Quick survey of animal vision

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2015-02-23

Sources:

Climbing Mount Improbable, Richard Dawkins – chapter 5

Invertebrate Vision, Edited by E. Warrant & D-E Nilsson, 2006 – especially chapter 1

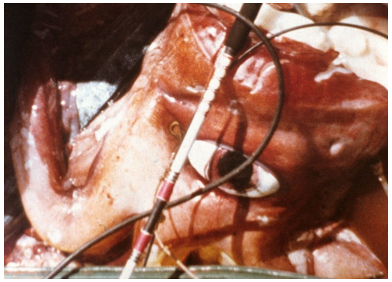
“The Optics of Insect Compound Eyes”, WH Miller, GD Bernard, JL Allen, *Science* 1968

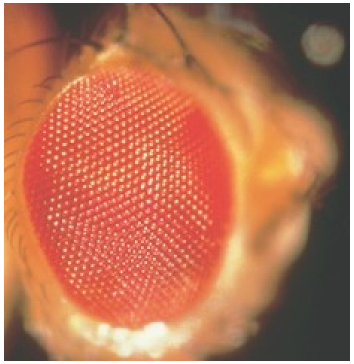
“Adaptations for nocturnal vision in insect apposition eyes”, B. Greiner, 2005 thesis, Lund

Outline

- Upside-down image
  - Camera-like
  - Cup-like
  - Pinhole camera
  - Mirror
- Rightside-up image
  - Apposition
  - Neural superposition
  - True superposition

Plus: Terrifying animal pictures!



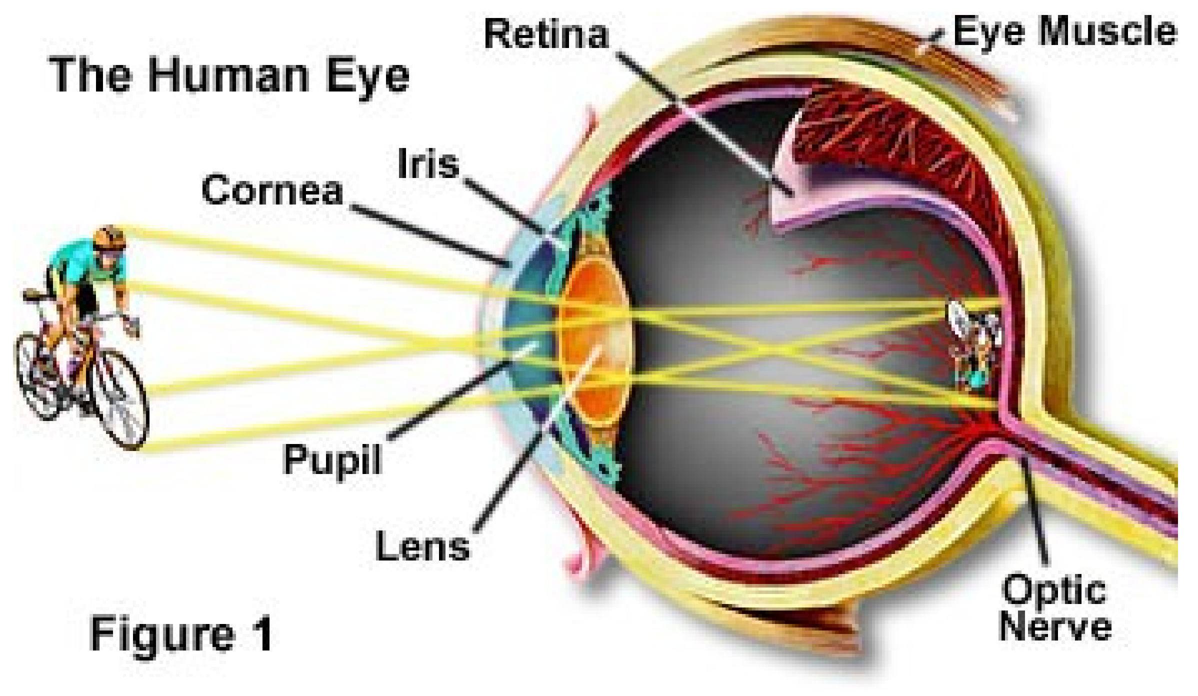


Beyond the scope of today's talk

- Color vision in humans and animals.
- Polarization detection.
- Details about detection photochemistry.
- How the brain analyzes the image data.

- ...I'm mainly going to discuss the basic imaging part.

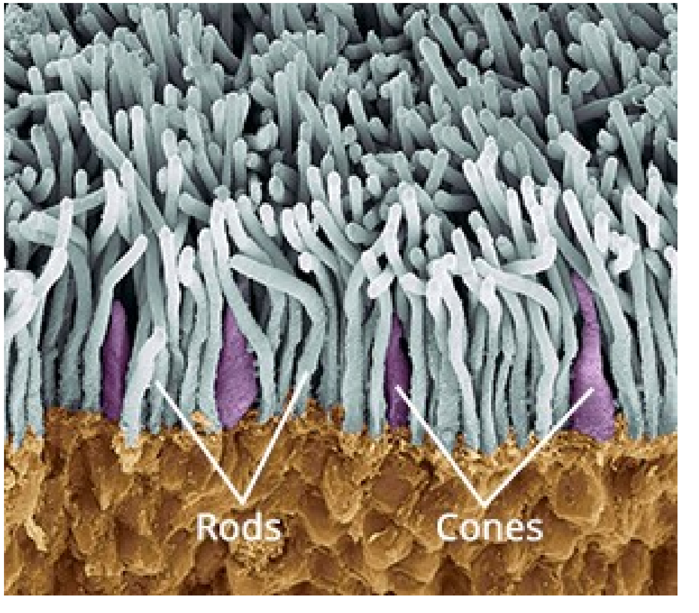
Human eye: Basically like a normal camera



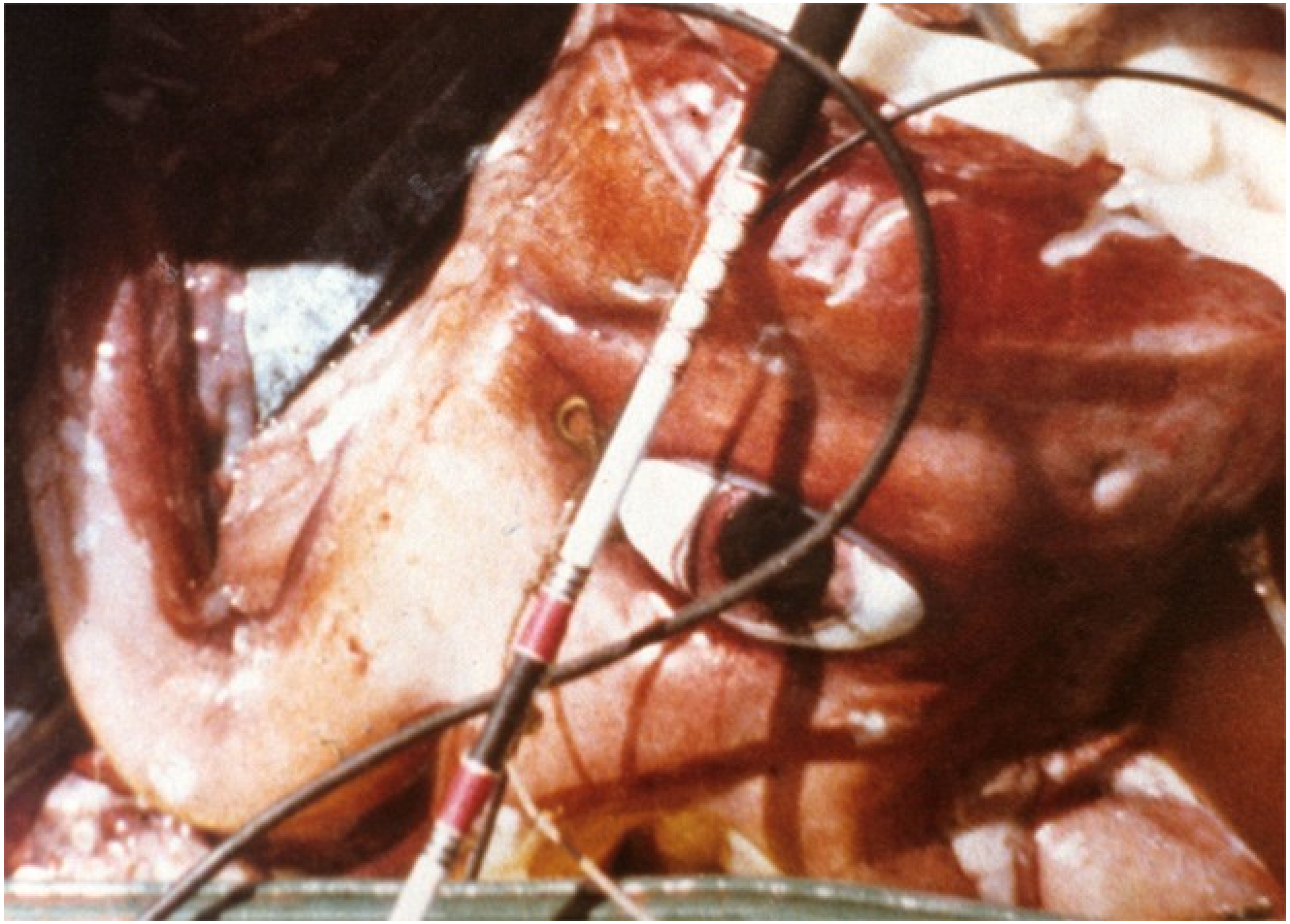
The lens is based on not only the shape but also a refractive index gradient

Human eye: Detectors

- 3 kinds of “cone” – color vision, esp. center
- 1 “rod” – night vision, esp. peripheral
- How do they work? A light-sensitive protein called **retinal**. It changes conformation when it absorbs a photon, then a neuron fires and the retinal is reset.

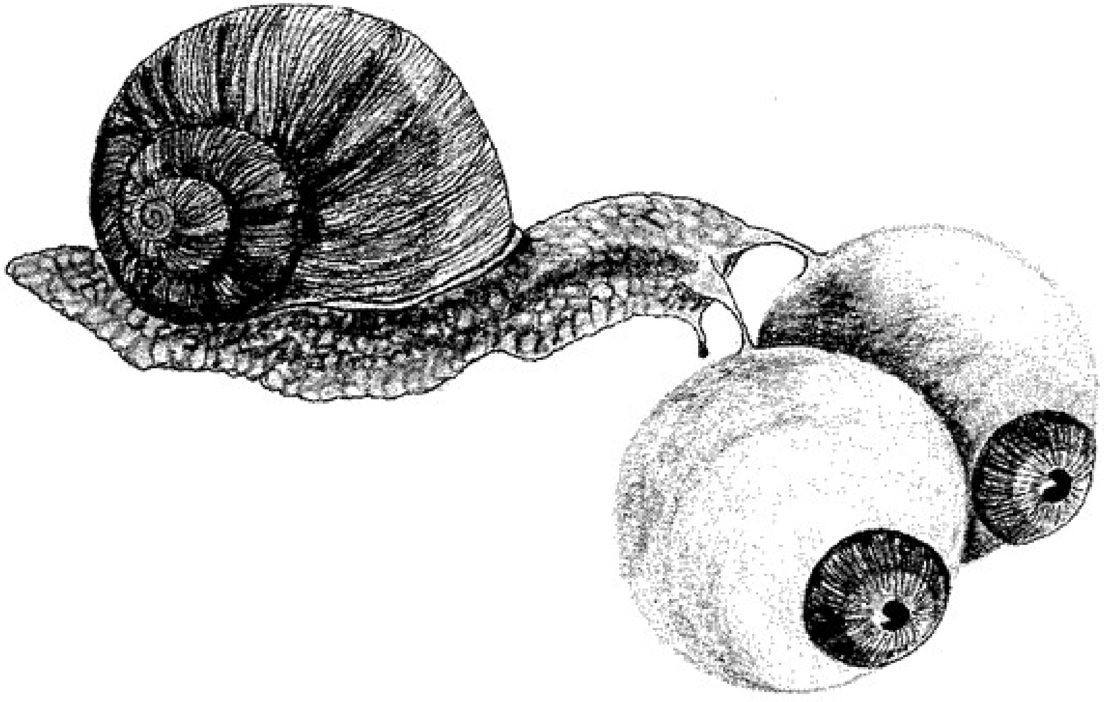


There is a squid whose camera-like eyes are 37cm in diameter



Camera-like eyes

- Diffraction limit → Resolution depends on absolute size → Not optimal for small animals



Imagining a snail with vision as good as a human's

Pupil

- Adjustable aperture is important for high dynamic range.
- Shape doesn't matter too much, therefore they come in a variety of shapes.

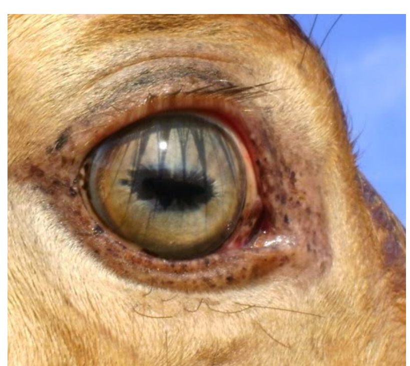
Cat-dark

Cat-bright

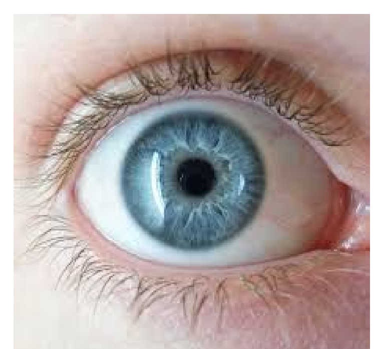
Reticulated python

Long-nosed tree snake

Horse



Human



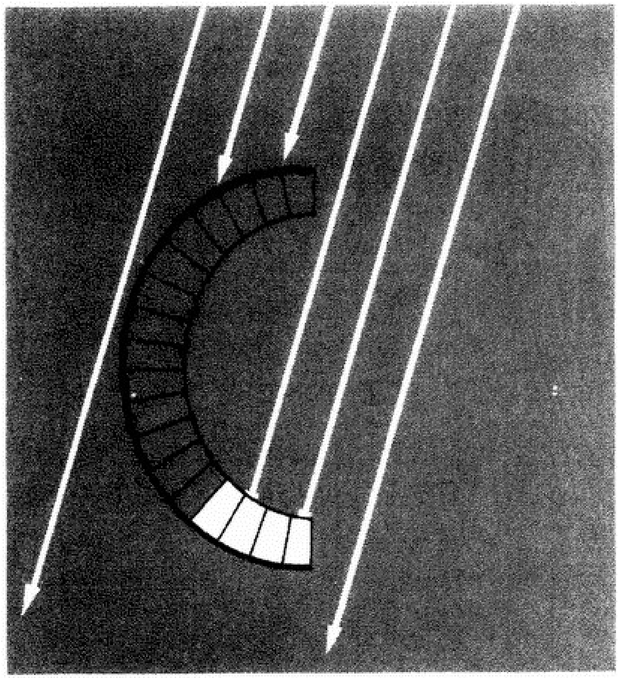
Camera

Adjusting focus

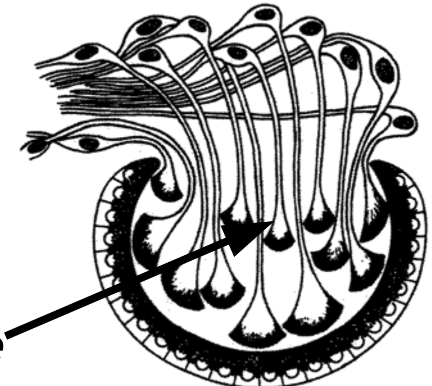
- Mammals, birds, reptiles have muscles that pull on the lens to change its shape
- Chameleons, snakes, fishes, frogs have muscles that move the lens forward or backward
- Many small animals do not have an adjustable focus at all.

“Cup eye”

This is like a compound eye, but concave rather than convex.

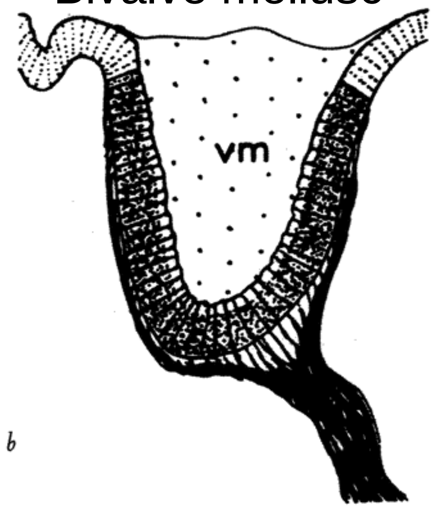


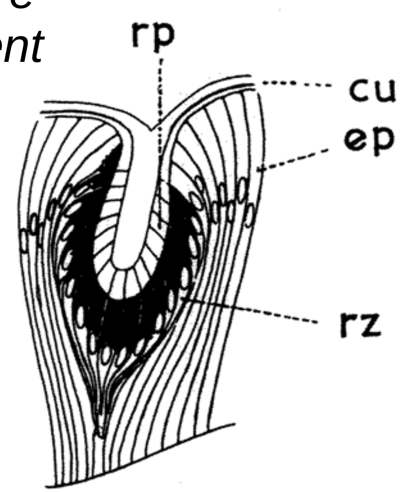
Flatworm



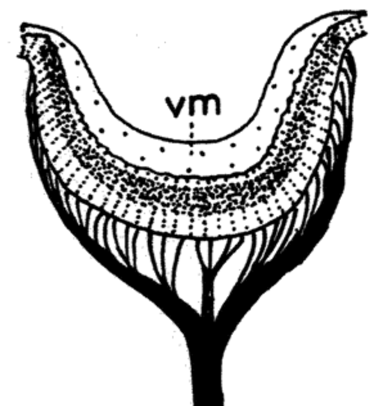
These nerves are transparent

Bivalve mollusc





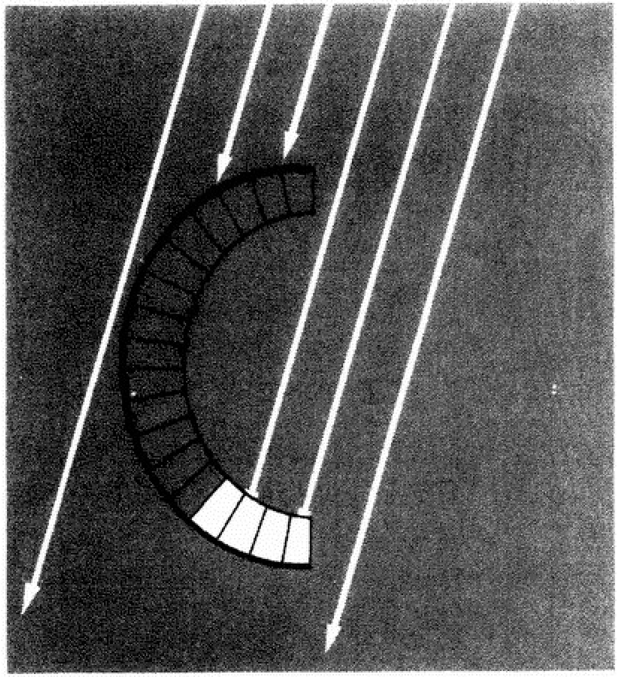
Polychaet worm

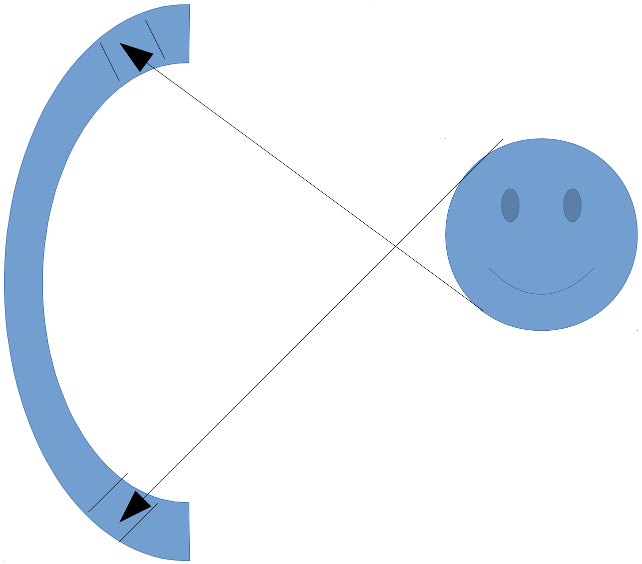


Limpet

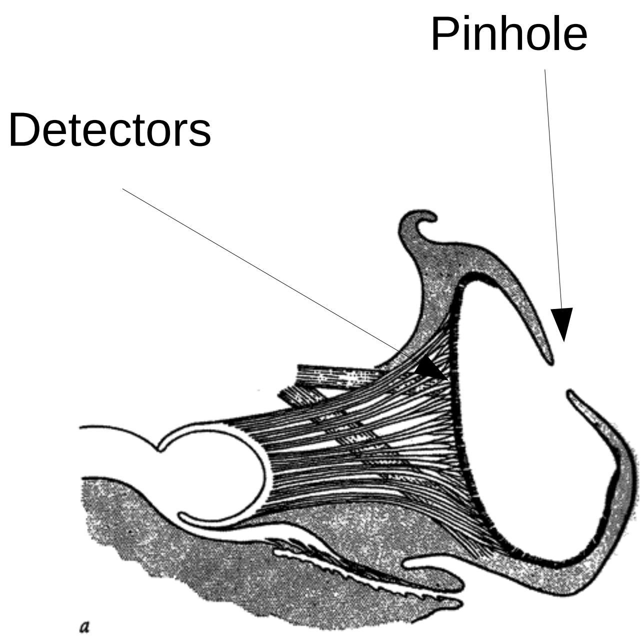
“Cup eye”

- Image is upside-down and very low-res

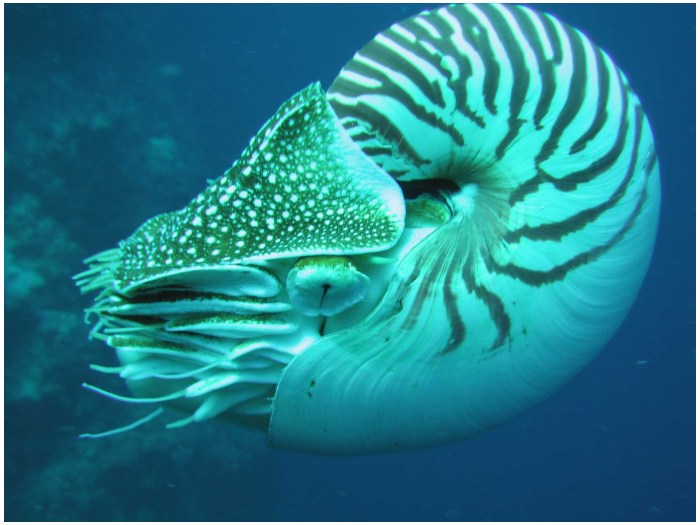




Pinhole camera eye



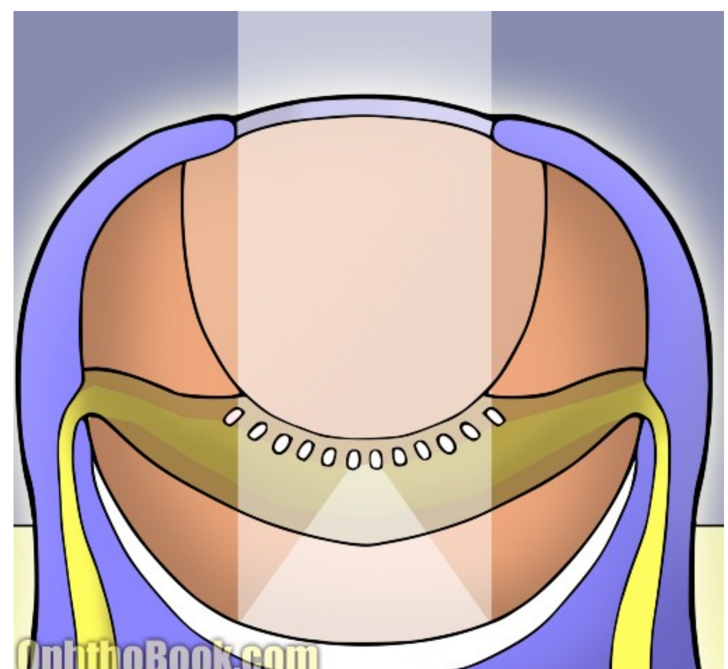
Nautilus



Scallops: Mirror focusing!

Eyes

(But there is a lens too.)

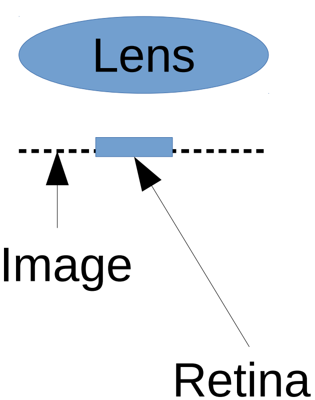


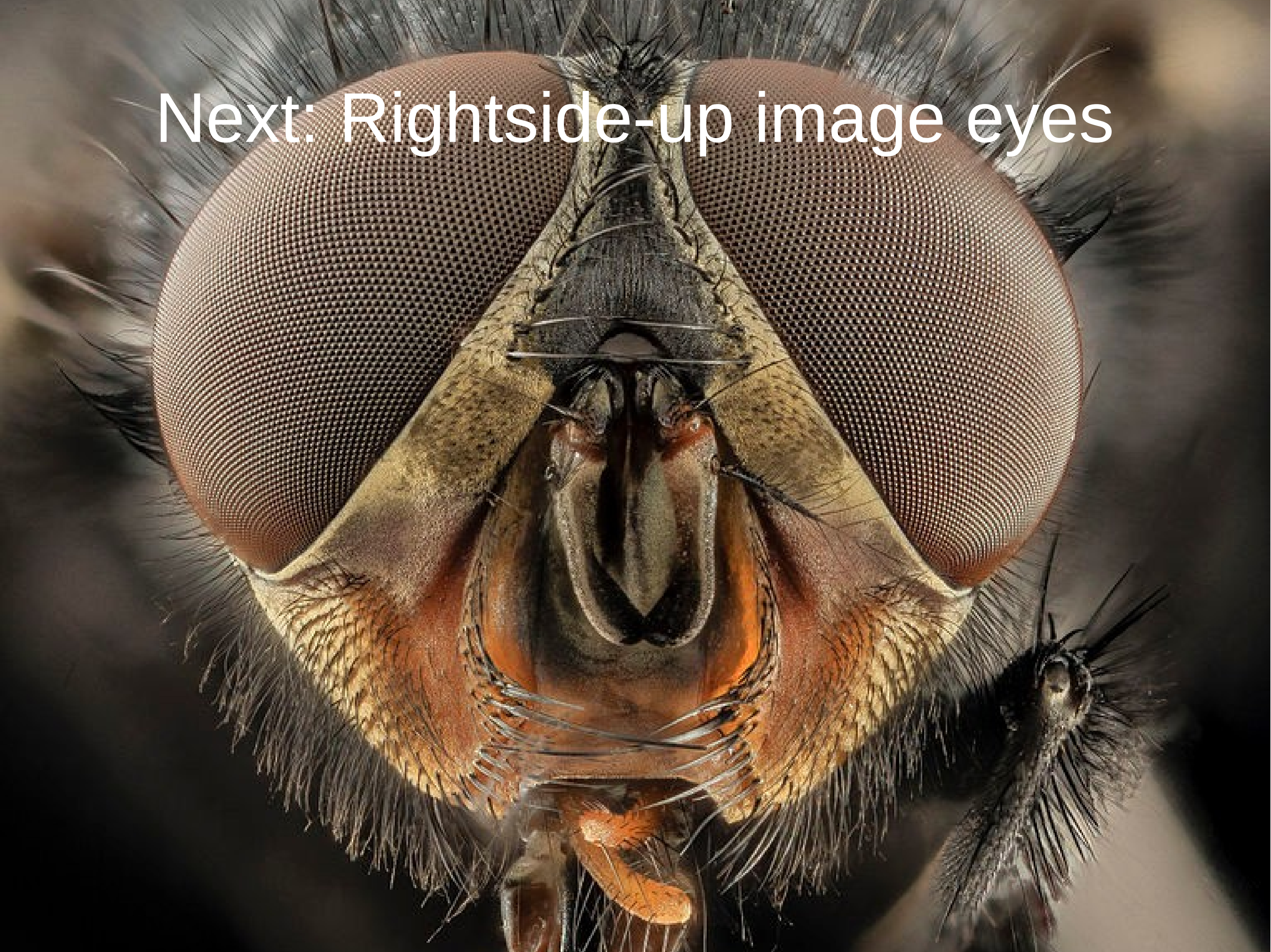
Camera eyes – more tricks

Jumping spiders have 8 eyes.

The two front ones are very sharp but small field-of-view.

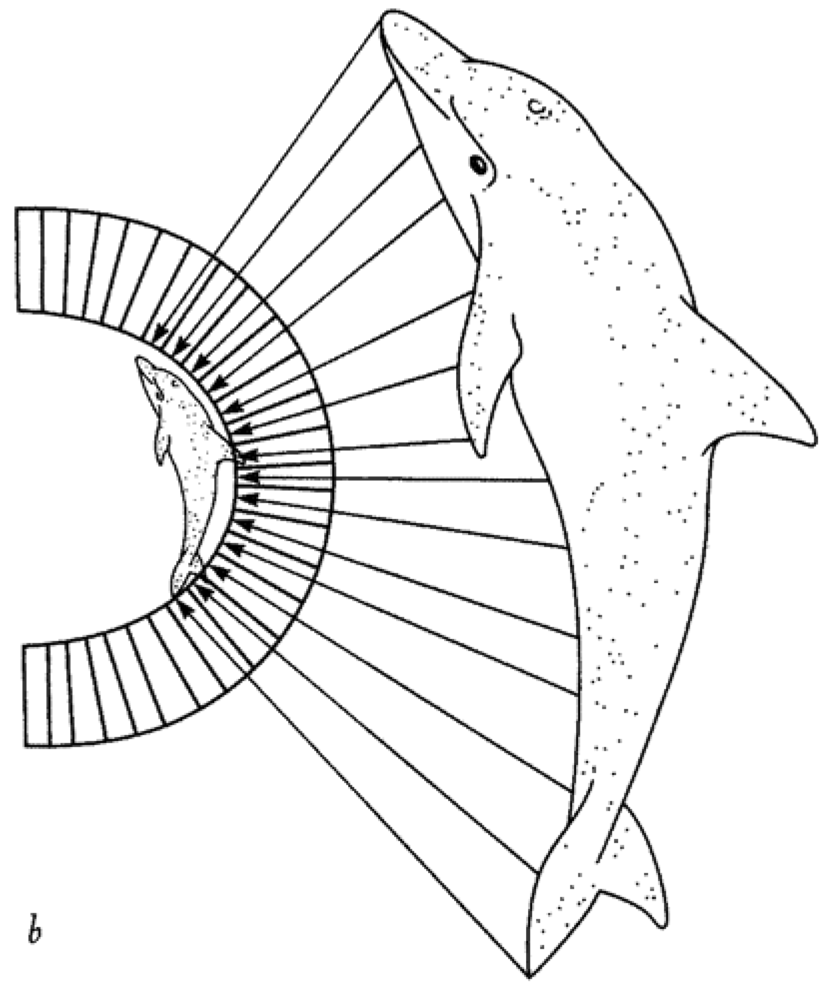
The retina is too small to see the whole projected image, so it constantly scans back and forth!




Next: Rightside-up image eyes

Apposition eye

- Like the cup eye earlier, but curved the other way.
- Unlike everything so far, this image is rightside-up!



For obvious reasons, it is very very rare for an eye with a rightside-up image to evolve from an eye with an upside-down image, or vice versa.

Apposition eye – details

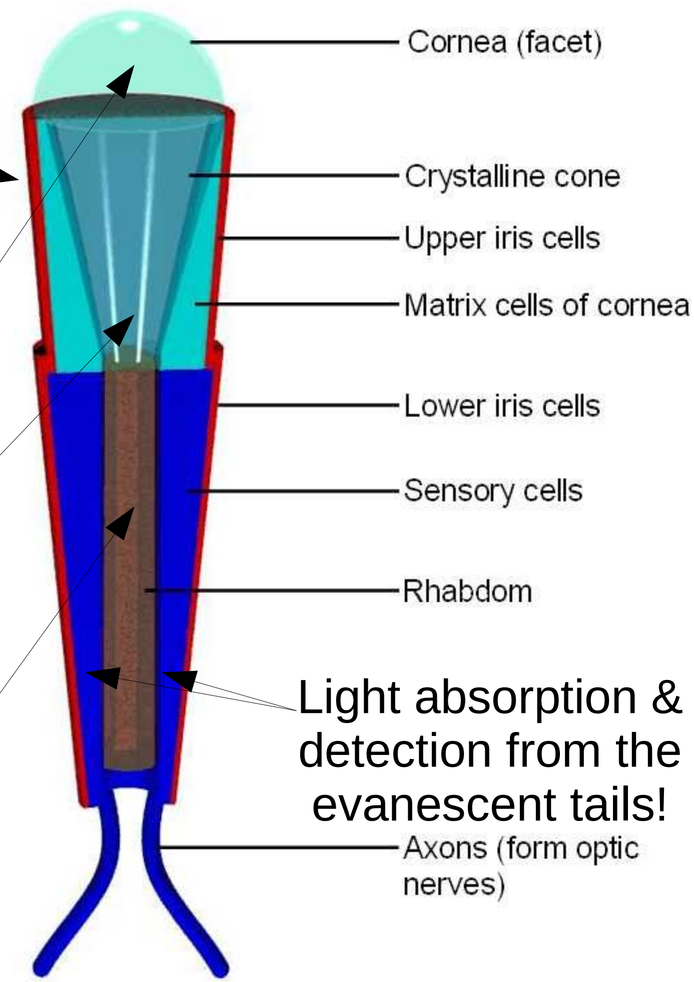
Thousands of little lenses. Each is the top of an ommatidium (“little eye”

“Screening pigment” (absorbing walls)

Biconvex lens

A second lens (gradient-index, immersion), made of crystallized protein.

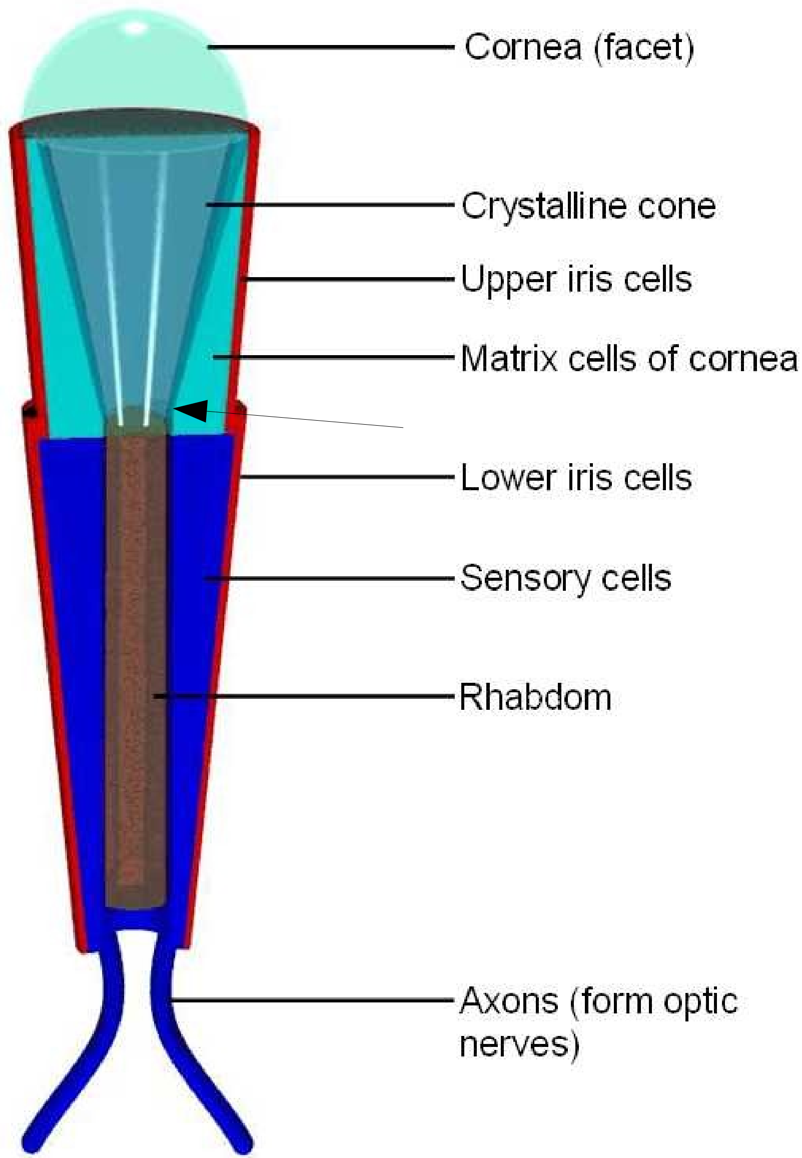
Optical waveguide



Light absorption & detection from the evanescent tails!

Structure of an ommatidium

Apposition eye – “pupil”



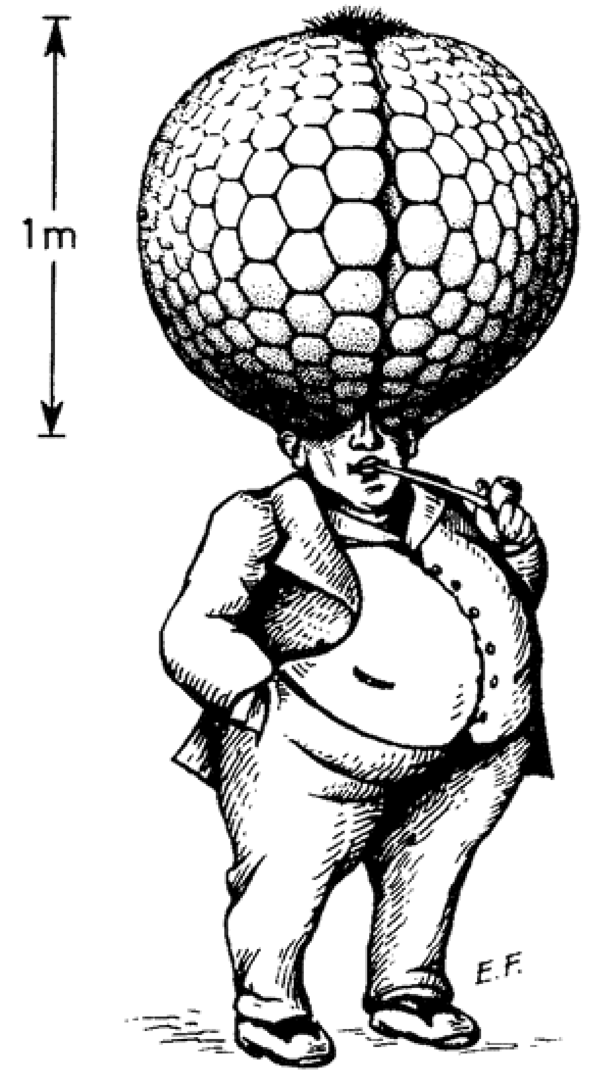
Structure of an ommatidium

In bright light, pigment granules are pumped in to scatter / absorb the higher-order waveguide modes. Only the fundamental mode gets detected. So angle sensitivity goes up as a nice side-effect.

Apposition eye – analysis

- N ommatidia → N-“pixel” image
  - To match human eye resolution, an apposition eye would need to be *meters* in diameter!!
- Infinite depth-of-field
  - Due to small apertures

1 hexagon =
10,000 ommatidia

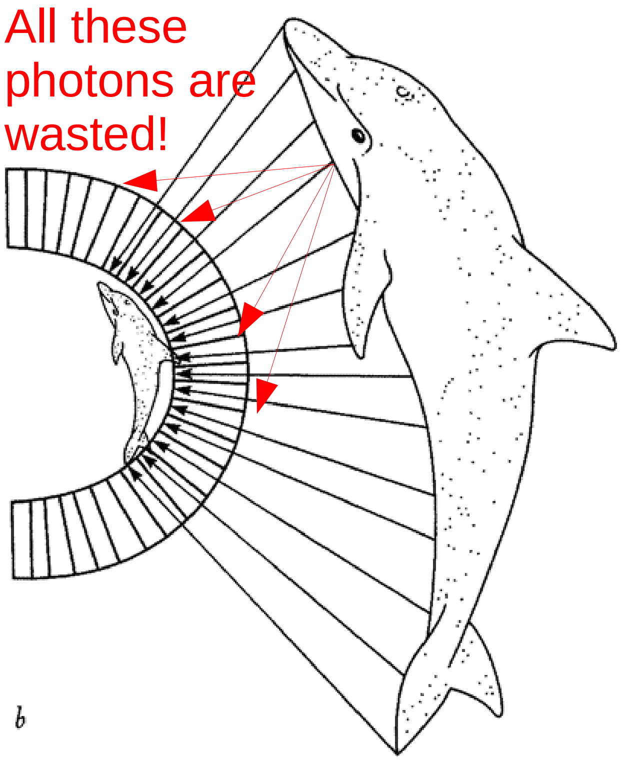


Apposition eye – analysis

- Exceptionally thin – important for small animals
  - e.g. fruit fly's eye is an 80um-thick layer.
- Exceptionally wide-angle, with uniform properties in whole visual field
  - (…or non-uniform if you want)

Apposition eye – analysis

- This is for daytime: Each "pixel" absorbs only the light hitting that lenslet from the right direction



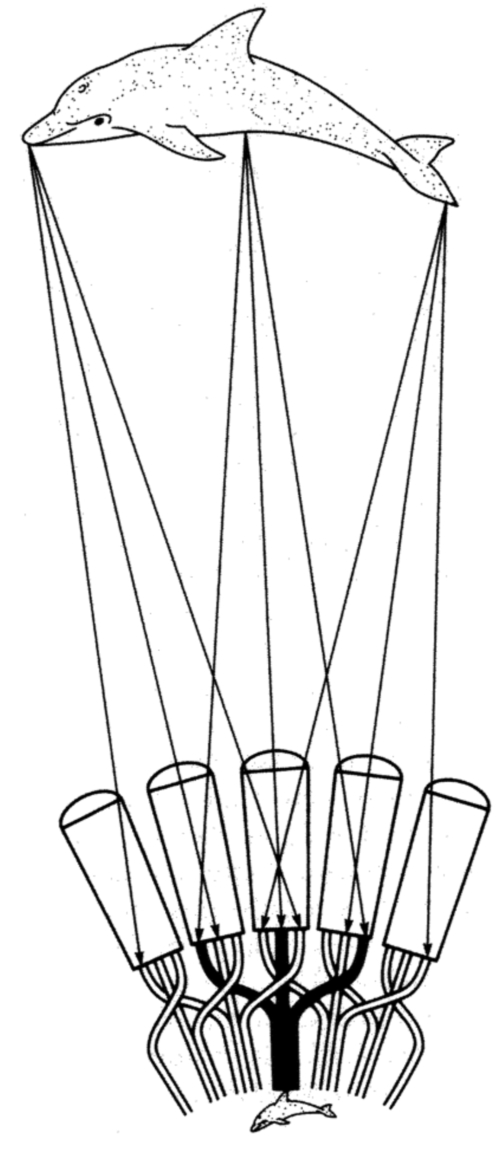
- One trick: Drain the "screening pigment" to make the walls between ommatidia semitransparent at night. This increases signal while blurring the image.

“Superposition” compound eyes

- Goal: Detect more photons, without sacrificing resolution
- The main types:
  - Neural superposition
  - True superposition
    - Refractive
    - Reflective

“Neural superposition” eyes

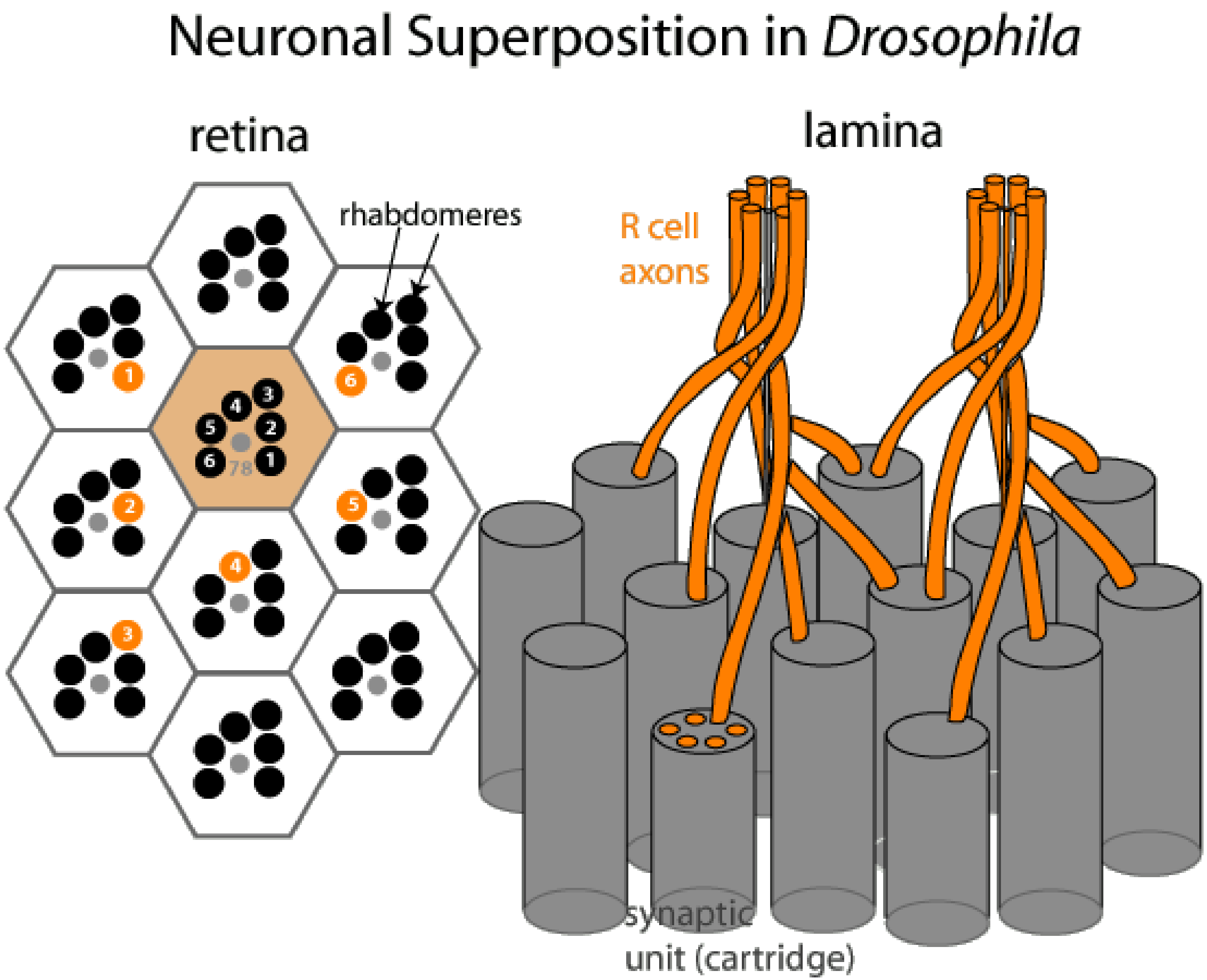
Make overlapping mini-images, and add up the signals in the areas of overlap!



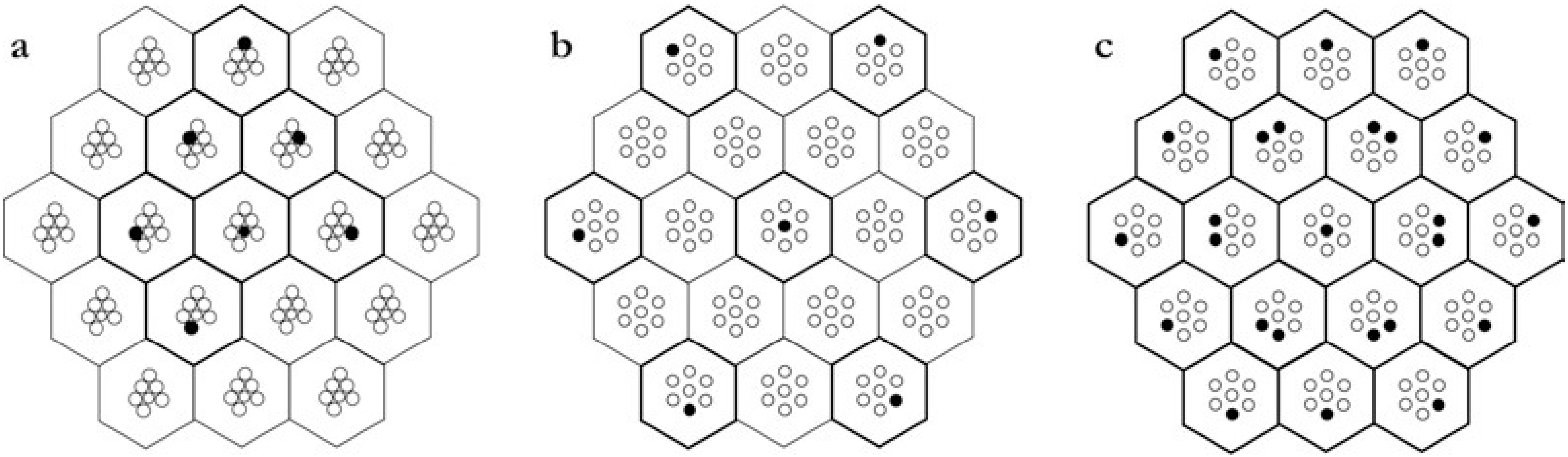
“Neural superposition” eyes

Each ommatidium has seven waveguides.

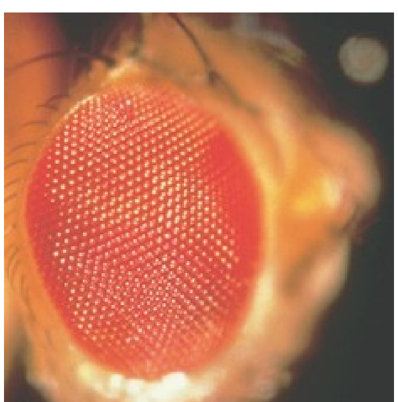
Thus, 7X more photons without losing resolution.



“Neural superposition” eyes



(a) advanced flies, (b) male bibionids and (c) chaoborid midges



True superposition eyes

mayflies, lacewings, beetles, moths, caddises, various crustaceans

Various crustaceans

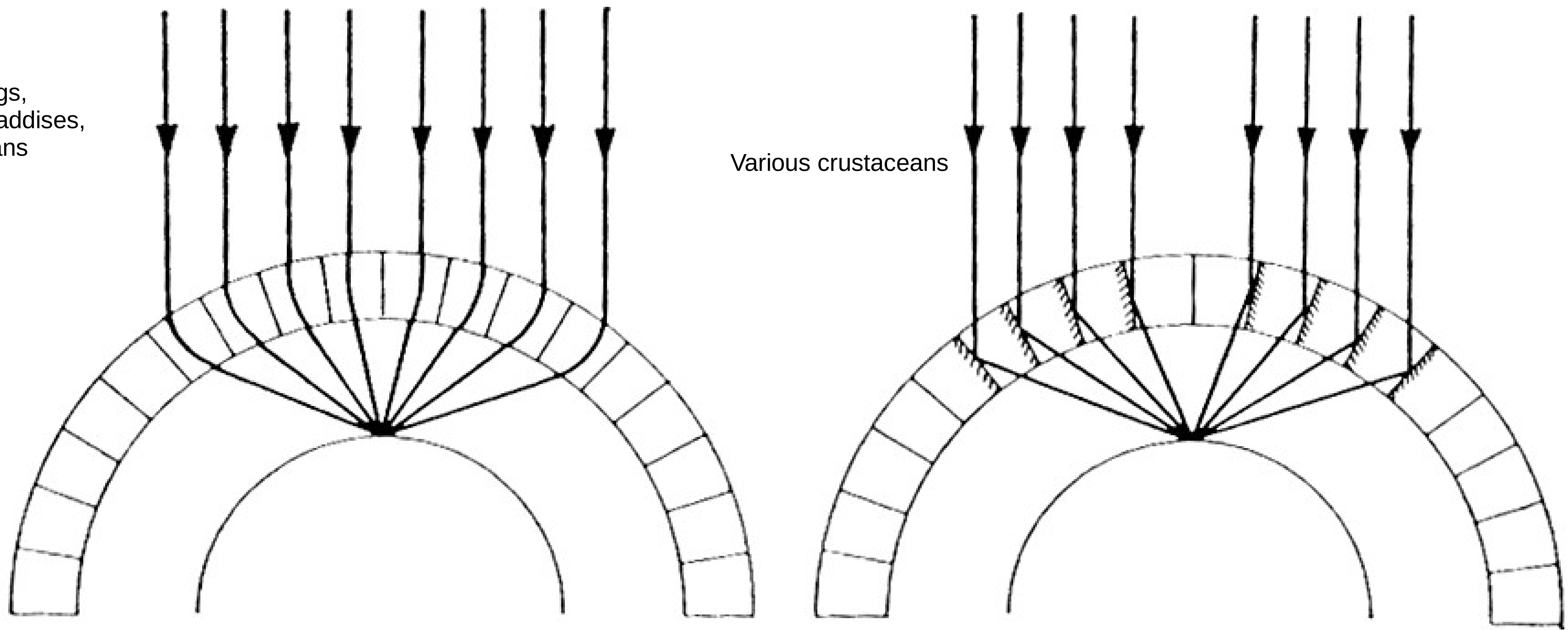
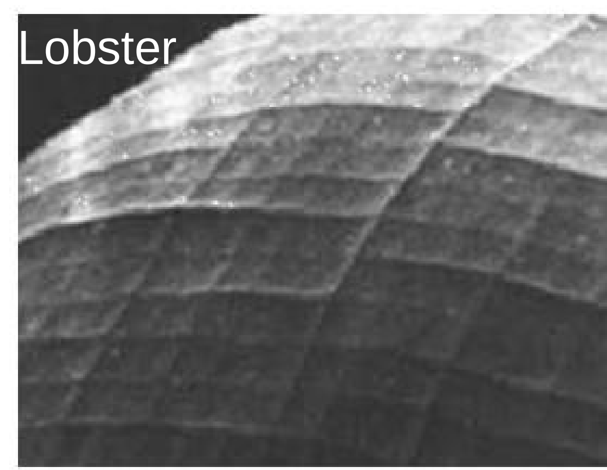


Fig. 8.14 Comparison of ray paths in a refracting (a) and reflecting (b) superposition eye. Both redirect the rays as required by Fig 8.3.

This time light comes from dozens or even hundreds of facets – great for night vision.

Note: Right-side-up image!



True superposition eyes

mayflies, lacewings,
beetles, moths, caddises,
various crustaceans

Various crustaceans

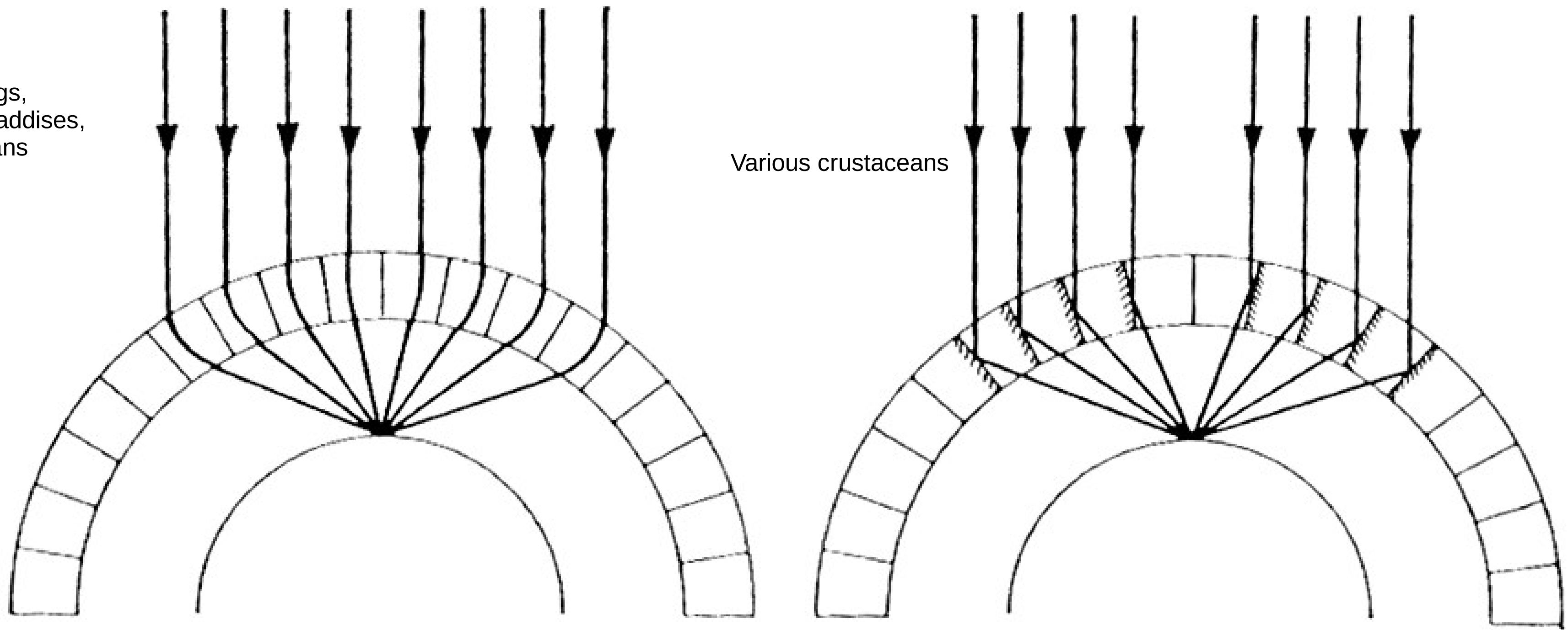


Fig. 8.14 Comparison of ray paths in a refracting (a) and reflecting (b) superposition eye. Both redirect the rays as required by Fig 8.3.

“Clear zone” - takes up space

For an optics-based analysis of why very small animals cannot have superposition eyes:
DOI: 10.1016/j.visres.2004.04.009

In some animals, you have apposition eyes at birth, superposition in adulthood!

2013: Biomimetic apposition eye

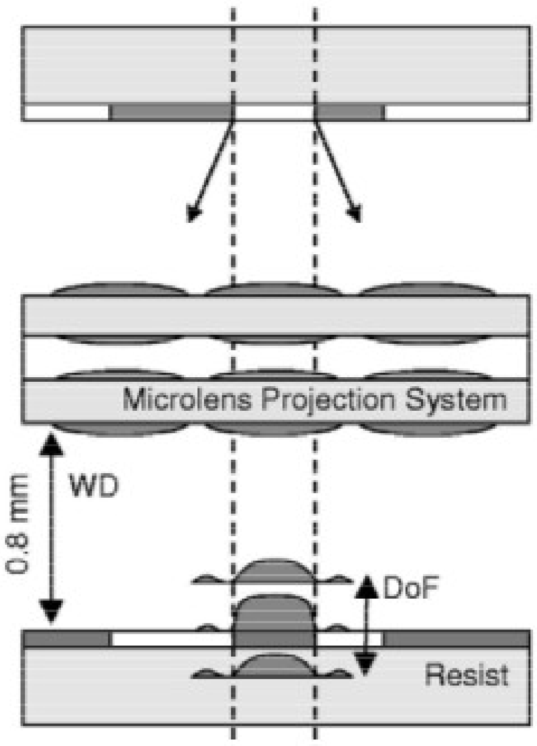
LETTER

doi:10.1038/nature12083

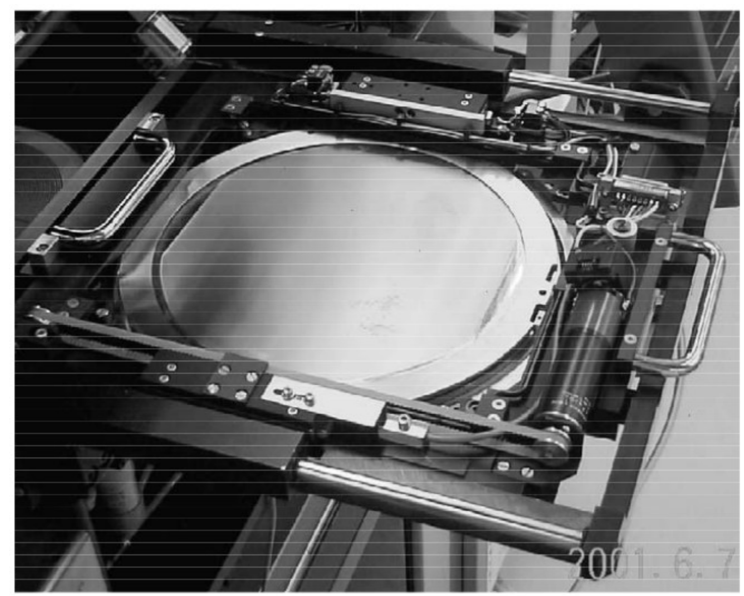
Digital cameras with designs inspired by the arthropod eye

Young Min Song[1]*, Yizhu Xie[1]*, Viktor Malyarchuk[1]*, Jianliang Xiao[2]*, Inhwa Jung[3], Ki-Joong Choi[4], Zhuangjian Liu[5], Hyunsung Park[6], Chaofeng Lu[7,8], Rak-Hwan Kim[1], Rui Li[8,9], Kenneth B. Crozier[6], Yonggang Huang[8] & John A. Rogers[1,4]

SUSS MA150-MPL mask aligner is a bit like a superposition eye



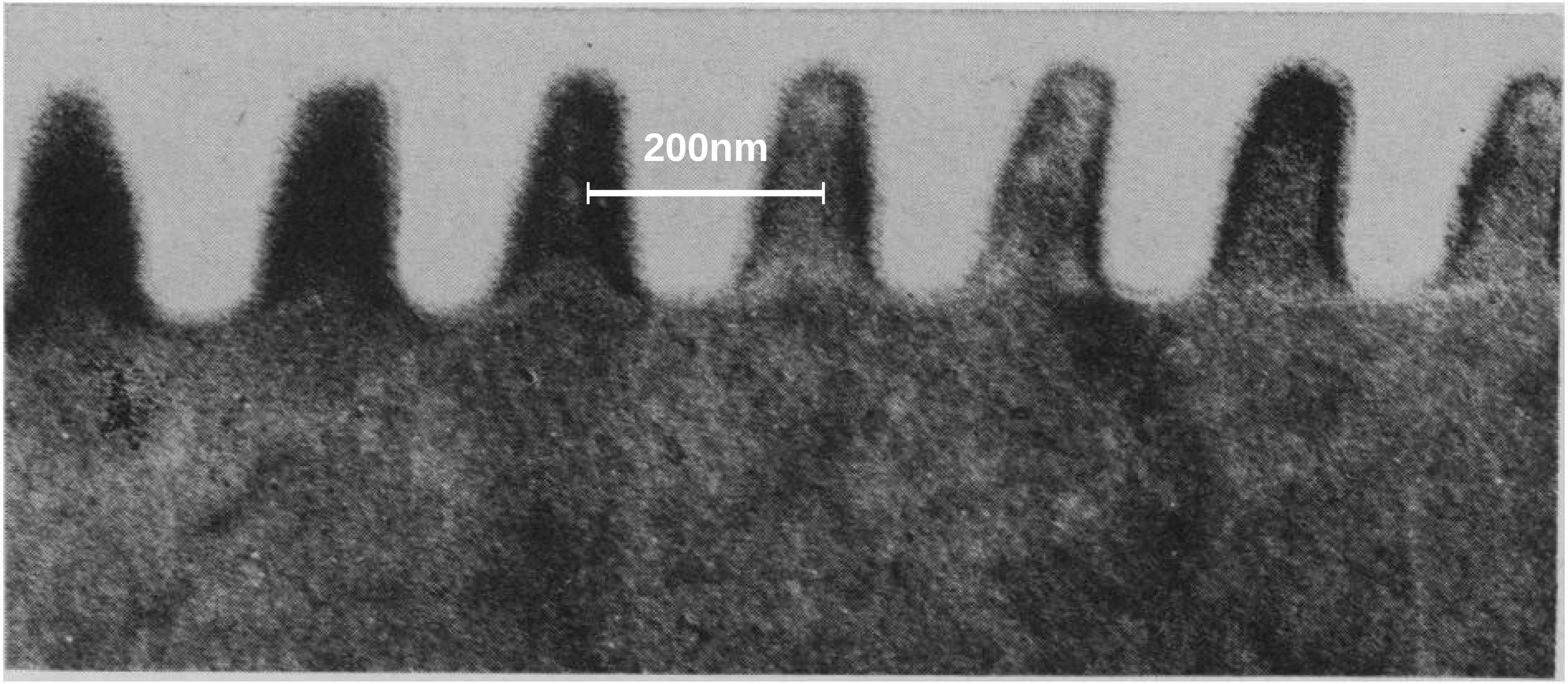
"...Each micro-objective images a small part of the photomask pattern onto the wafer. The partial images from different channels overlap consistently and form a complete aerial image of the photomask..."



"Fig. 10. Ultra-flat projection system integrated into the SUSS MA150-MPLA mask aligner."

"Miniaturized Imaging Systems", 2003,
doi:10.1016 / S0167-9317(03)00102-3

AR coatings

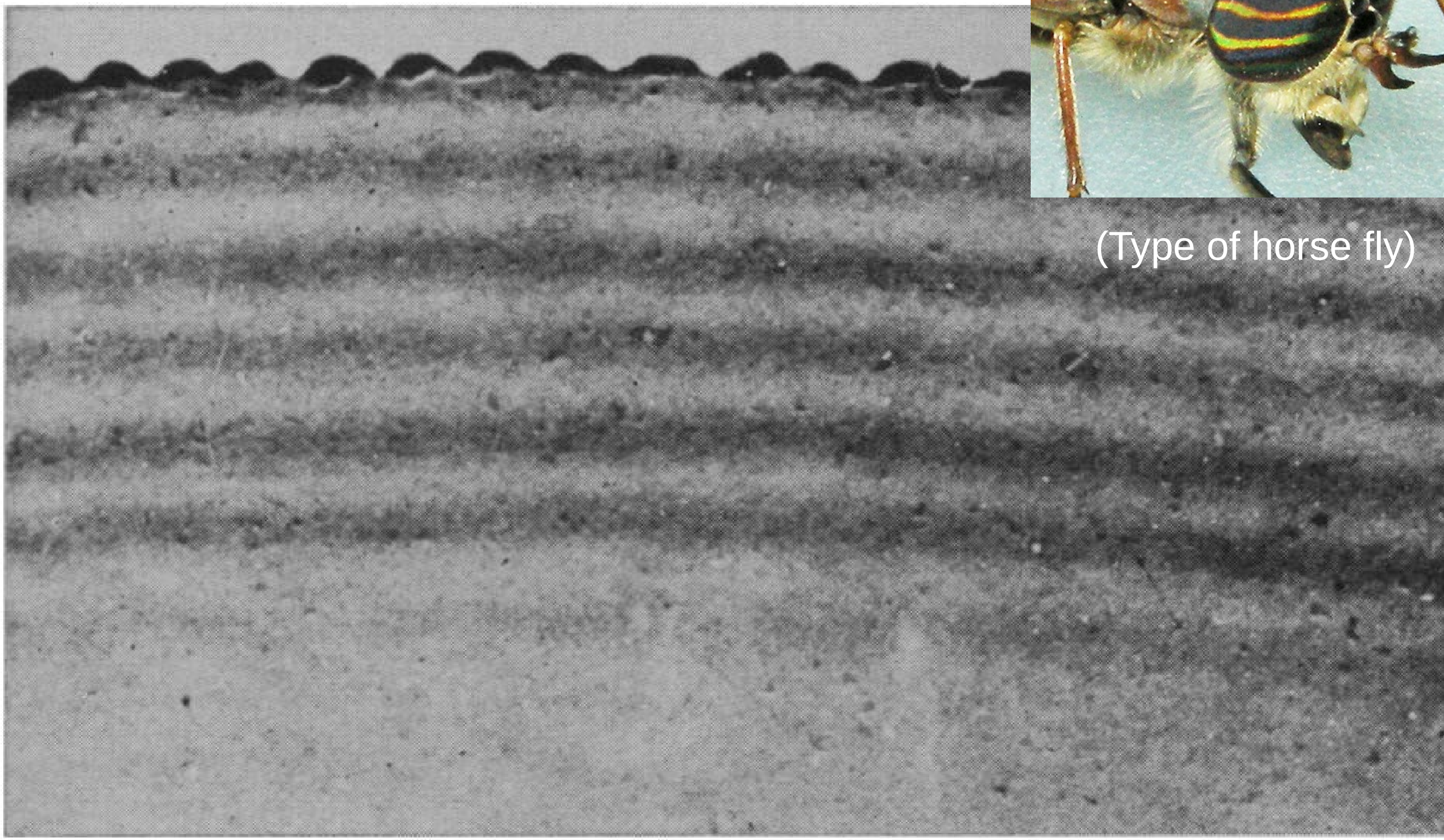


“Corneal nipples” in
a monarch butterfly

Why?
(A) 5% more transmission.
(B) 1000× less reflection

This Bragg filter is thought to reduce cross-talk between ommatidia, if I understand correctly.

AR coatings



(Type of horse fly)

Fig. 11. Electron micrograph of section taken normal to corneal surface from a bright facet of *Hybomitra lasiophthalma*. Dense layers are about 0.089 micrometer thick, rare layers about 0.112 micrometer thick. The set of dense and rare layers functions as a transmission interference-filter. [From (*26*)]