Introduction to the Retina

A.L. Yuille (JHU).

(with material from other sources).

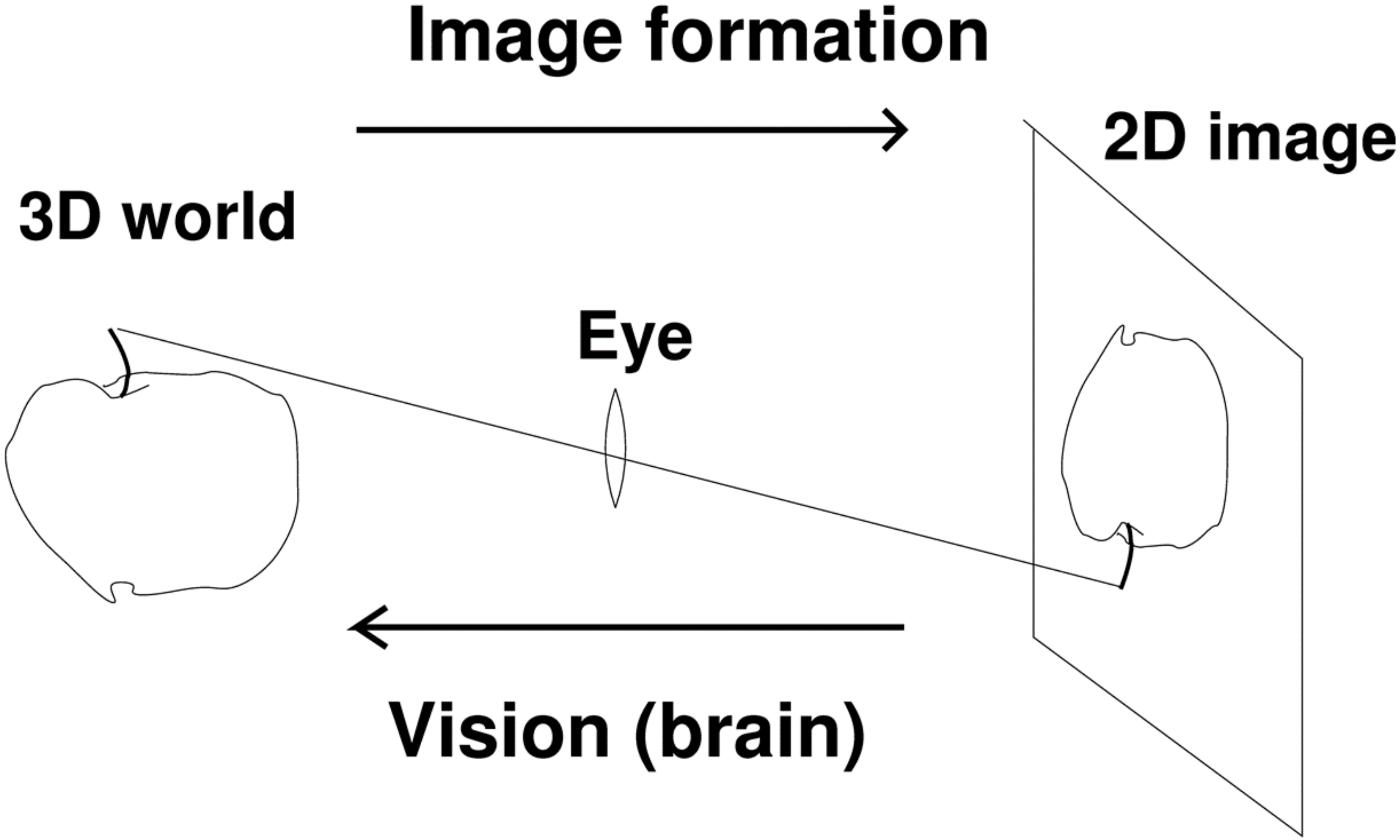
The Retina – basic properties

- ***Part 1. The Retina as the input to the visual system. The start of the visual hierarchy.***
- ***Part 2. The Purpose of the Retina.***
- ***Part 3. Complexity of the Retina.***

- ***Part 2. Neurons, basic properties.***

Part 1: Retina as the input to the visual system

- The retina



The Structure of the Eye

- *Only a small percentage of photons that enter the eye reach the photoreceptors.*
- *But the eye is extremely efficient at detecting photons which do (Bialek –optional reading).*
- *Light is transmitted by the Optic Nerve (biggest human nerve) to Visual Cortex (this causes a visual "blindspot").*
- *The transmission of the Optic Nerve is orders of magnitude less than are needed to download a movie from the internet.*

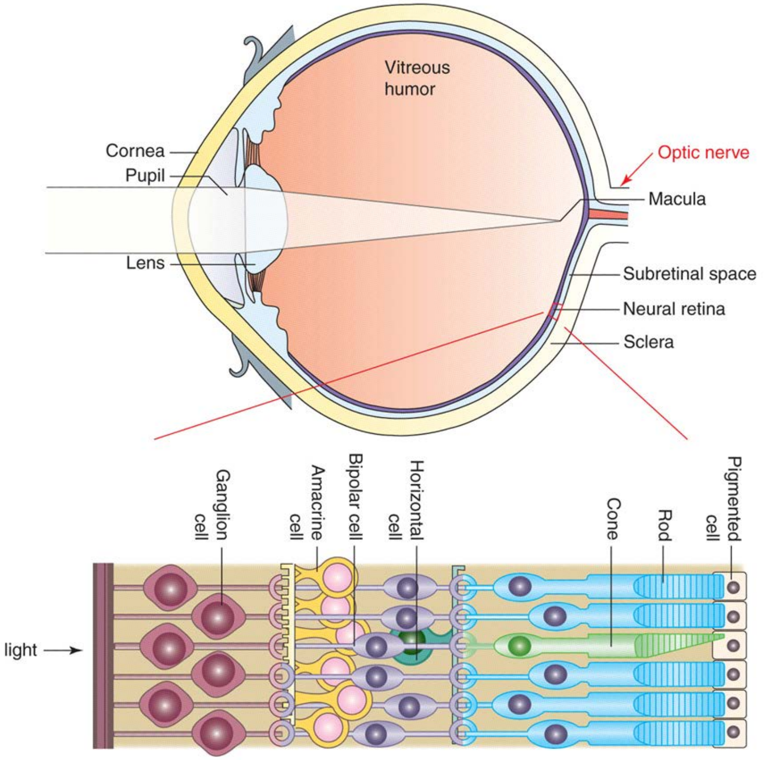


Figure from "Understanding Vision: theory, models, and data", Li Zaoping, Oxford University Press, 2014

The Fovea and the Periphery

- The density of cones (color) photoreceptors peaks at center(fovea) and falls off very rapidly.
- Gives high resolution in a very limited region.
- Rods (night vision) are mostly in the periphery.
- Two main consequences:
- (1) *Rapid eye movements (to move fovea)*
- (2) *Crowding effects (in the periphery)*

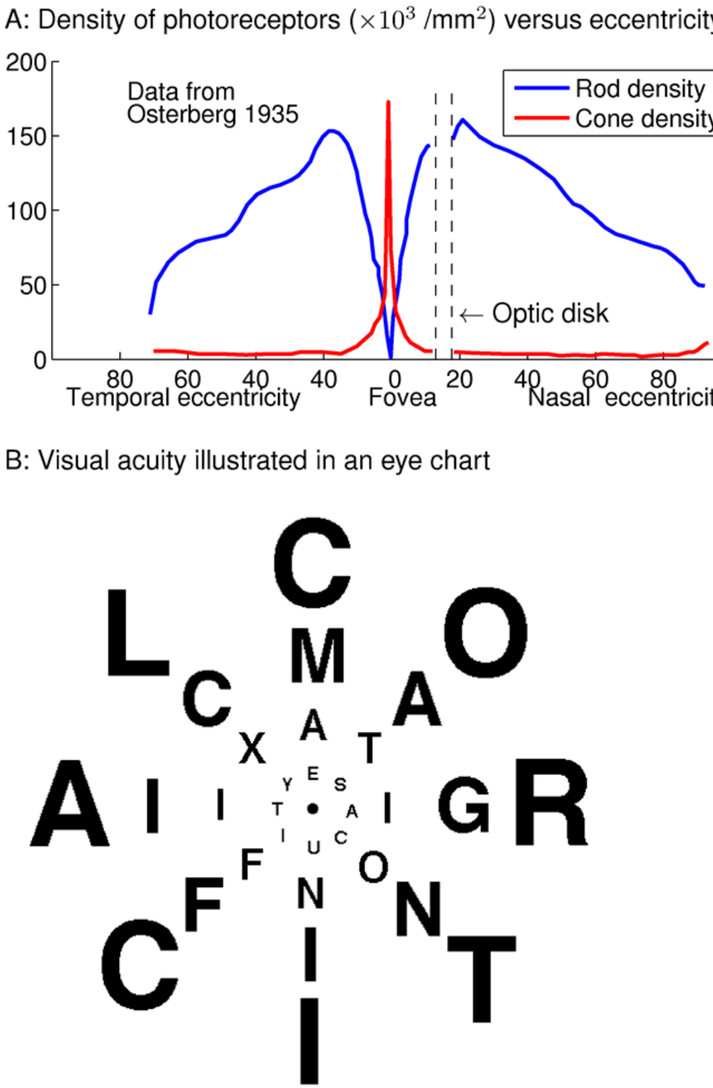


Figure from "Understanding Vision: theory, models, and data", by Li Zhaoping, Oxford University Press, 2014

Eye Movements: saccades

- Eyes are move frequently (several times a second). Movements take between 20-100 msec (10-3 seconds). These are saccades.
- NI-vision -- how do humans have consistent perception despite eye movements?
- Related phenomenon: In-attentional blindness – difficultly to spot the difference between two images – and crowding (see later).
- *Do AI-vision systems need to have a high-resolution fovea and a low-resolution periphery?*
- *Surely AI-vision does not need to make rapid eye movements (saccades)?*
- *Surely AI-vision would want to avoid in-attentional blindness, or crowding?*

Crowding: problems in the periphery.

- When humans fixate on an object they are only partially aware of objects in the rest of the visual environment.
- Many visual scenes includes multiple objects. So this impacts virtually all everyday tasks including reading, driving, and interacting with the environment.
- Crowding impairs the ability to recognize and scrutinize objects in the periphery, but it does not make them disappear. Sometimes it is impossible to recognize the spatial order of objects (or letters).
- *D. Whitney & D. M. Levi. Visual Crowding: a fundamental limit on conscious perception and object recognition. Trends Cogn Sci. 2011 Apr; 15(4): 160–168.*

Crowding.

- A. Fixate at the bull’s-eye, near the construction zone. Observe it is difficult or impossible to recognize the child on the left side of the road, because of the presence of the nearby signs. The child on the right, on the other hand, is relatively easier to recognize.
- B. While fixating the crosses, identifying the middle shape, letter, or line orientation—or even the number of tilted lines—is difficult or impossible on the bottom half of the panel. Crowding impairs the ability to recognize and scrutinize objects, but it does not make them disappear; one can see that some thing is present in panel (A), but it is difficult to identify the thing as a child as opposed to another sign. Crowding defines the spatial resolution of conscious object recognition throughout most of the visual field. (see handout paper by Whitney and Levi for more details).

Retinotopy: spatial organization

- The retina has natural spatial organization (like a camera).
- Higher visual areas – e.g., V1, V2 in visual cortex also have similar spatial organization to retina. This is called Retinotopy.

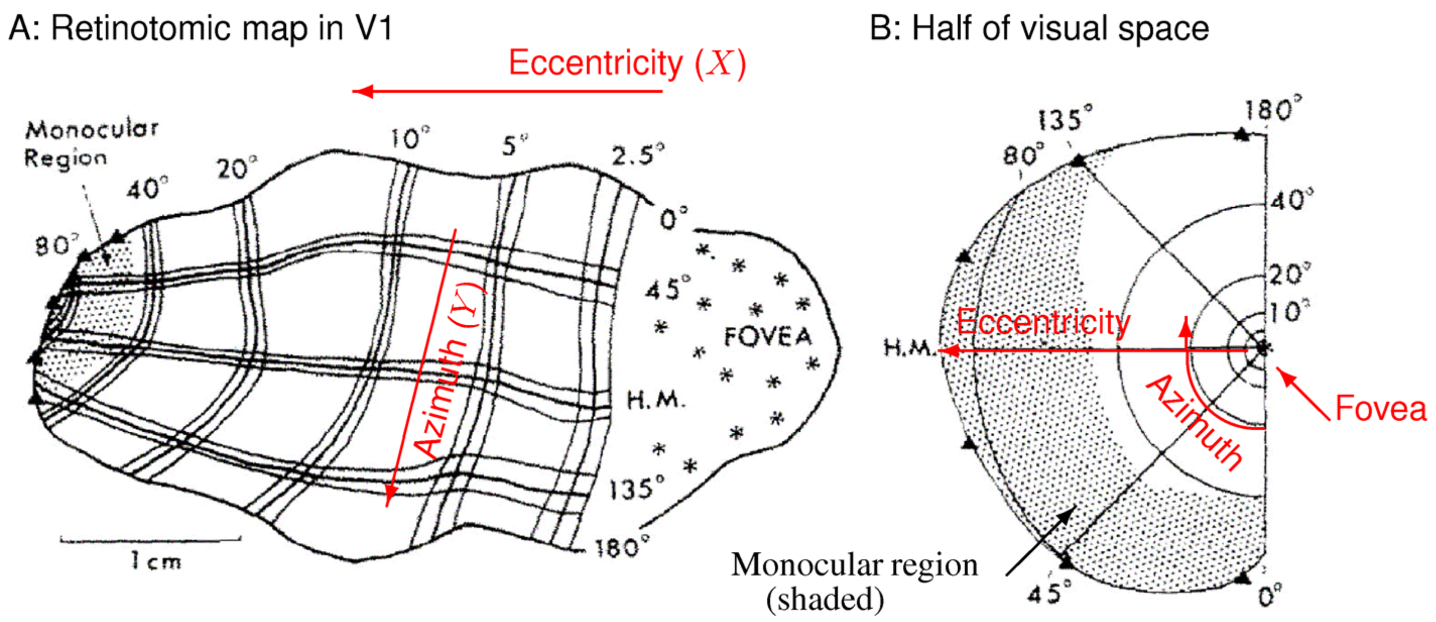
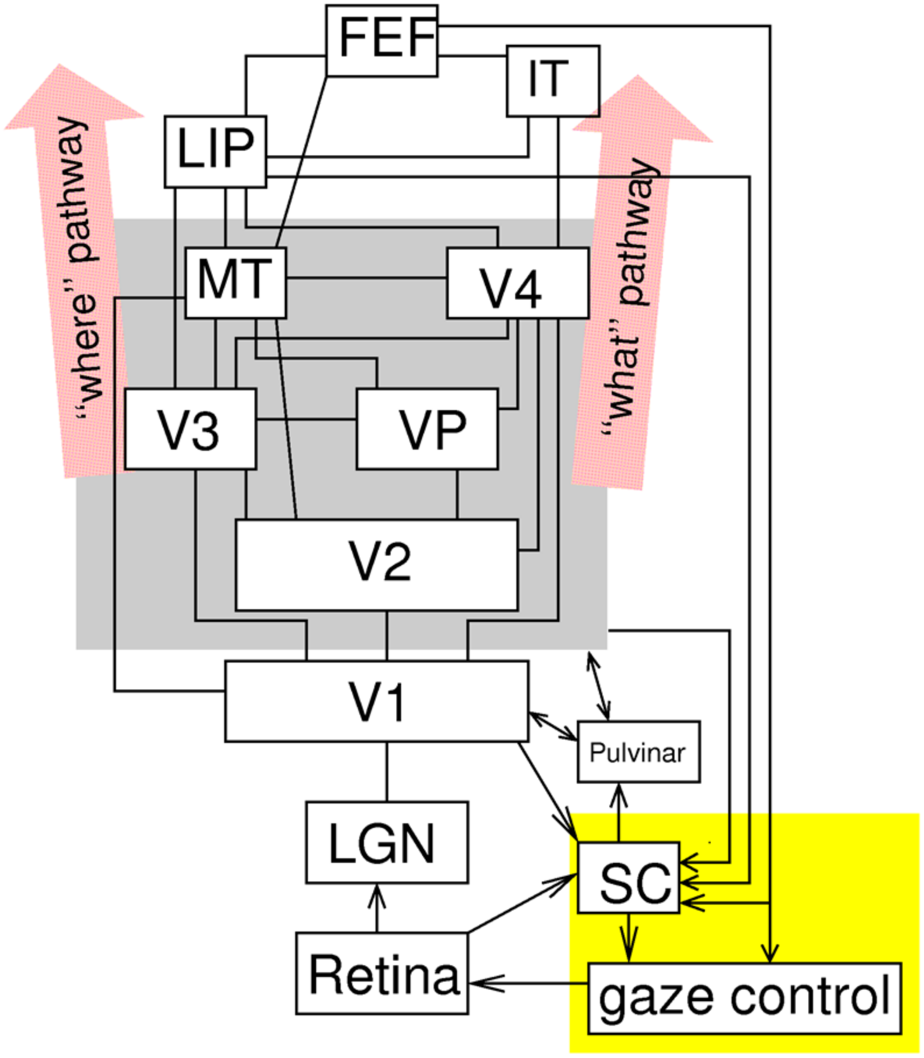


Figure from "Understanding Vision: theory, models, and data", by Li Zhaoping, Oxford University Press, 2014

Retina as the start of visual hierarchy

- The Retina has no direct top-down input from the visual cortex.
- But the Retina is influenced by the Superior Colliculus (SC), which controls muscles for gaze control.

A schematic of the visual processing hierarchy



Part 2: Purpose of the Retina

- With about 10 million retinal receptors, the human retina makes on the order of 10 to 100 million measurements per second. These measurements are processed by about a billion plus cortical neurons.
- *How sensitive is the eye? What are the limits of vision?*

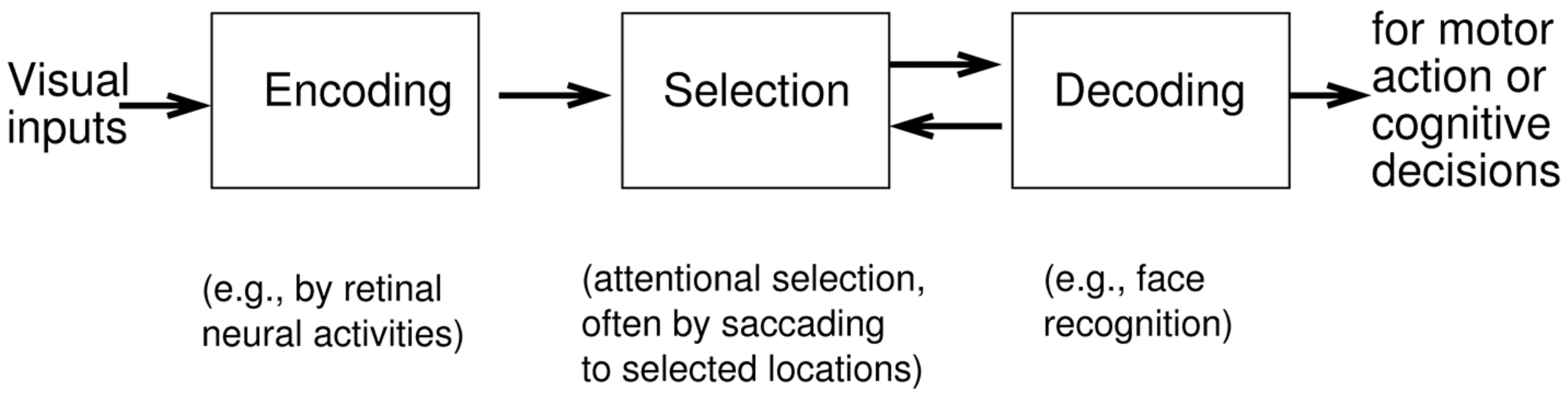
- It can be shown that the retina can be sensitive to a very small number of photons. This is close to theoretical predictions based on the biophysics of neurons (W. Bialek handout). Even more impressive that this knowledge can be transmitted to the decision-making brain areas.

Purpose of the Retina

- The anatomy and electrophysiology of the retina has been studied extensively – in far more detail than the cortex (it is “approachable”).
- The main functions of the retina are believed to be:
- (i) *Capturing images* – i.e., converting image intensity patterns to neural activity patterns. (see Bialek handout).
- (ii) *Encoding these patterns so they can be transmitted efficiently to the visual cortex.* (see Zhaoping Li book).
- (iii) *Dealing with the enormous dynamic range of visual stimuli, ranging from 1 photon to 10^9 photons* (e.g., direct gaze at the sun).
- Note: modern digital cameras have to address similar challenges and require many tricks to do so. But, unlike humans, they also require postprocessing to edit images (e.g., Picassa).

Encoding Images for Transmission

- Zhaoping Li's conceptual picture. Retina captures image and encodes for transmission to LGN (Thalamus) and then to visual cortex V1.
- This can be formulated in terms of Information Theory (Shannon). How to best encode images so as to transmit them to the visual cortex efficiently (where they can be decoded and processed).



3. Complexity of the Retina

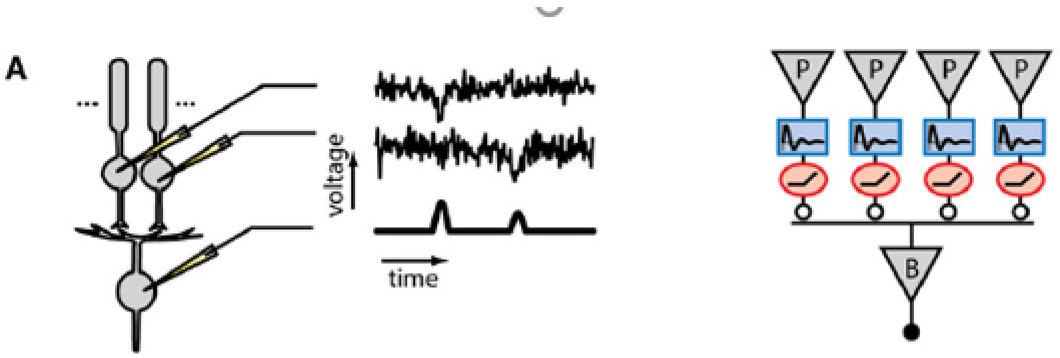
- Does the retina *simply* capture images and transmit them to the visual cortex?
- Standard models (see next lecture) can predict some retinal properties using simple linear models of neurons. *But there are problems:*
- (I) Studies of the retina of other (simpler) animals suggest that their retinas do more complex processing "smart animals have dumb retinas and dumb animals have smart retinas." (*Current models are based on experimental findings using simple stimuli, but neurons may behave differently when they see more natural stimuli).*
- (II) Smart camera are much more complex than standard models of the retina. They involve complex nonlinear algorithms to deal with saturation, color changes, blurring.
- (III) If the retina is so simple (as standard models), then why does it have so many neurons and why so many diverse types and so many diverse shapes/morphology?

The Retina is Complex

- Gollisch and Meister claim that the primate retina is much more complex than standard models.

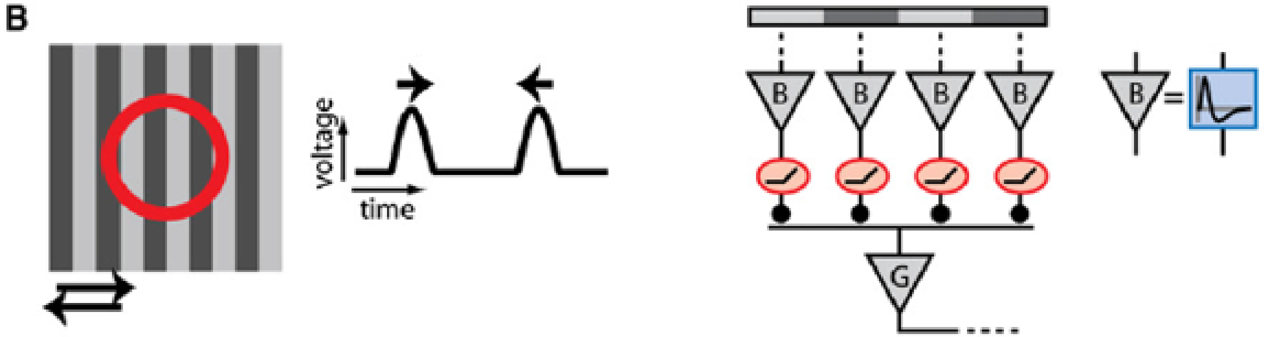
- They describe six computations performed by the retina and their underlying microcircuits:
- (A) Dim Light. (B) Moving Textures. (C) Differential Motion.
- (D) Approaching Motion. (E) Spatial Structures. (F) Switching Circuits.

Gollisch and Meister: (A) Dim Light.



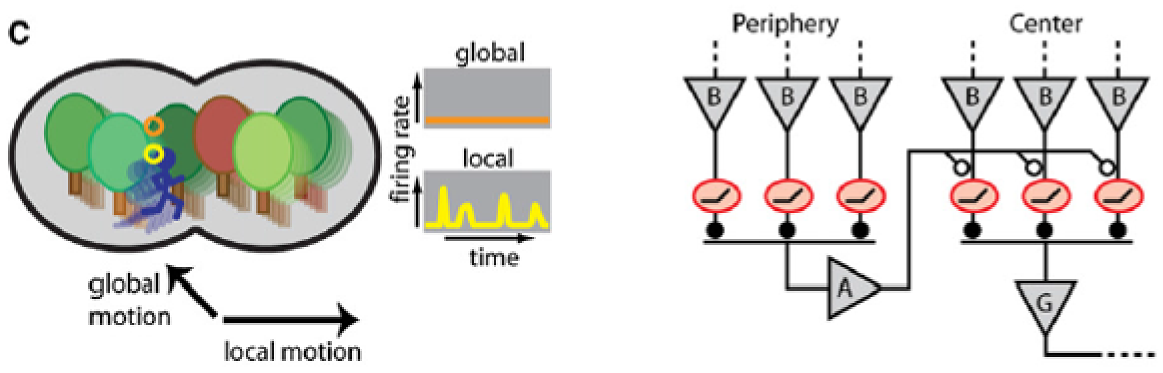
(A) Detection of dim light flashes in the rod-to-rod bipolar pathway. (Left) Rod bipolar cells pool over many rod photoreceptors, which show distinct responses to single-photon activation embedded in noise. Bipolar cell potentials are not swamped by the accumulated noise in all rods, but instead show distinct activations from single photons, as shown by the voltage traces from a simple model simulation. (Right) The important elements of the corresponding retinal microcircuitry. Each photoreceptor output is sent through a band-pass temporal filter followed by a thresholding operation before summation by the rod bipolar cell (Field and Rieke, 2002). Notation for this and all circuit diagrams: triangle, neuron; rectangle, temporal filter function; oval, instantaneous rectifier; closed/open circle, sign-preserving/inverting synapse.

Gollisch and Meister: (B) Moving Texture.



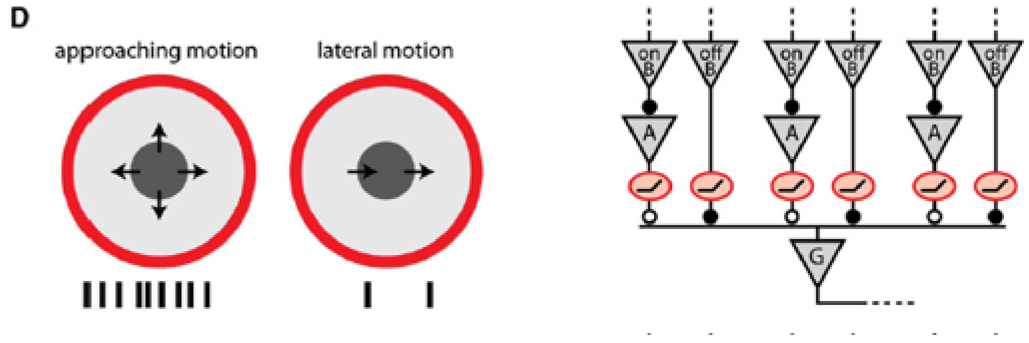
(B) Sensitivity to texture motion. (Left) Y-type ganglion cells show activation when a fine grating shifts in either direction over the receptive field (circle), even though the average illumination remains constant. (Right) The underlying microcircuit. Each shift of the grating excites some bipolar cells and inhibits others. The bipolar cells have biphasic dynamics (see impulse response in inset) and thus respond transiently. Only the depolarized bipolar cells communicate to the ganglion cell, because of rectification in synaptic transmission. Thus, the ganglion cell fires transiently on every shift (Hochstein and Shapley, 1976).

Gollisch and Meister: (C) Differential Motion



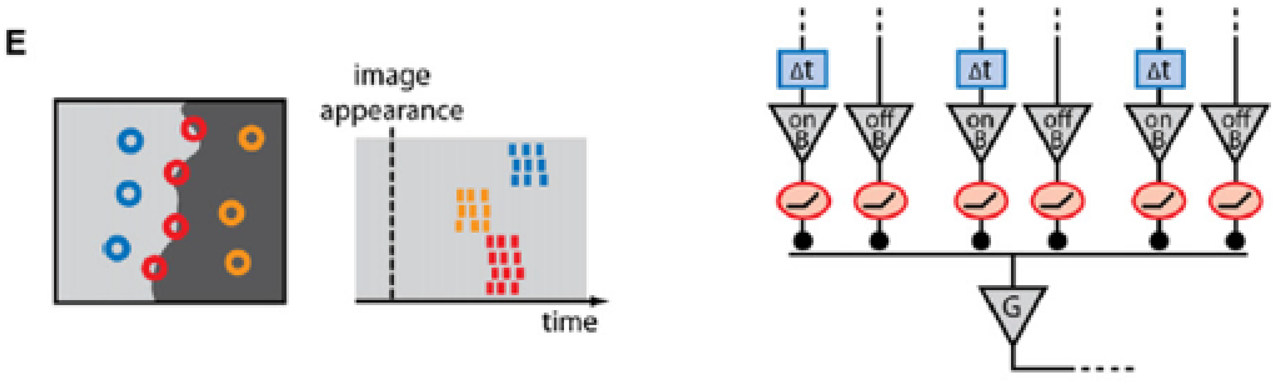
(C) Detection of differential motion. (Left) An object-motion-sensitive ganglion cell remains silent under global motion of the entire image but fires when the image patch in its receptive field moves differently from the background. (Right) The circuitry behind this computation is based on similar elements as for the Y cell (panel B). Rectification of bipolar cell signals in the receptive field center creates sensitivity to motion. Polyaxonal amacrine cells in the periphery are excited by the same motion-sensitive circuit and send inhibitory inputs to the center. If motion in the periphery is synchronous with that in the center, the excitatory transients will coincide with the inhibitory ones,

Gollisch and Meister: (D) Approaching Motion



(D) Detection of approaching motion. (Left) A certain type of retinal ganglion cell responds strongly to the visual pattern of an approaching dark object, as indicated by the schematic spike train below, but only weakly to lateral object motion. (Right) The circuit that generates this approach sensitivity is composed of excitation from OFF bipolar cells and inhibition from amacrine cells that are activated by ON bipolar cells, at least partly via gap junction coupling. Importantly, these inputs are nonlinearly rectified before integration by the ganglion cell (Münch et al., 2009).

Gollisch and Meister: (E) Spatial structures.



(E) Rapid encoding of spatial structures with spike latencies. (Left) Specific retinal ganglion cells encode the structure of a new image by their spike latencies. Cells with receptive fields (circles) in a dark region fire early, those in a bright region fire late. Cells whose receptive fields contain both dark and bright produce intermediate latencies and thus encode the boundary in their synchronous firing. (Right) The responses result from a circuit that combines synaptic inputs from both ON and OFF bipolar cells whose signals are individually rectified. The timing differences in the responses follow from a delay (Δt) in the ON pathway (Gollisch and Meister, 2008a).

Gollisch and Meister: (F) Switching Circuits

(F) Switching circuit. (Left) A control signal selectively gates one of two potential input signals. (Right) In the retina, such a control signal is driven by certain wide-field amacrine cells (A_1), which are activated during rapid image shifts in the periphery. Their activation leads to a suppression of OFF bipolar signals and, through a putative local amacrine cell (A_2), to disinhibition of ON bipolar signals (Geffen et al., 2007).

What do smart camera do?

- Engineers (and computer vision researchers) develop algorithms to enhance photographs and videos. E.g., to adjust color balance, prevent over- and under-exposure, and to avoid motion blur.
- These algorithms are complex – requiring those operations hypothesized by Gollisch and Meister (e.g., spatial and temporal grouping) and more.
- Simple example: X. Dong, B. Bonev, Y. Zhu, A.L. Yuille. "Region-based temporally consistent video post-processing". CVPR 2015.

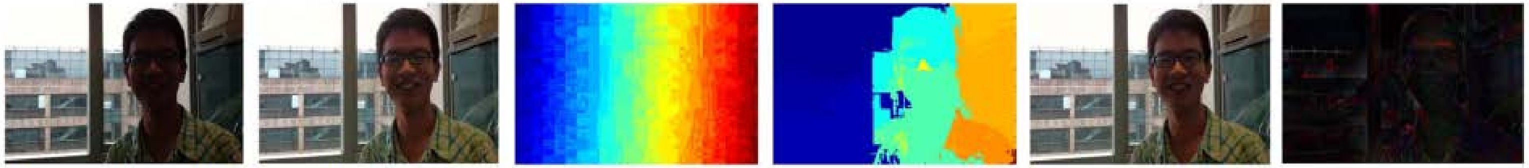


Figure 3. Example of region based reconstruction. Left to right: input map I, original enhancement result E using exposure correction [22], super pixels segmentation result [1], regions merging result, reconstruction result R, and absolute difference between E and R (enlarged in 5 times).

Complexity of the Retina and Neurons

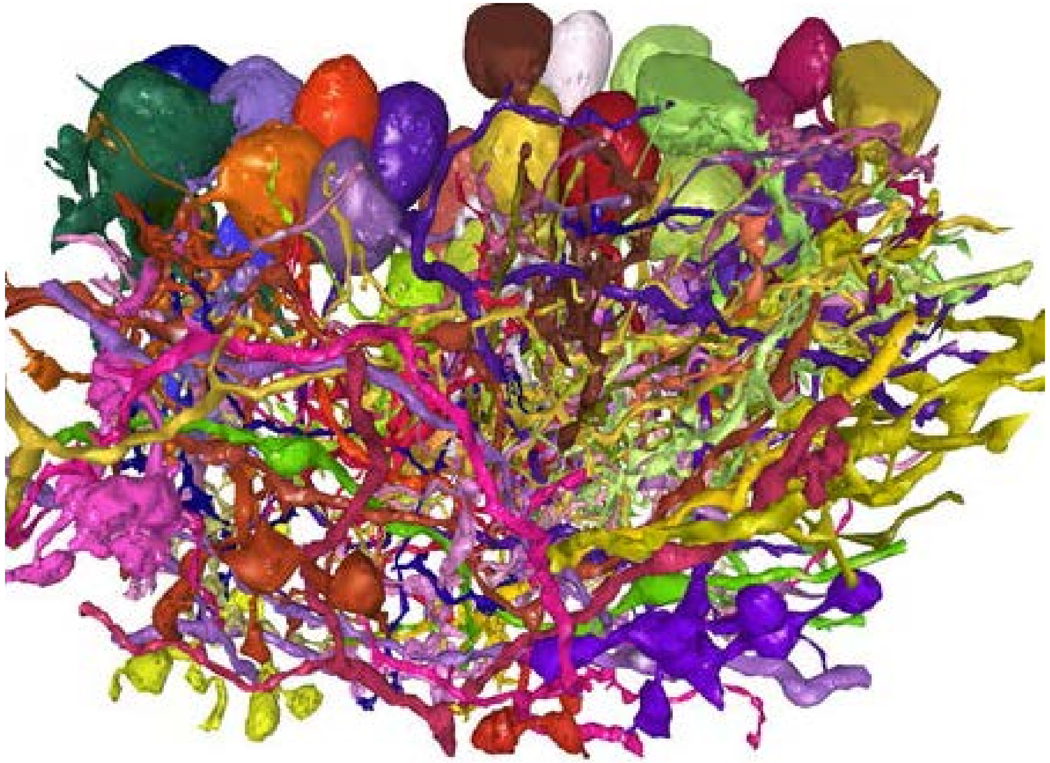
- The anatomical structure of the retina is very complicated
- There are many different types of neurons and they have many different shapes/morphologies.
- Neurons also have complex shapes. “Artificial Neurons” and “Artificial Neural Networks” may only be first order approximations to real neurons.

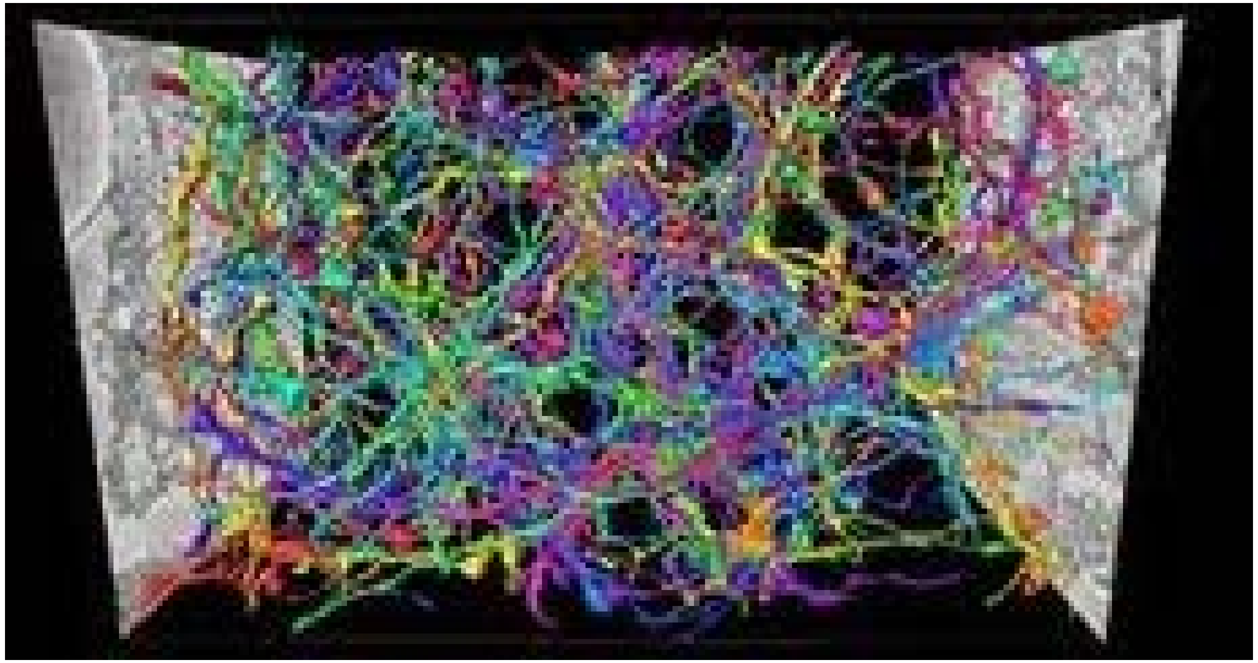
The anatomy of the retina is not simple.

- The anatomical structure of the retina gets increasingly complex the more scientists study it in detail. S. Seung. Connectonics.
- There are many different types of neurons when you consider their detailed anatomy (Masland). Seung recruited volunteers to label the three-dimensional structure of neurons in the retina.
- Scientists who study the visual cortex also find many different types of neurons (hundreds) the more they look into the details (although many are pyramidal).
- Note: Labeling the 3D structure of neurons in brains is a fascinating research field which is becoming big science (Allen Institute, Kalvi Neuroscience Discovery Institute JHU, Janelia Research Campus).

The Retina. Complex connections.

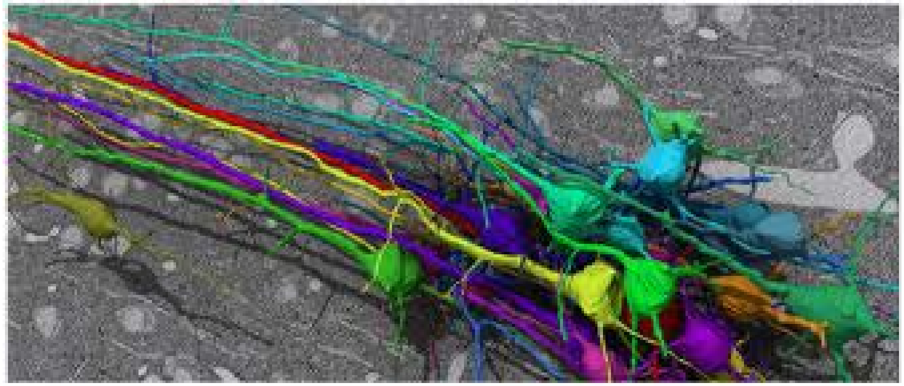
- There are many different types of neurons – neurons have complex dendritic structure – and complex connections between them.

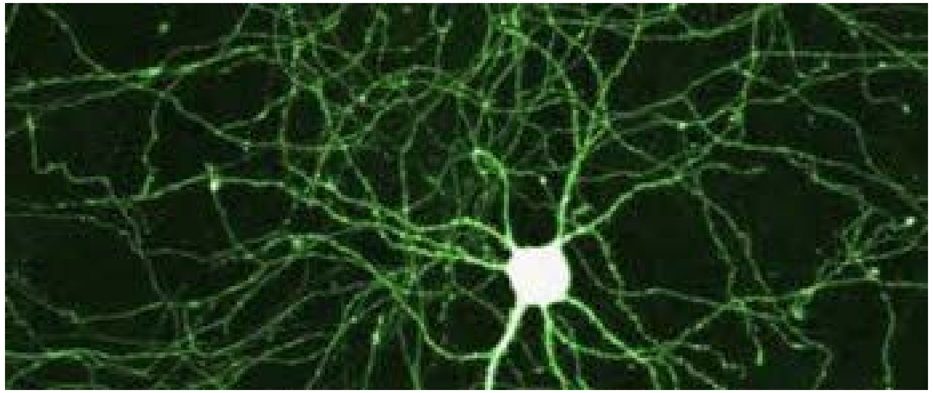


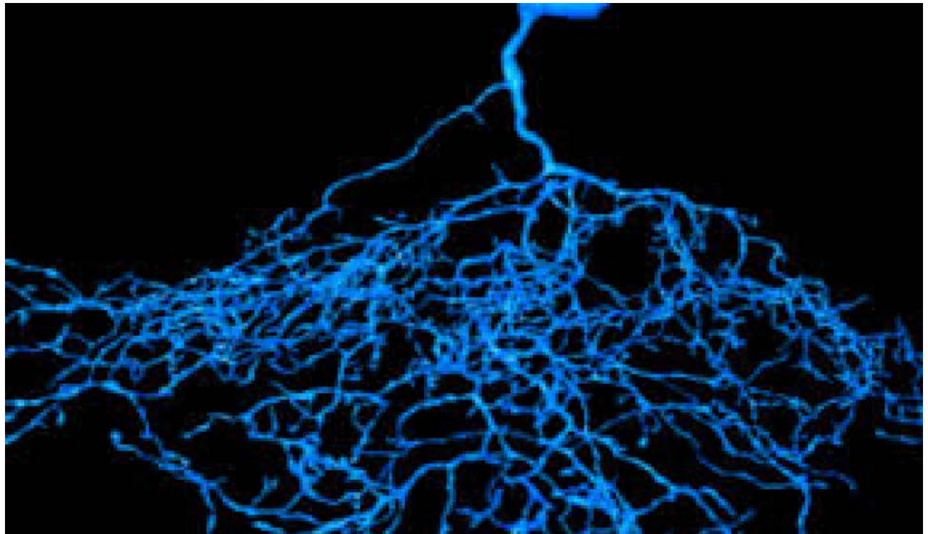


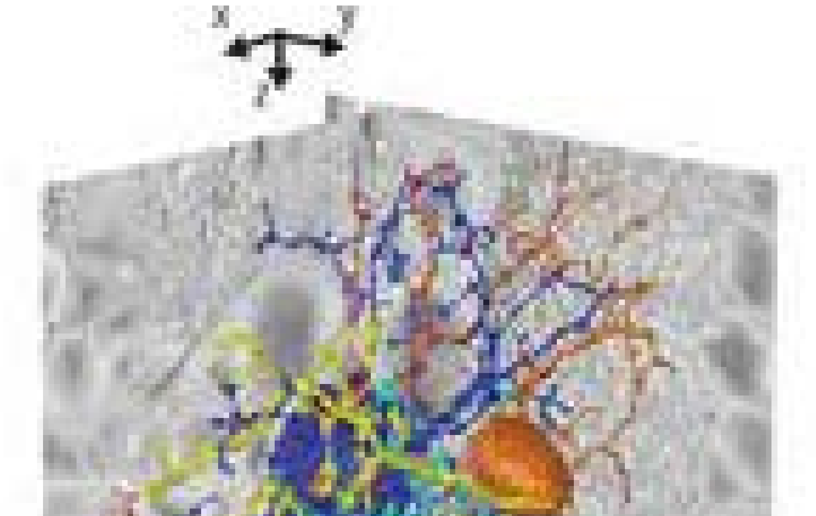
The Retina: Many different types of neurons.

- Neurons: Dendrites, Axons, and Soma (cell body).









Connectonics: The Big Debate.

- How much will wiring diagrams, or even detailed biophysical models, help understand the brain?
- *Scientists understood the wiring and biophysics of C. Elegans (150 neurons) but this failed to give much insight into the computations performed in its brain (after twenty years).* And mice and human/monkey brains are more complicated by many orders of magnitude.
- *Surely we must understand the types of computations being performed as well – it would be hard to understand the function of a TV by just analyzing its electrical circuits – and you certainly could not understand what program it was showing.*
- "Could a neuroscientist understand a microprocessor". Eric Jonas and Konrad Kording. PLOS.
- S. Seung and A. Movshon debate: http://www.youtube.com/watch?v=fRHzkRqGf-g

Lecture Summary

- This talk gave a brief introduction to the retina. The standard mathematical models will be described in the next lecture.
- Part 1. The Retina as the input to the visual system.
- Part 2. The Purpose of the Retina.
- Part 3. Complexity of the Retina and Neurons.

- Moral: the retina (like the rest of the primate visual system) is very complex and only partially understood.
- *Will AI learn from more knowledge of the retina? This is debatable.*

Artificial Neurons and Neural Circuits

- Real neurons and neural circuits. B. Mel handout.

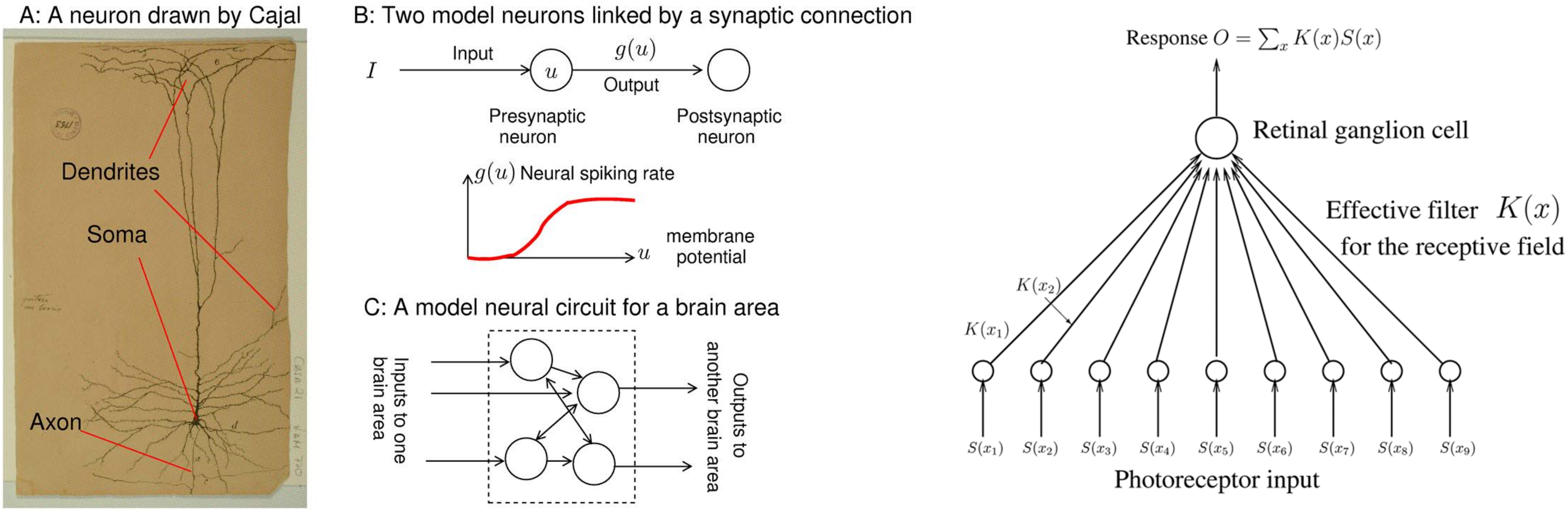


Figure from "Understanding Vision: theory, models, and data", by Li Zhaoping, Oxford University Press, 2014

Measuring Receptive Fields

- Electrophysiology: Move and vary stimulus until neuron fires.

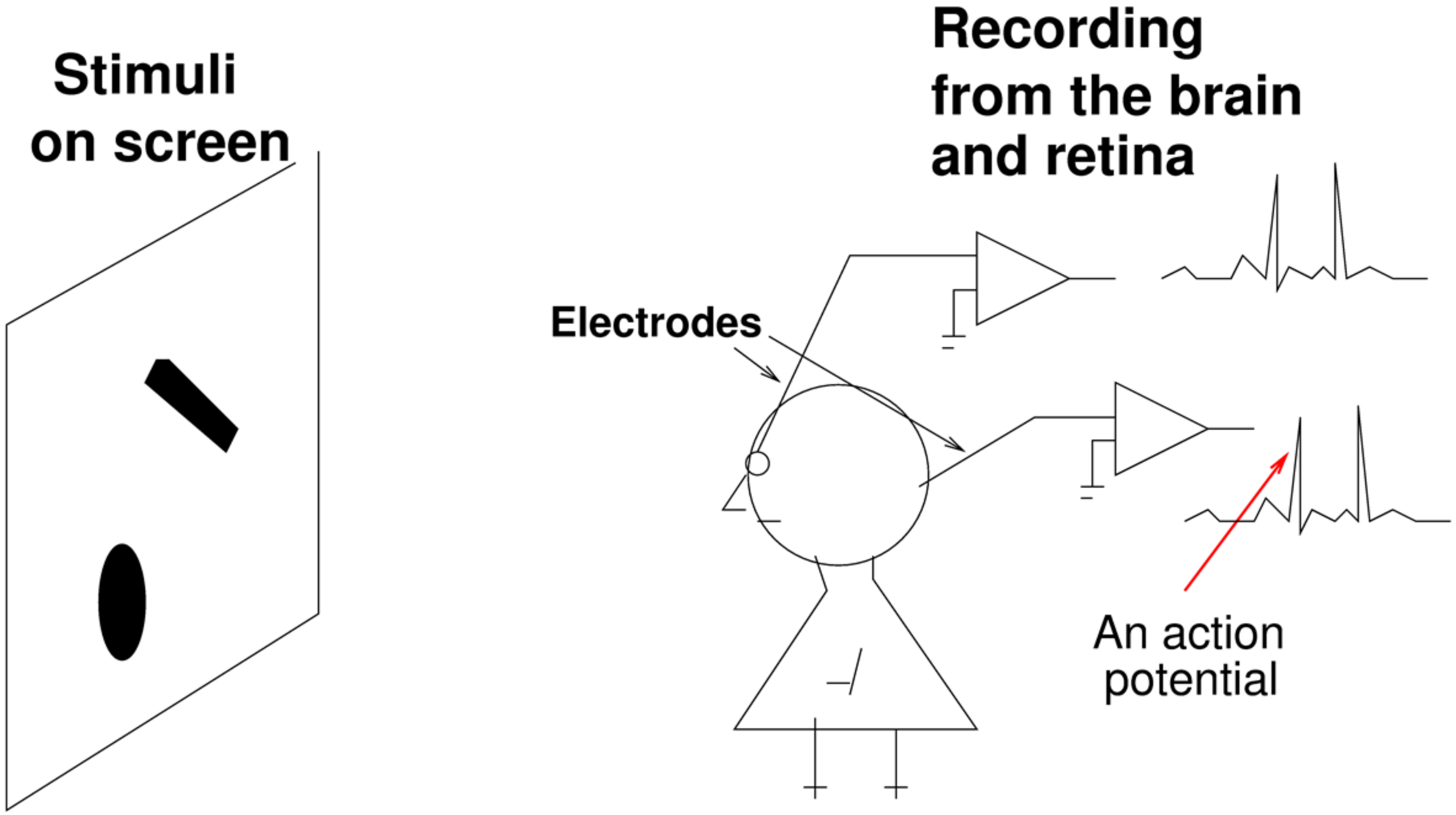
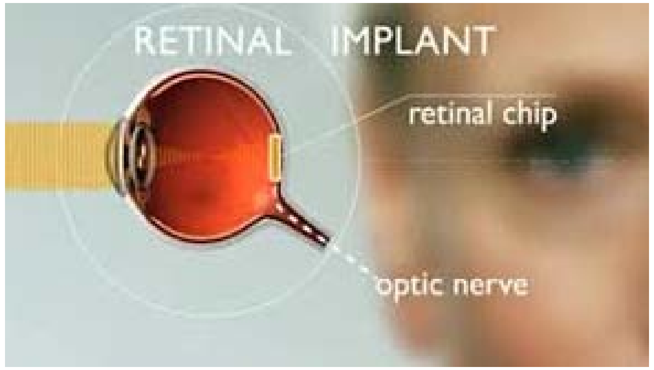


Figure from "Understanding Vision: theory, models, and data", by Li Zhaoping, Oxford University Press, 2014

Retina Implants: Artificial Retinas.



- Retinal implants are intended to help blind people see.
- Current implants 10x10 arrays.
- Performance is not yet very strong. But see Prosthetic Eyes; Sheila Nirenberg (TED talk).