COMP 546

Lecture 2

Focus

Tues. Jan. 16, 2018

Last lecture

- aperture (and f-number)
- visual angle
- binocular disparity and depth

Today

- Image sampling
- Lenses, blur, focus (accommodation)

The ability to see detailed patterns is limited by:

- image sampling (density of photoreceptors/pixels)

- defocus blur (due to finite size aperture)

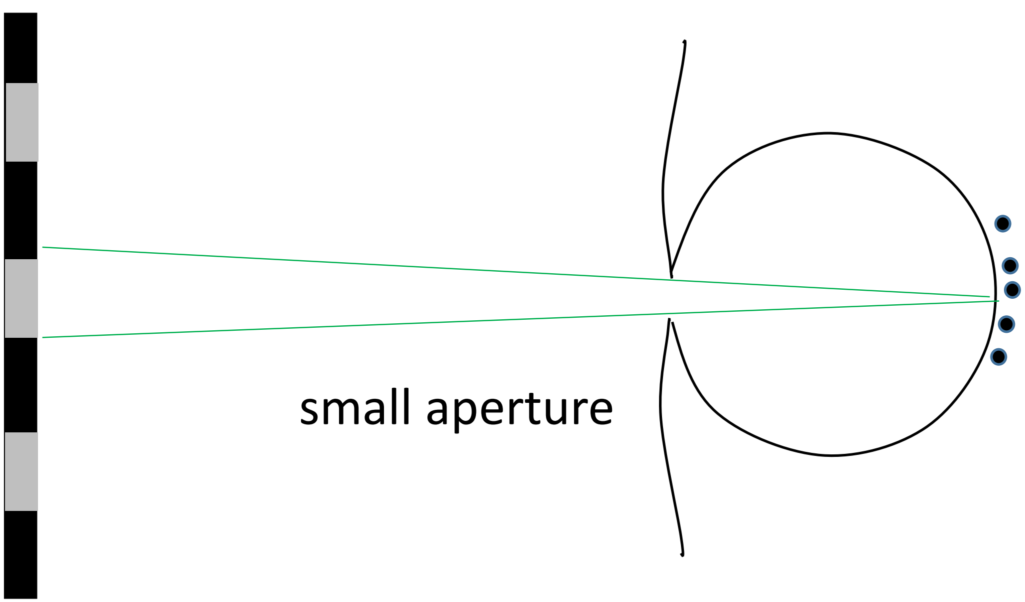
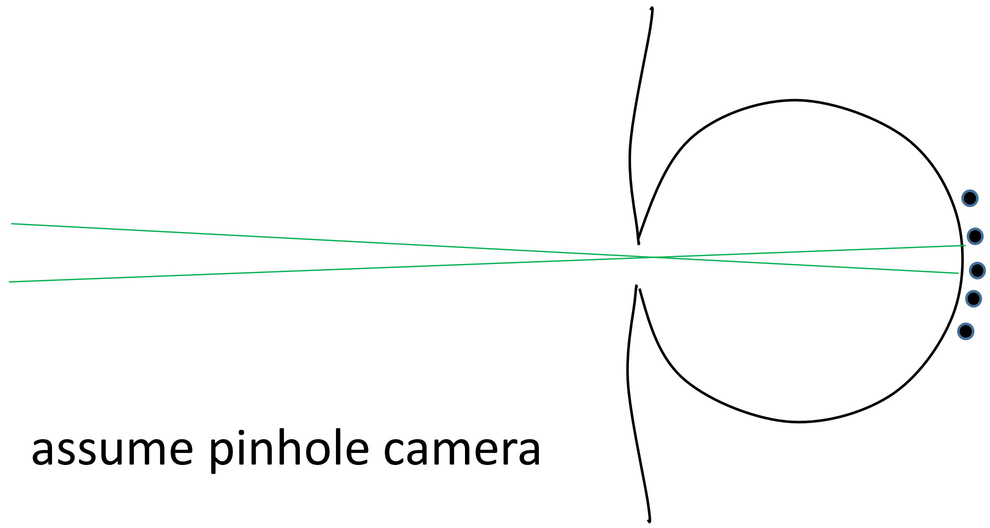
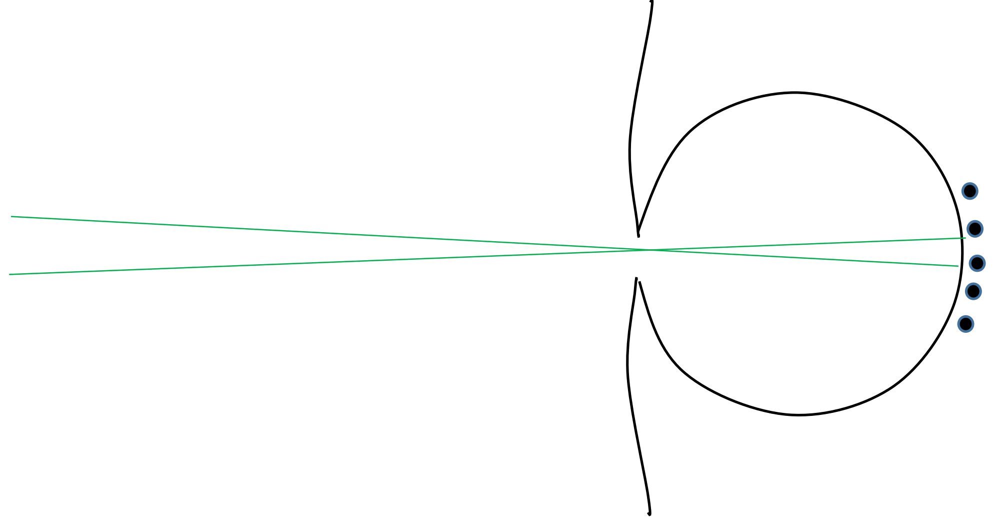


Image Sampling



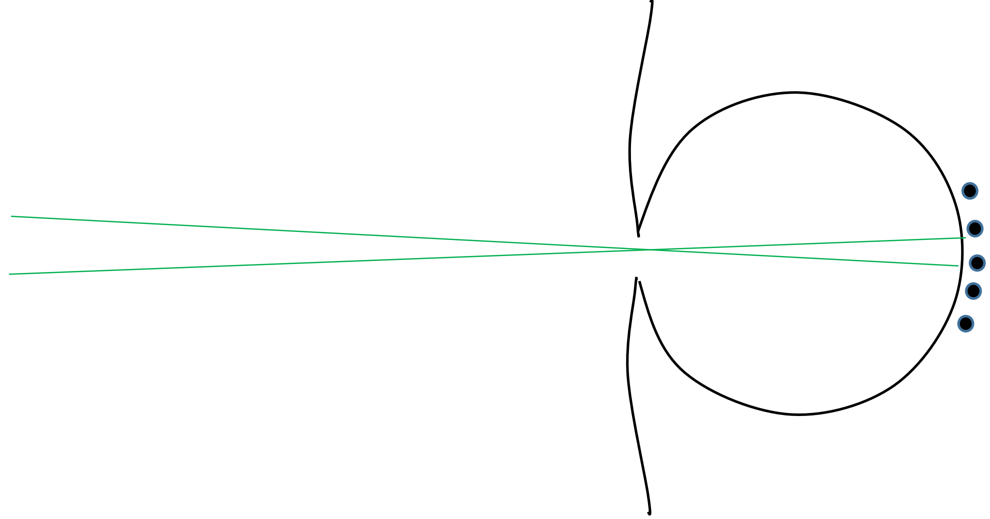
assume pinhole camera

What is the density of photoreceptors?
What is the angle between samples?



s = distance (mm) between samples

f = diameter of eye



s = distance (mm) between samples

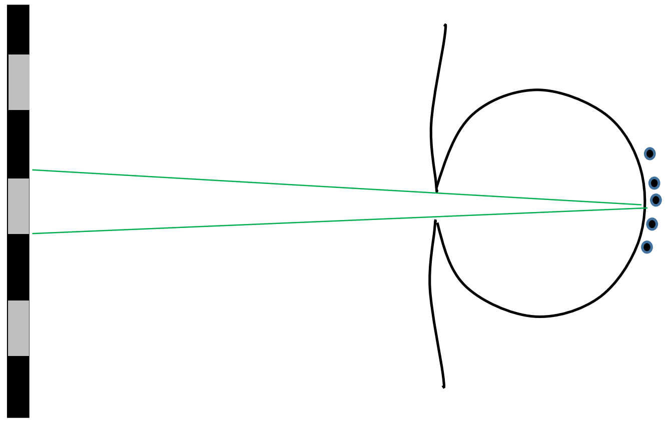
f = diameter of eye

$\frac{s}{f}$ = angle (radians) between samples

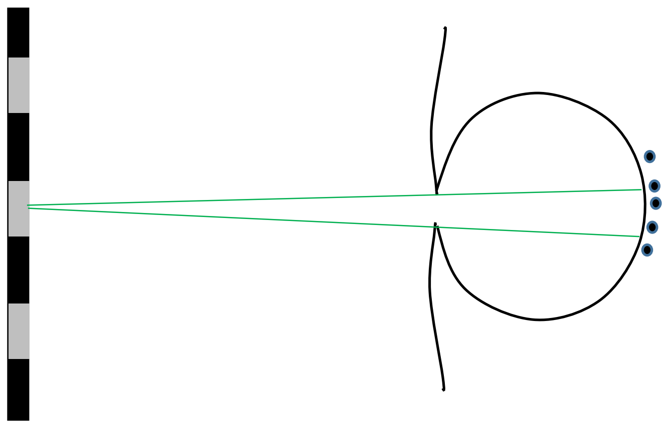
$\frac{f}{s}\left(\frac{\pi}{180}\right)$ = samples per visual angle (degrees)

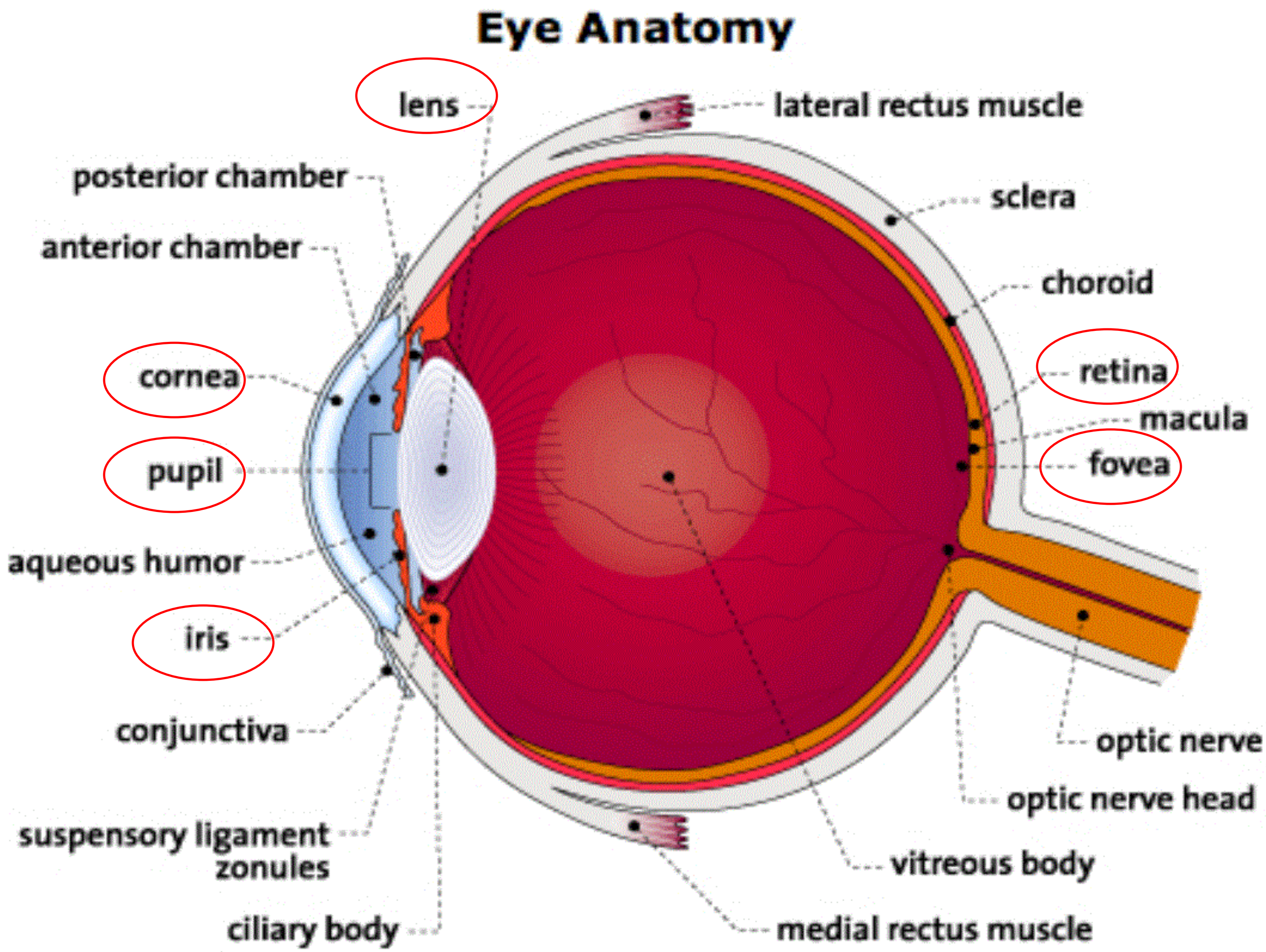
Defocus blur: two ways to think about it

Each image pixel receives light from many scene points.

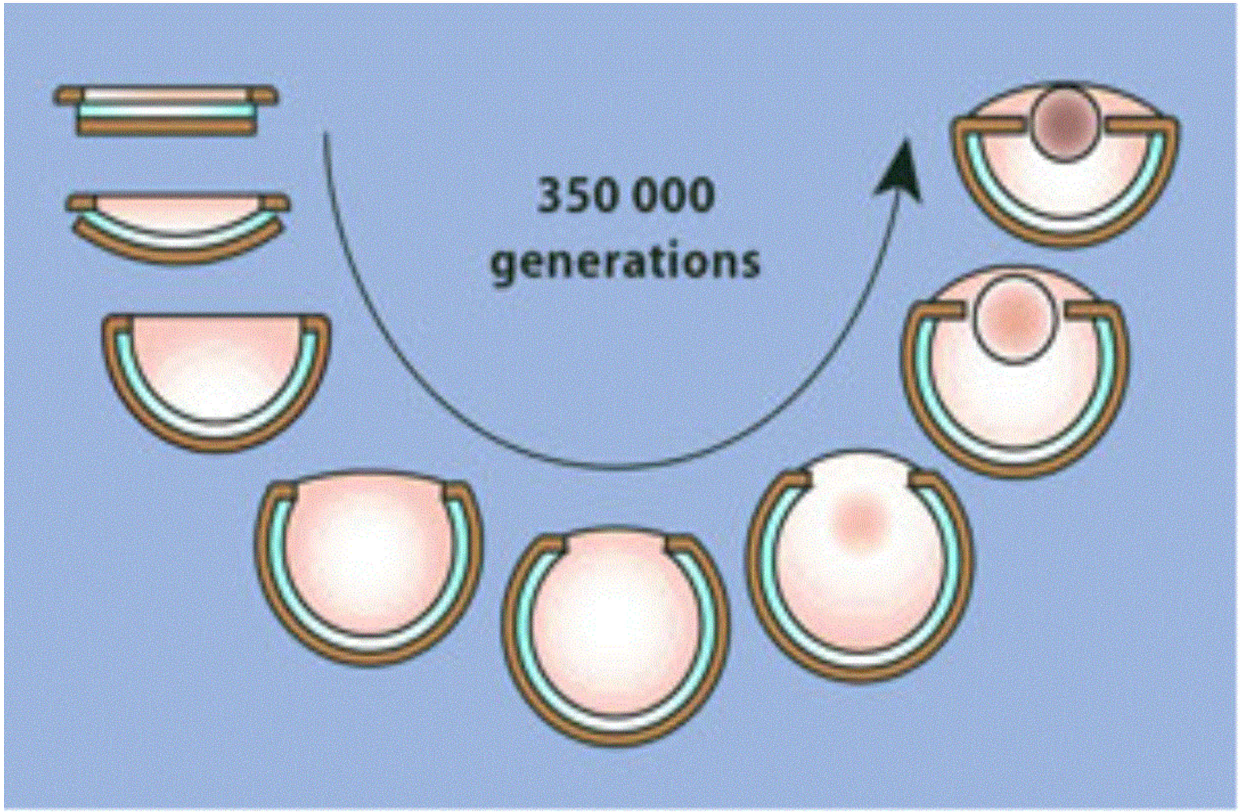


Each scene point sends light that reaches many image points.




Eye Anatomy
lens
lateral rectus muscle
posterior chamber
sclera
anterior chamber
choroid
cornea
retina
macula
pupil
fovea
aqueous humor
iris
conjunctiva
optic nerve
optic nerve head
suspensory ligament
zonules
vitreous body
ciliary body
medial rectus muscle

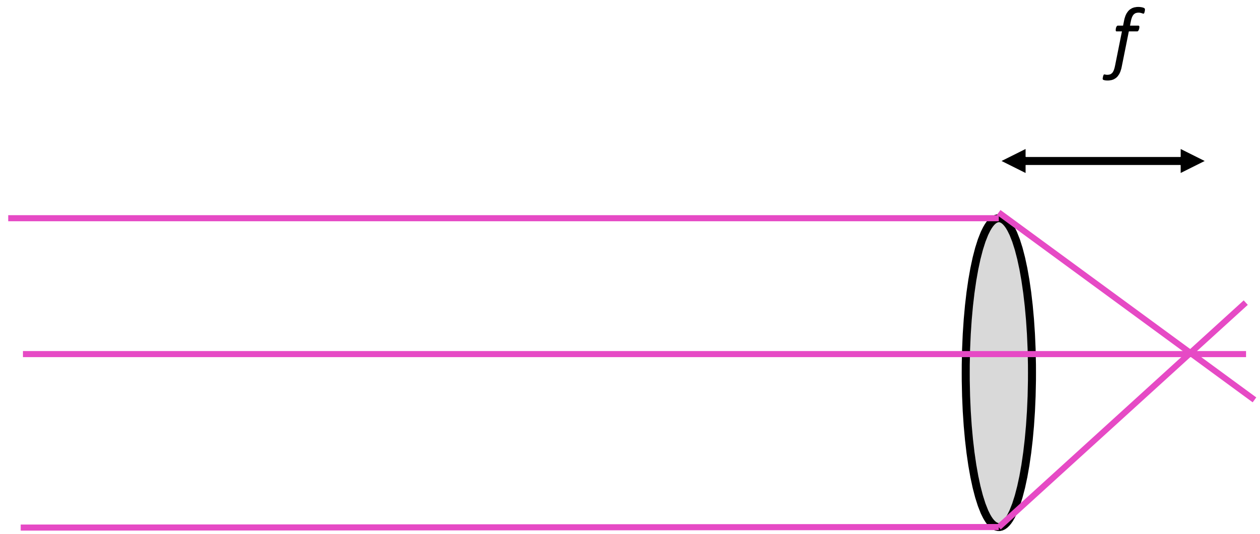
Evolution of the Lens of the Eye



http://www.youtube.com/watch?v=mb9_x1wgm7E
(Richard Dawkins video)

Focal length and power of a thin lens

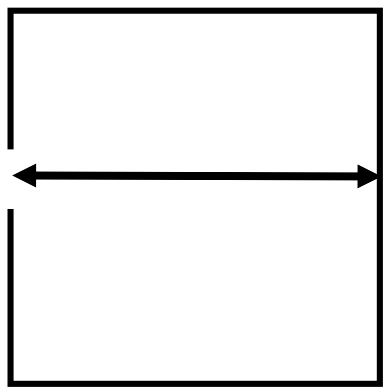
parallel rays of light



f is the focal length

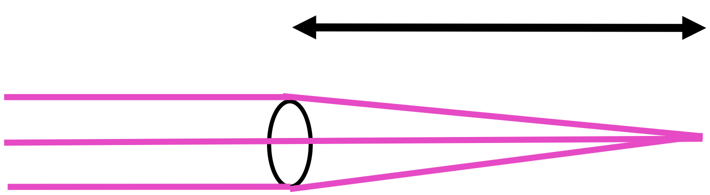
$1/f$ is the 'power'.

Focal length f used in two ways



Last lecture:

distance from aperture to sensor plane

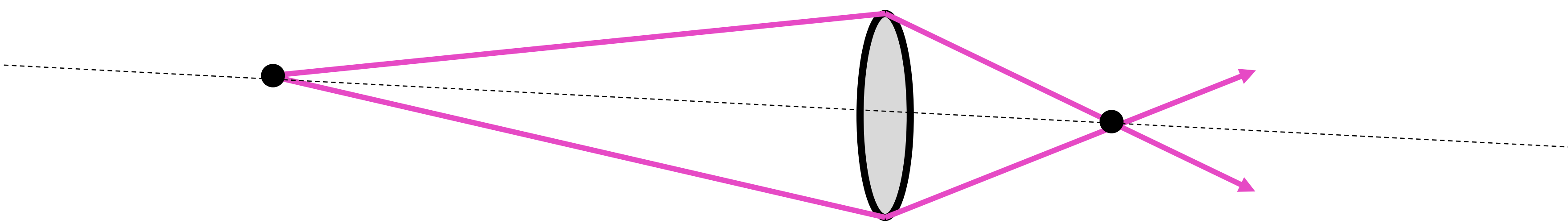


Today:

distance behind lens where parallel incoming rays converge (It may not coincide exactly with sensor plane.)

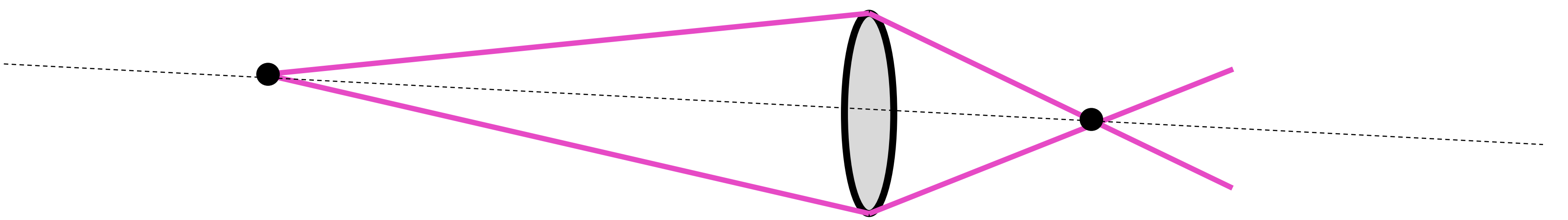
Conjugate points

For every 3D point on one side of a thin lens, the rays diverging from that point will converge at some other 3D point on the opposite side of the lens.



Thin lens model

$$\frac{1}{\text{focal length of lens}} = \frac{1}{\text{object distance}} + \frac{1}{\text{image distance}}$$



Units: $\dfrac{1}{\text{meters}}$ is called “diopters” (D)

Special case: object at infinity

$$\frac{1}{\text{focal length of lens}} = \cancel{\frac{1}{\text{object distance}}} + \frac{1}{\text{image distance}}$$

Which scene points are in focus?

$$\frac{1}{\text{focal length of lens}} = \frac{1}{\text{focal plane distance}} + \frac{1}{\text{sensor distance}}$$

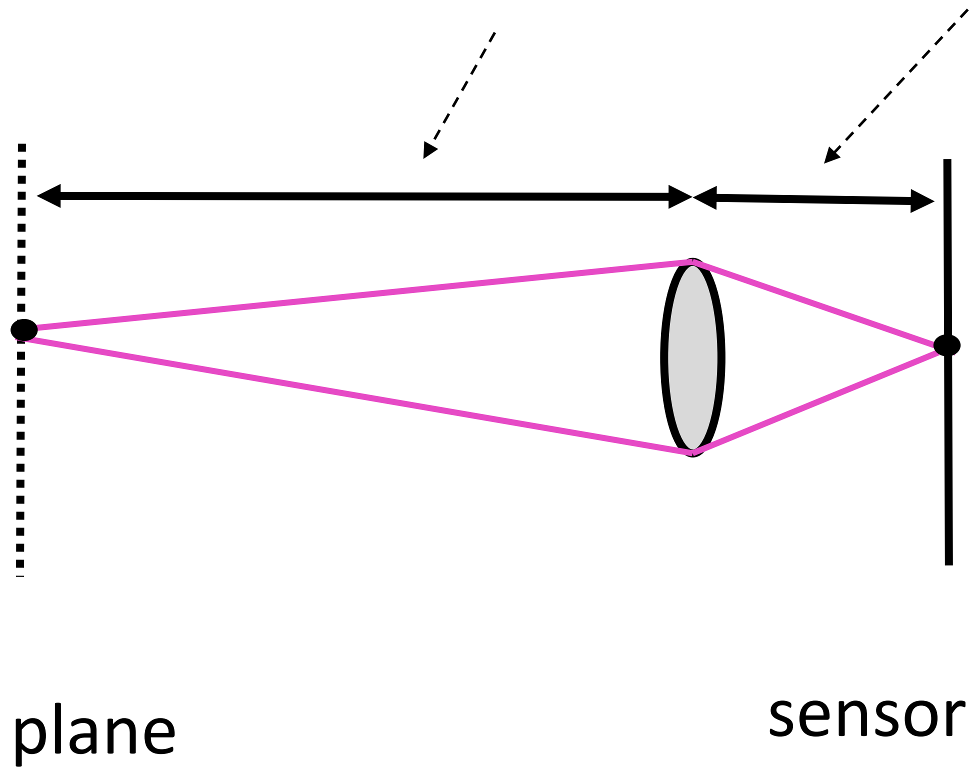
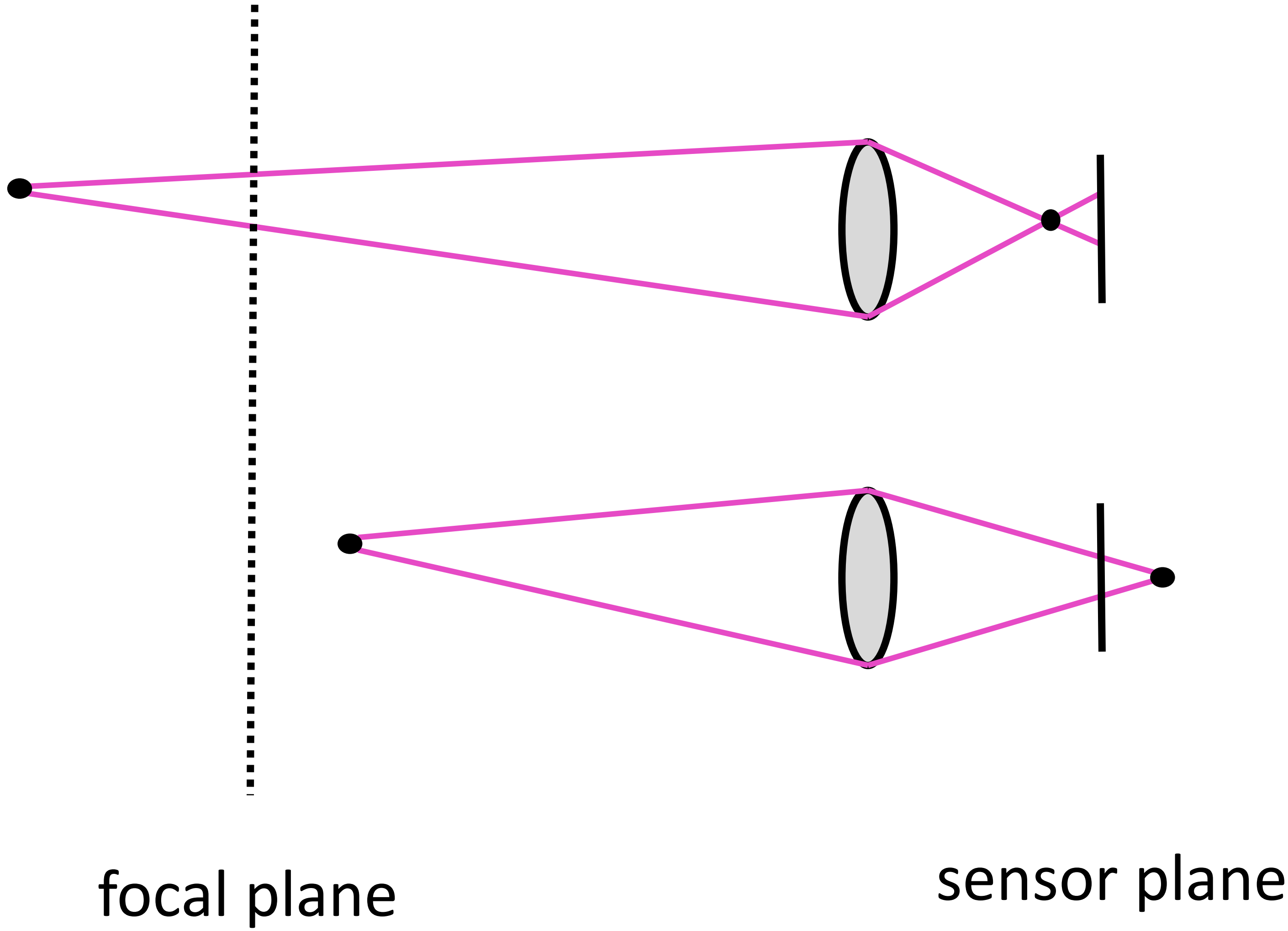


Image Blur



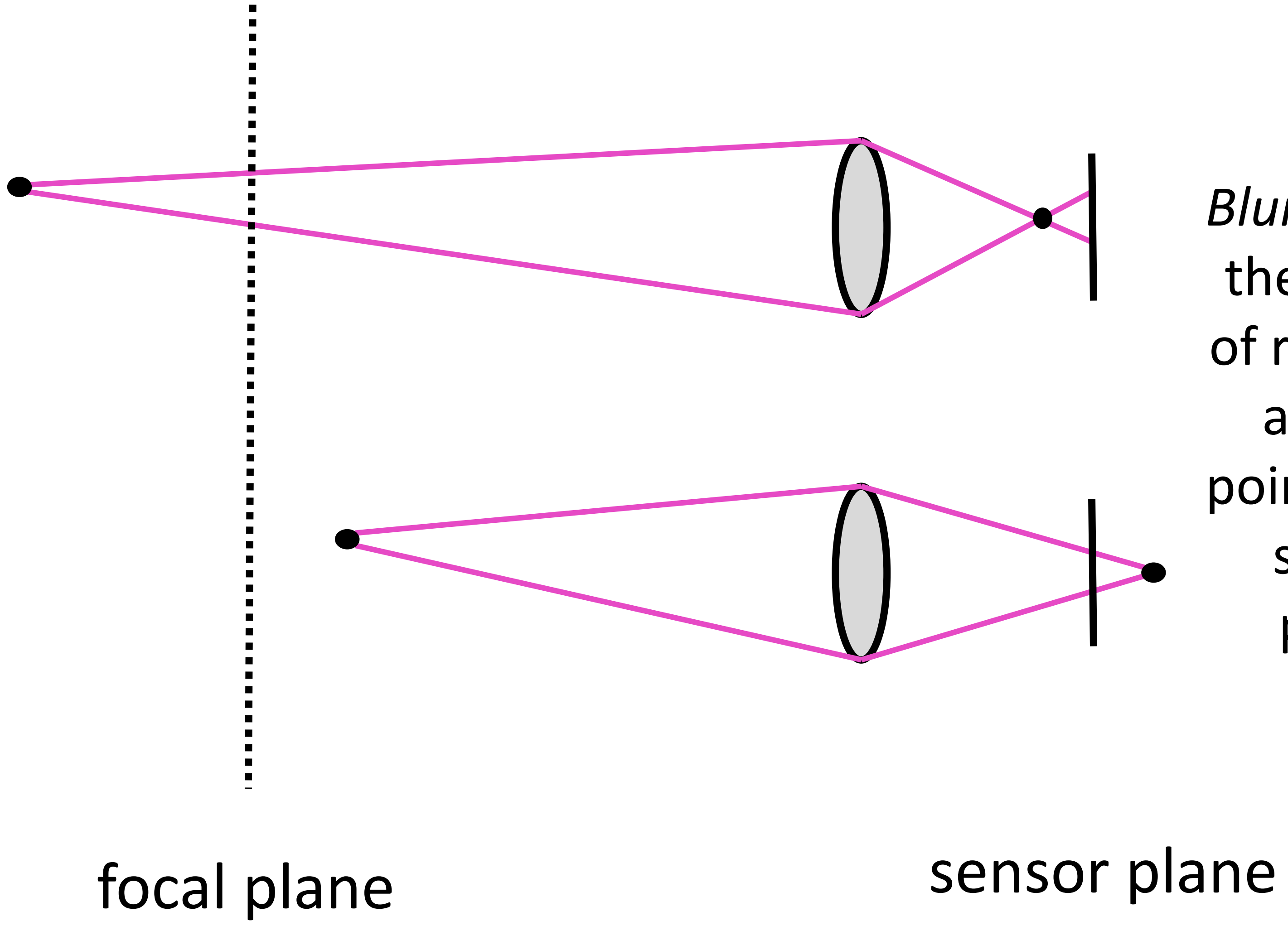
Blur and depth

beyond
focal plane

at focal plane

closer than
focal plane

Blur width



Blur width is the spread of rays from a scene point on the sensor plane.

Exercise

Hold up a finger up at arm’s length: 57 cm.

Focus at a distance of 10 m.

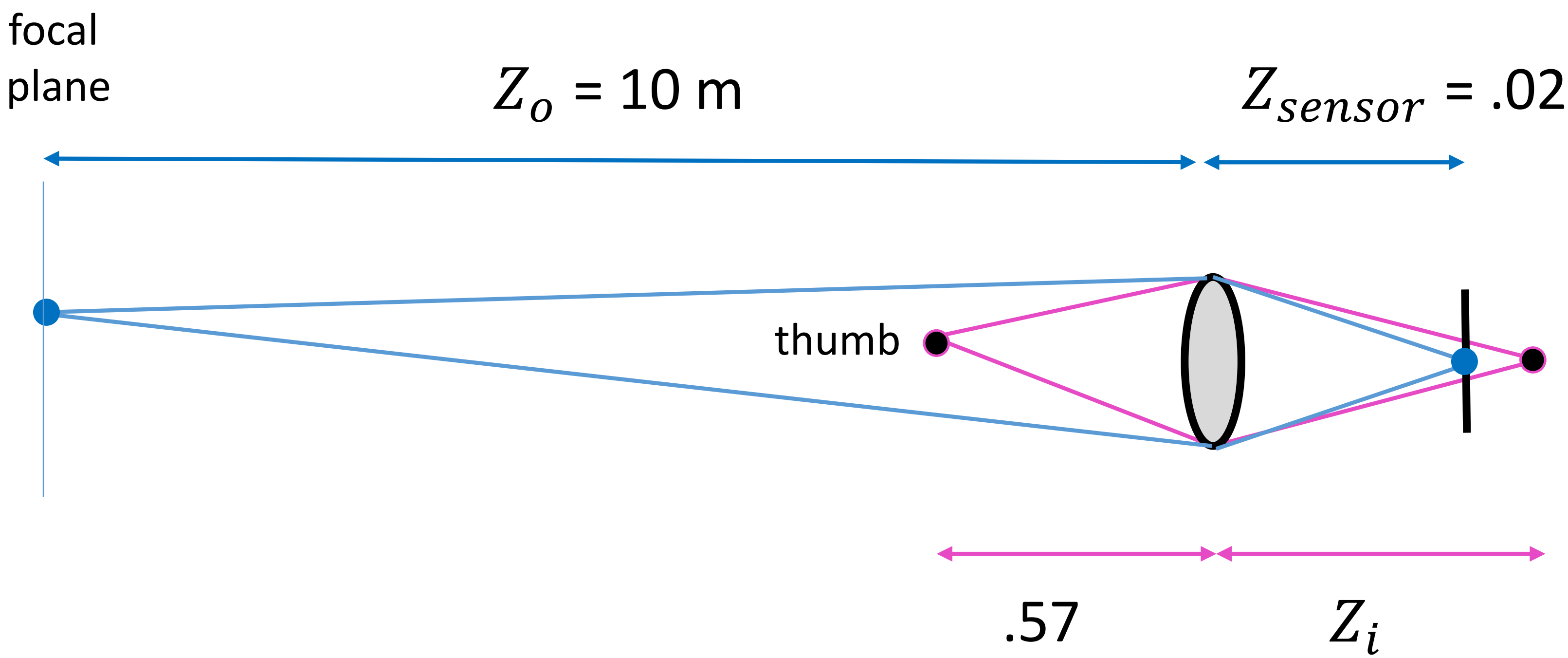
Eye is 2 cm long.

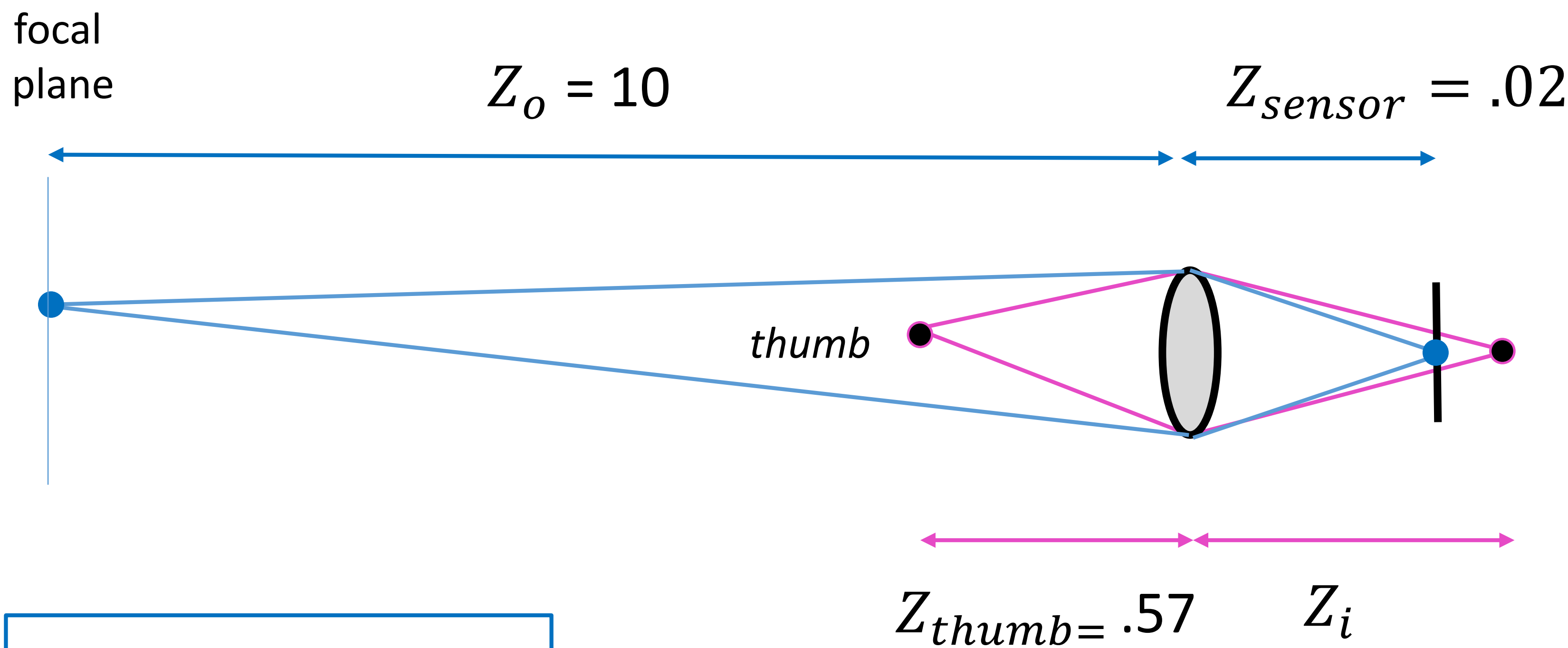
Aperture (pupil) is 3 mm.

[I am not claiming that the above numbers correspond to this photo.]

Q: What is the visual angle of the finger blur width ***w*** ?

w


focal plane
Z_o = 10 m
Z_{sensor} = .02
thumb
.57
Z_i



$$
\begin{aligned}
\frac{1}{f} &= \frac{1}{Z_o} + \frac{1}{Z_{sensor}} \\
&= \frac{1}{10} + \frac{1}{.02}
\end{aligned}
$$

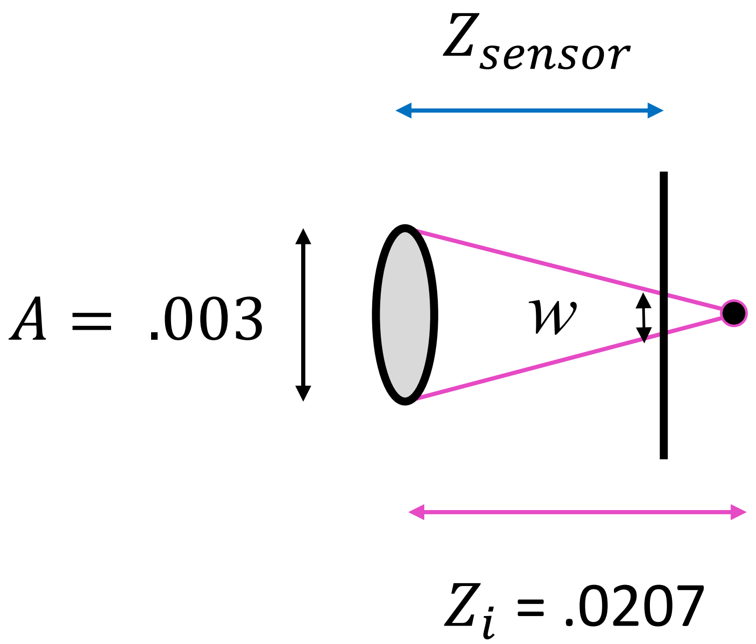
$$
\frac{1}{f} = \frac{1}{.57} + \frac{1}{Z_i}
$$

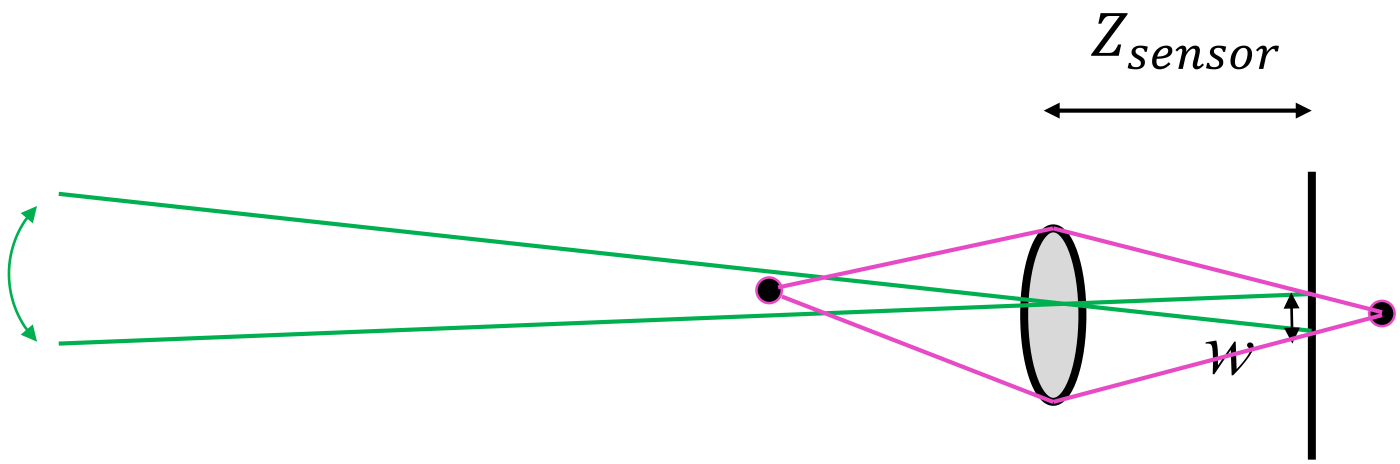
Solve for Z_i

$$\frac{A}{Z_i} = \frac{w}{Z_i - Z_{sensor}}$$

$$\frac{.003}{.0207} = \frac{w}{.0007}$$

$$\rightarrow \quad w \approx .0001\ m$$



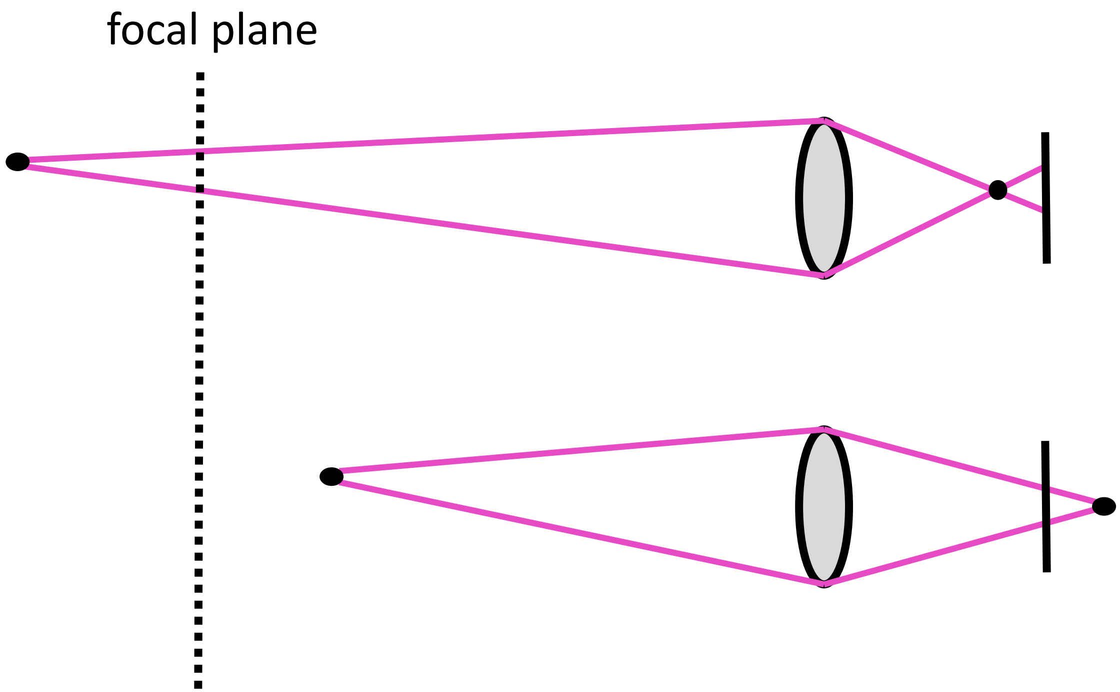


blur width angle $= \dfrac{w}{z_{sensor}} \approx \dfrac{1}{200}\ rad$

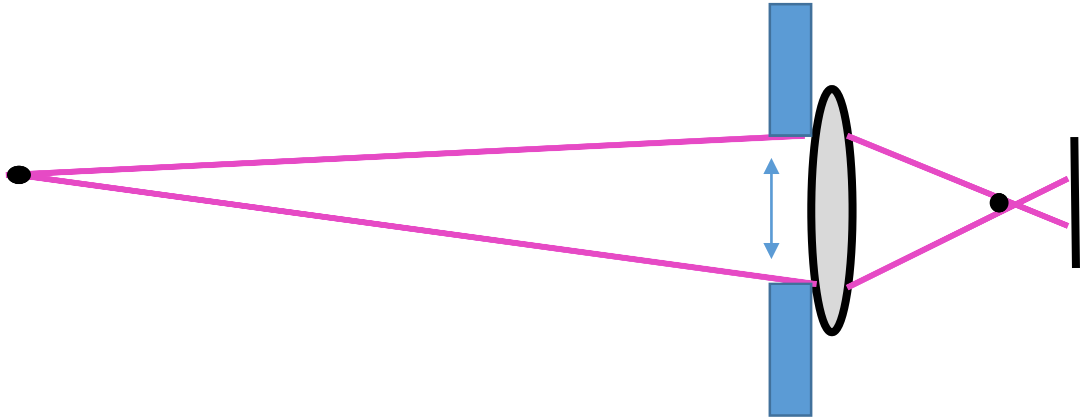
$\approx .3\ deg$

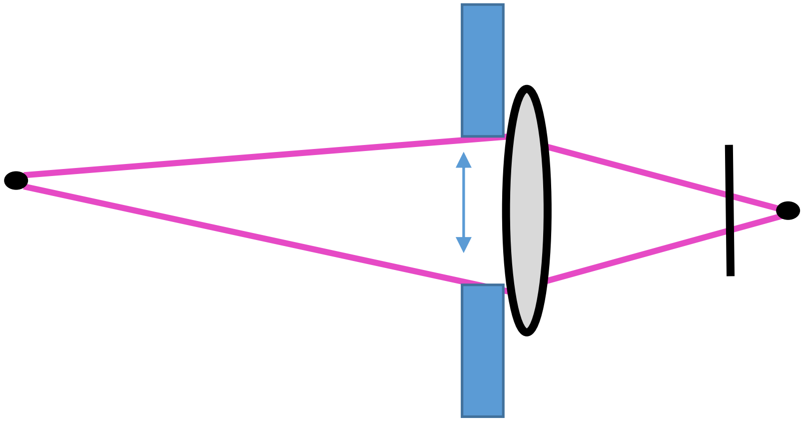
Exercise: show that blur width (in radians) is:

$$A \left| \frac{1}{Z_o} - \frac{1}{Z_{focalplane}} \right|$$



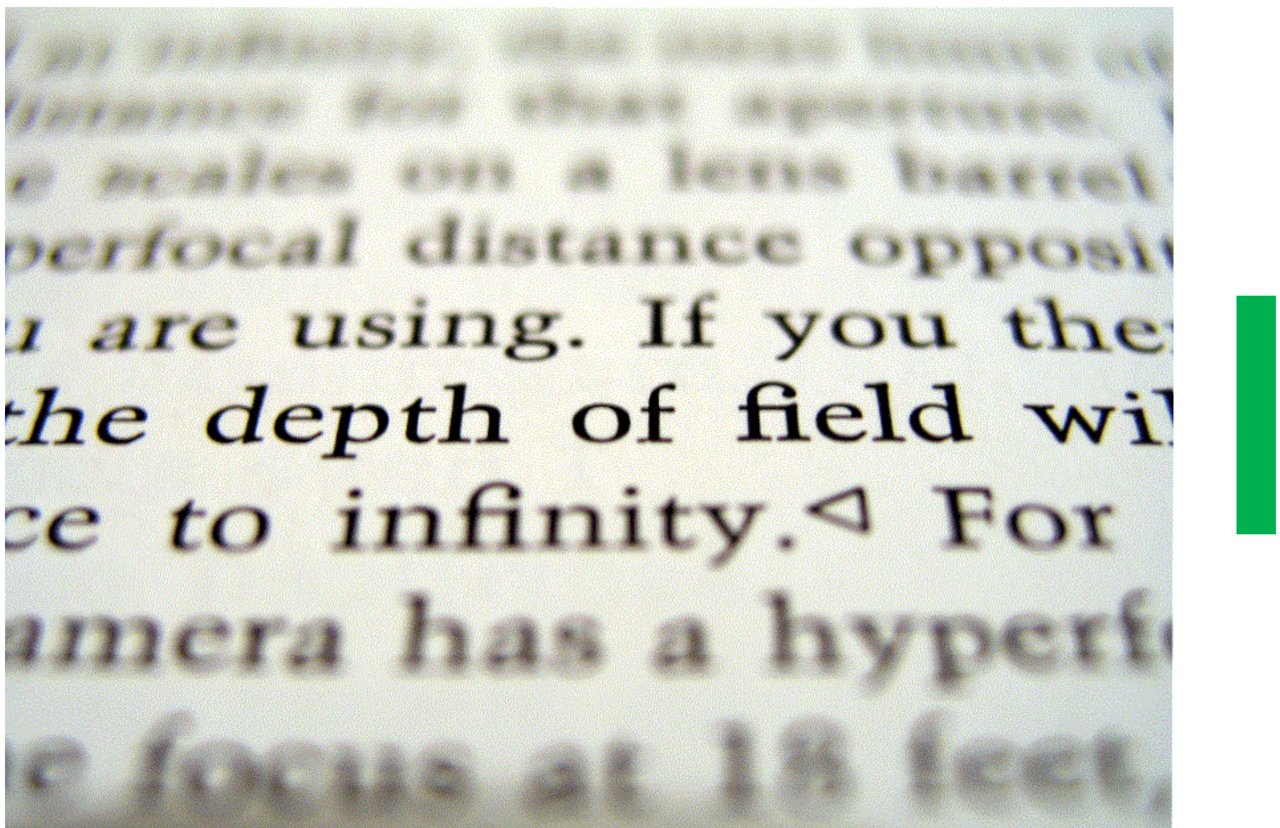
The aperture (pupil) is the hole in the iris. The iris is in front of the lens. For simplicity, I will not draw the iris in the remaining figures.

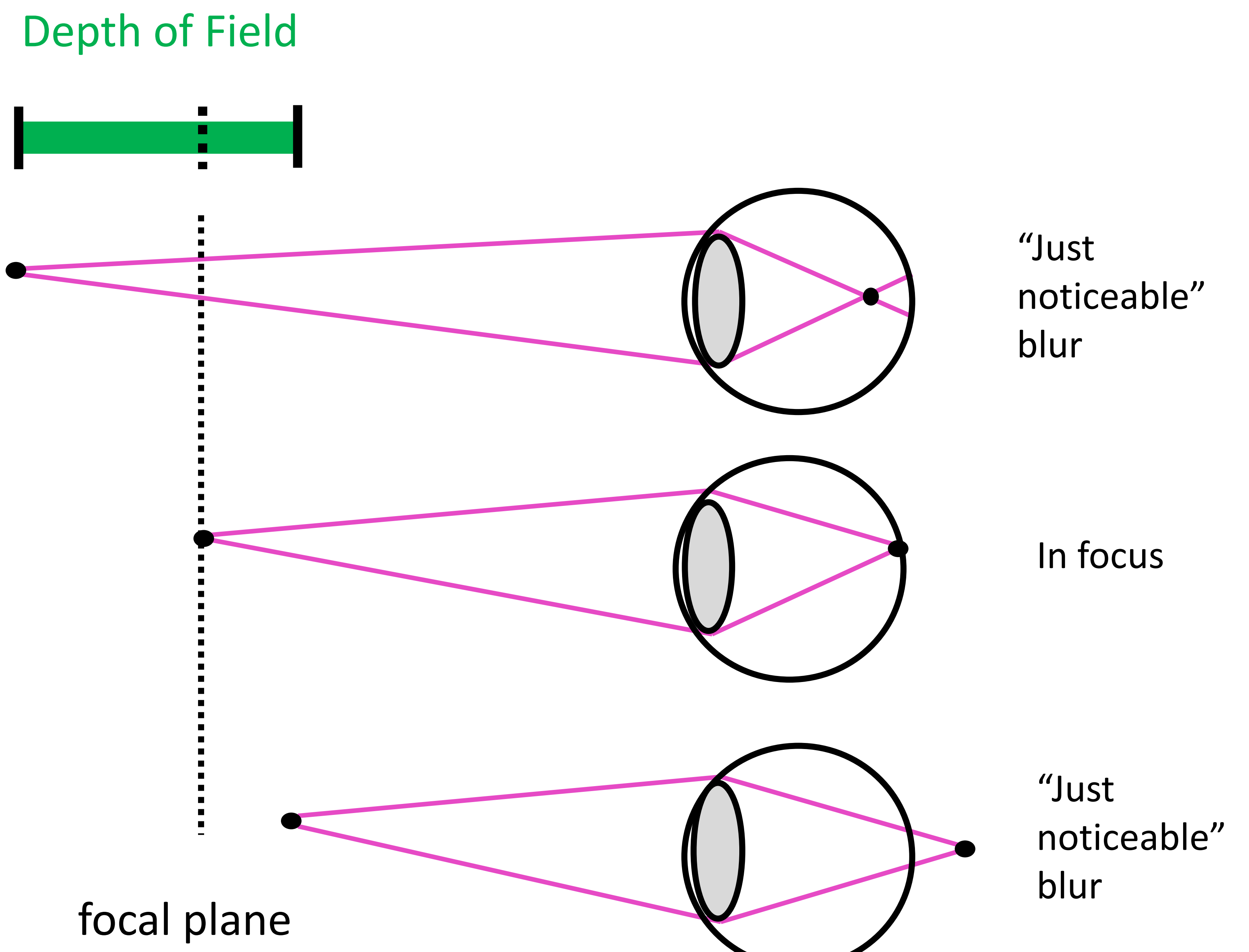




Depth of Field

Depth of field is the range of depths that are *perceived* to be in focus.   (In fact, only one depth is in perfect focus.)




Depth of Field
"Just noticeable" blur
In focus
"Just noticeable" blur
focal plane

Typical depth of field in human vision is said to be about 0.3 diopters (D).

But it depends on many factors:

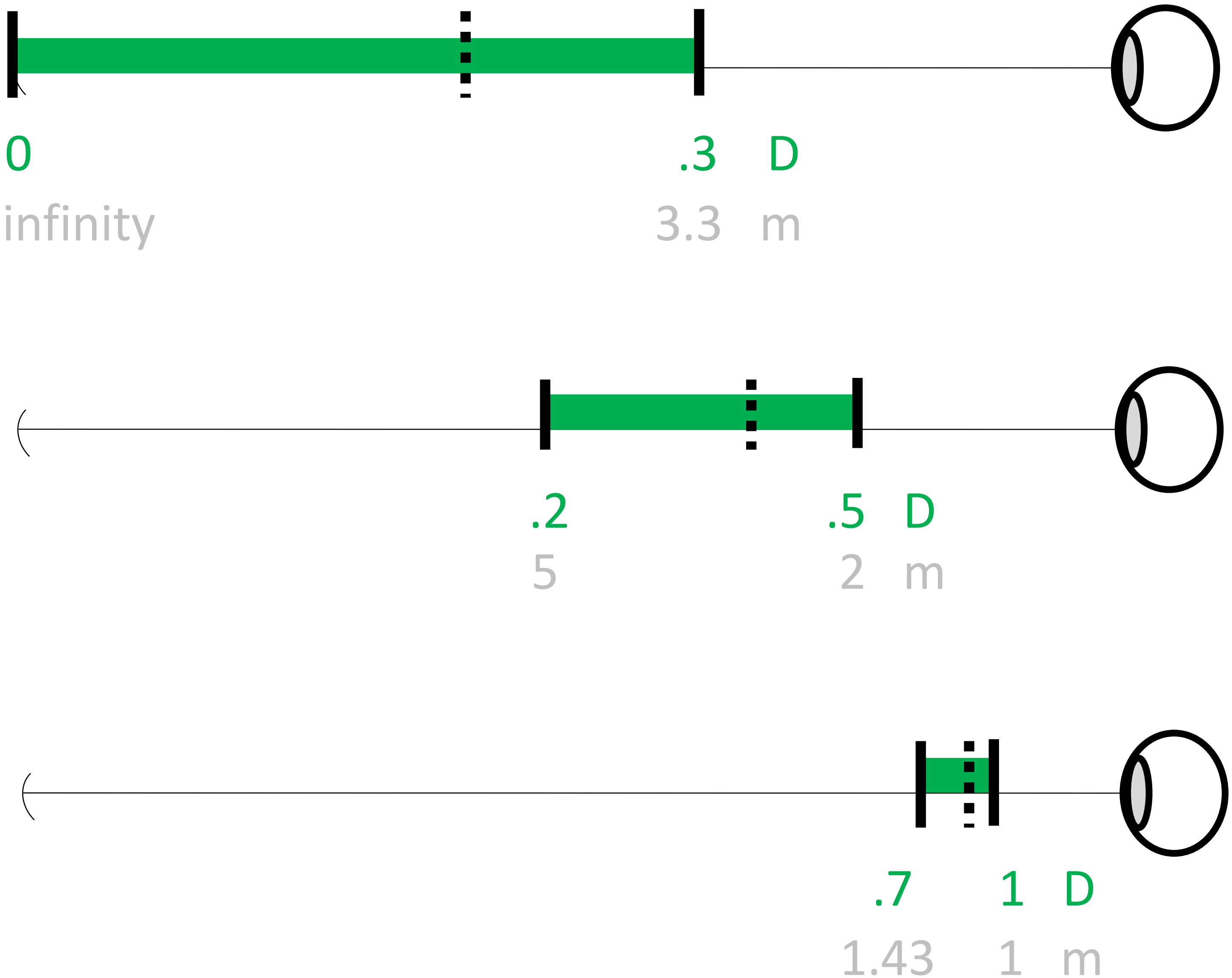
Typical depth of field in human vision is said to be about 0.3 diopters (D).

But it depends on many factors:

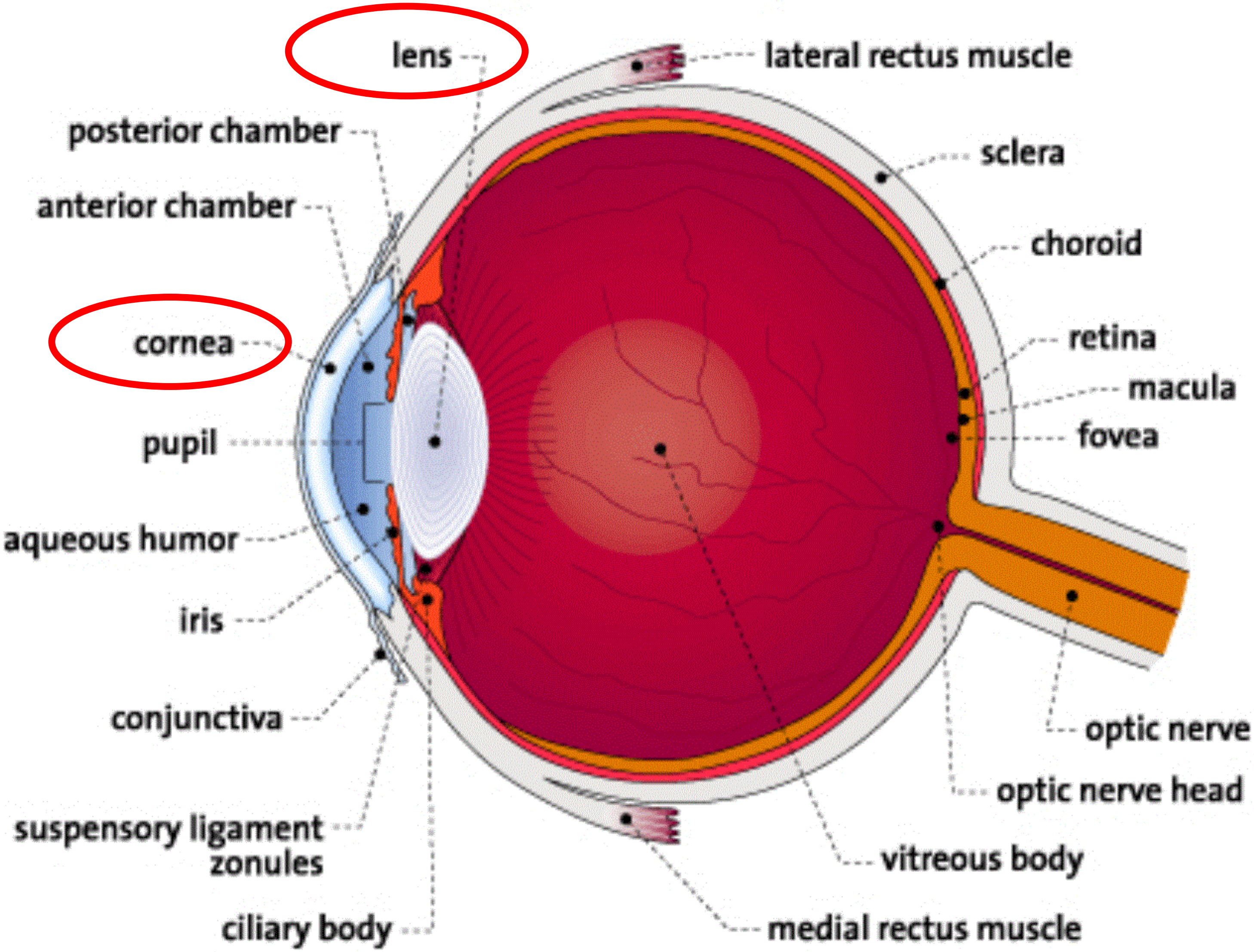
- pupil diameter
- variations between people
- what is the image being judged ?
- …

NOTE: it does not depend on the depth of focal plane.

Examples where depth of field is about 0.3 diopters.

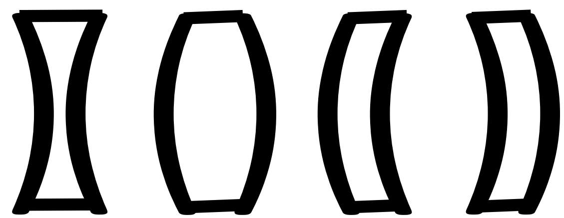


Eye Anatomy



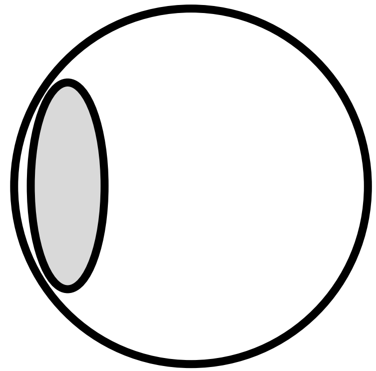
lens
lateral rectus muscle
posterior chamber
sclera
anterior chamber
choroid
cornea
retina
macula
pupil
fovea
aqueous humor
iris
conjunctiva
optic nerve
optic nerve head
suspensory ligament zonules
vitreous body
ciliary body
medial rectus muscle

Thin lens optics



$$\frac{1}{f_1} + \frac{1}{f_2} + \frac{1}{f_3} + \frac{1}{f_4} = \frac{1}{f}$$

Equivalent power for a single lens



$$\frac{1}{f_{cornea}} + \frac{1}{f_{lens}} \equiv \frac{1}{f}$$

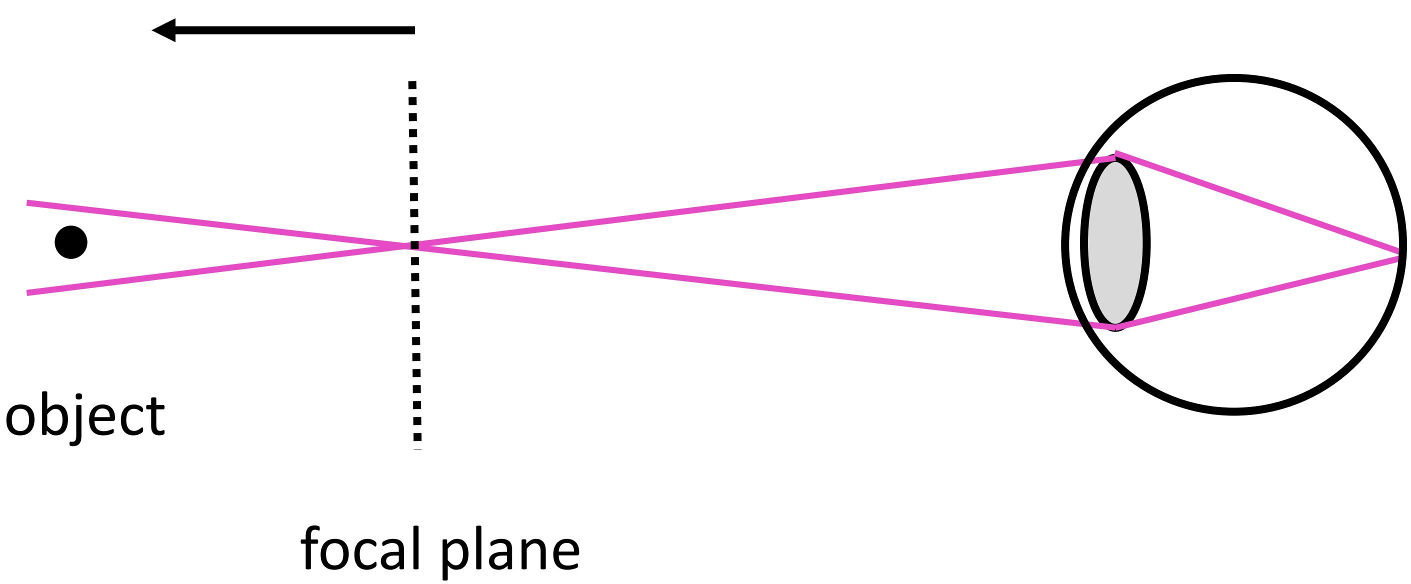
e.g. 40 + 20 = 60 (diopters, D)

typical values

The cornea has more refractive power than the lens.

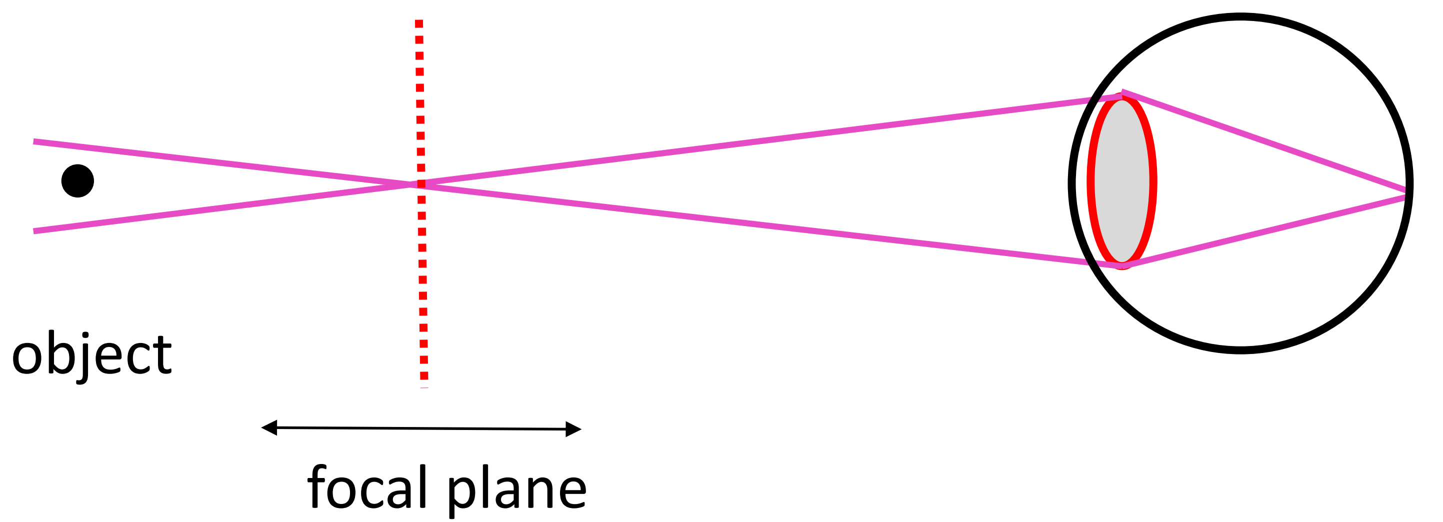
Accommodation

The lens shape can change: muscles squeeze the lens and change its curvature (and power).



$$\overbrace{\frac{1}{f_{cornea}} + \frac{1}{f_{lens}}}^{\frac{1}{f}} = \frac{1}{z_{focalplane}} + \frac{1}{z_{sensor}}$$

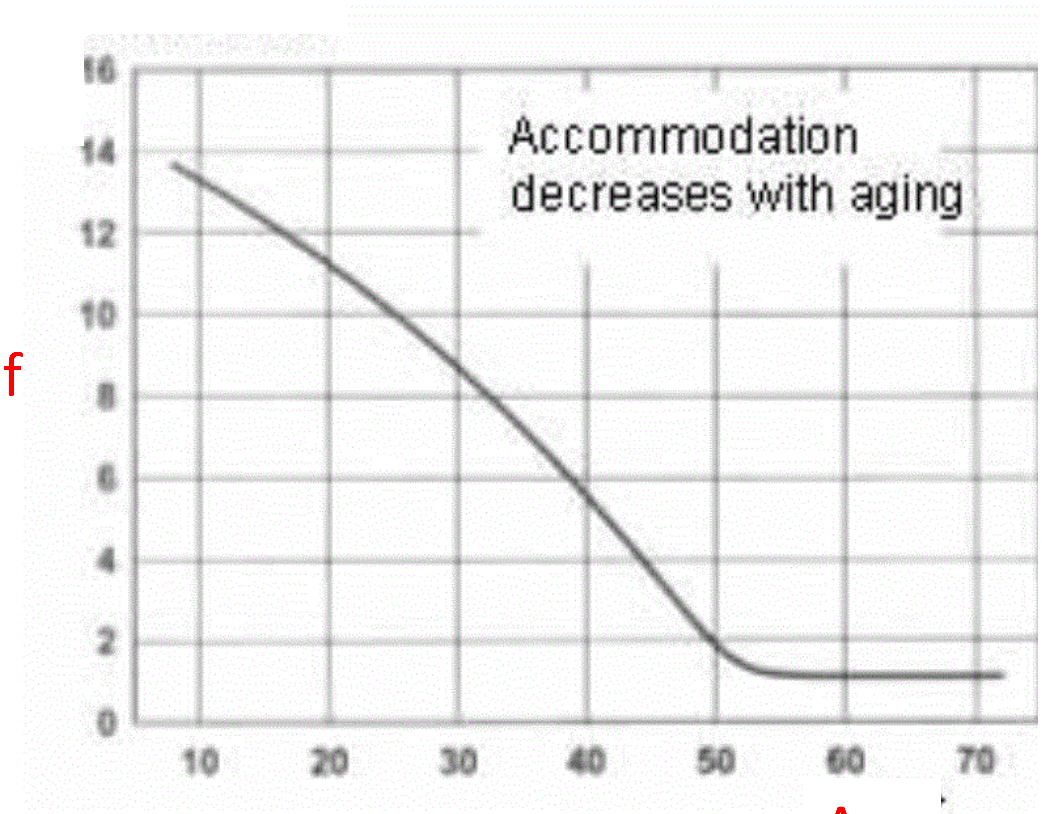
Adjusting power of lens changes the focal plane distance



Presbyopia

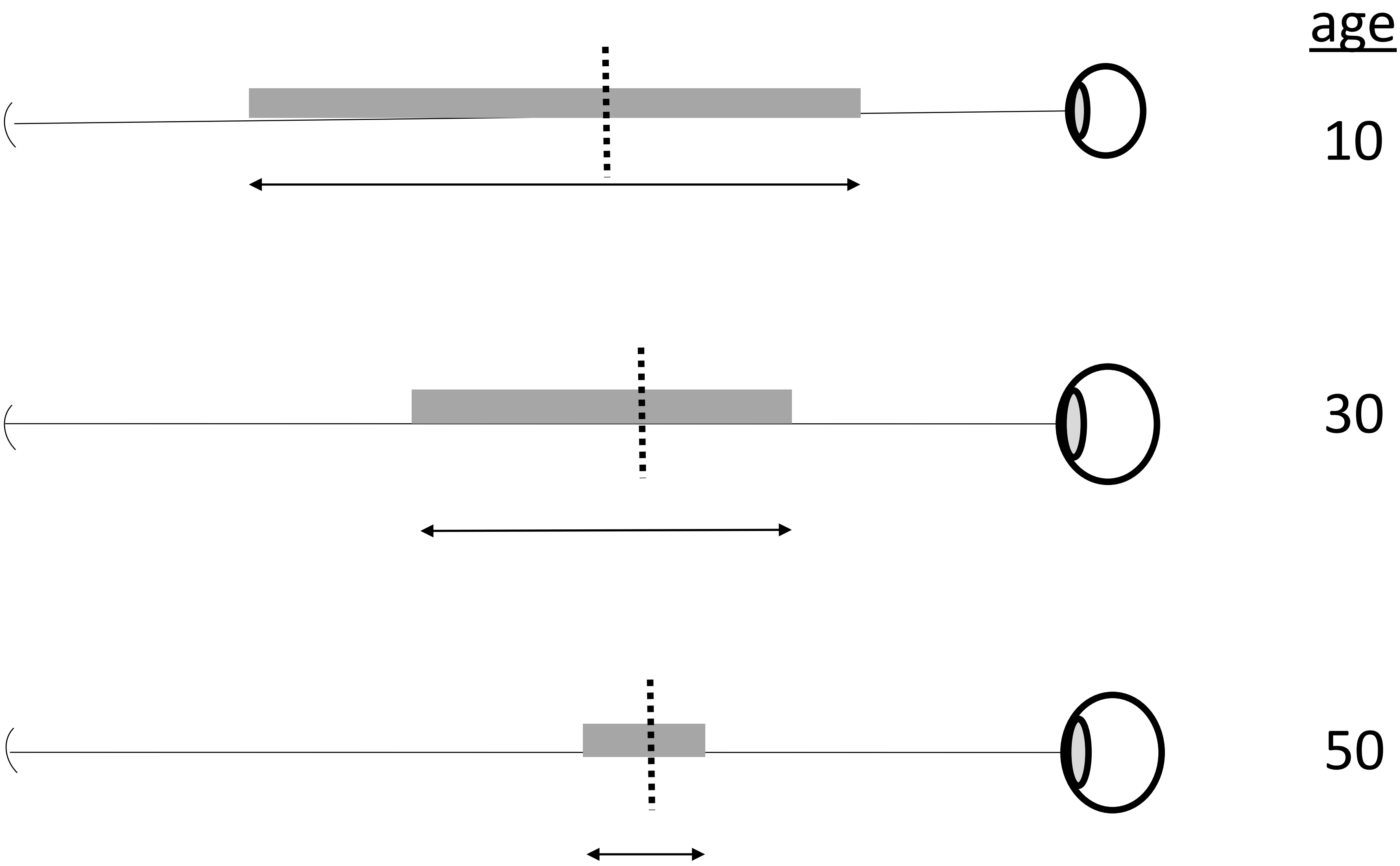
Older lenses resists shape change.

Range of adjustment of lens power (diopters)



Age

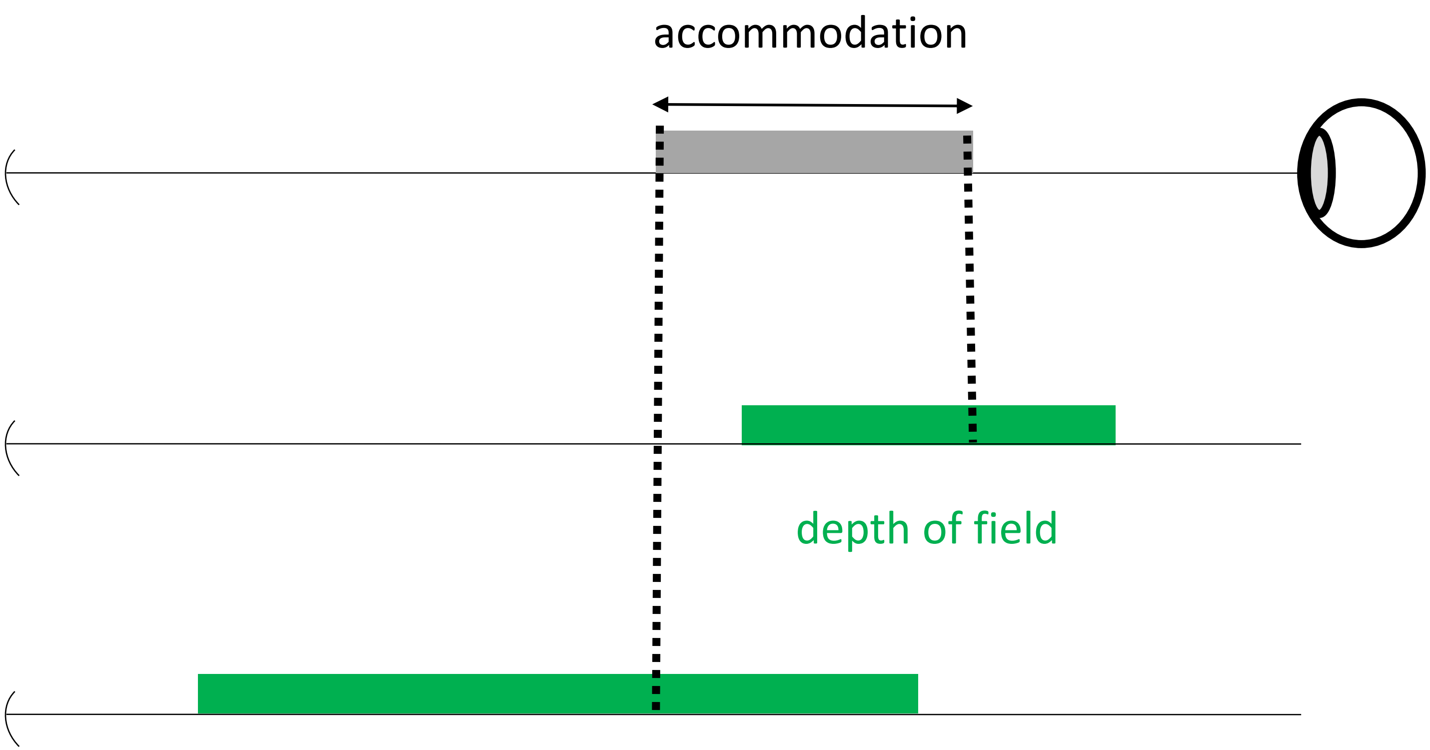
Accommodation & presbyopia



Myopia

"short sighted": can't focus at infinity

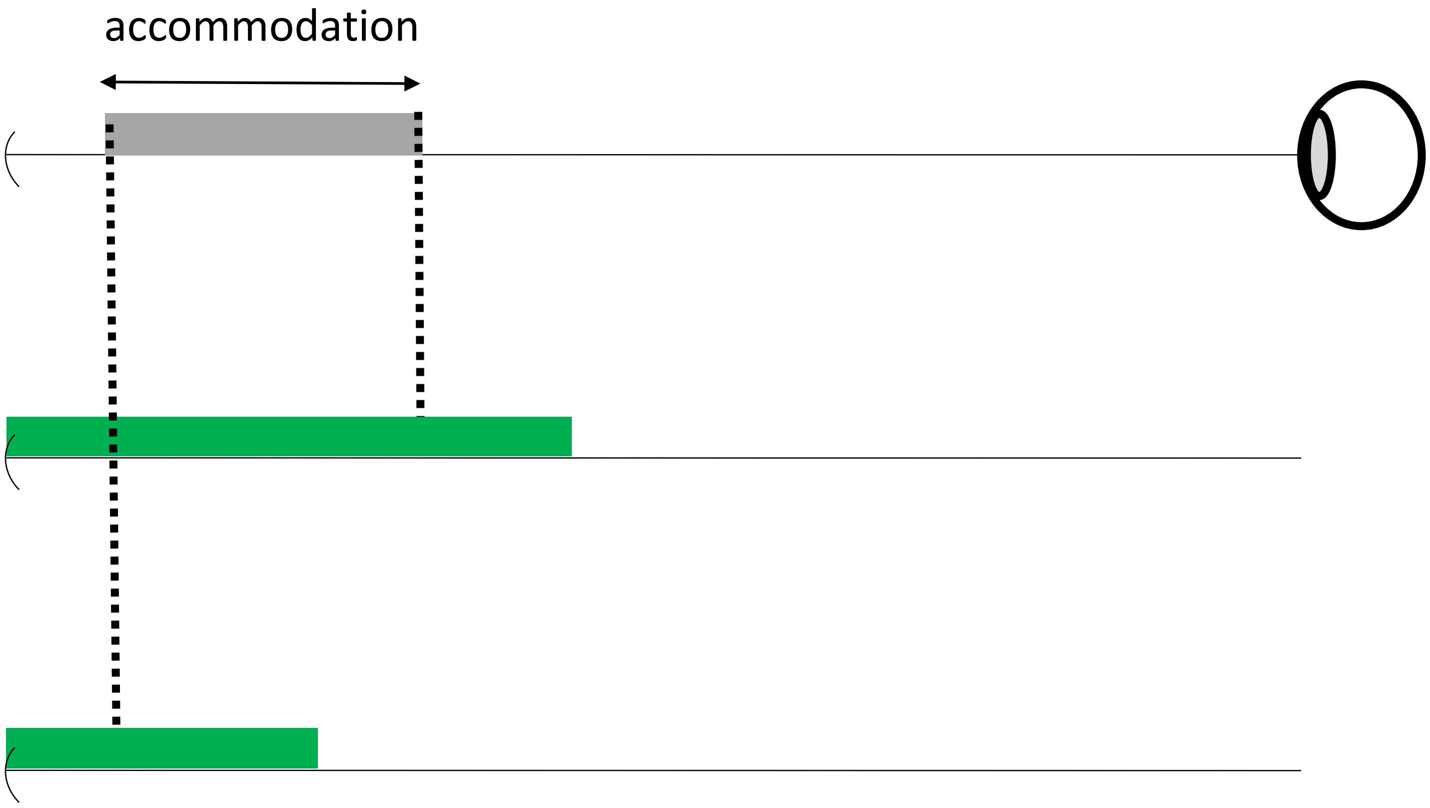
cornea power is too high, given size of eye



Hyperopia

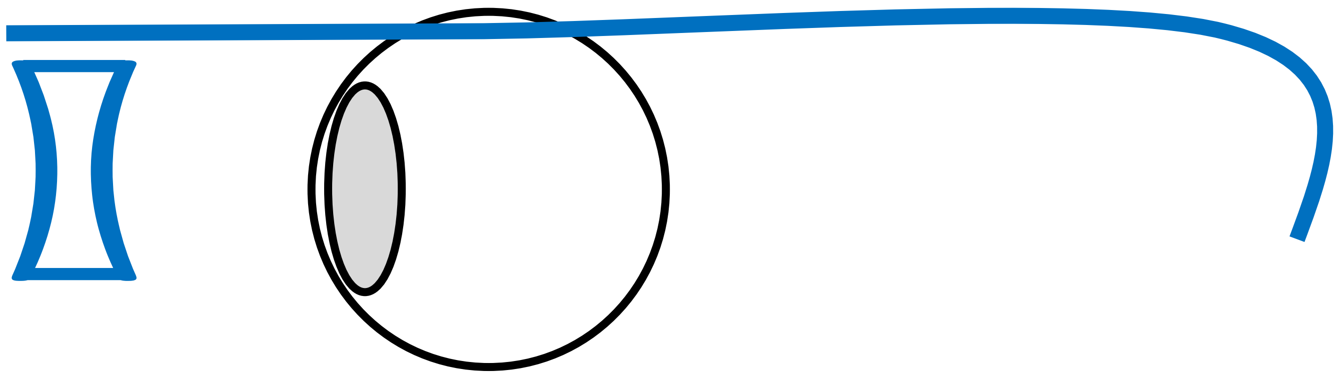
"far sighted": can't focus on near field

lens + cornea power are too low, given size of eye



e.g. I am myopic. My cornea + lens is too strong.

Lens with negative power

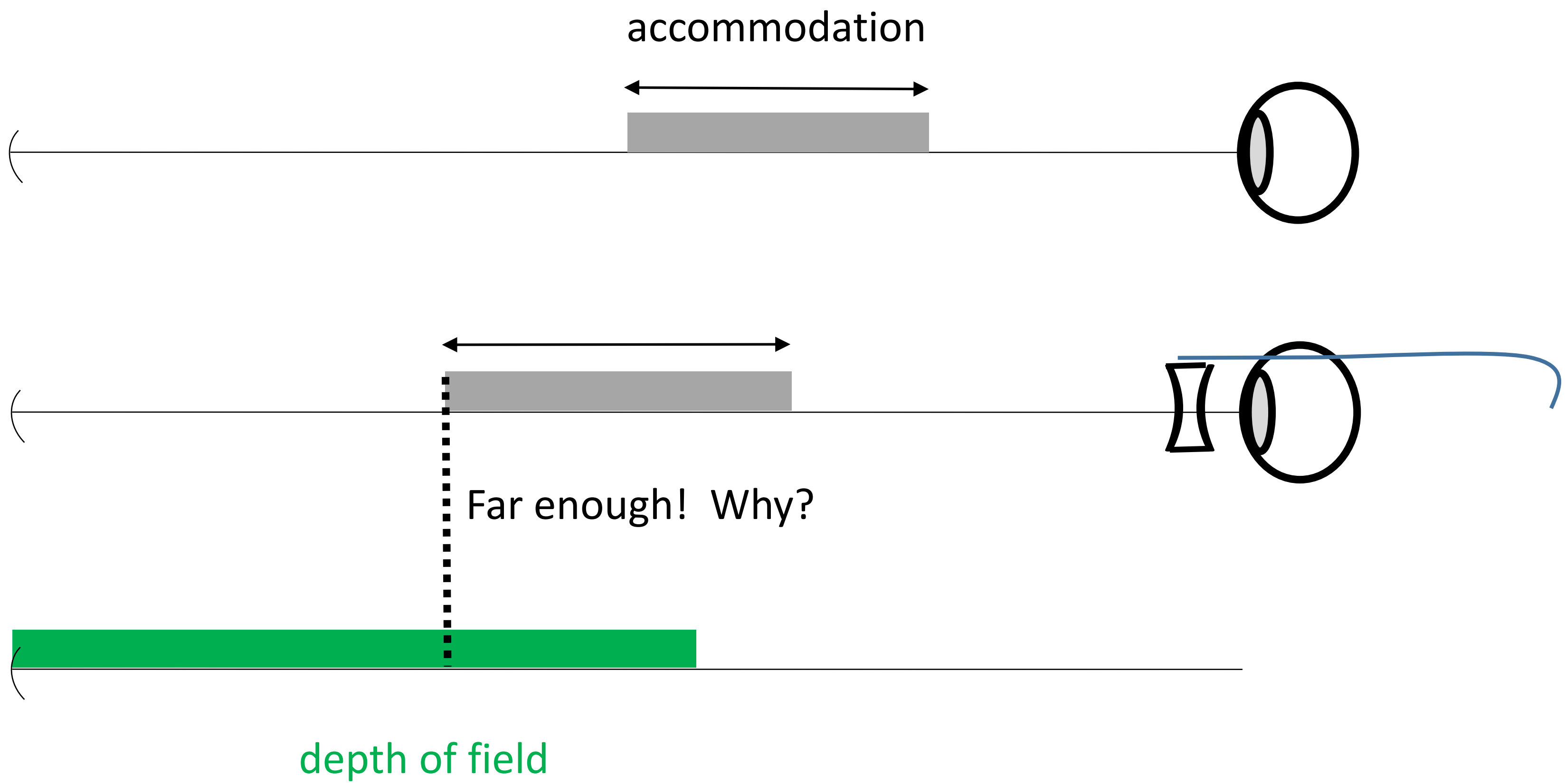


$$\frac{1}{f_{glasses}} + \frac{1}{f_{cornea}} + \frac{1}{f_{lens}} \equiv \frac{1}{f}$$

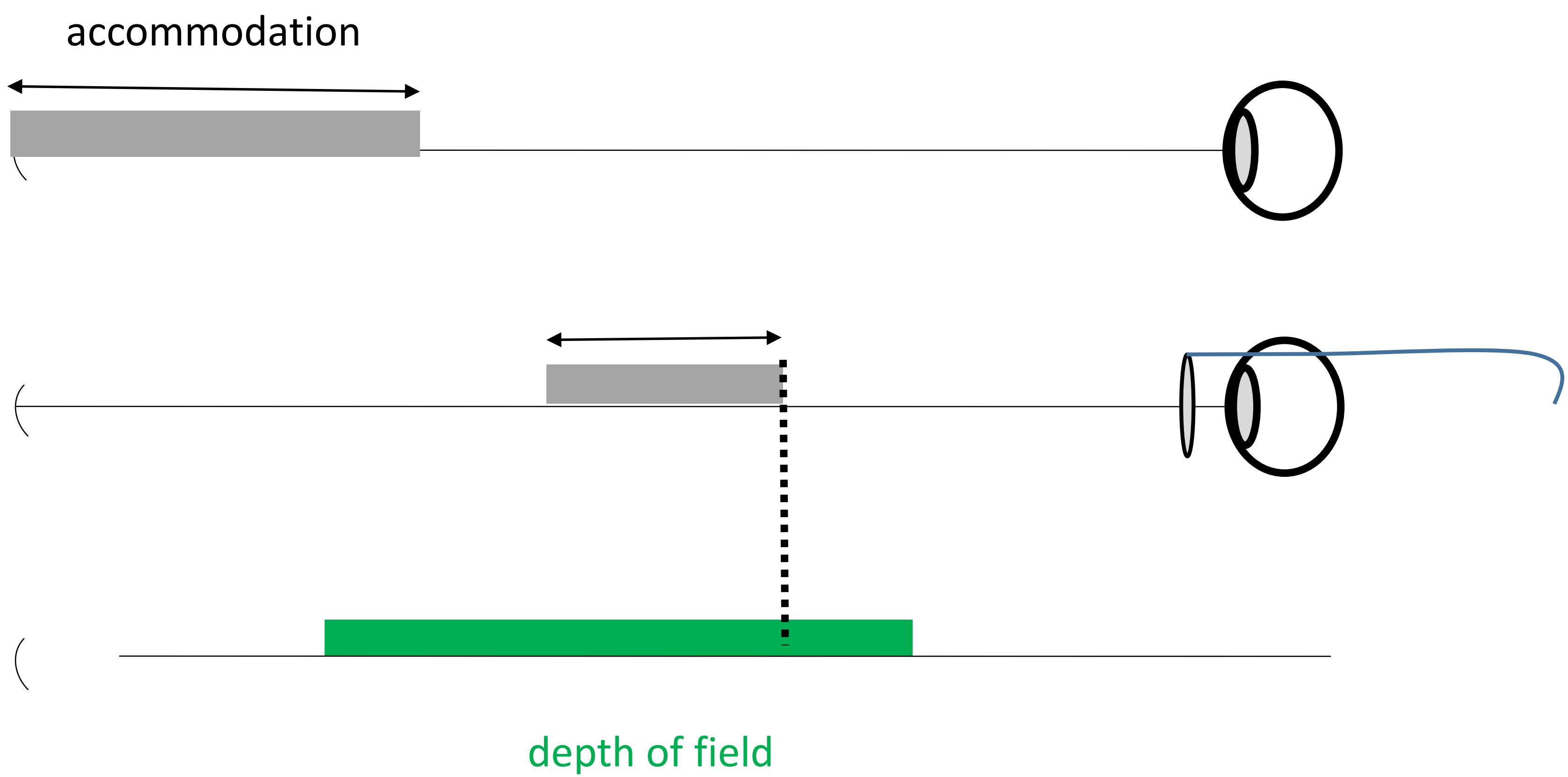
- 3 + 40 + 20 D

ish ish

Corrected Myopia:
allows distant vision



Corrected Hyperopia:
allows near vision



Open questions

- How does the visual system determine if an image is in focus ?   (Define blur.)
- How does the visual system accommodate ? (Accommodation interacts with binocular vergence)
- Is defocus blur a “depth cue” ?