General Physics (PHY 2130)

Lecture XIII

- Refraction of light
  - Snell's law
  - Dispersion and rainbow
- Mirrors and lens
  - Plane mirrors
  - Concave and convex mirrors
  - Thin lenses

WAYNE STATE UNIVERSITY

http://www.physics.wayne.edu/~apetrov/PHY2130/

Lightning Review

Last lecture:

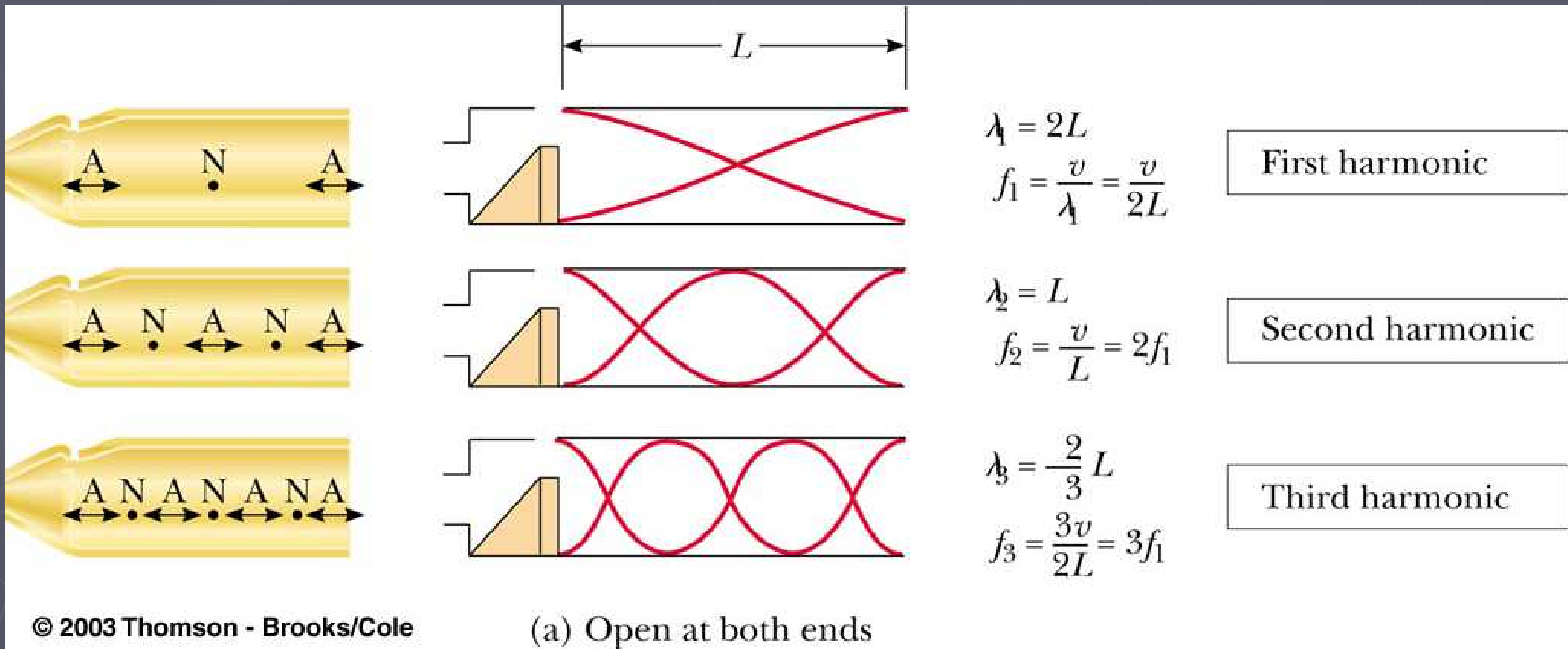
1. Sound
   - ✓ Hooke's law
   - ✓ Potential energy of an oscillator

Review Problem: Explain why your voice seems to sound richer than usual when you sing in a shower (for those of you who does)…

Standing Waves in Air Columns

- If one end of the air column is closed, a node must exist at this end since the movement of the air is restricted
- If the end is open, the elements of the air have complete freedom of movement and an antinode exists

Tube Open at Both Ends



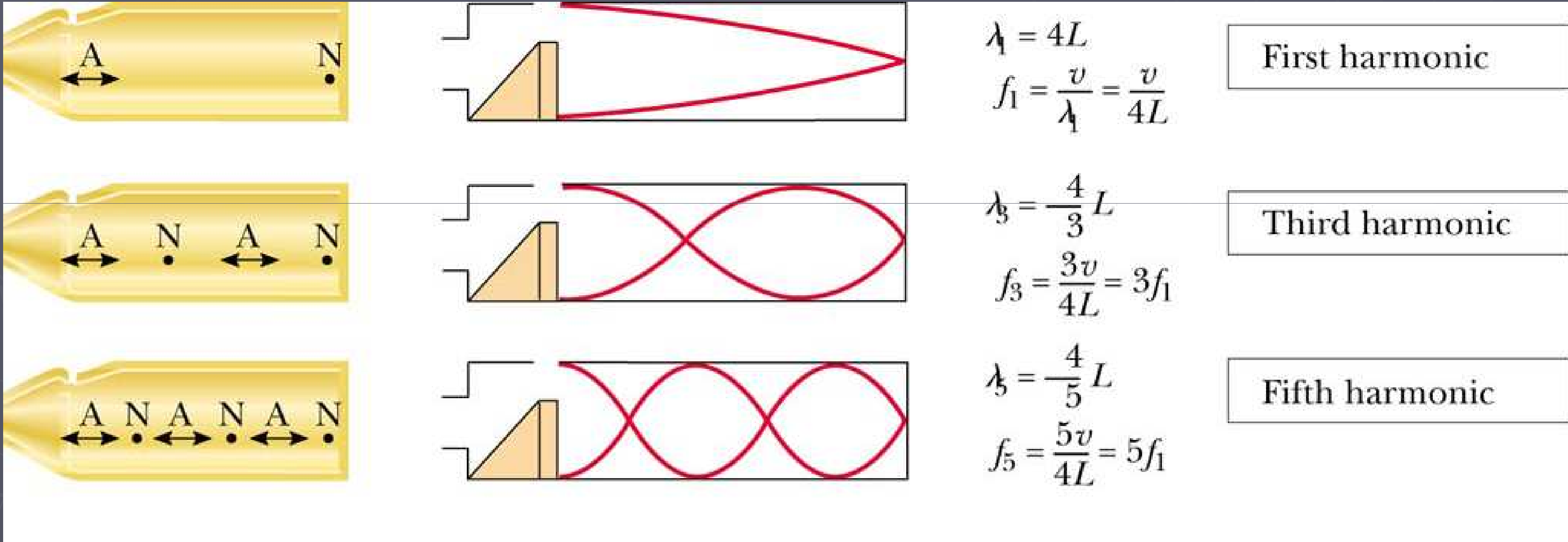
(a) Open at both ends

Resonance in Air Column Open at Both Ends

- In a pipe open at both ends, the natural frequency of vibration forms a series whose harmonics are equal to integral multiples of the fundamental frequency

$$f_n = n\frac{v}{2L} \quad n = 1, 2, 3, \ldots$$

Tube Closed at One End



(b) Closed at one end, open at the other

Resonance in an Air Column Closed at One End

- The closed end must be a node
- The open end is an antinode

$$f_n = n\frac{v}{4L} \quad n = 1, 3, 5, \ldots$$

The Ear

- The outer ear consists of the ear canal that terminates at the eardrum
- Just behind the eardrum is the middle ear
- The bones in the middle ear transmit sounds to the inner ear

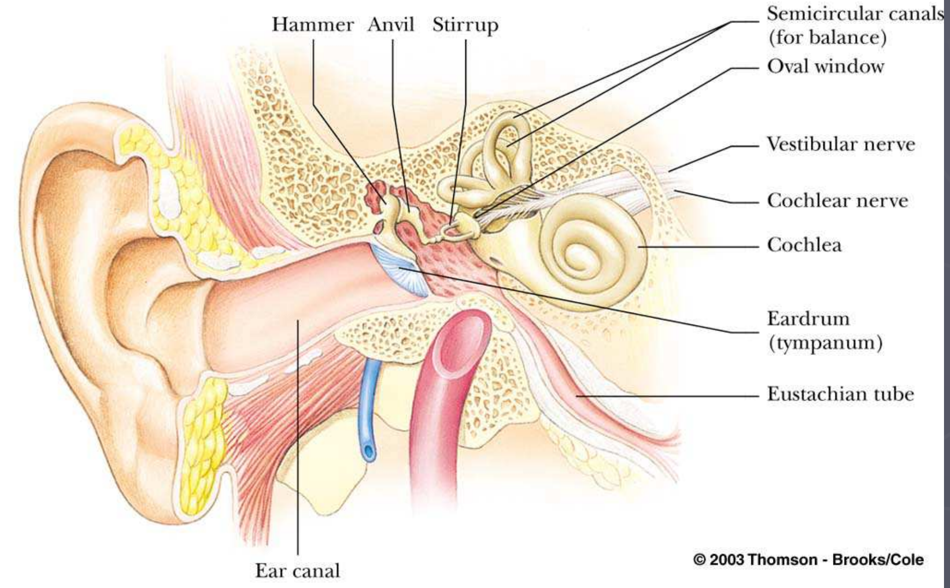


Fig 14.27, p. 452

Reflection and Refraction of Light

Dual nature of light

- In some cases light behaves like a *wave* (classical E & M – light propagation)
- In some cases light behaves like a *particle* (photoelectric effect)
- Einstein formulated theory of light:

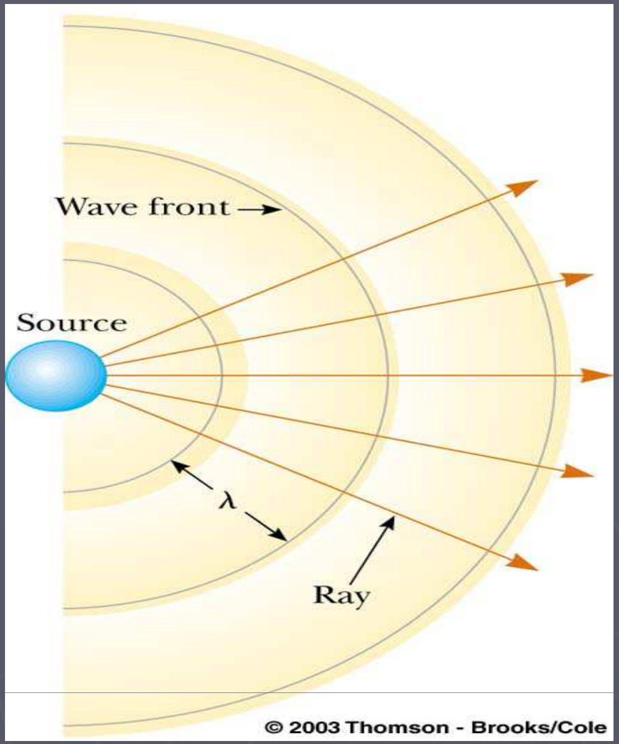
$$E = hf$$

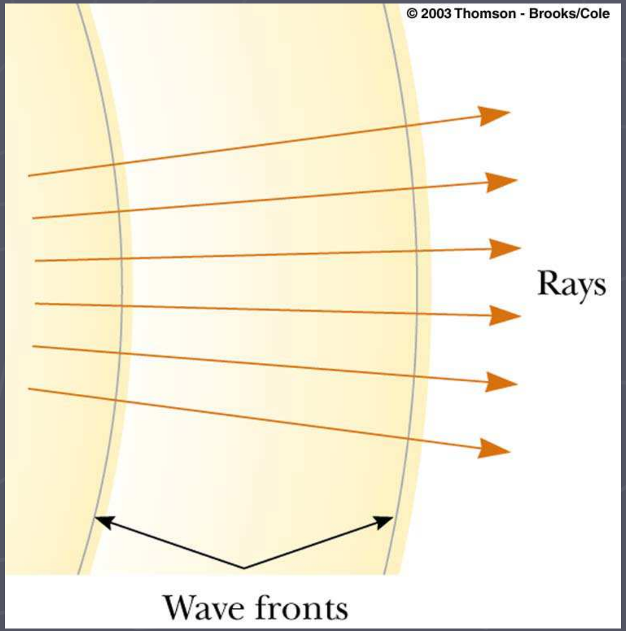
$$h = 6.63 \times 10^{-34}\, J \cdot s$$

Plank's constant

Optics

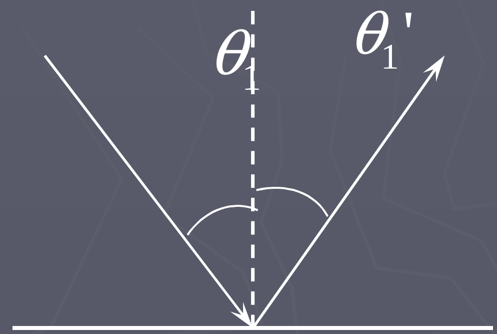
- Light travels at
  3.00 x 10^8 m/s in vaccum
  - travels slower in liquids and solids (in accord with predictions of particle theory)
- In order to describe propagation: Huygens method
  - All points on given wave front taken as point sources for propagation of spherical waves
- Assume wave moves through medium in straight line in direction of rays





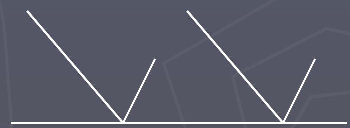
Reflection of Light

- When light encounters boundary leading into second medium, part of incident ray reflects back



$$\theta_1 = \theta_1'$$

- Smooth surface:



Angle of incidence = angle of reflection

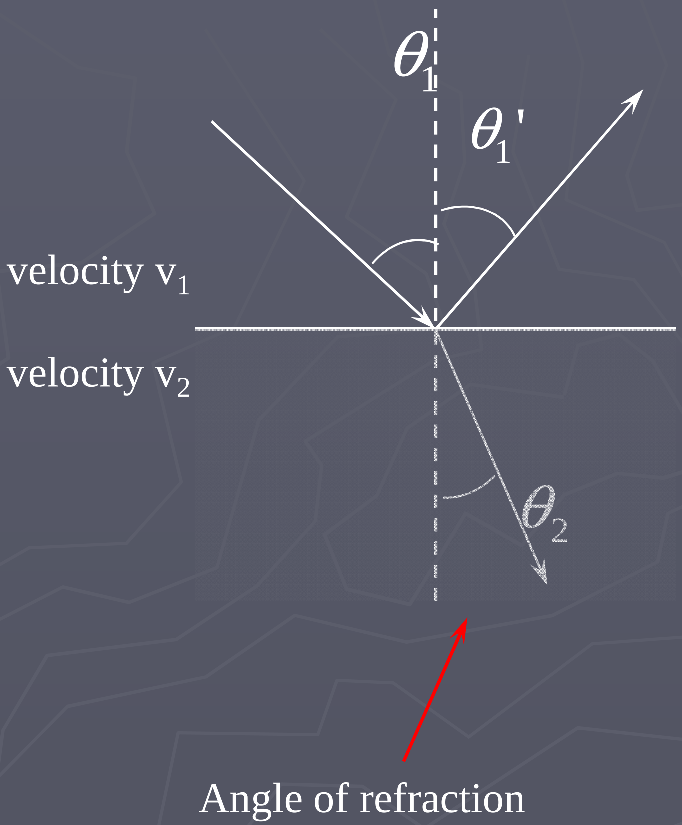
- Rough surface:

Question

Explain the nature of the “red eye” effect in photography: Why some of your pictures show your eyes to be glowing red?

Refraction of Light

- Also, when light encounters boundary leading into second medium, part of incident ray enters the second medium and said to be *refracted*
- The path of a light ray through a refracting surface is *reversible*

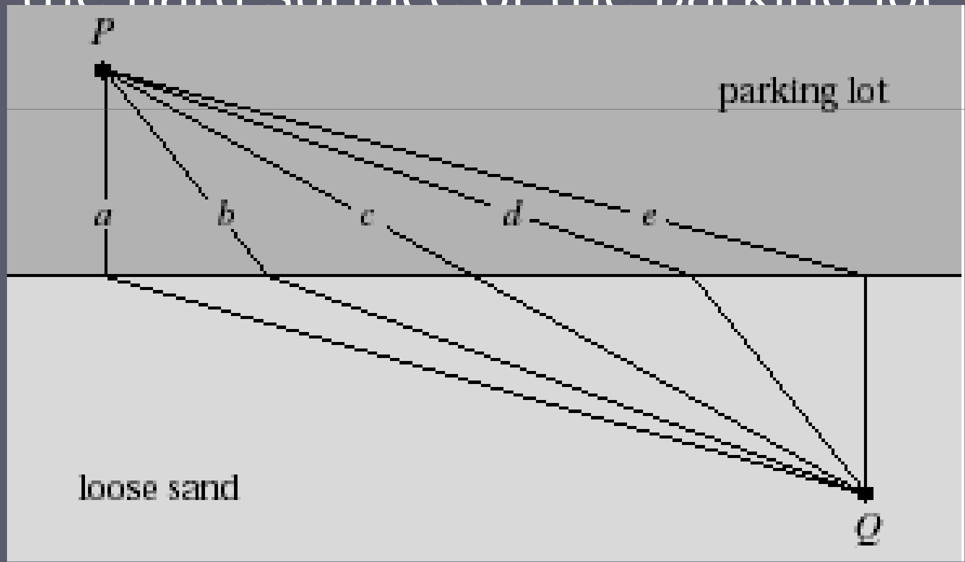


if velocity decreases: $\theta_2 < \theta_1$
if velocity increases: $\theta_2 > \theta_1$

$$\frac{\sin \vartheta_2}{\sin \vartheta_1} = \frac{v_2}{v_1} = const$$

ConcepTest

A group of sprinters gather at point *P* on a parking lot bordering a beach. They must run across the parking lot to a point *Q* on the beach as quickly as possible. Which path from *P* to *Q* takes the least time? You should consider the relative speeds of the sprinters on the hard surface of the parking lot and on loose sand.

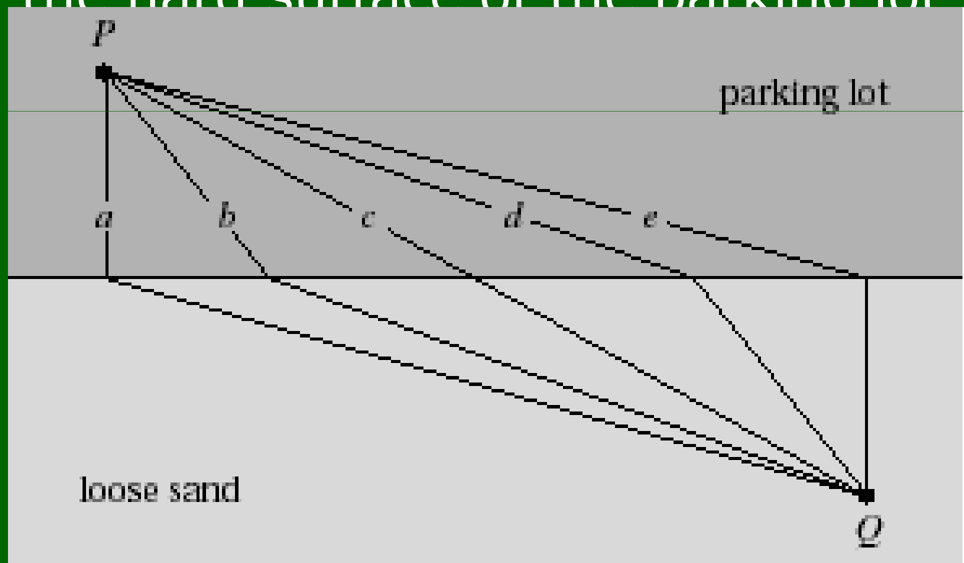


1. *a*
2. *b*
3. *c*
4. *d*
5. *e*
6. All paths take the same amount of time.

ConcepTest

Convince your neighbor

A group of sprinters gather at point *P* on a parking lot bordering a beach. They must run across the parking lot to a point *Q* on the beach as quickly as possible. Which path from *P* to *Q* takes the least time? You should consider the relative speeds of the sprinters on the hard surface of the parking lot and on loose sand.



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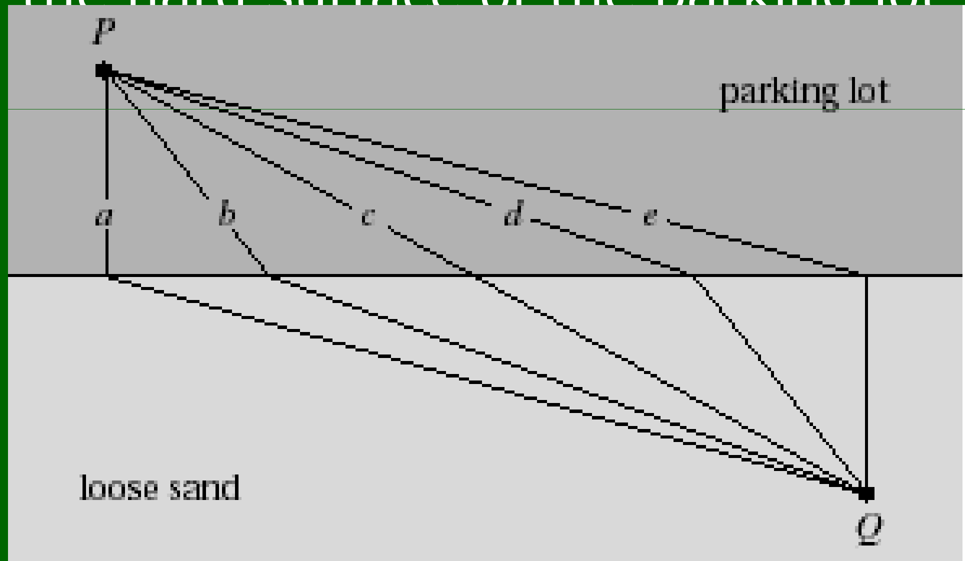

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2. *b*
3. *c*
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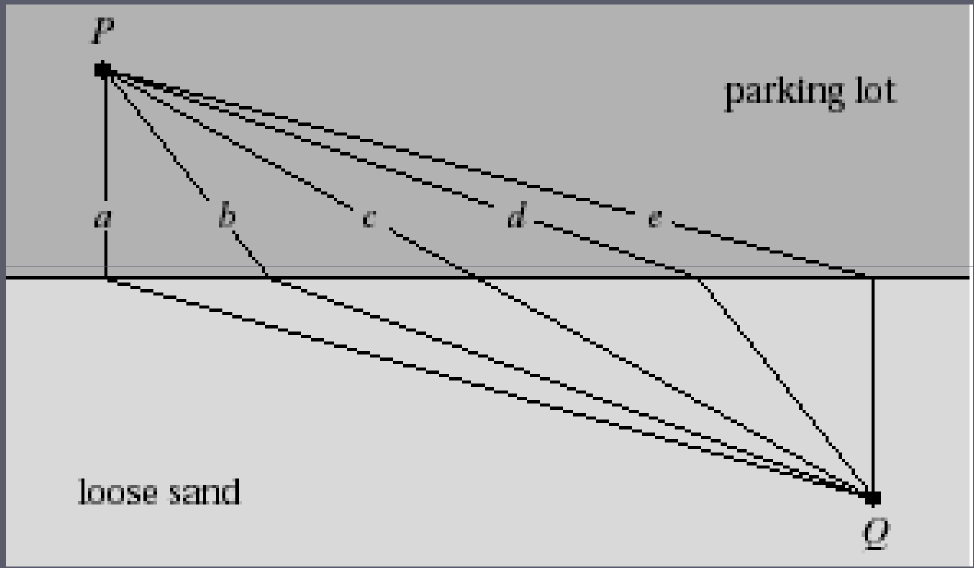
6. All paths take the same amount of time.

Note: Anybody can run faster on a hard surface than on loose sand. While the sand distance is smaller for e, the run over the parking lot is much longer.

ConcepTest

Suppose the sprinters wish to get from point *Q* on the beach to point *P* on the parking lot as quickly as possible. Which path takes the least time?



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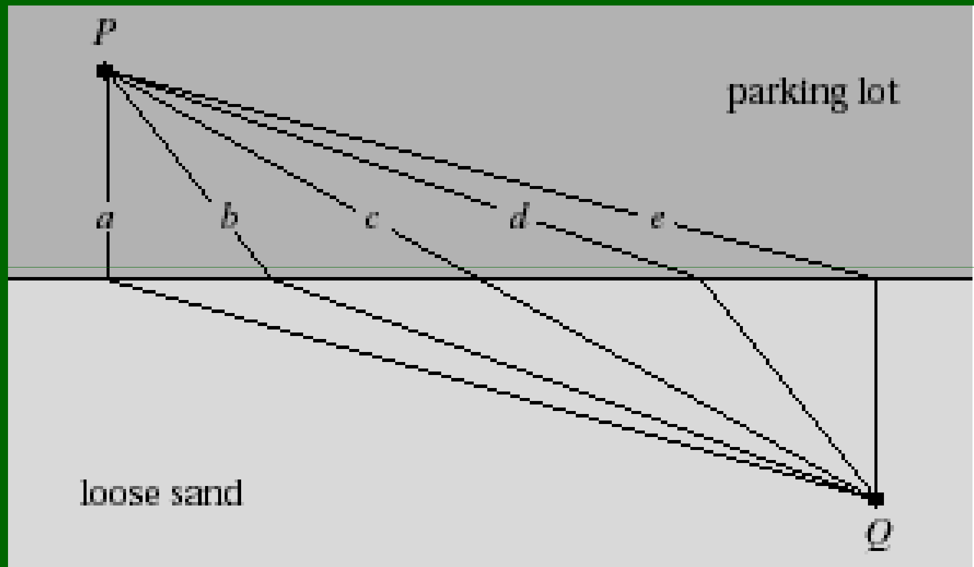

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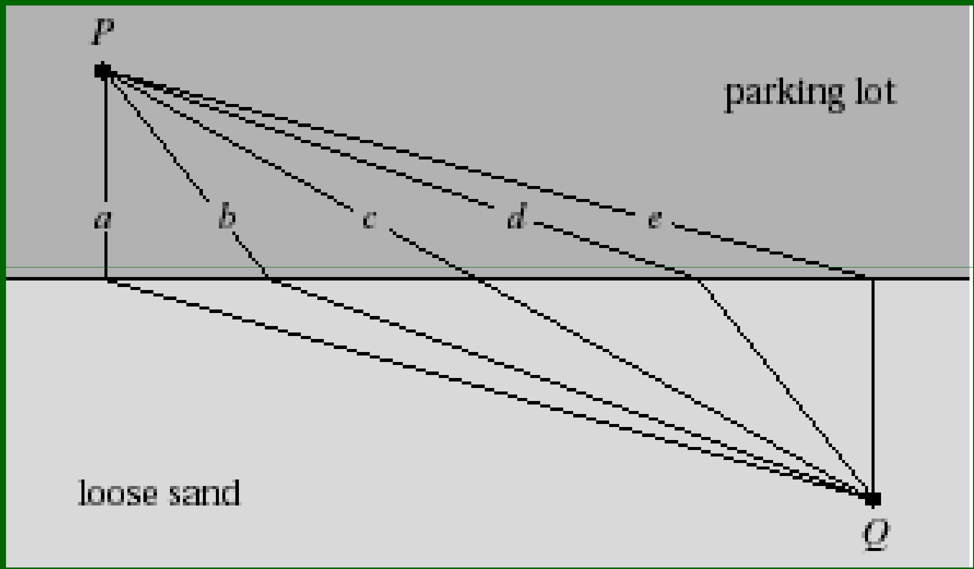

1. *a*
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The law of refraction

- Introduce a concept of ***index of refraction in medium***

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} = \frac{c}{v}$$

- *Note:* n is *dimensionless* and *n>1*

  greater index of refraction, slower speed of light *in medium*

- As light travels from one medium to another, its *frequency* ***does not change.***

The law of refraction

- Rewrite the law of refraction using the concept of index of refraction:

$$\frac{v_1}{v_2} = \frac{c/n_1}{c/n_2}, \; thus$$

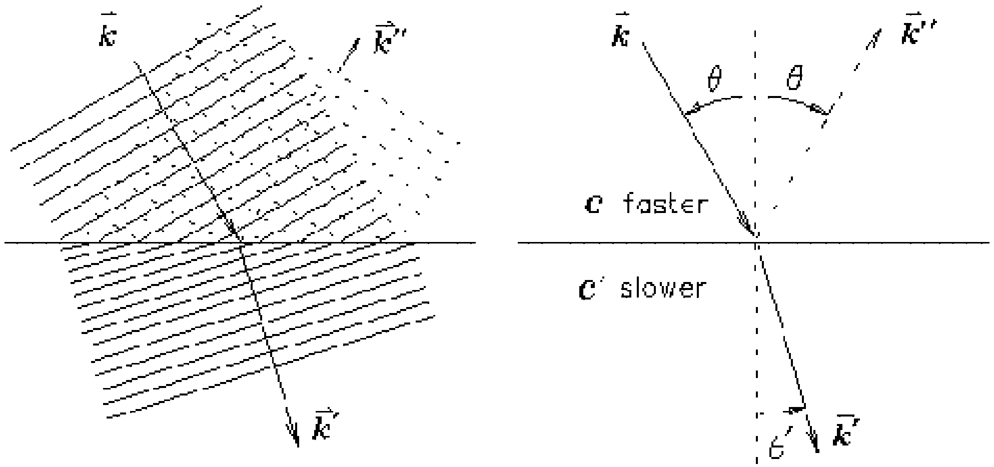
$$\frac{\sin \vartheta_1}{\sin \vartheta_2} = \frac{n_2}{n_1}, \; or \quad n_1 \sin \vartheta_1 = n_2 \sin \vartheta_2$$

Snell's law

diamond	2.42
glass	1.52
zircon	1.92
water	1.33
air	1.000293

Example: angle of refraction in glass

A light ray of wavelength 589 nm (produced by a sodium lamp) traveling through air is incident on a smooth, flat slab of crown glass at an angle of 30.0º to the normal, as sketched in the figure. Find the angle of refraction.



Example:

Given:

indexes of refraction:
air: $n_1 = 1.00$
glass: $n_2 = 1.52$
wavelength: $\lambda = 589\ nm$

Find:

$\theta_2 = ?$

Let's rewrite Snell's law as

$$\sin \vartheta_2 = \frac{n_1}{n_2} \sin \vartheta_1 \qquad (1)$$

Inserting the table data for n in the air and in glass the unknown refraction angle can be determined as

$$\sin \vartheta_2 = \frac{1.00}{1.52} \sin 30^\circ = 0.329 \qquad (2)$$

$$\vartheta_2 = \sin^{-1}(0.329) = \underline{19.2^\circ}$$ ✓

Note: the ray is bent *toward* the normal, as expected.

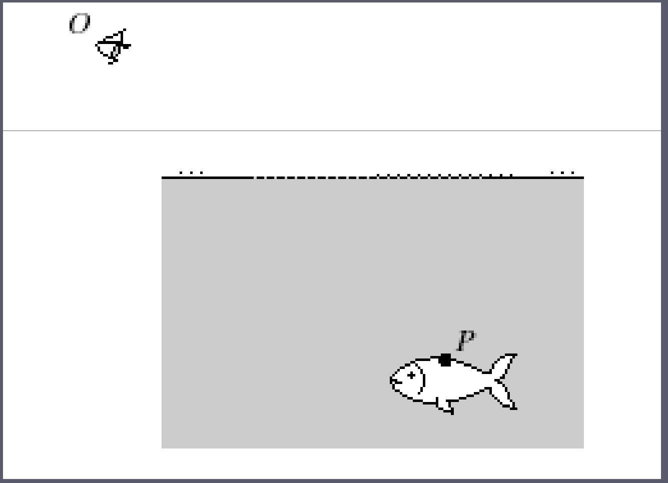
Q: What is the wavelength of this light in glass?

$$\lambda_n = \frac{\lambda_0}{n} = \frac{589\ nm}{1.52} = 387.5\ nm$$ ✓

ConcepTest

A fish swims below the surface of the water at *P*. An observer at *O* sees the fish at

1. a greater depth than it really is.
2. the same depth.
3. a smaller depth than it really is.



ConcepTest

Convince your neighbor!

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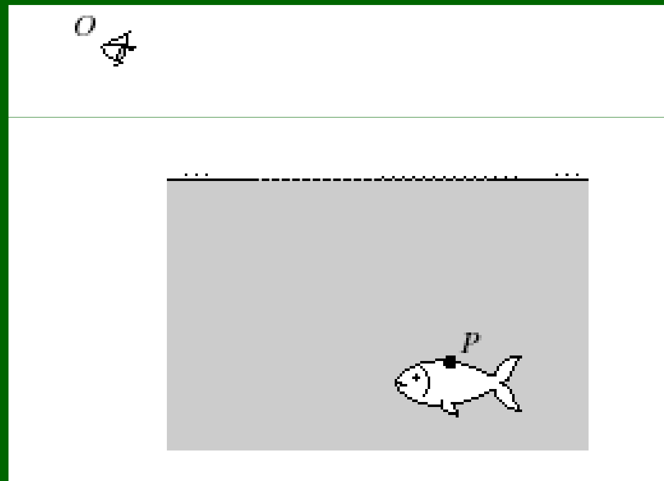

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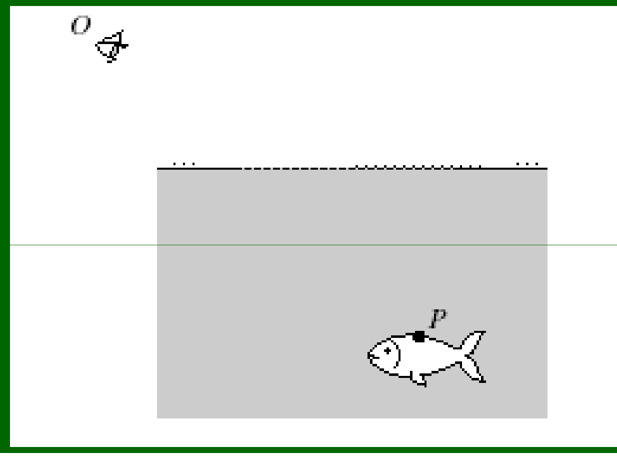

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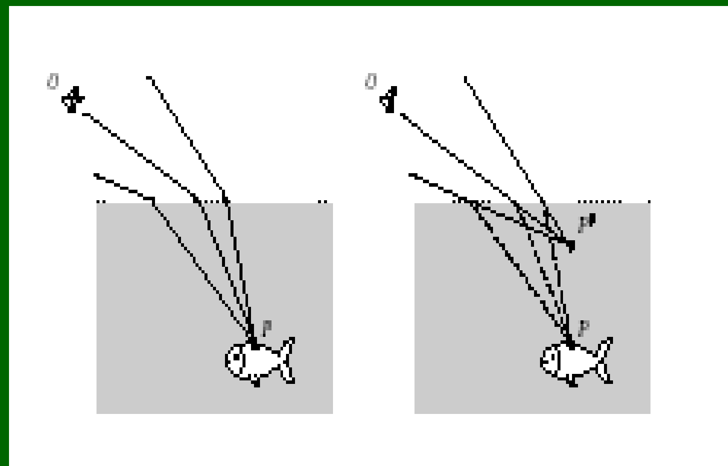
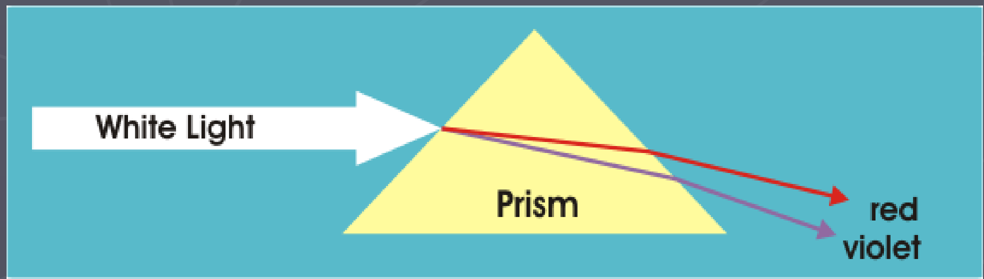


Note: The rays emerging from the water surface converge to a point above the fish.

Dispersion and prisms

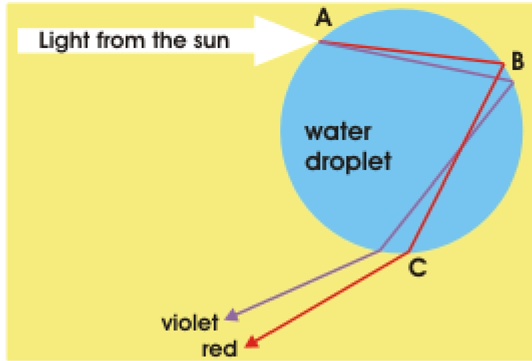
- An important property of the index of refraction: its value in anything but vacuum depends on the wavelength of light. This phenomenon is called *dispersion*.
- Snell's law indicates: light of different wavelengths is bent at different angles when incident on a refracting material.

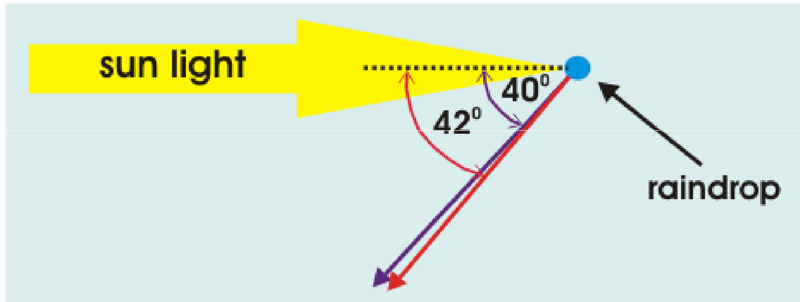
  - Prisms
  - Rainbow

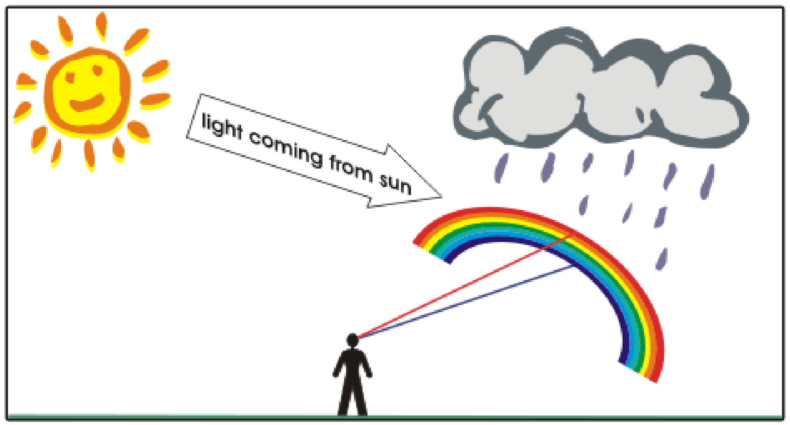


Rainbow

- In a rainbow, *raindrops* in the air act like tiny *prisms*. Light enters the drop at A, is reflected at the back of the drop at B and leaves the drop at C. In the process the sunlight is broken into a spectrum just like it is in a triangular glass prism.
- The angle between the ray of sunlight coming in and the ray coming out of the drops is 42 degrees for red and 40 degrees for violet rays.
- This small angular difference between the returning rays causes us to see the bow.

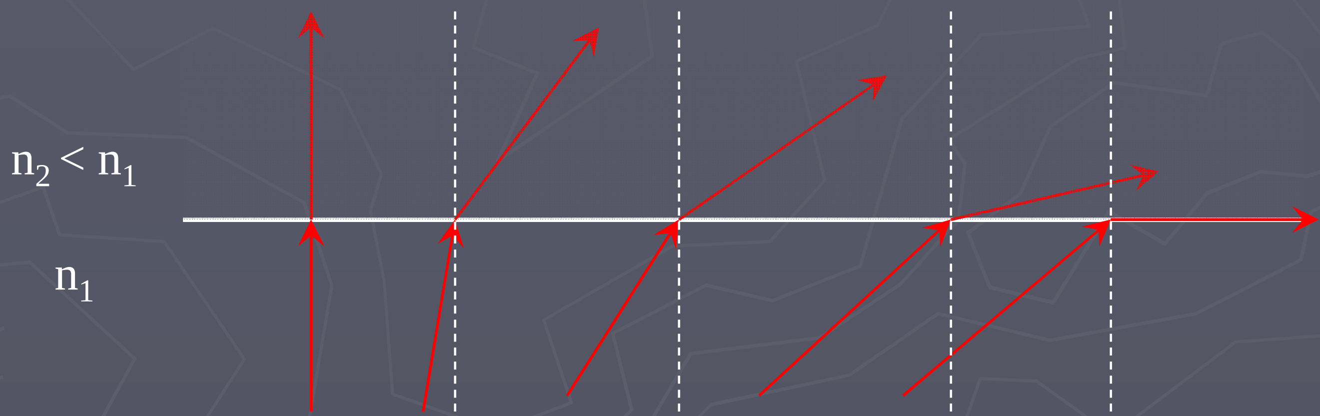






Total internal reflection

- Consider light moving from the medium with a *high* index of refraction into one with a *lower* index of refraction.



- At some angle, θ_c, the refracted light moves parallel to the boundary:

total internal reflection

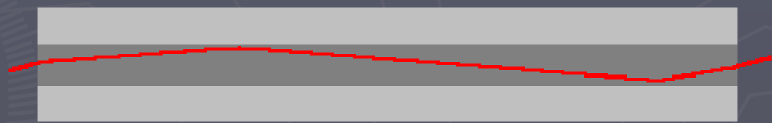
$$n_1 \sin \vartheta_c = n_2 \sin 90^\circ = n_2$$

$$\sin \vartheta_c = n_2 / n_1$$

Applications:

- Diamond sparkling (low θ_c and proper faceting)

- Fiber optics

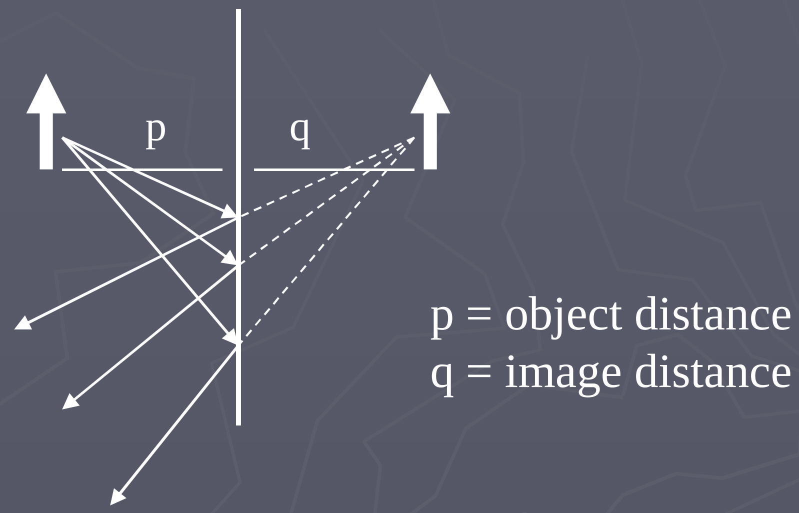


- Microscopes, binoculars, periscopes…

Mirrors and Lens

Plane (flat) mirrors

- Images are formed at the point at which rays of light actually intersect or at which they appear to originate.
- Images can be
  - Real (light rays actually intersect – can be displayed on a screen)
  - Virtual (where light rays appear to come from)



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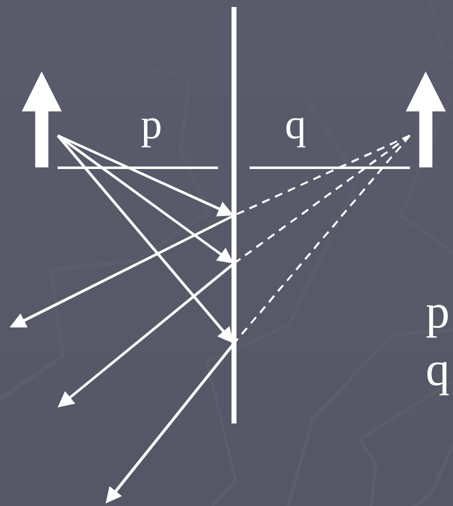

p = object distance
q = image distance

Q: What kind of image does the plane mirror have?

Plane (flat) mirrors

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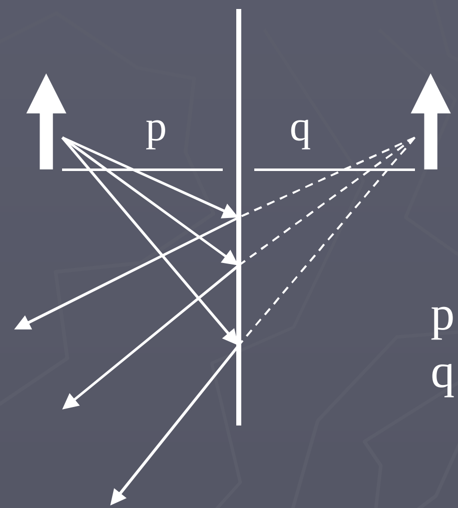


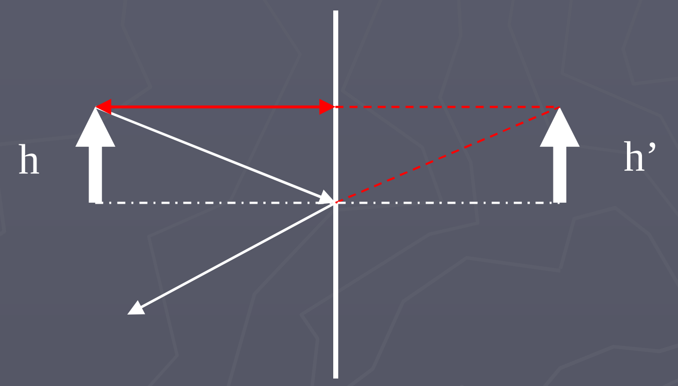
p = object distance
q = image distance

Q: What kind of image does the plane mirror have?

A: virtual

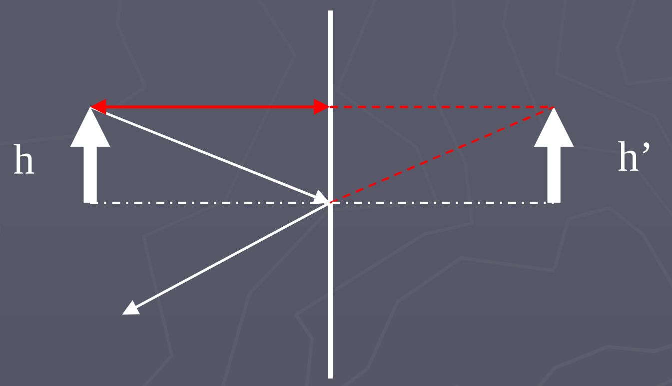
Construction of images: flat mirrors

- Use two (or more) rays to construct an image



Construction of images: flat mirrors

- Use two (or more) rays to construct an image
- Note: the image formed by an object placed in front of a flat mirror is as far behind the mirror as the object is in front of it.



Construction of images: flat mirrors

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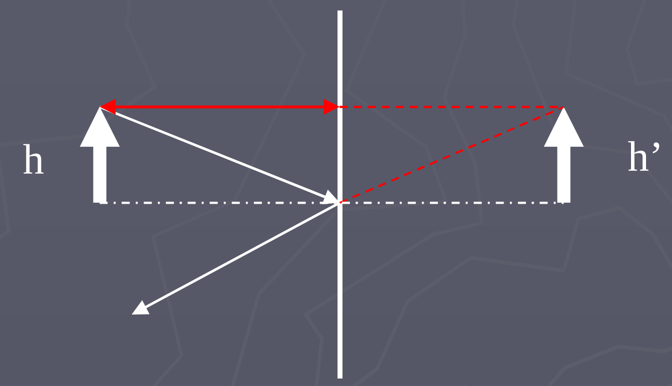


- Note: the image formed by an object placed in front of a flat mirror is as far behind the mirror as the object is in front of it.

- Lateral magnification

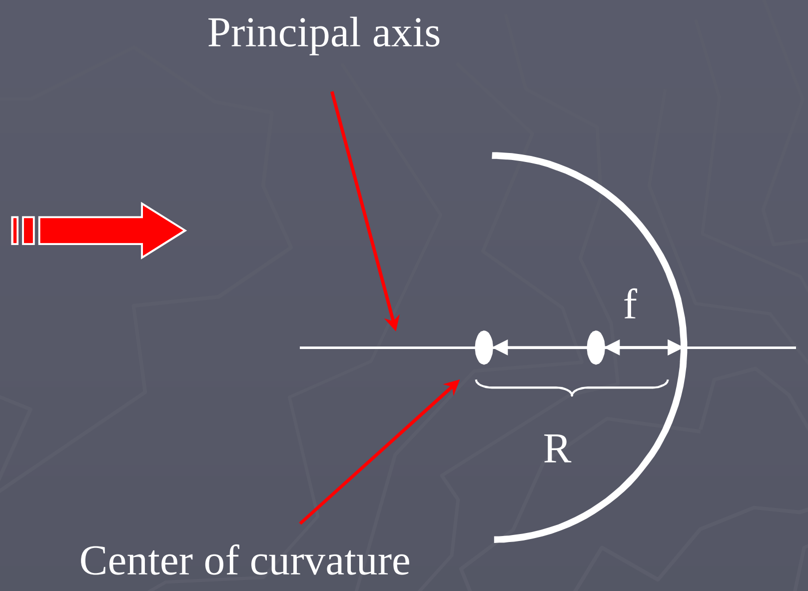
$$M = \frac{image\ height}{object\ height} = \frac{h'}{h}$$

Plane (flat) mirrors: summary

1. The image is as far behind the mirror as the object is in front.
2. The image is unmagnified, virtual and upright (i.e. if the object arrow points upward, so does the image arrow. The opposite of an upright image is an inverted image.)

Spherical mirrors

- Spherical mirrors can be concave (light reflecting from its silvered inner) or convex (light reflecting from its silvered outer surface).
- Useful property: all light rays parallel to the principal axis will reflect through the *focal point* (where the image will be located).



R = radius of curvature
f = focal length = R/2

We will use it to build images…

Mirror equations

- Can use geometry to compute image magnification and image position.

$$\frac{1}{p}+\frac{1}{q}=\frac{2}{R}=\frac{1}{f}$$

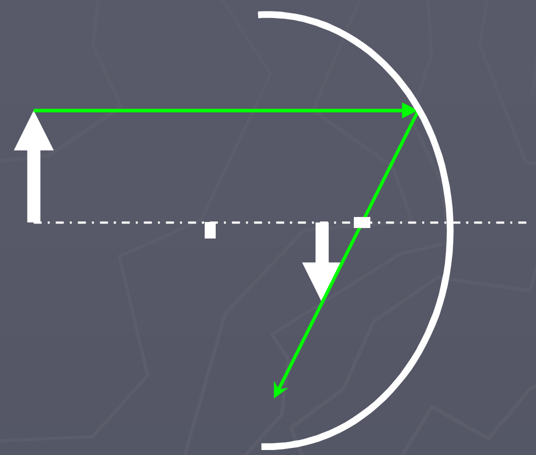
$$M=\frac{h'}{h}=-\frac{q}{p}$$

p = object distance
q = image distance

- Note:
  - both q and p are positive when both image and object are on the same side of the mirror (q<0 if "inside the mirror").
  - f is positive for concave mirror and negative for convex mirror.
  - Plane mirror: q=-p, so M=-q/p=1 (virtual and upright image).

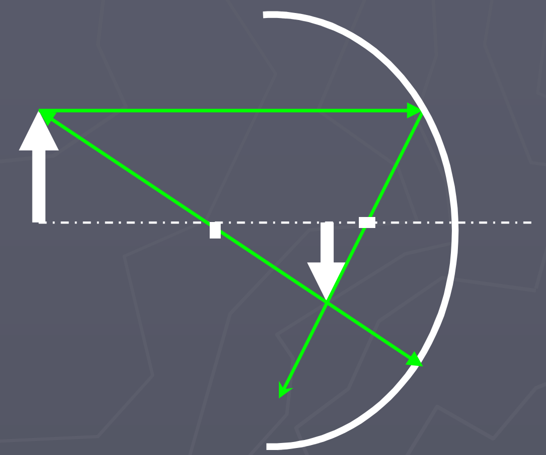
Construction of images: concave mirrors

- Use two (or more) rays to construct an image
- Case 1: p>R
  - Light ray parallel to the principal axis will be reflected through the focal point



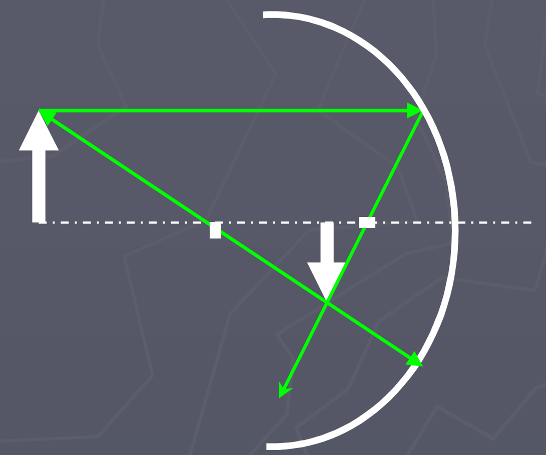
Construction of images: concave mirrors

- Use two (or more) rays to construct an image
- Case 1: $p>R$
  - Light ray parallel to the principal axis will be reflected through the focal point
  - Light ray passing through the curvature center will be reflected back



Construction of images: concave mirrors

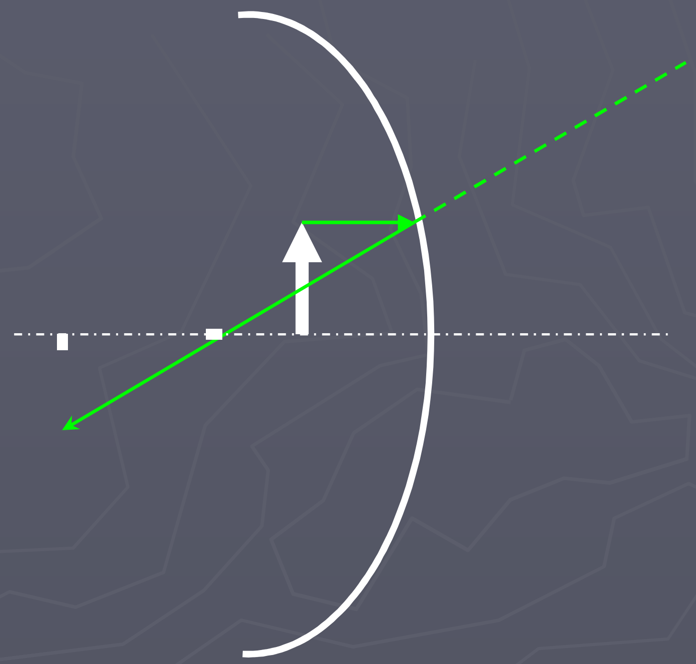
- Use two (or more) rays to construct an image
- Case 1: p>R
  - Light ray parallel to the principal axis will be reflected through the focal point
  - Light ray passing through the curvature center will be reflected back
  - Light ray passing through the focal point will be reflected parallel to the principal axis.



Note: image is real and inverted

Construction of images: concave mirrors

- Use two (or more) rays to construct an image
- Case 2: $p<f$
  - Light ray parallel to the principal axis will be reflected through the focal point



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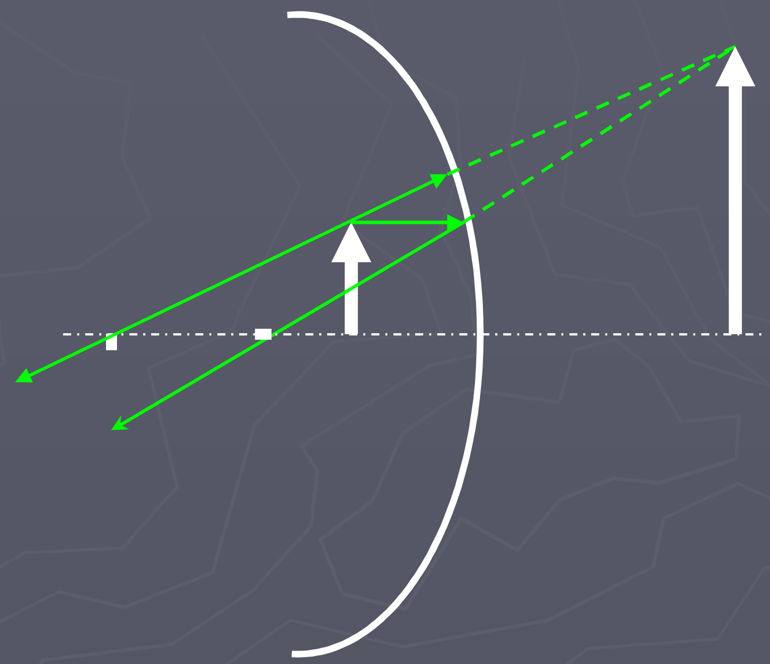

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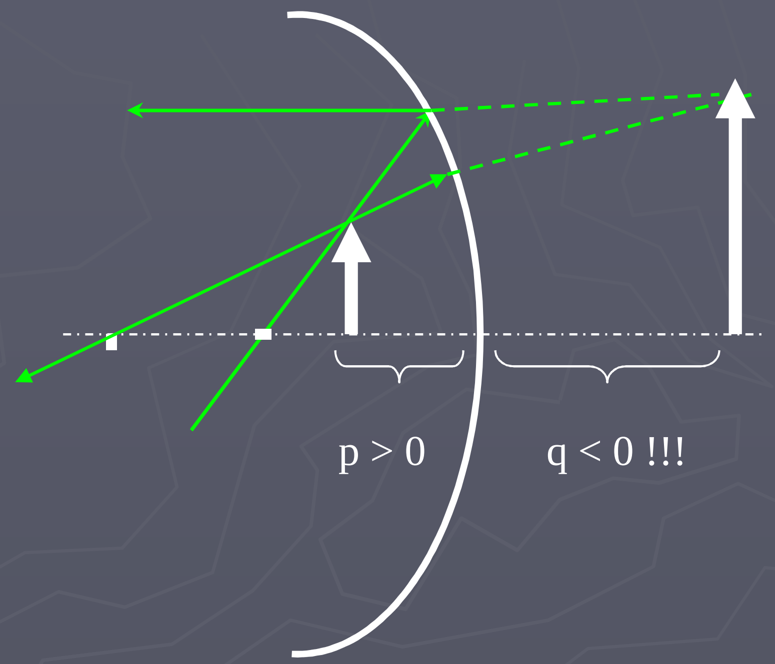


Note: image is virtual and upright

Example 1: concave mirrors

An object is placed in front of a concave mirror at the distance of 80.0 cm. Find (a) distance between the image and the mirror (b) lateral magnification if the focal distance of the mirror is 20.0 cm.

Example 1:

Given:

mirror parameters:
focal distance: f = 20.0 cm
radius: R = 2 f = 40.0 cm
p = 80.0 cm

Find:

q = ?
M = ?

(a) Use mirror equation:

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f} \quad (1)$$

Inserting the available data for f and p the unknown image distance can be determined as

$$\frac{1}{q}=\frac{1}{f}-\frac{1}{p}=\frac{1}{20cm}-\frac{1}{80cm}=\frac{3}{80cm} \quad (2)$$

$$q=\frac{80cm}{3}=+26.7cm$$

✓

(b) Lateral magnification can be found from

$$M=-\frac{q}{p}=-\frac{26.7cm}{80.0cm}=-0.33$$

✓

The image is smaller than the object!

Example 2: concave mirrors

An object is placed in front of a concave mirror at the distance of 10.0 cm. Find (a) distance between the image and the mirror (b) lateral magnification if the focal distance of the mirror is 20.0 cm.

Example 2:

<u>Given:</u>

mirror parameters:
focal distance: f = 20.0 cm
radius: R = 2 f = 40.0 cm
p = 10.0 cm

<u>Find</u>:

q = ?
M = ?

(a) Use mirror equation:

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f} \qquad (1)$$

Inserting the available data for f and p the unknown image distance can be determined as

$$\frac{1}{q}=\frac{1}{f}-\frac{1}{p}=\frac{1}{20cm}-\frac{1}{10cm}=-\frac{1}{20cm}$$
$$q=\frac{20cm}{1}=-20cm \qquad (2)$$

✓

(b) Lateral magnification can be found from

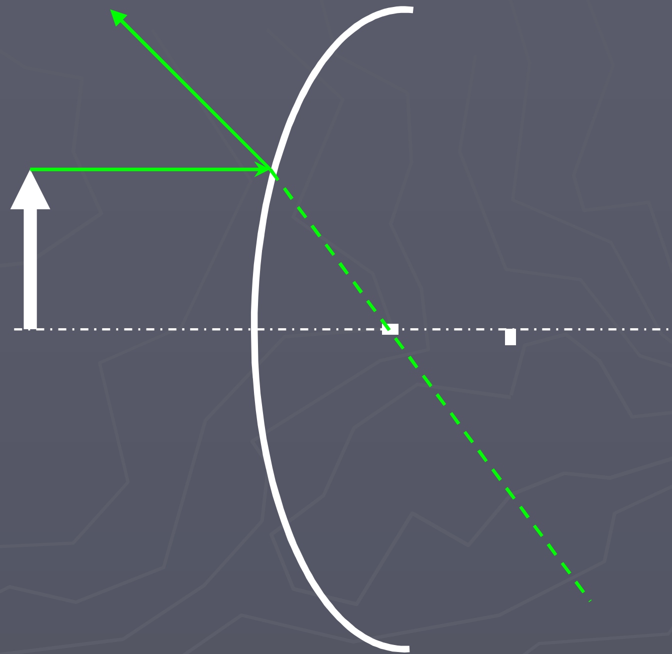
$$M=-\frac{q}{p}=-\frac{(-20.0cm)}{80.0cm}=+2.00$$

✓

The image is larger than the object!

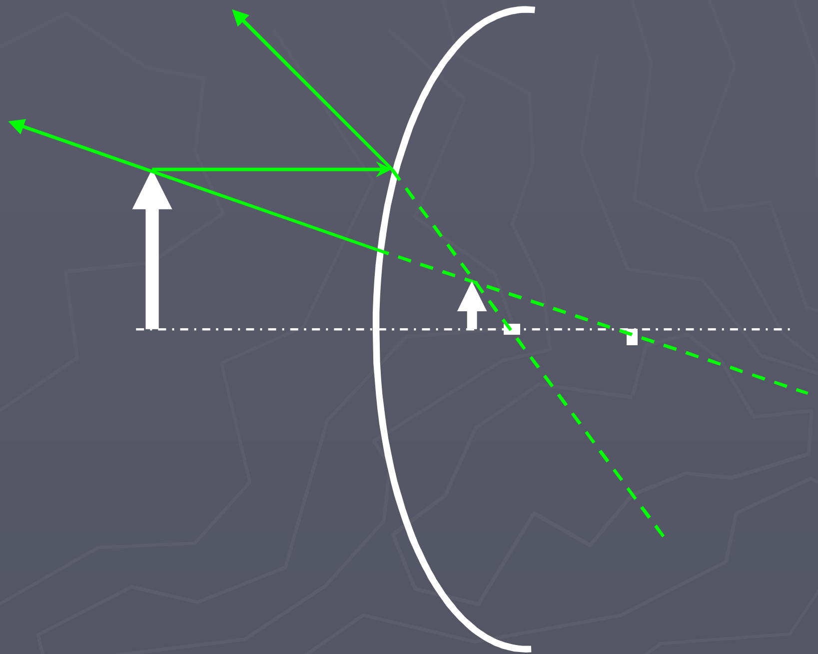
Construction of images: convex mirrors

- Use two (or more) rays to construct an image
- Same method:
  - Light ray parallel to the principal axis will be reflected through the focal point



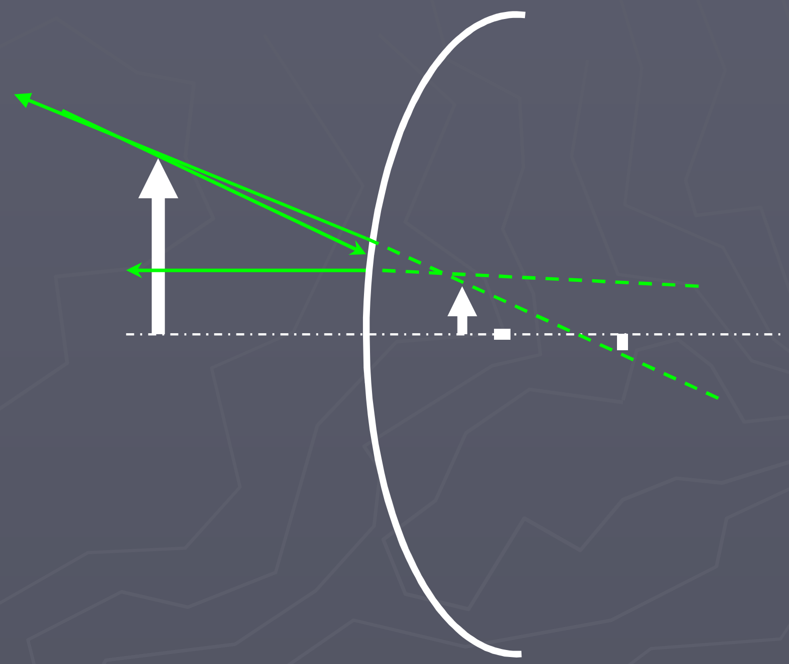
Construction of images: concave mirrors

- Use two (or more) rays to construct an image
- Same method:
  - Light ray parallel to the principal axis will be reflected through the focal point
  - Light ray passing through the curvature center will be reflected back



Construction of images: concave mirrors

- Use two (or more) rays to construct an image
- Same method:
  - Light ray parallel to the principal axis will be reflected through the focal point
  - Light ray passing through the curvature center will be reflected back
  - Light ray passing through the focal point will be reflected parallel to the principal axis.



Note: image is virtual and upright

Example: convex mirrors

An object is placed in front of a convex mirror at the distance of 30.0 cm. Find (a) distance between the image and the mirror (b) lateral magnification if the focal distance of the mirror is 20.0 cm.

Example:

<u>Given:</u>

mirror parameters:
focal distance: f = 20.0 cm
radius: R = 2 f = 40.0 cm
p = 30.0 cm

<u>Find</u>:

q = ?
M = ?

(a) Use mirror equation:

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f} \qquad (1)$$

Inserting the available data for f and p the unknown image distance can be determined as

$$\frac{1}{q}=\frac{1}{f}-\frac{1}{p}=\frac{1}{-20cm}-\frac{1}{80cm}=-\frac{5}{60cm}$$

$$q=-{}^{60cm}\!/_{5}=-12cm \qquad (2)$$

✓

(b) Lateral magnification can be found from

$$M=-\frac{q}{p}=-\frac{-12cm}{-20cm}=+0.40$$

✓

The image is smaller than the object!