LECTURE 5: LIGHT AND OPTICS

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Recall: Chaining Transformation

- We now discuss the set of transformation to display geometric models on to a display (for each eye)
- Some of the matrices may appear unnecessarily complicated
  - Design motivated by algorithm and hardware issues
  - Simplify/complicate things to make algebraic calculations efficient later
- The chain generally appears as follows

$$T = T_{vp} T_{can} T_{eye} T_{rb}$$

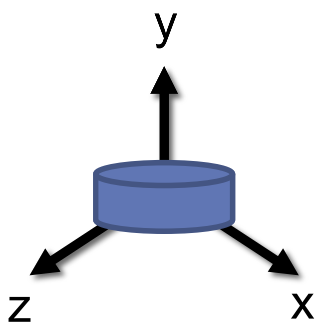
Applied to every point (x,y,z,1) in the world!

- Remember that we added an auxiliary fourth dimension and divide by that to get the three dimensions!

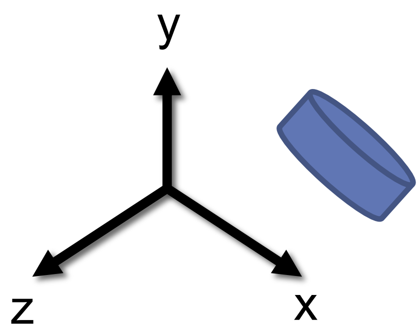
$$T = T_{vp} T_{can} T_{left} T_{eye} T_{rb}$$

Recall: Chaining Transformations

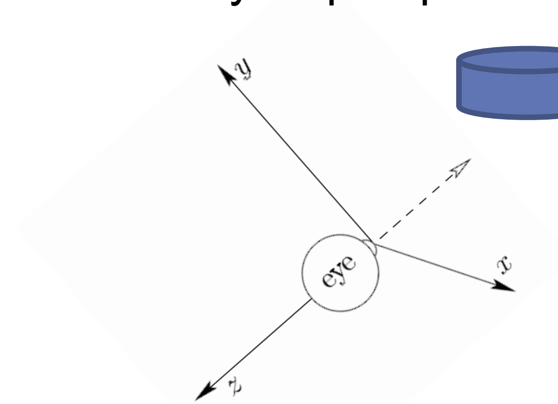
Objects in their local coordinates



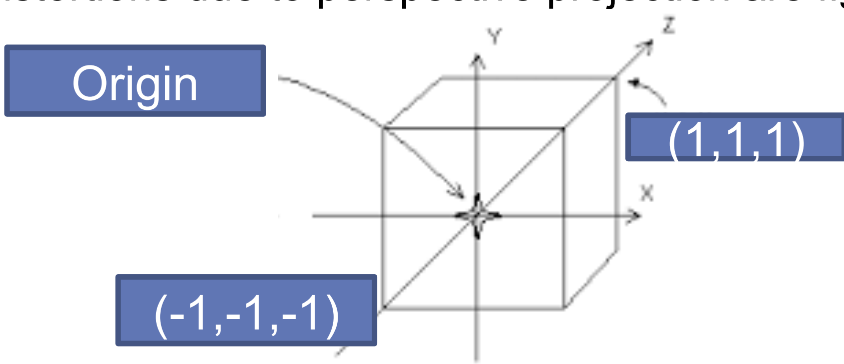
Place Objects in the virtual world



Bring the world into eye's perspective

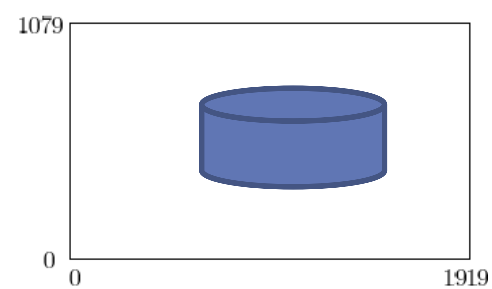


Form a viewing frustum (what goes on screen), scale it to a perfect cube, and center it at the origin. At this point, all distortions due to perspective projection are figured out



Canonical View Transform

Bring the x, y projected points to coordinates used to index pixels on a physical display



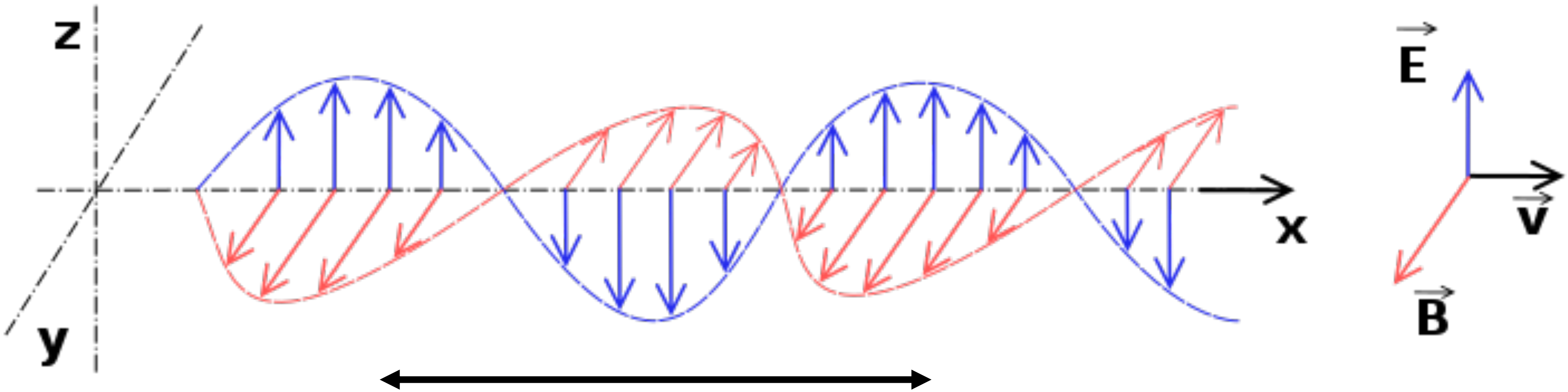
Viewport Transform Pixel Coordinates

Outline

- Model physics of light propagation from display to eyes (VR systems use lenses between displays and eyes, why?)
  - Physical properties of light
  - Modeling lenses
  - Lens imperfections
  - Human eye as an optical system of lenses
  - Cameras
  - Visual display technologies

What is light?

- Light is a form of electromagnetic wave which can be detected by human eye
- Electromagnetic waves (EW) are created as a result of vibration of an electric filed and a magnetic filed
  - Travel at speed of light in vacuum ($3x10^8$ meters per second)
  - Does not need matter to travel
  - Example EWs: communication signals (LTE, WiFi), light, x-ray, gamma-ray



λ = c . T = c / f

What is the relationship between f and T?

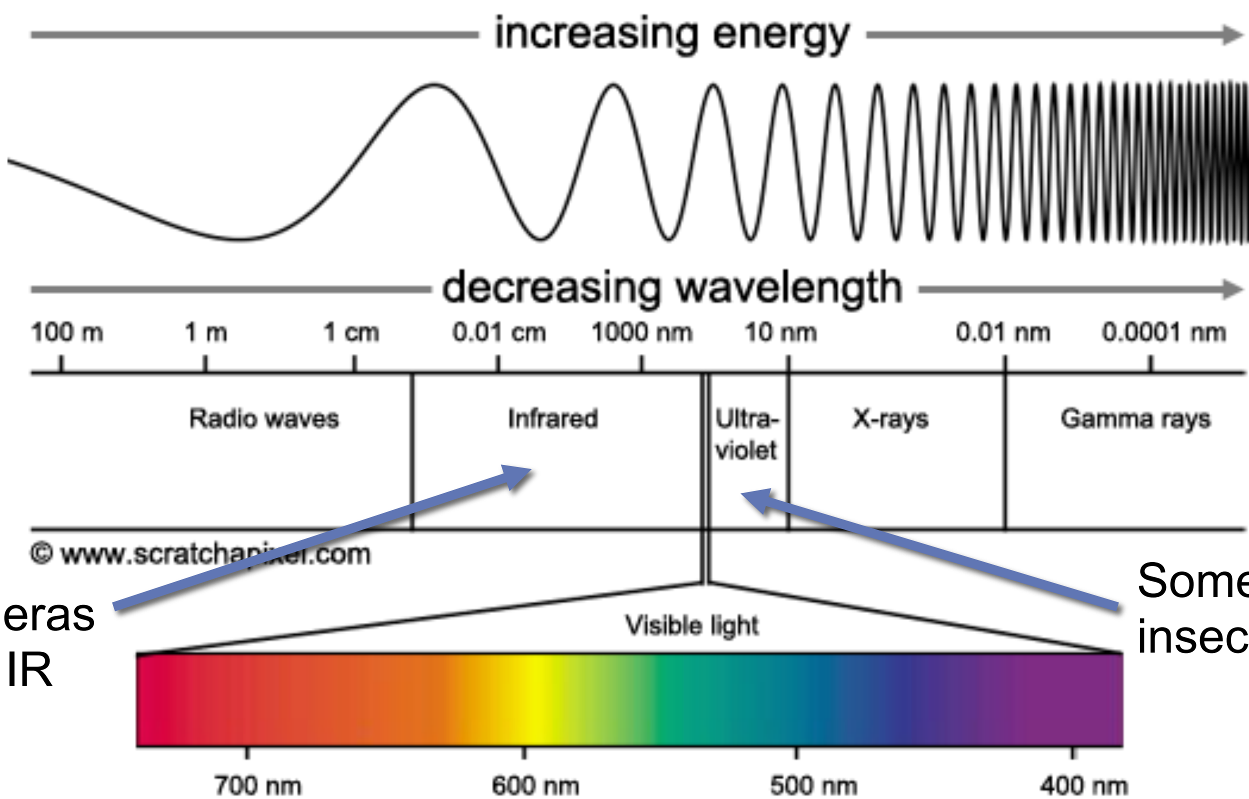
Freq: # of times in 1 sec that a wave passes a fixed location

λ: wavelength (meters)
c : speed of light
f: frequency (Hertz)
T: period/time (second)

Spectrum

- The set of frequencies occupied by the EW

Just energy of a single photon



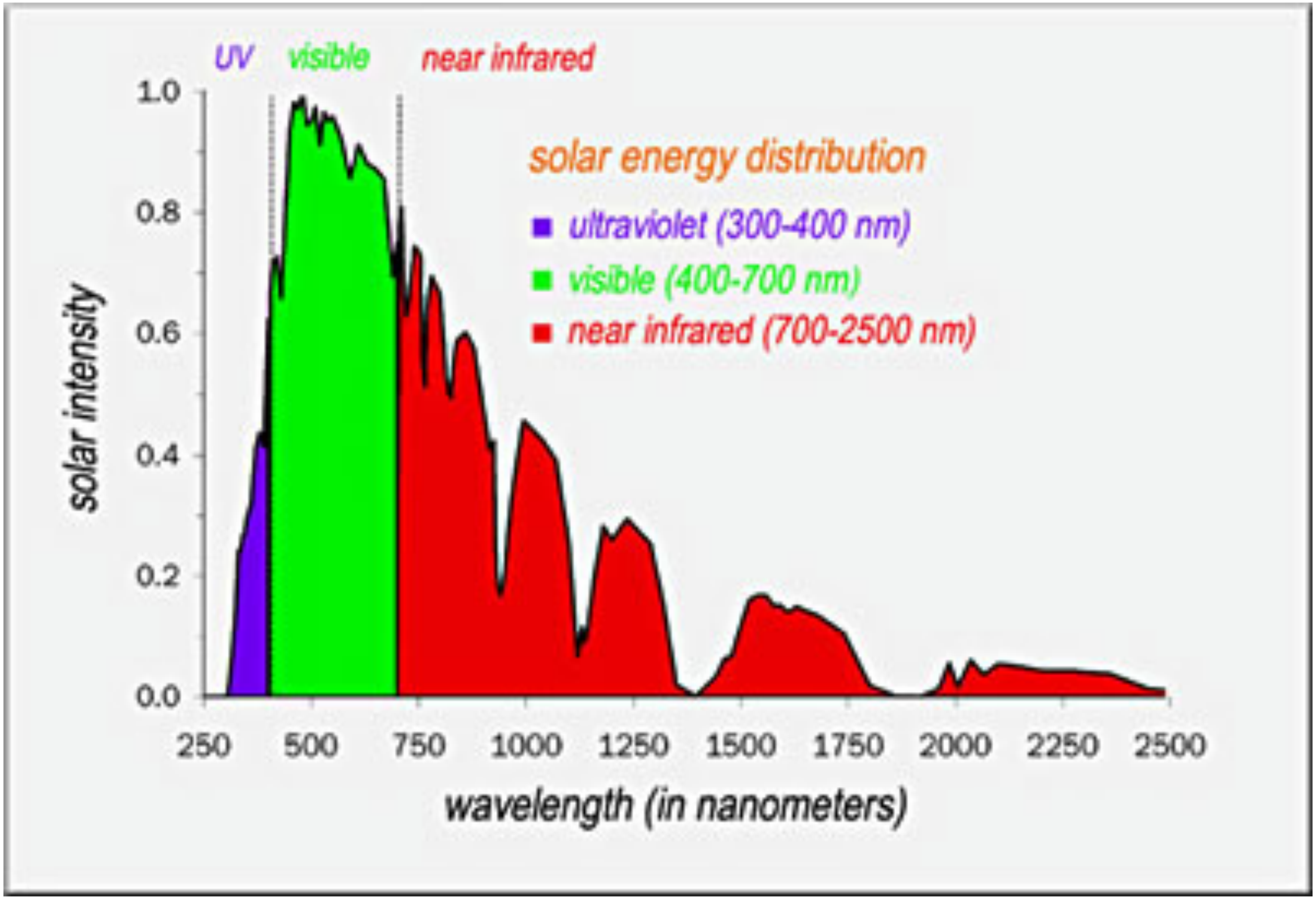
Some cameras can sense IR

Some birds and insects can sense UV

Different interpretations of EWs (e.g., light) help explain their different properties

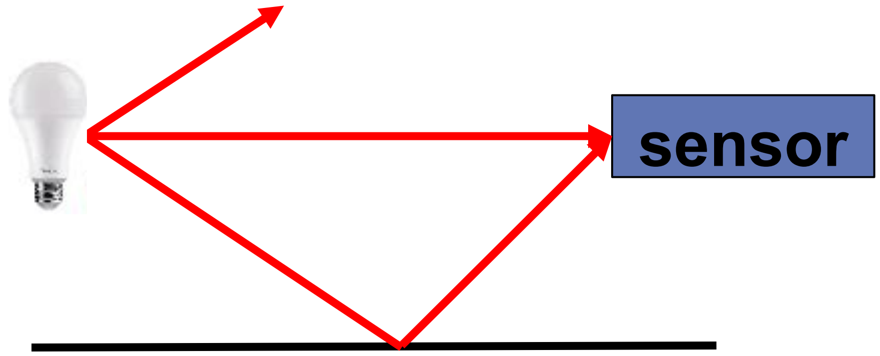
Visible light is tied to humans!

Wavelengths in Sun Light



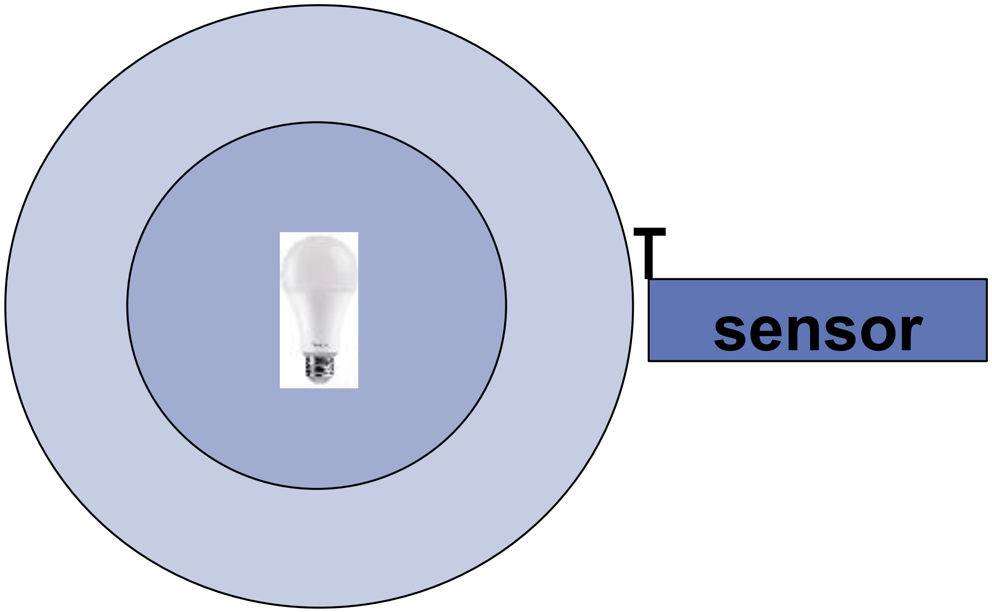
EW View 1: Rays of Energy

- Can view it as a combination of “rays” that propagate between two points
- Rays can be reflected
- The **channel** between two end points includes multiple “rays” that take different paths (multiple-path)
  - Each path has a different delay and attenuation
  - Explains lens properties



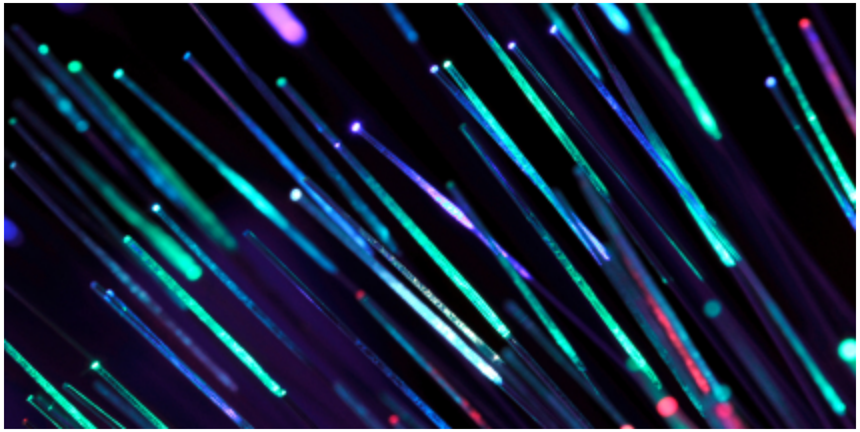
EW View 2: A Wave of Energy

- Think of it as energy that radiates from a source and is picked up by our eyes
- Density of energy reduces over time and with distance
  - Explains attenuation
  - **Receiving sensor (photoreceptors in eyes) catches less energy with distance**



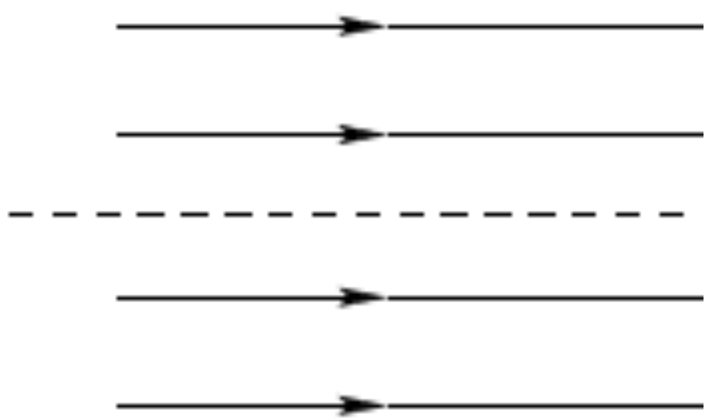
EW View 3: Photons

- Tiny particles of energy moving through space at high speeds
  - Helps explain properties such as the amount of light received by a sensor or receptor



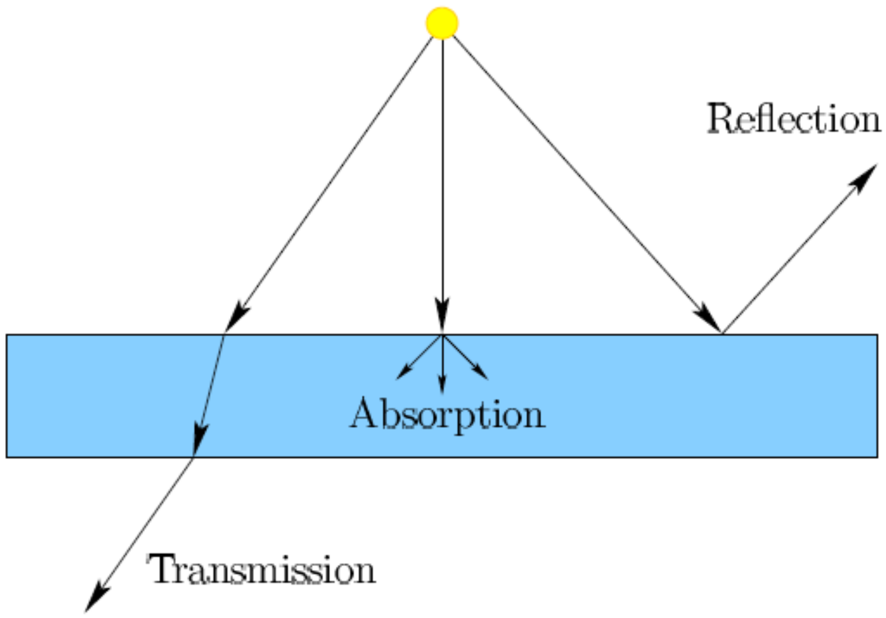
Parallel Waves

- When light (or any EW) radiates from far away
  - **Far with respect to the wavelength**
  - Then EWs become parallel



Interactions with Materials

- When an EW (e.g., light) hits the boundary of a different medium, three things can happen:
  - Absorption: energy is absorbed
  - Reflection: rays are reflected from the surface
  - Transmission: rays pass through the material



The percentage of light absorbed, reflected, and transmitted is a function of the underlying material, e.g., mirror is a perfect reflector

Coherent vs Jumbled Light

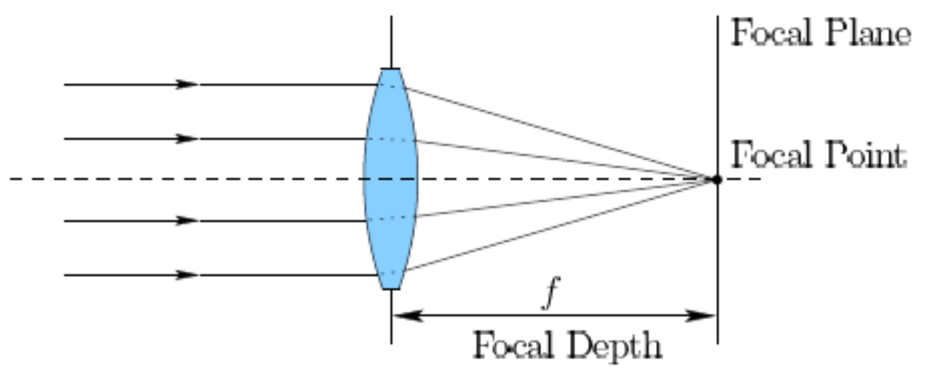
- Light sources (e.g., sun, light bulb) emit a jumble of wavelengths
  - Laser is a coherent source of light: it emits parallel waves of a constant wavelength that are also synchronized in time so that their peaks align as they propagate

Color Perception

- An idealized light source would have all visible wavelengths with equal energy leading to idealized white light
- In order for us to see something, we need light
  - An object that does not reflect any light is perceived as black
    - Black colors are warmer because they absorb all light and turn the energy into heat
  - An object that is red is because it reflects mostly red wavelength of light and absorbs most of the other wavelengths
- We observe light (wavelengths) that are reflected from objects and perceive them in different colors!

Lenses

- Lenses have been made for 1000s of years
  - Bend rays of light so that a focused image is formed
  - Gave rise to eyeglasses, telescopes, magnifying glass, cameras
  - **Design of lenses for VR has particular challenges**

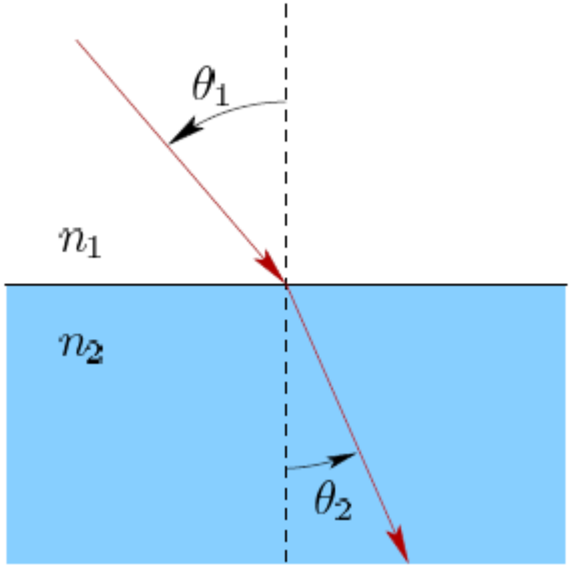


A simple **convex** lens

Snell's Law

- Speed of light in a medium is less than its speed in vacuum
  - Let c be the speed of light in vacuum
  - Let s be the speed of light in a medium
  - Then, the medium refractive index is: $n = \frac{c}{s}$,
- Let a ray of light pass to a new medium. Snell law relates the four quantities as:

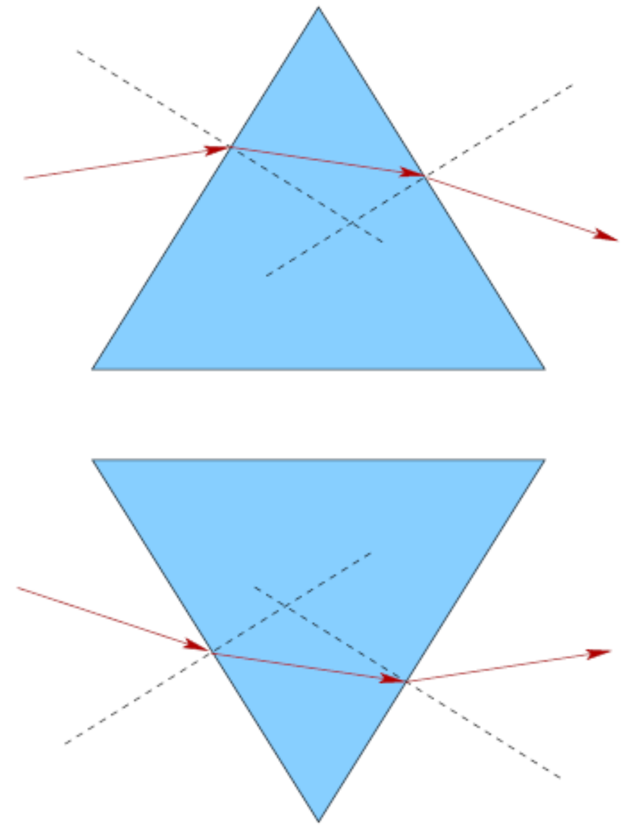
$$n_1 \sin \theta_1 = n_2 \sin \theta_2.$$



If $n_1 < n_2$, then $\Theta_1 > \Theta_2$

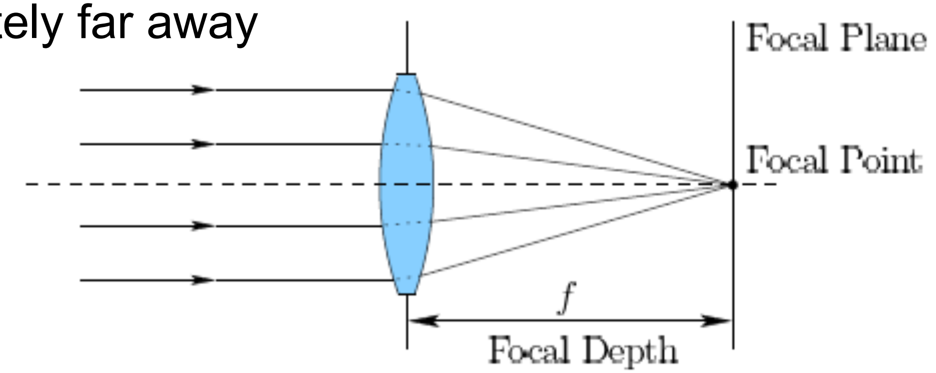
Prisms and Lenses

- Prisms naturally follow Snell's law
- Can be used to bend light
- Imagine shining a laser through a prism
- A lens is similar to a curved prism



Source that is infinitely far away

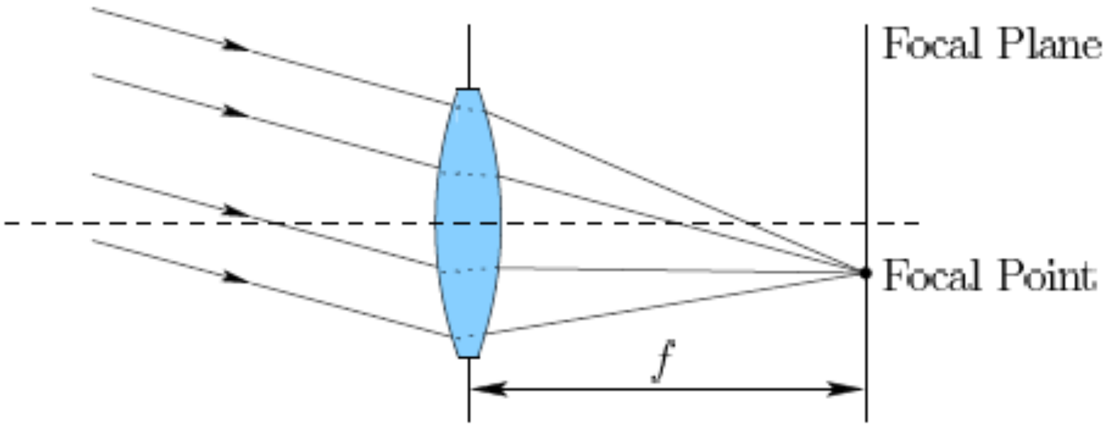
Convex lens



Also called the focal length

Focal Plane

- When incoming rays are not perpendicular to the lens, then the focal point is shifted away from the optical axis



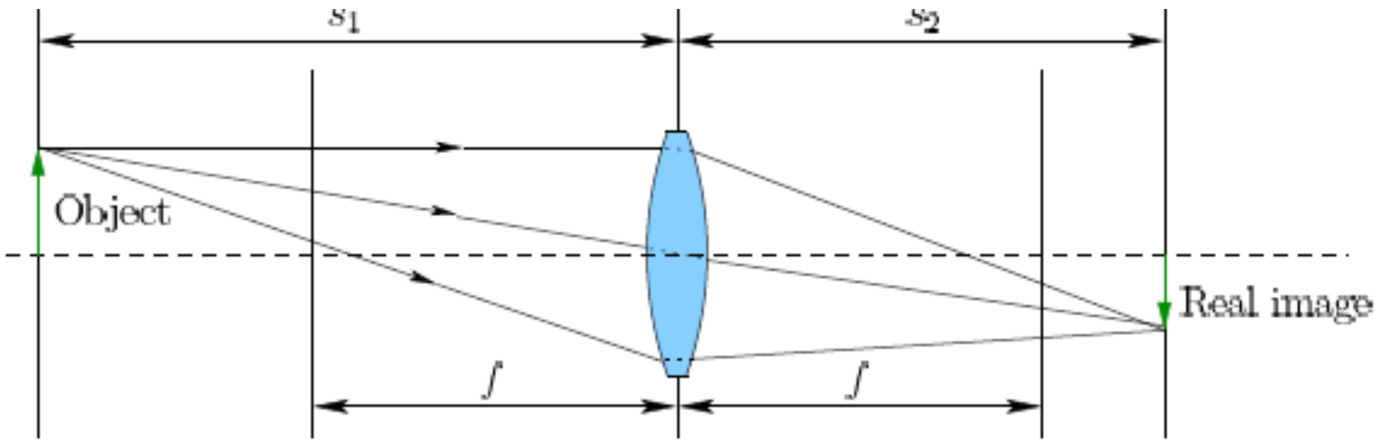
The focal length can be calculated using the Lensmaker's equation:

$$(n_2 - n_1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right) = \frac{1}{f}$$

r_1 and r_2 are radiuses of lens sides' curvatures

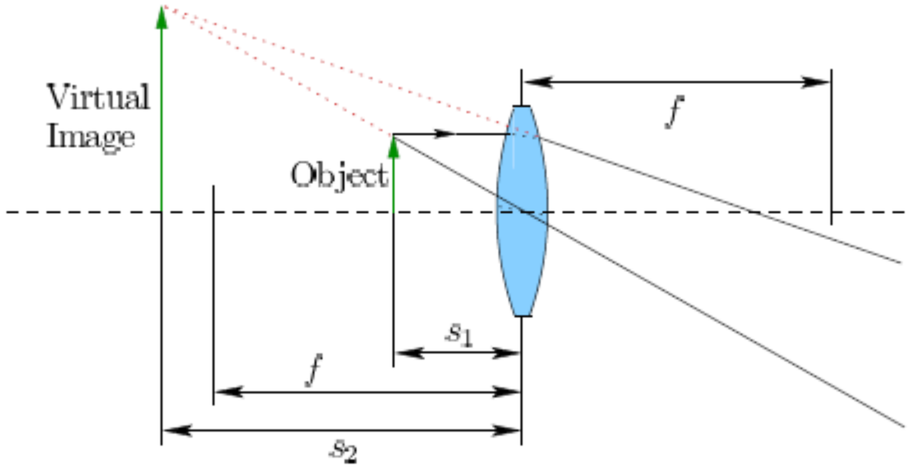
Forming a Real or Imaginary Image

- If the rays are not parallel, it may still be possible to focus them and form a real image
- Suppose a light source at distance s_1 from the lens
- Leveraging Snell equation we have $\frac{1}{s_1} + \frac{1}{s_2} = \frac{1}{f}$



If the object being viewed is not flat and perpendicular to the plane containing lens, there is not a single lens that brings focus. This problem is also faced by the lens in our eyes, but our brain can compensate that!

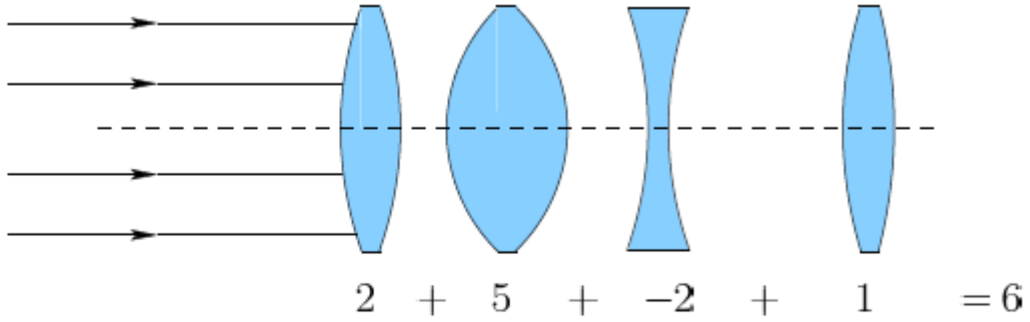
Virtual Image



- If the object is very close to the lens, then the lens cannot force the outgoing light rays to converge to a focal point. In this case, a virtual image appears and the lens acts as a magnifying glass
  - This is the way lenses are commonly used in VR headsets
  - To the user looking through the lens, it appears as if the screen is infinitely far away and quite enormous!

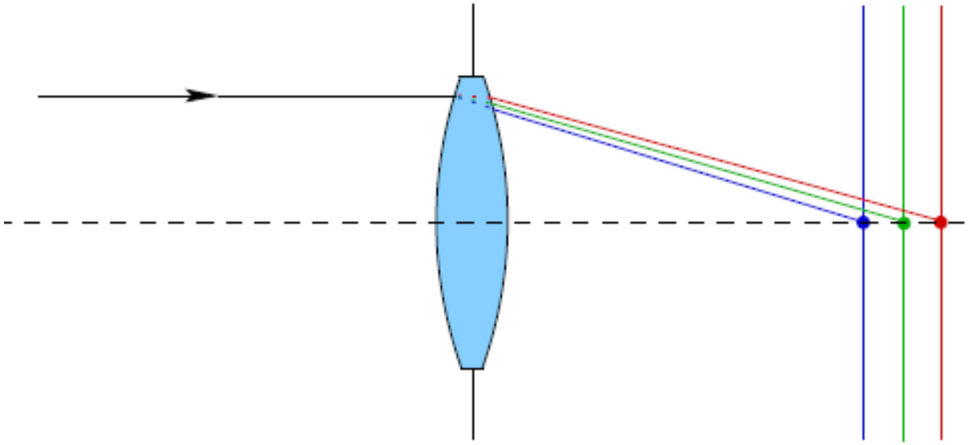
Diopters

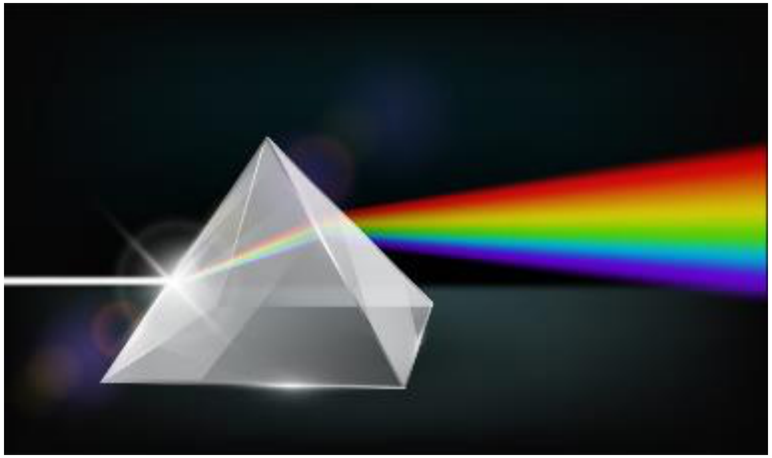
- Diopter is the reciprocal of focal length
  - A larger Diopter D means a greater converging power
  - Negative Diopter means divergence
- VR systems leverage multiple lenses
- To combine several nearby lenses in succession, we add their diopters to determine their equivalent power as a single, simple lens!



Optical Aberrations

- Imperfections (called aberrations) degrade the images formed by lenses
  - Important to understand to compensate for them in VR headsets
- Chromatic aberrations
  - Light is a jumble of waves
  - The speed of light through a medium, and hence the refractive index and focal depth are all a function of wavelength
  - Can be reduced by combining concave and convex lenses



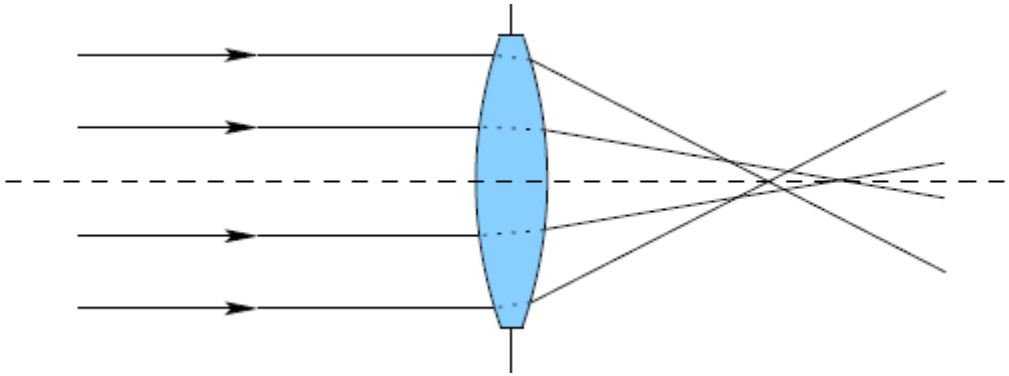


Chromatic Aberrations

The upper image is properly focused, whereas the lower image suffers from chromatic aberrations

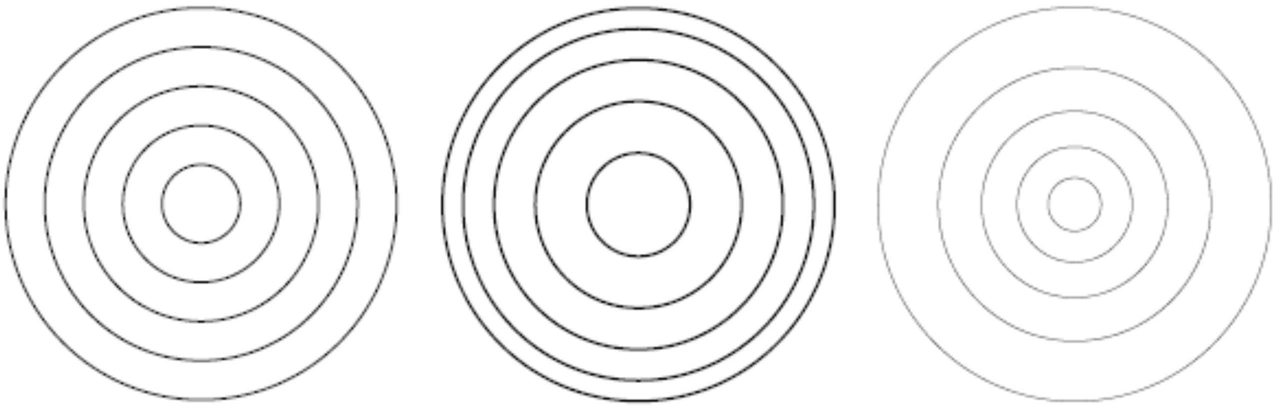
Spherical Aberrations

- Rays further away from the lens center are refracted more than the rays near the center
  - This applies to light of even a single color (e.g., laser)
  - The result is a blur that can be removed by moving the object, lens
  - There are complex aspheric lenses that can eliminate the issue



Optical Distortion

- The image might be distorted at the periphery
- Applicable to some lenses
  - The distortion can be described as compression or stretching that increasingly becomes sever away from the center of the lens
  - Higher distortion for lenses with a wide field-of-view (e.g., fisheye lens)



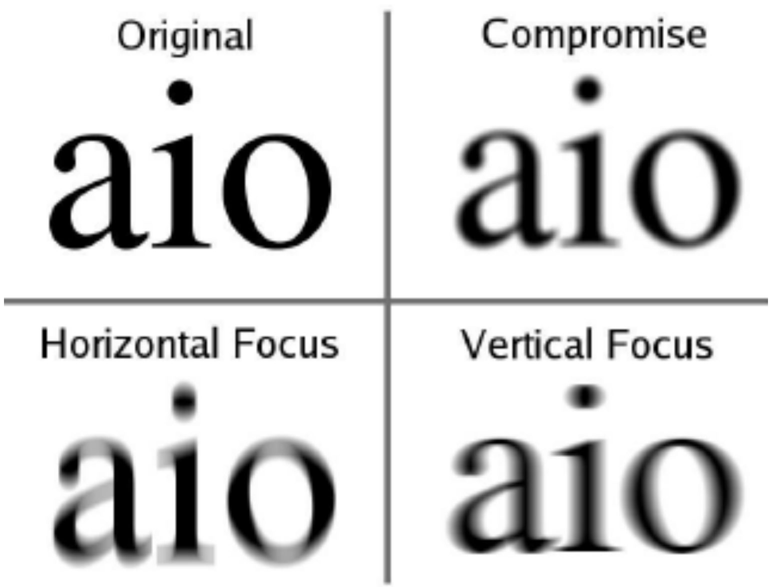
Original image | Barrel distortion | Pincushion distortion

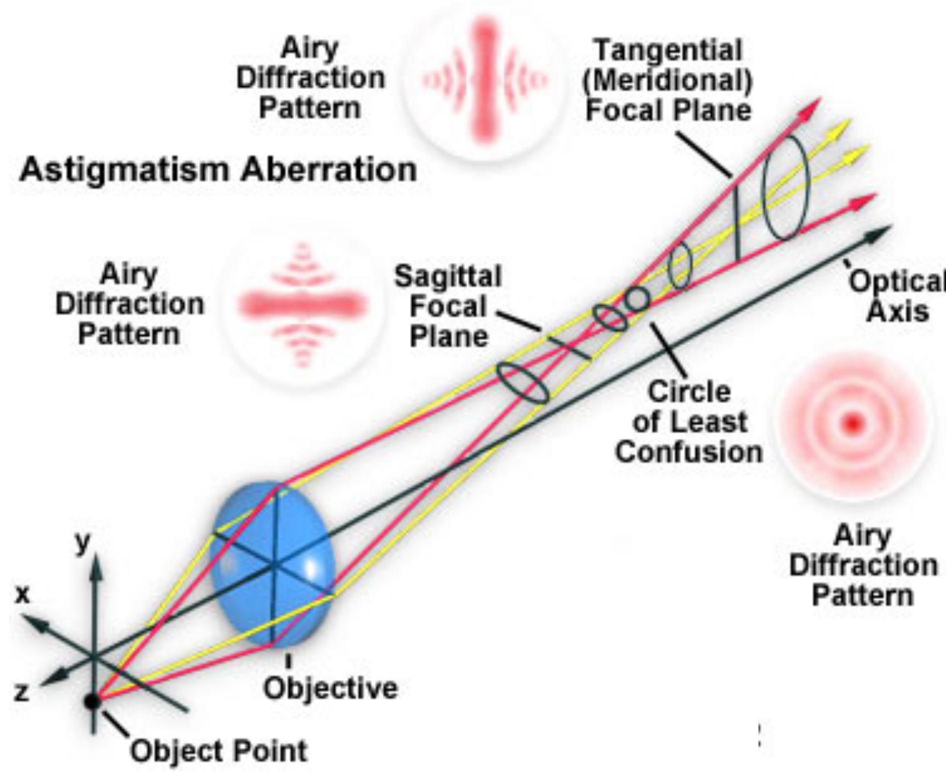
Fish-eyed Lens

- Used to capture images with large field-of-view
  - Example to create a wide panoramic view

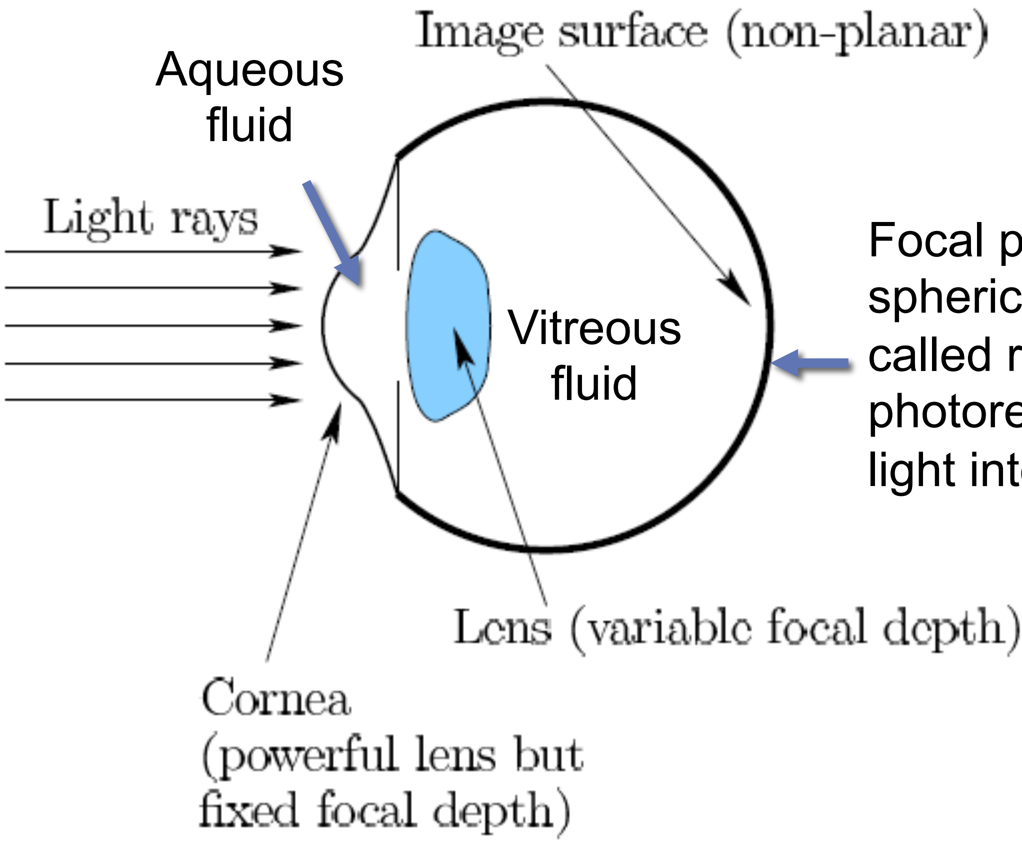
Astigmatism Aberration

- Real lenses are 3D
- The aberration happens because the lens vertical and horizontal planes have different focal lengths
  - The image cannot be brought into focus





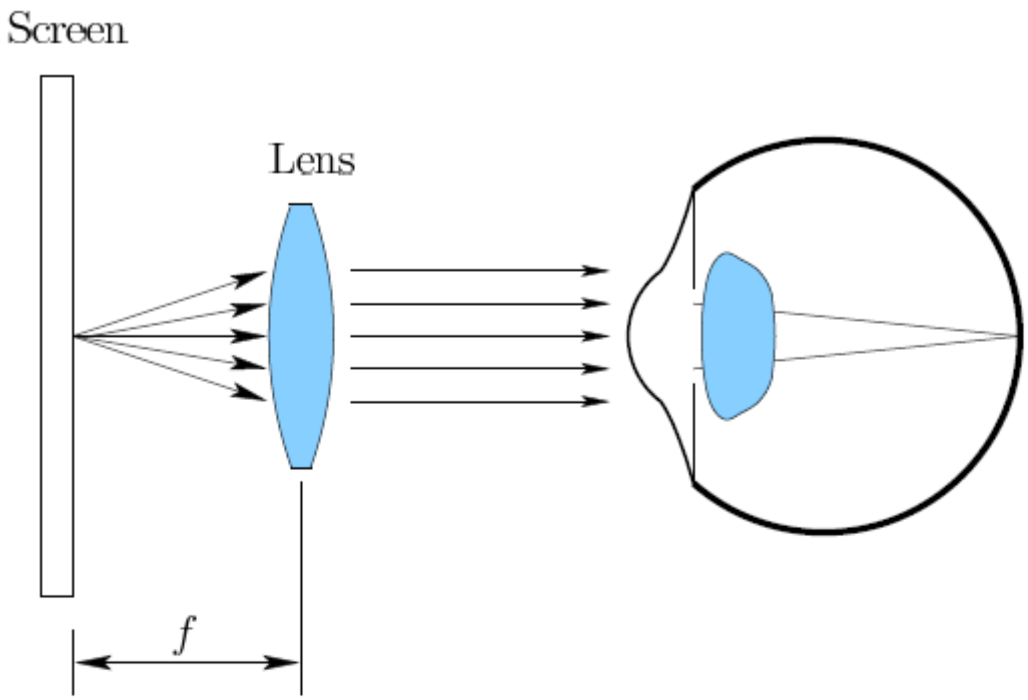
Human Eye



Focal plane is replaced by a spherically curved surface called retina, which contains photoreceptors that convert light into neural impulses

The greatest lenses are cornea (40D optical power) and lens (20D optical power)
The eye lens automatically changes its diopter so that we can focus on near objects
The children lens has 20D more optical power. A child may bring something right to your face and expect you to see (it's because they can!)

A Simple VR Headset

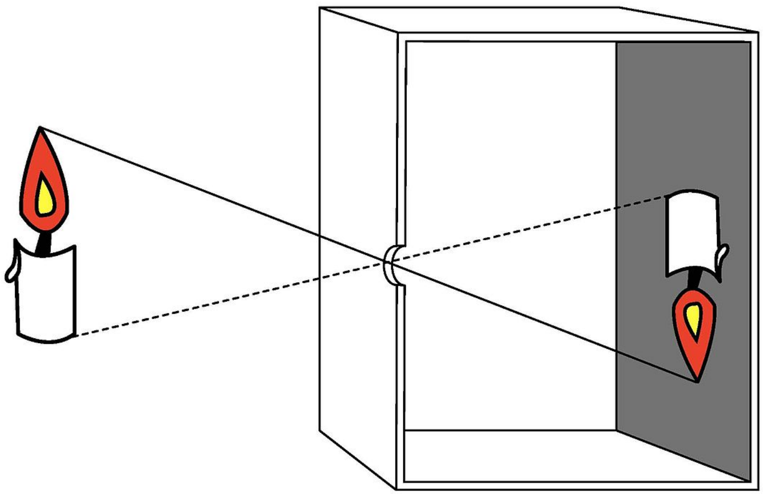


- The lens is placed at its focal length. A virtual image (and enormous) is formed behind it. A real image is formed on your retina

Some Problems for VR

- There should be a single lens for each eye
- The distance between the two lenses should be adjustable (similar to binoculars)
  - Because the distance between eyes is different among people
- Note that eyes rotate within their sockets
  - Changes the position and orientation of cornea with respect to lens
  - **This amplifies some of the aberrations that we covered**

Cameras



Simple pinhole camera

Camera before the digital camera revolution!

Cameras

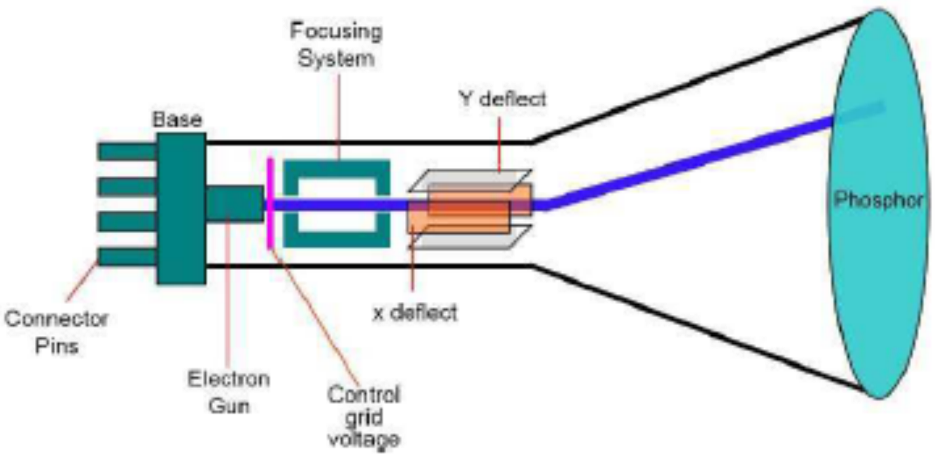
- Digital cameras electronically capture image using sensors
- Two popular technologies
  - Charged-coupled device (CCD)
  - CMOS active-image pixel sensor
- Digital cameras capture the amount of light hitting each pixel location along the image
  - Each pixel records the R (red), G (green), and B (blue) values
  - Typically range from 0 to 255
  - Each sensing element (one per pixel per color) captures photons
  - The amount of light captured is controlled by shutter
    - Shutter blocks all the light, opens for a fixed interval, and closes again

Cameras

- CCD sensors grab the entire image at once
  - There is a single global shutter, more expensive than CMOS
- CMOS sensors send image info line by line
  - They are coupled with a rolling shutter
  - Capture is not synchronized over the entire image, which results in problems like below

Displays: Cathode ray tubes (CRT)

- Gave birth to displays such as TVs (older)
- An electron gun emits a beam of electrons, which are deflected in both x and y directions according to an analog signal. When the beam hits the screen, an element of phosphor briefly lights up



Flat Panel Displays

- LCD and LED technologies allow for flat panel displays
  - Used in today’s TVs and smartphones
  - **In the case of LED, each individual pixel can be directly lit**
  - Low-cost VR solutions put a lens right in front of a smartphone

- Research VR displays
  - Virtual retina display: draw the image directly onto human retina