

2.9. Geometrical optics: Refection & refraction

os21 - magic mirror

How does this set-up work?

- ray model
- mirrors & reflection
- real & virtual images

solution 1 & solution 2



Geometrical optics: What, why & when?

- light exhibits both particle and wave properties
- **for objects much larger than the wavelength, light can be approximated as rays**
- geometric/ray optics describes light propagation in terms of rays
- → **reflection & refraction**



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Ray model of light

- light travels in straight-line paths called rays
- each ray is considered an extremely narrow beam of light
- this model explains many everyday optical phenomena:
 - when light reaches a surface, it can be **reflected, absorbed, or transmitted**
 - the ray model simplifies the understanding of **reflection, refraction**, and later, optical instruments

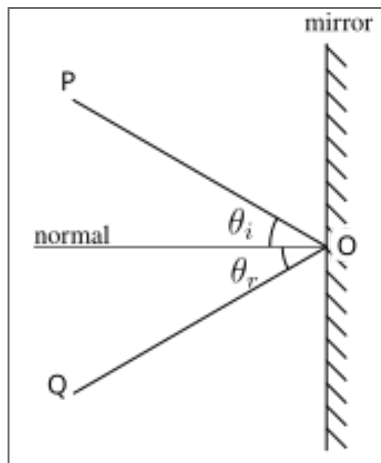


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Reflection & plane mirror

os01 - Haftoptik: plane mirror reflection

- for a plane mirror, follow these steps to construct the **incident** and **reflected ray**:
 - find the normal perpendicular to the surface
 - determine the angle of incidence θ_i , between the normal and the incident ray
 - the angle of reflection θ_r , between the normal and the reflected ray, equals the angle of incidence
- **law of reflection is:** $\theta_i = \theta_r$

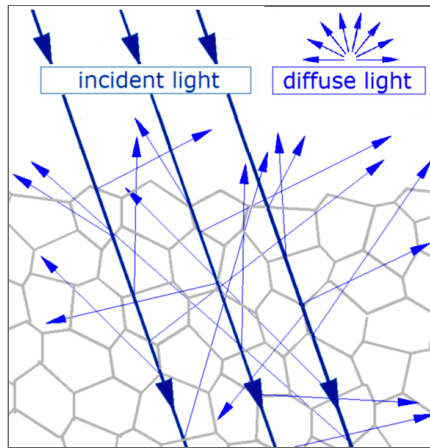


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Diffuse vs. specular reflection

sim - (bumpy) mirror

- eye perceives an image when reflected light rays enter the eye in a converging (or nearly parallel) pattern
- **specular reflection:** occurs on smooth surfaces; parallel incident rays remain parallel after reflection.
- **diffuse reflection:** occurs on rough surfaces; parallel rays are reflected in many directions due to surface irregularities
- "eye see's" specular reflections only from specific viewing angles; diffuse reflections are visible from most directions



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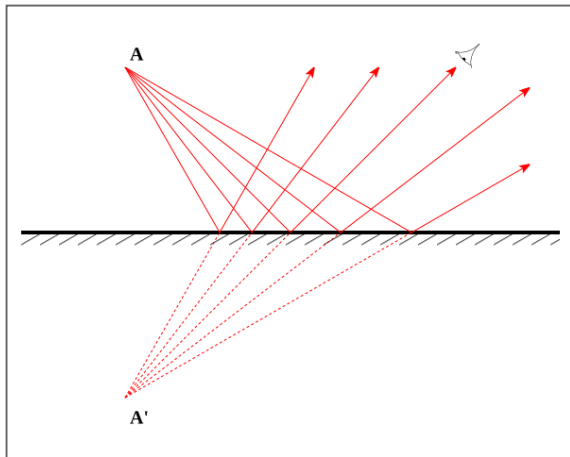
Image formation at plane mirrors: Every-day observations

- although the **object is in front of the mirror**, the **brain perceives** its **image as behind the mirror**
- **left and right flipped but not up and down**
- the object distance d_o (measured perpendicular to the mirror) equals the image distance d_i
- the object's height h_o equals the image's height h_i

Image formation at plane mirrors: real vs. virtual images

sim - virtual image at flat mirror

- an object in front of a plane mirror produces two rays per point that obey the law $\theta_i = \theta_r$
- image reconstruction is achieved by extending the reflected rays behind the mirror
- images that cannot be projected (because the rays do not actually intersect) are called virtual images



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Curved mirrors

os01 - Haftoptik: bendable mirror

- curved mirrors are typically spherical and can be:
 - **convex** – surface bulges toward the viewer; extends the field of view
 - **concave** – surface bulges inward; used for magnifying images
- the **principal axis** is the straight line perpendicular to the mirror at its center
- the **focal point** F is defined as **the image point for an object at infinity**
- for spherical mirrors, the radius of curvature r is related to the **focal length** f by: $r = 2f$

Image formation at curved mirrors: Principal rays

- image construction for objects **not at infinity** uses at least two the **principal rays**:
 - **parallel ray**: travels parallel to the principal axis; reflects through the focal point;
 - **focal point ray**: passes through the focal point at distance f ; reflects parallel to the principal axis
 - **central point ray**: aimed at the center of curvature at distance r ; reflects back along the same path

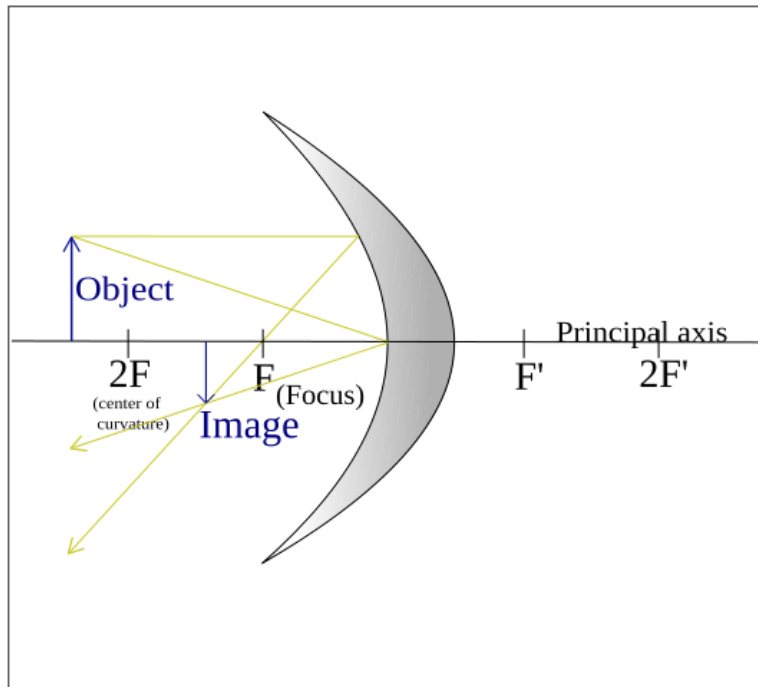
Image formation at curved mirrors: Concave mirror

sim - concave mirror

os01 - Haftoptik: concave mirror

Image formation at curved mirrors: Concave mirror $d_o > 2 \cdot f$

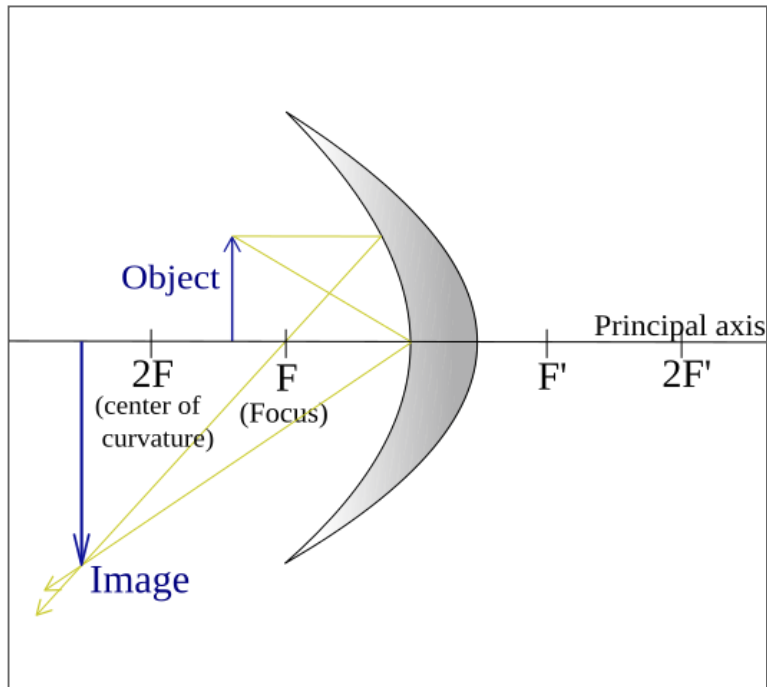
- real, inverted, smaller image



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Image formation at curved mirrors: Concave mirror $2 \cdot f > d_o > f$

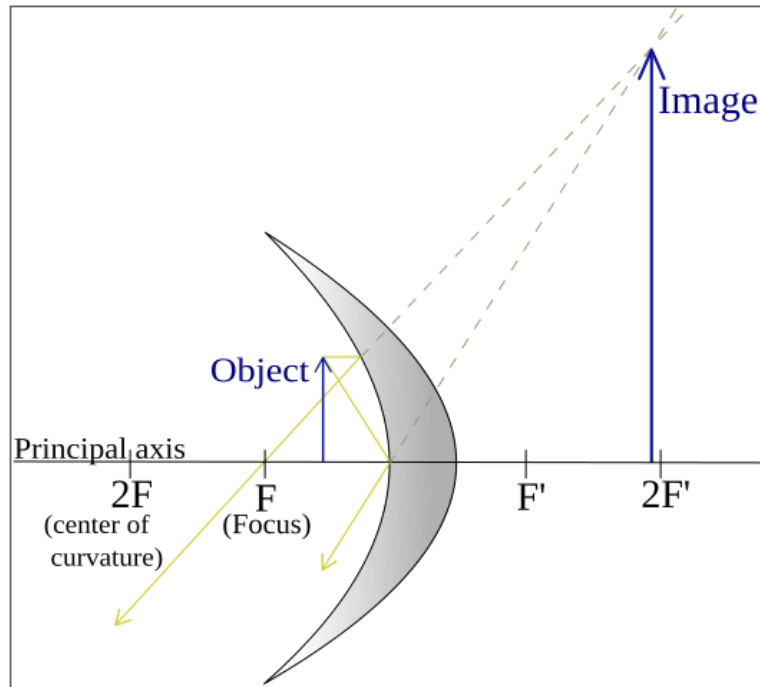
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Image formation at curved mirrors: Concave mirror $d_o < f$

- virtual, upright, larger image



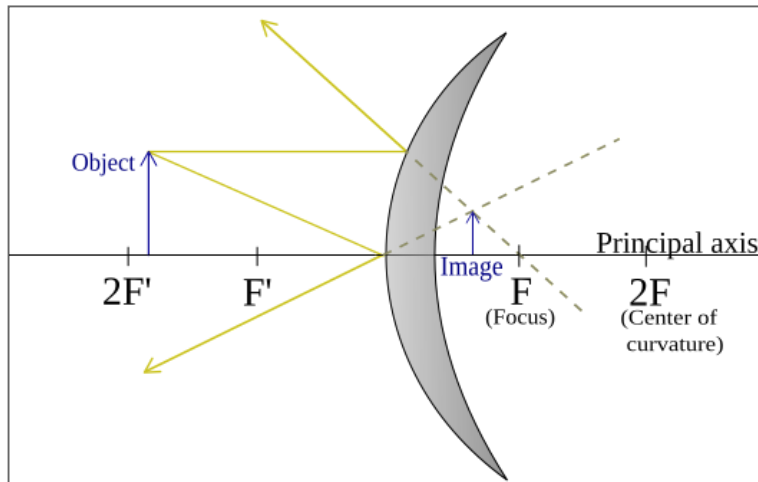
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Image formation at curved mirrors: Convex mirror

sim - convex mirror

Image formation at curved mirrors: Convex mirror (cont')

- virtual, upright, smaller image



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Image formation at curved mirrors: Summary

	Real Image	Virtual Image
Image enlarged	Concave mirror: $f < d_o < 2f$	Concave mirror: $d_o < f$
Image diminished	Concave mirror: $d_o > 2f$	Convex mirror: always

- **real image:**

- formed where reflected rays converge (on opposite side of mirror surface)
- can be projected onto a screen

- **virtual image:**

- formed where rays appear to diverge from
- located behind the mirror (same side as object); cannot be projected

Image formation at curved mirrors: Equations

- **mirror equation:**

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

- **lateral magnification** is given by:

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

- h_o positive by convention; $h_i > 0$ for upright image; $h_i < 0$ for inverted images
- **angular magnification** compares the apparent size of the image formed by curved mirrors to that seen in a plane mirror:

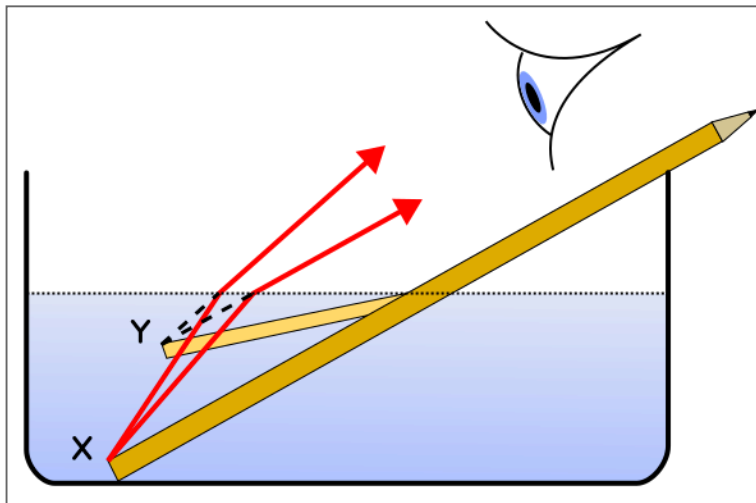
$$M = \frac{\theta_C}{\theta_P}$$

Hunting a fish

os22

Why is it so hard "hit" the fish?

→ when light passes from one medium to another with a different refraction index, both **reflection** and **refraction** occur at boundary



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Refraction index

- in vacuum, light travels at speed $c \approx 300 \times 10^6 \text{ m/s}$ and nearly the same in air
- in other transparent materials, light slows down; for example, in water
 $v \approx \frac{3}{4}c$
- the index of refraction n is defined as:

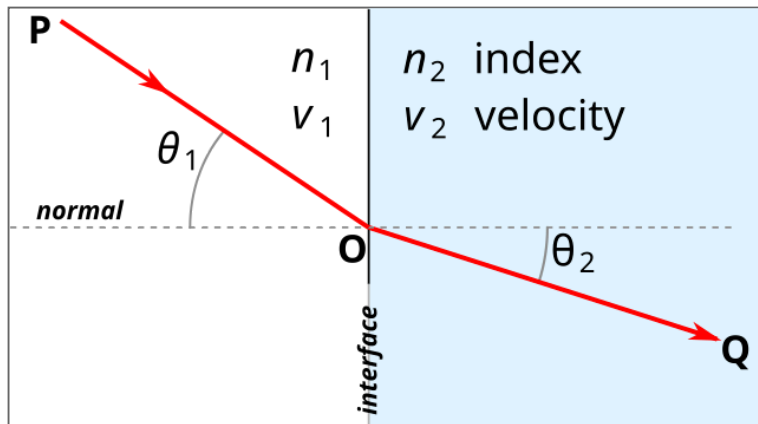
$$n = \frac{c}{v}$$

- typical values:
 - $n_{\text{air}} = 1.00$
 - $n_{\text{water}} = 1.33$
 - $n_{\text{glass}} = 1.46$

Snell's law

os01 - Haftoptik: air-glass

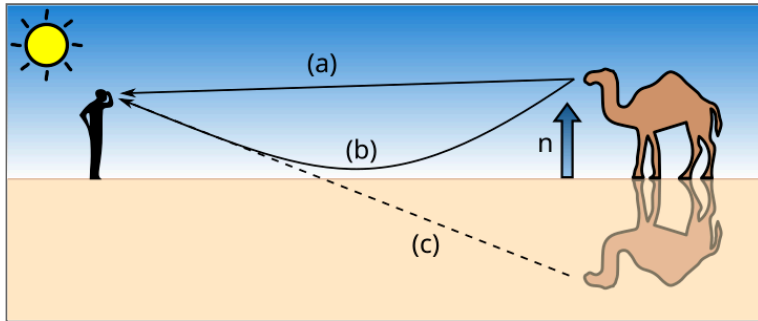
- transmitted light will be bent towards or away from the normal w.r.t. boundary surface
- Snell's law describes refraction: $n_1 \sin \theta_1 = n_2 \sin \theta_2$
 - θ_1 is the angle of incidence and θ_2 the angle of refraction
- bending toward the normal occurs if speed of light slower in the second medium, i.e. $n_2 > n_1$



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Refraction: Mirage

- temperature gradient causes a gradient in refraction index
- light is bend onto a curved path
- rays going straight and as well as tangent extensions of bend rays form mirage



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Reflection vs. refraction

os02 - water ray

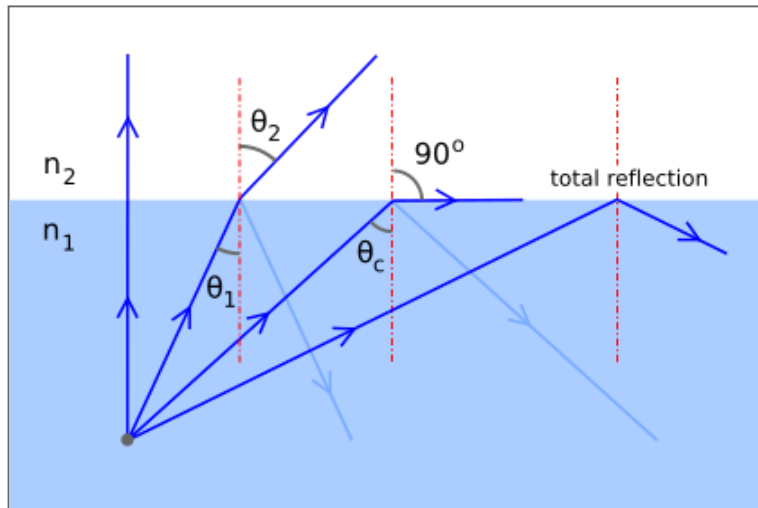
What happens here? What causes this phenomena? Reflection or refraction?

- simplify set-up → os03

Total reflection

sim - total reflection

- when the **refracted ray would bend $\geq 90^\circ$, no light is transmitted**
- critical angle θ_c can be derived from Snell's law when $\theta_2 = 90^\circ$:
 - $n_1 \sin \theta_c = n_2 \sin 90^\circ$
 - $\sin \theta_c = \frac{n_2}{n_1}$
- total internal reflection occurs when light travels **from a medium with higher to lower refractive index ($n_1 > n_2$)**



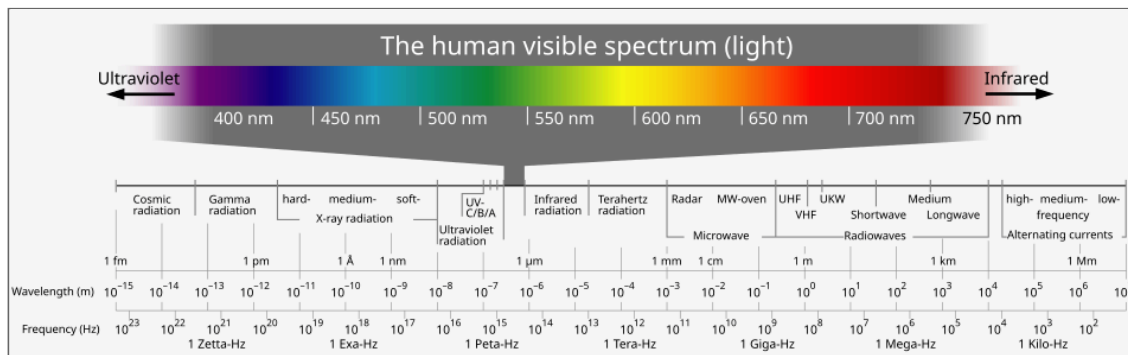


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Prism & visible spectrum

ow32

- light consists of a spectrum of wavelengths
- visible light spans wavelengths approximately from 400 nm (violet) to 700 nm (red)
- a prism can decompose white light into its constituent colors through dispersion

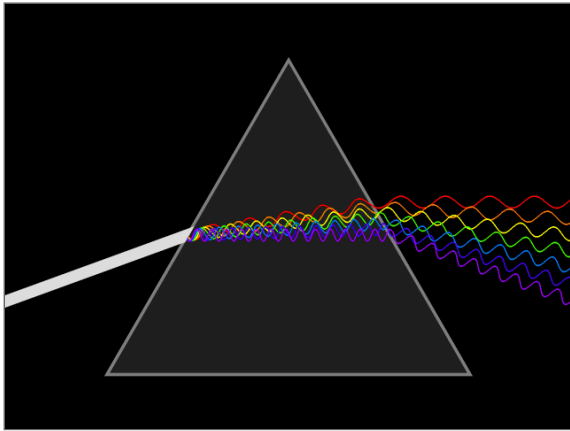


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Dispersion: Understanding the prism

- the index of refraction n depends on the wavelength λ of light
- the frequency f remains constant across media
- in a medium, the wavelength is given by:

$$\lambda_n = \frac{v}{f} = \frac{c}{nf}$$



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