Geometric Optics (lenses)

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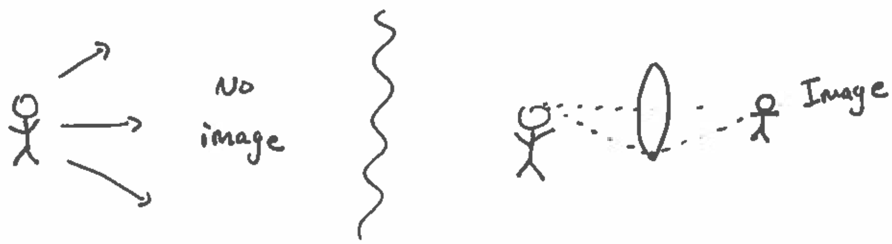
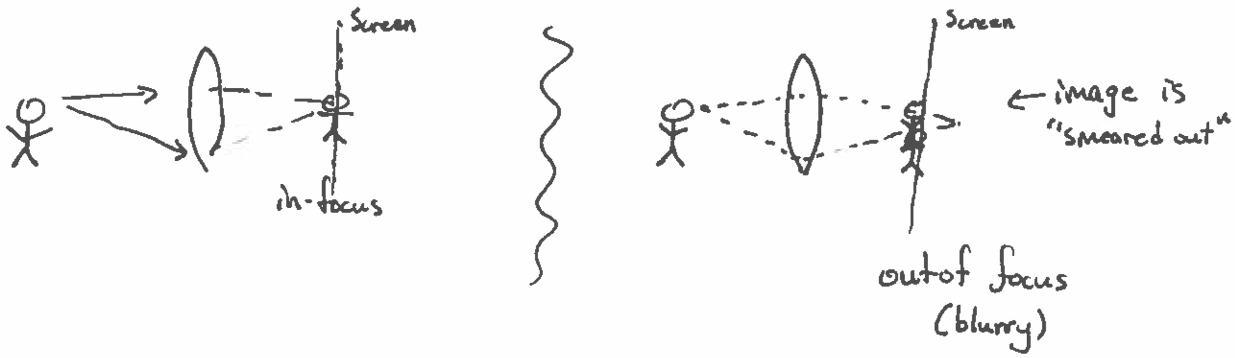
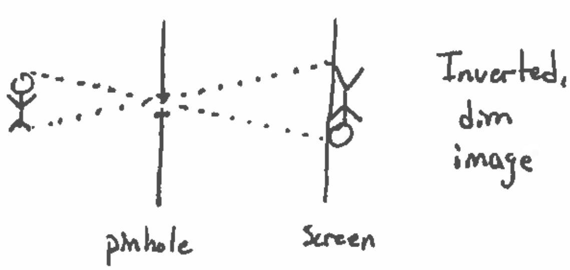
- What is an image?
  - an object formed at a location where light <u>rays</u> from a real thing are concentrated.



- In focus: an image is formed when all of the light from a single point ends up at another single point (otherwise, it is blurry). The location of the image is where it is focused.

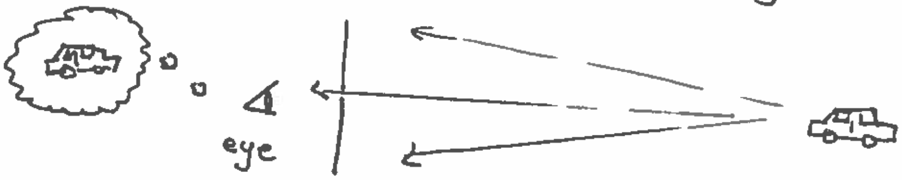


- Simple Image → Pinhole camera / projector



- A pinhole is so small that each incoming ray can only come from one point ⇒ image is always focused.
- A large amount of light is lost.

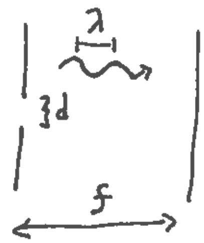
- Fun with pinholes: can focus light from a distant, bright object.



(even if vision is bad, and without glasses! (Dim, though)

- Can project image onto a screen → great for Solar viewing.

Optimal pinhole size: $d = 2\sqrt{f\lambda}$



- White light ($\lambda \approx 550\,nm$), 1 inch away (25 mm)

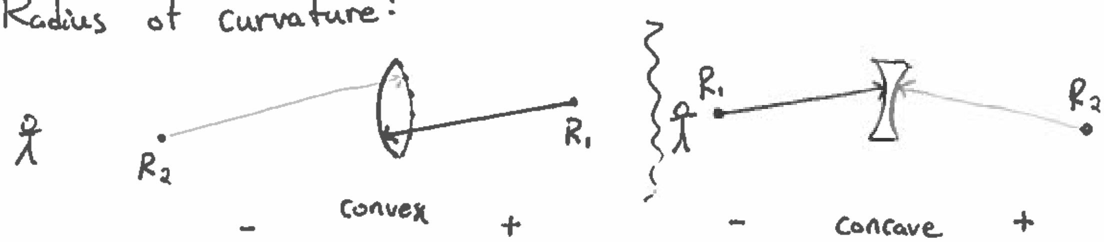
  $d \sim 0.234\ mm$ ← for by-eye veiwing

- Spherical Lenses

"convex" "converging"

"concave" "diverging"

Radius of curvature:



- Surface of lens is part of a sphere with radius "R"
- R_1 is surface that is closer to object being viewed
- Convex: $R_1 > 0$, $R_2 < 0$ (see diagrams)
- Concave: $R_1 < 0$, $R_2 > 0$

- Each side can have it's own radius of curvature:

etc.

Flat (planar) surface: $R \to \infty$

- Lens Maker's Equation:

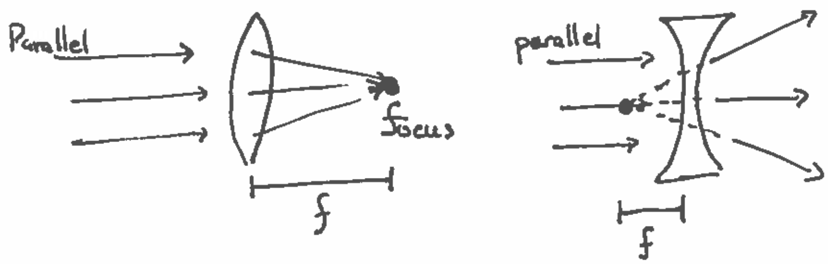
$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$$

Big Deal!

f = focal length

n = index of refraction of material

Focal length: distance at which parallel incoming light rays will intersect, after passing through lens.



$f < 0$ (negative) for concave / diverging lenses.

- Images from Lenses [s = object position, s' = image position]

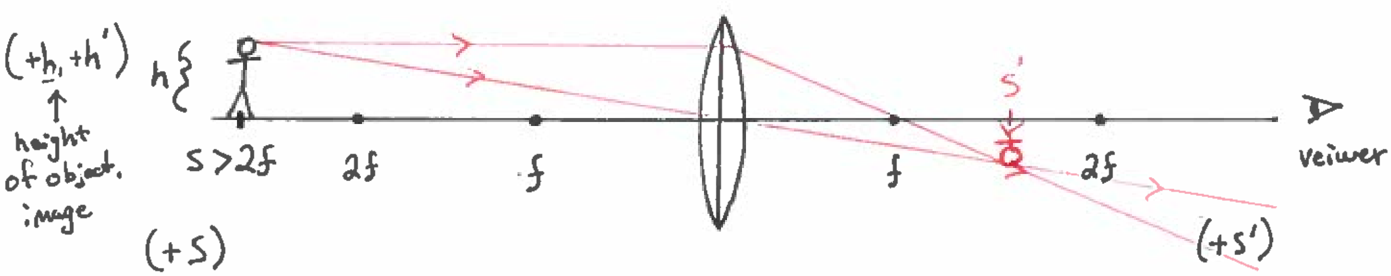


Image is: Real (on same side as viewer) ($s' > 0$)

Inverted ($h' < 0$, flipped)

Reduced ($|h'| < |h|$, smaller)

For $s > 2f$, convex lens

• for $2f > s > f$, convex lens:

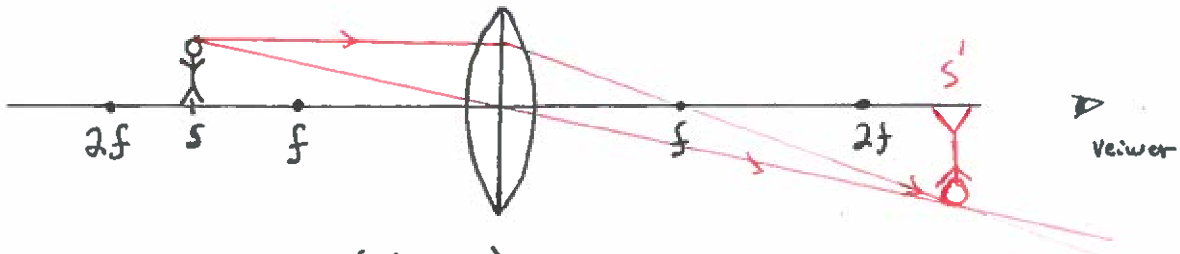


Image is: Real $(s' > 0)$
Enlarged $(|h'| > |h|)$
Inverted $(h' < 0)$

• for $s < f$, convex lens:

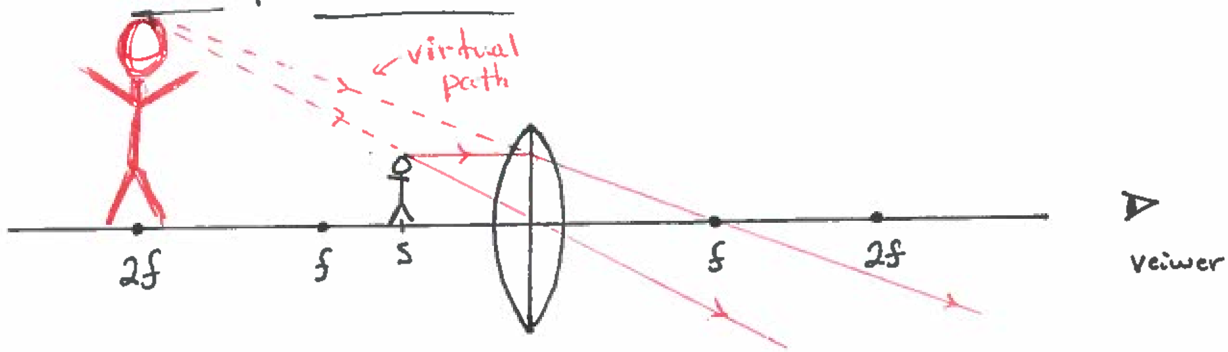


Image is: Virtual $(s' < 0)$
Enlarged $(|h'| > |h|)$
Upright $(h' > 0)$

• for any concave lens and object location:

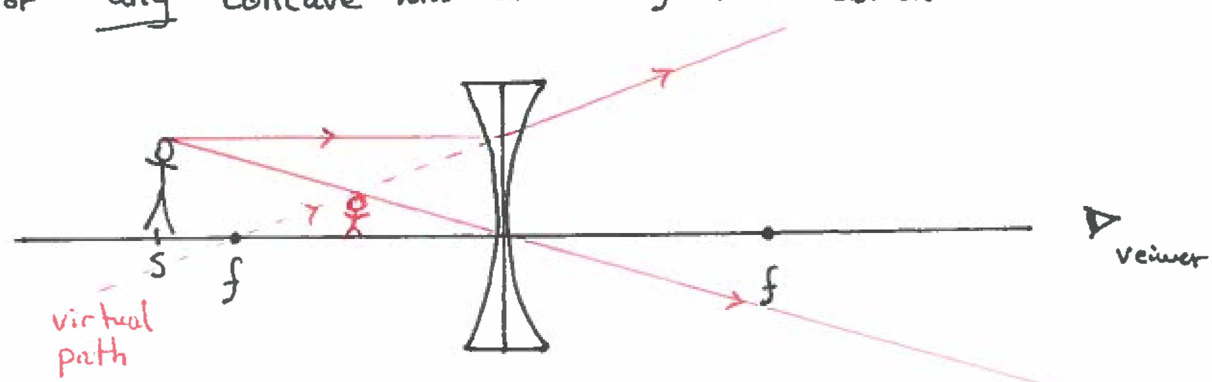


Image is: Virtual $(s' < 0)$
Reduced $(|h'| < |h|)$
Upright $(h' > 0)$

- Lens summary:

type	object position	image position	real/virtual	orientation	size
Convex	$s > 2f$	$f < s' < 2f$	real	inverted ($h' < 0$)	Reduced
Convex	$f < s < 2f$	$s' > 2f$	real	inverted ($h' < 0$)	Enlarged
Convex	$s < f$	$s' < 0$	virtual	upright ($h' > 0$)	Enlarged
Concave	any	$s' < 0$	virtual	upright ($h' > 0$)	Reduced

- Lens Equation:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

Big Deal

$s > 0$ on far side (from viewer)

$s' > 0$ on near side

$f > 0$ for convex lens

$f < 0$ for concave lens

- "Power" of lens (not related to energy)

Big Deal!

$$P = \frac{1}{f}$$

units of P: $\frac{1}{m} \Rightarrow$ "Diopter"

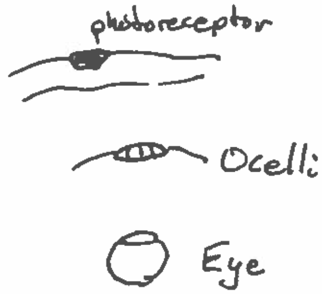
$$P = 0.1 \text{ diopter} \Rightarrow f = 10 \text{ m}$$

- Magnification:

$$M = \frac{h'}{h} = -\frac{s'}{s}$$

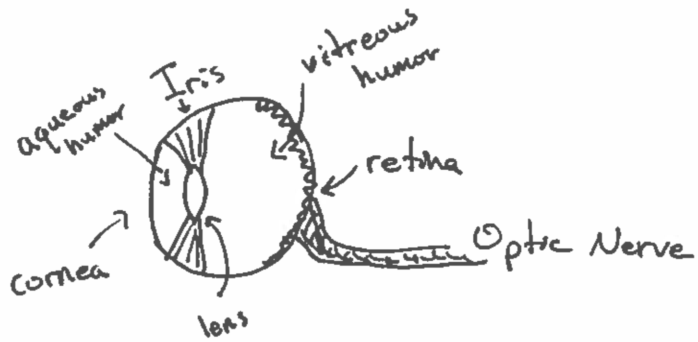
The Eye

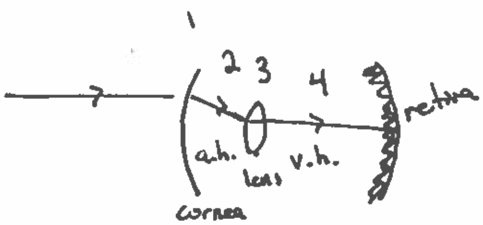
Eye versus Photoreceptor:



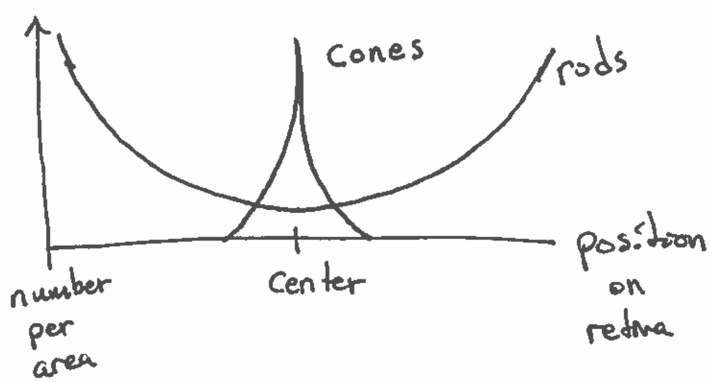
- Eye has a lens
- Ocelli "Eye spots", no lens or simple lens
- Photoreceptors only sense light levels

Human Eye



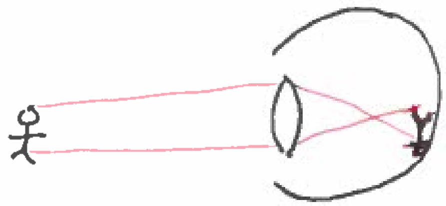


- Multiple index of refraction changes!



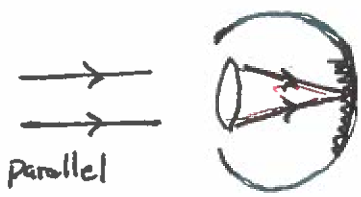
Rods:
- Red, Green, & Blue color vision (in average human)
- Centered on middle of eye → plenty of light

Cones:
- Black/White (no color) vision
- sees light intensity
- Responsible for night vision, peripheral vision.



- Inverted, real, reduced ("situation 1")
- Brain flips image!

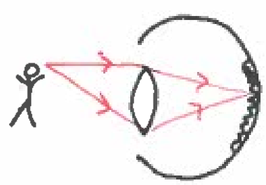
Far away → light rays parallel, $d \to \infty$



"Far point": maximum distance that can be focused by eye

- Far point for most humans is ∞

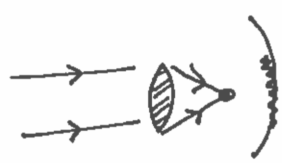
Nearby:



"Near point": nearest distance the eye can focus on.

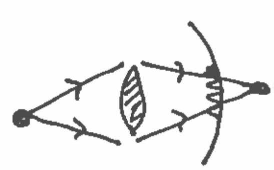
- Near point for most humans is 25cm

- Nearsighted (myopic)



- Image in front of retina
- Blurry view of distant objects

- Farsighted (hyperopic)



- Image behind retina
- Blurry view of near objects.
- Affects almost everyone as they age.

Vision Correction

- Use a lens between object and eye
- Make an image at person's near or far point

Ex

Nearsighted with farpoint at 200 m

- Need an object at ∞ to appear (image) at 200 m.

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}, \quad s = \infty, \; s' = -200\,m$$

{negative b/c on same side as object}

$$\Rightarrow \frac{1}{\infty} + \frac{1}{-200m} = \frac{1}{f} \Rightarrow f = -200\,m$$

or $P = \frac{-1}{200m} = -0.005\,\frac{1}{m}$ = **-0.005** diopter lens

Ex

Farsighted with near point at 50 cm

- Need object at 25 cm to have image at 50 cm

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \qquad s = 0.25m, \; s' = -0.5m$$

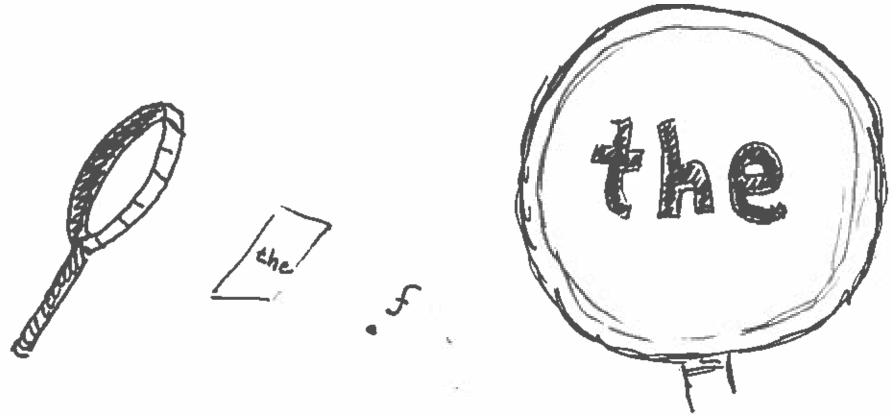
$$\frac{1}{0.25} + \frac{1}{-0.5} = \frac{1}{f} \Rightarrow f = 0.5\,m$$

or $P = \frac{1}{f} = 2.0$ diopters

• Lens Applications

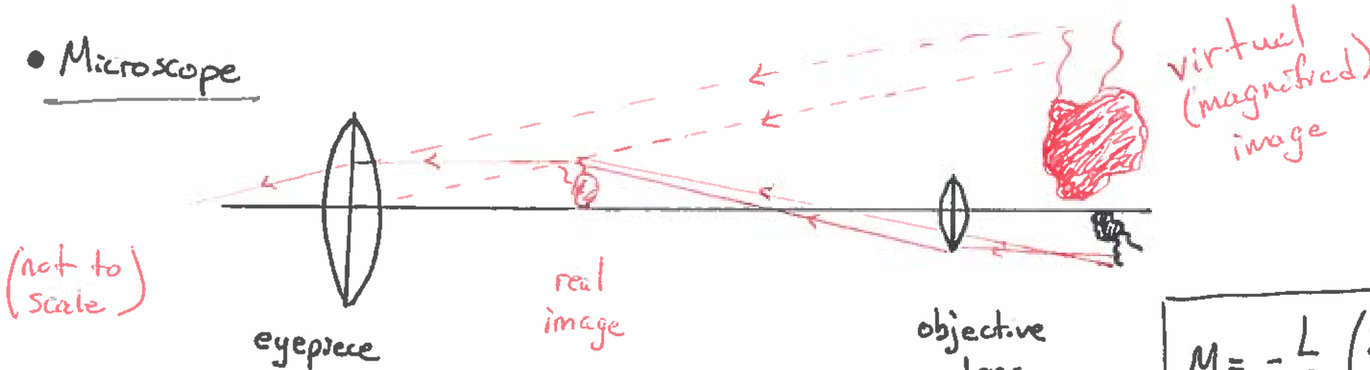
• Magnifying Glass

"Search" and "zoom" icons



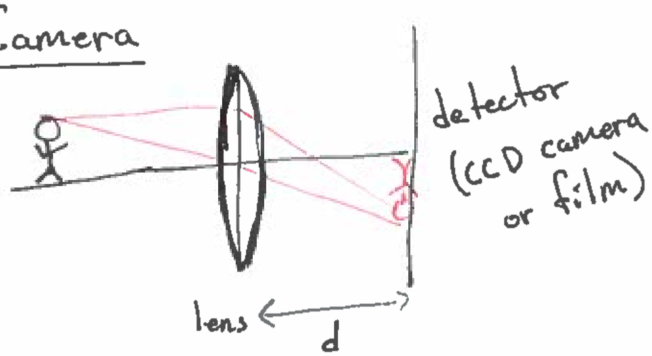
"Situation 3": convex, $s < f \Rightarrow$ virtual, upright, enlarged

• Microscope



$$M = -\frac{L}{f_o}\left(\frac{25\text{cm}}{f_e}\right)$$

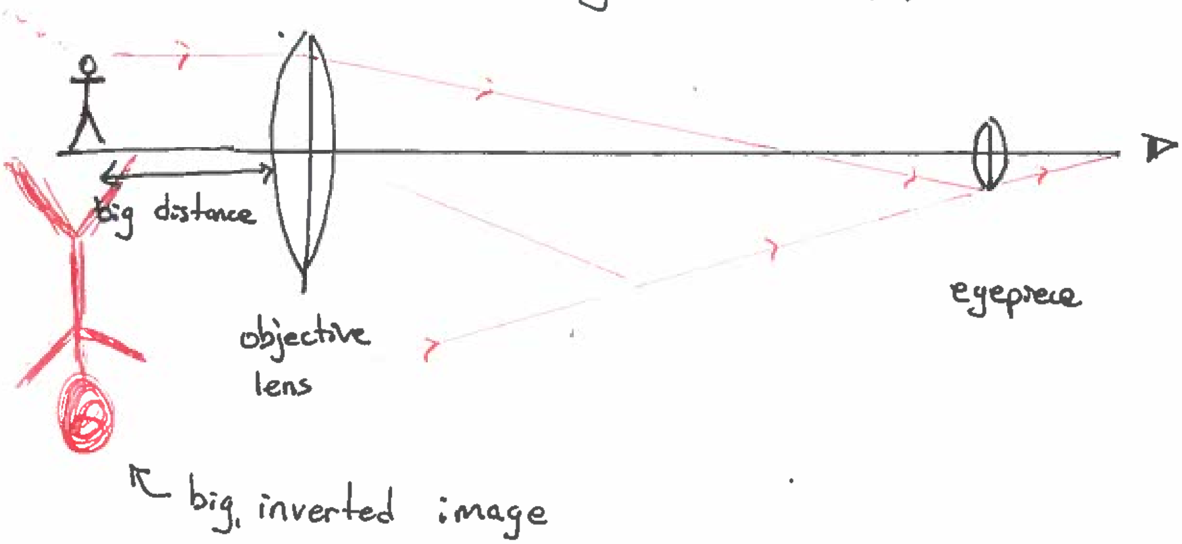
• Camera



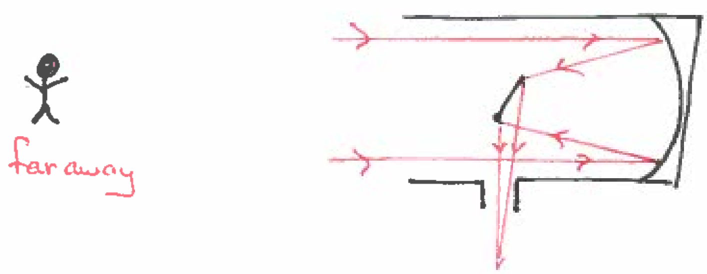
- Adjustable distance (d) allows to focus on different distances
- "Situation 1", convex, $s > 2f$ $\Rightarrow$ real, inverted, reduced
- An image/video projector works this way, too; real image is placed on screen.

- Telescopes

Refracting: uses lenses

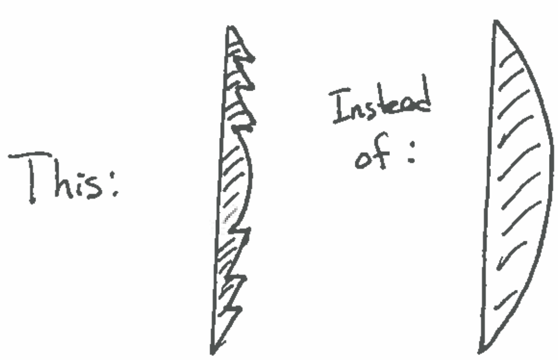


Reflecting: uses mirrors



- Also produces a large, inverted image
- Note: the main purpose of a telescope is to gather enough light to see faint objects! Magnification is usually secondary.

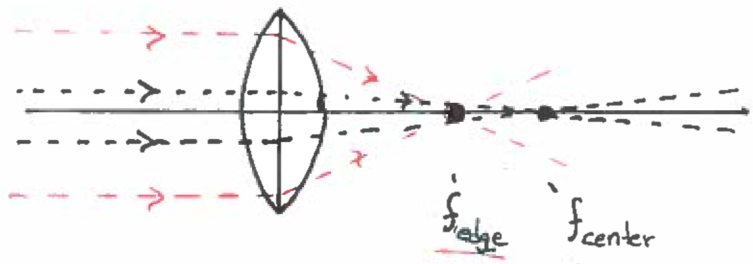
- Fresnel ("fra-nel") Lens:



- Same effect, lighter weight
- Great for concentrating light
- Used in lighthouses, projectors, + more.

Optical Aberrations

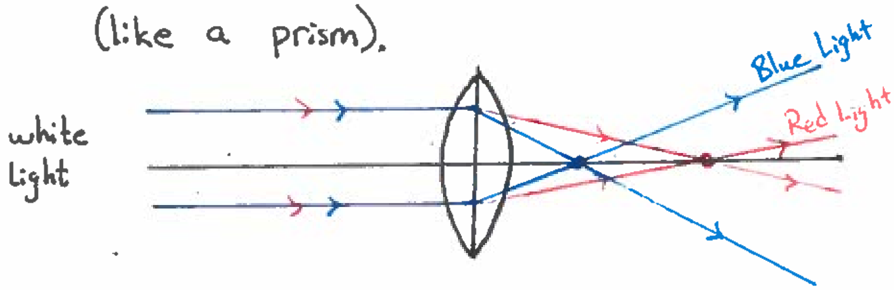
Spherical Aberration: focal length is different from center of lens (or mirror) to edge.



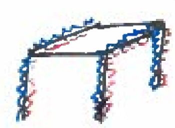
View

bright, in focus center with fuzzy rings around it

Chromatic Aberration: The index of refraction of a material is different for each λ, so colors have different focal lengths (like a prism).



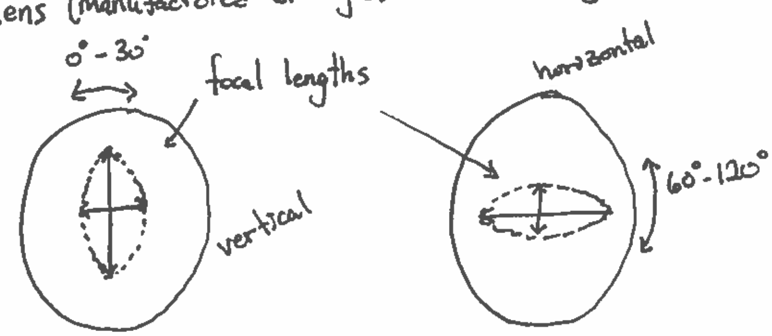
View



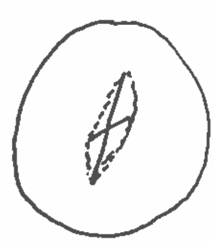
edges in image have rainbow fringes.

Astigmatism: Vertical + horizontal focal lengths are not the same.

- Lens (manufactured or eye) is not symmetric - radius of curvature changes.



Normal astigmatism: vision axes are perpendicular to each other



Irregular: vision axes are not perpendicular.

View

when one plane is in focus, the other is out of focus; always blurry.