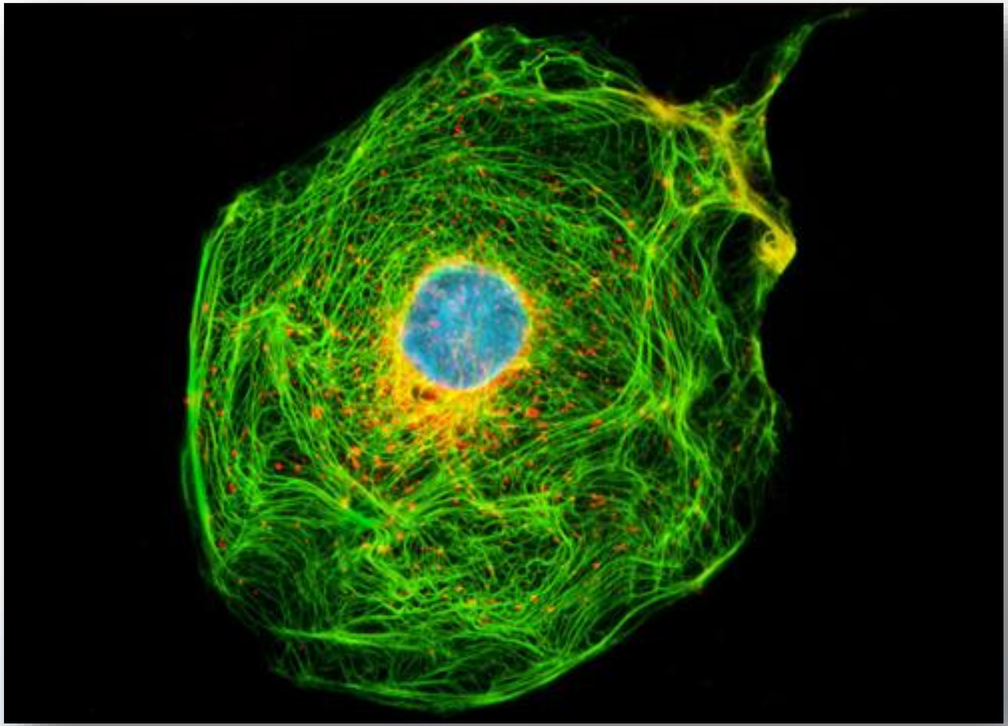


Phys 102 – Lecture 21

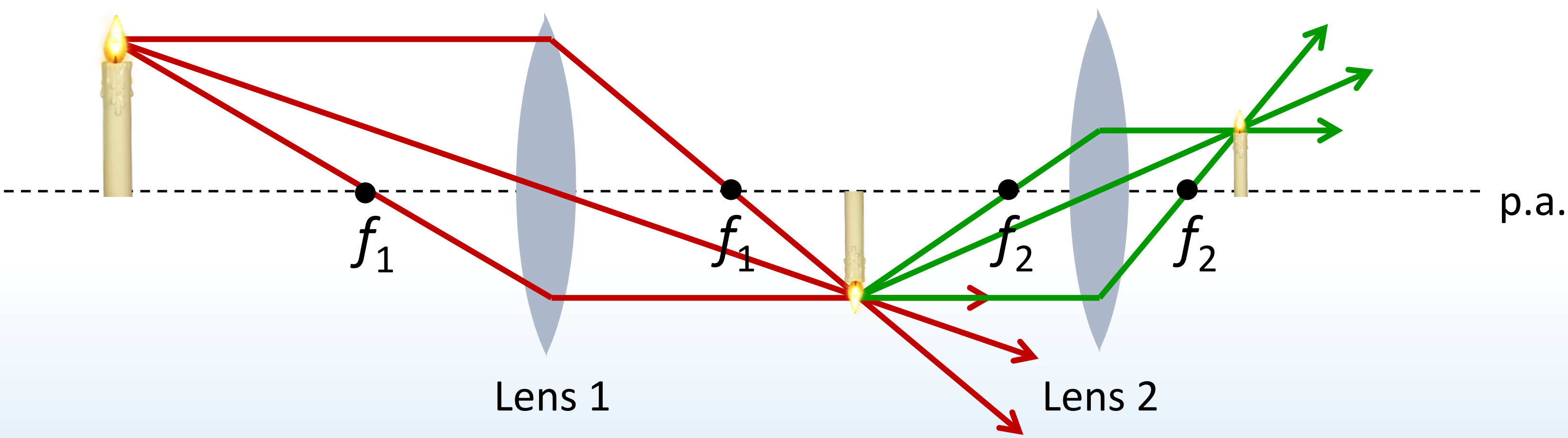
Optical instruments

Today we will...

- Learn how combinations of lenses form images
  - Thin lens equation & magnification
- Learn about the compound microscope
  - Eyepiece & objective
  - Total magnification
- Learn about limits to resolution
  - Spherical & chromatic aberrations
  - Dispersion

CheckPoint 1.1–1.2: multiple lenses

Image of first lens becomes object for second lens, etc...



Lens 1 creates a real, inverted and reduced image of the object 65%

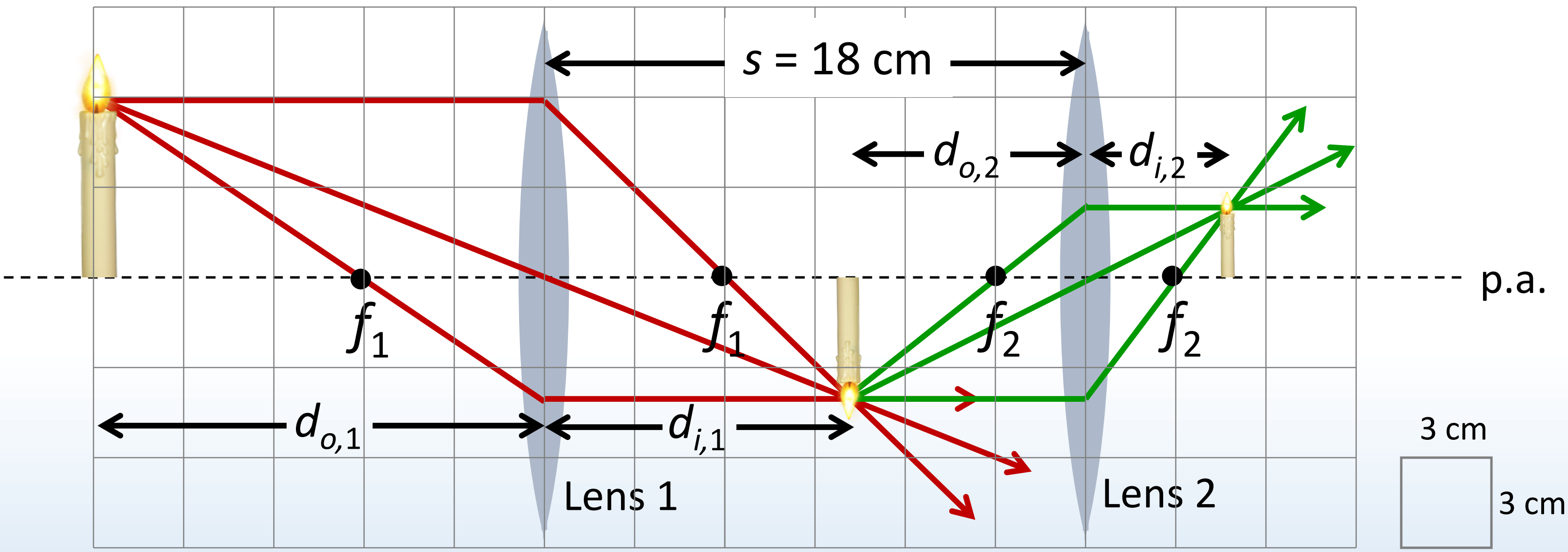
Lens 2 creates a real, inverted and reduced image of the image from lens 1

The combination gives a real, upright, reduced image of the object 52%

DEMO

Calculation: final image location

Determine the final image location for the 2-lens system



$$\frac{1}{d_{i,1}} = \frac{1}{f_1} - \frac{1}{d_{o,1}} = \frac{1}{6} - \frac{1}{15} = \frac{1}{10}$$

$$d_{i,1} + d_{o,2} = s \qquad d_{o,2} = 18 - 10 = 8\,\text{cm}$$

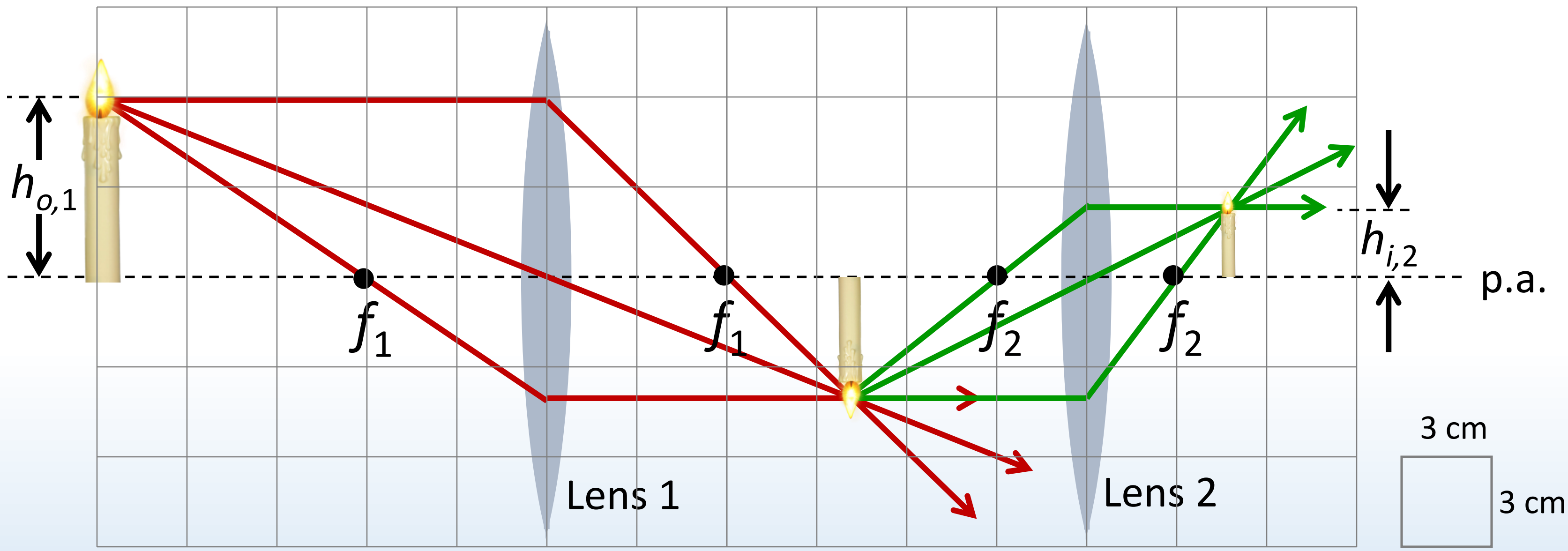
$$\frac{1}{d_{i,2}} = \frac{1}{f_2} - \frac{1}{d_{o,2}} = \frac{1}{3} - \frac{1}{8} = \frac{1}{4.8}$$

$$d_{i,2} = 4.8\,\text{cm}$$

Diagram should agree!

Calculation: final magnification

Determine the final image size for the 2-lens system



$$m_{tot} = m_1 m_2 = \frac{h_{i,1}}{h_{o,1}} \frac{h_{i,2}}{h_{o,2}} = \frac{h_{i,2}}{h_{o,1}}$$

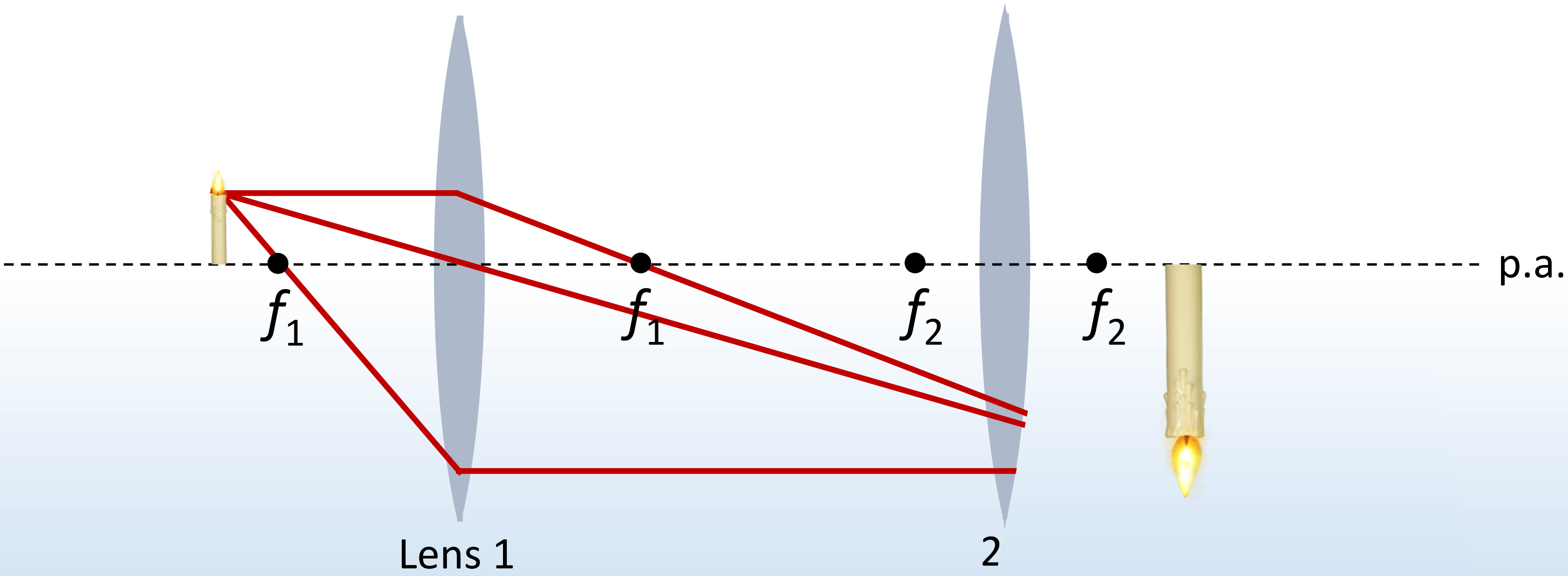
$$= \left(-\frac{d_{i,1}}{d_{o,1}}\right)\left(-\frac{d_{i,2}}{d_{o,2}}\right) = \left(-\frac{10}{15}\right)\left(-\frac{4.8}{8}\right) = +0.4$$

$$h_{i,2} = m_{tot} h_{o,2} = +0.4 \cdot 6 = +2.4\,\text{cm}$$

Upright, reduced image

ACT: CheckPoint 1.3

Now, the second converging lens is placed to the left of the first lens' image.



Which statement is true?

30% A. Lens 2 has no object

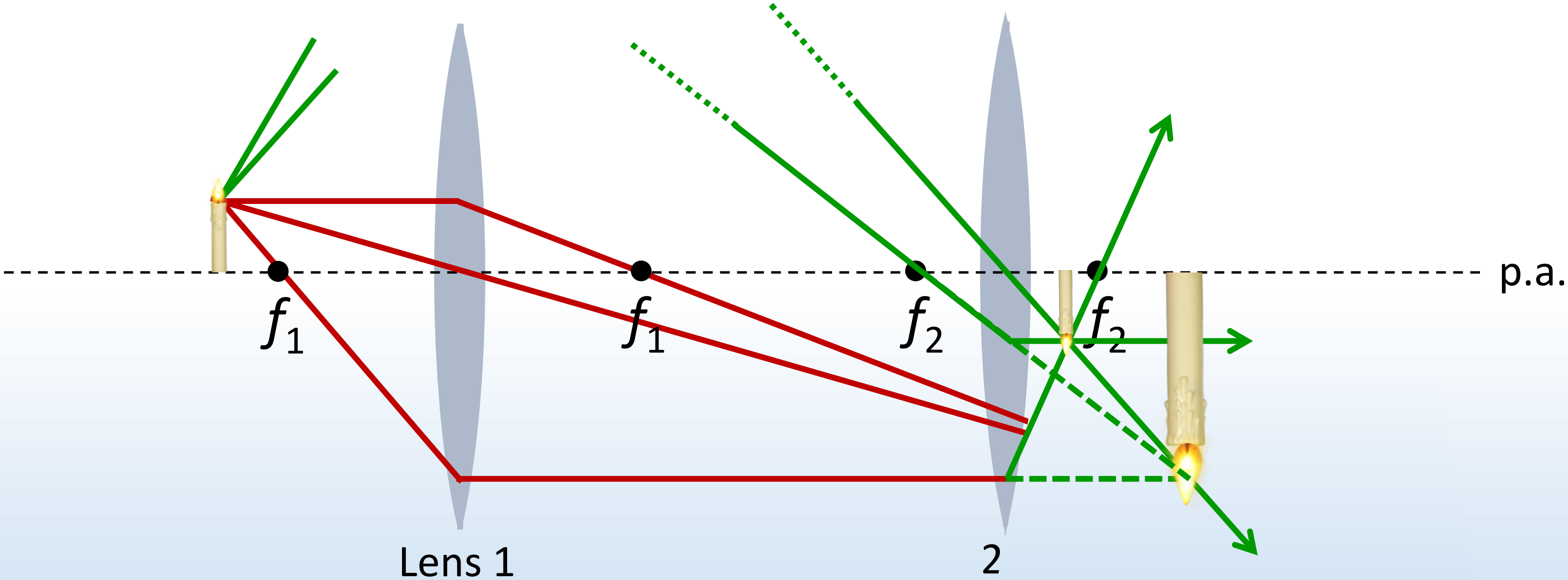
38% B. Lens 2 has a real object

32% C. Lens 2 has a virtual object

Object after lens 2 is virtual: $d_{o,2} < 0$
Image still forms but rays seem to originate from point after lens 2

ACT: CheckPoint 1.4

Now, the second converging lens is placed to the left of the first lens' image.



What is the image formed from lens 2?

33% A. There is no image

36% B. Real

31% C. Virtual

$$\frac{1}{d_{i,2}} = \frac{1}{f_2} - \frac{1}{d_{o,2}}$$

$d_{o,2} < 0$, so $d_{i,2} > 0$

Lens combination: summary

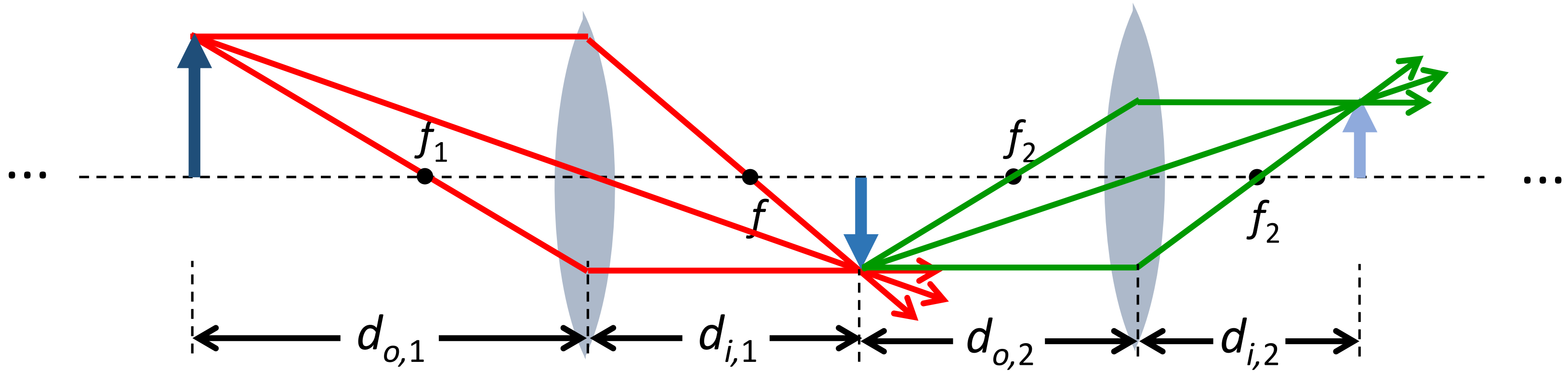


Image of first lens becomes object of second lens, ...

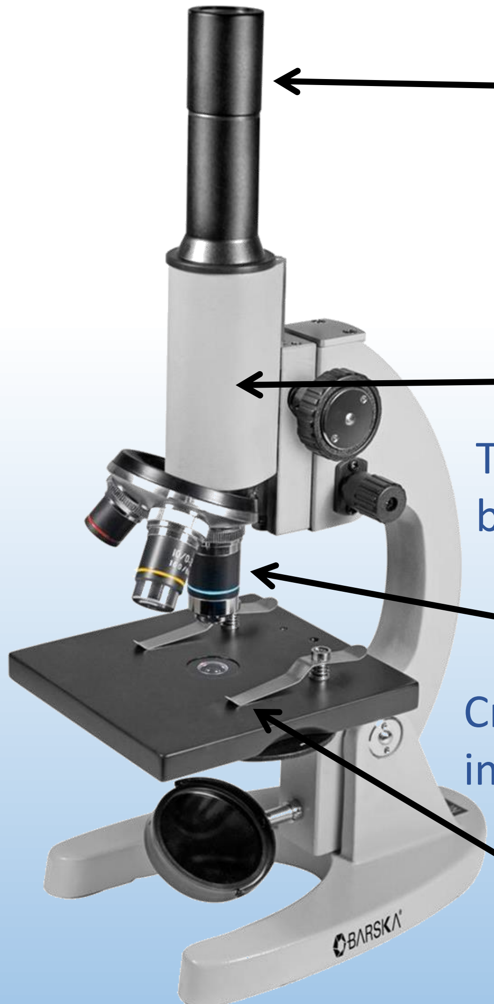
$$m_{tot} = m_1 m_2 m_3 ...$$

- d_o = distance object is from lens:
  - > 0: real object (before lens)
  - < 0: virtual object (after lens)
- d_i = distance image is from lens:
  - > 0: real image (after lens)
  - < 0: virtual image (before lens)
- f = focal length lens:
  - > 0: converging lens
  - < 0: diverging lens

Watch your signs!

Compound microscope

A compound microscope is made up of two converging lenses



Eyepiece (ocular)

Acts as a magnifying glass

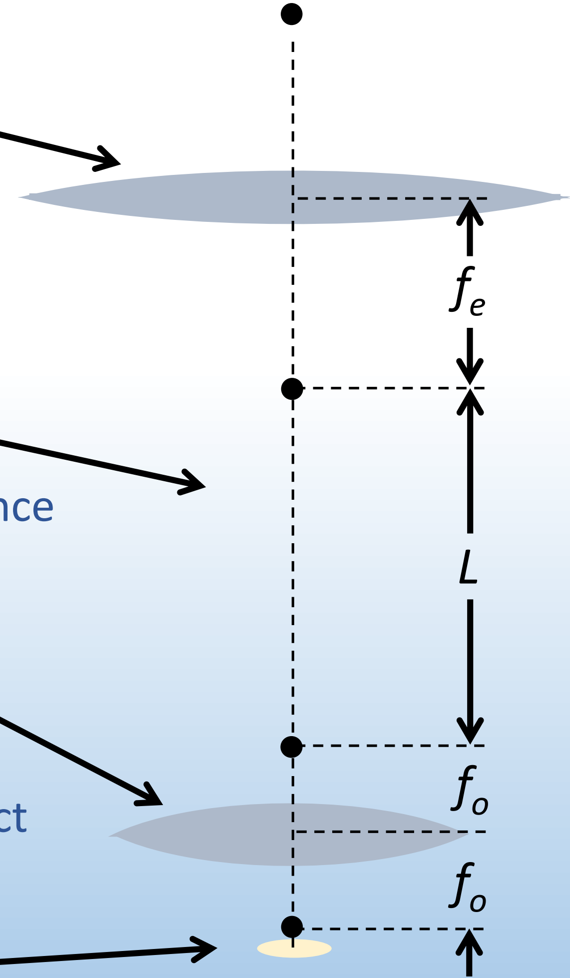
Body tube

Tube length *L* = distance between focal points

Objective

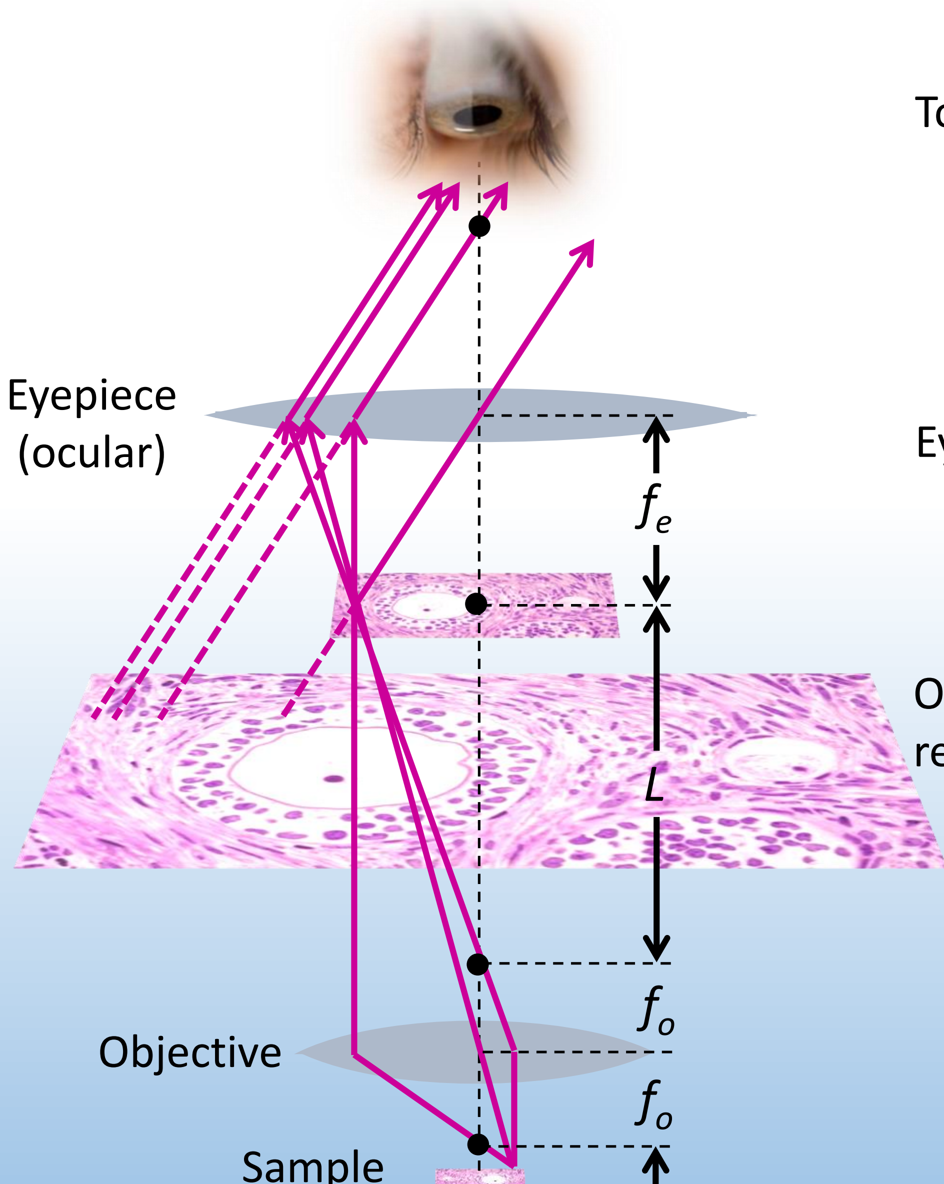
Creates real, enlarged image of sample object

Sample



DEMO

Microscope ray diagram



Total image magnification:

$$M_{tot} = M_e m_o = -\frac{d_{near}}{f_e}\frac{L}{f_o}$$

Eyepiece creates virtual, upright image at ∞

$$M_e = \frac{d_{near}}{f_e}$$ Recall Lect. 20

Object just past objective focal pt. creates real, inverted image at eyepiece focal pt.

$$\frac{1}{d_i} = \frac{1}{f_o} - \frac{1}{d_o}$$

$$1 = \frac{d_i}{f_o} - \frac{d_i}{d_o} = \frac{L + f_o}{f_o} + m_o$$

$$m_o = -\frac{d_i}{d_o} = -\frac{L}{f_o}$$

ACT: Microscope eyepiece

The magnification written on a microscope eyepiece assumes the user has "normal" adult vision

10× means M_e = 10

$$M_e = \frac{d_{near}}{f_e}$$

In normal vision d_{near} = 25 cm

$$f_e = \frac{d_{near}}{M_e} = \frac{25}{10} = 2.5\,\text{cm}$$

What is the focal length of a 10× eyepiece?

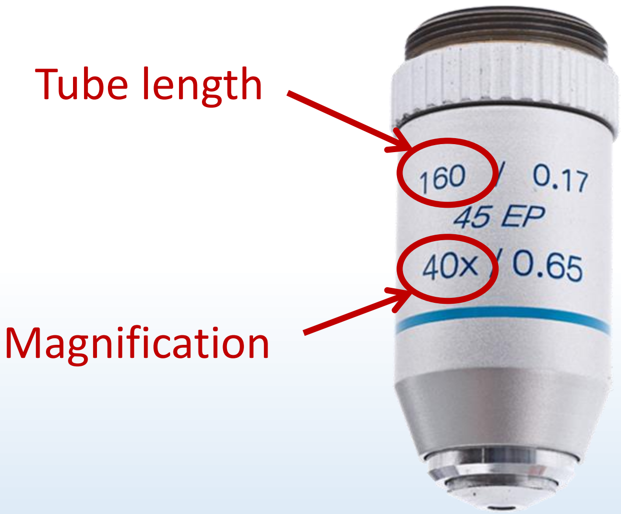
A. f_e = 2.5 cm

B. f_e = 10 cm

C. f_e = 25 cm

ACT: Microscope objective

A standard biological microscope has a 160 mm tube length and is equipped with a 40× objective



40× means $m_o = -40$

$$m_o = -\frac{L}{f_o}$$

$$f_o = -\frac{160}{-40} = 4\text{mm}$$

What is the focal length of the objective?

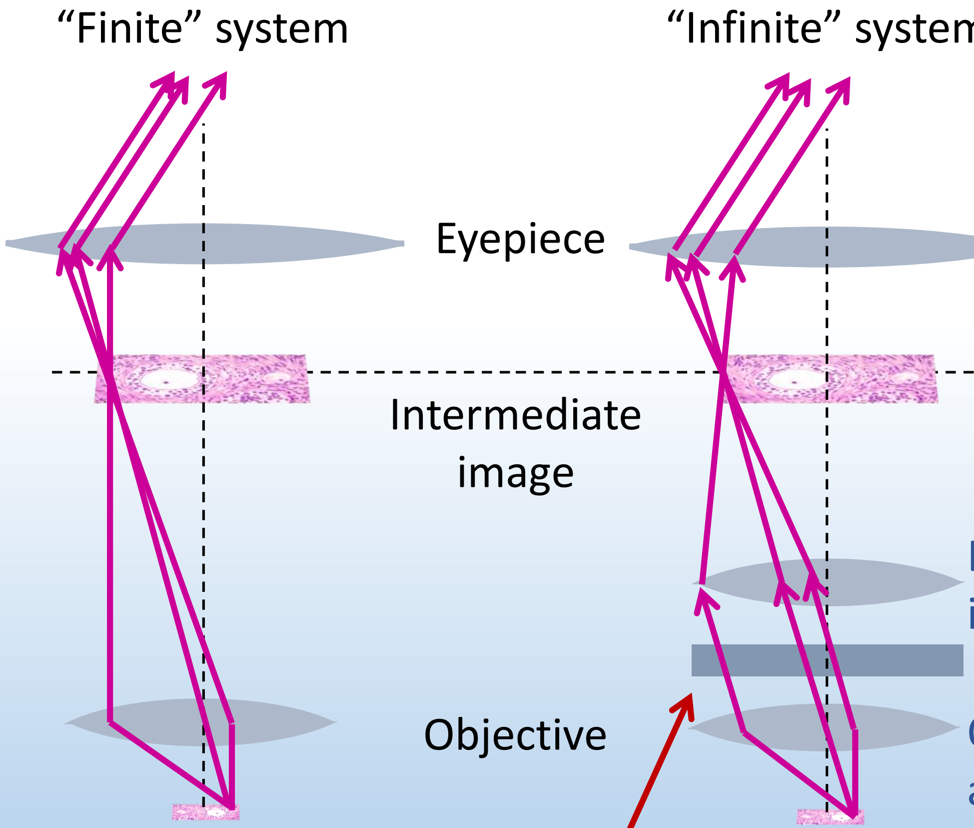
A. $f_o = 4$ mm

B. $f_o = 8$ mm

C. $f_o = 16$ mm

Modern microscope objectives

Most modern objectives are "infinity corrected"



Extra "tube" lens creates intermediate image

Objective creates image at ∞; rays are ||

Infinite system allows filters to be inserted in optical path without affecting image

Calculation: Angular size

A microscope has a 10× eyepiece and a 60× objective. How much larger does the microscope image appear to our eyes?

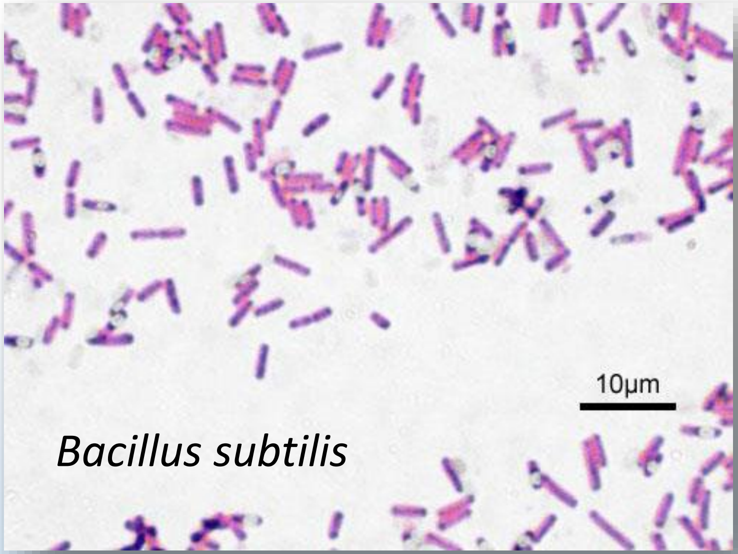
$$M_{tot} = M_e m_o = \frac{\theta_{mic}}{\theta_{unaided}}$$
$$= -600$$

At a near pt. of 25 cm, a 2-μm bacterium has angular size to an unaided eye of:

$$\theta_{unaided} \approx \frac{h_o}{d_{near}} = \frac{2\times10^{-6}}{0.25} = 8\times10^{-6}\,\text{rad}$$

In the microscope the angular size is:

$$\left|\theta_{mic}\right| = 600\cdot 8\times10^{-6} = 4.8\times10^{-3}\,\text{rad}$$



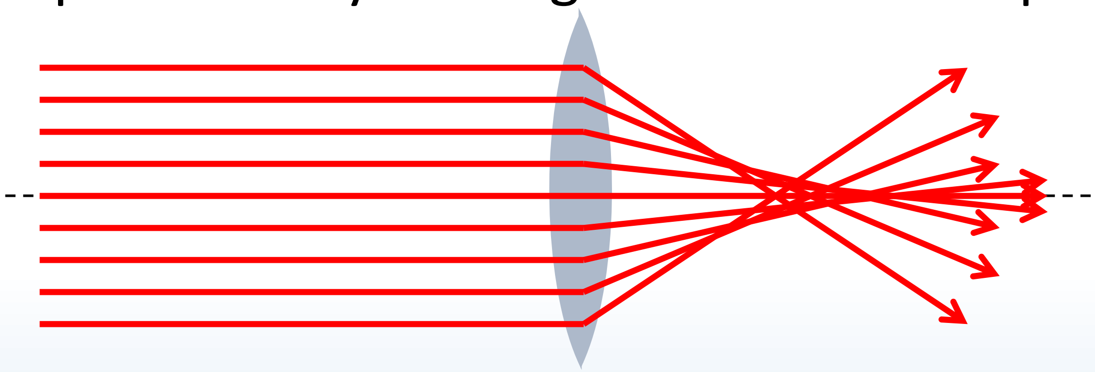
Equivalent to a 600 × 2 μm = 1.2 mm object at 25 cm

What limits the resolution of a light microscope?

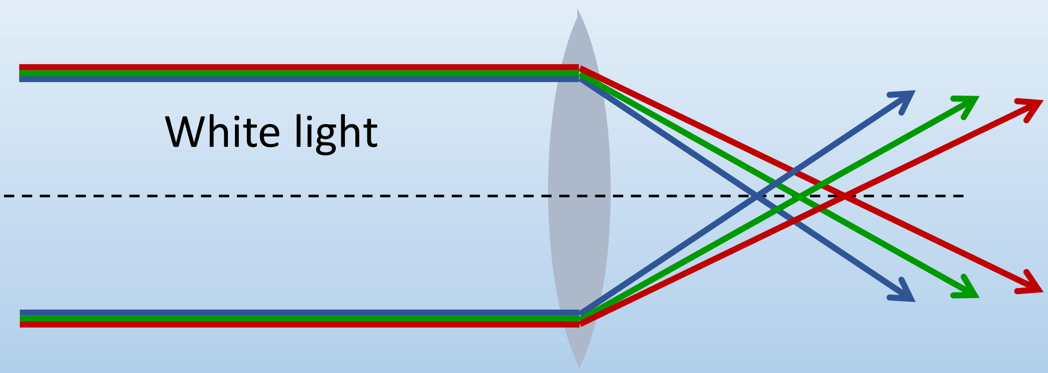
Aberrations

<u>Aberrations</u> are imperfections relative to ideal lens

Spherical: rays hitting lens at different points focus differently



Chromatic: rays of different color focus differently



Where do chromatic aberrations come from?

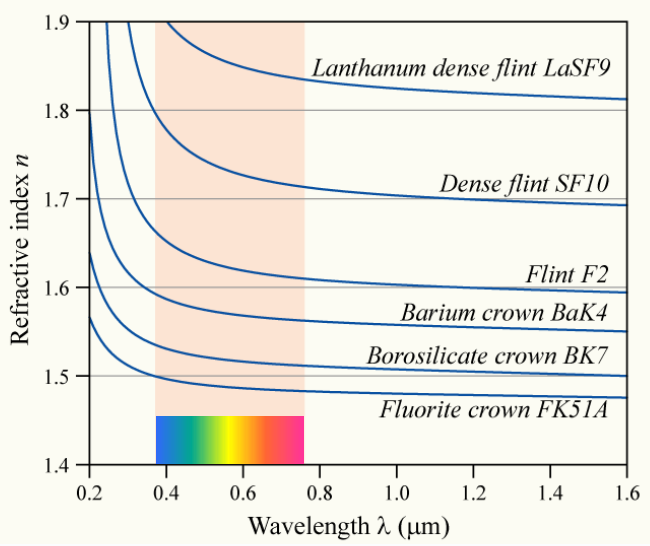
DEMO

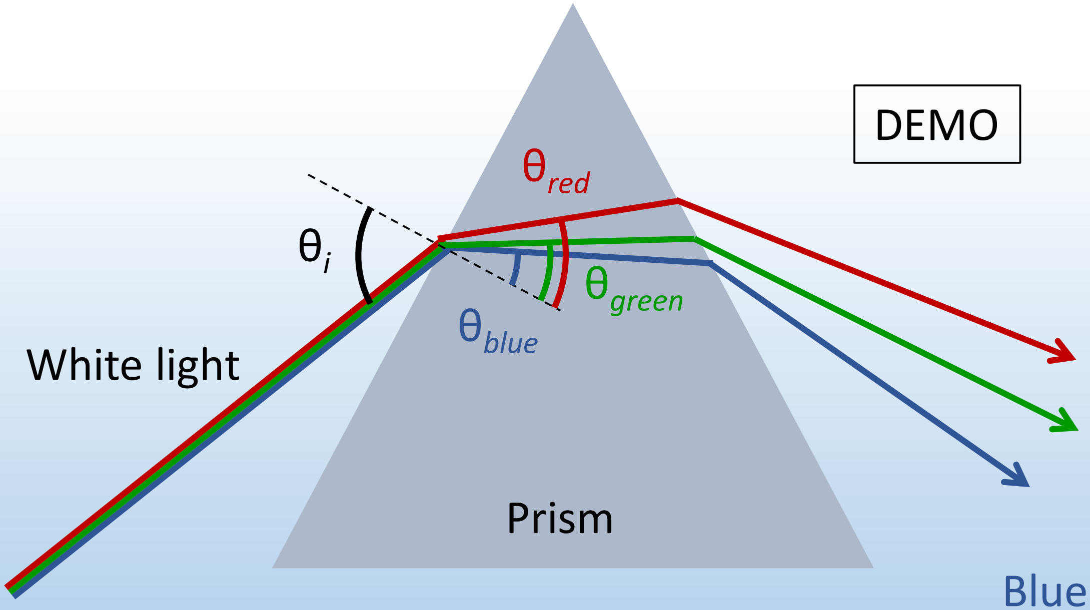
Dispersion

The index of refraction n depends on λ

In glass, $n_{blue} > n_{green} > n_{red}$

In prism, $\theta_{blue} < \theta_{green} < \theta_{red}$





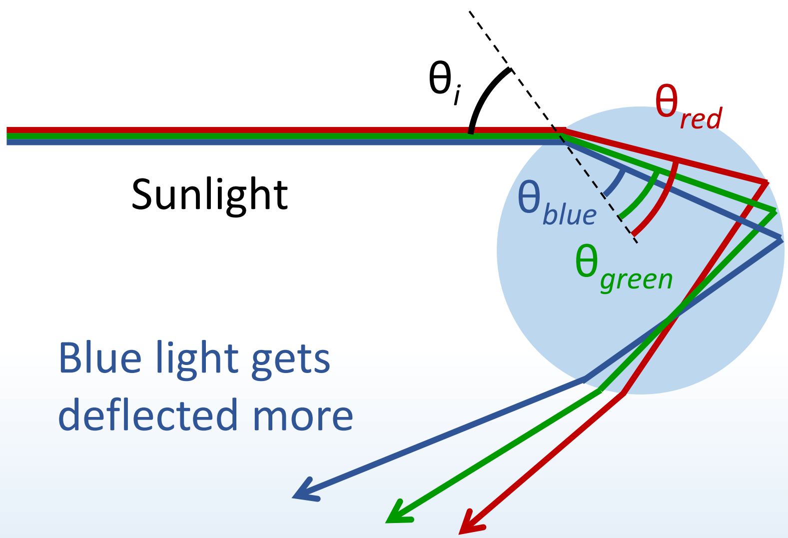
DEMO

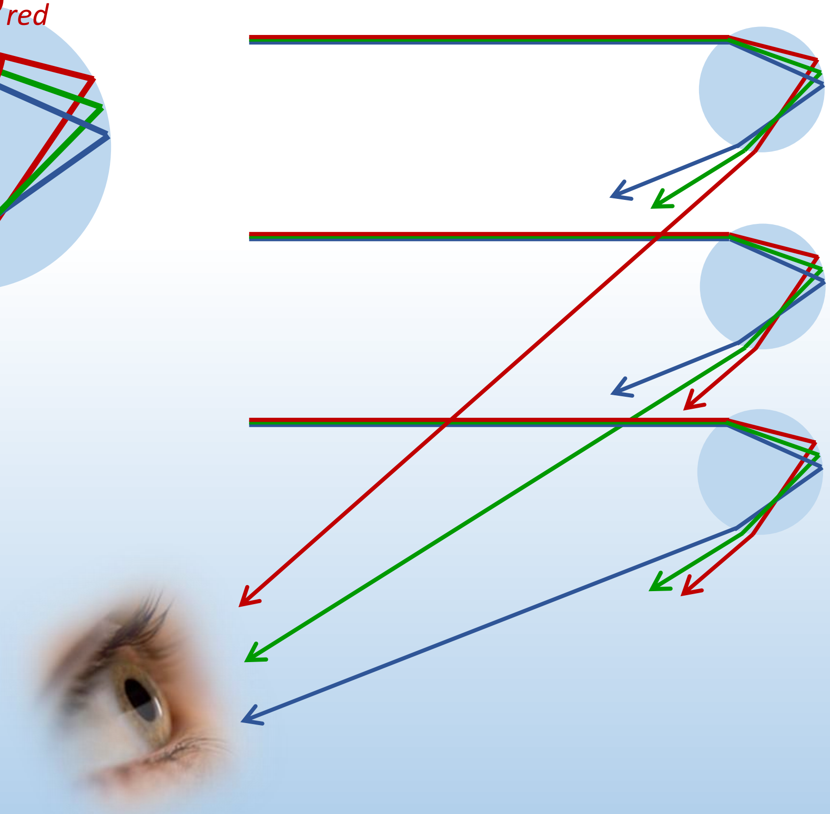
Blue light gets deflected more

$$n_i \sin\theta_i = n_{blue} \sin\theta_{blue} = n_{green} \sin\theta_{green} = n_{red} \sin\theta_{red}$$

CheckPoint 2.1: Rainbows

Dispersion in water droplets create rainbows





In water, $n_{blue} > n_{green} > n_{red}$

Red rays from higher droplet, blue rays from lower droplet reach eye

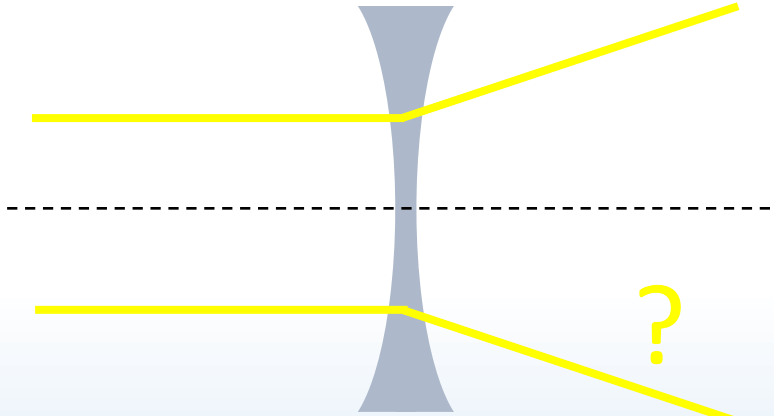
See a rainbow with red on top, blue on the bottom 53%

Double rainbow

[Double rainbow]

ACT: Dispersion

A diverging lens made of flint glass has n_{red} = 1.57, n_{blue} = 1.59. Parallel rays of white light are incident on the lens.

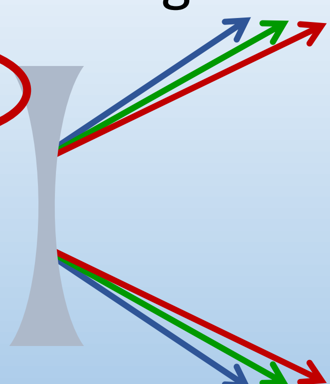


$n_{blue} > n_{red}$

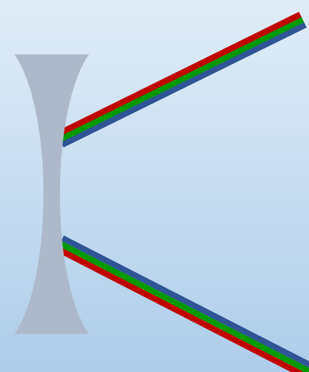
Blue light gets deflected more

Which diagram best represents how light is transmitted?

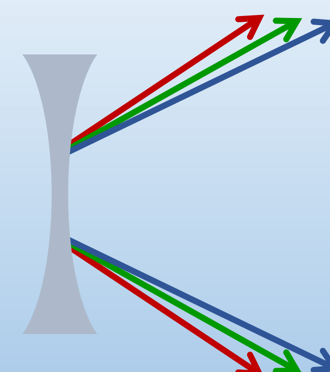
A.



B.



C.



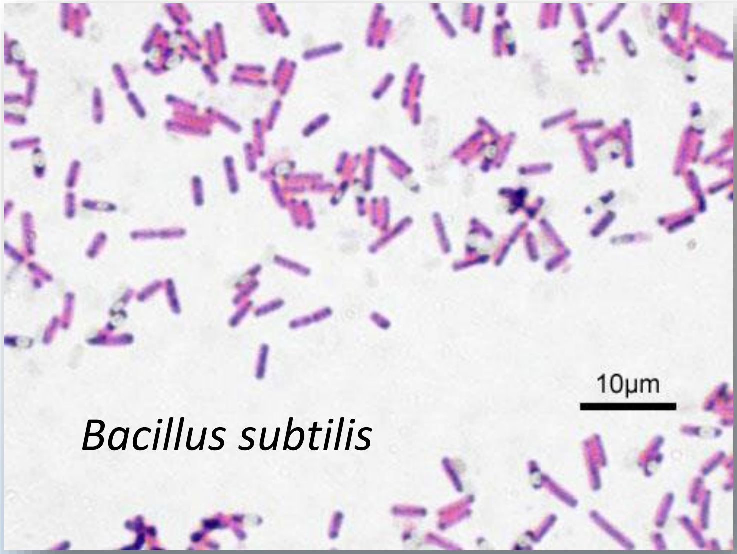
Ultimate limit of resolution

One can play clever tricks with combinations of lenses to compensate for spherical and chromatic aberrations

Ultimately, even with *ideal* lenses resolution of light microscope is limited to ~λ of light (~500 nm)

We won't understand why using *ray picture* of light; we have to treat light as a *wave* again

Next two lectures!



Ray optics works for objects >> λ

Summary of today's lecture

- Combinations of lenses:

  Image of first lens is object of second lens... Watch signs!

- The compound microscope

  Objective forms real image at focal pt. of eyepiece

  Eyepiece forms virtual image at ∞

- Limits to resolution

  Spherical & chromatic aberrations

  Dispersion

  Diffraction limit – next week!