MÁTÉ LENGYEL: BIOLOGICAL VISION WITH AN ENGINEER'S EYE

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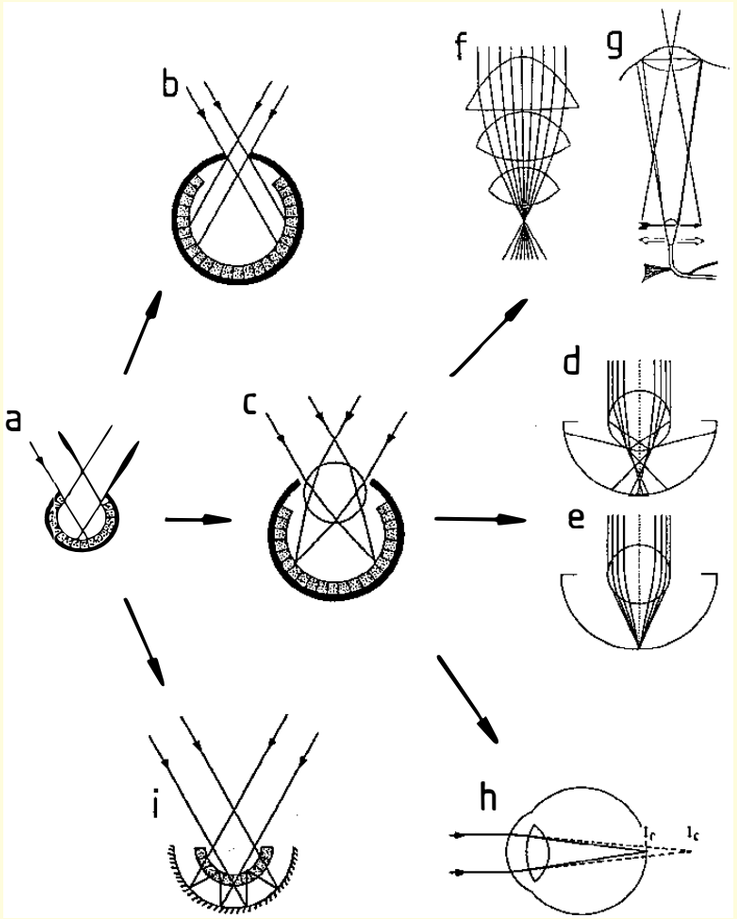
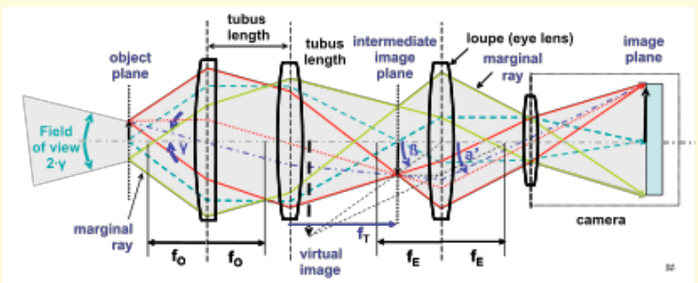
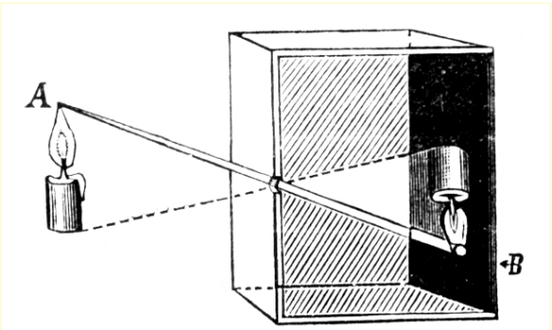
I. optical properties of eyes







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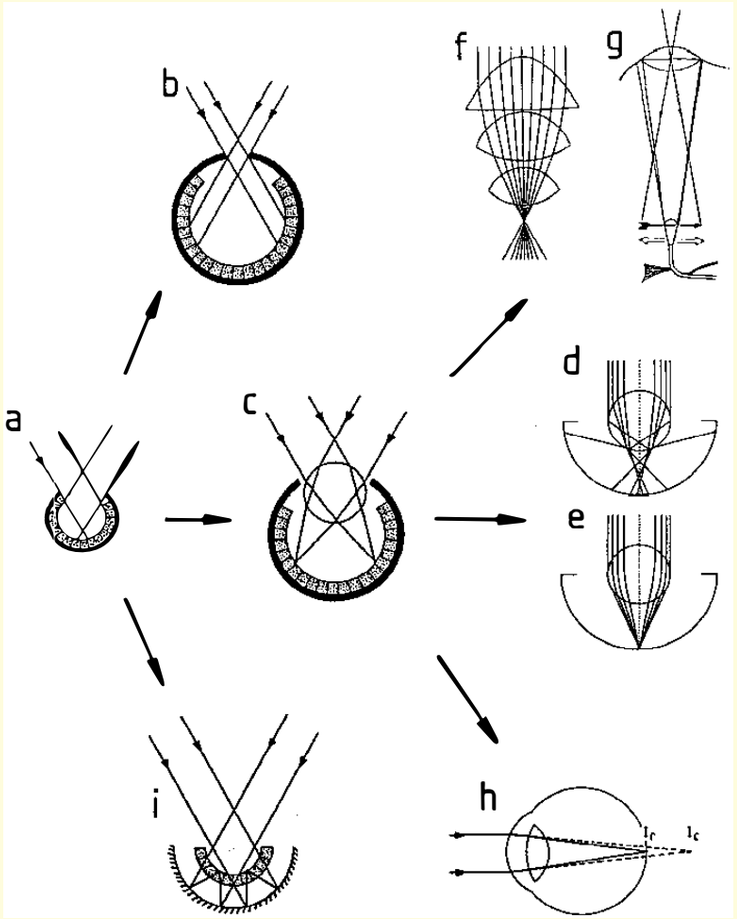
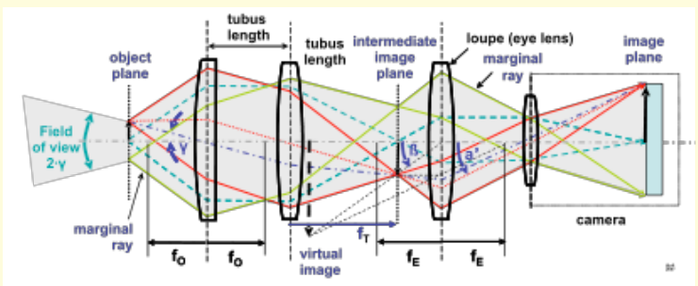
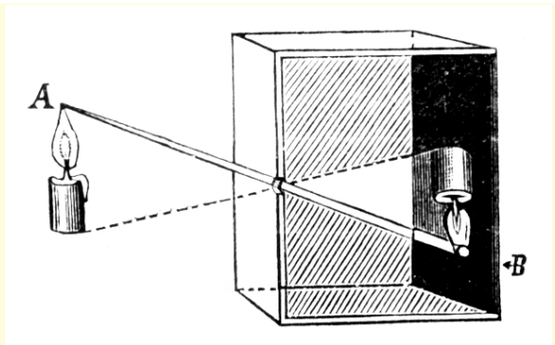
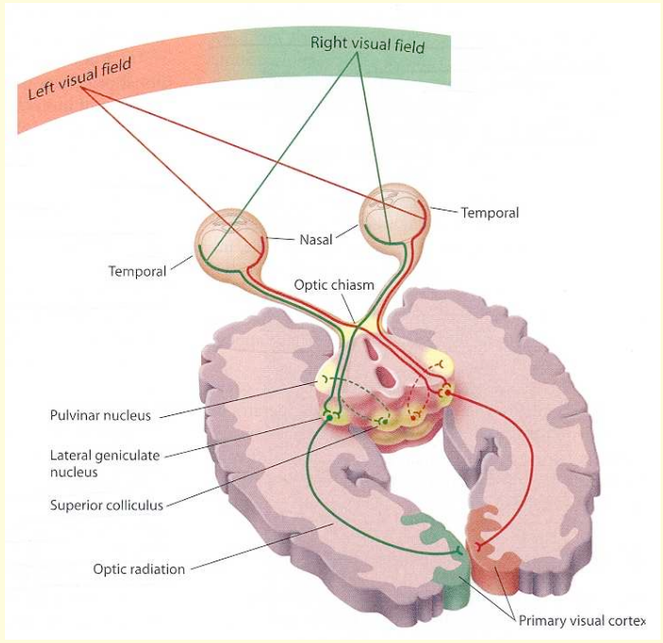
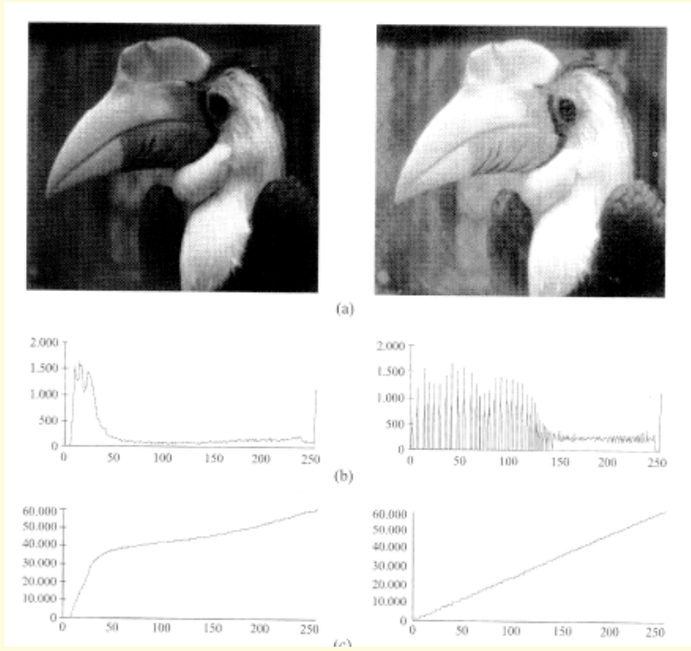






II. information transmission in the visual pathway





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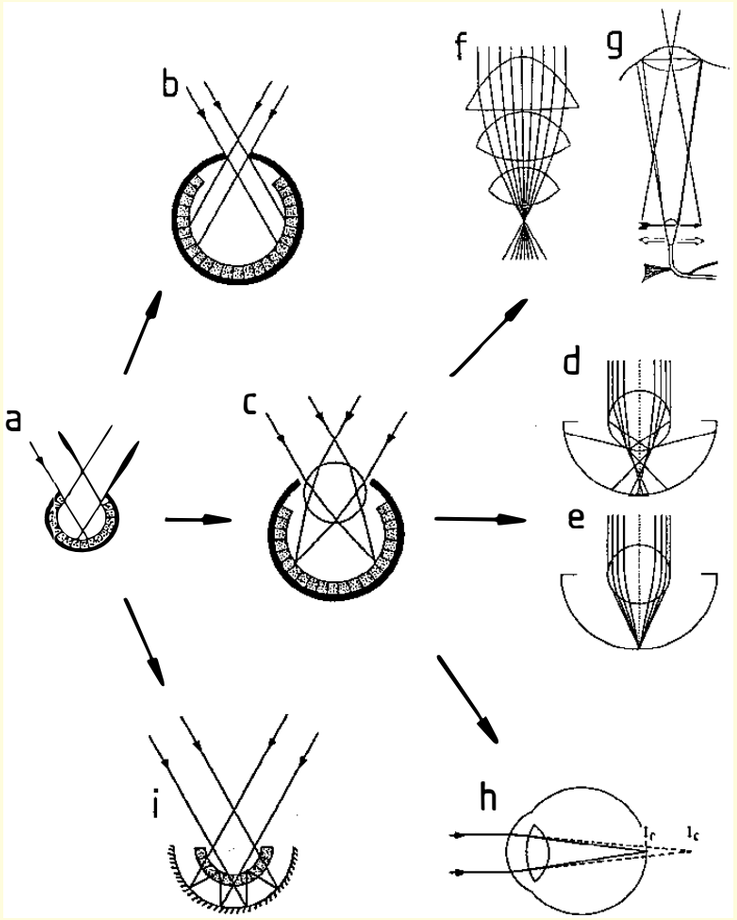

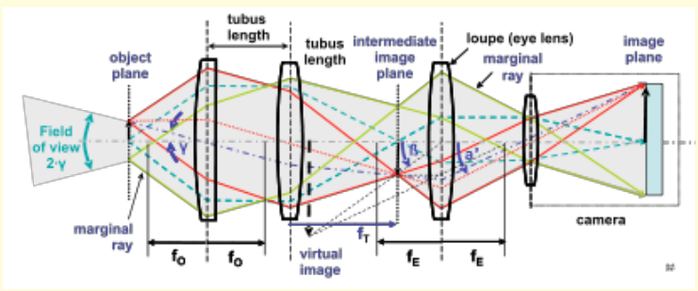

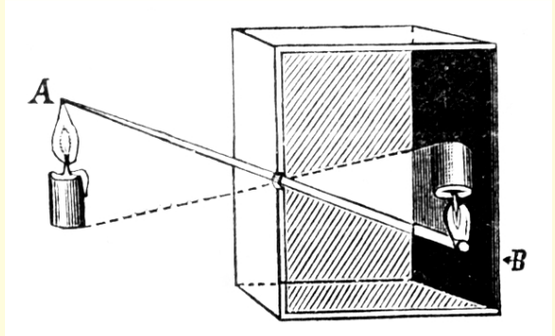

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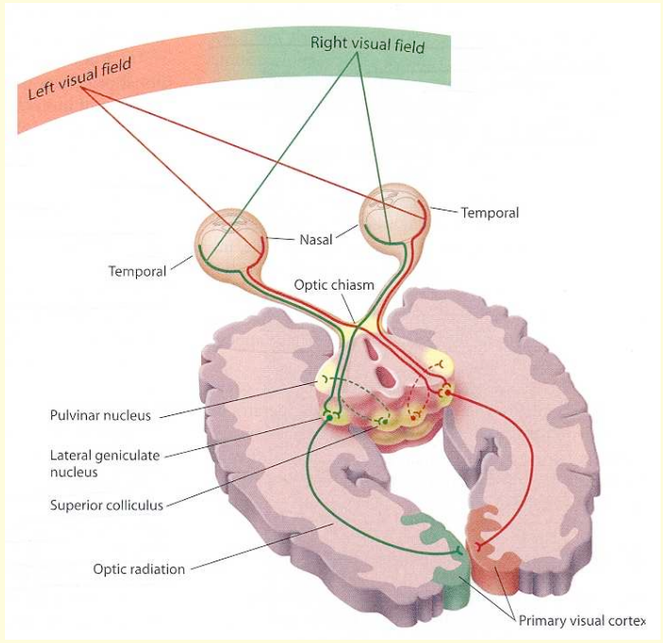
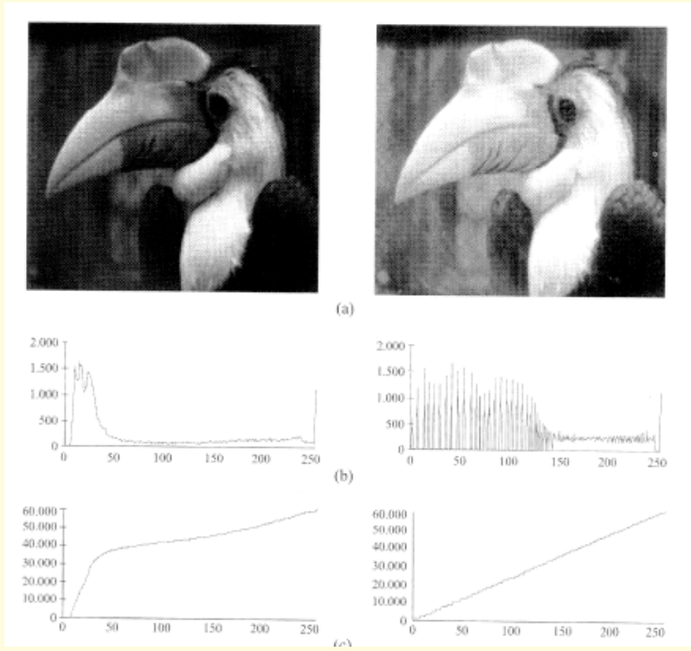
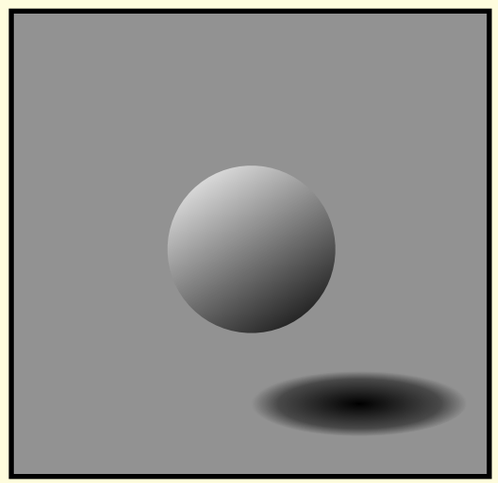
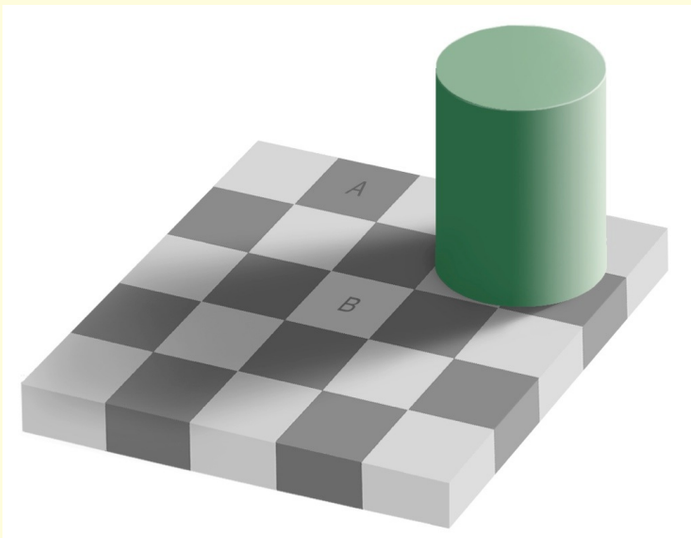




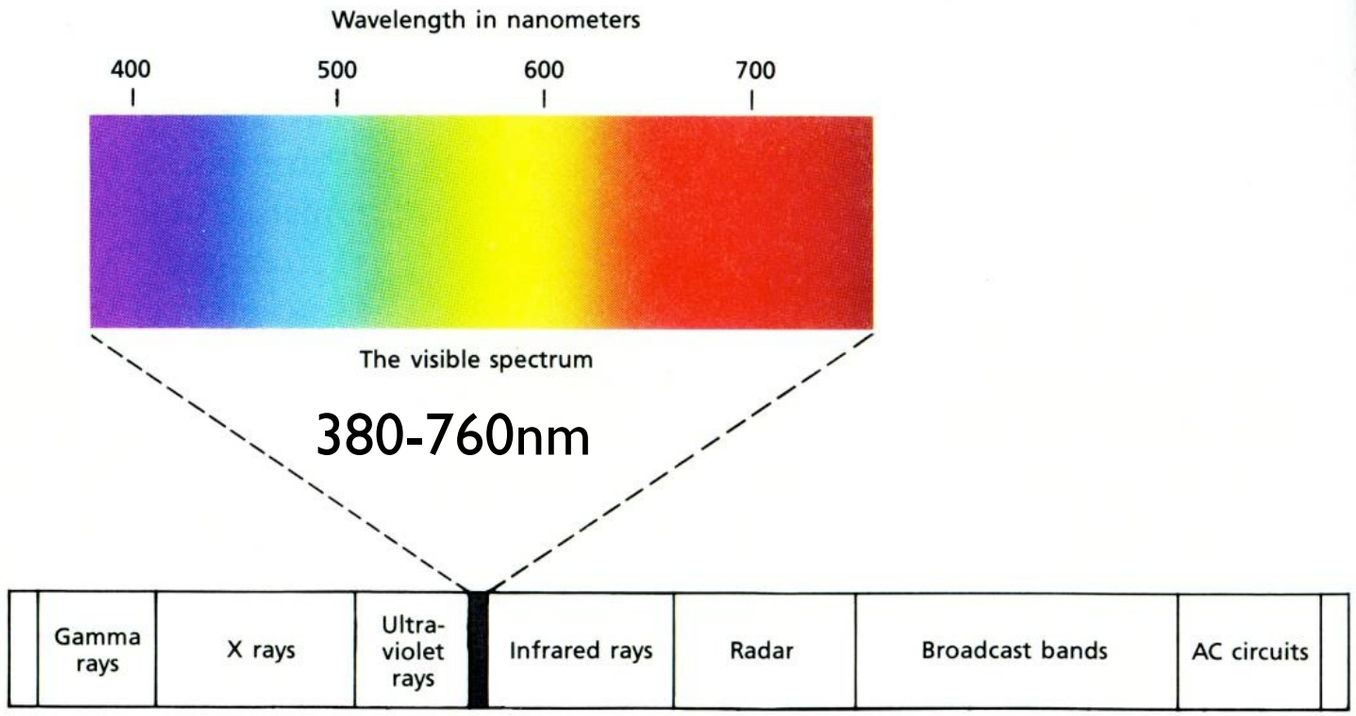
III. internal models and illusions in visual perception





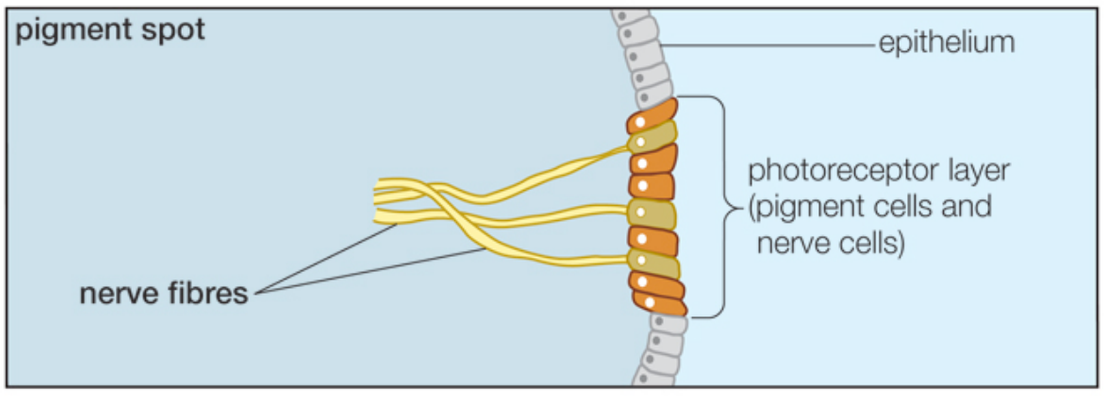
Vision

Humans perceive the visible spectrum of electromagnetic radiation



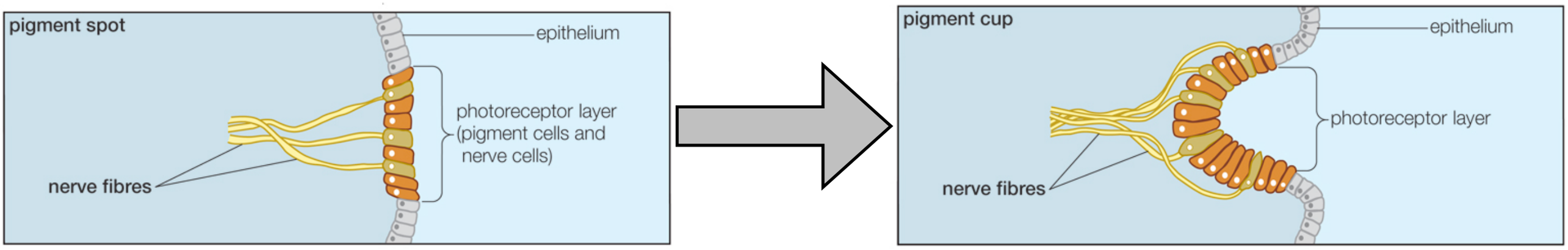
- Vision is our ability to determine
  - Form, Motion, Depth & Colour
  - To bind these percepts together

PIT EYE



light / dark

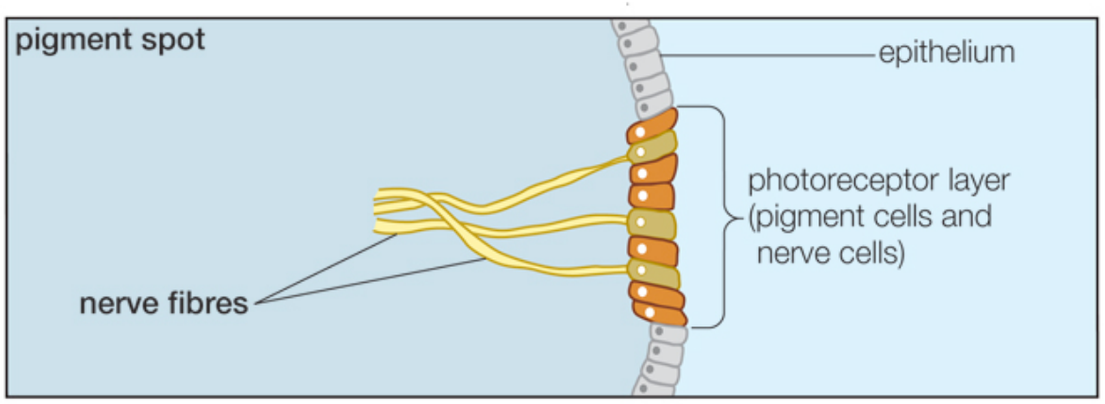
PIT EYE

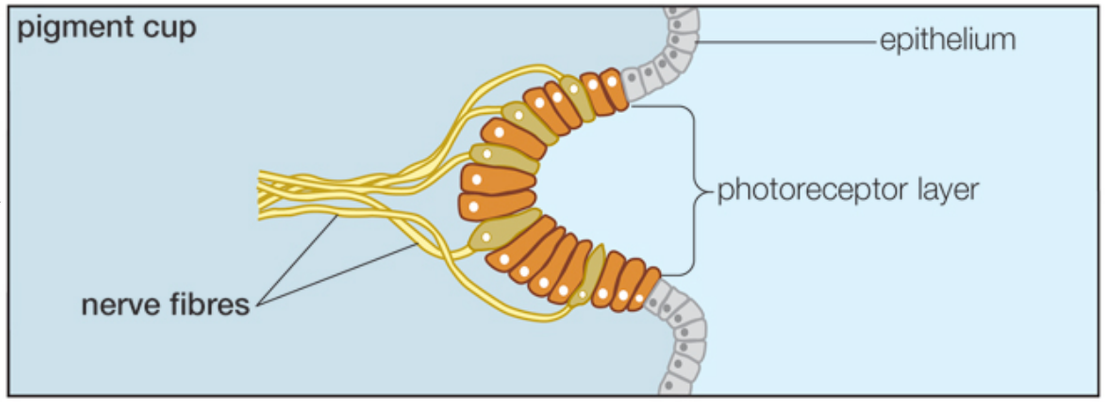


light / dark

direction of light

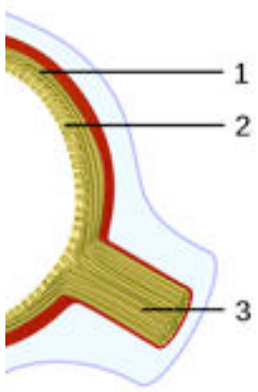
PIT EYE

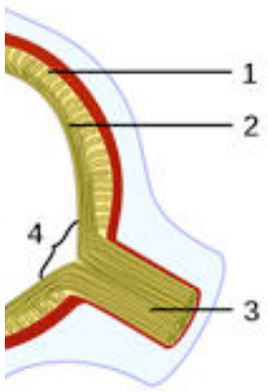




light / dark **direction of light**

- evolved separately over 40 times
- 1-100 receptors
- everse or inverse





1: sense cells (retina)

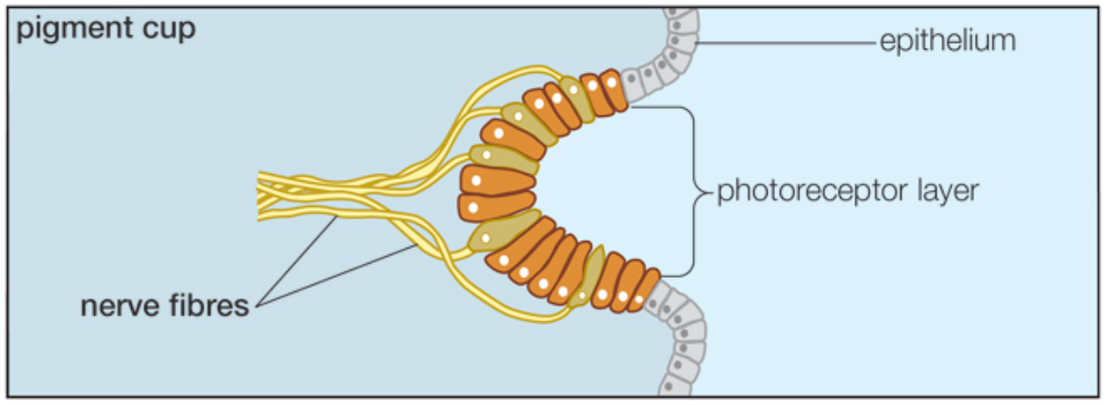
2: nerve cells

3: optical nerve

4: blind spot

- vague indication about the distribution of brightness in the surroundings
- **3 possible improvements have evolved**

1. PIN HOLE CAMERA



direction of light

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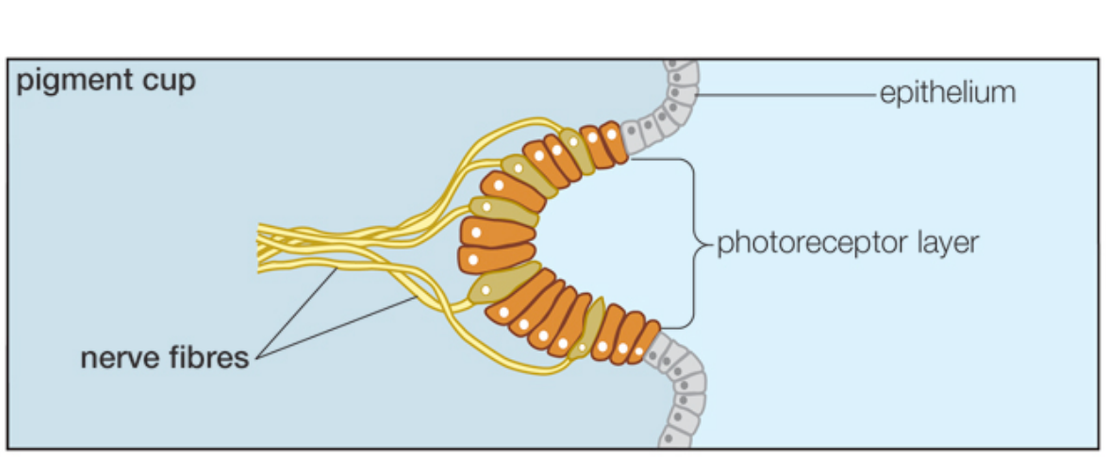

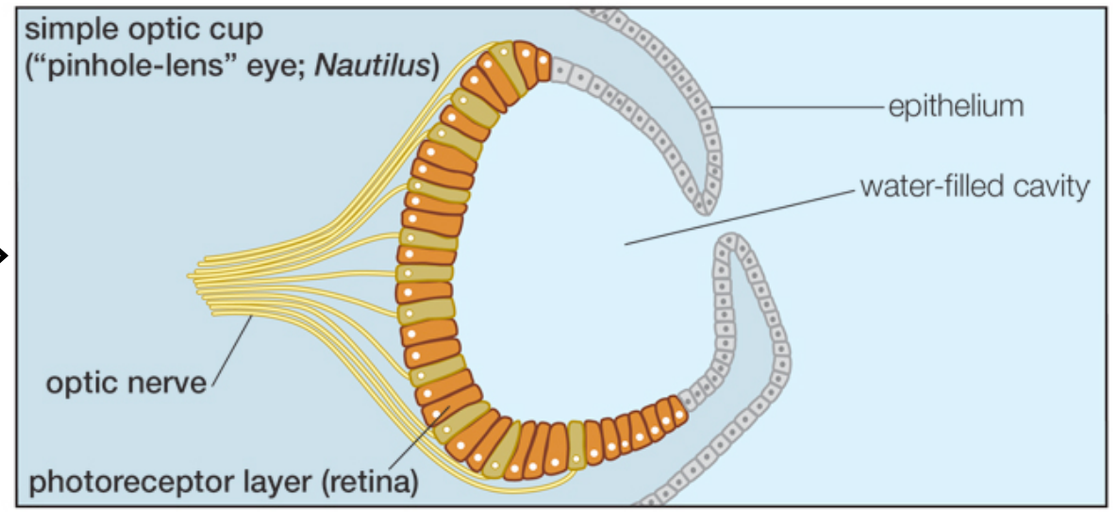

direction of light

image

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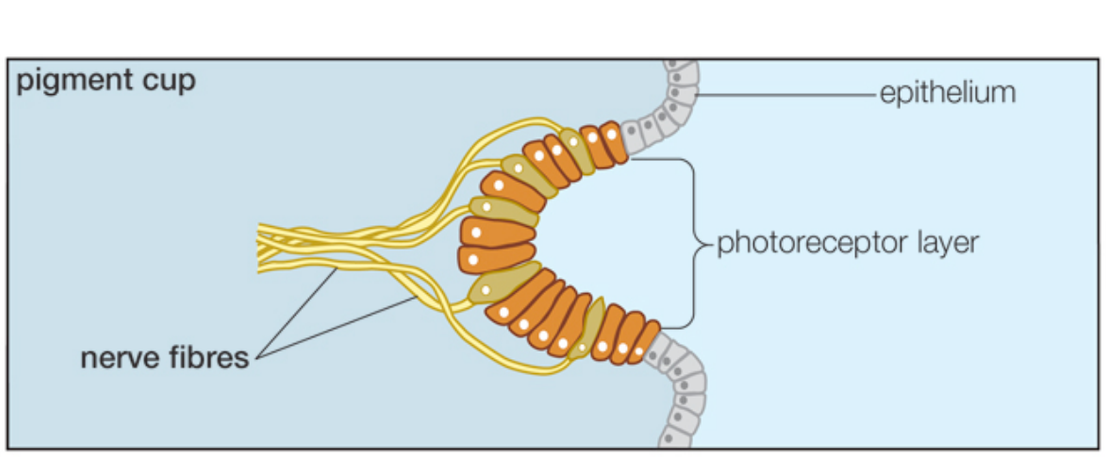

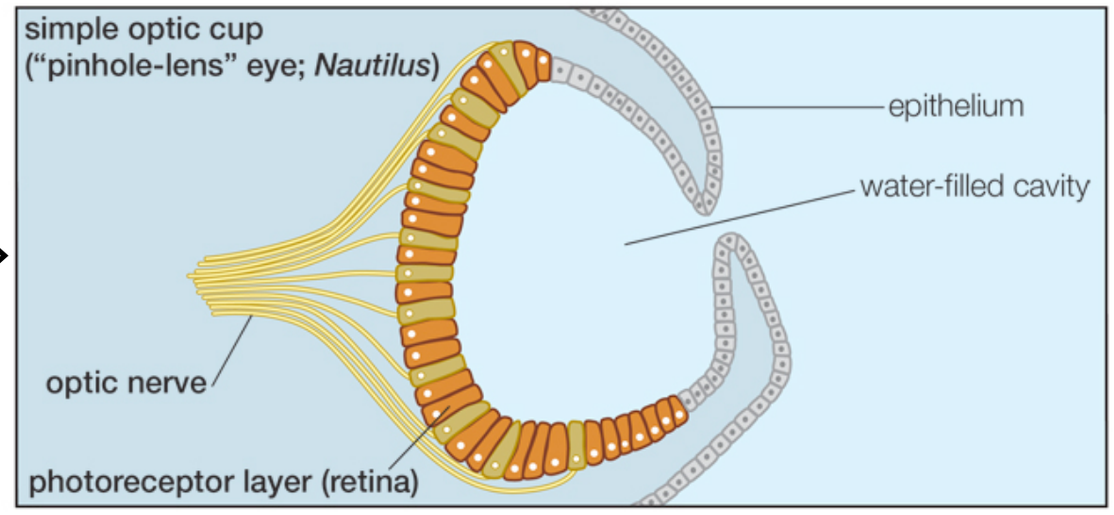

direction of light

image

Nautilus

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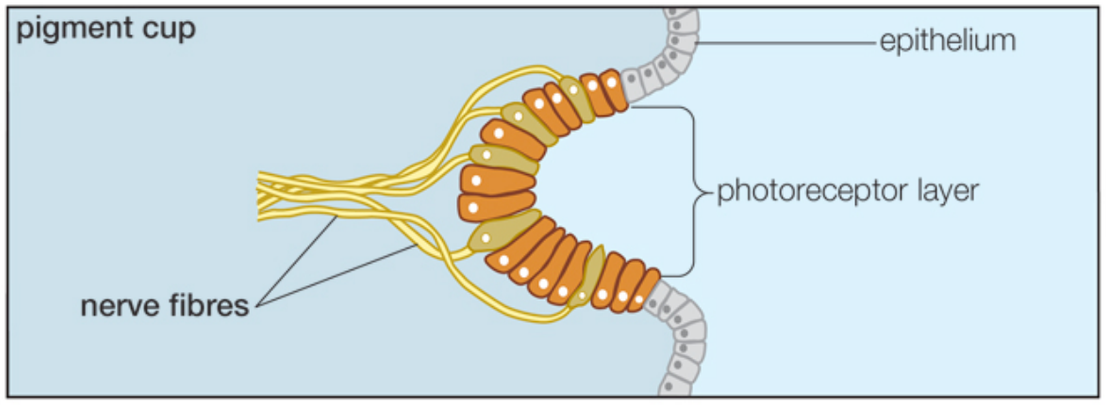
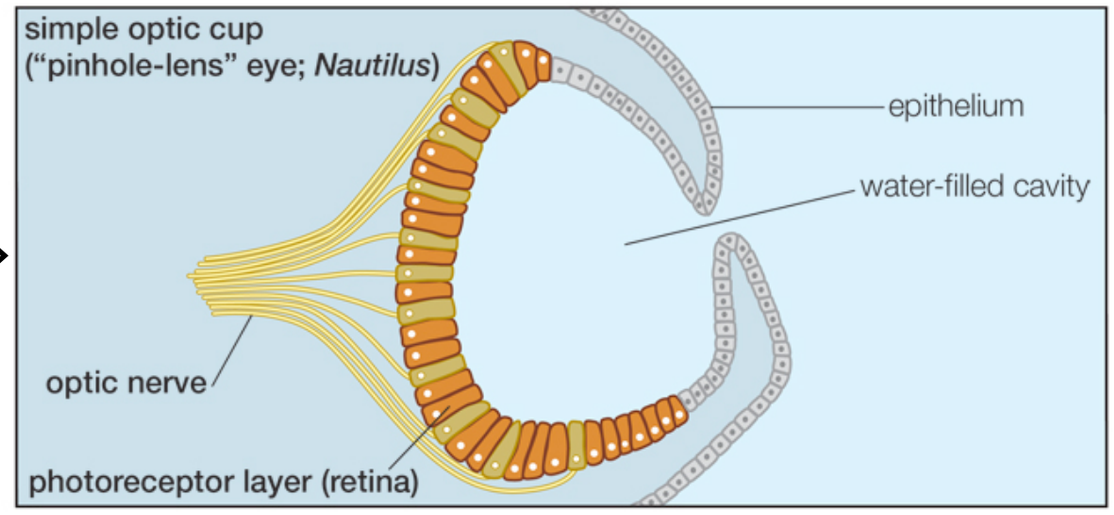


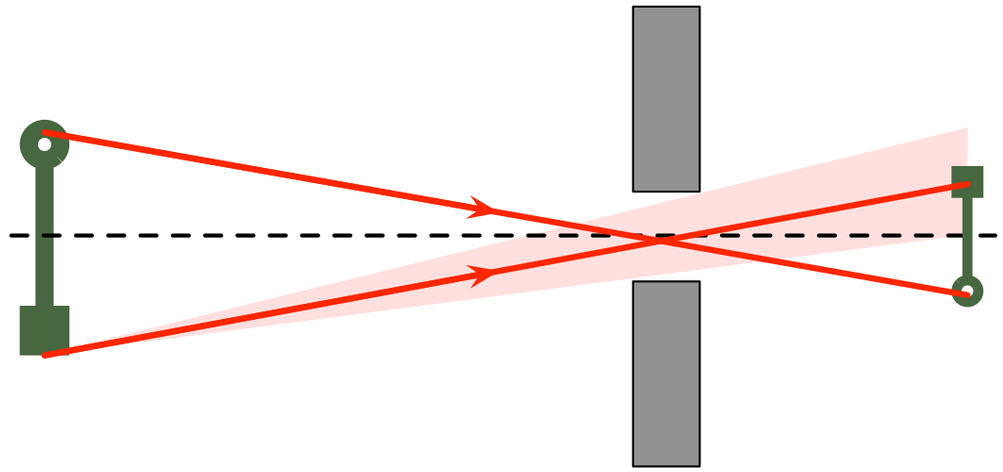


direction of light

image

Nautilus

- enlarge cup and reduce aperture → image



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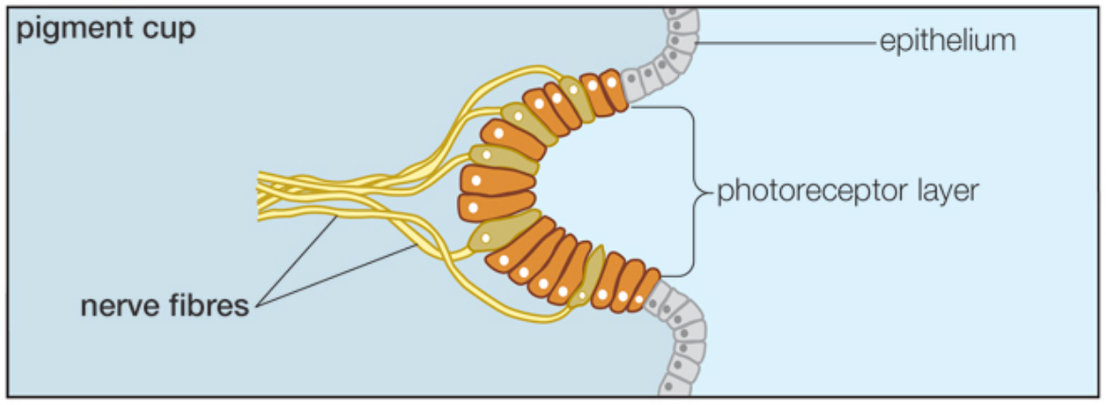

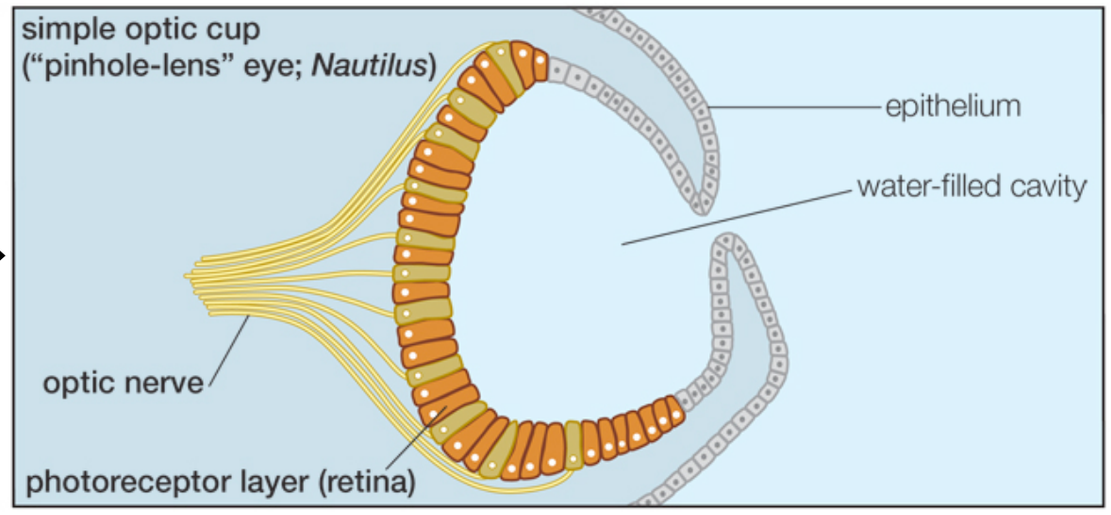

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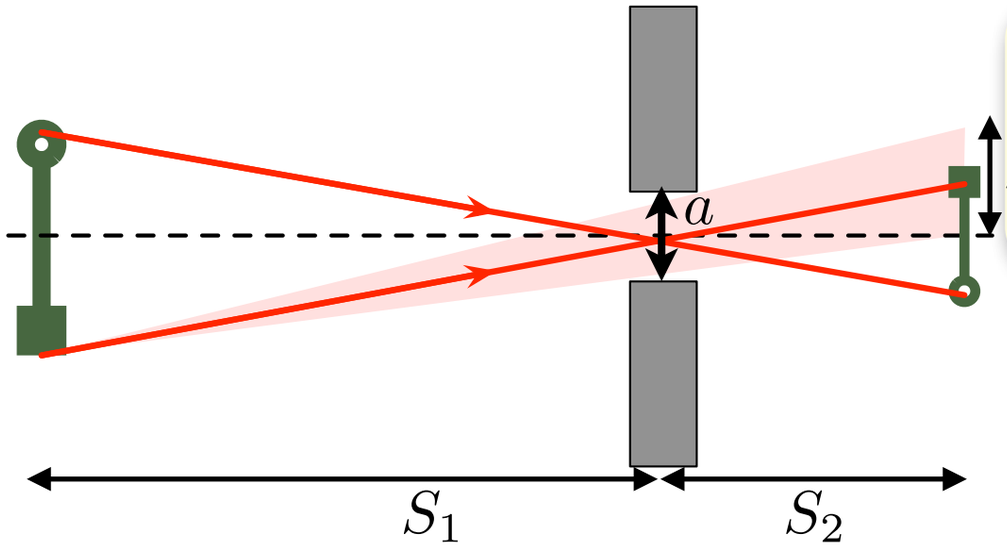

point spread function

$$\Delta d = a\left(1 + \frac{S_2}{S_1}\right)$$

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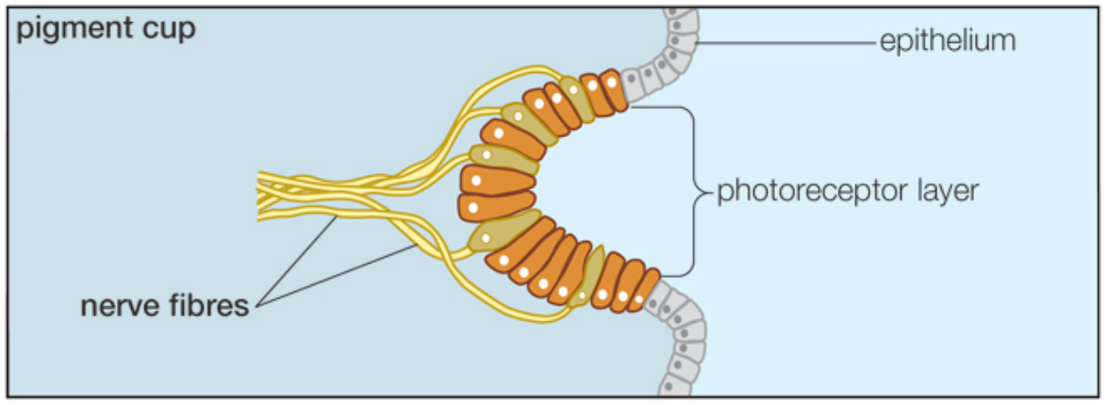

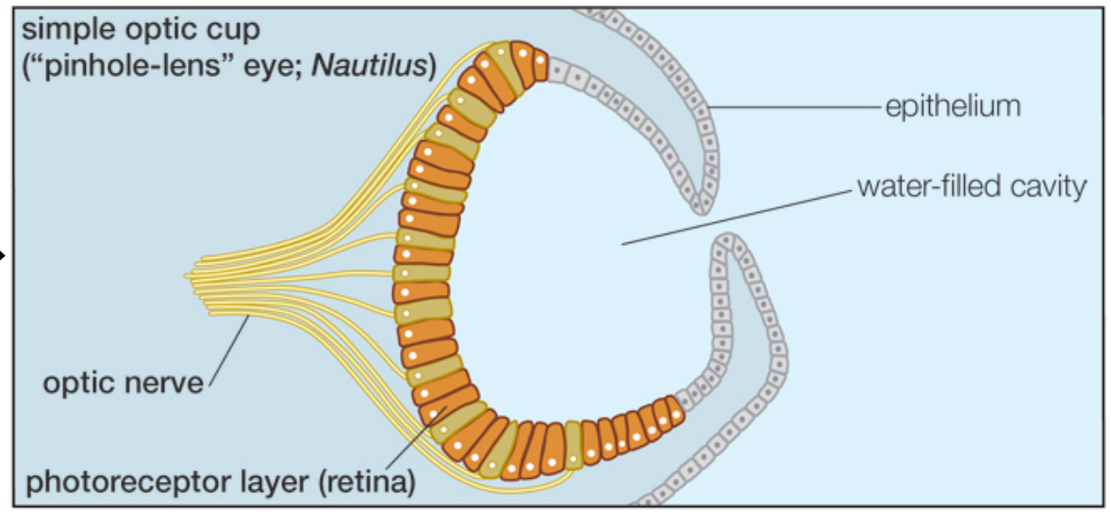

direction of light

image

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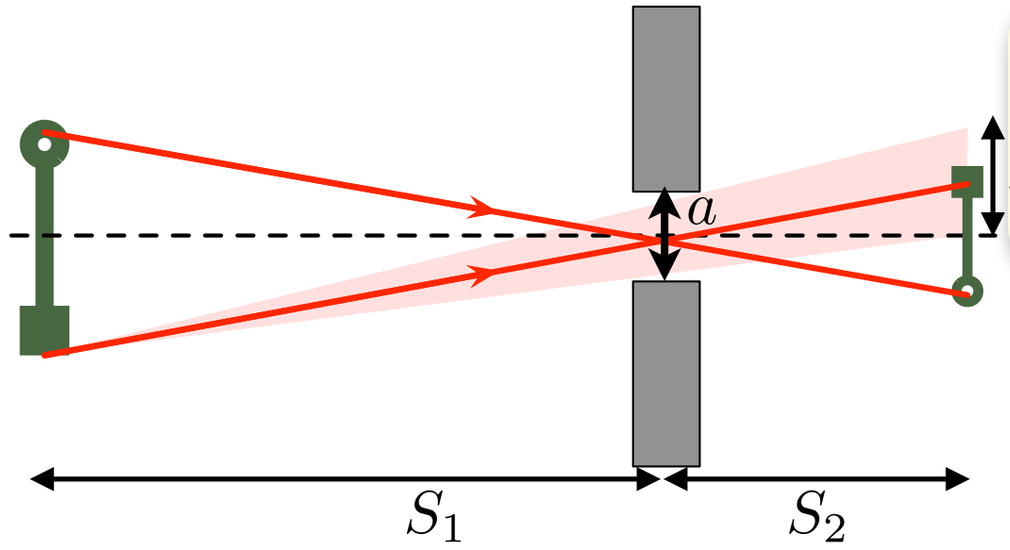
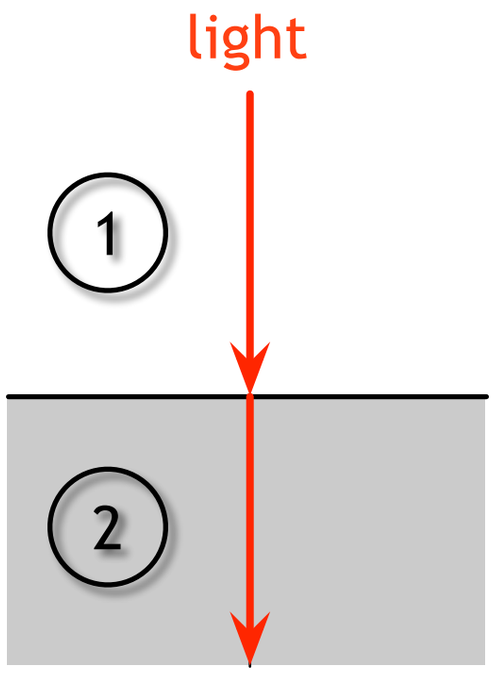


point spread function

$$\Delta d = a\left(1 + \frac{S_2}{S_1}\right)$$

- increase resolution by narrowing aperture (pupil)
- but illuminance (contrast) is reduced

RECAP: REFRACTION & LENSES



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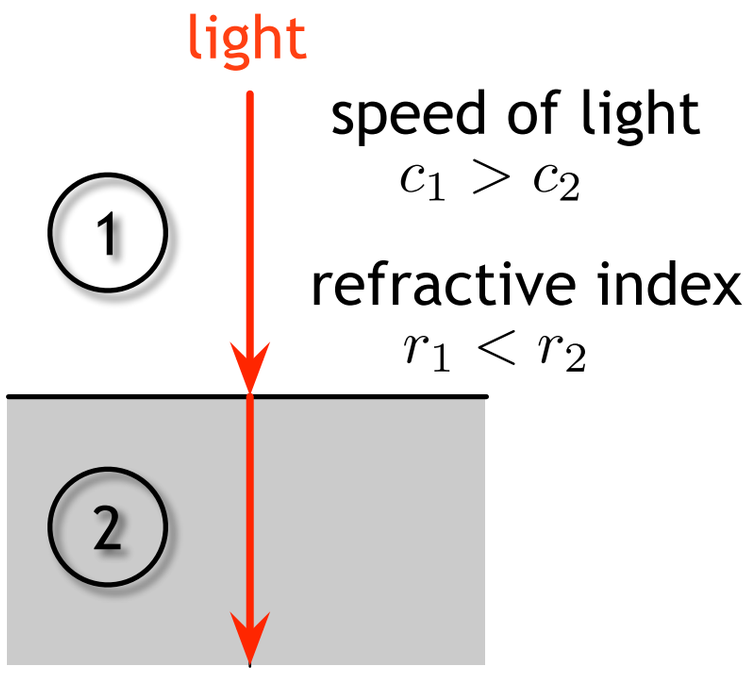

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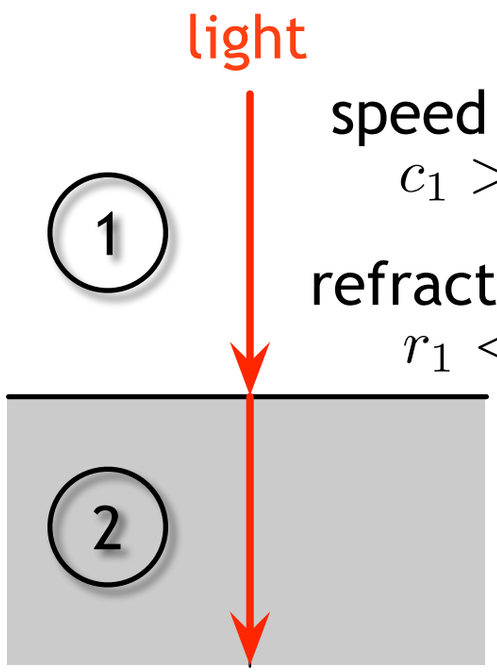

speed of light

$c_1 > c_2$

refractive index

$r_1 < r_2$

$r_{\text{air}} \simeq 1.0$

$r_{\text{water}} \simeq 1.3$

$r_{\text{glass}} \simeq 1.5$

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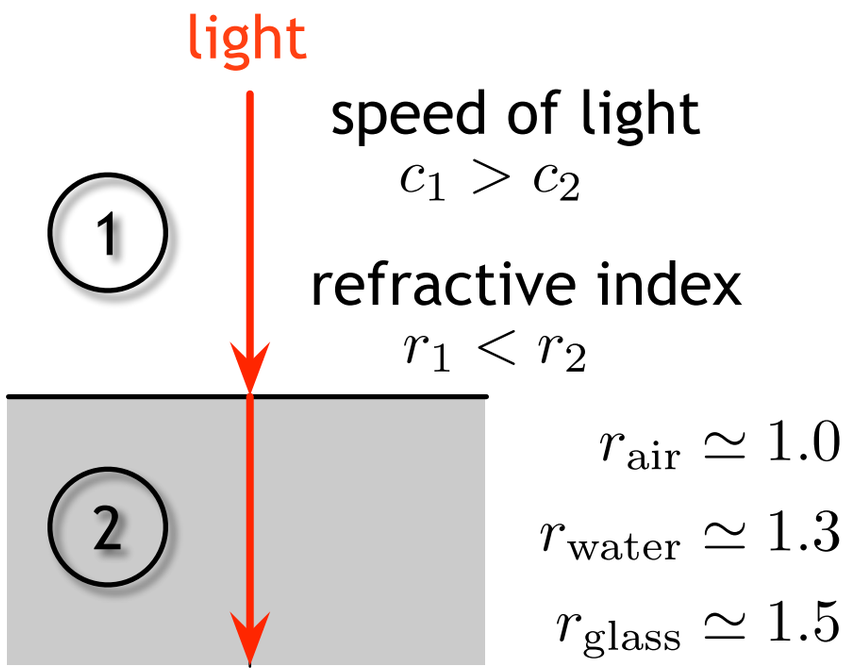

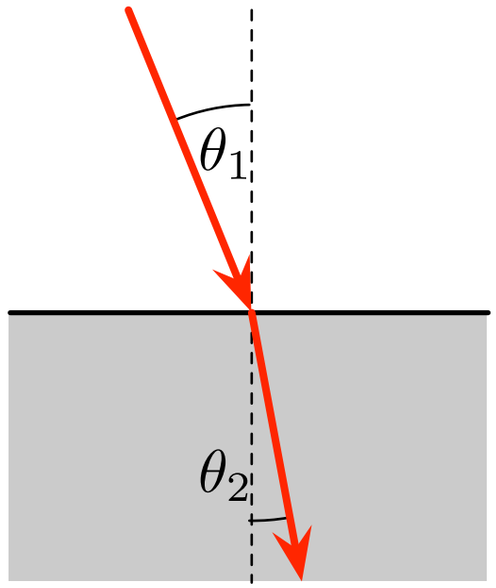

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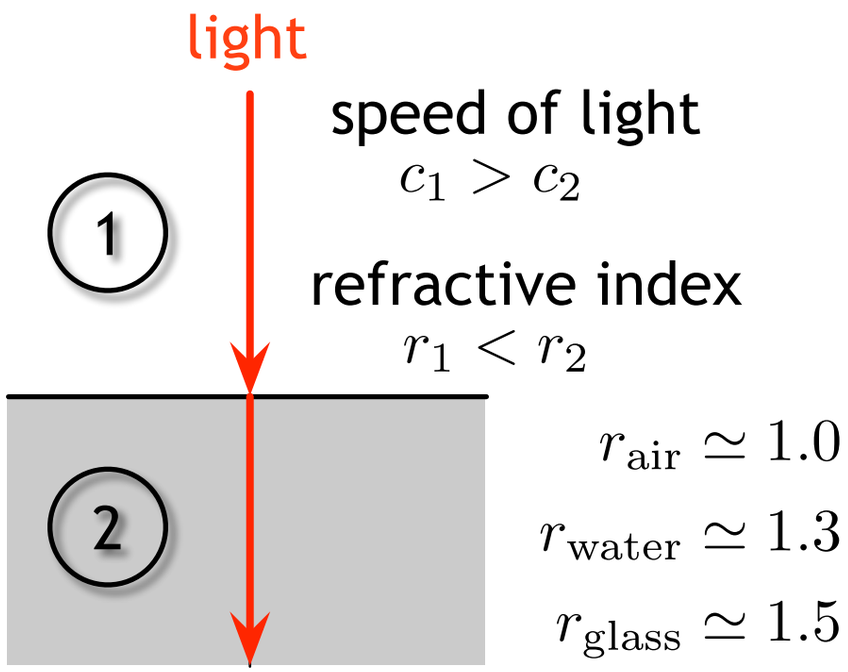

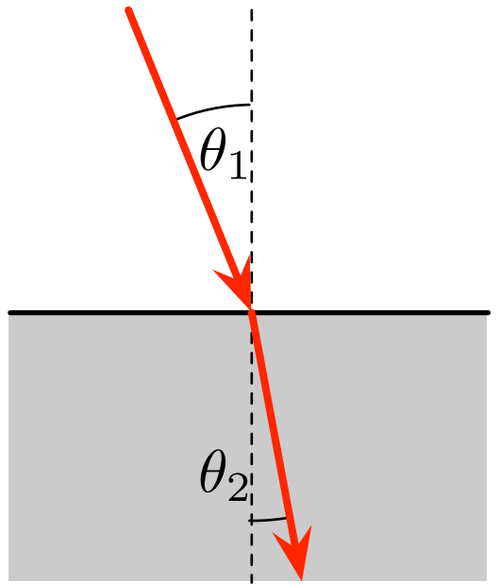

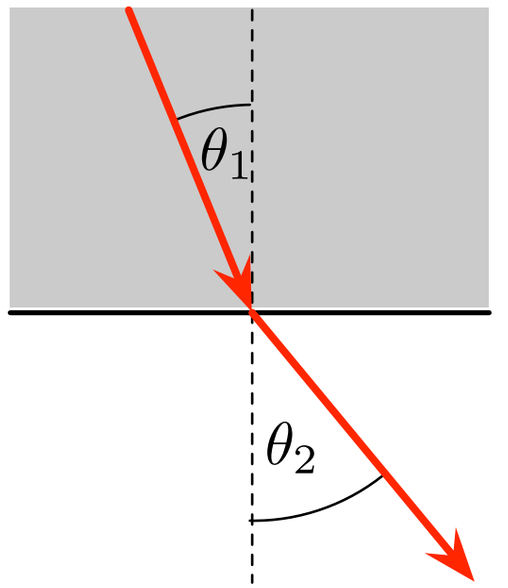

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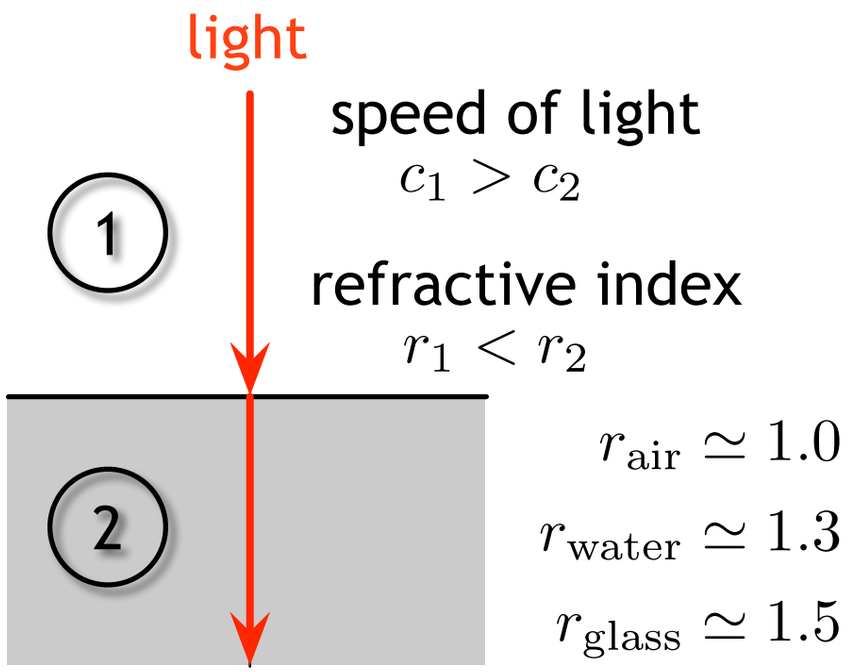
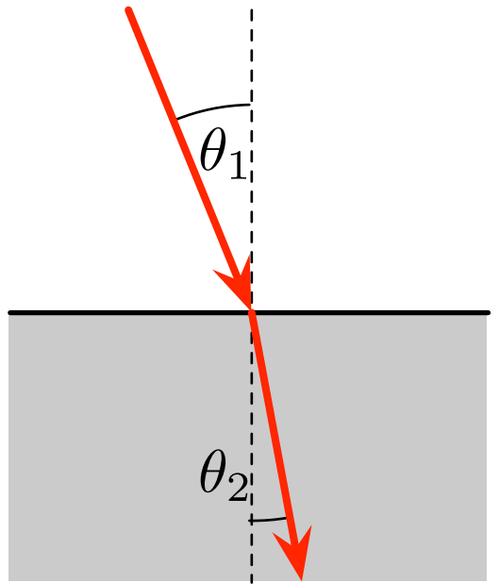
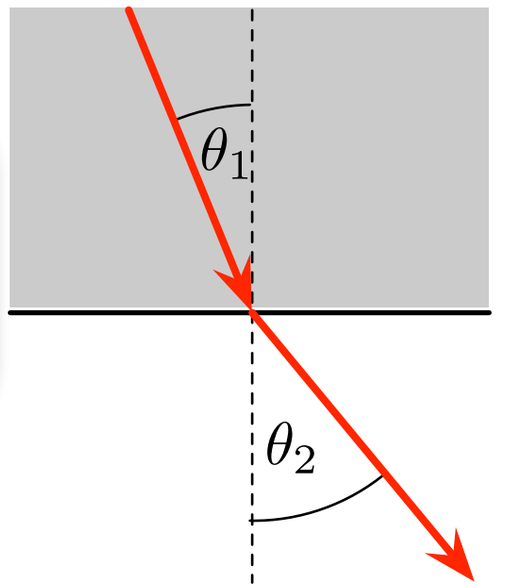




Snell's law

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{c_1}{c_2} = \frac{r_2}{r_1}$$



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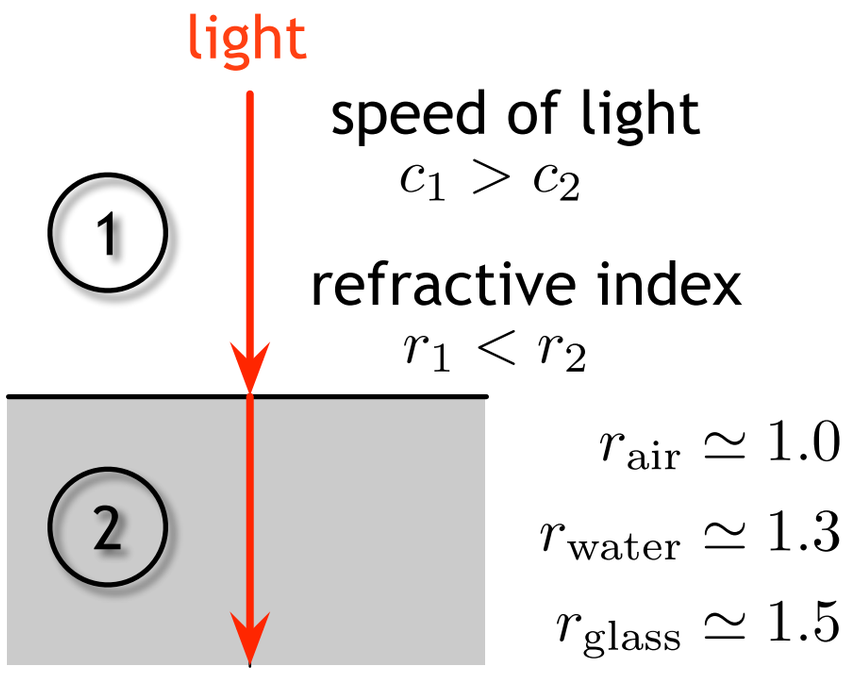

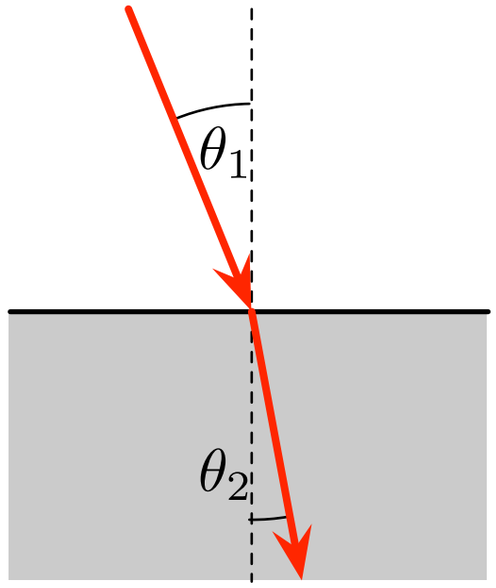

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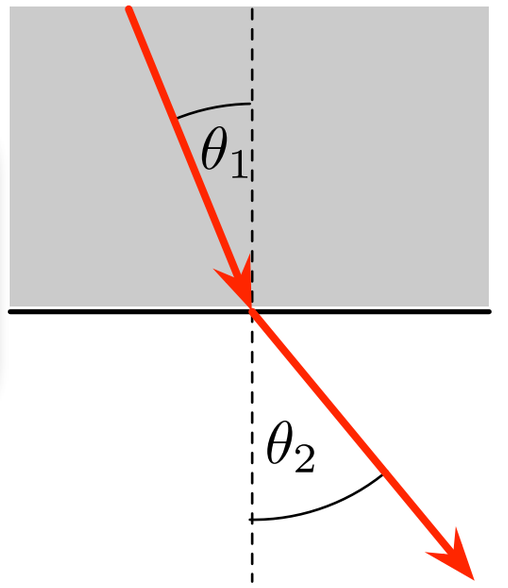
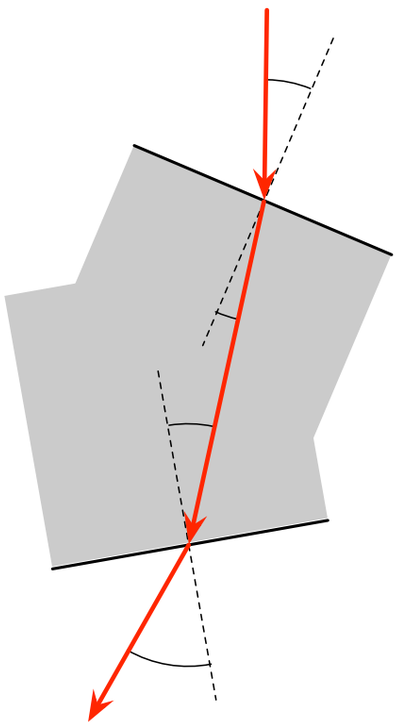


use two interfaces
to bend light



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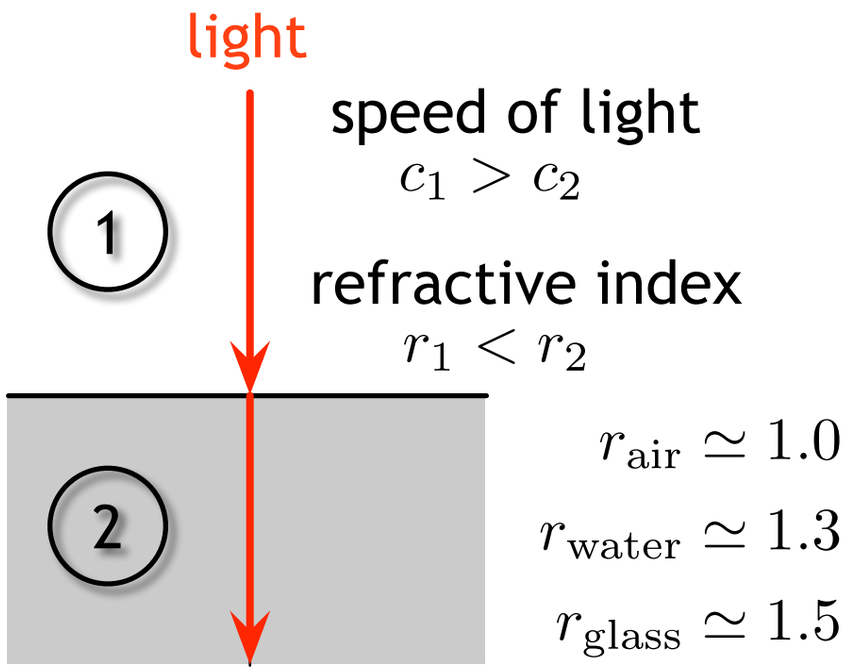

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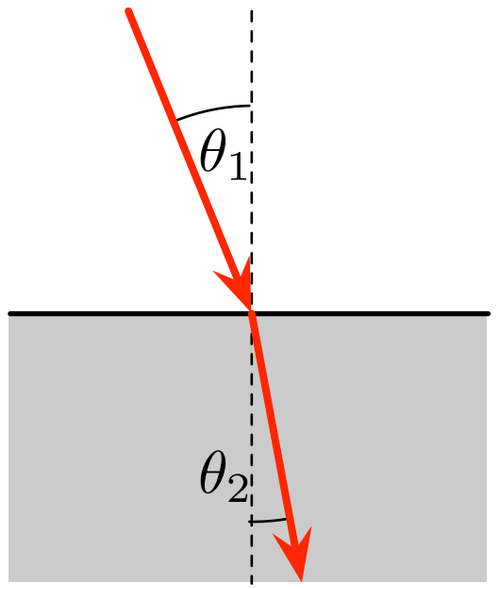

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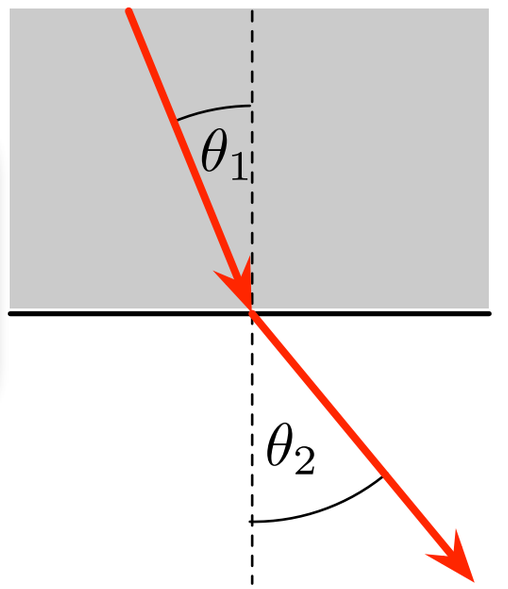

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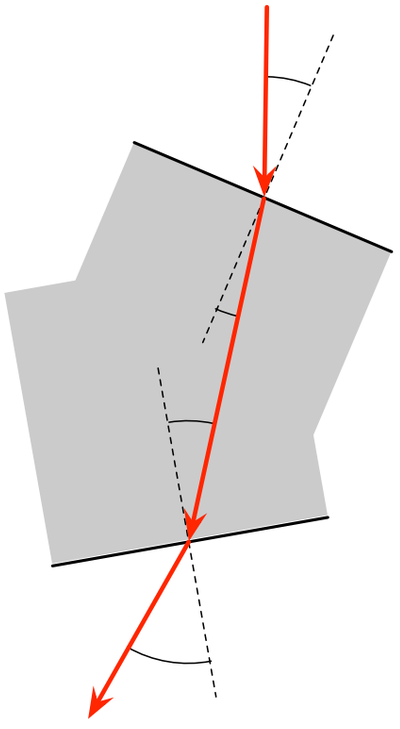
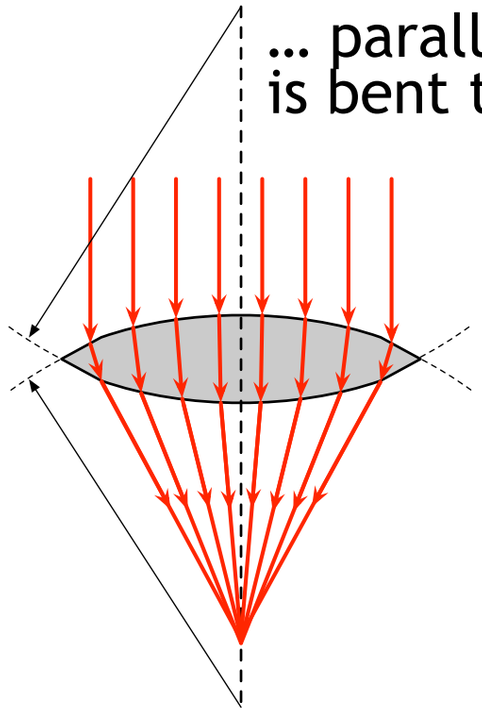


change angle of
interfaces such that …



… parallel light
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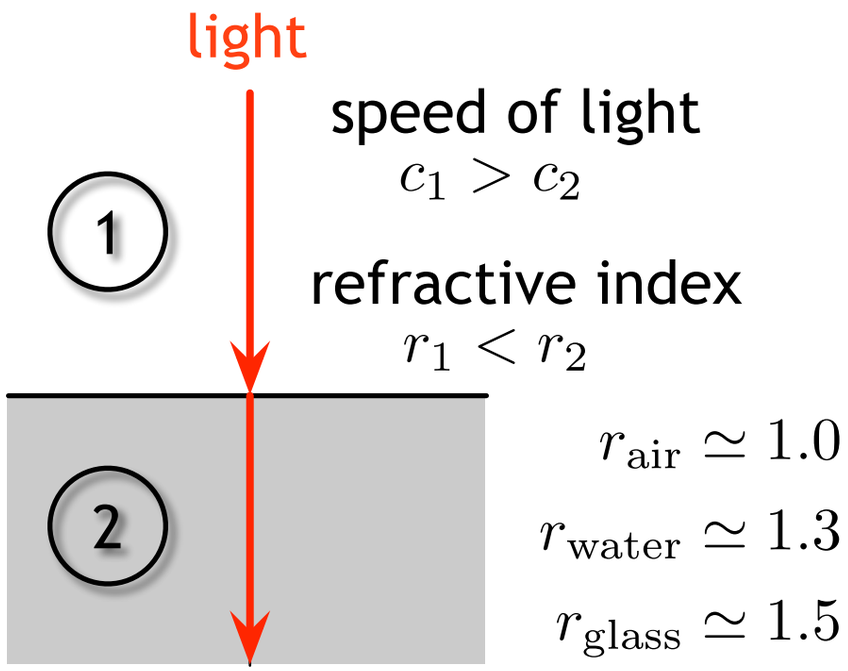
RECAP: REFRACTION & LENSES



speed of light

$c_1 > c_2$

refractive index

$r_1 < r_2$

$r_{\text{air}} \simeq 1.0$

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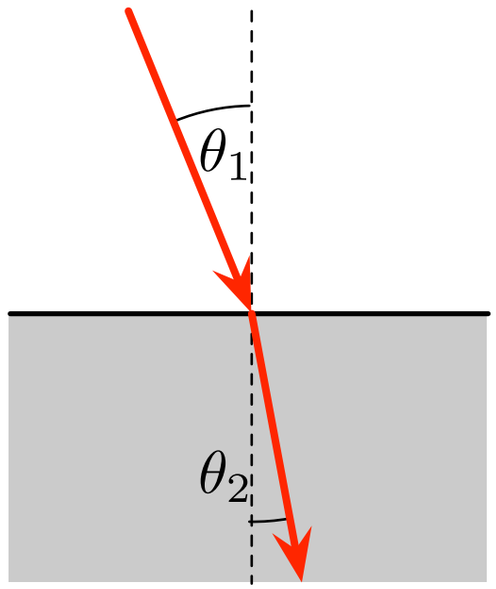

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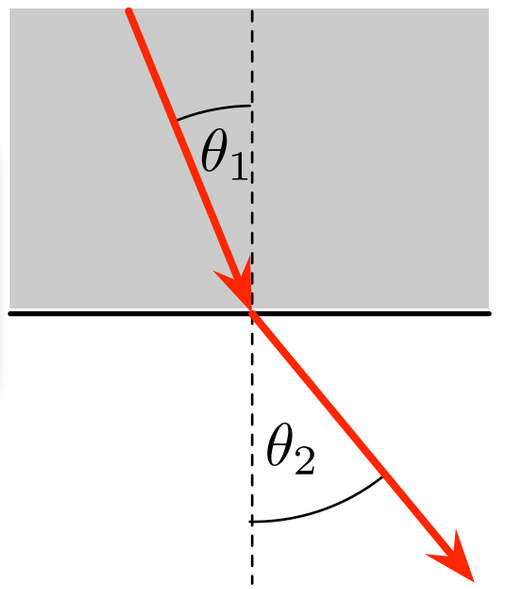
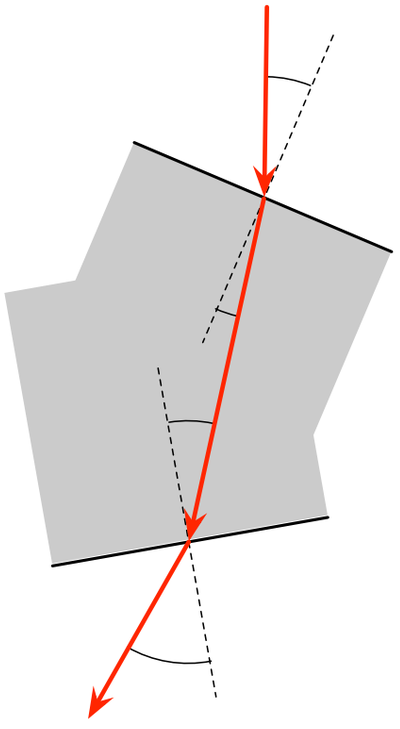


use two interfaces to bend light



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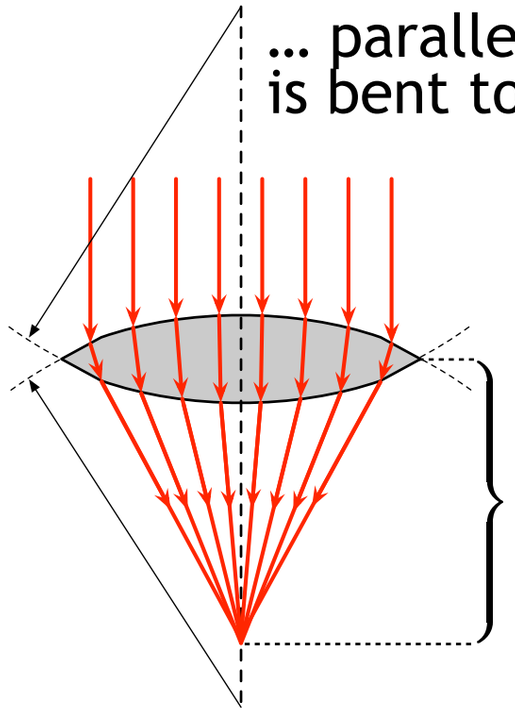

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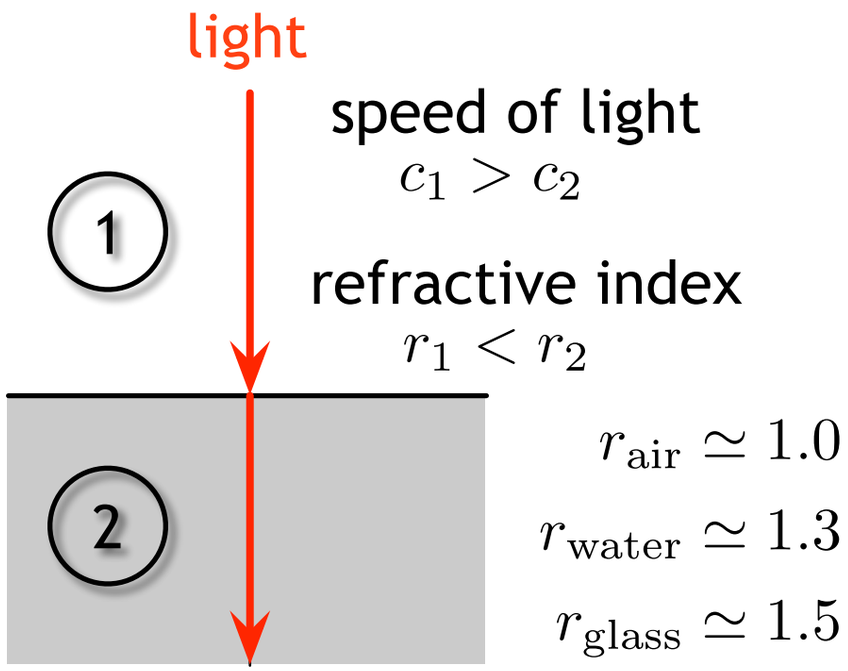

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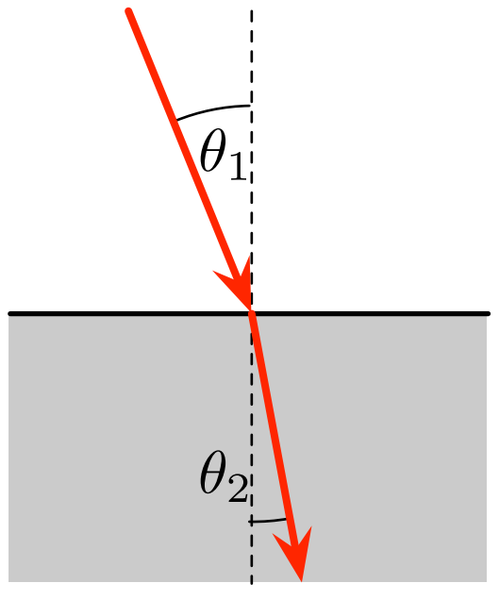

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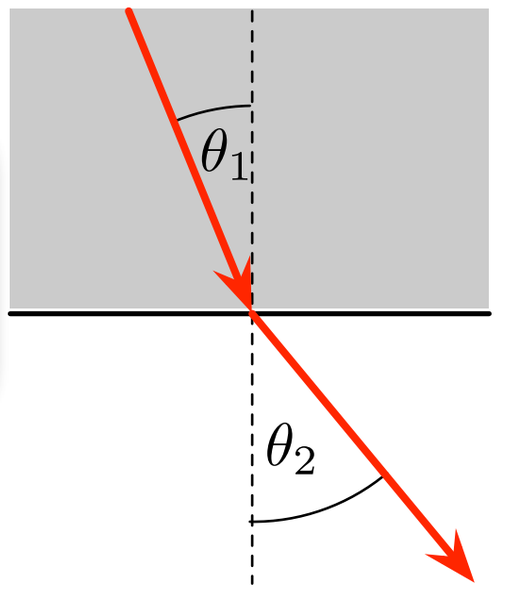

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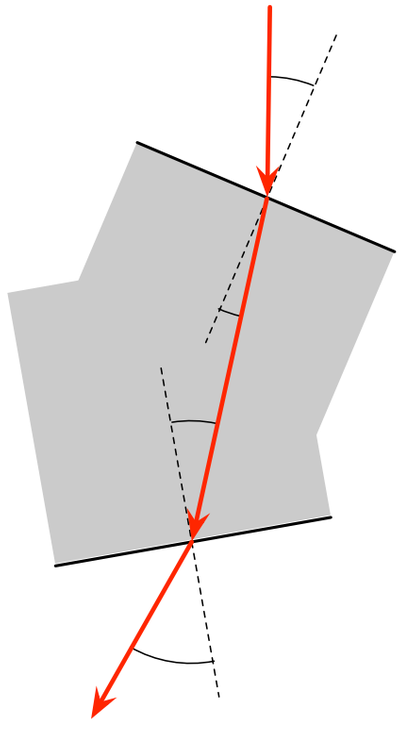

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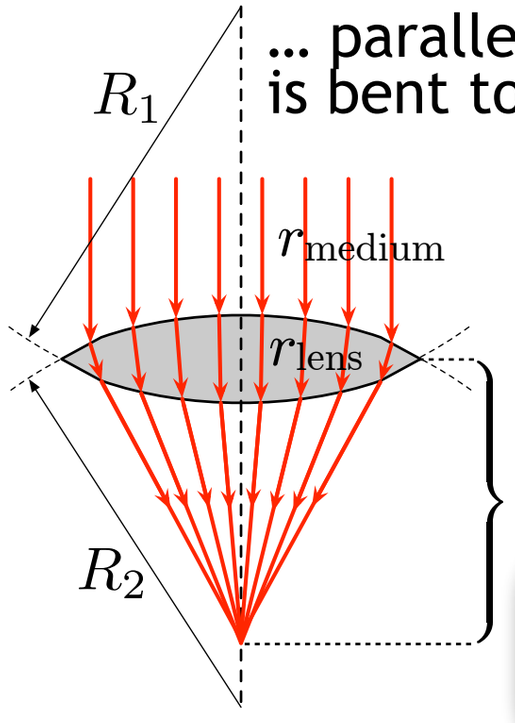

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lensmaker's formula for thin lens

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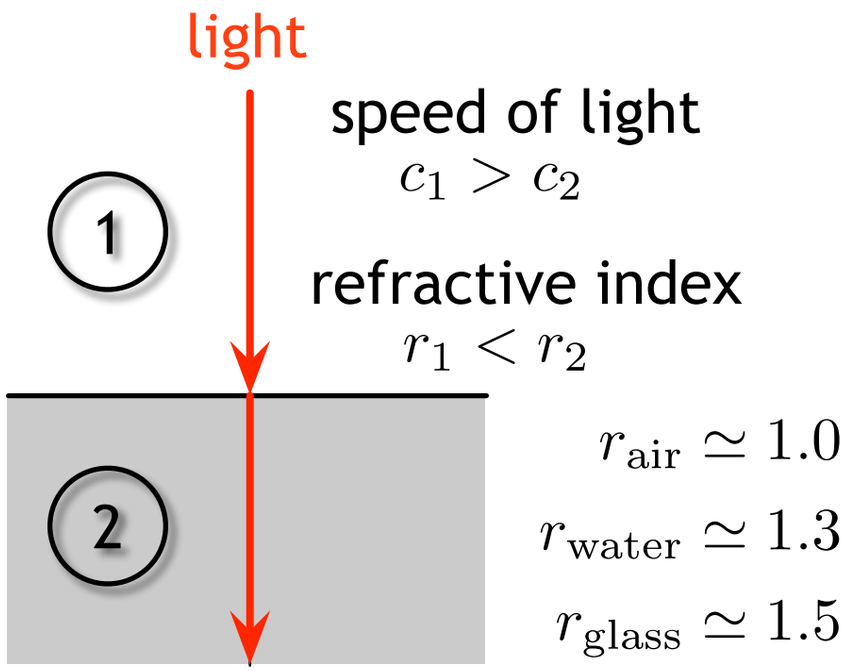

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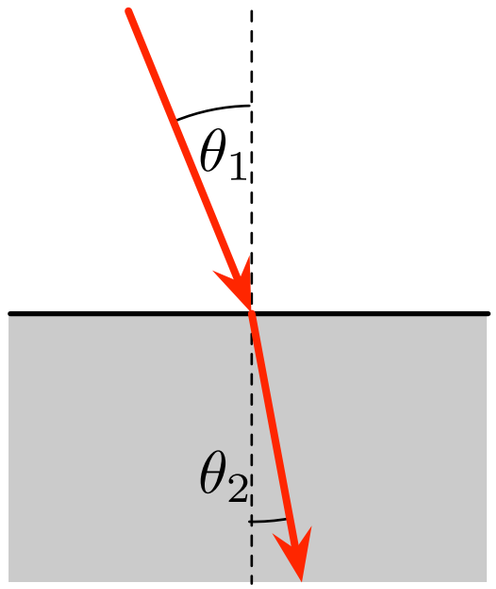

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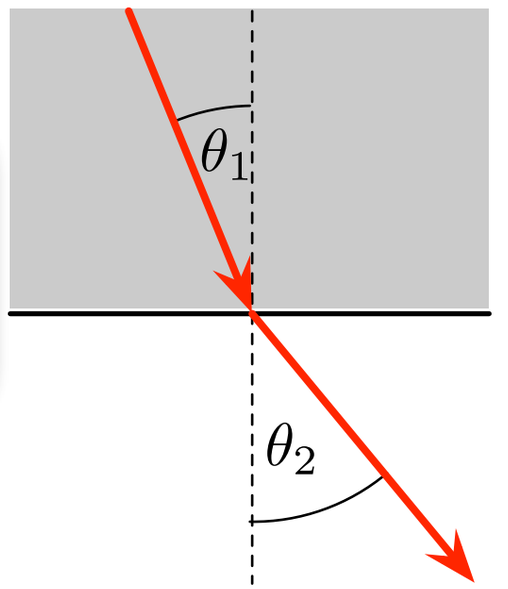

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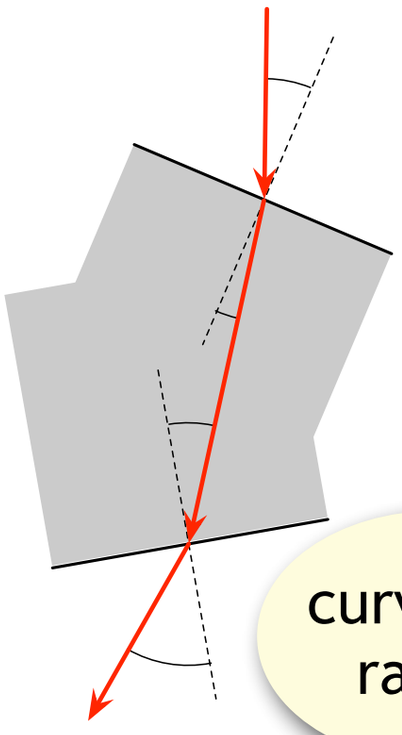

curvature radius

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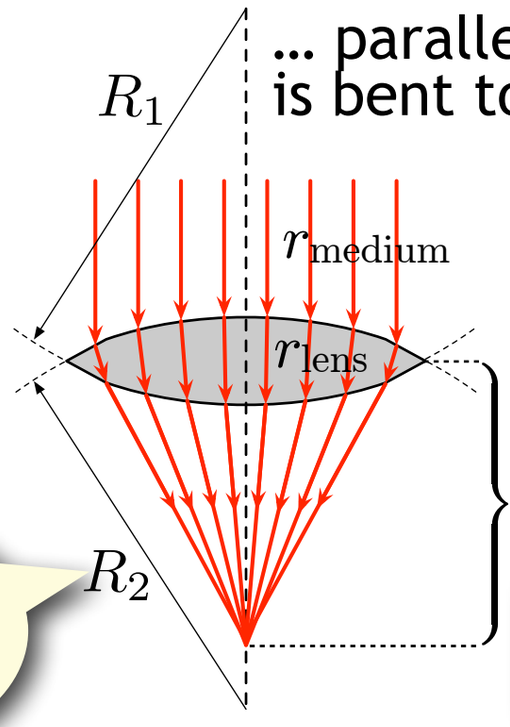

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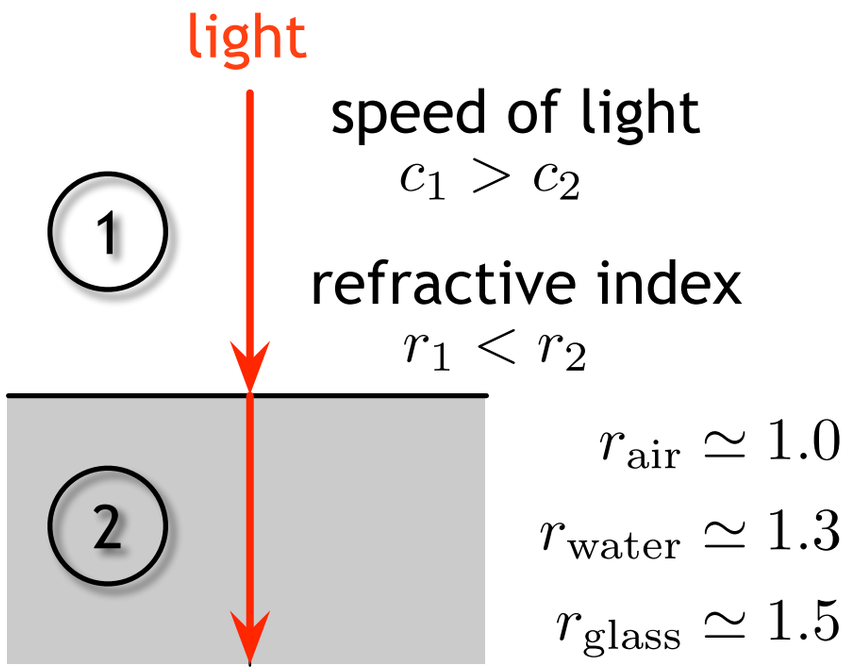

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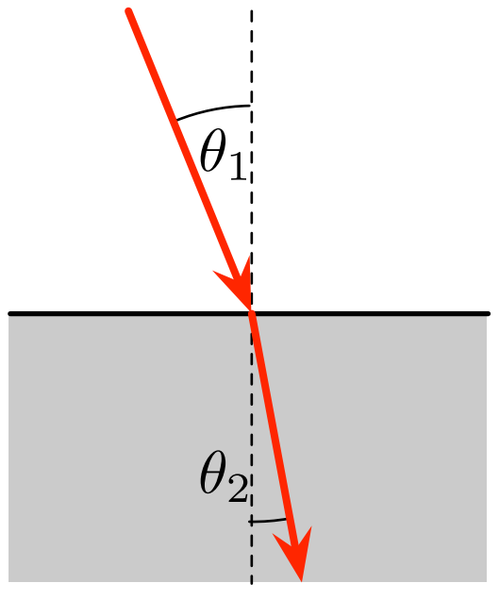

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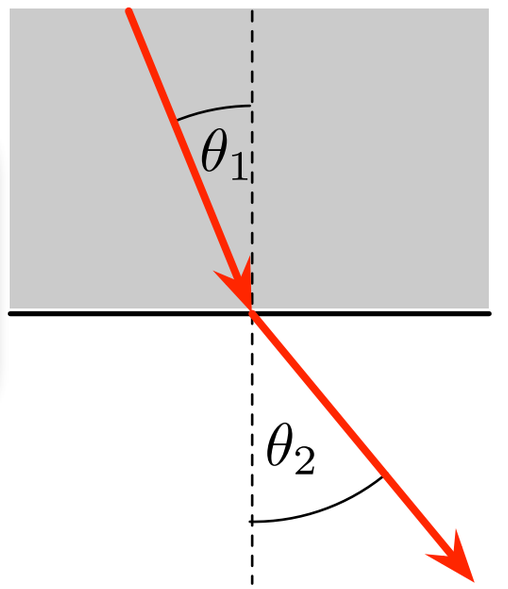

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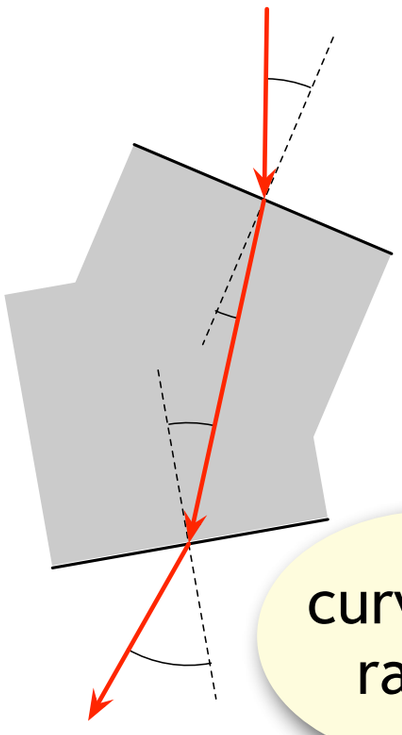

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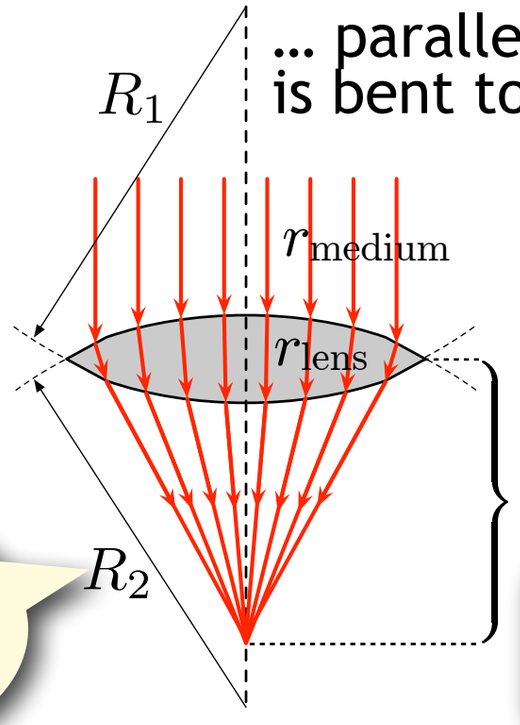
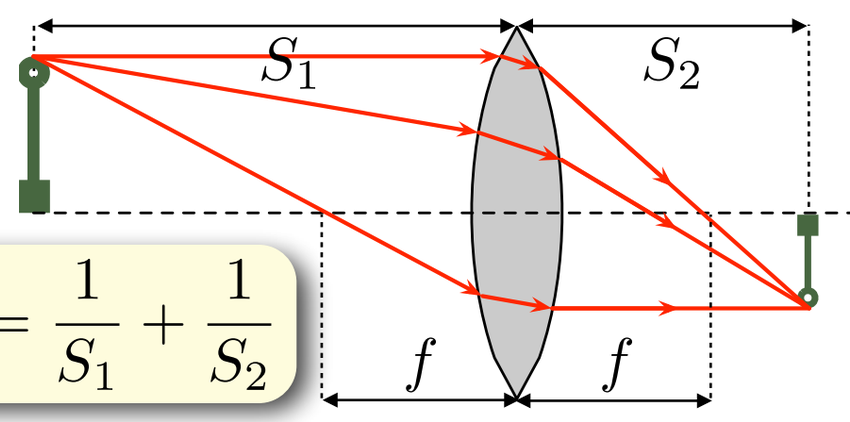


… parallel light is bent to a single point

focal length f

… "all" beams from a single point are collected to a single point → form image



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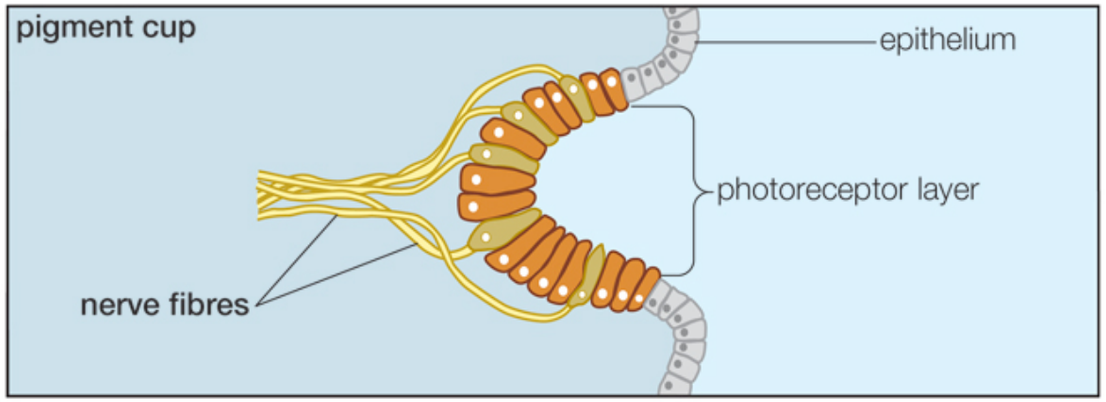

direction of light

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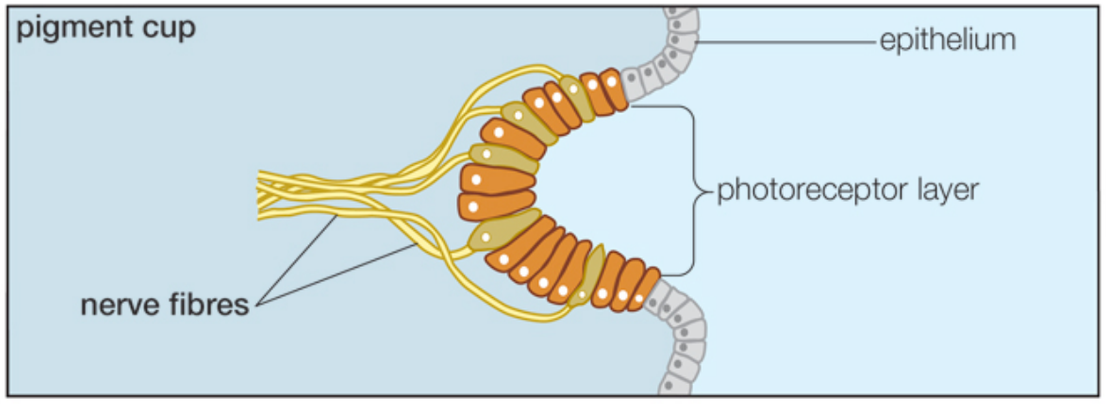

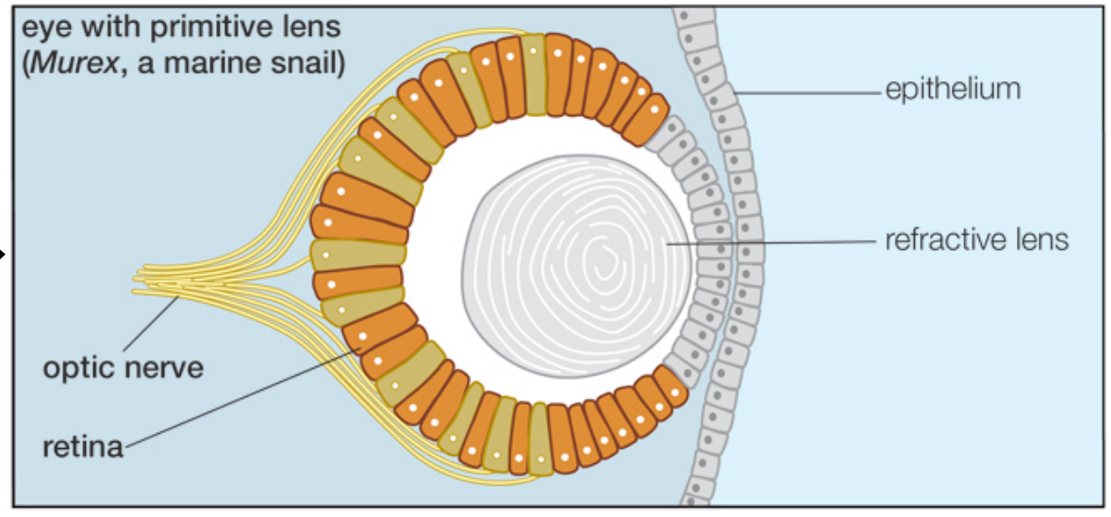

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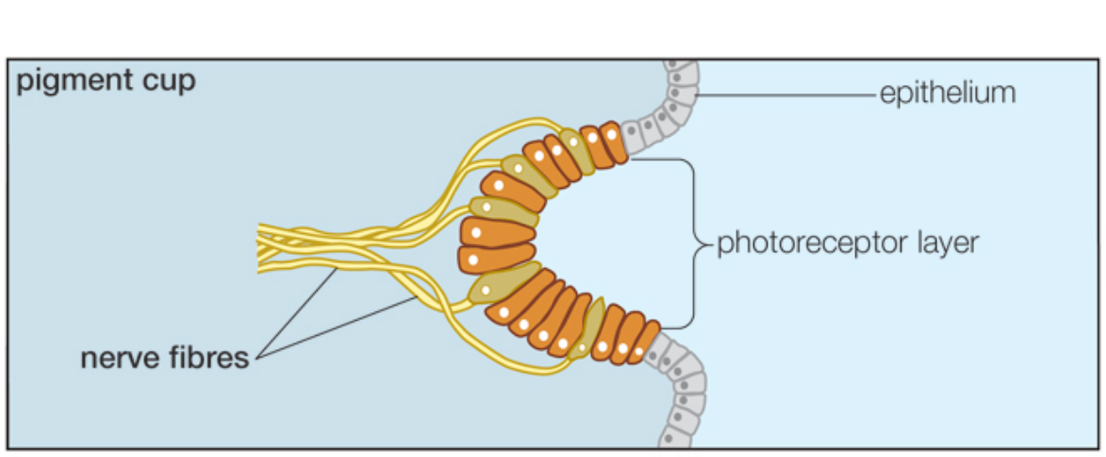

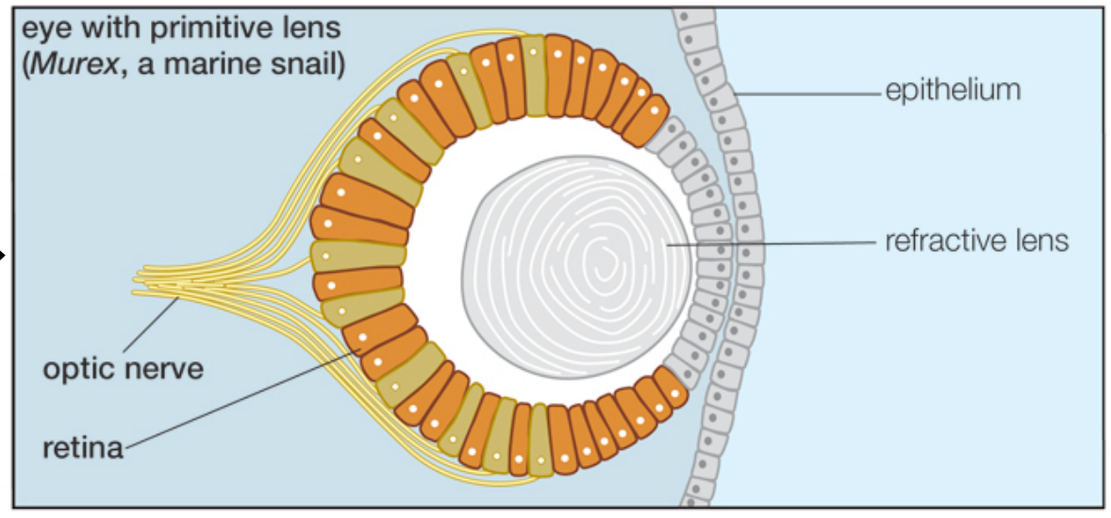

direction of light

image

- to capture light over a greater area, we need a lens

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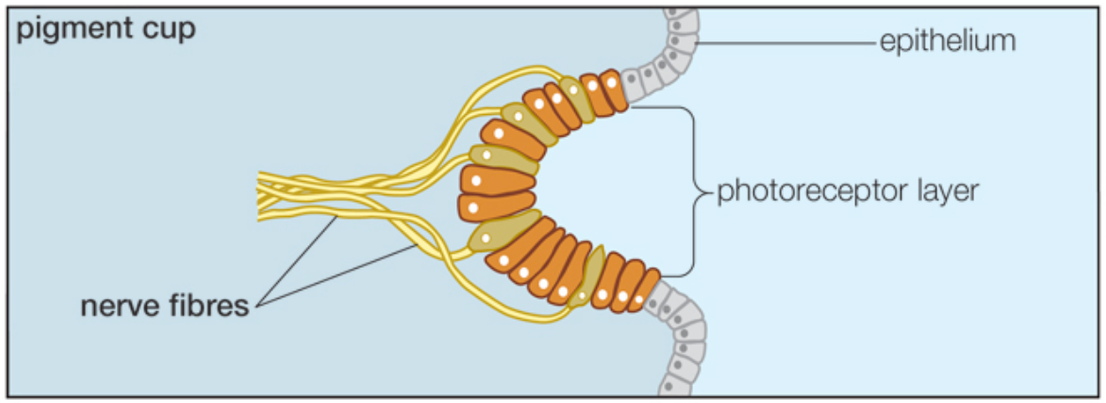

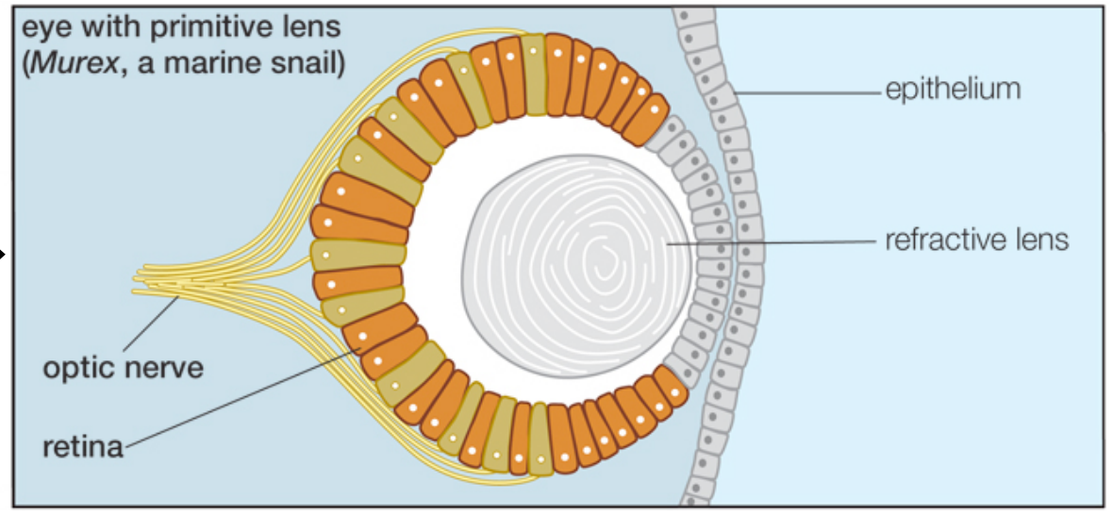

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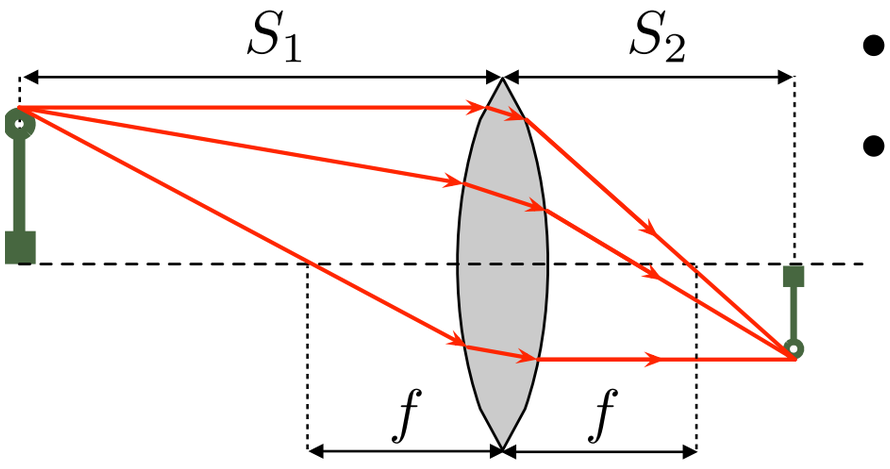

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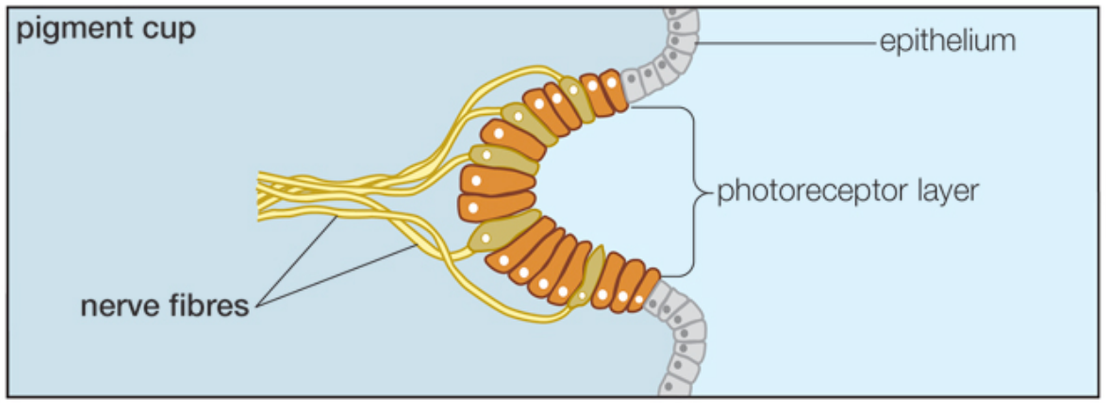

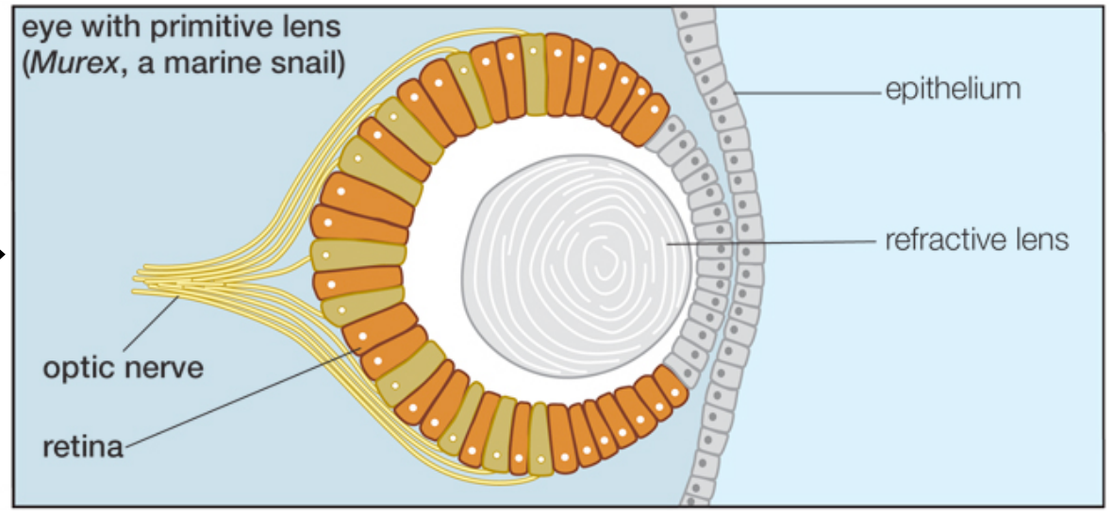

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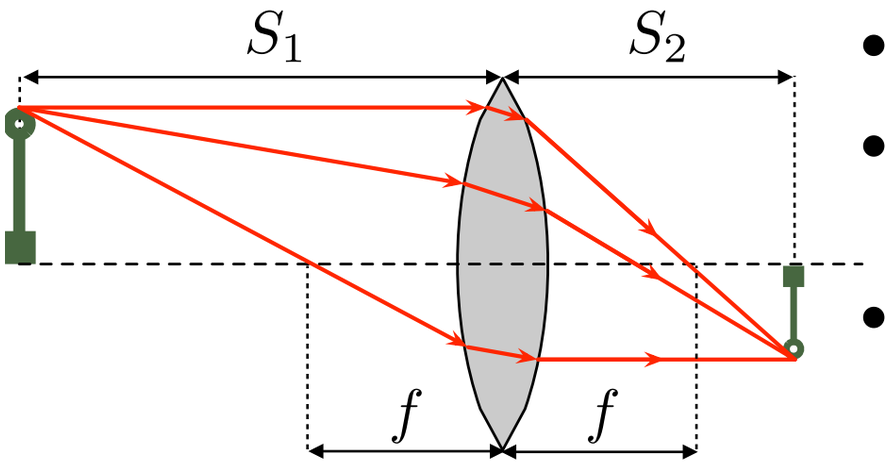

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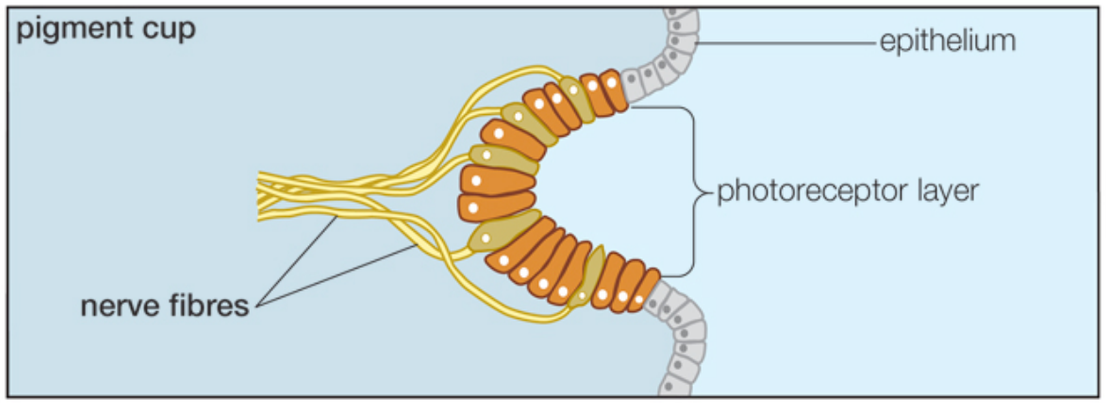

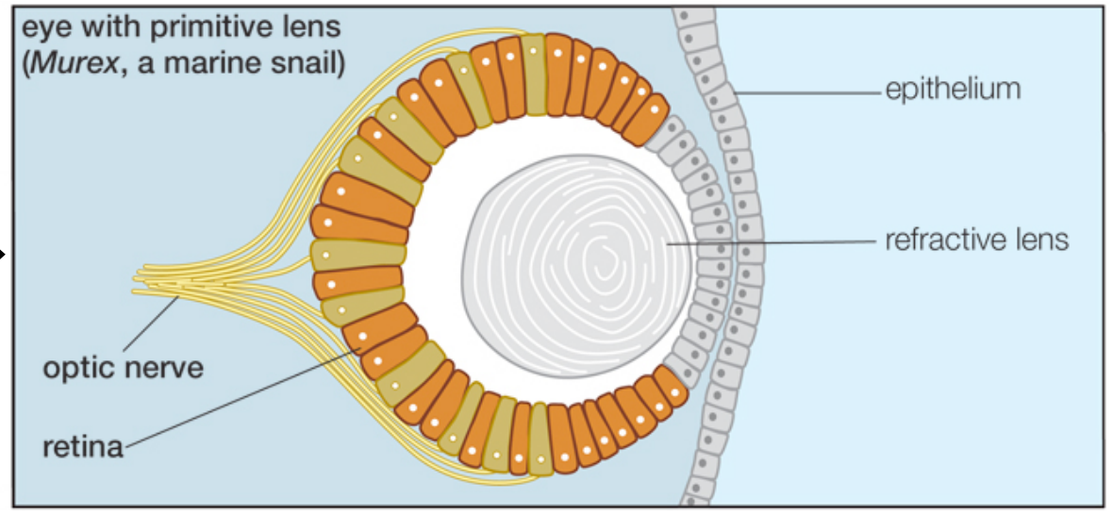

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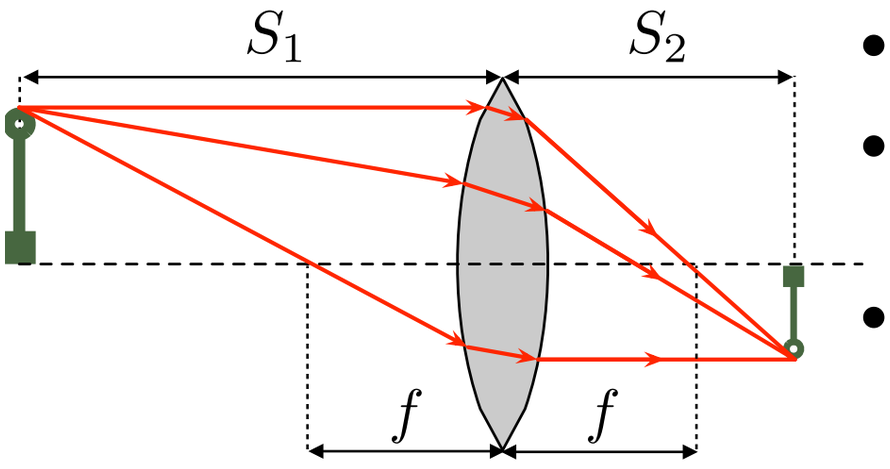

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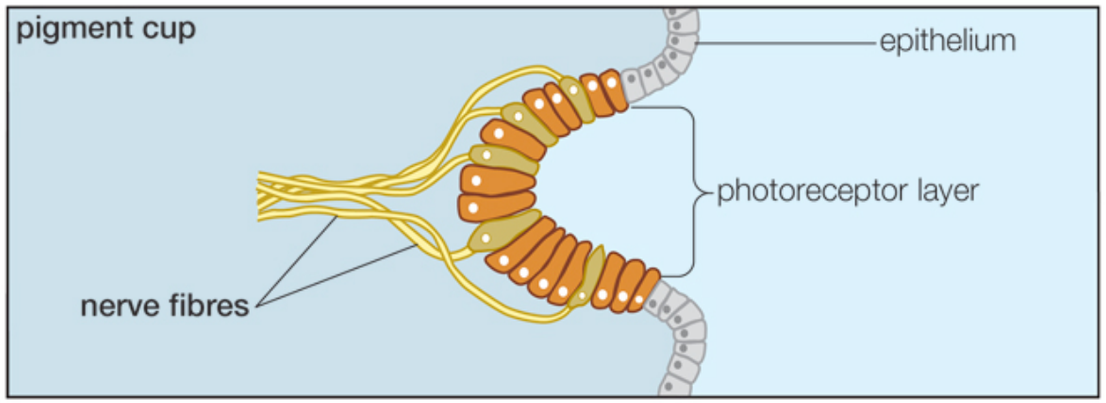

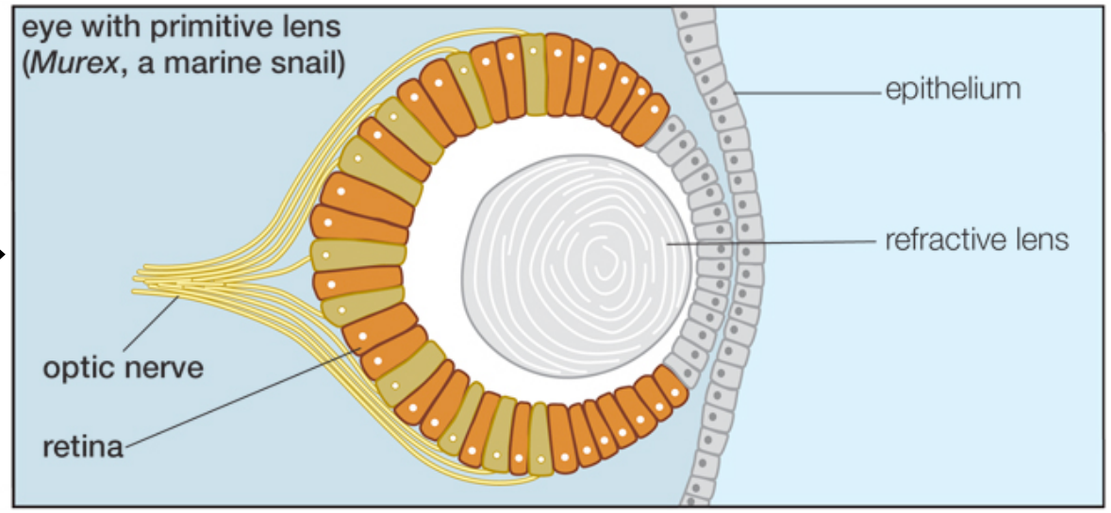

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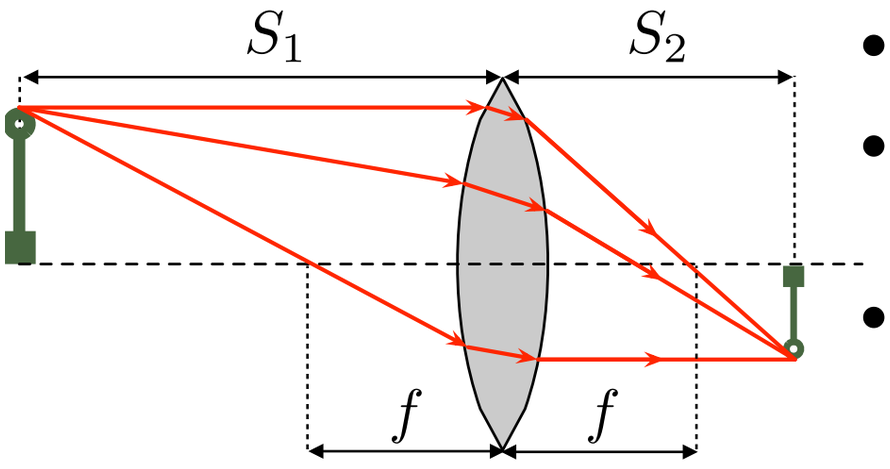

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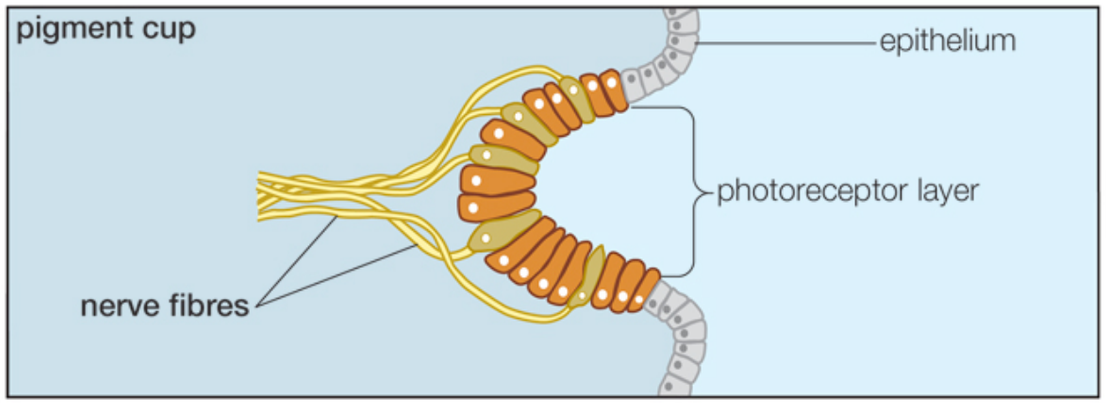

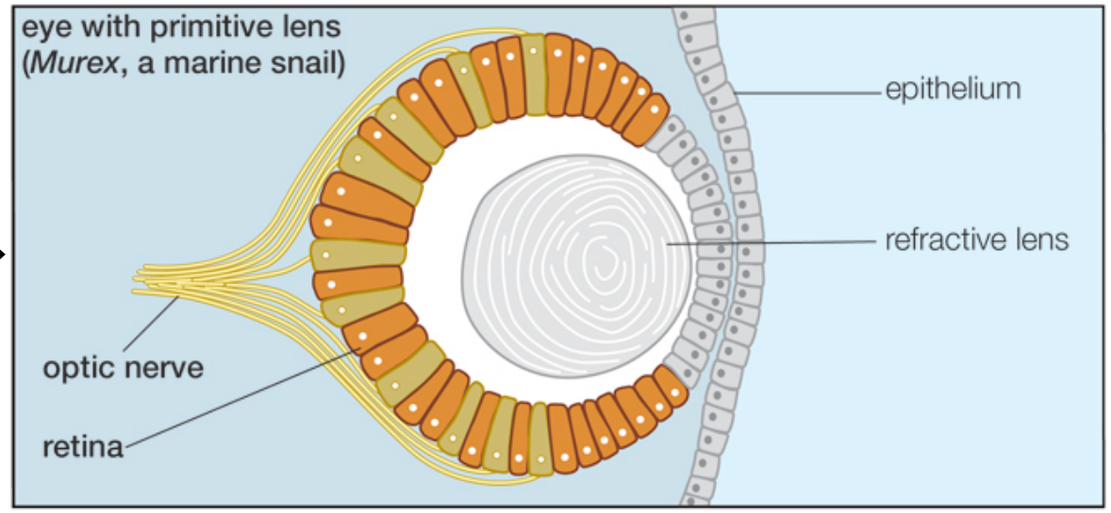

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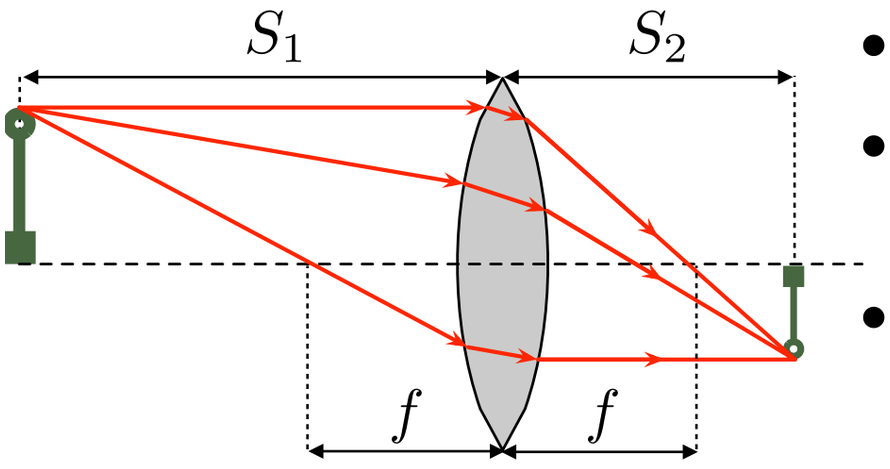

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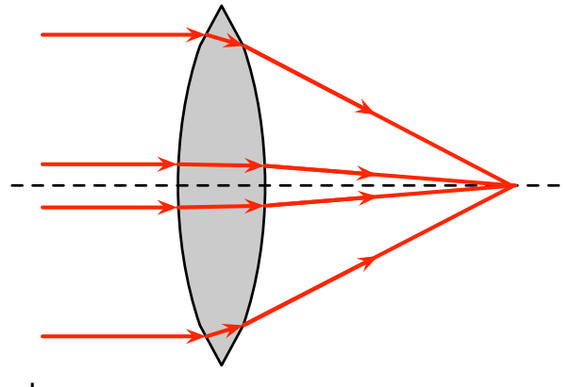

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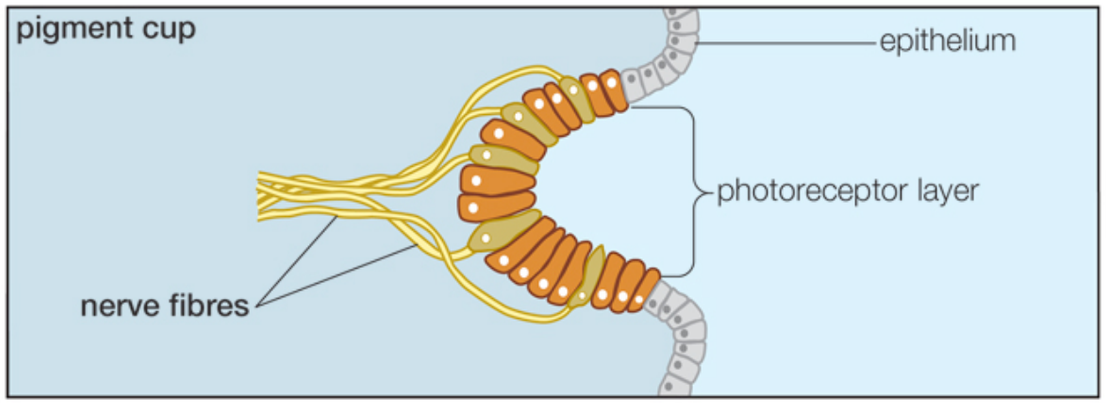

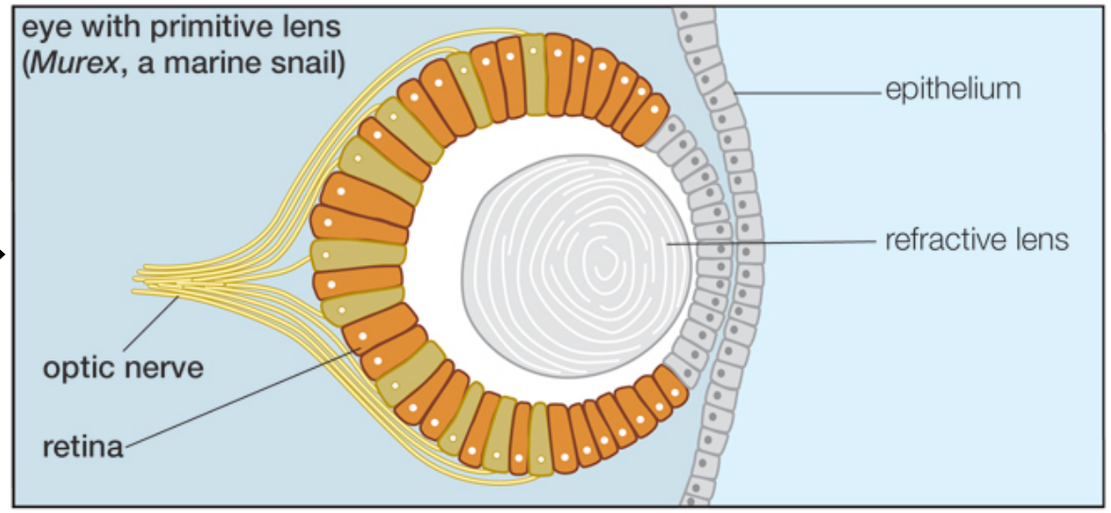

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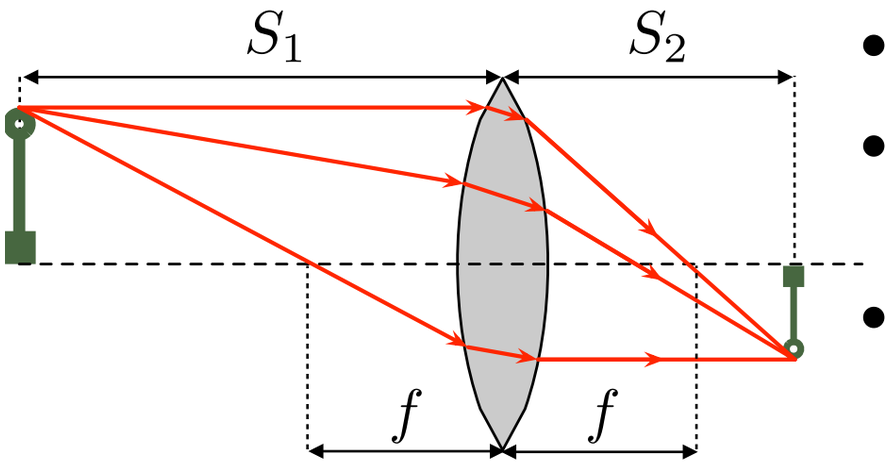

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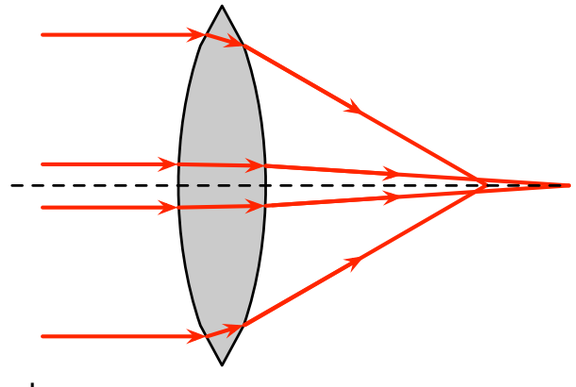
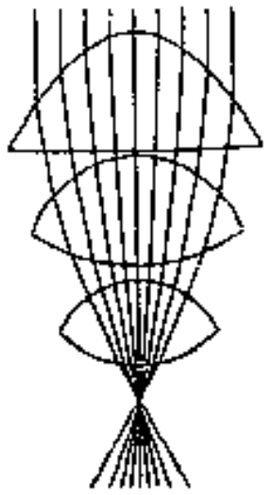
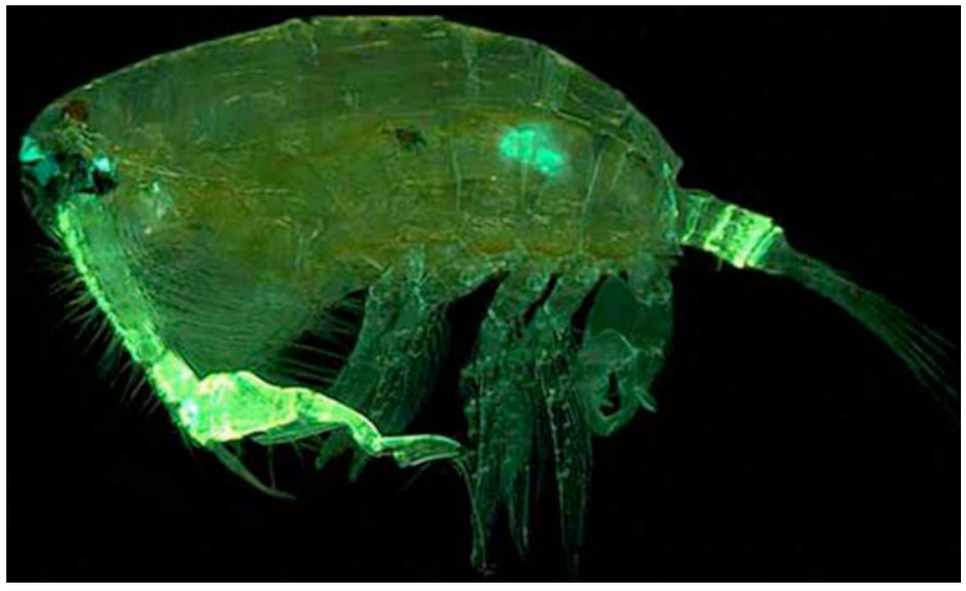


2.1 MULTIPLE LENSES





Pontella

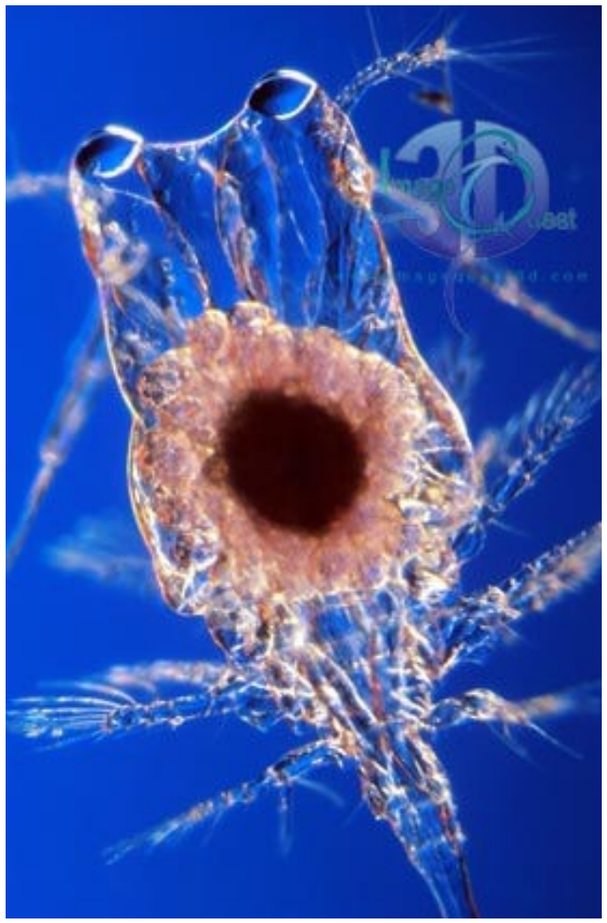
- triplet lens (two in females), outer elements outside the eye
- first surface is parabolic
  → corrects for spherical aberration of other 5 surfaces
- retina: just 6(!) receptors

2.2 SCANNING TELESCOPE

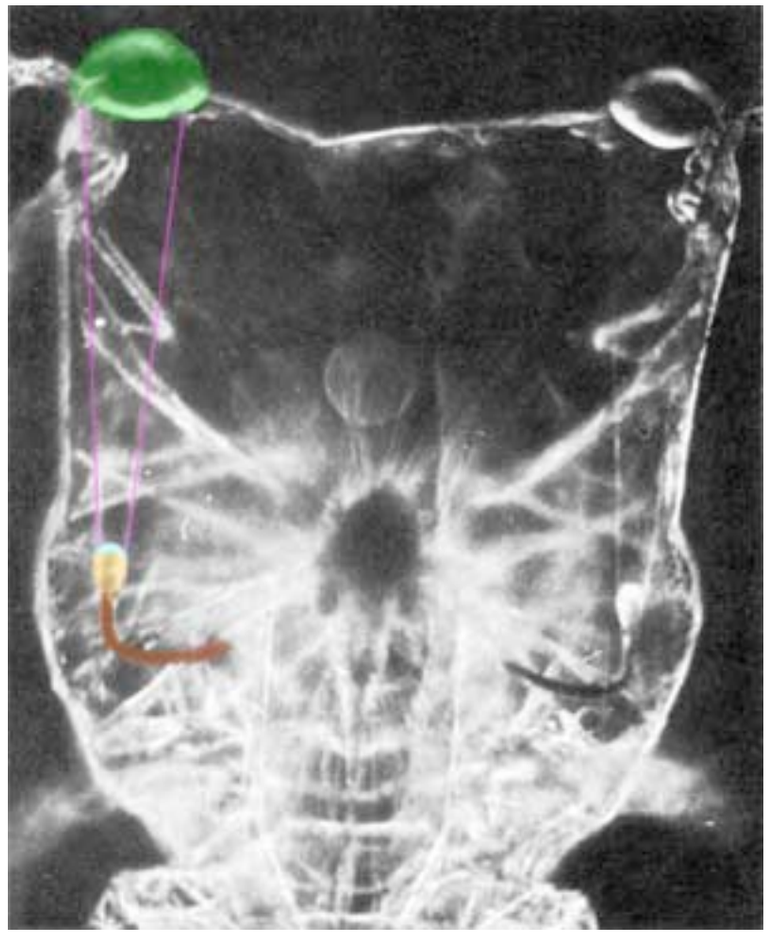
‘objective’

‘eyepiece’

retina: 5-7 receptors



Copilia



- two lenses work like a telescope
- ‘0-dimensional’ retina, 3° field of view
- horizontal scanning eye movements at max. 5 Hz
  bottom apparatus (‘eyepiece’ + retina) moves in image plane of ‘objective’
- prey (plankton) moves vertically → second dimension of ‘scanning’

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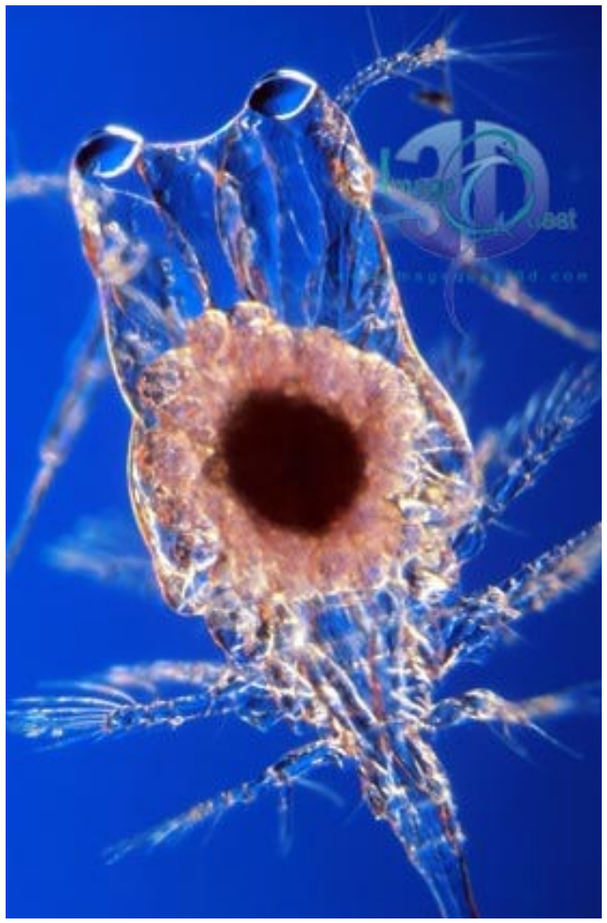

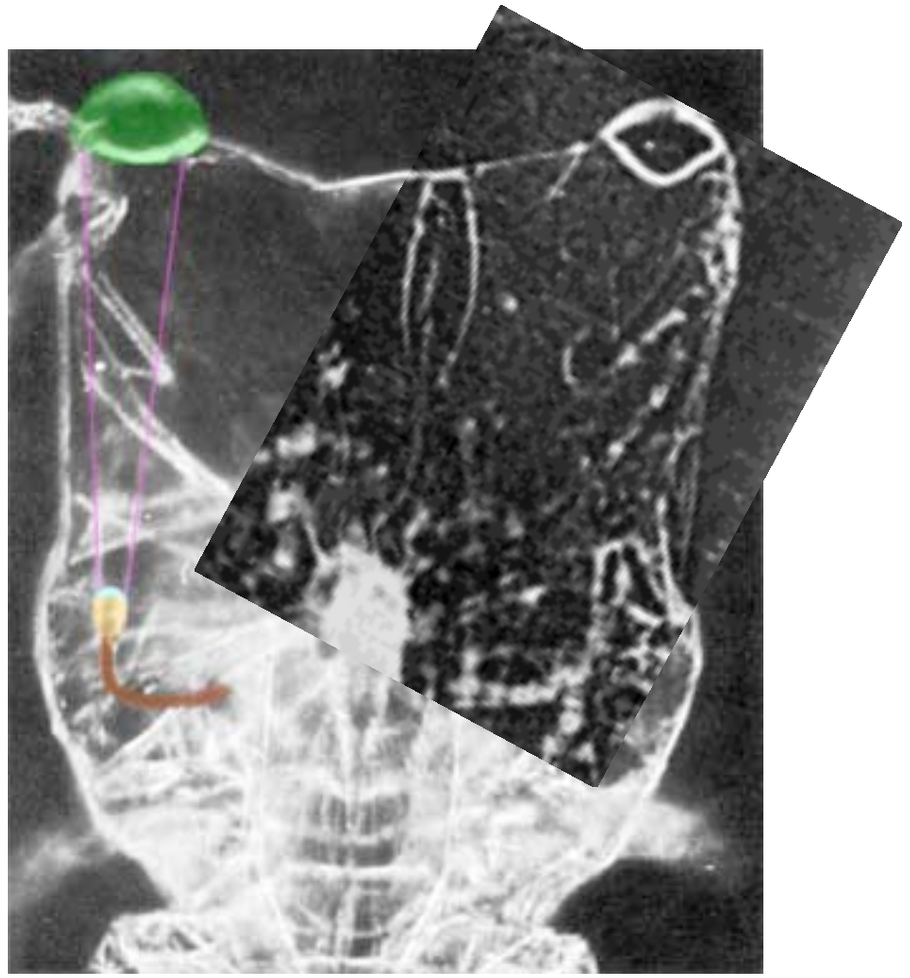

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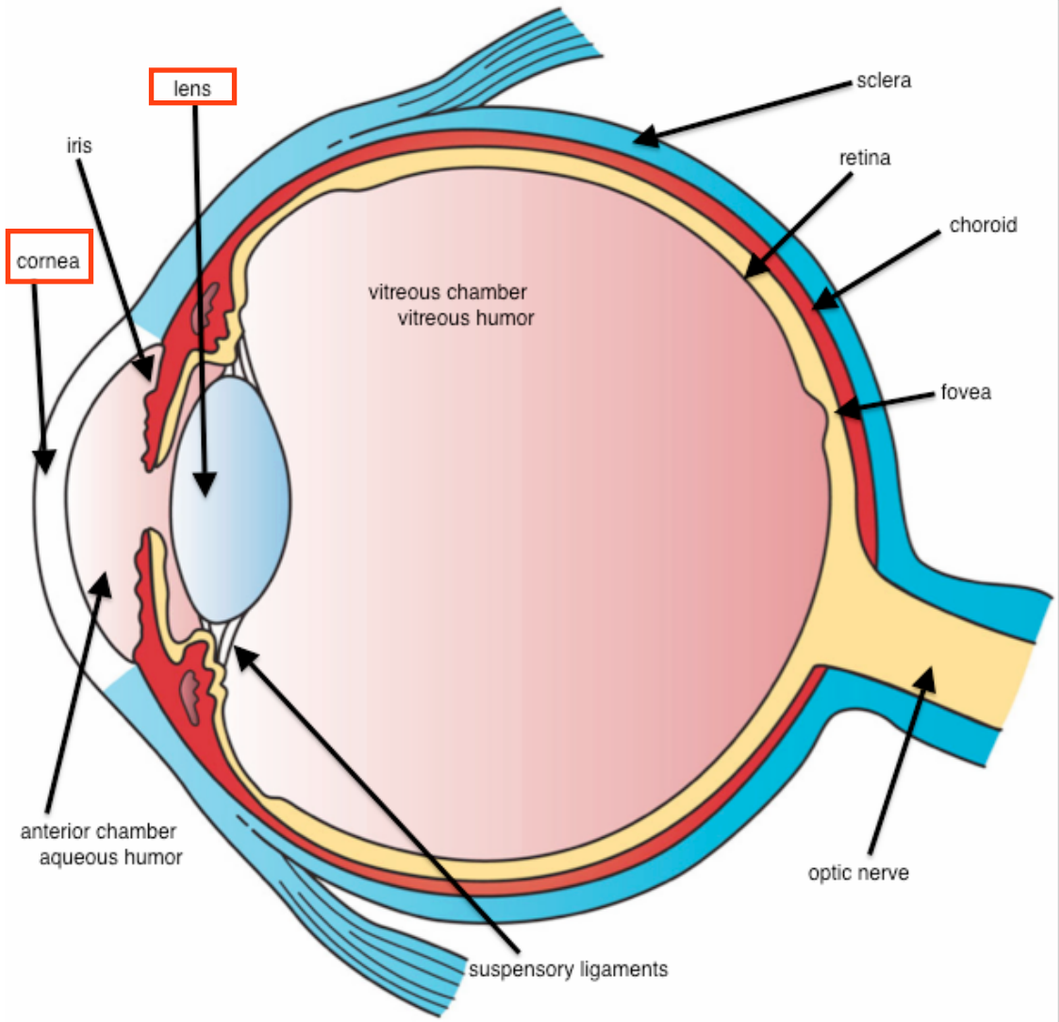

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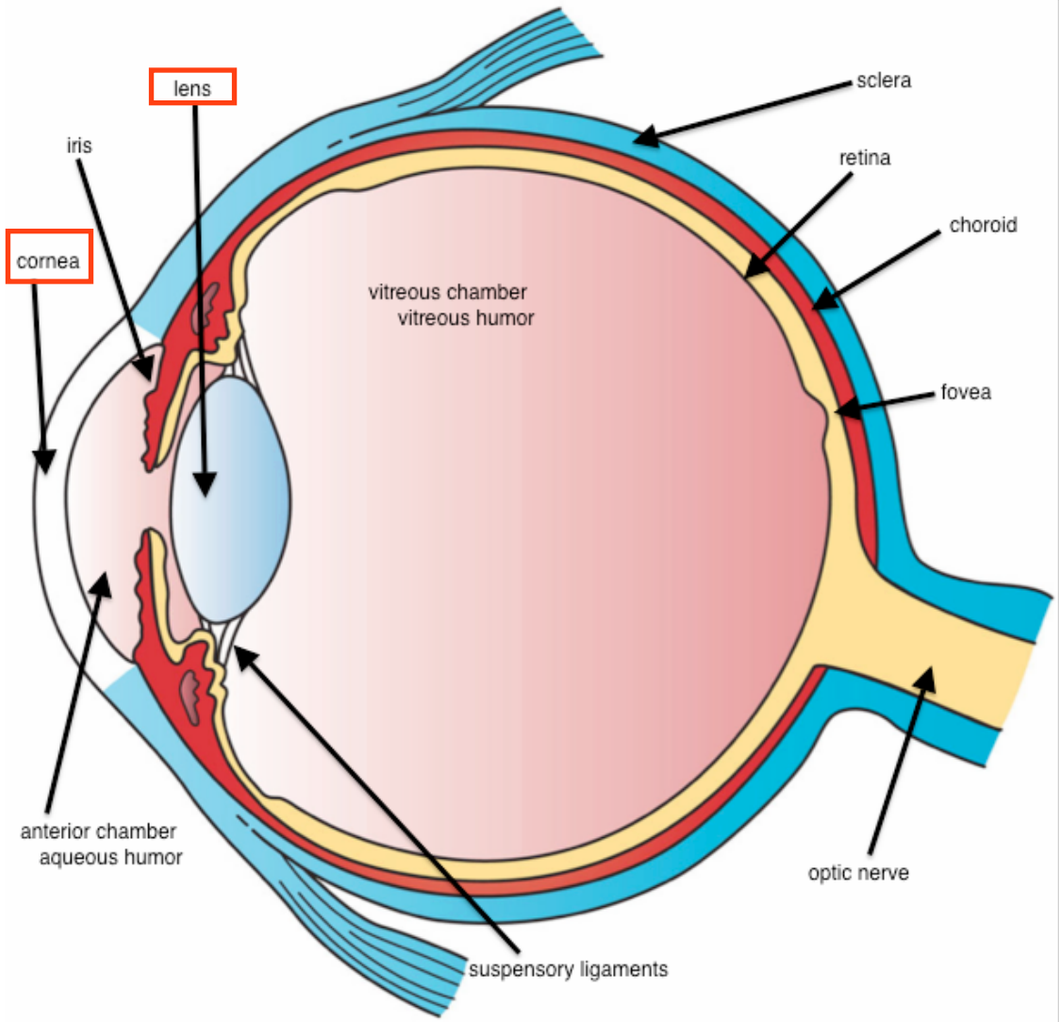
- terrestrial animals: curved air—tissue (water) interface can be used to focus image (but only vertebrates, spiders, and some insect larvae use it)



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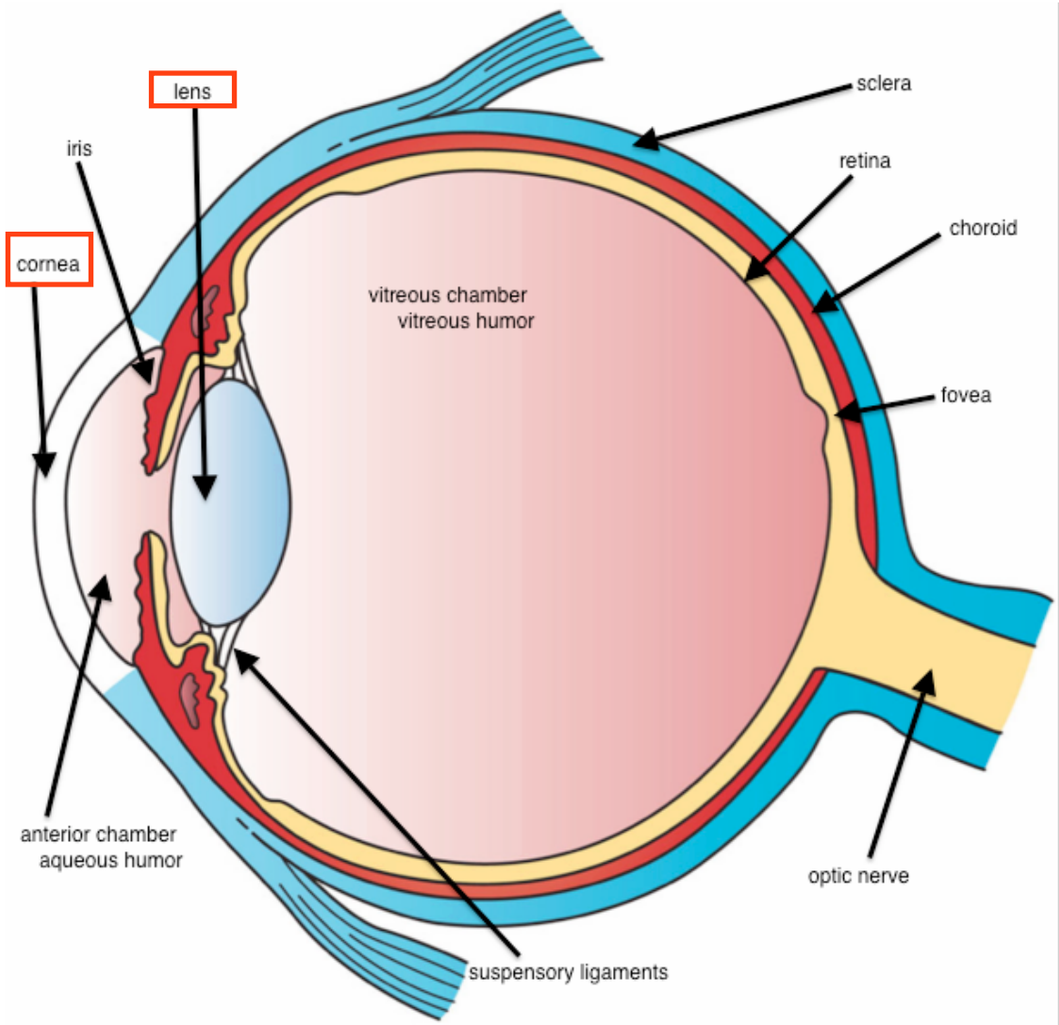

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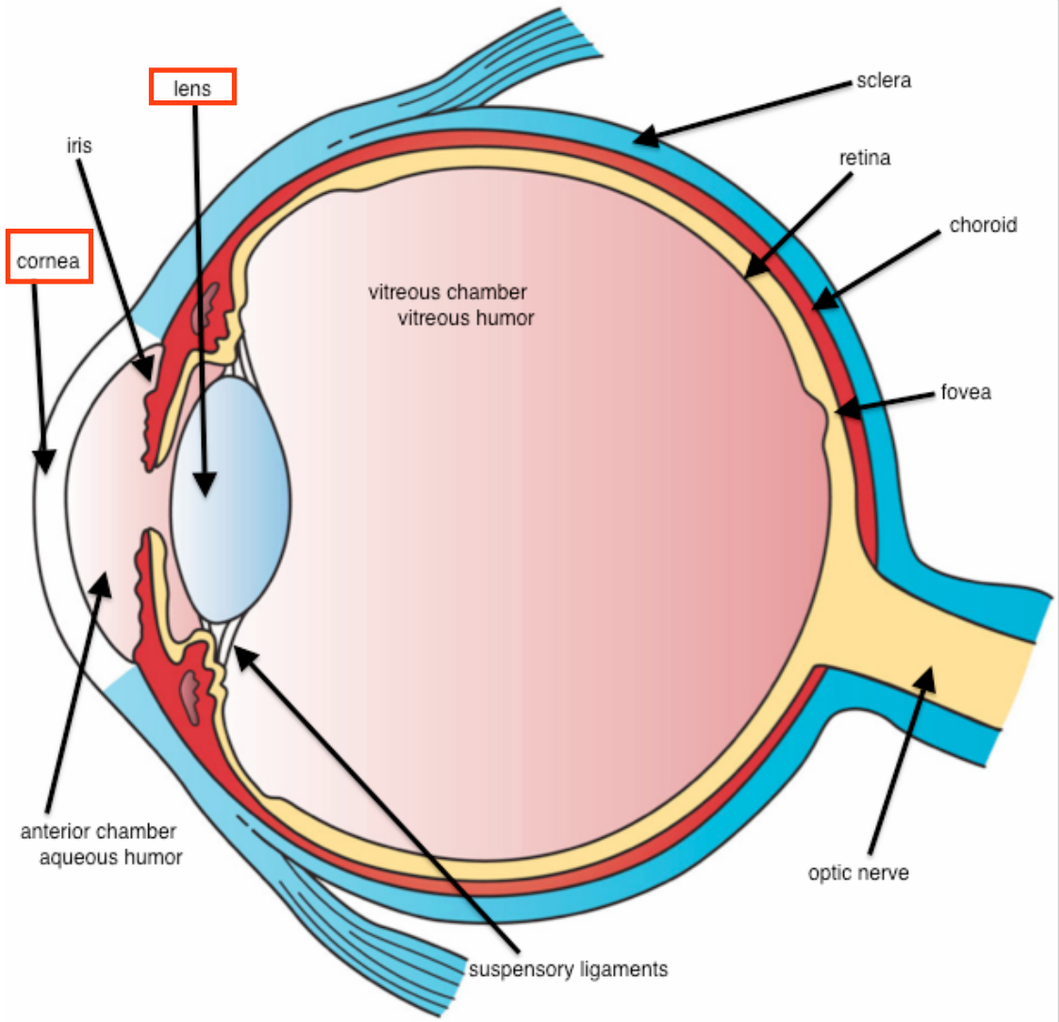

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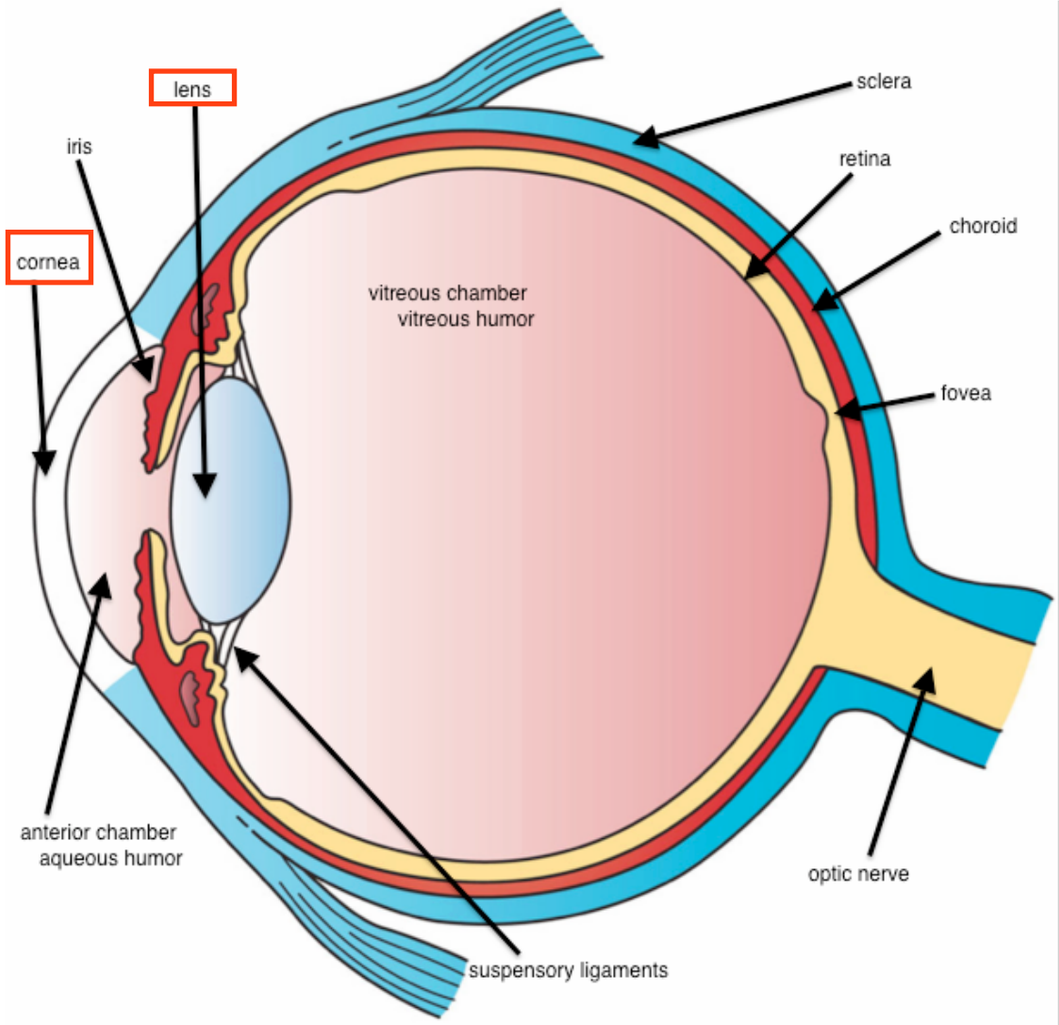

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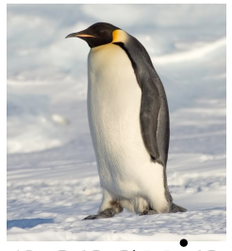
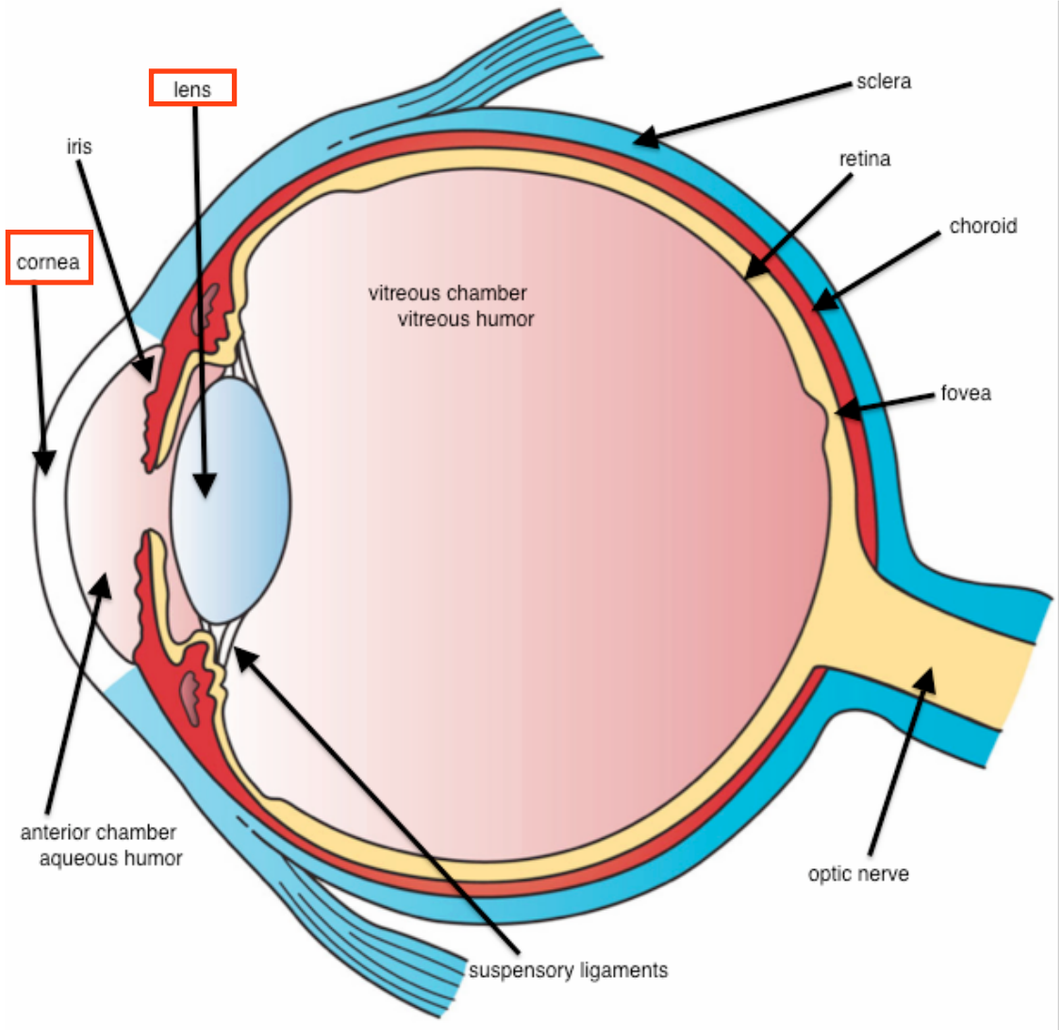
  - flat cornea
    + optical power in lens

seal



penguin



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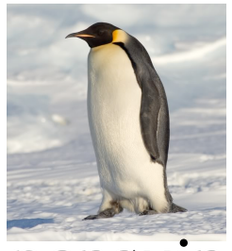
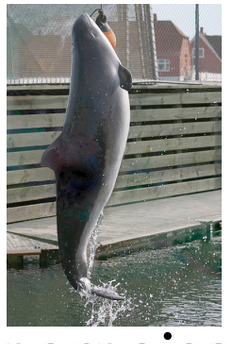
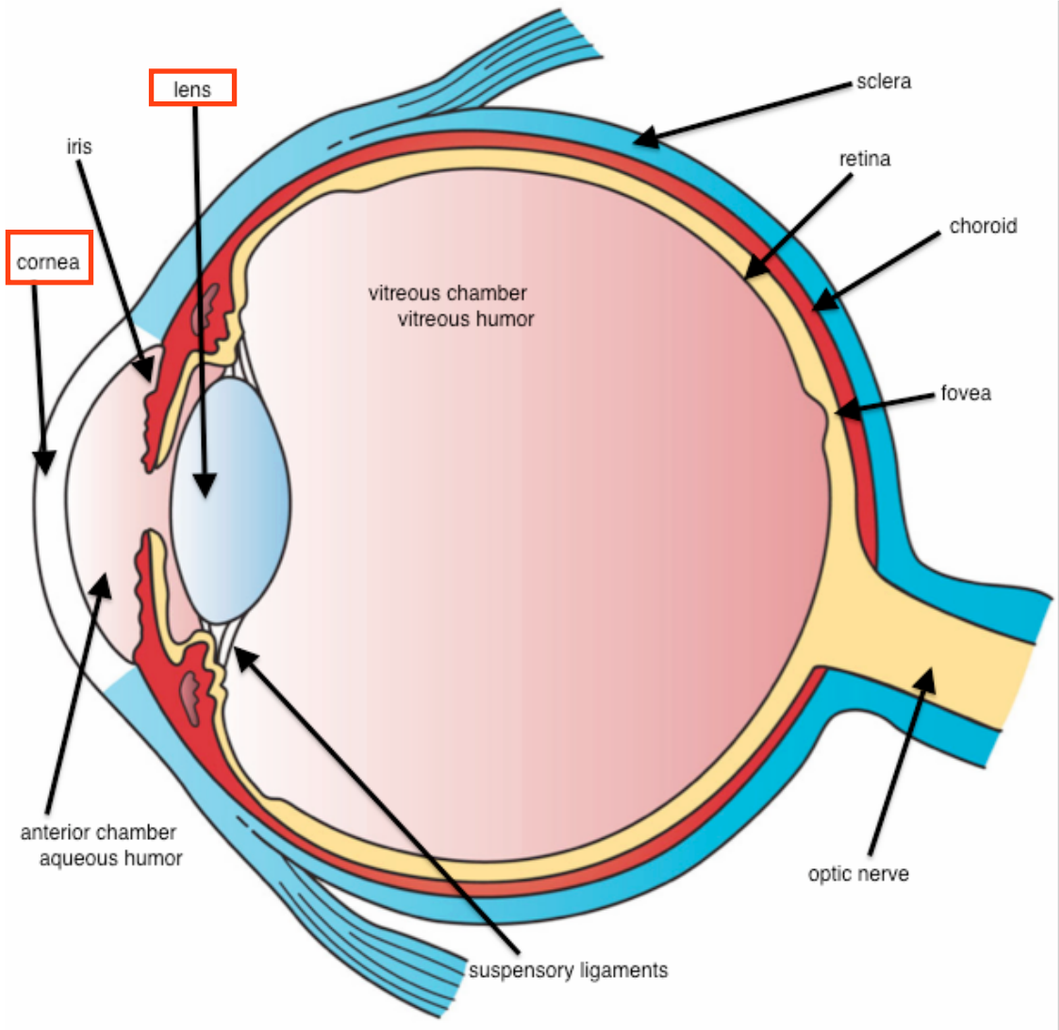


penguin

  - adjustable corneal curvature



porpoise



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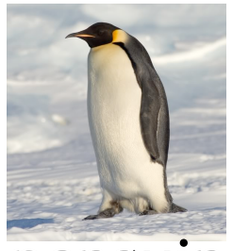

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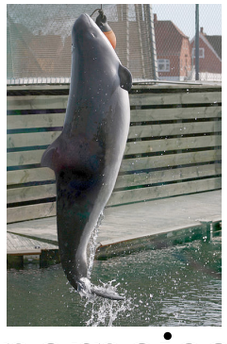
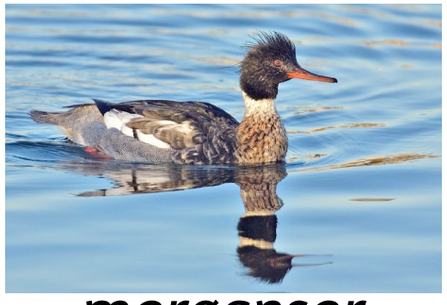
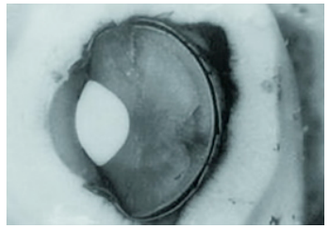


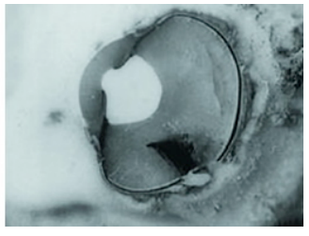
porpoise

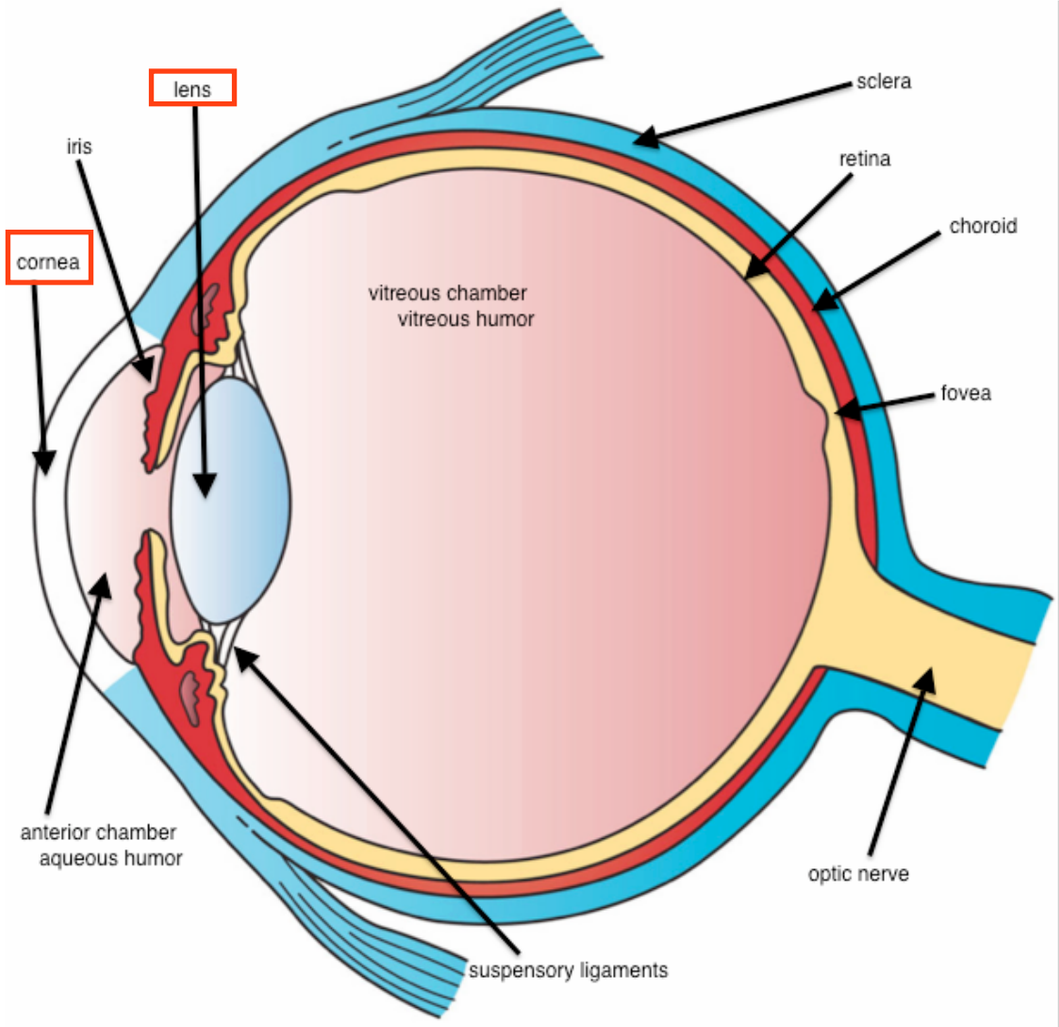
  - very strongly accommodating lens
    80× (usually 3-6×)



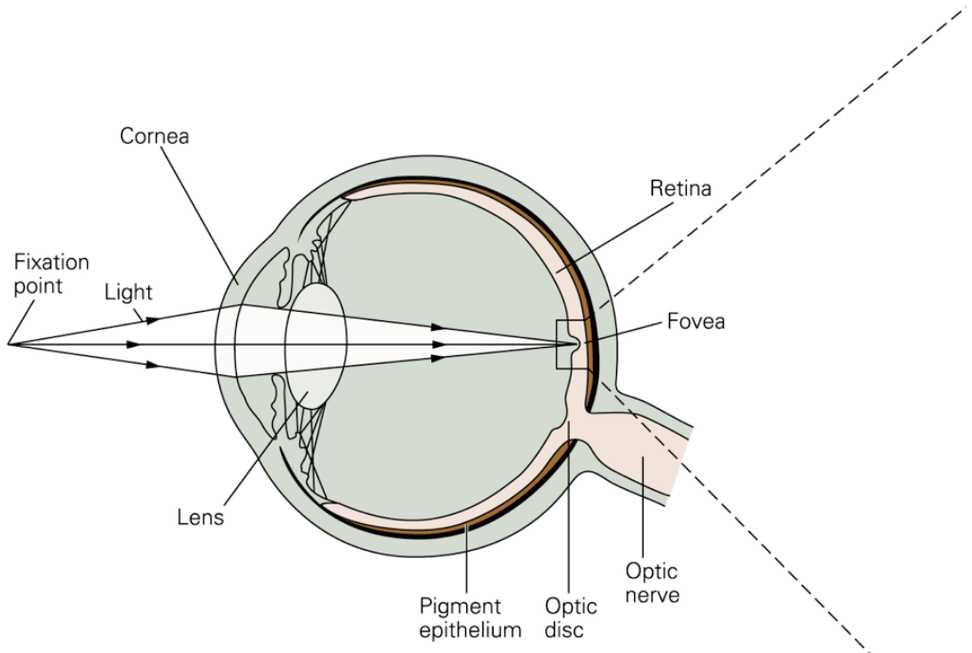
merganser

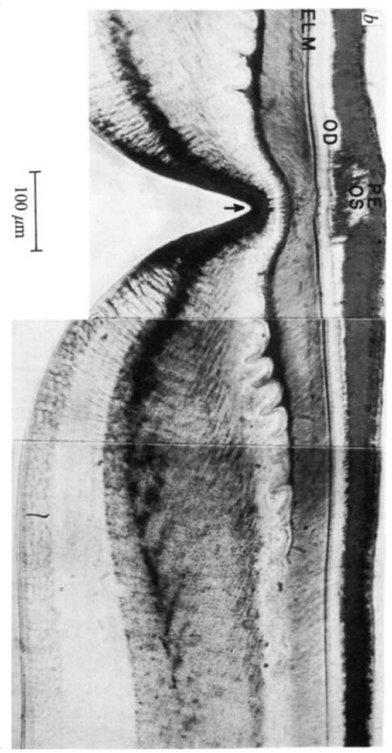






2.4 A NEGATIVE LENS





darkness ≈ refractive index

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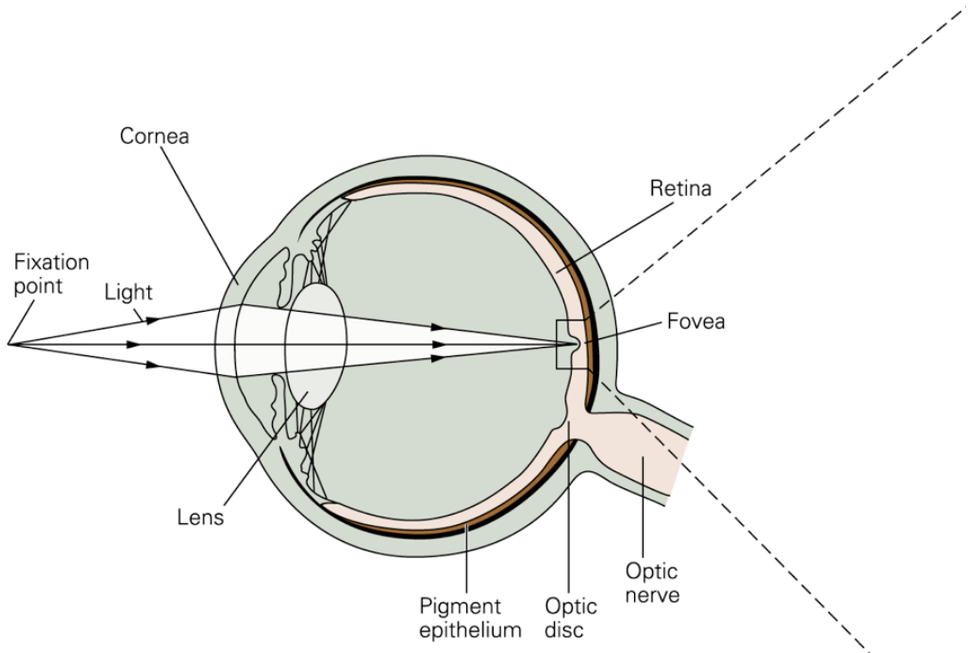

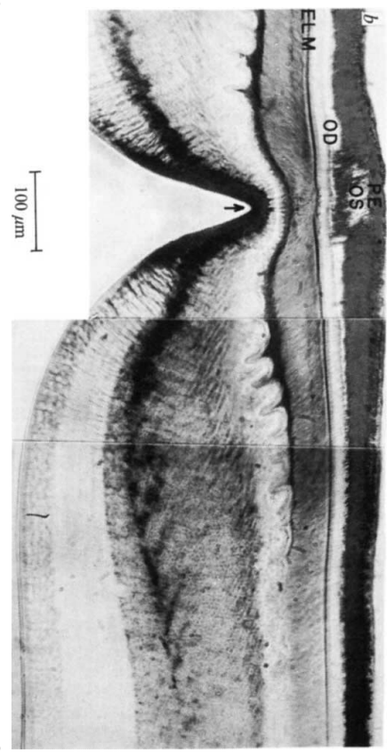

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- foveal pit + changing refractive properties → negative (magnifying) lens

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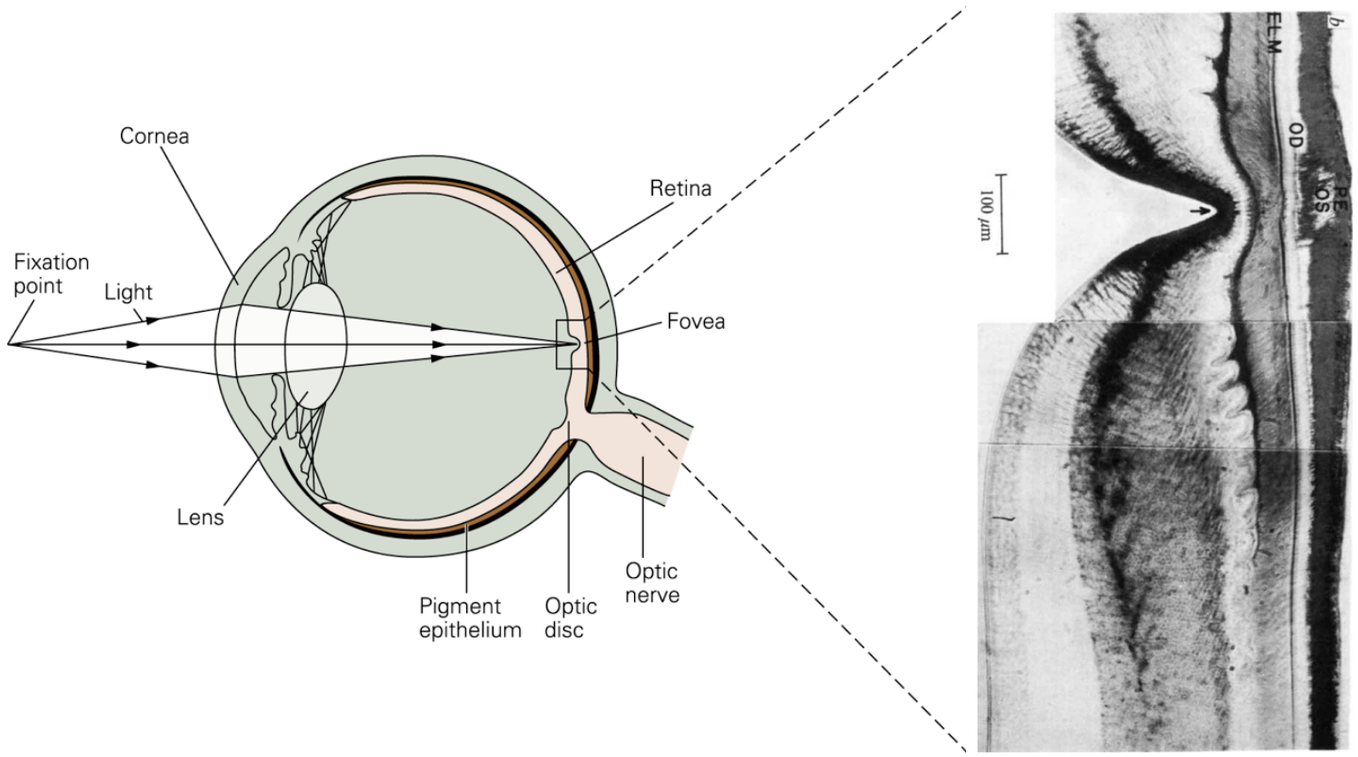

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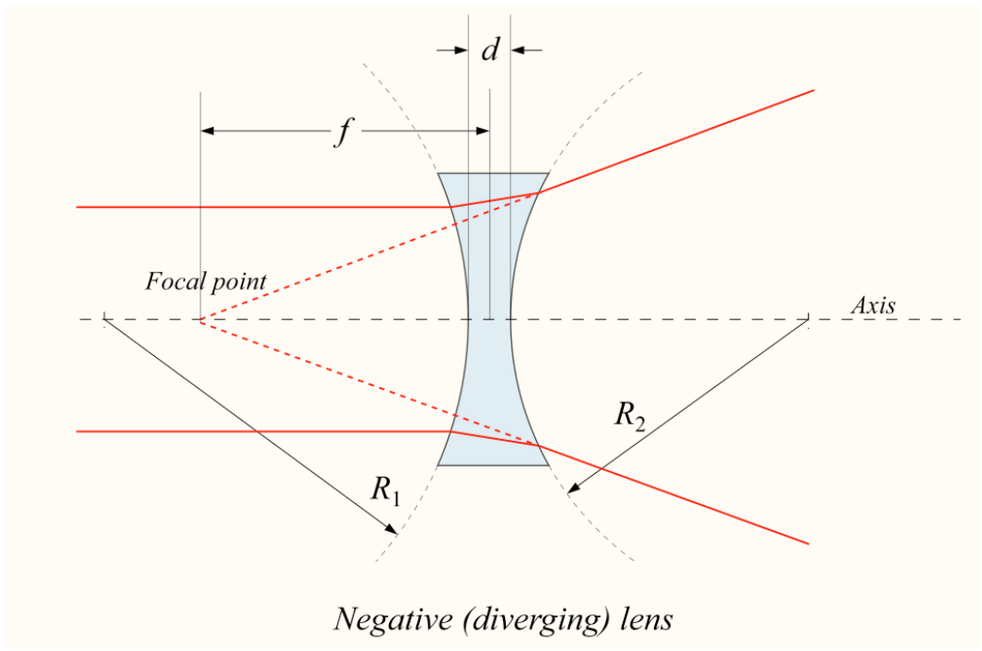
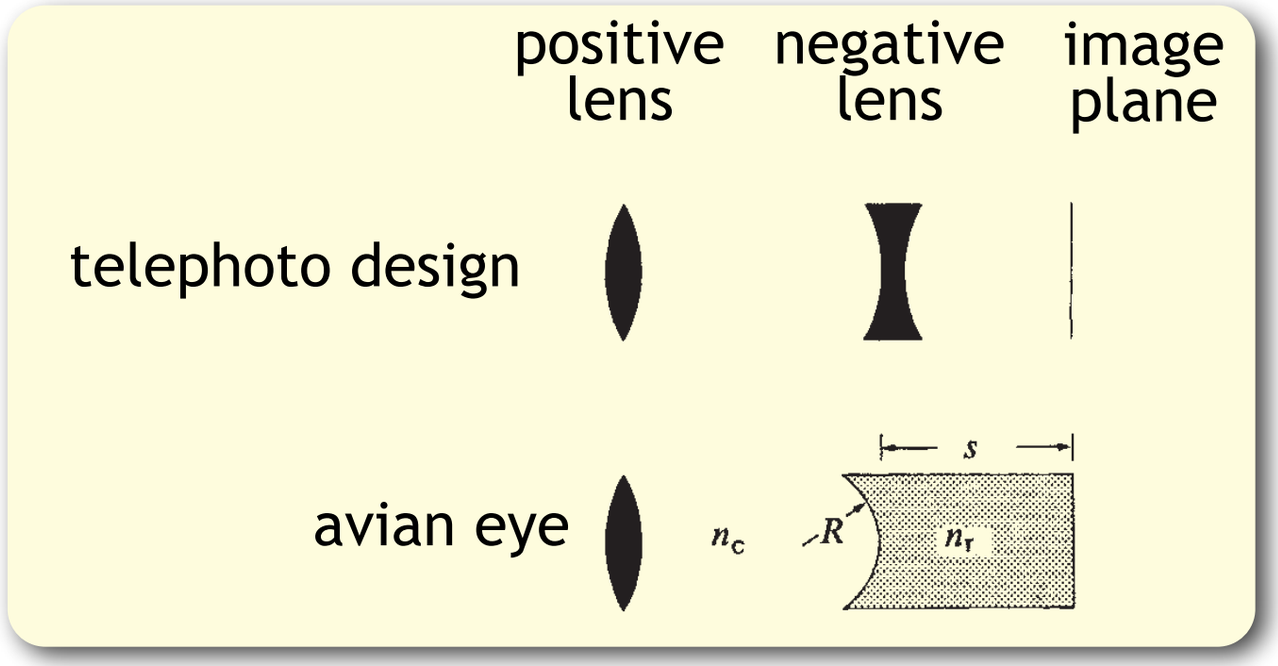
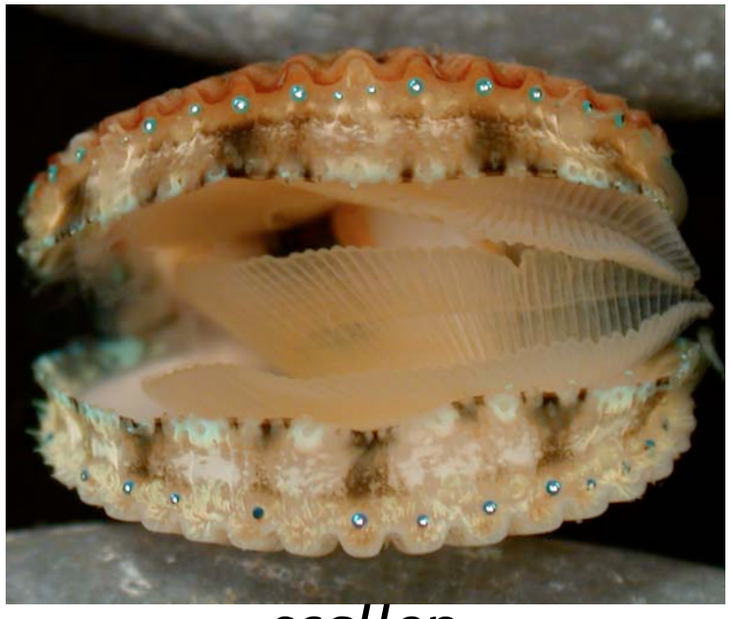




3. REFLECTIVE MIRROR



scallop

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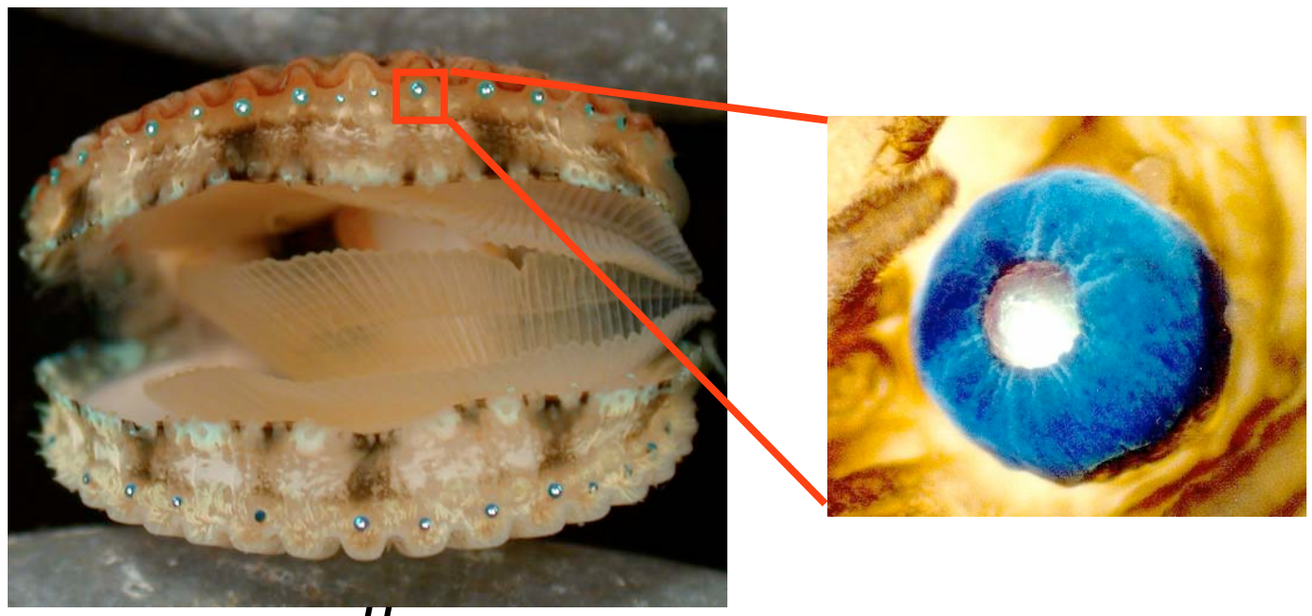

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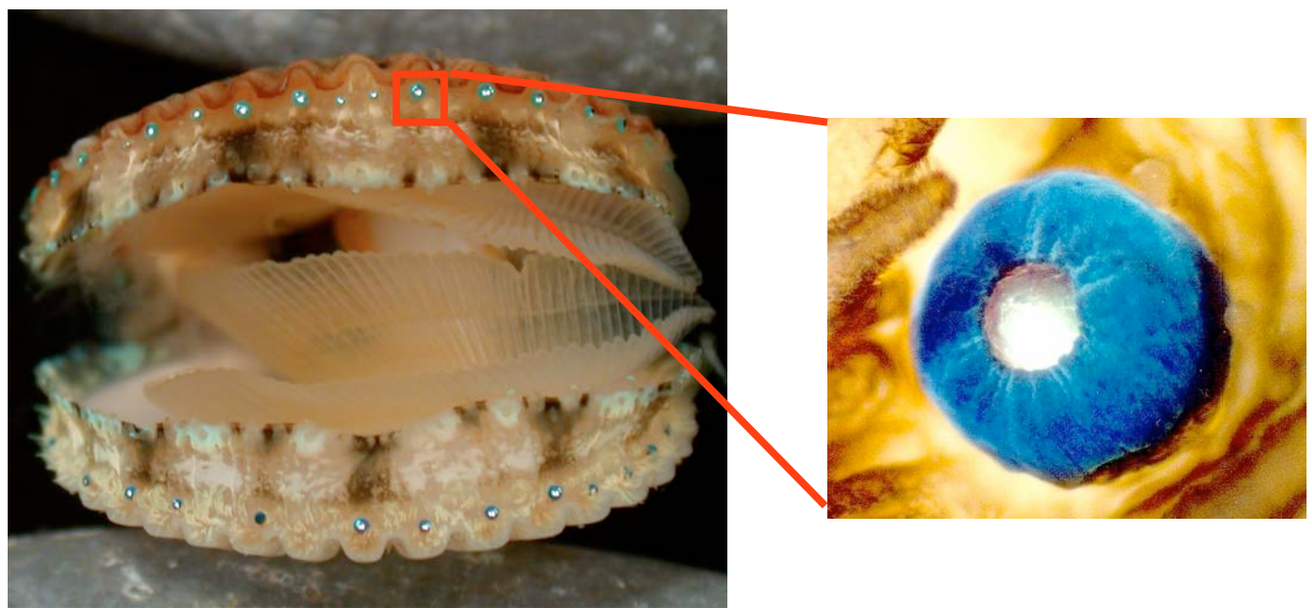

scallop

- 60-100 small (1 mm) eyes

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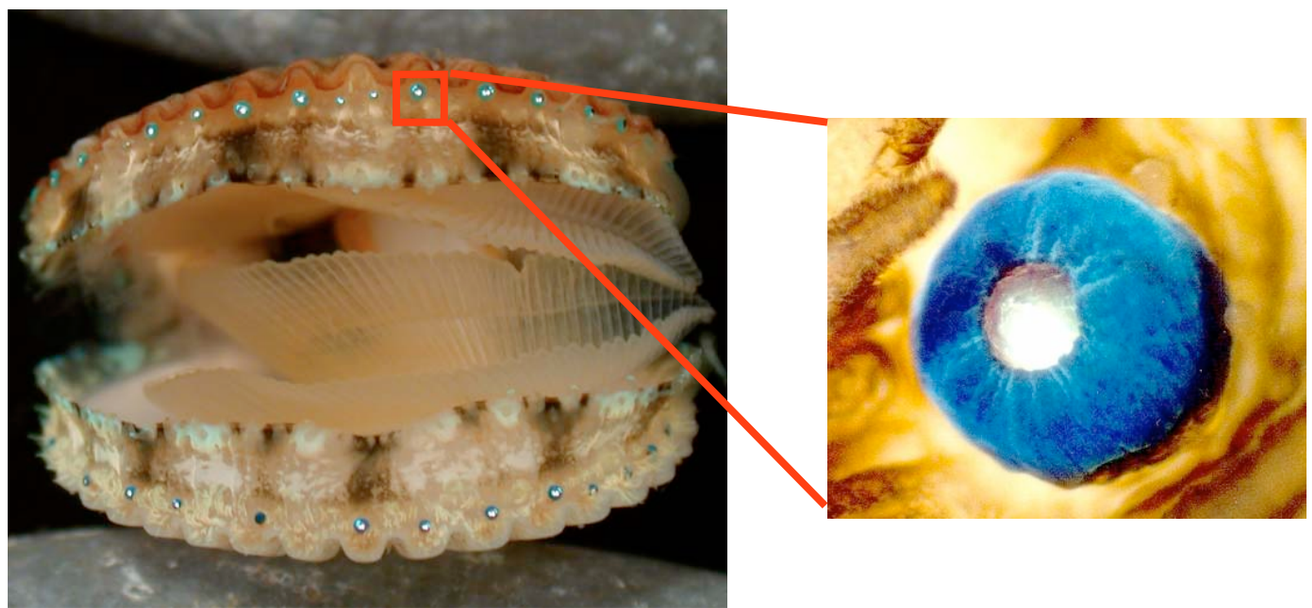

scallop

- 60-100 small (1 mm) eyes
- distant, moving objects → shells shut

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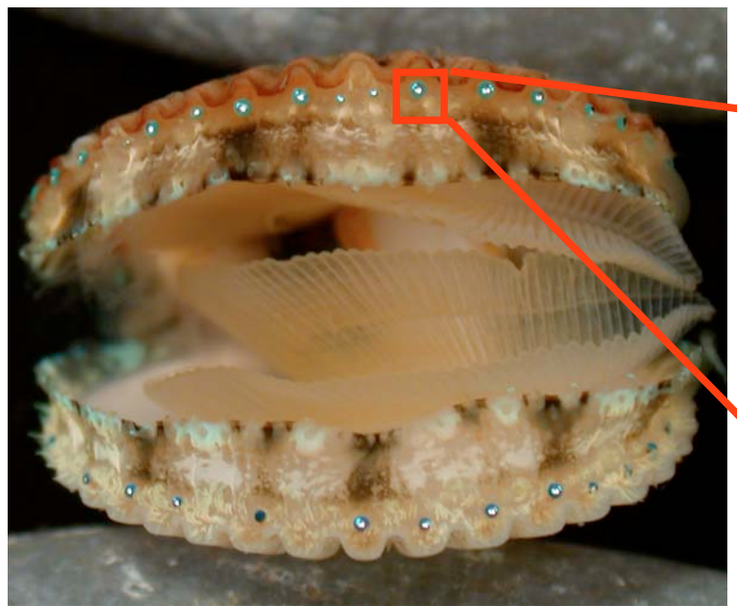
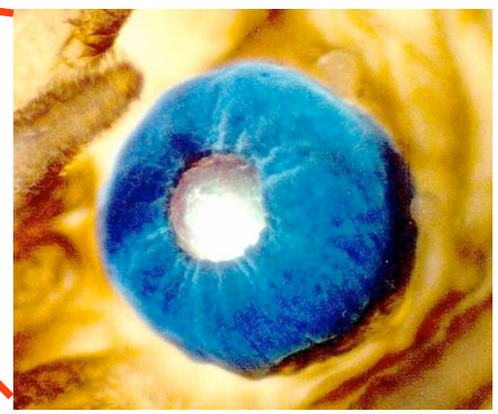
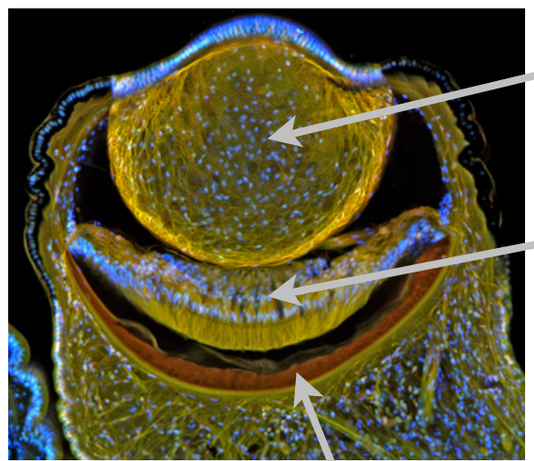


scallop





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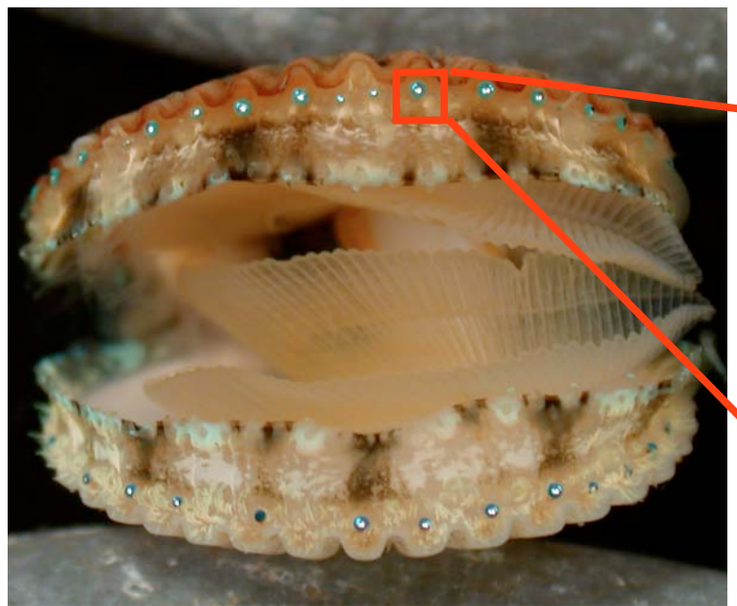

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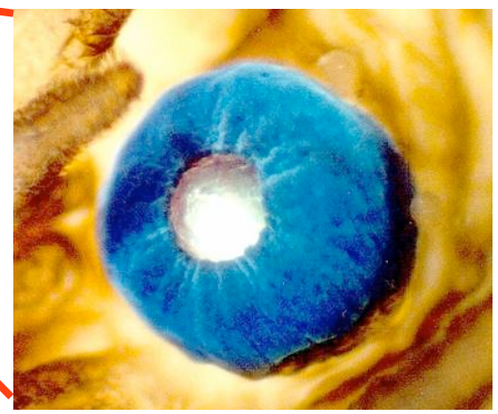

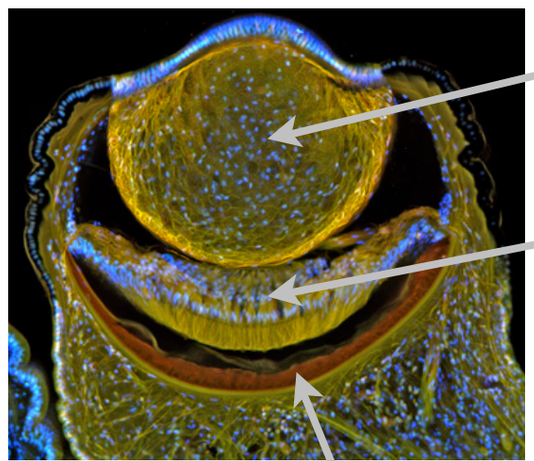

- 60-100 small (1 mm) eyes
- distant, moving objects → shells shut
- lens is not focussing
  corrects for spherical aberration
  (like ‘Schmidt corrector plate’)

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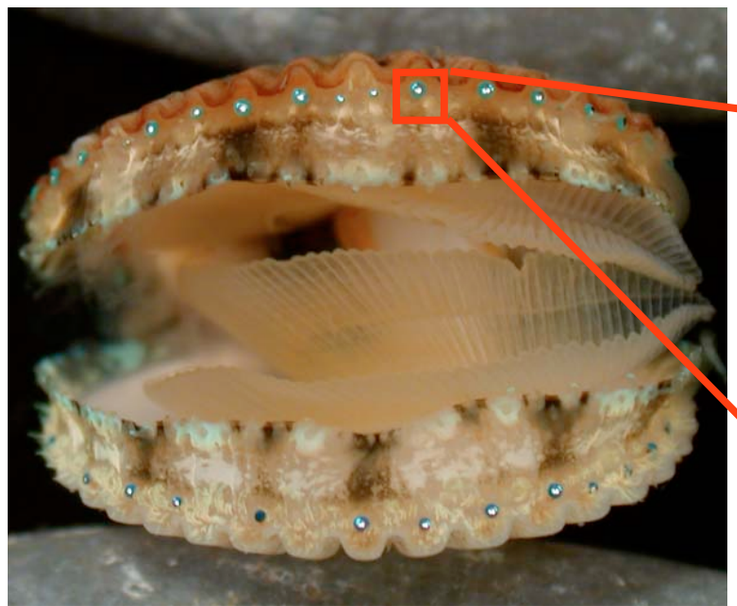

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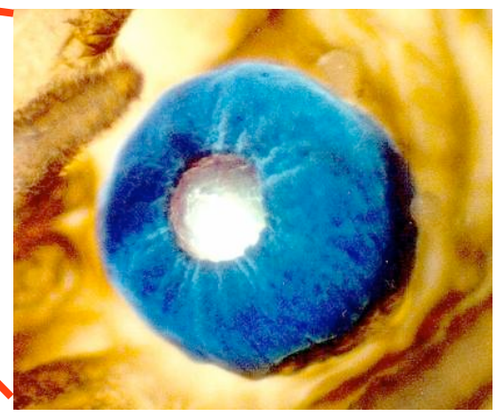

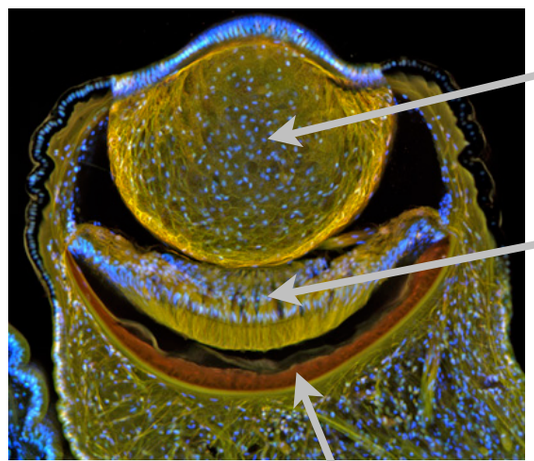

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  (like cats)

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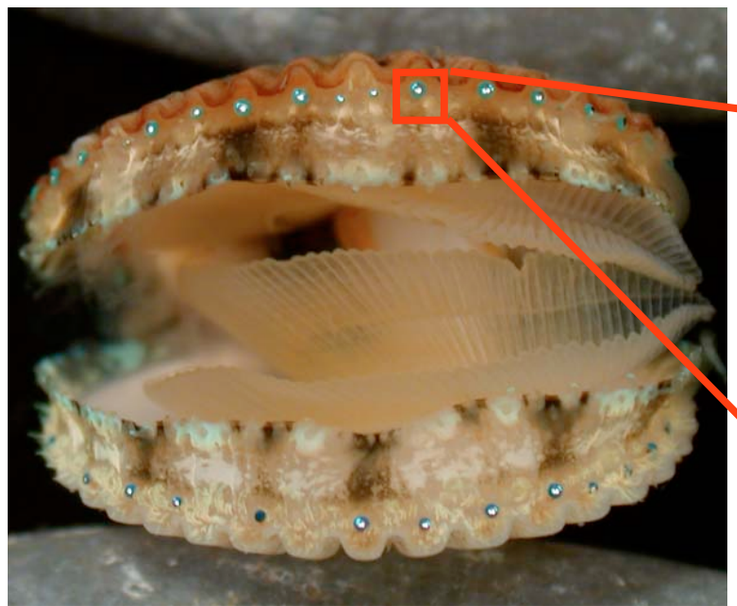

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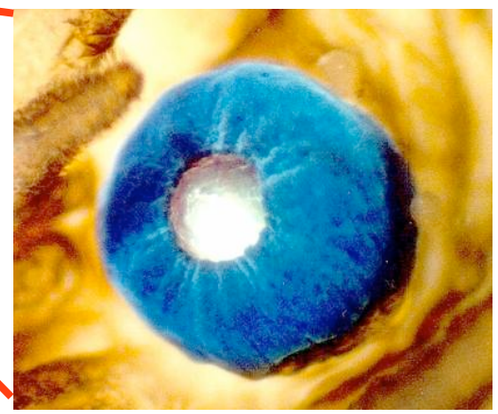

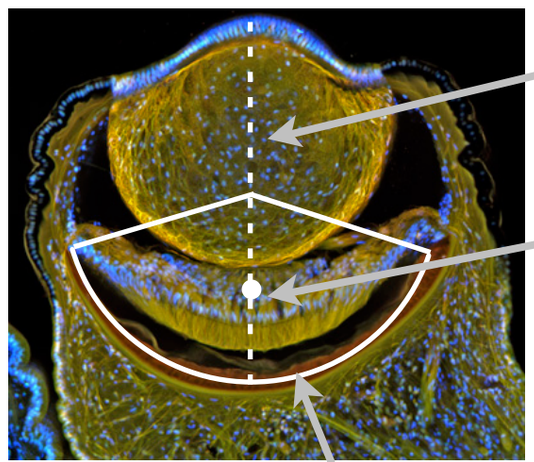

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- increase the light absorbed
  (like cats)
- make an image at a distance of
  half the curvature radius
  (spherical mirror, ‘infinite’ object distance)
  → that’s where the retina is!

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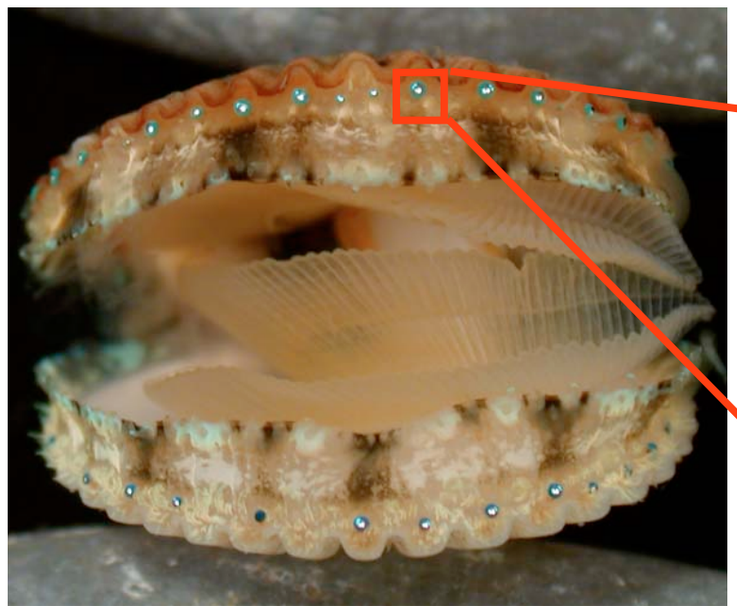

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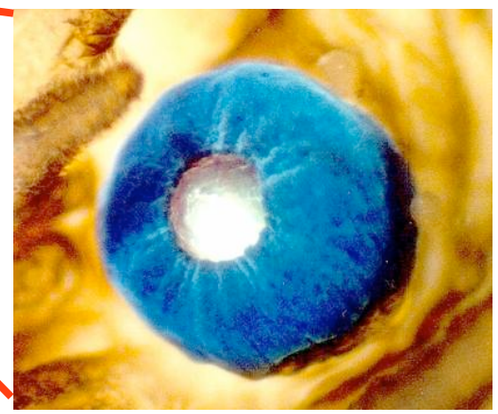

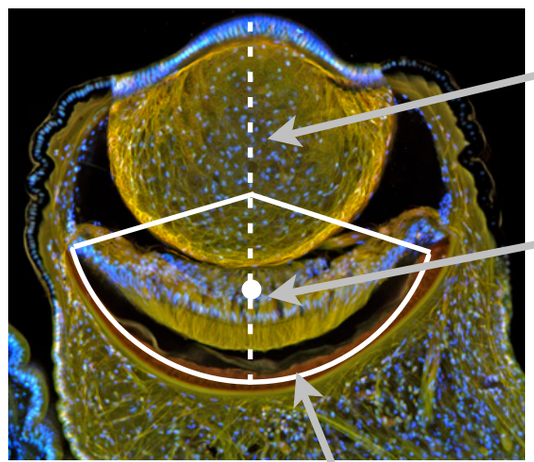

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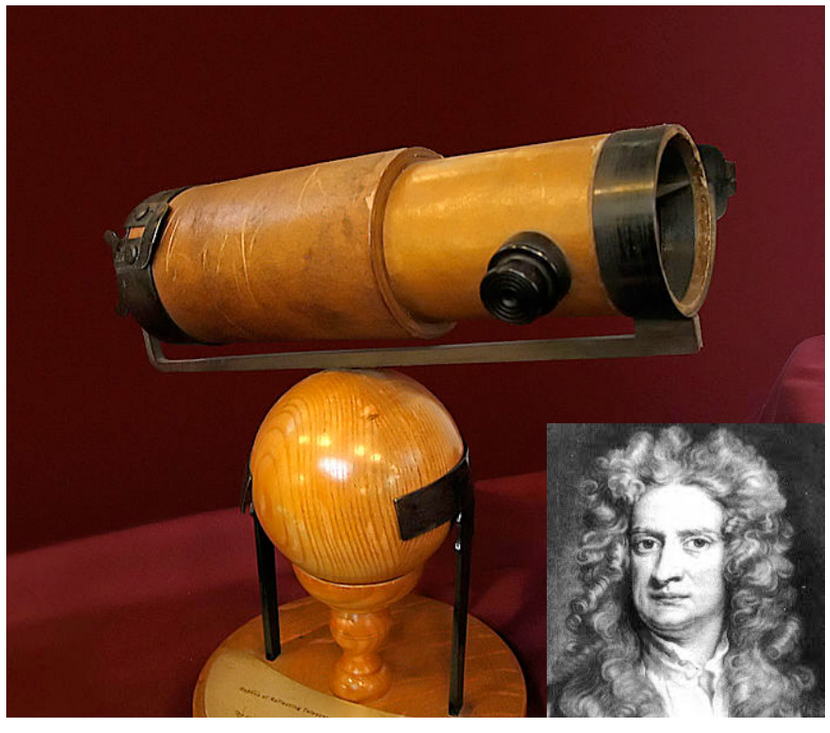
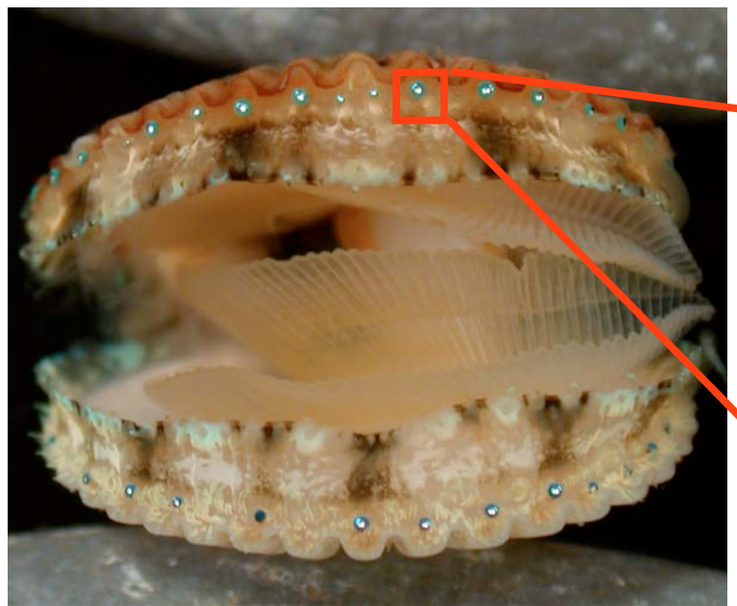
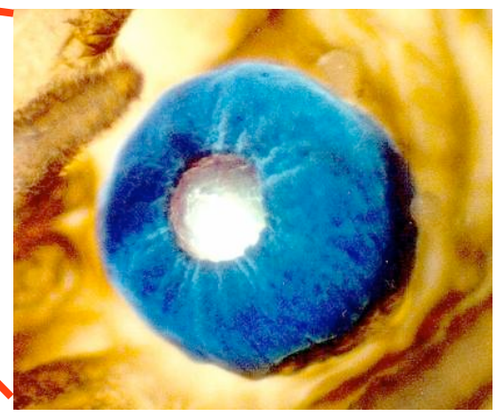
  (spherical mirror, ‘infinite’ object distance)
  → that’s where the retina is!

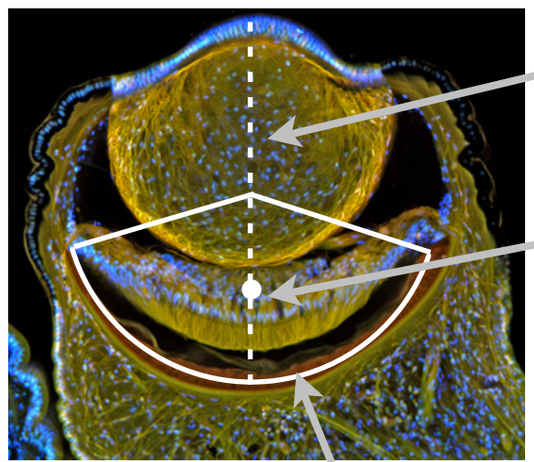


3. REFLECTIVE MIRROR



scallop



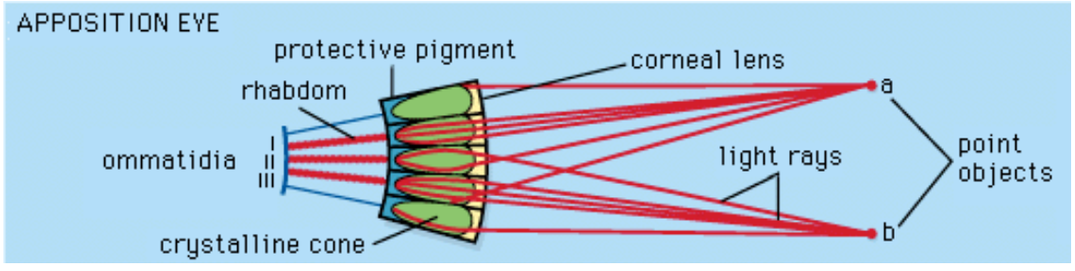


- 60-100 small (1 mm) eyes
- distant, moving objects → shells shut
- lens is not focussing
  corrects for spherical aberration
  (like ‘Schmidt corrector plate’)
- increase the light absorbed
  (like cats)
- make an image at a distance of
  half the curvature radius
  (spherical mirror, ‘infinite’ object distance)
  → that’s where the retina is!

COMPOUND EYES

COMPOUND EYES

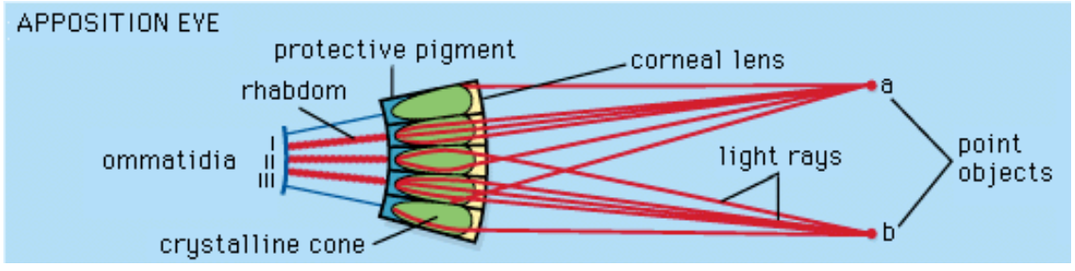
apposition eye



- photoreceptor cells directly behind optical apparatus
- image forms in each ommatidium but only 1 pixel / ommatidium is created
- visual image is formed by apposition of individual pixels in the brain
- lower light sensitivity

COMPOUND EYES

apposition eye



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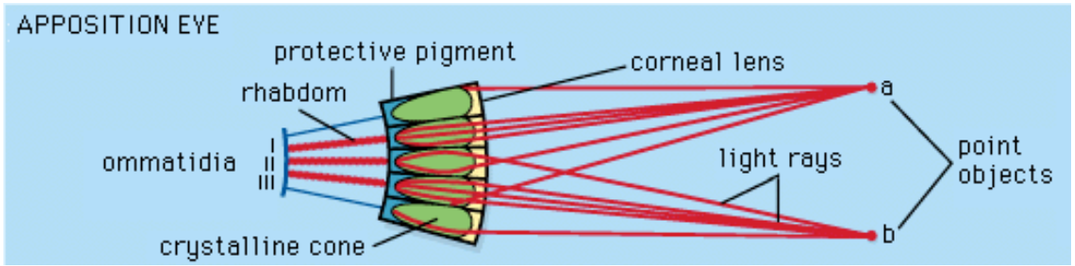

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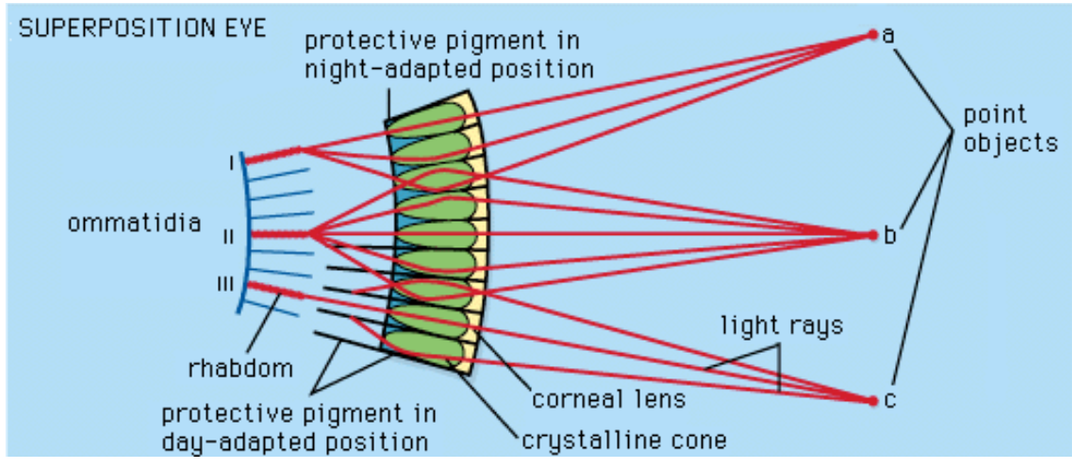
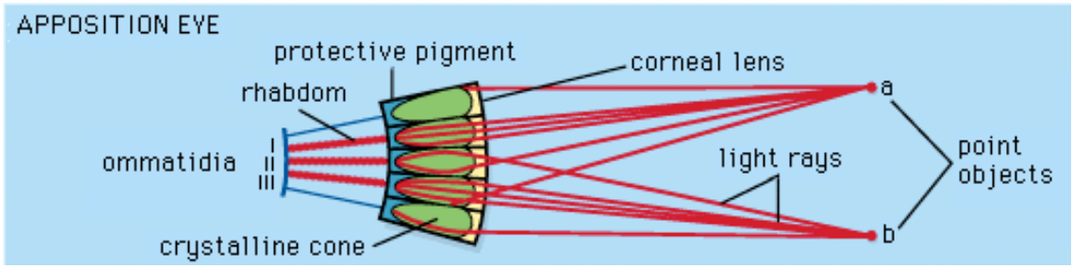
superposition eye



- photoreceptors (retina) lie deep, further away from lenses
- image forms at the level of retina by superpositions of rays coming through different ommatidia
- higher light sensitivity

COMPOUND EYES

apposition eye



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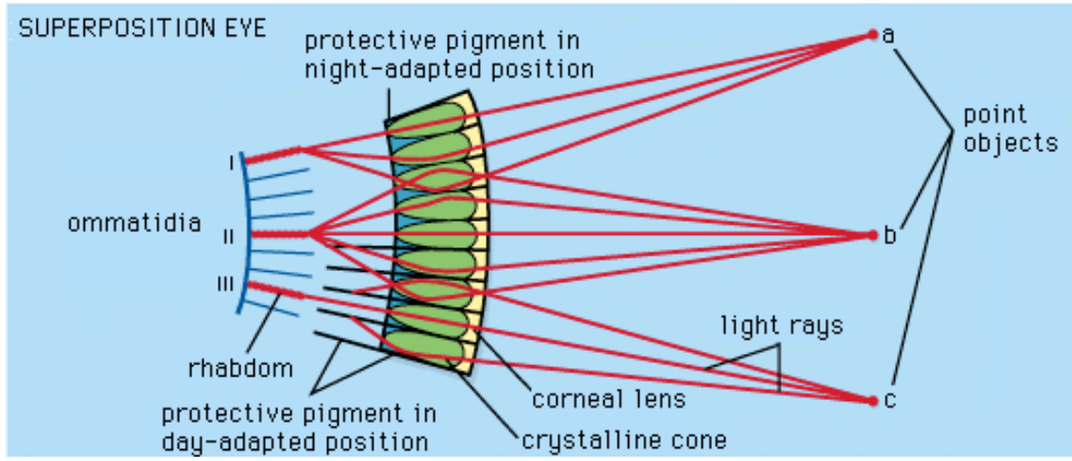

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common limitation due to small lenses: **diffraction**

point spread function due to diffraction

$\frac{2\lambda}{D}$

λ wave length — green light $\lambda = 0.5\,\mu\mathrm{m}$

D lens diameter (aperture) — $D = 25\,\mu\mathrm{m}$

1.1° resolution

INSPIRATION FOR ENGINEERS

LETTER

doi:10.1038/nature12083

Digital cameras with designs inspired by the arthropod eye

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