BIOPHYSICS @YORK

redefine THE POSSIBLE.

UNIVERSITÉ
UNIVERSITY

Peripheral sensory transduction

Christopher Bergevin (York University, Dept. of Physics & Astronomy)

BPHS 2090 (F19)

Questions/Themes to examine & discuss

- How is “information” encoded heading in towards the brain?
- What is “brain activity”?
- How does the central nervous system “convey” information?
- How is information “transformed”?
- Biomechanics of the ear
- Fourier transforms & convolutions (Aside: How does Photoshop work?)
- Phototransduction

Pop Quiz #1

How many neurons are there in the human brain? Synapses?

Pop Quiz #2

Is this “image” a bitmap or vector-based?

Pop Quiz #3

$$\frac{1}{2\pi a(r_o + r_i)} \frac{\partial^2 V_m}{\partial z^2} = C_m \frac{\partial V_m}{\partial t} + G_K(V_m, t)\,(V_m - V_K) + G_{Na}(V_m, t)\,(V_m - V_{Na}) + G_L(V_m - V_L)$$

$$G_K(V_m, t) = \overline{G}_K n^4(V_m, t)$$

$$G_{Na}(V_m, t) = \overline{G}_{Na} m^3(V_m, t) h(V_m, t)$$

$$n(V_m, t) + \tau_n(V_m) \frac{dn(V_m, t)}{dt} = n_\infty(V_m)$$

$$m(V_m, t) + \tau_m(V_m) \frac{dm(V_m, t)}{dt} = m_\infty(V_m)$$

$$h(V_m, t) + \tau_h(V_m) \frac{dh(V_m, t)}{dt} = h_\infty(V_m)$$

What do these equations represent?

$$\tau_x \frac{dx}{dt} + x = x_\infty \qquad \frac{dx}{dt} = \alpha_x(1 - x) - \beta_x x$$

$$x_\infty = \alpha_x/(\alpha_x + \beta_x) \text{ and } \tau_x = 1/(\alpha_x + \beta_x)$$

$$\alpha_m = \frac{-0.1(V_m + 35)}{e^{-0.1(V_m+35)} - 1},$$

$$\beta_m = 4e^{-(V_m+60)/18},$$

$$\alpha_h = 0.07e^{-0.05(V_m+60)},$$

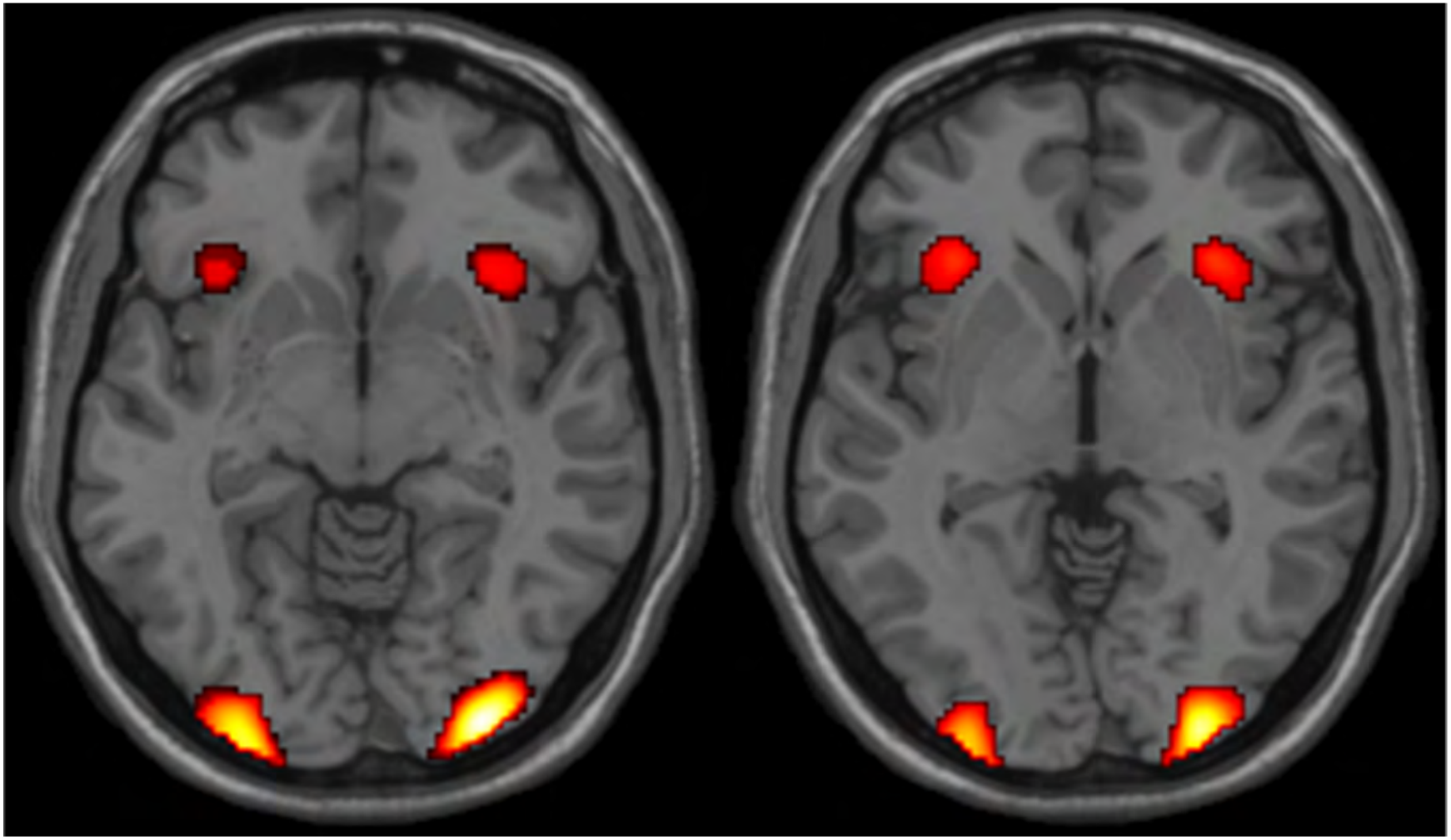
$$\beta_h = \frac{1}{1 + e^{-0.1(V_m+30)}},$$

$$\alpha_n = \frac{-0.01(V_m + 50)}{e^{-0.1(V_m+50)} - 1},$$

$$\beta_n = 0.125e^{-0.0125(V_m+60)},$$

Pop Quiz #4

What precisely is being shown here?



- How is “information” encoded heading in towards the brain?
- What is “brain activity”?
- How does the central nervous system “convey” information?
- How is information “transformed”?
- Biomechanics of the ear
- Fourier transforms & convolutions
- Phototransduction

Pop Quiz #1

How many neurons are there in the human brain? Synapses?

Human brain contains ~10^{11} (100 billion) neurons!

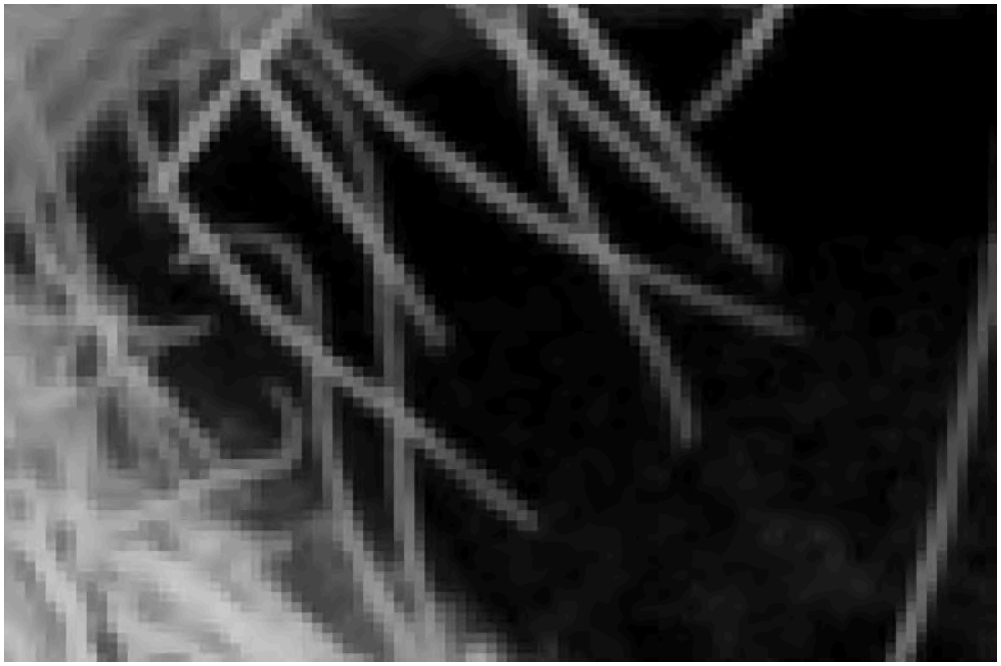
(with 100 trillion+ connections inbetween)

Pop Quiz

Is this “image” a bitmap or vector-based?

Many ways to “encode” something....

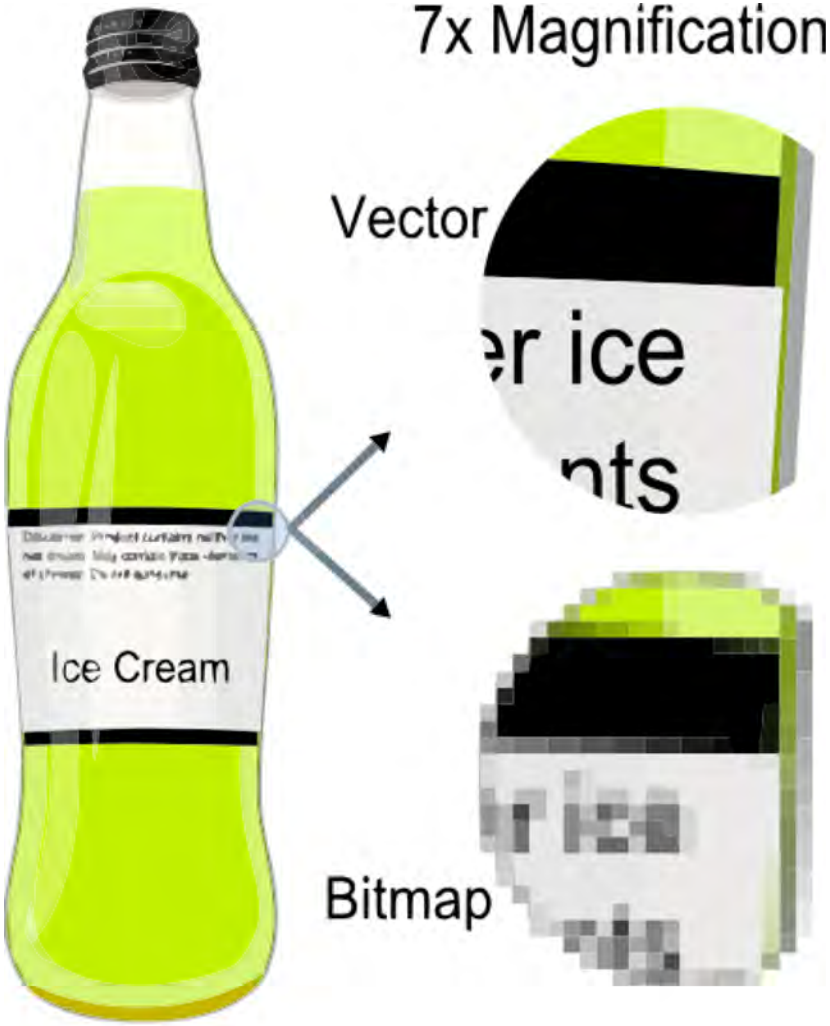
Bitmap version



Vector version

zoom-in about corner of eye

Many ways to “encode” something....



Bitmap version

Vector version

→ “Same” image, two very different representations

Wikipedia

Pop Quiz

$$\frac{1}{2\pi a(r_o + r_i)} \frac{\partial^2 V_m}{\partial z^2} = C_m \frac{\partial V_m}{\partial t} + G_K(V_m, t)\,(V_m - V_K) + G_{Na}(V_m, t)\,(V_m - V_{Na}) + G_L(V_m - V_L)$$

$$G_K(V_m, t) = \overline{G}_K n^4(V_m, t)$$

$$G_{Na}(V_m, t) = \overline{G}_{Na} m^3(V_m, t) h(V_m, t)$$

$$n(V_m, t) + \tau_n(V_m) \frac{dn(V_m, t)}{dt} = n_\infty(V_m)$$

$$m(V_m, t) + \tau_m(V_m) \frac{dm(V_m, t)}{dt} = m_\infty(V_m)$$

$$h(V_m, t) + \tau_h(V_m) \frac{dh(V_m, t)}{dt} = h_\infty(V_m)$$

What do these equations represent?

$$\tau_x \frac{dx}{dt} + x = x_\infty \qquad \frac{dx}{dt} = \alpha_x(1 - x) - \beta_x x$$

$$x_\infty = \alpha_x/(\alpha_x + \beta_x) \text{ and } \tau_x = 1/(\alpha_x + \beta_x)$$

$$\alpha_m = \frac{-0.1(V_m + 35)}{e^{-0.1(V_m+35)} - 1},$$

$$\beta_m = 4e^{-(V_m+60)/18},$$

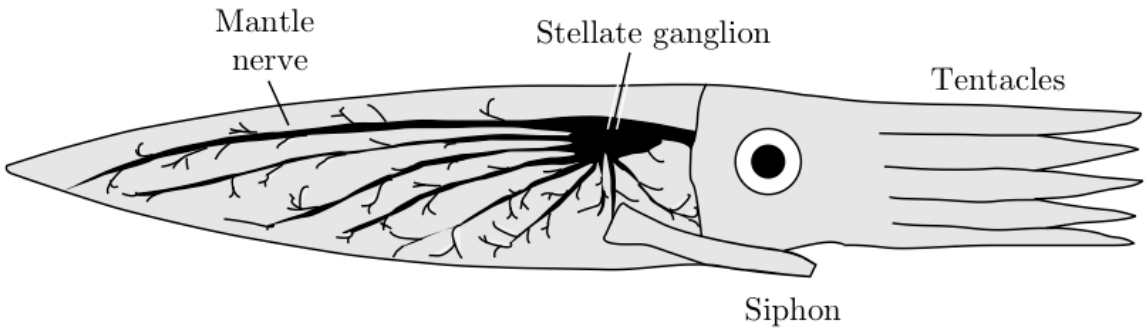
$$\alpha_h = 0.07e^{-0.05(V_m+60)},$$

$$\beta_h = \frac{1}{1 + e^{-0.1(V_m+30)}},$$

$$\alpha_n = \frac{-0.01(V_m + 50)}{e^{-0.1(V_m+50)} - 1},$$

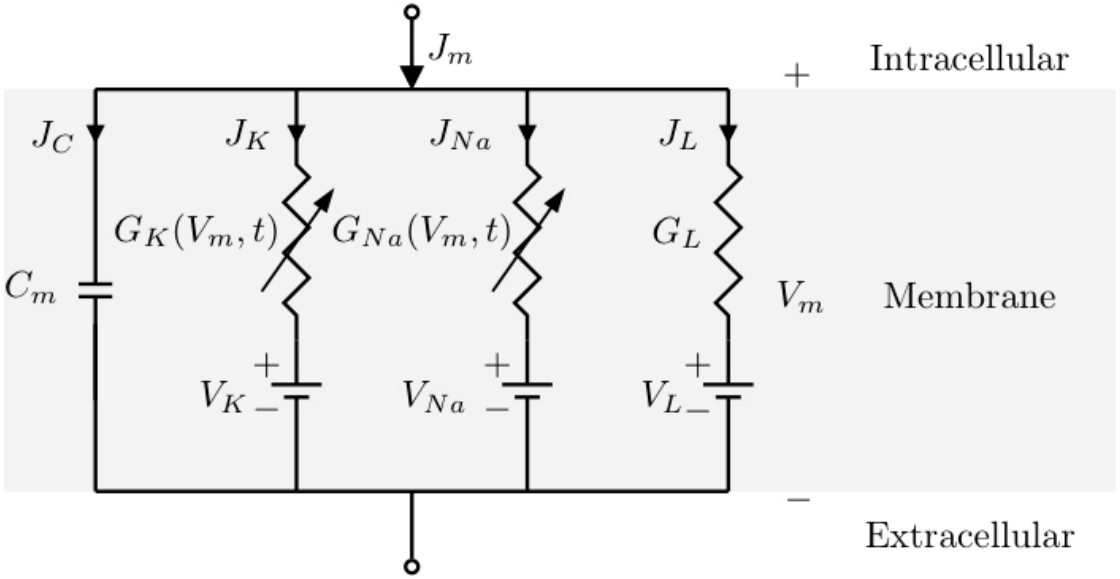
$$\beta_n = 0.125e^{-0.0125(V_m+60)},$$

Biophysical model of a neuron



Hodgkin Huxley model

Variable Na+ and K+ conductances

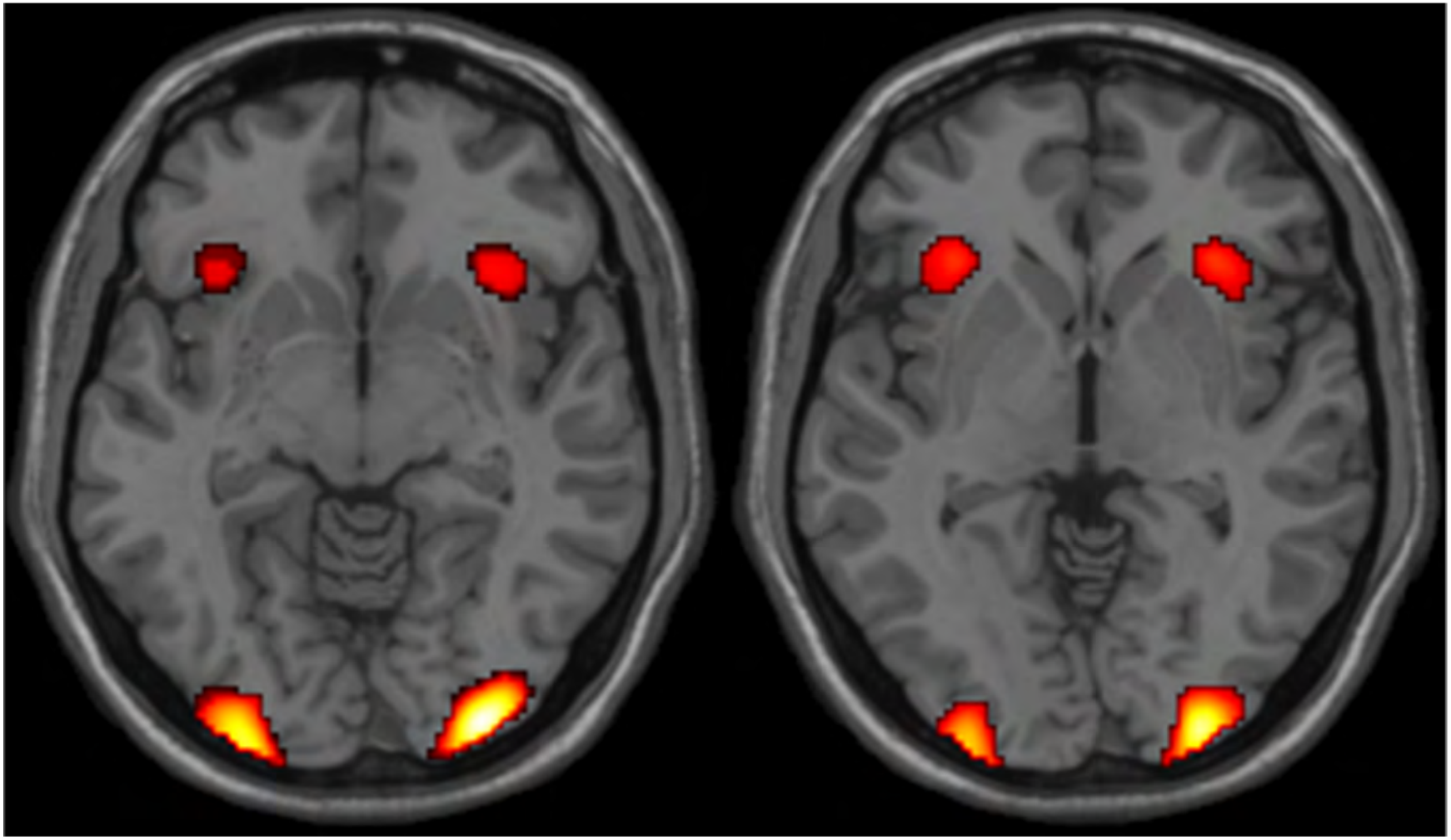


Weiss (1996)

Pop Quiz

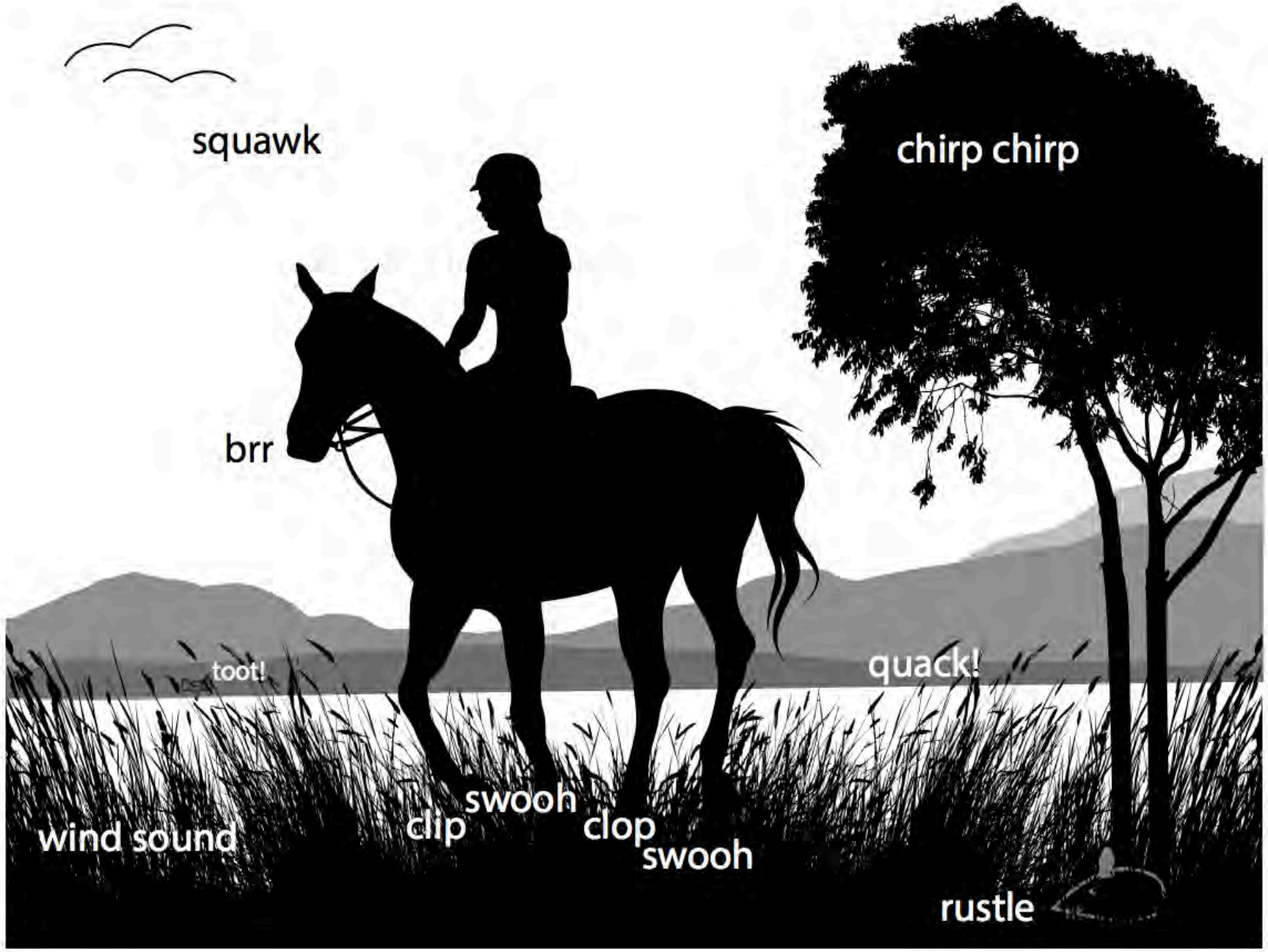
What precisely is being shown here?

- NMR → MRI
- "fMRI" re BOLD



Big Picture Theme

How do our sensory systems encode “information” about the world around us?



Pulkki & Karjalainen (2015)

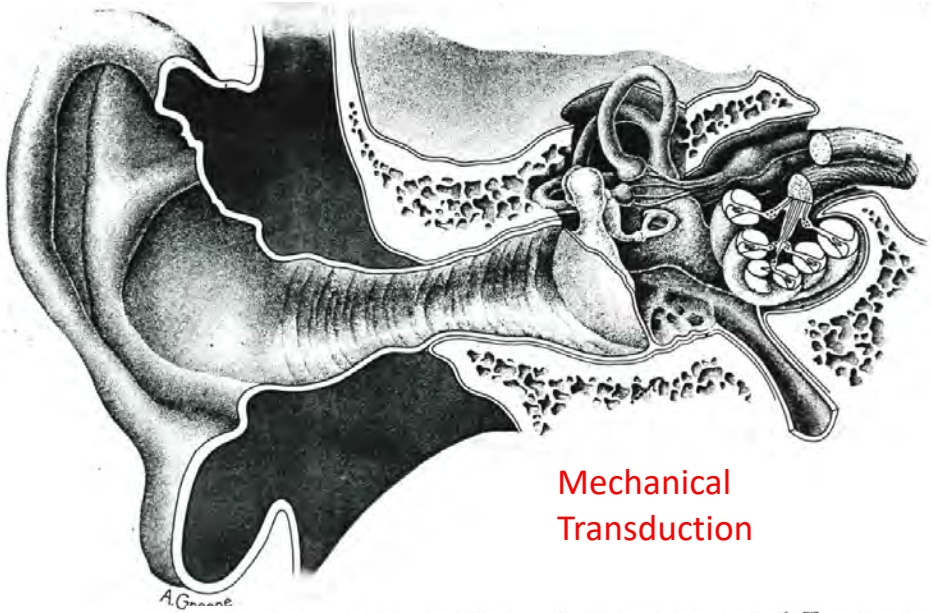
Transduction

1. the transfer of genetic material from one organism (as a bacterium) to another by a genetic vector and especially a bacteriophage

2. the action or process of converting something and especially energy or a message into another form

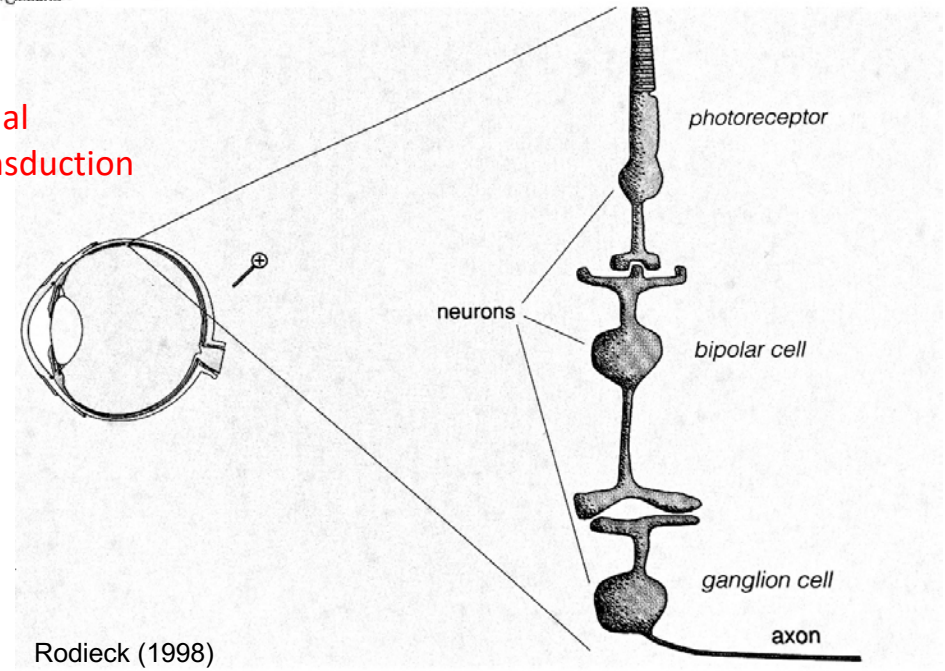
Merriam-Webste
http://www.jungleae.com/how-to-hold-a-microphoner

Peripheral sensory transduction



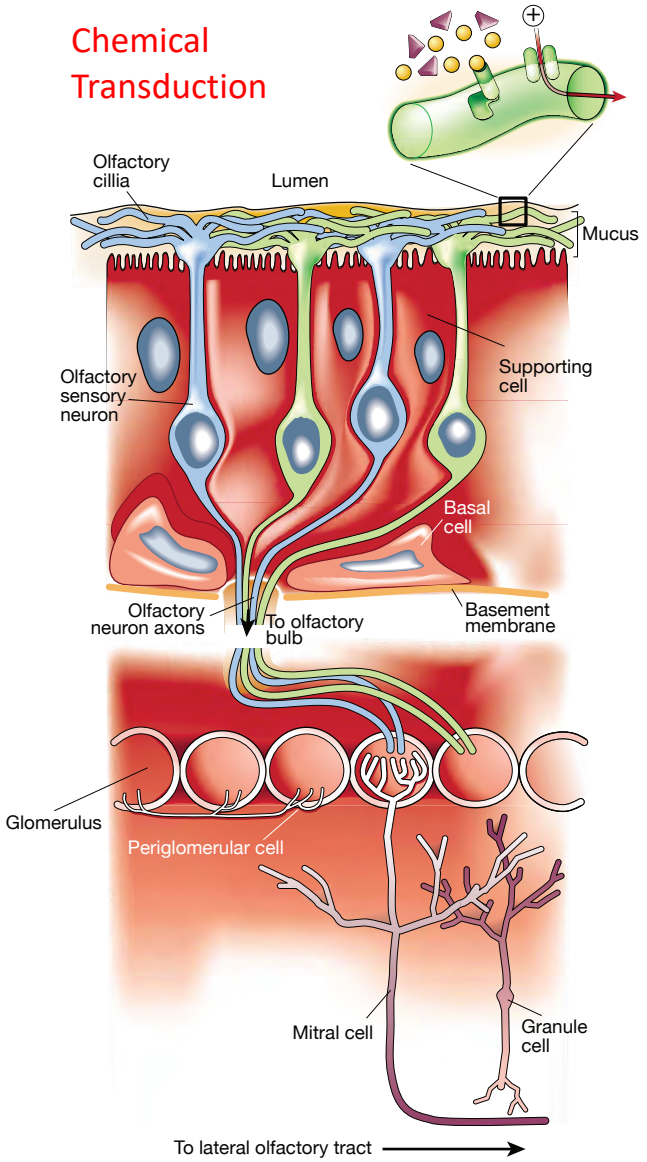
Mechanical Transduction

Visual Transduction



Rodieck (1998)

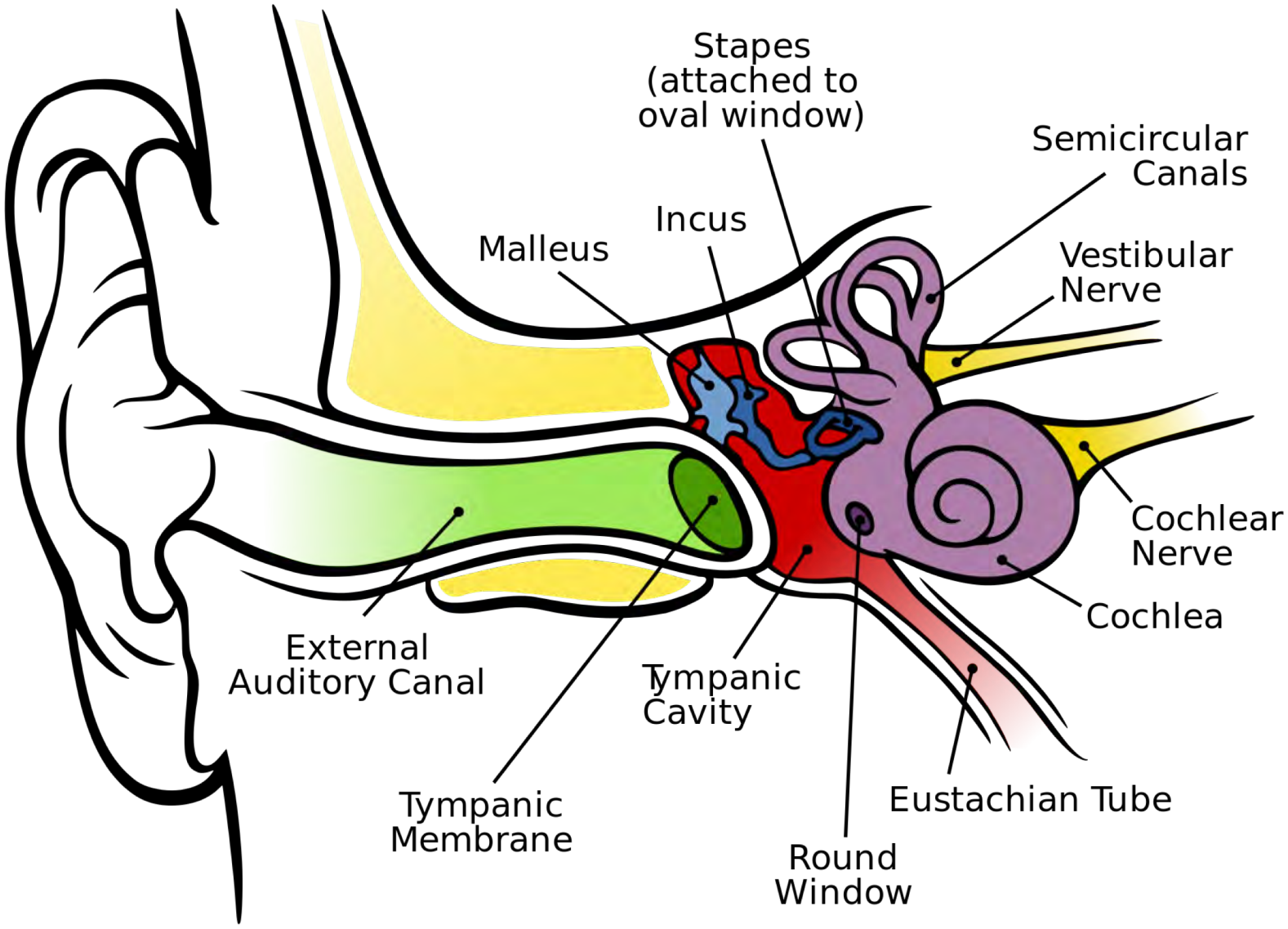
Chemical Transduction



Firestein (2001)

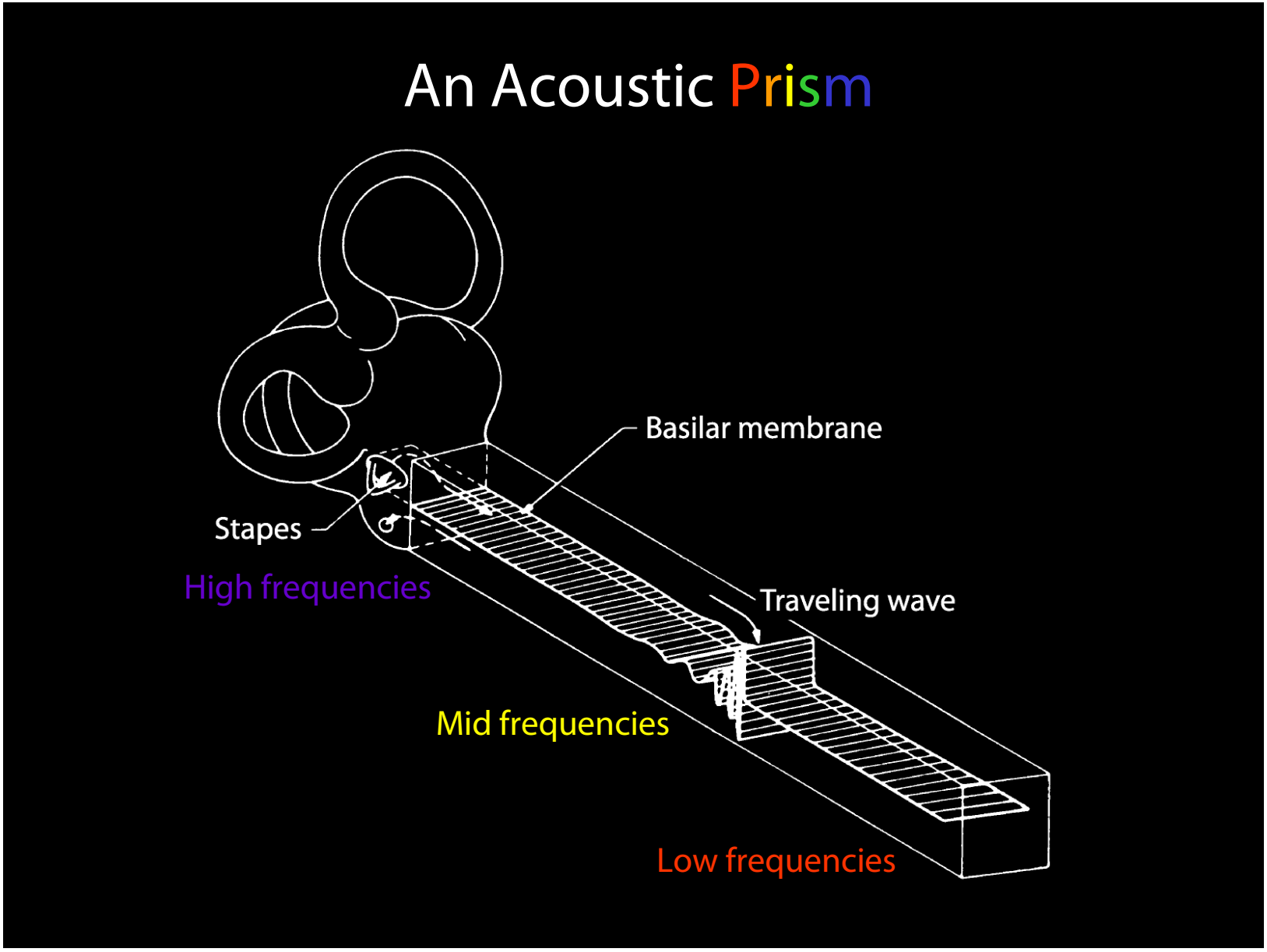
Ex. Neural coding of sound

Cochlear nerve contains ~30000 fibers

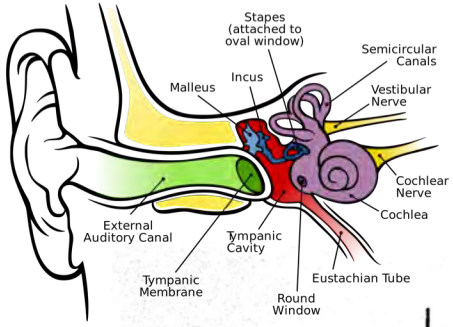


https://en.wikipedia.org/wiki/Auditory_system

Spectral Decomposition



Zweig et al. (1976)



Response of a single cochlear nerve fiber

Voltage

Time

No stimulus

Clicks

Tone bursts

Tone

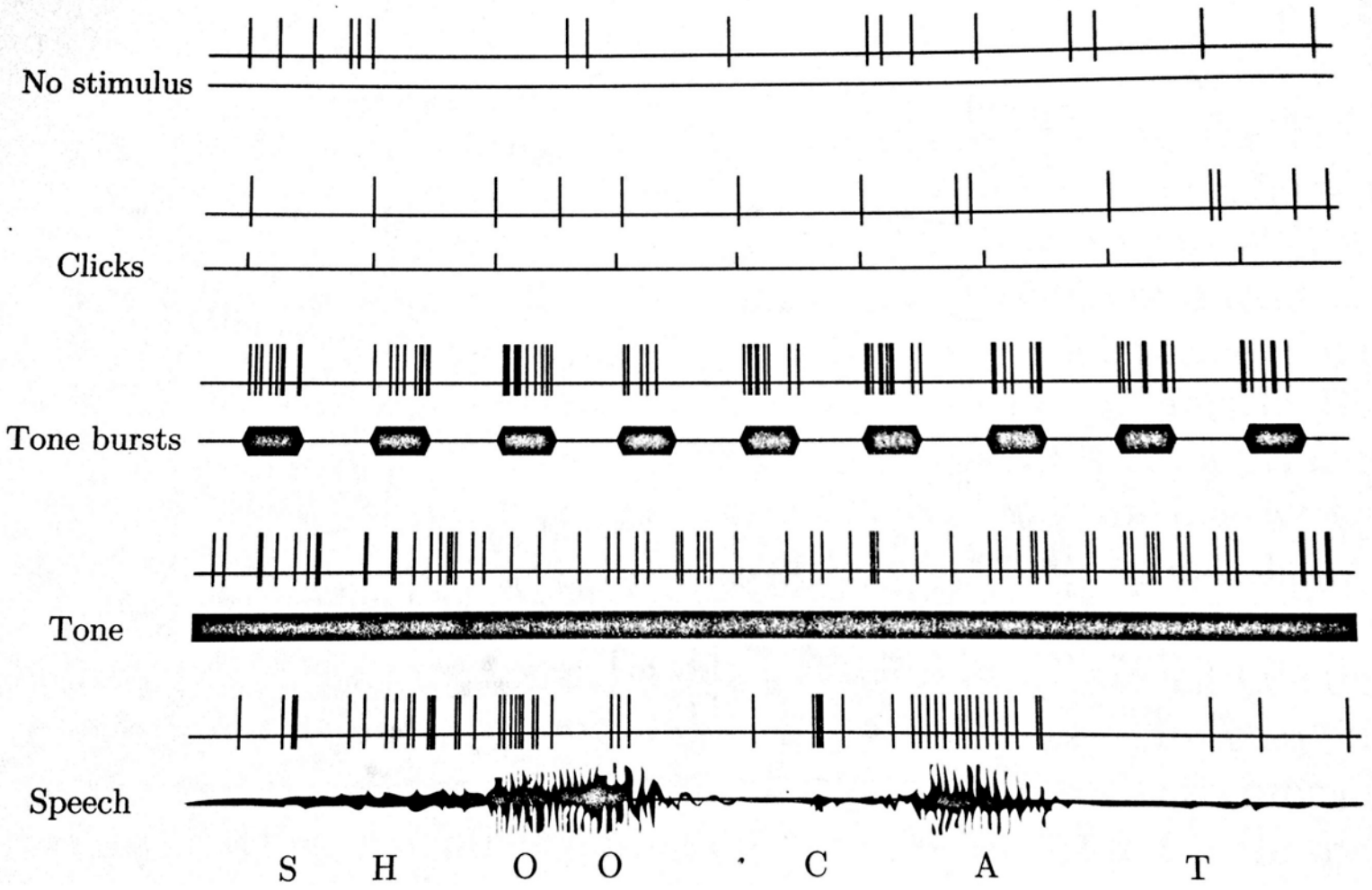
Neuron

Speech

Mic

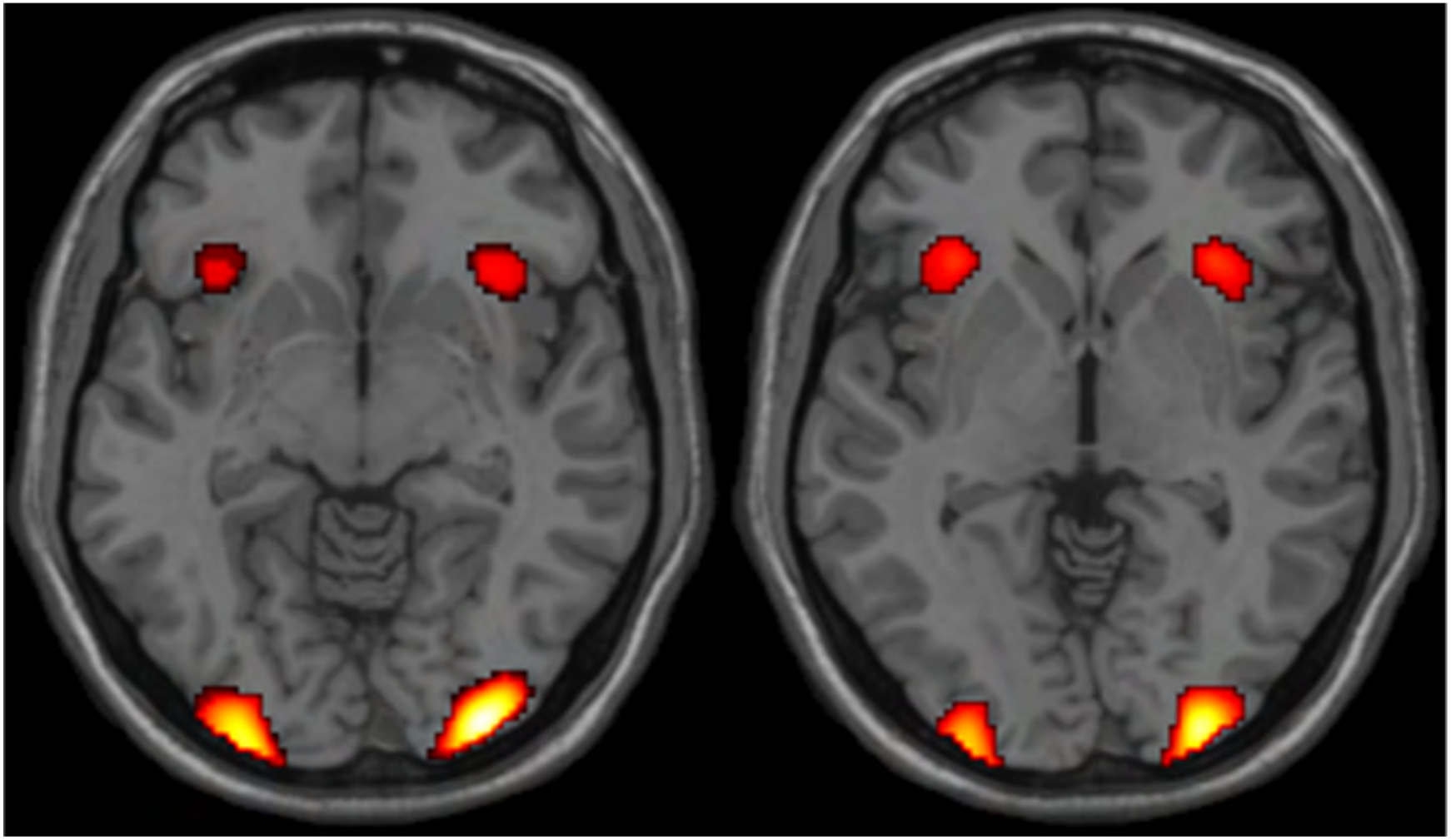
S H O O · C A T

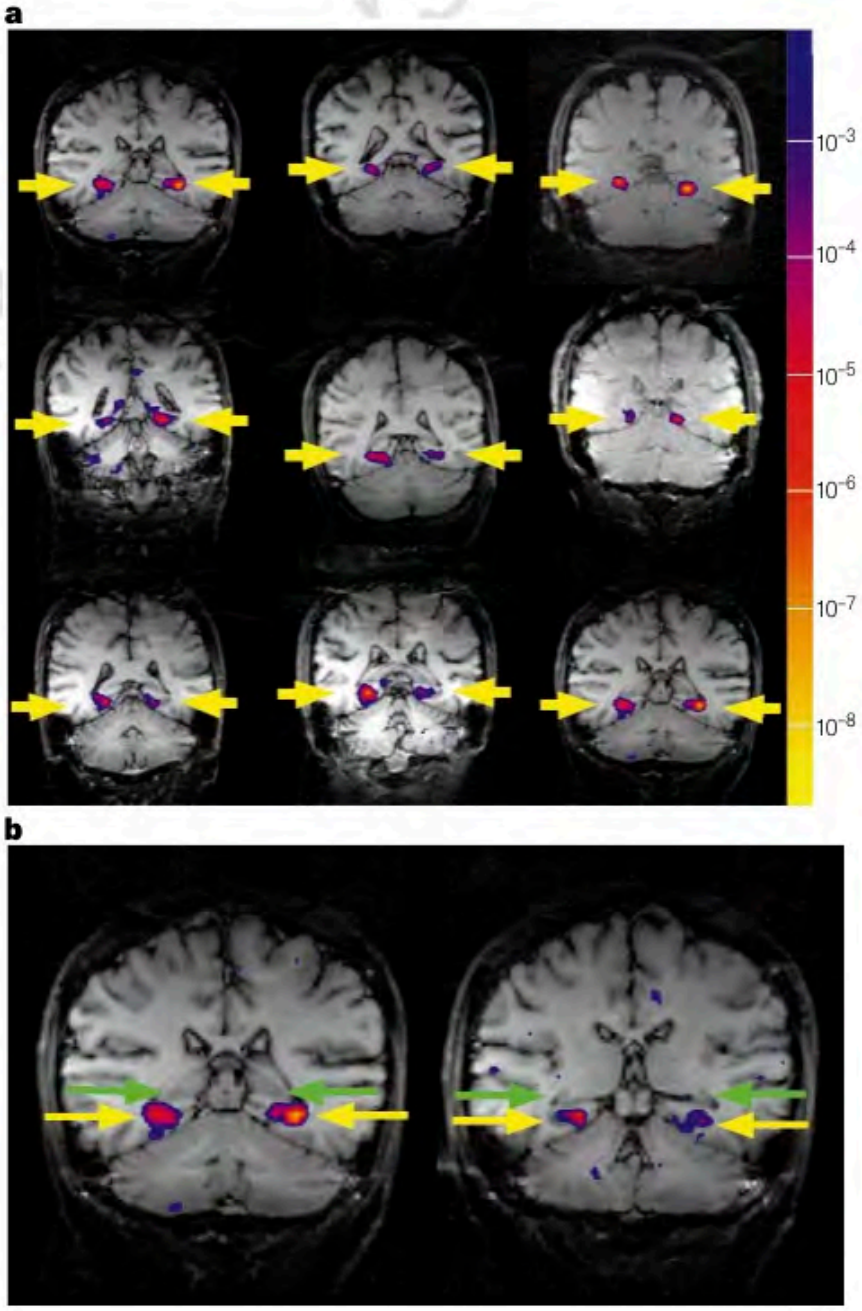
Kiang



Question: How similar/different is the “input” versus the “output”?

→ How might you go about measuring “brain activity”?





Epstein & Kanwisher (1998)

What are these methods used to "measure neural activity" actually telling us?

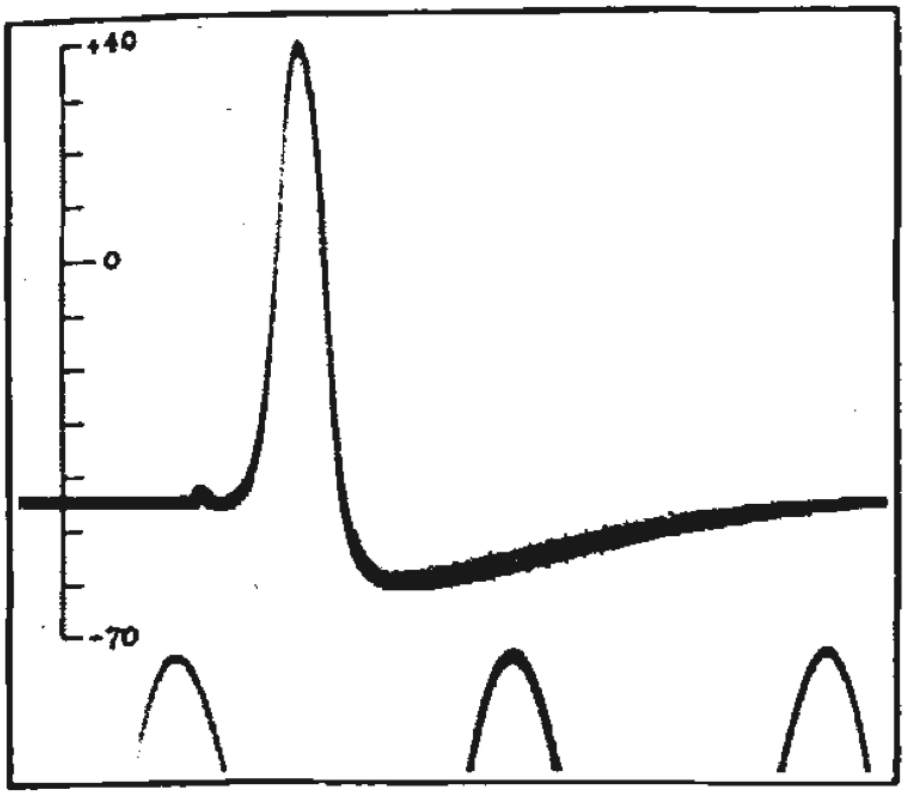
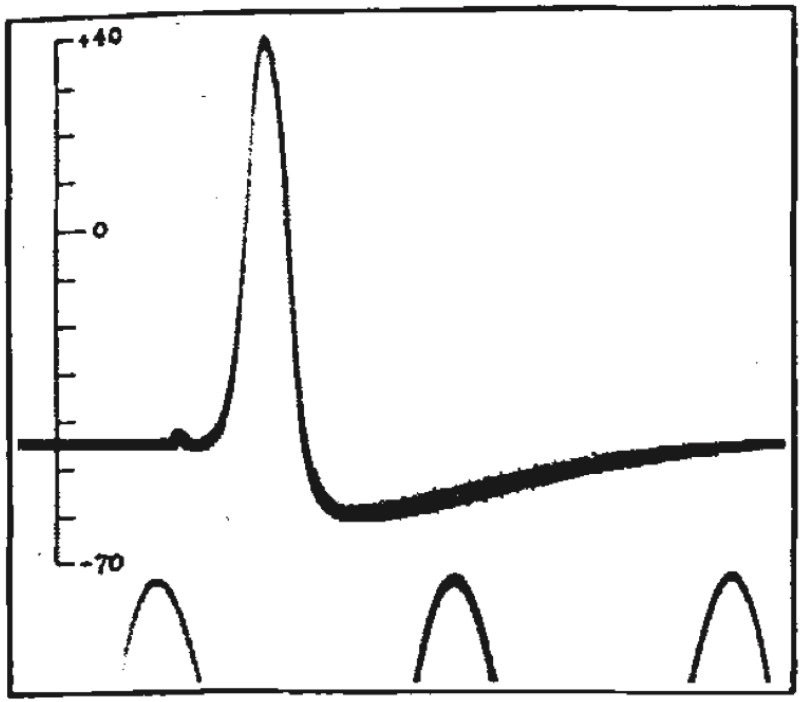


Fig. 1.

PHOTOMICROGRAPH OF ELECTRODE INSIDE GIANT AXON. 1 SCALE DIVISION = 33 μ.

Hodgkin & Huxley (1939)

Pop Quiz



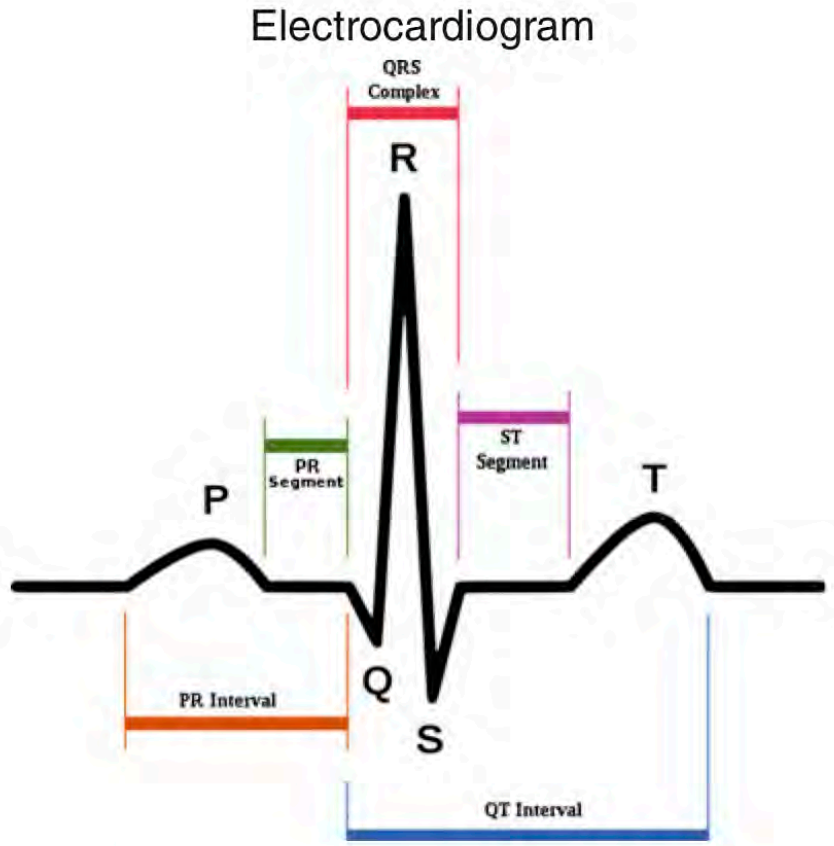


Fig. 1.2 Electrocardiogram depicting *P* wave, *QRS* complex, and *T* wave. (*Source* Wikipedia)

What is the difference between these two different types of "spikes"?

Fox, Pandit-Taskar, Strauss (2013)

Neurons

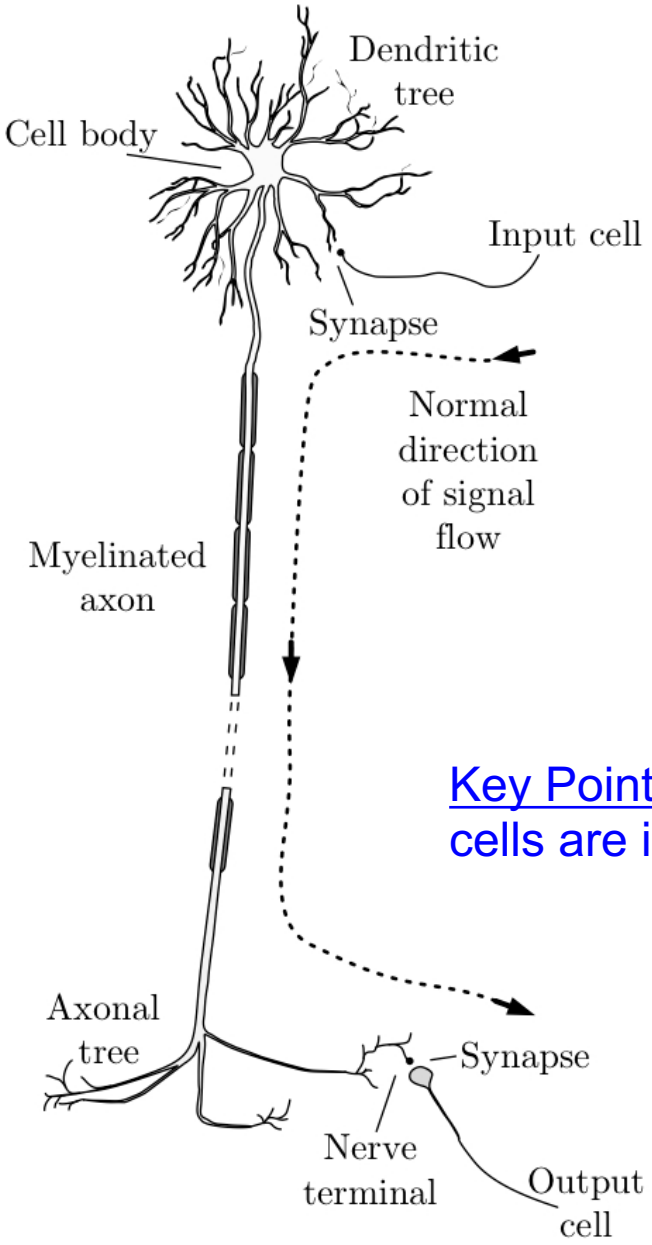


Figure 1.22

Neurons ("fibers")
= Information highway

Key Point: Electrical properties of cells are important

Weiss (1996)

Action potentials

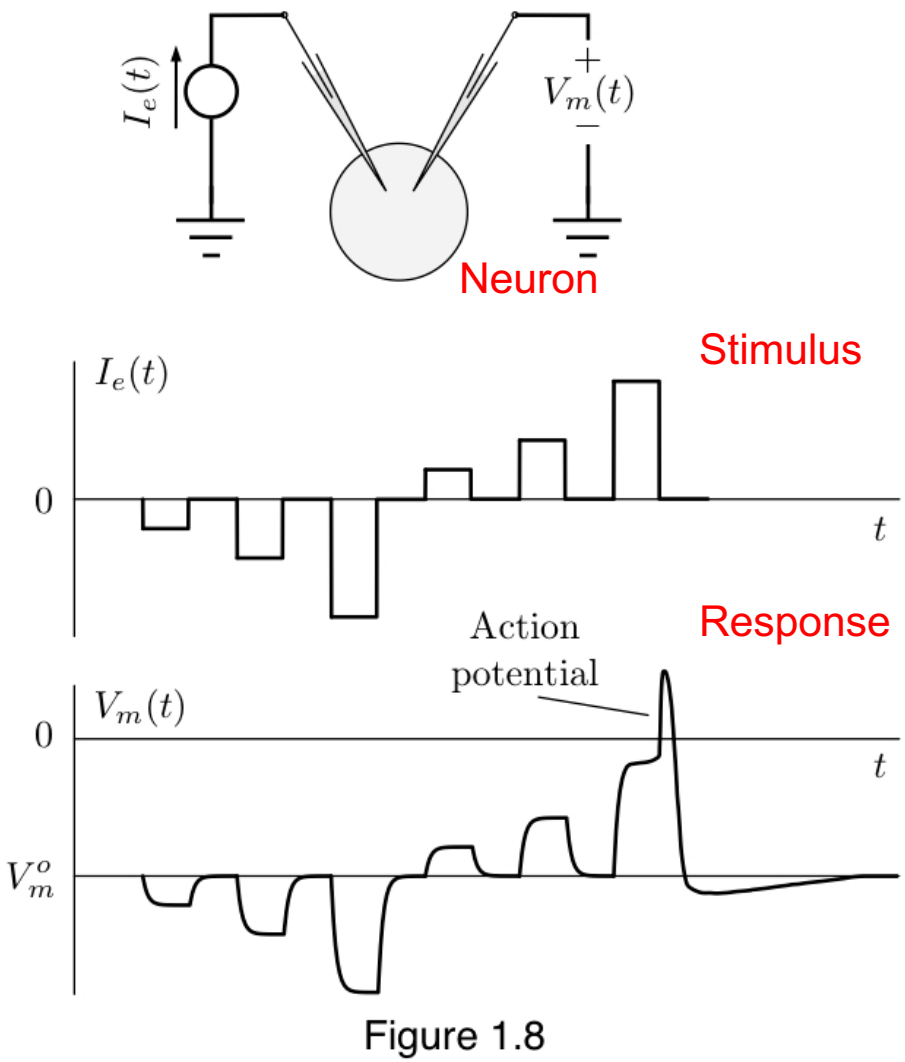


Figure 1.8

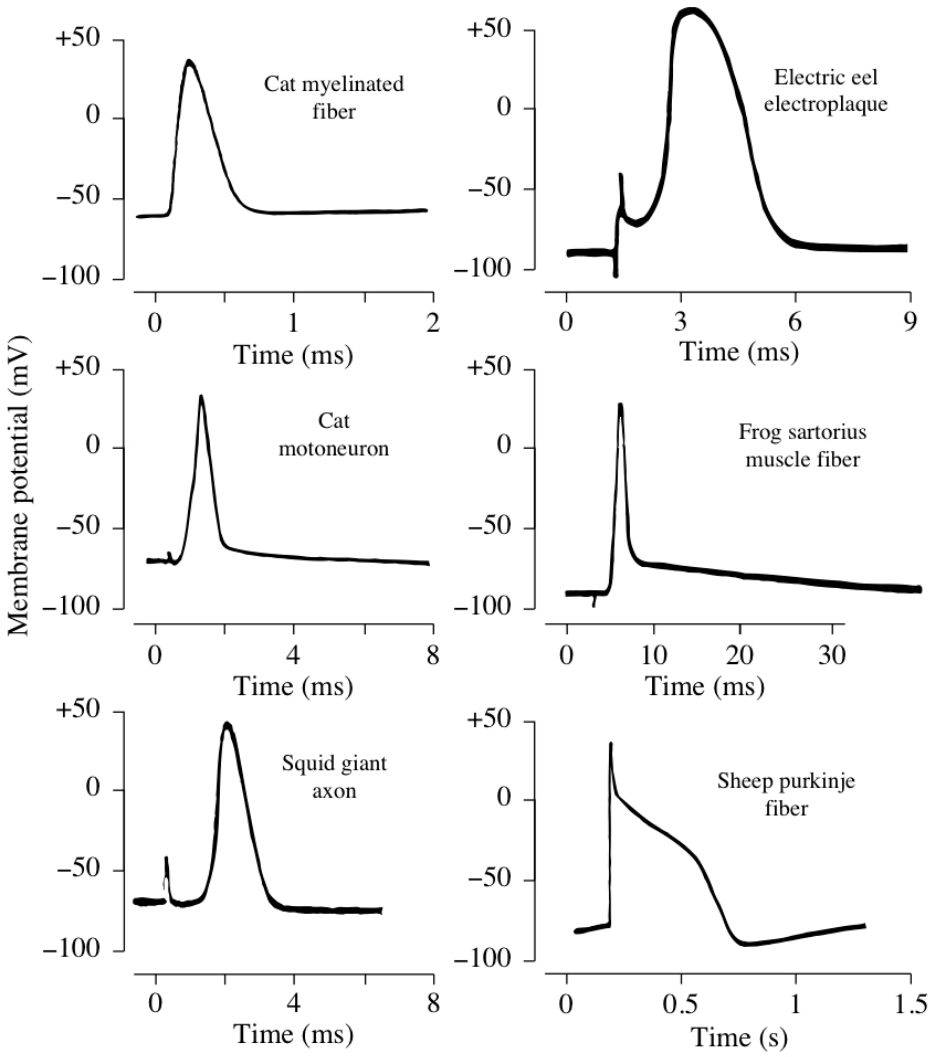
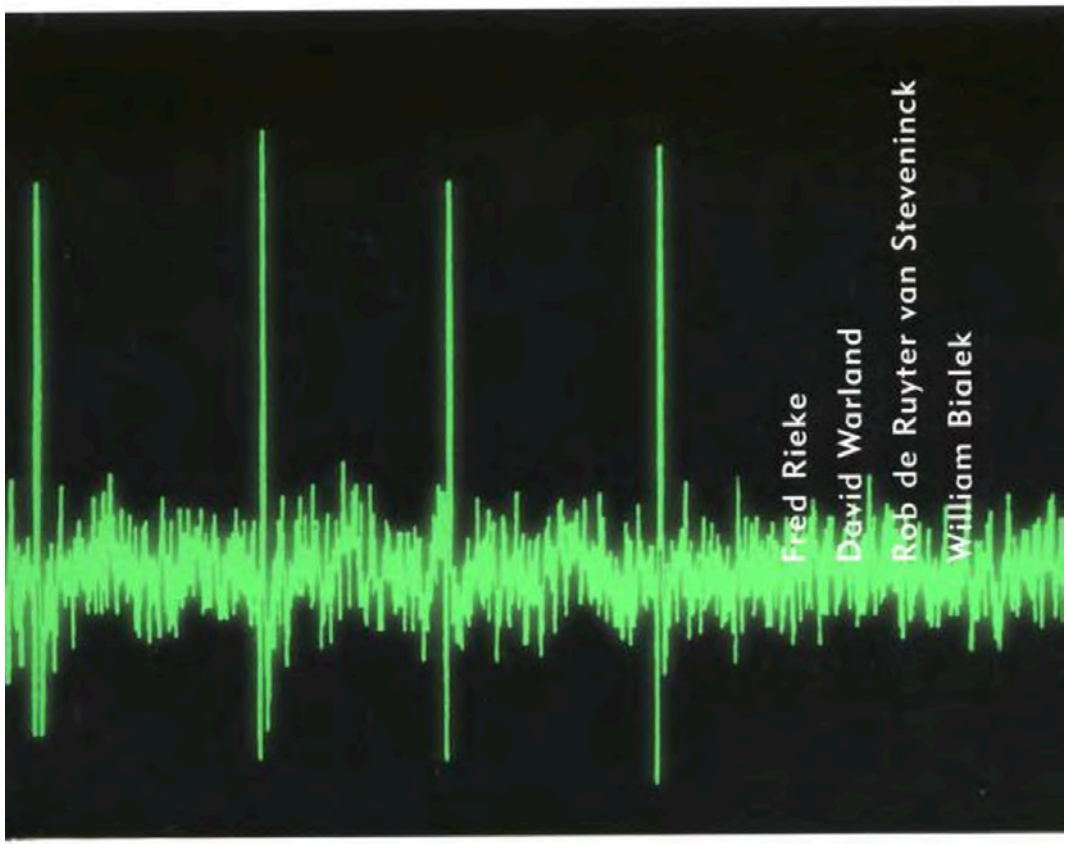


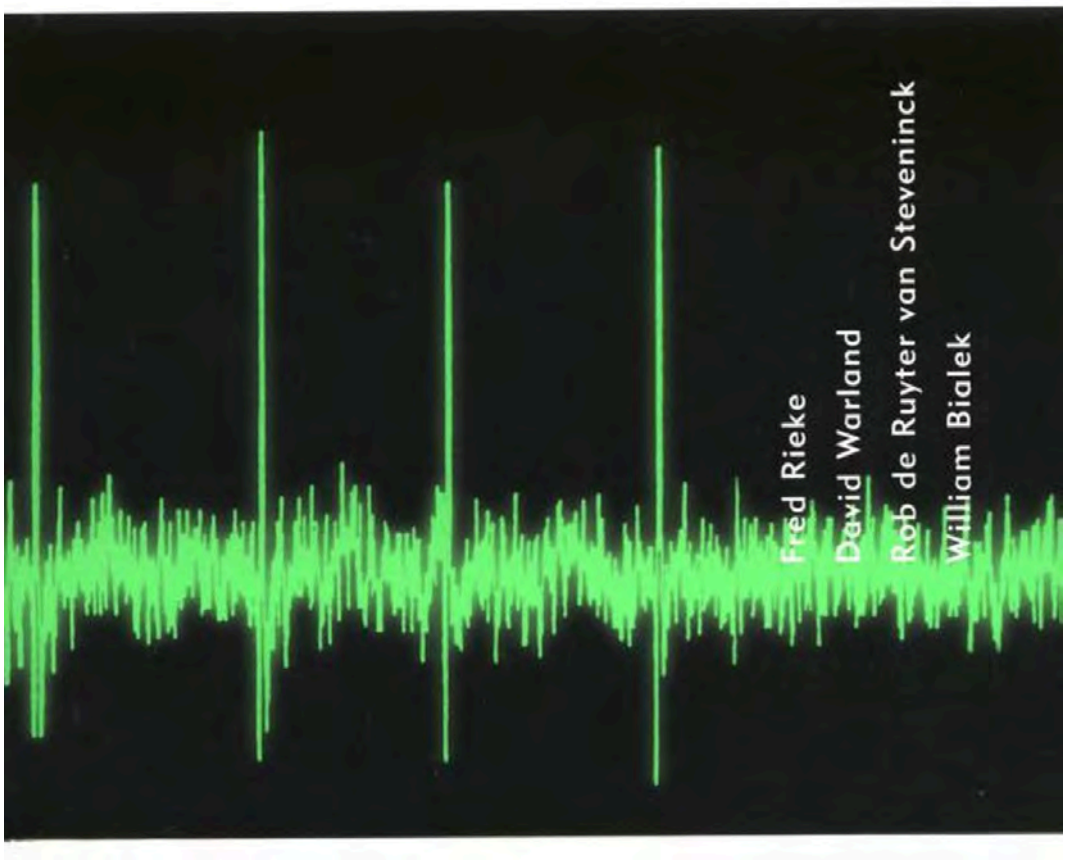
Figure 1.9

→ Neurons send info via electrical pulses (spikes) occurring ***across*** the cell membrane

Weiss (1996)

Somehow, the information is "transformed", encoded into some other "language"....





"Neural code"

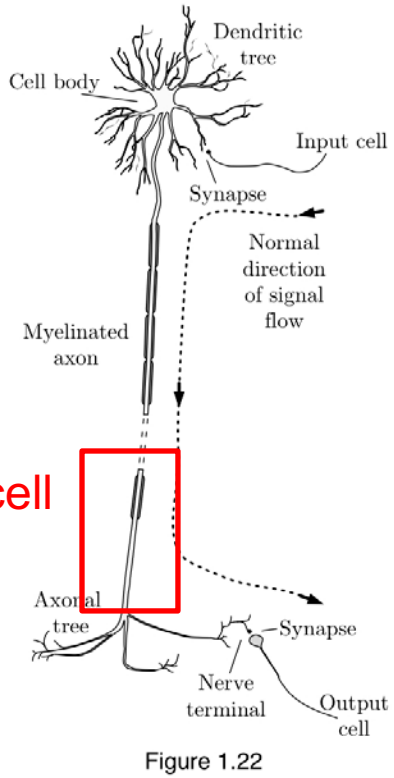
Aside

Is our central nervous system essentially "digitized"?

Cell membrane

- Membrane primarily consists of a "lipid bilayer" (to separate inside from outside)

- All sorts of "stuff" embedded inside, to allow for "communication" across membrane



zoom in on cell membrane

Figure 1.22

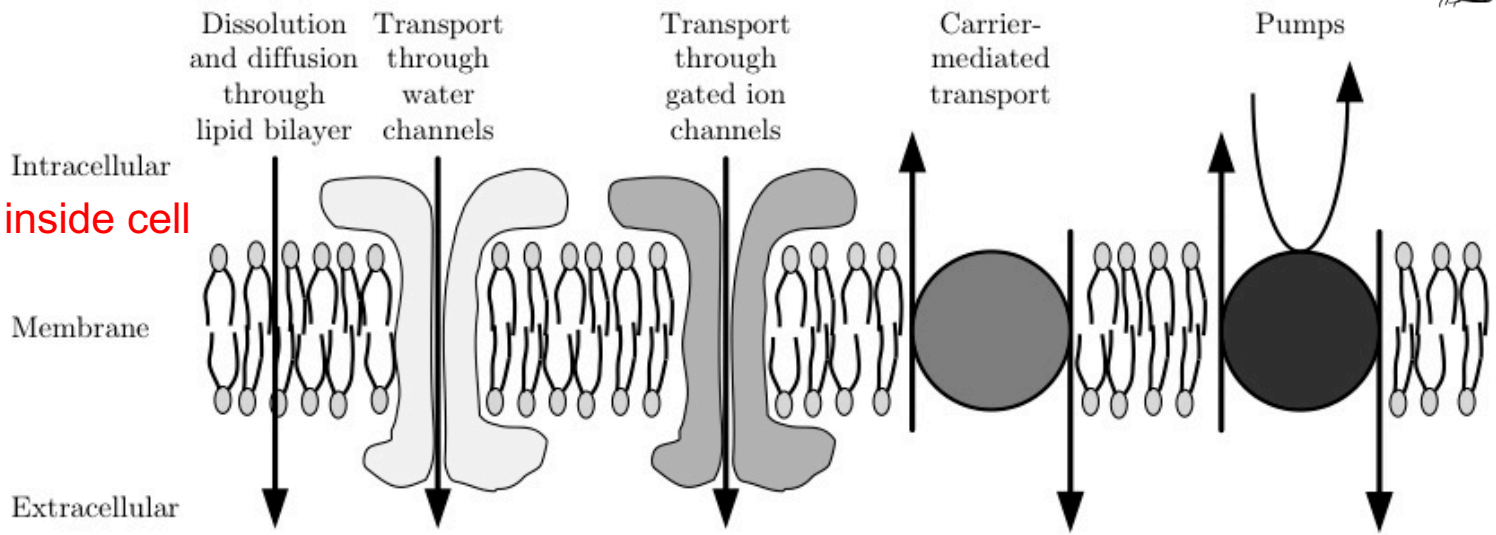
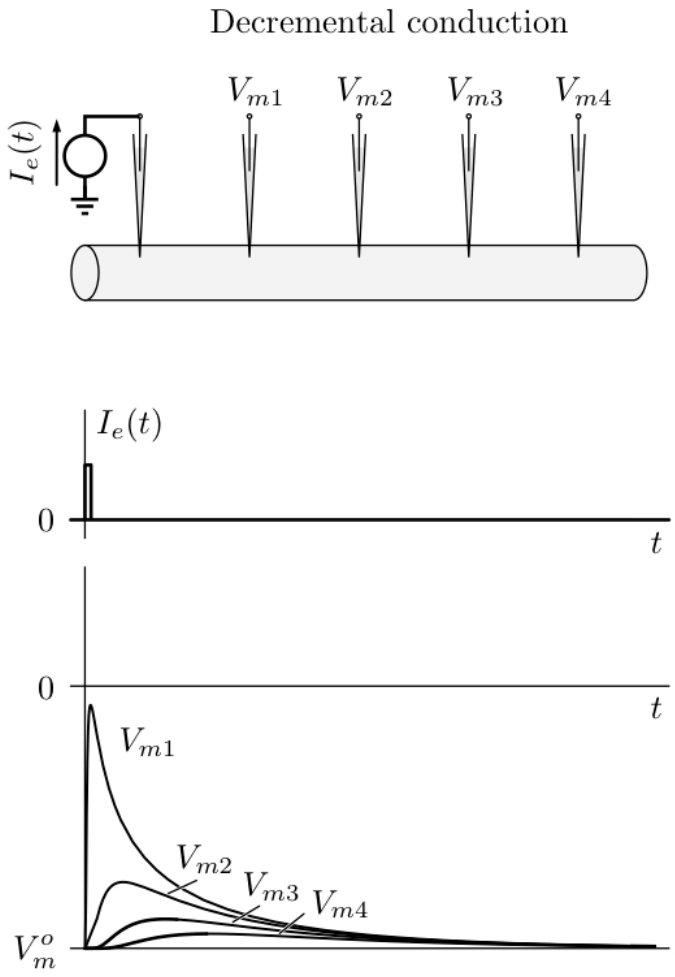


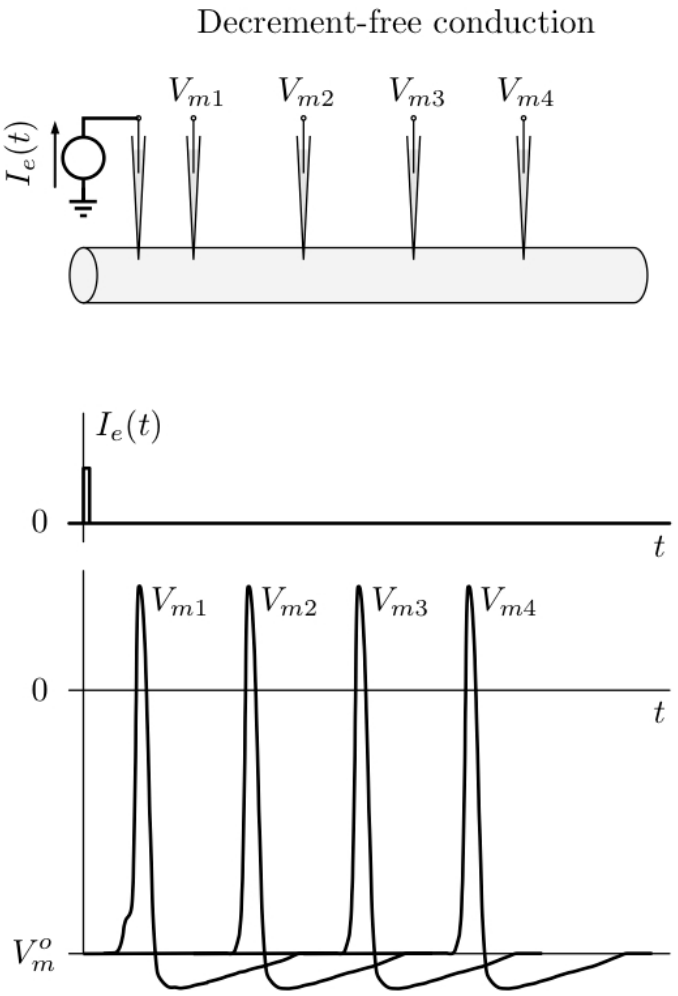
Figure 2.19

Weiss (1996)

Electrical excitability



electrically inexcitable cell



electrically excitable cell

Weiss (1996)

Cable model

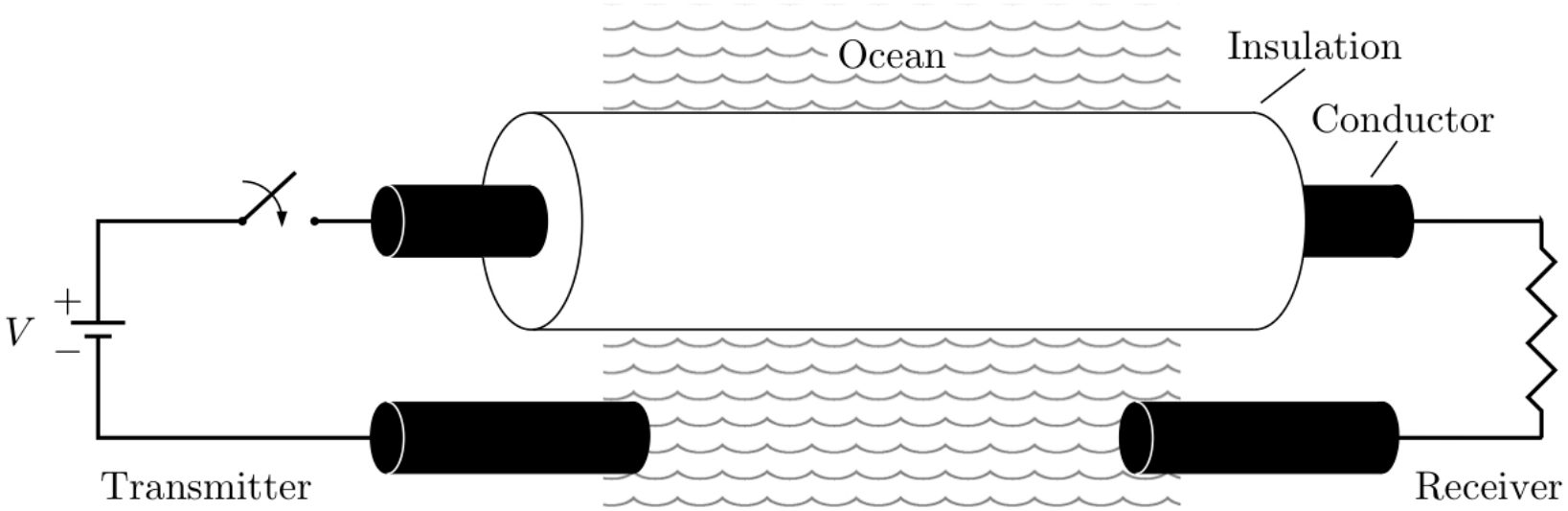


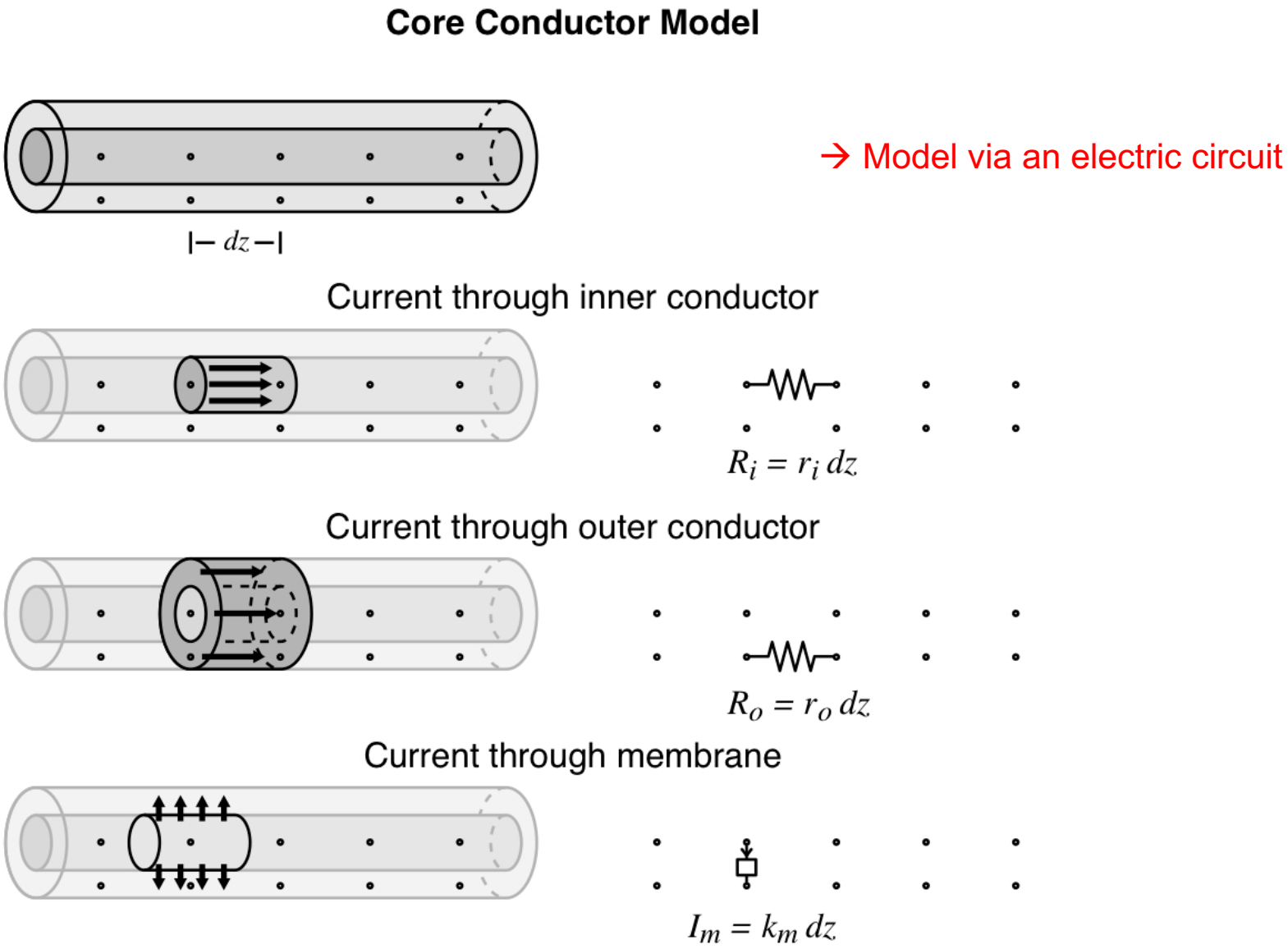
Figure 3.8

- First solved by William Thomson (aka Lord Kelvin) in ~1855

- Motivated by Atlantic submarine cable for intercontinental telegraphy

Weiss (1996)

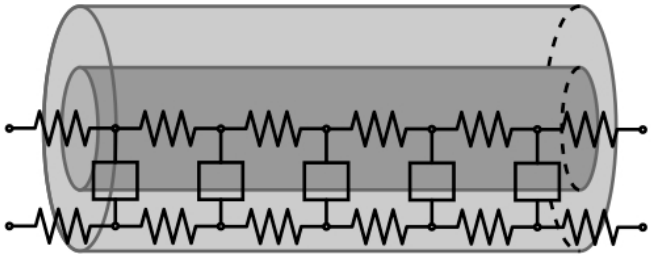
Biophysical model of a neuron



→ Model via an electric circuit

Biophysical model of a neuron

Core Conductor Model



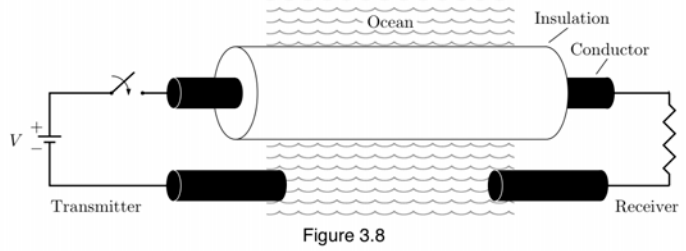


Figure 3.8

→ Cell behave like a leaky submarine cable!

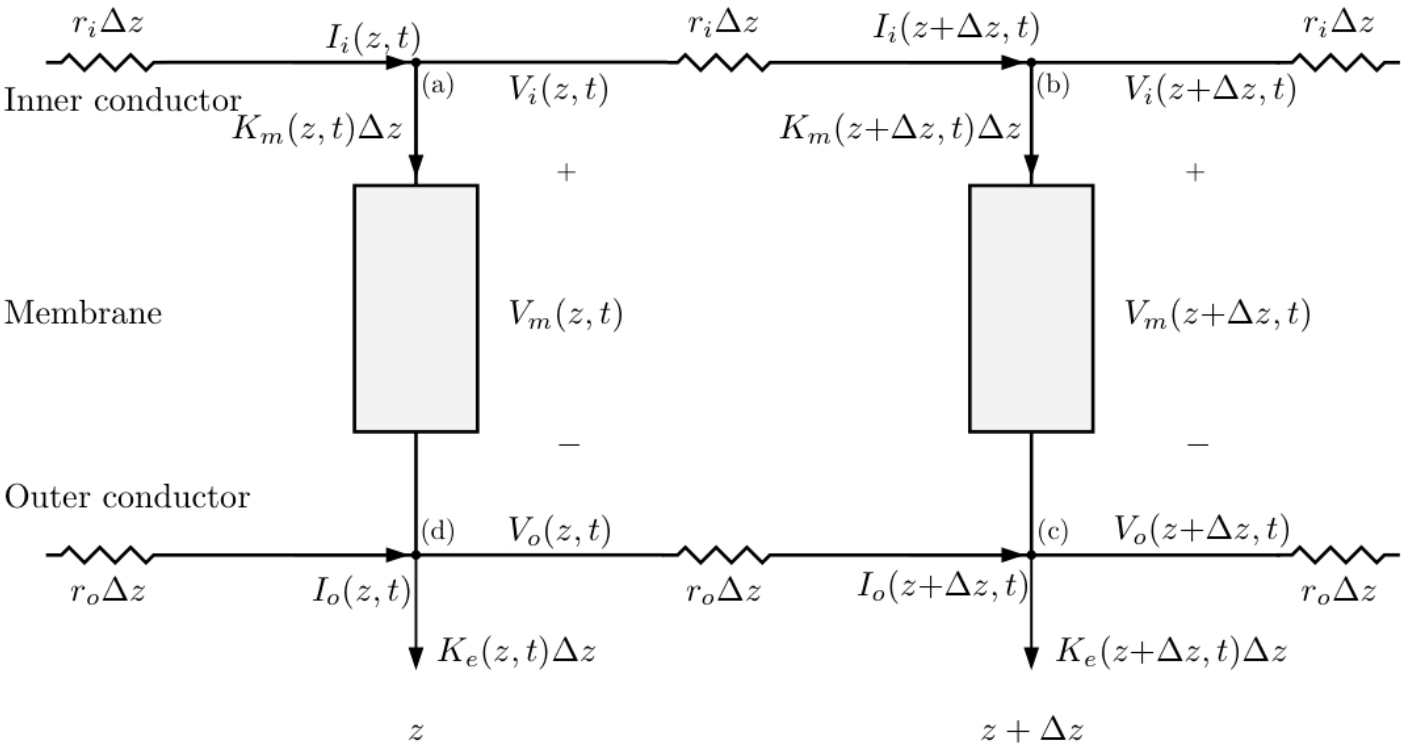
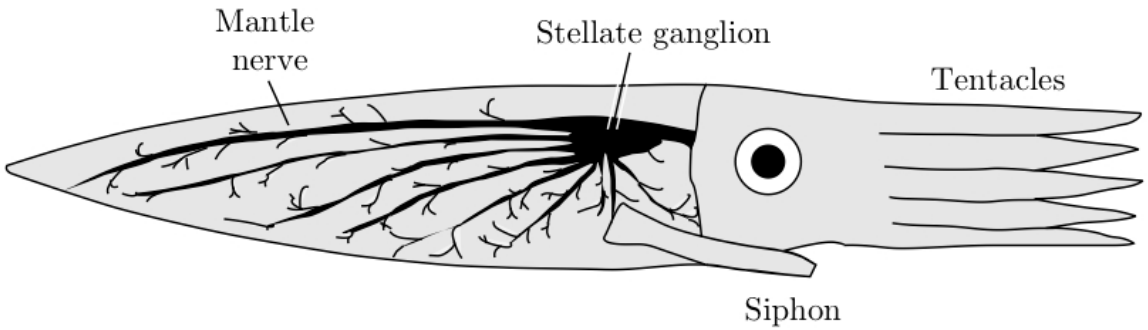


Figure 2.7

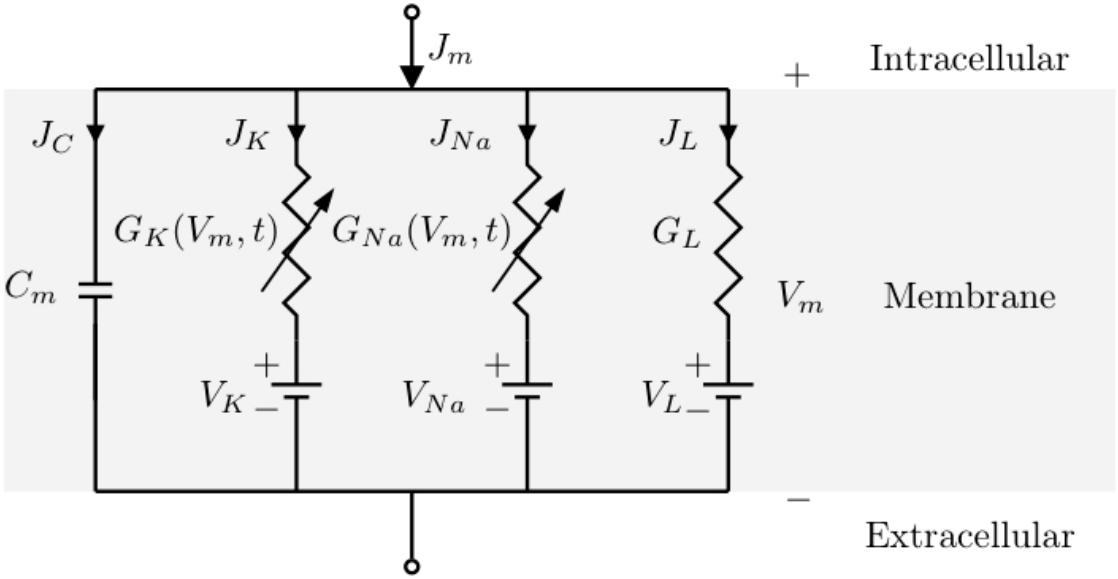
Weiss (1996)

Biophysical model of a neuron



Hodgkin Huxley model

Variable Na+ and K+ conductances



Weiss (1996)

Hodgkin-Huxley equations

$$\frac{1}{2\pi a(r_o + r_i)} \frac{\partial^2 V_m}{\partial z^2} = C_m \frac{\partial V_m}{\partial t} + G_K(V_m, t)\,(V_m - V_K) + G_{Na}(V_m, t)\,(V_m - V_{Na}) + G_L(V_m - V_L)$$

$$\tau_x \frac{dx}{dt} + x = x_\infty \qquad \frac{dx}{dt} = \alpha_x(1 - x) - \beta_x x$$

$$x_\infty = \alpha_x/(\alpha_x + \beta_x) \text{ and } \tau_x = 1/(\alpha_x + \beta_x)$$

$$G_K(V_m, t) = \overline{G}_K n^4(V_m, t)$$

$$G_{Na}(V_m, t) = \overline{G}_{Na} m^3(V_m, t) h(V_m, t)$$

$$n(V_m, t) + \tau_n(V_m) \frac{dn(V_m, t)}{dt} = n_\infty(V_m)$$

$$m(V_m, t) + \tau_m(V_m) \frac{dm(V_m, t)}{dt} = m_\infty(V_m)$$

$$h(V_m, t) + \tau_h(V_m) \frac{dh(V_m, t)}{dt} = h_\infty(V_m)$$

$$\alpha_m = \frac{-0.1(V_m + 35)}{e^{-0.1(V_m+35)} - 1},$$

$$\beta_m = 4e^{-(V_m+60)/18},$$

$$\alpha_h = 0.07e^{-0.05(V_m+60)},$$

$$\beta_h = \frac{1}{1 + e^{-0.1(V_m+30)}},$$

$$\alpha_n = \frac{-0.01(V_m + 50)}{e^{-0.1(V_m+50)} - 1},$$

$$\beta_n = 0.125e^{-0.0125(V_m+60)},$$

Finally there was the difficulty of computing the action potentials from the equations which we had developed. We had settled all the equations and constants by March 1951 and hoped to get these solved on the Cambridge University computer. However, before anything could be done we learnt that the computer would be off the air for 6 months or so while it underwent a major modification. Andrew Huxley got us out of that difficulty by solving the differential equations numerically using a hand-operated Brunsviga. The propagated action potential took about three weeks to complete and must have been an enormous labour for Andrew. But it was exciting to see it come out with the right shape and velocity and we began to feel that we had not wasted the many months that we had spent in analysing records.

—Hodgkin, 1977

Putting the pieces together....

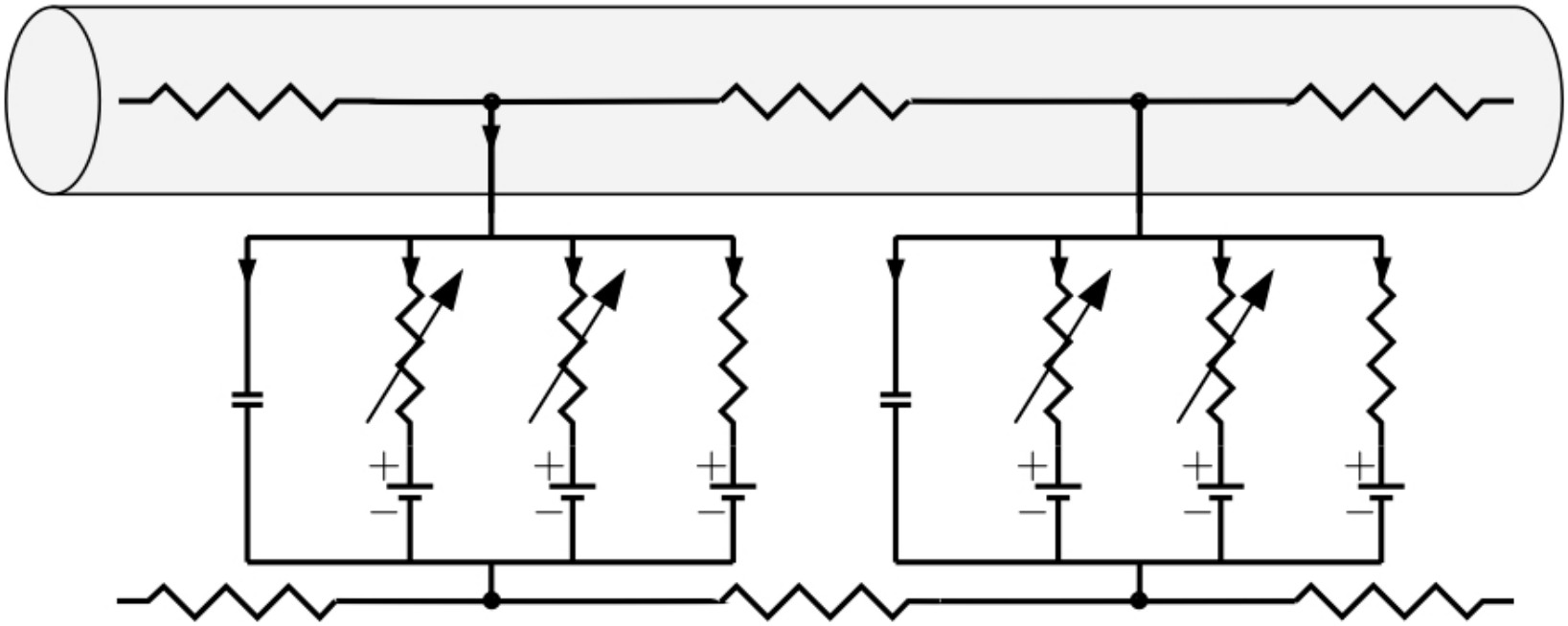


Figure 4.7

Weiss (1996)

Summary (re neurons)

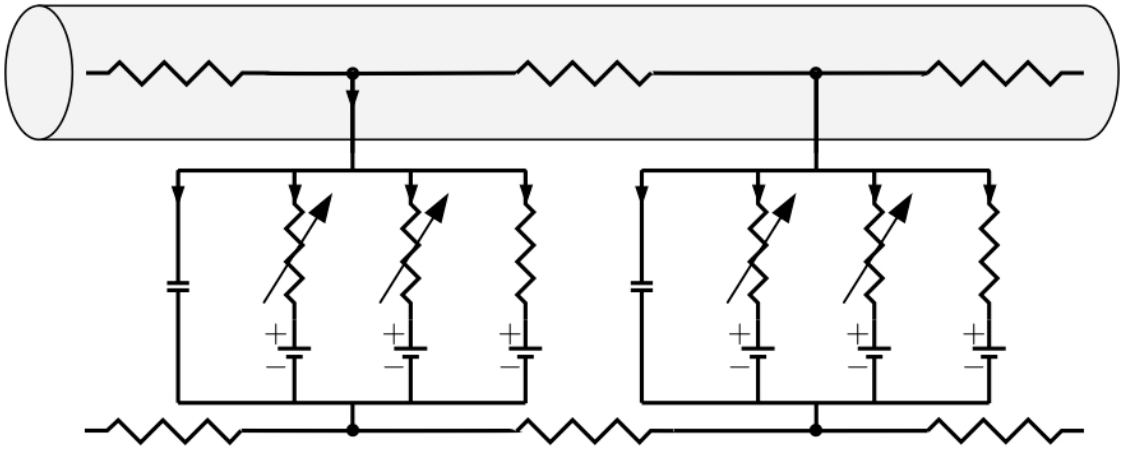


Figure 4.7

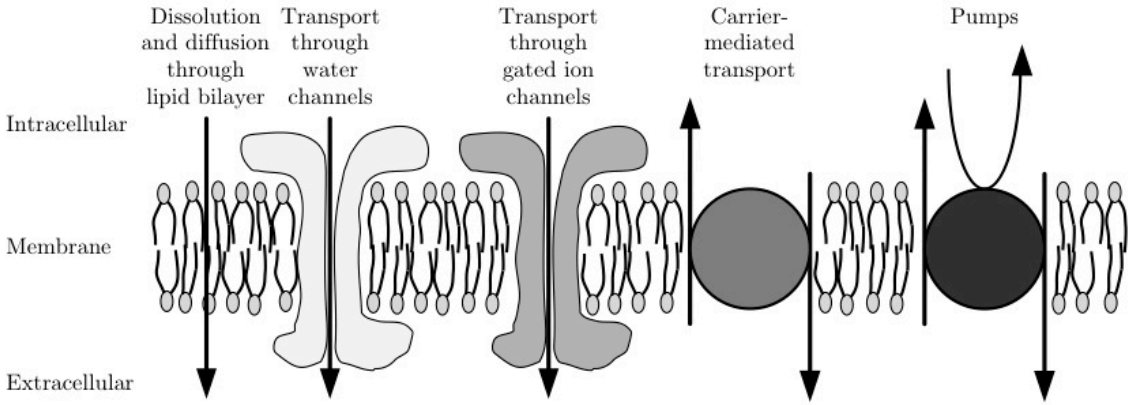


Figure 2.19

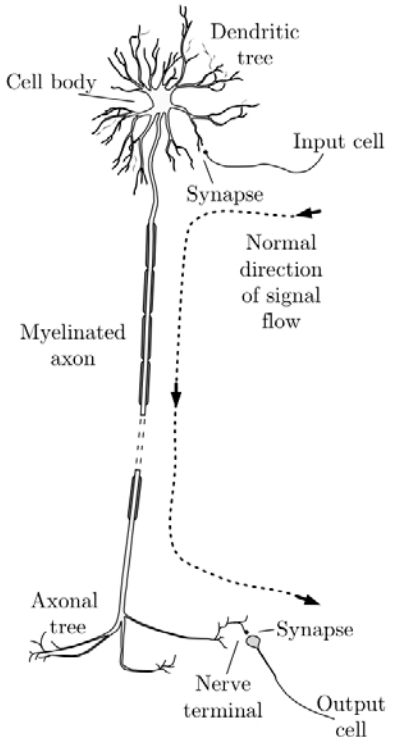


Figure 1.22

Weiss (1996)

Question:
How do our sensory systems encode “information” about the world around us?

Electrical Responses in Sensory Systems

Photoreceptors

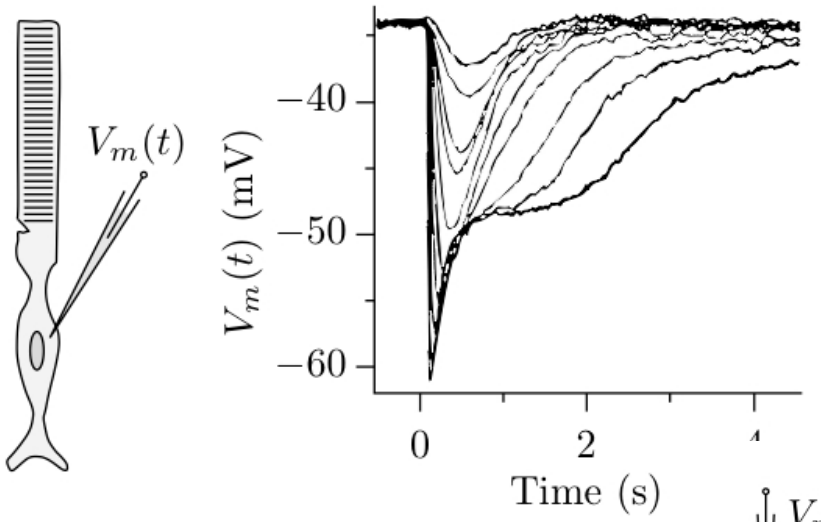


Figure 1.3

→ Not always "electrically excitable" per se, but role as "transducers" critically tied to electrical responses

Auditory Hair Cells

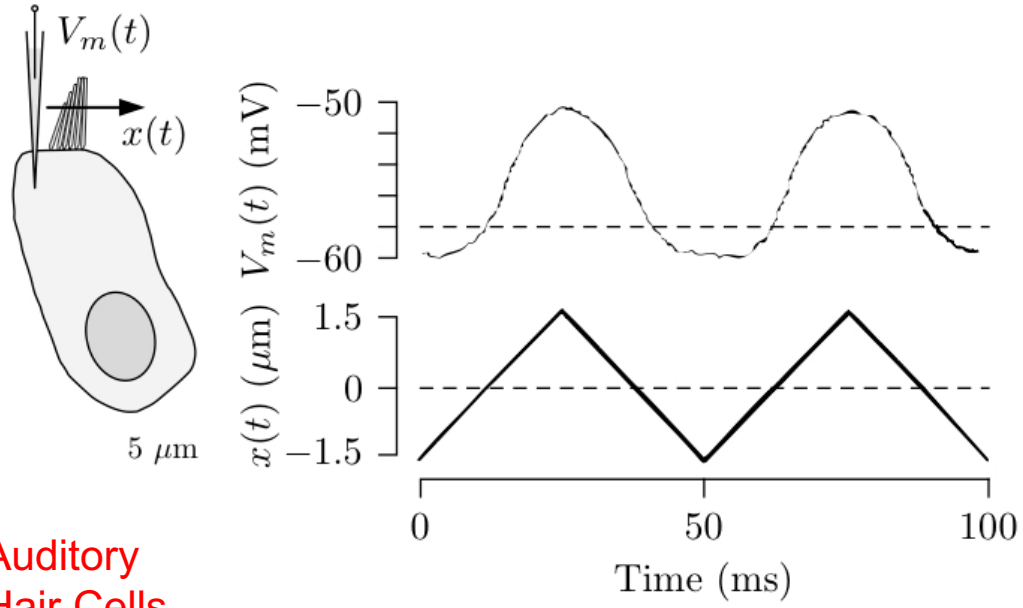


Figure 1.5

Consider how you “process” this picture....

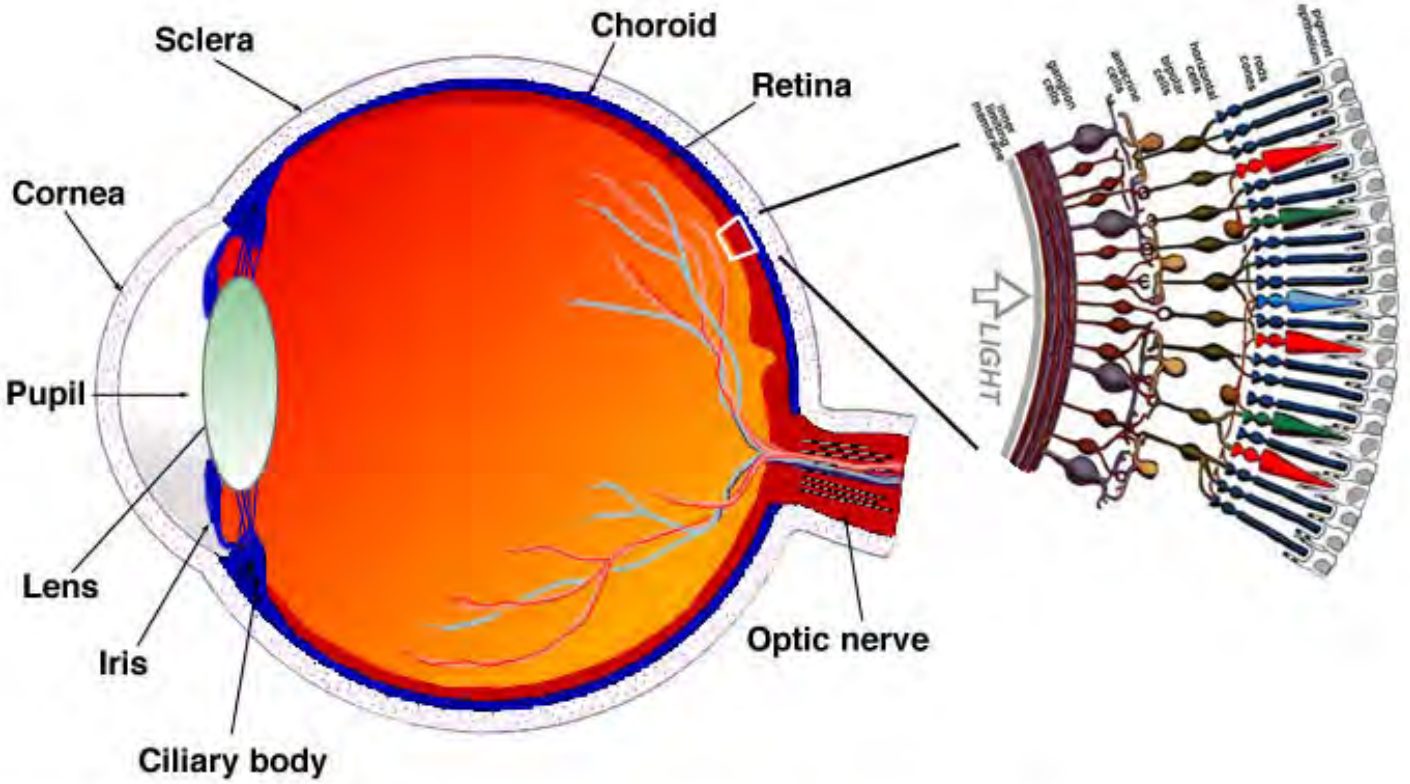
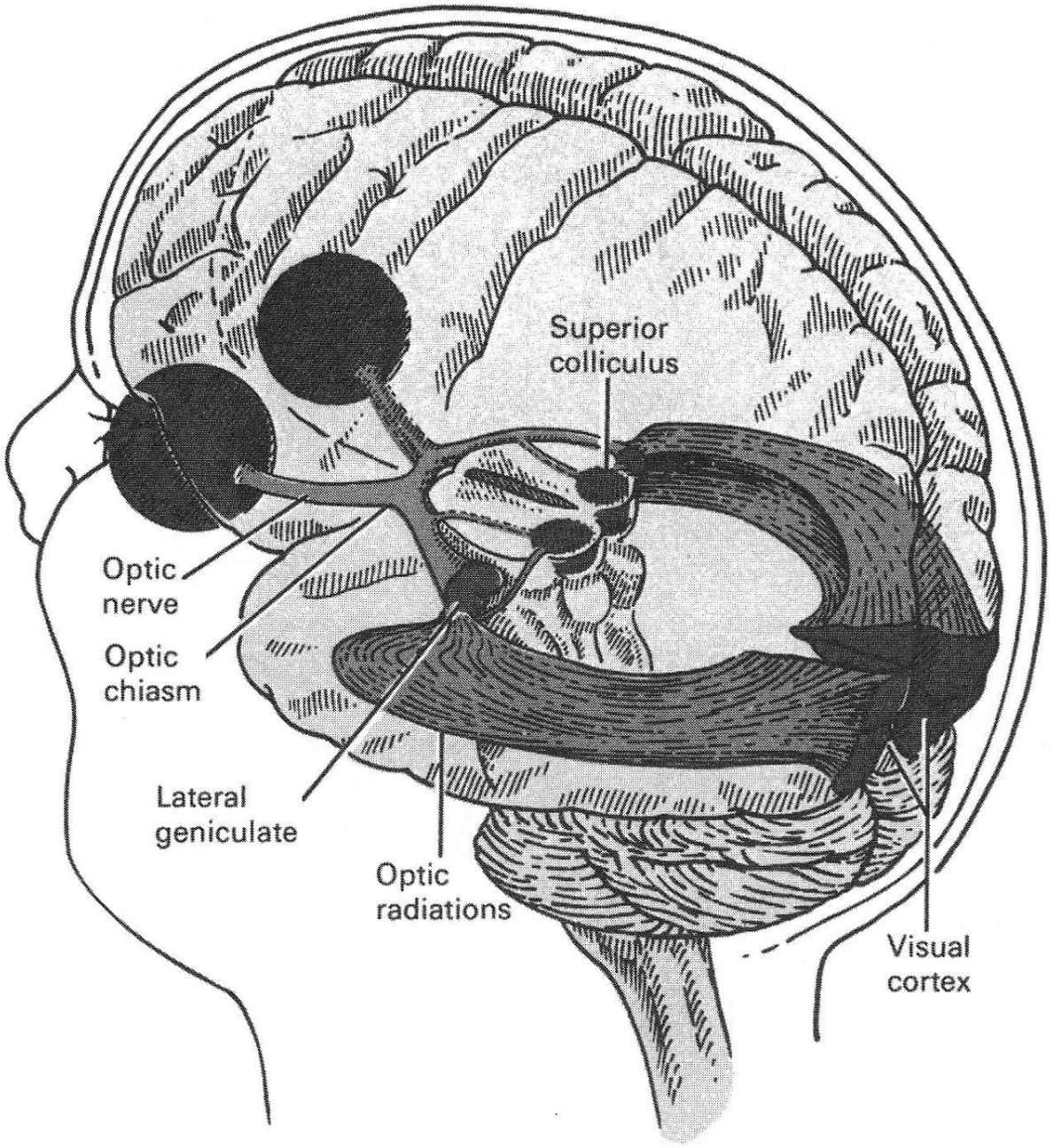
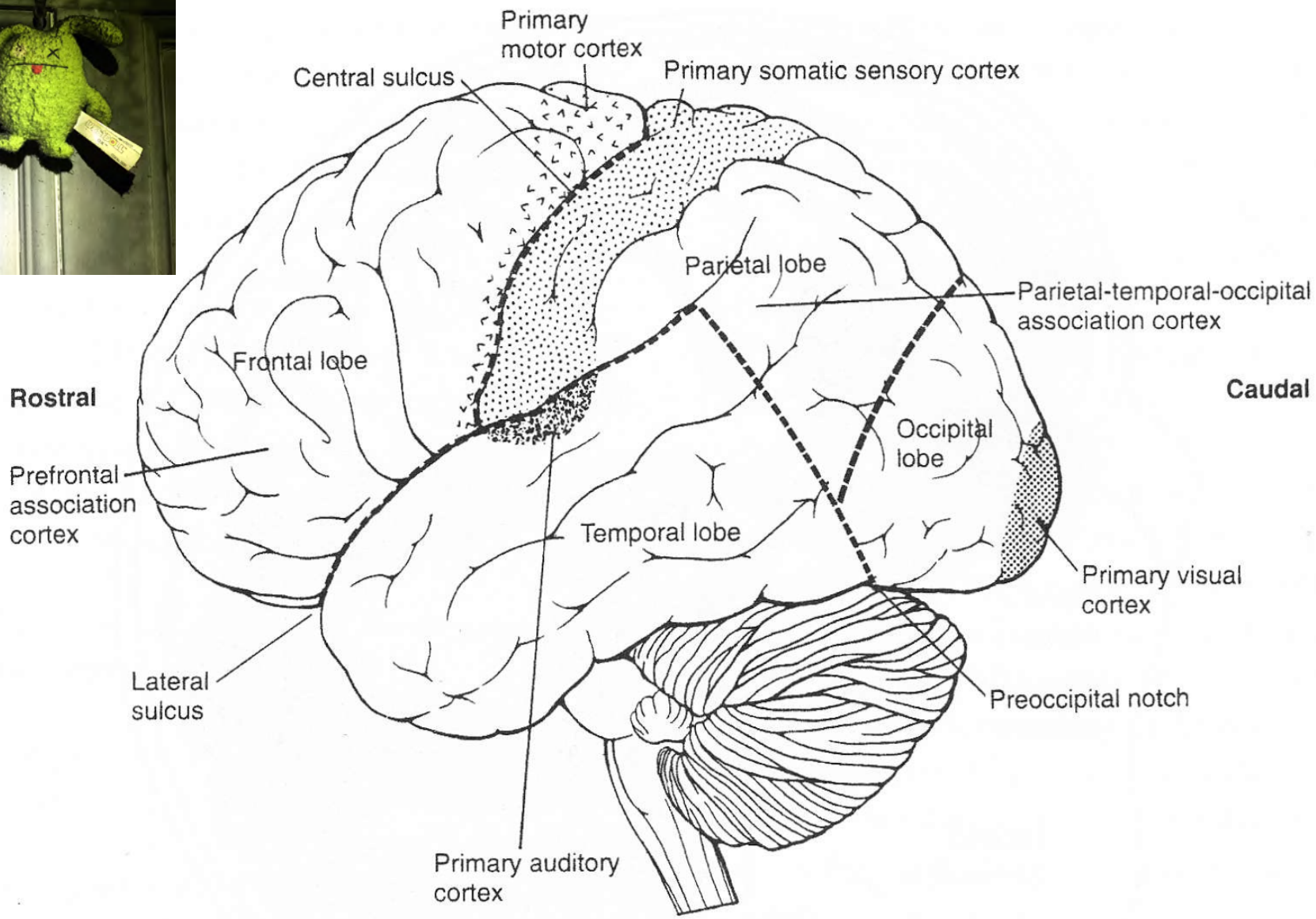


Fig. 1.1. A drawing of a section through the human eye with a schematic enlargement of the retina.

Question: How is information being "transduced" here?


Superior colliculus
Optic nerve
Optic chiasm
Lateral geniculate
Optic radiations
Visual cortex

Palmer (1999)


Primary
motor cortex
Central sulcus
Primary somatic sensory cortex
Parietal lobe
Parietal-temporal-occipital
association cortex
Frontal lobe
Rostral
Caudal
Occipital
lobe
Prefrontal
association
cortex
Temporal lobe
Primary visual
cortex
Lateral
sulcus
Preoccipital notch
Primary auditory
cortex

Palmer (1999)

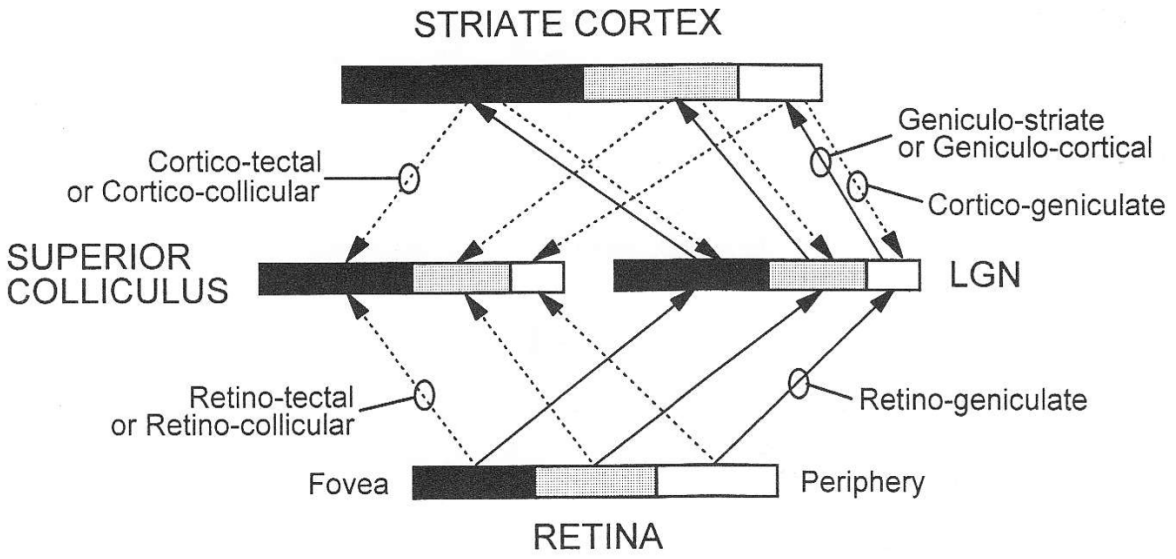
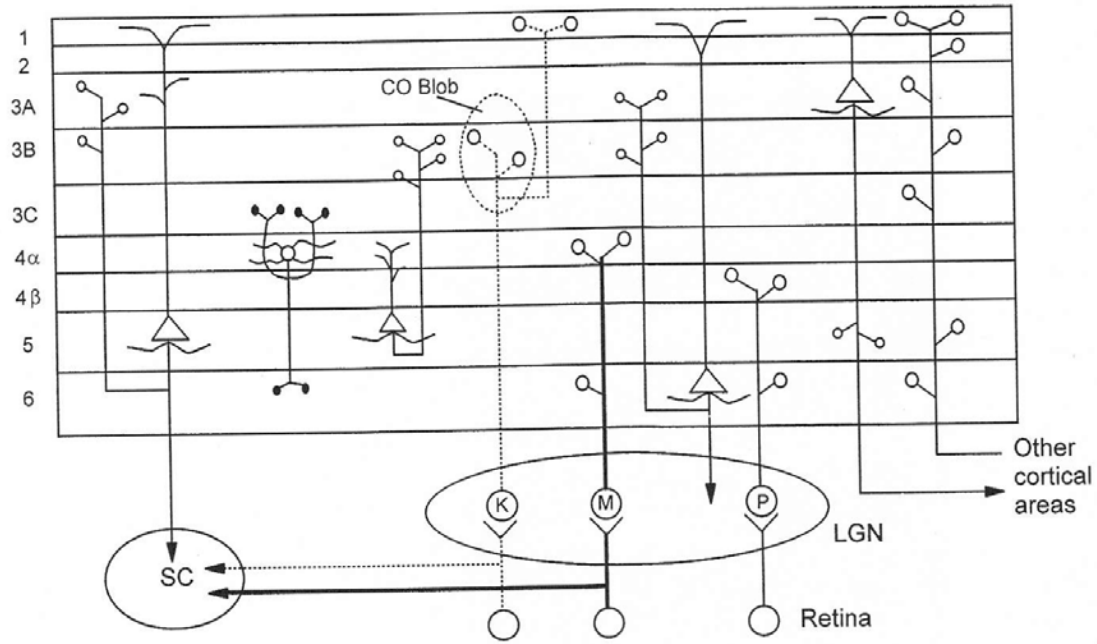


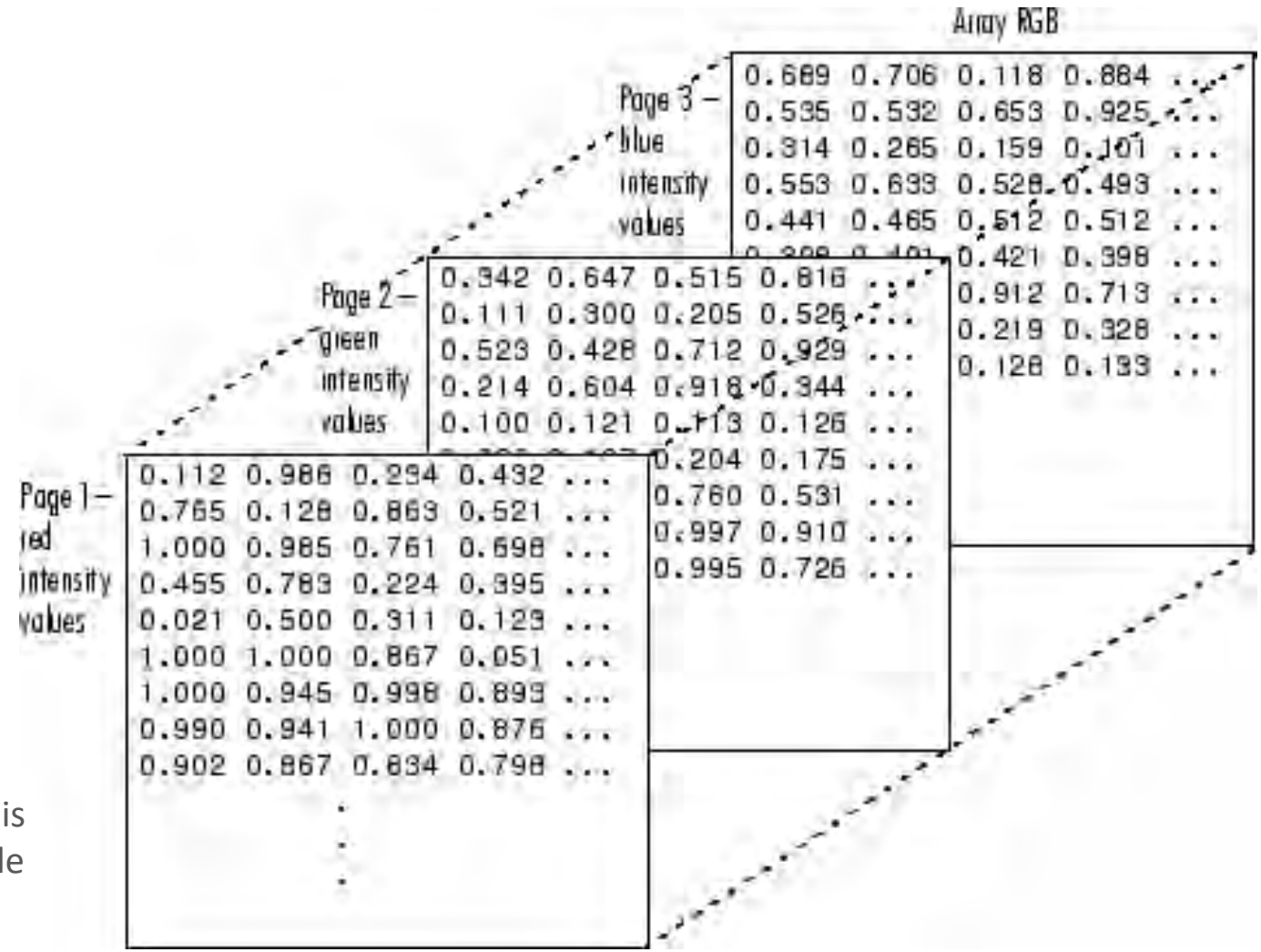
Figure 4.9. Schematic representation of the retino-geniculo-striate and retino-tectal projections and the return projections from the visual cortex.



Question: What are the basic building blocks that make up these “circuits”?

McIlwain (1996)

Aside: Images as numbers (i.e., a “bitmap”)

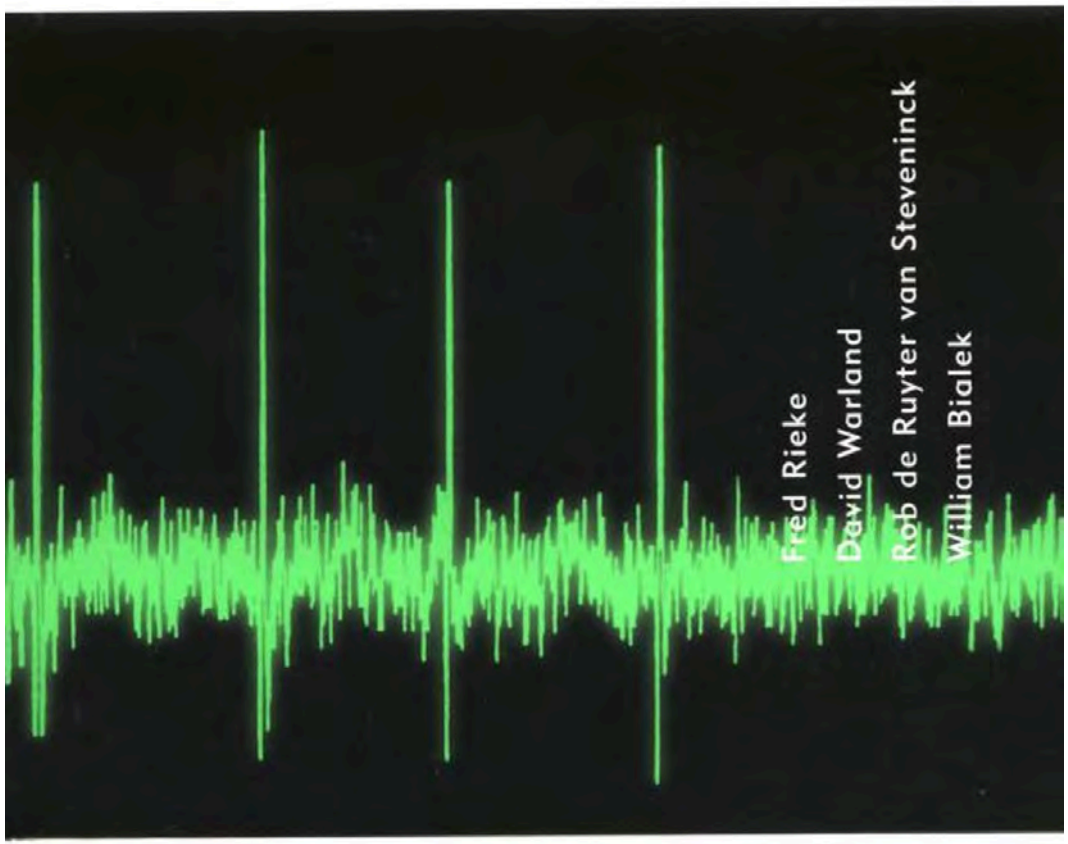


Note
Even this basic picture is too simple for a jpeg file

Question: Does your eye/nervous system process and store this image like a computer does?

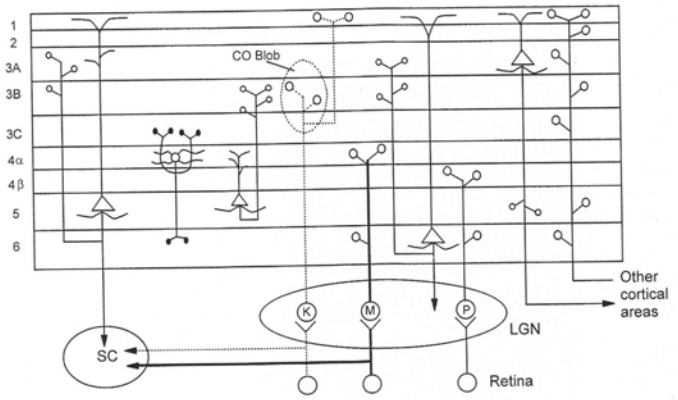
http://i.stack.imgur.com/kl65e.gif

Somehow, the information is "transformed", encoded into some other "language"....



Human brain contains ~10^{11} (100 billion) neurons

(with 100 trillion+ connections inbetween)



→ This is a pretty hard problem!

BIOPHYSICS @YORK

redefine THE POSSIBLE.

UNIVERSITÉ
UNIVERSITY

- Slides available for download: http://www.yorku.ca/cberge/
- Questions? cberge@yorku.ca