Current Topics in Biophysics (BPHS 2090)

Instructor: Prof. Christopher Bergevin (cberge@yorku.ca)

Website: http://www.yorku.ca/cberge/2090F2015.html

York University
Fall 2015 (11/26/15)

References/Acknowledgement:
→ see webpage

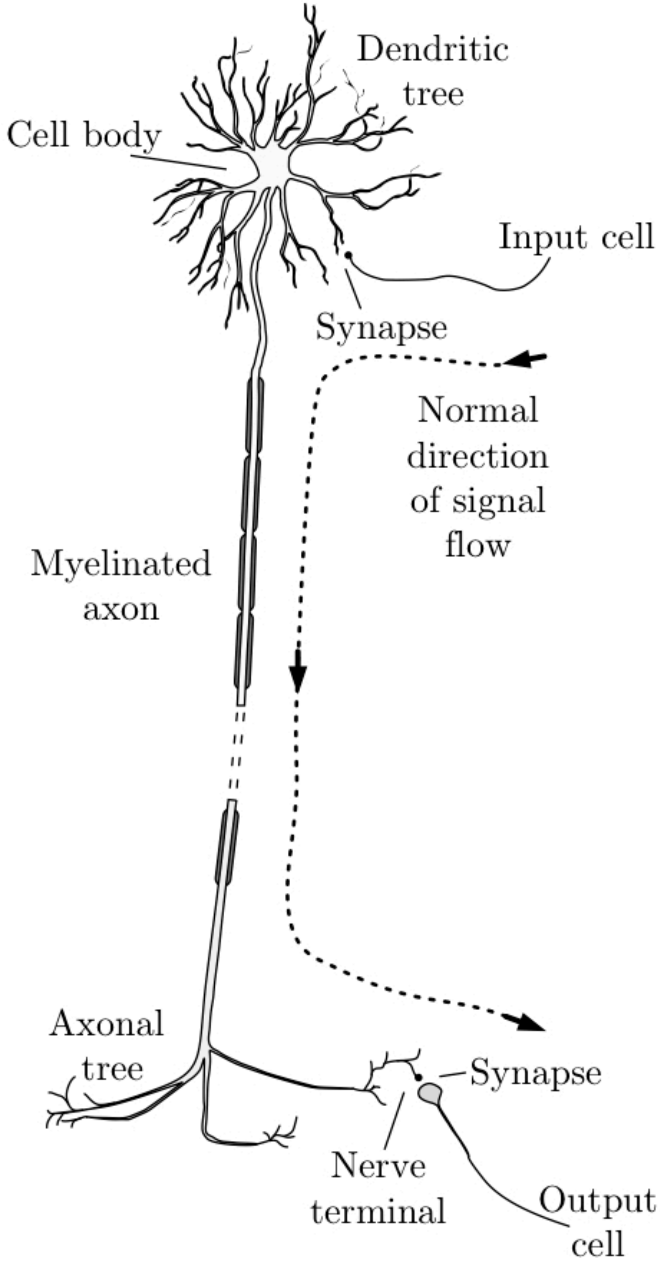


Figure 1.22

Weiss (1996)

Modeling neurons → Electrical circuits

Key Point: Electrical properties of cells are important

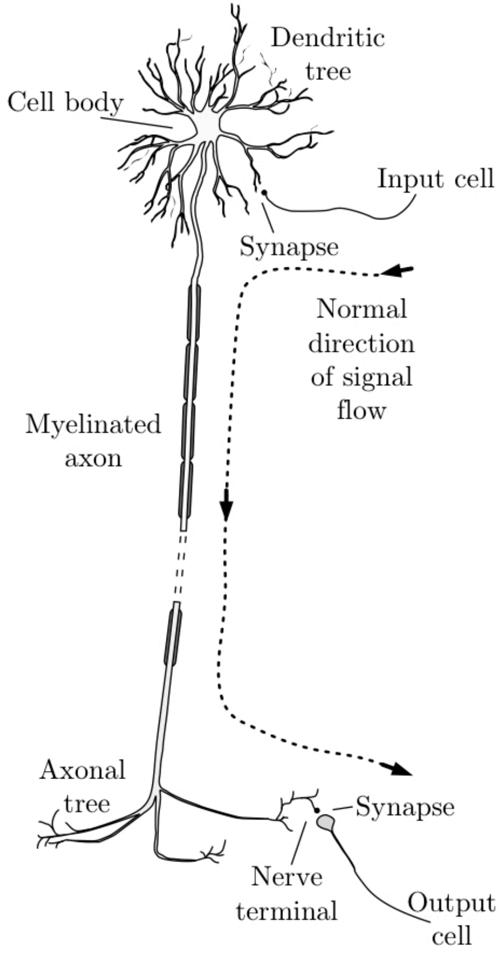


Figure 1.22

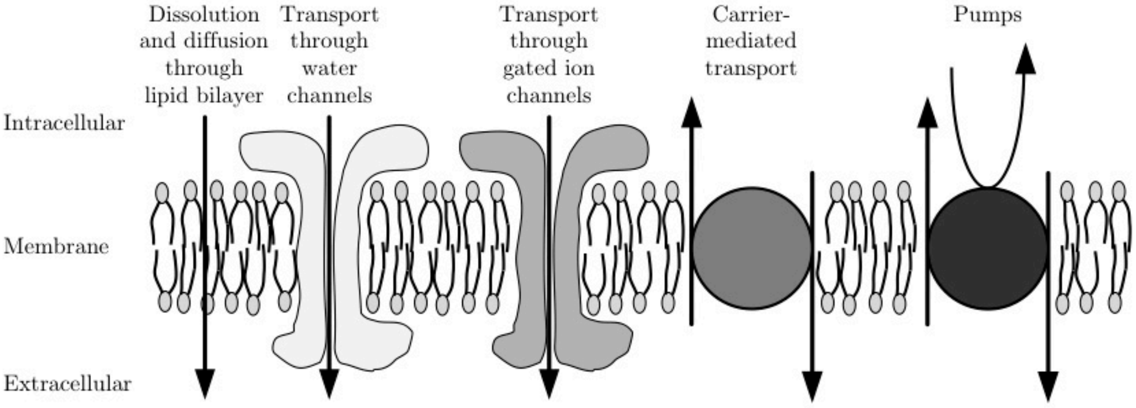
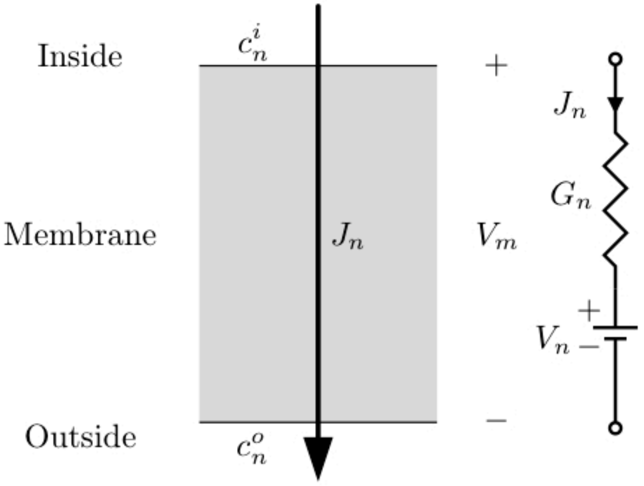


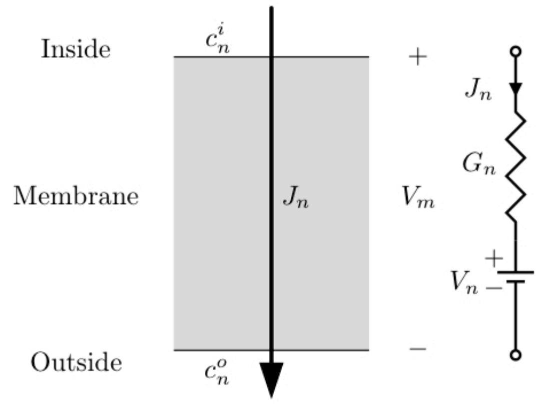
Figure 2.19

Model of Steady-State Electrodiffusion through Membranes



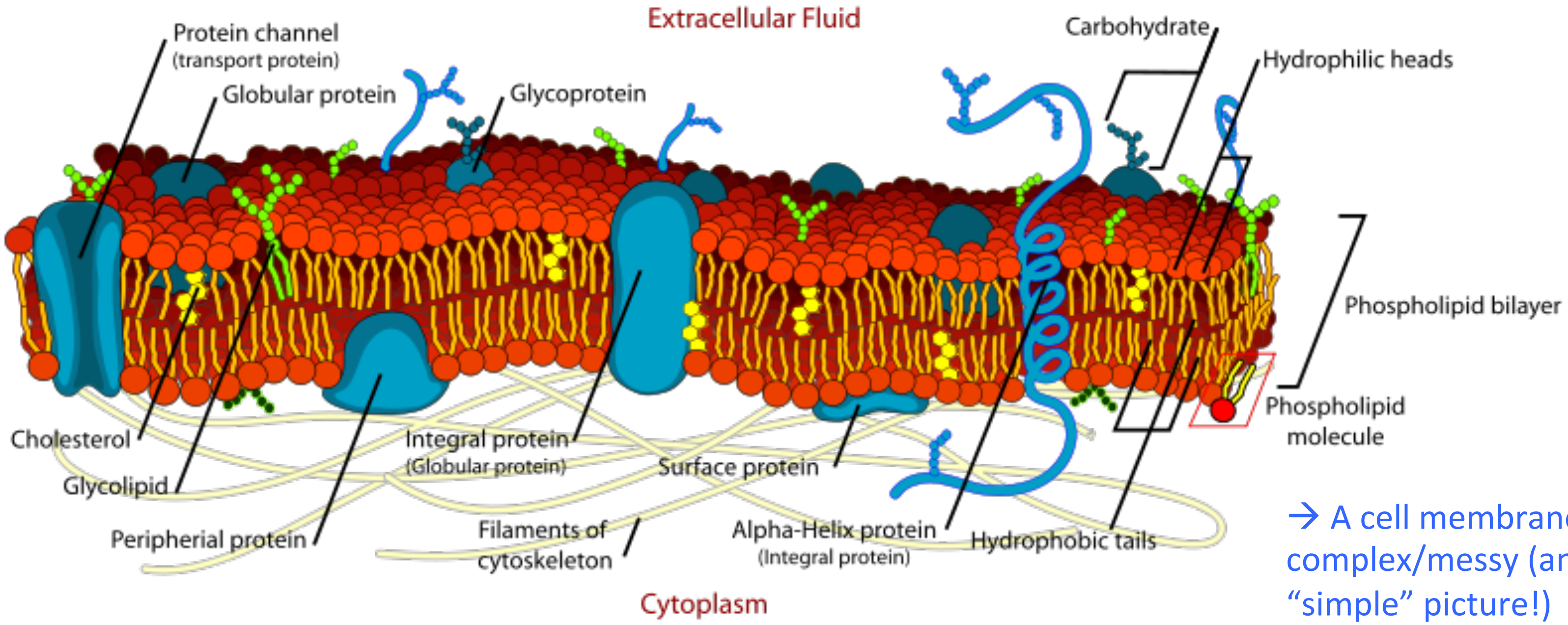
Weiss (1996)

Model of Steady-State Electrodiffusion through Membranes



Deep "biophysical" idea here!

That we can effectively "model" an essential aspect of cell membranes by treating it as an electric circuit (ignoring a lot of messy/excess detail)



→ A cell membrane is complex/messy (and this is a "simple" picture!)

Wikipedia

Modeling neurons → Core-conductor & Cable models

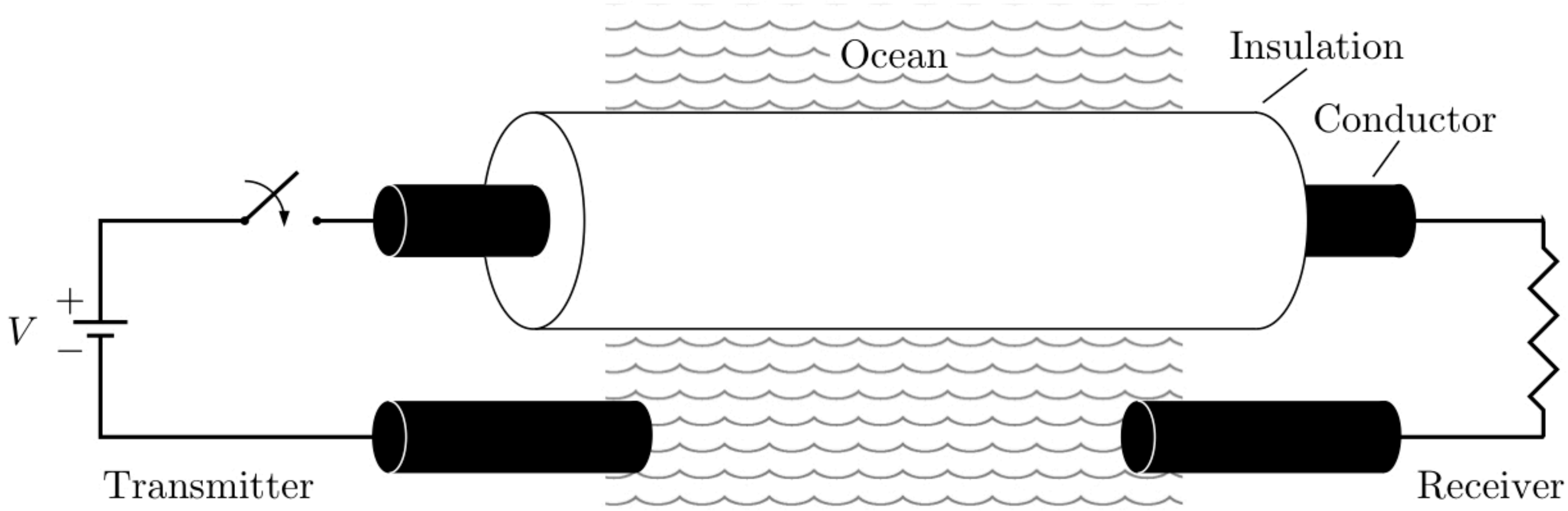
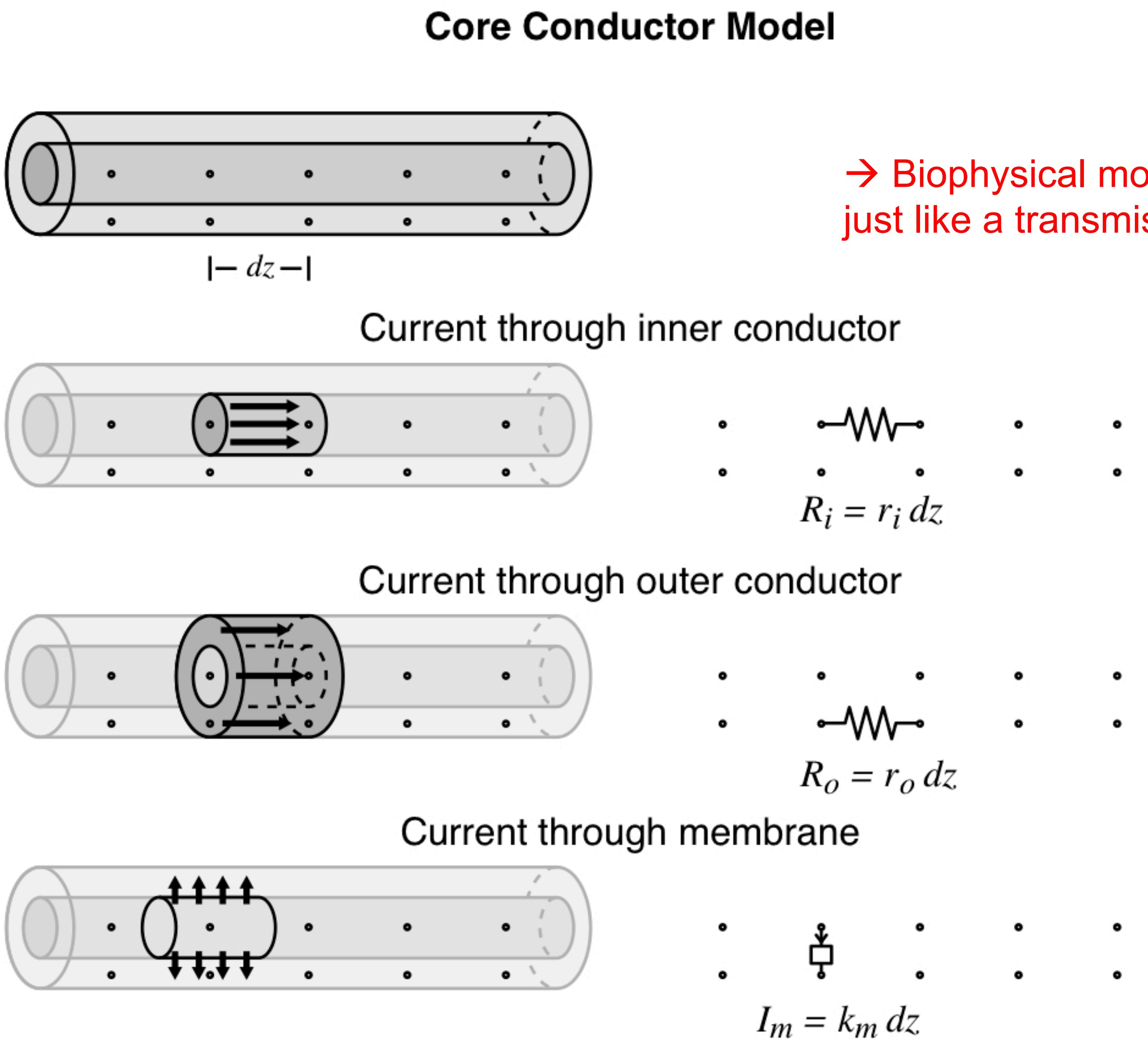


Figure 3.8

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

Weiss (1996)

Modeling neurons → Core-conductor & Cable models



→ Biophysical model of a neuron is just like a transmission line!

Freeman

Modeling neurons → Electrical circuits

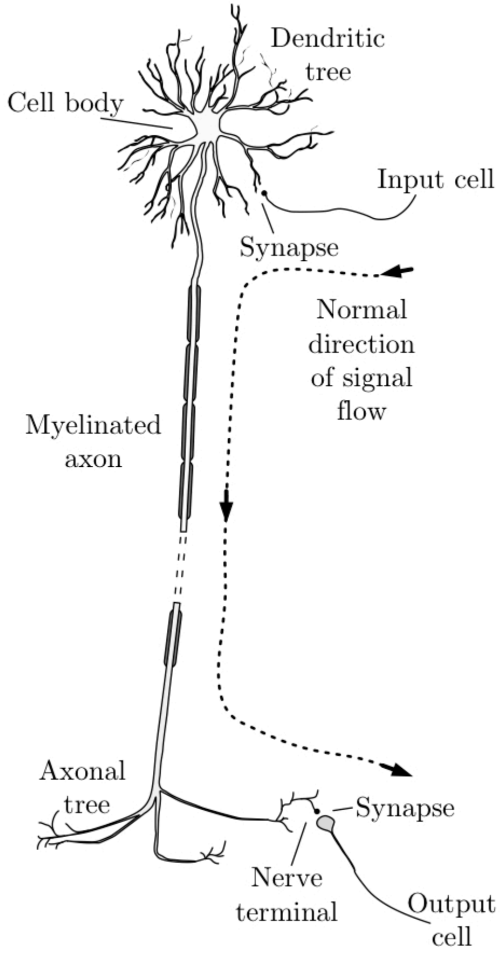


Figure 1.22

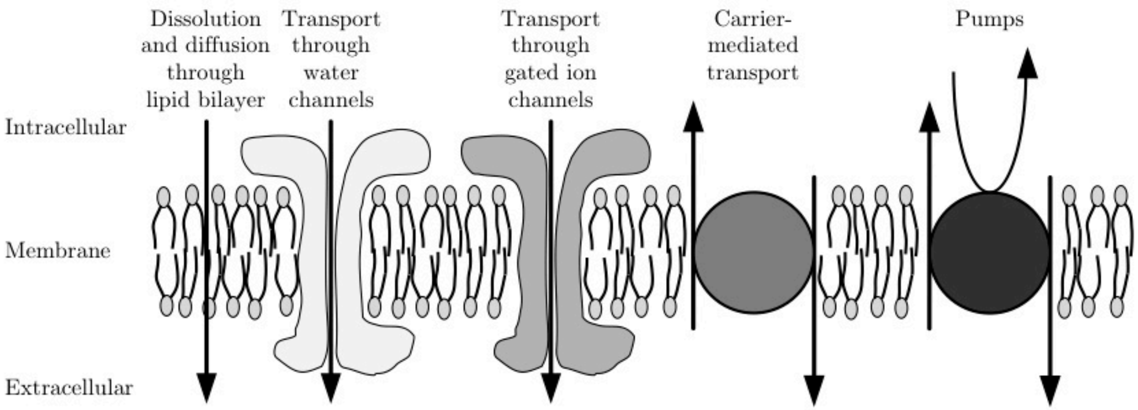
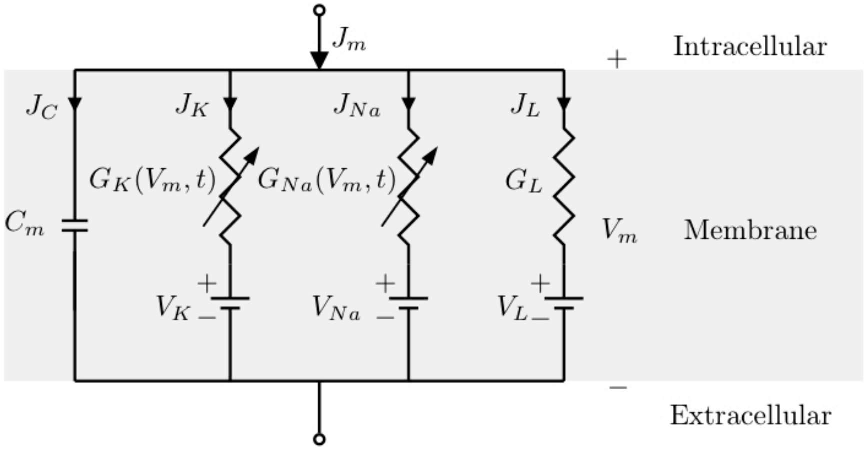


Figure 2.19

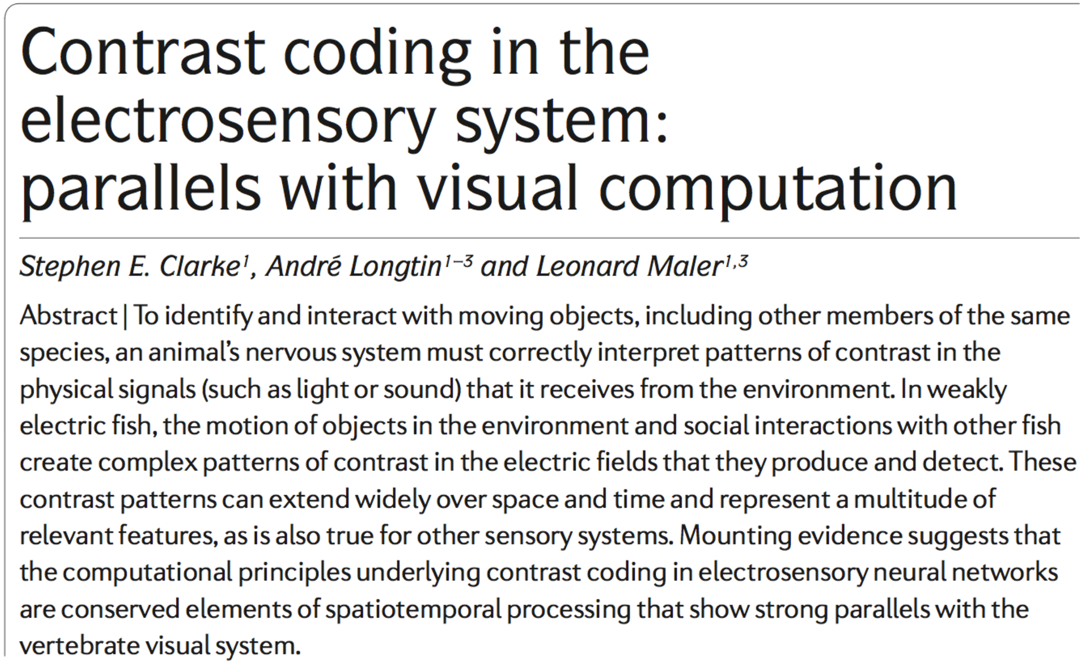
Hodgkin Huxley model



→ This all forms a core narrative thread of BPHS 3090/4080

Weiss (1996)

“Current Topic”



Contrast coding in the electrosensory system: parallels with visual computation

Stephen E. Clarke[1], André Longtin[1–3] and Leonard Maler[1,3]

Abstract | To identify and interact with moving objects, including other members of the same species, an animal's nervous system must correctly interpret patterns of contrast in the physical signals (such as light or sound) that it receives from the environment. In weakly electric fish, the motion of objects in the environment and social interactions with other fish create complex patterns of contrast in the electric fields that they produce and detect. These contrast patterns can extend widely over space and time and represent a multitude of relevant features, as is also true for other sensory systems. Mounting evidence suggests that the computational principles underlying contrast coding in electrosensory neural networks are conserved elements of spatiotemporal processing that show strong parallels with the vertebrate visual system.

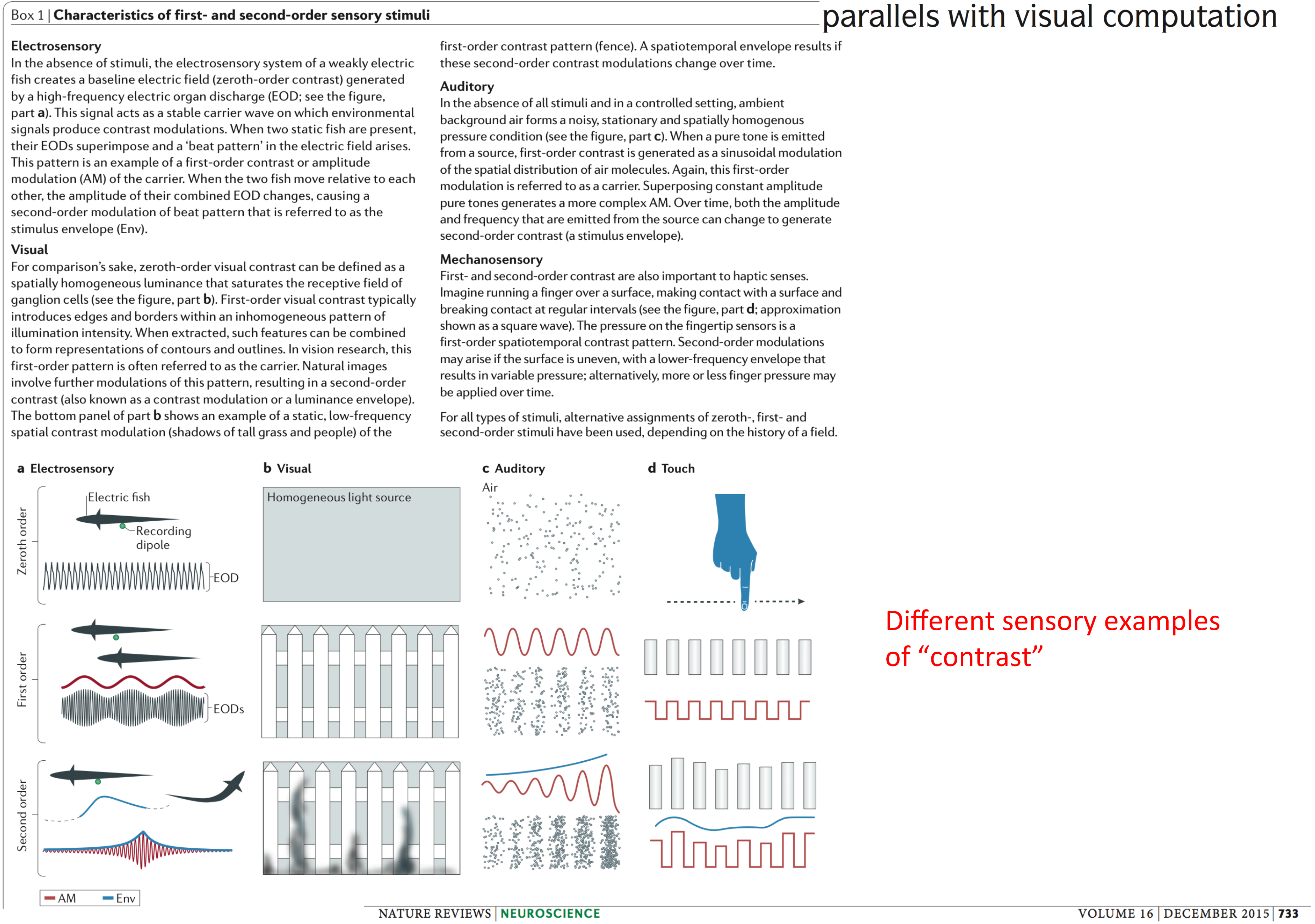
http://www.npr.org/2014/06/26/325246710/a-shocking-fish-tale-surprises-evolutionary-biologists

→ How does the sensory system encode “contrast”?

NATURE REVIEWS | NEUROSCIENCE VOLUME 16 | DECEMBER 2015 | 733

“Current Topic”

Contrast coding in the electrosensory system: parallels with visual computation



Box 1 | **Characteristics of first- and second-order sensory stimuli**

Electrosensory

In the absence of stimuli, the electrosensory system of a weakly electric fish creates a baseline electric field (zeroth-order contrast) generated by a high-frequency electric organ discharge (EOD; see the figure, part **a**). This signal acts as a stable carrier wave on which environmental signals produce contrast modulations. When two static fish are present, their EODs superimpose and a ‘beat pattern’ in the electric field arises. This pattern is an example of a first-order contrast or amplitude modulation (AM) of the carrier. When the two fish move relative to each other, the amplitude of their combined EOD changes, causing a second-order modulation of beat pattern that is referred to as the stimulus envelope (Env).

Visual

For comparison’s sake, zeroth-order visual contrast can be defined as a spatially homogeneous luminance that saturates the receptive field of ganglion cells (see the figure, part **b**). First-order visual contrast typically introduces edges and borders within an inhomogeneous pattern of illumination intensity. When extracted, such features can be combined to form representations of contours and outlines. In vision research, this first-order pattern is often referred to as the carrier. Natural images involve further modulations of this pattern, resulting in a second-order contrast (also known as a contrast modulation or a luminance envelope). The bottom panel of part **b** shows an example of a static, low-frequency spatial contrast modulation (shadows of tall grass and people) of the first-order contrast pattern (fence). A spatiotemporal envelope results if these second-order contrast modulations change over time.

Auditory

In the absence of all stimuli and in a controlled setting, ambient background air forms a noisy, stationary and spatially homogenous pressure condition (see the figure, part **c**). When a pure tone is emitted from a source, first-order contrast is generated as a sinusoidal modulation of the spatial distribution of air molecules. Again, this first-order modulation is referred to as a carrier. Superposing constant amplitude pure tones generates a more complex AM. Over time, both the amplitude and frequency that are emitted from the source can change to generate second-order contrast (a stimulus envelope).

Mechanosensory

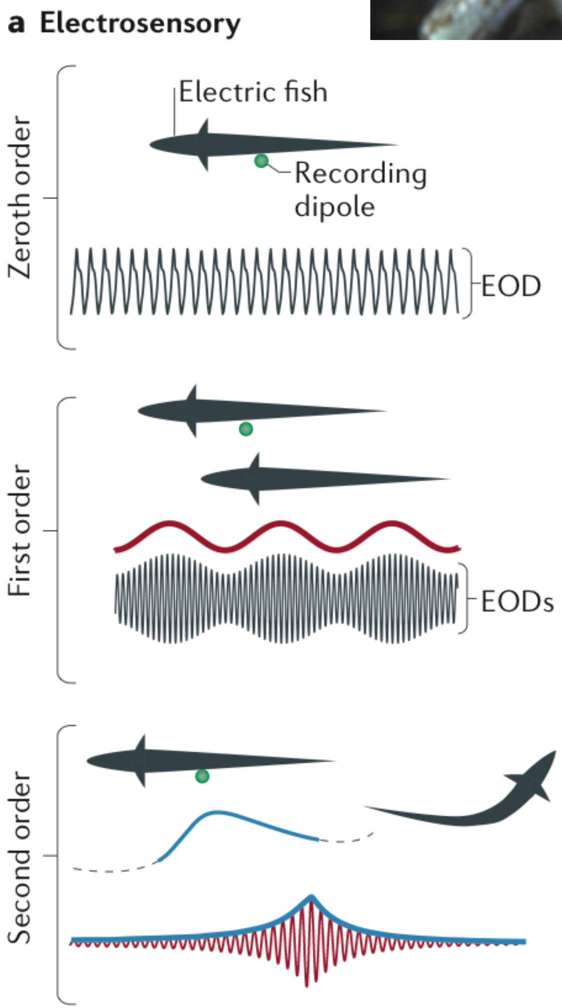
First- and second-order contrast are also important to haptic senses. Imagine running a finger over a surface, making contact with a surface and breaking contact at regular intervals (see the figure, part **d**; approximation shown as a square wave). The pressure on the fingertip sensors is a first-order spatiotemporal contrast pattern. Second-order modulations may arise if the surface is uneven, with a lower-frequency envelope that results in variable pressure; alternatively, more or less finger pressure may be applied over time.

For all types of stimuli, alternative assignments of zeroth-, first- and second-order stimuli have been used, depending on the history of a field.

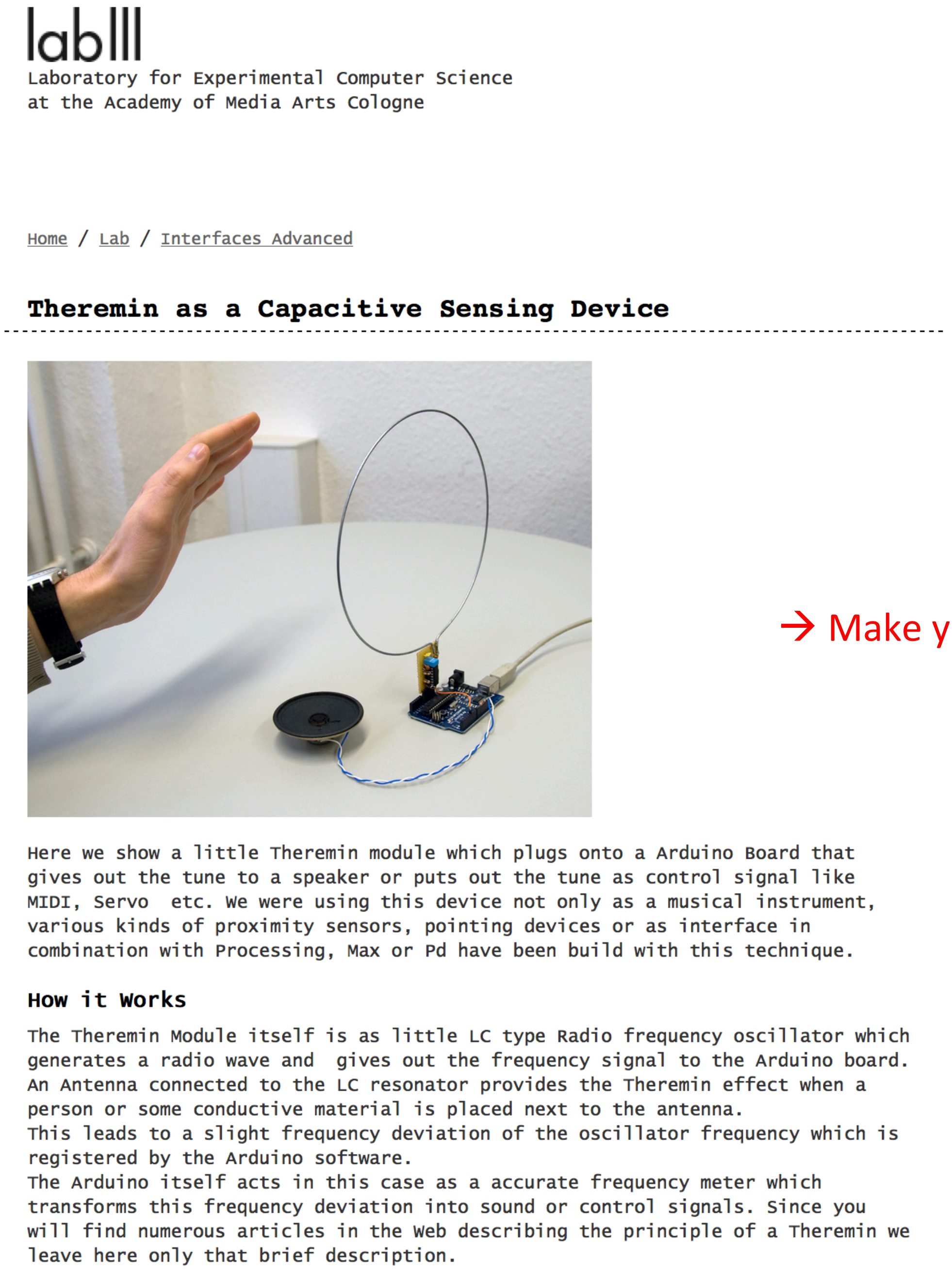
Different sensory examples of “contrast”

"Current Topic"

Contrast coding in the electrosensory system: parallels with visual computation



→ Theremin (the only musical instrument you play by not actually touching!)



labIII

Laboratory for Experimental Computer Science
at the Academy of Media Arts Cologne

Home / Lab / Interfaces Advanced

Theremin as a Capacitive Sensing Device

Here we show a little Theremin module which plugs onto a Arduino Board that gives out the tune to a speaker or puts out the tune as control signal like MIDI, Servo etc. We were using this device not only as a musical instrument, various kinds of proximity sensors, pointing devices or as interface in combination with Processing, Max or Pd have been build with this technique.

How it Works

The Theremin Module itself is as little LC type Radio frequency oscillator which generates a radio wave and gives out the frequency signal to the Arduino board. An Antenna connected to the LC resonator provides the Theremin effect when a person or some conductive material is placed next to the antenna.
This leads to a slight frequency deviation of the oscillator frequency which is registered by the Arduino software.
The Arduino itself acts in this case as a accurate frequency meter which transforms this frequency deviation into sound or control signals. Since you will find numerous articles in the Web describing the principle of a Theremin we leave here only that brief description.

→ Make your own Theremin (via an Arduino)

http://interface.khm.de/index.php/lab/interfaces-advanced/theremin-as-a-capacitive-sensing-device/

“Current Topic”

Contrast coding in the electrosensory system: parallels with visual computation

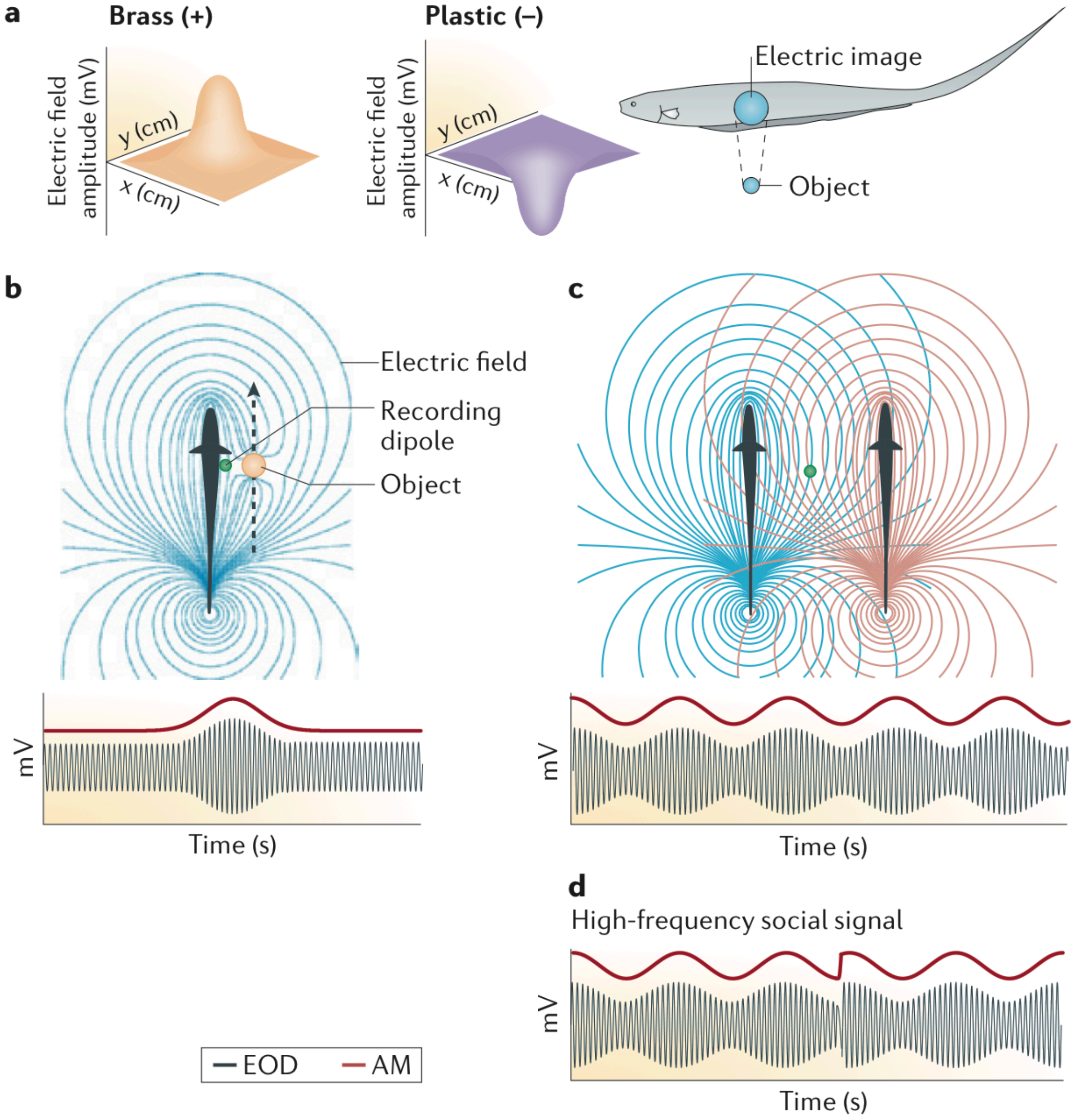


Figure 1 | **Natural electrosensory signals.** **a** | The formation of static electric images. Conductive objects, such as those made of brass, cause a localized increase in the amplitude of the electric field relative to its background levels (driven by the electric organ discharge (EOD)). By contrast, non-conductive objects, such as plastic, cause a localized decrease in the amplitude of the electric field. Thus, these two object classes create either positive or negative local-to-background, or spatial, contrast. There is no focusing mechanism and so the electric image spreads across the skin in a roughly Gaussian manner. **b** | The formation of a dynamic electric image. The green dot indicates the location of a small recording dipole, which measures the amplitude of the electric potential experienced across the skin. As the fish swims by an object (a conductive sphere in this illustration), the EOD is locally increased above its baseline amplitude. The movement of the sphere through the electric field thus causes a low-frequency amplitude modulation (AM) that, in turn, excites the primary electrosensory neurons. **c** | The effects of EOD summation when two fish are in close proximity. The summation of the EODs of the two fish results in a global sinusoidal AM (beat), the frequency of which equals the difference of the EOD frequencies. **d** | A high-frequency communication signal that results from a purposeful frequency modulation of the EOD. This creates another type of AM, which occurs on timescales shorter than the typical beat period shown in part **c**. The top panels of parts **b** and **c** are reproduced with permission from REF. 3, Elsevier.

“Current Topic”

Contrast coding in the electrosensory system: parallels with visual computation

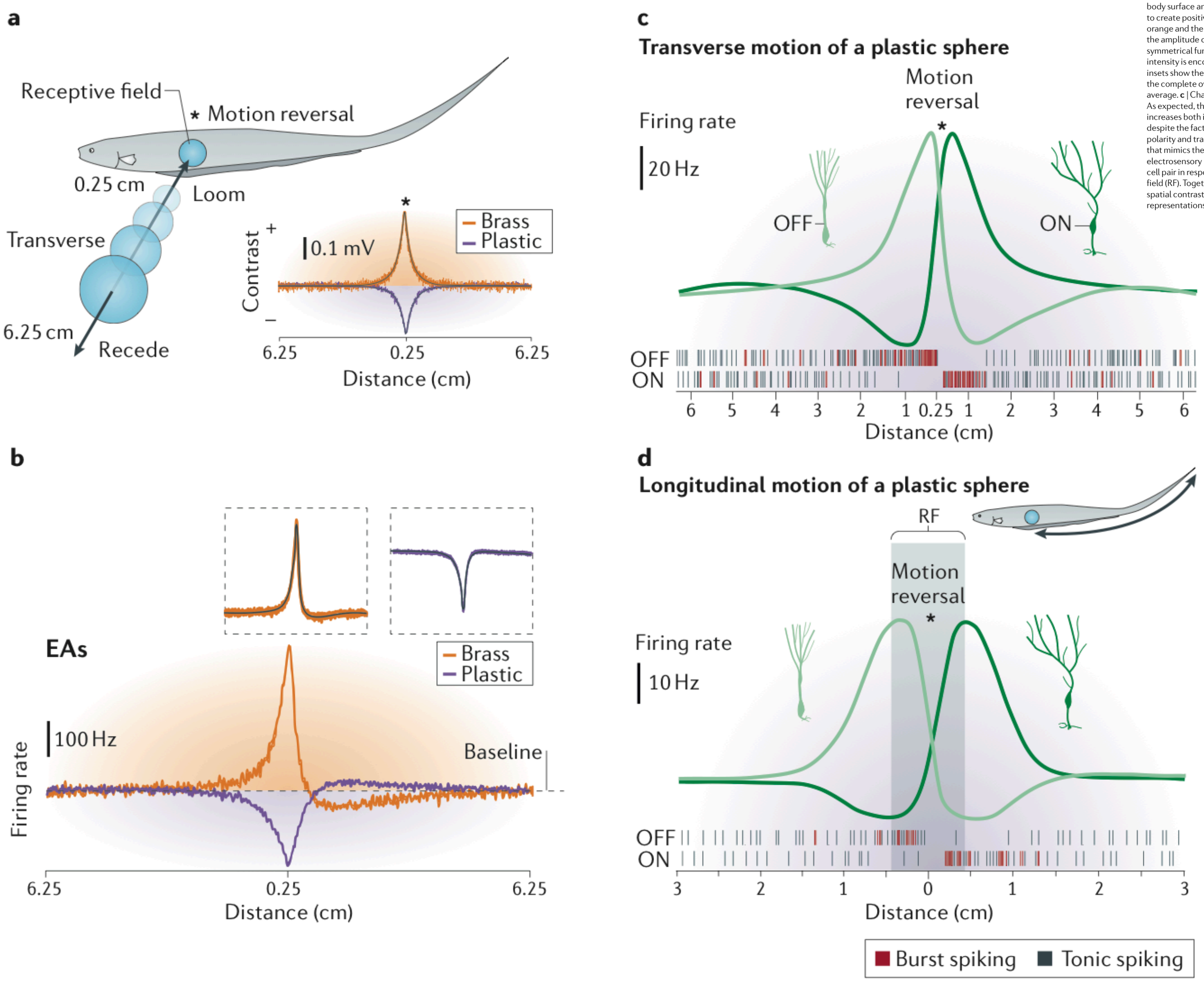
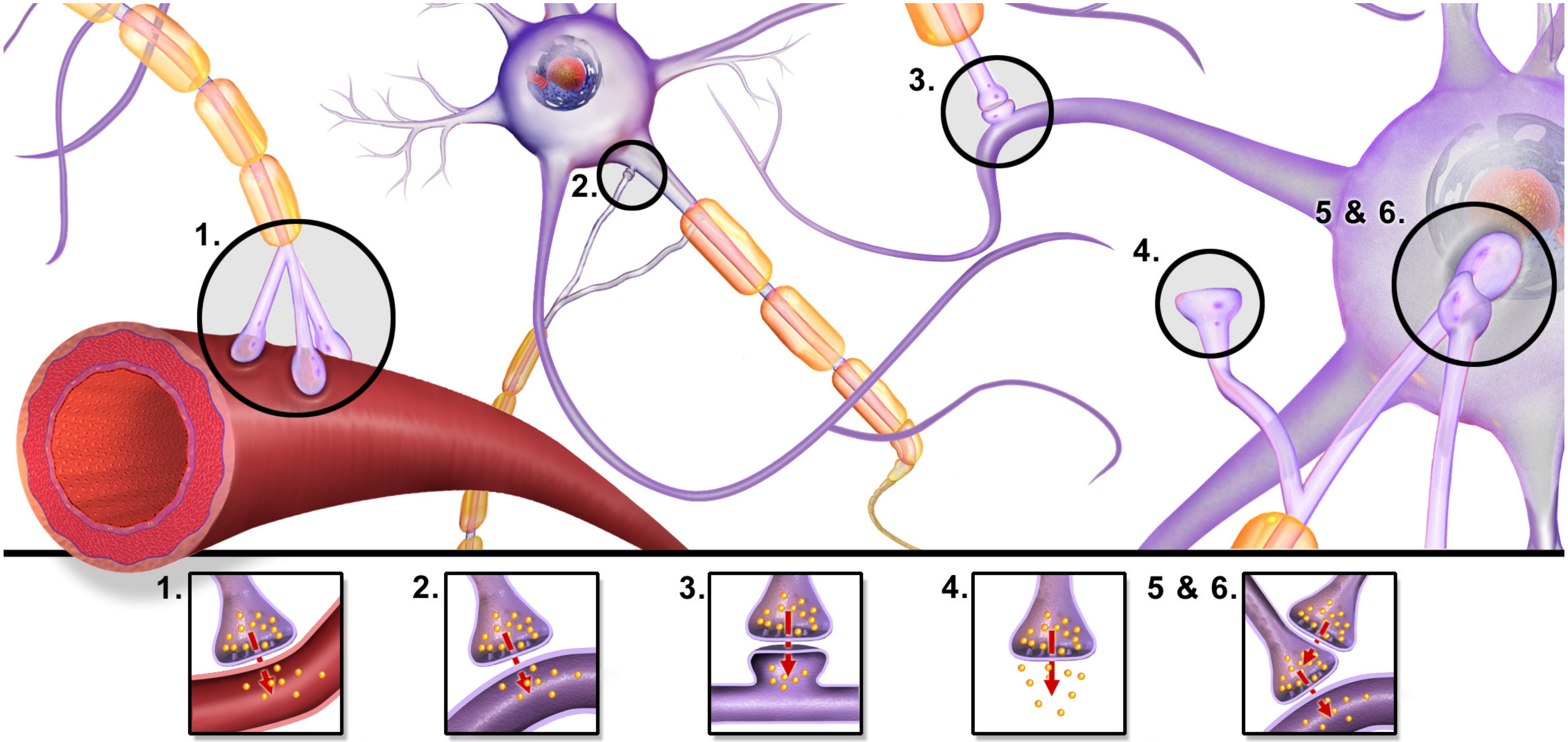


Figure 5 | **Motion reversal and distributed contrast coding.** **a** | Looming and receding stimuli that follow trajectories perpendicular to the electrosensory surface (transverse) are shown. In the model shown[15,21], motion along the transverse axis was set at 2 cm s^{-1}, with a rapid period of acceleration (150 cm s^{-2}). The spherical stimuli started 6.25 cm from the fish’s body surface and reversed motion at 0.25 cm, before returning to the original position. Brass and plastic spheres were used to create positive and negative contrast stimuli, respectively[21]. Experimental data are shown in the graph in purple and orange and the predictions of a model[5] are shown in grey. The plastic stimulus generates an electrical contrast that is half the amplitude of the brass stimulus, but otherwise the contrast intensities are reflections of each other and are symmetrical functions of distance regardless of the time course of motion. **b** | This symmetry is broken when the contrast intensity is encoded into the firing rates of the primary electroreceptor afferents (EAs), shown for an example cell. The insets show the predictions of the power law adaptation model (FIG. 2), superimposed onto many recorded EA responses; the complete overlap of model and data curves demonstrates that the model captures this skew in the population average. **c** | Changes in the firing rate of an ON and OFF cell pair in response to motion reversal along the transverse axis[21]. As expected, the OFF cell responds to the decreasing, negative local contrast caused by a looming plastic object and increases both its tonic and burst spiking rates. Upon motion reversal, it transitions from burst spiking to no spiking, despite the fact that the local-to-background contrast is still strongly negative. Surprisingly, the ON cell switches its polarity and transitions from silence to bursting under these negative contrast conditions, generating a receding response that mimics the OFF cell’s looming response. The skew introduced in the EAs has been removed at this stage of electrosensory processing. **d** | Polarity switches are also observed for longitudinal motion reversal, shown for an ON/OFF cell pair in response to 2 cm s^{-1} looming motion of a plastic sphere, moving +/– 3 cm from the very centre of the receptive field (RF). Together these results indicate that ON and OFF cells are coding the sign of temporal contrast (regardless of spatial contrast) and that sequential activation of electrosensory ON and OFF cell subsets are combined to produce representations of motion in the three spatial dimensions.

→ Different neuron “types” can differentially encode contrast via firing rate patterns

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

National Geographic



Axosecretory
Axon terminal secretes directly into bloodstream

Axoaxonic
Axon terminal secretes into another axon

Axodendritic
Axon terminal ends on a dendrite spine

Axoextracellular
Axon with no connection seccretes into extracellular fluid

Axosomatic
Axon terminal ends on soma

Axosynaptic
Axon terminal ends on another axon terminal

→ Neurons (e.g., your brain, right now) does a LOT of communicating via diffusion....

wikipedia (re synapse)

TECHNOLOGY FEATURE

A DEEP LOOK AT SYNAPTIC DYNAMICS

The processes behind neuronal communication have not yet been resolved in detail, but dyes, microscopy and protein analysis are beginning to fill in the gaps.

Synapses are crucial to the communication between neurons, but the events that happen there have been difficult to capture.

Synapses

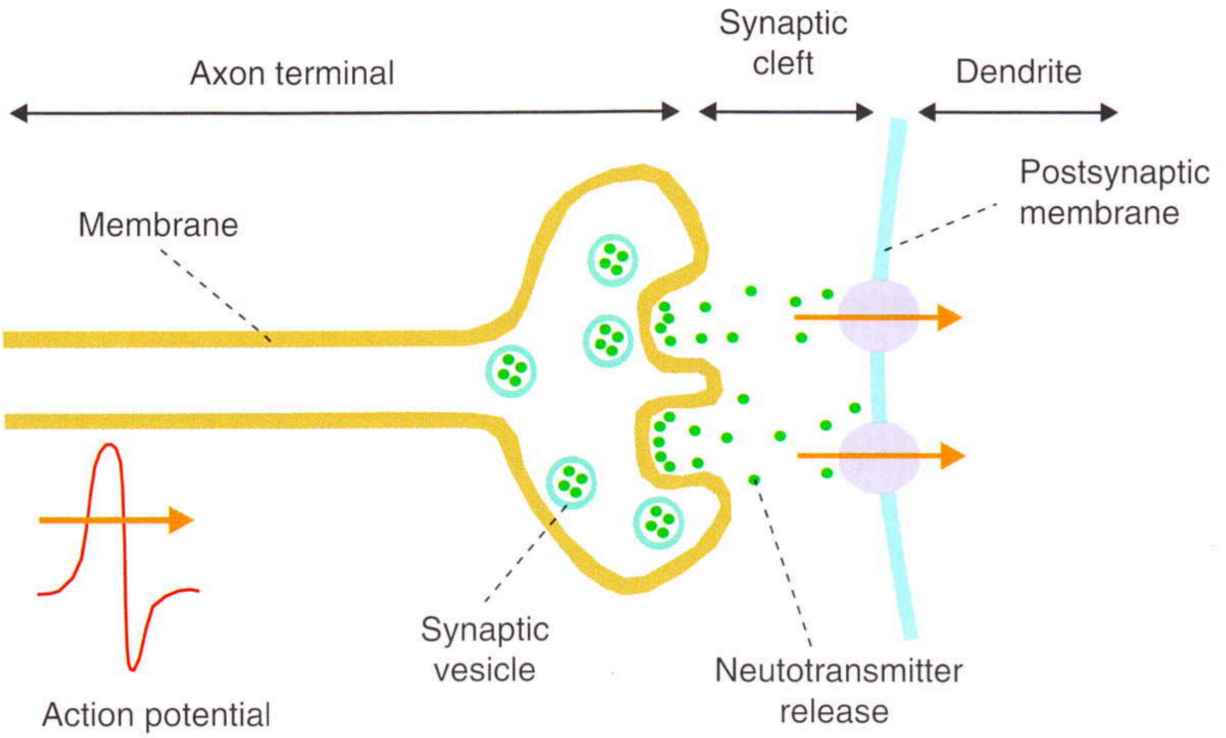
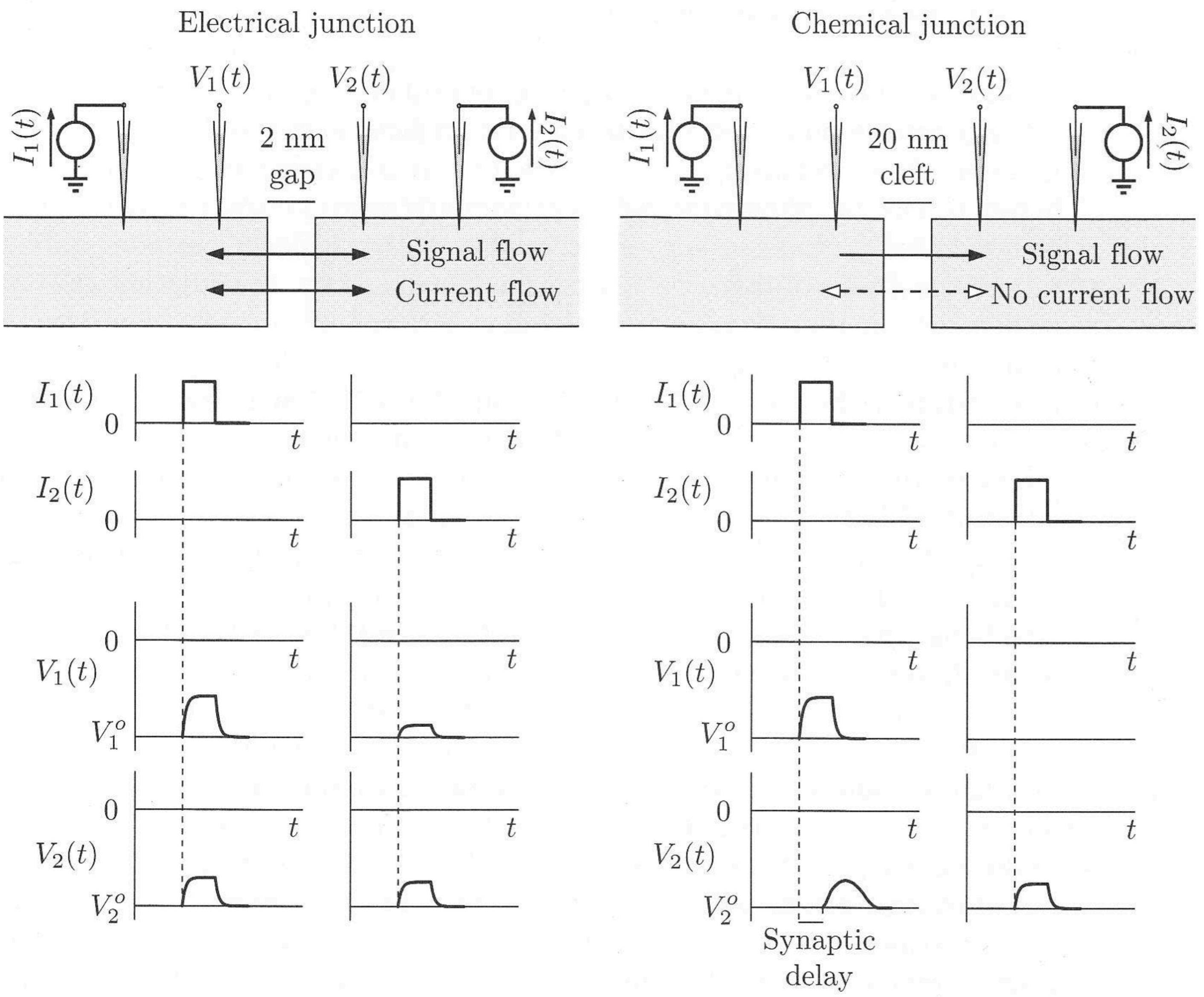


Figure 23.3 *Schematic diagram of an axon terminal in a neuron (**Figure 23.2**). Action potentials cause the release of neurotransmitters in vesicles that have an excitatory or inhibitory role on the spiking potentials formed by neighbouring dendrites.*

Waigh (2014)

Synapses



Two basic flavors of synapses

- Electrical
- Chemical

Figure 1.17 Schematic diagram illustrating the flow of signals and electric current at an electrical junction (left panel) and at a chemical junction (right panel).

Remember: Electrical properties of cells are important

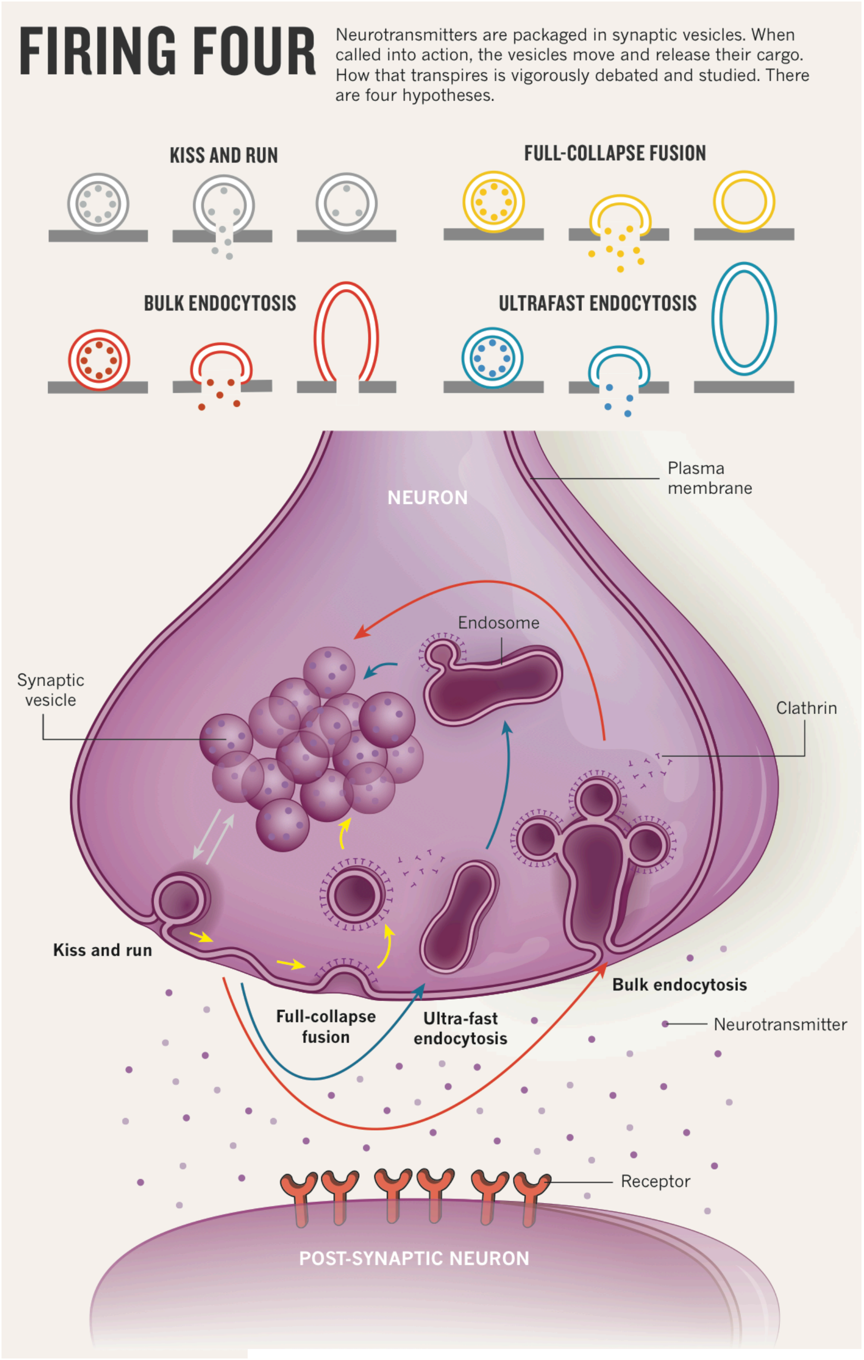
Weiss (1996)

Chemical synapses

- ➢ Still much is not well understood about the physical mechanism(s) underlying synaptic dynamics

- ➢ Different models proposed for how vesicles interact w/ (pre-synaptic) membrane

→ How might one explore such experimentally?

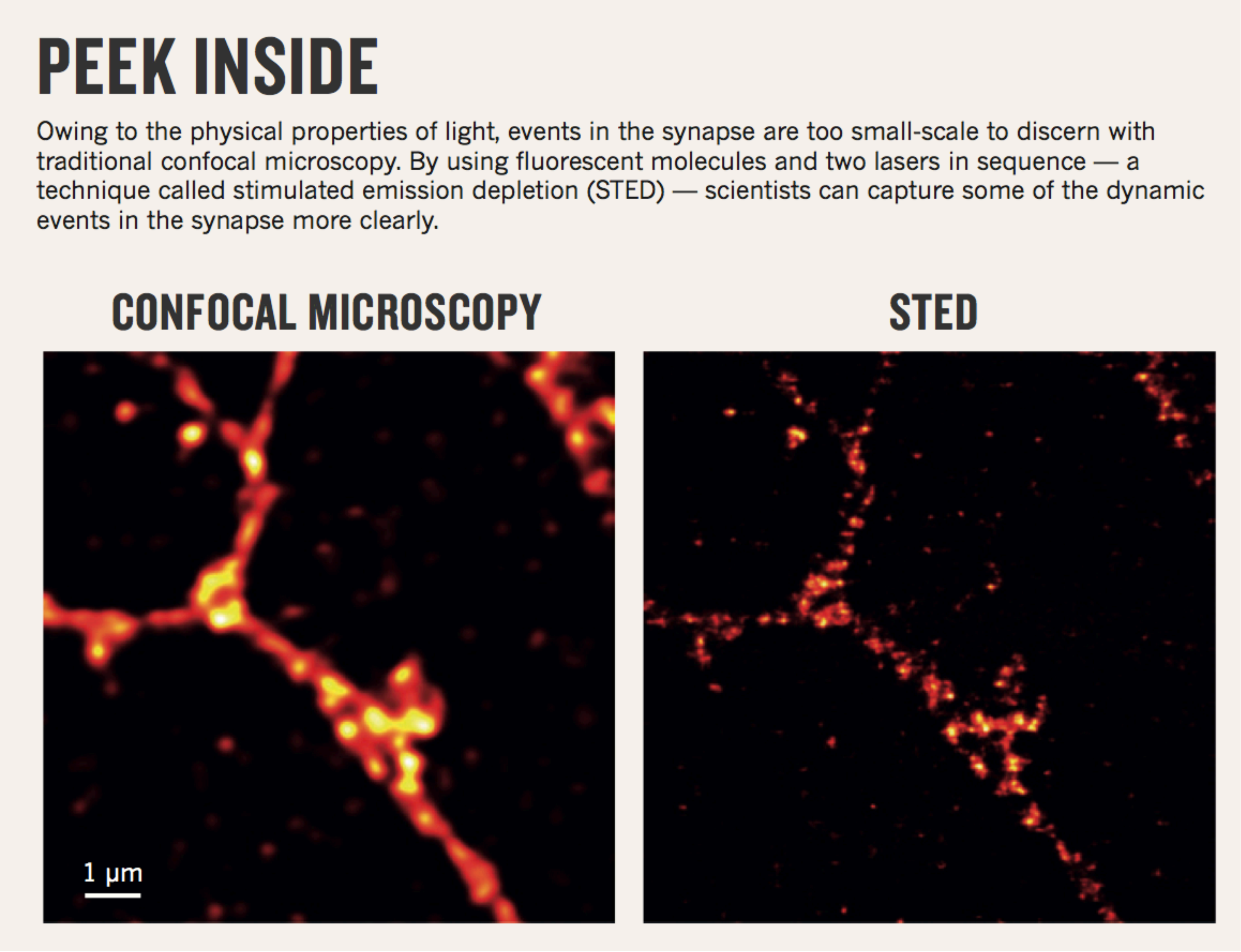


FIRING FOUR

Neurotransmitters are packaged in synaptic vesicles. When called into action, the vesicles move and release their cargo. How that transpires is vigorously debated and studied. There are four hypotheses.

13 NOVEMBER 2014 | VOL 515 | NATURE | 293

Synapses



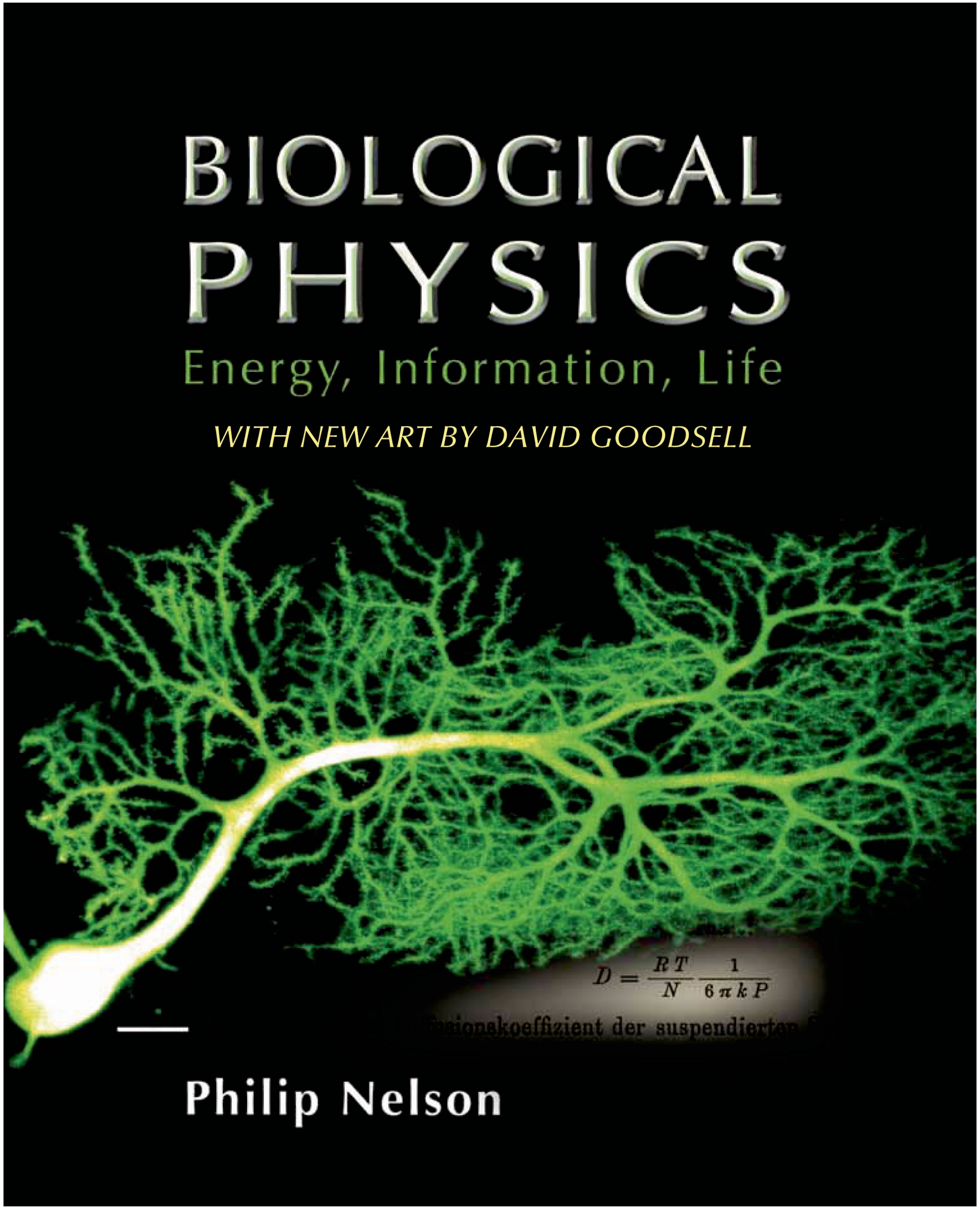
PEEK INSIDE

Owing to the physical properties of light, events in the synapse are too small-scale to discern with traditional confocal microscopy. By using fluorescent molecules and two lasers in sequence — a technique called stimulated emission depletion (STED) — scientists can capture some of the dynamic events in the synapse more clearly.

CONFOCAL MICROSCOPY

STED

13 NOVEMBER 2014 | VOL 515 | NATURE | 293



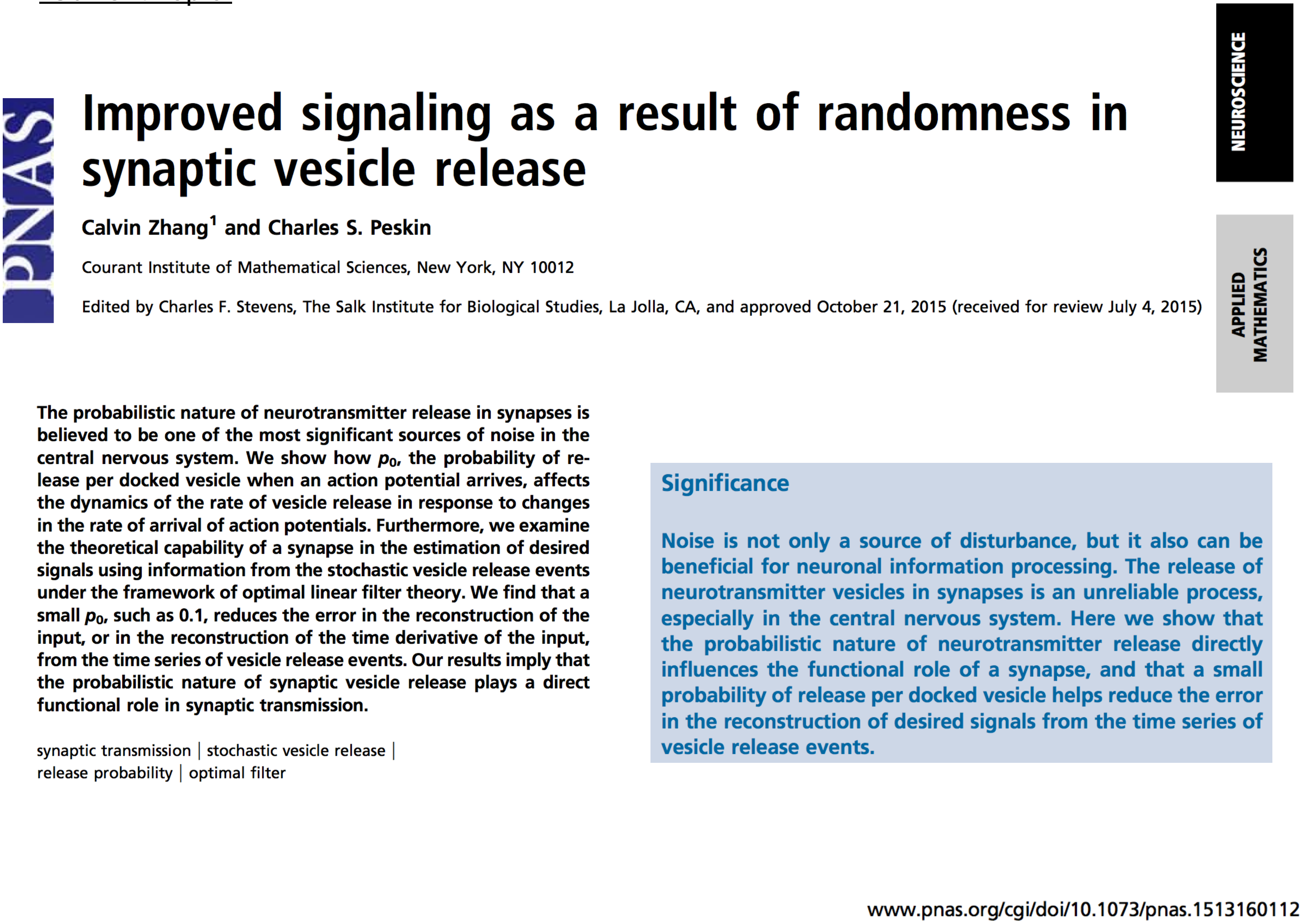
BIOLOGICAL
PHYSICS
Energy, Information, Life

WITH NEW ART BY DAVID GOODSELL

Philip Nelson

→ This image of a neuron was captured via “two photon” microscopy (covered in BPHS 4090), which also allows for probing synaptic dynamics

“Current Topic”



NEUROSCIENCE

APPLIED MATHEMATICS

Improved signaling as a result of randomness in synaptic vesicle release

Calvin Zhang[1] **and Charles S. Peskin**

Courant Institute of Mathematical Sciences, New York, NY 10012

Edited by Charles F. Stevens, The Salk Institute for Biological Studies, La Jolla, CA, and approved October 21, 2015 (received for review July 4, 2015)

The probabilistic nature of neurotransmitter release in synapses is believed to be one of the most significant sources of noise in the central nervous system. We show how p_0, the probability of release per docked vesicle when an action potential arrives, affects the dynamics of the rate of vesicle release in response to changes in the rate of arrival of action potentials. Furthermore, we examine the theoretical capability of a synapse in the estimation of desired signals using information from the stochastic vesicle release events under the framework of optimal linear filter theory. We find that a small p_0, such as 0.1, reduces the error in the reconstruction of the input, or in the reconstruction of the time derivative of the input, from the time series of vesicle release events. Our results imply that the probabilistic nature of synaptic vesicle release plays a direct functional role in synaptic transmission.

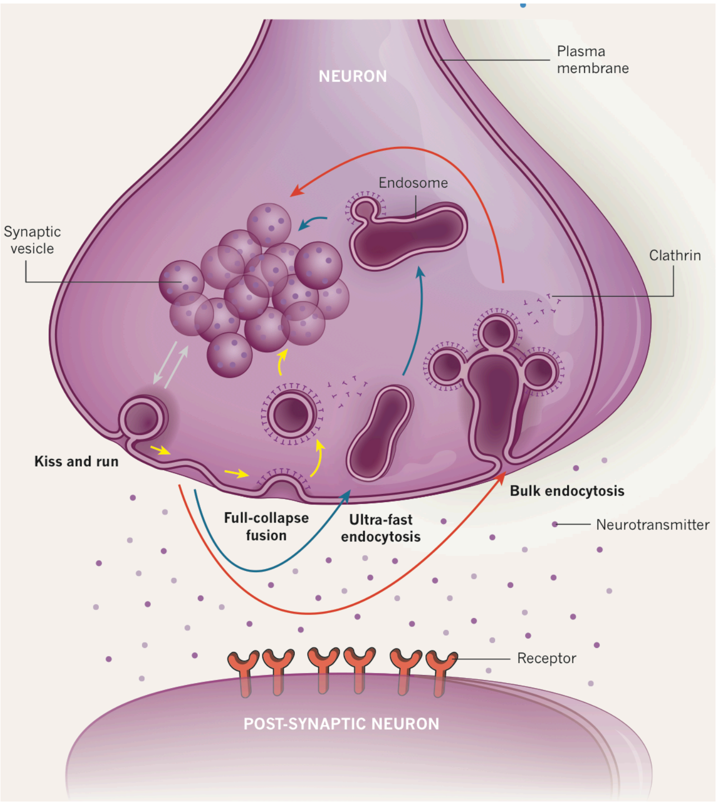
synaptic transmission | stochastic vesicle release | release probability | optimal filter

Significance

Noise is not only a source of disturbance, but it also can be beneficial for neuronal information processing. The release of neurotransmitter vesicles in synapses is an unreliable process, especially in the central nervous system. Here we show that the probabilistic nature of neurotransmitter release directly influences the functional role of a synapse, and that a small probability of release per docked vesicle helps reduce the error in the reconstruction of desired signals from the time series of vesicle release events.

www.pnas.org/cgi/doi/10.1073/pnas.1513160112

“Current Topic”



- Noise may actually help in some way to preserve “signals”

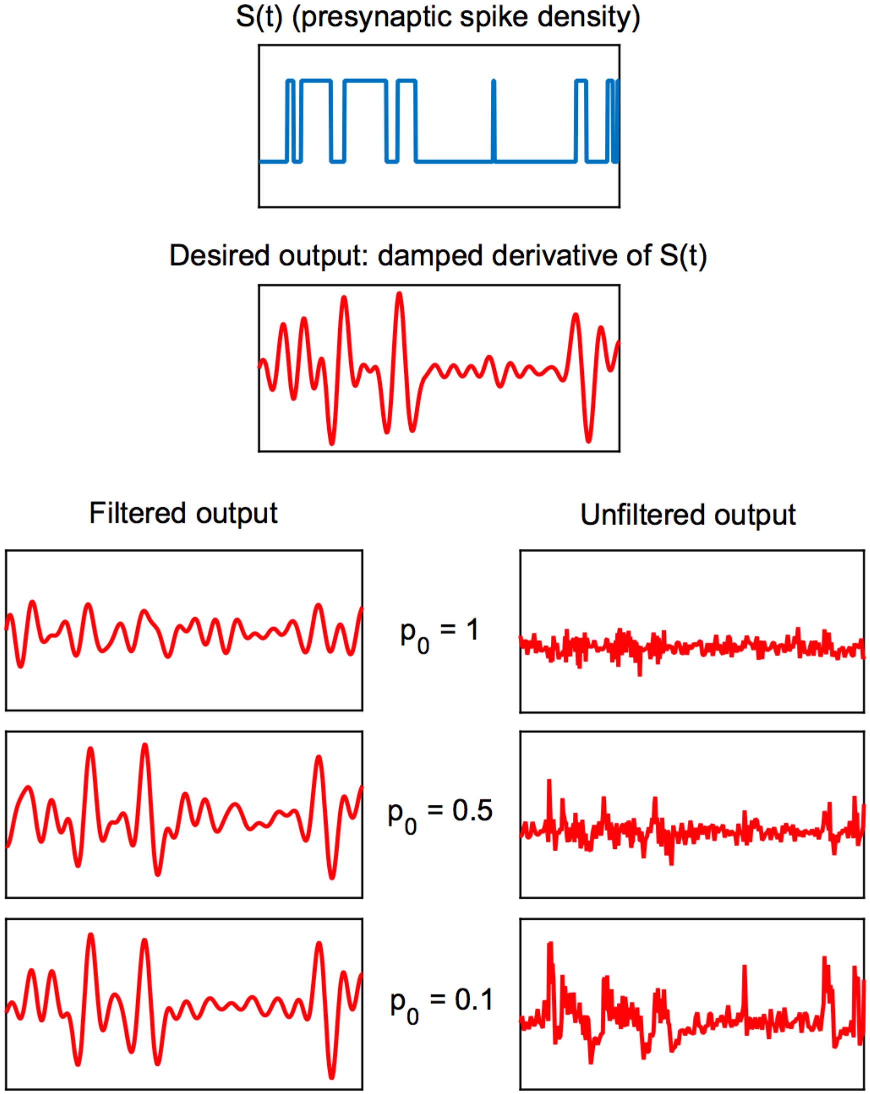
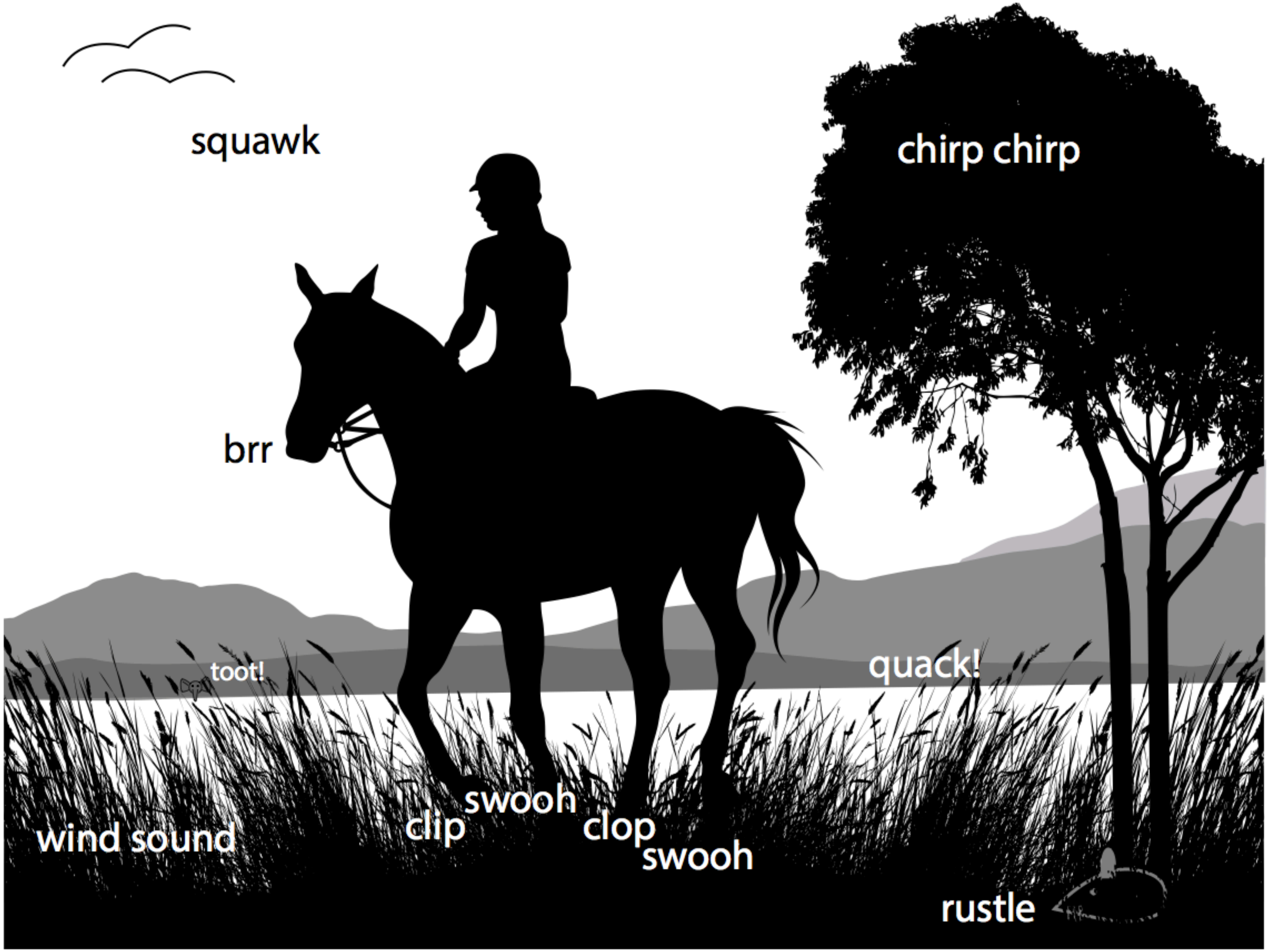


Fig. 3. Effect of probability of release per docked vesicle (p_0) on the synapse’s ability to estimate the damped derivative of the presynaptic spike density, plotted in the second frame. Layout of panels and parameter values are as in Fig. 2.

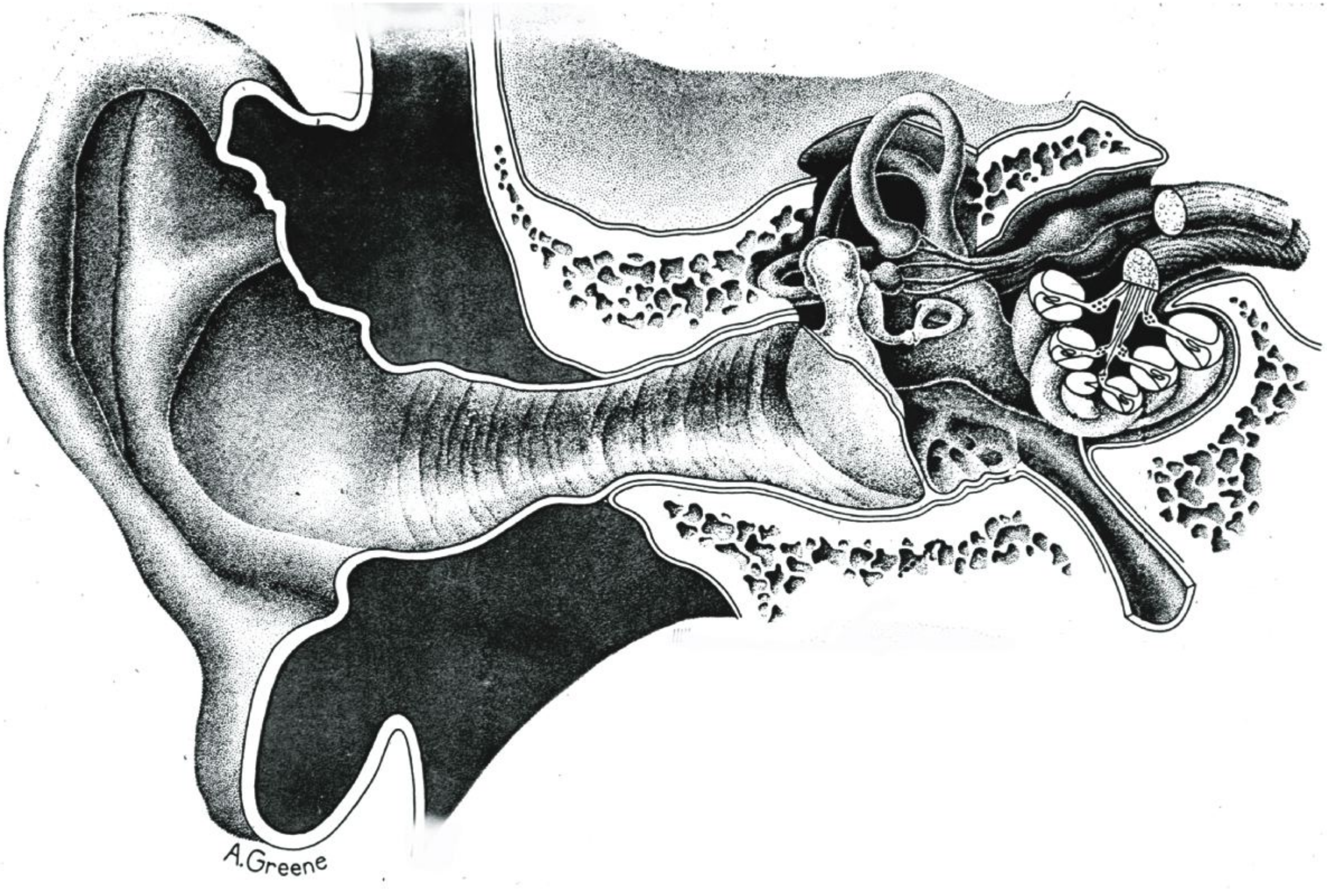
www.pnas.org/cgi/doi/10.1073/pnas.1513160112

Moving on: Sensory systems

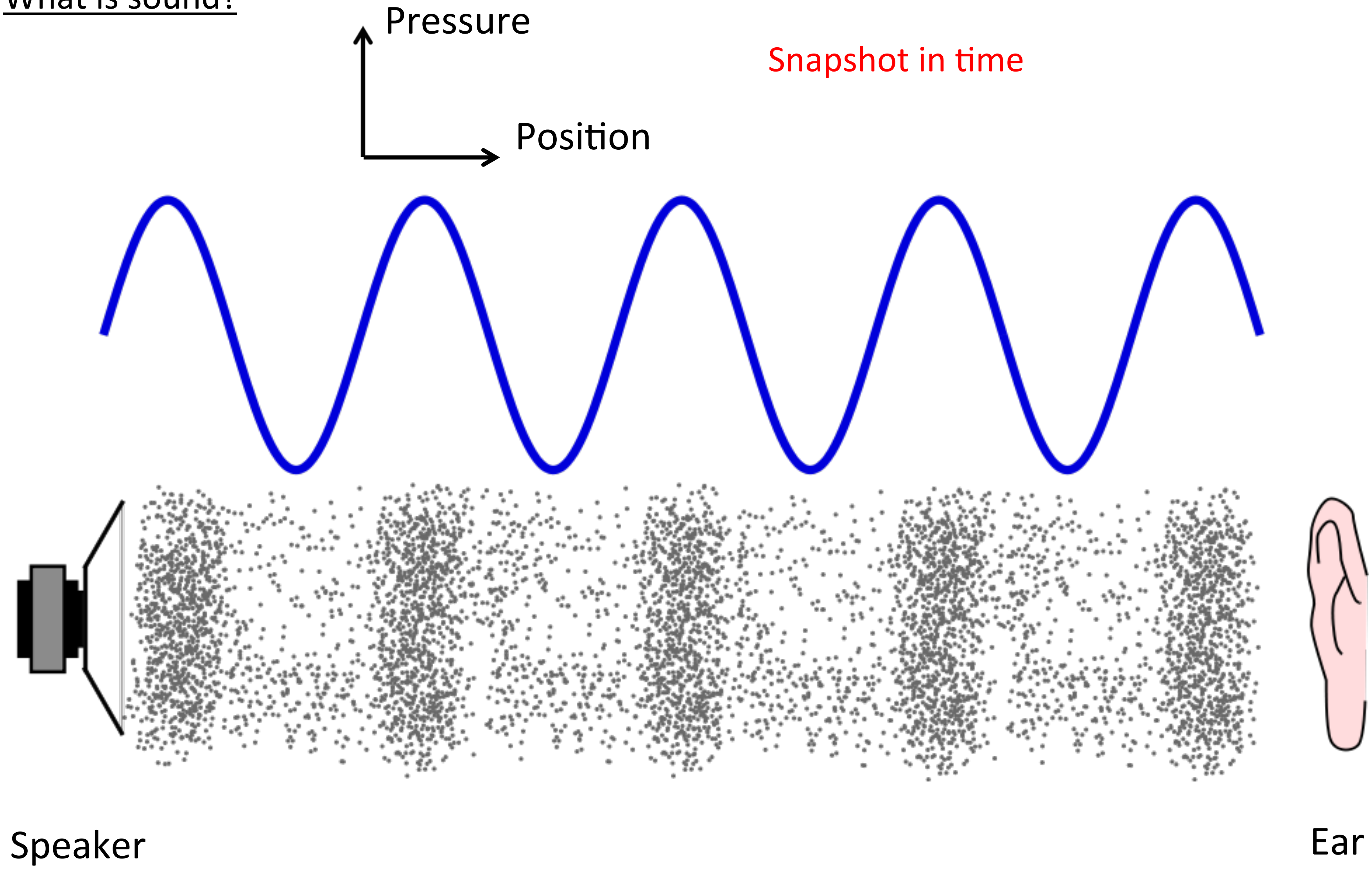


Pulkki & Karjalainen (2015)

Auditory periphery



What is sound?



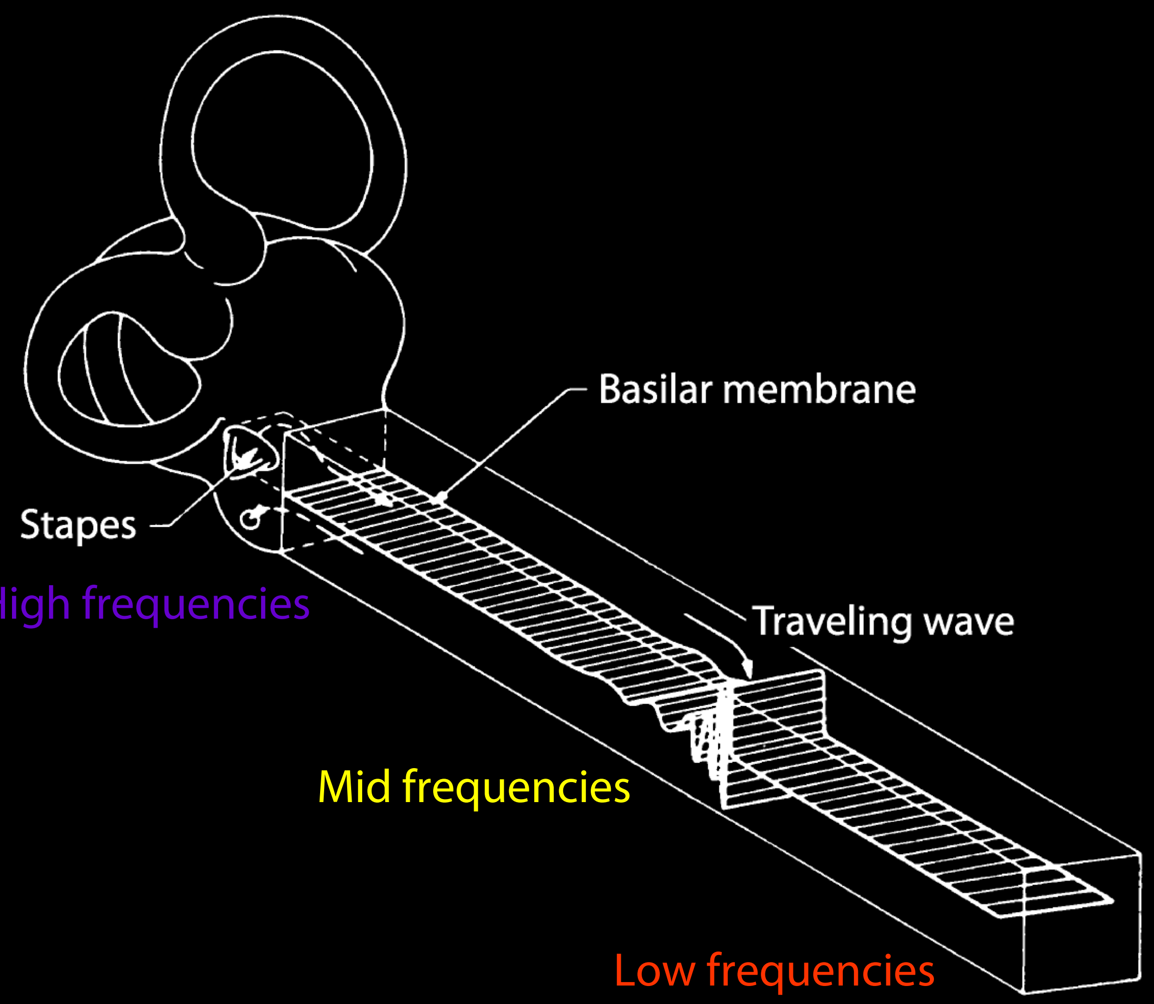
Snapshot in time

→ Note the periodic nature present....

Pulkki & Karjalainen (2015)

Tonotopicity

An Acoustic Prism



Zweig et al. (1976)