Fluids, Thermodynamics, Waves, & Optics
Optics
Lab 8
Lenses

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Overview

- Purpose
- Theory
- Part 3.1: behavior of a converging lens
- Part 3.2: the lens equation
- Part 3.3: thick converging lens

Purpose of the Lab

To explore the use of lenses to form images.

You will use the Geometric Optics and Bending Light PhET simulations to explore the how light is manipulated by a lens to form images, both with a thin lens and with a thick lens.

Images Formed by Refraction

In the previous lab, we used this expression,

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R}$$

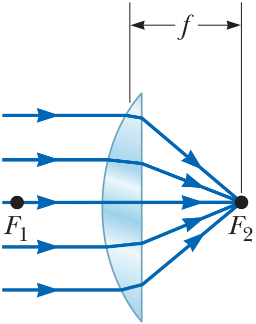
which relates the object and image distances to the radius of curvature of a refracting surface.

Focal Length of a Lens

Lenses are optical devices that can be used to create images.

focal length

The focal length of a lens is the distance from a thin lens to where an image is formed when the object is at infinity.
For converging lenses, this the the distance to where the incoming parallel rays are focused.



Images Formed by Thin Lenses

We will derive the **thin lens equation**

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$$

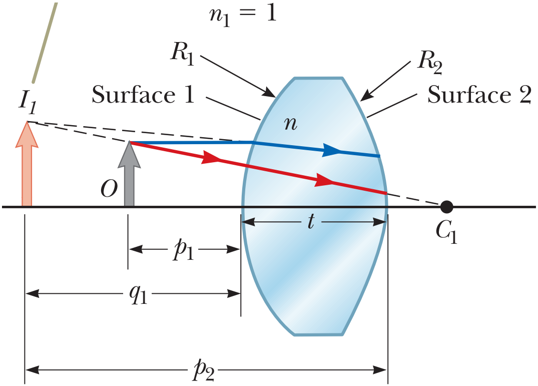
And the **lens maker's equation**

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

We do this by considering each side of the lens as a refracting surface.

Images Formed by Thin Lenses

A thick lens:

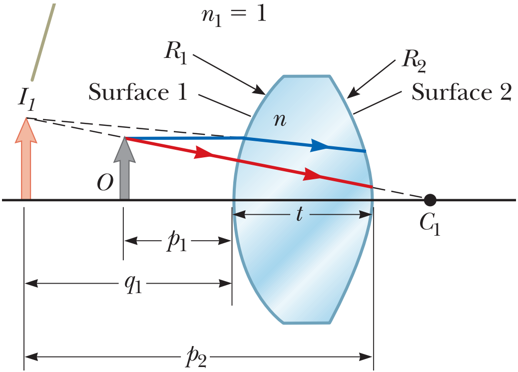


We can imagine that there first surface forms an image I_1, and that image becomes the *object* for the second surface.

The pink arrow shows I_1

First image formed

Let $n_1 = 1$, $n_2 = n$.



$$\frac{1}{p_1} + \frac{n}{q_1} = \frac{n-1}{R_1}$$

Second image formed

$$\frac{n}{p_2} + \frac{1}{q_2} = \frac{1-n}{R_2}$$

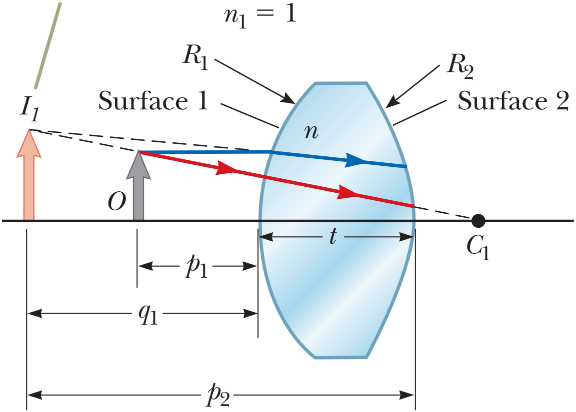
We must relate p_2 to q_1. The new object is the image from the previous surface so:

$$p_2 = -q_1 + t$$

where t is the lens thickness.

p_2 could be positive (real object)...

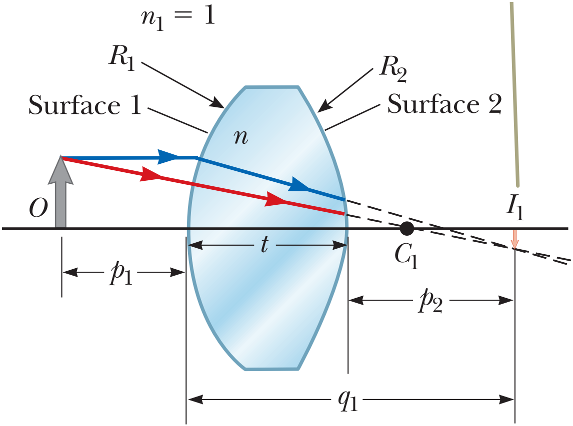
If q_1 is negative (virtual image 1)...



... p_2 is positive (object in front of surface).

p_2 could be negative (virtual object)...

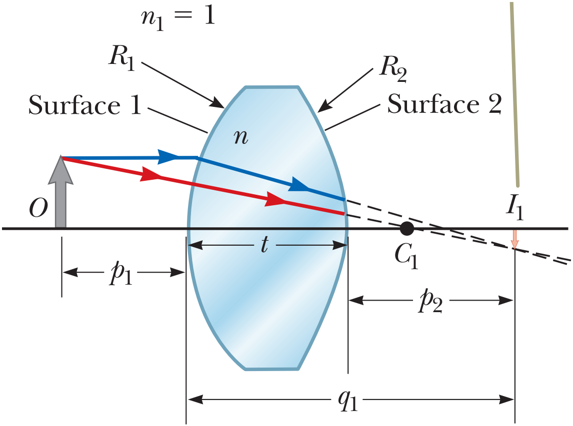
If q_1 is positive (real image 1)...



... p_2 is negative (object behind surface).

p_2 could be negative (virtual object)...

If q_1 is positive (real image 1)...



... p_2 is negative (object behind surface).

Either way, the sign is taken care of in the expression $p_2 = -q_1 + t$.

Relate the original object to the final image

$$\text{surface 1} \qquad \frac{1}{p_1} + \frac{n}{q_1} = \frac{n-1}{R_1} \tag{1}$$

$$\text{surface 2} \qquad \frac{n}{(-q_1 + t)} + \frac{1}{q_2} = \frac{1-n}{R_2}$$

For a **thick** lens, you need to use these two equations!

Relate the original object to the final image

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$$\text{surface 2} \qquad \frac{n}{(-q_1 + t)} + \frac{1}{q_2} = \frac{1-n}{R_2}$$

For a **thick** lens, you need to use these two equations!

For a thin lens, t is negligible, so take it to be zero.

$$\text{surface 2} \qquad -\frac{n}{q_1} + \frac{1}{q_2} = \frac{1-n}{R_2} \tag{2}$$

Add equation (1) to equation (2) to get

$$\frac{1}{p_1} + \frac{1}{q_2} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Thin Lens Equation

Lastly, measure the object distance to be $p = p_1 + t/2$ and $q = q_2 + t/2$.

Since t is effectively zero, we have:

$$\frac{1}{p} + \frac{1}{q} = (n - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

p and q can vary, but since n, R_1, and R_2 are constant for a fixed lens, we know $\frac{1}{p} + \frac{1}{q} = \text{const}$.

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If $p \to \infty$, $q \to f$, by the definition of the focal length.

This gives the **thin lens equation**

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

Lens Maker's Equation

Thin lens equation

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

and

$$\frac{1}{p} + \frac{1}{q} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

The LHS is the inverse of the focal length, giving the lens maker's equation:

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

Magnification with a Lens

By definition,

$$M = \frac{h'}{h}$$

And it follows from simple trigonometry that

$$M = -\frac{q}{p}$$

Sign Conventions for Lenses!

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

Variable	is Positive	is Negative
p	object in front of surface	[virtual object][1]
q	image behind lens (real)	image in front of lens (virtual)
h' (and M)	image upright	image inverted
R_1 and R_2	object faces convex surf. (C behind surface)	object faces concave surf. (C in front of surface)
f	lens is **converging**	lens is **diverging**

[1] Useful in derivations.

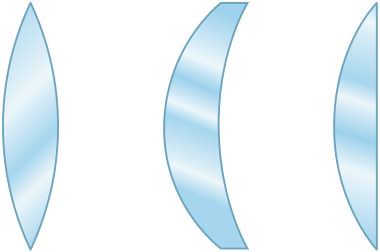
Understanding the Sign of f

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

Always $n \geqslant 1$, so $(n-1)$ is positive (if zero, there's no lens!).

$\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$ could be positive or negative, depending on the signs and magnitudes of R_1 and R_2.

Sign Examples: Converging Lenses



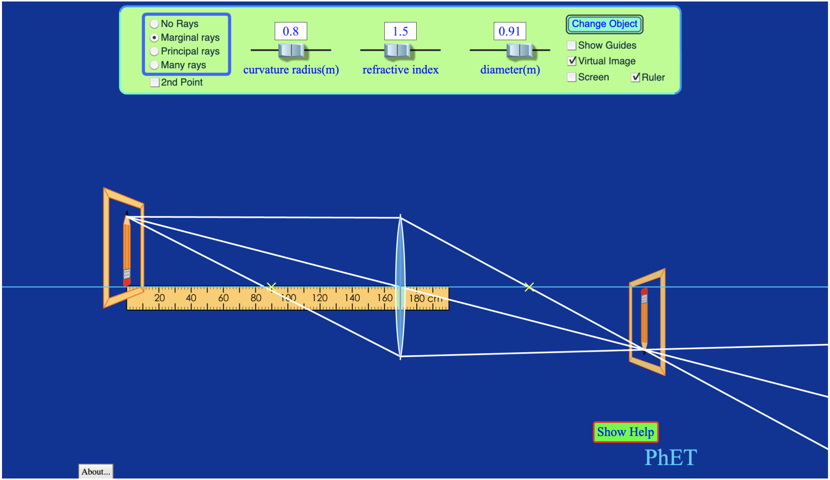
Biconvex	Convex-concave	Plano-convex
R_1 R_2	R_1 R_2	R_1 R_2
R_1 +ve	R_1 +ve	R_1 +ve
R_2 −ve	R_2 +ve	R_2 ∞
	$R_1 < R_2$	
f +ve	f +ve	f +ve

Sign Examples: Diverging Lenses

Biconcave	Convex-concave	Plano-concave

R_1 −ve	R_1 +ve	R_1 ∞
R_2 +ve	R_2 +ve	R_2 +ve
	$R_1 > R_2$	
f −ve	f −ve	f −ve

Geometric Optics: Parts 3.1-3.2



Lab Activity - Part 3.2

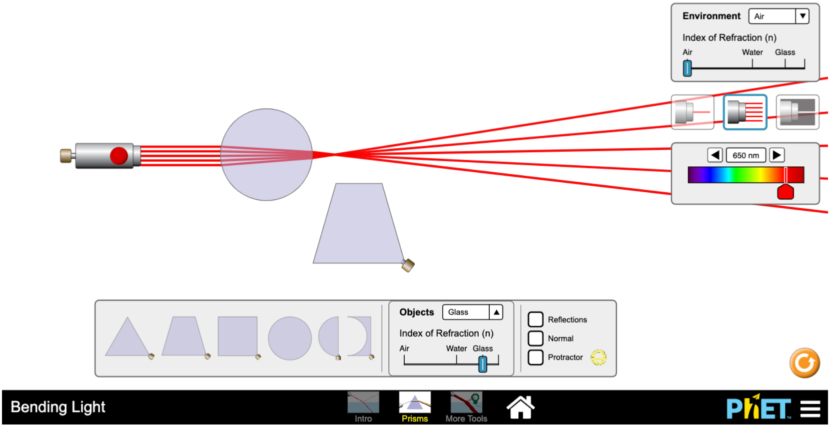
You will plot a graph based on data taken for your object and image distances. From the instruction sheet:
"Measure the object distance p and, without moving the object, measure the image distance q. For a virtual image, record q as negative. Record these points in a table and their inverses. Repeat so that you have 8 pairs of values for p and q. Plot a graph of two of the columns in your table, one on the horizontal axis and one on the vertical, so that the result is a **straight line**. From the graph, extract a value for the focal length. Make sure to include your graph in your submission."

p (cm)	q (cm)	$\frac{1}{p}$ (cm^{-1})	$\frac{1}{q}$ (cm^{-1})

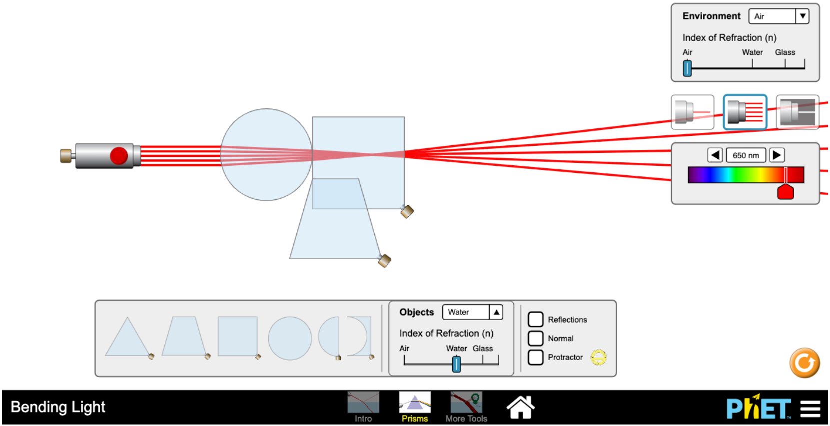
Lab Activity - Part 3.2

- Make sure to label your axes.
- Put a best-fit line through your data points and show the equation of the line on your graph.
- From the best-fit line, find f.

Bending Light, Prisms: Part 3.3



Bending Light, Prisms: Part 3.3



Bending Light, Prisms: Part 3.3