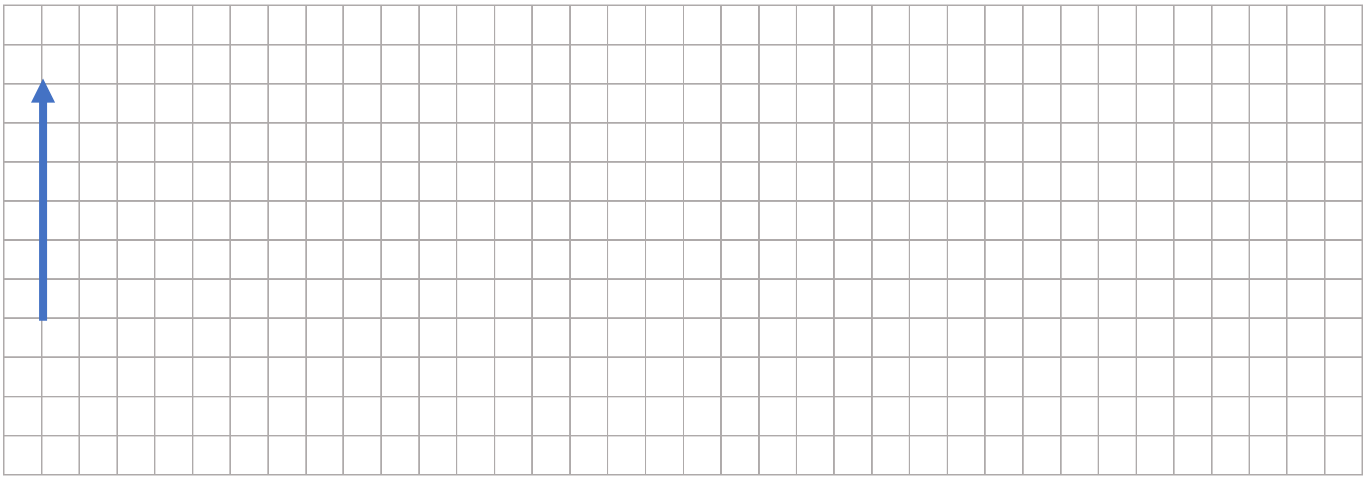
Name……………………………………………………………………………………Date……………………………………………………

Faculty…………………………………………………….

Eye

3. Image construction



f = ……………………………cm	x =………………………………cm	y (draw) =……………………………cm
y (mod) =…………………………………cm	Δy=……………………………… %	

4. Dependence of the focal length on the index of refraction the surrounding medium	
x =………………………………cm	f_s = ………………………………cm
5. Accommodation	
x =……………………………… cm	f = …………………………… cm

6. Far-sightedness		**7. Near-sightedness**	
f =……………………….cm	Z =……………… dioptres	f = …………………….cm	Z = ……………… dioptres

8. Astigmatism		
the angle between the cylindrical axes of the lenses is approximately ……………………… degrees		
9. The focal length of the lens system		
f_c =……………………………… cm	R =……………………………cm	
f_l' = ………………………… cm	f_s =…………………………… cm	Δf_s = ……………………………%

Eye

1. Introduction.

The human eye is an optical system created naturally through evolution. It achieves vision by forming an image of objects on the retina of the eye. In the retina there are cells equipped with detectors of electromagnetic waves, which convert the received light stimuli into biological signals, directed to the appropriate centres in the brain. Although the eye is an organ made of tissues, in its "physical" principle of operation does not differ much from optical devices that are constructed by men, such as a camera. The basis of all optical instruments are lenses, and we will first try to understand how a lens produces an image. **Lenses** are transparent bodies with two walls, at least one of which is curved. Lenses can be **convergent** or **divergent** (Fig. 1).

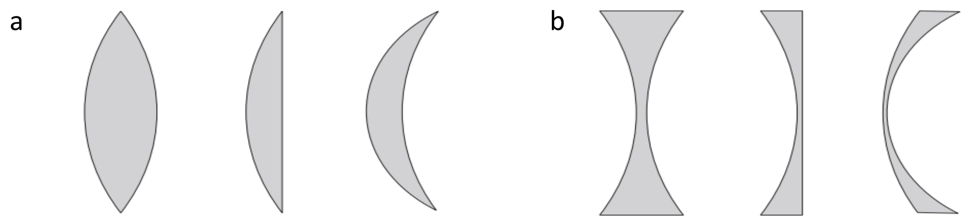


Fig. 1 Shapes of a) convergent, b) divergent lenses.

When light rays pass through the lens, **refraction** occurs on the walls - the direction of the rays changes. The reason for the refraction of light is the change in the speed of light when light passes through the boundary of two transparent media that differ in refractive index. The **index of refraction** is the ratio of the speed of light in the two media. When the incident rays are parallel to the main optical axis (Fig. 2), after passing through the convergent lens, the rays intersect at a point called the **focal point** (or **focus**) of the lens (F). The distance from the focus to the lens is called the **focal length** (f). In a divergent lens, the extensions of the rays coming out of the lens are concentrated at the focal point. Such a focus is called apparent, and the focal length takes a negative value.

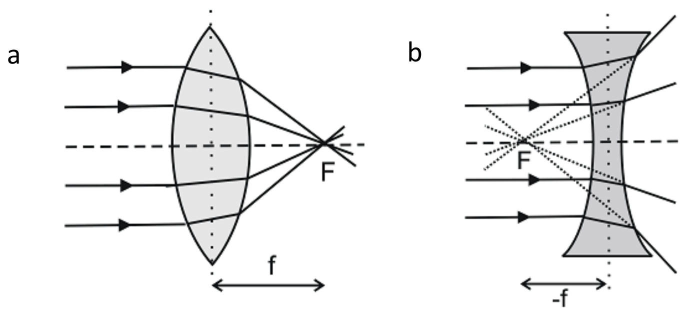


Fig. 2 Refraction of light rays in a) convergent, b) divergent lens.

When an object is placed in front of a lens, the light from the object passing through the lens forms an image. In Fig. 3 we can see how the image of a point is graphically constructed using two rays. We draw one ray parallel to the main optical axis, and behind the lens we guide it through the focus. The second ray, from the same point, is drawn through the centre of the lens. This beam doesn't change direction! The intersection of both rays behind the lens creates an image of a point.

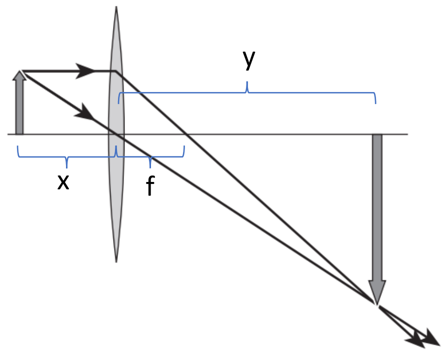


Fig. 1 Constructing the image formed by a convergent lens.

Assume that the distance from the lens to the object is ***x*** and the distance from the lens to the image is ***y*** (Fig. 3). The focal length ***f*** is related to the object distance and the image distance by the **thin lens formula**:

$$\frac{1}{f} = \frac{1}{x} + \frac{1}{y} \qquad (1)$$

The focal length of a lens is determined by the curvatures of its front and back surfaces (R_i), its absolute index of refraction (**n**), and the absolute index of refraction of the material surrounding the lens (n_o). The **radius of curvature** is the radius of a sphere with the same surface curvature as the lens wall. The **absolute index of refraction** defines how many times the speed of light in a vacuum is greater than the speed of light in a given medium.

$$\frac{1}{f} = \left(\frac{n}{n_o} - 1\right)\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad (2)$$

The human eye is a two lens system consisting of **corneal** and **crystalline lenses** (Fig. 4).

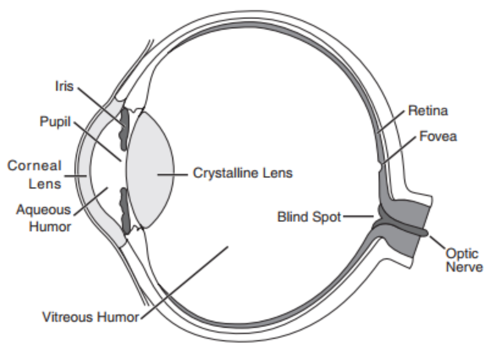


Fig. 4 Eye anatomy.

The space between the lenses is filled with a transparent fluid called the **aqueous humour**. Also between the lenses is the **iris**, an opaque, coloured membrane. At the centre of the iris is the **pupil**, a muscle-controlled, variable-diameter hole, or aperture, which controls the amount of light that enters the eye. The interior of the eye behind the crystalline lens is filled with a colourless, transparent material called the **vitreous humour**. On the back wall of the eye is the **retina**, a membrane containing light-sensitive nerve cells known as rods and cones. **Rods** are very sensitive to low light levels, but provide us only with low-resolution, black-and-white vision. **Cones** allow us to see in colour at higher resolution, but they require higher light levels. The **fovea**, a small area near the centre of the retina, contains only cones and is responsible for the most acute vision. Signals from the rods and cones are carried by nerve fibres to the optic nerve, which leads to the brain. The **optic nerve** connects to the back of the eye; there are no light-sensitive cells at the point where it attaches, resulting in a **blind spot**.

The corneal lens and crystalline lens together act like a single, convergent lens. Light entering the eye from an object passes through this lens system and forms an inverted, real image on the retina:

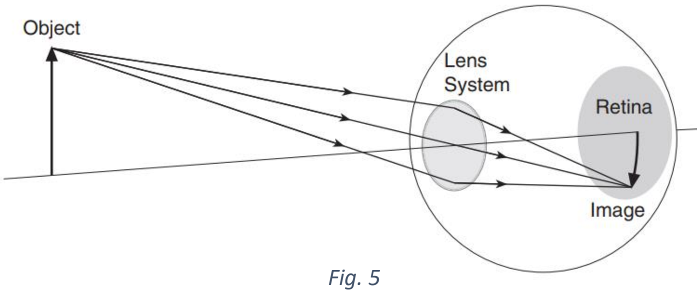
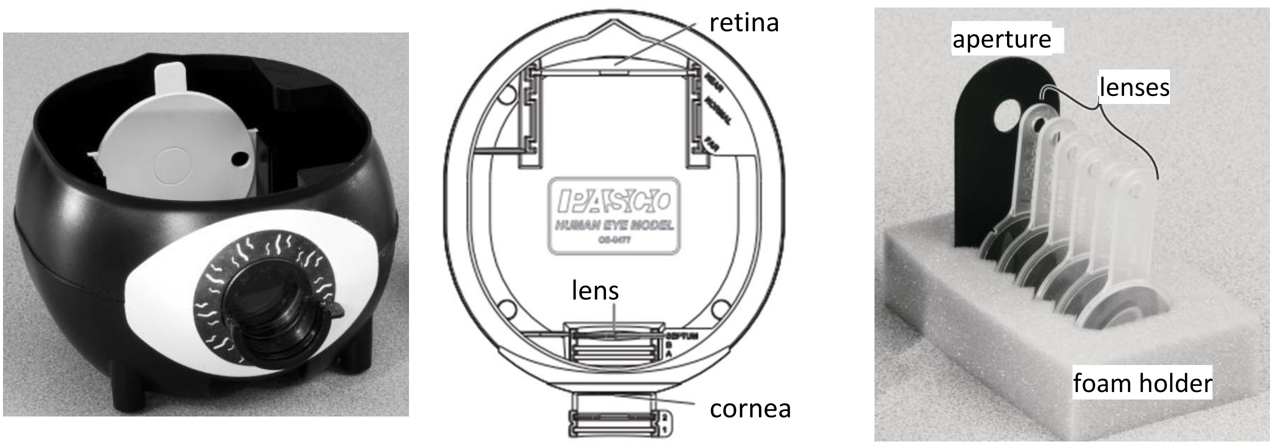


Fig. 5

The lens of the eye, unlike glass or plastic lenses, has a variable focal length. The eye focuses on objects at varying distances by **accommodation**, or the use of muscles to change the curvature, and thus the focal length, of the crystalline lens. Ligaments are attached to the lenses, the tension of which is regulated by the ciliary muscle. The relaxation of the ciliary muscle tighten the ligaments, flattens the lens and increases the focal length. In its most relaxed state, the crystalline lens has a long focal length, and the eye can focus the image of a distant object on the retina. Contraction of the ciliary muscle relaxes the ligaments, the centre of the lens bulges, causing the focal length to shorten, and allowing the eye to focus on closer objects. To form a clear image of an object on the retina, the total effective focal length of the two-lens system, the distance of the object and the distance of the image must fulfil the thin lens formula.

2. Preparation of the measuring system

ATTENTION. Hold the lenses by the handle.
Do not touch, wipe or rub the lenses!!!
Put the lenses down to the foam holder.



Rys. 6 The eye model.

In the exercise we will use the eye model (Fig. 6). To study the physics of the eye, we will use a set of spherical lenses with focal lengths: +400 mm, +120 mm, +62 mm, -1000 mm, and cylindrical lenses -128 mm and +307 mm. As an "object" we will use a sheet of paper with a drawing of a house illuminated from the back with a lamp. Put the retina screen in the middle slot, marked NORMAL. Put the +400 mm lens in the slot labelled SEPTUM. Put the eye model in front of the object. Place the lamp behind the object and turn it on. Adjust the distance of the eye model. Try to find the closest position relative to the object, at which the image on the retina screen is clear.

3. Image construction

The image we see on the retina screen is created by the corneal lens and the +400 mm lens. Their **total effective focal length *f*** can be approximated by the formula:

$$\frac{1}{f} = \frac{1}{f_c} + \frac{1}{f_l}$$

f_c – focal length of the corneal lens = +140 mm, f_l = focal length of the replaceable lens = +400 mm.

Calculate the total effective focal length f of the system. Use a ruler to measure the object distance x. The front of the rim is a convenient place to measure to and marks the centre of the eye model's two-lens system:

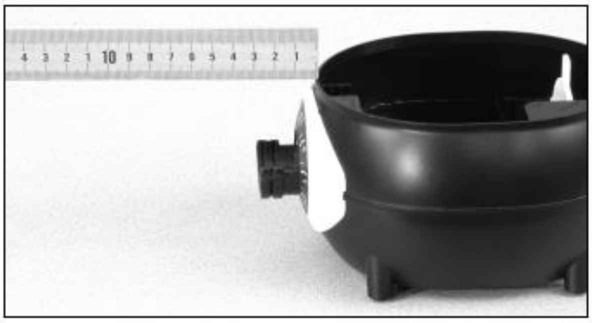


Fig. 7

On a piece of squared paper, draw an object (e.g. an arrow) and a lens (or two lenses side by side) at the right distance, assuming a scale of 1:4. Mark focus F and find the position of the image. Draw an image. Note the size of the image compared to the object. Is the image enlarged or reduced? Is the image straight or inverted? Read the image distance ***y (fig)*** from the drawing and compare it with the actual distance ***y (mod)*** (measure the distance of the retina screen from the front edge of the model). Calculate the percentage difference Δy between the distance determined from the drawing and the distance measured on the eye model. Do you think that the difference is big or small?

4. Dependence of the focal length on the index of refraction of the surrounding medium

Check again if you can see a clear image on the retina. Fill the eye model with distilled water so that the lens is covered. The water here will imitate the vitreous humour that fills the inside of a real eye. Is the image still in focus? Of course it isn't. You can try to move the eye model away from the object, but the image will remain out of focus. Why did the water change the focus of the image? Does a lens submerged in water still have a focal length of +400mm? Remove the lens out of the SEPTUM slot and replace it with the +62mm lens. By moving the eye model, find the closest position of the model to the object, where you can see a clear image. Measure the distance x of the object from the eye model. Calculate the focal length f_s of such an optical system using the thin lens equation (1).

5. Accommodation

Let's try to bring the eye model closer to the object. We will notice that the image becomes blurry. In the real eye, focusing would occur due to the work of the eye muscles that regulate the thickness of the lens. This would change the focal length of the eye's lens system. In our eye model, accommodation will be carried out using a second lens with a focal length of +400 mm, which we will add to the +62 mm lens. Let's put it in slot B. Is the image clearer? Correct the position of the model if necessary. Calculate the focal length $\boldsymbol{f}$ of such an optical system using the thin lens equation (1).

6. Far-sightedness (Hypermetropia)

Farsightedness is a defect of vision in which a clear image is formed behind the retina:

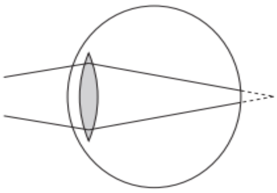
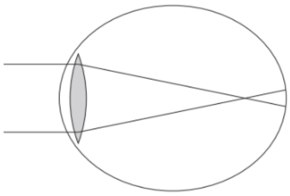


Fig. 8

Remove the +400mm lens from slot B and adjust the eye-object distance so that the image is in focus again. Farsightedness in the eye model can be realized by moving the retina screen closer to the lens. To do this, insert the retina screen into the slot labelled FAR. The image has become blurry. Find a lens that brings the image into focus. We wear glasses in front of our eyes, so place the lenses in slot 1. Is a correcting lens a convergent or divergent lens? How does this lens improve vision? Calculate the correcting lens's power $\boldsymbol{Z}$. The **lens's power** is the reciprocal of the focal length in meters. The reciprocal of a meter here is called a **dioptre**.

7. Near-sightedness (Myopia)

Near-sightedness is a defect of vision in which a clear image is formed in front of the retina:



Rys. 9

Remove the corrective lens from slot 1. Put the retina screen in the NORMAL slot and find a clear image. The simulation of myopia in the eye model can be obtained by moving the retina screen to the slot labelled NEAR. The image has become blurry. Try to find the correcting lens. Is a correcting lens a converging or diffusing lens? How does this lens improve vision? Calculate the correcting lens's power $\boldsymbol{Z}$.

8. Astigmatism

In a normal eye, the lens surfaces are spherical and rotationally symmetrical; but an eye with astigmatism has lens surfaces that are not rotationally symmetrical. This makes the eye able to focus only on lines of certain orientations, and all other lines look blurred. The figure below is a test chart for astigmatism.

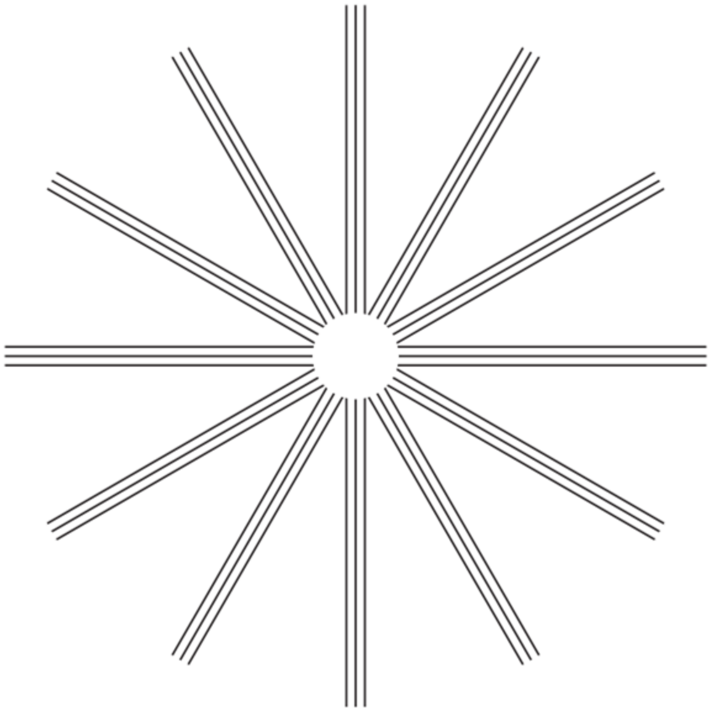


Fig. 10

Cover one eye and look at the chart. Do some of the lines look darker than others? If they do, rotate the figure 90° to convince yourself that the lines are actually the same and it is only your eye that causes the effect.

To simulate astigmatism in the eye model, first set it to normal, near vision, i.e. remove the lens from slot 1 and put the retina screen in the NORMAL position. Adjust the eye-object distance so that the image is in focus. Place the -128 mm lens in slot A next to the +62 mm lens. The surfaces of this lens are cylindrical. The axis of the cylindrical curvature is indicated by a pair of notches on the edge of the lens (Fig. 11). Rotate this lens with the handle and observe the image. Use the +307 mm lens in slot 1 to correct astigmatism. See what happens to the image when you rotate this lens. Try rotating

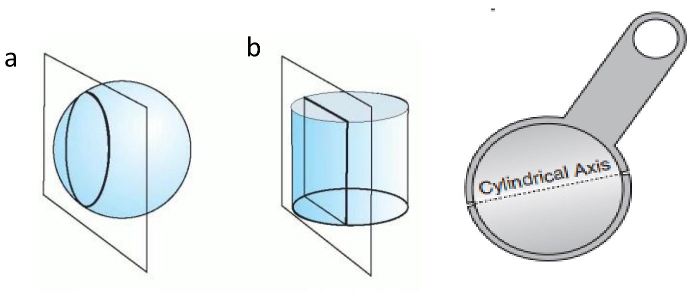
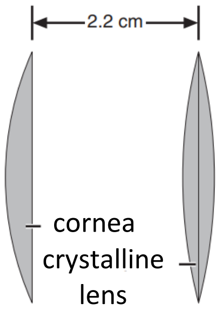


Fig. 11 Convergent lens a) spherical i b) cylindrical.

the -128 mm lens and the +307 mm lens to get the best image. Compare the position of the grooves in both lenses when the image is the clearest. What is the angle between the cylindrical axes of the two lenses?

9. Focal length of the two-lens system

Finally, we will try to more accurately calculate the focal length of the two-lens system based on the model specifications:



n_{air}	1
n_{glass}	1,524
n_{plastic}	1,585
n_{water}	1,33
R_{cornea}	7,1 cm
d	2,2 cm
f_l	6,2 cm

First, let us calculate the focal length of the cornea $\boldsymbol{f_c}$ with the formula (2). The corneal lens is a plano-convex glass lens, which means that only one wall has a radius of curvature ***R***. A flat wall has an infinitely large radius of curvature, i.e. for a flat wall 1/R=0. Next, let's calculate the focal length of the lens +62 mm in water f_l' using the same formula (2), but we need the radius of curvature R for the calculation. The +62 mm lens is spherical, with the same radii of curvature R on both sides. It's made of plastic. From the formula (2) we will calculate the radius of curvature ***R*** using the value of the focal length in air $\boldsymbol{f_l}$. Given the radius R, let us now calculate the focal length of the lens in the water $\boldsymbol{f_l'}$. Finally, let's calculate the focal length of the two-lens system ($\boldsymbol{f_s}$). To do this, we will use the formula for the focal length of the two-lens system, with a correction, when the lenses are not in contact with each other.

$$\frac{1}{f_s} = \frac{1}{f_c} + \frac{1}{f_l'} + \frac{d}{f_c \cdot f_l'}$$

Compare the f_s value calculated from this formula with the focal length calculated from the thin lens equation in chapter "4. Dependence of the focal length on the index of refraction of the surrounding medium ". Calculate the percentage difference $\boldsymbol{\Delta f_s}$. <u>Is it a big difference?</u>

ATTENTION! Answers to all the questions highlighted in this instruction manual should be included in the exercise report.