Before starting the experiment, check out the new equipment.

- Small optical bench, 30 cm long, mounted adjustable on stand. In order to describe positions of optical elements on the bench it is assumed in the text that you look onto the scale, which is located on one side of the bench, in such a way that the 0 mark is on the left while the 30 cm mark is to your right.
- Optical mounts, with identifying letter as follows:
  - (A) Lens, +40 mm f.l., 6 mm aperture;
  - (B) Lens, +40 mm f.l., 12 mm aperture;
  - (C) Reticule, horizontal lines spaced 1 mm;
  - (D) Lens, +105 mm f.l., 12 mm aperture;
  - (E) Lens, +25 mm f.l., 6 mm aperture;
  - (F) Lens, -50 mm f.l., 12 mm aperture;
- Stage mount with fine adjustment
- Light ray box (from Part I), placed in upright position into metal holder B, as an incandescent light source. (You may use the half-transparent plastic sheet as a light diffuser.)

The focal lengths of the various lenses may vary somewhat from the values given herein. For this reason you should use in subsequent experiments, as much as possible, the experimentally determined focal length for each lens.

The mount for each element has one side partially open to expose the edge of the lens or reticule. Note that these elements vary in thickness. It is sufficiently accurate for the experiments suggested here to consider the plane through the center of each lens as representing the principal plane of that lens, from which all measurements are made. One can easily visualize and locate the position of this plane along the scale within a millimeter.

The equipment provides the student with an interesting and convenient means for learning the principles of image formation by various types and combinations of lenses, and for becoming familiar with the corresponding quantitative relationships between object distance, image distance, and focal length. The device has been named a “Telemicroscope” because several types of telescopes and microscopes can be made with it.

The following suggested experiment is typical for many other ones, and you are certainly encouraged to branch out and design alternative experiments.

For each optical setup with a symbol, a ray diagram should be drawn in proper scale (one-to-one as long as you can) on graph papers. The ray diagrams should indicate how an image is formed and thereby showing the principle of the particular optical instrument. As a reminder for you, each section which requires a ray-diagram is marked with a sign.
III.A  Focal Length of a Lens by Forming an Image of a Distant Object *(Report errors in measured quantities only)*

Background: The quickest way to determine the focal length of a convex lens is the formation of the image of a distant object. As the rays from the distant object are essentially parallel, the image is formed at the principal focus of the lens.

Experiment: Using the mobile stage mount (with an inserted piece of paper) as an adjustable screen to observe the image, determine f for the lens D and, in addition, one of the other three converging lenses (A, B, or E) as accurate as possible.

☛ Draw a ray diagram illustrating the above method using the example of lens D.

III.B  Focal Length Using the Lens Formula *(The experiment III.C can be done with the same set-up.) (Report errors in measured quantities and do error propagation)*

Background: The lens formula

\[
\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}
\]

gives the general relation between object distance s_o, image distance s_i and focal length f for thin lenses. In III.A we had 1/s_o = 0, so that s_i=f. Now we use various measured values of s_o and s_i to determine f.

Experiment: Place the stage mount with screen at the right end of the bench (near the 30 cm mark), the reticule mount C at the left end (0 cm), and the lens (A, B, or E) to be tested between them. Illuminate the reticle with the incandescent lamp, lined up with the optical bench. Move the lens slowly toward the reticule until the image of the reticule is focused on the screen. To obtain a real image the object distance must be greater than the focal length of the lens. Using the fine-motion control, vary the screen position slightly until the sharpest image is formed.

☛ Record the positions of the screen, lens, and reticule. Determine s_o and s_i, then calculate f. Move the screen a few cm to another position and repeat the same procedure.

☛ Why is it not possible to determine the focal lengths of lenses D and F with this method on the given optical bench? Try to answer this question by thinking or experimental attempts.

☛ Note that the lens equation is unaltered if s_o and s_i are interchanged. Thus for a given separation between the reticule and the screen (separation = s_o + s_i) there exist two lens positions that yield a sharply focused image. Use one of the converging lenses (A, B, or E) to verify this. What is the difference of images between different lens positions?
III.C  **Real Image Magnification** *(Report errors in measured quantities and do error propagation)*

Background: The image, projected on the screen in III.B may be larger or smaller than the object. The transverse magnification (ratio of image to object size) is determined by the ratio of the image to object distance.

\[
| M_T | = \left| \frac{s_i}{s_o} \right| = \left| \frac{y_i}{y_o} \right|
\]

Experiment: With the same setup as in III. B, form a sharp image of the reticule on the screen, and record object and image distance.

- Measure the distance between the lines of the image and compare it to the distance between the lines on the reticule (1 mm). Verify the above relation for the magnitude of the transverse magnification by comparing the ratios of \( s_i \) to \( s_o \) and the ratio of the observed line spacing of reticule and reticule image.

III.D  **Virtual Image Magnification: The simple Magnifier** *(Report errors in measured quantities only)*

Background: A converging lens of short focal length, when placed slightly less than one focal length from an object, becomes a simple microscope or “reading glass”. For most distinct vision for the average individual the lens should be positioned so that the image is formed \(~25\text{cm}\) from the eye. The image is virtual and the magnification is

\[
| M | = \frac{25\text{cm}}{f} + 1
\]

Experiment: 

- Place lens B at the 30-cm mark. Position reticule C slightly less than one focal length from it, view through the lens with one eye close to it, and slide the reticule back and forth until the magnified image is clear. In order to measure the magnification of the magnifier, locate the stage mount at the 5 cm mark, at a distance 25 cm from the lens. Insert a piece of mm-ruled paper into the stage mount, in order to use it as a “scale” at the normal viewing distance of 25 cm. With one eye view the reticule through the lens while sighting the scale directly with the other. Superimpose the reticule image and the scale. (This may require a little practice). The virtual magnified image of the reticule should be formed at the position of the scale. To check this, move your eye up and down across the lens and look for relative motion (parallax) between the image and scale superimposed. Determine how many vertical mm-spaces on the scale correspond to a given number of spaces of the image. The ratio of the former to the latter is the magnification of lens B.

- Determine the magnification and compare with the result obtained with the above equation.
III.E  The Compound Microscope (*Report errors in measured quantities only*)

**Background:** This instrument consists of two lenses, an objective and an eyepiece. The objective produces a real, magnified image of the object. This image is viewed, with additional magnification, through the eyepiece. This is just a combination of III.C and III.D.

☛ What is the resulting magnification?

**Experiment:** ☞ A microscope is to be set up using lens A as an objective and lens B as an eyepiece. To obtain the initial magnification, i.e., the magnification due to the objective, use the reticule as an object and a screen to locate the image, permitting s₀ and sᵢ to be measured. Place reticule C at 1 cm, objective A at about 6 cm, and the stage mount with small screen in its clip at about 24 cm. Adjust A until a sharp image of the reticule is formed on the screen.

☛ Record the position of each element and determine the values of s₀ and sᵢ. Place eyepiece B about one focal length to the right of the screen, remove the screen from its clip, and adjust B until the image is in focus when viewed through the eyepiece.

☛ Knowing the focal length of B, compute the magnification.

☛ Use the same method as in III.D to determine the magnification experimentally.

III.F  The Measuring Microscope (*Report errors in measured quantities only*)

**Background:** A very small object can be accurately measured by a reticule scale if an enlarged image of the object is formed in the plane of the scale (no parallax error). The scale and superimposed image are viewed under the additional magnification of an eyepiece. Thus a measuring microscope is similar to a compound microscope but with the addition of a reticule scale in the image plane of the objective lens.

**Experiment:** Build a microscope of your choice making best use of the available lenses. Your microscope should have a known magnification for the objective. Place the reticule as a scale in the image plane of the objective.

☛ Determine the size of the unknown objects (obtained from the TA), and describe your procedure of determination briefly.
III.G The Astronomical Telescope (Report errors in measured quantities only)

Background: An astronomical telescope consists of an objective lens at focal length $f_o$ and an eyepiece of short focal length $f_e$ separated by a distance $f_o + f_e$ so that their focal planes coincide. Rays from a distant object incident upon the objective, being nearly parallel, are brought to focus in the common focal plane. The real, inverted image formed there is the object for the eyepiece, which acts as a magnifier [see Exp. III.D] forming a virtual image at infinity.

The magnifying power $M$ of the telescope is the ratio of the angle subtended at the eye by the image as viewed through the telescope to the angle subtended by the object when viewed by the unaided eye.

☛✍ Illustrate how the telescope works with a ray diagram which includes two distant object points and their virtual images.

Experiment: Set up the telescope using lens $D$ as the objective and lens $E$ as the eyepiece by separating them by the sum of their focal lengths. A direct measurement of $M$ can be obtained by drawing a scale of equally spaced horizontal lines (say 5 cm apart) on the white board to serve as an object. View the scale through the telescope with one eye and directly with the other, and superimpose the image and object. Observe the number of divisions of the scale (object) that correspond to a given number of divisions of the magnified image. The ratio of the former to the latter is the magnifying power.

☛ Determine the magnification.

☛ Show with simple geometrical arguments that (for objects far away from the telescope) the magnifying power can also be computed from focal lengths of the lenses used. (Result: $M = f_o / f_e$)

A third method for determining the magnifying power is by finding the ratio

$$ M = \frac{\text{diameter of entrance pupil}}{\text{diameter of exit pupil}} $$

For the telescope, the entrance pupil is the objective lens (that is, the aperture of the objective) and the exit pupil is its image formed by the eyepiece. The diameter of the exit pupil can be found by illuminating the objective with a frosted, incandescent lamp and moving a screen to a position behind the eyepiece where the sharply defined disk of light is focused on it and can be measured.

☛✍ Show with a simple ray-diagram and simple geometry that this yields the proper result.

Hint: In this set-up the objective lens (or better its aperture) is just the object which is imaged by the eyepiece.

☛ Measure the entrance and exit pupils and determine $M$. 