Human Vision: Anatomy & Physiology

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Alexei Efros, CS 280, Spring 2024

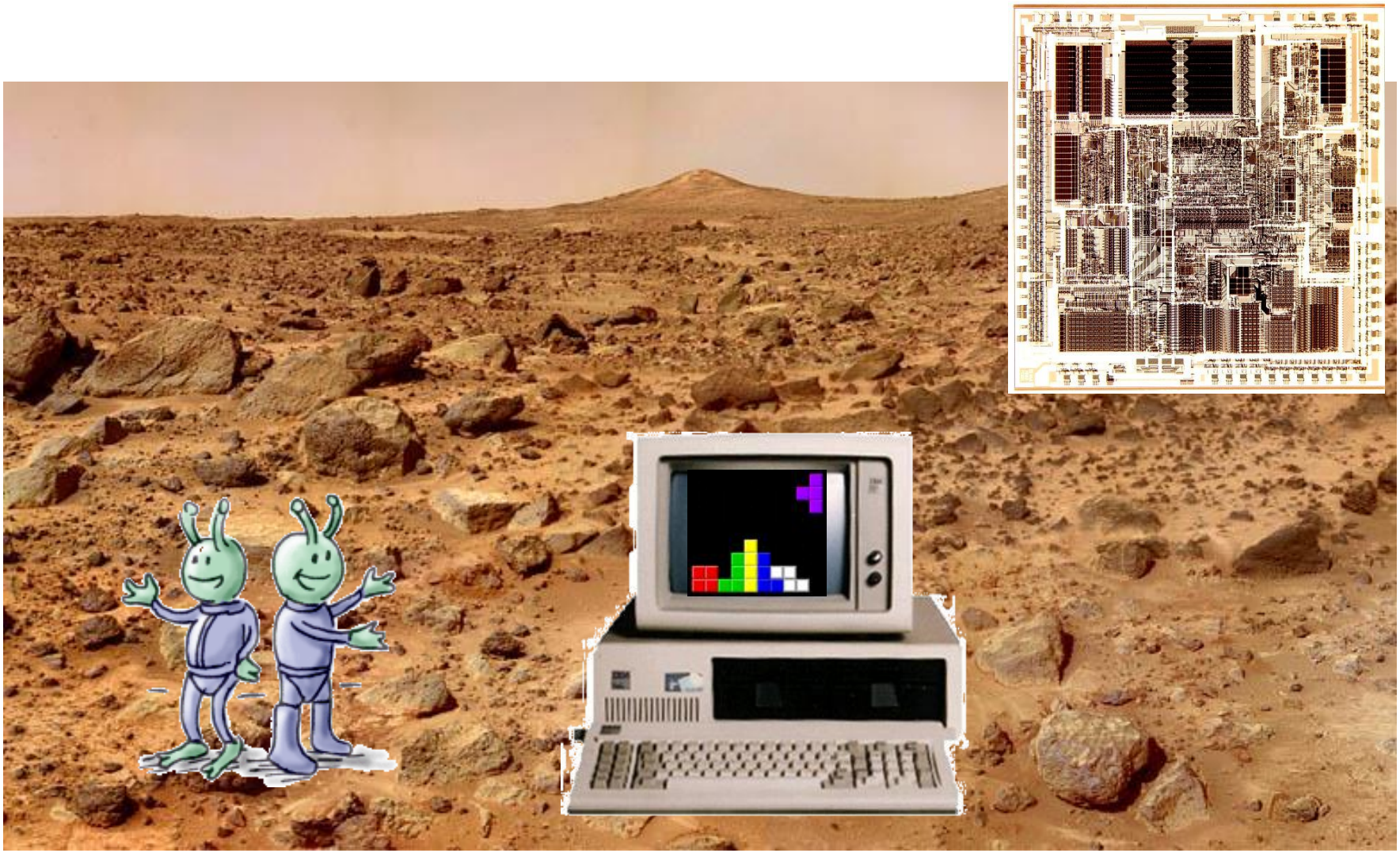
Understanding the Brain

Anatomy versus Physiology

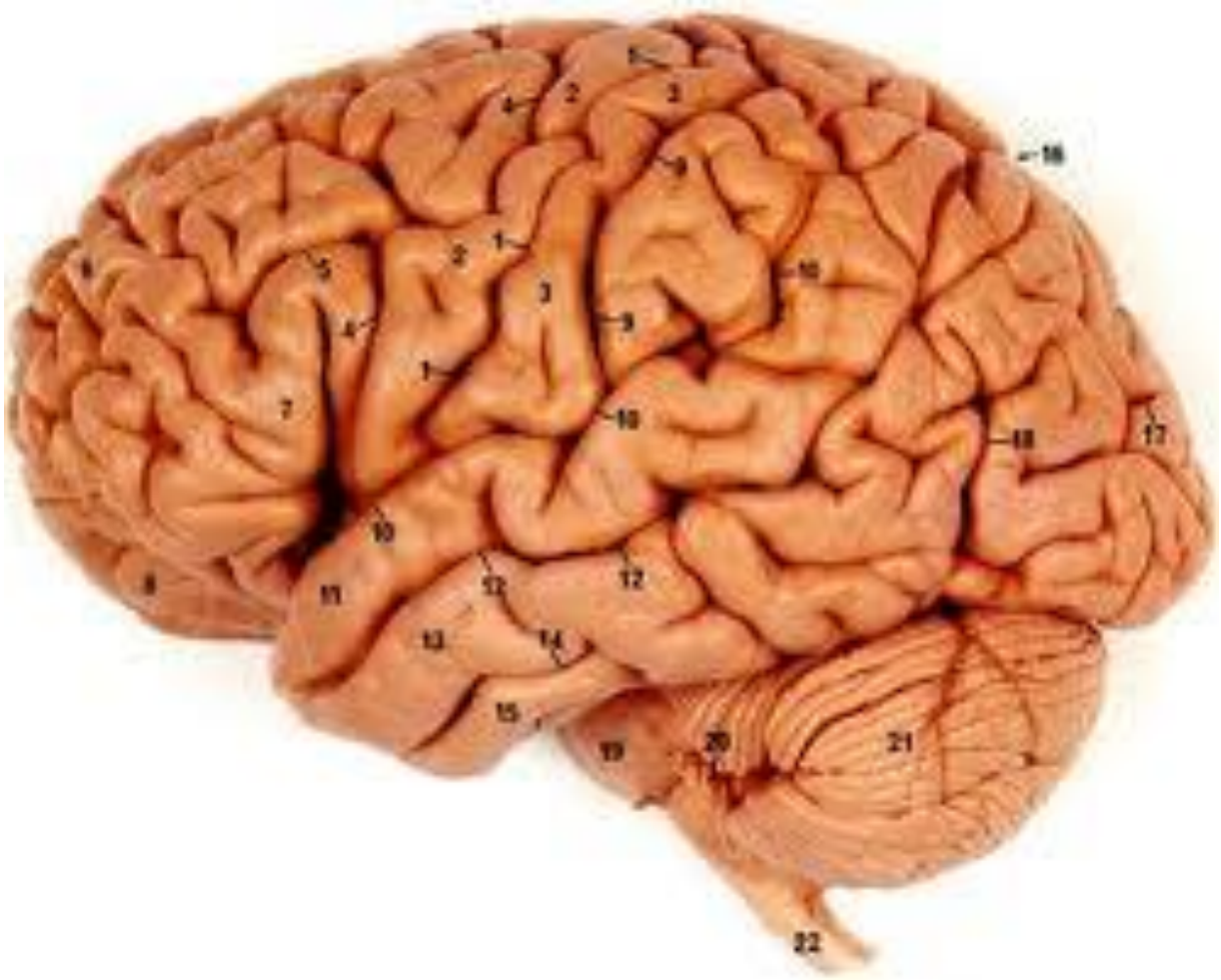
Anatomy: The biological study of the physical structure of organisms.

Physiology: The biological study of the functional structure of organisms.

Tale of Martians with an old PC

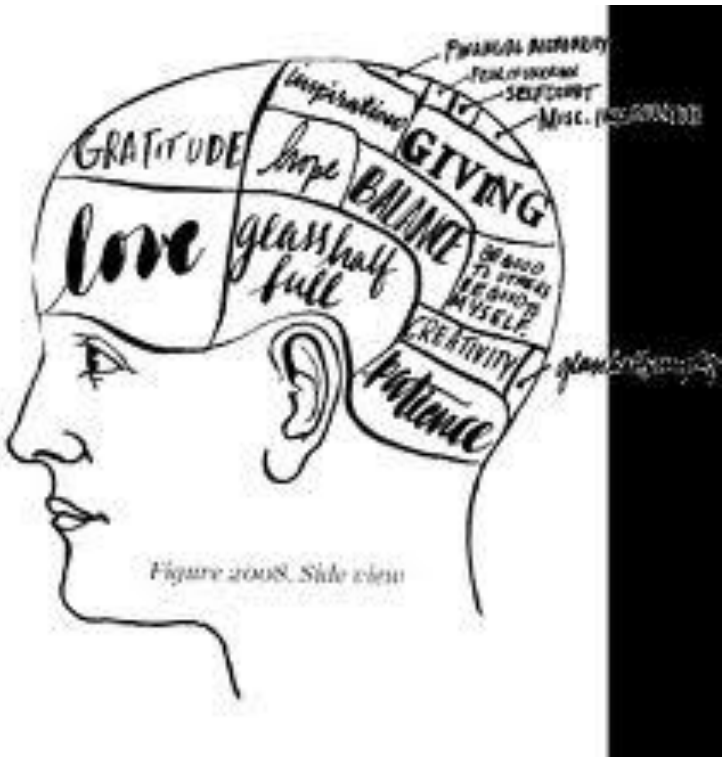


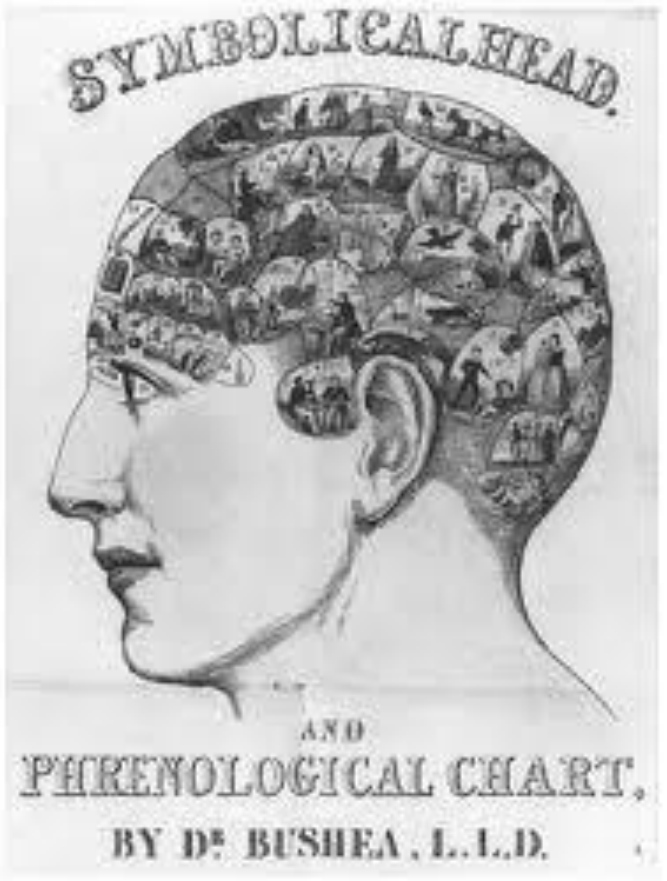
The Brain is tricky business



- Aristotle thought it's for cooling the blood
- Localized or distributed?

Phrenology





One of the first application of statistics

This is how bad Machine Learning got started…

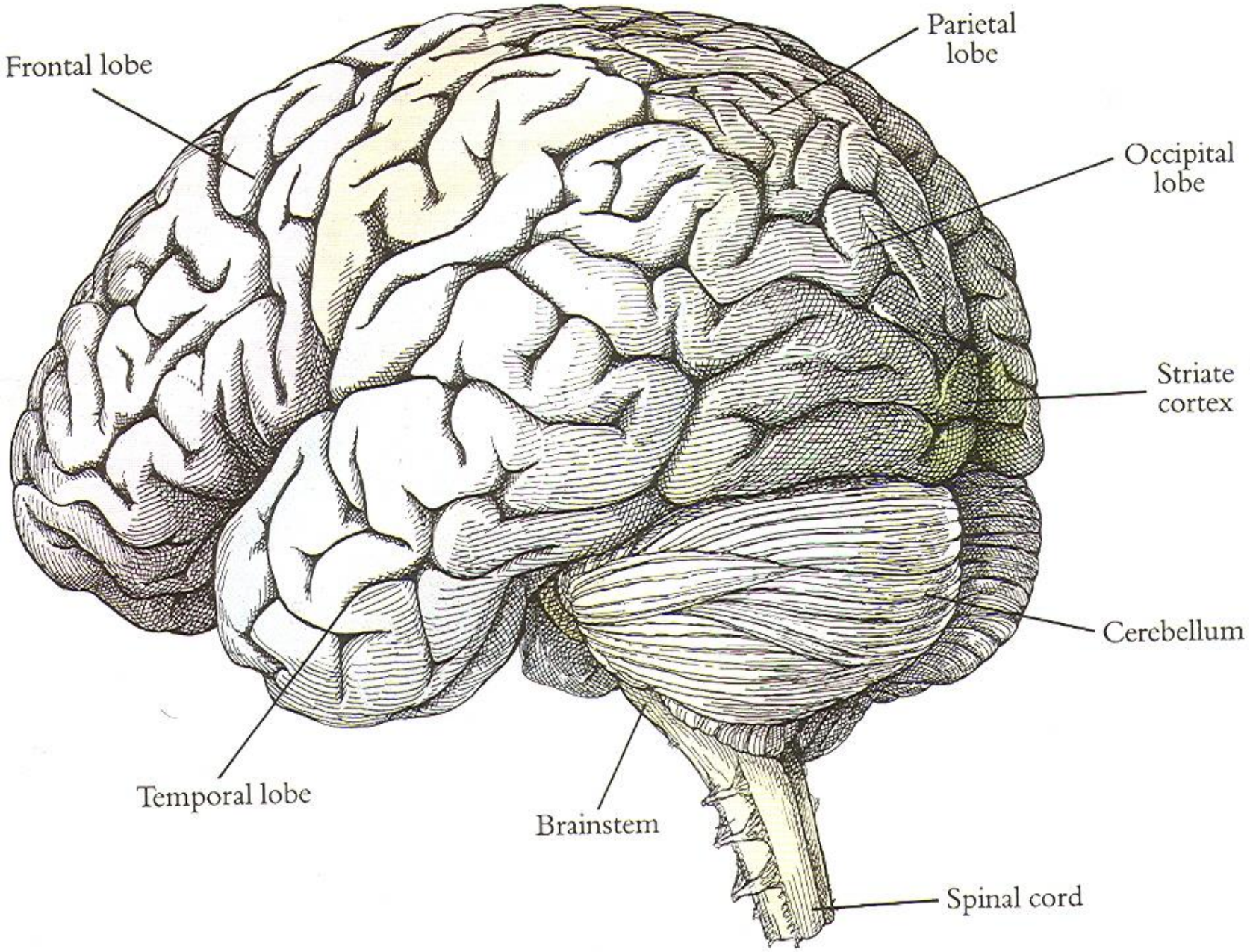
Localized or Distributed?

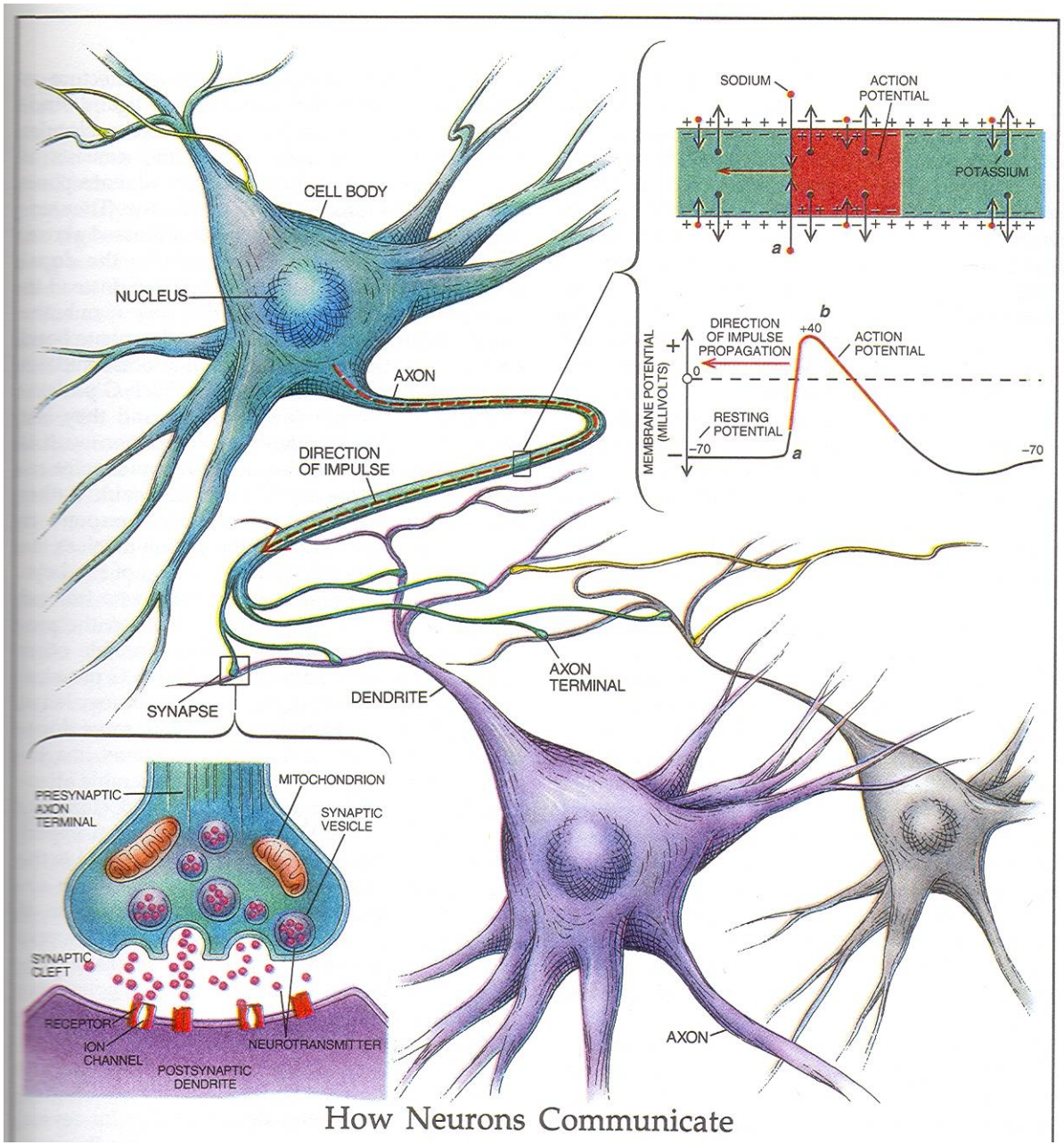
Evidence from patients with partial brain damage

- Lots of useful data from soldiers in the Russo-Japanese war

But also evidence for distributed nature of processing

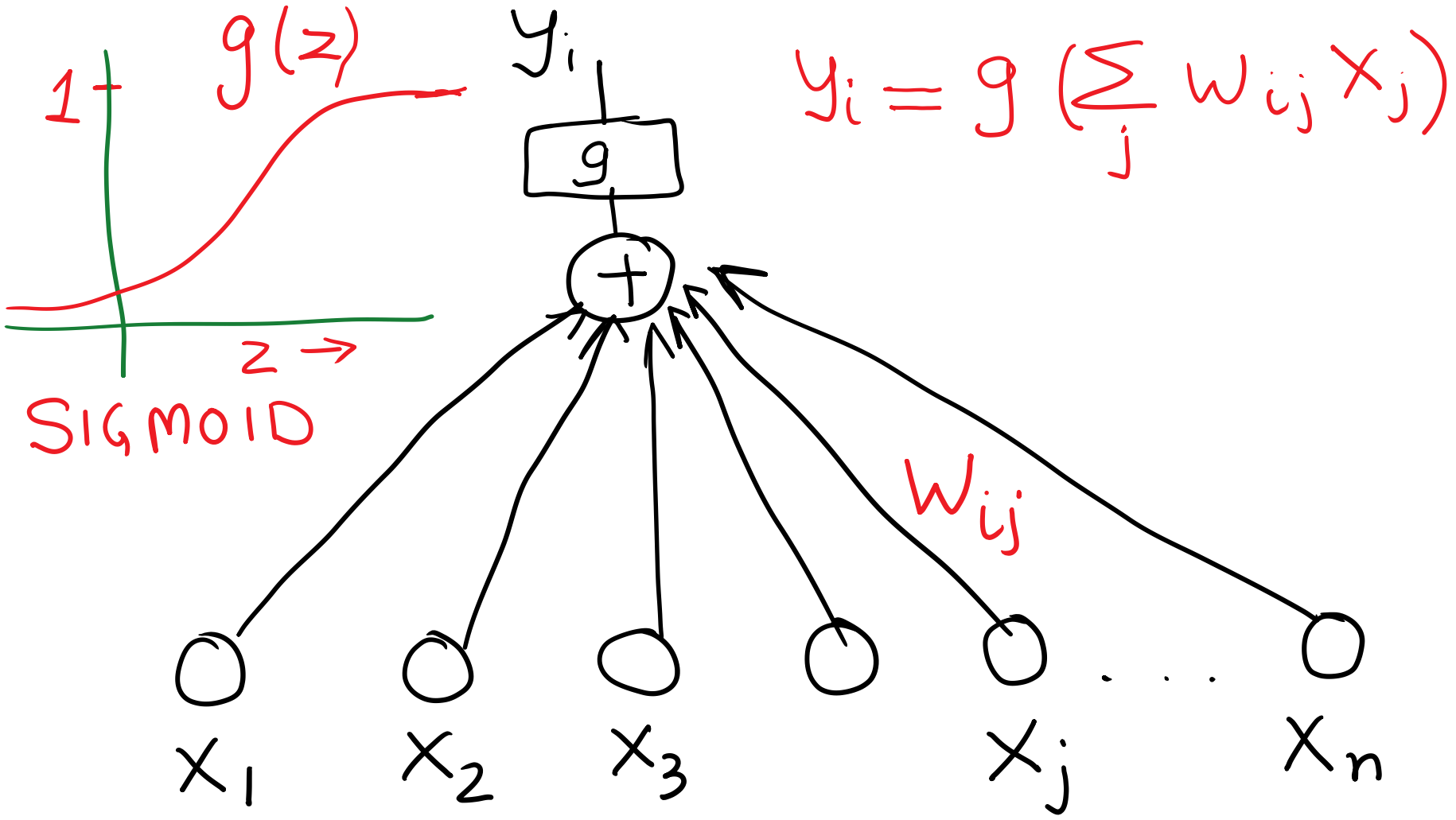
- E.g. [Lashley] showed “graceful degradation” of memory performance in rats


Frontal lobe
Parietal lobe
Occipital lobe
Striate cortex
Cerebellum
Temporal lobe
Brainstem
Spinal cord



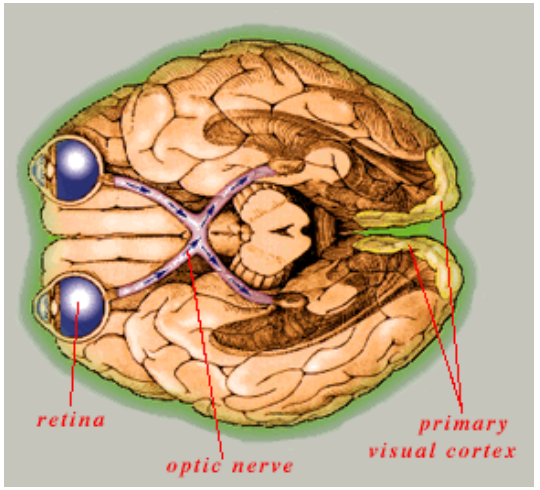
How Neurons Communicate

Mathematical Abstraction



The Visual System

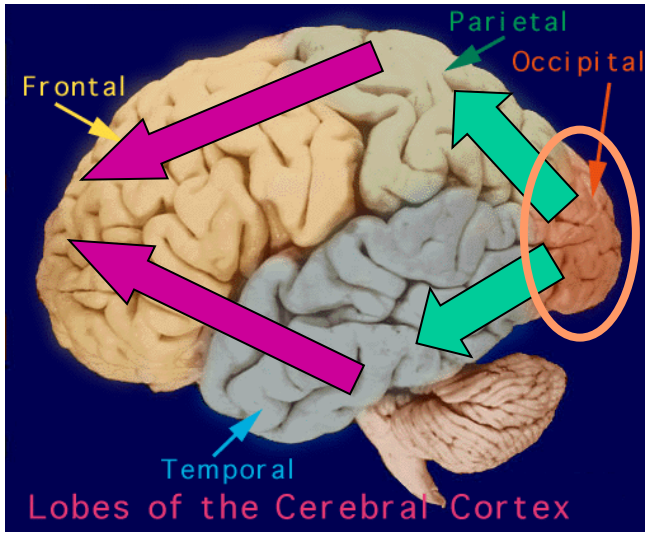
Both eye and brain are required for functional vision



Two kinds of blindness:

- Normal blindness (eye dysfunction)
- Cortical blindness (brain dysfunction)

The Visual System



Eyes register optical information

Pathways to occipital cortex

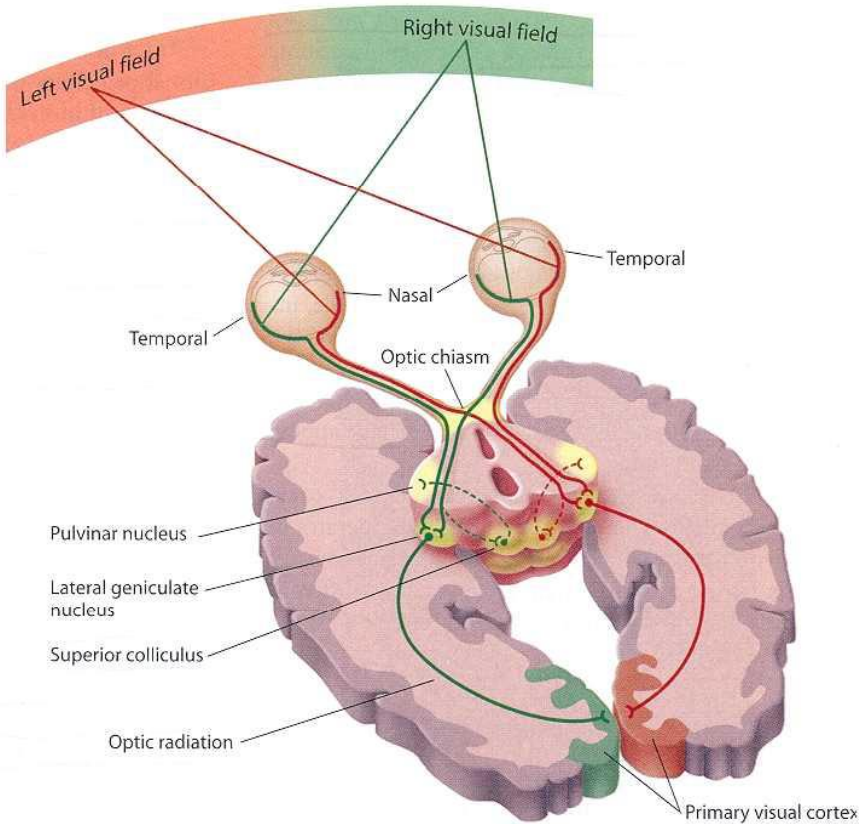
Two pathways from V1

- "What" pathway to temporal cortex
- "Where" pathway to parietal cortex

Convergence on frontal cortex

Pathways to the Brain

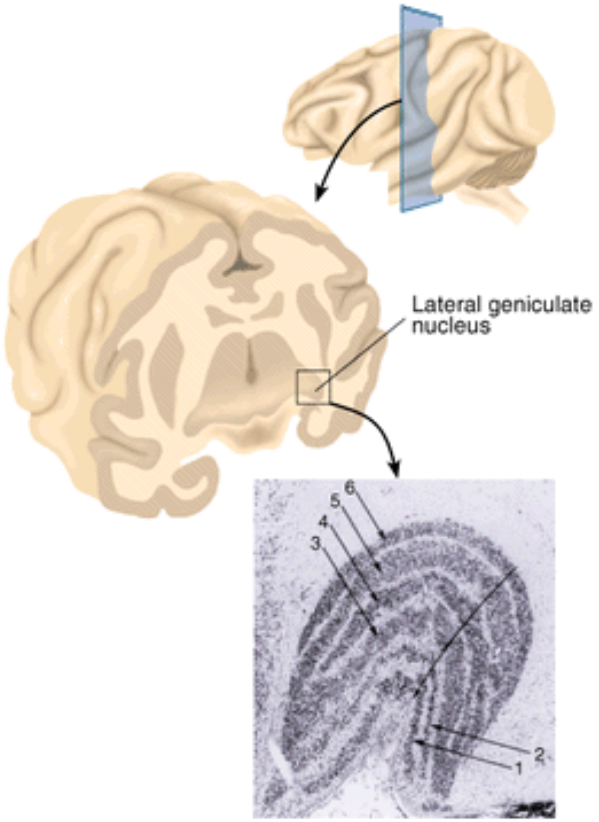
Anatomy of Pathway to Visual Cortex



Pathways to the Brain

The Lateral Geniculate Nucleus (LGN)

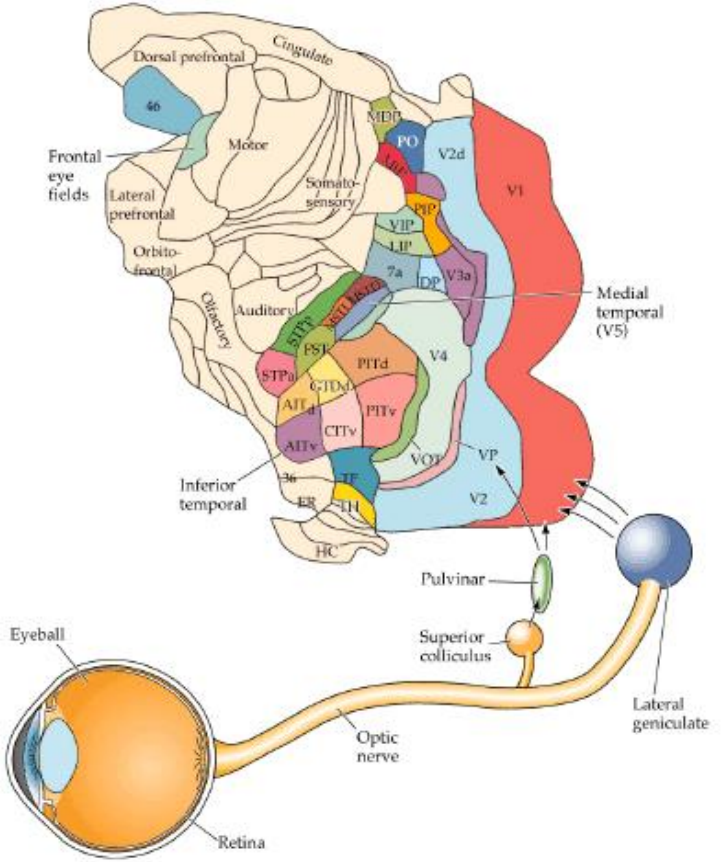
Waystation in Thalamus
Projections from both eyes
Six layers
Projects to cortical area V1



Visual Cortex

Map of Visual Areas in Cortex

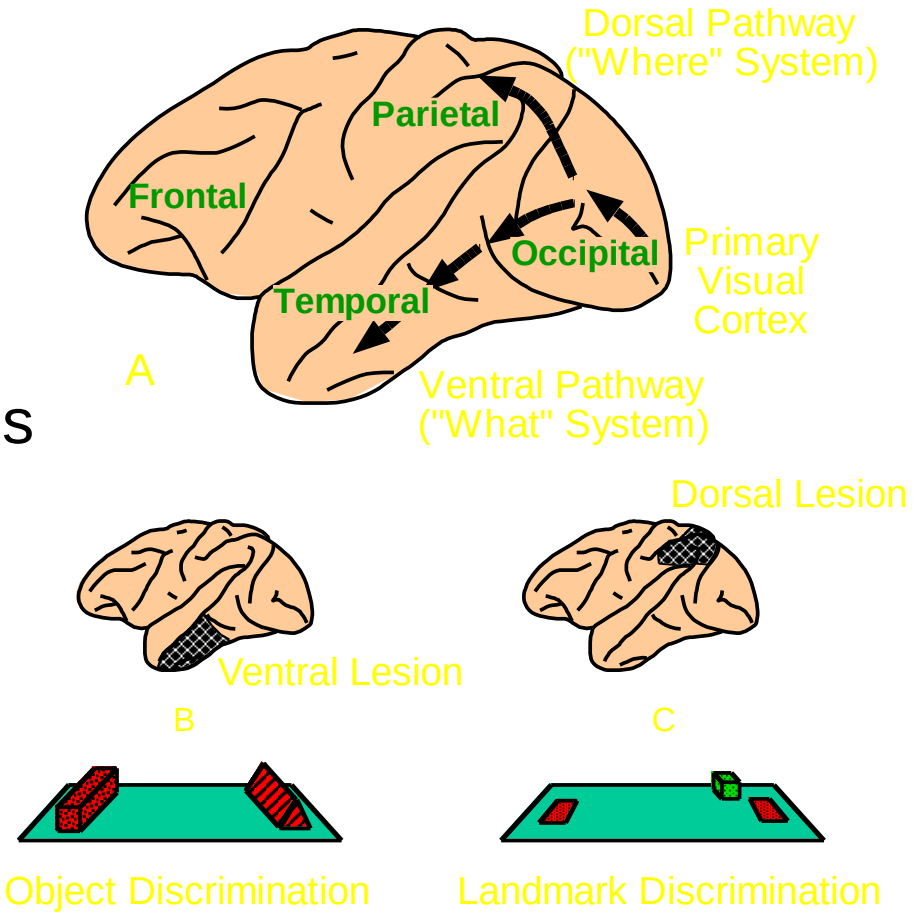
"Unfolded" view of visual areas in the macaque cortex (sizes not to scale).



Visual Cortex

What/Where Pathways

Evidence from lesions of monkey cortex



Visual Cortex

What/Where Pathways
Evidence from Neuropsychology

Visual agnosia:

- Inability to identify objects and/or people
- Caused by damage to inferior (lower) temporal lobe
- Disruption of the “what” pathway

Visual neglect:

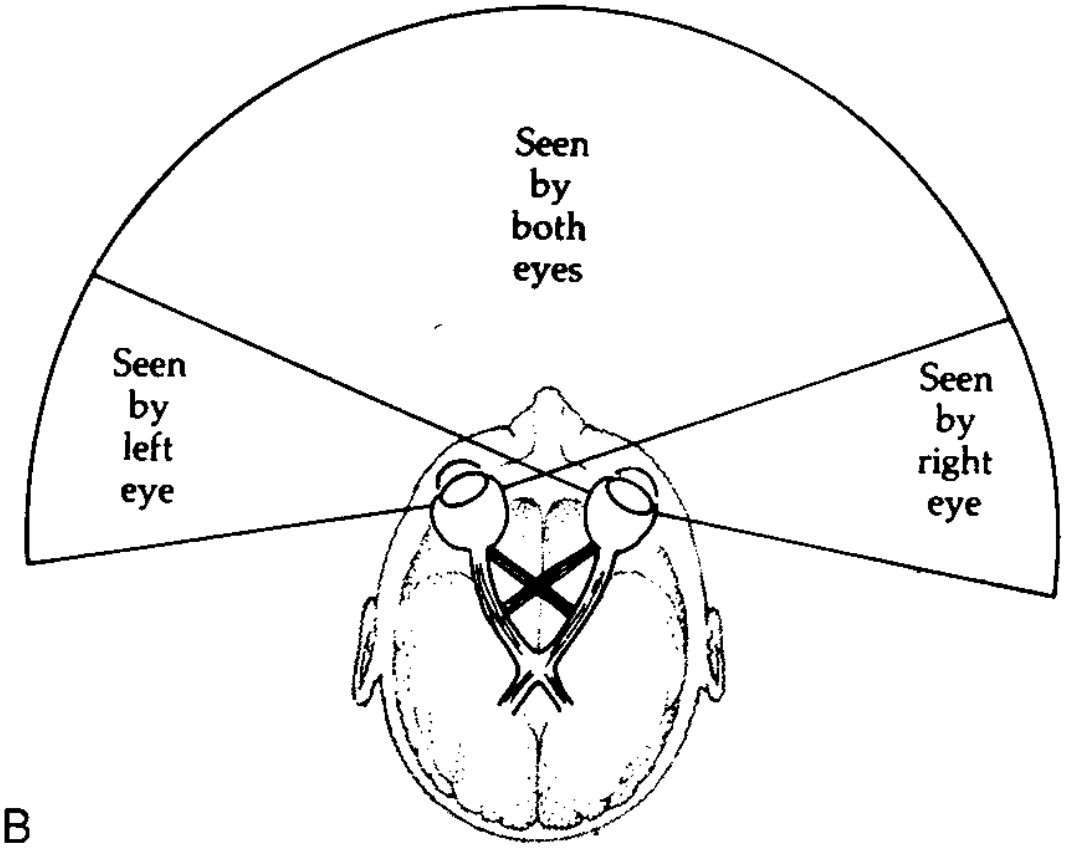
- Inability to see objects in the left visual field
- Caused by damage to right parietal lobe
- Disruption of the “where” pathway

The Gross Summary

The visual system is composed of many interactive functional parts:

- Eye (optics of image formation)
- Retina (light transduction)
- LGN (waystation?)
- Area V1 (hypercolumns)
- Higher cortical areas (features)
- Cortical pathways (what/where)

Monocular Visual Field: 160 deg (w) X 135 deg (h)
Binocular Visual Field: 200 deg (w) X 135 deg (h)

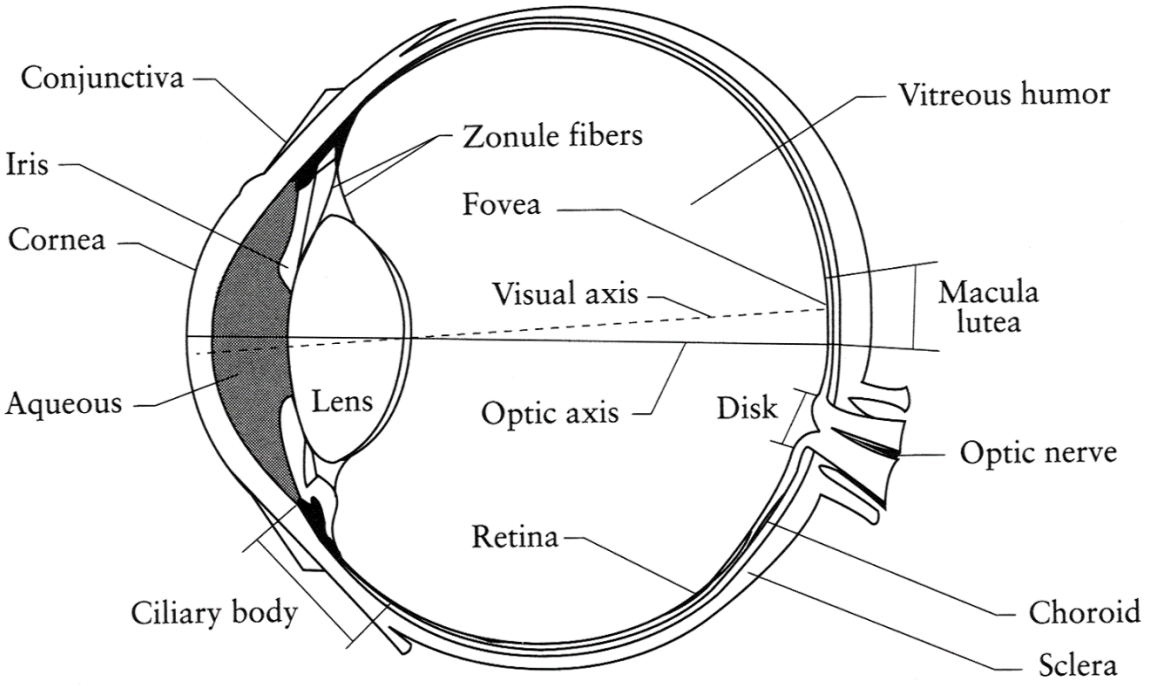


B

Ways to understand human vision

- Psychophysics
  - Present humans/animals with stimuli
  - Quantitatively measure perceptual response
- Electrophysiology
  - Stick probes into brains
  - Present stimuli
  - Quantitatively measure electrical response
- Imaging (e.g. fMRI)

The Eye

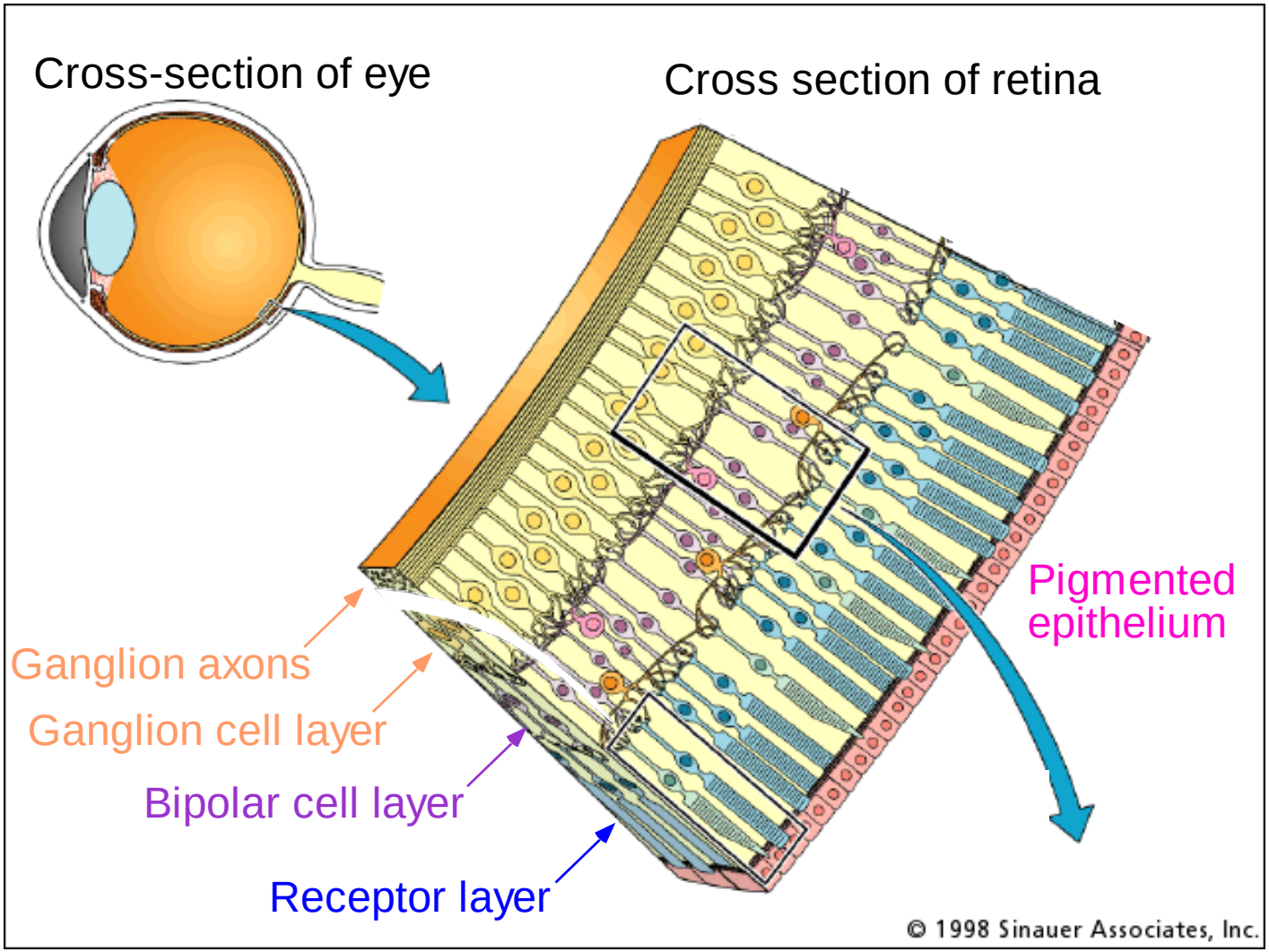


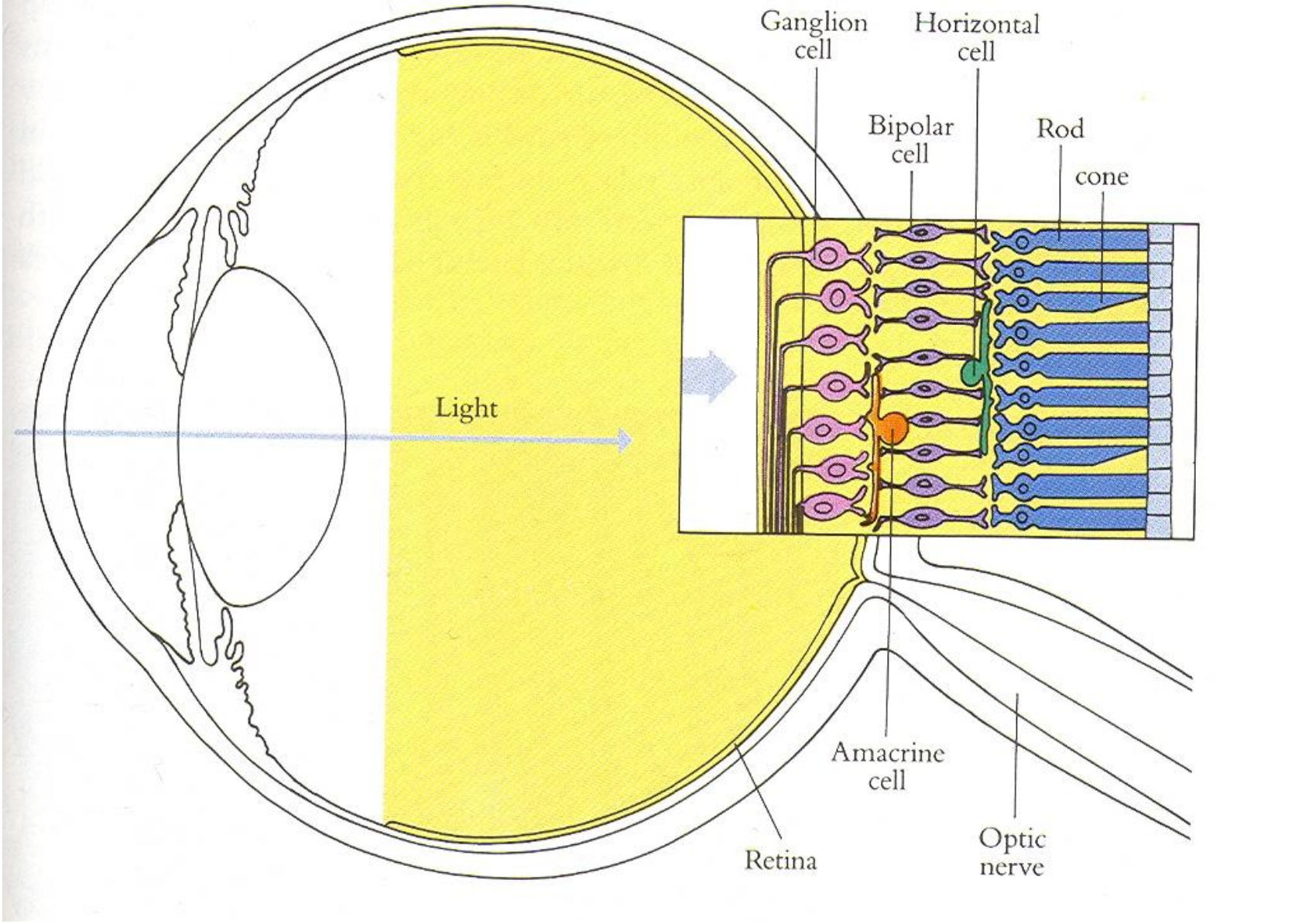
The human eye is a camera!

- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- What's the "film"?
  - photoreceptor cells (rods and cones) in the **retina**

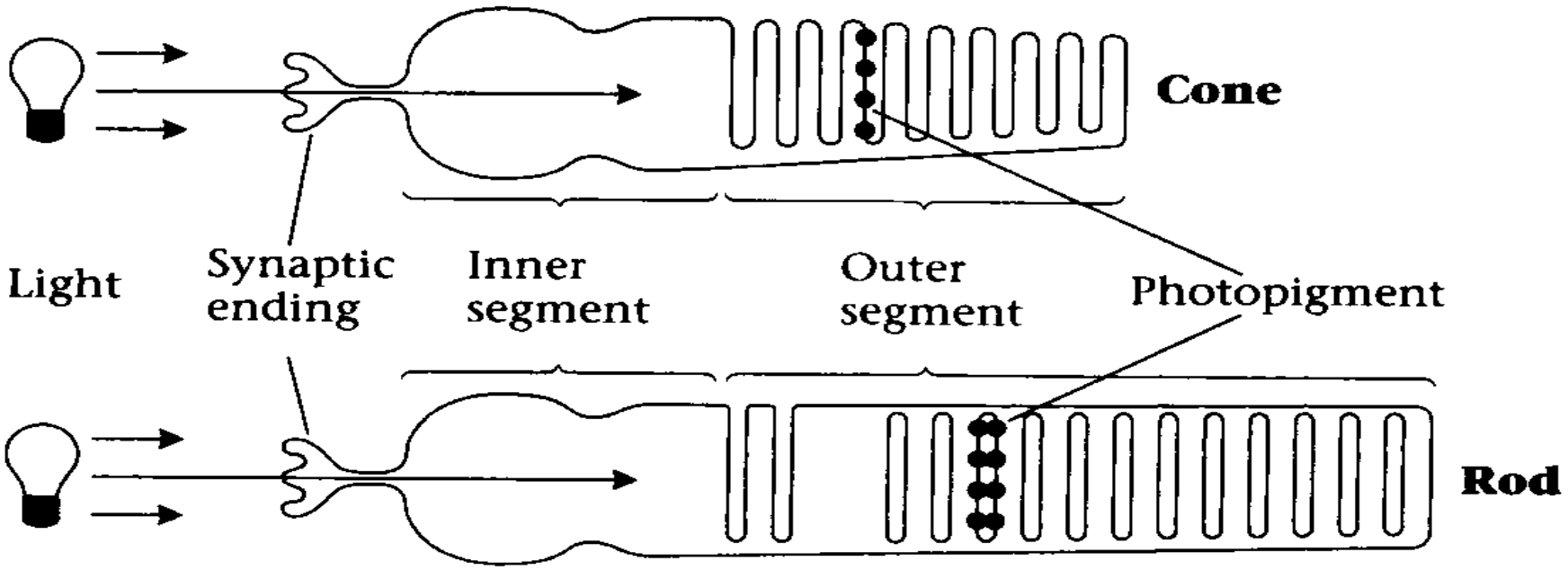
Slide by Steve Seitz

The Retina

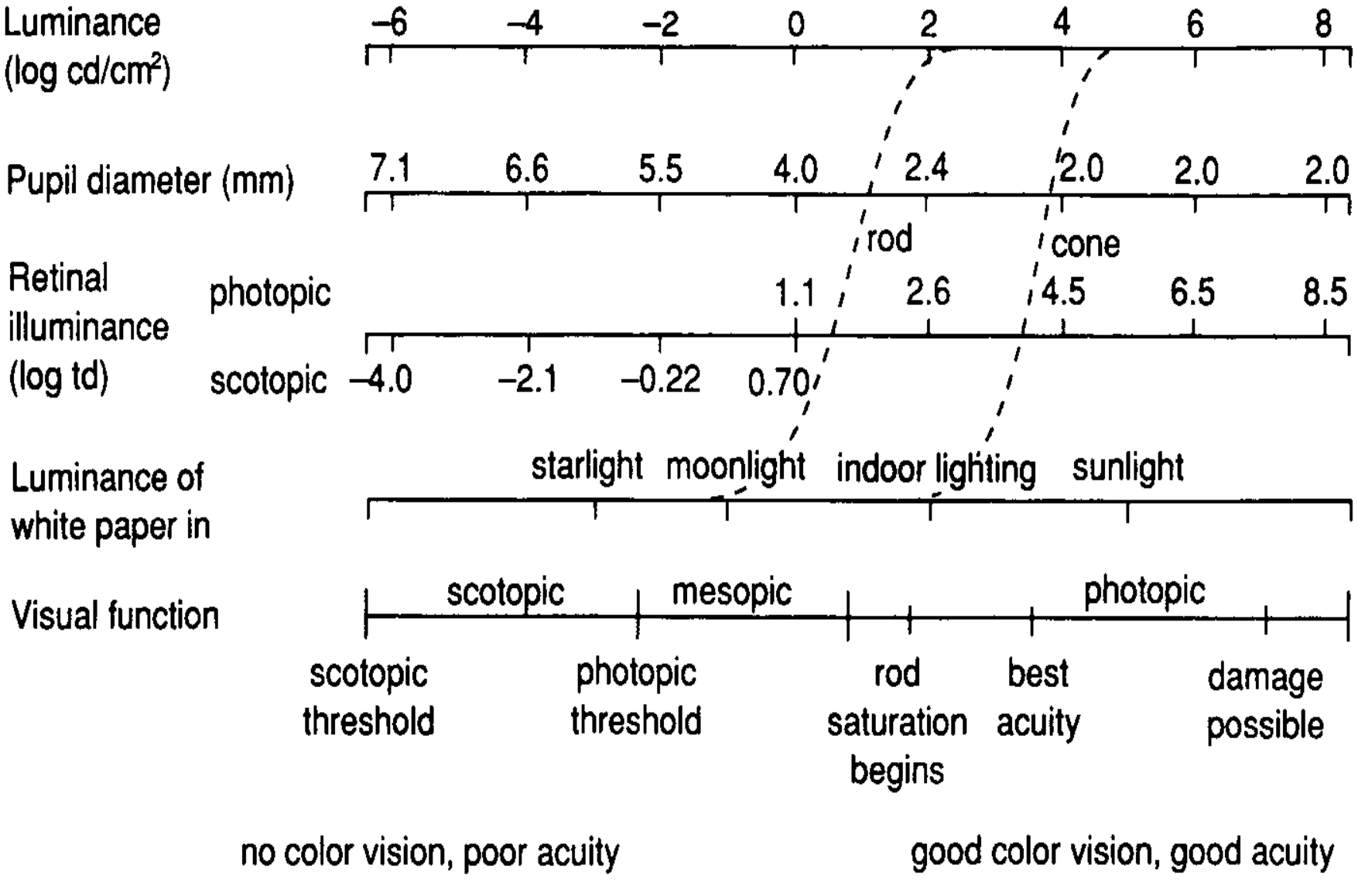

Cross-section of eye
Cross section of retina
Pigmented epithelium
Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer
© 1998 Sinauer Associates, Inc.


Ganglion cell
Horizontal cell
Bipolar cell
Rod
cone
Light
Amacrine cell
Retina
Optic nerve

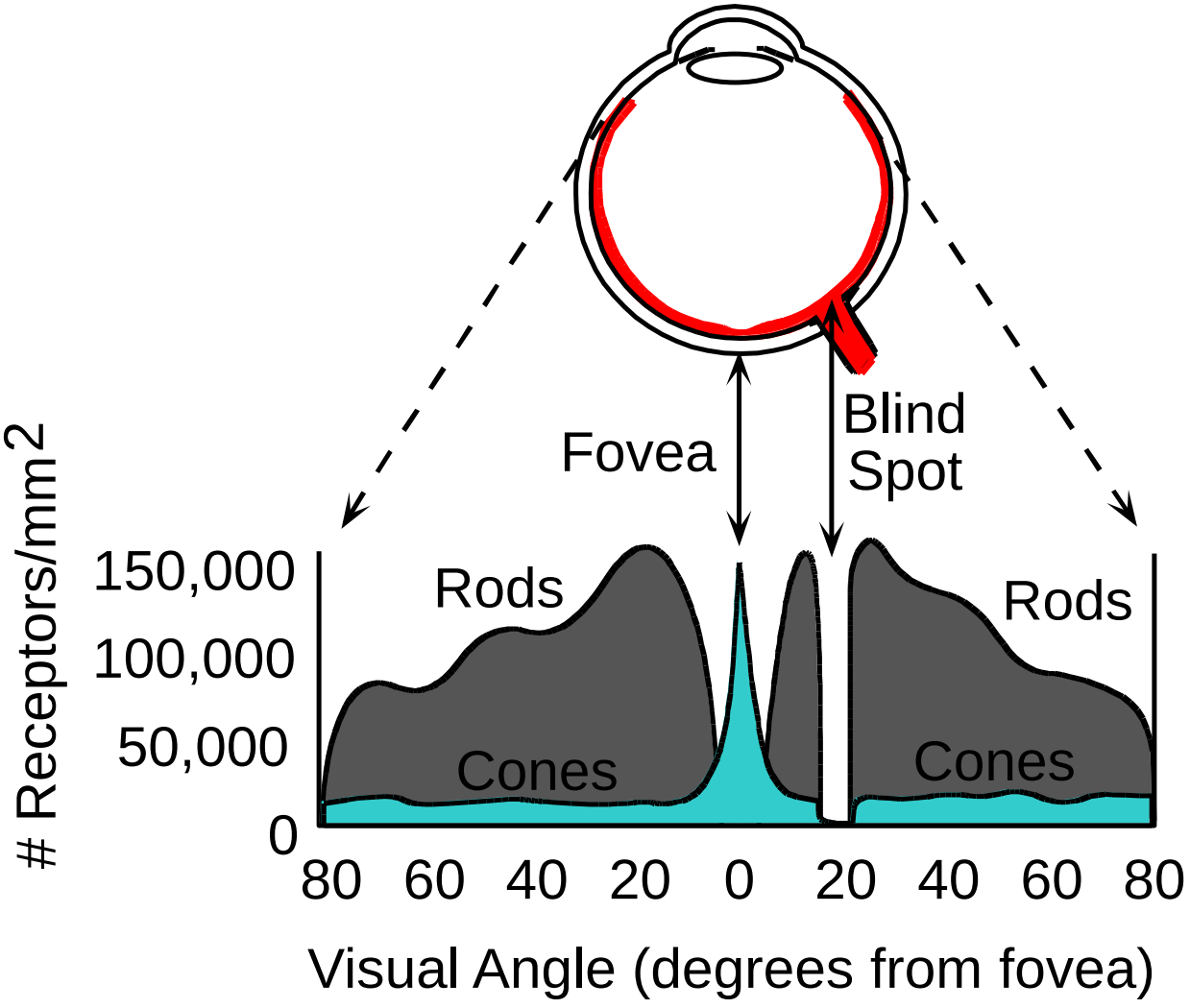
Cones and Rods



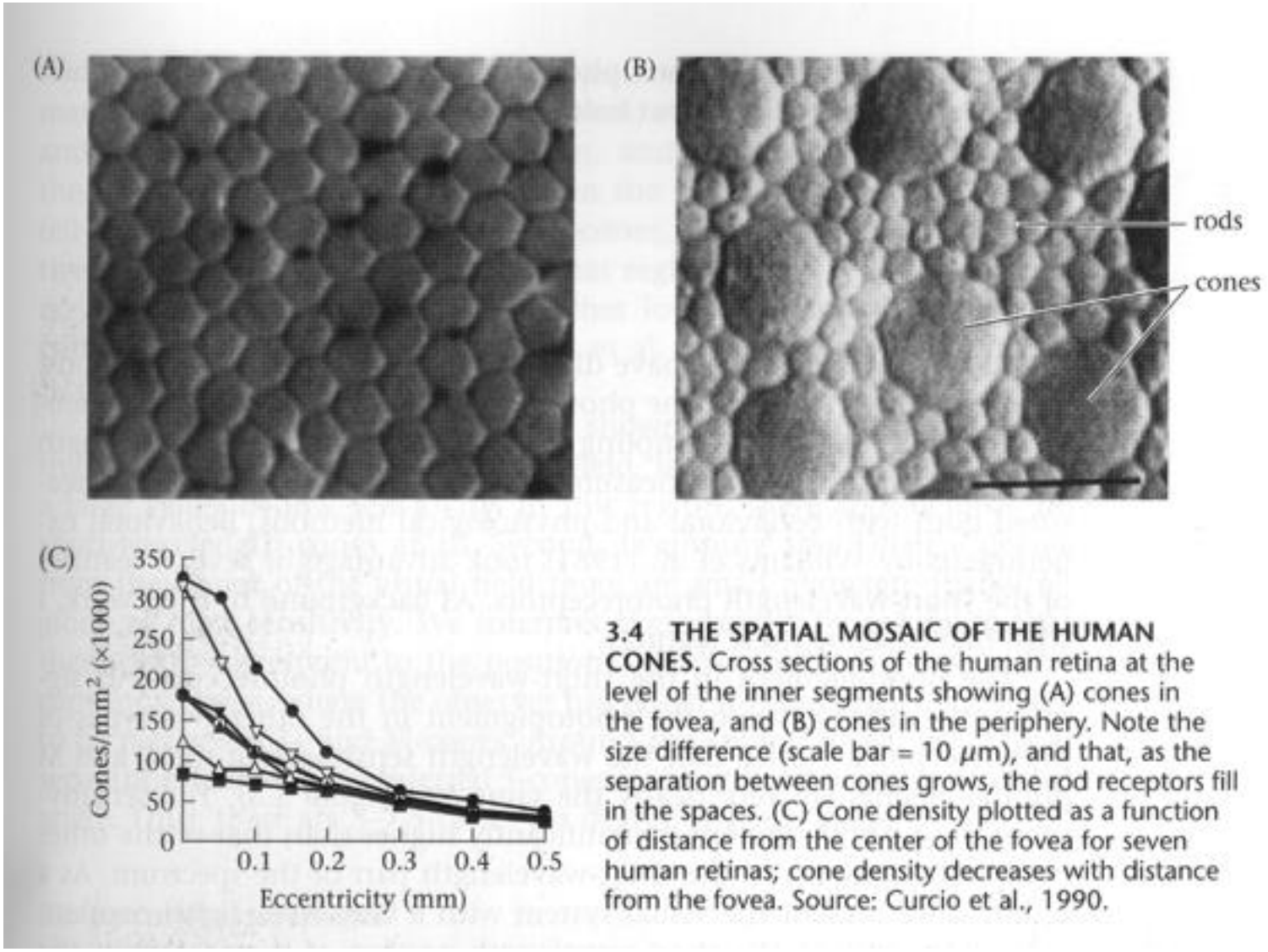
After dark adaptation, a single rod can respond to a single photon


Luminance (log cd/cm²)
−6
−4
−2
0
2
4
6
8
Pupil diameter (mm)
7.1
6.6
5.5
4.0
2.4
2.0
2.0
2.0
rod
cone
Retinal illuminance (log td)
photopic
1.1
2.6
4.5
6.5
8.5
scotopic
−4.0
−2.1
−0.22
0.70
Luminance of white paper in
starlight
moonlight
indoor lighting
sunlight
Visual function
scotopic
mesopic
photopic
scotopic threshold
photopic threshold
rod saturation begins
best acuity
damage possible
no color vision, poor acuity
good color vision, good acuity

Distribution of Rods and Cones



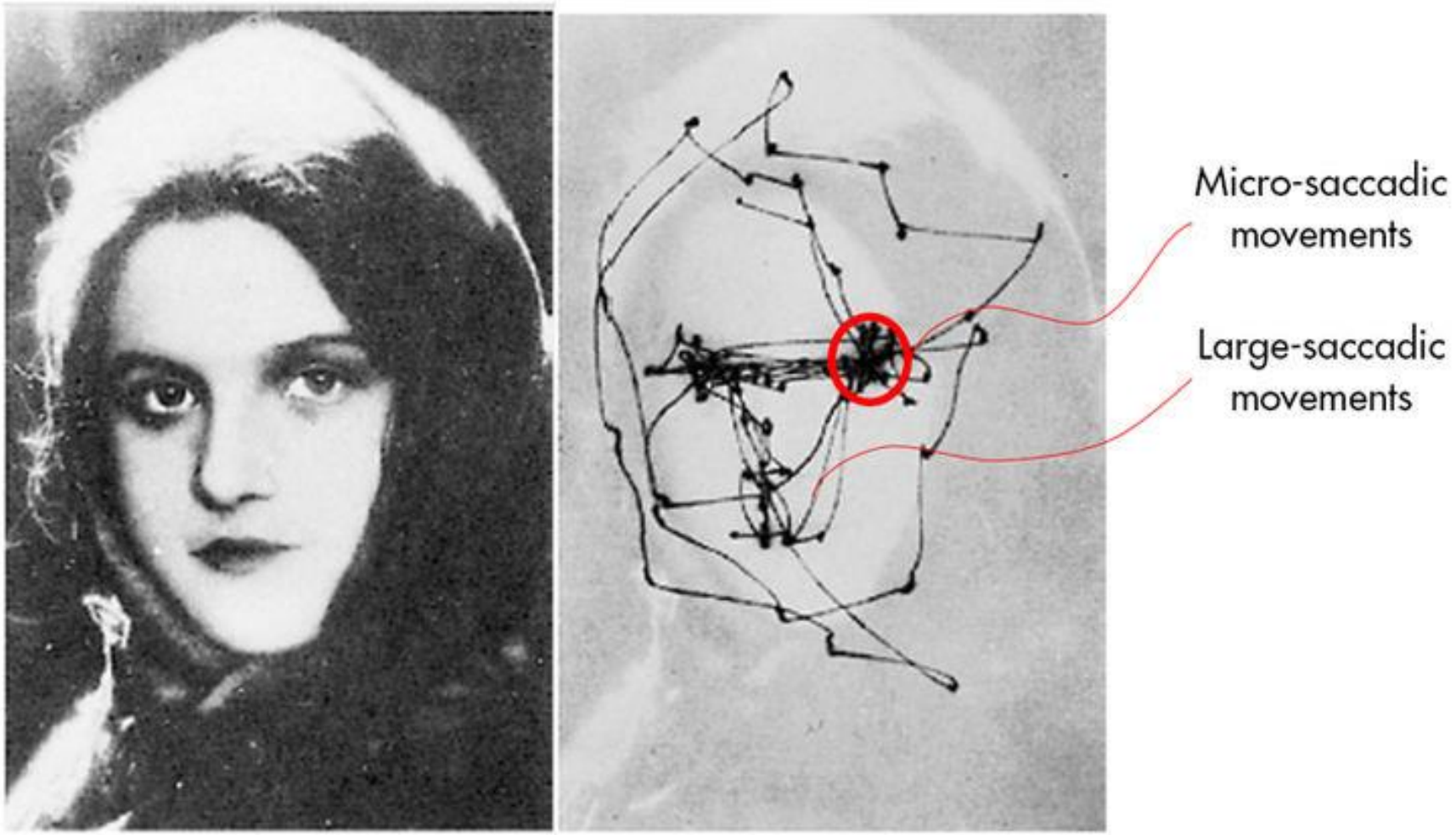
Night Sky: why are there more stars off-center?



3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the level of the inner segments showing (A) cones in the fovea, and (B) cones in the periphery. Note the size difference (scale bar = 10 μm), and that, as the separation between cones grows, the rod receptors fill in the spaces. (C) Cone density plotted as a function of distance from the center of the fovea for seven human retinas; cone density decreases with distance from the fovea. Source: Curcio et al., 1990.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

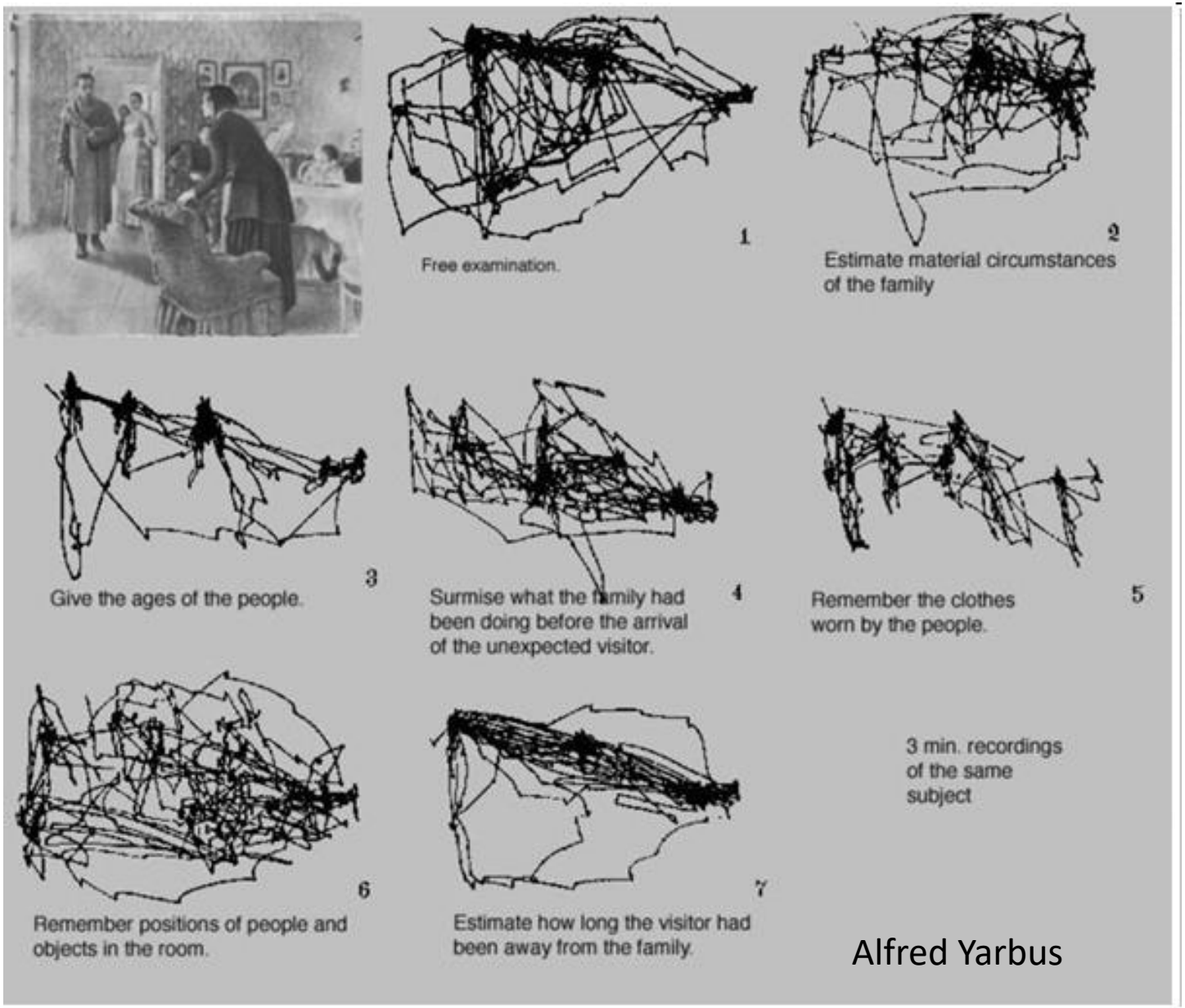
Saccadic eye movement



Saccadic eye movement

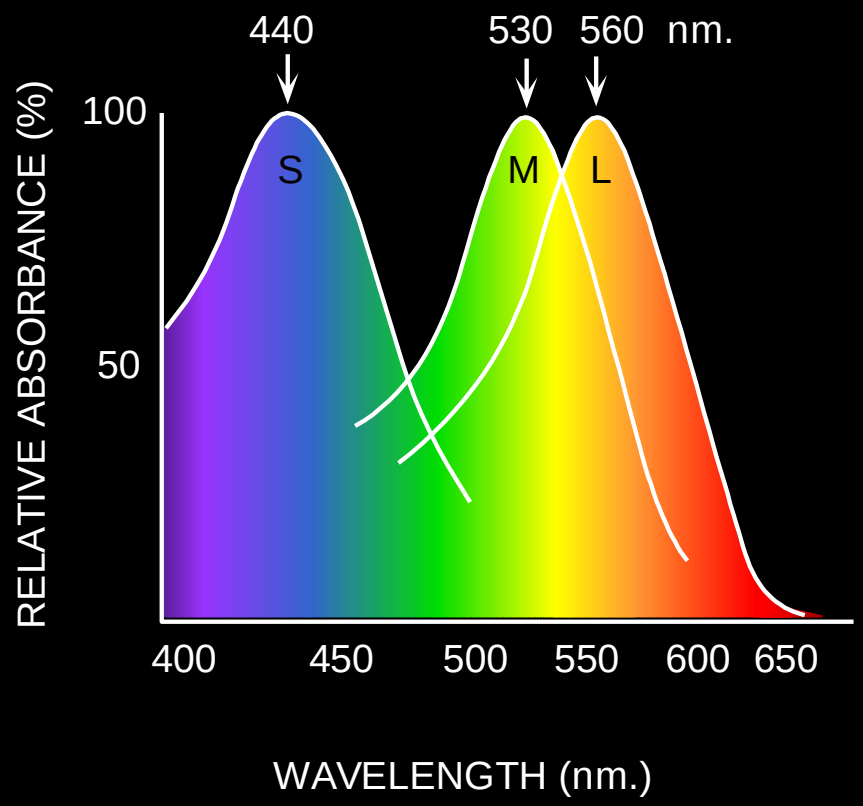
Unexpected Visitor (Yarbus)

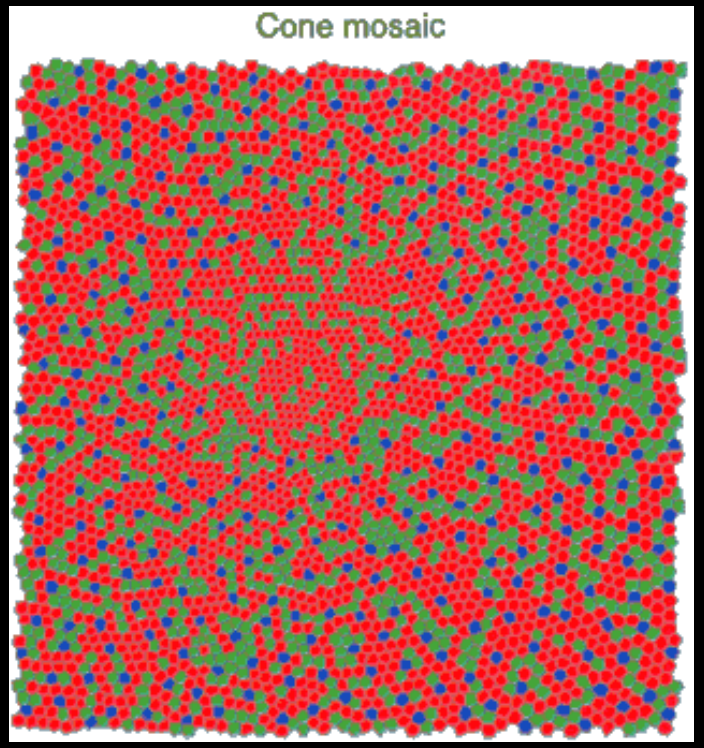
goal-attenuated (Yarbus)



Physiology of Color Vision

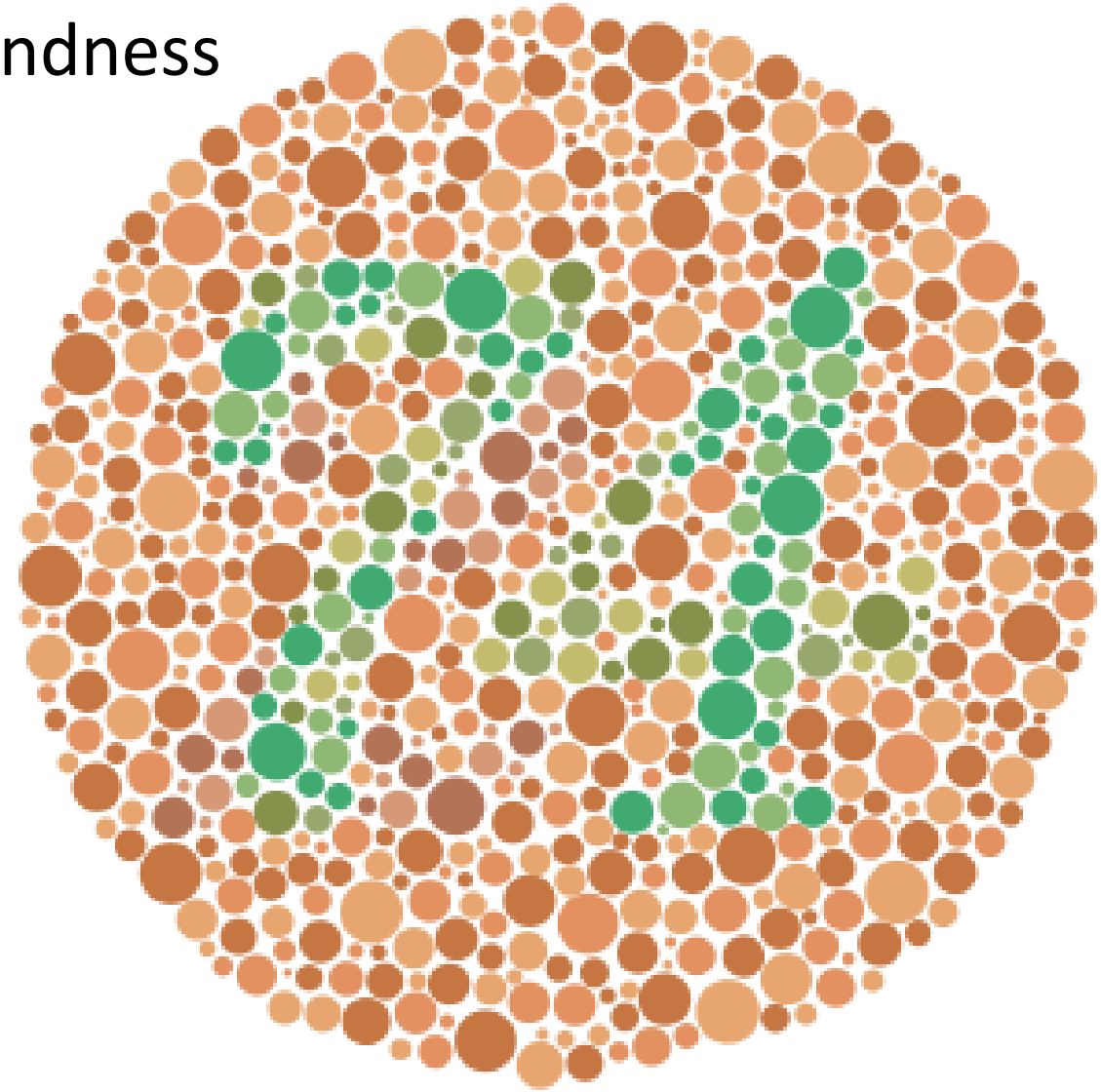
Three kinds of cones:





- Why are M and L cones so close?
- Why are there 3?

Color Blindness



Ishihara color test plate. The number "74" should be clearly visible to viewers with normal color vision. Viewers with red-green color blindness will read it as "21", and viewers with monochromacy may see nothing.

https://en.wikipedia.org/wiki/Color_blindness

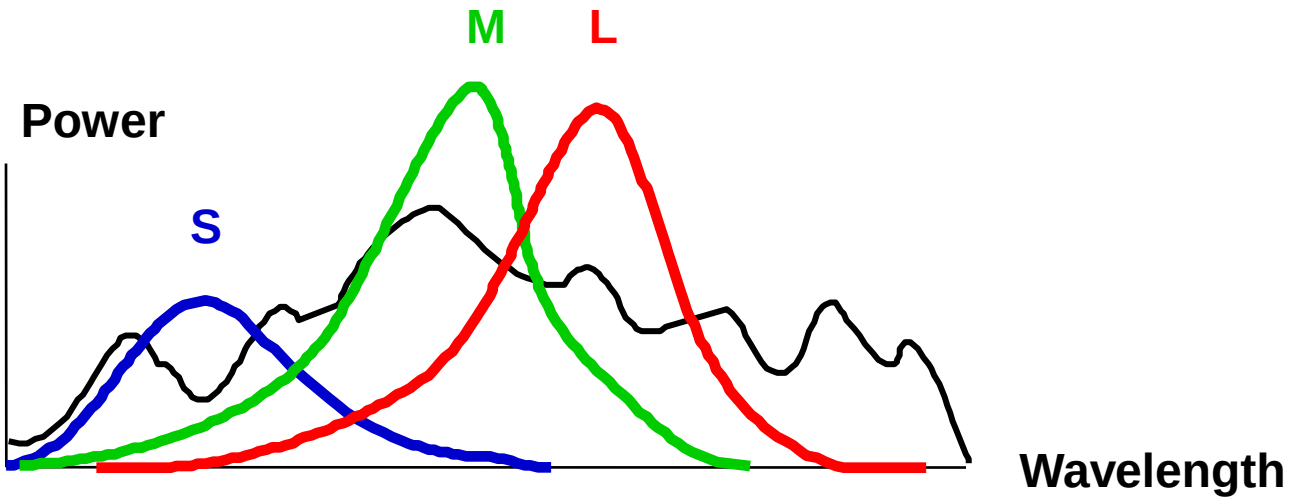
Not everyone is trichromat

- Types of Dichromacy:
  - Deuteranopia: missing M cones
  - Protanopia: missing L cones
  - Tritanopia: missing S cones

- "M" and "L" on the X-chromosome
  - Why men are more likely to be color blind
  - "L" has high variation, so some women are tetrachromatic
- Some animals have
  - 1 (night animals)
  - 2 (e.g., dogs)
  - 4 (fish, birds)
  - 5 (pigeons, some reptiles/amphibians)
  - 12 (mantis shrimp)
- See Ren Ng's class for whole semester on this!

http://en.wikipedia.org/wiki/Color_vision

Trichromacy



Rods and cones act as *filters* on the spectrum

- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number

Slide by Steve Seitz

We can approximate the spectral power distribution and receptor sensitivity function as vectors indexed by wavelength

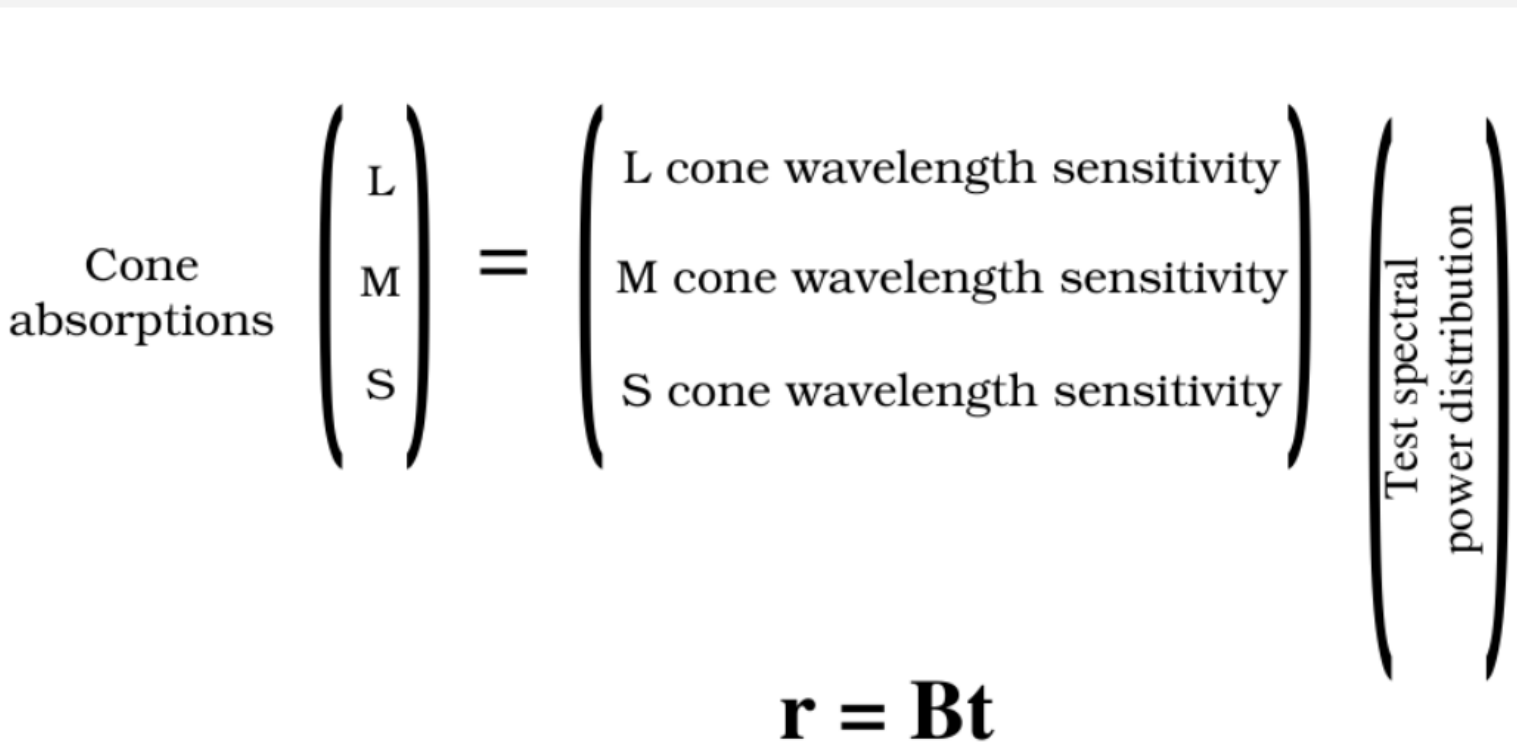
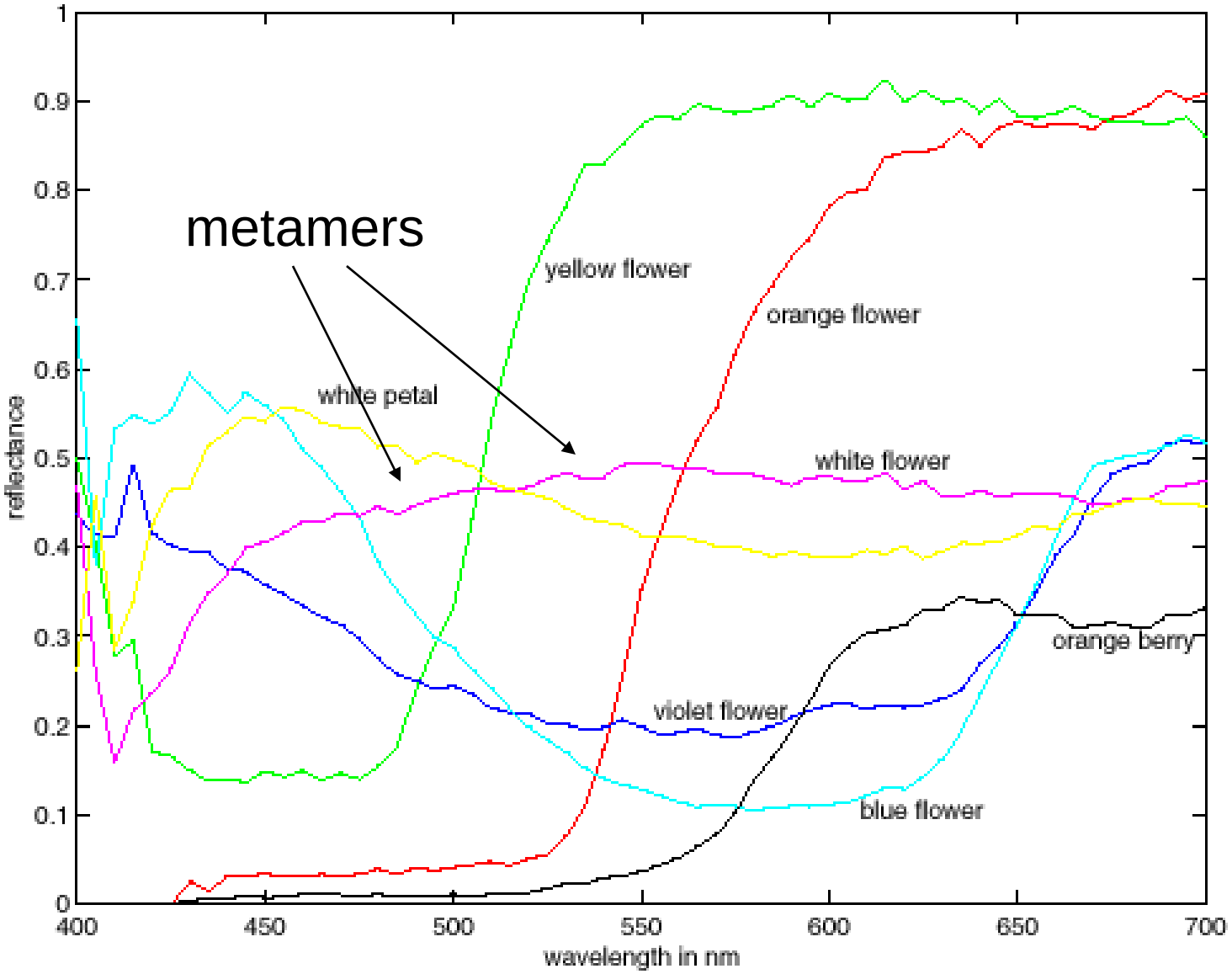


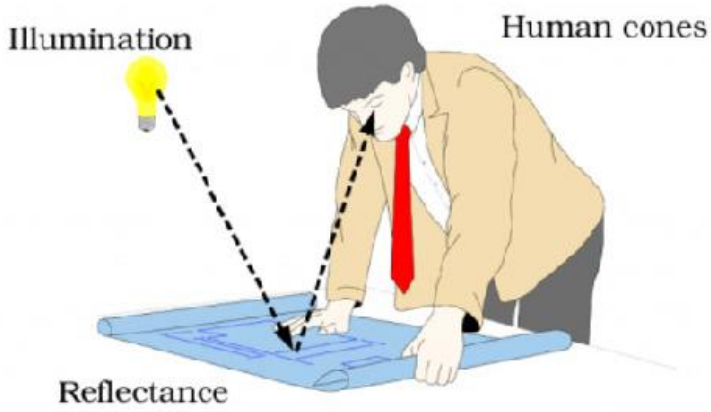
Figure 4.18: Cone photopigments and the color-matching functions. If we measure the wavelength sensitivity of each of the cone photopigments, we can create a 3 x N system matrix to describe the cone absorptions. Then, we

We get metamers when two lights result in the same (L,M,S) values

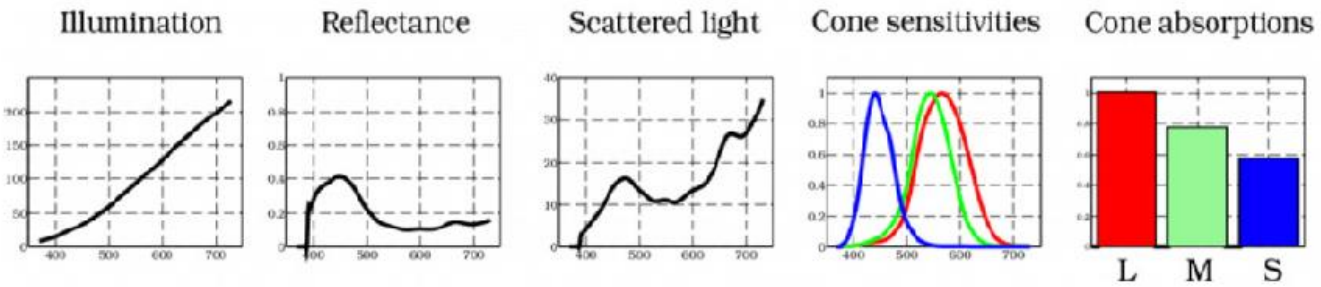
We are all color-blind!



Spectral Radiometry: Color Image Formation



Wandell 1995

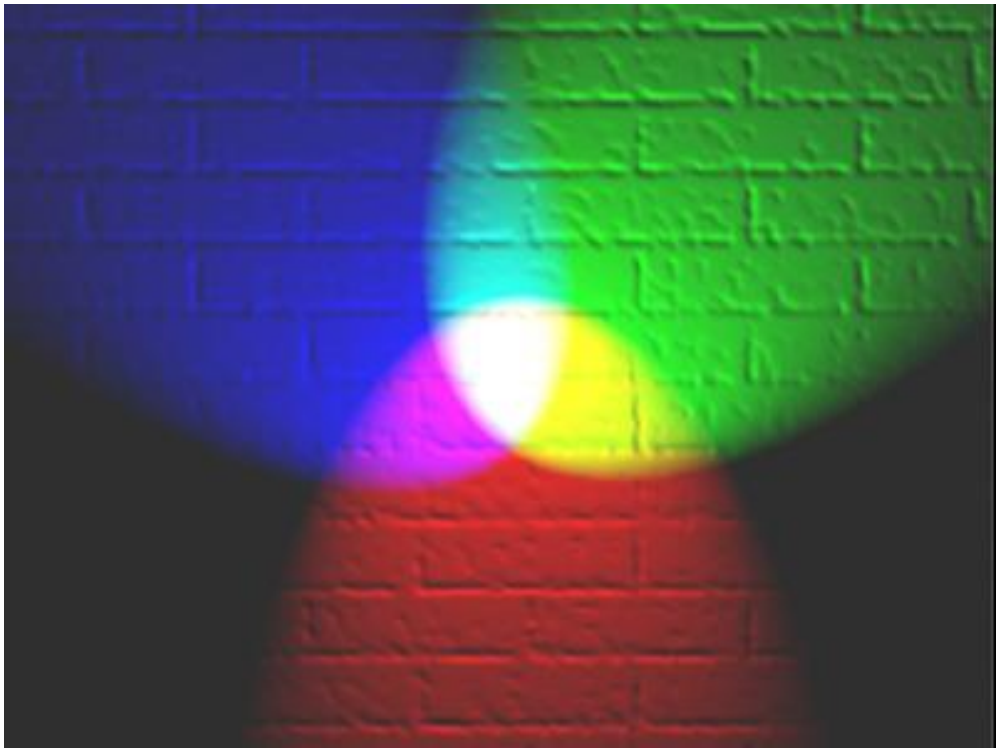


incoming illumination × reflectance = outgoing scene radiance

$$\int_{\lambda} \text{scene radiance} \times \text{cone sensitivities}\ d\lambda = \text{cone absorptions}$$

Color spaces

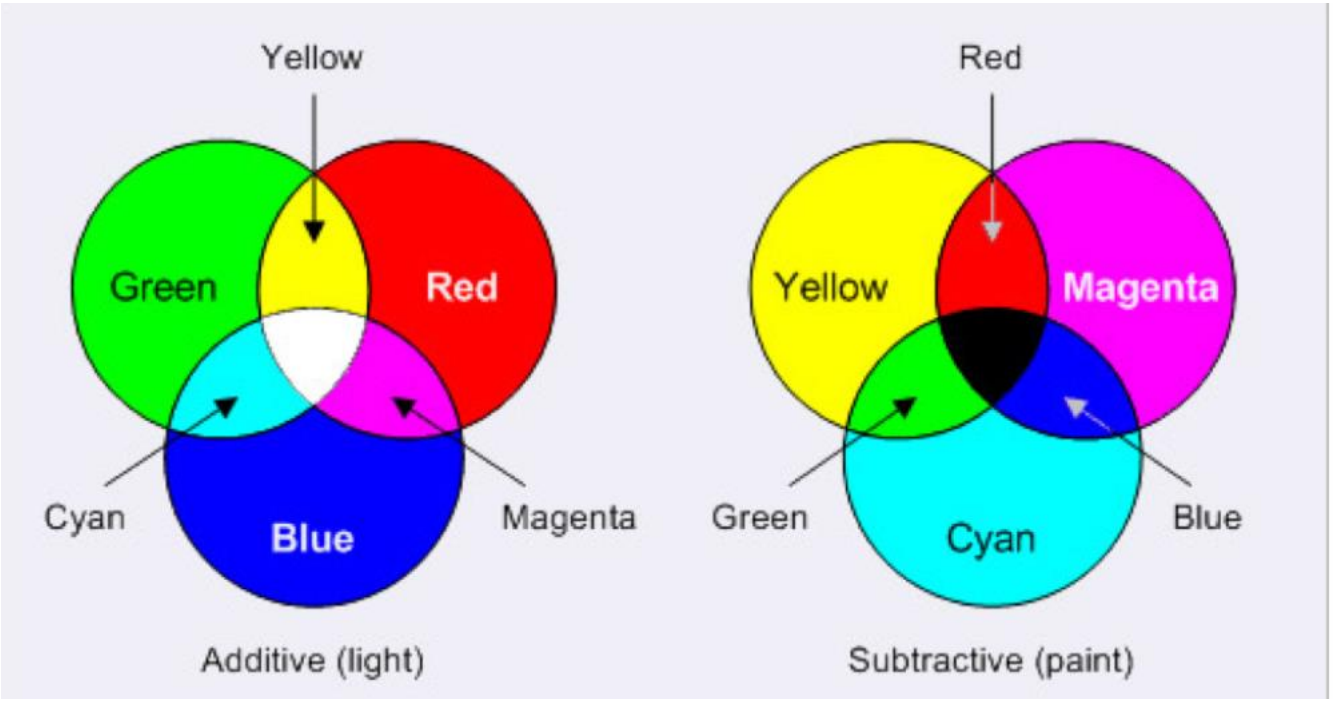
- How can we represent color?



http://en.wikipedia.org/wiki/File:RGB_illumination.jpg

Color spaces: RGB vs. CMY(K)

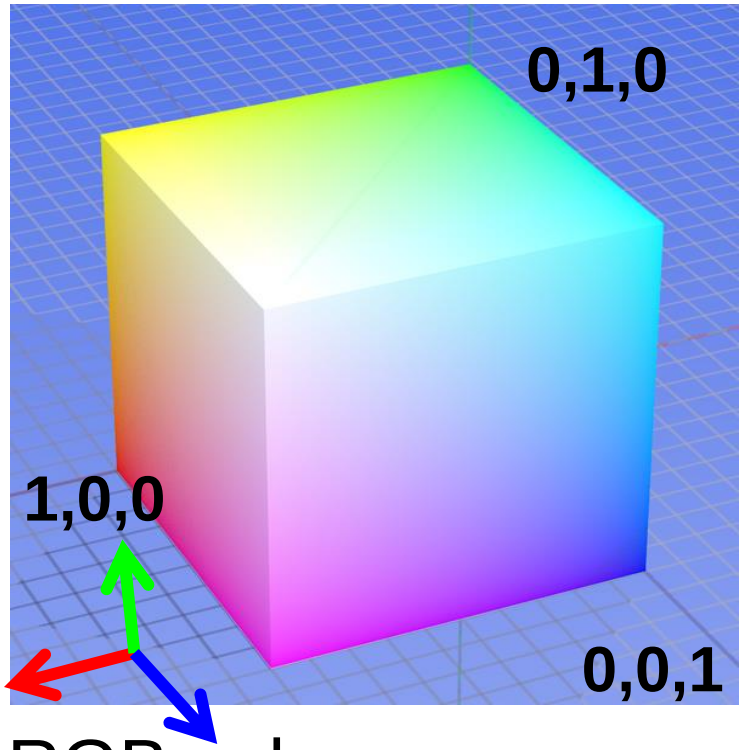
- Light projection vs paint



Source: https://intranet.mcad.edu/kb/cmyk-vs-rgb-what-color-space-should-i-work

Color spaces: RGB

Default color space



RGB cube

- Easy for devices
- But not perceptual
- Where do the grays live?
- Where is hue and saturation?

R
(G=0,B=0)

G
(R=0,B=0)

B
(R=0,G=0)

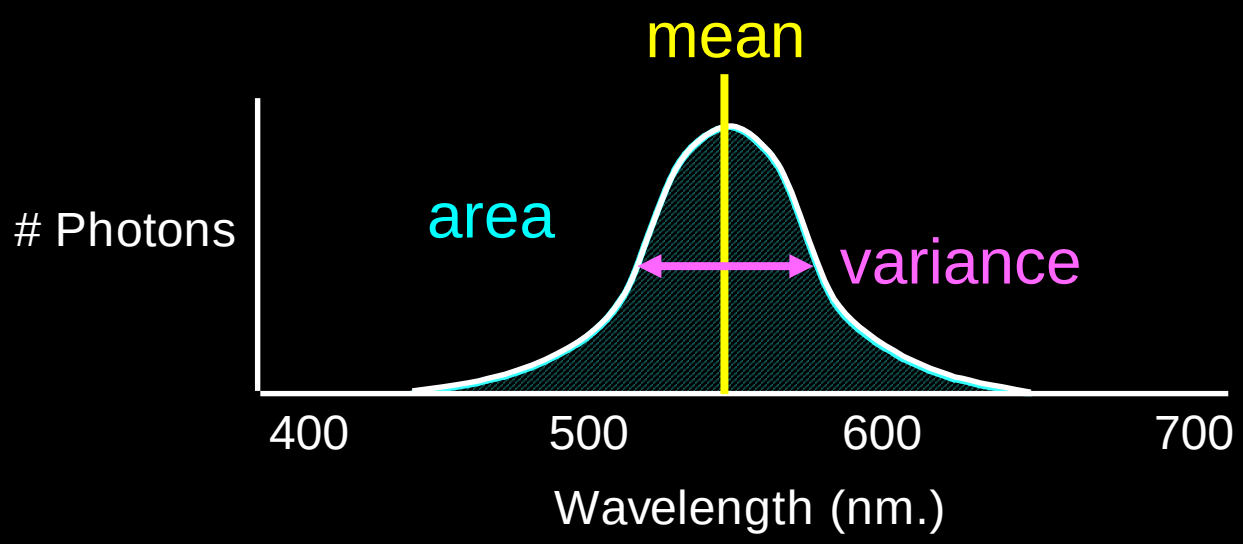
Image from: http://en.wikipedia.org/wiki/File:RGB_color_solid_cube.png

The Psychophysics of "Color"

There is no simple functional description for the perceived color of all lights under all viewing conditions, but ……

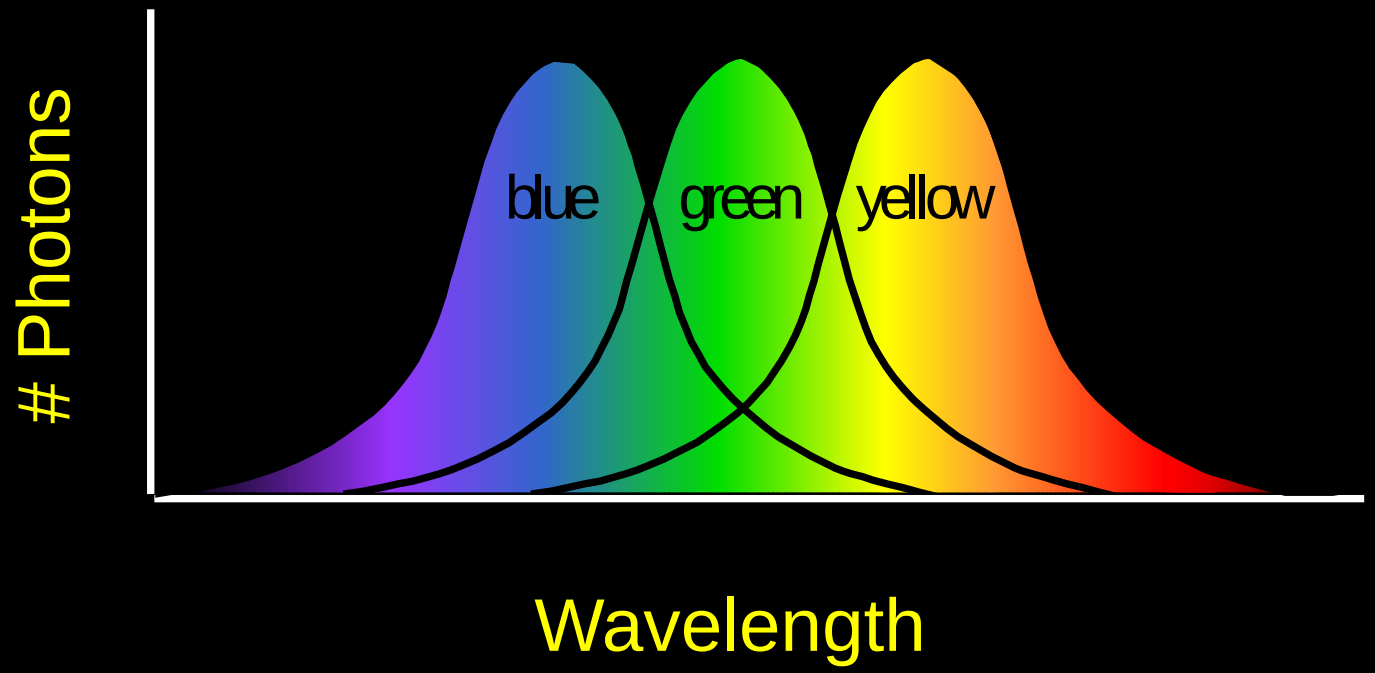
A helpful constraint:

Consider only physical spectra with normal distributions



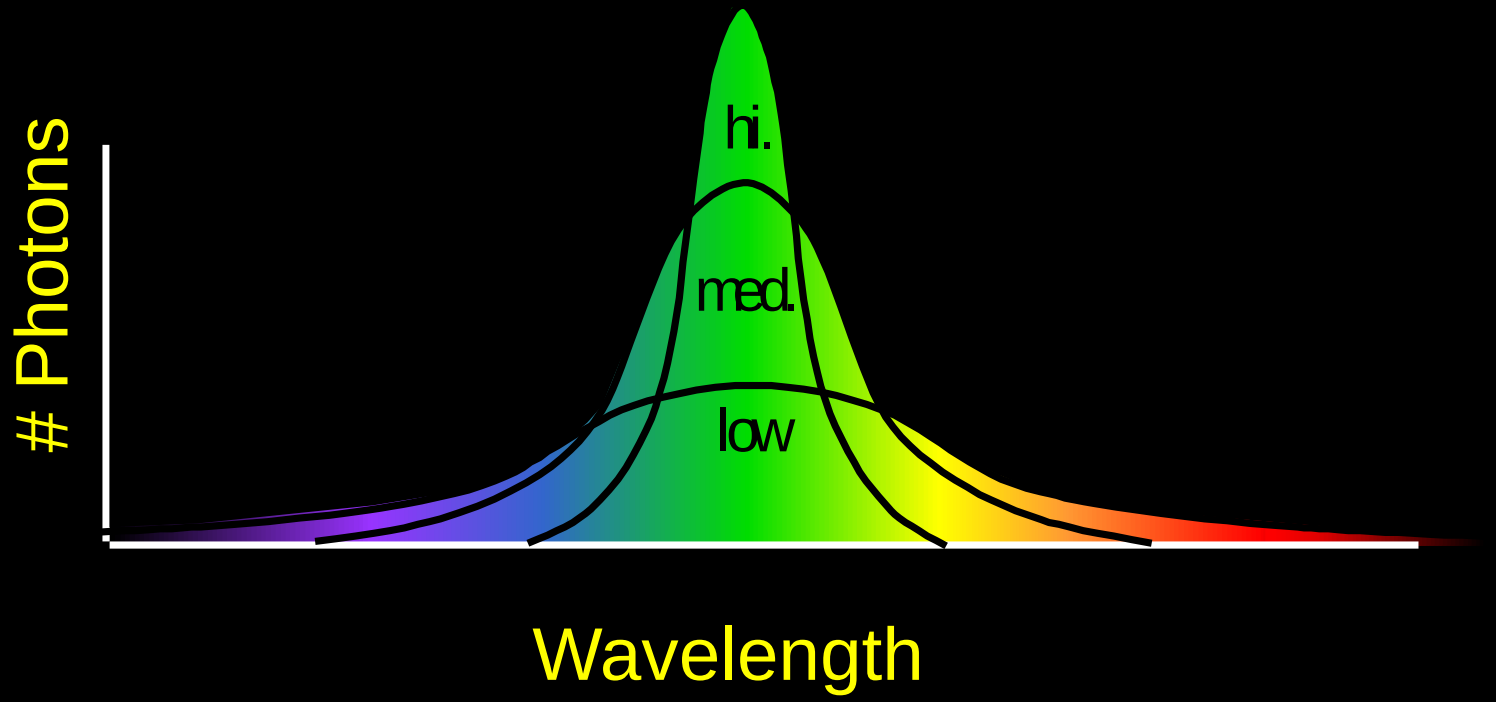
The Psychophysical Correspondence

Mean ⟷ Hue



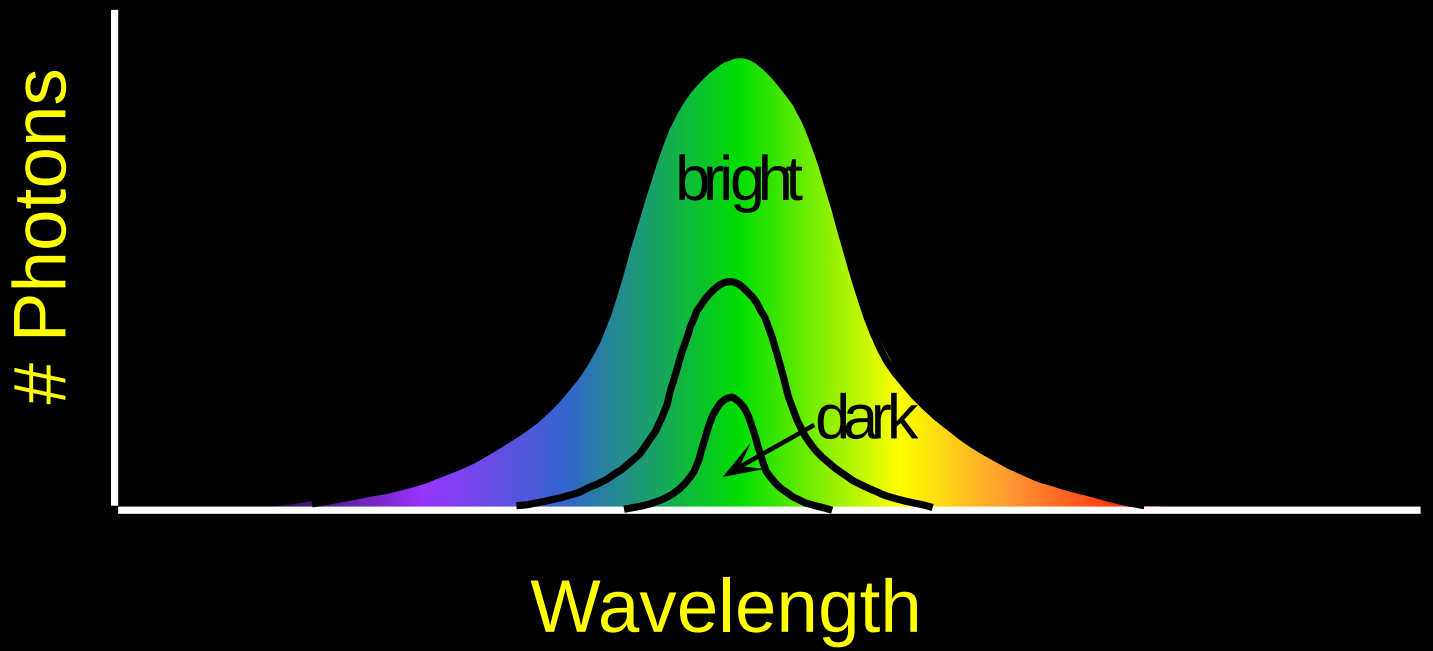
The Psychophysical Correspondence

Variance ⟷ Saturation



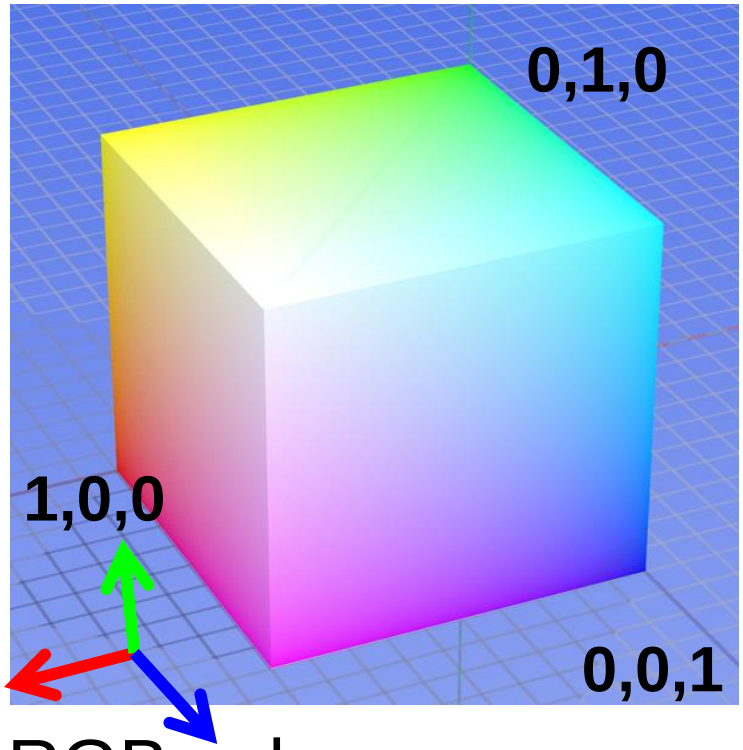
The Psychophysical Correspondence

Area ⟷ Brightness



Color spaces: RGB

Default color space



RGB cube

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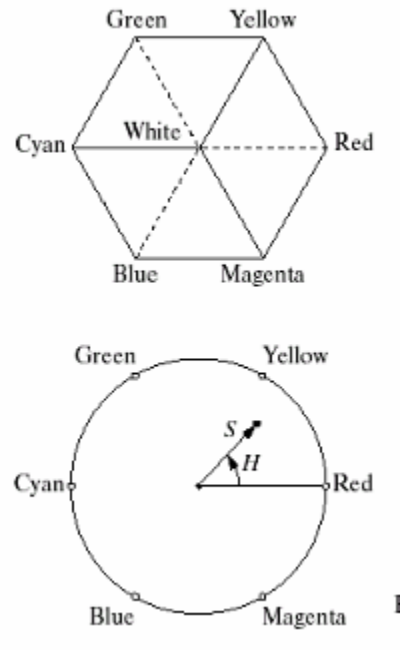
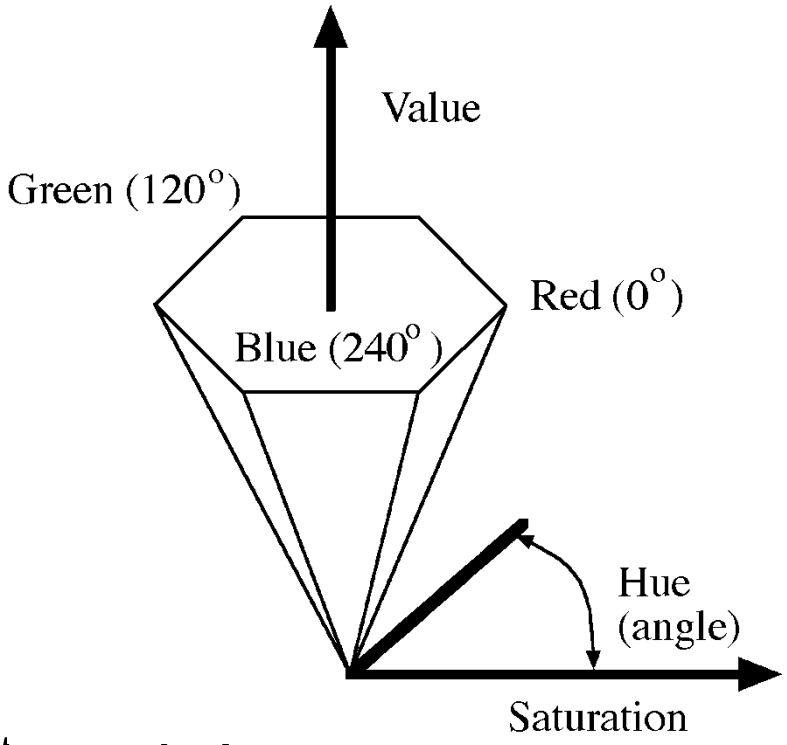
G
(R=0,B=0)

B
(R=0,G=0)

Image from: http://en.wikipedia.org/wiki/File:RGB_color_solid_cube.png

HSV





Hue, Saturation, Value (Intensity)

- RGB cube on its vertex

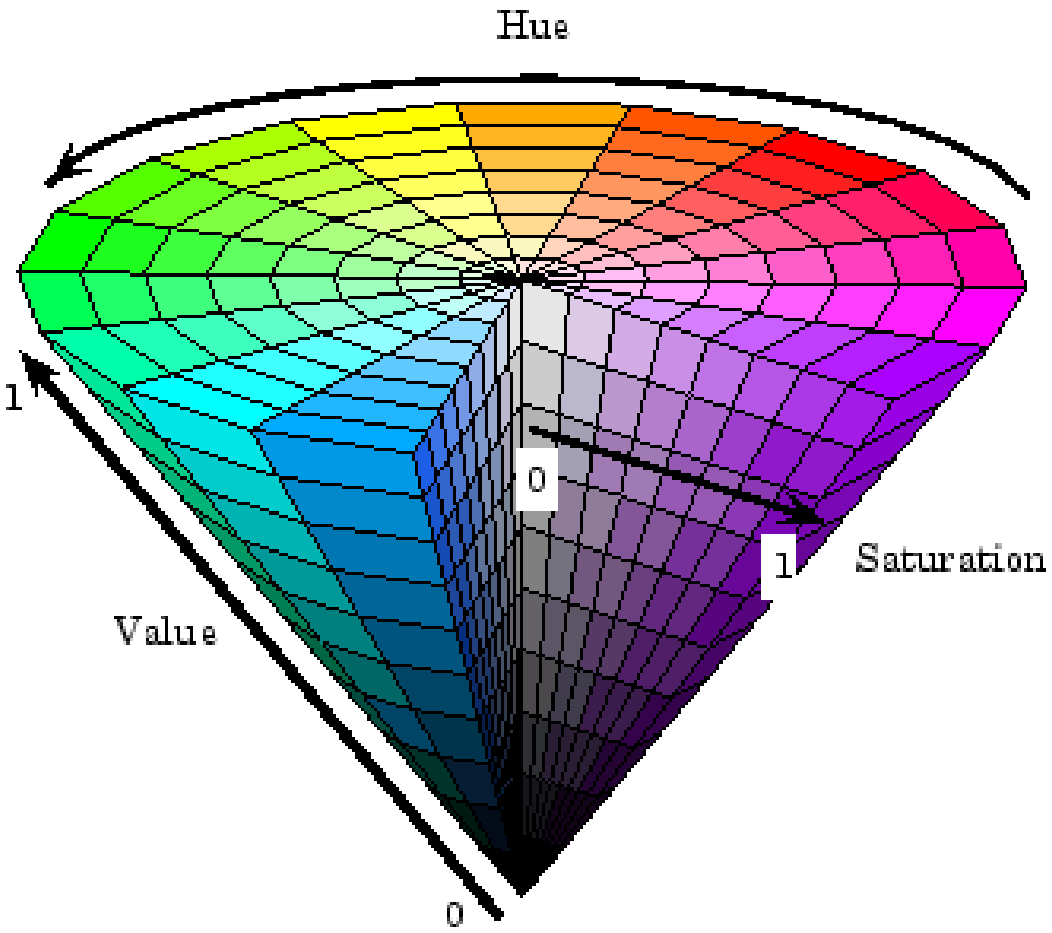
Decouples the three components (a bit)

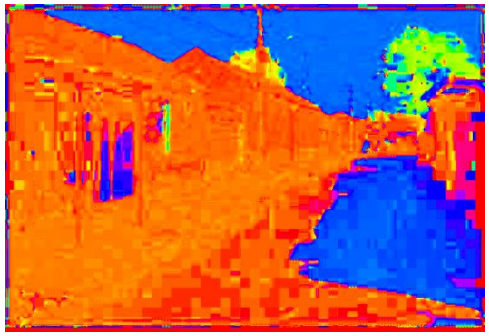
Use rgb2hsv() and hsv2rgb() in Matlab

Slide by Steve Seitz

Color spaces: HSV

Intuitive color space





H

(S=1,V=1)

S

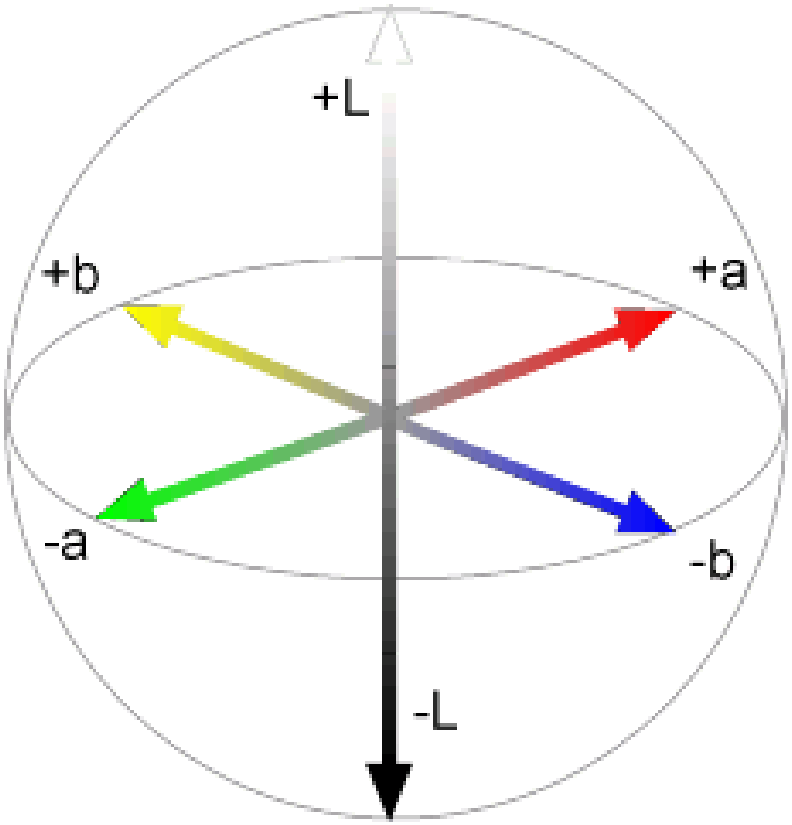
(H=1,V=1)

V

(H=1,S=0)

Color spaces: L*a*b*

"Perceptually uniform"* color space



L
(a=0,b=0)

a
(L=65,b=0)

b
(L=65,a=0)

Color Constancy

The "photometer metaphor" of color perception:
Color perception is determined by the spectrum of light on each retinal receptor (as measured by a photometer).

Color Constancy

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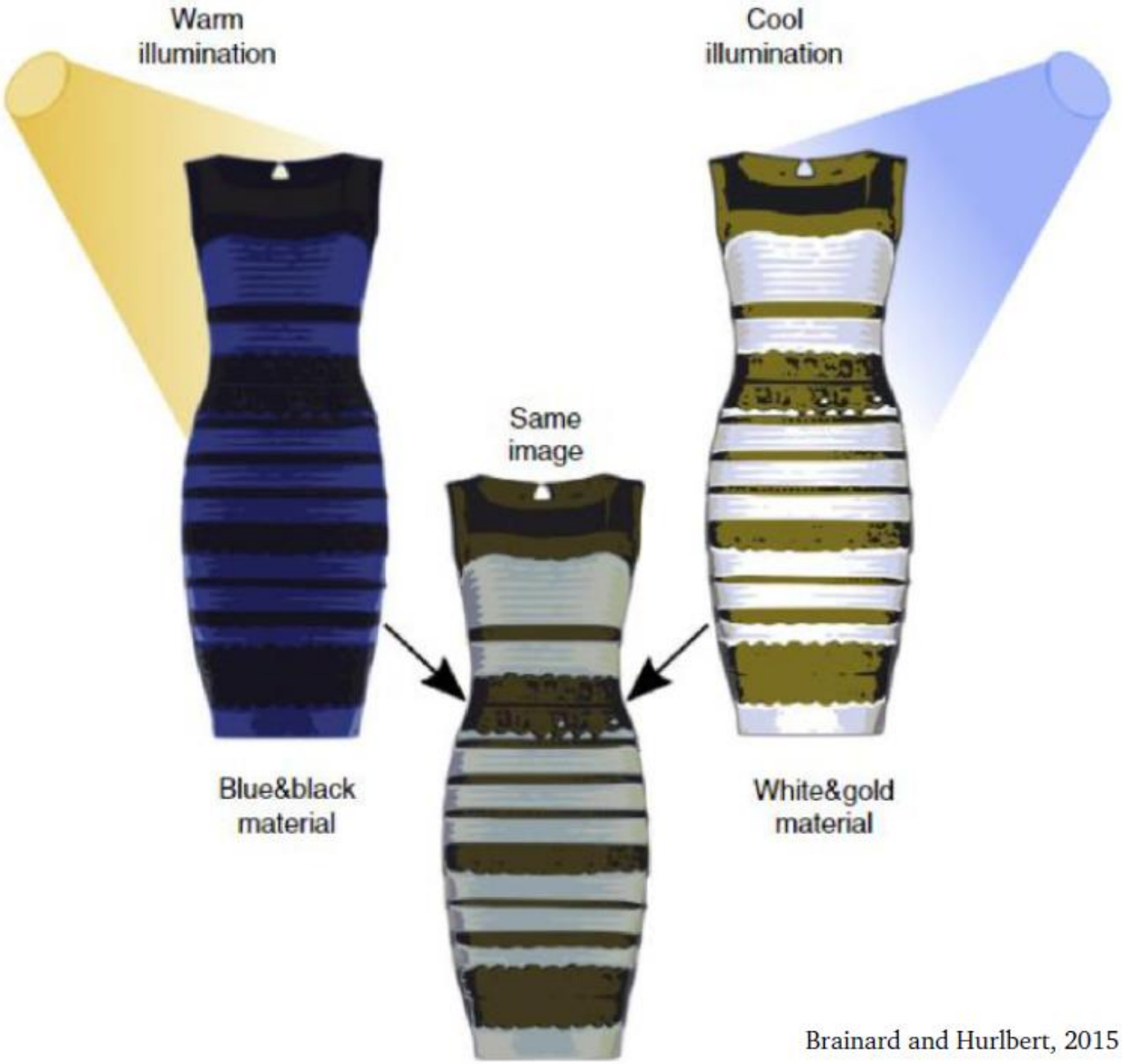
Color Constancy

The "photometer metaphor" of color perception:
Color perception is determined by the spectrum of light on each retinal receptor (as measured by a photometer).

What color is the “The Dress”?

https://en.wikipedia.org/wiki/The_dress

Two Scene Interpretations of #thedress



Brainard and Hurlbert, 2015

Color Constancy

Do we have constancy over
all global color transformations?

60% blue filter

Complete inversion

Color Constancy

Color Constancy: the ability to perceive the invariant color of a surface despite ecological Variations in the conditions of observation.

Another of these hard inverse problems:

Physics of light emission and surface reflection underdetermine perception of surface color

Camera White Balancing

- Manual
- Automatic (AWB)

Color Correction

- Simple idea: multiply R, G, and B values by separate constants

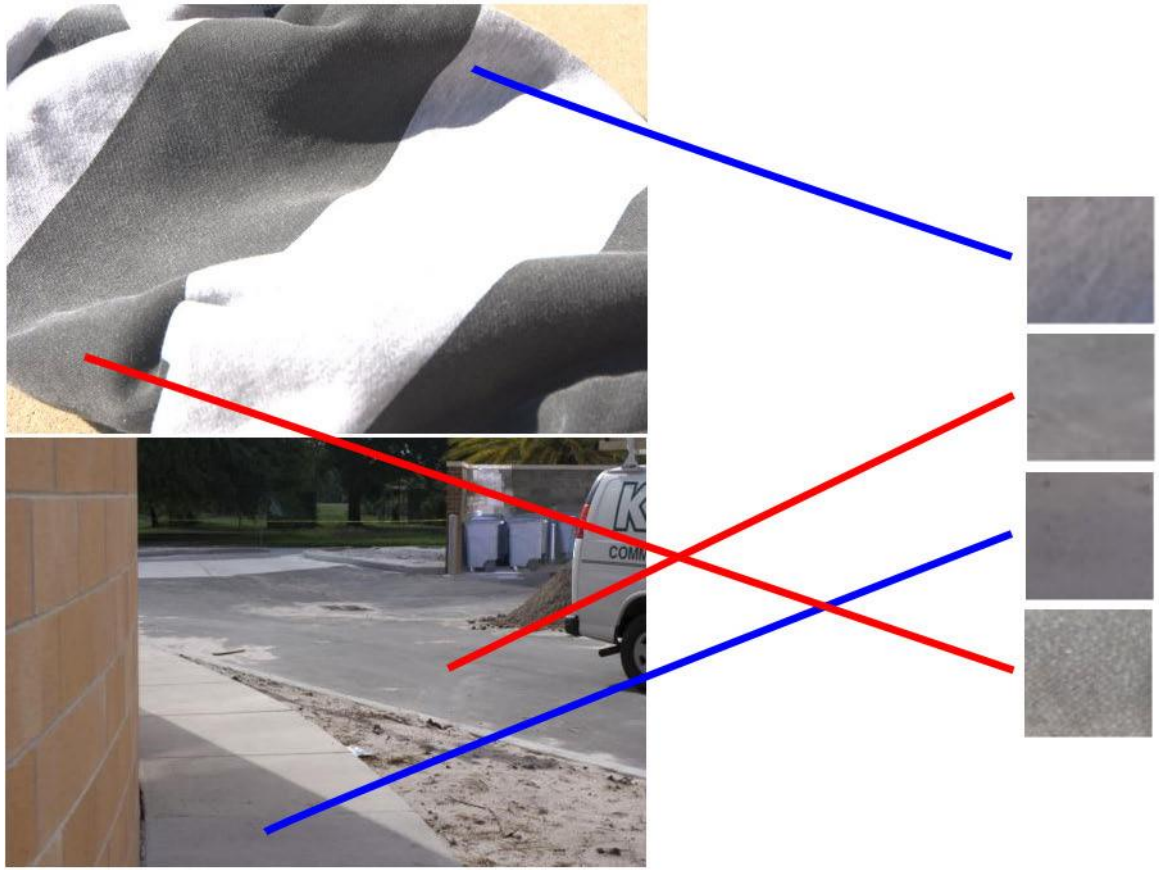
$$\begin{bmatrix} \tilde{r} \\ \tilde{g} \\ \tilde{b} \end{bmatrix} = \begin{bmatrix} \alpha_r & 0 & 0 \\ 0 & \alpha_g & 0 \\ 0 & 0 & \alpha_b \end{bmatrix} \begin{bmatrix} r \\ g \\ b \end{bmatrix}$$

- How to choose the constants?
  - "White world" assumption: brightest pixel is white
    - Divide by largest value
  - "Gray world" assumption: average value should be gray
    - E.g., multiply r channel by avg((r+g+b)/3) / avg(r)
    - White balancing: choose a reference as the white or gray color

Lightness constancy

Interpret surface in terms of albedo or “true color”, rather than observed intensity

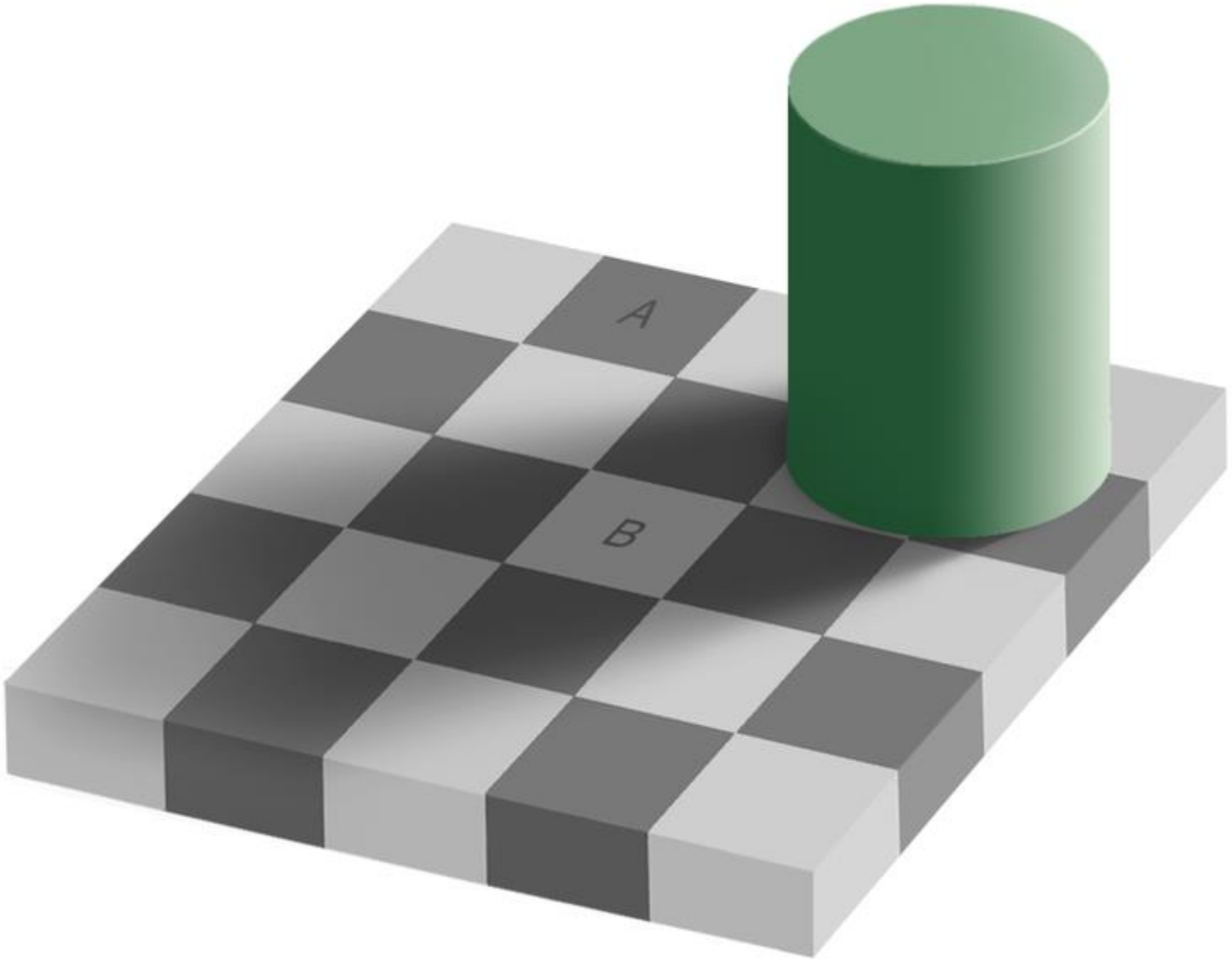
- Humans are good at it
- Computers are not nearly as good



It’s all about the gradients...?

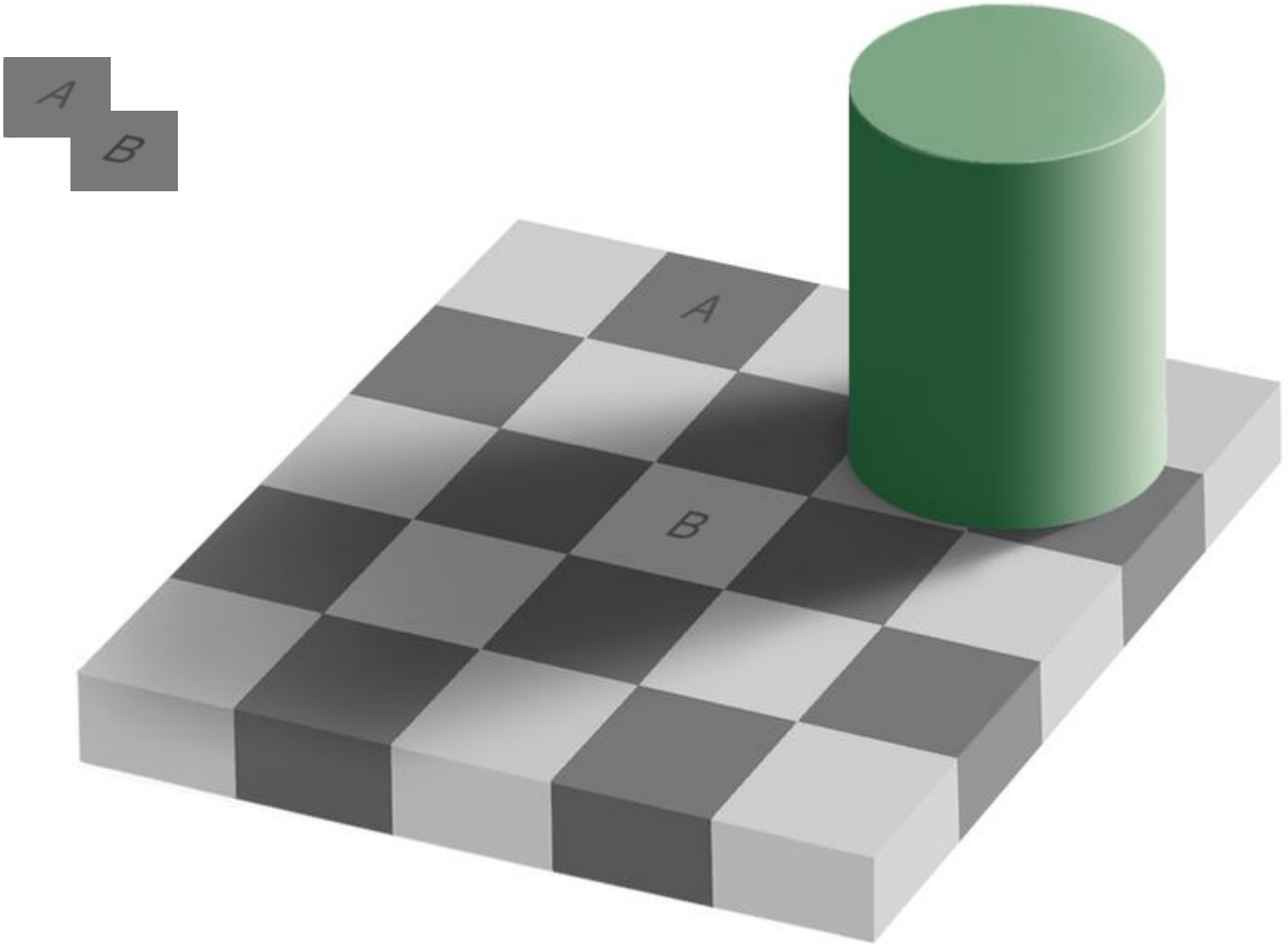
- *"Every light is a shade, compared to the higher lights, till you come to the sun; and every shade is a light, compared to the deeper shades, till you come to the night."*
  — John Ruskin, 1879

Perception of Intensity



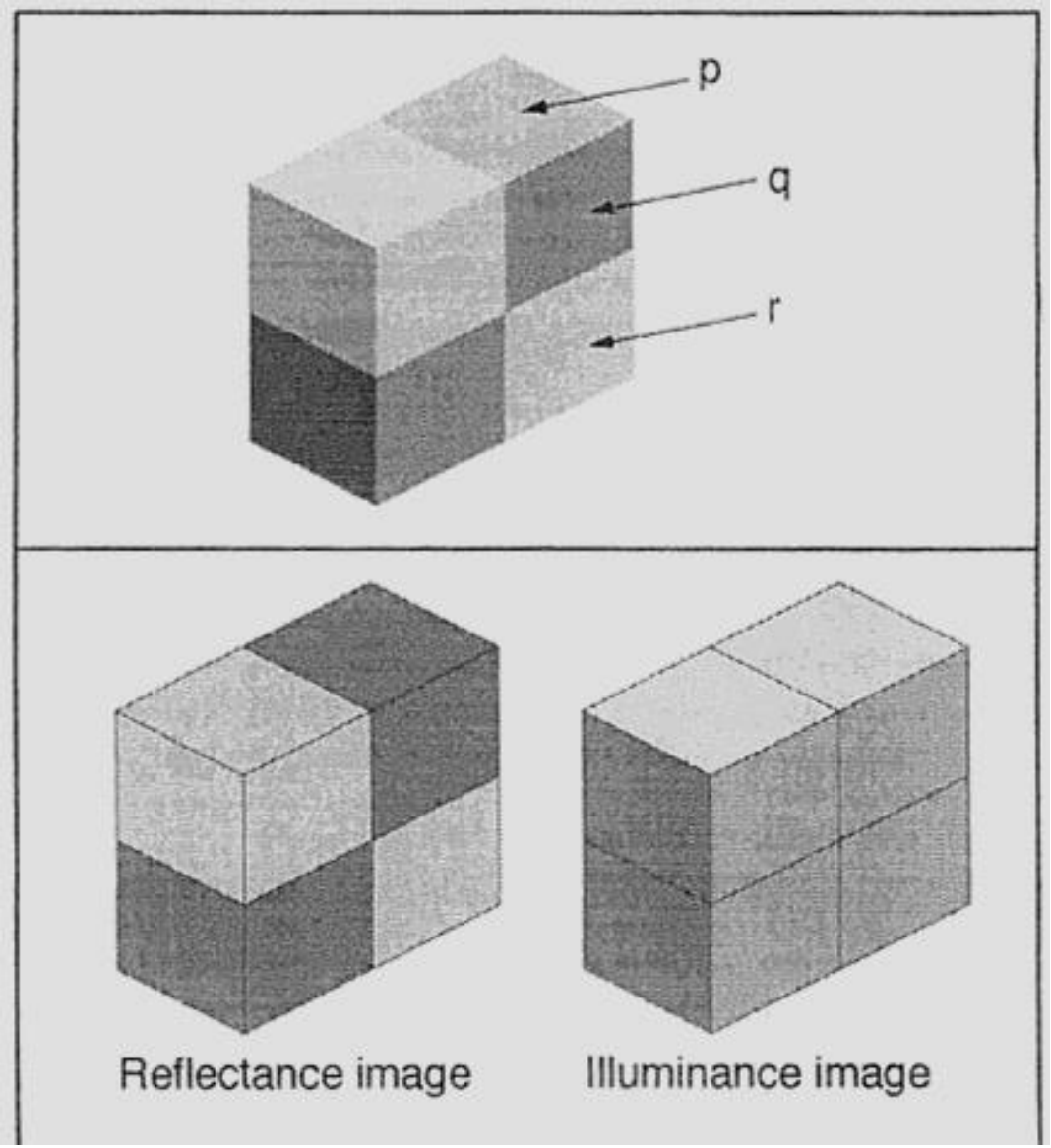
from Ted Adelson

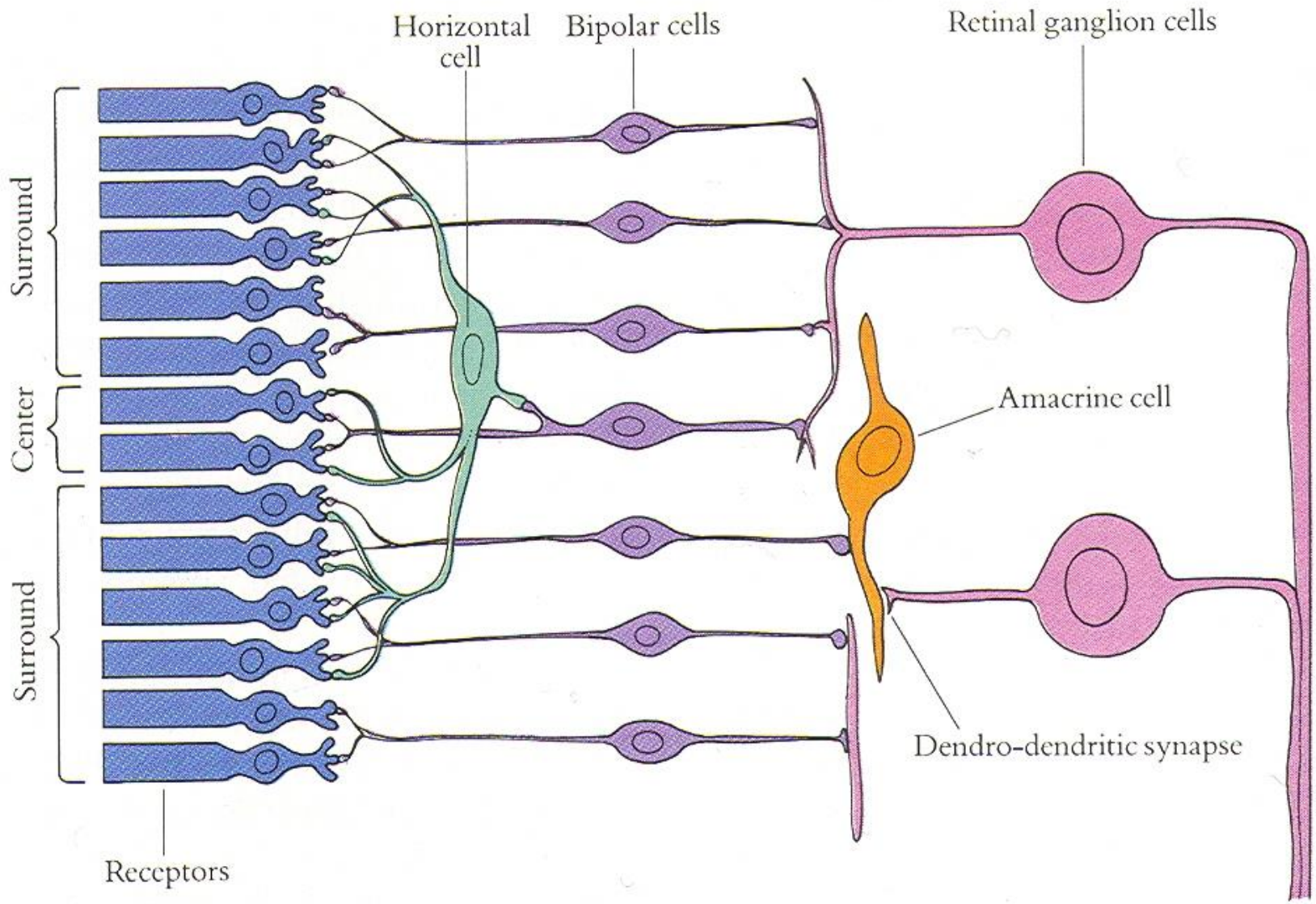
Perception of Intensity



from Ted Adelson

Intrinsic Images



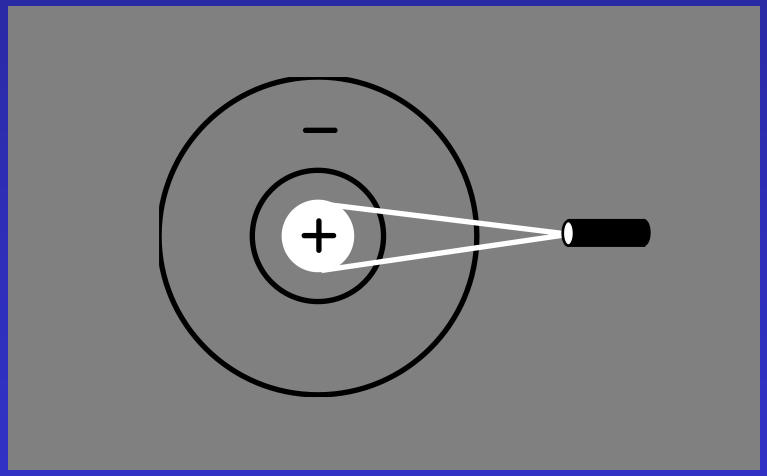

Horizontal cell
Bipolar cells
Retinal ganglion cells
Surround
Center
Surround
Amacrine cell
Dendro-dendritic synapse
Receptors

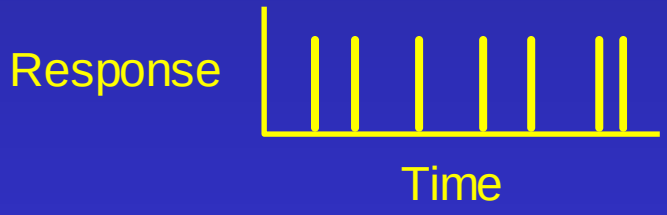
Single Cell Recording

Kuffler got Nobel Prize for this

Retinal Receptive Fields

Receptive field structure in ganglion cells:
On-center Off-surround



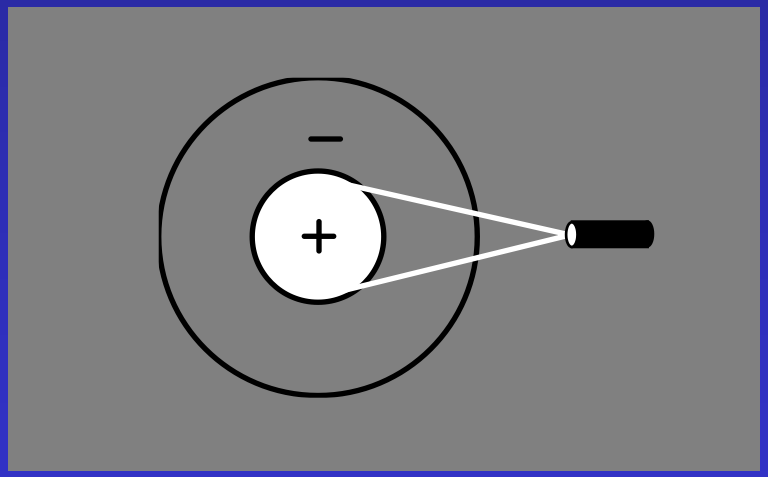


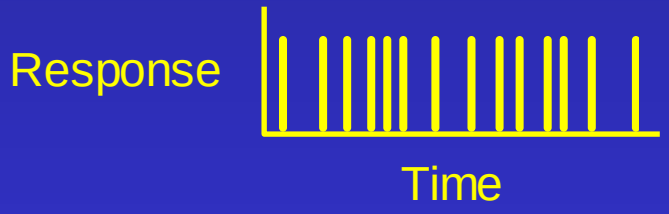
Stimulus condition

Electrical response

Retinal Receptive Fields

Receptive field structure in ganglion cells:
On-center Off-surround





Stimulus condition

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Retinal Receptive Fields

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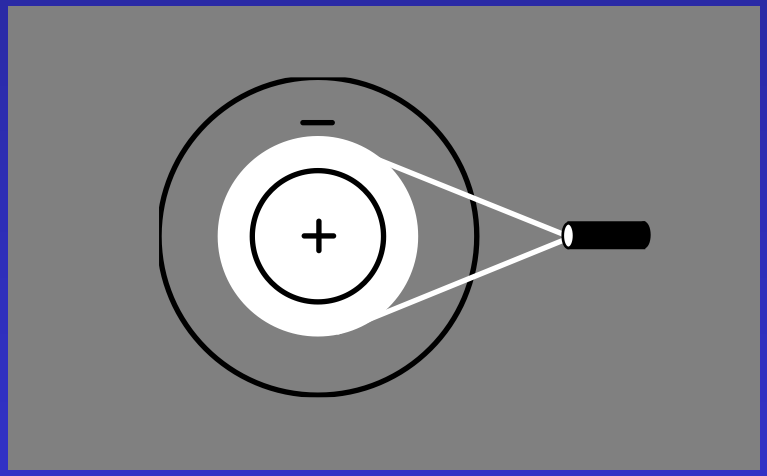
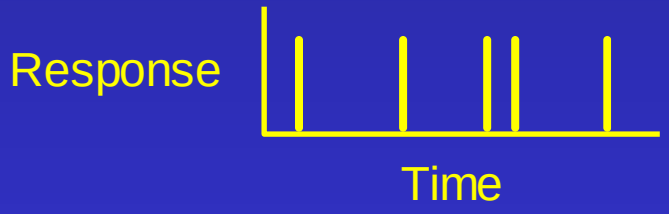


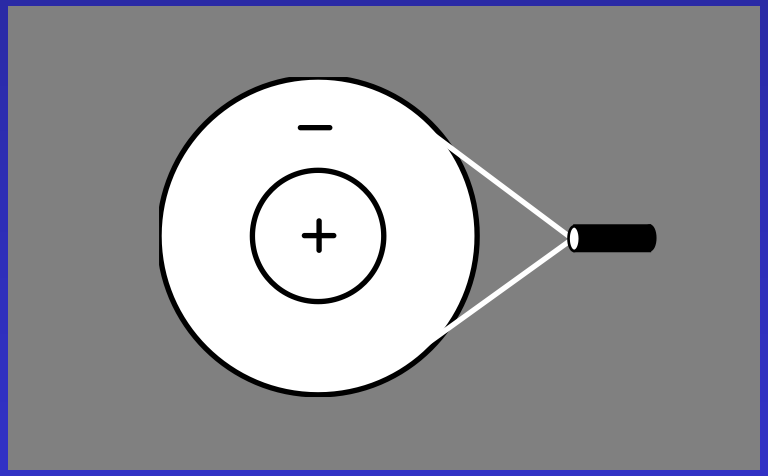


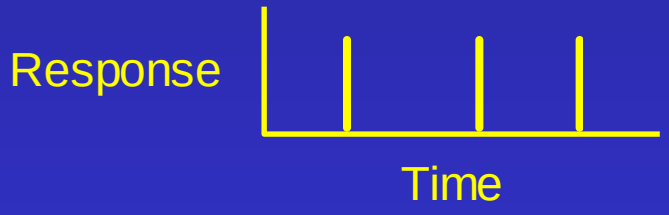
Stimulus condition

Electrical response

Retinal Receptive Fields

Receptive field structure in ganglion cells:
On-center Off-surround



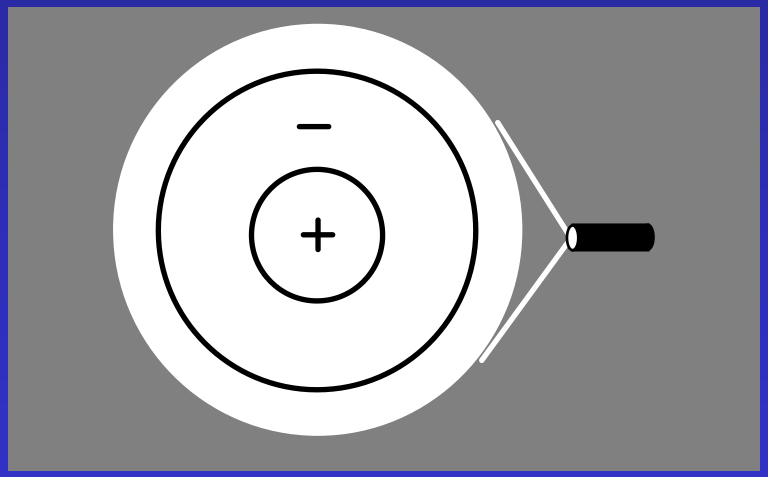


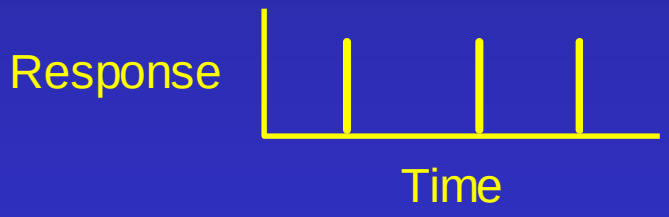
Stimulus condition

Electrical response

Retinal Receptive Fields

Receptive field structure in ganglion cells:
On-center Off-surround



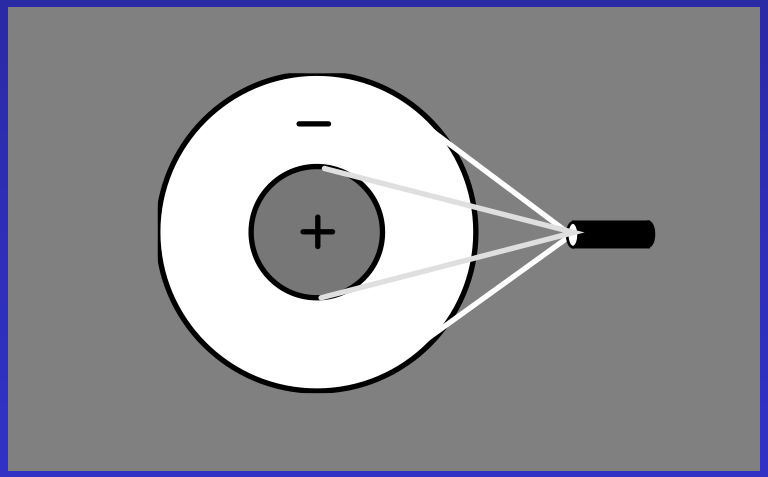


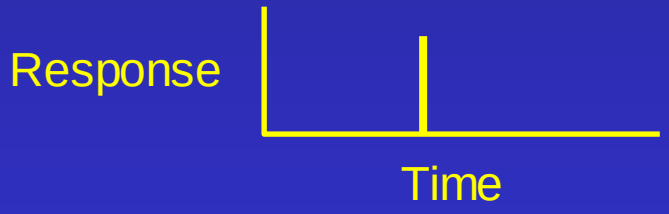
Stimulus condition

Electrical response

Retinal Receptive Fields

Receptive field structure in ganglion cells:
On-center Off-surround



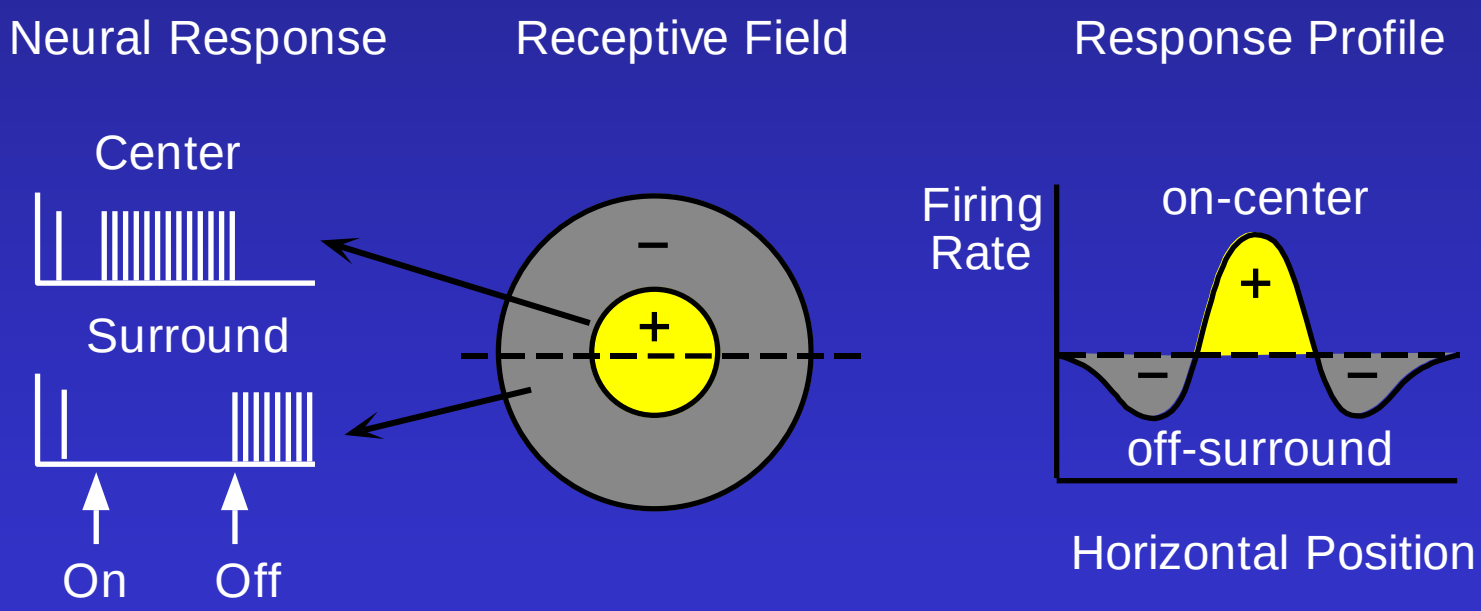


Stimulus condition

Electrical response

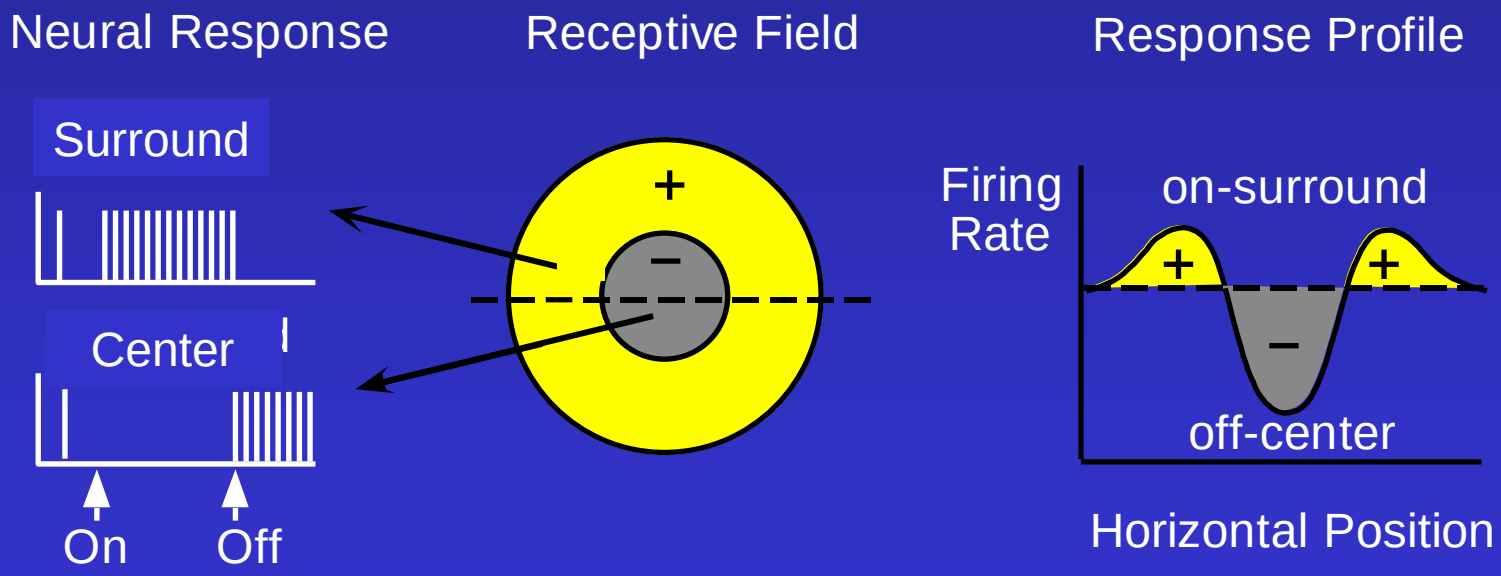
Retinal Receptive Fields

RF of On-center Off-surround cells



Retinal Receptive Fields

RF of Off-center On-surround cells



Receptive Fields

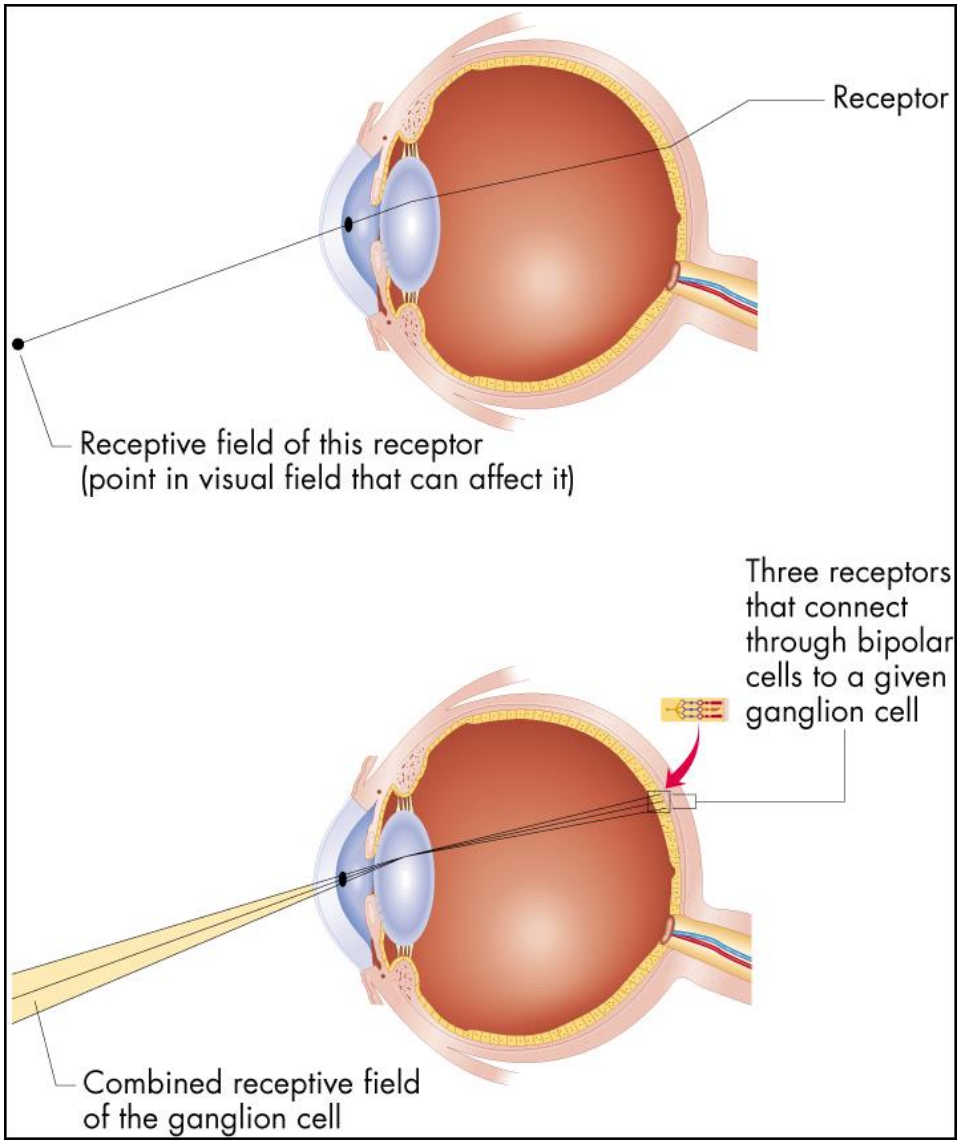
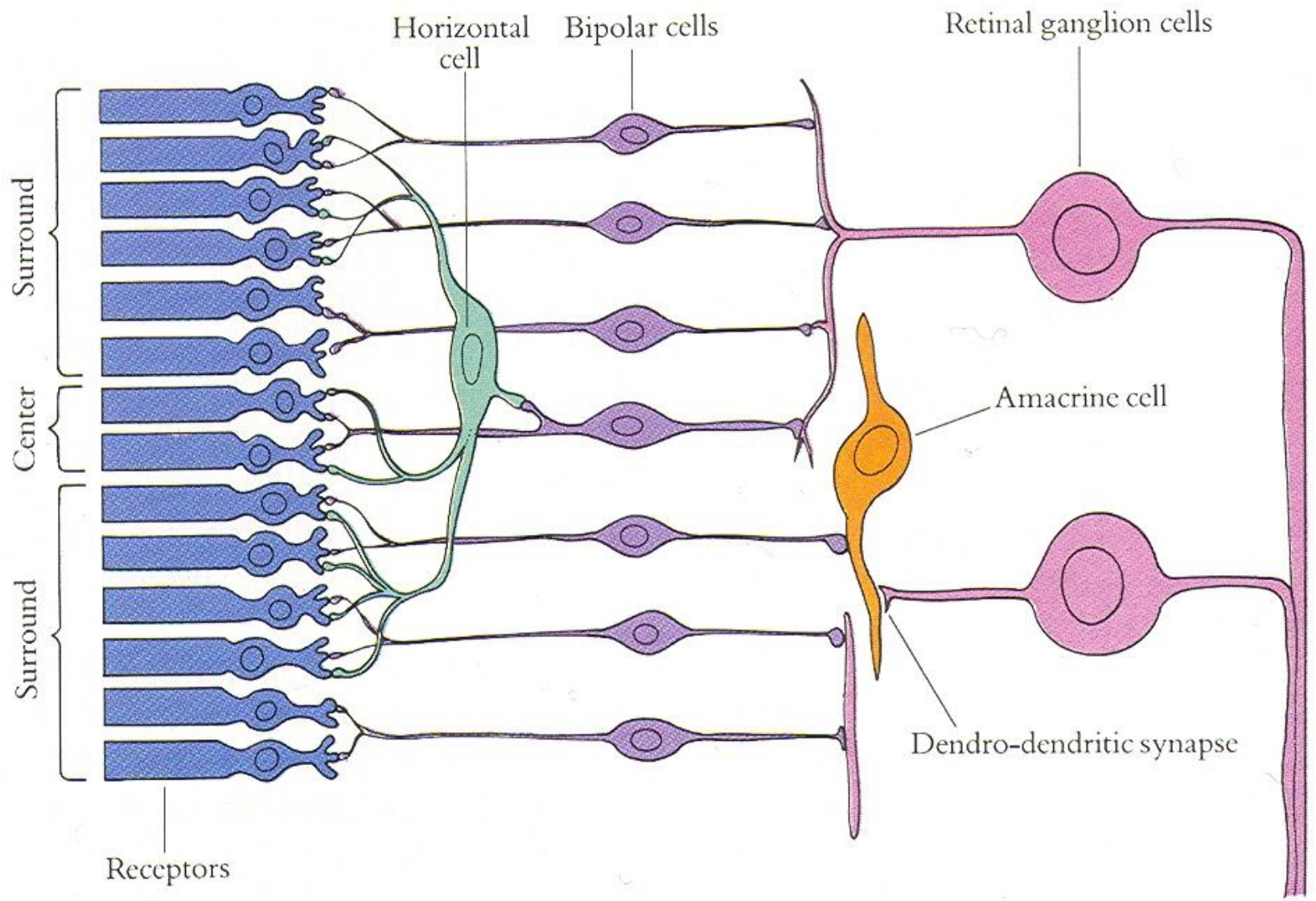


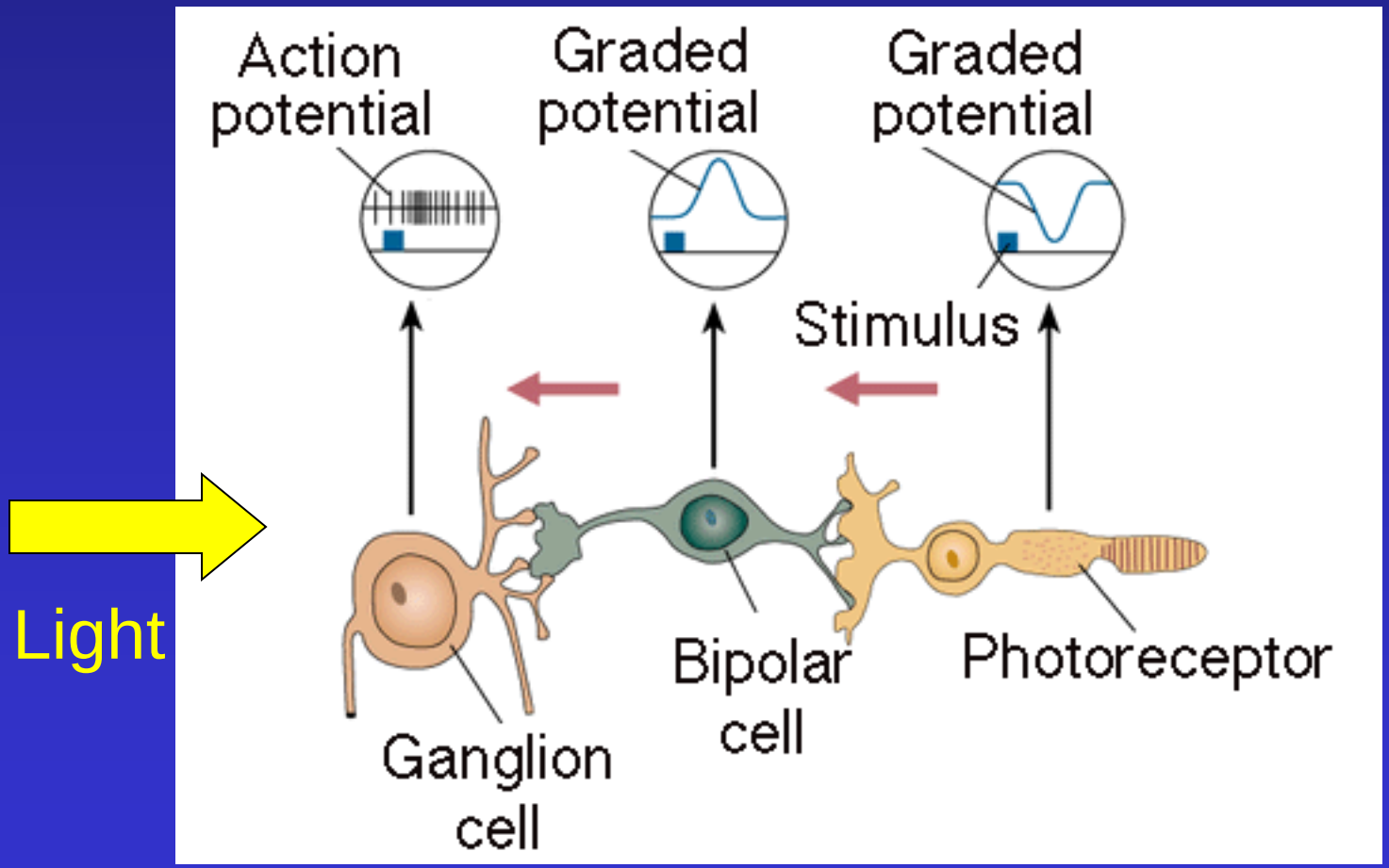
Figure 6.16 Receptive fields
The receptive field of a receptor is simply the area of the visual field from which light strikes that receptor. For any other cell in the visual system, the receptive field is determined by which receptors connect to the cell in question.

Retinal Receptive Fields



Retinal Receptive Fields

Receptive field structure in bipolar cells



Retinal Receptive Fields

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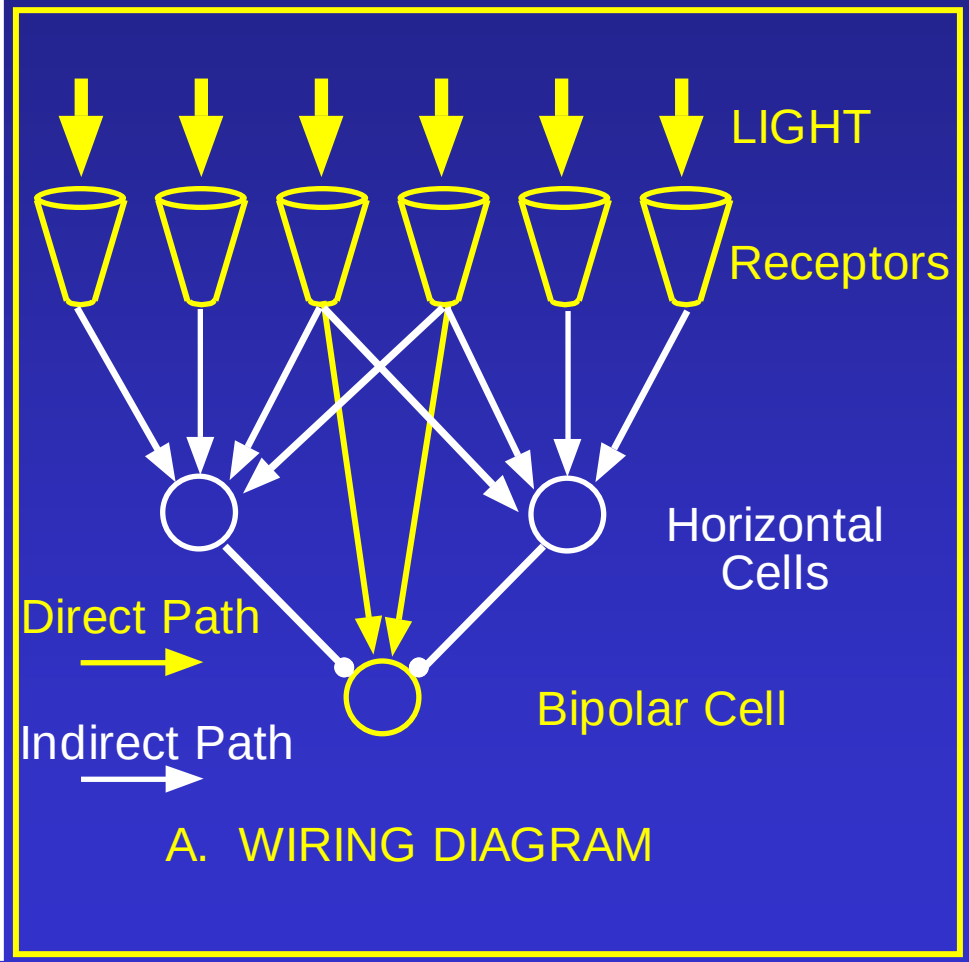
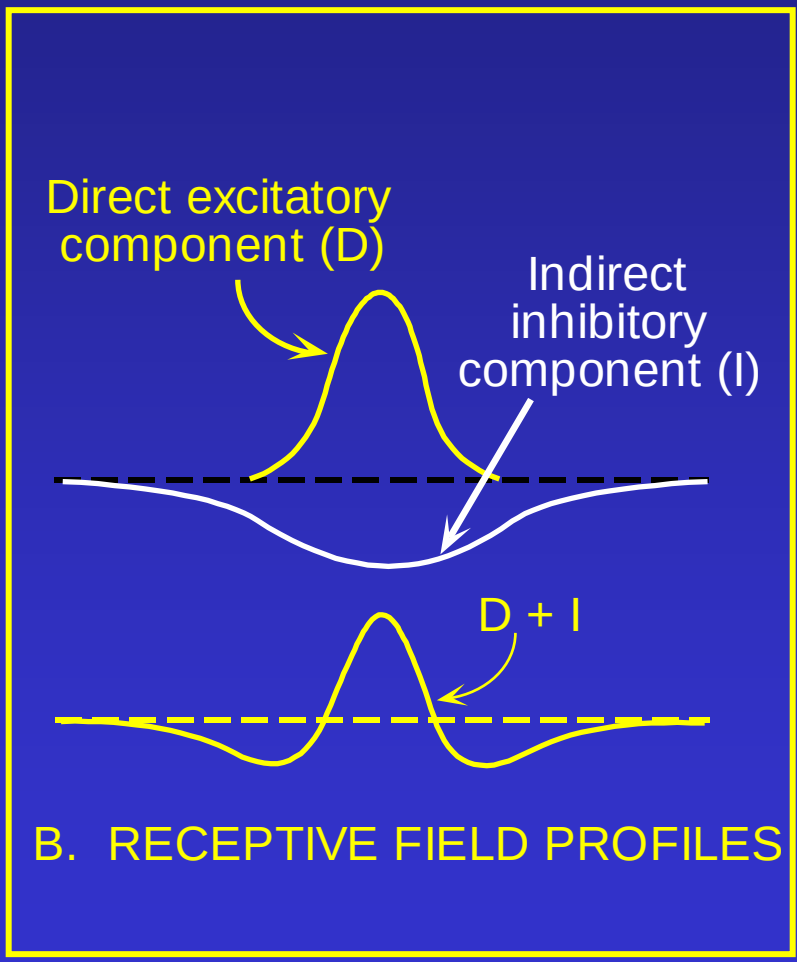
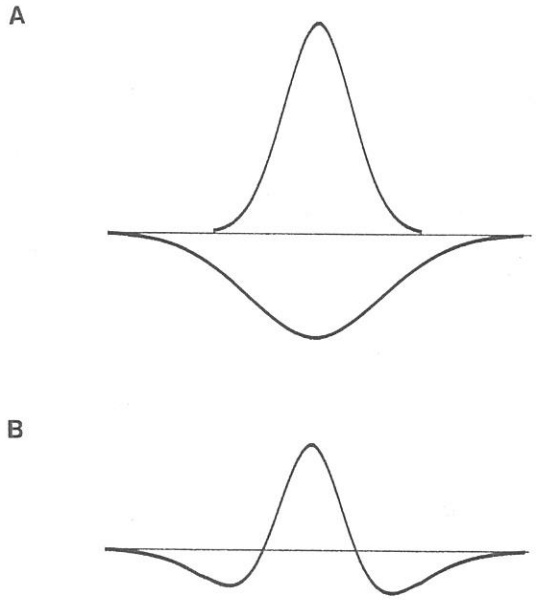
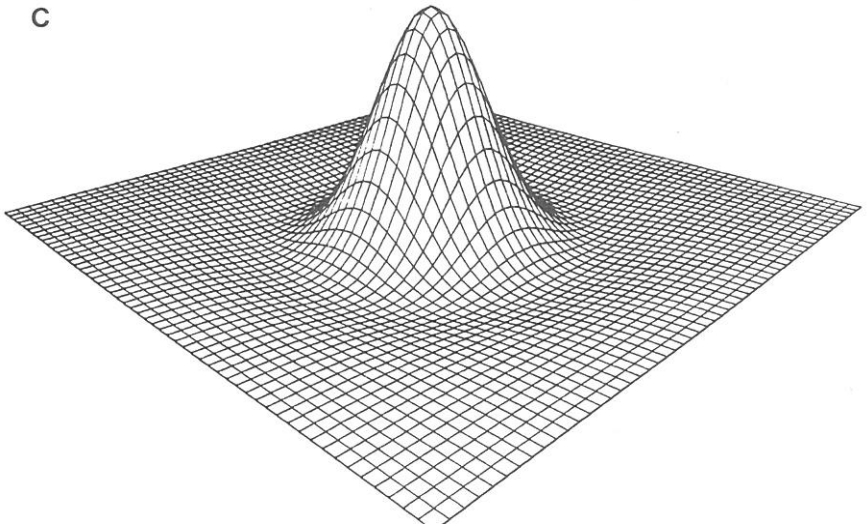




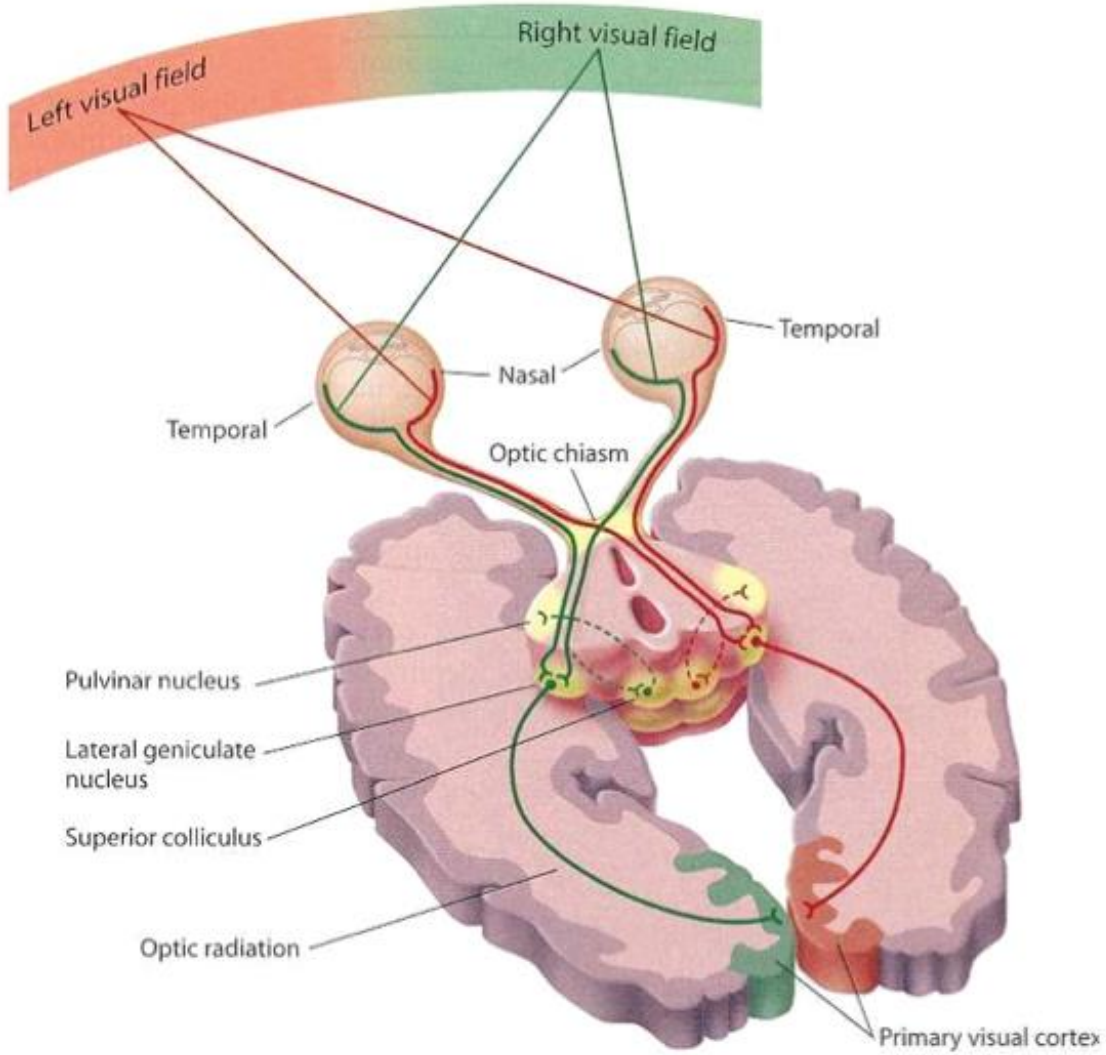
The receptive field of a retinal ganglion cell can be modeled as a “Difference of Gaussians”





$$G_\sigma(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{r^2}{2\sigma^2}}$$

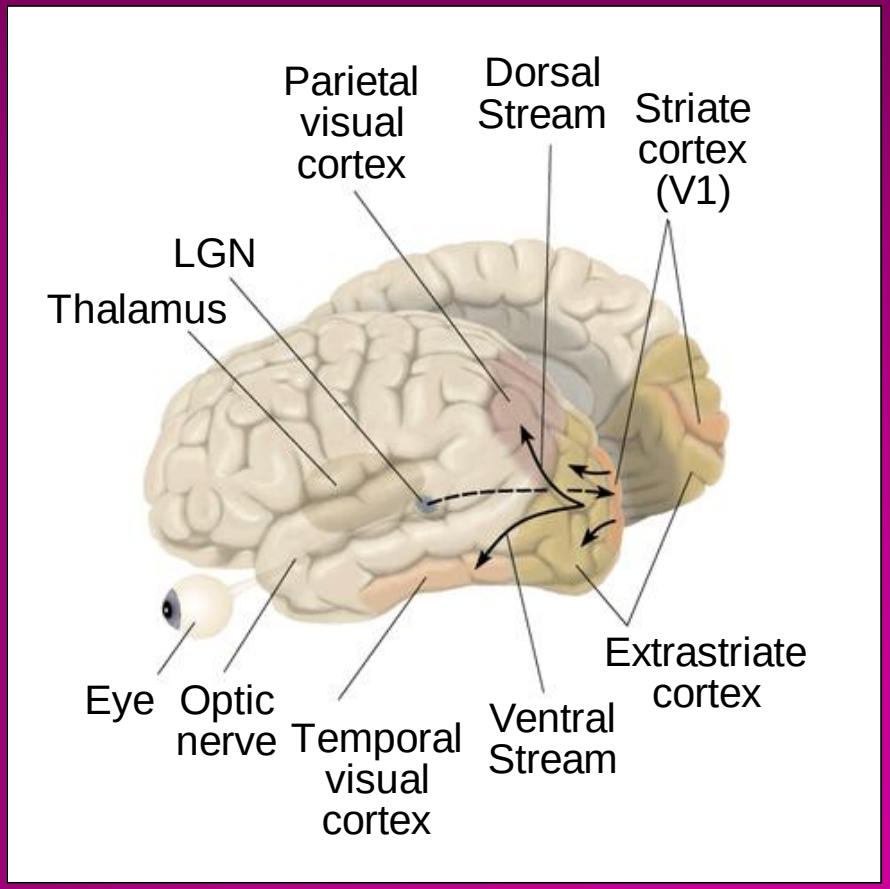
Anatomy of Pathway to Visual Cortex



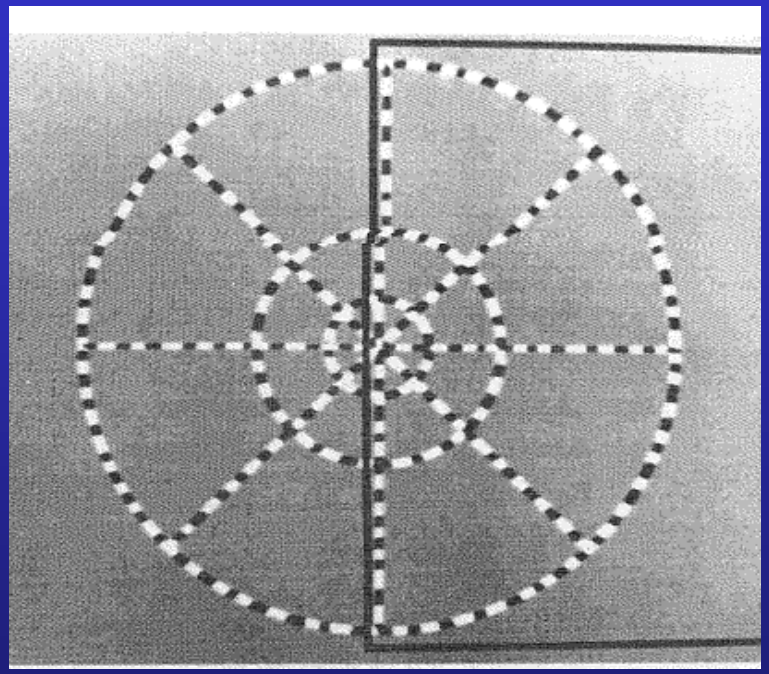
Visual Cortex

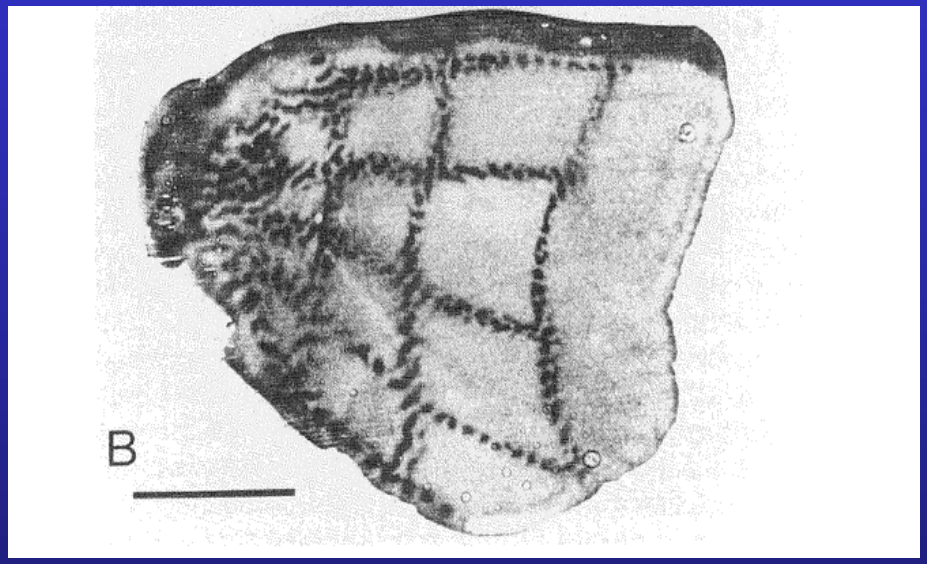
Cortical Area V1

aka:
Primary visual cortex
Striate cortex
Brodman's area 17



Mapping from Retina to V1





Cortical Receptive Fields

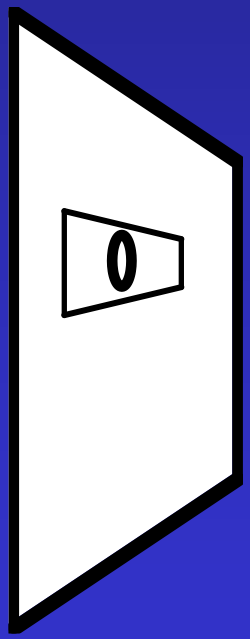
Single-cell recording from visual cortex

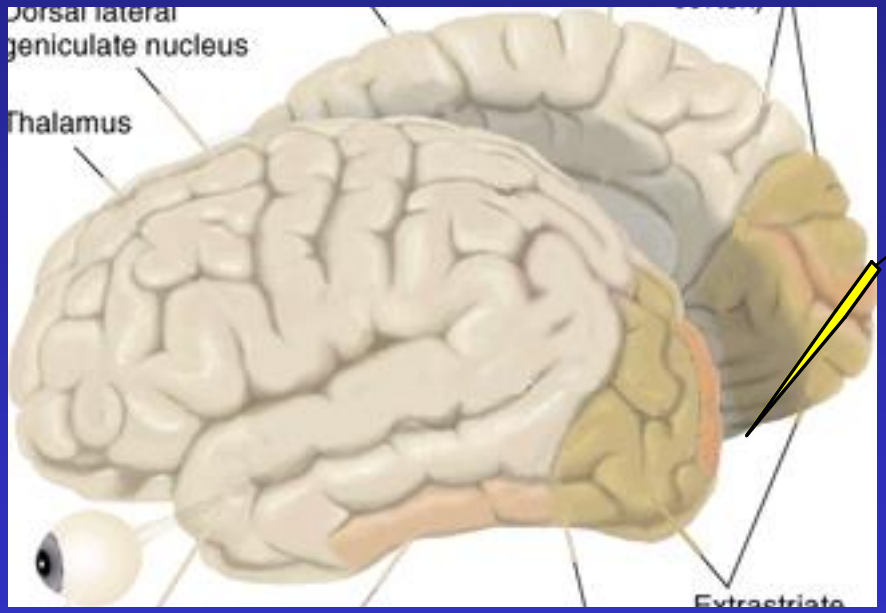
David Hubel & Thorston Wiesel

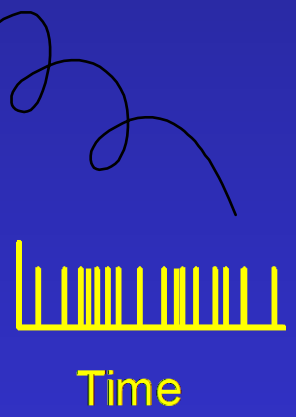
https://www.youtube.com/watch?v=IOHayh06LJ4

Cortical Receptive Fields

Single-cell recording from visual cortex







https://www.youtube.com/watch?v=IOHayh06LJ4

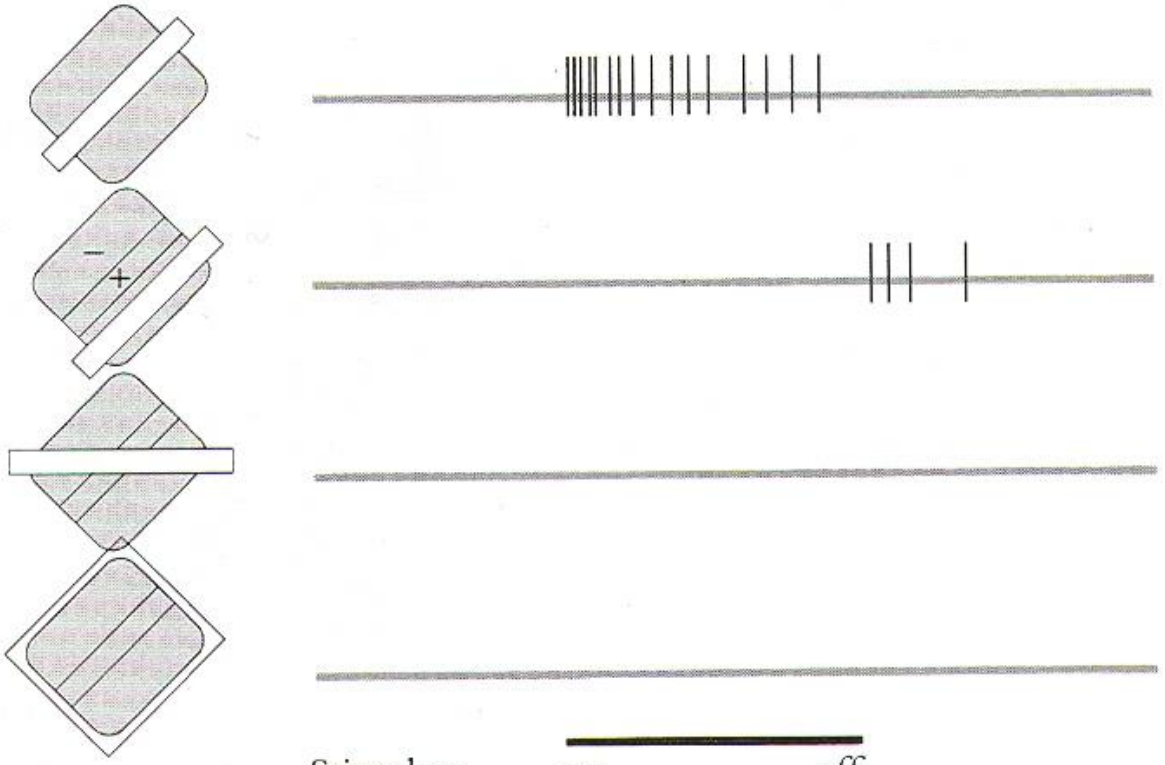
Cortical Receptive Fields

Three classes of cells in V1

Simple cells

Complex cells

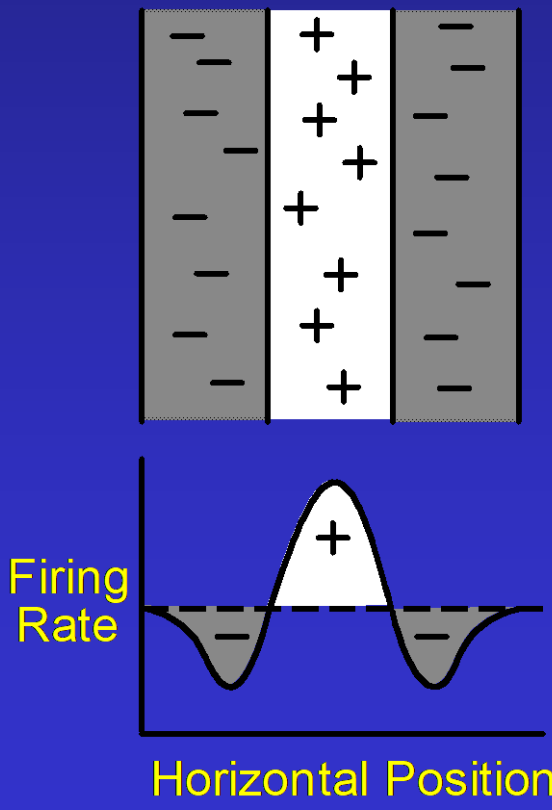
Hypercomplex cells


−
+
Stimulus:
on
off

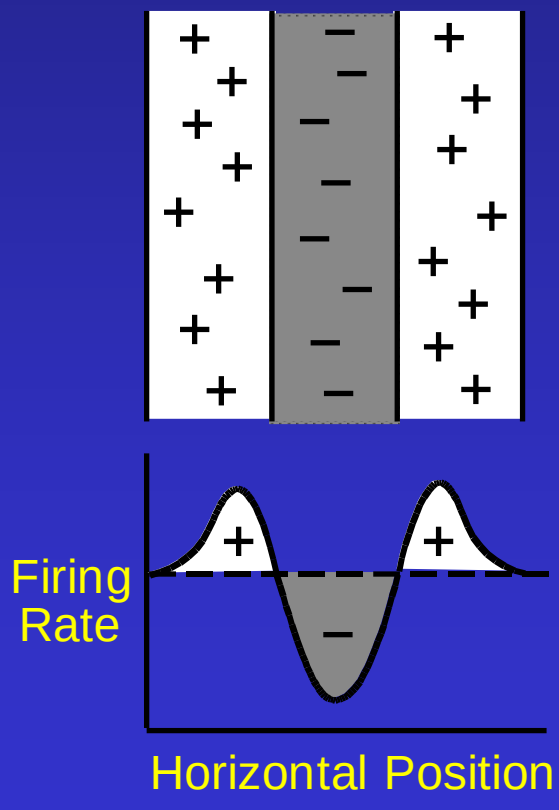
Cortical Receptive Fields

Simple Cells: "Line Detectors"

A. Light Line Detector



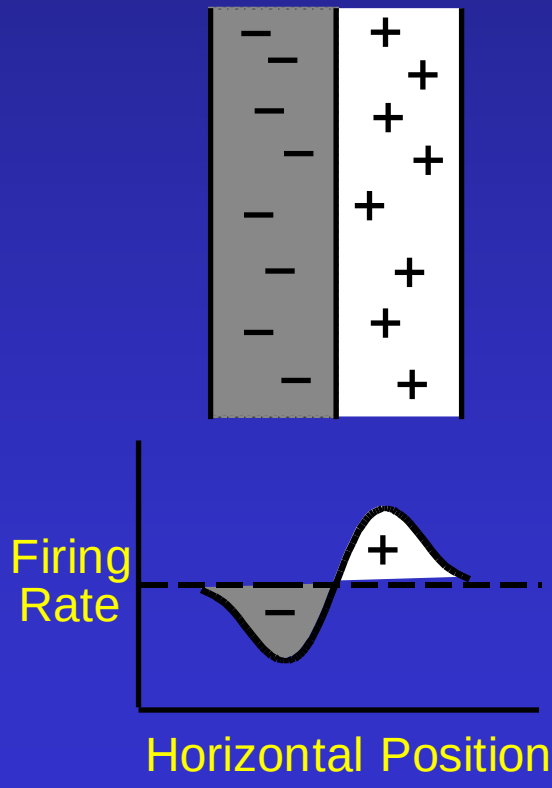
B. Dark Line Detector



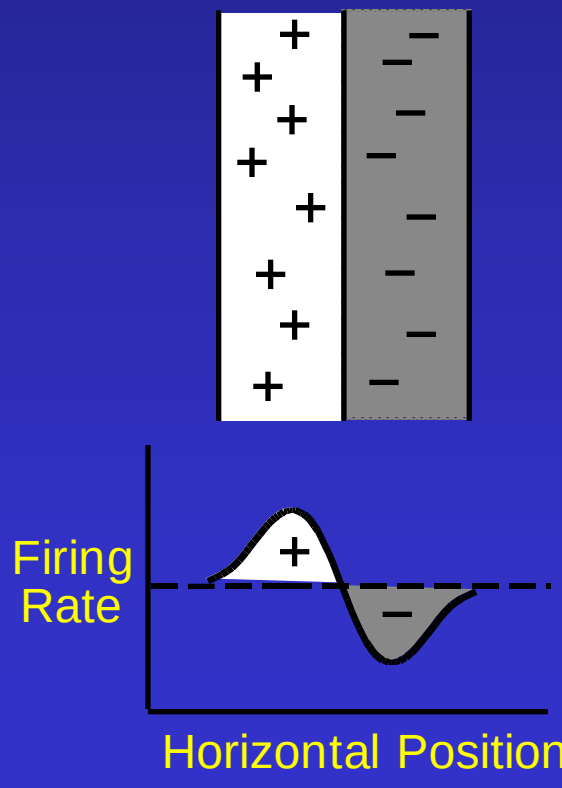
Cortical Receptive Fields

Simple Cells: "Edge Detectors"

C. Dark-to-light Edge Detecto

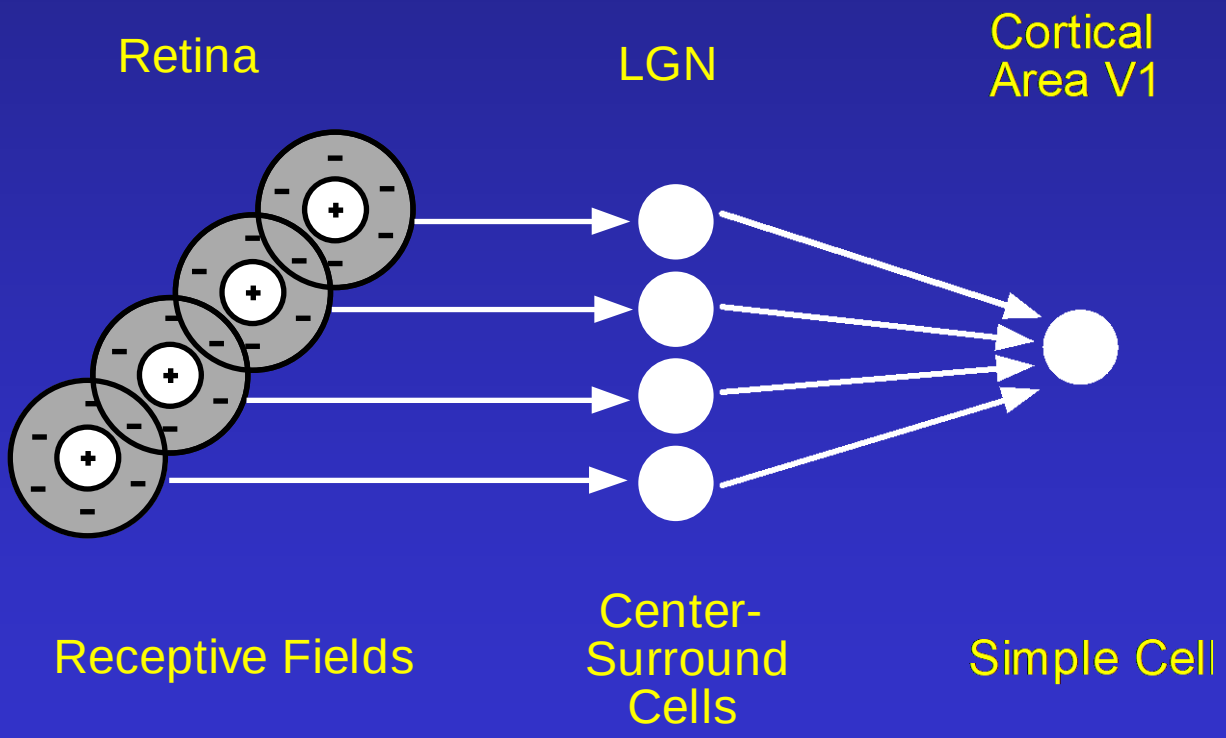


D. Light-to-dark Edge Detecto

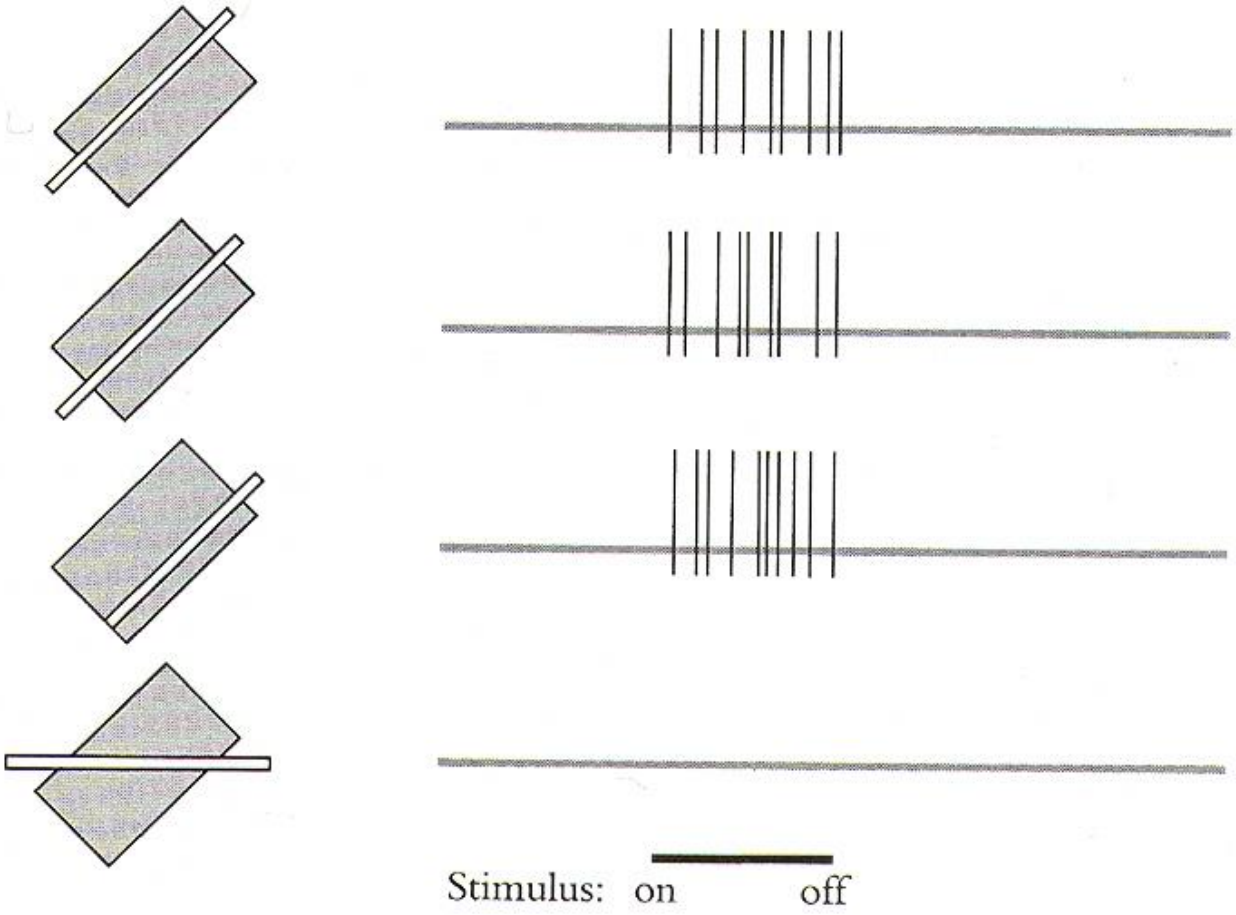


Cortical Receptive Fields

Constructing a line detector

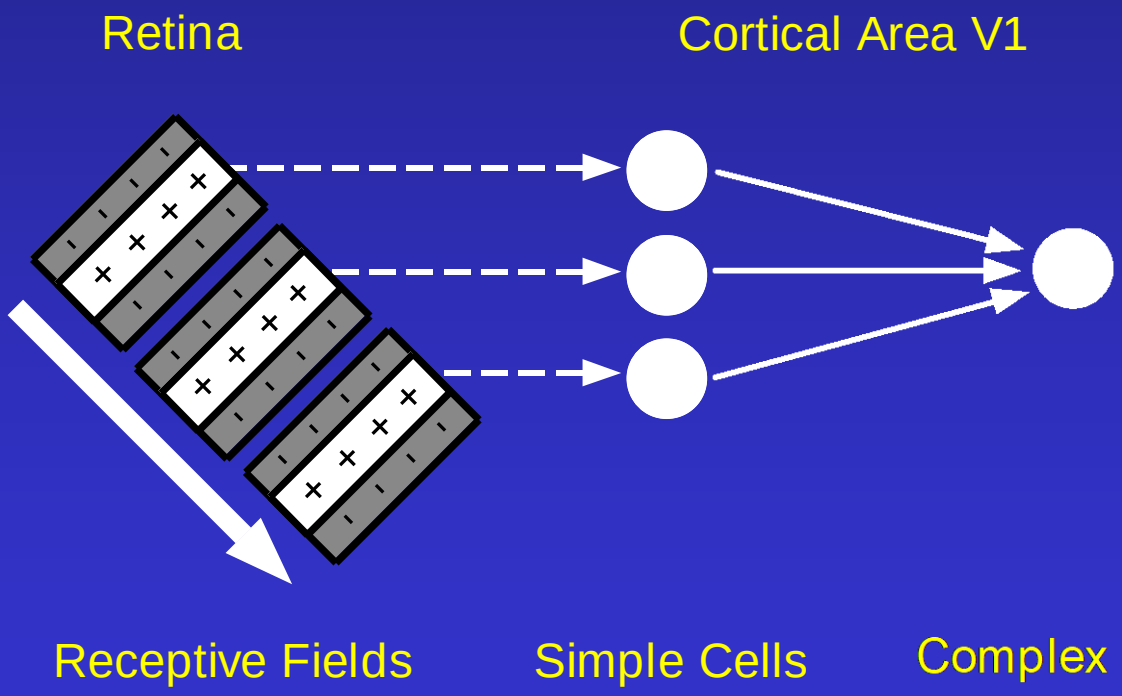


Receptive fields of complex cells



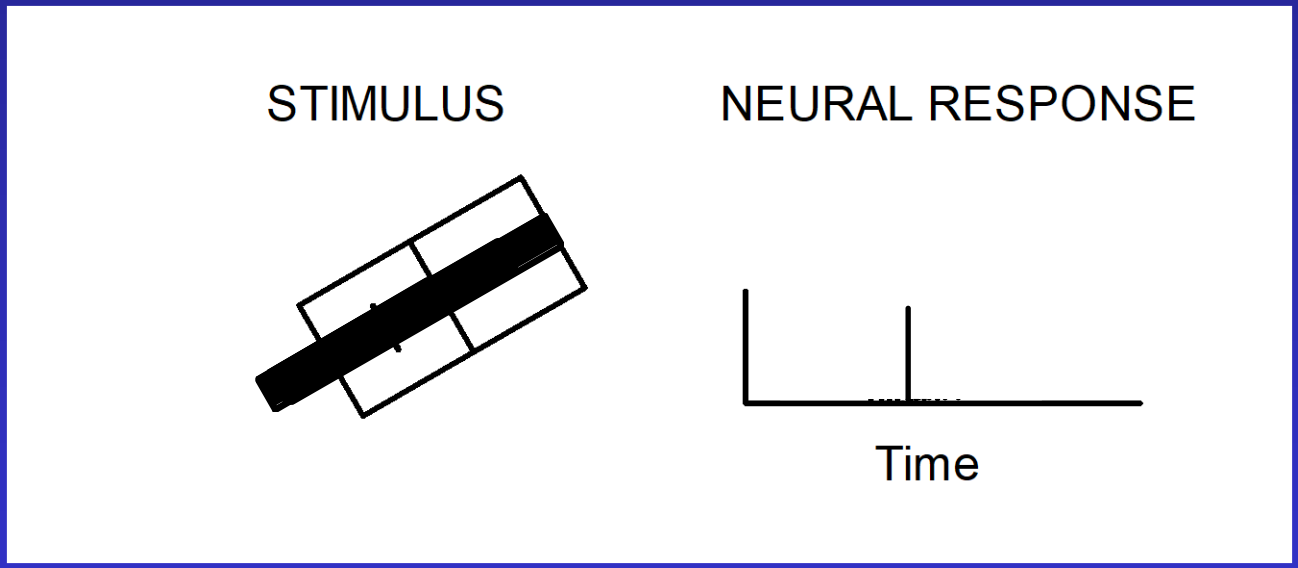
Cortical Receptive Fields

Constructing a Complex Cell



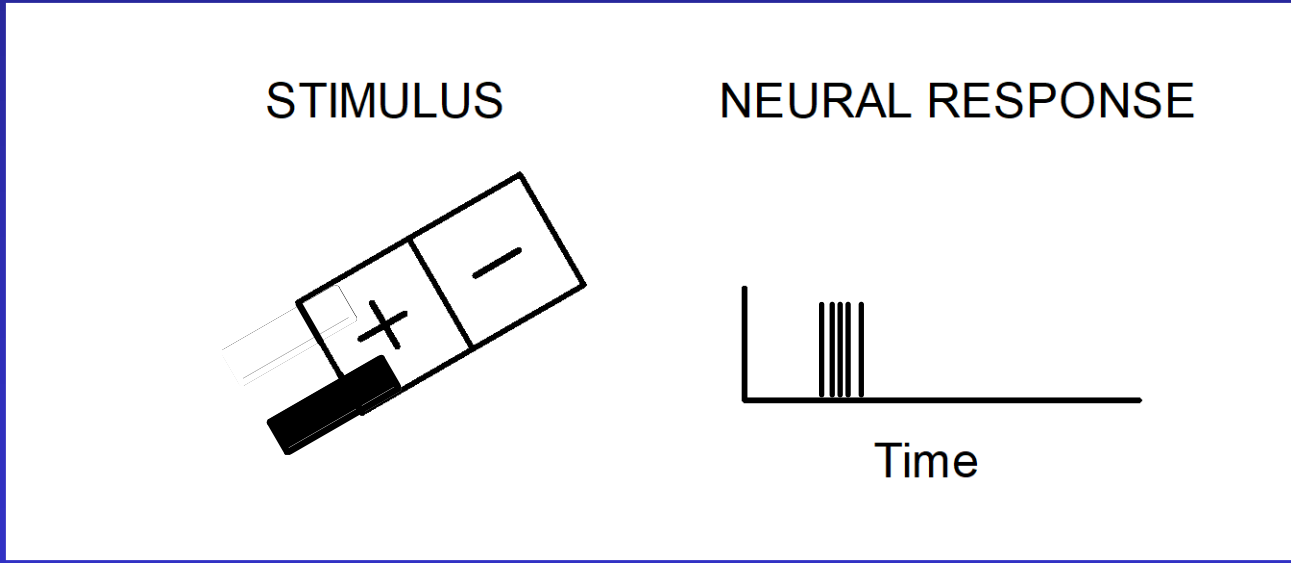
Cortical Receptive Fields

"End-stopped" Simple Cells



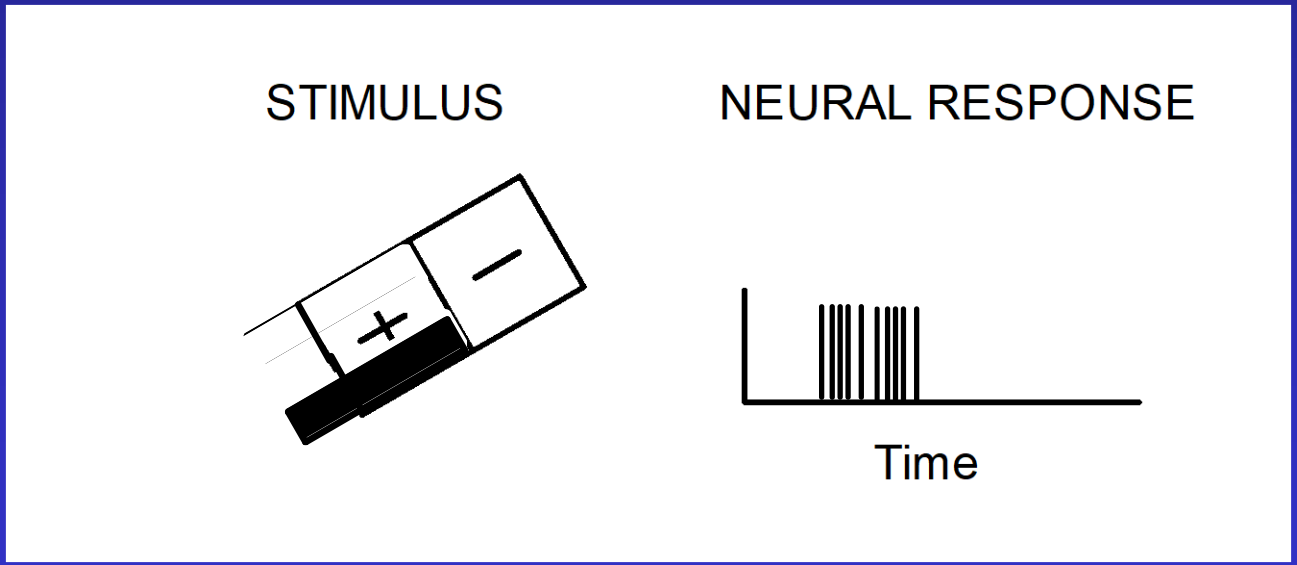
Cortical Receptive Fields

Hypercomplex Cells



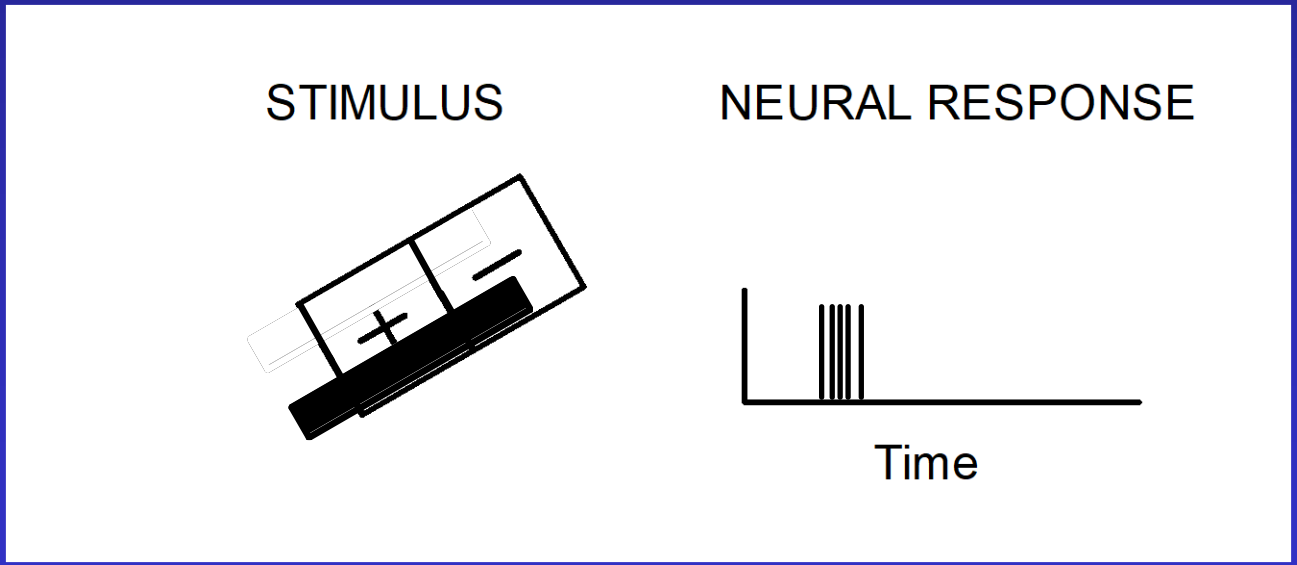
Cortical Receptive Fields

Hypercomplex Cells



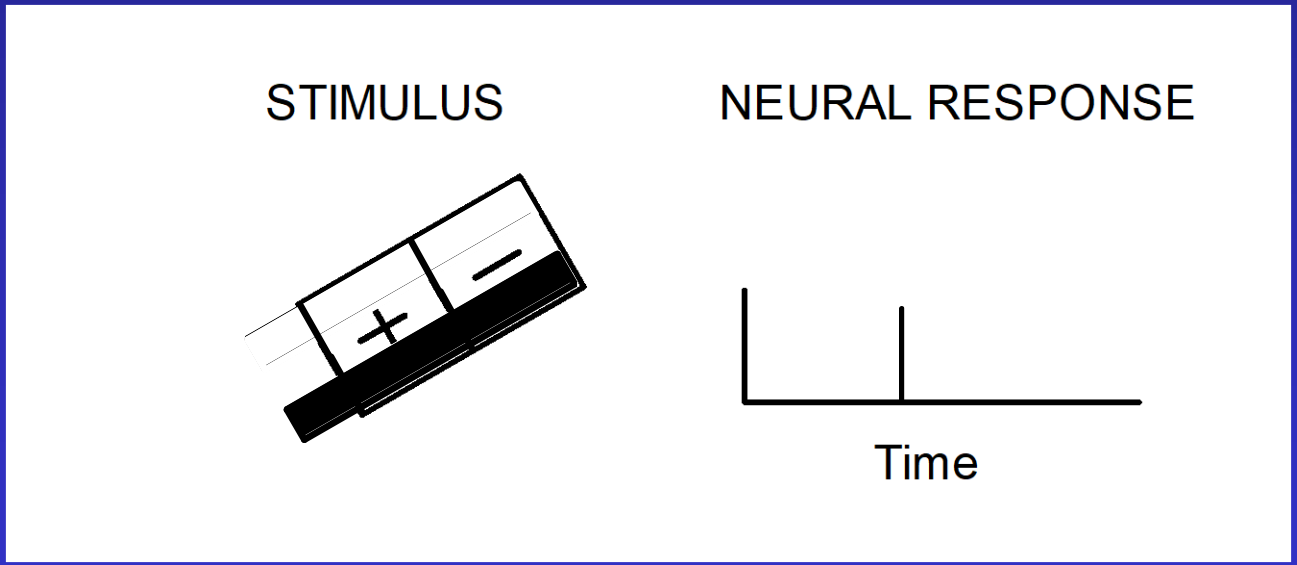
Cortical Receptive Fields

Hypercomplex Cells



Cortical Receptive Fields

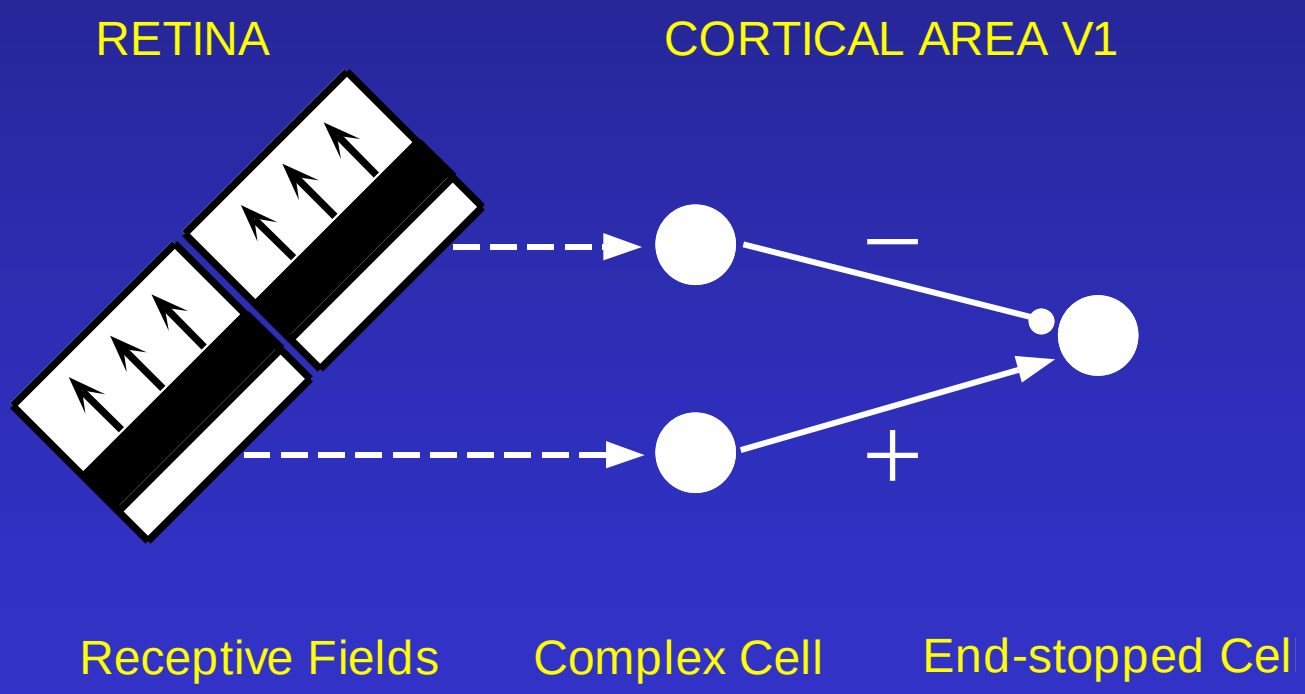
Hypercomplex Cells



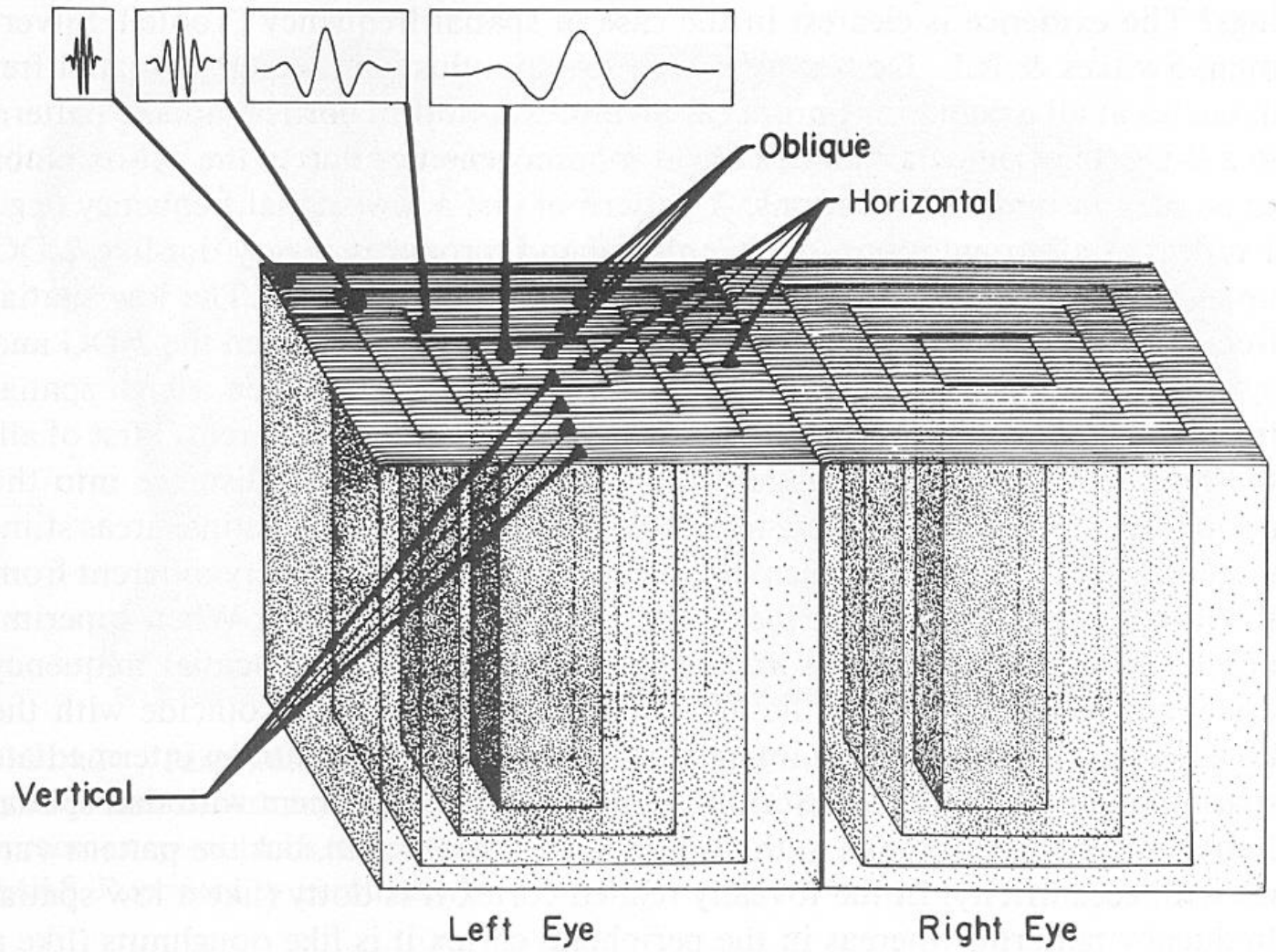
"End-stopped" Cells

Cortical Receptive Fields

Constructing a Hypercomplex Cell



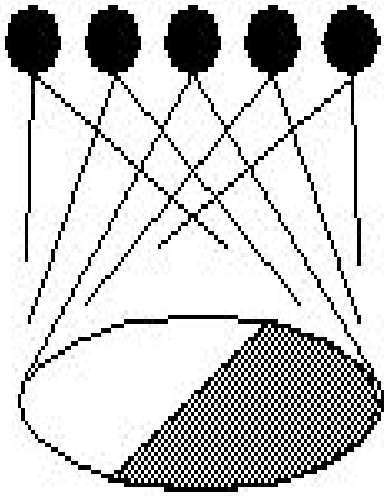
Hypercolumns in visual cortex



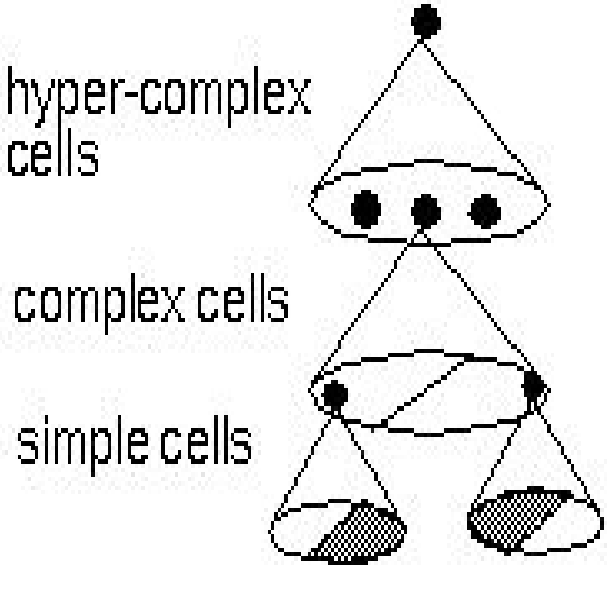
Model of Striate Module in Monkeys

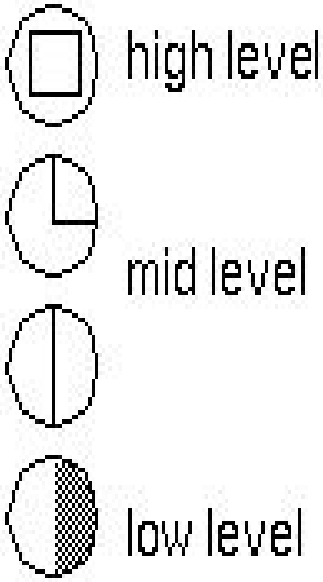
Hubel & Weisel

topographical mapping



featural hierarchy





Rolls et al (2000) model of ventral stream