

# ***Your questions/comments***

## **IMPORTANT ANNOUNCEMENT:**

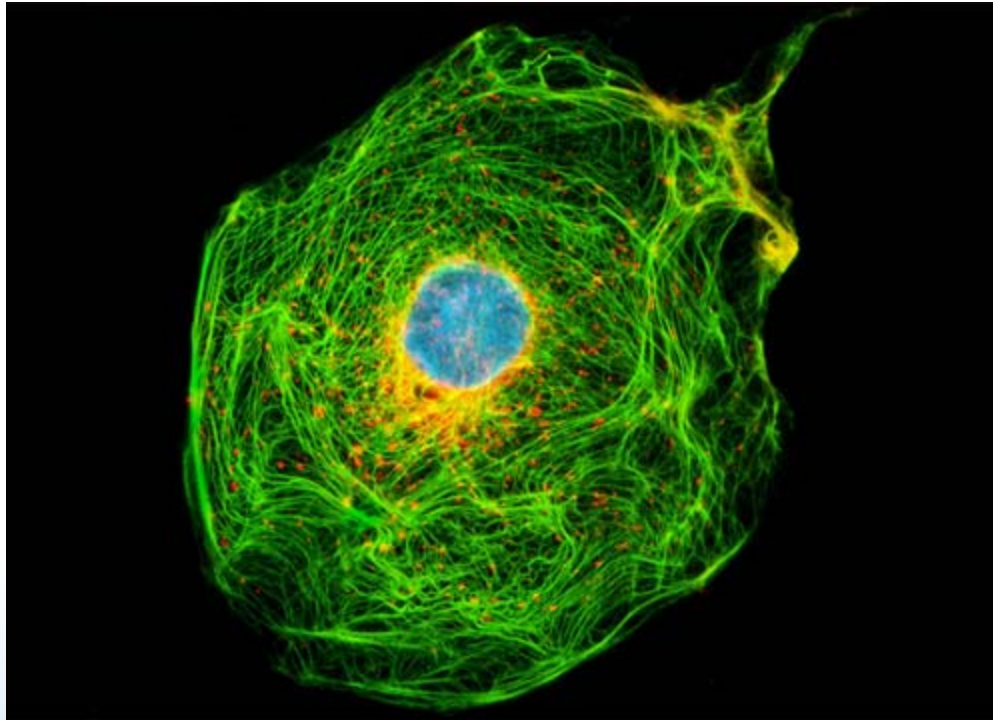
EXAM 3 in two weeks (!) on Lect. 13 (Lenz' law) – Lect. 21 (Optical instruments)  
Lab 8 (Interference & diffraction): Please go through next pre-lecture

“The only thing I see through the telescope is me failing the class. Help!!!”

“Prelecture where the lens 2 is moved closer to lens 1 (and how the image looks as a result), and how to think about this qualitatively to get the answer quick (if this is possible)”

“I'm still confused about what is considered a real/virtual image.”

“The take away message about the focal points of the types of aberrations are unclear.”



# Phys 102 – Lecture 21

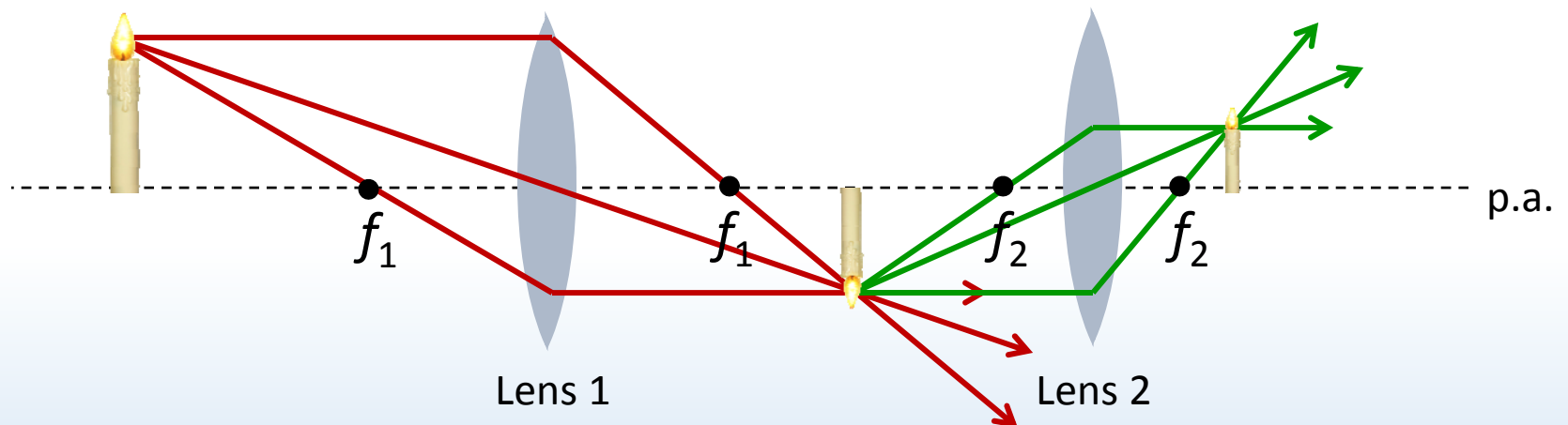
Optical instruments

# *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 63%

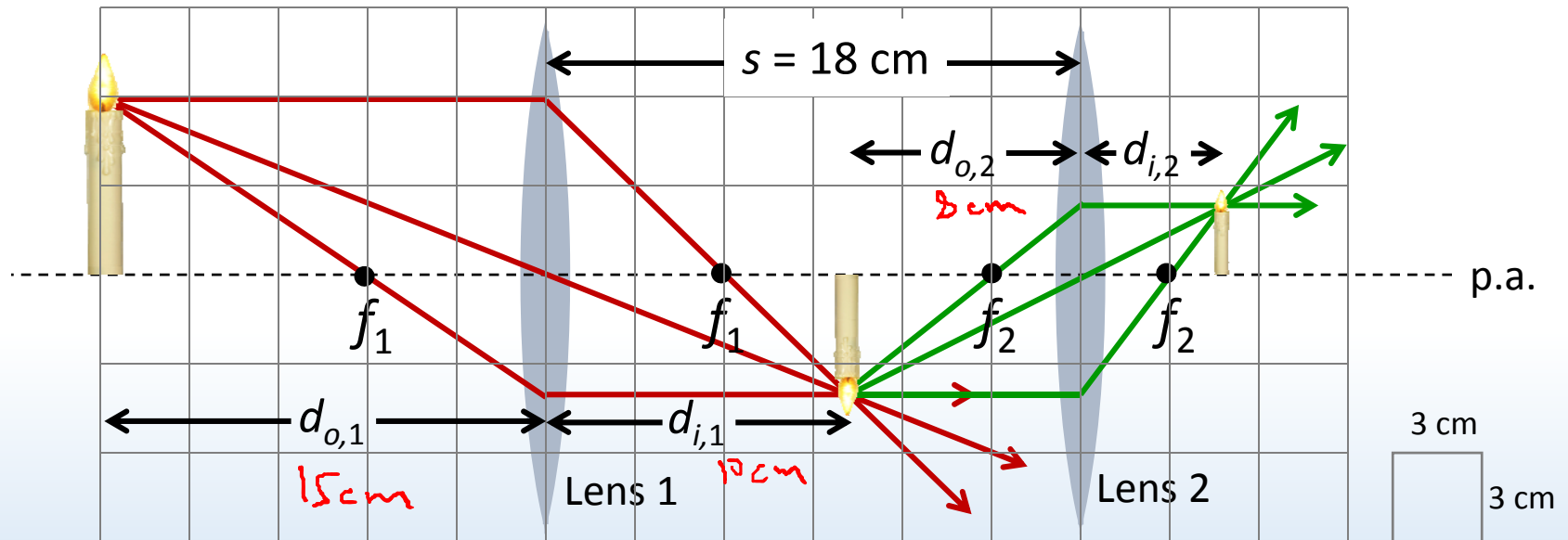
Lens 2 creates a real, inverted and reduced image of the image from lens 1

The combination gives a real, upright, reduced image of the object 55%

DEMO

# Calculation: final image location

Determine the final image location for the 2-lens system



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

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

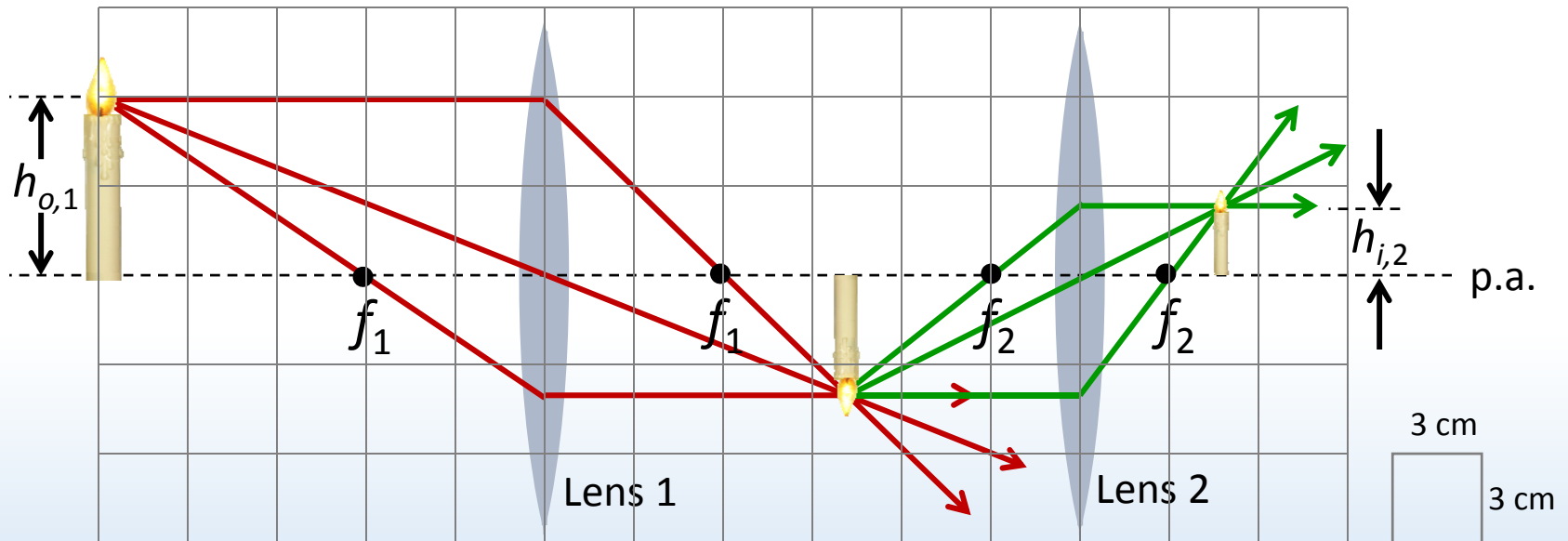
$$d_{i,1} + d_{o,2} = s \quad d_{o,2} = 18 - 10 = 8 \text{ cm}$$

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

Diagram should agree!

# Calculation: final magnification

Determine the final image size for the 2-lens system



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

$$h_{i,2} = m_{tot} h_{o,1} = +0.4 \cdot 6 = +2.4 \text{ cm}$$

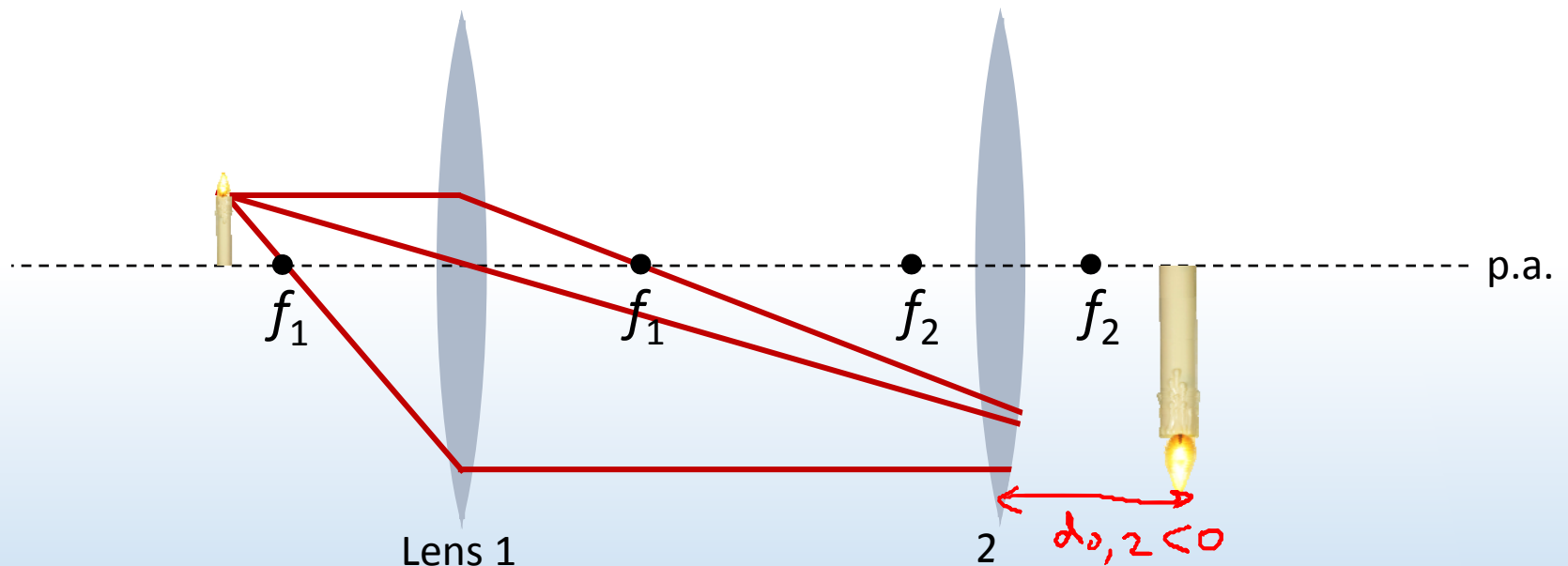
$$= \left( -\frac{d_{i,1}}{d_{o,1}} \right) \left( -\frac{d_{i,2}}{d_{o,2}} \right) = \left( -\frac{10}{15} \right) \left( -\frac{4.8}{8} \right) = +0.4$$

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?

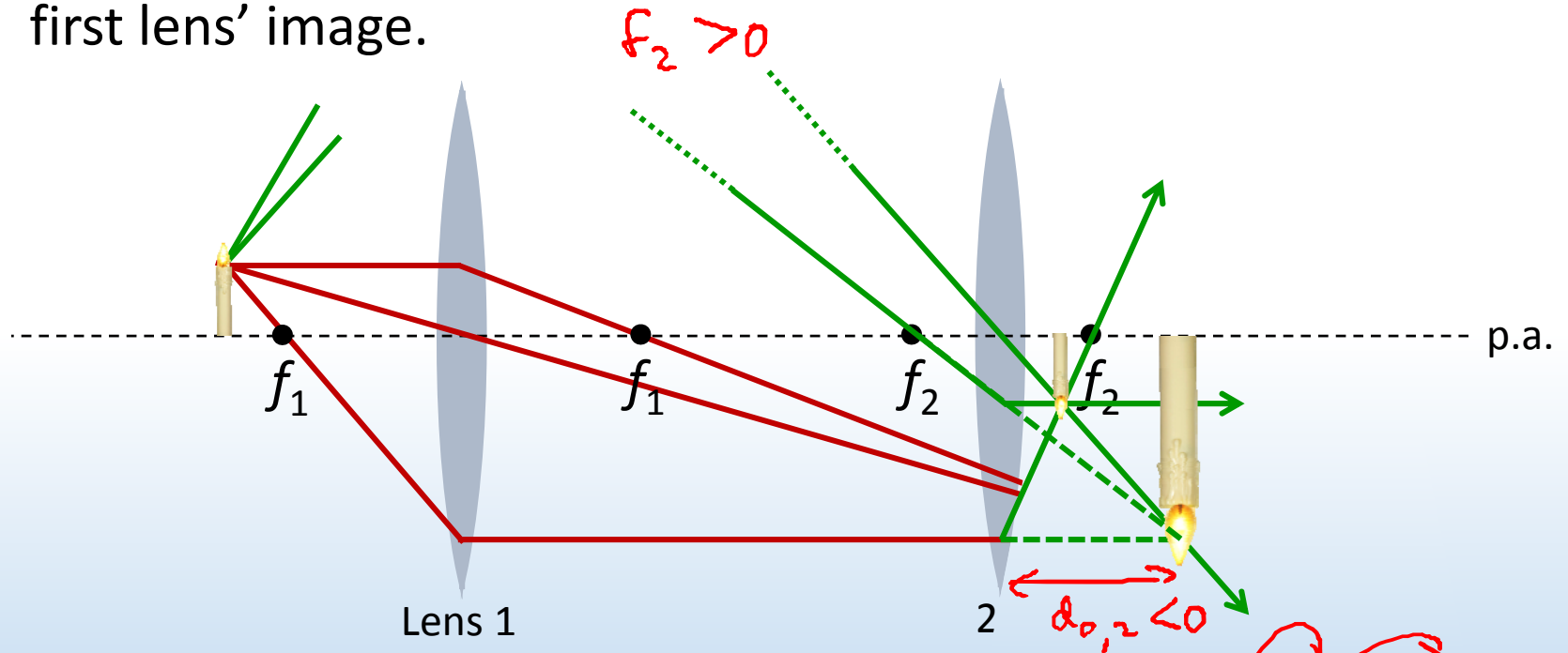
- 24% ~~A. Lens 2 has no object~~
- 38% B. Lens 2 has a real object
- 38% C. Lens 2 has a virtual object

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?

- 29% A. There is no image  
34% **B. Real**  
37% C. Virtual

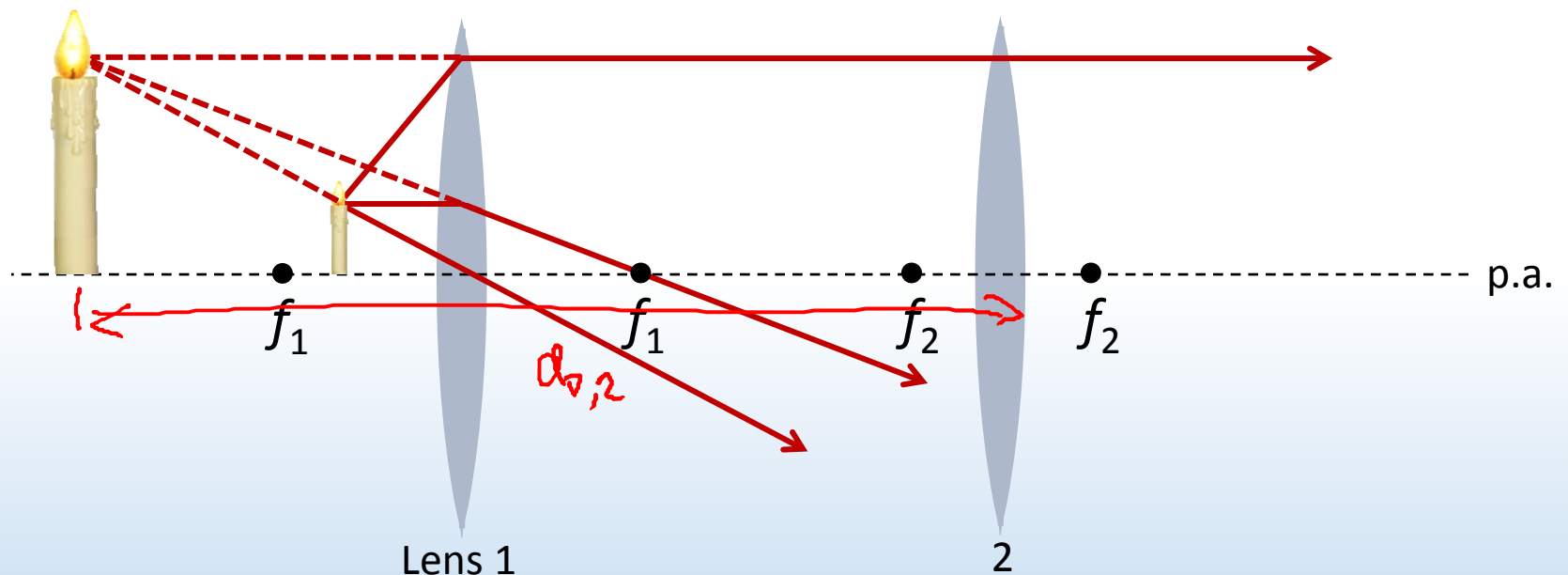
$$\frac{1}{d_{i,2}} = \frac{1}{f_2} - \frac{1}{d_{o,2}}$$

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



# ACT: Multiple lenses

A converging lens creates a virtual upright image. A second converging lens is placed after the first lens.



Which statement is true?

~~A. Lens 2 has no object~~

B. The object distance for lens 2  $> 0$

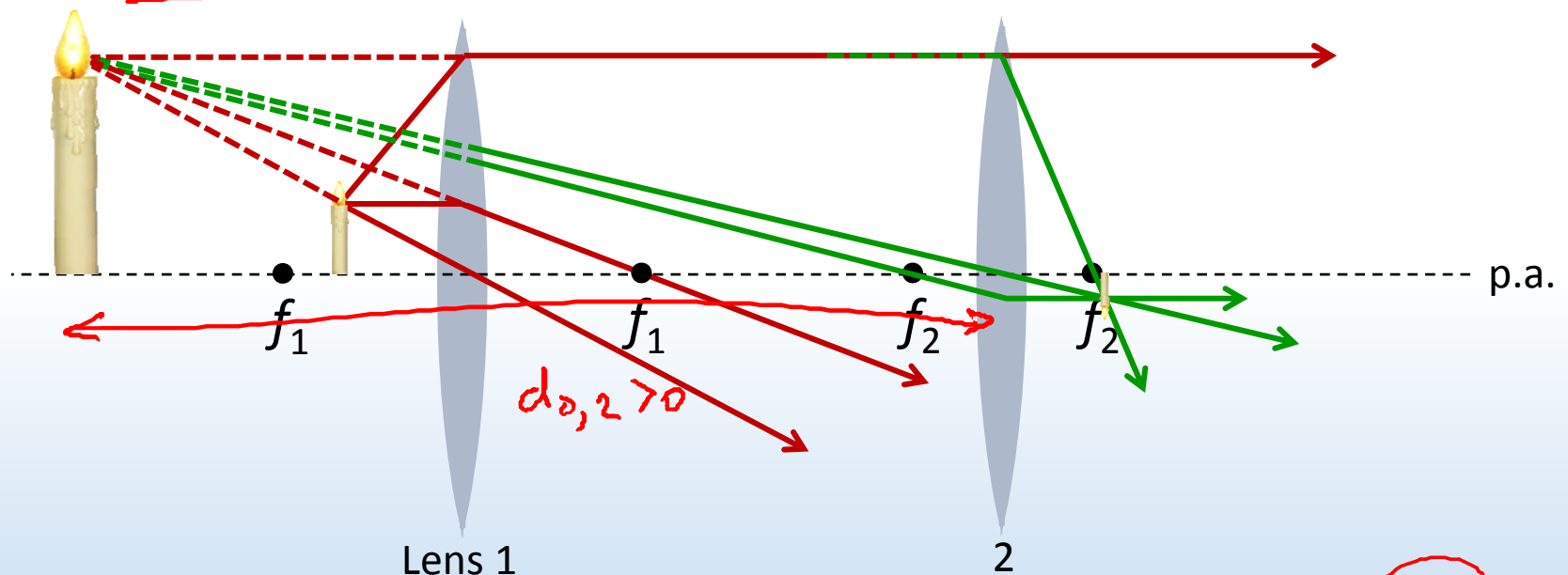
C. The object distance for lens 2  $< 0$

Object before lens 2,  $d_{o,2} > 0$ !



# ACT: Multiple lenses image

A converging lens creates a virtual upright image. A second converging lens is placed after the first lens.



The final image is

- A. Real and inverted
- B. Real and upright
- ~~C. Virtual and upright~~

$$\frac{1}{d_{i,2}} = \frac{1}{f_2} - \frac{1}{d_{o,2}} \quad m_2 = -\frac{d_{i,2}}{d_{o,2}}$$

$$d_{o,2} > f_2 > 0, \text{ so } d_{i,2} > 0$$

# ***Lens combination: summary***

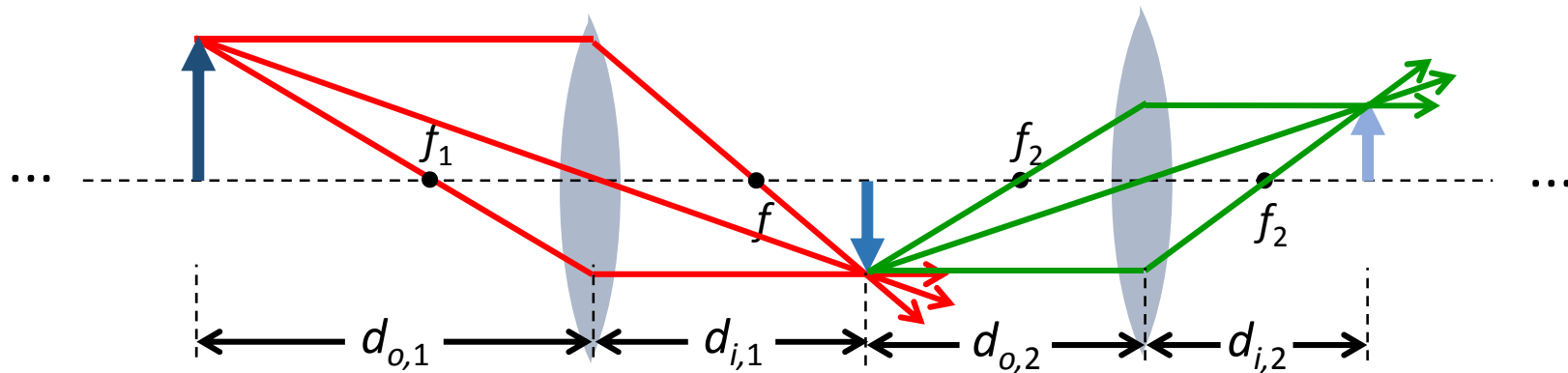


Image of first lens becomes object of second lens, ...

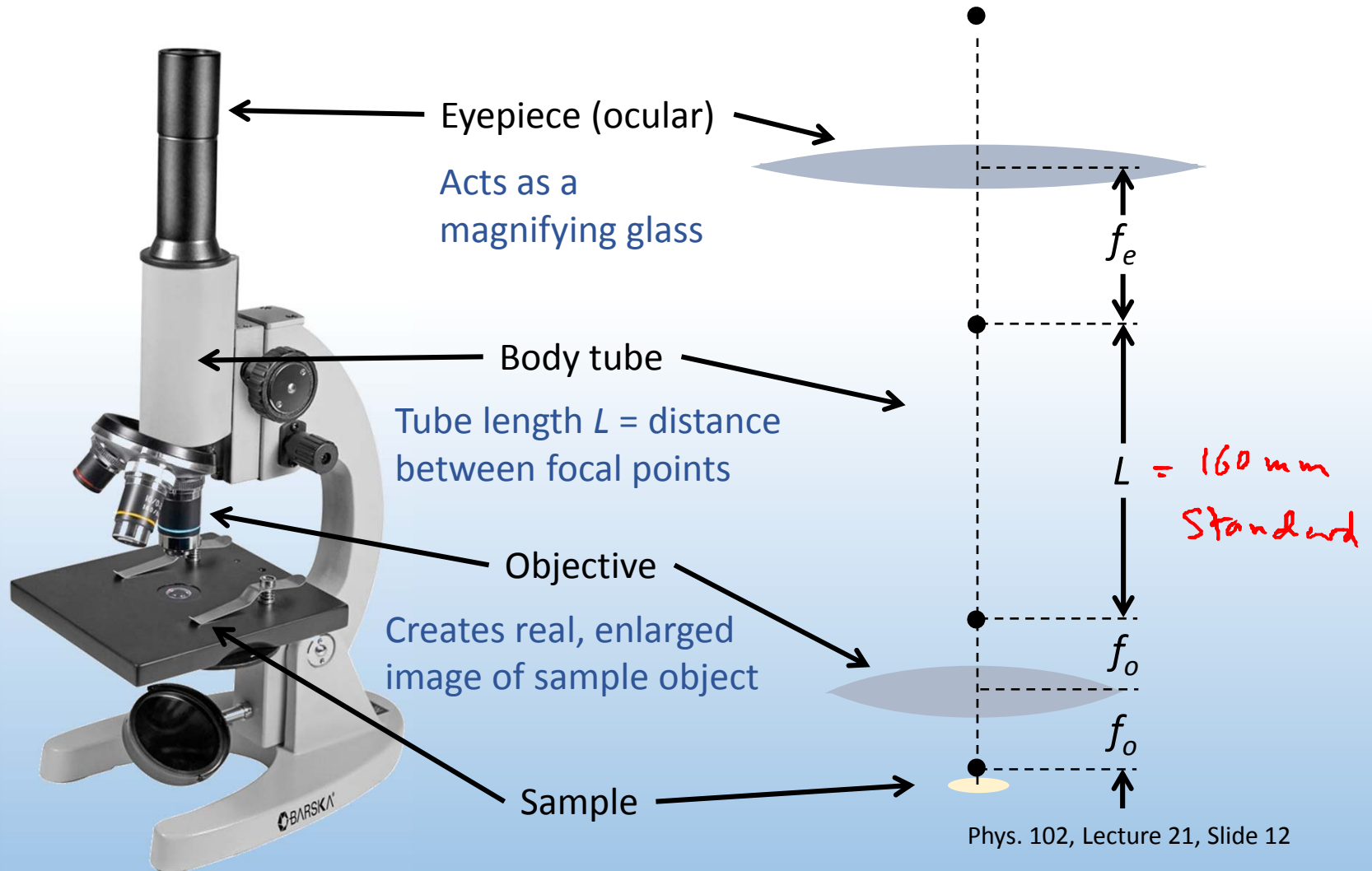
$$m_{tot} = m_1 m_2 m_3 \dots$$

- $d_o$  = 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!**

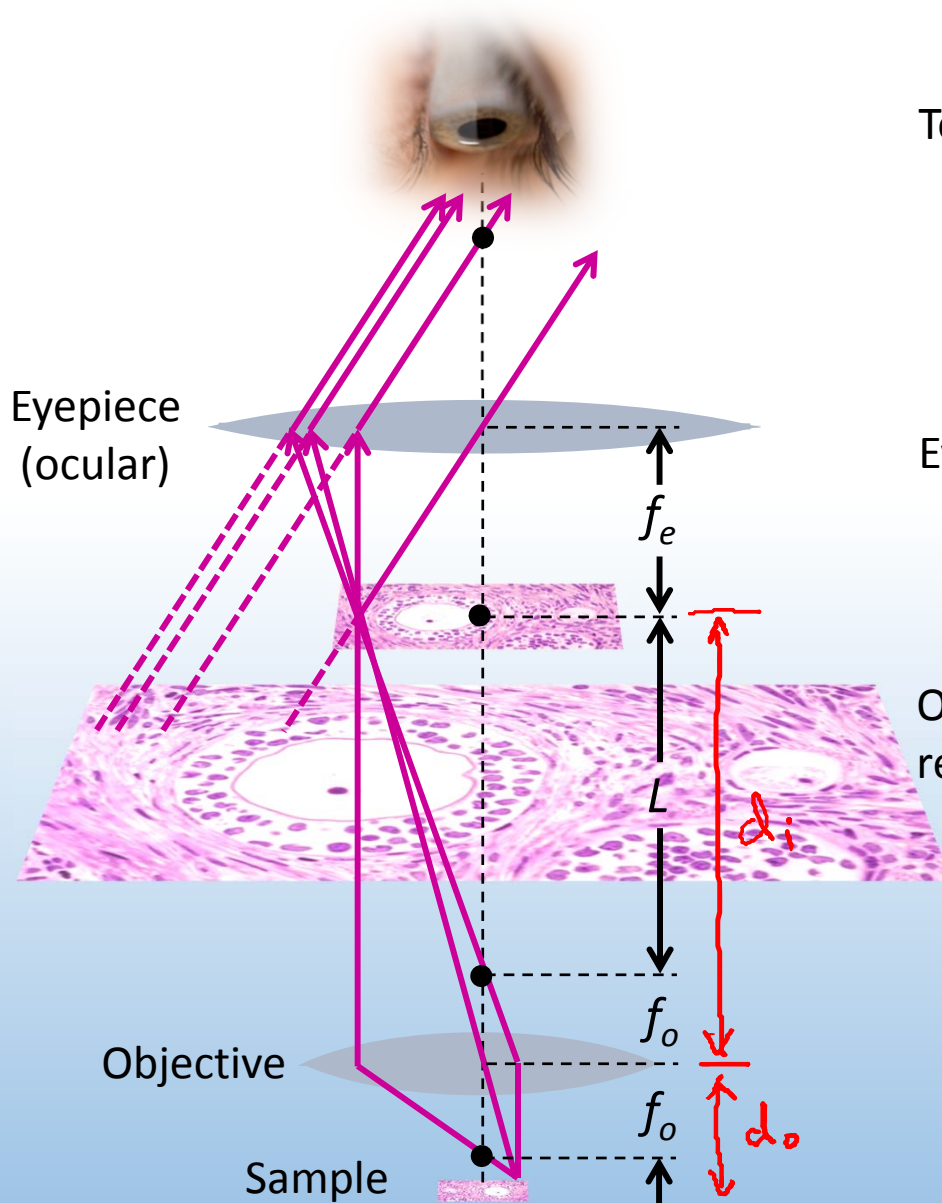
# Compound microscope

A compound microscope is made up of two converging lenses



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  $\infty$

$$M_e = \frac{d_{near} = 25 \text{ cm}}{f_e} \quad \text{Recall Lect. 20}$$

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

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

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



# ACT: Microscope eyepiece

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



Magnification

10× means  $M_e = 10$

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

In normal vision  $d_{near} = 25 \text{ cm}$

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

What is the focal length of a 10× eyepiece?

A.  $f_e = 2.5 \text{ cm}$

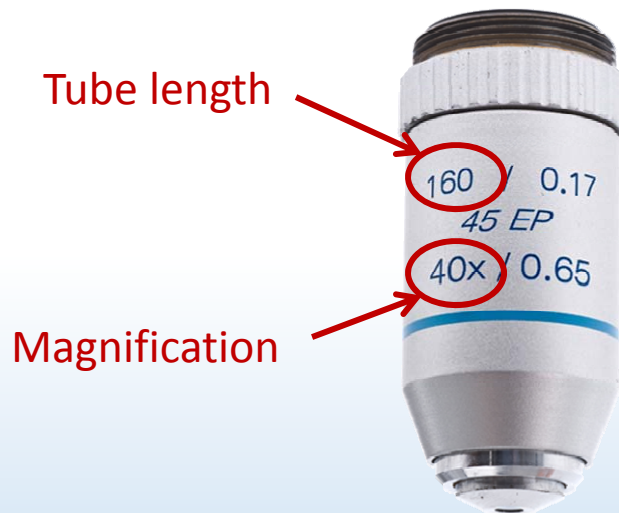
B.  $f_e = 10 \text{ cm}$

C.  $f_e = 25 \text{ cm}$



# 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?

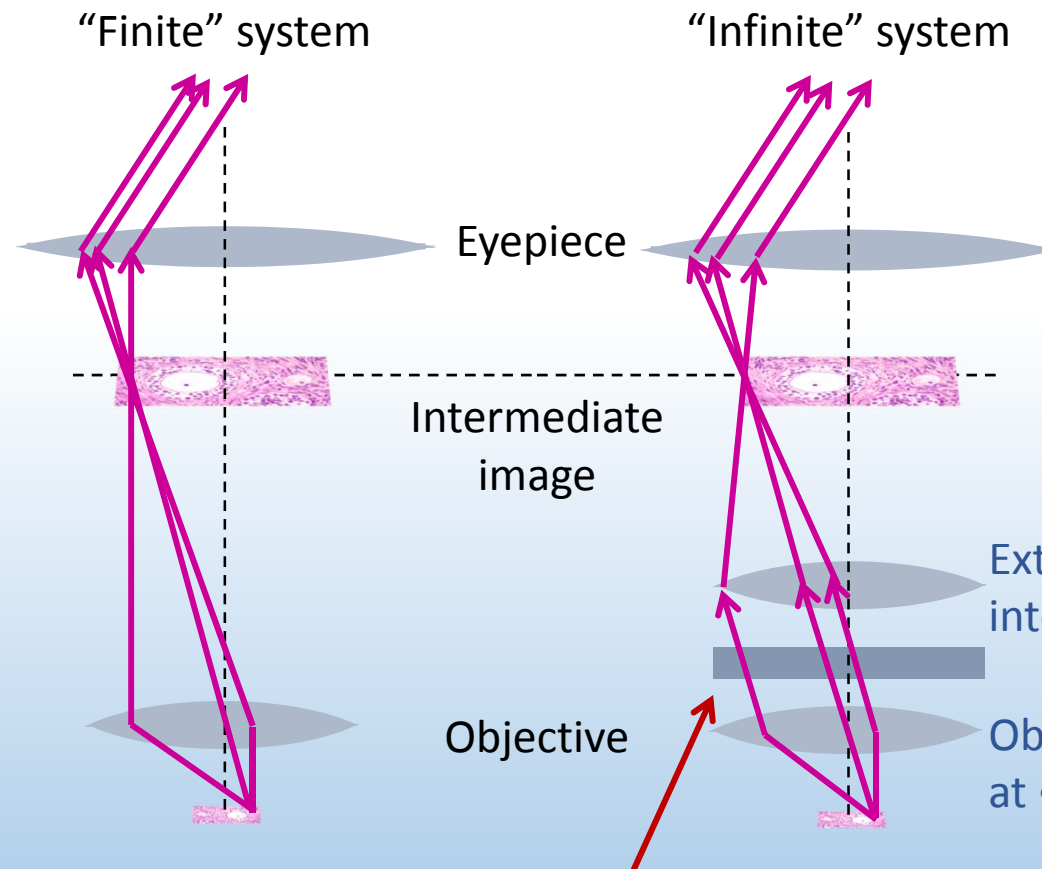
A.  $f_o = 4\text{ mm}$

B.  $f_o = 8\text{ mm}$

C.  $f_o = 16\text{ mm}$

# Modern microscope objectives

Most modern objectives are “infinity corrected”



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

# Calculation: Angular size HW

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

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

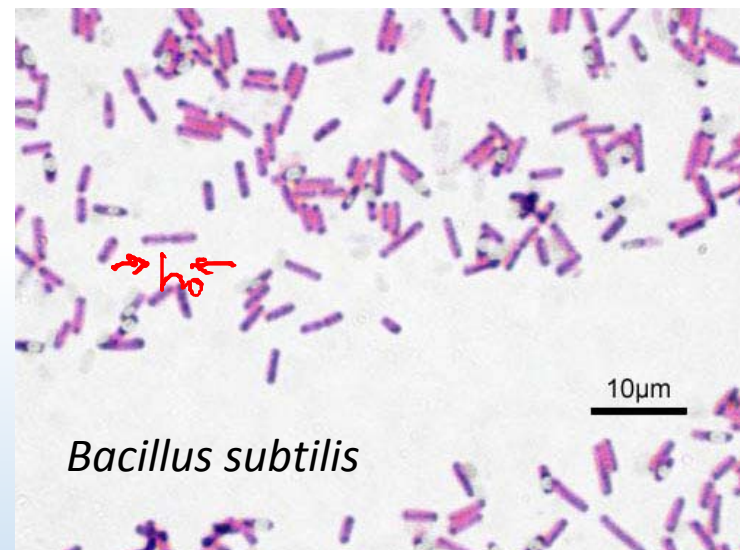
At a near pt. of 25 cm, a 2-μm bacterium has angular size to an unaided eye of:

$$\theta_{unaided} \approx \frac{h_o}{d_{near}} = \frac{2 \times 10^{-6}}{0.25} = 8 \times 10^{-6} \text{ rad}$$

In the microscope the angular size is:

$$|\theta_{mic}| = 600 \cdot 8 \times 10^{-6} = 4.8 \times 10^{-3} \text{ rad}$$

Equivalent to a  $600 \times 2 \text{ μm} = \underline{1.2 \text{ mm}}$  object at 25 cm

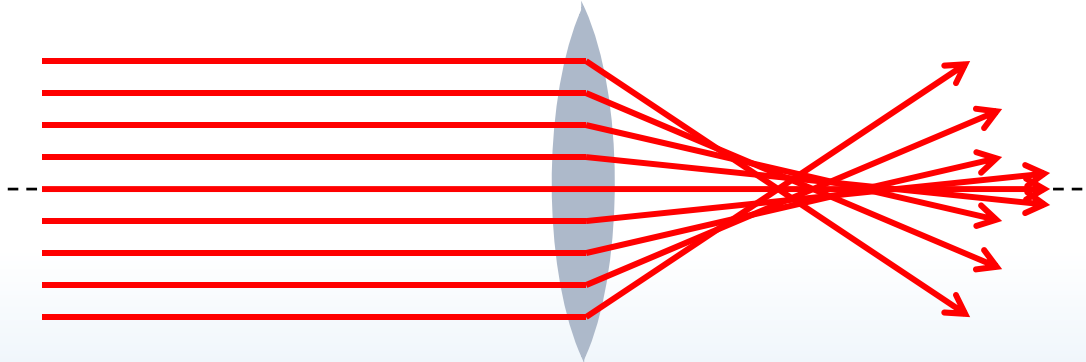


**What limits the resolution of a light microscope?**

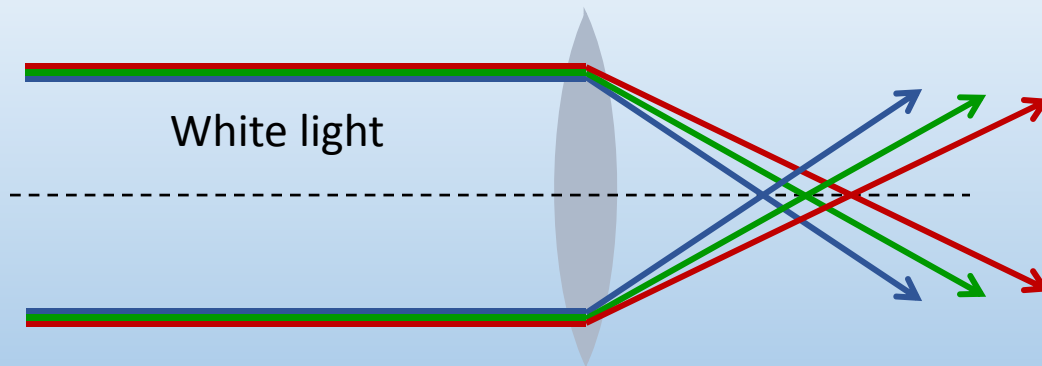
# Aberrations

Aberrations 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

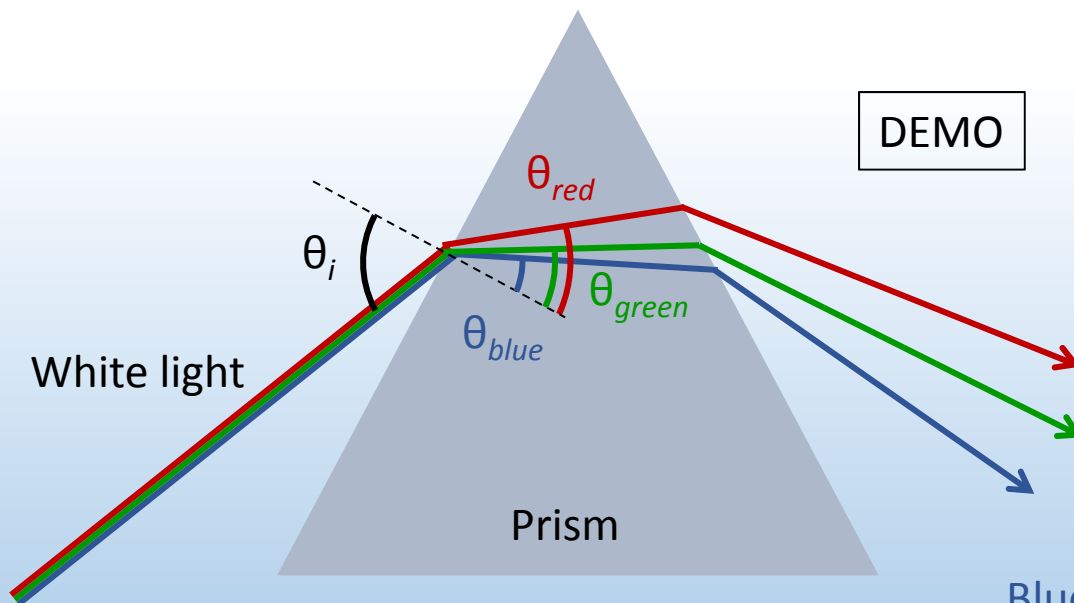
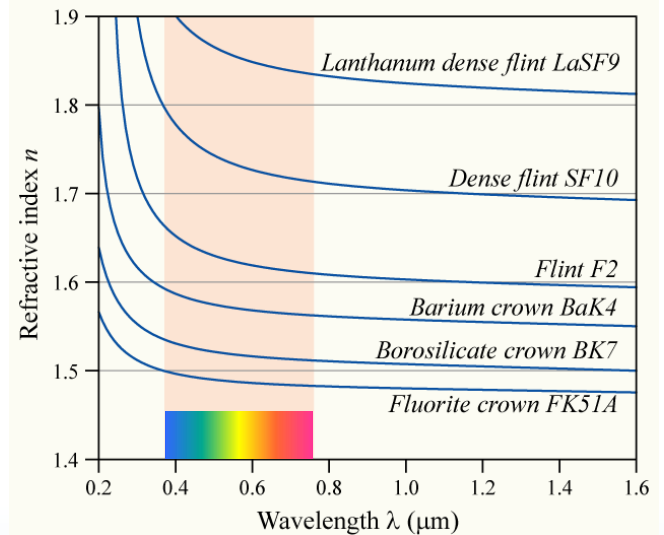
Lab 7

# Dispersion

The index of refraction  $n$  depends on  $\lambda$

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

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



DEMO

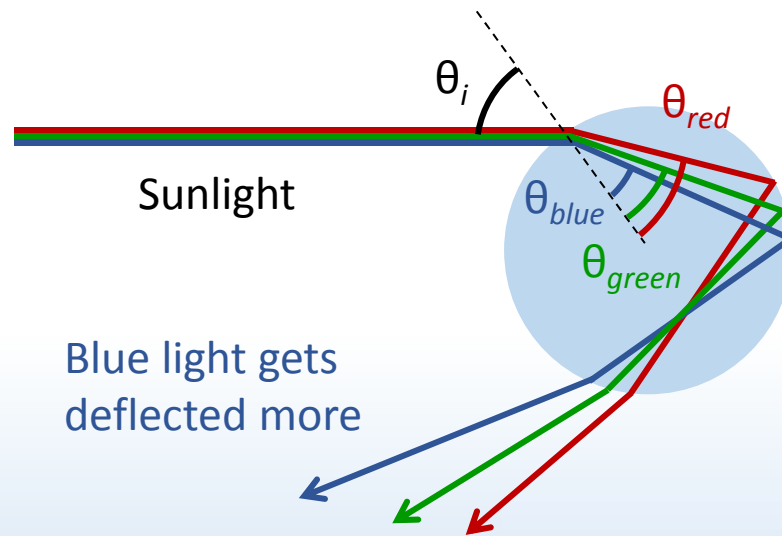


Blue light gets deflected more

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

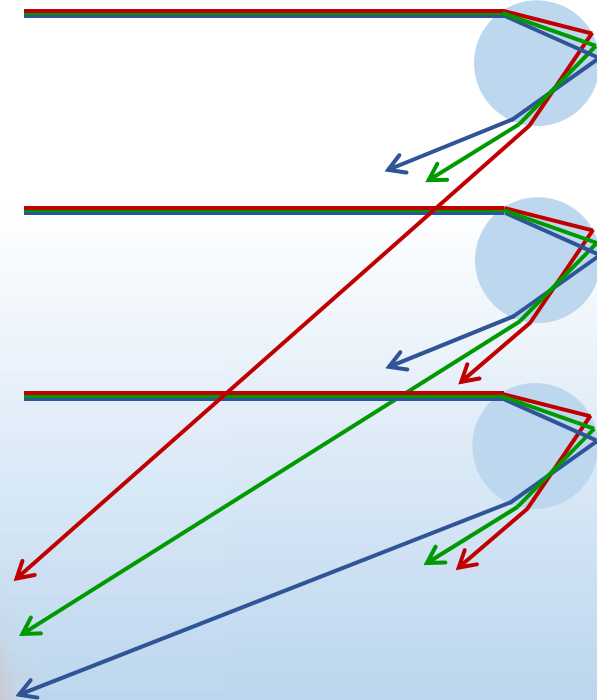
# CheckPoint 2.1: Rainbows

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 49%

# *Double rainbow*

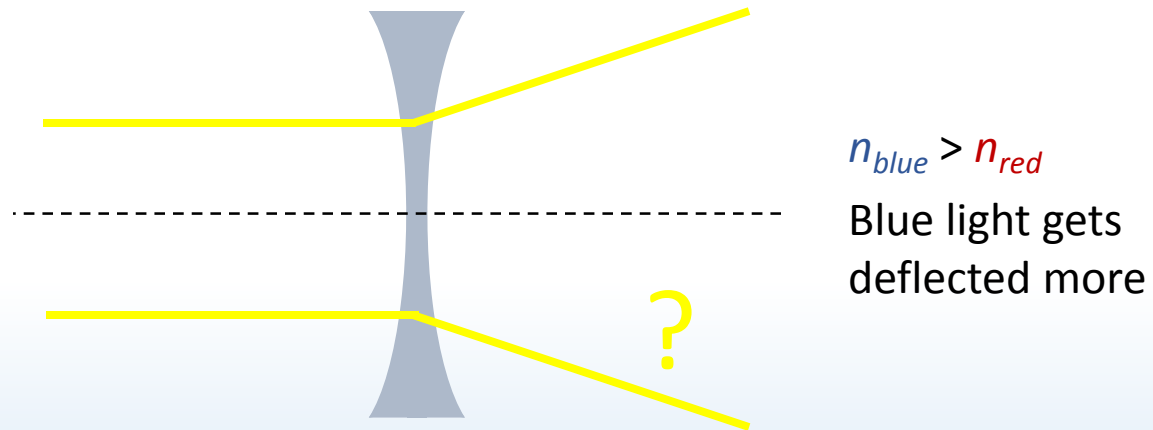


[Double rainbow](#)

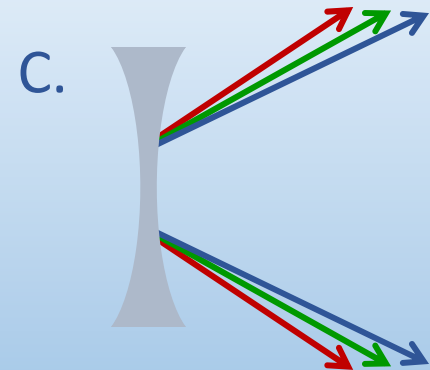
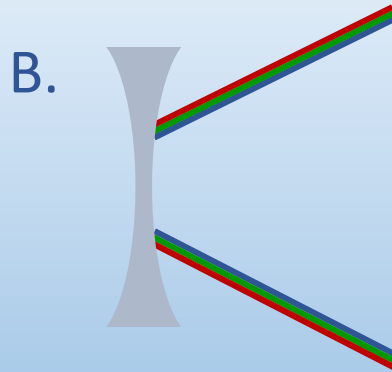
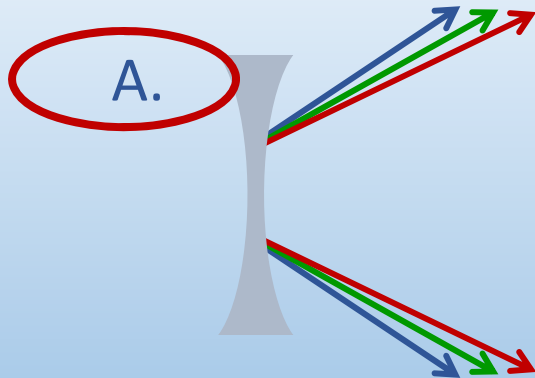


# ACT: Dispersion

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.



Which diagram best represents how light is transmitted?



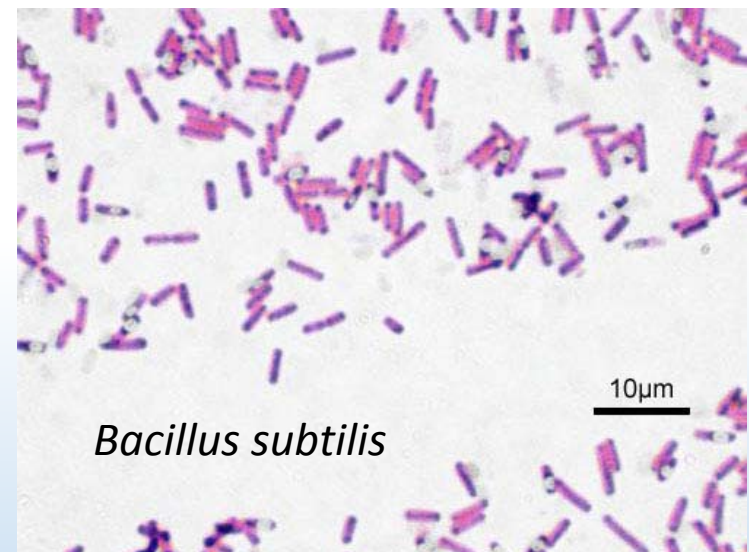
# *Ultimate limit of resolution*

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  $\sim\lambda$  of light ( $\sim 500\text{ nm}$ )

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  $\gg \lambda$

# *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  $\infty$

- Limits to resolution

Spherical & chromatic aberrations

Dispersion

*Diffraction limit* – next week!