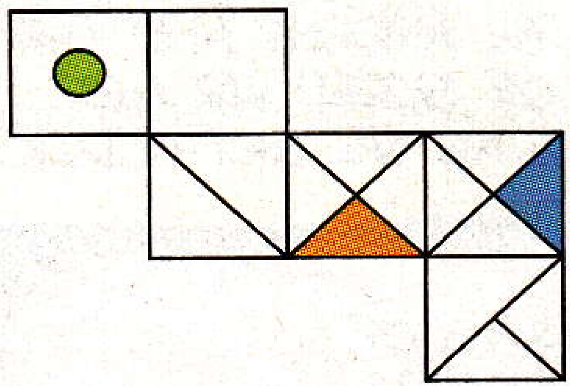
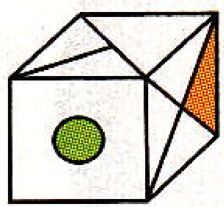
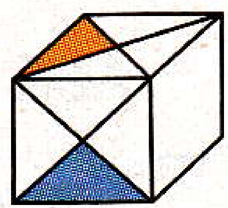
Which of the six boxes below cannot be made from this unfolded box? (There may be more than one.)

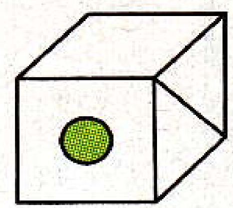




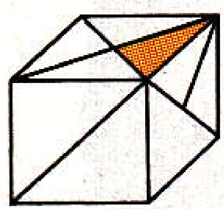
A



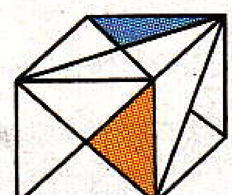
B



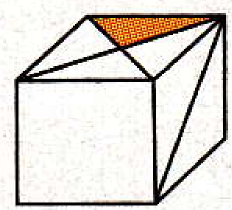
C



D



E



F

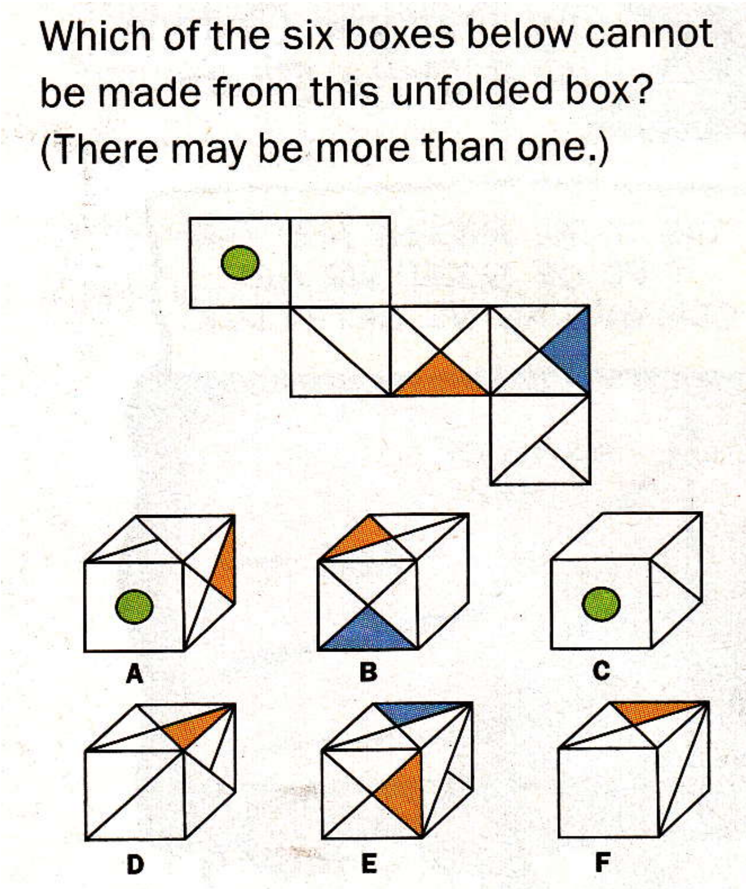
BIOPHYSICS @YORK

UNIVERSITÉ
UNIVERSITY

redefine THE POSSIBLE.

Sensing the World Around Us

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



Question:
Physiologically, how did you (try to) solve this puzzle?

→ We'll come back to this thing in a bit

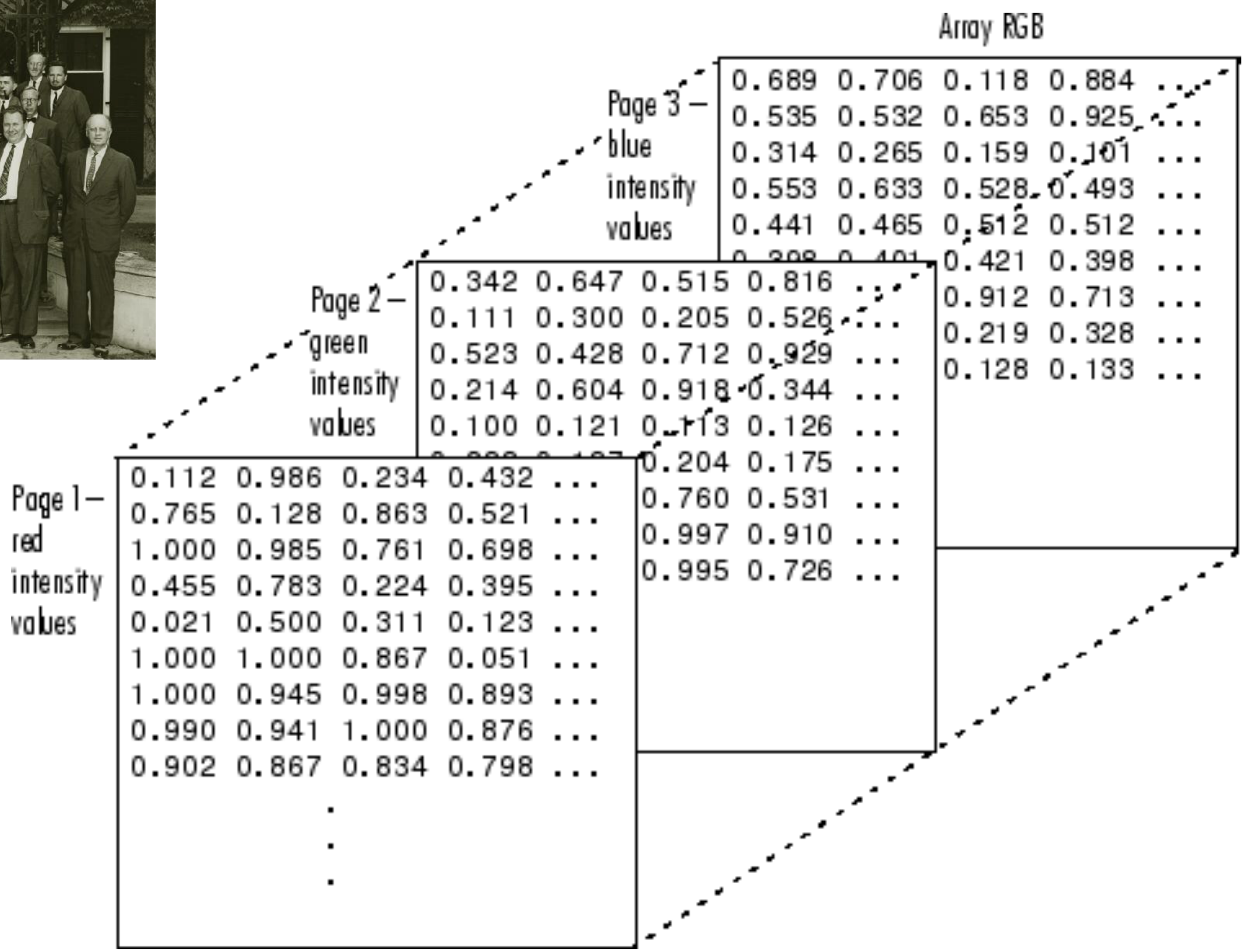
National Geographic

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

York University faculty (1961)

Consider how you “process” this picture and extract information from it....

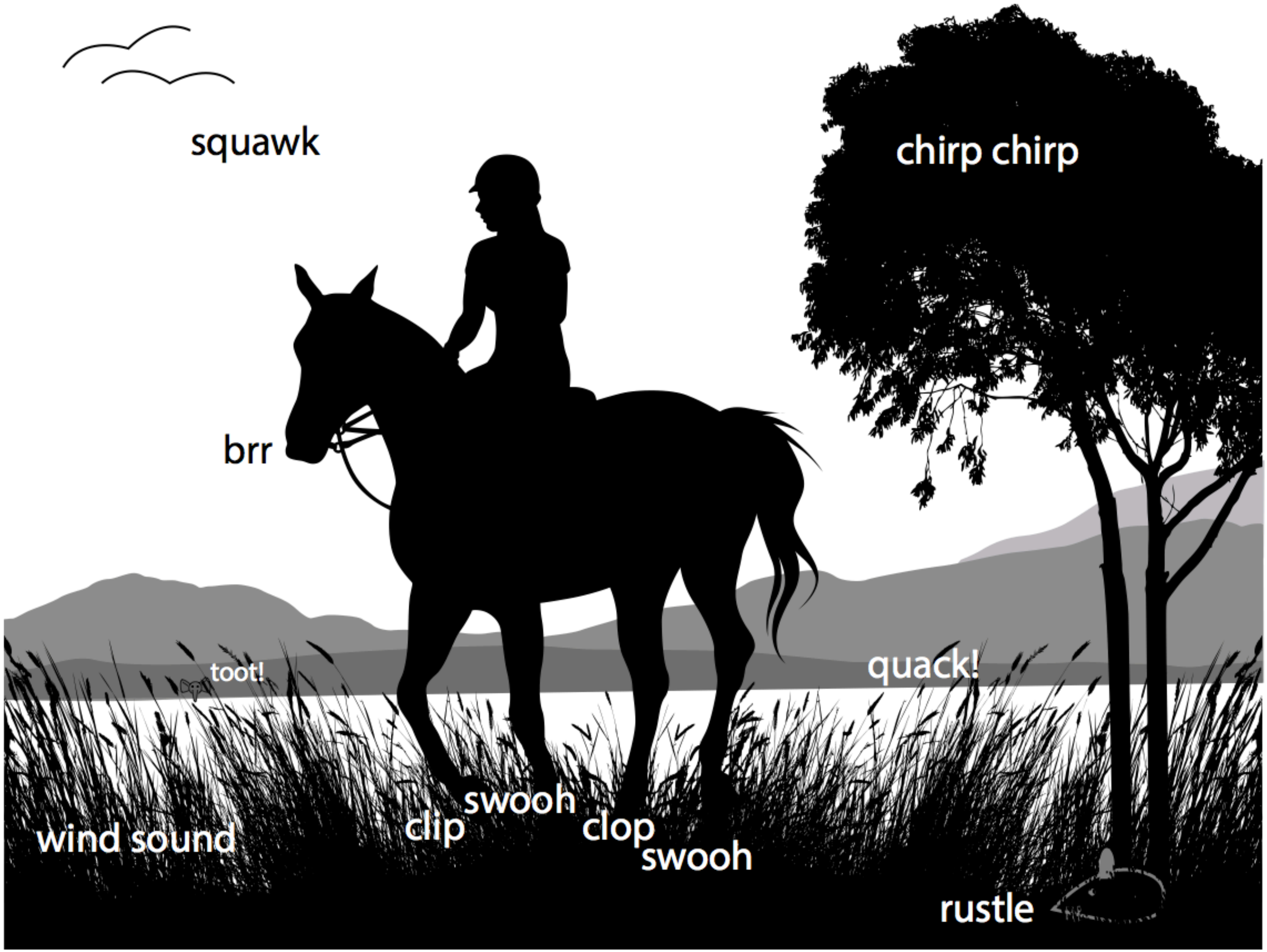
https://en.wikipedia.org/wiki/York_University



Aside

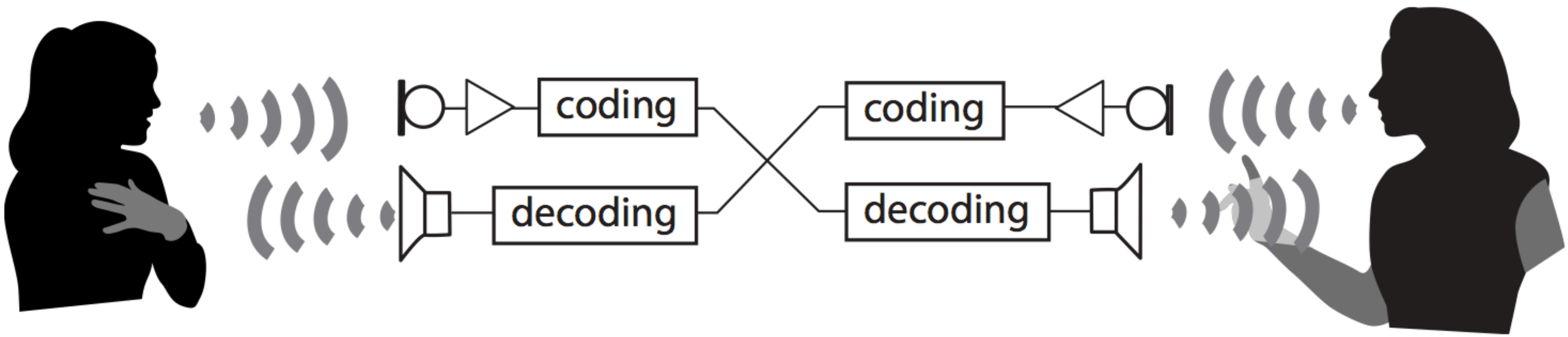
Does your eye/nervous system process and store this image like a computer does?

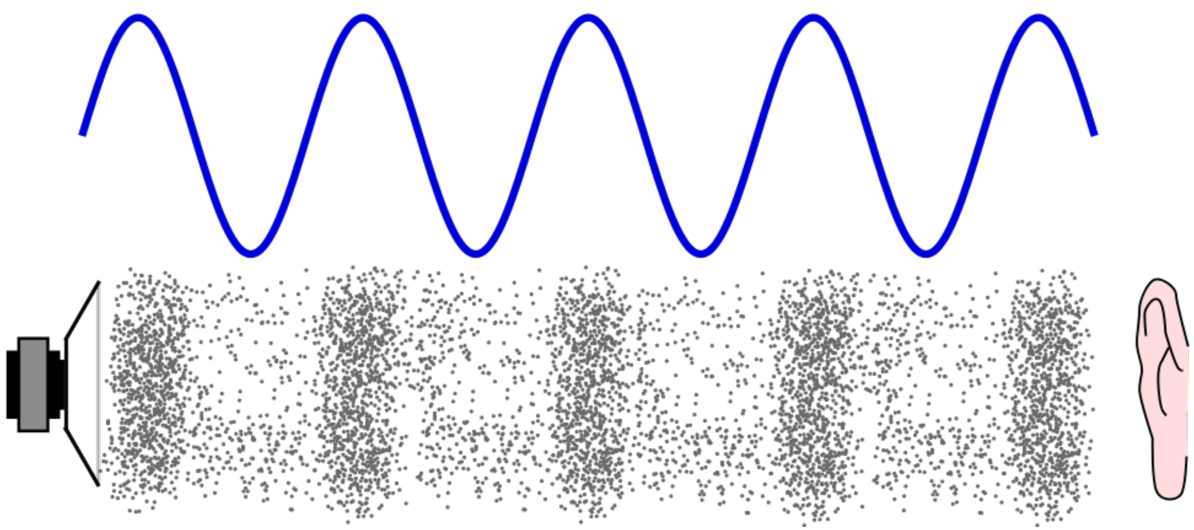
http://i.stack.imgur.com/kI65e.gif



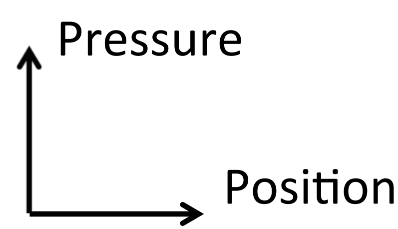
Pulkki & Karjalainen (2015)

e.g., "Speech chain"





Snapshot in time

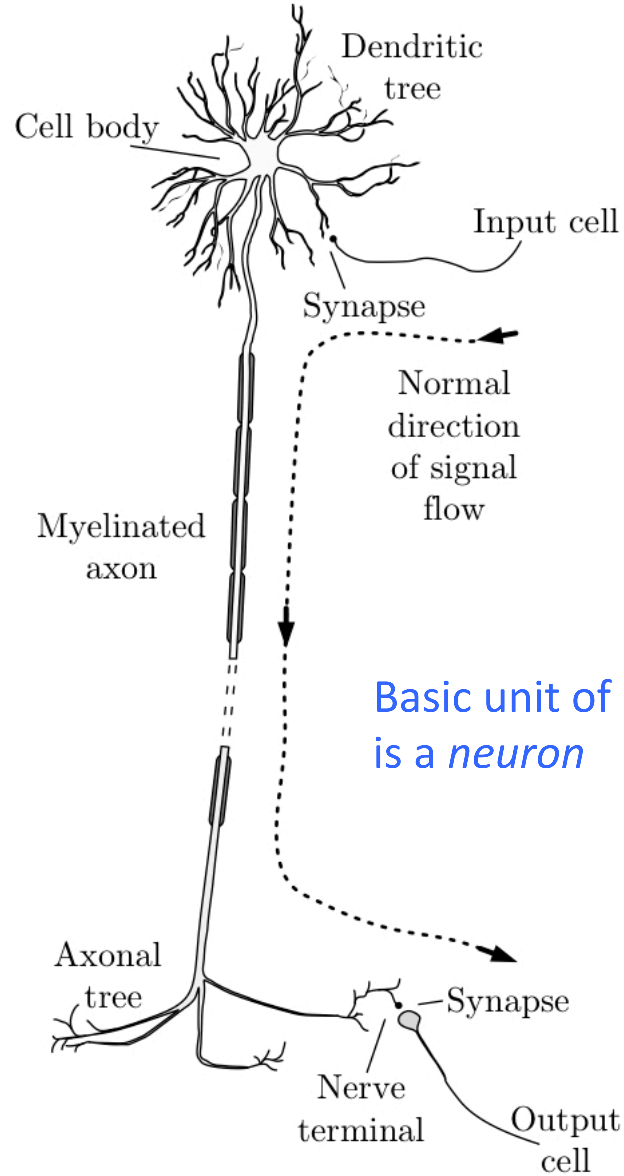


Pulkki & Karjalainen (2015)

How does our CNS process information?

Neurons (type of cell) = Information highway

CNS = Central Nervous System



Basic unit of CNS is a *neuron*

Figure 1.22

Weiss (1996)

How many neurons are there in the brain?

Human brain contains ~10^{11} (100 billion) neurons!
(with 100 trillion+ connections in between)

→ Understanding how all this works is a pretty hard problem!

Neurons are "spike-y"…..

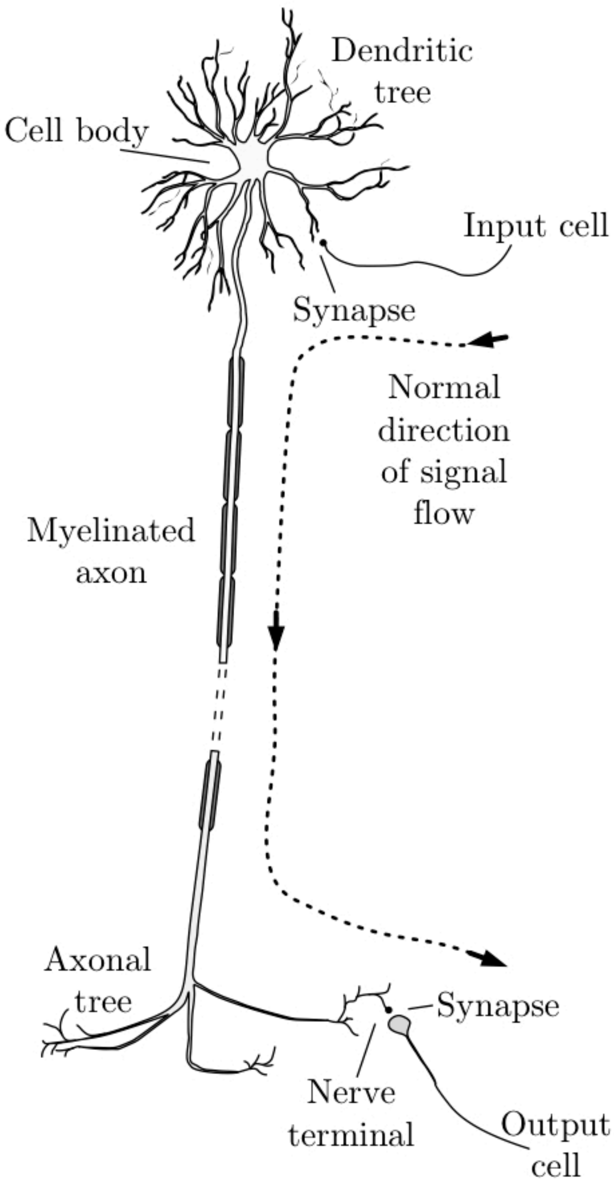
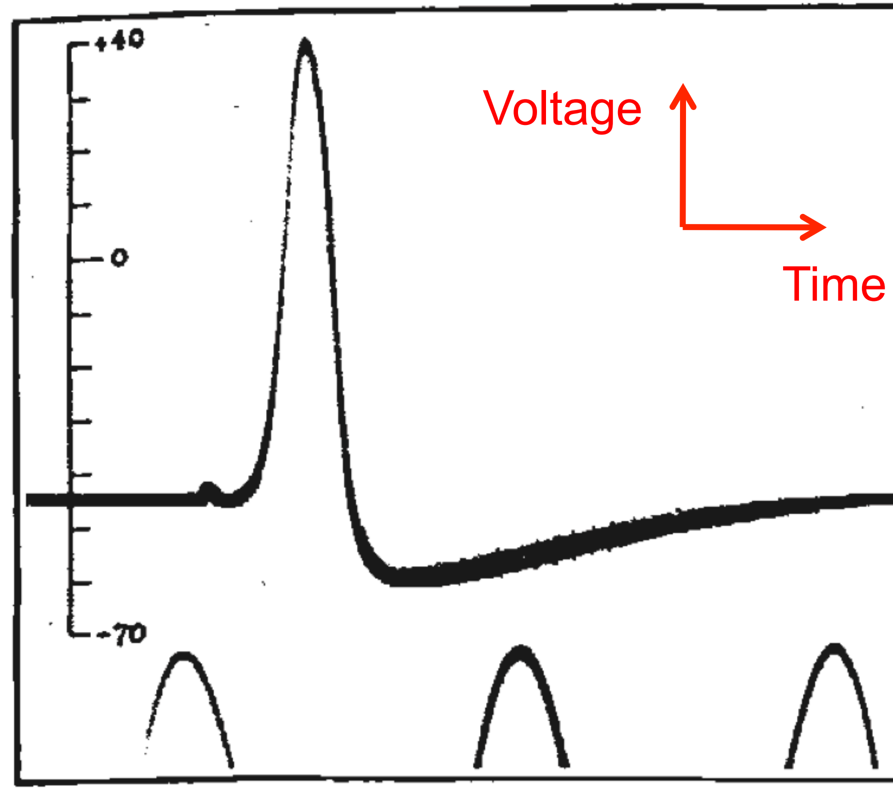


Figure 1.22

Weiss (1996)



Hodgkin & Huxley (1939)

Fig. 2.

ACTION POTENTIAL RECORDED BETWEEN INSIDE AND OUTSIDE OF AXON. TIME MARKER, 500 CYCLES/SEC. THE VERTICAL SCALE INDICATES THE POTENTIAL OF THE INTERNAL ELECTRODE IN MILLIVOLTS, THE SEA WATER OUTSIDE BEING TAKEN AT ZERO POTENTIAL.

(propagating) "action potentials"

Biophysical aside

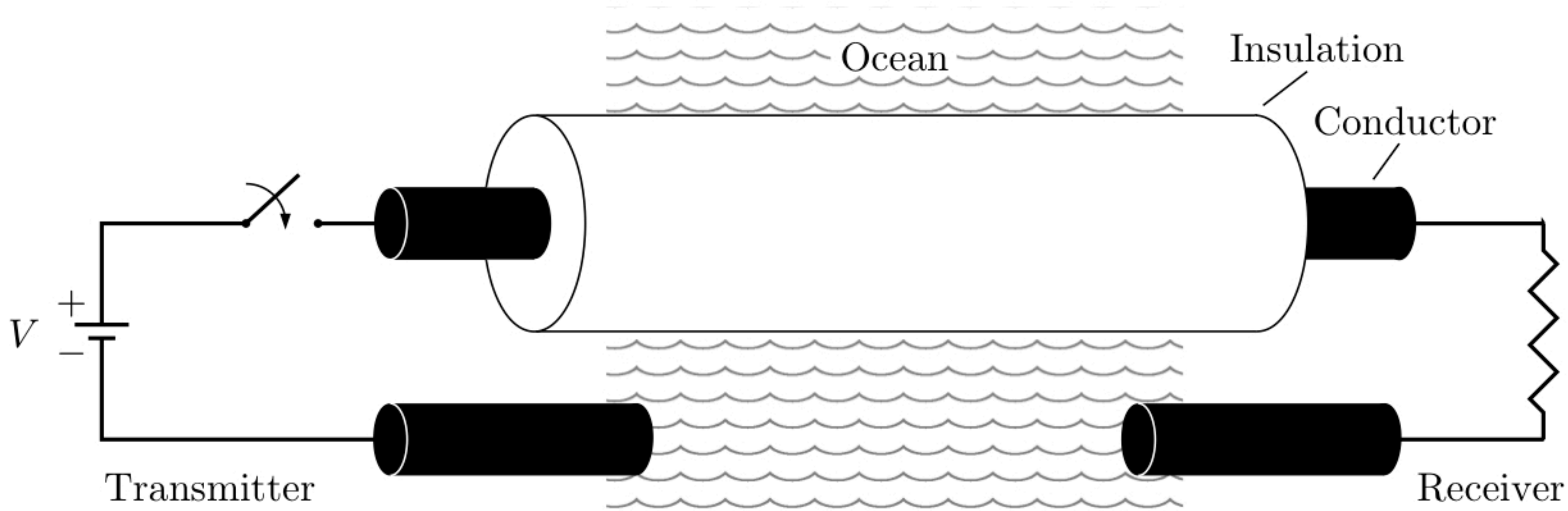


Figure 3.8

- Trans-Atlantic submarine cable for intercontinental telegraphy
- First “solved” by William Thomson (aka Lord Kelvin) in ~1855

Neurons behave in a very similar fashion
(i.e., leaky submarine cables!)

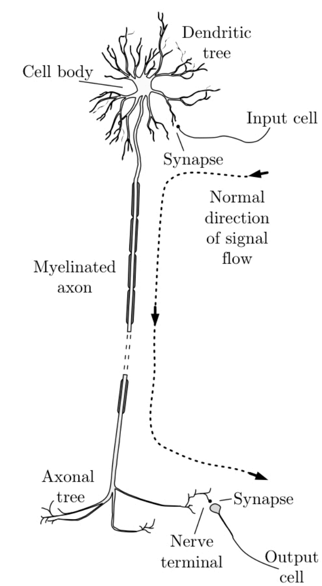
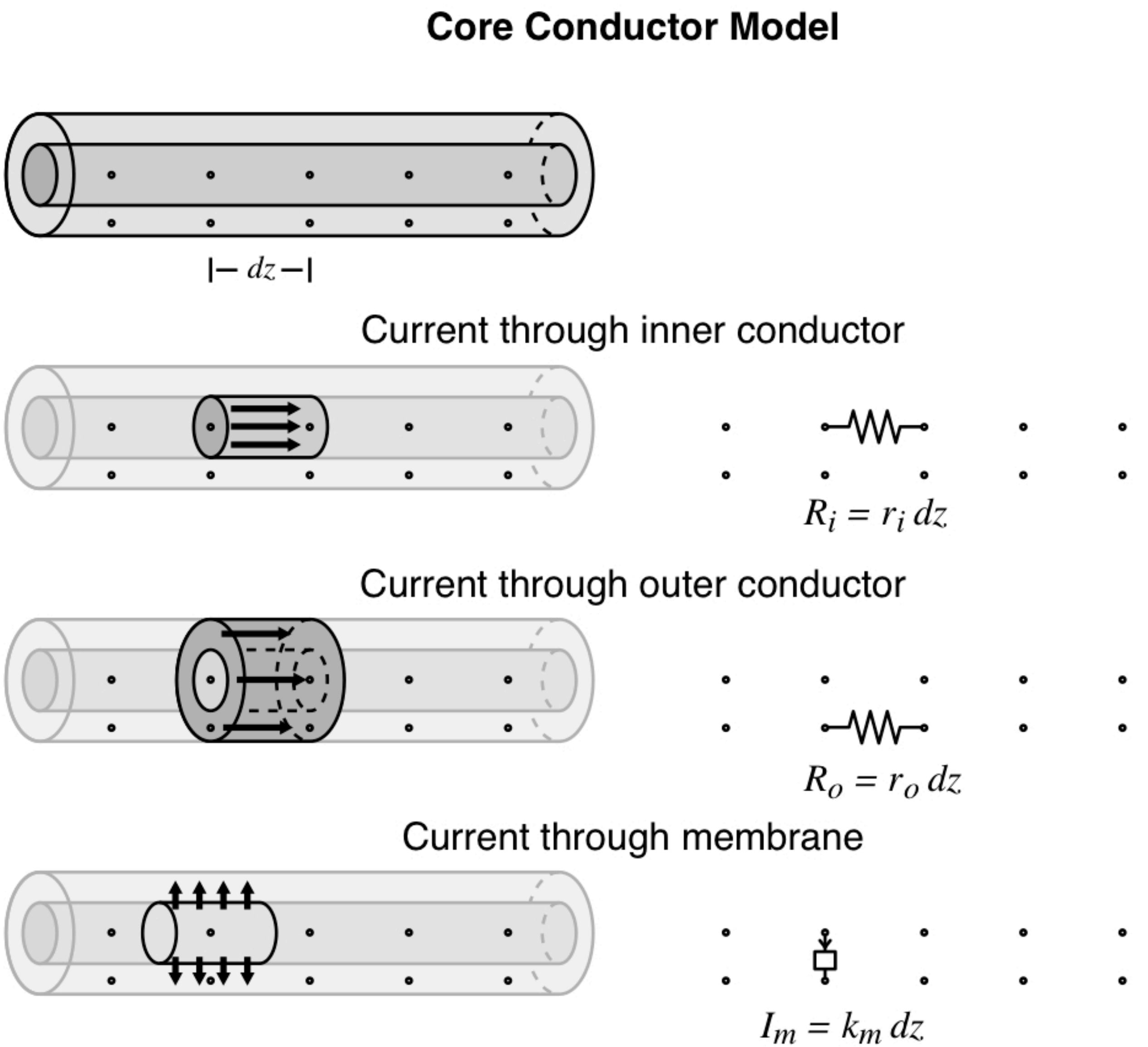


Figure 1.22

Weiss (1996)

Biophysical aside



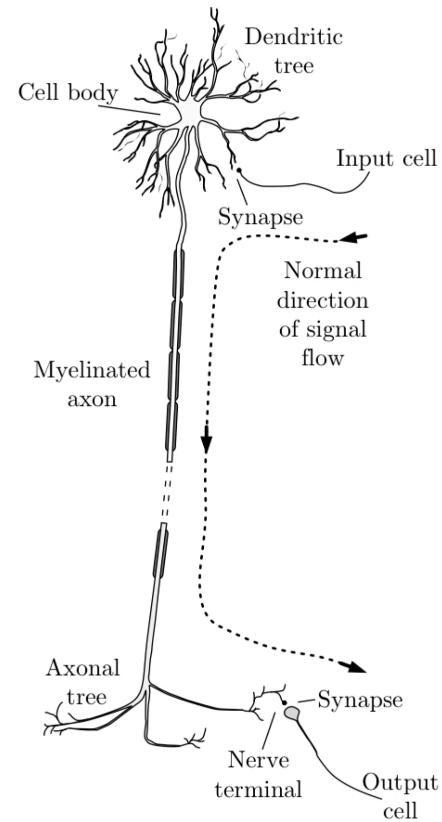
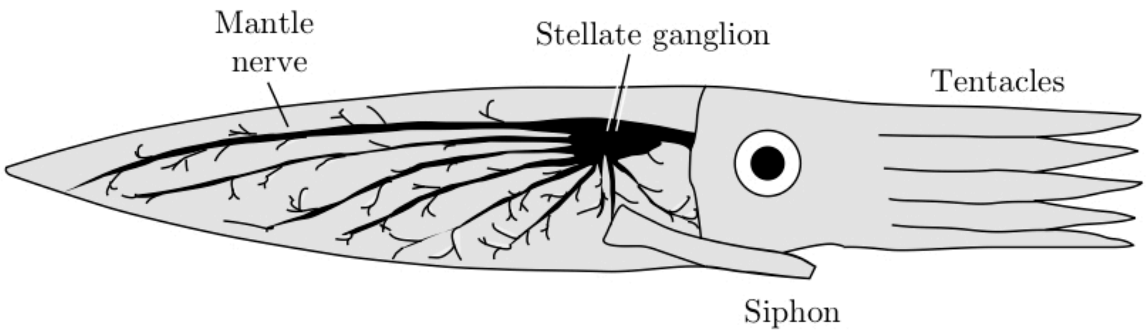


Figure 1.22

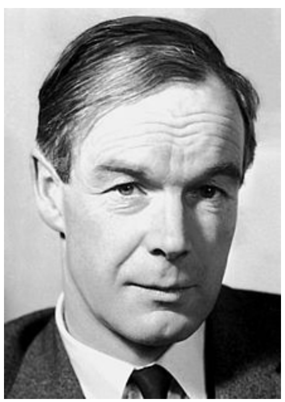
→ Model neurons via an electric circuit

Freeman

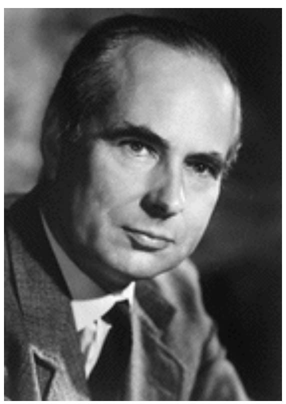
Biophysical aside



Hodgkin Huxley model

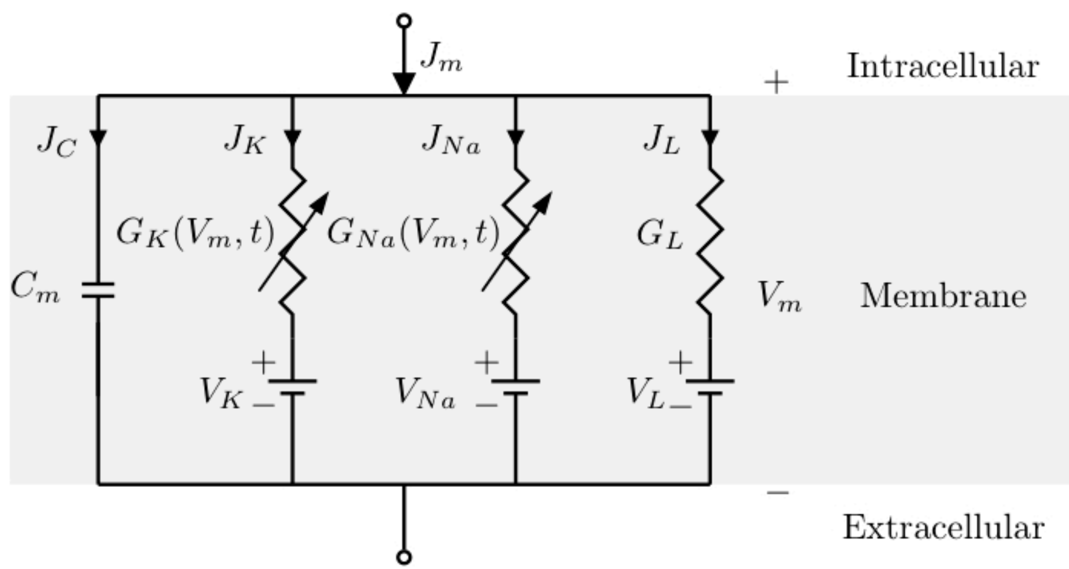


Alan Hodgkin



Andrew Huxley

1963 Nobel Prize



Variable Na+ and K+ conductances

Weiss (1996)

Hodgkin-Huxley equations

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Keep in mind that this is a relatively simple model for a single neuron....

Weiss (1996)

How many neurons are there in the brain?

→ Understanding how all this works is a pretty hard problem!

Human brain contains ~10^{11} (100 billion) neurons!
(with 100 trillion+ connections inbetween)

Historical aside

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

Sans computing power, one actually needs to think carefully about things....

Weiss (1996)

At the most basic level, problem boils down to how things move across the cell membrane

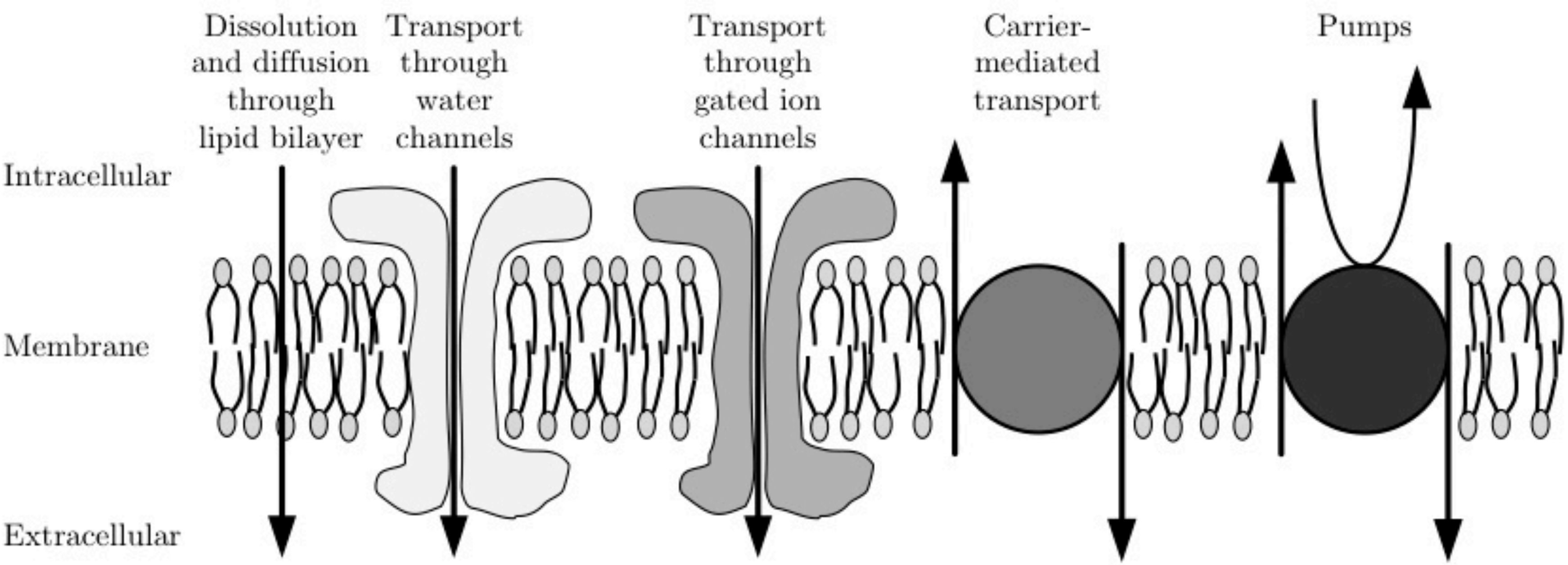
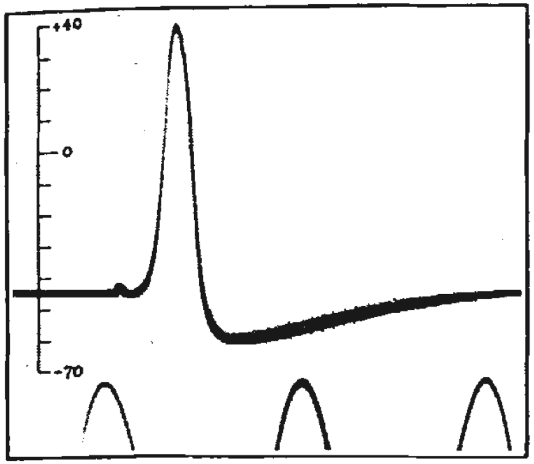
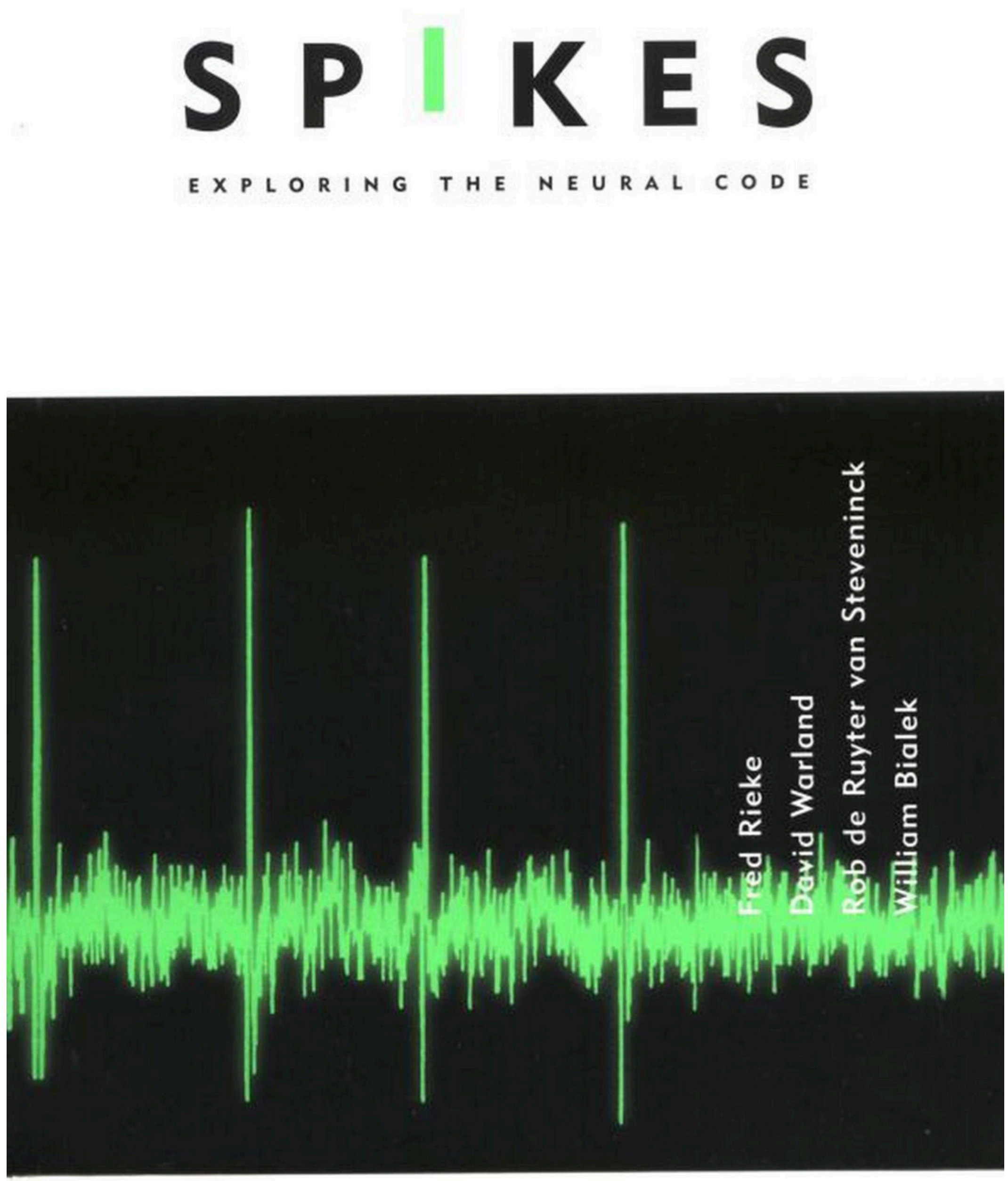


Figure 2.19

Weiss (1996)



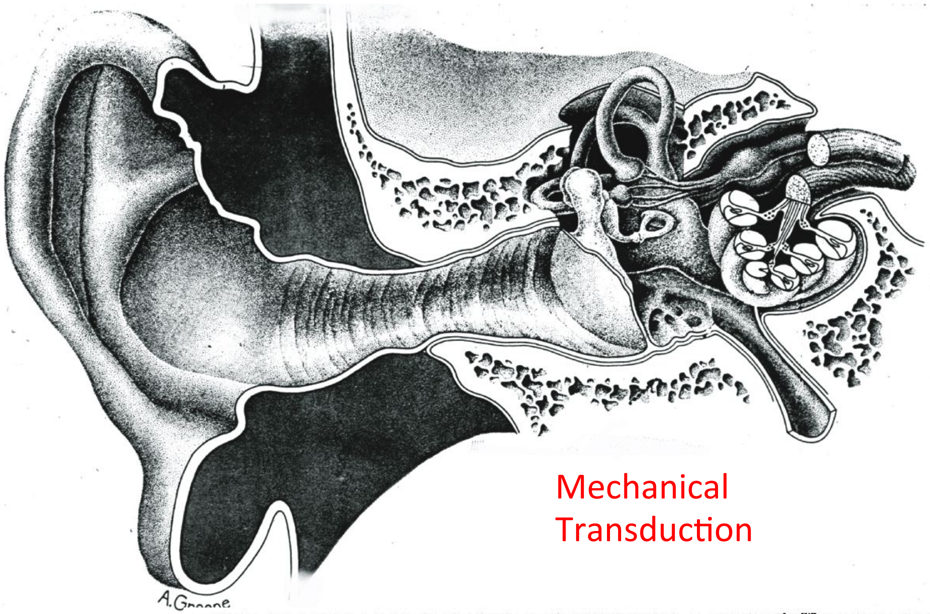


"Neural code"

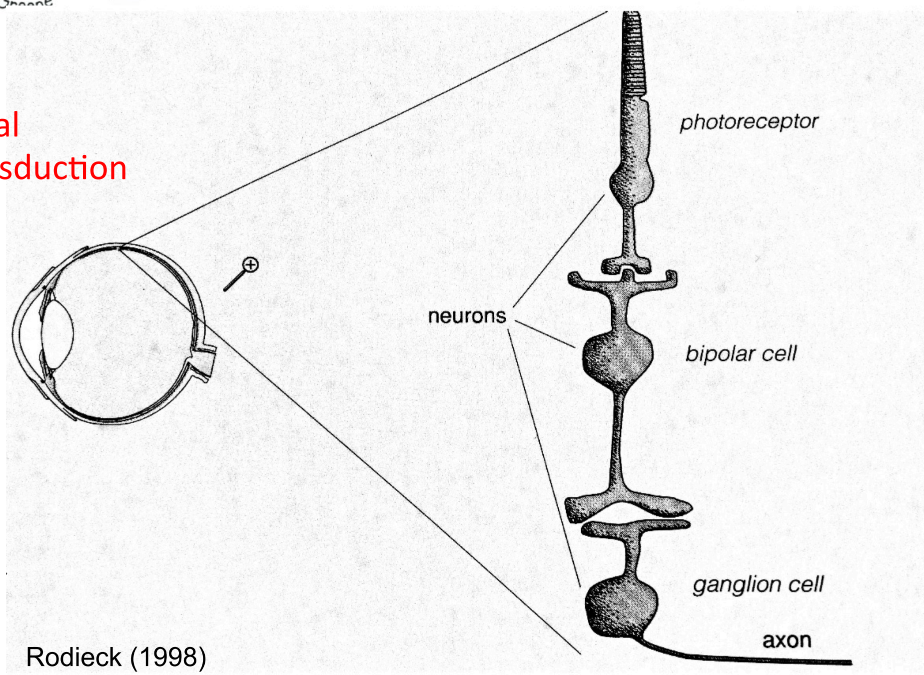
<u>Aside</u>
Is our central nervous system essentially "digitized"?

→ We'll come back to spikes in a bit....

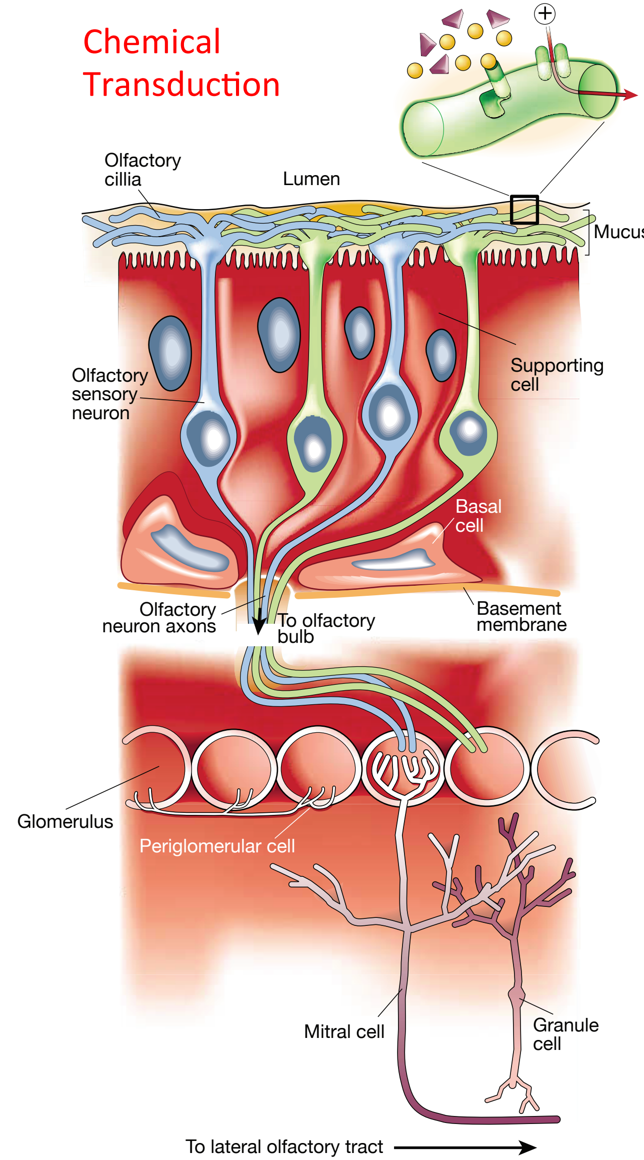
Our “senses”



Visual
Transduction



Rodieck (1998)



Firestein (2001)

<u>Transduction</u>

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

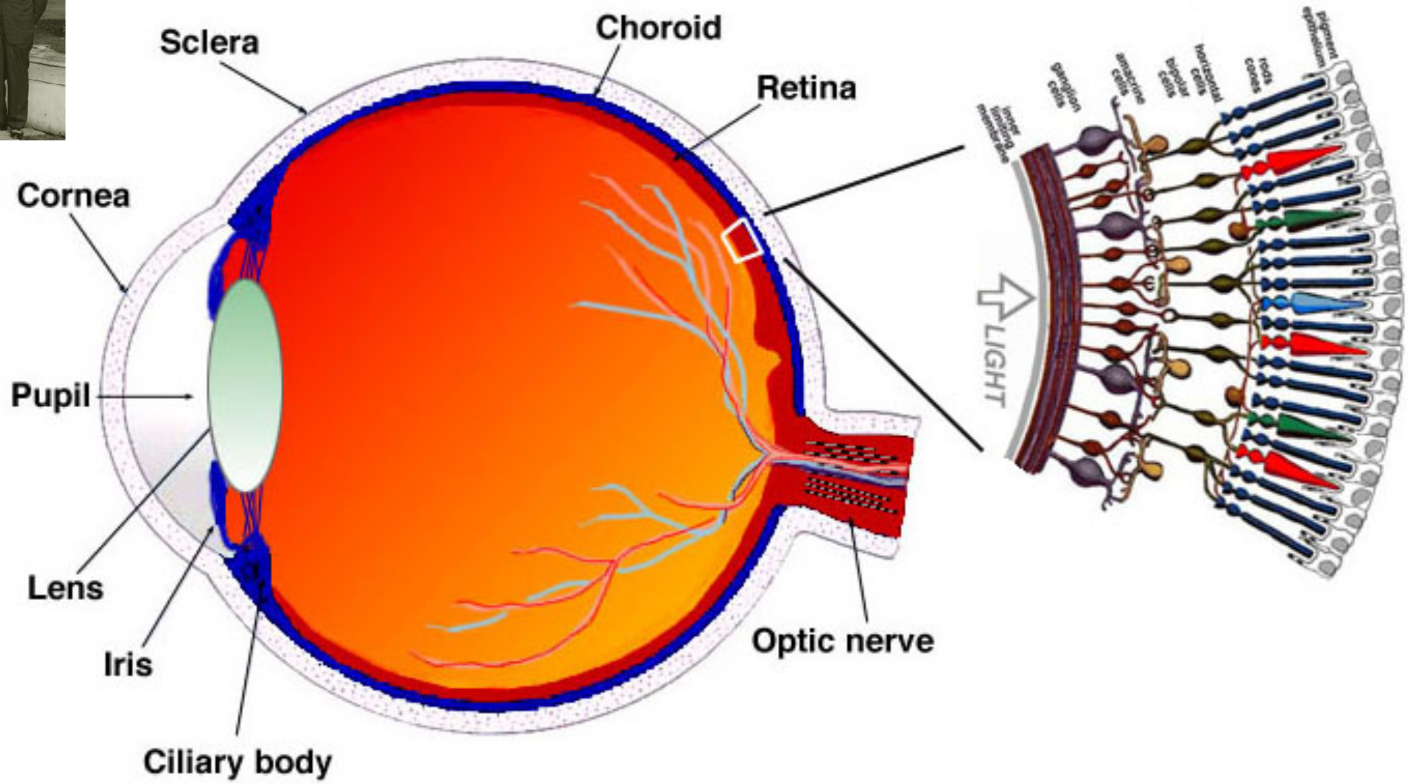
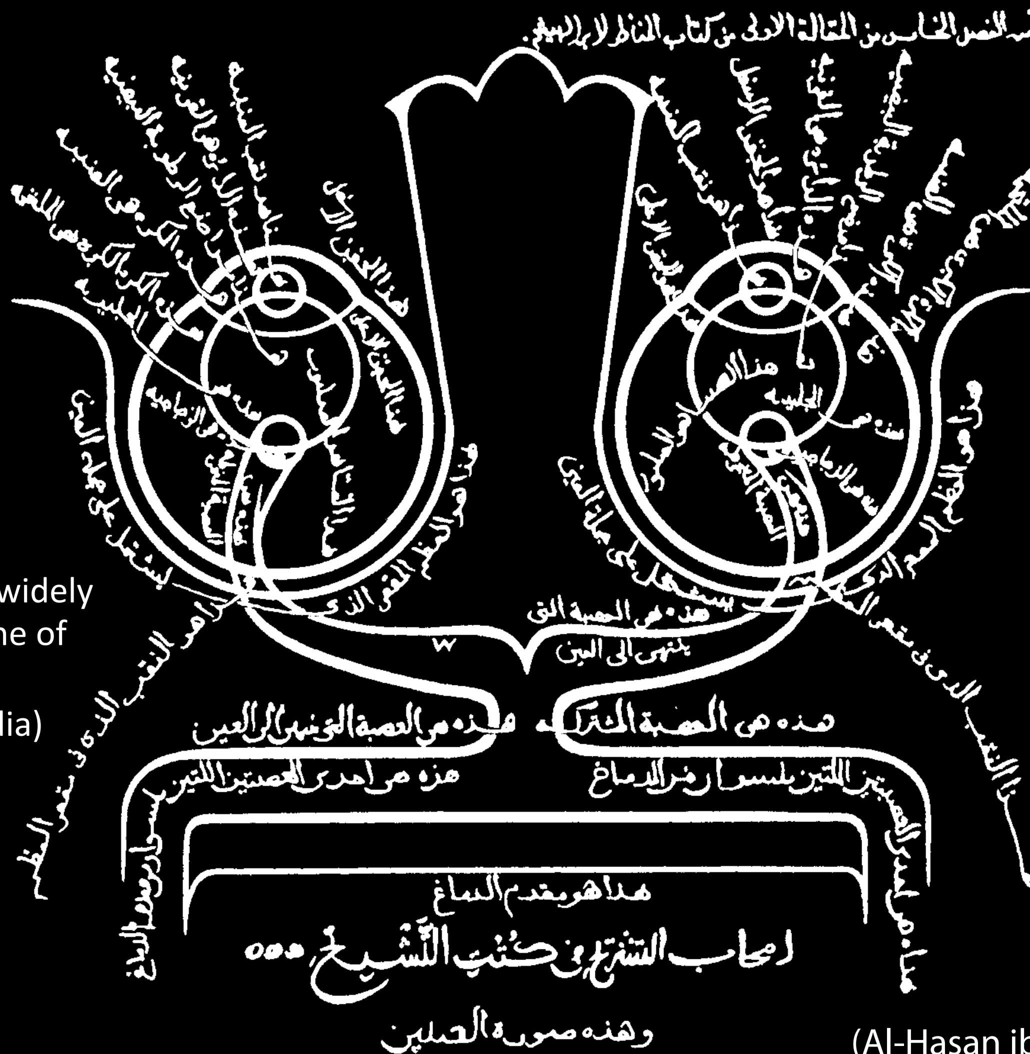


Fig. 1.1. A drawing of a section through the human eye with a schematic enlargement of the retina.

<u>Question</u>: How is information being “transduced” here?

WebVision (Utah)

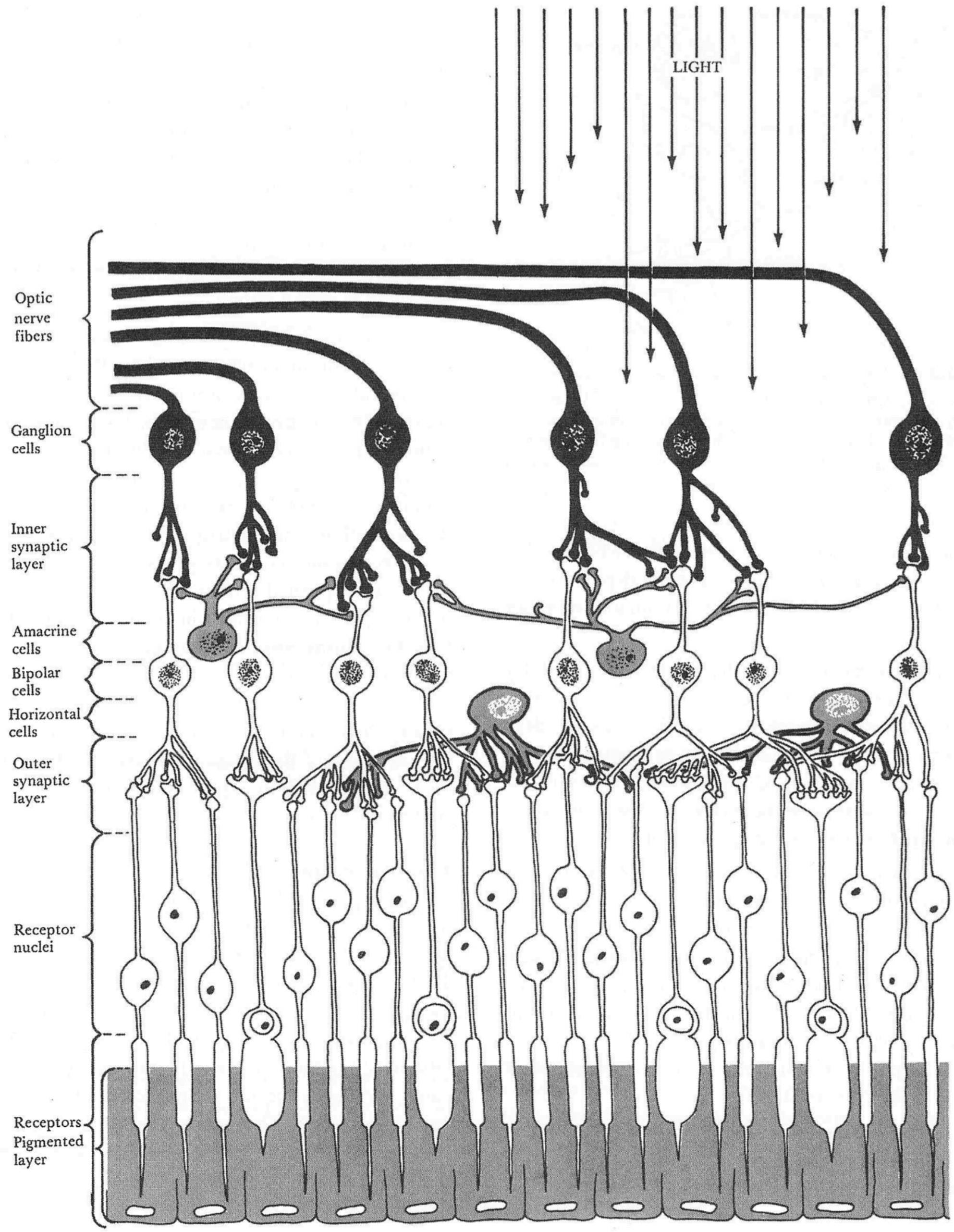
The Eye



“Ibn al-Haytham is widely considered to be one of the first theoretical physicists” (wikipedia)

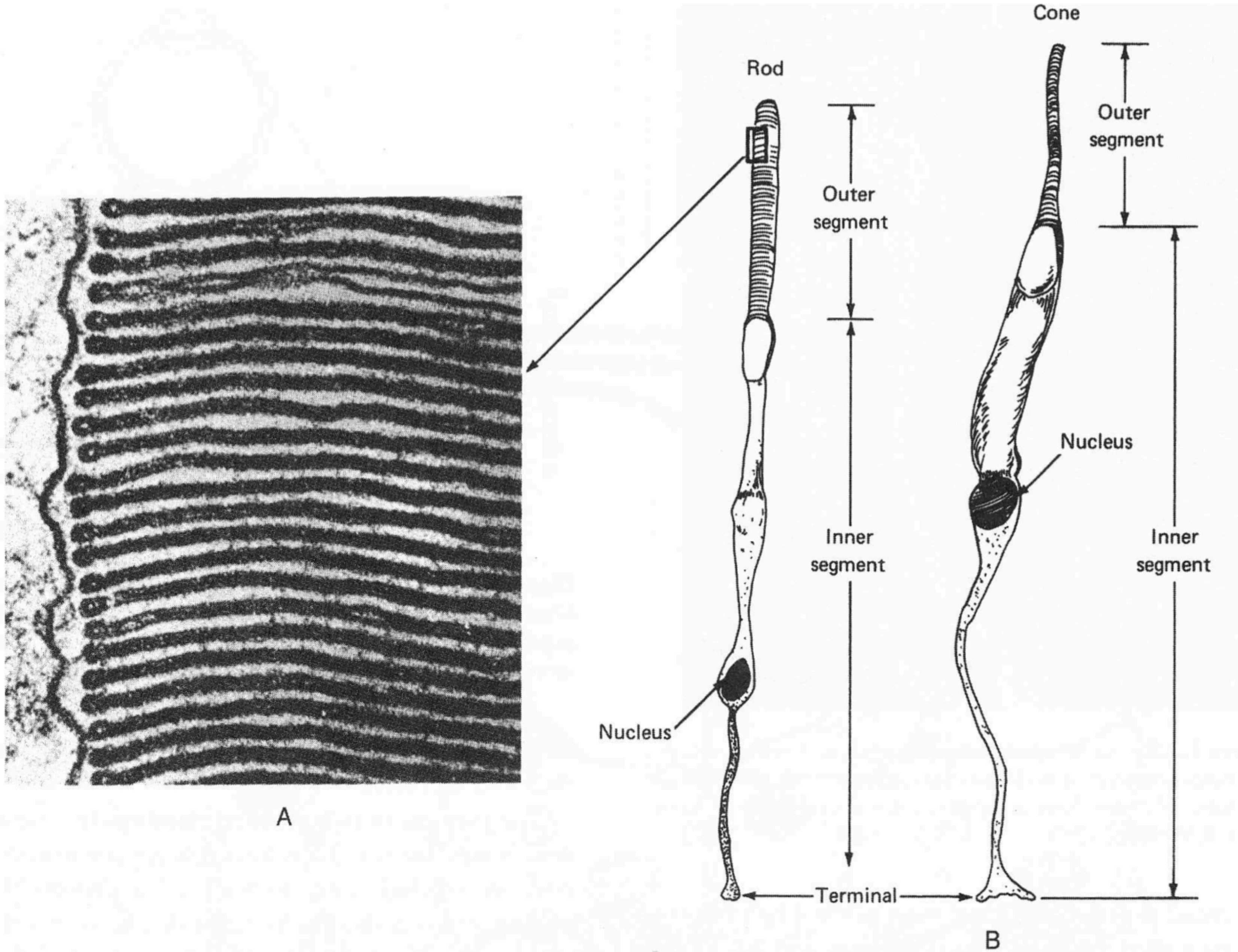
(Al-Hasan ibn al-Haitham 1083)

Phototransduction



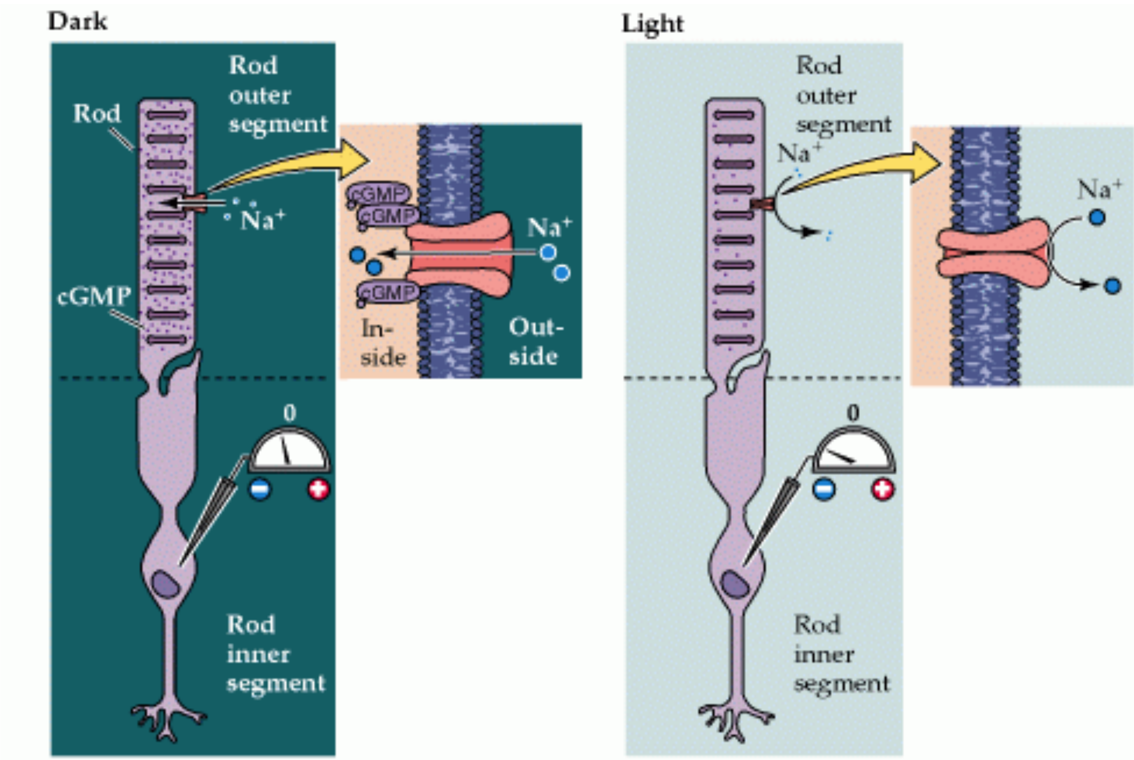
Palmer (1999)

Phototransduction



McIlwain (1996)

Phototransduction



http://openwetware.org/wiki/BIO254:Phototransduction

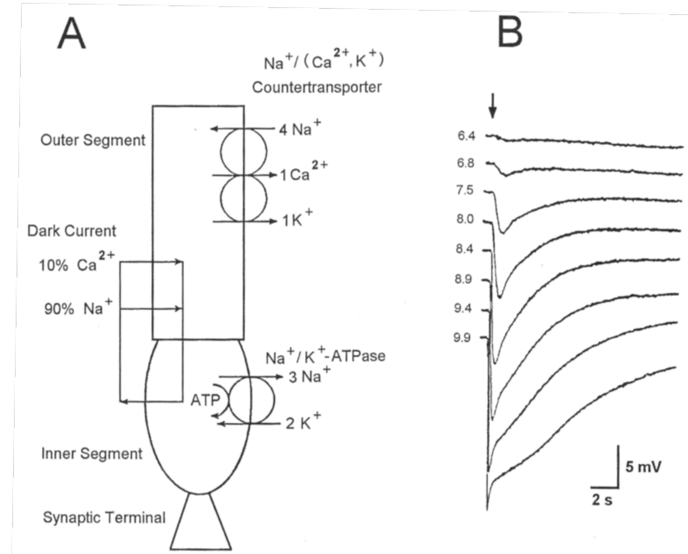
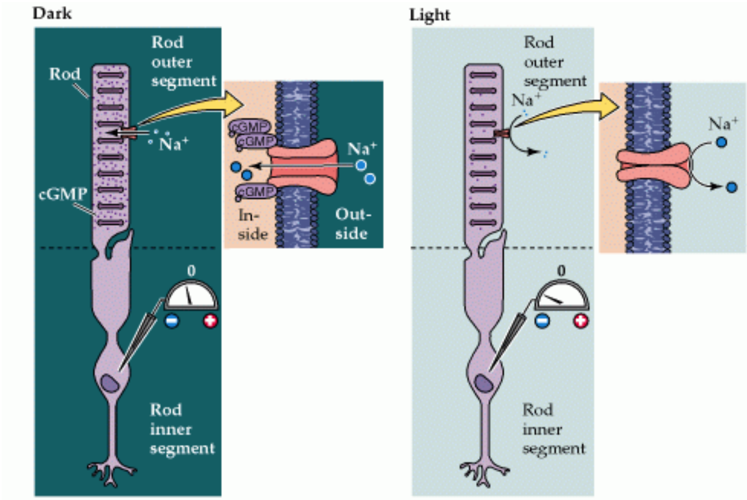


Figure 5.3. (A) Diagram of rod photoreceptor showing dark-current path and ion transporters and pumps. (Reprinted from G. L. Fain and H. R. Matthews: Calcium and the mechanism of light adaptation in vertebrate photoreceptors. *Trends in Neurosciences* 13:378–84, 1990, with permission of Elsevier Trends Journals.) (B) Intracellular recordings from a toad rod showing hyperpolarizing responses to a light flash (arrow). Numbers to left show stimulus intensity in units of log quanta per square millimeter per flash. (Reprinted from G. L. Fain, G. H. Gold, and J. E. Dowling: Receptor coupling in the toad retina. *Cold Spring Harbor Symposium on Quantitative Biology* 40:547–61, 1975, with permission of the Cold Spring Harbor Laboratory.)

McIlwain (1996)

<u>In a nutshell</u>: Light causes channels in cell membrane to close, thereby triggering an electrical response



In a nutshell: Light causes channels in cell membrane to close, thereby triggering an electrical response

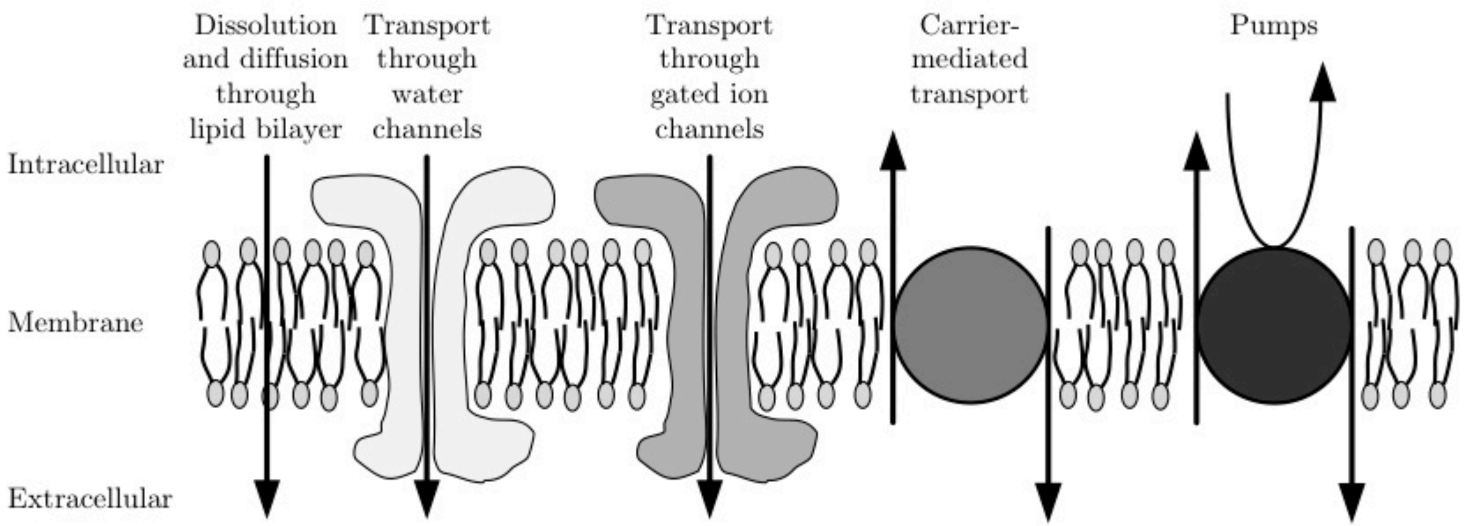
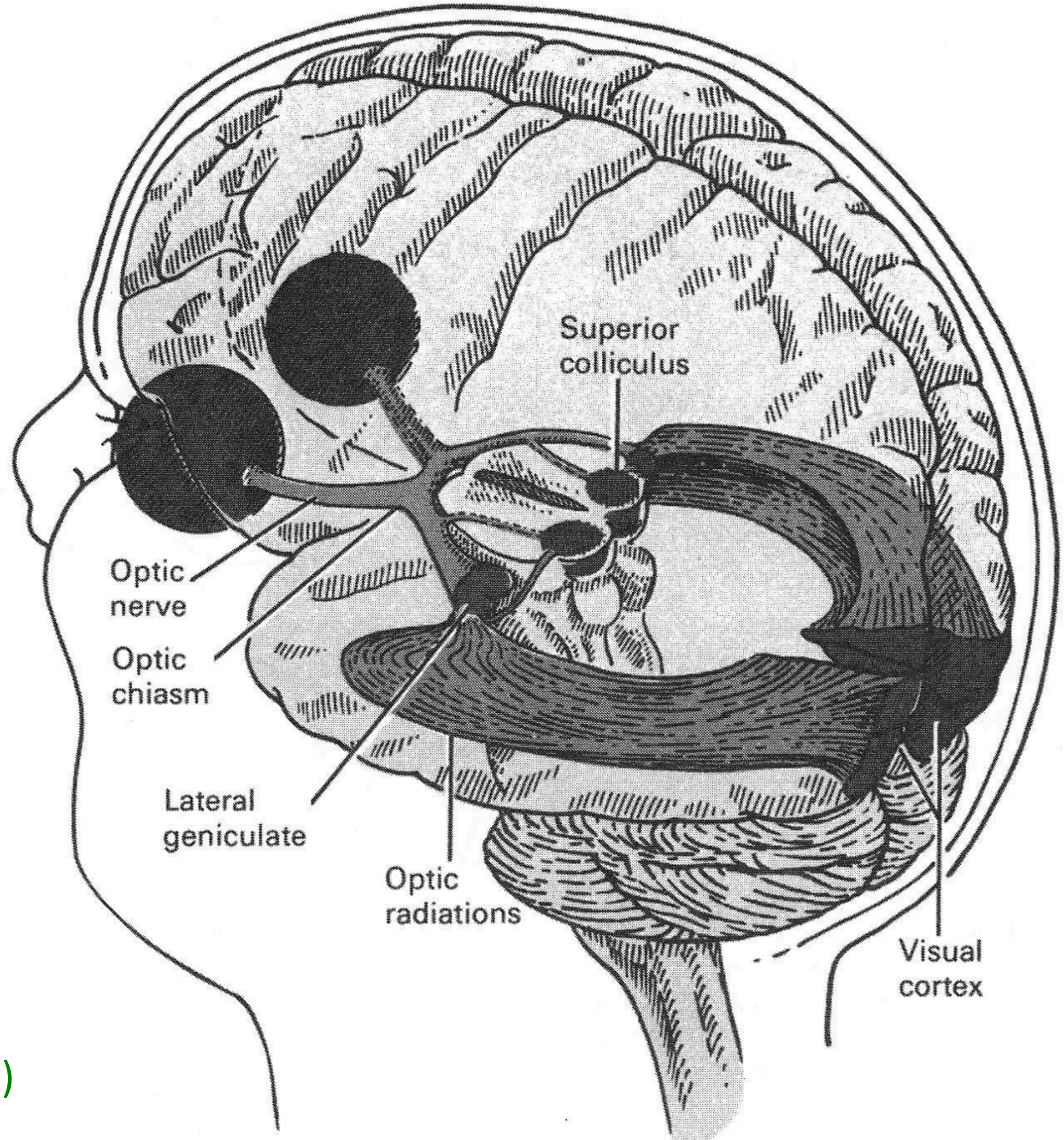


Figure 2.19

Take Home: *Electrical responses* (and how charged bits flow across the cell membrane) are fundamental aspects of our CNS and "senses"

<u>Note</u>: Studying “vision” is a great way to understand how the brain works!

York University
Centre for Vision Research (CVR)



Palmer (1999)

Eye is "quantum sensitive"

- Seeing in low-light conditions = *scotopic vision*

The Journal of General Physiology

ENERGY, QUANTA, AND VISION*

By SELIG HECHT, SIMON SHLAER, and MAURICE HENRI PIRENNE‡

(*From the Laboratory of Biophysics, Columbia University, New York*)

(Received for publication, March 30, 1942)

The minimum energy required to produce a visual effect achieves its significance by virtue of the quantum nature of light. Like all radiation, light is emitted and absorbed in discrete units or quanta, whose energy content is equal to its frequency ν multiplied by Planck's constant h. At the threshold of vision these quanta are used for the photodecomposition of visual purple, and in conformity with Einstein's equivalence law each absorbed quantum transforms one molecule of visual purple (Dartnall, Goodeve, and Lythgoe, 1938). Since even the earliest measurements show that only a small number of quanta is required for a threshold stimulus, it follows that only a small number of primary molecular transformations is enough to supply the initial impetus for a visual act. The precise number of these molecular changes becomes of obvious importance in understanding the visual receptor process, and it is this which has led us to the present investigation.

Eye is “quantum sensitive”

nature COMMUNICATIONS

ARTICLE

Received 15 Jan 2016 | Accepted 7 Jun 2016 | Published 19 Jul 2016

DOI: 10.1038/ncomms12172

OPEN

Direct detection of a single photon by humans

Jonathan N. Tinsley[1,2,†,*], Maxim I. Molodtsov[1,2,3,*], Robert Prevedel[1,2,3], David Wartmann[1,†], Jofre Espigulé-Pons[2,4], Mattias Lauwers[1] & Alipasha Vaziri[1,2,3,5]

Despite investigations for over 70 years, the absolute limits of human vision have remained unclear. Rod cells respond to individual photons, yet whether a single-photon incident on the eye can be perceived by a human subject has remained a fundamental open question. Here we report that humans can detect a single-photon incident on the cornea with a probability significantly above chance. This was achieved by implementing a combination of a psychophysics procedure with a quantum light source that can generate single-photon states of light. We further discover that the probability of reporting a single photon is modulated by the presence of an earlier photon, suggesting a priming process that temporarily enhances the effective gain of the visual system on the timescale of seconds.

Reference point

Midterm problem from BPHS 4090 (this was a bonus "easy" problem")

6. (*13 points*)
A 100 W incandescent lightbulb emits about 5 W of visible light. The average wavelength of the visible light is about 600 nm.

a. What happens to the other 95 W of energy?

Lost as heat to surrounding (including infrared radiation)

b. How many visible-light photons does the bulb emit per second? Note any assumptions made.

• Assume all emitted power has this wavelength (600 nm)

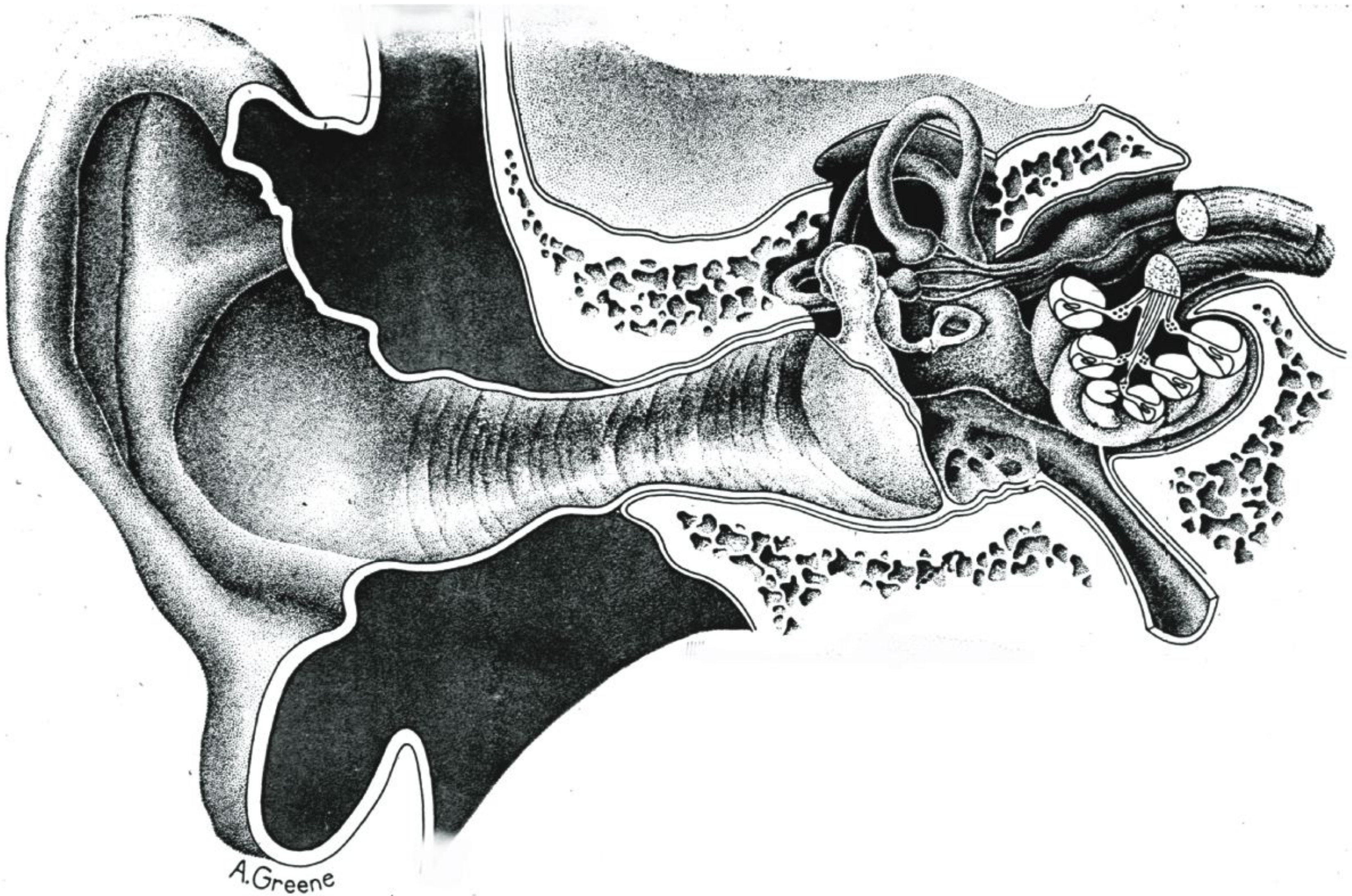
$$R = \frac{\text{power}}{h\nu} = \frac{5\ \text{W}}{6.63\times10^{-34}\ \text{J}\cdot\text{s}\cdot 5\times10^{14}\ \text{Hz}}$$

$$= 1.5\times10^{19}\ \text{photons/s}$$

Where $\nu = \frac{c}{\lambda} = \frac{3\times10^{8}\ \text{m/s}}{6\times10^{-7}\ \text{m}} = 5.0\times10^{14}\ \text{Hz}$

A 100 W lightbulb is:

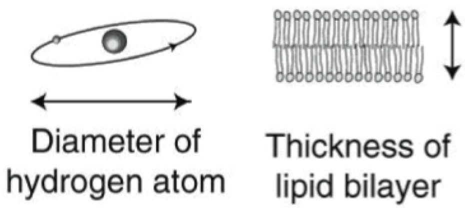
- ~5% efficient
- emits ~10^{19} photons/s


A.Greene

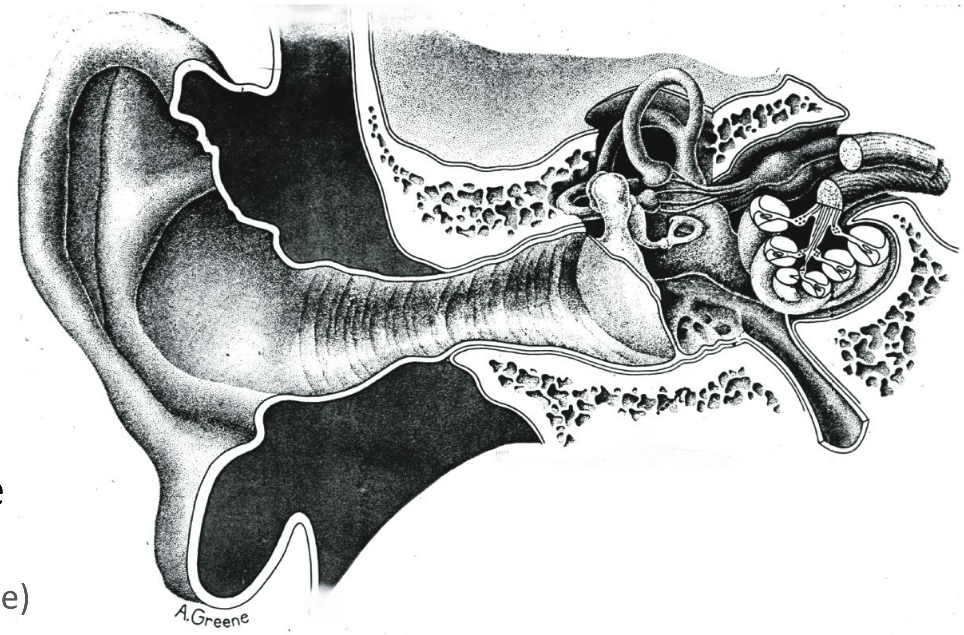
Cool factoids about the ear....

- At threshold, eardrum move ~1 pm

100 pm



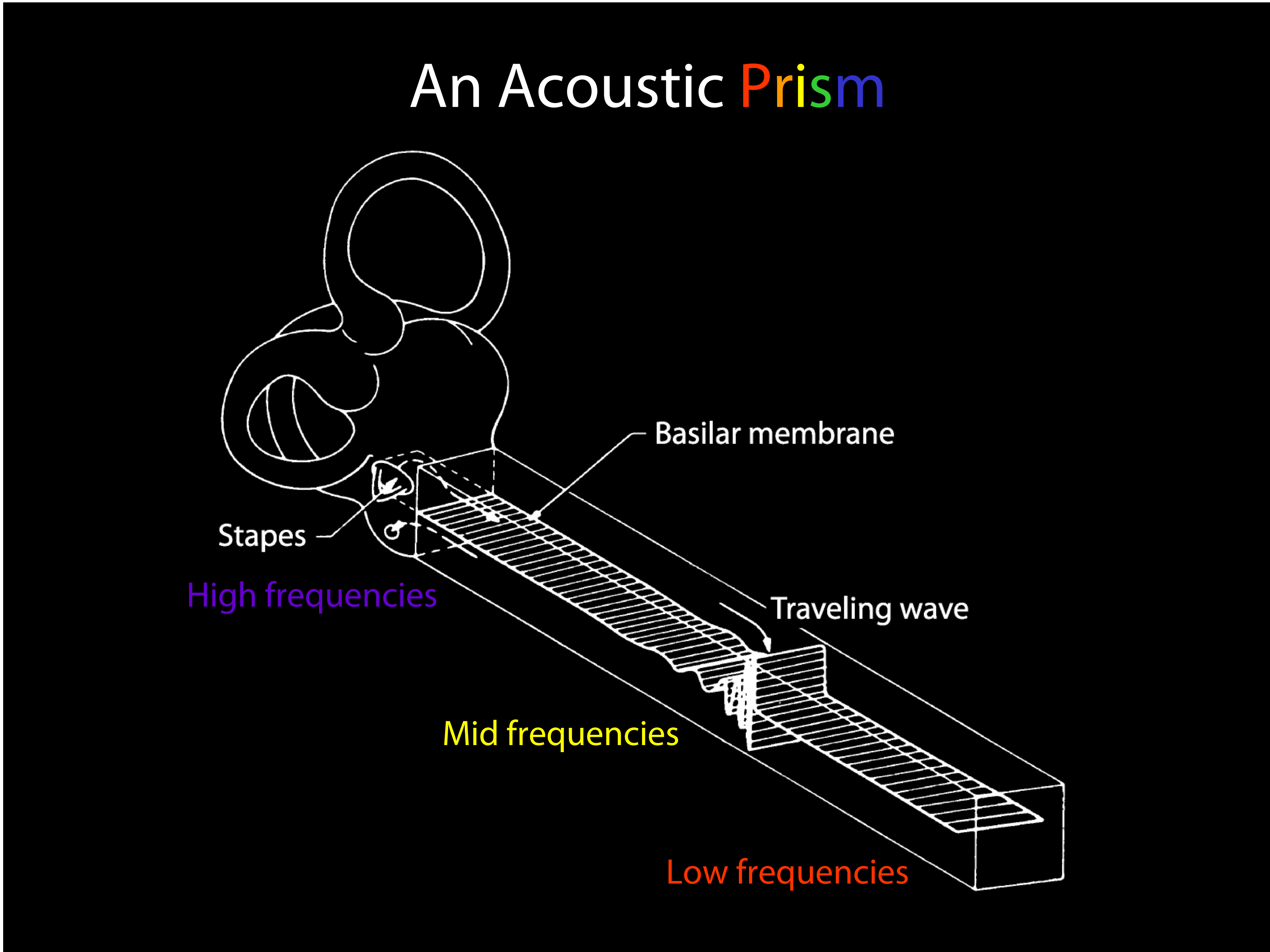
10000 pm



- At threshold, sensory cells move on the order of 100 pm (despite thermal noise agitating them roughly an order of magnitude more)
- Dynamic range spans 12+ orders of magnitude (in terms of incident energy)
- Spectral range spans 6-12 octaves (1 oct = x2 in Hz)
- Highest resting trans-membrane potential in whole body (≈130–170 mV)
- Middle ear contains three smallest bones in the body (ossicles)
- Cochlea encased in the hardest bone in the body (petrous part of temporal bone)

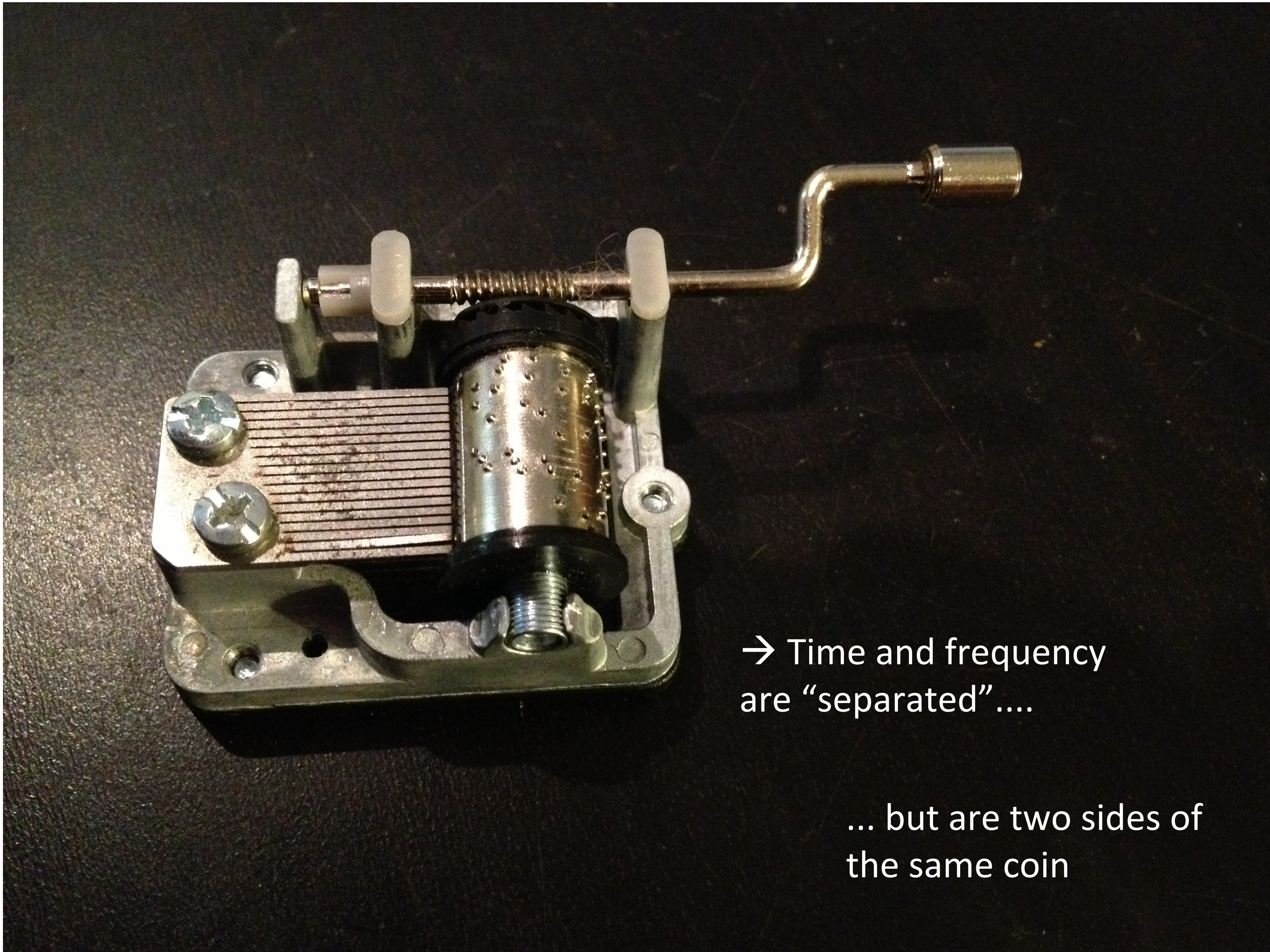
Bonus:
Inner ear has the most vascularized tissue in your whole body!

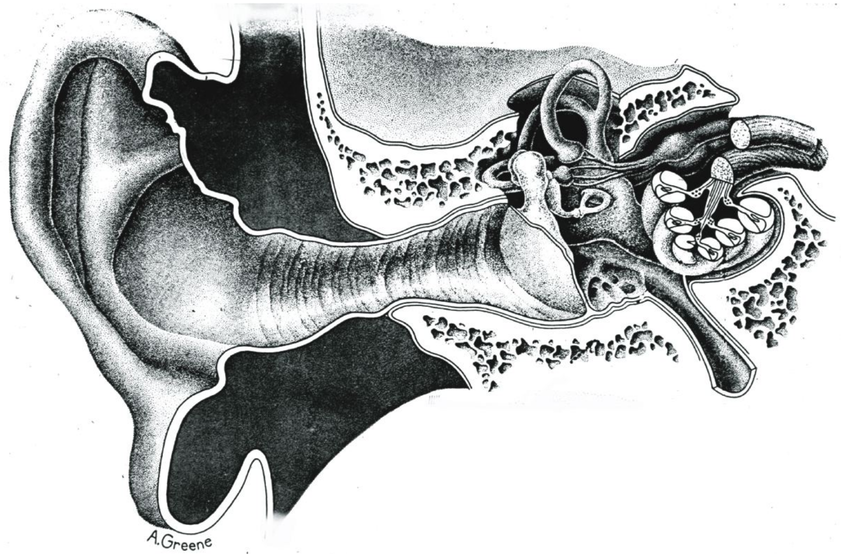
Spectral Decomposition

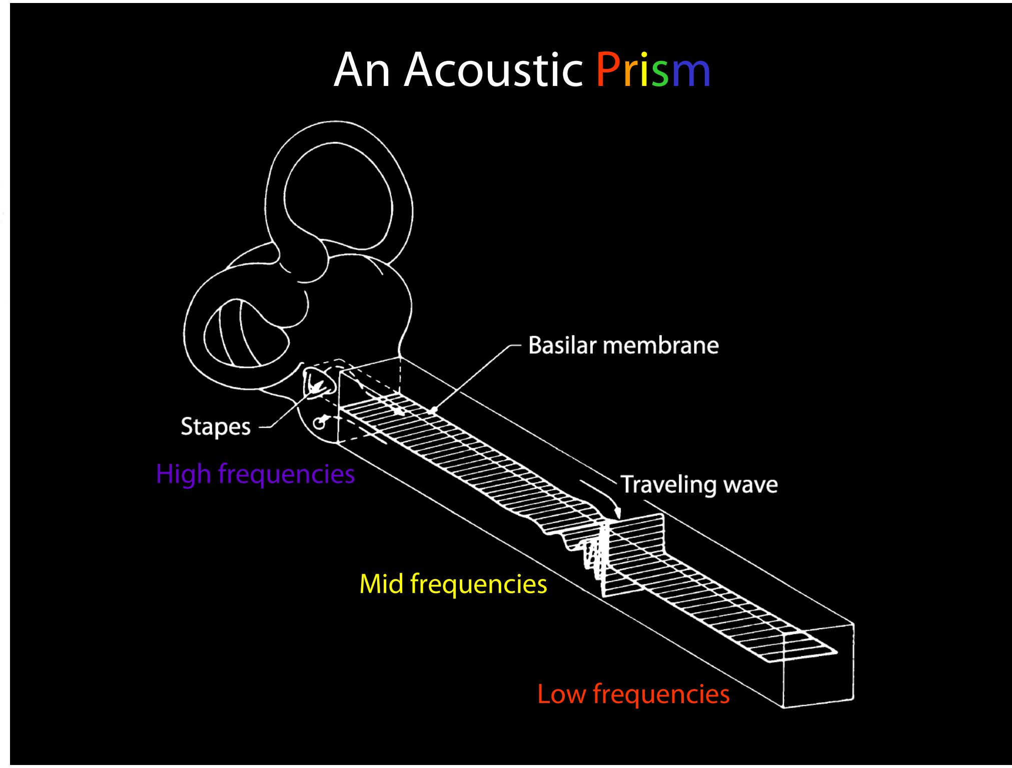


Zweig et al. (1976)

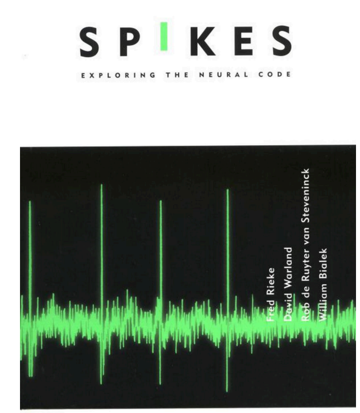
Spectral Decomposition





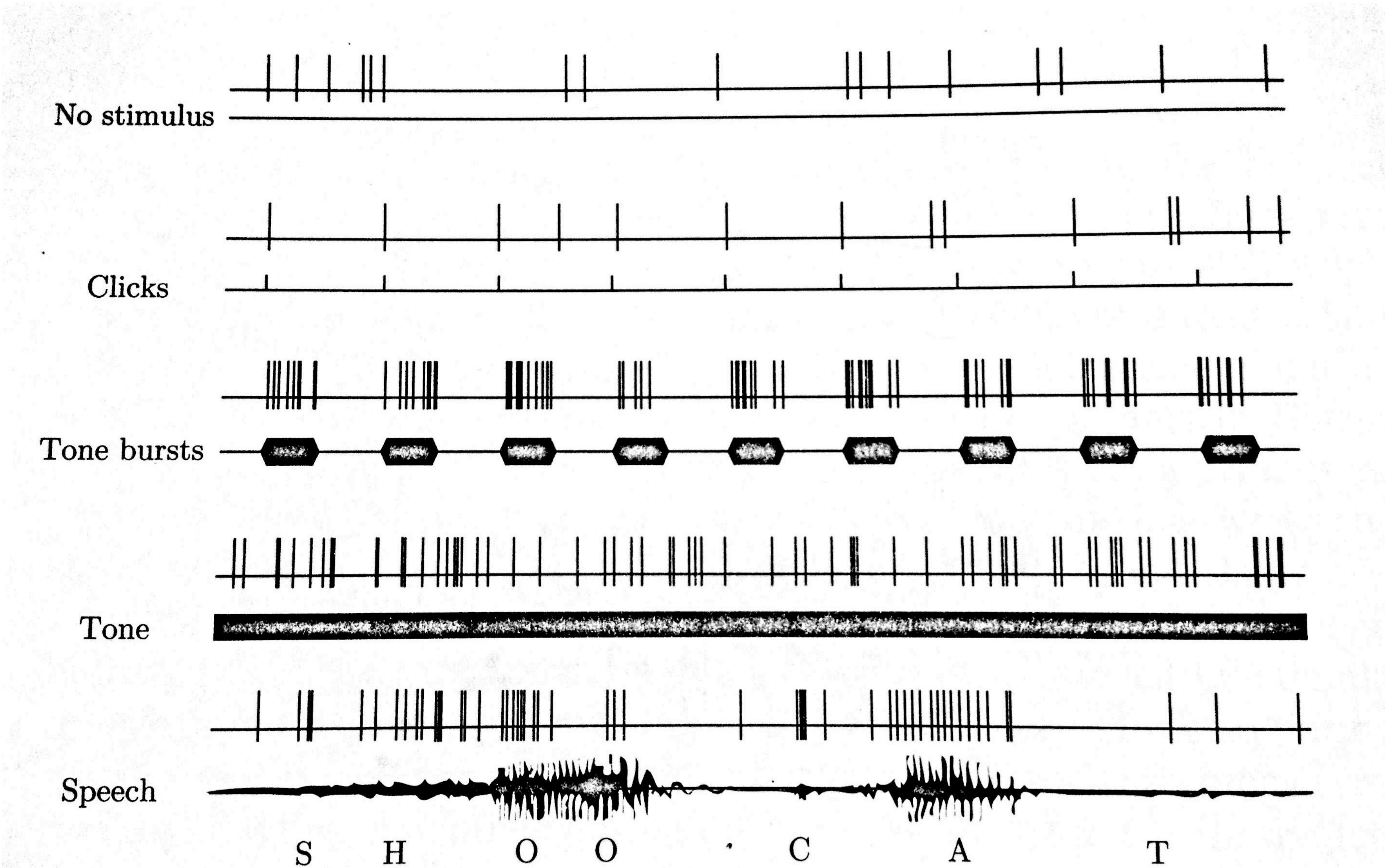


- Ear acts as a hydrodynamic spectrum analyzer
  (spatial location ←→ frequency)



- Spectral decomposition serves as an underlying basis for auditory "neural code"

Single unit auditory nerve fiber responses



Kiang (1986)

Note: Owls don't "see in the dark" (e.g., infrared sensitivity in total darkness), but in fact localize based upon sound

Konishi (1973)

→ Ear actually **EMITS** sound!

otoacoustic emissions – OAEs

http://www6.miami.edu/UMH/CDA/UMH_Main/

→ OAEs used for newborn hearing screening (only healthy ears emit)

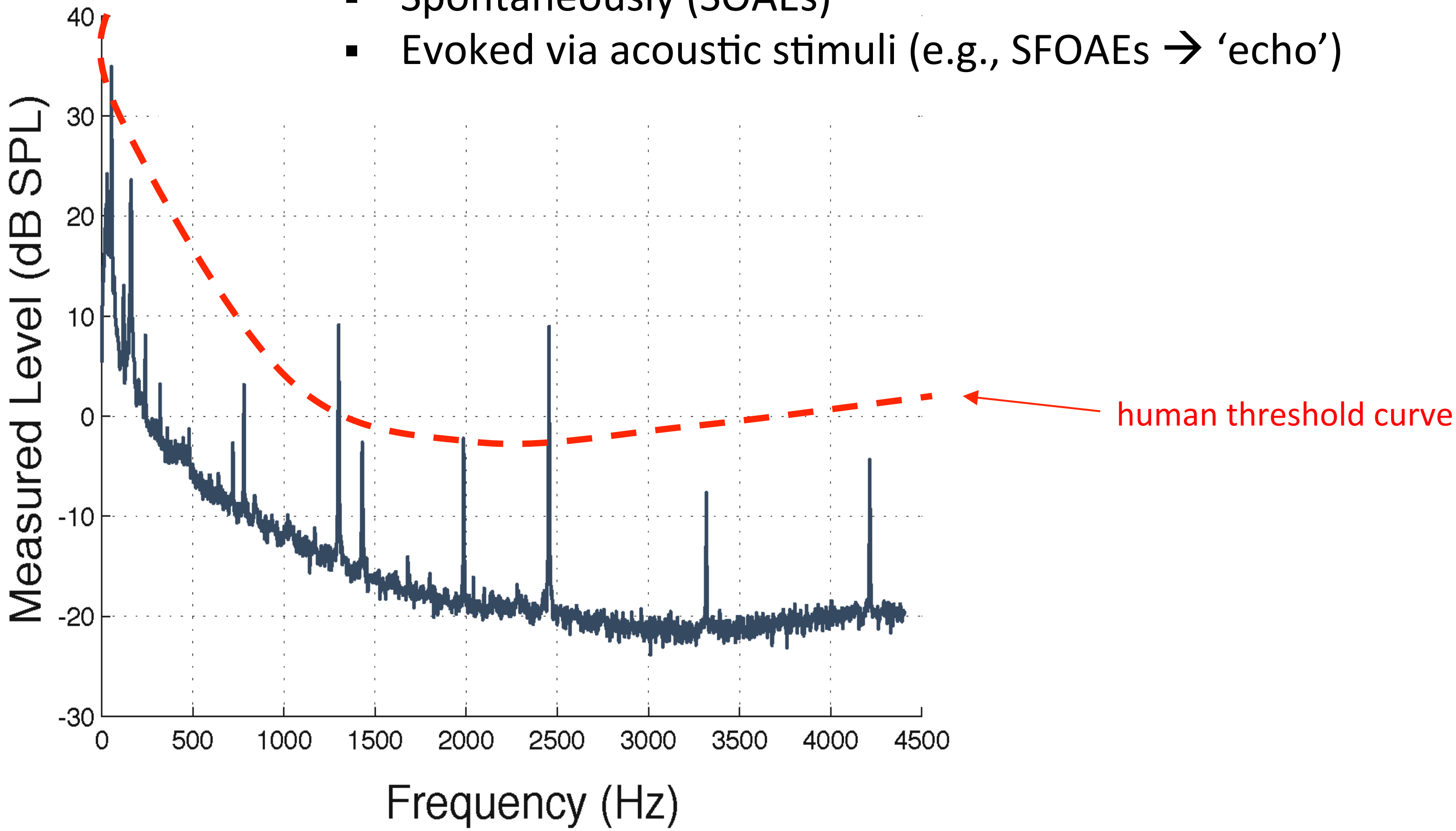
→ Much faster/easier than evoked potentials (i.e., ABR)

OAEs

- Only healthy ears actually *emit* sound

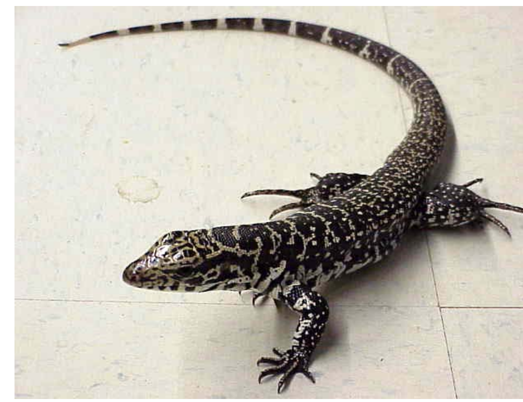
- At threshold, eardrum move ~1 pm
(diameter of a hydrogen atom is 100 pm!)

  - Spontaneously (SOAEs)
  - Evoked via acoustic stimuli (e.g., SFOAEs → 'echo')



⇒ OAEs byproduct of an *amplification* mechanism?

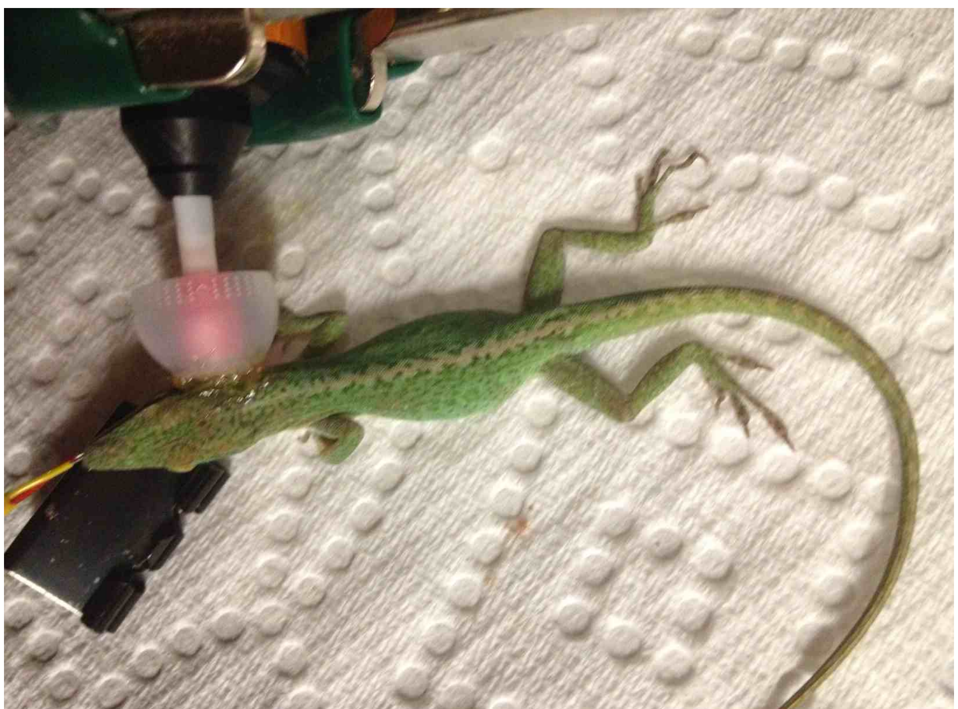
Comparative Approach



- Wide variation in morphology/physiology
- Relatively ‘simpler’ ears
- Extensive neurophysiology, behavioral measures
- OAEs fairly universal

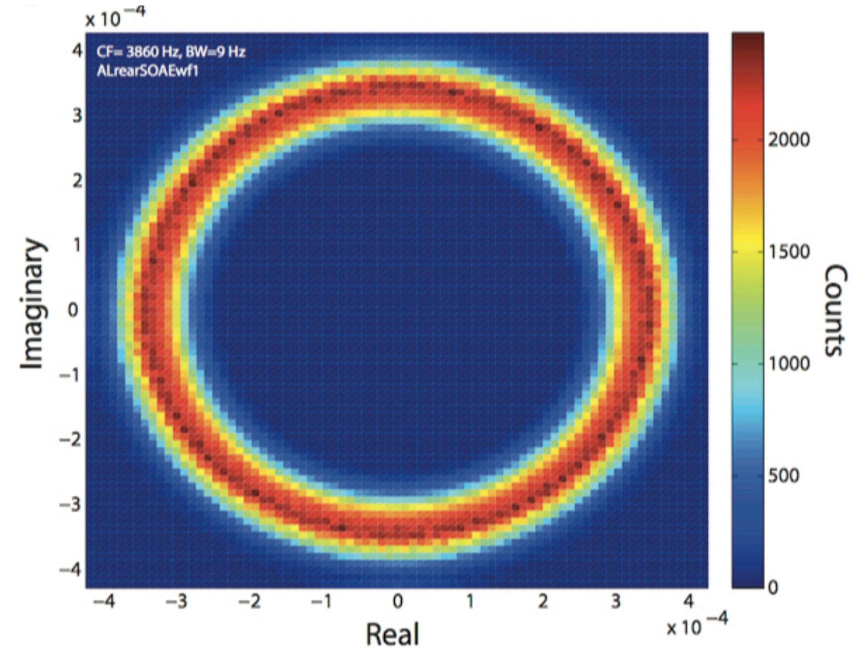

Anolis carolinensis

3 – Otoacoustics

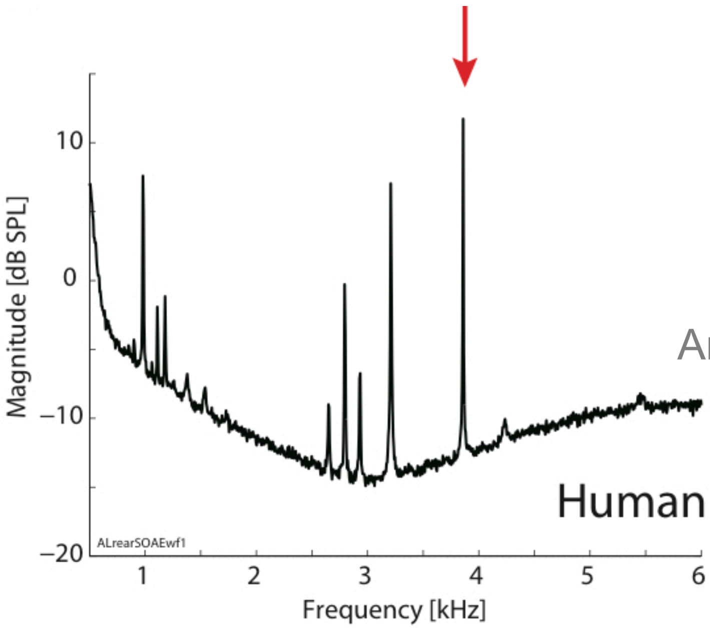



Vaseline

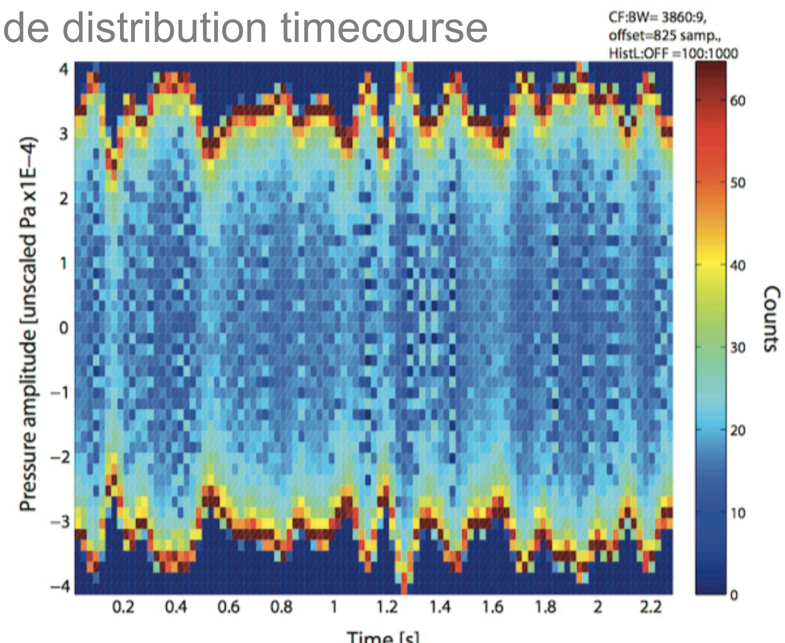
Analytic signal distribution (filtered peak)



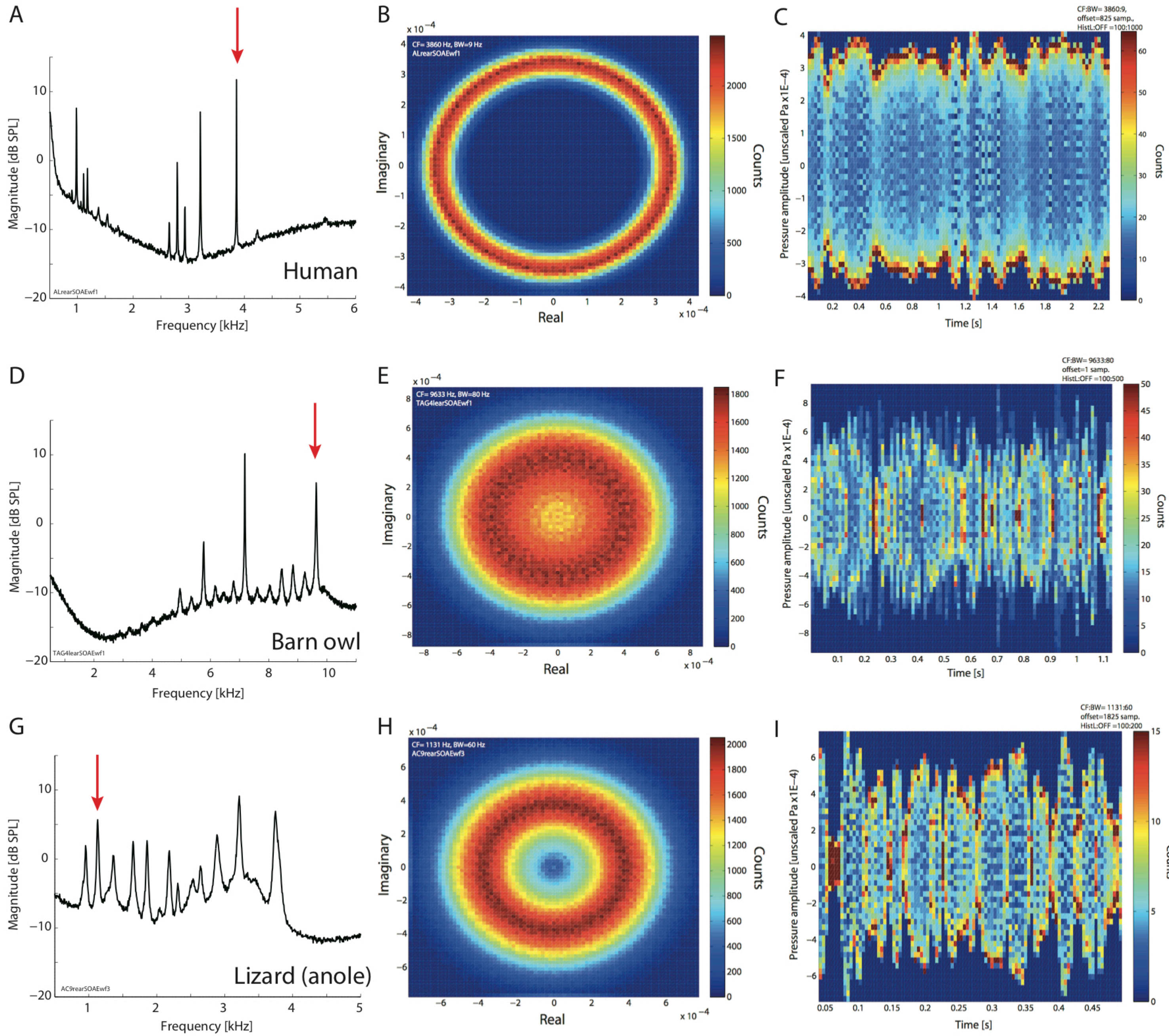
Fourier transform (spectral averaging)



Amplitude distribution timecourse



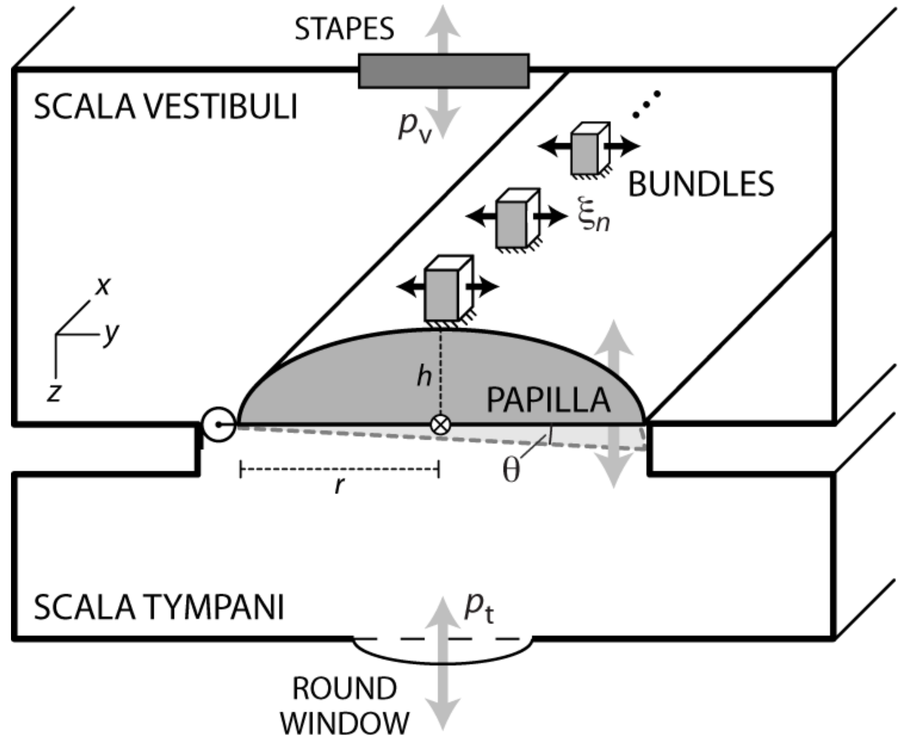
Bergevin et al. (PNAS 2015)



→ (Noisy) Self-sustained oscillators, suggestive of an 'active' mechanism

Bergevin et al. (PNAS 2015)

Theoretical Models for OAE Generation

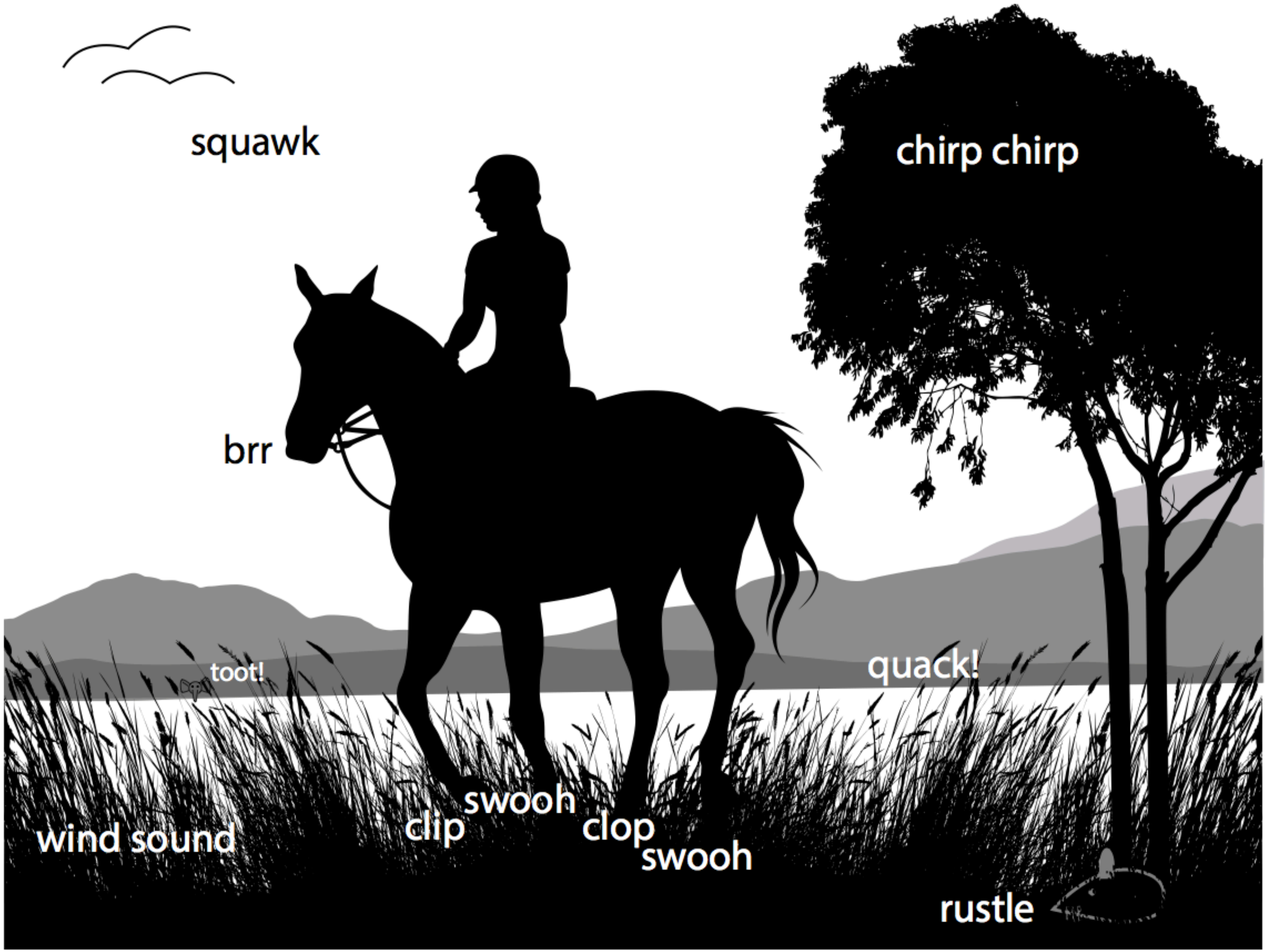


$$m\ddot{x} - \mu(1 - x^2)\dot{x} + kx = 0$$

Ear as a collection of coupled (nonlinear) limit-cycle oscillators

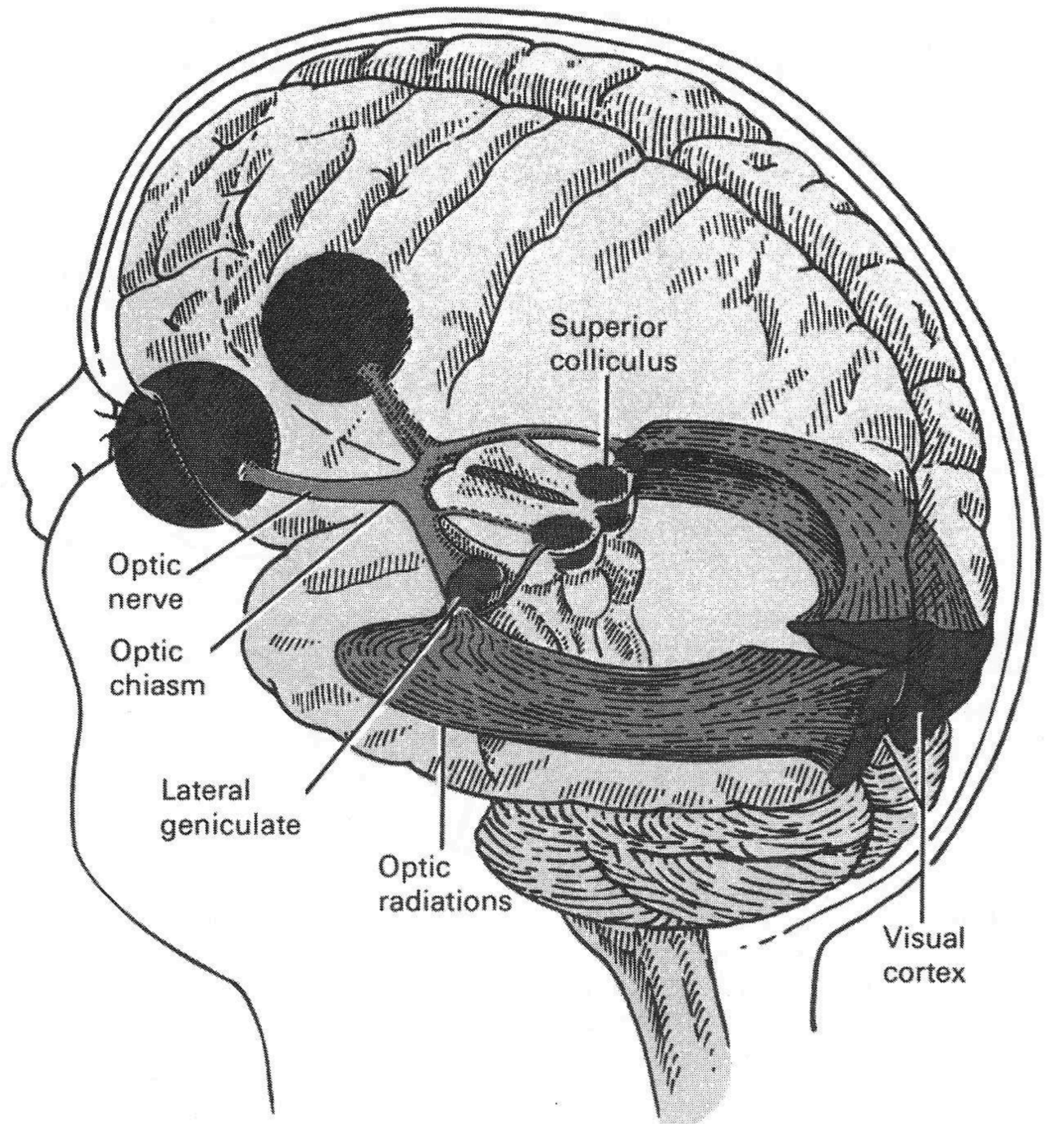
Bergevin & Shera (2010)

<u>“Encoding” the world around us....</u>

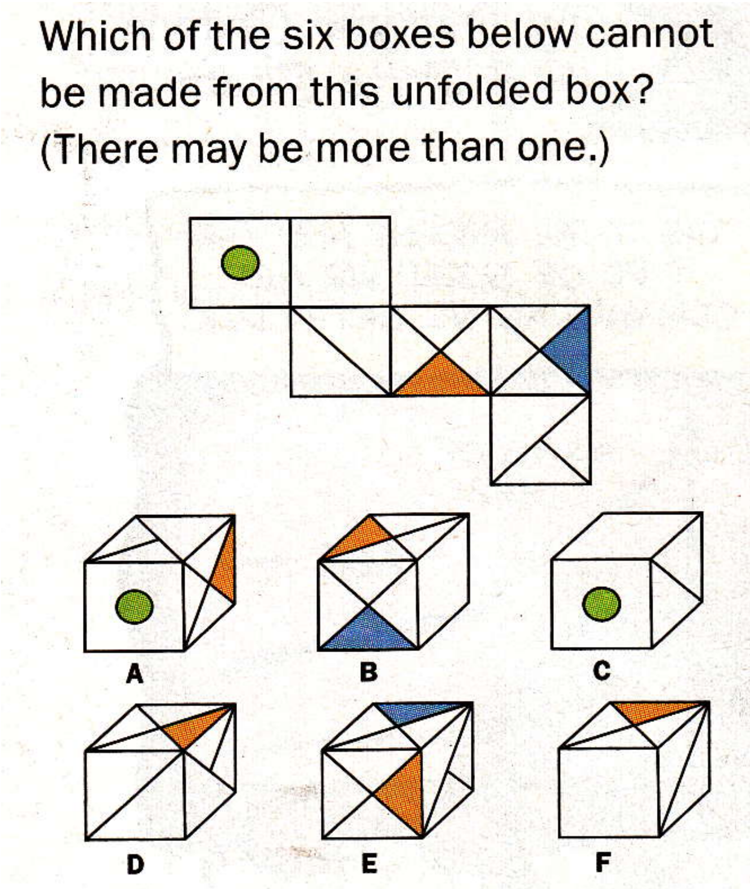


Pulkki & Karjalainen (2015)

“Encoding” the world around us....



Palmer (1999)



Question:
Physiologically, how did you (try to) solve this puzzle?

→ A very hard (but interesting!) question to try to answer....

National Geographic

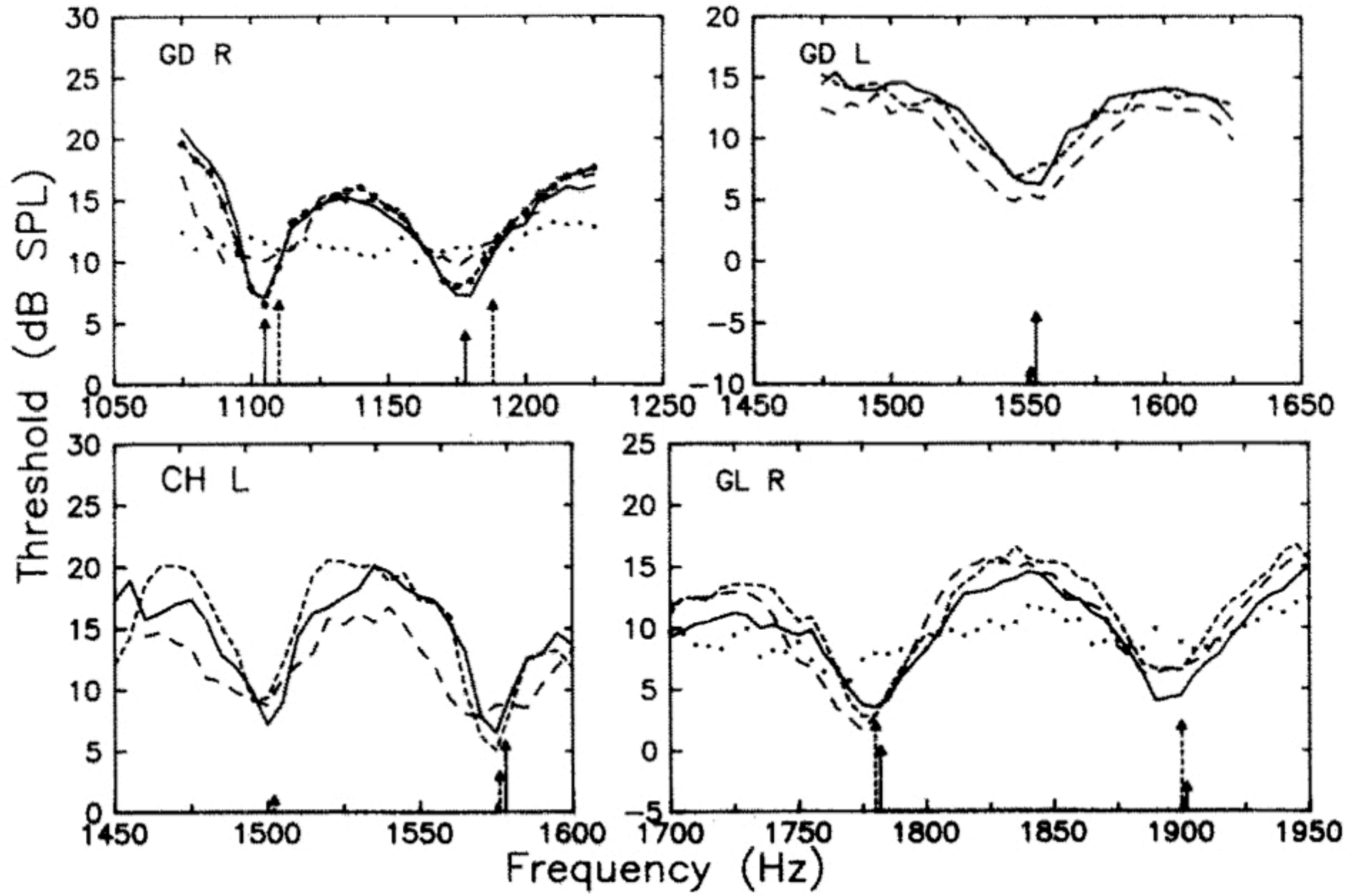
BIOPHYSICS @ YORK

UNIVERSITÉ
UNIVERSITY

redefine THE POSSIBLE.

- Slides available for download: http://www.yorku.ca/cberge/
- Questions? cberge@yorku.ca
- Interested in biophysics? undergrad? grad school?

Spontaneous Emissions (SOAEs) & Threshold



➢ OAEs directly tied to forward auditory transduction (i.e., neural responses)

Long & Tubis (1988)

<u>Question</u>:

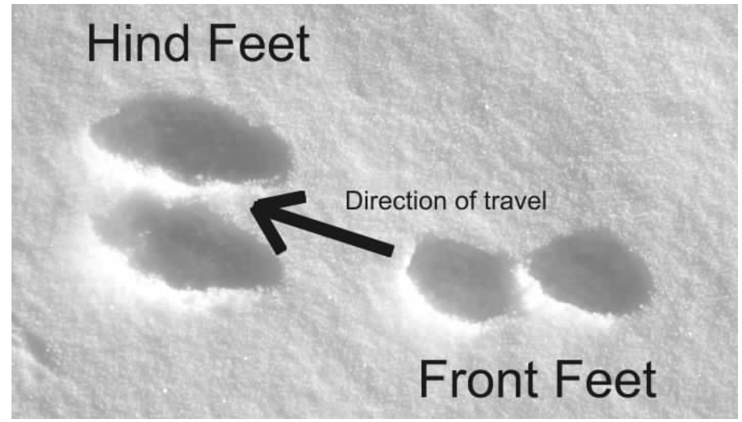
What made these tracks?

(pic taken on abandoned on-ramp to the DVP, so within GTA)

that's my glove

(for reference)

One hypothesis:
"melted bunny paw prints"

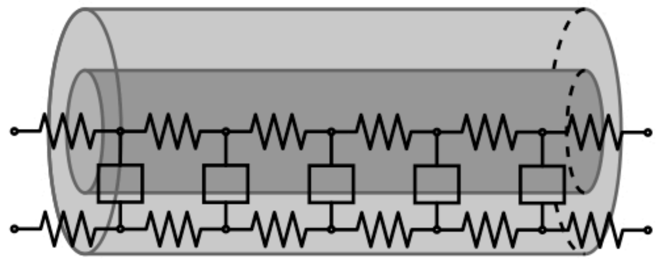


Rabbit of Caerbannog?

C. Bucking

Biophysical aside

Core Conductor Model



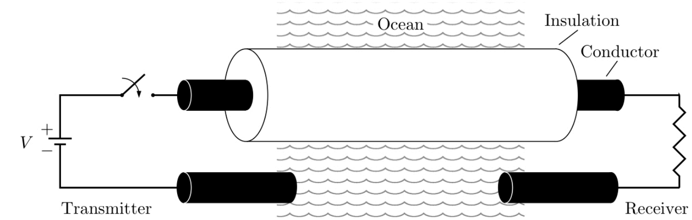


Figure 3.8

Neuron behaves like a leaky submarine cable!

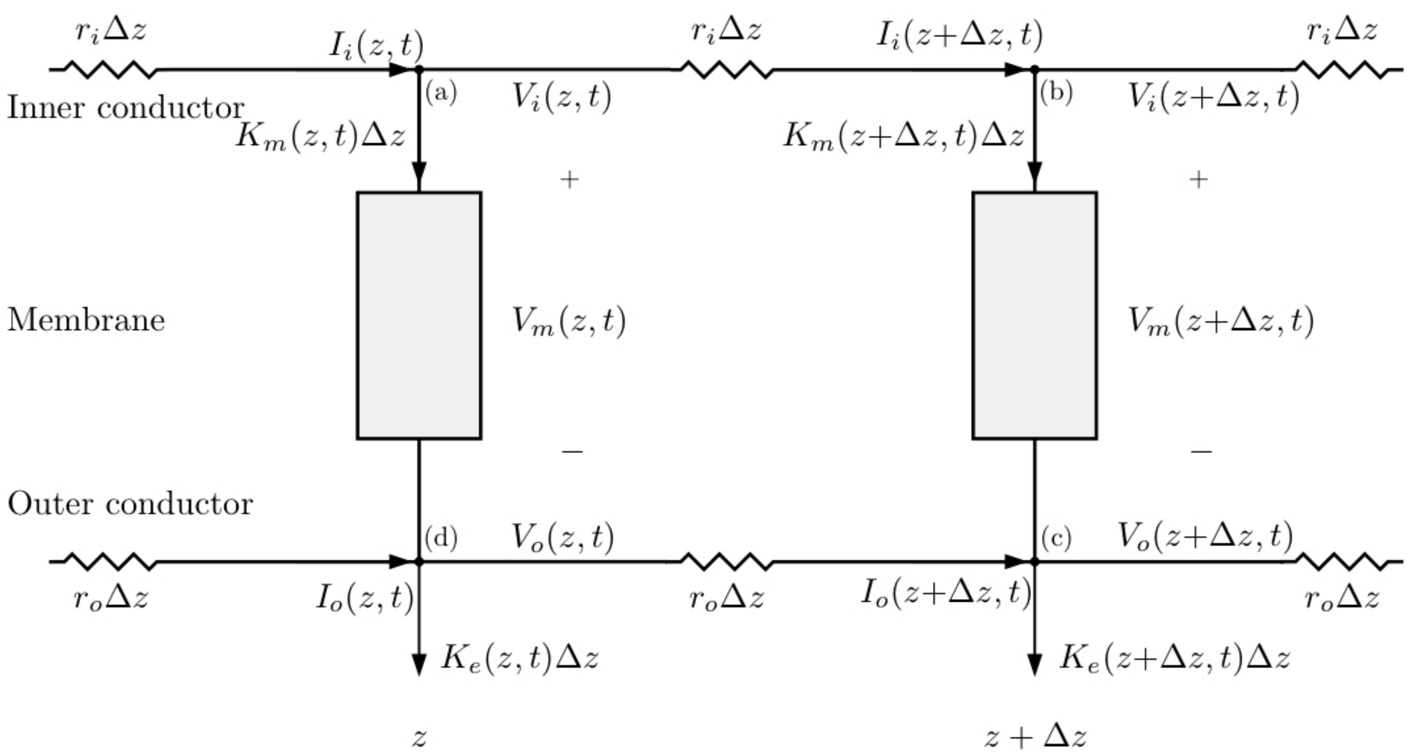
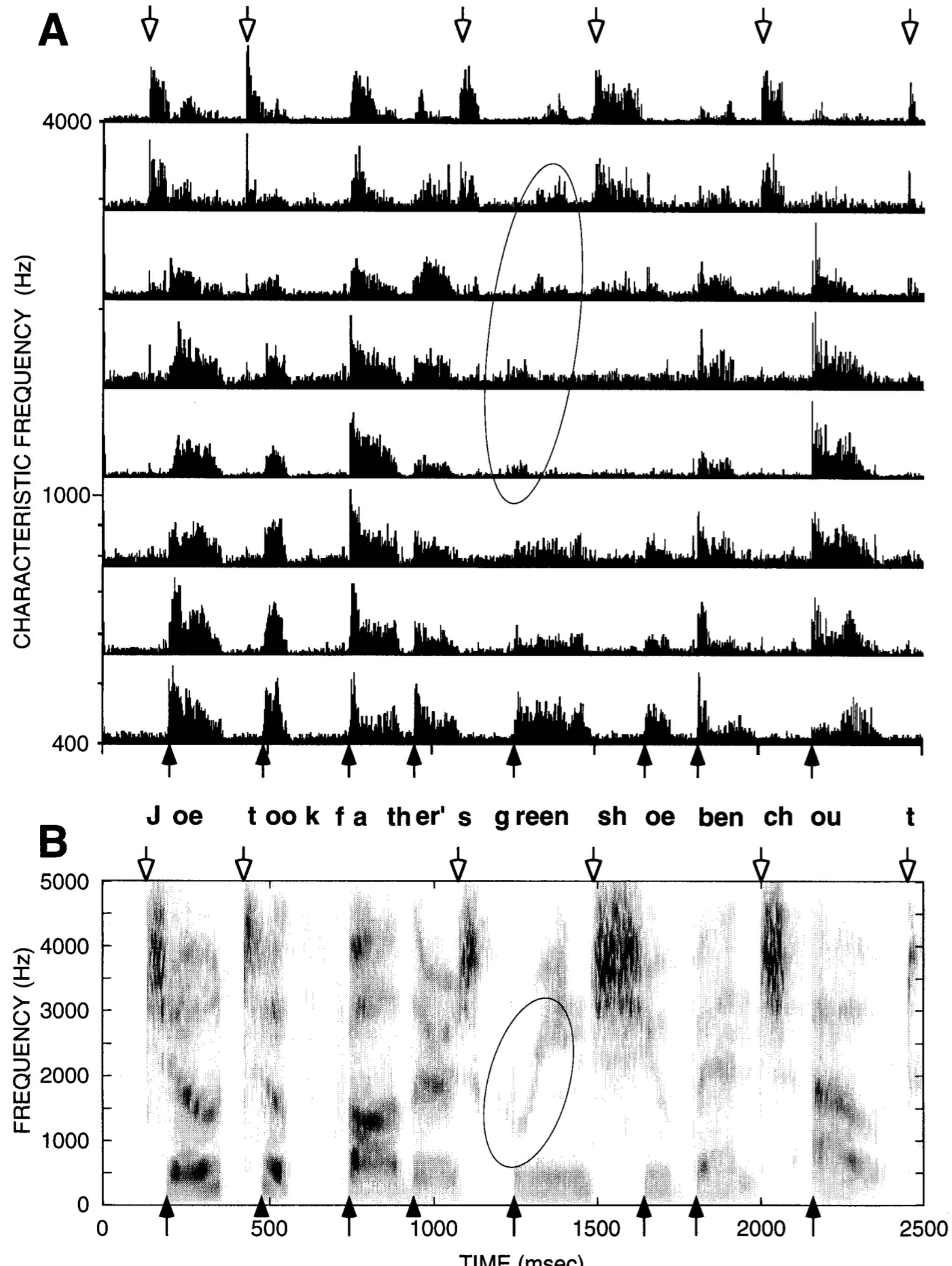


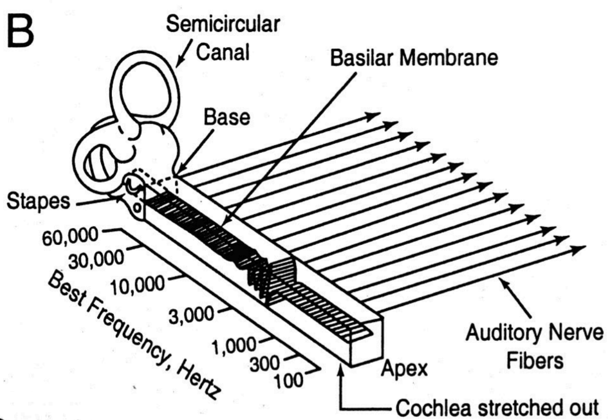
Figure 2.7

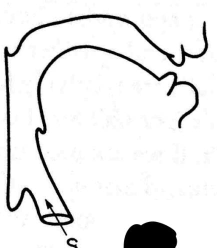
Weiss (1996)

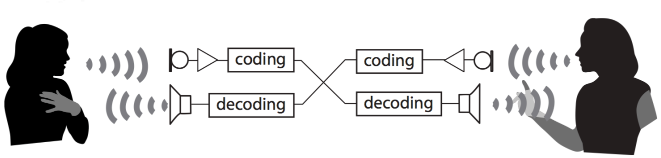
Neural coding of speech

Fig. 1. Neurogram and spectrogram for a speech utterance produced by a female speaker. A. Neurogram display of the activity of the cat auditory nerve in response to the utterance. Each trace represents the average post-stimulus-time histogram for 2-7 auditory-nerve fibers whose CFs are located in a 1/2 octave band centered at the vertical ordinate. All histograms were computed with a bin width of 1 msec, and have been normalized to the same maximum in order to emphasize temporal patterns. The stimulus level was such that the most intense vowels were at 50 dB SPL. B. Broadband spectrogram of the utterance. Filled arrows point to rapid increases in amplitude in the low frequencies (and their neural correlates on top), while open arrows point to rapid increases in amplitude in the high frequencies. The ovals show the second-formant movement in "green" and its neural correlate.



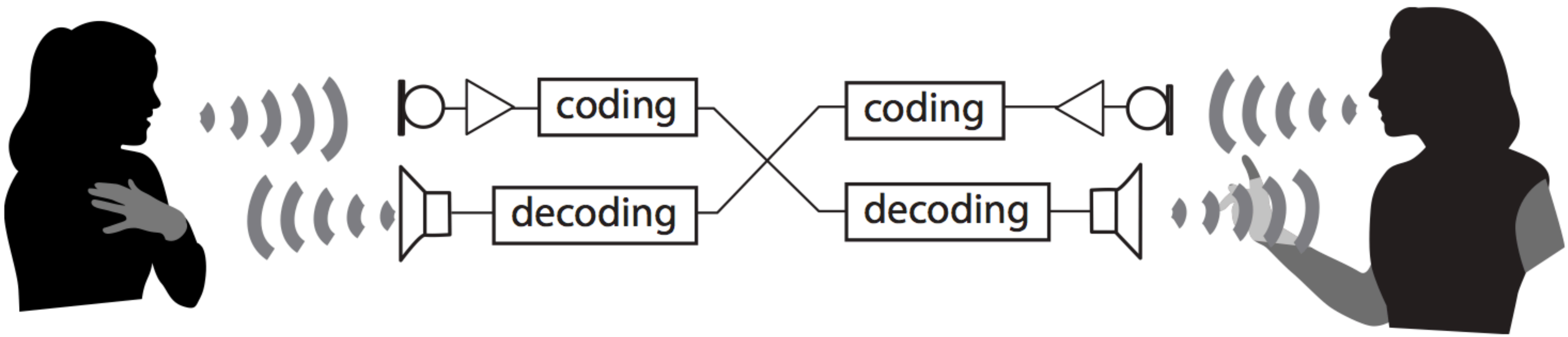


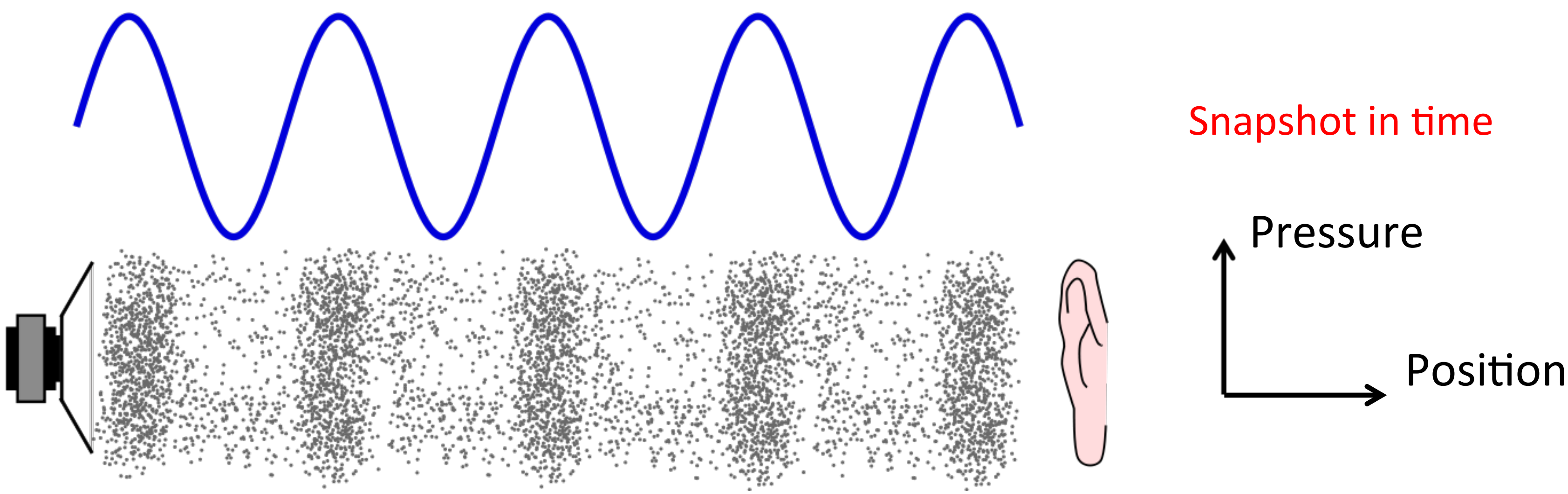




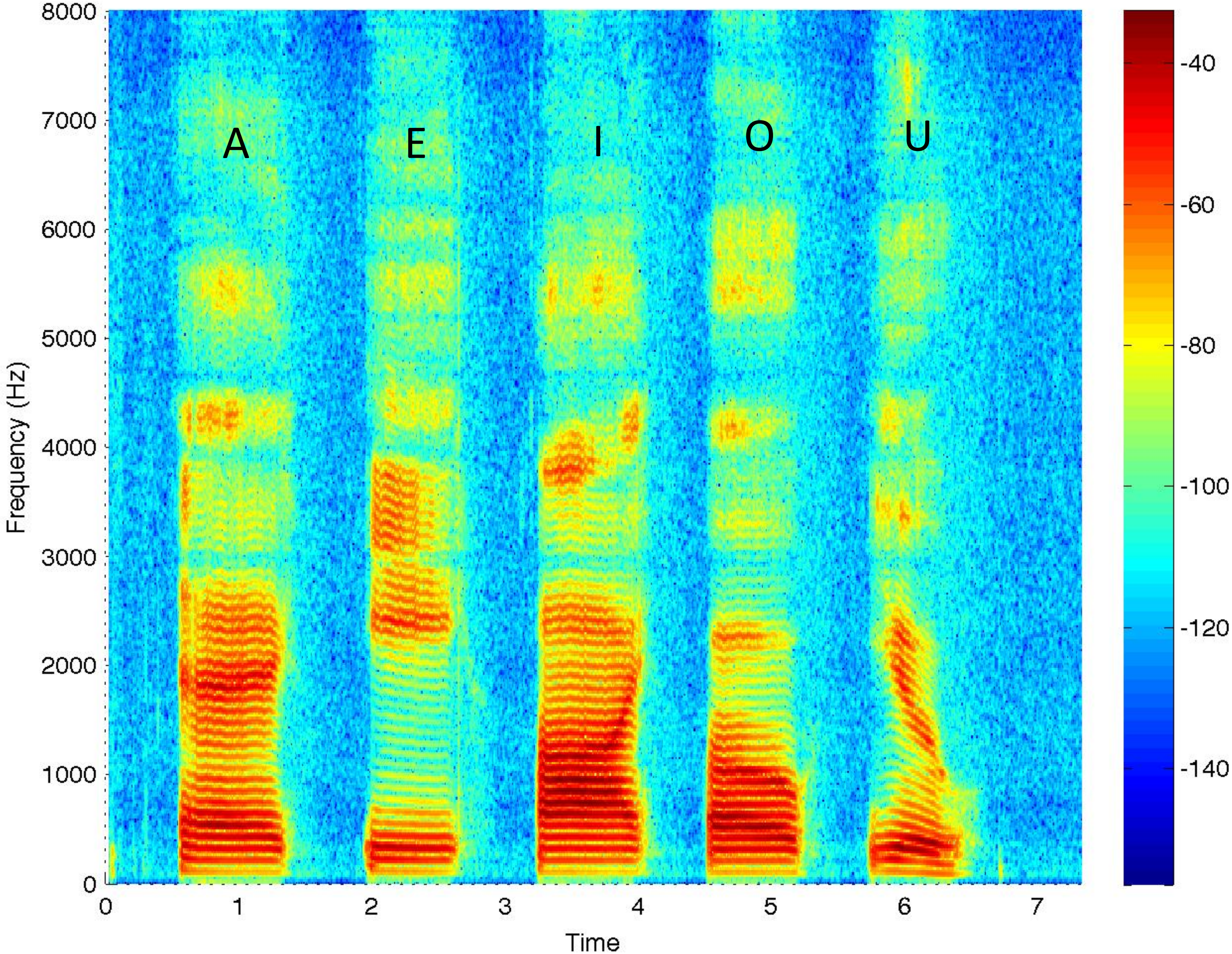
Delgutte (1997)

e.g., “Speech chain”



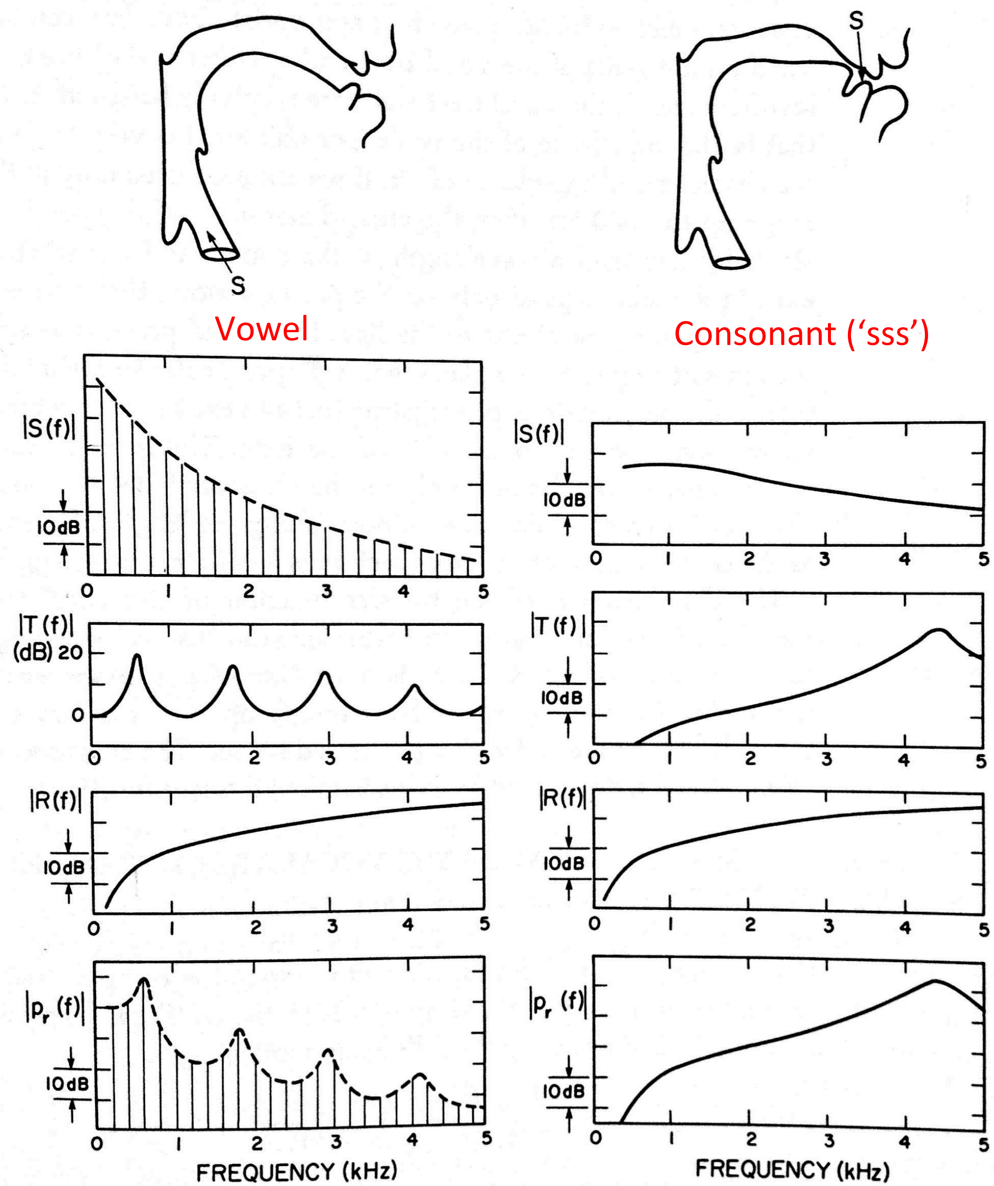


Pulkki & Karjalainen (2015)



A
E
I
O
U
Frequency (Hz)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
Time
-40
-60
-80
-100
-120
-140

Speech



Source (vocal folds)

Filter I (vocal tract)

Filter II (radiation)

Speech signal

Figure 3.1 Sketches indicating components of the output spectrum $|p_r(f)|$ for a vowel and a fricative consonant. The output spectrum is the product of a source spectrum $S(f)$, a transfer function $T(f)$, and a radiation characteristic $R(f)$. The source spectra are similar to those derived in figures 2.10 and 2.33 in chapter 2. For the periodic source, $S(f)$ represents the amplitudes of spectral components; for the noise source, $S(f)$ is amplitude in a specified bandwidth. See text.

- Vibrating vocal folds make 'broadband' sound
- Vocal tract shapes that sound
- Resulting 'shape' emphasizes features which we then pick up with our ear (e.g., formants of vowels)

→ But what does it mean for everything to be a function of frequency?

Stevens (2000)