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 &amp 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
- $\rightarrow$ **reflection** & **refraction**

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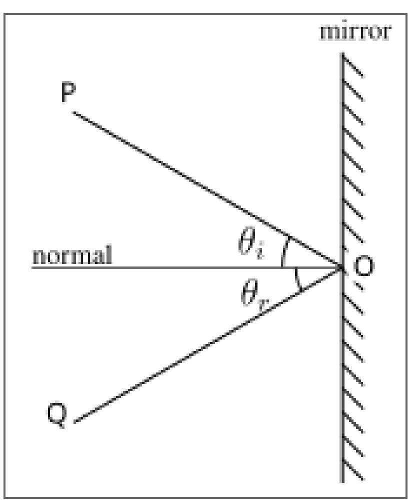
Ray model of light

- 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

Reflection &amp 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**: $\theta_i = \theta_r$



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

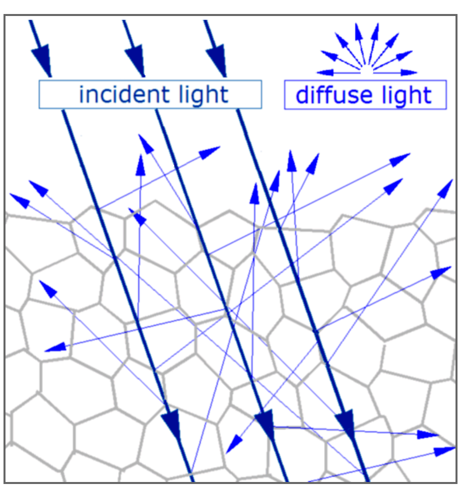


Image formation at plane mirrors: Observation

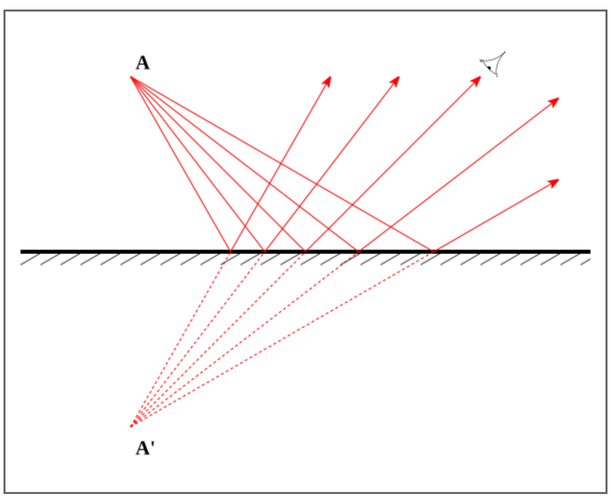
`os08 - Bildentstehung: plane mirror`

- 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 $\theta_\mathrm{i} = \theta_\mathrm{r}$
- 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

- 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: $\mathrm{r} = 2\mathrm{f}$

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: Equations

- **mirror equation**:

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

- **lateral magnification** is given by:

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

  - $\mathrm{h_o}$ positive by convention; $\mathrm{h_i} > 0$ for upright image; $\mathrm{h_i} < 0$ for inverted images

- **angular magnification** compares the apparent size of the image formed by curved mirrors to that seen in a plane mirror:

$$\mathrm{M} = \frac{\theta_\mathrm{C}}{\theta_\mathrm{P}}$$

Image formation at curved mirrors: Concave mirror

`os08 - Bildentstehung: concave mirror`

`sim - concave mirror`

Image formation at curved mirrors: Concave mirror

$d_o > 2 \cdot f$

- real, inverted, smaller image

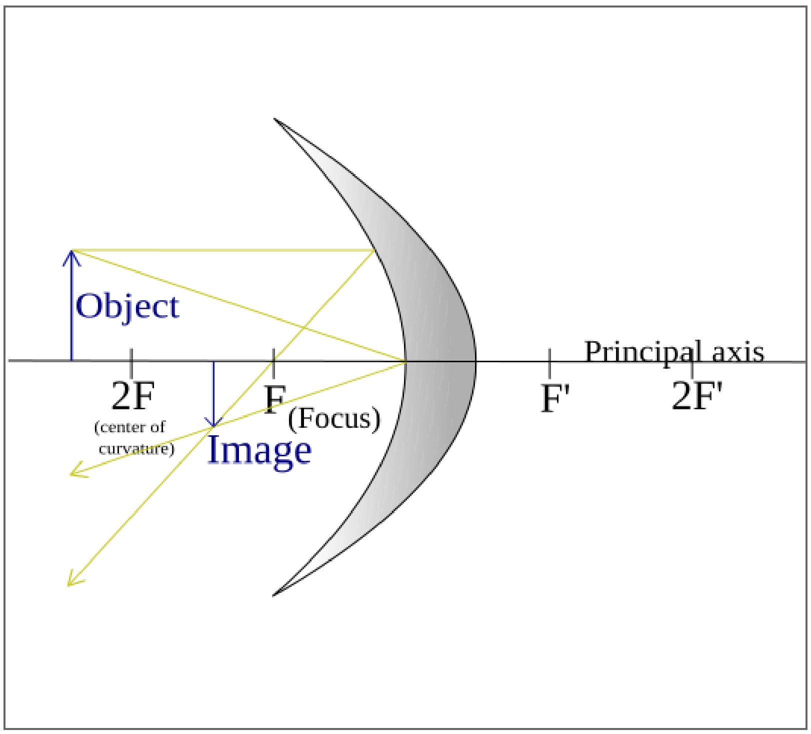

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Image formation at curved mirrors: Concave mirror

$2 \cdot f > d_o > f$

- real, inverted, larger image

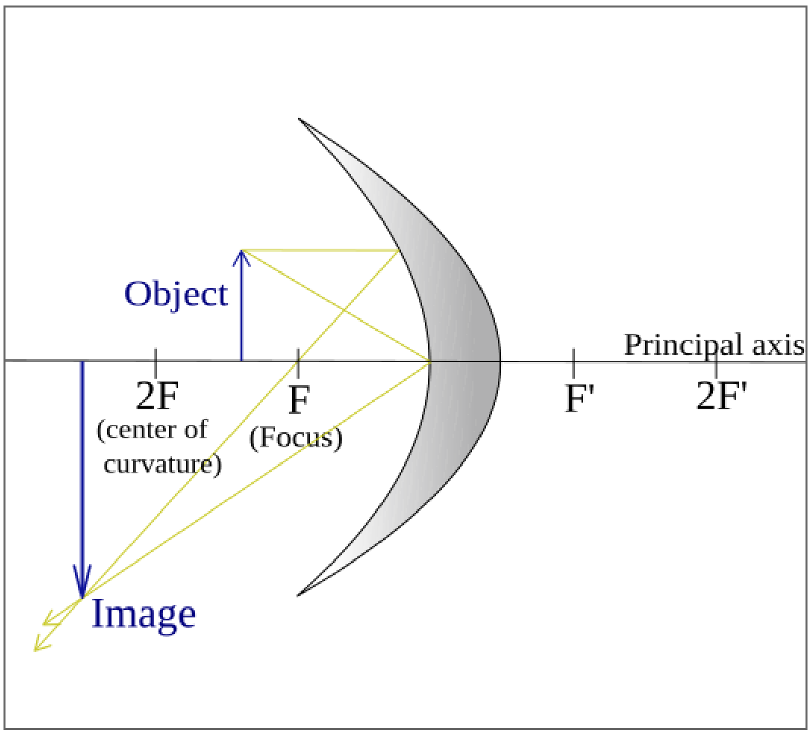

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Image formation at curved mirrors: Concave mirror

$d_o < f$

- virtual, upright, larger image

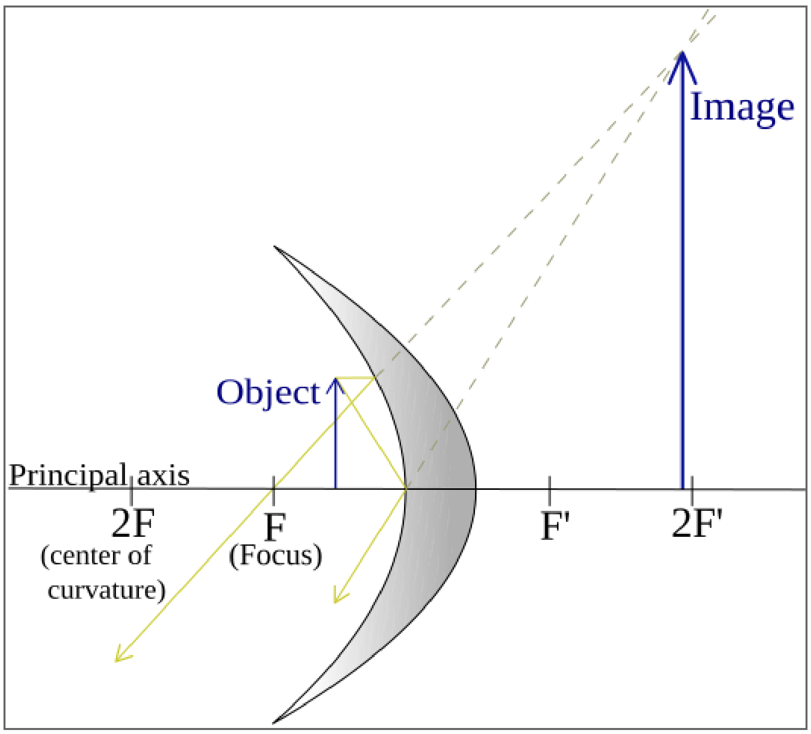

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Image formation at curved mirrors: Convex mirror

`os08 - Bildentstehung: convex mirror`

`sim - convex mirror`

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

- virtual, upright, smaller image

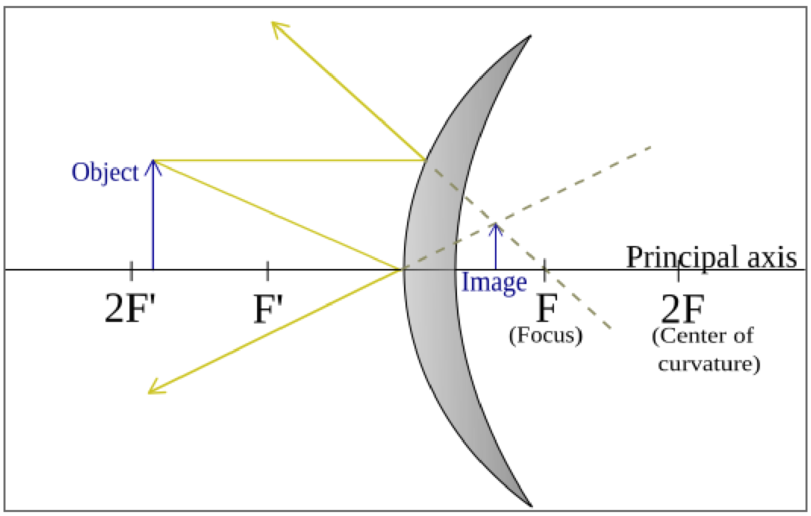

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Image formation at curved mirrors: Summary

- **concave mirrors:**
  - $d_o > f$: real image, m depends on d_o and f
  - $d_o < f$: virtual image, $m > 1$ because $d_i \geq d_o$
- **convex mirrors:**
  - always produce a virtual, upright, and reduced image, regardless of object distance
  - image is formed by extension of diverging reflected rays
- **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

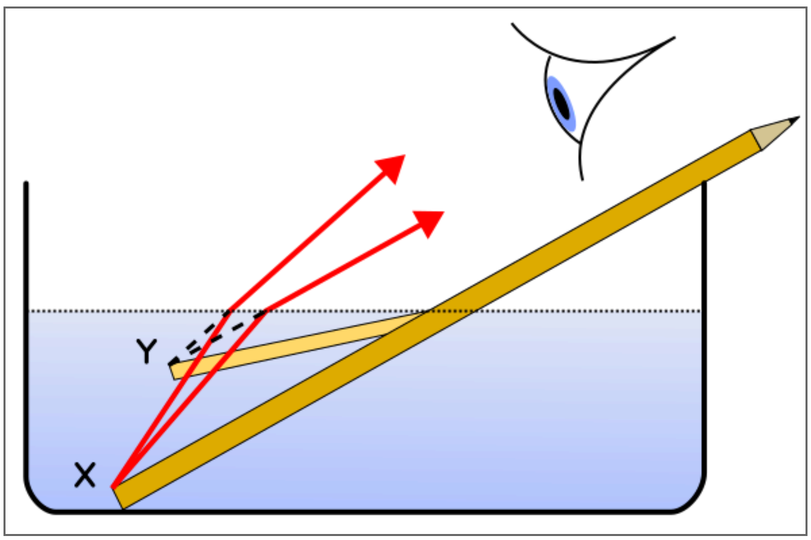
- located behind the mirror (same side as object); cannot be projected

Hunting a fish

`os22`

Why is it so hard "hit" the fish?

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

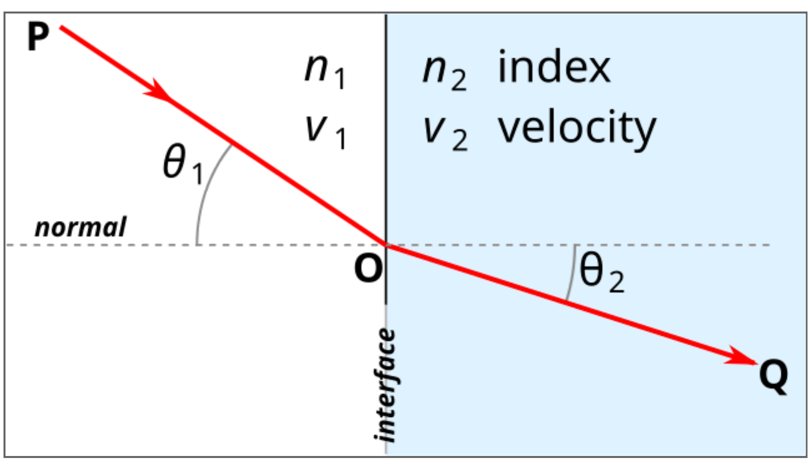
$$\mathrm{n} = \frac{\mathrm{c}}{\mathrm{v}}$$

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

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:
  $\mathrm{n}_1 \sin\theta_1 = \mathrm{n}_2 \sin\theta_2$
    - θ_1 is the angle of incidence and θ_2 the angle of refraction
- bending toward the normal occurs if if speed of light slower in the second medium, i.e. $\mathrm{n}_2 > \mathrm{n}_1$



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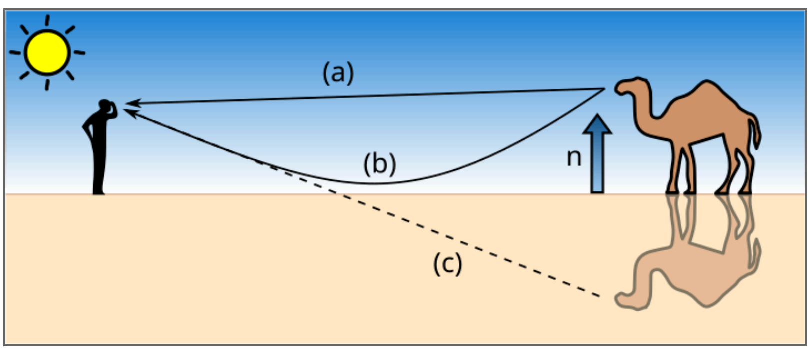
Refraction: Mirage

- 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



Reflection vs. refraction

`os02 - water ray`

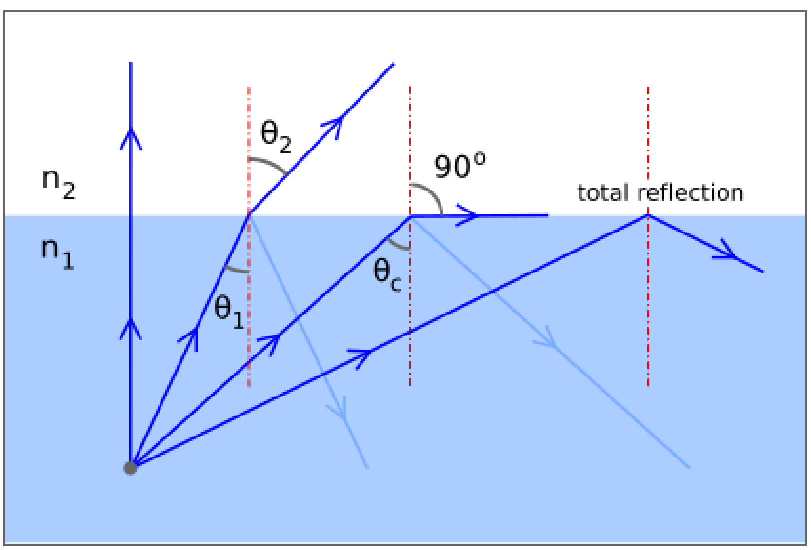
What happens here? What causes this phenomena? Reflection or refraction?

- simplify set-up → `os03`

Total reflection

`sim - total reflection`

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



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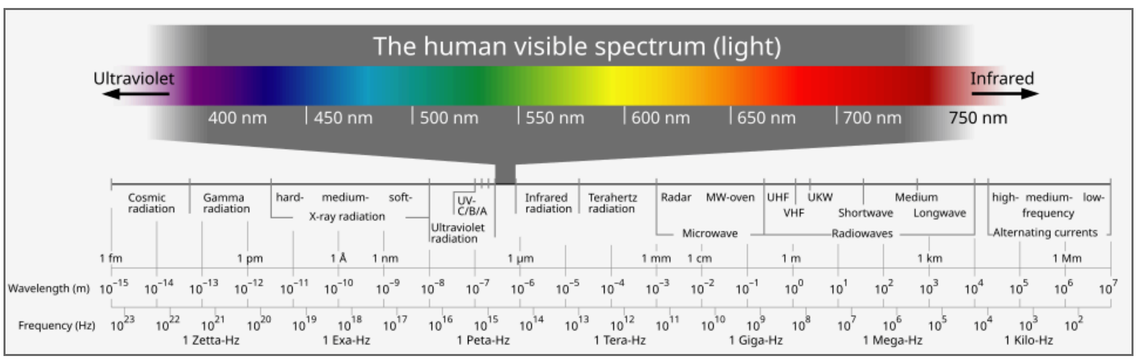
Prism &amp visible spectrum

`ow32`

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



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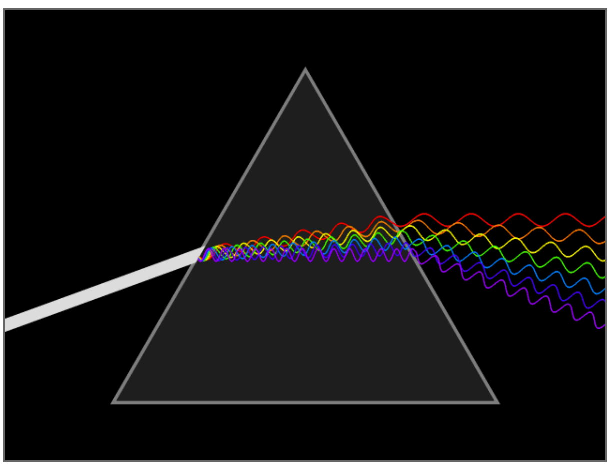
Dispersion: Understanding the prsim

- 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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