Electromagnetic Rays

High School Physics

Unit 11

NAD 2023 Standard ER2 (Electromagnetic Radiation)

Credits

- This Slideshow was developed to accompany the textbook
  - *OpenStax High School Physics*
    - *Available for free at https://openstax.org/details/books/physics*
    - *By Paul Peter Urone and Roger Hinrichs*
    - *2020 edition*
- Some examples and diagrams are taken from the *OpenStax College Physics, Physics,* and *Cutnell & Johnson Physics* 6th ed.

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11-01 Electromagnetic Spectrum and Behavior

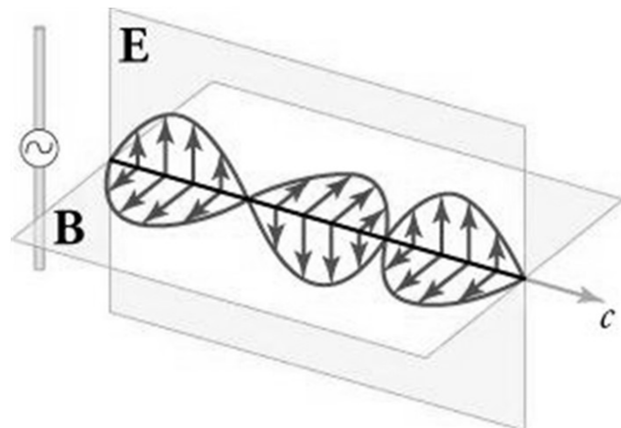
In this lesson you will…

- Explain the electromagnetic spectrum
- Explain emission and aborption spectrums

OpenStax High School Physics 15.1, 15.2, 22.1
OpenStax College Physics 2e 24.2-24.3, 30.3, 30.6

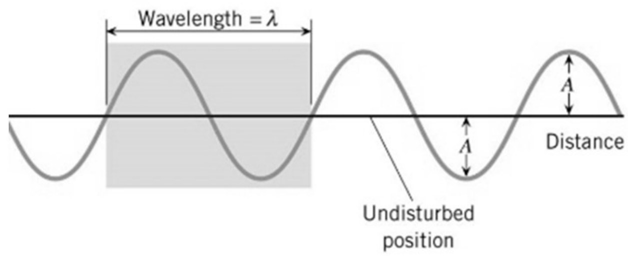
11-01 Electromagnetic Spectrum and Behavior

- How to create electromagnetic (EM) waves
  - Move a charge (current)
  - This creates an electric field
  - Also creates a magnetic field
  - These are 90° to each other



11-01 Electromagnetic Spectrum and Behavior

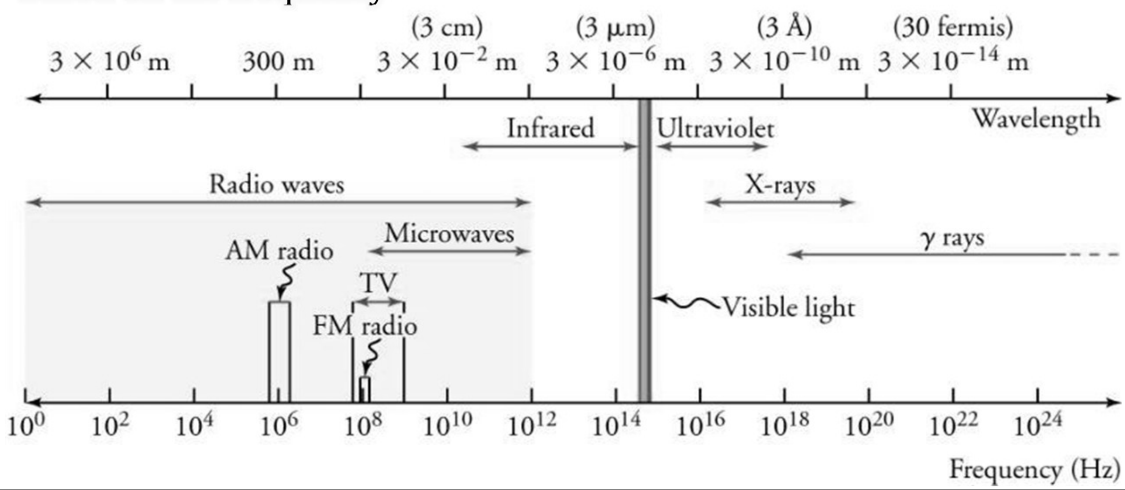
- EM Waves
  - Wavelength – distance of one cycle
  - Frequency – number of cycles per second
  - Amplitude – height of a crest above the undisturbed position
  - $v = f\lambda$
- In vacuum, $v = c = 3.00 \times 10^8\ m/s$



(a) At a particular time

11-01 Electromagnetic Spectrum and Behavior

- Types of EM radiation
  - Based on the frequency



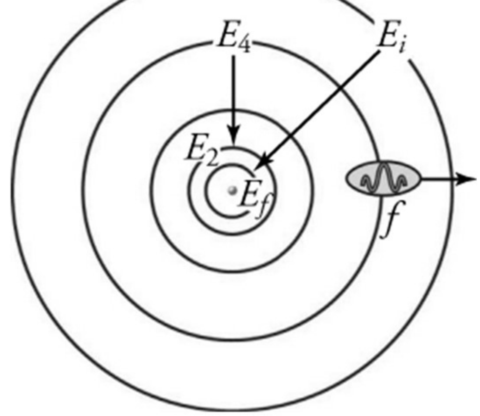
X-rays come from outside the nucleus
Gamma rays come from inside the nucleus

Types of EM Wave	Production	Applications	Life Sciences Aspect	Issues
Radio / TV	Accelerating charges	Communications, remote control	MRI	Requires controls for band use
Microwaves	Accelerating charges & thermal agitation	Communications, cooking, radar	Deep heating	Cell phone use
Infrared	Thermal agitation & electronic transitions	Thermal imaging, heating	Absorption by atmosphere	Greenhouse effect
Visible Light	Thermal agitation & electronic transitions	All pervasive	Photosynthesis, vision	
Ultraviolet	Thermal agitation & electronic transitions	Sterilization, slowing abnormal growth of cells	Vitamin D production	Ozone depletion, causes cell damage
X-rays	Inner electronic transitions & fast collisions	Medial, security	Medical diagnosis, cancer therapy	Causes cell damage
Gamma Rays	Nuclear decay	Nuclear medicine, security	Medical diagnosis, cancer therapy	Causes cell damage, radiation damage

11-01 Electromagnetic Spectrum and Behavior

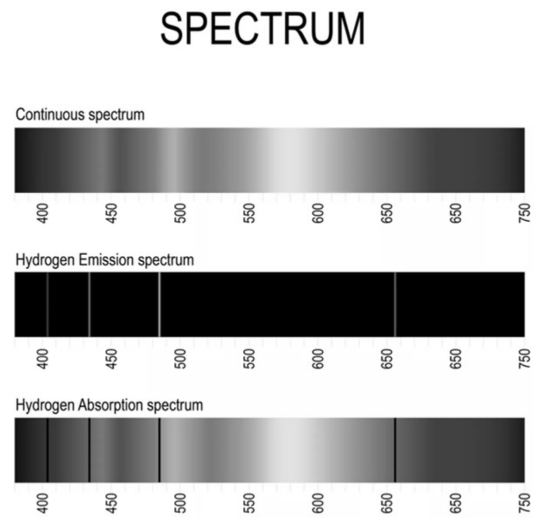
- Electron transitions
  - Bohr model of the atom
  - Electrons orbit the nucleus
  - When an electron gains energy it gets excited, it jump out to a higher orbital
    - Electrons gain energy when they are struck by a photon
    - Photons are particles of light
    - Too much energy and electron completely removed from atom, ionizes, allows chemical reactions
  - When the excited electron falls back down to its orbital, it releases energy as a photon
  - The energy released is based on the distance between the orbitals
  - The frequency (and wavelength) of the released photon is based on the energy released
  - So only a few certain frequencies are emitted

$$\Delta E = E_i - E_f = hf$$



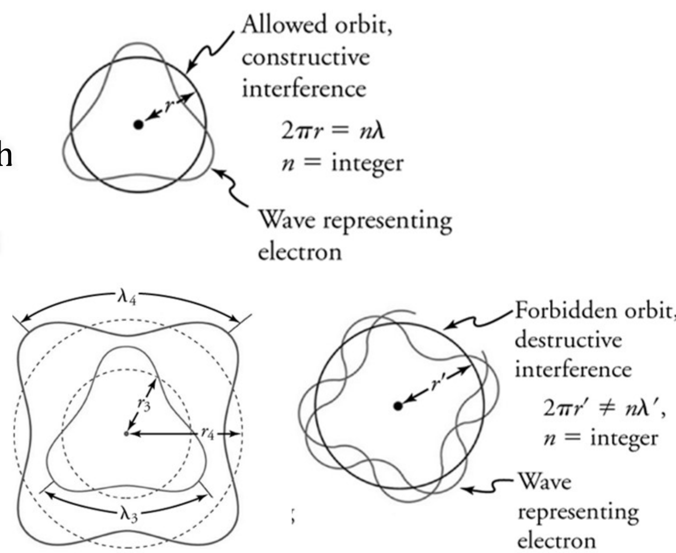
11-01 Electromagnetic Spectrum and Behavior

- Emission spectrum
  - Shows the wavelengths (or frequencies) of the emitted light
- Absorption spectrum
  - Shows the wavelengths (or frequencies) of the absorbed light
- They are negatives of each other
  - The frequencies emitted = the frequencies absorbed



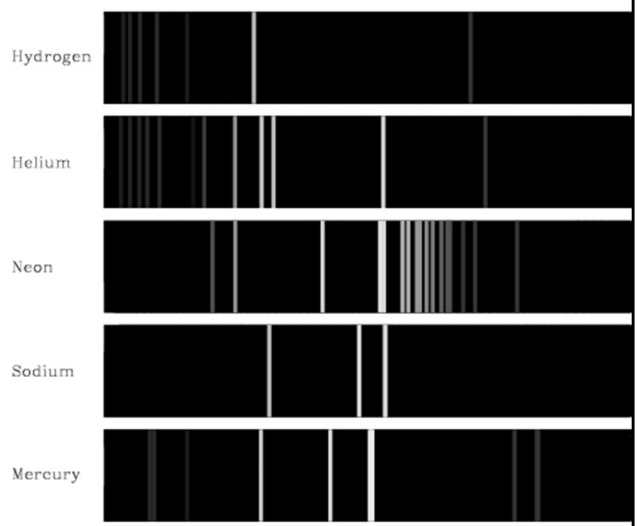
11-01 Electromagnetic Spectrum and Behavior

- The Bohr model only works for hydrogen
- De Broglie model
  - Electrons behave like waves with a set wavelength
  - Each electron orbits the nucleus in standing waves
  - This allows for orbitals in more complicated atoms



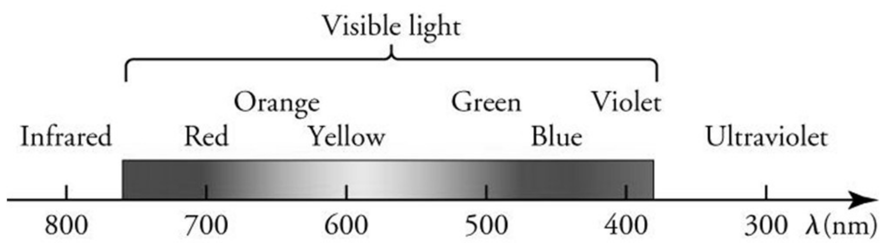
11-01 Electromagnetic Spectrum and Behavior

- Each element has its own spectrum
- Astronomers can look at the spectrum from a star (emission spectrum) and determine the atoms that the star is made of
  - Or they can look at light coming through the atmosphere of a planet and look at the absorption spectrum to see what it is made of



11-01 Electromagnetic Spectrum and Behavior

- Visible Light
  - Between $4.0 \times 10^{14}\ Hz$ and $7.9 \times 10^{14}\ Hz$
  - Usually by wavelength
    - 750 nm (end of red)
    - 380 nm (end of violet)



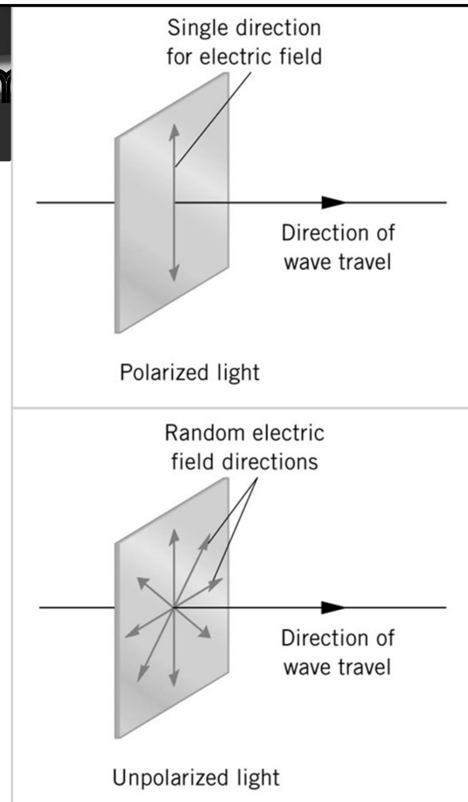
11-01 Electromagnetic Spectrum and Behavior

- Speed of light in a vacuum (space)
  - $3.00 \times 10^8\ m/s$
  - $c = f\lambda$
- When light travels through a material it slows down due to the absorption and reemission of the photons

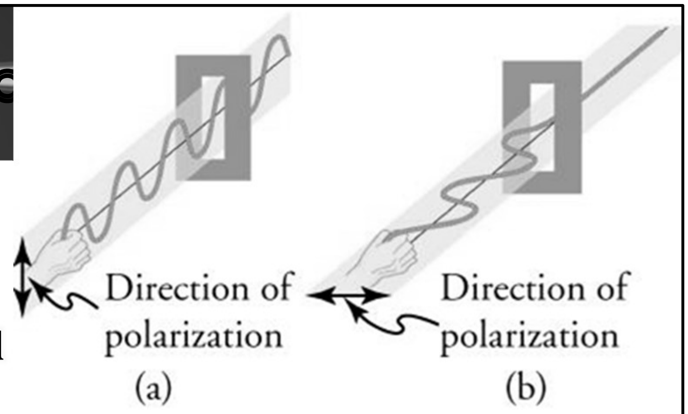
11-01 Electromagnetic Spectrum

- Linearly polarized light vibrates in only one direction

- Common non-polarized light vibrates in all directions perpendicular to the direction of travel.



11-01 Electromagnetic Spec



- How to make EM waves polarized
  - Straight wire antenna
  - Reflections of flat surfaces
  - Passing through a polarizing material
- Polarizing materials
  - Light is polarized along the transmission axis
  - All components of the wave are absorbed except the components parallel to the transmission axis
  - Since unpolarized light vibrates equally in all directions, the polarizing material absorbs ½ the light.
  - $I = \frac{1}{2} I_0$

Have some polarizing filters

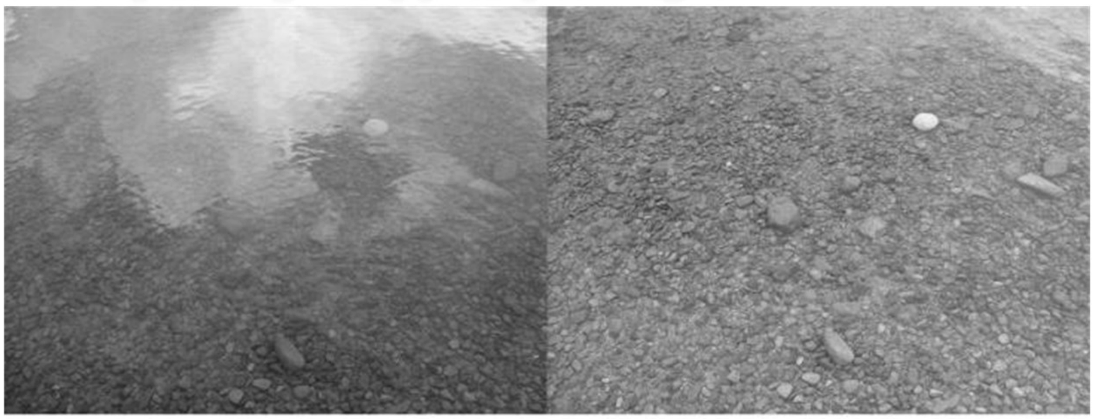
I = intensity of light

11-01 Electromagnetic Spectrum and Behavior

- Uses of polarization
  - Sunglasses
    - Automatically cuts light intensity in half
    - Often the sunlight is reflected off of flat surfaces like water, roads, car windshields, etc. With the correct polarization, the sunglasses can eliminate most of those waves.
  - 3-D movies
    - Cameras are side-by-side.
    - The movies is projected by two projectors side by side, but polarized at 90°.
    - The audience wears glasses that have the same polarization so the right eye only sees the right camera and the left eye only sees the left camera.
  - LCD
    - Voltage changes the direction of the LCD polarization. The pixels turned on are transmitted (parallel), the pixel turned off are not transmitted (perpendicular).

11-01 Electromagnetic Spectrum and Behavior

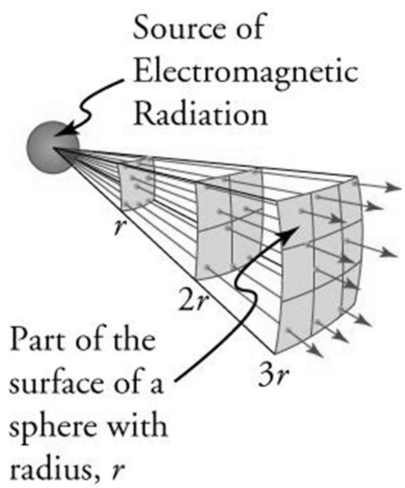
- Polarizing filter on a camera can removed the reflected polarized light glare.
- (a) without polarizing filter (b) with polarizing filter



(a) (b)

11-01 Electromagnetic Spectrum and Behavior

- Measurements of light
  - Luminous flux
    - Rate at which light is radiated from a source
    - Unit: lumens (lm)
  - Illuminance
    - Light is radiated in all directions
    - Amount of light falling on an object
    - Lumens per area
    - $illuminance = \frac{P}{4\pi r^2}$
    - Unit: lux (lx)



11-01 Practice Work

- Let your light shine before others, that they may see your good deeds and glorify your Father in heaven.
  - Matthew 5:16

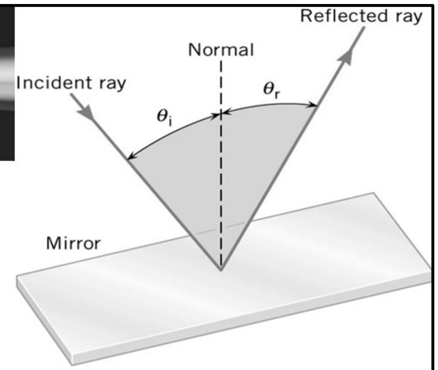
- Read
  - OpenStax College Physics 2e 25.1-25.2, 25.7
  - OR
  - OpenStax High School Physics 16.1

11-02 Reflection

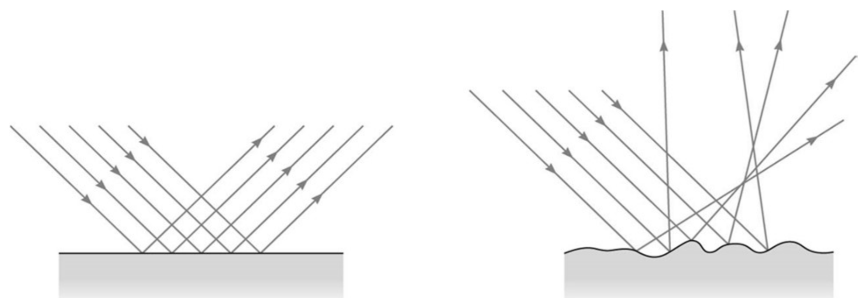
In this lesson you will…
- Use the law of reflection with plane mirrors.
- Use spherical mirrors.
- Use the mirror equation.

OpenStax High School Physics 16.1
OpenStax College Physics 2e 25.1-25.2, 25.7

11-02 Reflection



- Law of Reflection: $\theta_r = \theta_i$
- Specular Reflection
  - Parallel light rays are reflected parallelly
- Diffuse Reflection
  - Parallel light rays are scattered by irregularities in the surface.

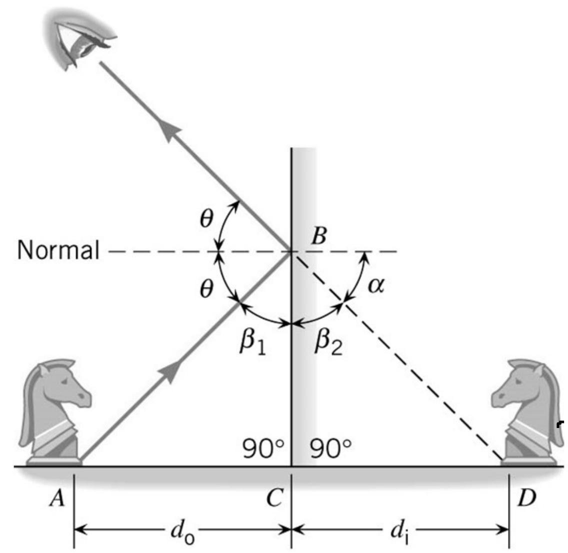


(*a*) Specular reflection (*b*) Diffuse reflection

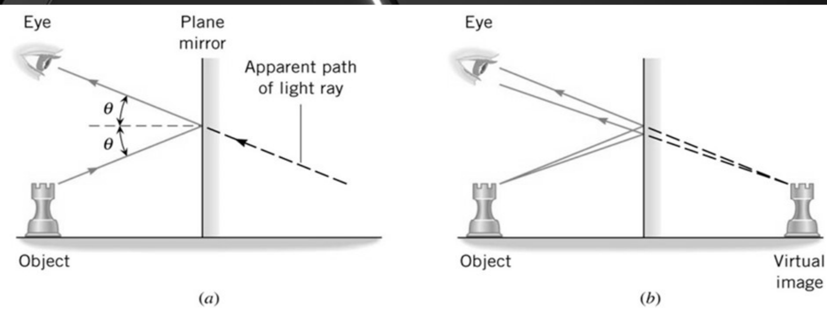
11-02 Reflection

Plane Mirror

- Image is upright
- Image is same size
- Image is located as far behind the mirror as you are in front of it



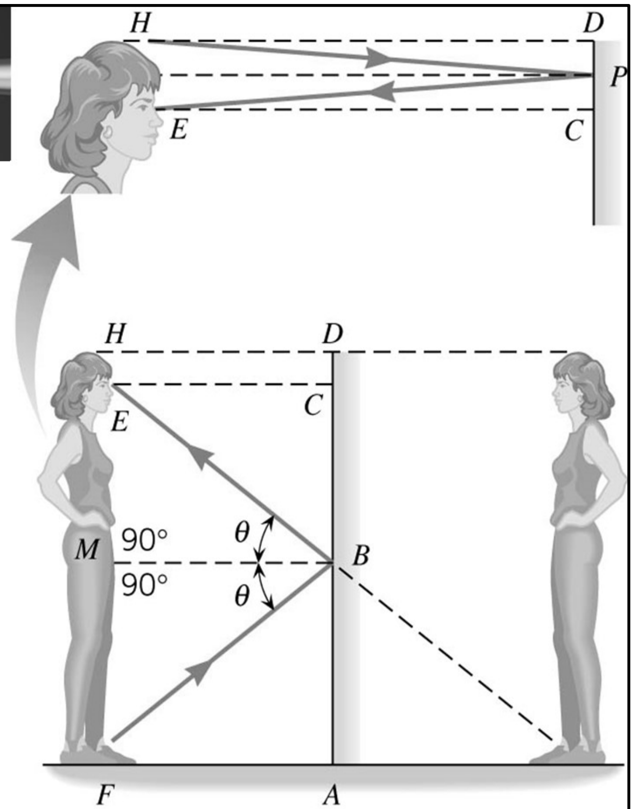
11-02 Reflection



- Since light rays appear to come from behind mirror, the image is called a **virtual image**.
- If light rays appear to come from a real location, the image is called a **real image**.
  - Real images can be projected on a screen, virtual images cannot.
- Plane mirrors only produce virtual images.

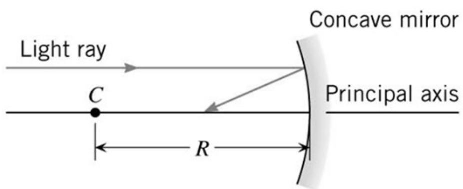
11-02 Reflection

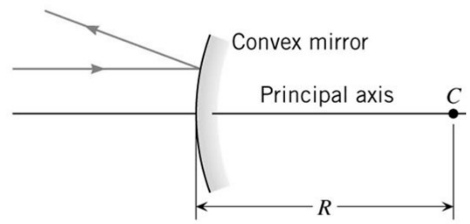
- How long must a plane mirror be to see your whole reflection?
- From halfway between your eyes and floor to halfway between your eyes and the top of your head.



11-02 Reflection

- Spherical Mirrors
- Concave: bends in
- Convex: bends out

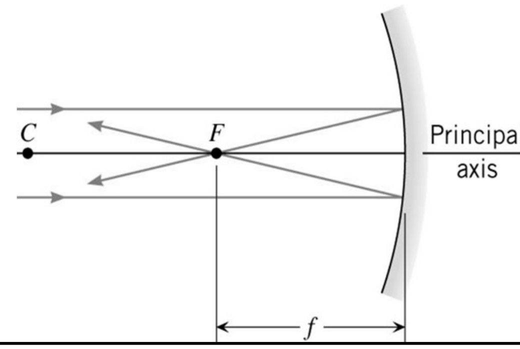




Remember concave because it makes a small cave

11-02 Reflection

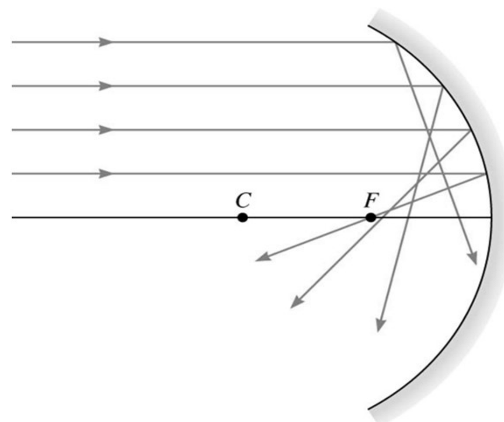
- Normals are always perpendicular to the surface and pass through the center of curvature, *C*.
  - Law of Reflection says that the angle to the normal is the same for the incident and reflected rays
- Principal axis: imaginary line through *C* and the center of the mirror.
- Focal point (*F*): parallel rays strike the mirror and converge at the focal point.
- Focal length (*f*): distance between F and mirror
  - Concave mirrors: $f = \frac{1}{2}R$
  - Convex mirrors: $f = -\frac{1}{2}R$



R = radius of curvature

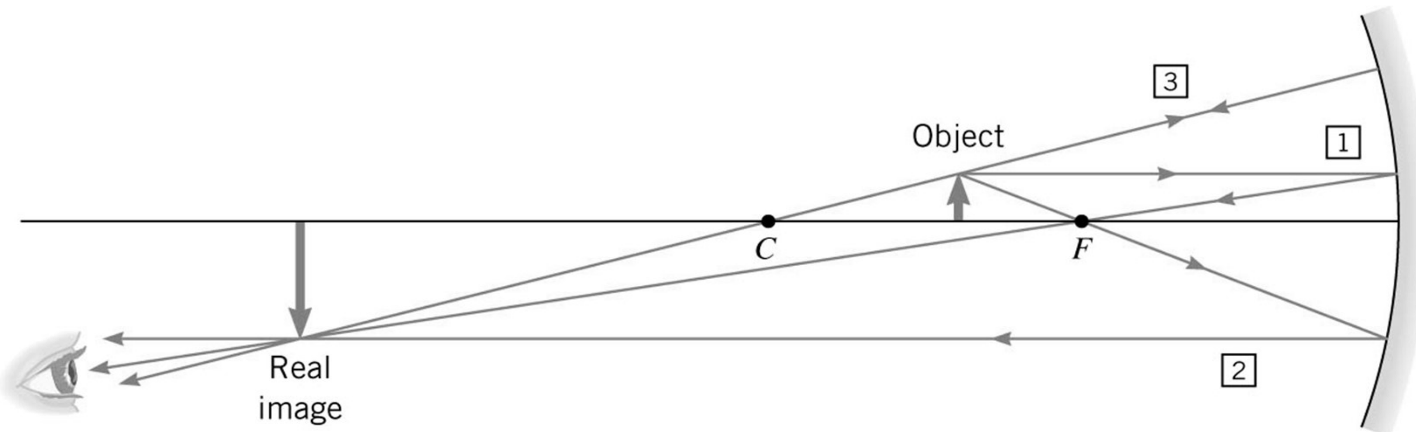
11-02 Reflection

- Spherical aberration
  - Rays far from the principal axis actually cross between *F* and the mirror.
  - Fix this by using a parabolic mirror.



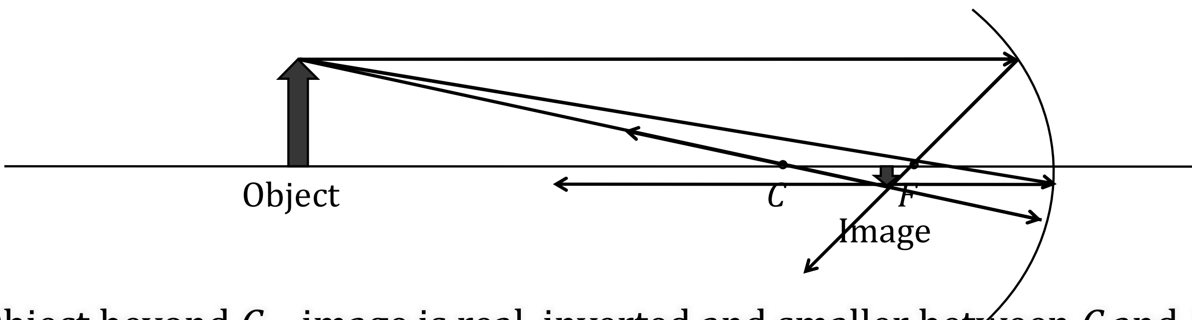
11-02 Reflection

- Ray tracing diagram: Diagram used to find the location and type of image produced.
- Notice the rays start at the top of the object.



11-02 Reflection

- Concave Mirror
  - Ray 1 – Parallel to principal axis, strikes mirror and reflects through *F*
  - Ray 2 – Through *F*, strikes mirror and reflects parallel to principal axis
  - Ray 3 – Through *C*, strikes mirror and reflects back through *C*

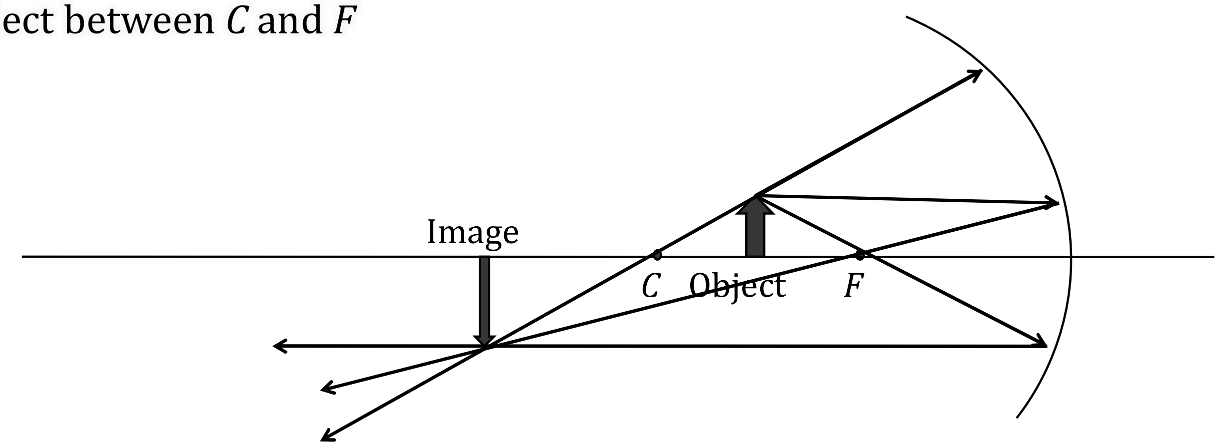


  - Object beyond *C* – image is real, inverted and smaller between *C* and *F*

Like a telescope

11-02 Reflection

- Object between C and F

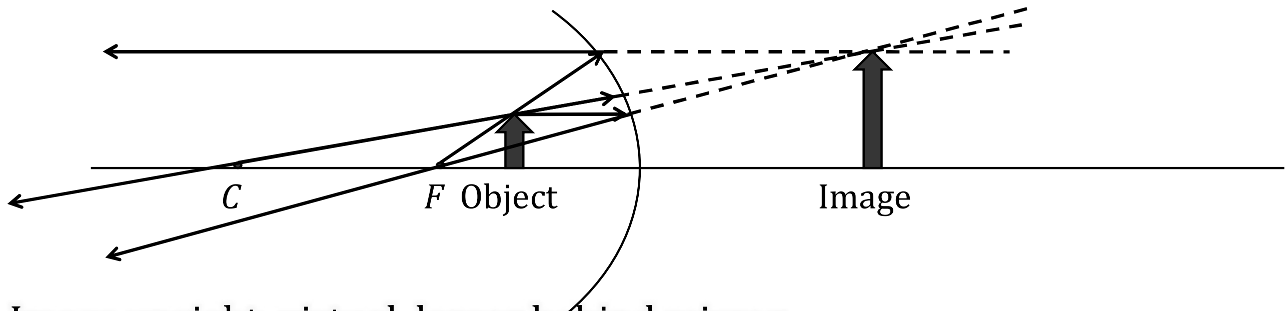


- Image inverted, real, and larger beyond C

Like a projector

11-02 Reflection

- Object between F and mirror

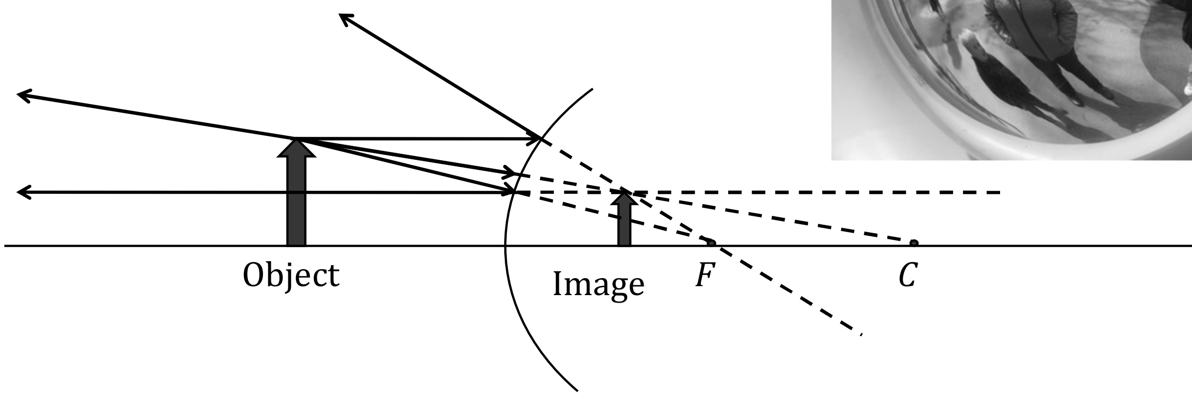


- Image upright, virtual, larger behind mirror

Like a makeup mirror

11-02 Reflection

- Convex Mirrors



- Image upright, virtual, smaller behind mirror between F and mirror

Like passenger side view mirror

11-02 Reflection

- Mirror Equation:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

- Where
  - f = focal length (negative if convex)
  - d_o = object distance
  - d_i = image distance (negative if virtual)

f= distance between F and mirror
d_0 = distance between object and mirror
d_i = distance between image and mirror

These were discovered through the use of geometry and similar triangles.

11-02 Reflection

- Magnification Equation:

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

- Where
  - m = magnification
  - h_o = object height
  - h_i = image height (negative if inverted)
  - d_o = object distance
  - d_i = image distance (negative if virtual)

11-02 Reflection

- A 0.5-m high toddler is playing 10 m in front of a concave mirror with radius of curvature of 7 m.
  - What is the location of his image?
    - d_i = 5.38 m
  - What is the height of his image?
    - h_i = −0.269 m

$$f = \frac{1}{2}R = \frac{1}{2}(7\ m) = 3.5\ m$$

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \rightarrow \frac{1}{3.5} = \frac{1}{10} + \frac{1}{d_i} \rightarrow \frac{1}{3.5} - \frac{1}{10} = \frac{1}{d_i} \rightarrow \frac{1}{d_i} = 0.1857 \rightarrow d_i = 5.38\ m$$

$$m = -\frac{d_i}{d_o} = \frac{h_i}{h_o} \rightarrow -\frac{5.38}{10} = \frac{h_i}{0.5} \rightarrow h_i = -0.269m$$

11-02 Reflection

- A 0.5-m high toddler is playing 10 m in front of a convex mirror with radius of curvature of 7 m.
  - What is the location of his image?
    - d_i = -2.59 m
  - What is the height of his image?
    - h_i = 0.130 m

$$f = -\frac{1}{2}R = -\frac{1}{2}(7\ m) = -3.5\ m$$

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \rightarrow \frac{1}{-3.5} = \frac{1}{10} + \frac{1}{d_i} \rightarrow \frac{1}{-3.5} - \frac{1}{10} = \frac{1}{d_i} \rightarrow \frac{1}{d_i} = -0.3857 \rightarrow d_i = -2.59\ m$$

$$m = -\frac{d_i}{d_o} = \frac{h_i}{h_o} \rightarrow \frac{2.59}{10} = \frac{h_i}{0.5} \rightarrow h_i = 0.130\ m$$

11-02 Practice Work

- Let your life reflect the love of God to others.

- Read
  - OpenStax College Physics 2e 25.3-25.5
  - OR
  - OpenStax High School Physics 16.2

11-03 Refraction

In this lesson you will…

- Use the Snell's Law of Refraction.
- Understand internal reflection and its uses.
- Explain how dispersion creates a rainbow.

OpenStax High School Physics 16.2
OpenStax College Physics 2e 25.3-25.5

11-03 Refraction

- Speed of light in a vacuum:
  - $c = 3.00 \times 10^8$ m/s
- Light travels slower through materials due to light hitting, absorbed by, emitted by, and scattered by atoms.

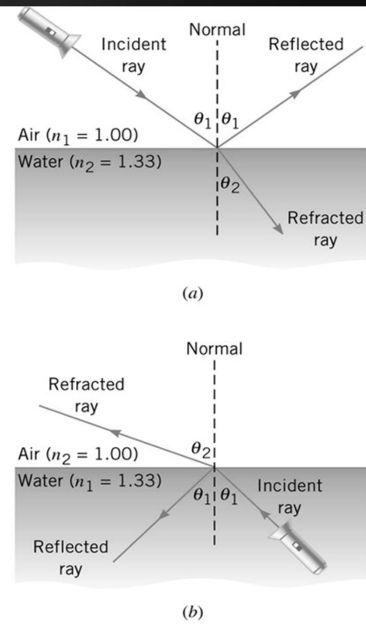
- Index of Refraction
  - Number to indicate relative speed of light in a material

$$n = \frac{c}{v}$$

n = index of refraction
c = speed of light in vacuum
v = speed of light in material

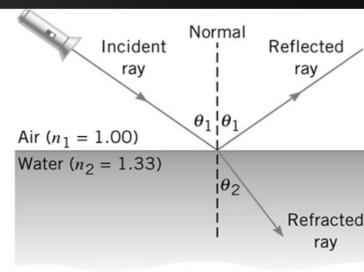
11-03 Refraction

- When light hits the surface of a material part of it is reflected
- The other part goes into the material
- The transmitted part is bent (***refracted***)

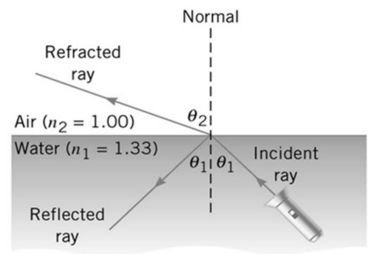


11-03 Refraction

- Snell's Law (The Law of Refraction)
  $$n_1 \sin\theta_1 = n_2 \sin\theta_2$$
- Where
  - n_1 = index of refraction of incident medium
  - n_2 = index of refraction of second medium
  - θ_1 = angle of incidence (measured to normal)
  - θ_2 = angle of refraction (measured to normal)



(a)

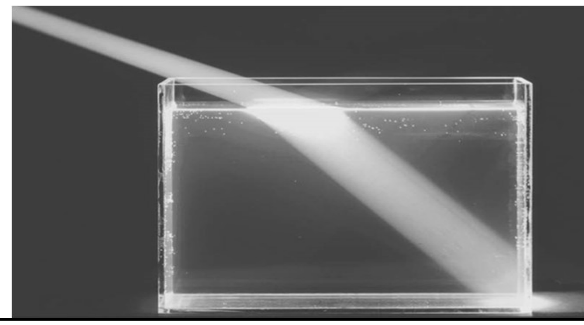


(b)

To go from less optically dense to more optically dense, the ray is bent towards normal.
To go from more optically dense to less optically dense, the ray is bent away from the normal.
When the light goes from one material to another, it bends towards the slower material.

11-03 Refraction

- You shine a laser into a piece of clear material. The angle of incidence is 35°. You measure the angle of refraction as 26°. What is the material?
  - Ice
- What is the speed of light in the material?
  - $v = 2.29 \times 10^8$ m/s

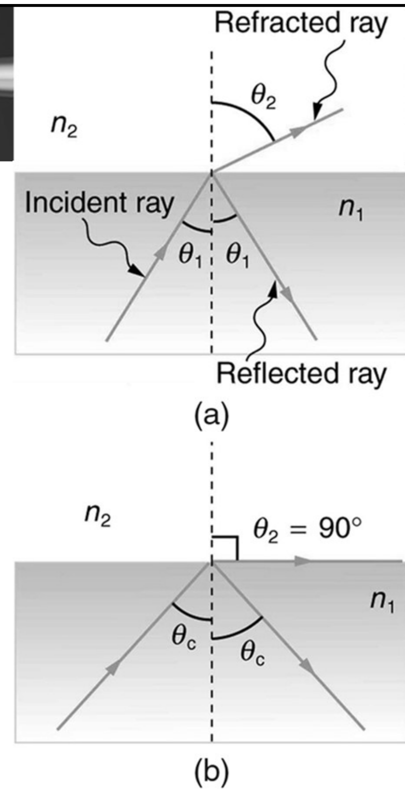


$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$
$$1.00 \sin 35° = n \sin 26° \rightarrow n = 1.308$$
$$\textit{Table says this should be ice.}$$

$$n = \frac{c}{v} \rightarrow 1.308 = \frac{3.00 \times 10^8 \frac{m}{s}}{v} \rightarrow v = 2.29 \times 10^8\ m/s$$

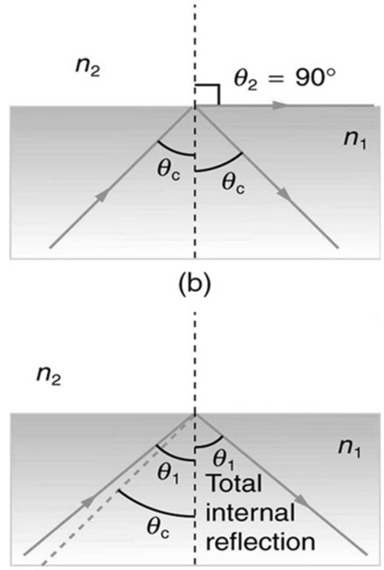
11-03 Refraction

- Total Internal Reflection
  - When light hits an interface between two types of media with different indices of refractions
    - Some is reflected
    - Some is refracted
  - Critical angle
    - Angle of incidence where refracted angle is 90°
    - Angles of incidence larger than this cause the refracted angle to be inside the material. This can't happen, so no refraction occurs.



11-03 Refraction

- Critical angle
  - $\theta_2 = 90°$
  - $n_1 \sin\theta_1 = n_2 \sin\theta_2$
  - $n_1 \sin\theta_c = n_2 \sin 90°$
  - $\theta_c = \sin^{-1}\frac{n_2}{n_1}$
    - Where $n_1 > n_2$



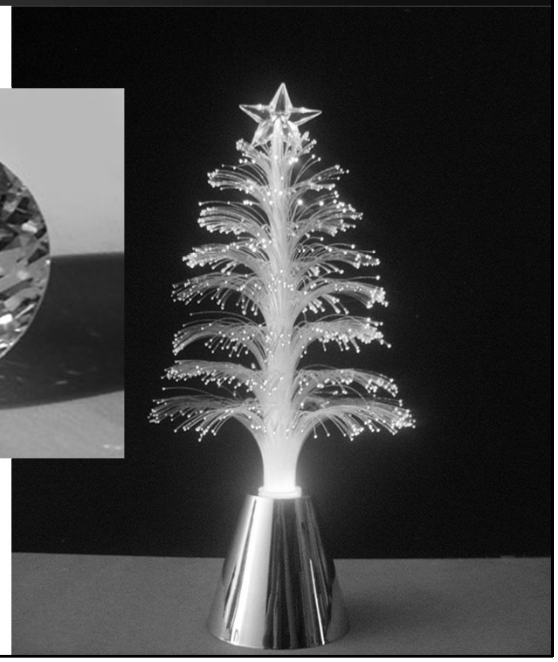
11-03 Refraction

- What is the critical angle from cubic zirconia (n=2.16) to air? Will an angle of 25° produce total internal reflection?
- 27.7°
- No

$$\theta_c = \sin^{-1}\frac{n_2}{n_1}$$
$$\theta_c = \sin^{-1}\frac{1.000293}{2.15}$$
$$\theta_c = 27.7°$$

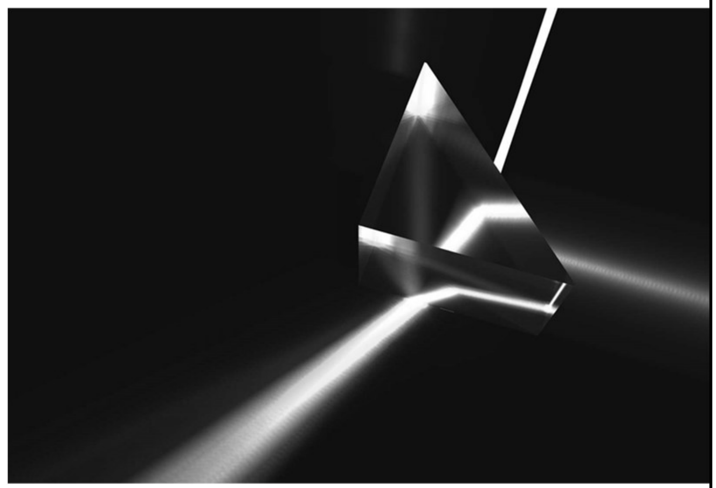
11-03 Refraction

- Uses of total internal reflection
  - Fiber optics for
    - Endoscopes
    - Telecommunications
    - Decorations
  - Binoculars/telescopes
    - Makes them shorter
  - Reflectors
  - Gemstones
    - Cut so that light only exits at certain places



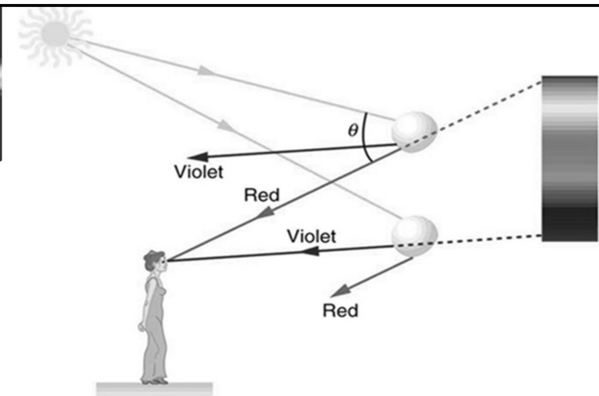
11-03 Refraction

- Dispersion
  - Each wavelength of light has a different index of refraction
  - Red — lowest
  - Violet — highest
  - When light is refracted, the violet bends more than red, which splits the colors

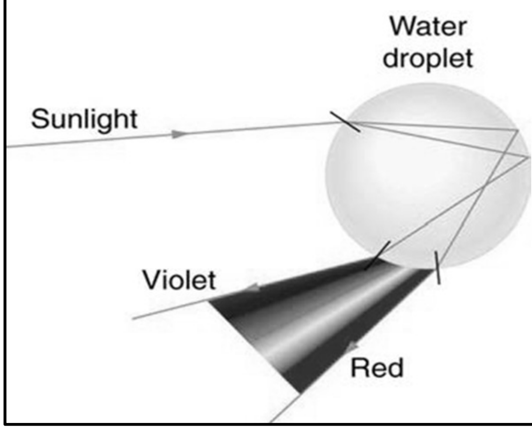


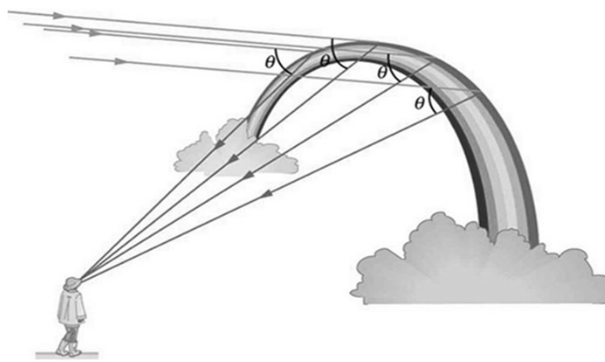
11-03 Refraction

- Rainbows
  - Dispersion by refraction with internal reflection



(a)





11-03 Practice Work

- “I have set my rainbow in the clouds, and it will be the sign of the covenant between me and the earth.” Genesis 9:13

- Read
  - OpenStax College Physics 2e 25.6, 26.1-26.3
  - OR
  - OpenStax High School Physics 16.3

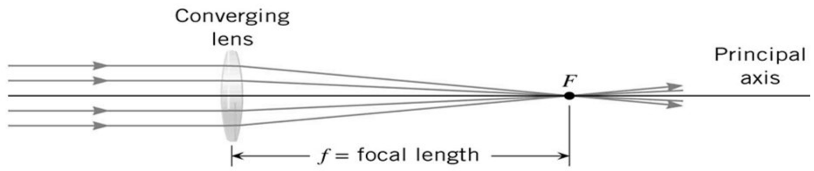
11-04 Lenses

In this lesson you will…
- Use lenses to describe an image.
- Use the thin-lens equation.
- Explain how the eye works.

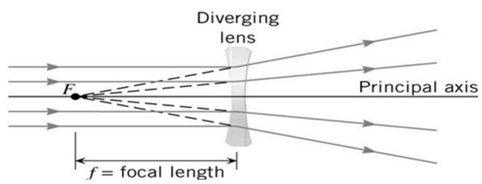
OpenStax High School Physics 16.3
OpenStax College Physics 2e 25.6, 26.1-26.3

11-04 Lenses

- Lens - Made from transparent material, usually with a curved edge.
- Converging Lens – thick middle, thin edge (convex)

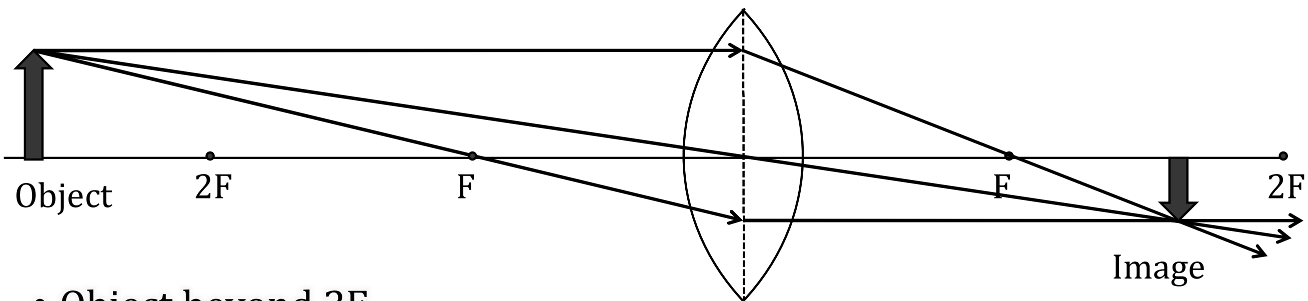


- Diverging Lens – thin middle, thick edge (concave)
- Power of lens
- $P = \frac{1}{f}$
  - Unit: diopters (D)



11-04 Lenses

- Ray Diagrams - Converging Lenses
  - Ray 1 – Parallel to principal axis, bends through F
  - Ray 2 – Through F, bends parallel to principal axis
  - Ray 3 – Goes through center of lens, does not bend

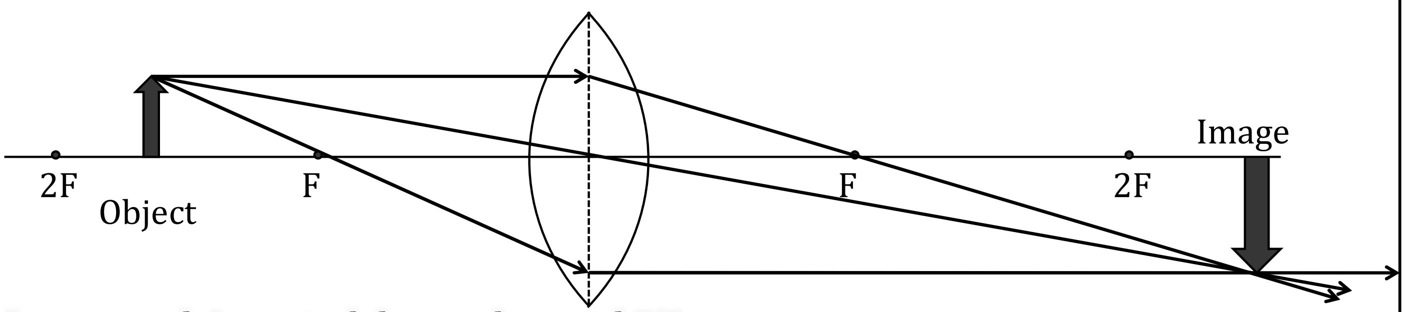


  - Object beyond 2F,
  - Image inverted, real, smaller between F and 2F

Like camera

11-04 Lenses

- Object between 2F and F

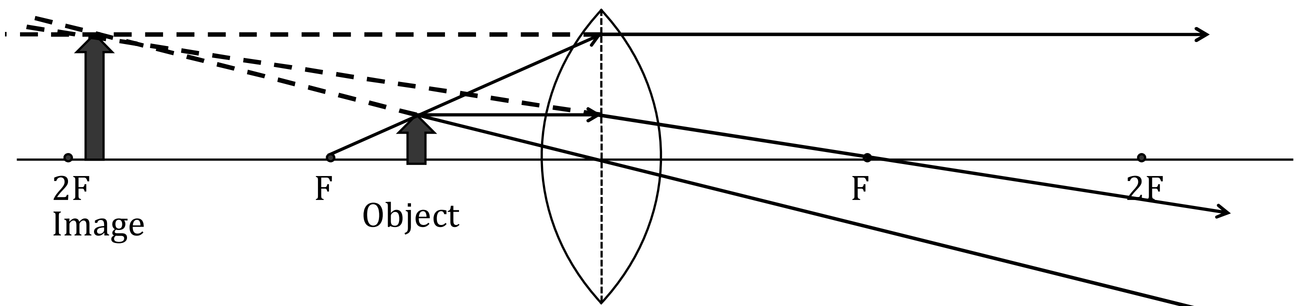


- Image real, inverted, larger beyond 2F

projector

11-04 Lenses

- Object between F and lens



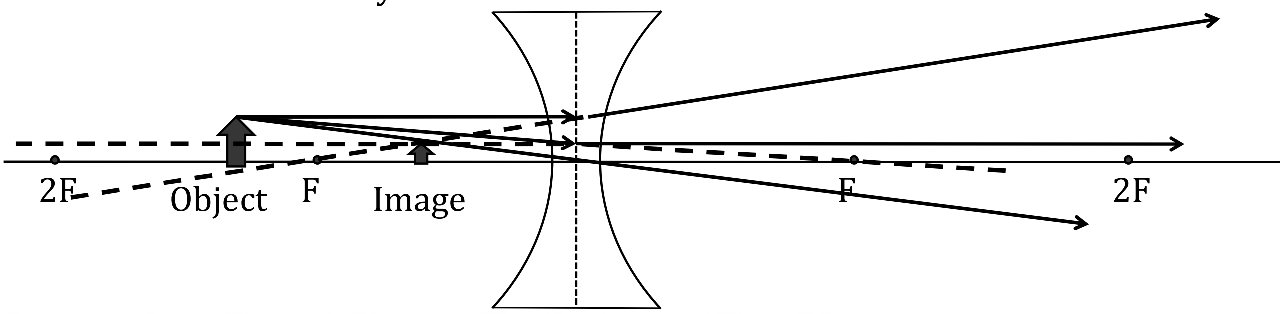
- Image virtual, upright, between 2F and F on side with object

Like magnifying glass

11-04 Lenses

- Diverging Lens

Ray 1 now bends away from axis so that it looks like it came from F
Ray 2 starts by aiming at far F
Ray 3 same as before



- Image virtual, upright, smaller between F and lens

Ray 1 now bends away from axis so that it looks like it came from F
Ray 2 starts by aiming at far F
Ray 3 same as before

Like some glasses

11-04 Lenses

- Thin-lens equation
- $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$
- Converging Lens
  - f +
  - d_o + if real (left side)
  - d_i + if real (right side)
- Magnification equation
- $m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$
- Diverging Lens
  - f -
  - d_o + if real (left side)
  - d_i - if virtual (left side)

Lenses can be put in combination where a real image from the first lens is the object of the second lens. This is done in a microscope and telescope.

Lab idea: make a telescope or microscope on optics bench.

11-04 Lenses

- Lens Reasoning Strategy
    1. Examine the situation to determine that image formation by a lens is involved.
    2. Determine whether ray tracing, the thin lens equations, or both are to be employed. A sketch is very useful even if ray tracing is not specifically required by the problem. Write symbols and values on the sketch.
    3. Identify exactly what needs to be determined in the problem (identify the unknowns).
    4. Make a list of what is given or can be inferred from the problem as stated (identify the knowns). It is helpful to determine whether the situation involves a case 1, 2, or 3 image. While these are just names for types of images, they have certain characteristics that can be of great use in solving problems.
    5. If ray tracing is required, use the ray tracing rules listed near the beginning of this section.
    6. Most quantitative problems require the use of the thin lens equations. These are solved in the usual manner by substituting knowns and solving for unknowns. Several worked examples serve as guides.
    7. Check to see if the answer is reasonable: Does it make sense? If you have identified the type of image (case 1, 2, or 3), you should assess whether your answer is consistent with the type of image, magnification, and so on.

11-04 Lenses

- A child is playing with a pair of glasses with diverging lenses. The focal length is 20 cm from the lens and his eye is 5 cm from the lens. A parent looks at the child's eye in the lens. If the eye is the object, where is the image located?
  - 4 cm behind the lens
- If his eye is really 3 cm across, how big does it appear?
  - h_i = 2.4 cm

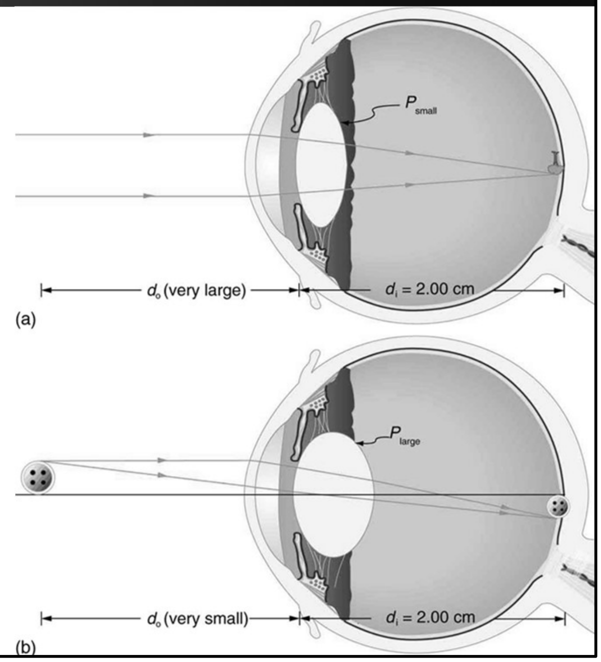
$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \rightarrow \frac{1}{-20\ cm} = \frac{1}{5\ cm} + \frac{1}{d_i} \rightarrow \frac{1}{-20} - \frac{1}{5} = \frac{1}{d_i} \rightarrow \frac{1}{d_i} = -0.25 \rightarrow -4\ cm$$

$$\frac{h_i}{h_o} = -\frac{d_i}{d_o} \rightarrow \frac{h_i}{3\ cm} = -\frac{-4\ cm}{5\ cm} \rightarrow h_i = 2.4\ cm$$

This is like "Coke bottle" lenses.

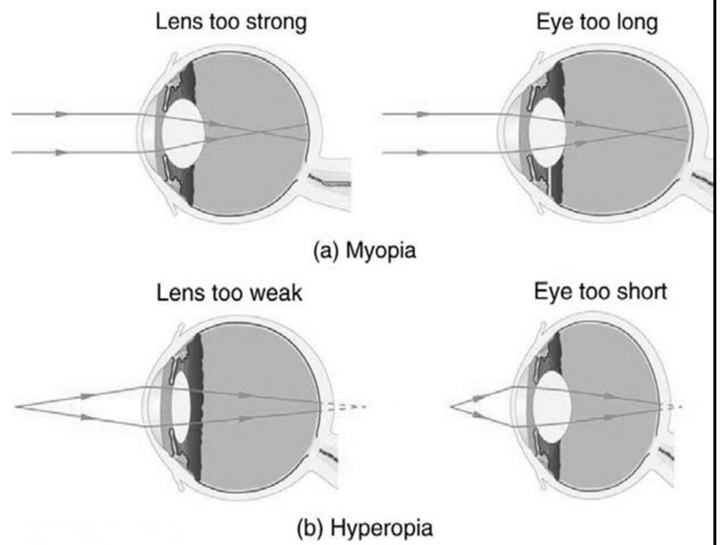
11-04 Lenses

- Cornea/Lens act as single thin lens
- To see something in focus the image must be on the retina at back of eye
- Lens can change shape to focus objects from different object lengths



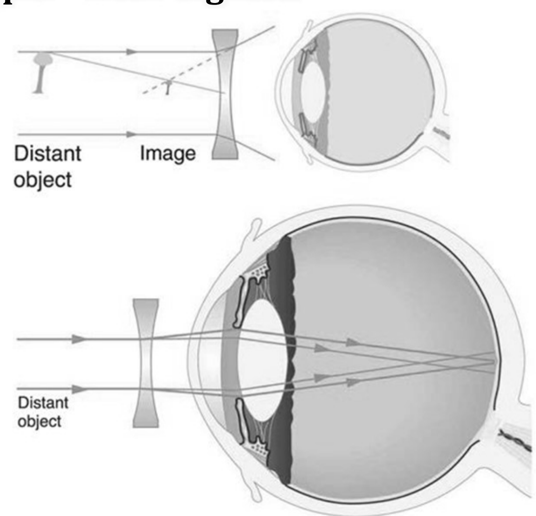
11-04 Lenses

- Near-sightedness
  - Myopia
  - Image in front of retina
  - Correct with diverging lens
- Far-sightedness
  - Hyperopia
  - Image behind retina
  - Correct with converging lens

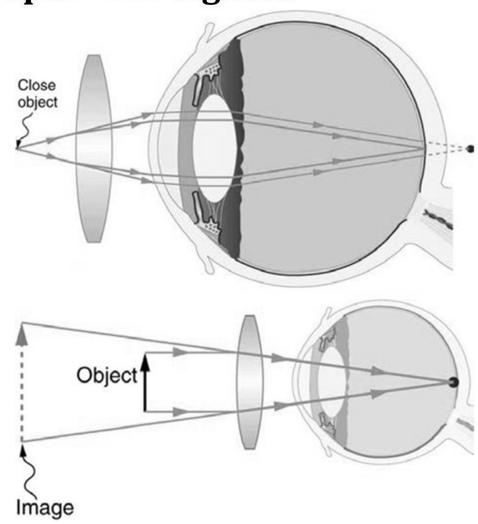


11-04 Lenses

Myopia – Near-sighted



Hyperopia – Far-sighted



11-04 Lenses

- What power of spectacle lens is needed to correct the vision of a nearsighted person whose far point is 20.0 cm? Assume the spectacle (corrective) lens is held 1.50 cm away from the eye by eyeglass frames.
- -5.41 D

You want this nearsighted person to be able to see very distant objects clearly. That means the spectacle lens must produce an image 20.0 cm from the eye for an object very far away. An image 20.0 cm from the eye will be 18.5 cm to the left of the spectacle lens (see **Figure 26.6**).
Therefore, we must get $d_i = -18.5$ cm when $d_o \approx \infty$. The image distance is negative, because it is on the same side of the spectacle as the object.

Solution

Since d_i and d_o are known, the power of the spectacle lens can be found using $P = \frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$ as written earlier:

$$P = \frac{1}{\infty} + \frac{1}{-0.185}$$

Since $\frac{1}{\infty} = 0$, we obtain:

$$P = 0 - 5.405\ /m = -5.41\ D$$

11-04 Lenses

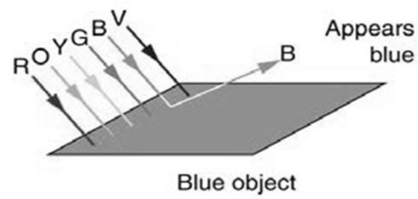
- Color Vision
  - Photoreceptors in Eye
    - Rods
      - Very sensitive (see in dark)
      - No color info
      - Peripheral vision
- Cones
  - Centered in center of retina
  - Work in only in bright light
  - Give color info
  - Essentially three types each picking up one primary color

Color vision is actually much more complicated

And they say this just “happened”

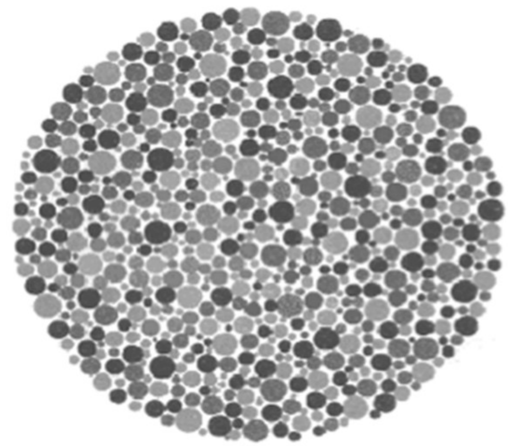
11-04 Lenses

- Color
  - Non-light producing
    - The color we see is the color that reflects off the object
    - The object absorbs all the other colors
- Light-producing
  - The color we see is the color produced



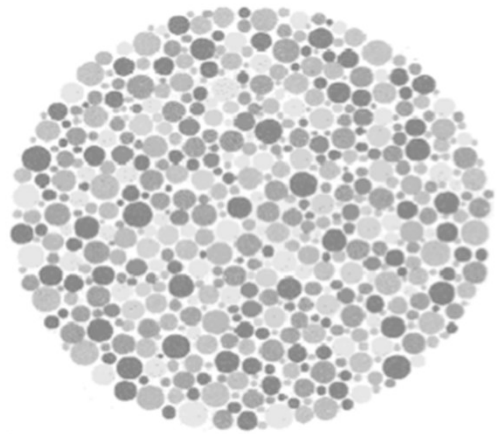
11-04 Lenses

- If you have normal color vision, you'll see a **42**.
- Red colorblind people will see a **2**.
- Green colorblind people will only see a **4**.



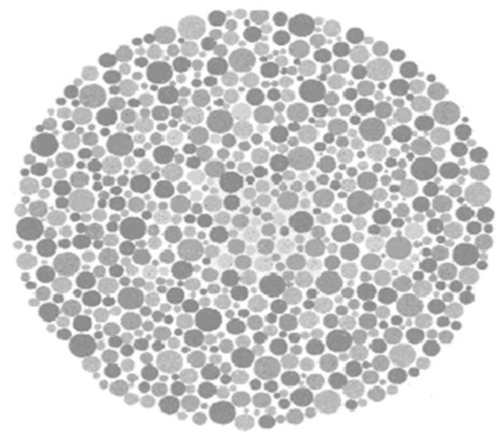
11-04 Lenses

- If you have normal color vision, you see a **73** above.
- If you are colorblind you will not see a number above.



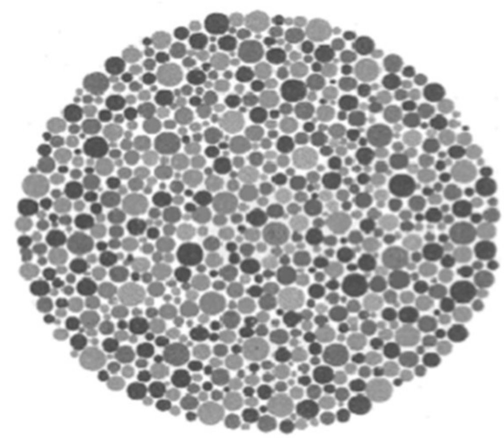
11-04 Lenses

- If you have normal color vision you'll see a **74** above.
- If you are red green colorblind, you'll see a **21**.
- If you are totally colorblind you will not see a number above.



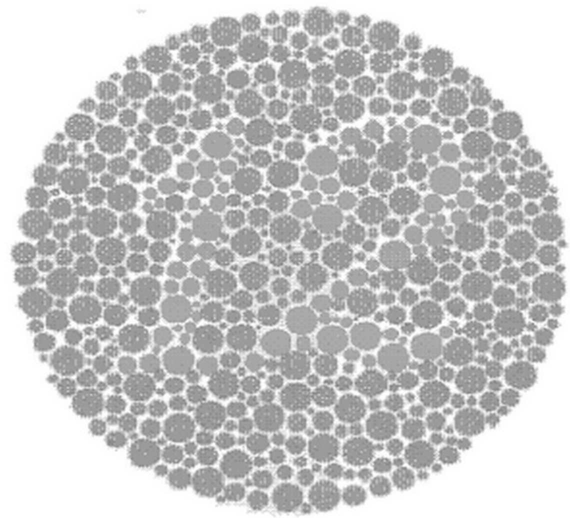
11-04 Lenses

- If you have normal color vision you'll see a **26**.
- If you are red colorblind you will see a **6,** if you're mildly red colorblind you'll see a faint **2** as well.
- If you are green colorblind you'll see the a **2**, and if you're mildly green colorblind a faint **6** as well.



11-04 Lenses

- If you have normal color vision you'll see a **12**.
- If you do not see **12** you are a liar. Everyone can see this one!



11-04 Practice Work

- Isn't it amazing how the eye works?