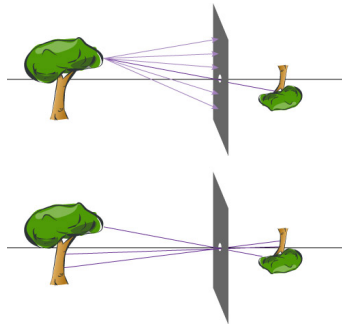


# Instruments

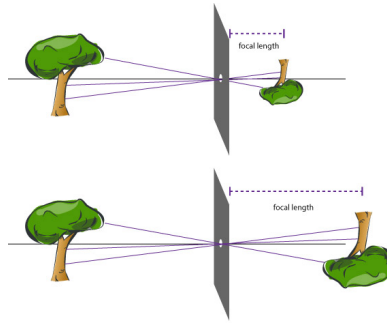
1. [Basic Optics](#)
  1. [Rays of Light](#)
  2. [Waves of light](#)
  3. [Basic Imaging Systems](#)
  4. [A Basic Telescope](#)
  5. [Aberrations](#)
  6. [Mirrors](#)
2. [Some Real Instruments](#)
  1. [Keplerian Optics](#)
  2. [Newton's Telescope](#)
  3. [Astronomical seeing](#)
  4. [Detectors](#)
3. [Other Wavelengths](#)
  1. [Radio Telescopes](#)
  2. [Orbiting Astronomical Observatory](#)
  3. [Hubble](#)
4. [Other improvements](#)
  1. [Adaptive Optics](#)

## I. Basic Optics

### I.1 Rays of Light



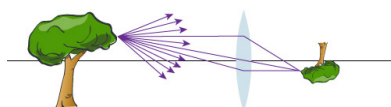
A pinhole will project an inverted image on a plane.



The image will be in focus everywhere. It's size changes based on the position of the focal plane.

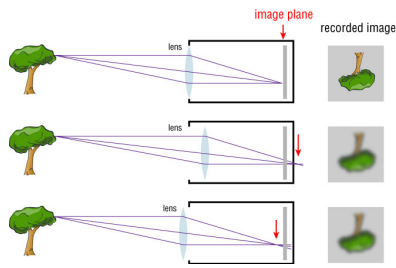
The pin-hole camera allows a small amount of light to pass through an opening. However, because the hole is small, very little light passes, which makes measurements difficult. If the hole's diameter is increased, then the image becomes blurred.

### Converging Lens



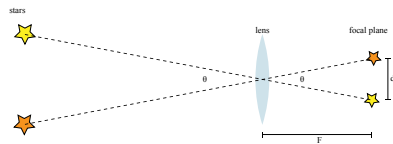
By using a converging lens, we can allow more light to pass through the hole, which increases our 'photon count.' A consequence of using a lens however, is that now the focal length,  $F$ , is fixed.

### Images



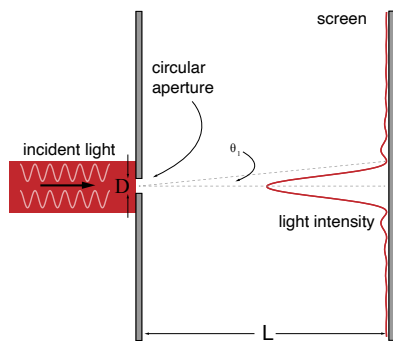
Changing the position of the screen will result in a blurry image.

### Light from stars



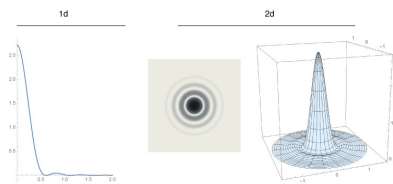
Two stars separated by an angle  $\theta$  in the sky, will create images separated by a distance  $d$  on the detection screen.

### 1.2 Waves of light

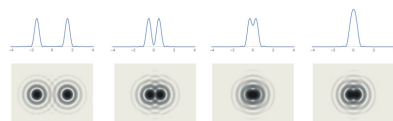


Coherent, mono-chromatic light passing through a circular aperture will be diffracted.

### Airy Disc



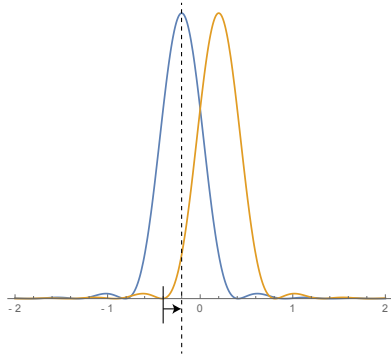
### There is a limit



Unresolved: if the central maximum falls inside the location of the first minimum.

Two point sources getting closer.

### Unresolved point sources

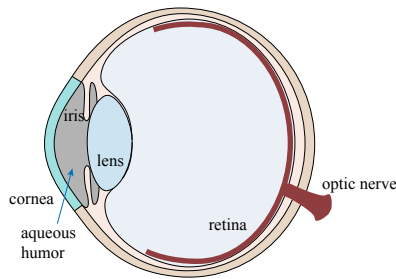


### Rayleigh Criterion

$$\theta_{\min} = 1.22 \frac{\lambda}{D}$$

## 1.3 Basic Imaging Systems

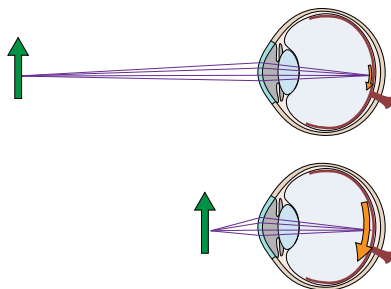
### The eye



Nature has made many different eyeballs. Most operate on the principles of lenses we've just looked at.

The human eye

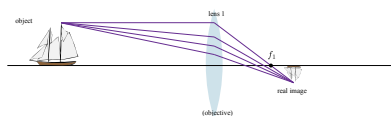
### focusing the eye



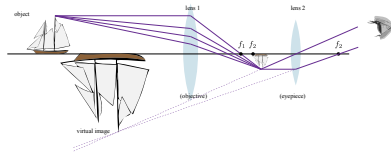
Focusing on objects: We cannot adjust the position of the lens with respect to the retina. So, the muscles around the eye change the shape of the lens, which then changes its focal length.

Focusing the eye

## 1.4 A Basic Telescope



Magnification:

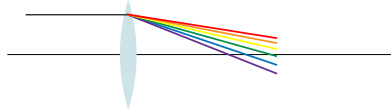


$$M = \frac{f_1}{f_2} = \frac{f_{\text{objective}}}{f_{\text{eyepiece}}} \quad (1)$$

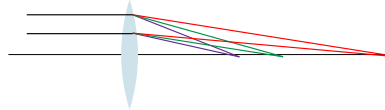
## 1.5 Aberrations

Lenses aren't perfect.

### Chromatic Aberration



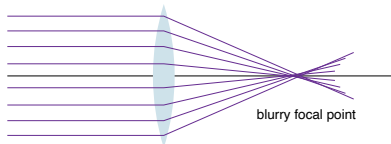
Chromatic Aberrations



Different Colors will have different focal points

Since different colors will refract at different angles, the focal point will be slightly different for different wavelengths. This leads to **Chromatic Aberration**.

### Spherical Aberration

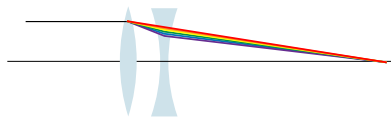


Spherical Aberrations

Earlier, our thin lens approximation ignored the fact that the thickness of the lens changed as a function of distance away from the central axis.

This leads to rays having slightly different focal points depending on where they are incident on the lens. The further the rays are away from the central axis, the worse the **Spherical Aberration** effect is.

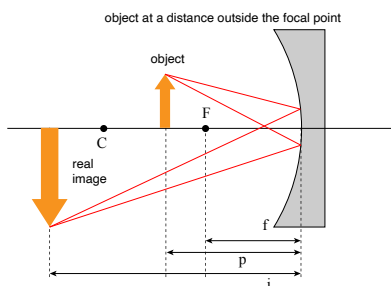
### Fixing aberrations



Fixing Aberrations

Fortunately, by using a multi lens setup, we can correct these aberrations. For example, to correct the chromatic aberration caused by a converging lens we can insert a diverging lens after the converging lens to refocus the different colors back to the same point.

## 1.6 Mirrors



A mirror ray diagram

## 2. Some Real Instruments

### Galileo's Telescope



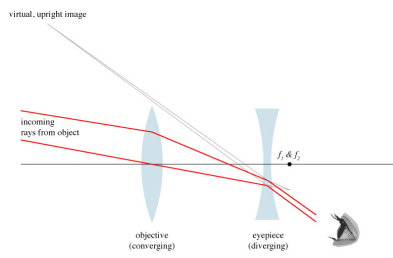
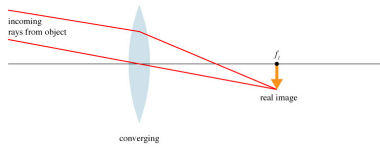
Galileo's Telescope



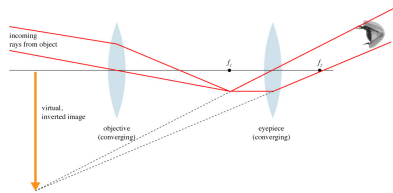
Saturn as viewed through Galileo's telescope

<https://www.astromatic.net/2009/05/23/see-saturn-as-galileo-did>

## Galileo's Telescope



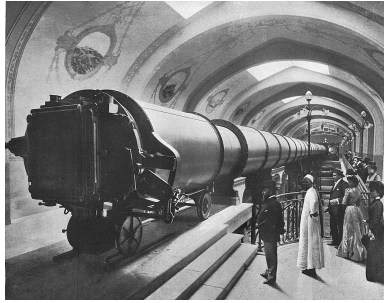
## 2.7 Keplerian Optics





Yerkes Observatory 40 inch Refractor Telescope ( It is the largest refracting telescope used for astronomical research.)  
Williams Bay, Wisconsin, US

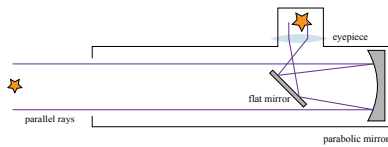
[https://commons.wikimedia.org/wiki/File:Yerkes\\_40\\_inch\\_Refractor\\_Telescope-2006.jpg](https://commons.wikimedia.org/wiki/File:Yerkes_40_inch_Refractor_Telescope-2006.jpg)



The Great Paris Exhibition Telescope of 1900, with an objective lens of 1.25 m (49 in) in diameter, was the largest refracting telescope ever constructed. It was built as the centerpiece of the Paris Universal Exhibition of 1900. 200 ft long. Too big to use.

By Unknown - Le panorama (Paris, 1900)., Public Domain,  
<https://commons.wikimedia.org/w/index.php?curid=20083299>

## A reflecting Telescope



A reflecting Telescope

## 2.8 Newton's Telescope



A replica of the Newton - Wickins telescope, Newton's third reflecting telescope that was presented to the Royal Society in 1766 after being restored by Thomas Heath. It is described as the better of the instruments Newton built

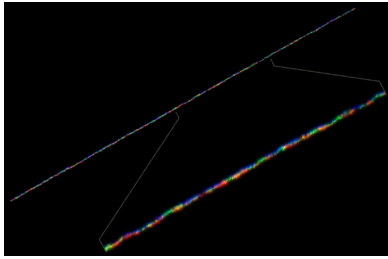
By User:Solipsist (Andrew Dunn) - [www.andrewdunnphoto.com](http://www.andrewdunnphoto.com), CC BY-SA 2.0,

<https://commons.wikimedia.org/w/index.php?curid=513483>

## Where should we put these telescopes?

Early telescopes could be placed near where people lived, since there were not a lot of lights to get in the way. Now, we usually put telescope as far away from people as possible.

## 2.9 Astronomical seeing



As light passes through the atmosphere, small variations in air density, usually caused by temperature fluctuations will disturb the incoming waves. There is turbulent mixing of air throughout much of the atmosphere (but not everywhere)

Scintillation of a star, over time

[http://spaceweathergallery.com/indiv\\_upload.php?upload\\_id=124490](http://spaceweathergallery.com/indiv_upload.php?upload_id=124490)



Moon Seeing Effect



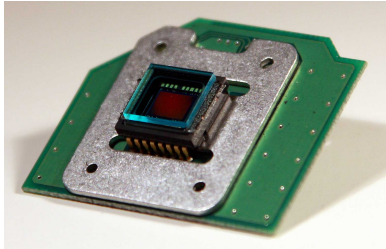
Mountain in the atmosphere

## 2.10 Detectors

We can classify most of the standard astronomical instruments as either imaging cameras or spectrometers. Either way, we need to collect photons. That used to be done with chemical film, but we use digital methods. They have a much greater **quantum efficiency**, which means that it requires fewer photons to trigger a detection by a pixel.

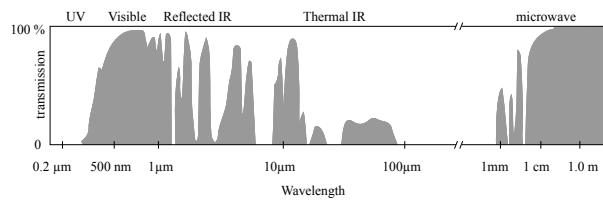
- Photographic Plate: 1%
- Human Eye: 10%
- CCD: 80-90%

### Charge-coupled Device: CCD



A CCD device

## 3. Other Wavelengths



The transparency of the atmosphere

Adapted from

[https://earthobservatory.nasa.gov/Features/RemoteSensing/remote\\_04.php](https://earthobservatory.nasa.gov/Features/RemoteSensing/remote_04.php)

### 3.11 Radio Telescopes



What about for EM radiation with frequencies and wavelengths not in the visible spectrum?

Clouds linger at twilight over the Karl G. Jansky Very Large Array in its most compact configuration.

Credit: NRAO/AUI/NSF [link](#)

What if  $\lambda$  is really big?

$$\theta_{\min} = 1.22 \frac{\lambda}{D}$$

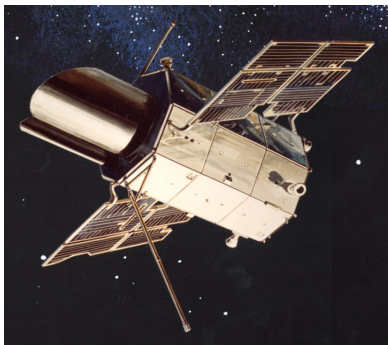
Arecibo





Credit: Author H. Schweiker/WIYN and  
NOAO/AURA/NSF [link](#)

### 3.12 Orbiting Astronomical Observatory



Let's put a telescope above the atmosphere. There, instruments will be able to reach the diffraction limit mentioned above, rather than the seeing limit of ground based observatories.

The Orbiting Astronomical Observatory (OAO) satellites were a series of four American space observatories launched by NASA between 1966 and 1972, which provided the first high-quality observations of many objects in ultraviolet light.

### 3.13 Hubble



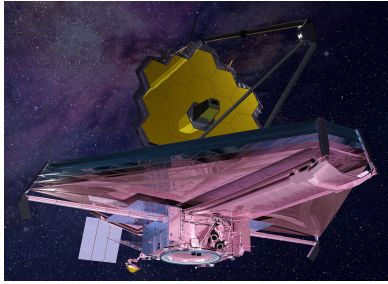
Launched in 1990, the Hubble Space Telescope has taken many of the most recognizable space images.

The Hubble Space Telescope



It didn't work too well at first, and so a repair mission had to be sent. Astronauts fixed it.

Hubble before and after



The telescope that ate astronomy.



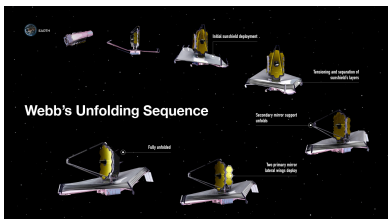
Inspecting the mirrors on the James Webb Space Telescope

Credit: NASA/Chris Gunn - <https://www.flickr.com/photos/nasawebbtelesc>



The primary mirror of NASA's James Webb Space Telescope, consisting of 18 hexagonal mirrors, looks like a giant puzzle piece standing in the massive clean room of NASA's Goddard Space Flight Center in Greenbelt, Maryland.

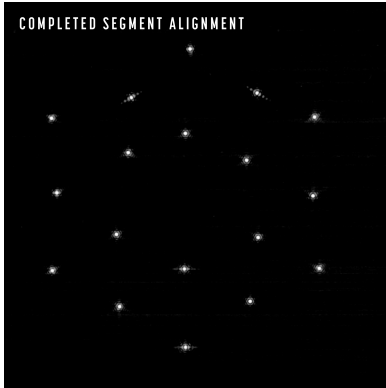
Image Credit: NASA/Chris Gunn - <https://www.flickr.com/photos/nasawebbtelescope/30116152713/>



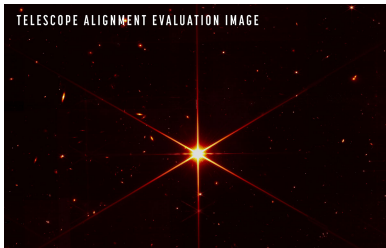
Credit: [NASA/STScI](https://www.nasa.gov/stsci/)



Credit: [NASA/STScI](#)



Credit: [NASA/STScI](#)



Credits: [NASA/STScI](#)

## 4. Other improvements

1. Active Optics - mirrors that move.
2. Adaptive Optics - guide stars

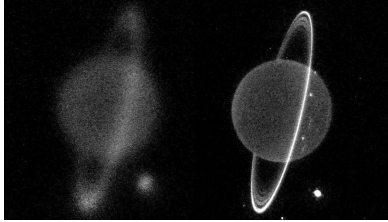
### 4.14 Adaptive Optics



Make a star using a laser.

The idea of adaptive optics has improved observing tremendously. If you create an artificial star using a laser, then you should know what it should look like. Simply adjust your optics in real-time to keep the laser-star looking good!

An artificial star



Saturn without and with Adaptive Optics

Credit: Heidi B. Hammel and Imke De Pater/WMKO [Keck](#)