E&M Laboratory 1106, Spring 2025

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https://www.physics.smu.edu/tneumann/110X_Spring2025/

Make-up lab — Properties of Lenses

Max. points: 52

Lenses are fundamental components in optical systems, from eyeglasses and cameras to microscopes and telescopes. They work by refracting (bending) light to form images. Understanding how lenses manipulate light and form images is crucial in physics and engineering. This lab focuses on the properties of thin lenses, characterized by their focal length, which determines their ability to converge or diverge light.

We will investigate image formation using the thin lens equation, which relates the object distance (d_o), image distance (d_i), and focal length (f). We will distinguish between real images, which can be projected onto a screen, and virtual images, which cannot. Ray diagrams, constructed using principal rays, provide a graphical method to understand image location, size, and orientation (upright or inverted).

In this experiment, you will use an optical bench to measure the focal lengths of converging (positive) lenses by forming real images. You will also explore the concept of magnification. Furthermore, you will combine lenses to construct a simple astronomical telescope and investigate its angular magnification, comparing experimental observations with theoretical predictions. This experiment provides hands-on experience with fundamental optical principles and techniques.

Your preparation: Work through before coming to the lab

- Prepare for the lab by thoroughly reading this worksheet, focusing on the concepts, measurement procedures, and analysis steps. Understand the thin lens equation, ray diagrams, real vs. virtual images, and magnification. Photos of the equipment and further introductory material will be available on the course website:
  https://www.physics.smu.edu/tneumann/110X_Spring2025/schedule-em/
- Note any questions you have and ask your instructor at the beginning of the lab.
- Review the following topics in Halliday, Resnick, and Walker [1]:
  - **Refraction:** Snell's Law (briefly).
  - **Thin Lenses:** Converging (positive) and diverging (negative) lenses, focal point, focal length (f).
  - **Ray Tracing:** Principal rays for converging and diverging lenses. Constructing ray diagrams to locate images.
  - **Thin Lens Equation:** $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$. Sign conventions for d_o, d_i, f.
  - **Image Formation:** Real vs. Virtual images, Upright vs. Inverted images.

- **Lateral Magnification:** $M = -d_i/d_o$. Relationship between sign of M and image orientation.
- **Lens Combinations:** How images formed by one lens act as objects for the next.
- **Telescopes (Refracting):** Basic principle (objective, eyepiece), angular magnification ($M \approx -f_o/f_e$ for astronomical telescope with object at infinity).

Pre-lab: Upload to Canvas before coming to the lab

A reminder: Upload your answers as a PDF to Canvas before the lab begins (uploads close 30 minutes prior).

Pre-lab 1 10 points

1. (1 point) Describe the physical difference between a converging (positive) lens and a diverging (negative) lens. How do parallel rays of light behave after passing through each type?
2. (1 point) State the thin lens equation, defining each variable (d_o, d_i, f). What is the standard sign convention for the focal length f for converging and diverging lenses?
3. (1 point) Define real image and virtual image. Which type of image can be projected onto a screen? For a single thin lens, where is a virtual image typically formed relative to the object?
4. (2 points) Draw a principal ray diagram for a single converging lens forming a real, inverted image of an object placed outside the focal point. Label the object, lens, focal points (F), principal rays, and the resulting image.
5. (2 points) Draw a principal ray diagram for a single diverging lens forming an image of an object. Label the object, lens, focal points (F), principal rays, and the resulting image. What are the characteristics of the image formed by a single diverging lens (real/virtual, upright/inverted, magnified/reduced)?
6. (1 point) State the formula for lateral magnification M in terms of object and image distances. If M is negative, what does this signify about the image orientation relative to the object?
7. (1 point) Briefly explain the function of the objective lens and the eyepiece lens in a simple astronomical telescope. State the formula for the angular magnification M_{ang} of an astronomical telescope focused for an object at infinity, in terms of the focal lengths of the objective (f_o) and eyepiece (f_e).
8. (1 point) What is spherical aberration in the context of lenses? How might it affect attempts to find a single, sharp focus point when forming an image?

Lab measurements and report: submission by end of class

A reminder: Document all measurements fully. Upload your final report (PDF with embedded plots/tables) to Canvas *by the end of class* (uploads close 10 minutes after). Submit your work even if incomplete.

Measurement 1 *Setup and Lens Identification* 1 point

This section guides you through setting up the optical bench and identifying your lenses.

Equipment: Optical bench with scale, light source (e.g., illuminated arrow or object), set of lenses (e.g., +100mm, +200mm, +250mm, -150mm nominal focal lengths), viewing screen, lens holders, meter stick or ruler.

1. **Identify Lenses:** Examine the provided lenses. Based on their shape (thicker or thinner in the middle) and possibly by looking through them at distant objects (magnifying/reducing, upright/inverted), identify each lens as converging (positive) or diverging (negative). Assign an identifier (e.g., L1, L2, L3, L4) to each lens and record its nominal focal length (often printed on the holder) and type (converging/diverging).
2. (1 point) **Record Lens Identification:** Create a table listing each lens identifier, its nominal focal length (if known), and your determination of whether it is converging (+) or diverging (-).
3. **Setup Optical Bench:** Place the light source at one end of the optical bench (e.g., at the 0 cm mark). Record its position x_{source}. Place the viewing screen near the other end. Ensure components are aligned along the optical axis.

Measurement 2 *Focal Length of Converging Lenses* 10 points

Here you will use the optical bench and the thin lens equation to measure the focal lengths of the converging lenses.

1. **Select First Converging Lens:** Choose one of your converging lenses (e.g., the one with nominal $f \approx 200$ mm). Place it in a holder on the optical bench between the source and the screen.
2. **Find First Image Position:** Adjust the position of the *lens* until a clear, sharp, *enlarged* image of the light source is formed on the screen. Record the position of the lens ($x_{lens,1}$) and the screen ($x_{screen,1}$). Estimate the uncertainty in the lens and screen positions based on the sharpness of focus (e.g., ± 0.5 cm or the range over which focus looks acceptable).
3. **Find Second Image (Conjugal) Position:** Keep the source and screen in the *same positions* (x_{source} and $x_{screen,1}$). Now, move the lens *closer to the screen* until a clear, sharp, *reduced* image is formed on the screen. Record this new lens position ($x_{lens,2}$). Note the uncertainty. (These two lens positions correspond to interchanging d_o and d_i).
4. (3 points) **Record Data (Lens 1):** For this first lens, record x_{source}, $x_{screen,1}$, $x_{lens,1}$, $x_{lens,2}$, and your estimated uncertainties (δx_{lens}, δx_{screen}). Describe the characteristics of the first (enlarged) and second (reduced) images (e.g., orientation: upright/inverted).
5. (3 points) **Repeat for Second Converging Lens:** Repeat steps 1-4 for your other converging lens (e.g., nominal $f \approx 100$ mm). You may need to adjust the screen position ($x_{screen,2}$) initially

to be able to find an image. Once found, keep that screen position fixed while finding both lens positions ($x_{lens,3}, x_{lens,4}$) for this second lens. Record all positions and uncertainties.

6. (2 points) **Lens Covering Observation:** Choose one of the image formations from above. Observe the image on the screen. Now, cover the top half of the lens with a piece of paper or your hand. Observe and record what happens to the image on the screen (Does it disappear? Move? Change brightness? Change shape?).

7. (2 points) **Data Table (Converging Lenses):** Organize your measurements in a table. Columns should include: Lens ID, Nominal f, x_{source}, x_{screen}, x_{lens} (for large image), x_{lens} (for small image), uncertainties, Image orientation.

Measurement 3 *Astronomical Telescope Setup* 4 points

Construct a simple refracting telescope and observe its properties.

1. **Select Lenses:** Use your longer focal length converging lens (e.g., $f \approx 200\,\text{mm}$) as the objective lens (L_o) and your shorter focal length converging lens (e.g., $f \approx 100\,\text{mm}$) as the eyepiece (L_e).

2. **Assemble Telescope:** Remove the light source and screen. Place the objective lens (L_o) near one end of the bench and the eyepiece (L_e) near the other. The initial separation distance between them should be approximately $L = f_o + f_e$ (using nominal or previously measured values).

3. **View Distant Object:** Aim the optical bench towards a distant object outside the lab window (e.g., a building, tree, sign). Look through the eyepiece (L_e).

4. **Focus Telescope:** Adjust the position of the *eyepiece* slightly back and forth until the distant object appears sharp and in focus when your eye is relaxed (as if looking very far away).

5. (2 points) **Record Lens Positions:** Record the final positions of the objective lens ($x_{objective}$) and the eyepiece ($x_{eyepiece}$) on the bench. Calculate the separation $L = |x_{eyepiece} - x_{objective}|$.

6. (2 points) **Estimate Angular Magnification:** Observe the distant object through the telescope with one eye, and directly with the other eye (alternate quickly or keep both open if possible). Estimate the angular magnification M_{ang} (how many times larger the image appears through the telescope compared to the naked eye view). Describe the image orientation (upright or inverted). Record your estimated M_{ang} and the method used.

Analysis 1 *Data Analysis and Interpretation* 27 points

In this section, you will analyze your data using the thin lens equation and telescope theory.

Part 1: Focal Length of Converging Lenses

1. (4 points) **Calculate d_o and d_i:** For each measurement set (each lens, both image positions), calculate the object distance $d_o = |x_{lens} - x_{source}|$ and the image distance $d_i = |x_{screen} - x_{lens}|$. Remember that for a real image formed by a single converging lens, d_o and d_i should both be

positive by convention when using the thin lens equation. Create a table showing d_o and d_i for each of the four measurements (2 per lens).

2. (4 points) **Calculate Focal Lengths:** Using the thin lens equation $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$, calculate the focal length f for each of the four measurements.

3. (2 points) **Average Focal Lengths:** For each converging lens, calculate the average focal length from the two measurements (corresponding to the two conjugal positions).

4. (2 points) **Compare with Nominal Values:** Compare your average measured focal lengths with the nominal values provided for the lenses. Calculate the percentage difference for each lens: $\%\text{diff} = \frac{|f_{measured} - f_{nominal}|}{f_{nominal}} \times 100\%$. Discuss the agreement or disagreement.

5. (2 points) **Uncertainty Discussion (Qualitative):** Based on your estimated uncertainties in measuring x_{lens} and x_{screen} (due to focusing limitations), how precise do you think your calculated focal lengths are? Which measurement (d_o or d_i) likely contributed more uncertainty? (discuss the sources). Note that d_o and d_i are not independent if $L = d_o + d_i$ is fixed; how does this relate to finding the two conjugal positions?

6. (1 point) **Lens Covering Explanation:** Explain your observation from Measurement 2, step 6. Why did covering half the lens affect the image brightness but not its completeness (assuming it didn't)? Relate this to ray diagrams.

7. (1 point) **Spherical Aberration:** Did you notice difficulty in getting the entire image perfectly sharp simultaneously (e.g., center vs. edges)? Relate this observation to spherical aberration, as mentioned in the pre-lab reading.

8. (2 points) **Maximum Focal Length (Theory):** What is the maximum focal length f_{max} measurable on an optical bench of total length $L = d_o + d_i$ (fixed distance between object and screen)? Show, using the thin lens equation and perhaps calculus (minimizing L for a fixed f, or maximizing f for a fixed L), that the minimum distance L requires $d_o = d_i = 2f$, meaning $L_{min} = 4f$. Therefore, the maximum focal length measurable for a given bench length L is $f_{max} = L/4$. Does this limit seem relevant to your experiment?

9. (2 points) **Measuring Diverging Lens Focal Length (Method):** Describe *one* method using a converging lens and the optical bench to determine the focal length of a diverging lens. (Hint: Use the converging lens to form a real image, then place the diverging lens *before* this image is formed, making the original real image act as a *virtual object* for the diverging lens. Adjust the screen to find the new *real image* formed by the combination). Draw a simple diagram illustrating the setup.

Part 2: Telescope Analysis

10. (2 points) **Astronomical Telescope Separation:** Compare the measured separation L between your objective and eyepiece (Measurement 3, step 5) with the sum of their *average measured* focal lengths ($f_o + f_e$) calculated in Part 1. How well do they agree? Should they be exactly equal for viewing a very distant object with a relaxed eye? Explain.

11. (2 points) **Astronomical Telescope Magnification:** Calculate the theoretical angular magnification using your *average measured* focal lengths: $M_{ang,theory} = -f_o/f_e$. Compare this theoretical value (including its sign) with your *estimated* angular magnification ($M_{ang,est}$) from

Measurement 3, step 6. Discuss the agreement and the significance of the sign regarding the image orientation you observed.

Part 3: Discussion and Conclusion

12. (2 points) **Sources of Error:** Discuss the main sources of uncertainty and potential systematic errors in your experiment. Consider:
    - Precision of reading positions on the optical bench scale (δx).
    - Difficulty in judging the point of sharpest focus (subjective judgment, spherical aberration). How large was the range (δx_{lens}) where the focus seemed acceptable?
    - Alignment of components (source, lens, screen) along the optical axis. Was the lens perfectly perpendicular to the axis?
    - Assumption of ”thin” lenses.
    - Accuracy of nominal focal lengths (if used for comparison).
    - Parallax error when reading the scale.
    - For the telescope: Accuracy of estimating magnification by eye, ensuring eye was fully relaxed, object truly ”distant”.
13. (1 point) **Conclusion:** Summarize your key findings. State your average measured focal lengths for the converging lenses and compare them to nominal values. Report your estimated and calculated angular magnification for the astronomical telescope. Briefly state whether your results are consistent with the thin lens theory and telescope principles, considering the experimental uncertainties.

References

[1] D. Halliday, R. Resnick, and J. Walker. *Fundamentals of Physics*. Fundamentals of Physics. John Wiley & Sons.