E&M Laboratory 1106, Summer 2025

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https://www.physics.smu.edu/tneumann/110X_Summer2025/

Lab 11 — Optics: Reflection, Refraction, Lenses Max. points: 52

Your preparation: Work through before coming to the lab

- Prepare for the lab by thoroughly reading and understanding the measurement and analysis procedures on this worksheet. Photos of the equipment (Ray Optics Kit, Ray Table, Light Source) and further introductory material will be made available on https://www.physics.smu.edu/tneumann/110X_Summer2025/schedule-em/.
- Collect all your questions and ask your instructor at the beginning of the lab.
- Study the following topics in Halliday, Resnick, and Walker [1]: Understand the nature of light as rays. Review the Law of Reflection ($\theta_i = \theta_r$). Study the Law of Refraction (Snell's Law, $n_1 \sin\theta_1 = n_2 \sin\theta_2$) and the concept of the index of refraction (n). Understand total internal reflection and the critical angle ($\sin\theta_c = n_2/n_1$). Review image formation by plane and spherical mirrors (concave and convex), including ray tracing, the mirror equation ($1/p + 1/i = 1/f$), and the relationship between focal length and radius of curvature ($f = R/2$). Study image formation by thin lenses (converging/convex and diverging/concave), including ray tracing, the thin lens equation ($1/p + 1/i = 1/f$), and the lensmaker's equation ($1/f = (n-1)(1/R_1 - 1/R_2)$). Understand the concept of dispersion and how the index of refraction varies with wavelength.

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

A reminder: Upload your answers as a text document (exported as PDF) to Canvas before the lab begins (Canvas uploads are no longer possible 30 minutes before the lab starts!).

Pre-lab 1 — 7 points

1. (1 point) State the Law of Reflection. Draw a simple diagram showing an incident ray, a reflected ray, the normal, the angle of incidence, and the angle of reflection relative to a plane mirror.
2. (1 point) State Snell's Law (the Law of Refraction). Define each variable in the equation. Explain what happens to a light ray when it passes from a medium with a lower index of refraction to one with a higher index of refraction, and vice versa, assuming it strikes the interface at an angle other than $0°$.

3. (1 point) Explain the phenomenon of total internal reflection. Under what conditions does it occur? Define the critical angle and write the formula relating it to the indices of refraction of the two media.
4. (1 point) What is the relationship between the focal length (f) and the radius of curvature (R) for a spherical mirror? Is the focal length positive or negative for a concave mirror? For a convex mirror?
5. (1 point) What is the sign convention for the focal length (f) of a converging (convex) lens? What about a diverging (concave) lens? Briefly describe how you can experimentally determine the focal point of a converging lens using parallel rays. How would you find the focal point for a diverging lens?
6. (1 point) Write down the lensmaker's equation for a thin lens in air. Explain what each variable represents. How could you use this equation to predict the focal length of the hollow lens when filled with water, given the radii of curvature of its surfaces and the index of refraction of water?
7. (1 point) What is dispersion? Briefly explain how a prism separates white light into different colors, relating this phenomenon to the index of refraction. Does the index of refraction typically increase or decrease with increasing wavelength for visible light in glass?

Lab measurements and report: submission by end of class

A reminder: All measurements must be fully documented. The final report must be uploaded to Canvas *by the end of the class* exported as PDF with plots and tables embedded as images. Canvas will stop accepting uploads 10 minutes after the class ends. If you have not fully completed your report, you must upload the documents as far as you have completed them for grading.

Measurement 1 *Warmup: Law of Reflection* Equipment: Ray optics kit (plane mirror), ray table, light source (single ray mode). 3 points

1. Set up the light source for a single ray and place the plane mirror on the ray table, aligning its reflecting surface with a convenient line (e.g., the normal line or the component line).
2. Shine the single ray onto the mirror at the point where the normal intersects the mirror surface.
3. Adjust the angle of incidence (θ_i) sequentially to values from $10°$ to $70°$ in steps of $10°$. Remember to measure the angle of incidence relative to the normal.
4. (3 points) For each angle of incidence, carefully measure and record the corresponding angle of reflection (θ_r), also measured relative to the normal. Estimate the uncertainty in your angle measurements. Create a table to record your data (θ_i vs θ_r).

Measurement 2 *Law of Refraction and Total Internal Reflection* 7 points
Equipment: Ray optics kit (D-shaped lens), ray table, light source (single ray mode).

1. Place the D-shaped lens on the ray table such that its flat surface aligns with the component line and its center aligns with the center of the ray table's degree scale.
2. Set the light source to a single ray. Direct the ray towards the center of the flat side, entering through the curved surface. Ensure the ray entering the curved surface travels along a radius, striking the center of the flat side perpendicularly (zero angle of incidence at the curved surface). This ensures no refraction occurs at the curved surface upon entry.
3. Adjust the angle of incidence (θ_1) at the flat surface (inside the lens) from $10°$ to $40°$ in steps of $10°$. Measure the angle of incidence within the lens material relative to the normal.
4. (2 points) For each θ_1 in the range $10°$ to $40°$, measure and record the angle of refraction (θ_2) in the air, relative to the normal. Add these to a data table.
5. (3 points) Continue increasing the angle of incidence θ_1 from $40°$ towards $45°$, reducing the step size to $1°$. Carefully observe and record θ_1 and θ_2 in your table. Note and record the specific angle of incidence θ_1 at which the angle of refraction θ_2 reaches $90°$. This is the critical angle (θ_c). Aim for a precision of $0.5°$.
6. (2 points) Increase the angle of incidence θ_1 further to $50°$, $60°$, and $70°$. Observe and describe in writing what happens to the light ray at the flat interface (total internal reflection). Record your observations. Complete your θ_1 vs θ_2 data table.

Measurement 3 *Focal Length of Spherical Mirrors* 8 points

Equipment: Ray optics kit (concave mirror, convex mirror), light source (3-ray and 5-ray modes), white paper, ruler.

1. **Concave Mirror:**
   (a) Draw two perpendicular lines on a piece of paper. This defines your principal axis and a line perpendicular to it.
   (b) Measure the physical width (chord length) of the concave mirror. Mark points at half this distance symmetrically on the perpendicular line.
   (c) Place the mirror on the paper such that its tips touch these marks. Trace the reflecting surface of the mirror. The point where the mirror curve intersects the principal axis is the vertex.
   (d) (1 point) Place the light source so its rays are parallel to the principal axis. Use the 3-ray setting, ensuring the central ray travels along the principal axis. Observe where the reflected rays converge. Mark this point – the focal point (F). Measure and record the distance from the vertex to F; this is the focal length (f_3).
   (e) (1 point) Switch the light source to the 5-ray setting, keeping the central ray on the principal axis. Observe where these reflected rays converge. Mark this point. Measure and record the focal length (f_5). Note if the convergence point is as sharp as with 3 rays.
   (f) (1 point) Calculate and record the average focal length $f_{\text{concave}} = (f_3 + f_5)/2$.

(g) (1 point) Devise a method to estimate the radius of curvature (R) of the mirror using the traced curve or the mirror itself and the ruler. Record your method description and the measured value of R.

Suggestion: One common method uses the mirror's width (chord length, w) and its maximum depth (sagitta, h). Measure w across the mirror's opening and h from the center of the chord line to the mirror's vertex. Let $x = w/2$. The radius of curvature can then be estimated using the formula: $R = \frac{x^2+h^2}{2h}$. Remember to consider the sign convention for R (typically positive for concave, negative for convex mirrors). Explain the specific steps you took to measure w and h and report your calculated R.

2. **Convex Mirror:**
   (a) Repeat steps (a)-(c) for the convex mirror.

   (b) Use the 3-ray setting with parallel incident rays. The reflected rays will diverge. Use a ruler to trace the reflected rays back behind the mirror. Mark the point where they appear to converge – this is the virtual focal point (F). (1 point) Measure the distance from the vertex to F; record this focal length (f_3) as a negative value.

   (c) Repeat with the 5-ray setting, back-tracing the diverging rays to find the virtual focal point. (1 point) Measure and record the focal length (f_5, also negative).

   (d) (1 point) Calculate and record the average focal length $f_{\text{convex}} = (f_3 + f_5)/2$.

   (e) (1 point) Estimate the radius of curvature (R) of the convex mirror using a similar method as before. Record your method description and the measured value of R (consider its sign).

3. Check the kit's manual or datasheet for the nominal focal lengths or radii of curvature for the mirrors provided. (Record these values for use in the analysis section).

Measurement 4 *Focal Length of Thin Lenses* 4 points

Equipment: Ray optics kit (convex lens, concave lens), light source (3-ray or 5-ray mode), white paper, ruler.

1. **Convex Lens:**
   (a) Draw a principal axis on a piece of paper. Place the convex lens centered on this axis. Mark the position of the center of the lens.

   (b) Use the light source (3 or 5 parallel rays) with the central ray aligned with the principal axis.

   (c) Observe where the refracted rays converge on the other side of the lens. Mark this focal point (F).

   (d) (2 points) Measure the distance from the center of the lens to the focal point F. This is the focal length (f_{convex}). Record this value (it should be positive). (You may repeat/average for better precision).

2. **Concave Lens:**

(a) Draw a principal axis and center the concave lens on it. Mark the lens center.

(b) Use parallel incident rays (3 or 5). The rays will diverge after passing through the lens.

(c) Use a ruler to trace the diverging rays back towards the incident side. Mark the point where they appear to originate – this is the virtual focal point (F).

(d) (2 points) Measure the distance from the center of the lens to this virtual focal point F. Record this focal length (f_{concave}) as a negative value. (You may repeat/average).

3. Check the kit's manual or datasheet for the nominal focal lengths of the lenses. (Record these values for use in the analysis section).

Measurement 5 *Hollow Lens Filled with Water* 3 points

Equipment: Ray optics kit (hollow lens), light source (3-ray or 5-ray mode), white paper, ruler, water.

1. (1 point) Measure the physical width or diameter of the hollow lens. Draw a principal axis and place the empty hollow lens centered on it. Observe that parallel rays pass through essentially undeviated. Record this observation.
2. Carefully fill the central cavity of the hollow lens with water. Place it back on the principal axis.
3. Use parallel incident rays (3 or 5) aligned with the principal axis. Observe that the lens now converges the light.
4. (2 points) Locate the focal point (F) where the rays converge. Measure the distance from the center of the lens to F. This is the measured focal length (f_{measured}) of the water-filled lens. Record this value.
5. Look up the radii of curvature (R_1 and R_2) for the surfaces of the hollow lens from the kit's manual or datasheet. Note the sign convention. Also, find or assume a value for the index of refraction of water (n_{water}, typically around 1.33). (Record these values for use in the analysis section).

Measurement 6 *Dispersion in a Prism* 2 points

Equipment: Ray optics kit (equilateral prism), light source (single ray mode, white light), white paper or screen.

1. Place the equilateral prism on a piece of paper.
2. Set the light source to a single ray of white light. Shine the ray onto one face of the prism.
3. (1 point) Observe the ray emerging from the opposite face. You should see the white light dispersed into a spectrum (rainbow). Note in writing which color is deviated the most and which is deviated the least from the original direction.
4. (1 point) Make a careful sketch showing the path of the white light ray entering the prism, refracting at the first surface, refracting and dispersing at the second surface, and showing

the relative angles of the different colors (e.g., red and violet) as they emerge. Label the incident ray, refracted rays inside the prism, emergent dispersed rays, and indicate the angles of deviation.

Analysis 1 *Data Analysis and Interpretation* 18 points

1. **Law of Reflection Analysis:**
   (a) (2 points) Create a plot of the measured angle of reflection (θ_r) versus the angle of incidence (θ_i) using your data from the plane mirror measurement. Include error bars based on your estimated uncertainty.

   (b) (1 point) Does your data support the Law of Reflection ($\theta_r = \theta_i$)? Discuss this, possibly by fitting a line to your data and examining the slope and intercept, or by calculating the difference $\theta_r - \theta_i$ for each point.

2. **Refraction and Total Internal Reflection Analysis:**
   (a) (2 points) Create a plot of the angle of refraction (θ_2) versus the angle of incidence (θ_1) using your data from the D-shaped lens measurement.

   (b) (1 point) Use Snell's Law ($n_1 \sin\theta_1 = n_2 \sin\theta_2$) to calculate the index of refraction (n_{lens}) of the lens material for each data point where refraction occurred (before TIR). Assume $n_2 = 1.00$. Show a sample calculation and the results (e.g., add a column to data table).

   (c) (1 point) Calculate the average value of n_{lens} and its standard deviation (or standard error of the mean) as the uncertainty. Report the result as $n_{\text{lens}} \pm \Delta n_{\text{lens}}$.

   (d) Report the critical angle (θ_c) you observed and recorded in Measurement 2, step 5.

   (e) (1 point) Calculate the theoretical critical angle using your average measured index of refraction: $\sin\theta_c = n_2/n_1 = 1/n_{\text{lens}}$. Compare this calculated value with your directly observed value. Discuss the agreement (e.g., calculate percentage difference).

3. **Mirror Focal Length Analysis:**
   (a) Report your average measured focal lengths (f_{concave} and f_{convex}) for both mirrors, including signs.

   (b) Report your estimated radii of curvature (R_{concave} and R_{convex}) and briefly restate the method used. Remember the sign conventions.

   (c) (1 point) Compare your measured focal lengths with the prediction $f = R/2$ for each mirror. Calculate the percentage difference for both.

   (d) (1 point) Record the nominal focal lengths (or calculate from nominal R) from the kit datasheet. Compare your measured focal lengths with these nominal values. Calculate the percentage difference for both.

   (e) (1 point) Discuss potential sources of error in these measurements (e.g., difficulty in locating the exact focal point, especially with 5 rays due to spherical aberration, uncertainty in measuring R, tracing rays).

4. **Lens Focal Length Analysis:**
   (a) Report your measured focal lengths for the convex (f_{convex}) and concave (f_{concave}) lenses. Remember the sign convention.
   (b) (1 point) Record the nominal focal lengths from the kit datasheet. Compare your measured focal lengths with the nominal values. Calculate the percentage difference for both.
   (c) (1 point) Discuss potential sources of error (e.g., lens thickness assumption, aligning rays precisely parallel, locating the virtual focus for the concave lens).
5. **Hollow Lens Analysis:**
   (a) Report your measured focal length (f_{measured}) for the hollow lens filled with water.
   (b) (2 points) Record the radii (R_1, R_2) from the manual and the value used for n_{water}. Use the lensmaker's equation ($1/f = (n_{\text{water}} - n_{\text{air}})(1/R_1 - 1/R_2)$) to calculate the theoretical focal length ($f_{\text{calculated}}$). Assume $n_{\text{air}} \approx 1$. Pay close attention to the sign conventions for R_1 and R_2. Show your calculation clearly.
   (c) (1 point) Compare your measured focal length (f_{measured}) with the calculated focal length ($f_{\text{calculated}}$). Calculate the percentage difference.
   (d) (1 point) Discuss possible reasons for any discrepancy (e.g., uncertainty in R_1, R_2, actual n_{water} vs assumed, lens alignment, measurement uncertainty).
6. **Dispersion Analysis:**
   (a) Include your sketch of the prism dispersion from the measurement section in your report.
   (b) (1 point) Based on your observation of which color was deviated most and which least, state how the index of refraction (n) of the prism material changes with the wavelength (λ) of light. Justify your statement using Snell's Law conceptually.

References

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