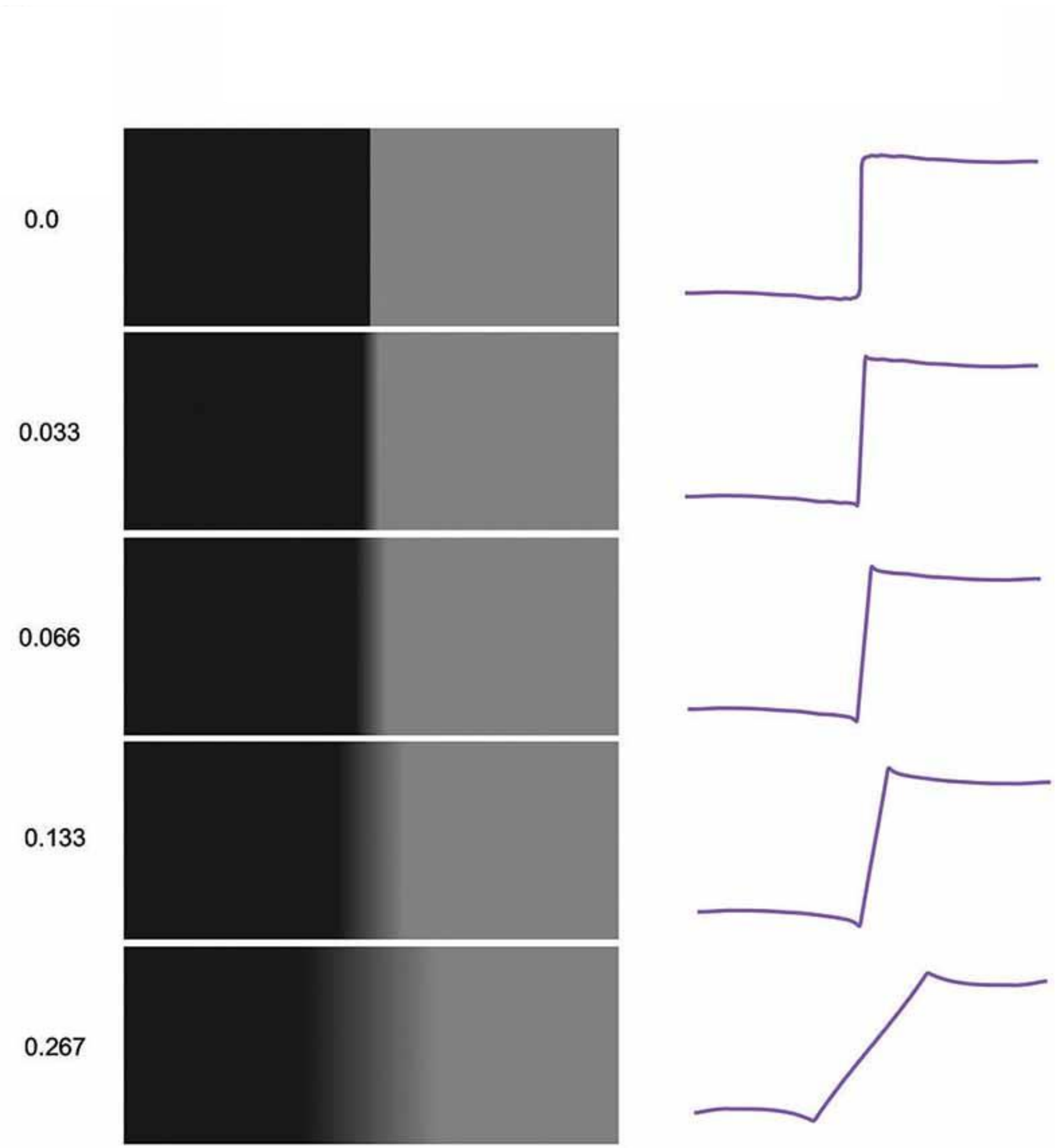
Lecture 3

Basics of Optics

Image is the result of contrast (difference in light intensity)

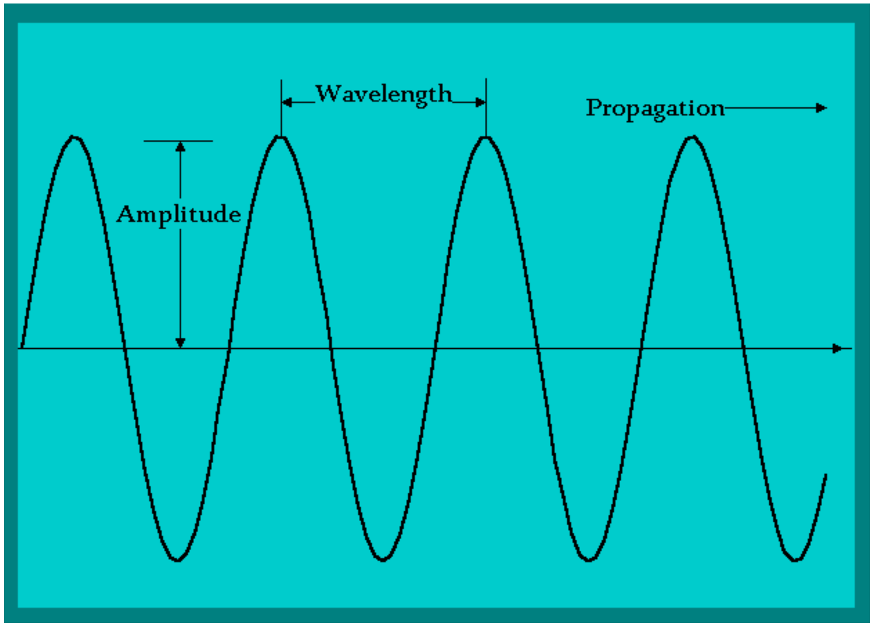


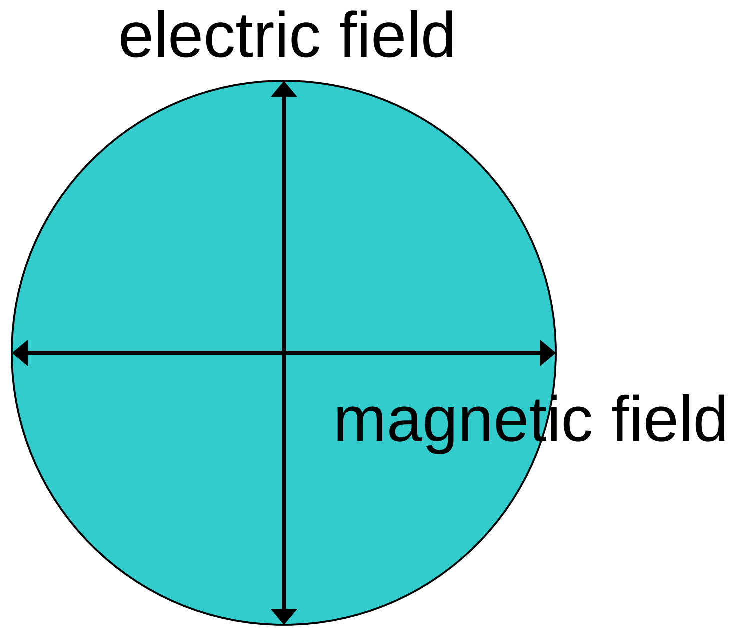
Dual Properties of Electromagnetic Radiation

- Wave properties (optical microscopy)
  1. Wavelength (λ) and frequency (ν)
  2. Interference (constructive & destructive)
  3. Diffraction (e.g., X-ray diffraction)

- Particle properties
  1. The photoelectric effect (PMT, XPS, etc)
  2. The Compton scattering of X-rays

Propagation of Electromagnetic Radiation

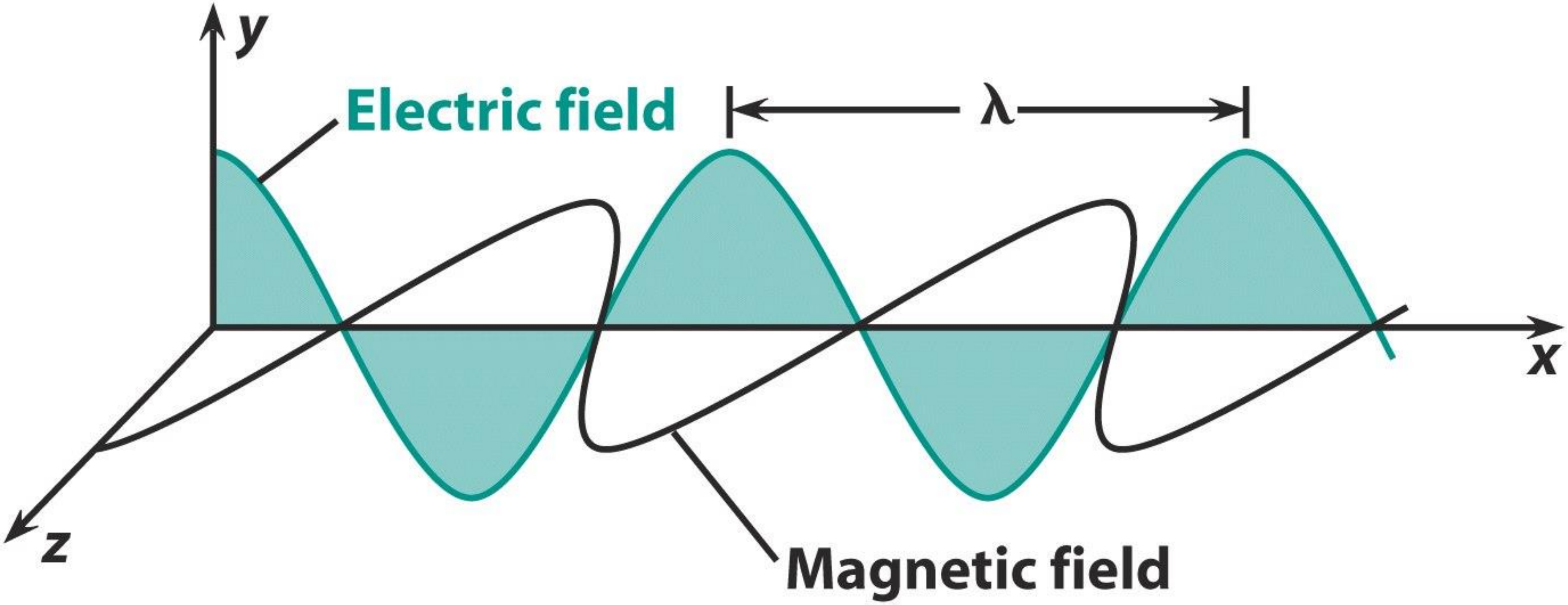




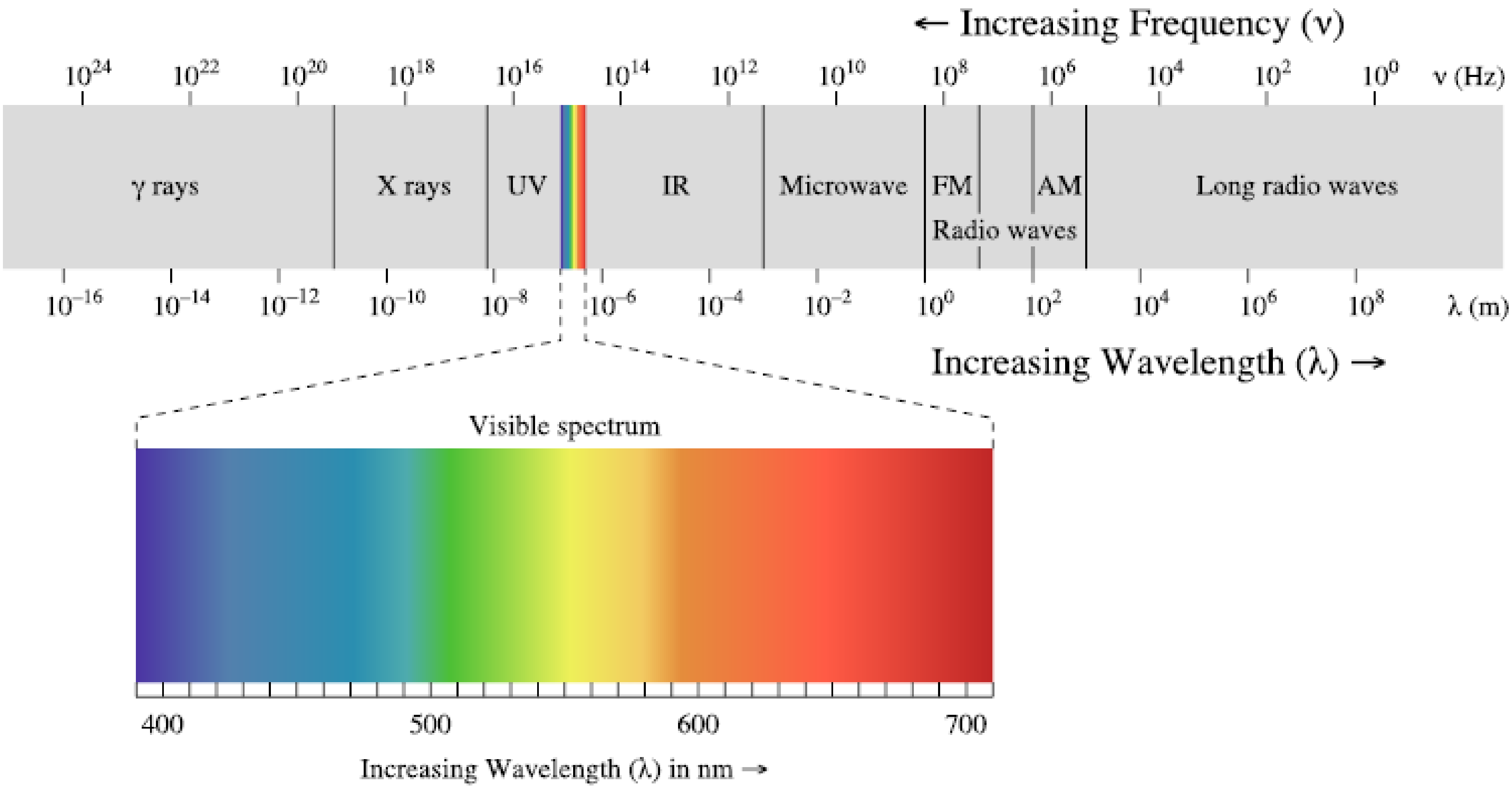
- Wavelength (λ): color

  1 nm = 10^{-9} m = 10^{-6} mm = 10^{-3} mm
- Frequency (ν): energy per photon
- Amplitude (A): intensity

Description of Propagation of Electromagnetic Radiation



Variations in Electromagnetic Radiation

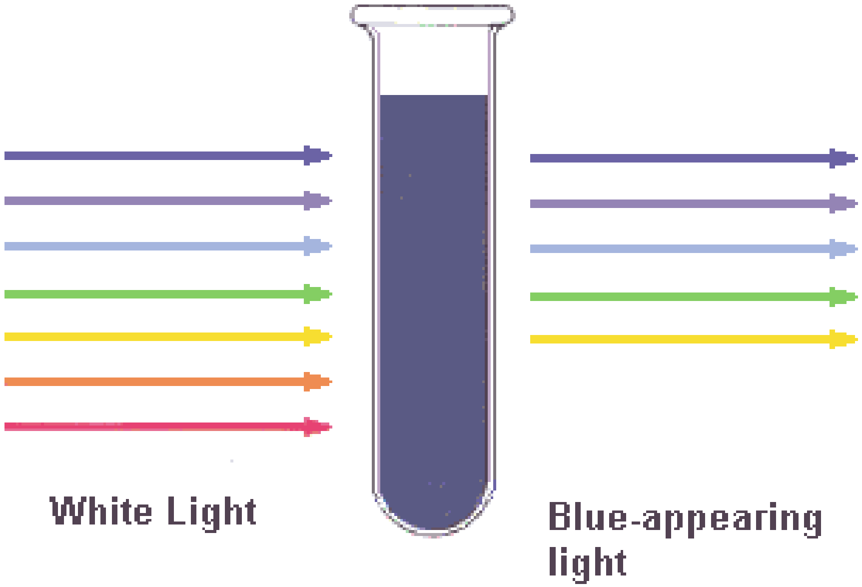


- Speed of light (c): ~300,000 km/s in a vacuum
- Wavelength (λ) and frequency (ν): $c = \nu \cdot \lambda$

Interaction of Light with Matter

- Absorption
- Reflection
- Transmission (Refraction)

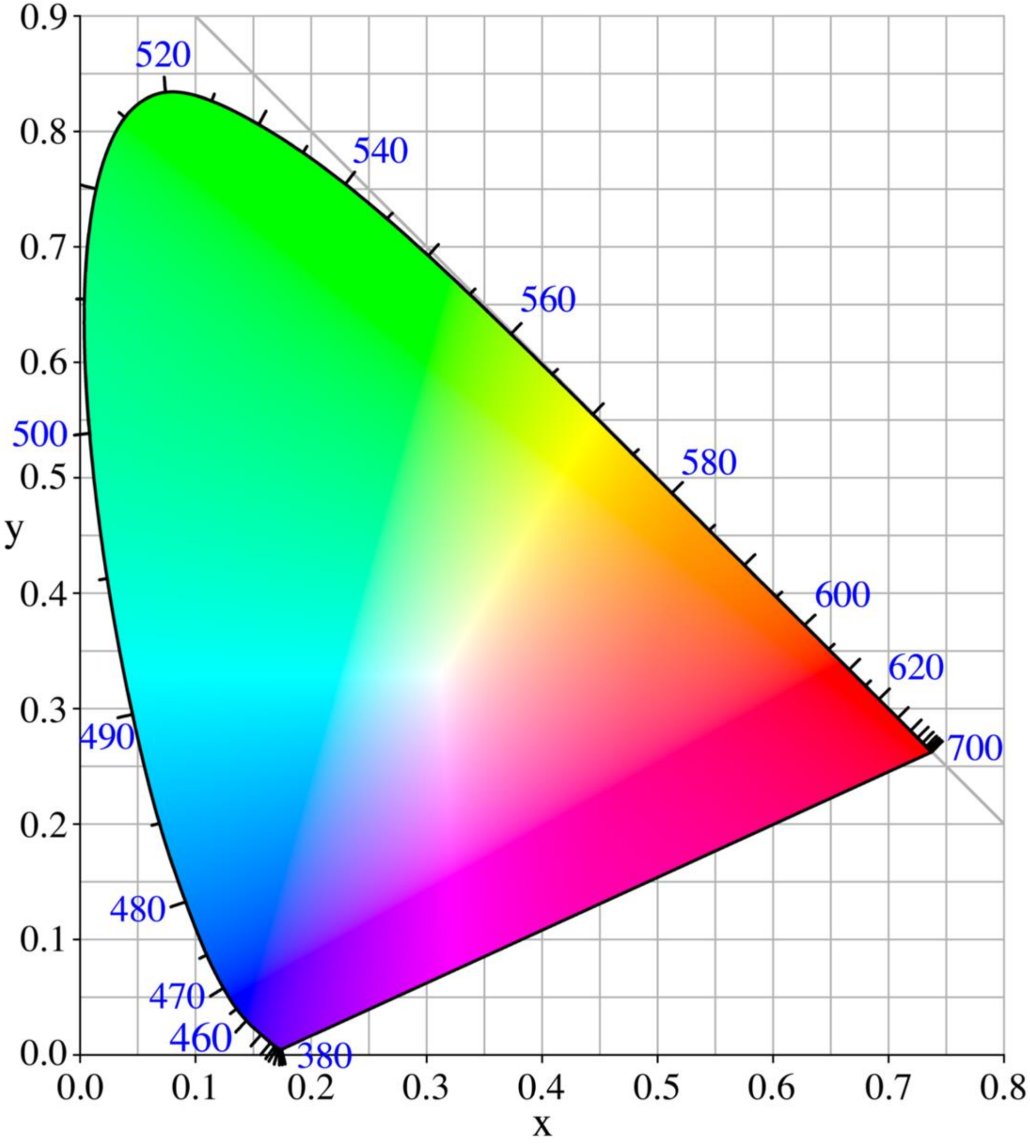
Absorption of Light (Color)



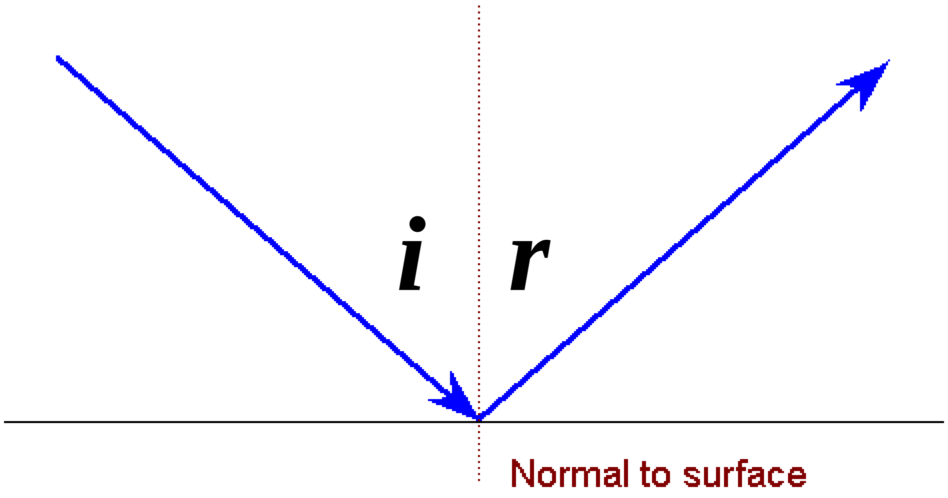
Rule: When a color is removed from white light by absorption, we can see the complementary color.

Complementary Color

CIE *xy* Chromaticity Diagram

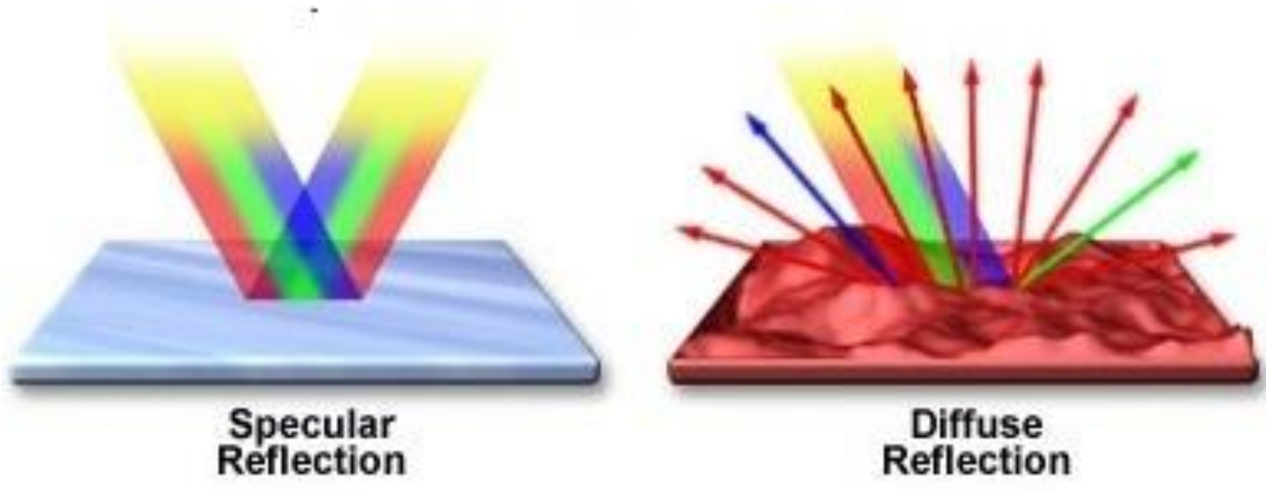


Reflection of Light

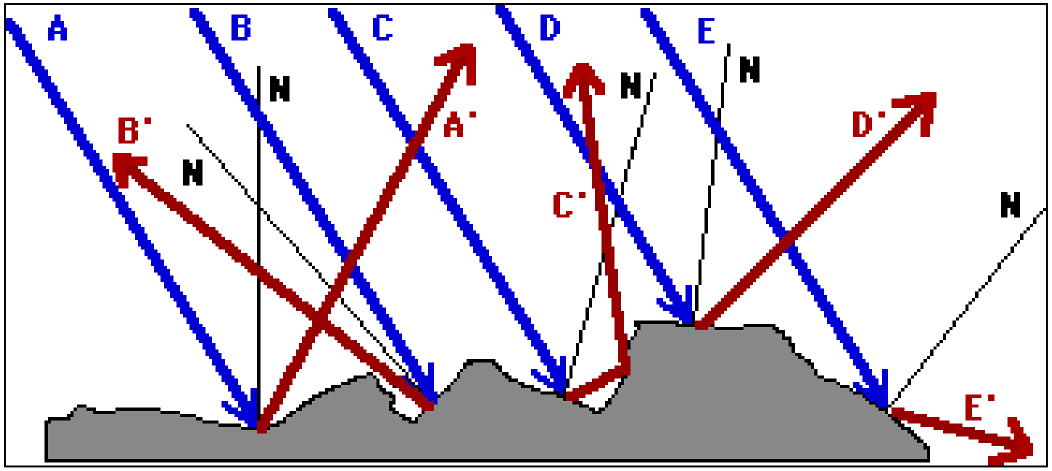


- The angle of incidence = **i**
- The angle of reflection = **r**
- Law of reflection: **i** = **r**

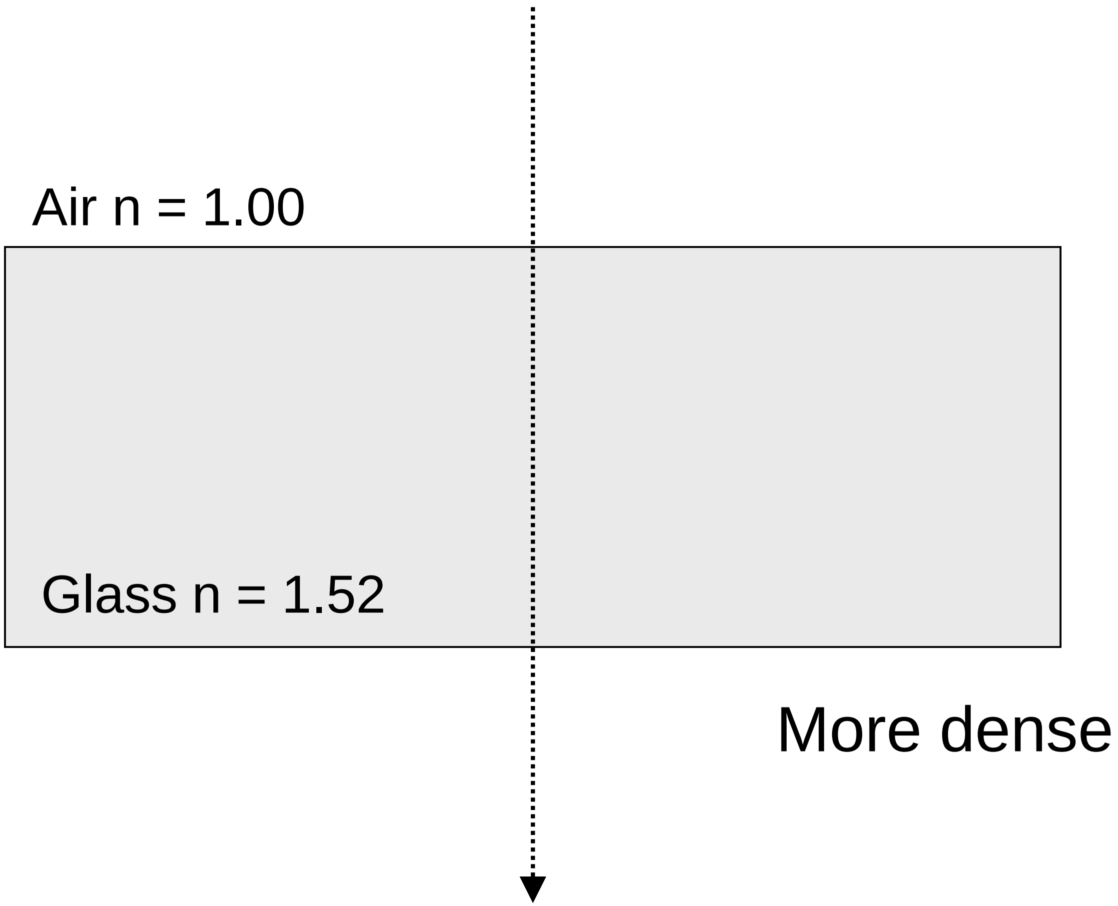
Specular and Diffuse Reflection



Microscopically rough surface



Transmission of Light



Light slows down due to the interaction with electrons.

Refractive Index (n)

Relative measurement how light interacts with a material

n_{sub} = (speed of light in a vacuum)/(speed of light in a sub)

e.g.,

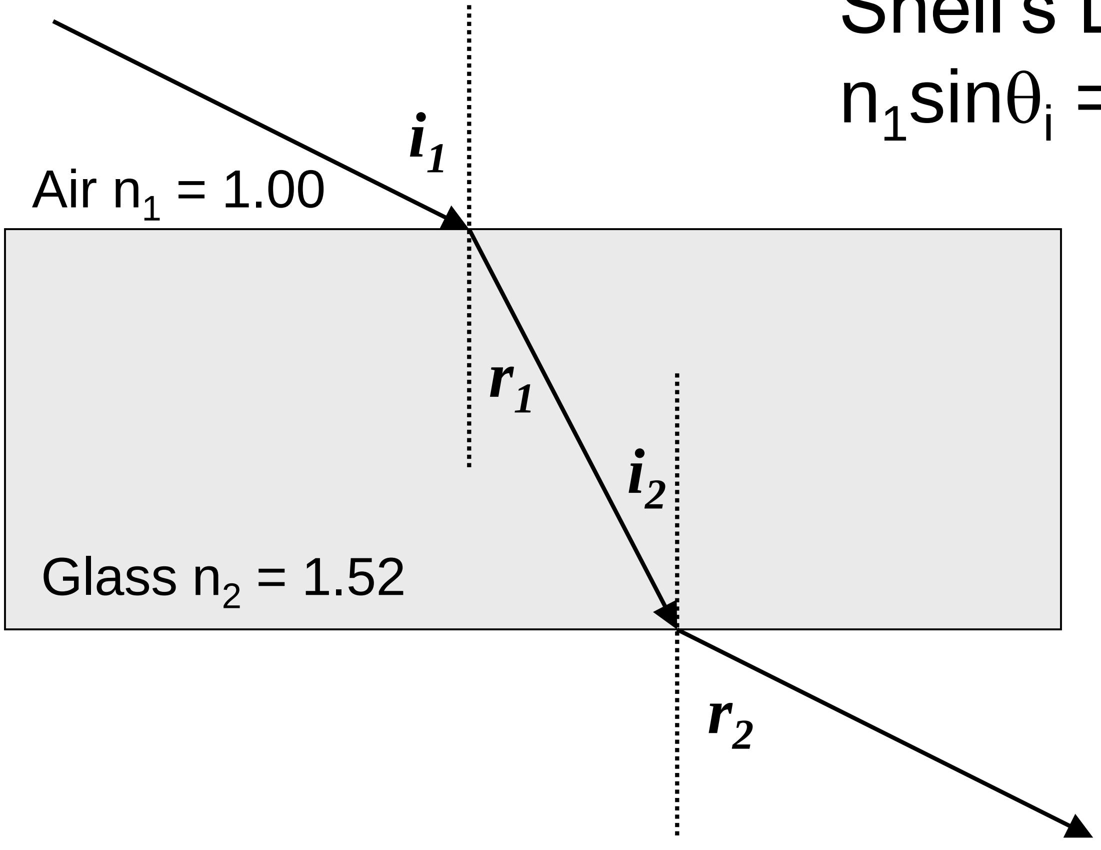
$n_{sub} = (3.0 \times 10^8 \text{ m/s})/(2.0 \times 10^8 \text{ m/s}) = 1.5$

$n_{air} = 1.52$
$n_{water} = 1.33$
$n_{diamond} = 2.4$

Refraction of Light

Snell's Law

$n_1 \sin\theta_i = n_2 \sin\theta_r$



Light bends toward (or away) from surface normal.

What Affects Refractive Index?

- Density
- Arrangement of atoms and molecules
- Atomic spacing
- Chemical bonds
- Molecular weight
- Wavelength of light

Density ↑, then speed of light ↓, then *n* ↑

Molecular weight ↑, speed of light ↓, then *n* ↑

Refractive Indices of Some Compounds

compounds	MW	n
NaF	42.00	1.3360
NaCl	58.45	1.5442
NaBr	102.91	1.6412
NaI	149.92	1.7745

Standard Refractive Index Liquid

$n_D^{25°C} = 1.81 \pm 0.005$

Temperature effect

T ↑, density↓, n ↓

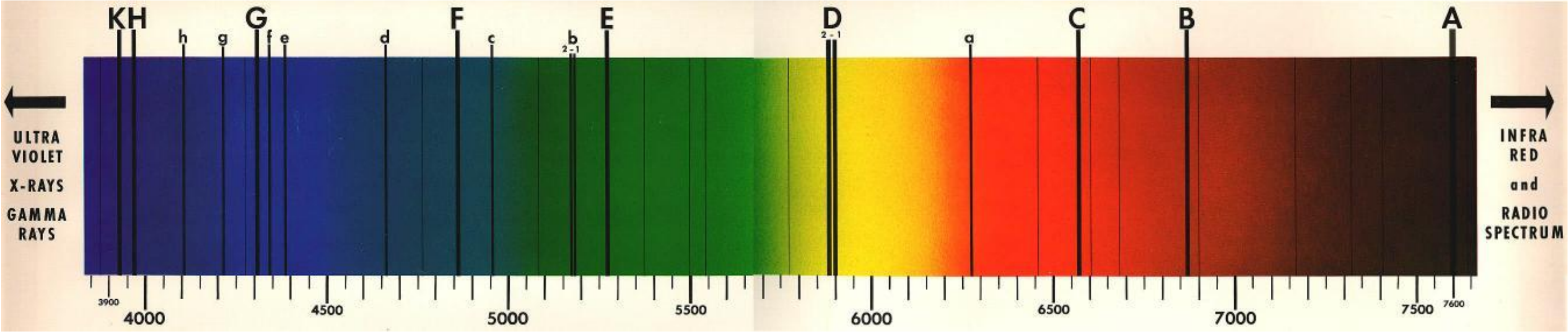
$-[dn_D/dT] = 4.70 \times 10^{-4}/°C$

n_D @ 30°C = ?

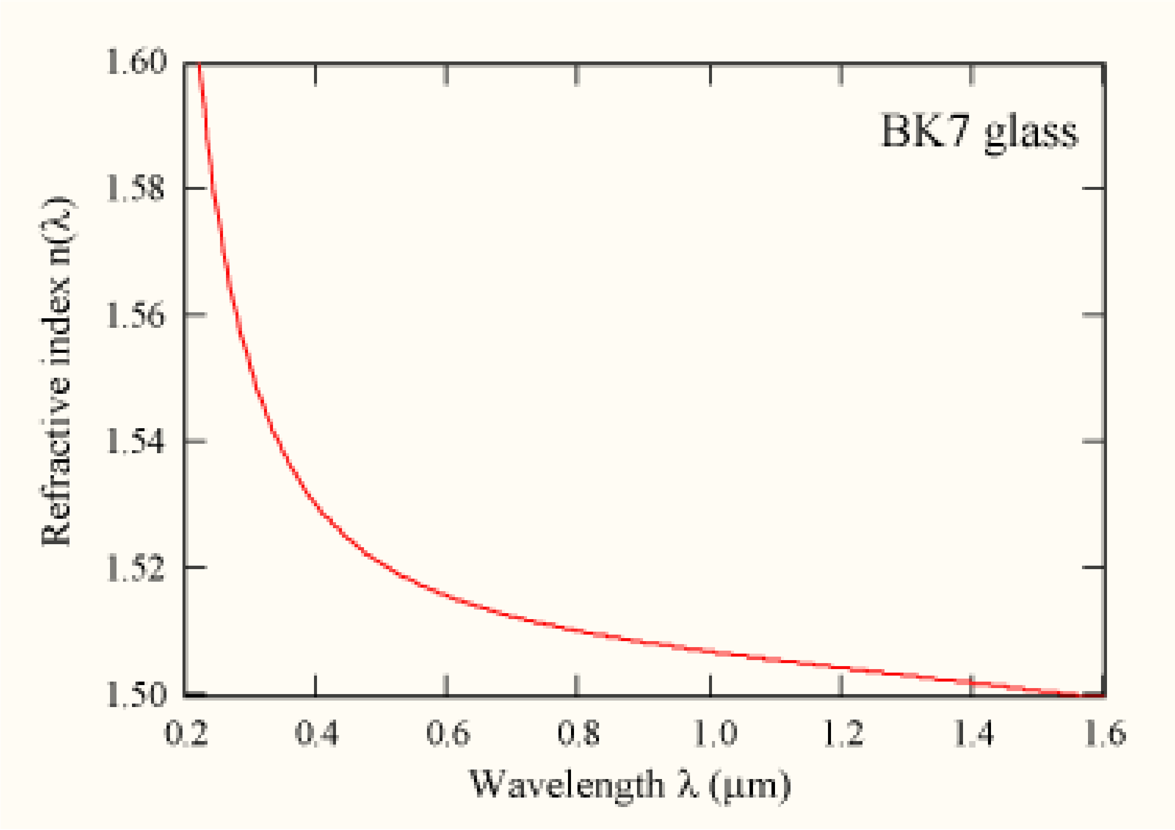
Subscript D in Standard Refractive Index n_D

- Fraunhofer Lines

- Sodium D-line (589.3 nm): Yellow (n_D)
- Hydrogen C-line (656.3 nm): Red (n_C)
- Hydrogen F-Line (486.1 nm): Blue (n_F)



Refractive Index as a Function of Wavelength



Demonstration

1. Standard Refractive Index Samples

2. Observation of image between two phases with different refractive indices

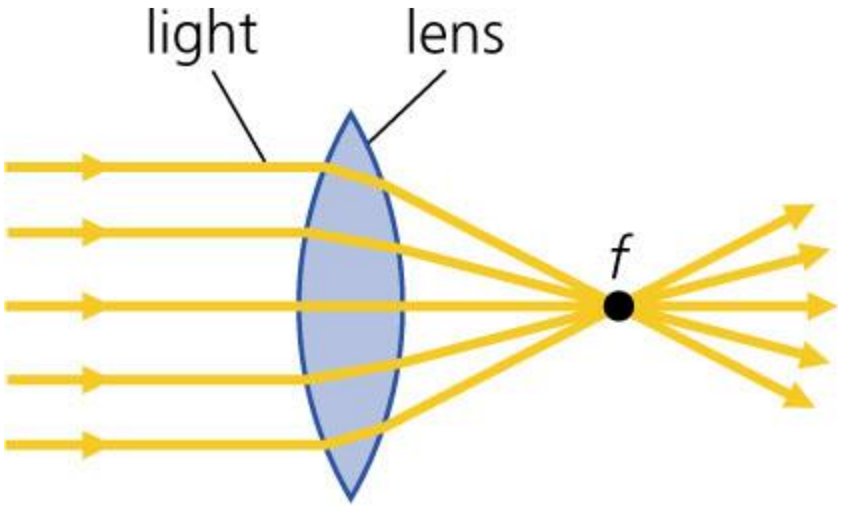
   (air = 1.0, water = 1.33, glass > 1.5)

Lecture 4

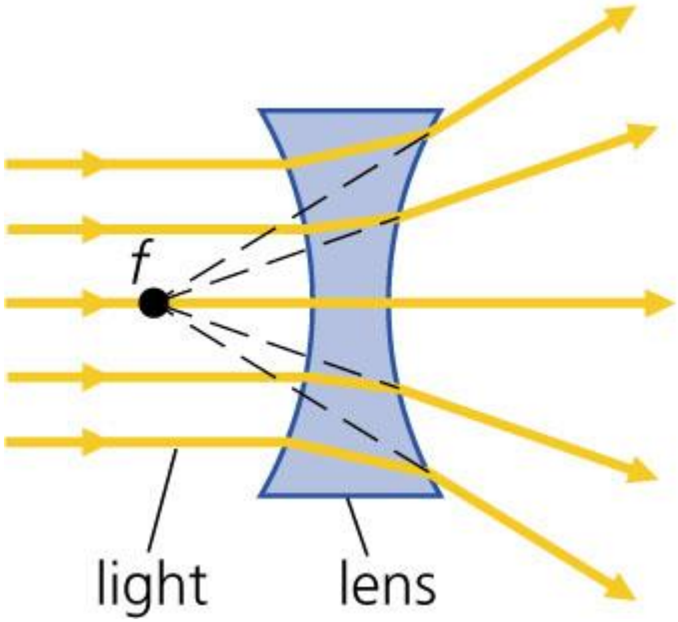
Lenses and Microscopes

Types of Lens

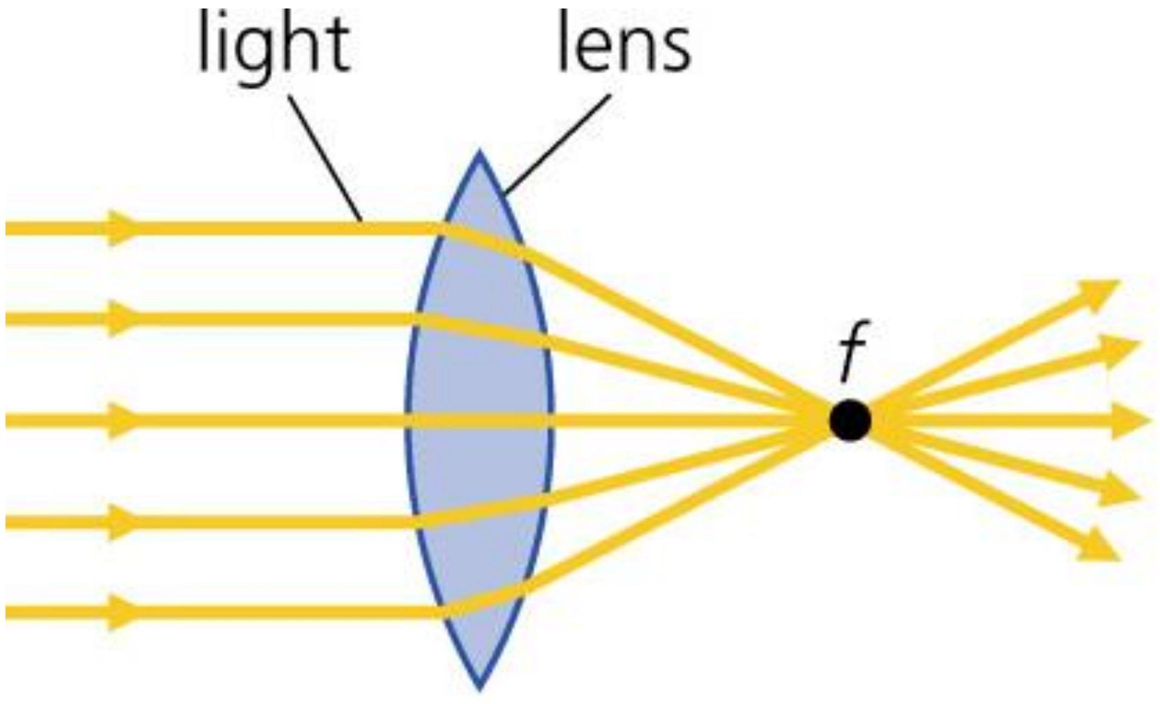
convex (converging) lens



concave (diverging) lens

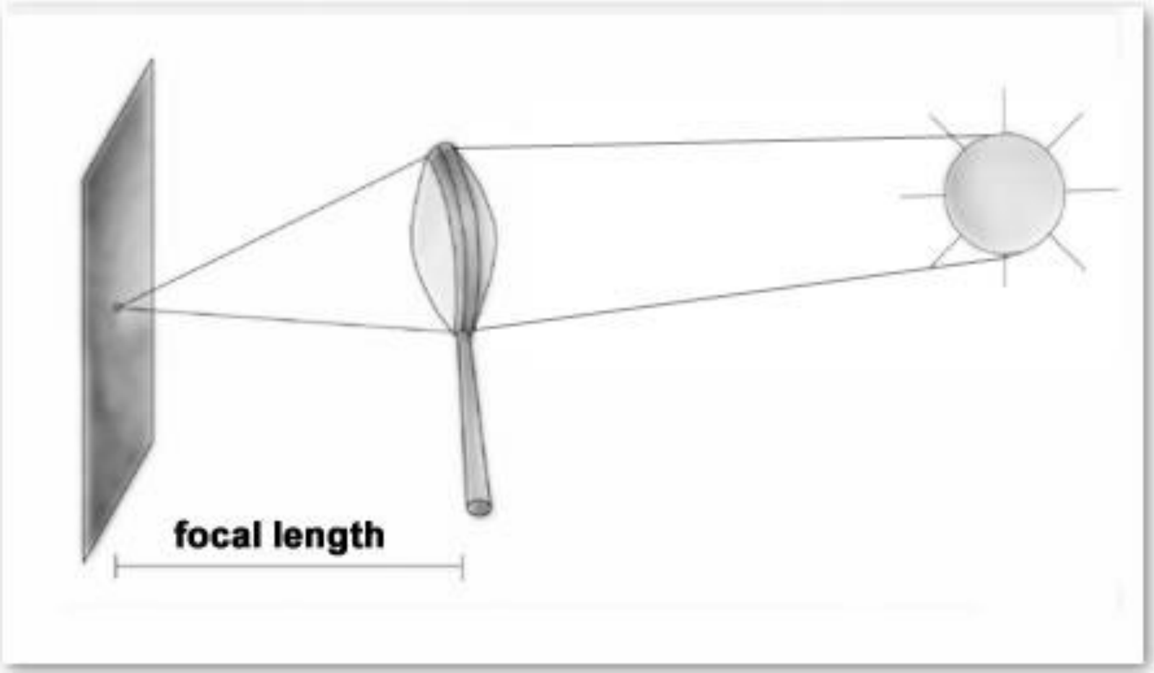


Ideal Convex Lens

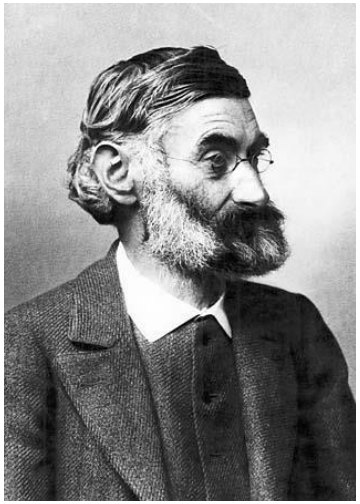


All rays should focus on the point

How to Find Focal Length



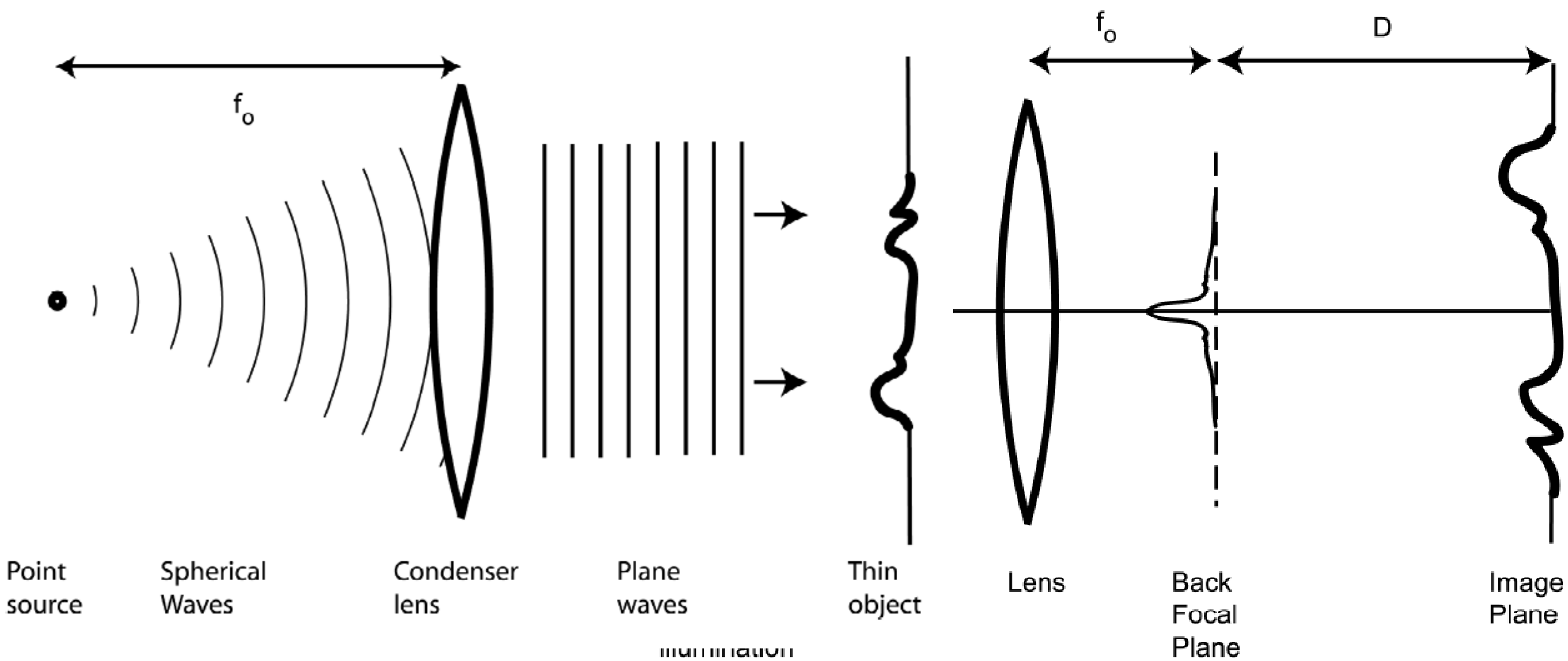
Abbe’s Theory of Image Formation



Ernst Karl Abbe (January 23, 1840 – January 14, 1905) German physicist

Image formation via contrast through constructive and destructive interference

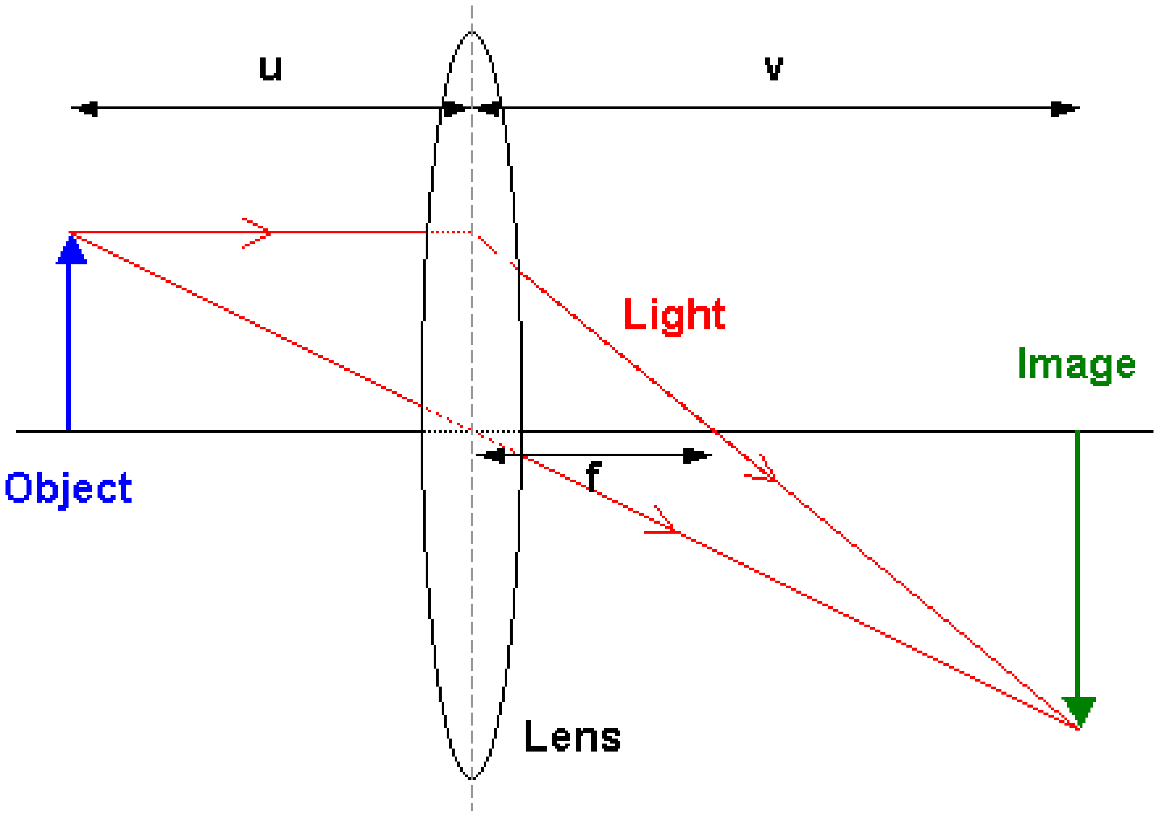
Inverted and different size



Convex Lens 1

Ray Diagrams

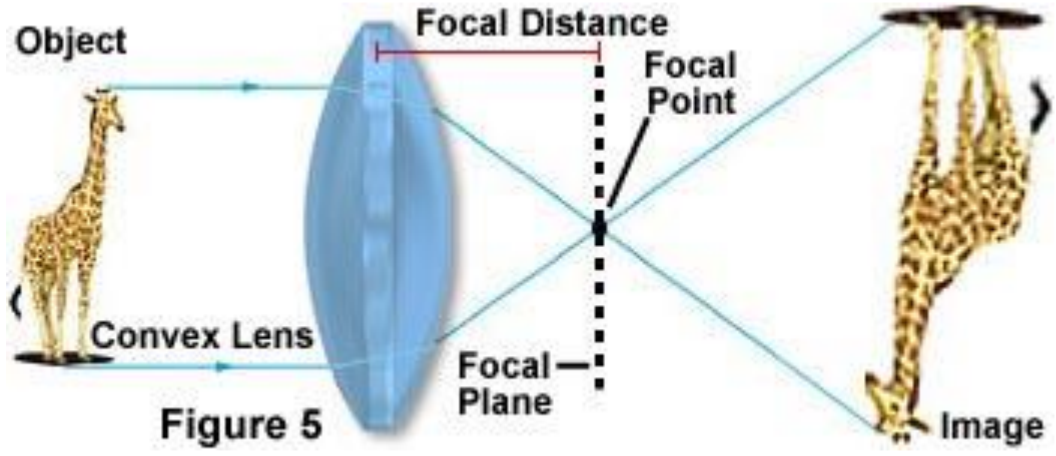
$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$$



- Inverted image
- The size of image depends on *f*

Convex Lens 2

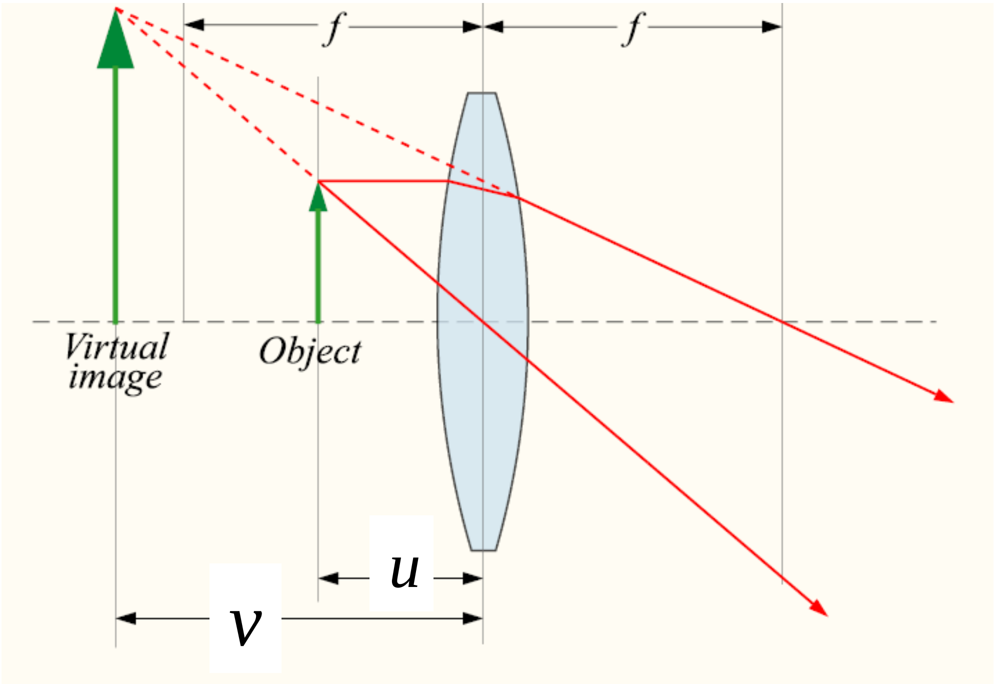
$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$$

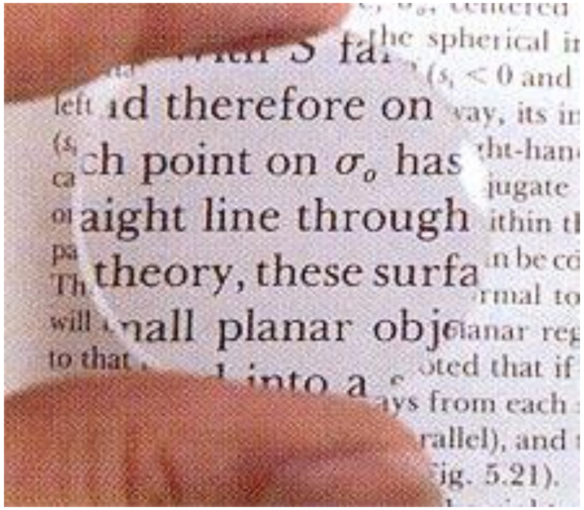


If $f < u < 2f$, then v is larger than u, *magnified and inverted image*

This is the typical case of microscope and camera

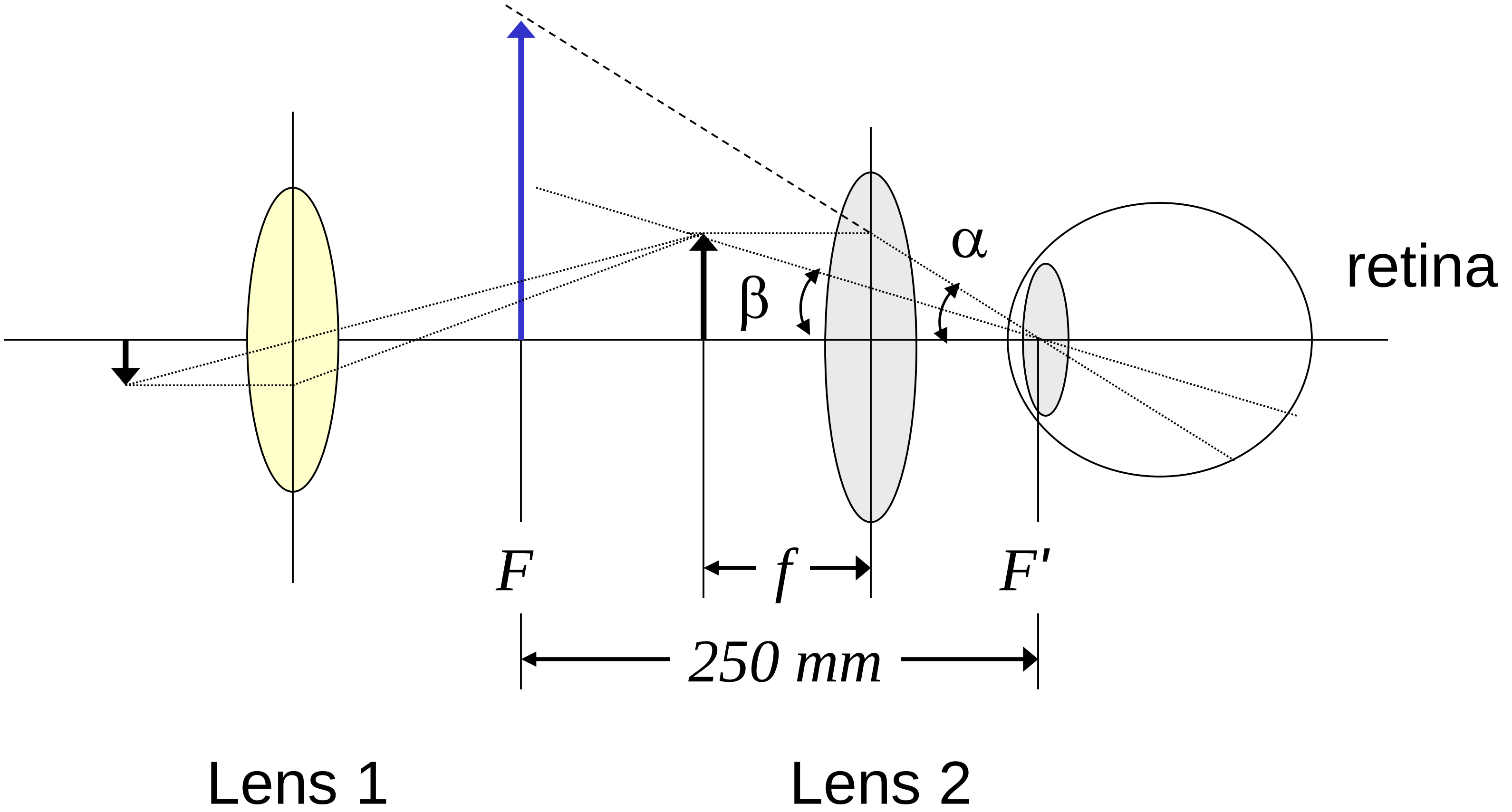
Convex Lens 3





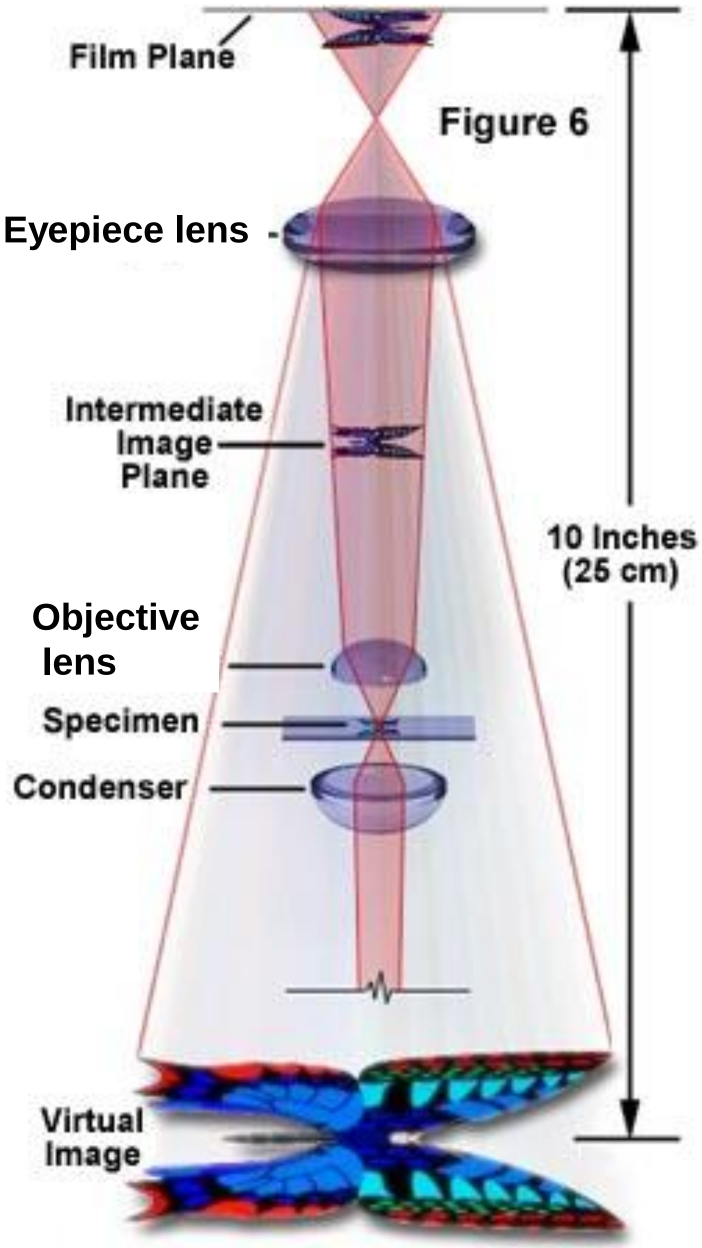
If $u < f$, then v is negative (image is located in front side) and *not inverted image. This is the typical magnification.*

Images After Two Successive Convex Lenses



You can see magnified inverted virtual image

Microscope with Two Convex Lenses



- Light is concentrated onto the **specimen** through the **condenser**.

- The objective lens produces a real, inverted, and magnified image of the specimen to a fixed plane (**intermediate** image plane).

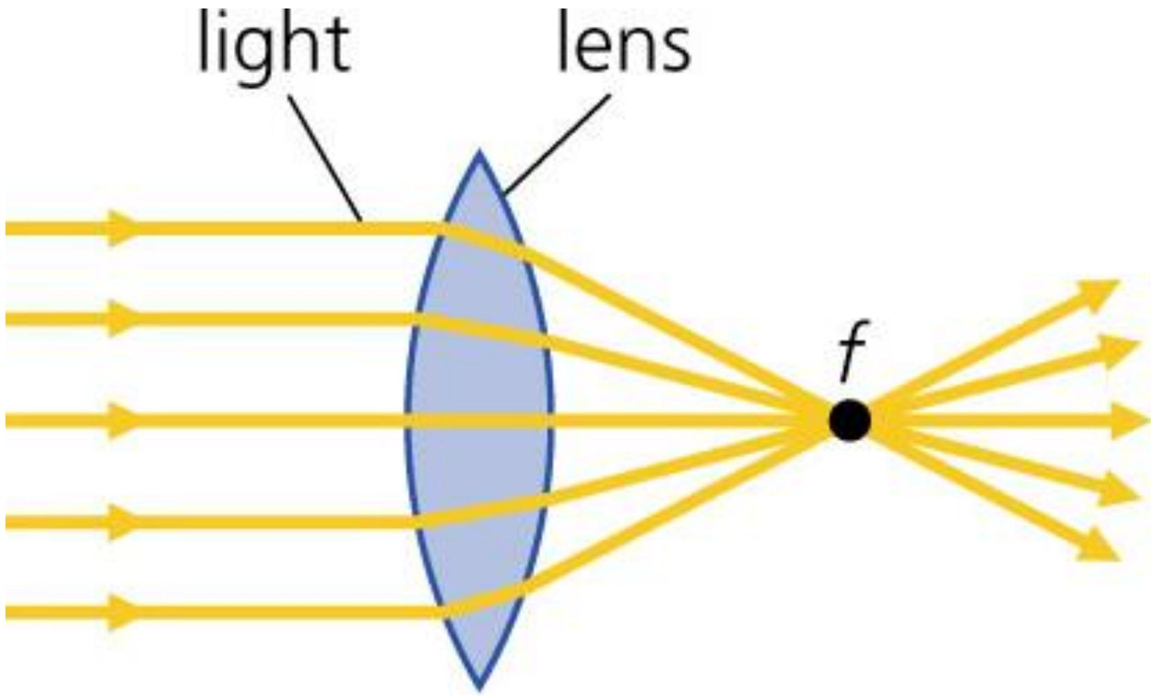
- The eyepiece lens produces further magnified virtual image at a distance of ~10 inches (250 mm) from the eye.

- Total **magnification** of the microscope:

Compound Microscopy

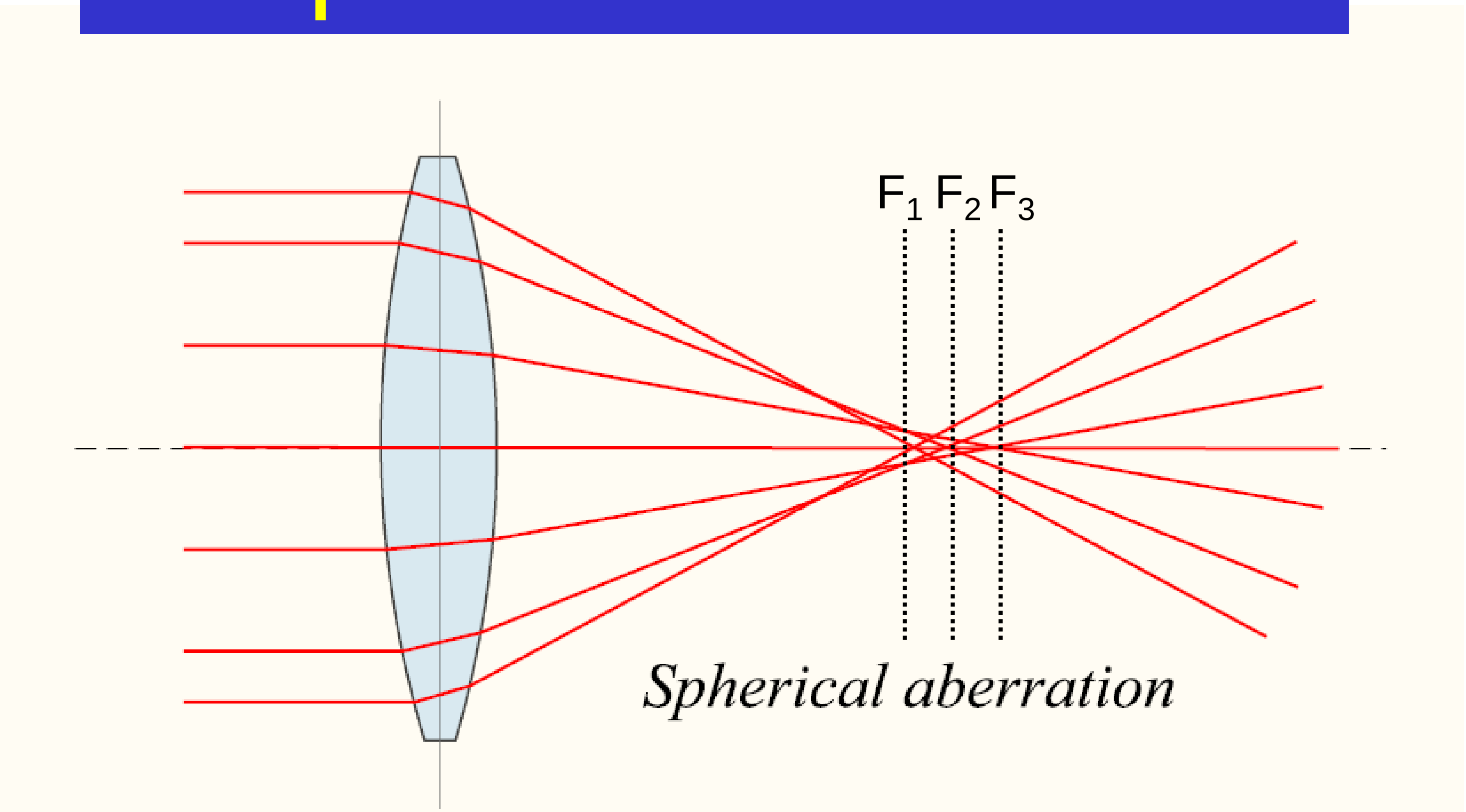
Aberration: Bad Images

Ideal Convex Lens



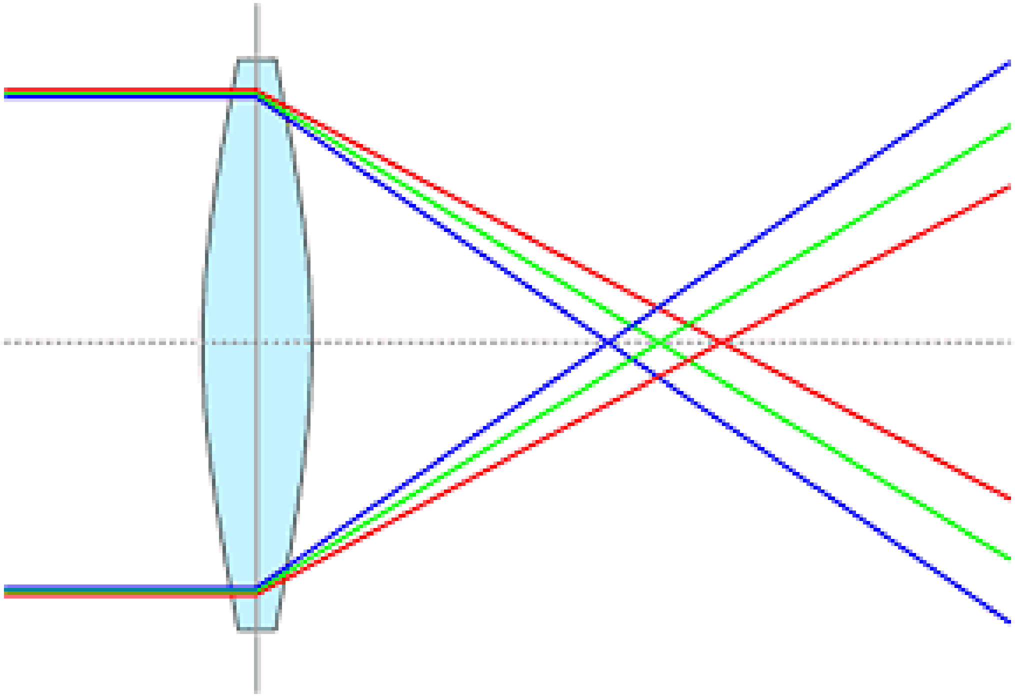
All rays should focus on one point

1. Spherical Aberration



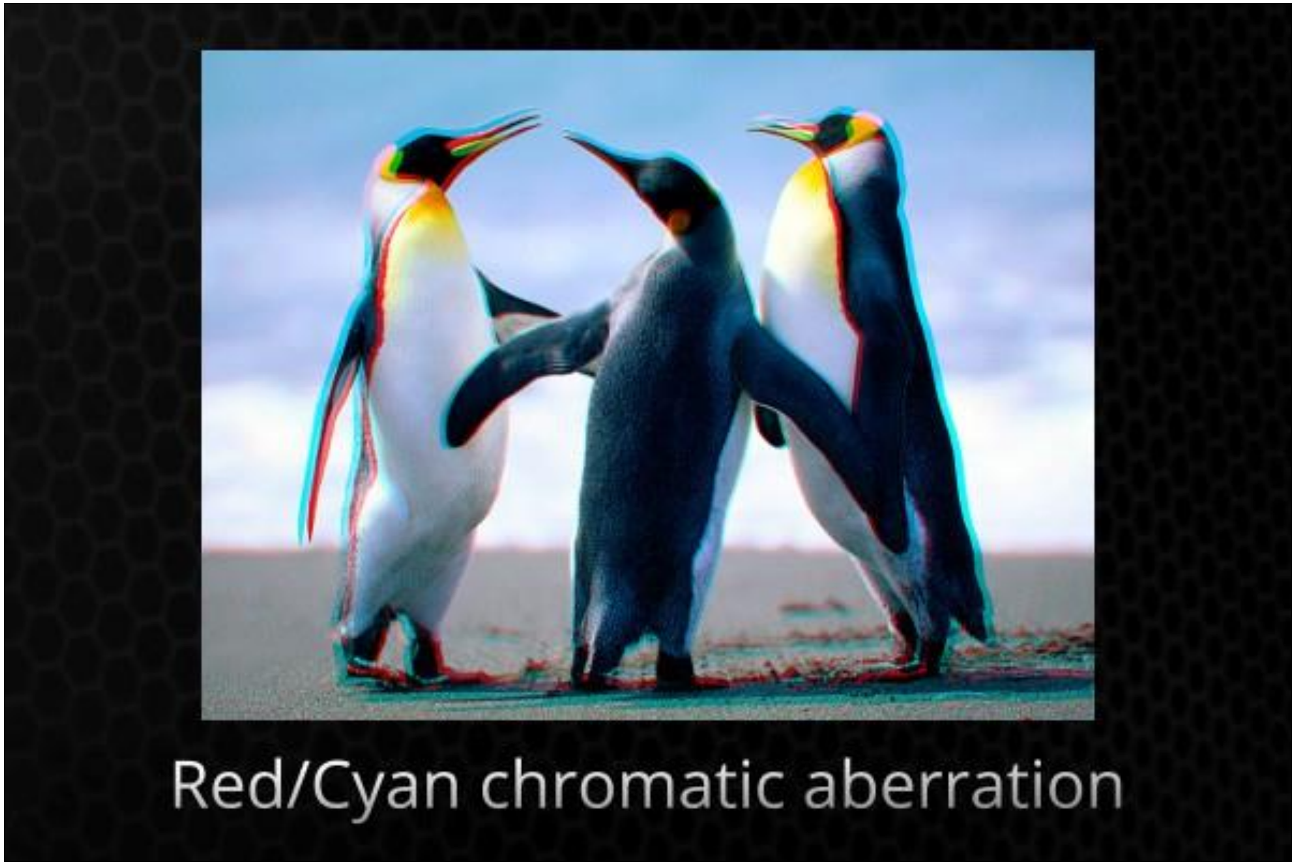
- lens surfaces are not the ideal spherical shape with which to make a lens.
- could be reduced by better mechanical manufacturing.
- Add collar adjustment ring to objective lens.

2. Chromatic Aberration

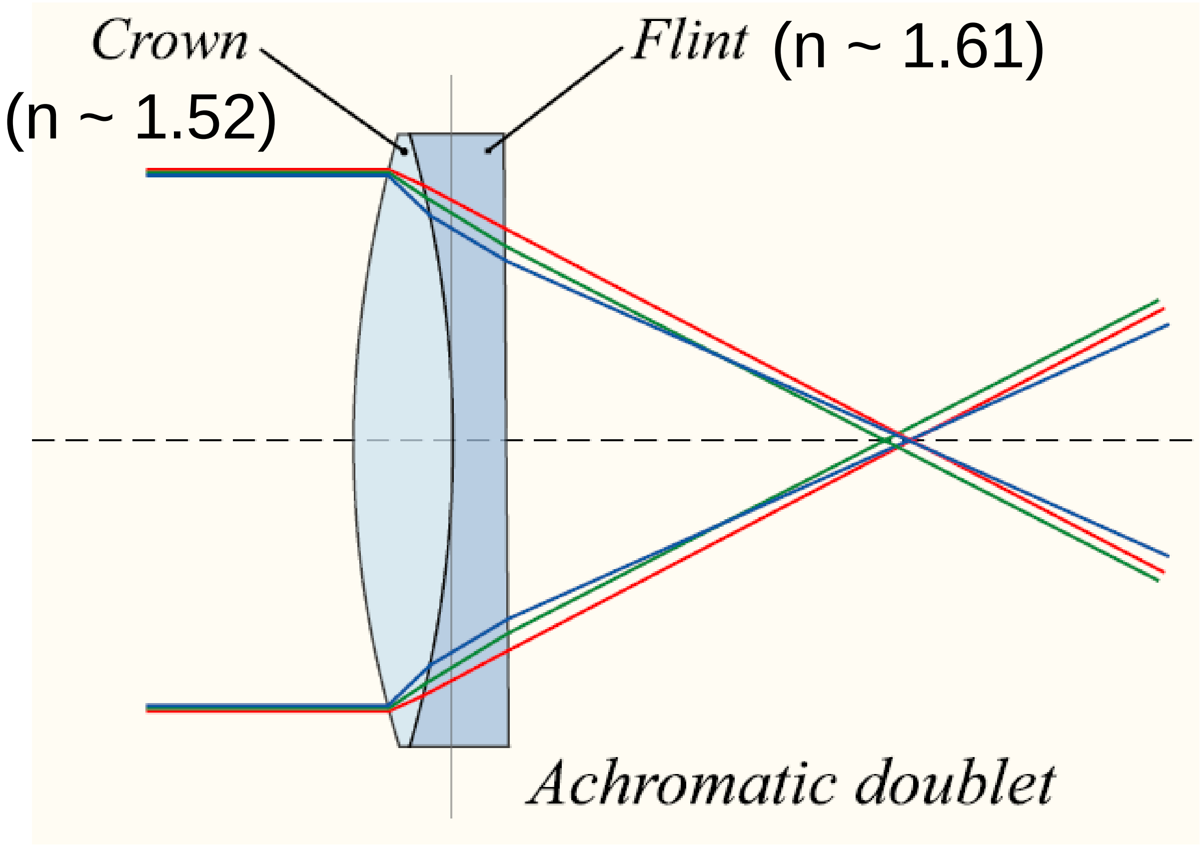


- Refractive index depends on wavelength
- The shorter the wavelength, the greater the refractive index, the more bent

Chromatic Aberration

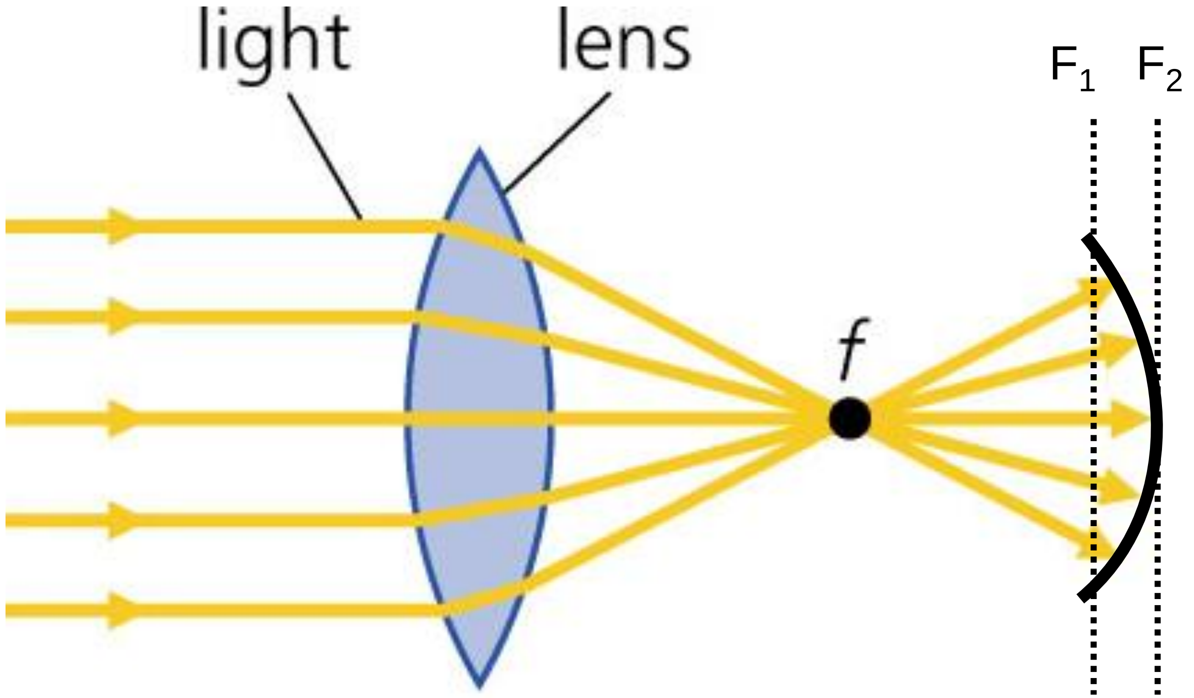


Doublet for Chromatic Aberration



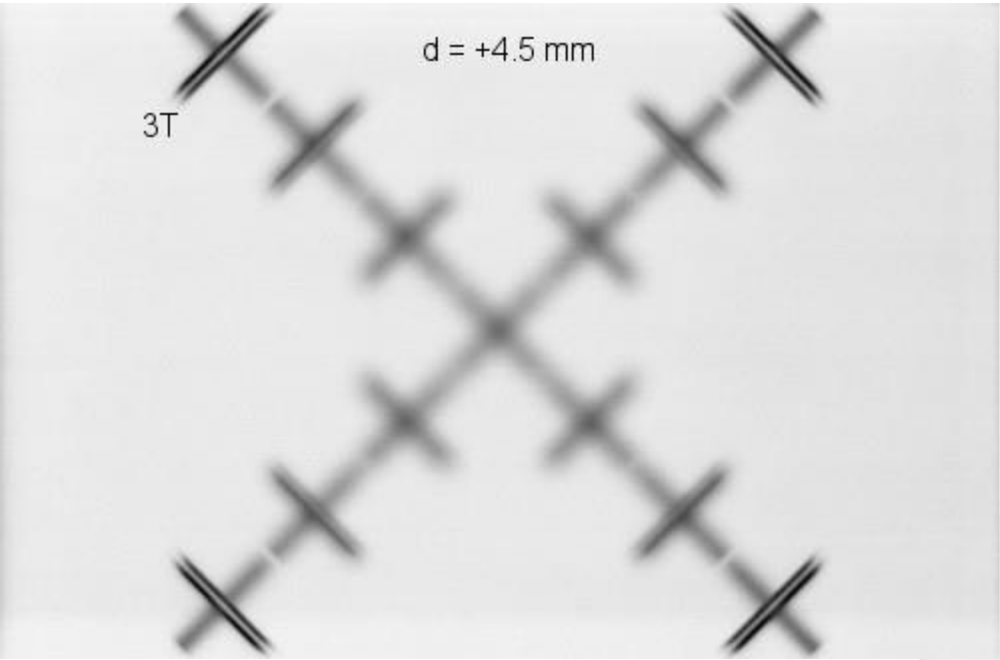
The use of a strong positive lens made from a low dispersion glass like crown glass coupled with a weaker high dispersion glass like flint glass (called achromat doublets) can correct the chromatic aberration for two colors, e.g., red and blue.

3. Field Curvature Aberration

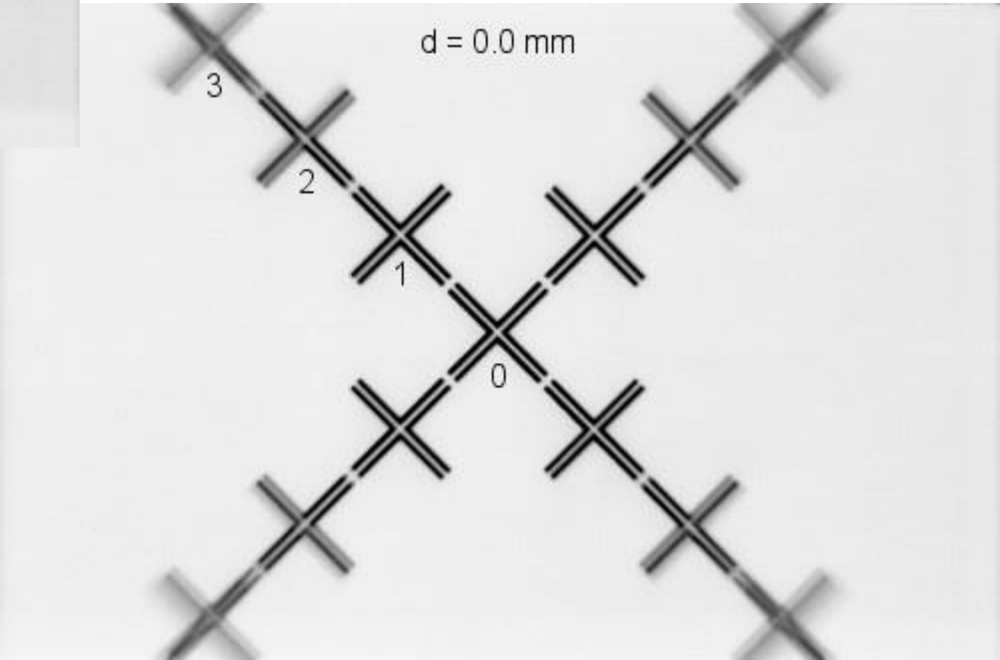


An optical aberration which results because the focal plane is actually not planar, but spherical

Images by Field Curvature

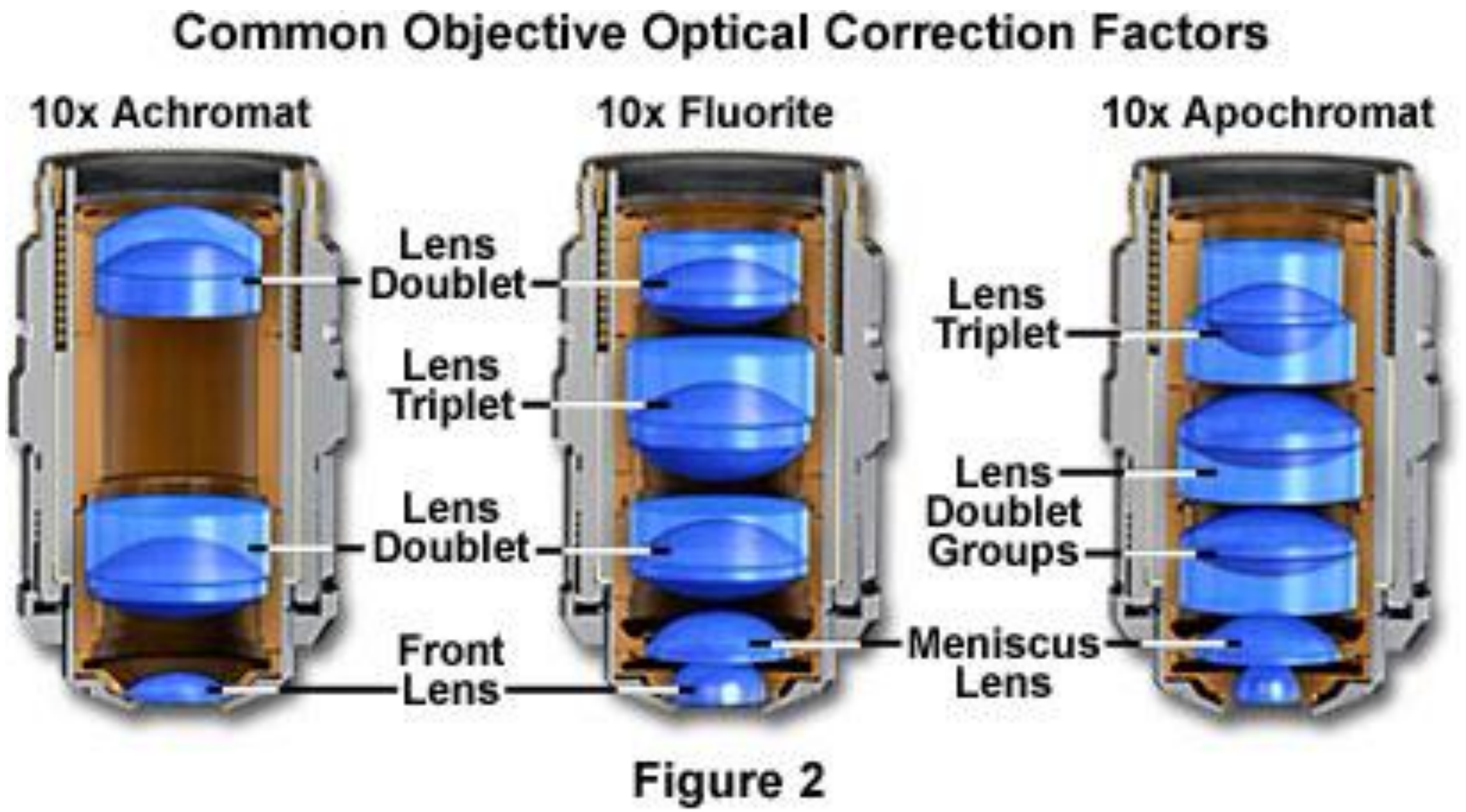


Focused on F_2 plane

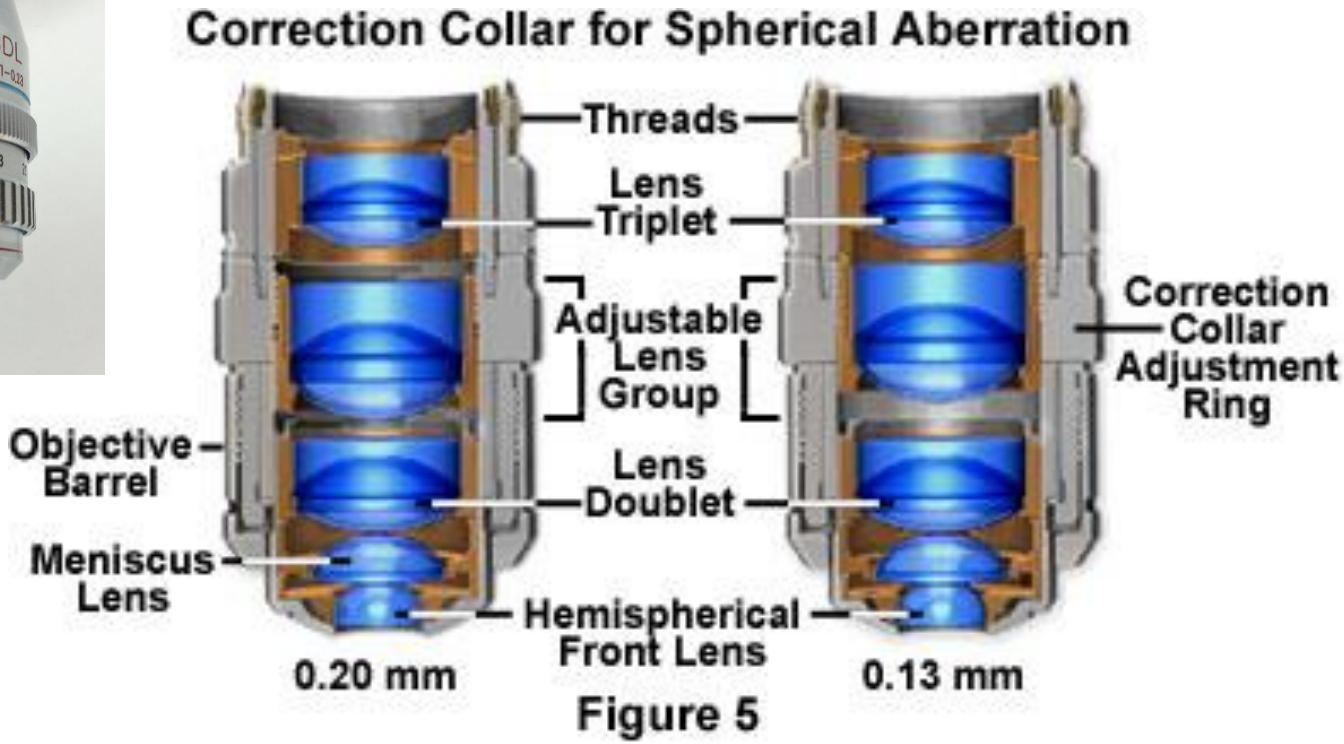


Focused on F_1 plane

Achromatic Aberration Corrected Lenses



Spherical Aberration Corrected Lenses



Plan Curvature Corrected Lenses

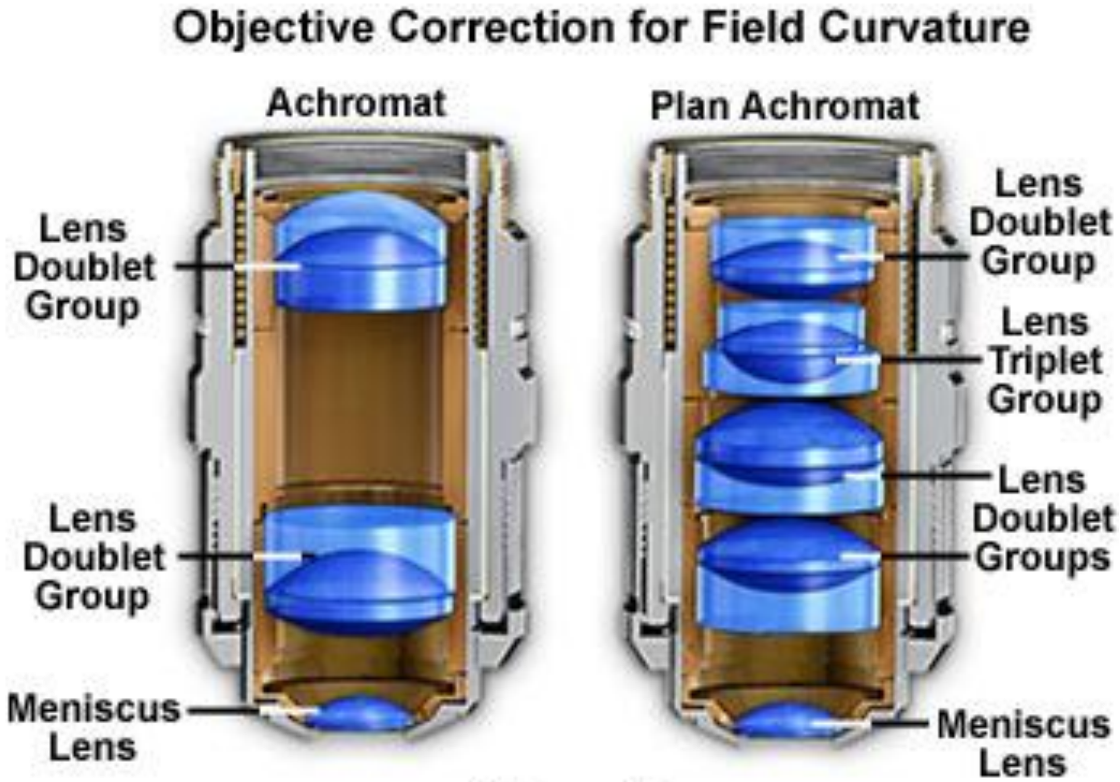


Figure 2

Corrected Objective Lenses

Objective Type	Spherical Aberration	Chromatic Aberration	Field Curvature
Achro(mat)	1 Color	2 Colors	No
Plan Achro(mat)	1 Color	2 Colors	Yes
Fluorite	2-3 Colors	2-3 Colors	No
Plan Fluorite	3-4 Colors	2-4 Colors	Yes
Plan Apochromat	3-4 Colors	4-5 Colors	Yes

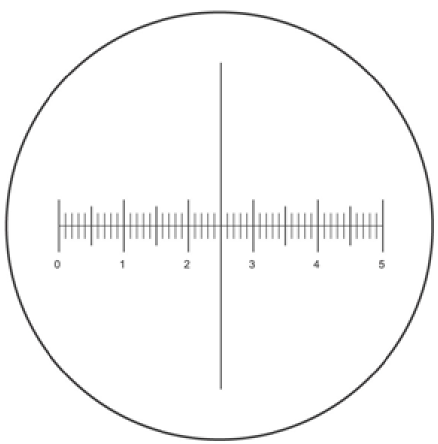
- Any of these can be corrected for field curvature-add a Plan prefix

Objective Lens

Eyepieces (X10)

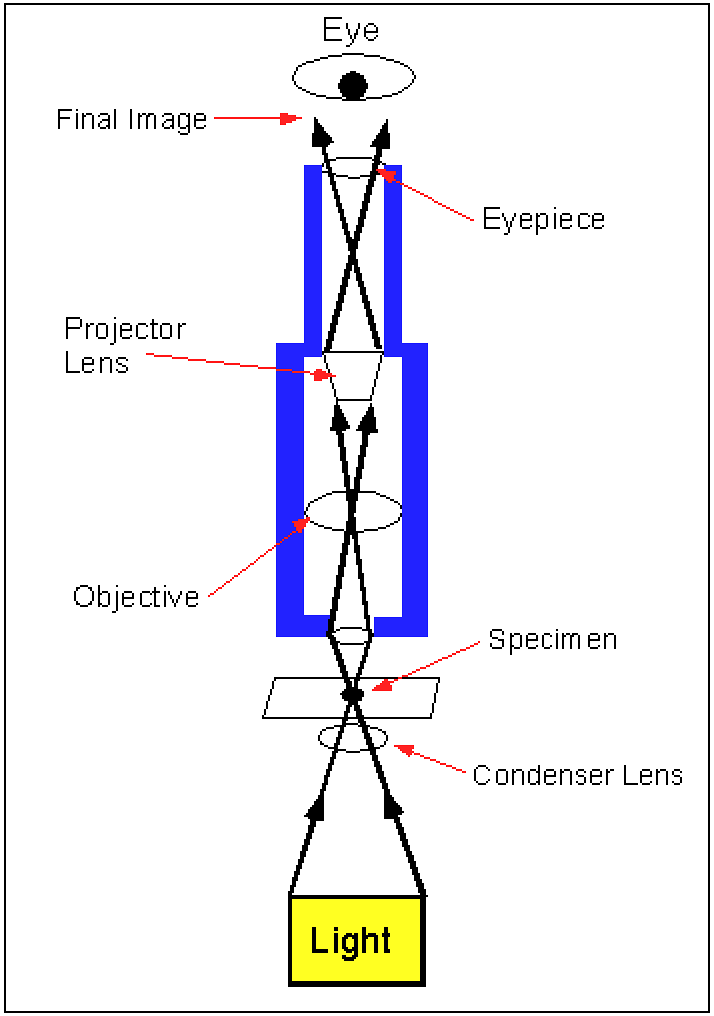
Typically X10 Magnification

WF (Wide Field): Large Image



Reticle: Size measurement

Alignment in Optical Microscope



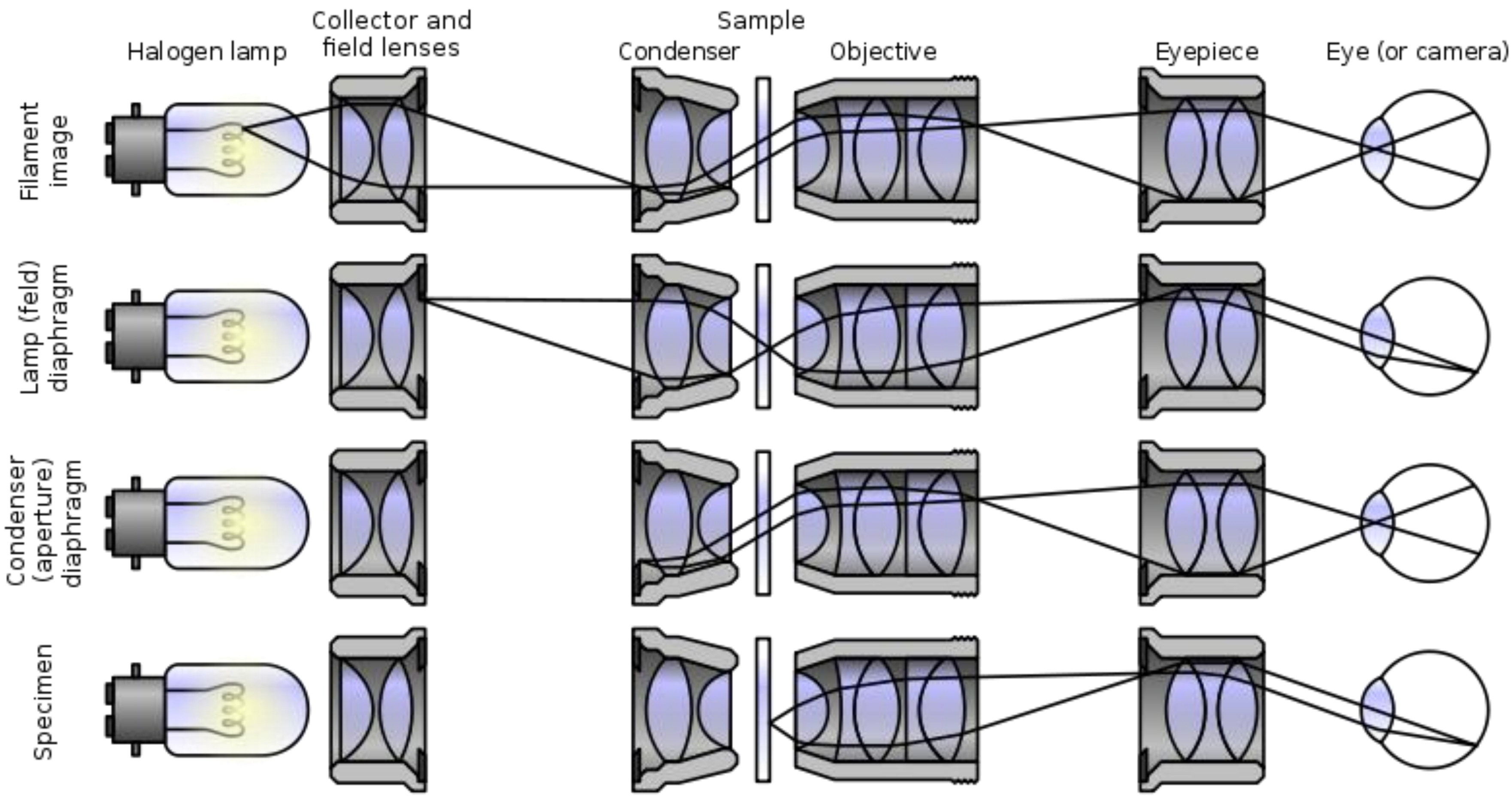
1. Sample should be focused
2. Light intensity should be homogeneous in the filed (light source, diaphragm, condenser)

Köehler illumination

Köehler illumination is a procedure for setting up and adjusting your microscope to achieve the best possible combination of contrast and resolution.

See manual

After Correct Köehler Illumination Adjustment



Exercise

1. How to find focal length

2. Koehler illumination