GUIDED NOTES

Unit 15: Waves and Optics – Geometric Optics

OBJECTIVES:

Big Idea 6: Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena.

Enduring Understanding 6.E: The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media.

Essential Knowledge 6.E.1: When light travels from one medium to another, some of the light is transmitted, some is reflected, and some is absorbed. (Qualitative understanding only.)

Learning Objective 6.E.1.1: The student is able to make claims using connections across concepts about the behavior of light as the wave travels from one medium into another, as some is transmitted, some is reflected, and some is absorbed.

Essential Knowledge 6.E.2: When light hits a smooth reflecting surface at an angle, it reflects at the same angle on the other side of the line perpendicular to the surface (specular reflection); this law of reflection accounts for the size and location of images seen in mirrors.

Learning Objective 6.E.2.1: The student is able to make predictions about the locations of object and image relative to the location of a reflecting surface. The prediction should be based on the model of specular reflection with all angles measured relative to the normal to the surface.

Essential Knowledge 6.E.3: When light travels across a boundary from one transparent material to another, the speed of propagation changes. At a non-normal incident angle, the path of the light ray bends closer to the perpendicular in the optically slower substance. This is called refraction.

a. Snell's law relates the angles of incidence and refraction to the indices of refraction, with the ratio of the indices of refraction inversely proportional to the ratio of the speeds of propagation in the two media.

b. When light travels from an optically slower substance into an optically faster substance, it bends away from the perpendicular.

c. At the critical angle, the light bends far enough away from the perpendicular that it skims the surface of the material.

d. Beyond the critical angle, all of the light is internally reflected.

Learning Objective 6.E.3.1: The student is able to describe models of light traveling across a boundary from one transparent material to another when the speed of propagation changes, causing a change in the path of the light ray at the boundary of the two media.

Learning Objective 6.E.3.2: The student is able to plan data collection strategies as well as perform data analysis and evaluation of the evidence for finding the relationship between the angle of incidence and the angle of refraction for light crossing boundaries from one transparent material to another (Snell's law).

Learning Objective 6.E.3.3: The student is able to make claims and predictions about path changes for light traveling across a boundary from one transparent material to another at non-normal angles resulting from changes in the speed of propagation.

GUIDED NOTES

Essential Knowledge 6.E.4: The reflection of light from surfaces can be used to form images.
a. Ray diagrams are very useful for showing how and where images of objects are formed for different mirrors and how this depends upon the placement of the object. Concave and convex mirror examples should be included.
b. They are also useful for determining the size of the resulting image compared to the size of the object.
c. Plane mirrors, convex spherical mirrors, and concave spherical mirrors are part of this course. The construction of these ray diagrams and comparison with direct experiences are necessary.

Learning Objective 6.E.4.1: The student is able to plan data collection strategies and perform data analysis and evaluation of evidence about the formation of images due to reflection of light from curved spherical mirrors.

Learning Objective 6.E.4.2: The student is able to use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the reflection of light from surfaces.

Essential Knowledge 6.E.5: The refraction of light as it travels from one transparent medium to another can be used to form images.
a. Ray diagrams are used to determine the relative size of object and image, the location of object and image relative to the lens, the focal length, and the real or virtual nature of the image. Converging and diverging lenses should be included as examples.

Learning Objective 6.E.5.1: The student is able to use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the refraction of light through thin lenses.

Learning Objective 6.E.5.2: The student is able to plan data collection strategies, perform data analysis and evaluation of evidence, and refine scientific questions about the formation of images due to refraction for thin lenses.

GUIDED NOTES

NOTES:

I. When light travels from one medium to another, some of the light is _________________, some is _________________, and some is _________________. Transmitted light may be refracted (bent) resulting in it changing direction.

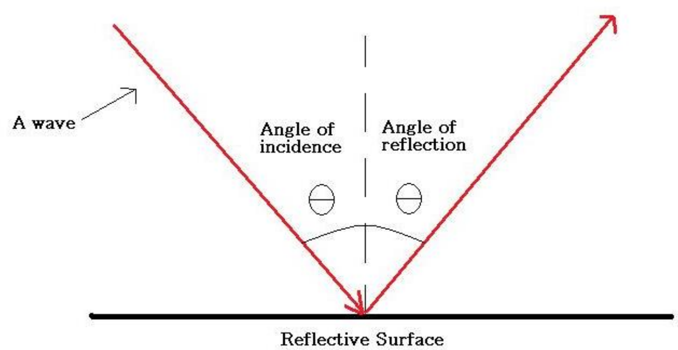
- A pigment absorbs all colors of light except for the wavelength it reflects.
    - A blue shirt absorbs every color of light except for the wavelength of blue light that we see.
    - Black pigment absorbs all light.
    - White pigment reflects all light.
    - Pigments in transparent filters behave the same way except that they transmit the wavelength that they don't absorb rather than reflecting it.

II. _________________

A. Reflection is the bouncing of a wave off of a surface, sending the wave's energy back.

B. A ray reflects at the same angle as its incident (initial) ray as measured against the normal. "____."

This is called ____________ reflection.



C. Images

1. When reflection occurs, images can form, duplicating the original object, possibly with distortion, such as magnification

2. There are two types of images

a. _____________________: Light rays actually come together to create an image (They are made from "real rays.")

b. _____________________: Light rays do *not* come together to create an image. (They are not made from actual physical rays but actually exist only in the mind.)

3. Images may be magnified.

a. _________________ compares image height to object height as a ratio.

b. Formula:

where s is distance and h is height and the subscripts i and o stand for image and object.

D. Reflection by Mirrors

1. _________________________ allow you to create a drawing to find where an image appears.

- You only need to draw two rays, but you *can* draw three to double check that you've drawn them correctly.
- Rules for rays are listed by each type of mirror.
- ***<u>If the rays do not cross in front of the mirror, extend them behind the mirror. If they cross there, you have a virtual image.</u>***

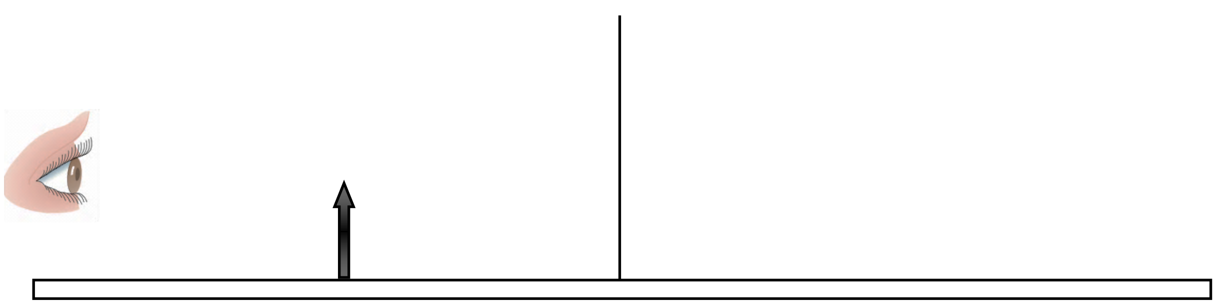
2. Mirror type #1: __________________________________ (a.k.a. plane mirrors):

a. Rays: ***Draw two (or three) where the angle of incidence equals the angle of reflection. Simply measure with a protractor.***

1.) The easiest ray is one that is perpendicular to the surface, reflecting back along itself.

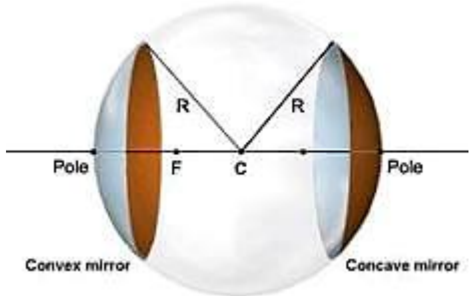
2.) Flat mirrors create virtual images with no magnification. Image height and distance equal object height and distance.

b. Sketch:



3. Mirror type #2: ___________________________________

a. Imagine spherical mirrors are cut from reflective spheres.



- __________________________ are reflective on the ______________ of the sphere.
- __________________________ are reflective on the ______________ of the sphere.

b. General information:

1.) _____________________________ (C) is the center of curvature for the sphere. Its distance from the mirror is the ____________ (R).

2.) ________________________ (f): This is *very* important. It is the point ____________ ____. Its distance from the mirror is ________.

3.) _____________: A straight line passing through the center of the mirror perpendicular to its surface

c. Rays diagrams for spherical mirrors:

- ***A horizontal incident ray reflects in the line of the focal point.***
- ***A incident ray in line with the focal point reflects horizontally.***
- ***To check yourself (if you want): A ray passing in line with C reflects back on itself.***

d. __________________________can be determined using the _________________________

where _____ is _____________:

Sign Conventions for Spherical Mirrors

Generally speaking, in front of the mirror's shiny surface is +, and behind is -.

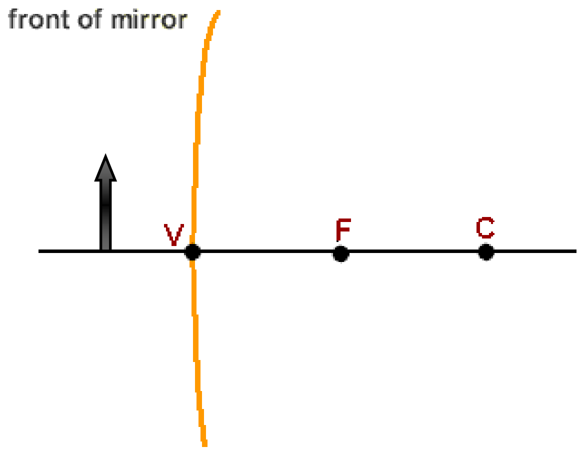
Focal Length	**+**	**Concave (in front)**
	-	**Convex (behind)**
So	**+**	**In front (real object)**
	-	**Behind (virtual object)***
Si	**+**	**Real image (in front)**
	-	**Virtual image (behind)**
M	**+**	**Upright**
	-	**Inverted**

*** How can an object be behind a mirror? In systems with more than one mirror, a virtual image formed by one mirror can be the object reflected by another mirror.**

Example: What type of image appears when an object is placed 2.3 cm from a concave mirror whose focal length is 3.0 cm? What is the magnification?

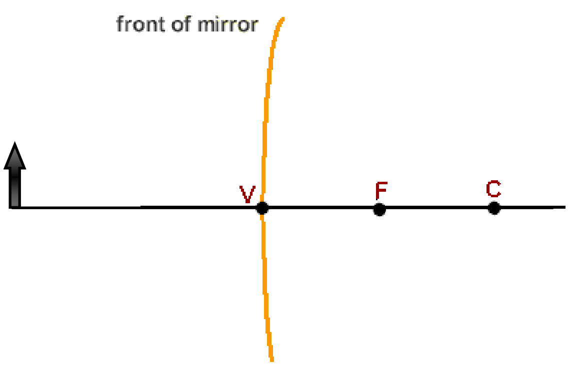
e. Practice with convex and concave mirrors:

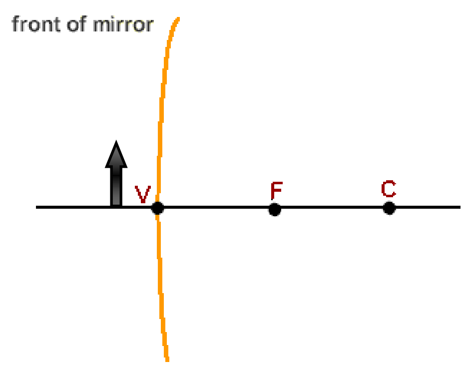
<u>Convex Mirrors</u>:



The image is (real/virtual) and (upright/inverted) and (bigger/smaller/the same size.)

P.S. All images from this type of mirror are the same. (Try to prove this wrong just to be sure.)

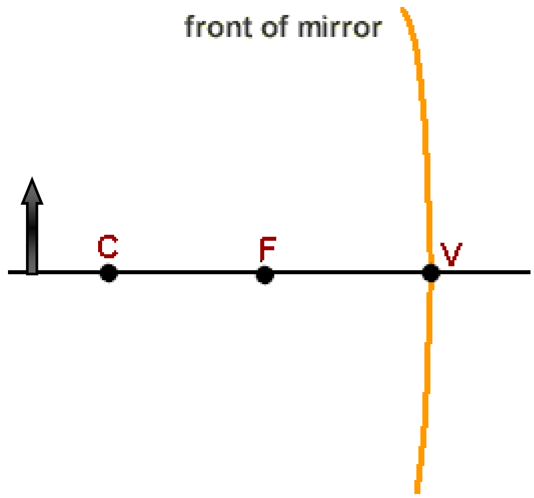




GUIDED NOTES

Concave Mirrors:

Object beyond the center of curvature



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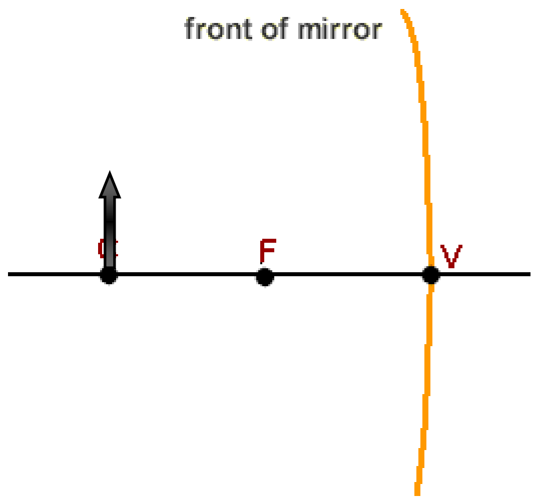
Object on the center of curvature



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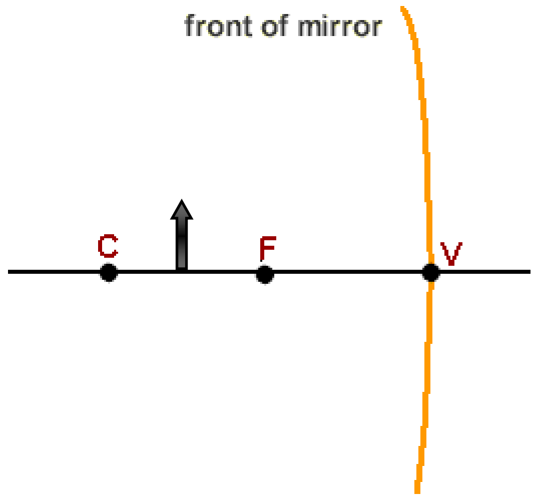
GUIDED NOTES

<u>Object between the center of curvature and the focal point</u>



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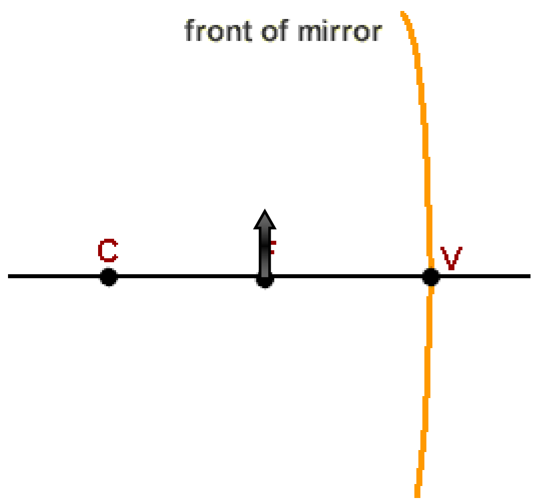
<u>Object on the focal point</u>



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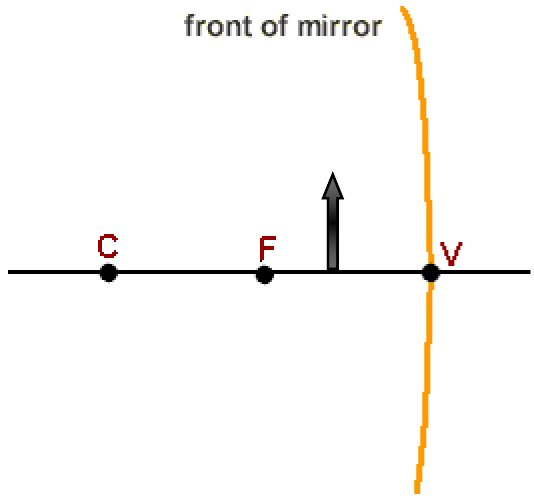
(*Wait a minute…*)

Object between the focal point and the mirror



The image is (real/virtual) and (upright/inverted) and (bigger/smaller/the same size.)

III. Refraction and Lenses

A. ______________

1. Refraction is the ____________________________.

2. ____,

it ____________________________. This ______________ it to ______________.

a. Speed of light and the index of refraction

1.) In a vacuum, light travels at speed $= 3x10^8 \mathrm{m}/s$, but in ______________ mediums, it ______________ down.

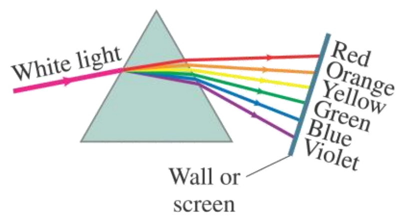
2.) ________________________________ (____): A value unique to each medium that refers to the extent to which light speed in that medium differs from c. The ______________ the value of n, the ______________ the speed of light in that medium.

a.) The index of refraction is the ratio of the speed of light in a vacuum to the speed of light in that material:

b.) The index of refraction of light varies inversely with wavelength.

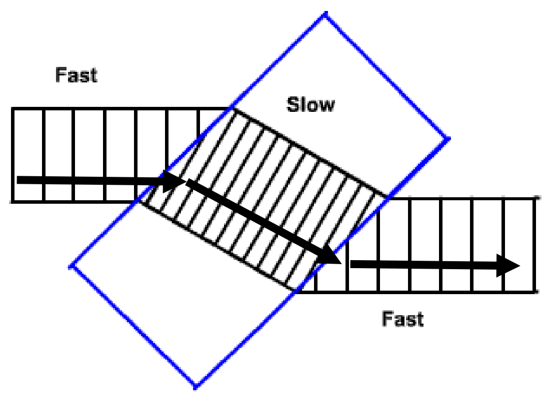
$$n = \frac{1}{\lambda}$$

- ___________________________: When light enters a medium at an angle, this variation in n causes each wavelength to refract differently. This allows light to spread, or disperse, into its component colors.



b. The angle of refraction is given by ___________________________[1]

When a ray _____________ a medium with a ___________________________, it bends ___________________________, and when it enters a medium with a lower index, it bends away from the normal. *Draw the normals on the picture at each interface.*



c. Total internal reflection and the critical angle

1.) _____________________________: When light travels from a medium with a large index of refraction (where it is slow) to a medium with a smaller index of refraction (where it speeds up,) there is an _____________________________ that results in a ____of the medium. This incident angle is called the critical angle.

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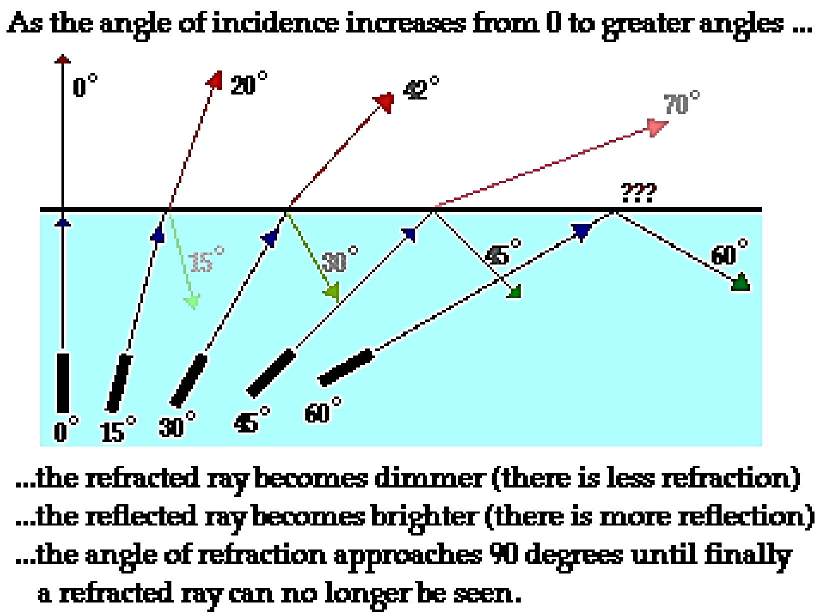
[1] Dutch astronomer and mathematician Willebrord Snellius (1580-1626) is given credit for this discovery, but the first person to discover it was actually Muslim mathematician and physicist Ibn Sahl in the year 980.

2.) Any ____will result in

____________________________. ____________________________that strikes the

boundary between the mediums ____.

This is called ____.



3.) Fiber optics is an example of an application of total internal reflection.

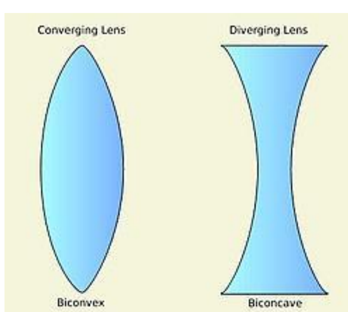
B. Refraction through thin lenses

1. General information: C, R, f, and axis all have the same definitions for lenses as they do for mirrors. However, they exist on BOTH sides of the lens.[2]

2. There are two types of thin lenses that we will focus on. (☺)

a. ____________________________bow _______________ with _______________ curves.

b. ____________________________bow _______________ with _______________ curves.



[2] This is true if both sides of the lens are equally curved. There are variations of lenses, some of which have planar sides or different curvatures on each side. We'll see some of these in lab as enrichment.

3. ______________________________: As the curvature increases, the focal point becomes shorter. ____. Therefore, as curvature increases, power increases. Lens power can also increase/decrease based on how close its index of refraction is to the index of refraction of the medium it is in.

4. The lens equation and thin lenses:
   a. The lens equation is identical to the mirror equation and provides the same information.

$$\frac{1}{s_i} + \frac{1}{s_0} = \frac{1}{f}$$

   b. The magnification equation also applies.

$$M = \left|\frac{h_i}{h_o}\right| = \left|\frac{s_i}{s_o}\right|$$

   c. There are *different* sign conventions from when the equation is used for mirrors.

Sign Conventions for Thin Lenses

Generally speaking, real is + and virtual is - .

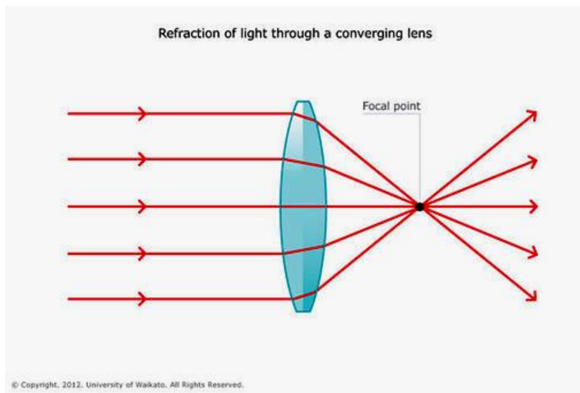
Focal Length	**+**	**Converging**
	-	**Diverging**
So	**+**	**Real object (usu. shown left of the lens)**
	-	**Virtual object (usu. shown right of the lens)***
Si	**+**	**Real image (opp. side from object)**
	-	**Virtual image (same side as object)**
M	**+**	**Upright**
	-	**Inverted**

*** How can an object be virtual? As with mirrors, this occurs when the image from one lens becomes the object for another.**

<u>Example</u>: What type of image appears when an object is placed 2.3 cm from a converging lens whose focal length is 3.0 cm? What is the magnification?

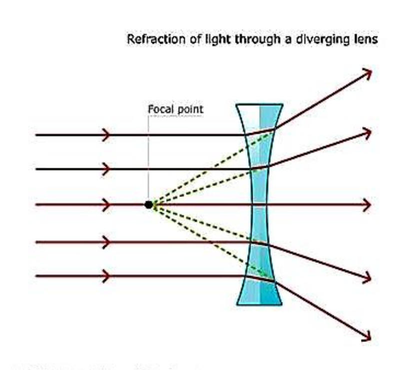
5. ***Rays diagrams for spherical mirrors:***

- ***A ray through the center goes straight.***
- ***Incident rays parallel to the axis refract in line with the focal point. Which focal point (same side or opposite side) depends on the type of lens. There are two types.***
- ***<u>Converging lens</u>: Rays parallel to the axis converge on the focal point on the opposite side of the lens from the object.***



Converging lenses always make real images.

- ***<u>Diverging lens</u>: Rays parallel to the axis on the opposite side diverge (spread out) but can be traced back to the f on the same side as the object.***



Diverging lenses always make virtual images.

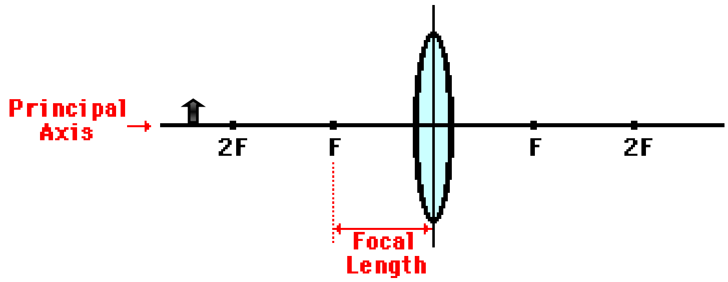
- ***Check yourself (if you want) with a third line:***
  - ***Converging: a line through the same-side focal point refracts parallel to the axis.***
  - ***Diverging: A line heading toward the opposite-side focal point refracts parallel to the axis.***

GUIDED NOTES

Practice with converging and diverging lenses:

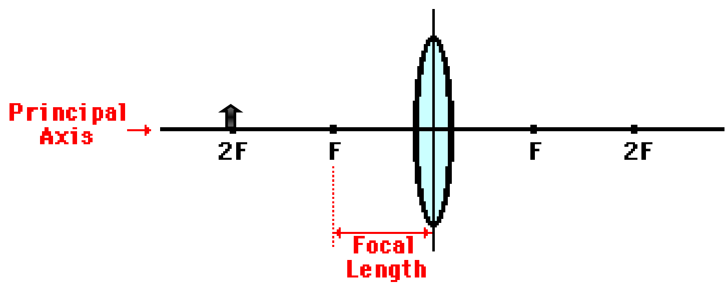
Converging Lenses:

Object beyond the center of curvature (C or $2F$)



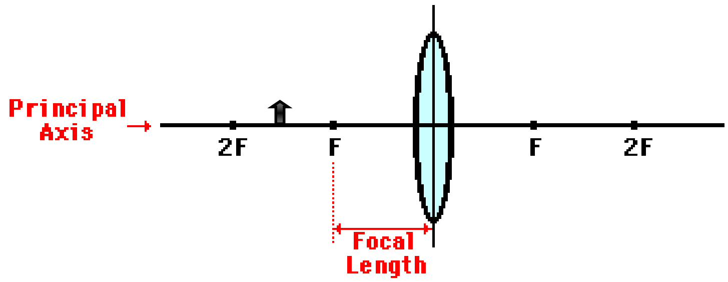
The image is (real/virtual) and (upright/inverted) and (bigger/smaller/the same size.)

Object the center of curvature



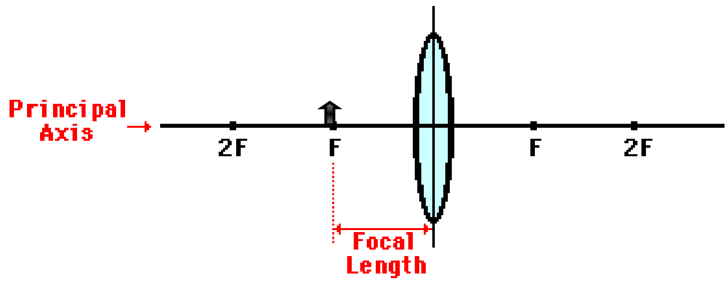
The image is (real/virtual) and (upright/inverted) and (bigger/smaller/the same size.)

Object between the center of curvature and the focal point



The image is (real/virtual) and (upright/inverted) and (bigger/smaller/the same size.)

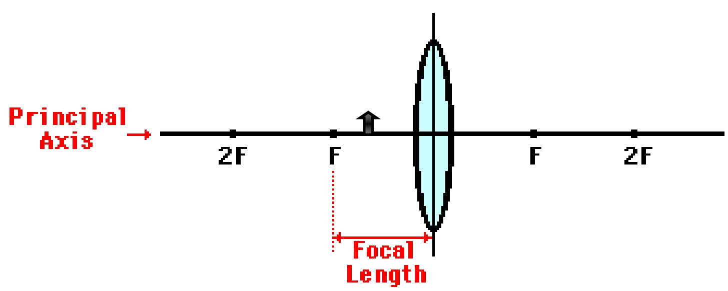
Object at the focal point



The image is (real/virtual) and (upright/inverted) and (bigger/smaller/the same size.)

No image

Object between the focal point and the lens

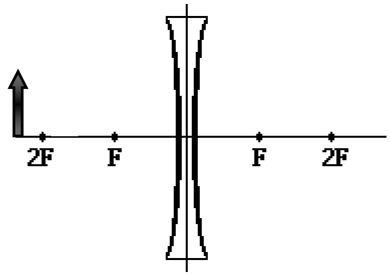


The image is (real/virtual) and (upright/inverted) and (bigger/smaller/the same size.)

GUIDED NOTES

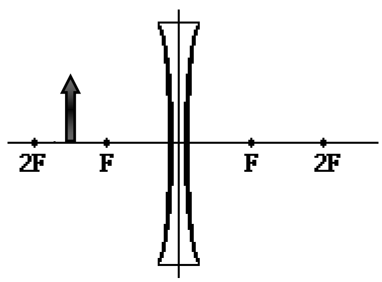
Diverging lenses:

Object beyond the center of curvature (C or $2F$)



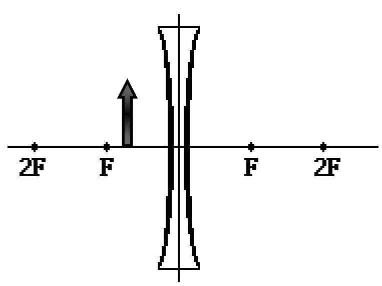
The image is (real/virtual) and (upright/inverted) and (bigger/smaller/the same size.)

Object between the center of curvature and the focal point



The image is (real/virtual) and (upright/inverted) and (bigger/smaller/the same size.)

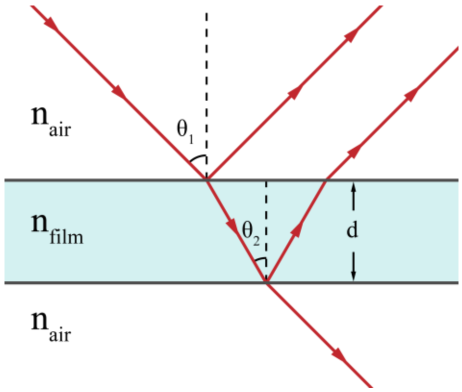
Object between the center of curvature and the focal point



The image is (real/virtual) and (upright/inverted) and (bigger/smaller/the same size.)

IV. Thin-Film Interference

A. When light enters a thin[3] film (such as a layer of soap or oil floating on water,) some light reflects from the top of the layer, and some penetrates the layer, refracts as it enters, reflects off the bottom, and refracts as it exits again into the original medium.



B. Phase reversal: When light reflects off a surface of higher index of refraction, the wave is inverted so that crests become troughs, and troughs become crests. This shifts the wave by half a wavelength. Because the index of refractions of both media determines whether a phase shift occurs, each situation is unique in terms of interference.

1. When $n_1 < n_2 < n_3$…

   a. A phase shift occurs twice, so…

   b. If the distance the light travels within the film (2x thickness, or $2t$) equals an integer multiple of the wavelength of the light[4], constructive interference occurs; a half-integer multiple results in destructive interference. Hence where $2t = m\lambda$, constructive interference occurs.[5]

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[3] For this to work, the thinness should be close to the wavelengths of the light involved.

[4] **When light travels through a medium, its frequency does not change. Therefore to account for the difference in speed the wavelength changes. Put a star by this! No, put two stars!!**

[5] Not on formula sheet. Know this conceptually.

2. When $n_1 < n_2 > n_3$ or the reverse…

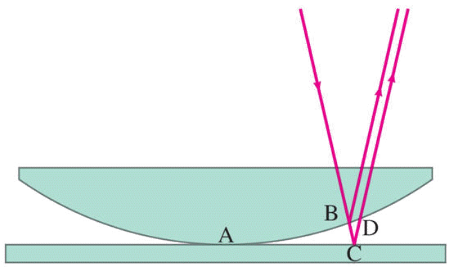
   a. A phase shift occurs once, so…

   b. If the distance the light travels within the film ($2t$) equals a half integer multiple of the wavelength of the light, constructive interference occurs; a whole integer multiple results in destructive interference. Hence where $2t = m\lambda$, destructive interference occurs.

C. Applications of thin-film interference:

1. Newton's Rings[6]:

   - When a curved glass is placed in contact with a flat glass, a thin film of varying thickness exists between the two pieces of glass such that it gets thicker farther from the center.
   - Therefore a varying pattern of constructive and destructive interference emerges, producing rings.



2. Non-reflective coatings

   - A very thin film of a material whose index of refraction is the average of air and glass is put on the glass surface. This means that a phase shift will occur twice. Next, the thickness is adjusted so that $2t = (m + \frac{1}{2})\lambda$ so that destructive interference occurs.
   - This destructive interference is optimized for the center of the visible light spectrum. Therefore red and blue still gets reflected, making a lens with non-reflective coating appear purple.

[6] Newton believed light was a particle. He actually proved that it was a wave by noting this ring phenomenon, although he never realized it. True to Newton, of course, is that someone else, his rival Robert Hooke, discovered it first, but Newton received the credit because he studied it in more depth.