm with 5 slits? Do you observe the same perfect convergence point for all rays?

5. Study of a Prism

5.1. Definition

A prism is a block of glass or Plexiglas bounded by two non-parallel plane faces (dihedral). The angle between these two faces is the apex angle of the prism, denoted A .

5.2. Path of a Ray Through a Prism

A light ray passing through a prism generally undergoes two refractions: one upon entering (air $\rightarrow$ glass interface) and one upon exiting (glass $\rightarrow$ air interface).

- At entry, the ray bends towards the normal.
- Inside, it propagates in a straight line.
- At exit, it bends away from the normal.

Total internal reflection can also occur on the internal face if the angle of incidence inside the prism is greater than the critical angle.

5.3. Deviation

The direction of the emerging ray is different from that of the incident ray. The total deviation angle D depends on the angle of incidence, the refractive index of the prism, and the apex angle A .

5.4. Applications

1. Replace the lens with a Plexiglas prism.
2. Direct a single light ray onto one face of the prism.
3. Observe the complete path of the ray: it undergoes two refractions (at entry and exit) and possibly total internal reflection inside.
4. Draw a diagram of the path and measure the total deviation angle of the ray.

6. Conclusion

Experiment N°2:

Focometry

Objectives:

- ✓ Measure the focal length of converging or diverging thin lens using various methods.
- ✓ Evaluate the expanded uncertainty and present the experimental result.
- ✓ Analyse the measurements.

I. Introduction

Focometry encompasses the methods for experimentally determining the elements of a centered optical system within the Gauss approximation. This involves thin lenses, rays with slight inclinations to the optical axis, and small angles relative to the lens surface normals.

II. Review of Thin Lenses

II-1 Notations and Constructions

Consider a lens L with optical center O and focal point F and F' (F being the object focal and F' the image focal), forming an image A'B' from an object AB. In the thin lens approximation, the conjugation and magnification relations are expressed as:

$$\frac{1}{OA'} - \frac{1}{OA} = \frac{1}{OF'} \quad \text{and} \quad \frac{A'B'}{AB} = \frac{OA'}{OA}$$

Setting $\overline{OA} = p, \overline{OA'} = p'$ and $\overline{OF'} = f'$

the conjugation relation becomes: $\frac{1}{p'} - \frac{1}{p} = \frac{1}{f'}$

The distance $f' = \overline{OF'}$ is the focal length: it is positive for a converging lens and negative for a diverging lens. The vergence C is defined by $C = 1/f'$, if f' is expressed in meters (m), C is in diopters (δ).

When two thin lenses with image focal lengths f'_1 and f'_2 are combined, the equivalent optical system has a focal length f'_T such that:

$$\frac{1}{f'_1} + \frac{1}{f'_2} = \frac{1}{f'_T} \quad \text{or else} \quad C_T = C_1 + C_2$$

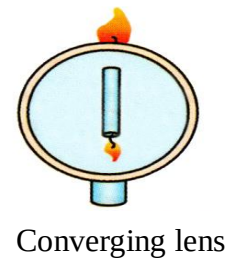
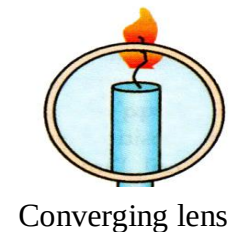
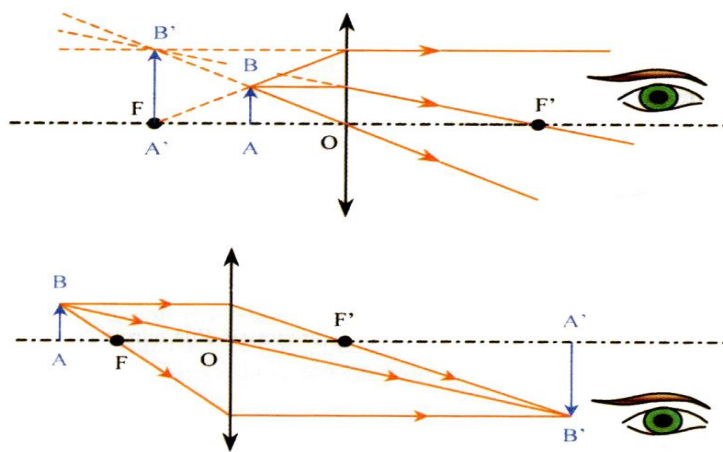
The "optical axis" (or principal axis) is the symmetry axis of the optical system, oriented positively in the direction of the incident light.

Given an object AB, its image through a lens is constructed by considering at least two of the following three principal rays:

- Any incident ray parallel to the optical axis exits the lens in a direction passing through the image focal point F'.
- Any ray passing through the optical center O of the lens is undeviated.

- Any incident ray passing through the object focal point F exits parallel to the optical axis.

The object point is at the intersection of the incident ray supports. The intersection of two outgoing ray supports gives the image position. The physical path of the light is represented with solid lines, while any necessary geometric extensions are dashed.

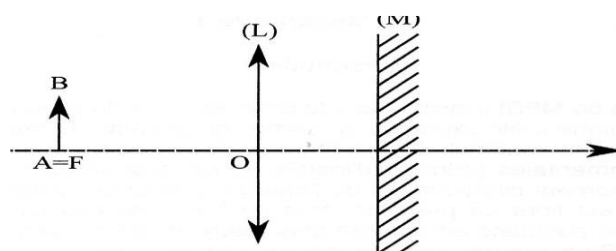


II-2 Quick Identification of a Lens: Converging or Diverging?

You have three lenses at your disposal. Carefully take each lens (**CAUTION, these are fragile objects**) and observe the text in your booklet. Each lens provides a clear image of the text but with different characteristics (e.g., relative size). Knowing that a converging lens can act as a magnifying glass, determine the nature of each lens (i.e., whether it is converging or diverging).

Another quick method to identify whether a lens is converging or diverging is to examine its center thickness relative to its edges. A converging lens is always thicker in the center than at the edges, whereas a diverging lens is thinner in the center than at the edges.

III. Autocollimation Method



III.1 Principle of the Method:

The system under study is a converging lens followed by a plane mirror. When the object AB is in the focal plane of the lens L, the image is also in the same plane as the object, and the magnification is -1.

Construct the geometric image of B in the system to verify this. Note that:

$$A = F \xrightarrow{L} A_{1\infty} \xrightarrow{M} A_{2\infty} \xrightarrow{\text{L With light coming from the right}} A' = F$$

III.2 Measurement of the Focal Length:

Mount the lens (value indicated $f'=100$) and the plane mirror on the same support. Move the "lens/plane mirror" assembly until the image appears in the object's plane. The object-lens distance is then equal to the focal length. Measure f' . Each pair should repeat the measurement three times and fill in the following table:

Measurement N°	1	2	3
f' in mm			

Having made N (3) independent measurements of a physical quantity X, here f' ,

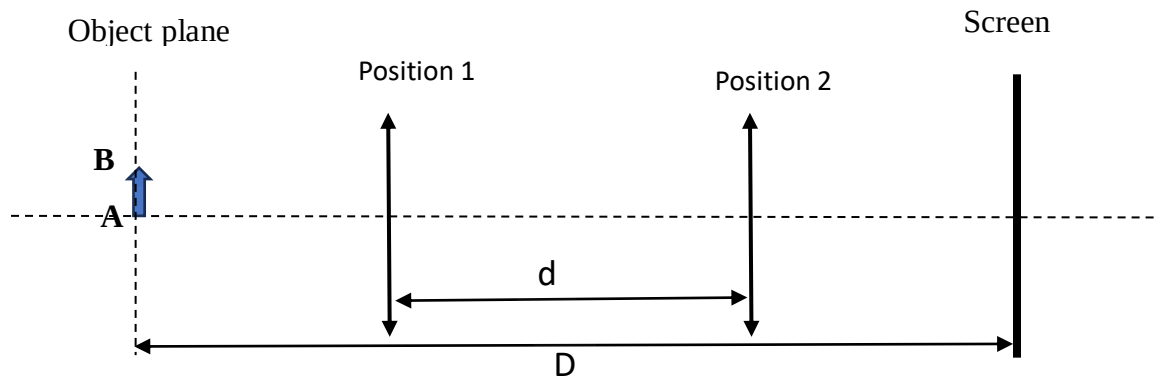
- ❖ Calculate the average value of f' . Present the result as $f' = \dots \pm \Delta f' = \dots \pm \Delta f'$.

Estimate the uncertainty in the object-lens distance measurement at 1 cm (image sharpness in the object plane): $\Delta f' \approx 1 \text{ cm}$.

The manufacturer certifies the value of f' within 5% (expanded uncertainty at 95%).

- ❖ Compare with the experiment. Conclude on the method, its implementation, and its accuracy.

IV. BESSEL Method



IV.1 Principle of the Method:

The idea is to use the condition derived in class for having real objects and images. It was shown that $D = AA' \geq 4f'$.

Using the most appropriate conjugation relation, show that when $D > 4f'$, the two lens positions that allow an image to be obtained on the screen are given by:

$$\overline{AO} = \frac{D}{2} \pm \sqrt{D^2 - 4Df'}, d = \sqrt{D^2 - 4Df'} \xrightarrow{\text{yields}} f' = \frac{D^2 - d^2}{4D}$$

The method involves measuring D and d and then deducing f' .

IV.2 Measurements of D and d

As in II), perform three measurements of d for different values of D with the same lens.

D	$\overline{AO_1}$	$\overline{AO_2}$	$d = \overline{AO_1} - \overline{AO_2}$	f'

- ❖ Calculate the average value of f' . Present the result as $f' = \dots \pm \Delta f'$. Estimate $\Delta D = 1\text{mm}$ (minimum graduation of the optical bench ruler or millimeter paper).

$$\Delta \overline{AO1} = \Delta \overline{AO2} = 1\text{cm}, (\text{image sharpness assessment}).$$

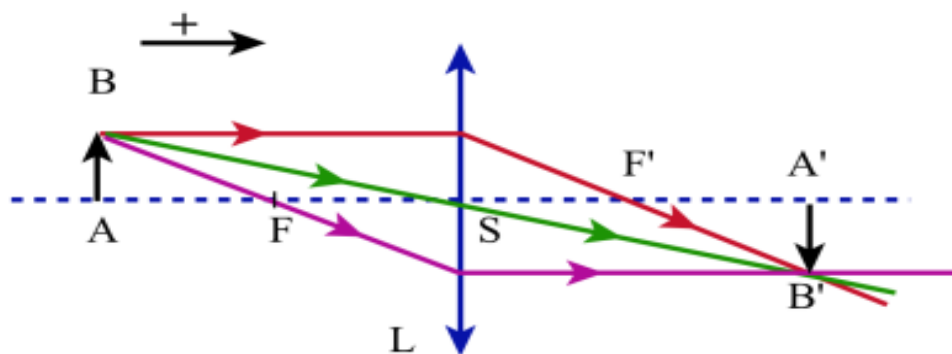
Using differential calculation, show that:

$$\Delta f' = \frac{D^2 - d^2}{4D} \Delta D + \frac{d}{2D} \Delta d$$

- ❖ Provide the measurement precision $\Delta f'/f'$.

V. SILBERMANN Method

As shown below, when the object is at $2f'$ from the lens and the image is at $2f'$ from the lens, we are in the Silbermann case.



V.1 Principle of the Method:

The Silbermann method is a special case of the Bessel method; it corresponds to $d=0$, i.e., *when there is only one possible image position* (sharp, same size, and inverted) for a certain screen position. The Bessel formula simplifies to:

$$f' = D/4$$

V.2 Measurement of D

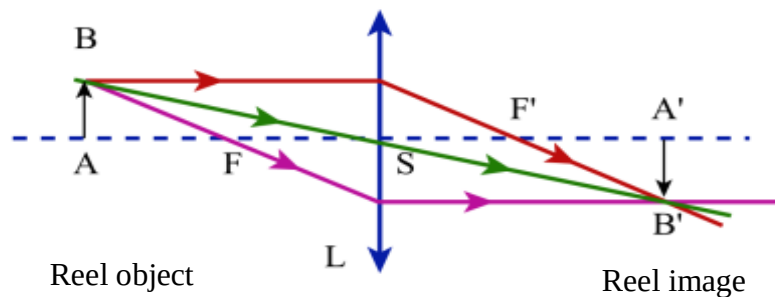
Record several measurements to minimize error.

$\overline{SA}$	$\overline{SA'}$	D	f'

- ❖ What focal length do you obtain? Compare with the theoretical value.
- ❖ Calculate the average value of f' . Present the result as $f' = \dots \pm \Delta f'$.
- ❖ Estimate ΔD by assessing the image sharpness and calculate Δf and $\Delta f'/f'$.

- ❖ Compare the accuracy of the SILBERMANN and BESSEL methods and provide your comments.

VI. Conjugate Points Method



VI.1 Principle of the Method:

The focal length can also be determined using Descartes' law:

$$\frac{1}{f'} = \frac{1}{p'} - \frac{1}{p}$$

$OA=p$ and $OA'=p'$ are respectively the lens-object and lens-image distance.

Position the light source at one end of the optical bench, and place the object in the designated location on the lantern. Add a lens with a focal length $f'=100$ mm (on a simple holder). The screen will then be placed on a simple holder after the lens. Using this setup, we will determine the focal length of a lens.

Fix the object at a known position. Position the lens at a distance L from the object, and then locate the image of the object through the lens. Record its position XA' . Next, change the position of the lens by 10 cm, for example, and find the new image. Continue this process, adjusting the lens position by 10 cm for each measurement until three measurements are obtained.

- ❖ Calculate the average value of f' . Present the result in the form $f'=\dots\pm\dots\Delta f'$.
- ❖ Estimate ΔD by assessing the sharpness of the image, and calculate $\Delta f'/f'$

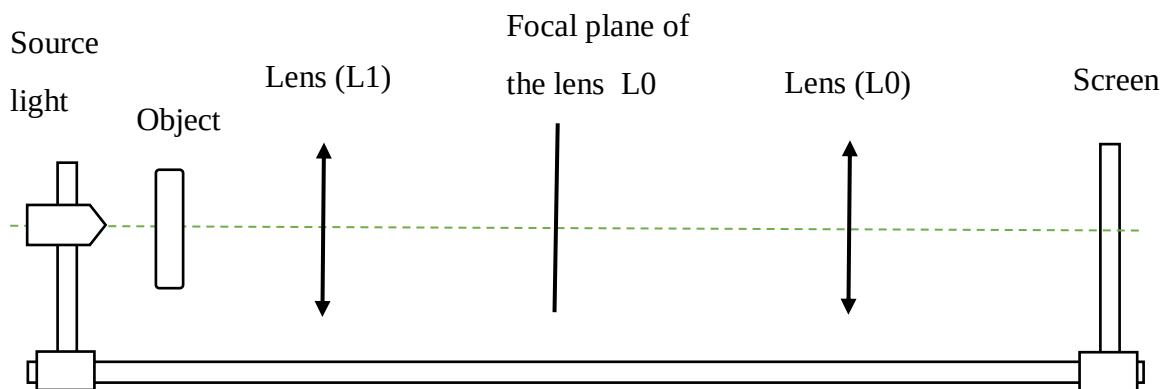
Remember that the formula for calculating uncertainty using the method of conjugation is:

$$\Delta f' = f'^2 \left(\frac{\overline{\Delta OA'}}{\Delta OA'^2} + \frac{\overline{\Delta OA}}{\Delta OA^2} \right)$$

❖ Criticising the results.

VII. Focometry of divergent lenses : BADAL's method

Set up the following arrangement:



The lens (L_1) produces an image of the object (slide) at infinity. The lens (L_0) with a known focal length must be placed at a distance d from (L_1), which is greater than f . The final image is projected onto a screen coinciding with the focal plane of the lens (L_0). Place the diverging lens (L), whose focal length we want to measure, in the focal object plane of lens (L_0).

To obtain a sharp image, the screen must be moved back by a distance D .

- Show that the focal length of (L) is : $f' = f_0^2/D$
- Measure D and calculate f' in a single measurement.

General Conclusion

In this lab session, we experimented with several methods for determining the focal length of thin converging and diverging lenses. Provide your conclusions by comparing the accuracy of these methods.

Experiment N°3:

Deviation by a Prism

Objective

- ❖ Understanding the phenomenon of deviation,
- ❖ Using a goniometer,
- ❖ Measuring the angle of the prism,
- ❖ Studying the variation of deviation as a function of the angle of incidence,
- ❖ Studying the minimum deviation and determining the refractive index of a prism.

Description:

A prism (Fig. 1) is a transparent medium (usually made of glass) bounded by two non-parallel plane surfaces, called the faces of the prism. The intersection of the two faces is called the edge of the prism. The planar angle (A) of the dihedral formed by the faces is called the prism angle. The dispersion of a prism is its ability to spatially separate the different spectral components of light. This is the decomposition or dispersion of light.

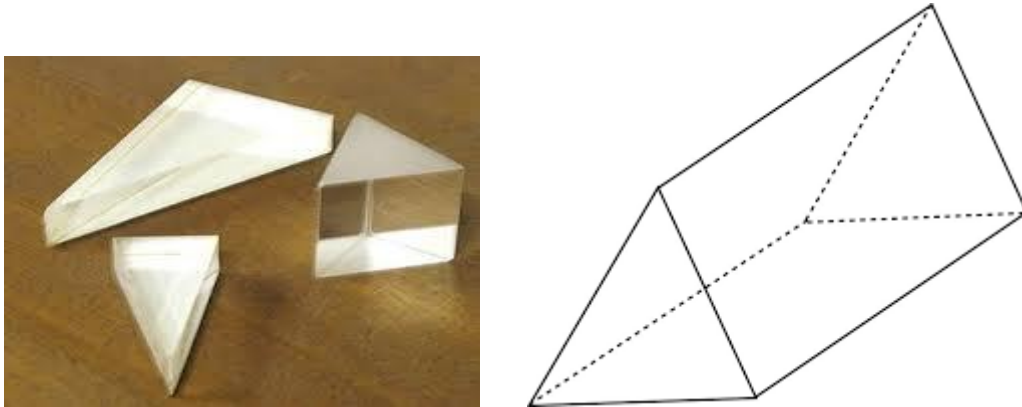


Figure 1. Prism

Prism Formula:

To simplify the study of the prism, we will assume that:

- The same medium (air, $n' = n_{\text{air}} = 1$) surrounds both faces of the prism,
- The prism is more refractive than the surrounding medium,
- The incident ray is situated in a principal section plane, which is the plane of incidence (formed by the incident ray and the normal IN) that contains the entire path $SII'S'$.

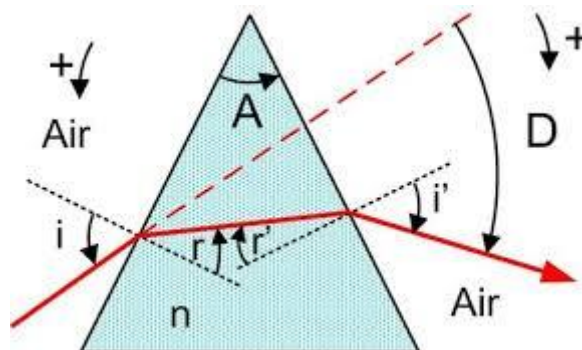


Figure 2: Deviation of a Light Ray by a Prism

The incident ray SI contained in the principal section plane (Figure 2) arrives at the first face of the prism at the angle of incidence i . Since the prism is more refractive than the surrounding medium, this ray can always enter (according to the refracted ray II') into the prism while remaining in the plane of incidence (1st law of Descartes). It then exits through the second face at the angle of incidence r' . The refractions at I and I' cause the rays to bend towards the base of the prism and can be expressed with the Snell-Descartes relations:

Thus, we have: $n \sin r = \sin i$ and $\sin i' = n \sin r'$ (1)

In triangle IKI', we can write: $A = r + r'$ (2)

The deviation D experienced by the incident ray is the sum of the deviations induced by the first (at I) and the second diopter (at I'): $d_1 = i - r$; $d_2 = i' - r'$; and $D = d_1 + d_2 = i + i' - (r + r')$ (3).

From this, we deduce the prism formulas:

$$\begin{cases} \sin i = n \sin r \\ \sin i' = n \sin r' \\ A = r + r' \\ D = i + i' - A \end{cases}$$

1- Emergence Conditions:

For the emerging ray to exist, it must be that $r' \leq i_{\text{limite}}$, with $\sin i_{\text{limite}} = 1/n$.

Consequently: $r \geq A - i_{\text{limite}}$ and $\sin i = n \sin r$ leads to: $\sin i \geq n \sin (A - i_{\text{limite}})$

Thus, finally: $\pi/2 \geq i \geq i_0$ with $\sin i_0 = n \sin (A - i_{\text{limite}})$

For example:

with a prism where $A = 60^\circ$ and $n = 1.7$, we have:

$$\sin i' \leq 1 \rightarrow \sin r' \leq 1/n \leq 36^\circ \text{ Thus, } r \geq 24^\circ \rightarrow i \geq 43.7^\circ$$

Therefore, deviation only exists if the angle of incidence exceeds a value i_0 . If i is too small, total internal reflection occurs inside the prism.

2- Study of Deviation:

According to the prism relations, the deviation can be considered a function of three independent parameters: the angle of incidence i , the refractive index n , and the angle of the prism A . The theoretical study of the function $D = f(i)$ (Figure 3), with n and A considered

constant, shows that it has a minimum deviation for $i = i_m$ (Figure 4). Thus, the path of the ray corresponding to the minimum deviation is symmetrical with respect to the prism's bisection plane. It is also demonstrated that at the minimum deviation we have:

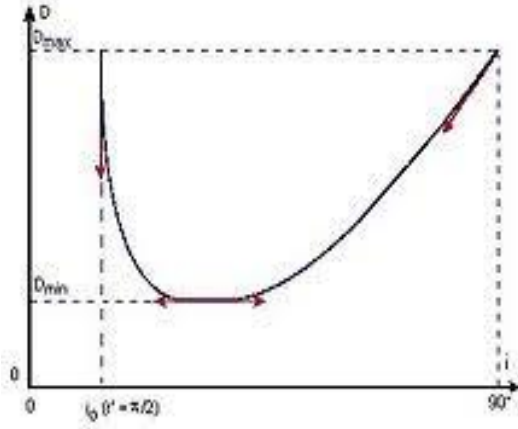


Figure 3 - Variation of Deviation.

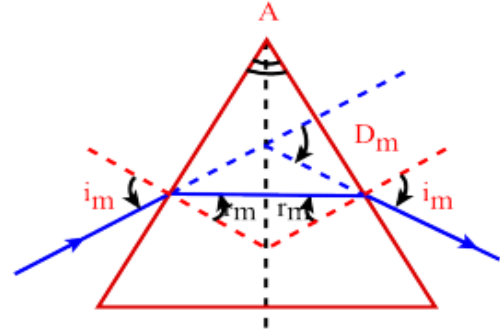


Figure 4: Prism at Minimum Deviation

as a function of the incidence angle

$$i = i' \text{ and } r = r' = r_m$$

Under these conditions, the prism formulas become (Figure 4):

$$D = 2i_m - A \text{ and } i = i_m = \frac{(D_m + A)}{2}$$

And Descartes' relation is written as:

$$\sin i_m = n \sin r_m$$

$$n(\lambda) = \frac{\sin((A + D_m)/2)}{\sin(A/2)} \text{ with } r = r' = r_m = A/2$$

Assuming $\Delta A = \Delta D_m$, it is shown that

$$\frac{\Delta n}{n} = \frac{1}{2} (\cot g(\frac{A}{2})) \Delta A$$

The refractive index of the prism depends on the angle A and the minimum deviation D_m . Since the latter depends on the wavelength λ of each radiation, the index also depends on it.

II. Experiment

Goniometer Adjustment

To adjust the goniometer, refer to the annex 2. Note that for each measurement you make, the absolute uncertainty is $\Delta\theta = 1'$.

I- Measuring the Angle A of the Prism

- ✓ Place the prism on the plate so that the bisection of the prism coincides with the direction of the beam from the collimator (approximate adjustment).
- ✓ A part of the beam is reflected by face 1; the other part by face 2.
- ✓ Note the value of the position θ_1 in the ocular: $\theta_1 \pm \Delta\theta_1$
- ✓ Proceed similarly on the other face by rotating the eyepiece. Let θ_2 be its new position: $\theta_2 \pm \Delta\theta_2$
- ✓ Deduce the value of angle α between the two positions θ_1 and θ_2 .
- ✓ Show by calculation that the angular separation between the two directions of the reflected beams is equal to $2A$. (**Work to be done before the lab session**)
- ✓ Calculate the value of angle A : $A \pm \Delta A$

II- Study of the Variation $D = f(i)$

Principle of Determining Angles D and i :

- Note the position of the non-reflected incident ray θ_0
- The angle i is determined from the direction θ_R of the reflected ray on face 1 and the direction θ_0 of the incident ray. Indeed, $2i = \theta_R - (\theta_0 - 180^\circ)$.
- The angle D is given by $D = \theta_E - \theta_0$. θ_E is the direction of the emerging ray.

Determining the Curve $D = f(i)$

- Place the prism on the plate so that its edge extends a few millimeters beyond the center of the plate and its base is to the left of the incident beam.
- For a chosen value of i , measure the corresponding value of θ_R (see table)

$i(\text{approximate})$	θ_R	i measured	θ_E	D
85°				
80°				
75°				
70°				

65°				
60°				
55°				
50°				
45°				
40°				
35°				

Plot and comment on the curve $D = f(i)$.

Example: For a value of $i = 80^\circ$

- Place the eyepiece in the direction θ_0 , then turn 20° towards face 1 while fixing the eyepiece.
- Rotate the prism until the observed line coincides with the reticle and measure θ_R .
- Rotate the eyepiece towards the base to observe the emerging line, which is θ_E and deduce D .

III- Determining the Refractive Index n of the Prism:

To calculate the value of the refractive index n of the prism, use the relation:

$$n = \frac{\sin((A + D_m)/2)}{\sin(A/2)}$$

However, the curve $D = f(i)$ does not provide a precise value for D_m and thus for n . Proceed as follows:

- Identify in the measurement table the smallest value of D and determine the corresponding values of θ_E and θ_R .
- Reposition the prism and the eyepiece in this configuration.
- Rotate the plate in either direction: the movement of the line should change direction when passing through an extreme position.
- Point the line and note the value of θ_{Em} and deduce the value of D_m .
- Calculate the numerical value of n and its uncertainty Δn : $n = \dots \pm \Delta n$.

The relative uncertainty on n is given by: $\frac{\Delta n}{n} = \frac{\Delta A}{A \cot(A/2)}$

Note: A fine slit allows for more precise pointing but is less luminous. Use a relatively wide slit for your initial settings, then narrow the slit for fine adjustment to achieve the best possible accuracy

Experiment N°4:

Magnifier and

Microscope

Objectives

- Use a simple eye model to study the increase in the viewing angle when using a magnifying glass and a microscope.
- Study how a converging lens can be used as a magnifying glass and to determine its magnification.
- Assemble a simple microscope and determine its magnification.

I. Definitions

I.1 The Magnifying Glass

A magnifying glass is an ocular instrument (i.e., intended for direct observation by the eye) which produces a magnified, virtual image of a nearby object (fig. 1). It is a simple converging lens with a short focal length (approximately ten centimeters), used under specific conditions: the object is placed at the object focus, or between the focus and the lens, in order to produce a virtual image, which is therefore upright and magnified.

The magnifying glass is used to observe small objects that are difficult to observe with the naked eye without causing strain. The object is placed between the object focal plane and the lens. The resulting image is thus virtual, upright, and magnified, allowing it to be comfortably observed by the eye.

I.2. Magnifying Power of a Magnifying Glass

Let AB is the size of the object and α is the viewing angle subtended by its image, as given by the magnifying glass (see Fig.1). The magnifying power P of a magnifying glass is the ratio:

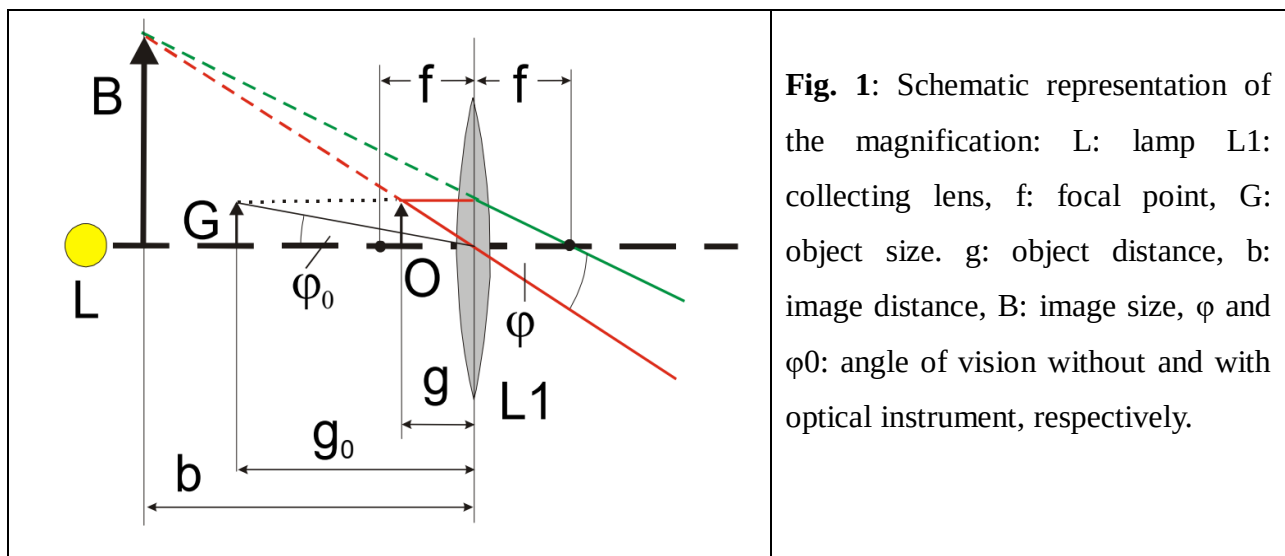
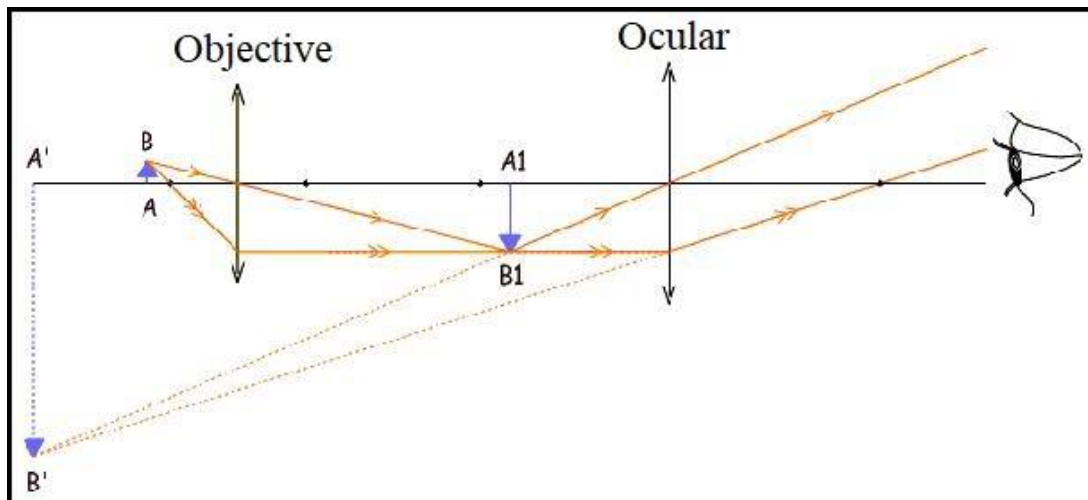
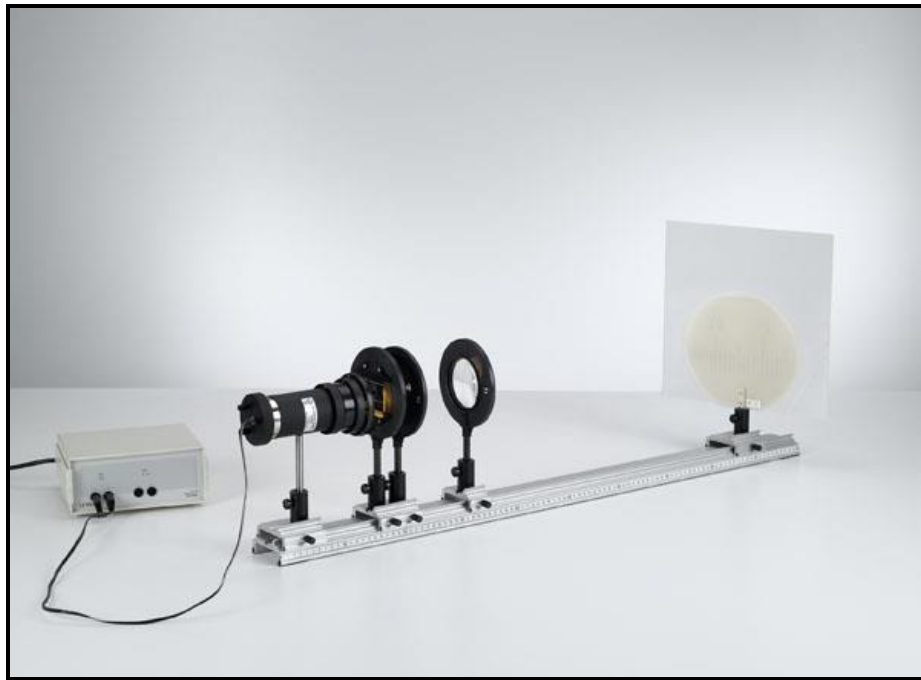
$$P = \varphi / AB$$

The unit of magnifying power is m^{-1} , also called the **dioptre** (symbol: δ), where α' is in radians and AB is in metres.

If the eye is placed at the image focus F' , then:

$$\varphi = AB / f' \text{ (where } C = 1 / f' \text{ is the lens power)}$$

In this case, $P = C$ and is independent of the object size. It is an intrinsic property of the magnifying glass, known as its **intrinsic magnifying power**.



II.1 Microscope

The microscope is an instrument used to achieve a much higher magnification than a simple magnifying glass. It consists of two groups of lenses: the **objective** and the **eyepiece** (ocular). The functioning of a microscope can be understood using a simplified model, in which both the objective and the ocular are replaced by two thin lenses.

The **objective** forms a magnified image $A'B'$ of the object AB , and the ocular acts as a magnifying glass through which this image is observed (Fig. 2). The objective has a very short focal length (on the order of a centimeter), thus allowing a greatly magnified image of the object to be obtained.

II. 2. Microscope Principle

A microscope is an optical system consisting essentially of two parts (fig. 2):

- The **objective** (a highly converging lens), which produces a magnified and inverted real image of a real object (placed very close to its object focal plane). This image is located in front of F_2 (the object focal point of the ocular).
- An ocular (or **eyepiece**), which produces a virtual image of this magnified and inverted image (which thus acts as a real object, or more precisely, as the *intermediate image* for the ocular). This final virtual image is observable by the eye. Most optical instruments are built upon these two fundamental components.

The image focus of L_1 (the objective) and the object focus of L_2 (the ocular) are separated by a distance (t) known as the **optical tube length** or **microscope tube length**.

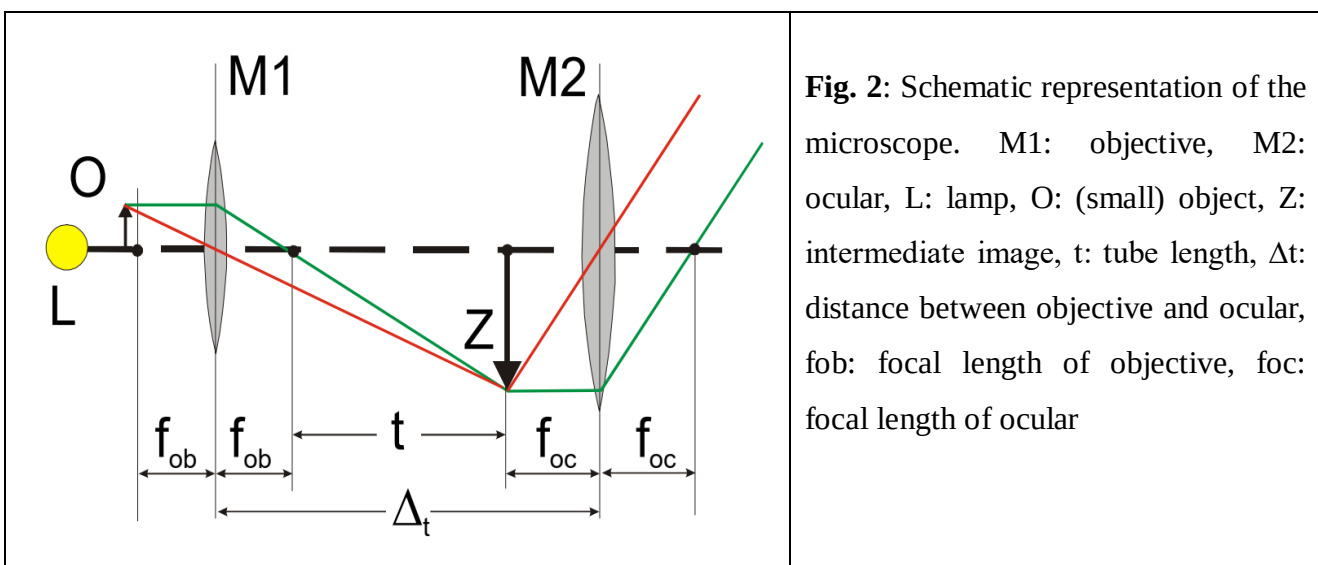


Fig. 2: Schematic representation of the microscope. M1: objective, M2: ocular, L: lamp, O: (small) object, Z: intermediate image, t : tube length, Δ_t : distance between objective and ocular, f_{ob} : focal length of objective, f_{oc} : focal length of ocular

The microscope will be assembled on an optical bench using the following components (confirm the focal lengths with the instructor):

- **Objective:** Lens L1 with a focal length $f_1 = +50$ mm.
- **Ocular (or Eyepiece):** Lens L2 with a focal length $f_2 = +200$ mm.
- **Object:** A grating will be used, in which the distance between two lines is $\frac{1}{4}$ mm.
- **Model Eye:** Consisting of a lens L3 with a focal length $f_3 = +100$ mm, combined with a screen.

III. Principles

The angle of vision ϕ determines the size of the image on the retina of the eye. According to Fig. 1 ϕ is defined by

$$\tan \phi = \frac{G}{g} = \frac{B}{b} \dots\dots\dots(1)$$

G: object size, B: image size

g: object distance, b: image distance

Basically, there are two reasons why the angle of vision ϕ is too small (i.e. the object cannot be seen as a sharp image on the retina of the eye). Either

- the object size G is too small or
- the object distance g is too large

The magnifier, the microscope and the telescope are optical instruments which primarily increase the angle of vision. The magnification is defined as follows:

$$V = \frac{\tan \phi}{\tan \phi_0} \dots\dots\dots(2)$$

ϕ : angle of vision with optical instrument

ϕ_0 : angle of vision without optical instrument

Using equation (I) and (II) gives the magnification of the magnifier (with $g = f$):

$$V_L = \frac{\tan \phi}{\tan \phi_0} = \frac{G/f}{G/g_0} = \frac{g_0}{f} \dots\dots\dots(3)$$

with

f : focal point of collecting lens L1

g_0 : clear field of vision

The distance between the object and the objective is a little bit larger than the focal length of the objective. The distance between the intermediate image and the ocular corresponds to the focal length of the ocular.

The microscope magnifies the object in two steps. For the total magnification the following applies:

$$V_M = V_{ob} \cdot V_{oc} \dots\dots\dots(4)$$

V_M : total magnification of the microscope

V_{ob} : magnification of the objective

V_{oc} : magnification of the ocular

With

$$V_{ob} = \frac{b}{g} \approx \frac{t}{f_{ob}} \dots\dots\dots(5)$$

b : image distance of the objective

t : tube length of the microscope, i.e. the distance between the internal focal points (Fig. 2)

f_{ob} : focal length of the objective

and

$$V_{oc} = \frac{g_0}{f_{oc}} \dots\dots\dots(6)$$

g_0 : clear field of vision

f_{oc} : focal length of the ocular

follows:

$$V_M = \frac{t g_0}{f_{ob} f_{oc}} \dots\dots\dots(7)$$

III. Manipulation

III.1. Magnifier

- Read a small inscription through two magnifying glasses with focal lengths $f_1 = 50$ mm and $f_2 = 200$ mm. Compare the two observations. Conclusion.
- Calculate the intrinsic magnifying power of each magnifying glass ($P_i = 1/f$ (δ , dioptries)).
- Compare the calculated magnifying powers with the observations made using the same magnifying glasses.

III.1.1. Determining the magnification of a magnifier

Set up the lamp L with the aspherical condenser as shown in Fig. 3 at the left side of the optical bench.

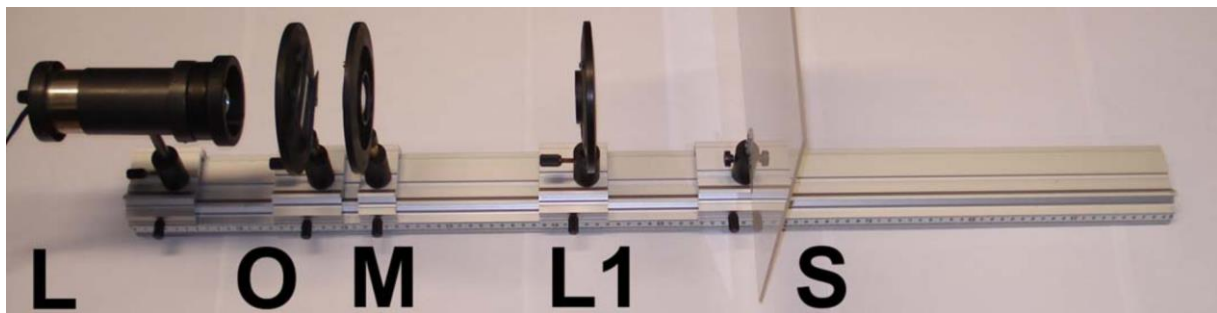


Fig. 3: Schematic representation of the experimental setup for the model of the **magnifier**. L: lamp, O: holder with object, M: magnifier (i.e. collecting lens) and model of eye, i.e.: L1: lens (of the eye), S: translucent screen (retina of the eye).

Test on the instruments use

- Set up the object O in front of the lens using the holder of spring clips (Fig. 1) and switch on the lamp.
- Position the lens L1 ($f = +100$ mm) at a distance of 25 cm in front of the object. This corresponds to the clear field of vision of the eye, i.e. $g_0 = 25$ cm.
- Position the translucent screen S at a distance of approx. 15 cm behind the lens. The screen corresponds to the retina of the eye.
- Depending on the object you use you should see an image!
- Measure the graduation distance on the translucent screen S

- Position the collecting lens M ($f = +50$ mm) at a distance of 5 cm in front of the object O (Fig. 3). The lens M corresponds to the magnifier.
- Position the lens L1 ($f = +100$ mm) at a distance of 10 cm in front of the translucent screen to view the object.
- You should observe a sharp image of the object O at the translucent screen S.
- Measure the graduation distance of the magnified image on the translucent screen.

III.1.2. Additional experiment:

- Shift the eye (i.e. the lens L1 ($f = +100$ mm) and the translucent screen S together) to the end of the optical bench (i.e. opposite to the lamp L).
- Observe the effect on the image on the translucent screen when shifting the eye (i.e. the distance between the lens L1 and the translucent screen S is kept constant while shifting the “eye model”).
- Measure the graduation distance of the magnified image on the translucent screen (i.e. size of the image on the retina of the eye model).

III. 2. Microscope

III.2.1. Determining the magnification of a microscope

- Set up the lamp L with the aspherical condenser at the left side of the optical bench as shown in Fig. 3 and switch on the lamp. The lamp corresponds to the microscope’s illumination of the object.

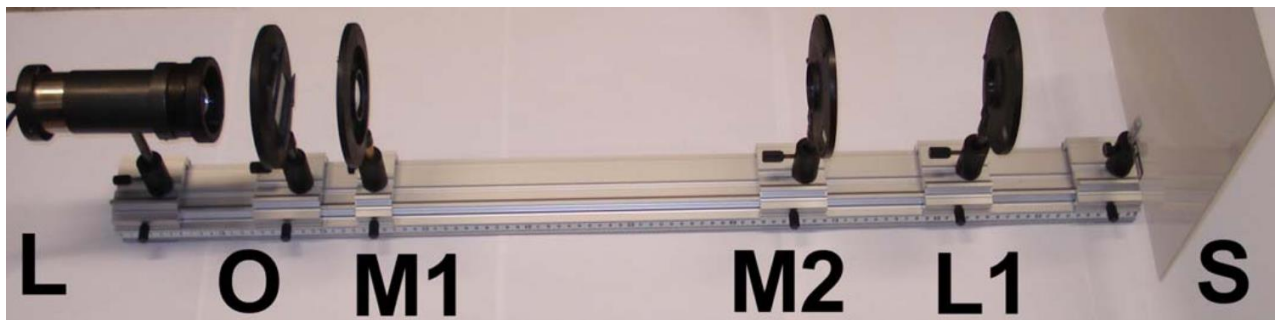


Fig. 4: Schematic representation of the experimental setup to view the image of the **microscope**. L: lamp, O: holder with object, M1: objective (i.e. collecting lens), Z: translucent screen, M2: ocular or eyepiece (collecting lens).

- Set up the object O in front of the lens (Fig. 4) using the holder of spring clips. The holder with spring clips corresponds to the object holder of the microscope.
- Position the lens M1 with $f = +50$ mm (objective) at a distance $d \approx 75$ mm in front of the object (i.e. $f < d < 2f$).

- Position the translucent screen Z on the optical bench at distance of approx. 30 cm after objective M1 to view the intermediate image of the microscope.
- Shift the object O (i.e. the object holder of the microscope) until you obtain a sharp intermediate image on the translucent screen Z.
- Position the lens M2 with $f = +200$ mm (ocular) at a distance f of 20 cm after the translucent screen Z.
- Setup the eye after the ocular M2 as shown in Fig. 3: Position the translucent screen S at the end of the optical bench. Place the eye lens L1 with $f = +100$ mm at a distance of 10 cm in front of the translucent screen S.
- Measure the graduation distance of the magnified image on the translucent screen (i.e. size of the image on the retina of the eye model) m and the distance Δt (Fig. 2).

III.2.2. Additional experiment: exchange of the ocular M2

- Position the translucent screen Z on the optical bench at distance of approx. 30 cm after objective M1 (Fig. 3) to view the intermediate image of the microscope.
- Shift the object O (i.e. the object holder of the microscope) until you obtain a sharp intermediate image on the translucent screen Z.
- Position the lens M2 with $f = +100$ mm (ocular) at a distance f of 10 cm after the translucent screen Z (Fig.4).
- Setup the eye after the ocular M2 as shown in Fig. 4: Position the translucent screen S at the end of the optical bench. Place the eye lens L1 with $f = +200$ mm at a distance of 20 cm in front of the translucent screen S.
- Measure graduation distance of the magnified image on the translucent screen (i.e. size of the image on the retina of the eye model) and the distance Δt (Fig. 2).

III.2.3. Additional experiment: change of tube length

- Position the translucent screen Z on the optical bench at distance of approx. 15 cm after objective M1 to view the intermediate image of the microscope.
- Shift the object O until you obtain a sharp intermediate image on the translucent screen Z.
- Position the ocular M2 with $f = +100$ mm at a distance of 10 cm after the translucent screen Z.
- Setup the eye after the ocular M2: Position the translucent screen S at the end of the optical bench. Place the eye lens L1 with $f = +200$ mm at a distance of 20 cm in front of the translucent screen S.
- Measure graduation distance of the magnified image on the translucent screen and the

distance Δt (Fig. 2).

- Shift the eye (i.e. the lens L1 and translucent screen S together) and note that the magnification does not change.

Experiment N°5: Modelling the Eye with an Optical Bench

Objectives

- ✓ Study the vision of a normal eye.
- ✓ Understand the definitions of the Near Point (PP) and the Far Point (PR) and their positions for a normal eye.
- ✓ Know the roles of the lens, cornea, and iris.
- ✓ Study the conditions for seeing an object.
- ✓ Identify the main defects of the eye and their corrections.

I. Brief Description of the Eye

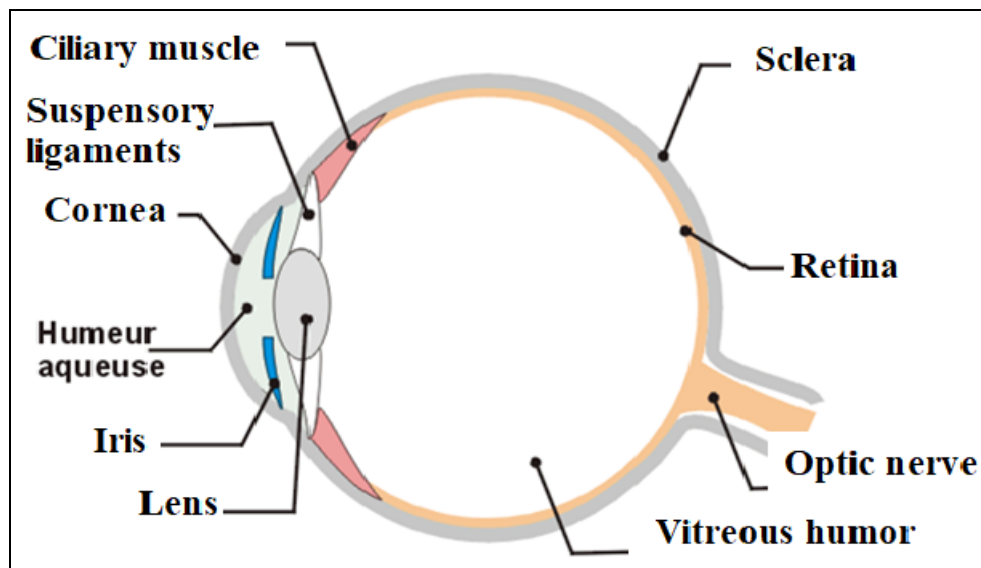


Figure 1: Description of the eye

The human eye consists of many elements, each with specific roles. The **iris** is the coloured membrane that gives colour to our eyes; by contracting and dilating, it modulates the amount of light that passes through the hole in its centre, called the pupil. It acts as a **diaphragm**. The **cornea** and then the **lens** function as converging lenses to form an image on the **retina**. The back of this internal membrane of the eye is lined with photosensitive cells. Once light is captured by the **retina**, the information is transmitted via the optic nerve to the brain for interpretation. It acts as a **screen**. The eye forms an image of viewed objects on the retina; thus, it is an optical instrument.

When a "normal" eye is at rest (lens relaxed), the image of an object at infinity forms on the retina (image focus on the retina); we say that its far point (PR: *punctum remotum*) is at infinity. When an object approaches, the image moves backward and forms behind the retina; consequently, the eye must accommodate to see clearly. A physiological change occurs in the eye: tension in the muscles surrounding the lens increases its convergence until the image forms again on the retina. This accommodation is limited, and we call the near point (PP: *punctum proximum*) the distance from eye to object reached when the eye has exhausted its accommodation capacity (standard value: 25 cm).

In conclusion, the eye has minimum and maximum distances for clear vision, defined respectively by the near point ($PP \sim 25 \text{ cm}$) and far point ($PR \sim \infty$). Beyond these distances, vision becomes blurry.

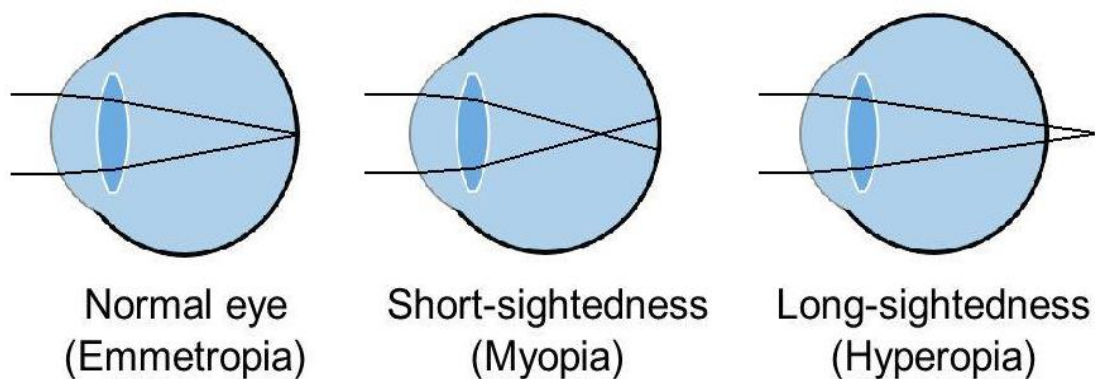
II. Eye Defects

II.1. Myopia

The crystalline lens in **myopic eyes** is too convergent or their eyeball depth is too large.

II.2. Hyperopia

The crystalline lens in **hyperopic eyes** is not convergent enough or their eyeball depth is too shallow.



II.3. Presbyopia

Over time, crystalline loses flexibility and becomes increasingly difficult to bulge, making near vision impossible. The crystalline no longer accommodates sufficiently; thus corrective lenses are needed while distance vision remains intact.

II.4. Astigmatism

It results largely from an irregular shape of cornea (it's not perfectly spherical). The image of a point appears as a blur instead of a dot; thus vision becomes blurry both up close and far away. To correct this defect, cylindrical lenses are used.

III. Manipulation: Modelling of the Eye

Complete the following table, indicating which part is modelled by the following optical instruments:

Model of Reduced Eye	Eye
Converging lens	
Diaphragm	
Screen Retina	

Draw an optical diagram representing this reduced eye.

III.1. Equipment

- ✚ An optical bench with a white light source + integrated condenser.
- ✚ Converging lenses with focal lengths +100 mm and +200 mm.
- ✚ A diverging lens with a focal length of -100 mm.
- ✚ Various diaphragms.
- ✚ An object P integrated into or placed on the optical bench.
- ✚ A white screen.

III.2. Creating a Reduced Eye

Setup

Place object P, integrated into the light source, on graduation 0 on the optical bench.

Place a white screen at graduation 180 cm. Insert a converging lens of 100 mm until a sharp image of the object is obtained on the screen.



Figure 2 : Reduced eye diagram.

Questions:

- ✓ How far from the screen should you place the lens to model a normal resting eye?
- ✓ What distance does this correspond to in a real eye?
- ✓ Are there multiple object positions for obtaining a sharp image on the retina?
- ✓ How does the image appear on the retina?
- ✓ Why don't we all see exactly the same thing with our eye?
- ✓ Conclusion.

III.3. Role of Iris-Pupil Assembly

Setup

Insert a diaphragm in front of the lens from the previous setup and change its opening.

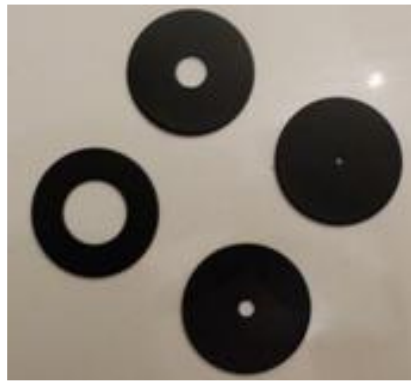


Figure 3 : Diaphragm with different opening.

- ✓ Describe how changing aperture affects light quantity and image sharpness.
- ✓ Conclusion.

III.4. Accommodation Phenomenon

Setup

For an "infinite" object:

place object P integrated into a light source at graduation 0.

Place a white screen at graduation 150 cm. Insert a converging lens of 200 mm until a clear image is obtained on screen (approximately at 125 cm). These roughly models viewing an object at infinity.

Trace light rays from object to retina.

For an object "seen up close":

The distance between lens (crystalline) – screen (retina) cannot be modified, so bring object closer to lens (approximately position 98 cm). The image becomes blurry. To obtain a clear image, replace previous lens with a converging lens (+100 mm).

Observation:

In conclusion, what does accommodation consist of?

III.5. Vision Defect: Myopia

If an image does not form correctly on the retina, vision is blurry or distorted. A myopic eye is too convergent; images from distant objects form in front of the retina (see diagram below). Thus, one sees clearly up close but blurry at distance. One solution for correcting myopia is corrective lenses.

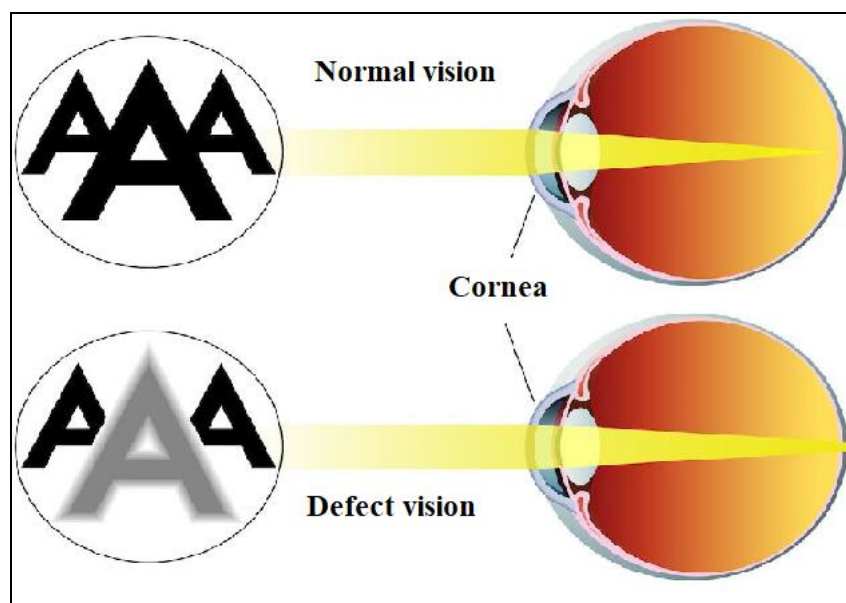


Figure 4: Normal and defect vision.

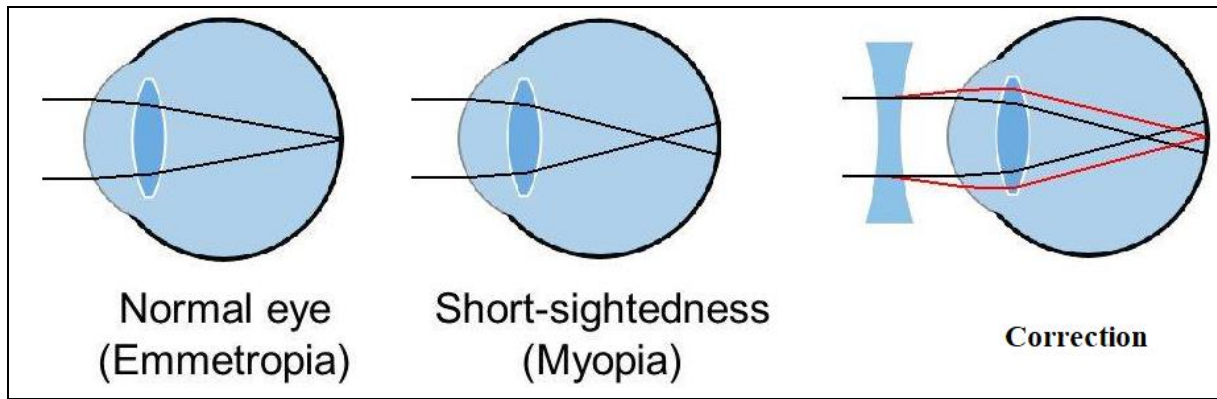


Figure 5: Myopia and its correction.

Setup

Of course, values for positions of different accessories are given as indicative only; adjust according to used lenses.

Place object P integrated into light source at graduation 0. Place white screen at graduation 50 cm. Insert converging lens +100 mm (crystalline) until a clear image is obtained on screen (approximately at 35 cm). The eye is normal.

- Move screen to position 53 cm. The observed image on screen becomes blurry.

You have just modelled a myopic eye; images form in front of screen (retina).

Insert between object P and lens a second diverging lens (-100 mm) (position approximately 16 cm).



Figure 6: Myopia eye diagram.

Questions:

- ✓ Provide your observations about how myopic eyes appear.
- ✓ Where does this image form?

- ✓ How can one correct myopia?

III.6. Another Vision Defect: Hyperopia

If an image does not form correctly on retina, vision is blurry or distorted. A hyperopic eye is not convergent enough; images from distant objects form behind retina (see diagram below). Thus, one sees clearly at distance but blurry up close. One solution for correcting hyperopia is corrective lenses.

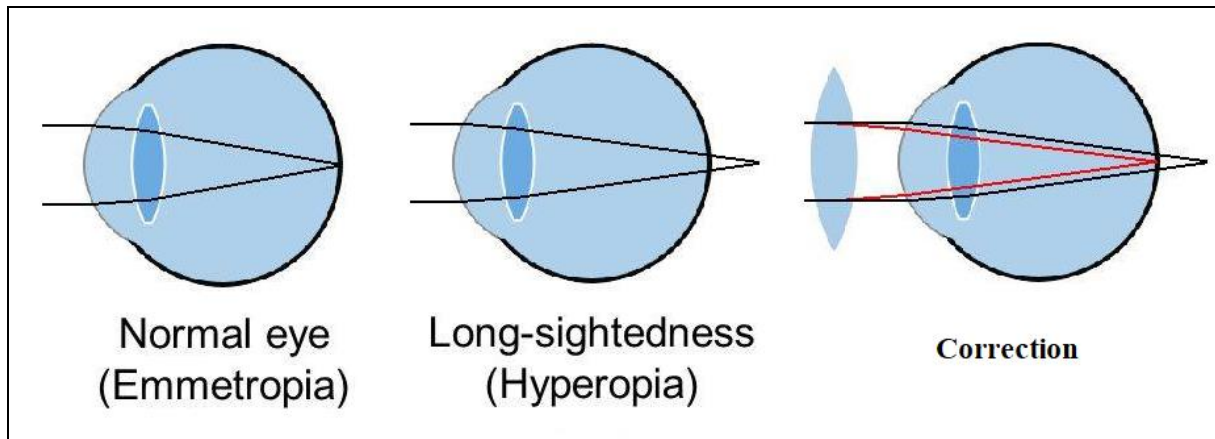


Figure 7: Hyperopia and its correction.

Setup

Place object P integrated into light source at graduation 0. Place white screen at graduation 50 cm. Insert converging lens +100 mm (crystalline) until clear image is obtained on screen (approximately at 35 cm). The eye is normal.



Figure 8: Hyperopia diagram.

- Move screen to position 47 cm. The observed image on screen becomes blurry.

You have just modelled a hyperopic eye; images form behind screen (retina).

Insert between object P and lens a second converging lens (+200 mm) (position approximately 14 cm).

Questions:

- ✓ Provide your observations about how hyperopic eyes appear.
- ✓ Where does this image form?
- ✓ How can one correct hyperopia?

Note

Values for positions of different accessories are given as indicative only; adjustments may be necessary based on used lenses.

APPENDIX 1: Practical work regulations

Necessary Equipment for Conducting a practical work:

Students must bring the following equipment: Graph paper, white paper, practical work notebook, pencil, eraser, calculator, lab coat.

Handling and Report:

To perform a good practical work, it is essential to read the handout and prepare the theoretical part of the report. A response sheet for each practical work will be provided. Follow the presented points step by step to prepare the theoretical part and the manipulation. The student must consult their course and practical work handout to assimilate the theoretical aspect of the manipulation and its equation.

Once in the practical work room, the student must be able to answer orally three important questions:

1. The purpose of the manipulation,
2. The quantities to be measured and the quantities sought,
3. The theoretical aspect introduced to explain or utilize the experimental results.

The report consists of two parts: a theoretical part and an experimental part:

- **The theoretical part is personal.** Each student must carefully prepare their practical work before each session. They will submit their personal work before the start of the session or undergo a 10-minute test. It is graded out of 5 points. Students are not allowed to use the manipulation and joint report time to do the theoretical part.
- **The experimental part** must be carried out in collaboration with the members of the pair or trio.

The final report, to be submitted at the end of the session, will consist of the experimental part and the theoretical parts of each student in the group.

Work During the practical work:

The student's behavior during the practical work is judged and graded out of 5 points (wearing a lab coat, punctuality, equipment, condition of the premises, and equipment storage). The

most important (and best graded) work is that which highlights the experimental results through their good presentation, analysis, and especially their critiques. At the end of each session, each pair must submit a report neatly presenting the results. The evaluation will be based not only on the precision and accuracy of the results but also on the relevance of the remarks and the clarity and neatness of the report presentation.

APPENDIX 2: Adjusting the Goniometer

3- Introduction to the Goniometer:

The spectrometer consists of a sturdy base on which three accessories are mounted:

- **The COLLIMATOR**, which gives an image of the source slit at infinity.

It consists of a lens with a focal length of 160 mm and a slit with an adjustable width. The main adjustment drum allows the source slit to be positioned in the focal plane of the collimator.

- **The PLATE (or stage)**, intended to hold the object to be studied.

It is movable around a vertical axis that is by design perpendicular to the optical axis of the collimator. One screw allows its rotation to be locked, and a second screw allows micrometric rotation. Three screws arranged in an equilateral triangle around the plate allow for the adjustment of its horizontal position.

- **The LUNETTE**, which is movable around the same vertical axis as the plate.

One screw allows its rotation to be locked, and a second screw allows micrometric rotation. The rotation of the telescope is marked on a graduated disc (or limb) with a diameter of 200 mm. A vernier allows measurement to the nearest arc minute.

The lunette itself consists of four parts:

- A lens with a focal length of 130 mm.
- A reticle with a horizontal and a vertical line. The reticle plane (R) corresponds to the shiny knurled ring. The adjustment drum allows the reticle to be positioned in the focal plane of the lens.
- The autocollimation device with a light source placed laterally and a semi-reflective plate whose orientation is controlled by a small lever. When the lever is pushed to the left, the plate is at 45° and the reticle is illuminated for autocollimation. When the lever is pushed to the right, diffuse lighting is obtained.
- The **eyepiece** simply allows visual observation of the reticle plane. Each person can adjust it to their vision, and the adjustment can be modified during manipulation.

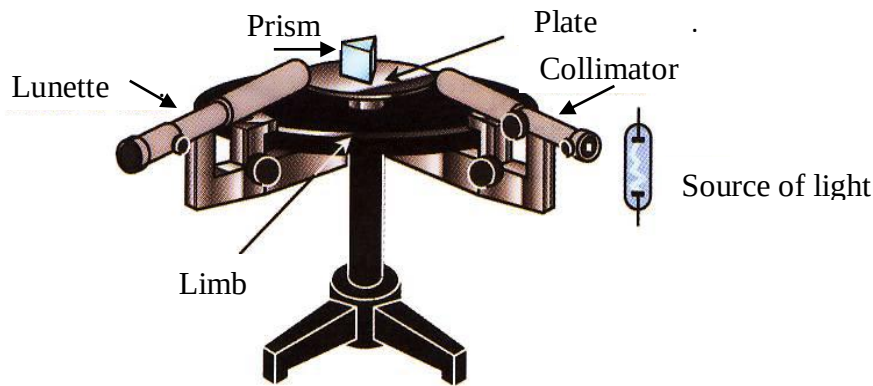


Figure 1: Descriptive diagram of the goniometer

4- Preliminary Adjustments of the Goniometer:

Before any measurements, it is necessary to adjust the goniometer so that the measurements are not skewed. The goniometer is correctly adjusted if:

1. Eyepiece Adjustment

Adjust the eyepiece to your vision to see the reticle clearly. Students wearing corrective lenses can choose to keep or remove them. This adjustment can be modified at any time.

2. Adjusting the telescope to infinity by autocollimation

- **Objective:** Bring the reticle into the focal plane of the telescope lens.
- **Note:** The telescope then becomes a dioptric sight allowing angular measurements; a telescope adjusted to a finite but fixed distance is called a fixed frontal sight allowing longitudinal alignments.

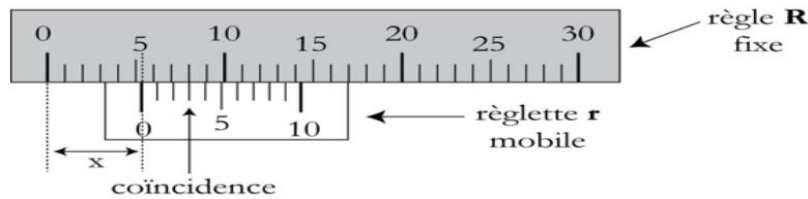
3. The collimator is adjusted to infinity.

4. The optical axis of the telescope is orthogonal to the rotation axis of the platform Δ .

5. The dispersive element used (prism or grating) is correctly positioned on the platform.

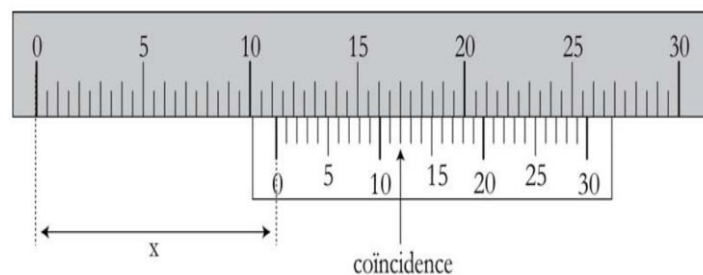
2.1 Principle of reading with a Vernier

A vernier (named after its inventor, Pierre Vernier) is a system that improves the precision of reading a position on a rule R . The vernier consists of a movable scale, r (vernier), which moves along a fixed rule, R . It is the position of the zero on the movable scale r that gives the position to be recorded.



In the example above, one reads $x = 5.3$.

In the case of angle reading, it is common to have verniers at the 30th: the scale r has 30 divisions corresponding to 29 divisions of R , graduated in half-degrees, i.e., 14.5° . In the example below, one reads: $x = 110^\circ 12'$.



ATTENTION! *The goniometer is a precision optical instrument; therefore, it is fragile and expensive. Care must be taken not to touch the lenses with fingers. Additionally, avoid touching the goniometer with the conductive branches of the lamp: this could cause a short circuit, potentially burning out the lamp.*

APPENDIX 3: Measurements, Errors, and Uncertainties

Error is not a fault. The measurement of a quantity, whatever it may be, gives a result X which is generally different from the value X_0 that we seek to measure (and which we will call the reference value). A poorly made measurement with bad equipment will give a result that can be very different from the sought value. A well-made measurement with good equipment will generally give a result close to the sought value. But in all cases, there is an inevitable gap between the measurement result and the reference value, regardless of the quality of the equipment and the precautions taken during the measurement.

Indeed, if several successive measurements of the same quantity are taken, it is observed that different results are obtained each time. The dispersion of measurement results is normal: the instruments are not perfect, the graduations are more or less thick, the measurement conditions (temperature, humidity) vary with each trial, poor lighting, poor eyesight, fatigue, etc. All these parameters cause varying degrees of reading errors. All these causes and many others lead to a dispersion of the results obtained during successive measurements. Of course, this dispersion is generally small for high-quality instruments and under good experimental conditions, but it is never zero. All these discrepancies, which add (or subtract) from each other, occur randomly, fluctuating from one measurement to another: this leads to an erroneous and variable result. We say that the result is tainted with random error. This means that the error occurs "randomly," in an unpredictable manner. When the random error is small, the measurement is said to be precise. The dispersion of successive measurement results is then small.

A small dispersion of measurements does not necessarily mean that the obtained results are close to the reference value. Indeed, an instrument may be poorly calibrated. This is the case with a scale that would indicate 515 g when a mass of 500 g is placed on it. Such a defect in the instrument causes a discrepancy between the measured value and the reference value. This phenomenon is called systematic error in the sense that it is reproducible and identical from one measurement to another, unlike random error. This does not mean that systematic error is inevitable: by using high-quality equipment, paying particular attention to zero settings, alignment, eliminating parasitic phenomena, etc., it can be reduced. However, the possibility of a systematic error remains if it is not detected.

When the systematic error is small, the measurement is said to be accurate. Again: this does not mean that the result of an accurate measurement is the reference value. Here it is important to distinguish between common language and scientific language. Finally, let's emphasize that the precision and accuracy of a measurement are independent: one can make an imprecise but accurate measurement, precise and accurate, etc.

Uncertainty is an assessment of the maximum error.

We define the error e as the difference between the measured value X and the reference value X_0 that we are trying to reach: $e = X - X_0$. Since the reference value X_0 is not known (because we are trying to measure it!), the error always remains unknown, both in magnitude and sign. Nevertheless, for each measurement, it has a well-determined algebraic value. Therefore, we seek to estimate a maximum value ΔX of the absolute value of the error, which we call uncertainty:

$$|e| = |X - X_0| \leq \Delta X.$$

We then write the sought value in the form:

$$X_0 = X \pm \Delta X \text{ or } X - \Delta X \leq X_0 \leq X + \Delta X.$$

These two notations are equivalent and define a confidence interval within which we assert that the reference value has "all the chances" (100%) of being found. To make this assertion as accurate as possible, it is essential to generously estimate the error with uncertainty. Overly optimistic uncertainty assessments risk leading to a too-narrow interval, for which the sought value is more likely to be outside than inside. Conversely, a too pessimistic (wide) confidence interval makes the measurement too imprecise. Neither extreme is satisfactory since neither will provide concrete information about the sought value.

Uncertainty can be estimated by a classical calculation, either from the manufacturer's specifications of the measuring instrument or by an evaluation (personal, therefore) if the measuring instrument is simple. For example, one can estimate that the measurement of a length is accurate to within 1/2 graduation (this is the general consensus) if the lighting is good and the experimenter has good eyesight. Whatever the choice of uncertainty, it is essential to discuss and explain it: this is a scientific approach. The uncertainty ΔX is called absolute uncertainty: it has the same dimensions as X and is therefore expressed in the same units. It is often this that is evaluated by a direct measurement, but it is not always a good

indicator of the precision of the measurement: measuring 10 km to within 10 cm is much more precise than measuring 1 m to within 10 cm.

It is therefore the comparison of the uncertainty with the measured value that represents the precision of the measurement: this is the relative uncertainty $\Delta X/X$. The relative uncertainty is a dimensionless quantity, usually expressed as a percentage. The lower it is, the more precise the measurement. Thus, 10 km measured to within 10 cm gives $\Delta X/X = 10 \cdot 10^{-2} / 10 \cdot 10^3 = 10^{-5} = 0.001\%$, while the second aforementioned case gives $\Delta X/X = 10 \cdot 10^{-2} / 1 = 10^{-1} = 10\%$, which restores the intuitive idea of the precision of these measurements.

- If several measurements of the same quantity are made, multiple confidence intervals for the reference value are obtained. To give a unique final result, the intersection of all these intervals must be determined. This final interval is generally smaller than all the intervals of all the measurements. If, after two measurements, for example, the two confidence intervals do not intersect, the results are said to be incompatible. They are clear evidence, in at least one of the measurements, of either a gross error (such as reading the scale) or an underestimation of the uncertainties.
- When the sought quantity is related to measurable quantities by a calculation ($R = U/I$), the uncertainty must be calculated based on the uncertainties of the measured quantities. This is the purpose of uncertainty calculations, generally performed using differentials. It is then good to remember the following two rules:

$$y = a + b - c \rightarrow \Delta y = \Delta a + \Delta b + \Delta c,$$

$$y = ab/c \rightarrow \Delta y/y = \Delta a/a + \Delta b/b + \Delta c/c$$

How many significant figures?

The number of significant figures is the number of digits that have real significance given the uncertainty. It should not be confused with the number of digits after the decimal point. For example:

- i) 85.639 has five significant figures (three after the decimal point). The uncertainty here is on the digit 9.
- ii) 8563.9 has five significant figures (one after the decimal point). The uncertainty is still on the digit 9.

- iii) 8563.900 has seven significant figures (three after the decimal point). The uncertainty is on the last 0. This notation corresponds to a result one hundred times more precise than the previous one.

Uncertainty, whether calculated or estimated, is never known with great precision itself. It is generally rounded to one or two significant figures. Since it must be an upper bound of the error, it is always rounded up. After calculating the uncertainty, the number of significant figures of the found result is adjusted. For example, one writes:

$X = (8.02 \pm 0.06) \text{ m}$ and not $X = (8.02137 \pm 0.0574) \text{ m}$

$X = (8.0 \pm 0.3) \text{ m}$ and not $X = (8 \pm 0.254) \text{ m}$

Classical Treatment and Statistical Treatment of Errors It is quite common, especially in the exact sciences, to make only one measurement of an unknown quantity. The uncertainty is then evaluated according to the principles explained in the previous paragraph, according to the characteristics of the used instruments, and the measurement conditions. This is the classical treatment. It is also possible to perform a statistical treatment of a series of several measurements of the same quantity. In this case — quite common in life sciences where result dispersion is often more significant than in physics or chemistry — it is no longer necessary to know the characteristics of the used instruments or the measurement conditions. The series of results itself allows determining the confidence interval within which the reference value can be asserted to be, with a certain probability.

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