NEURONAL SIGNALING +THE BOLD EXPERIMENT

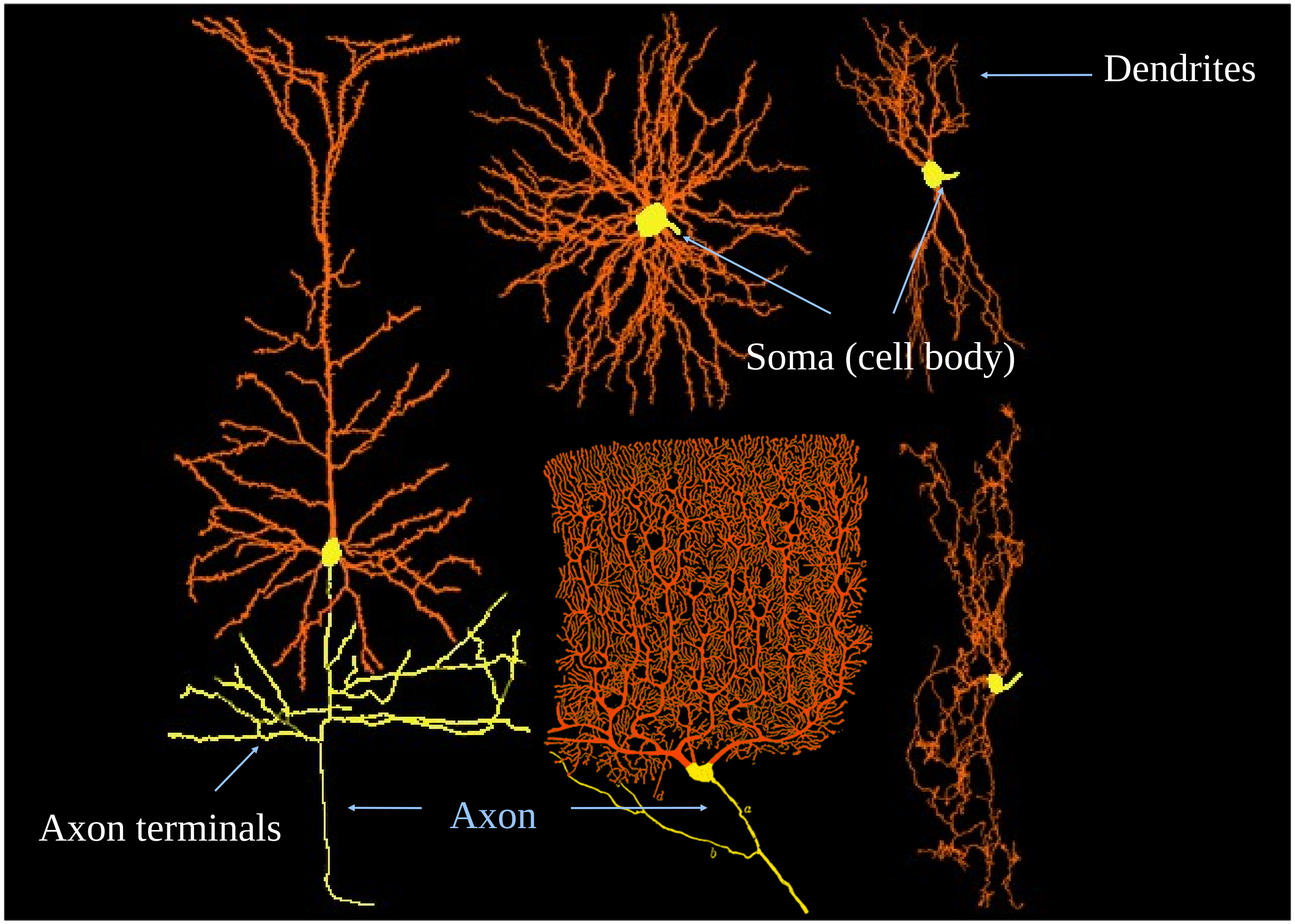
NeuroImaging Training Program

Mark Cohen, UCLA

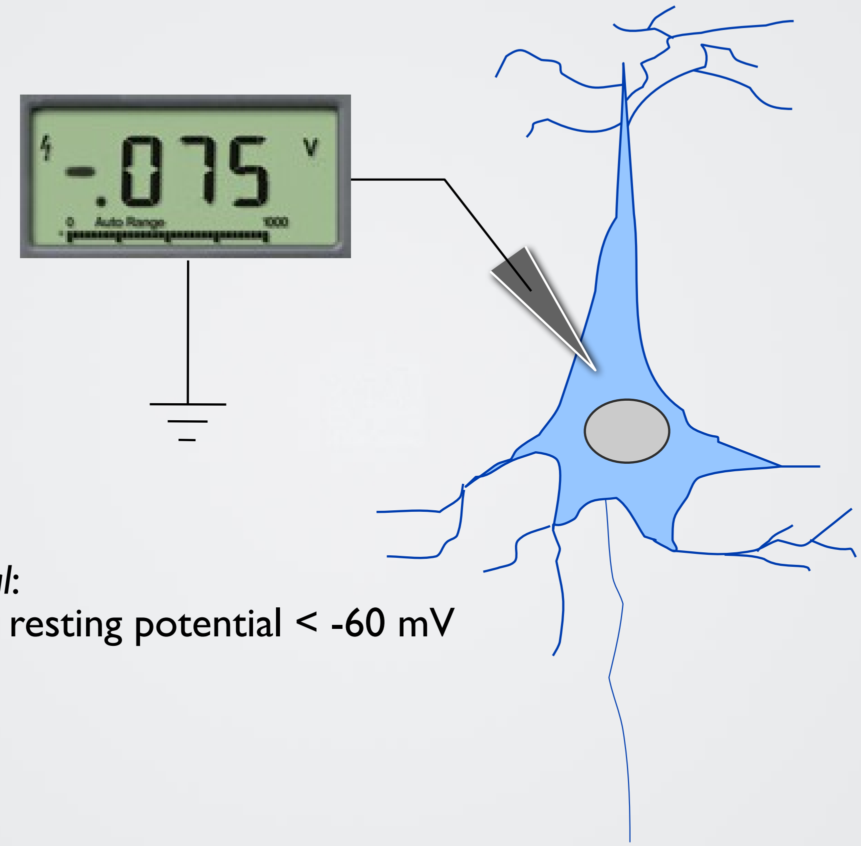
TOPICS

- anatomy of single neurons
- resting and action potentials
- transmission of signals
- chemical and electrical synapses
- information coding
- BOLD and unit activity
- EEG & SITE
- MR-visible effects

Types of Neurons

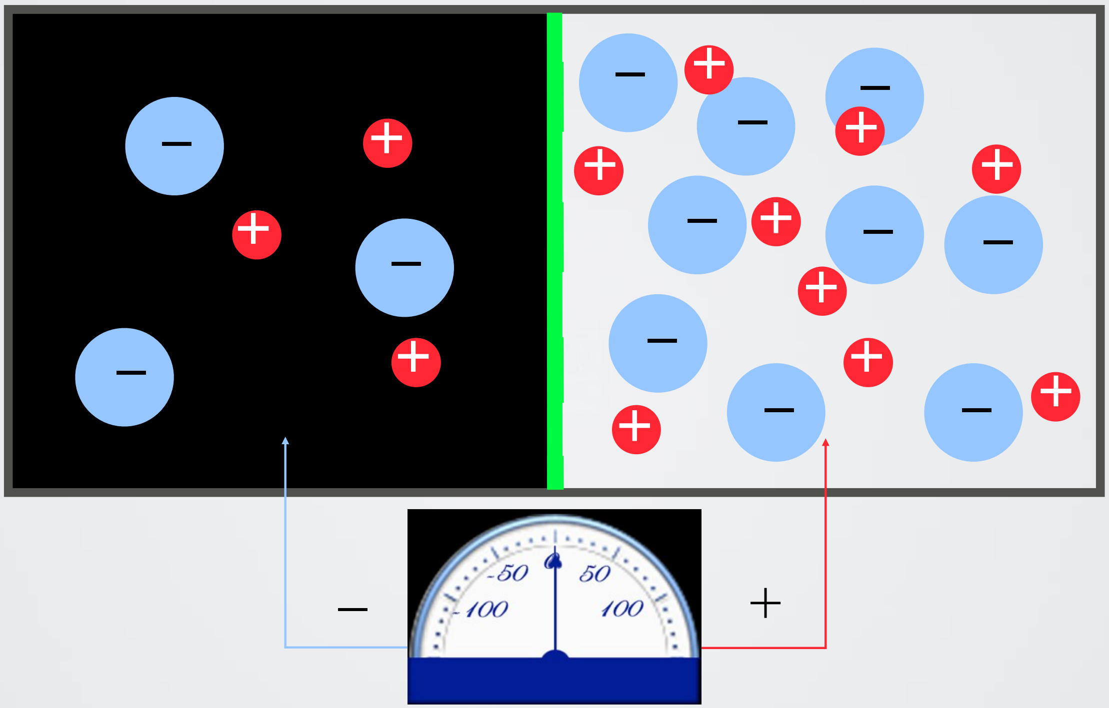


Resting Potential

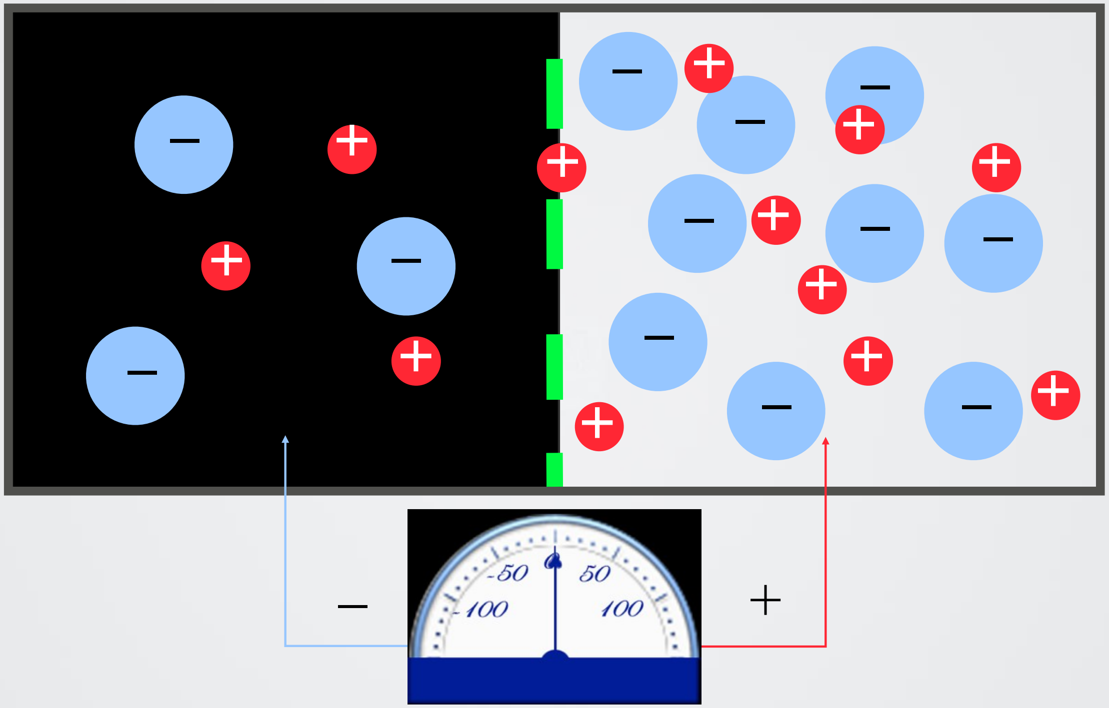


Typical:
-90 < resting potential < -60 mV

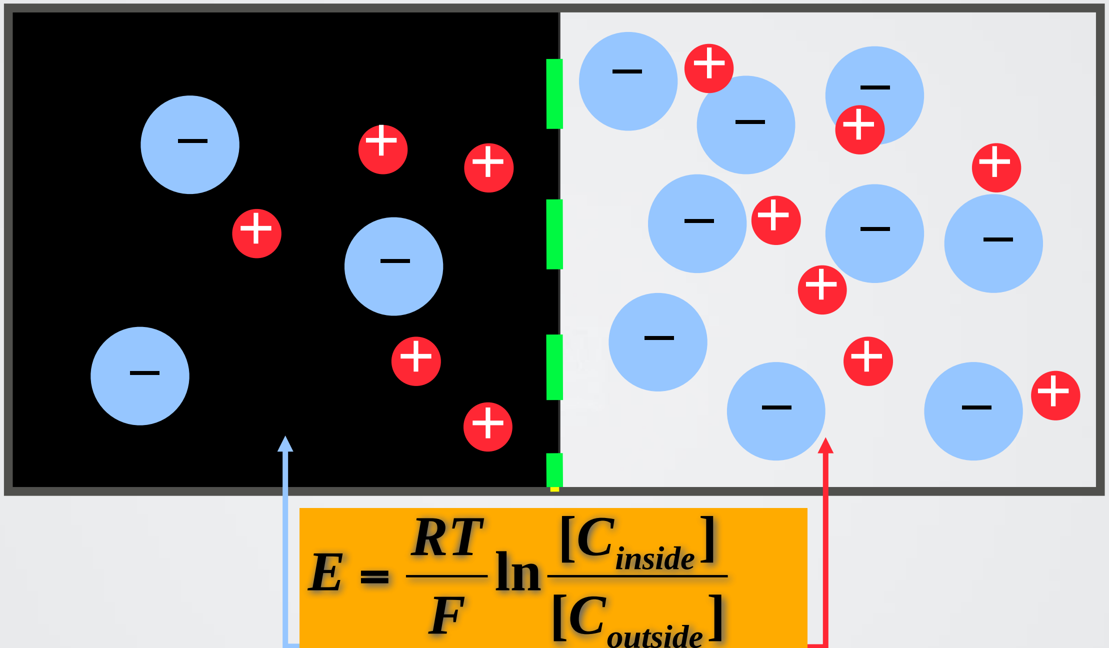
Development of the Membrane Potential



Development of the Membrane Potential



Development of the Membrane Potential



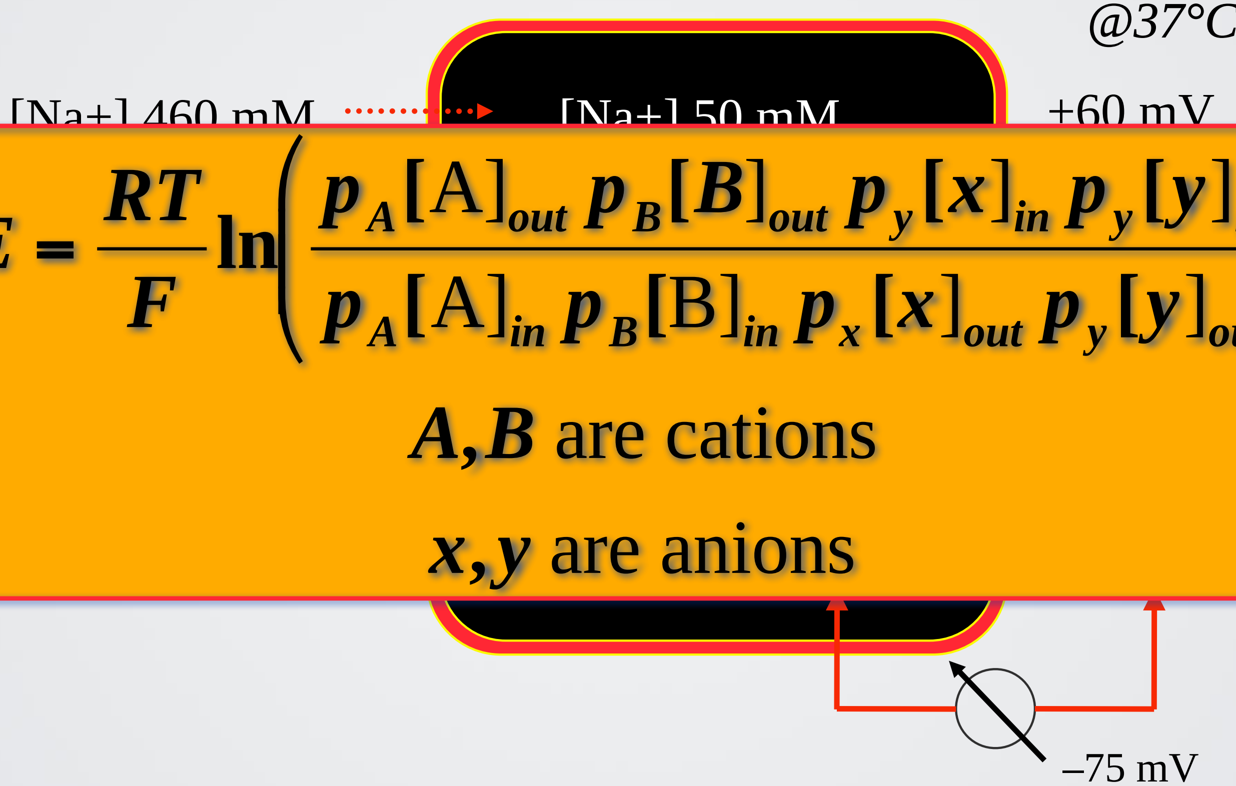
Nernst Potential:

$$E = \frac{RT}{F} \ln \frac{[C_{inside}]}{[C_{outside}]}$$

$$\approx 27\text{mV} \ \ln \frac{[C_{inside}]}{[C_{outside}]}$$

Observed Ion Concentrations

Nernst Potential
@37°C

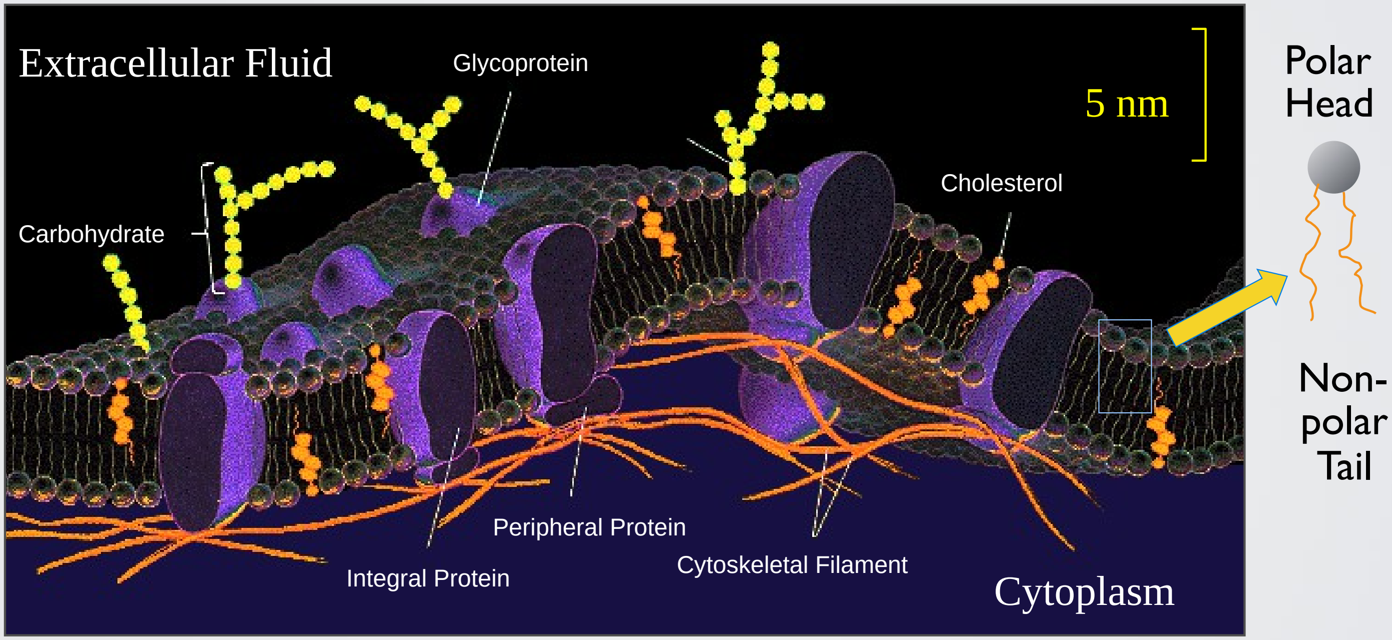


$$E = \frac{RT}{F}\ln\left(\frac{p_A[\mathrm{A}]_{out}\, p_B[B]_{out}\, p_y[x]_{in}\, p_y[y]_{in}}{p_A[\mathrm{A}]_{in}\, p_B[\mathrm{B}]_{in}\, p_x[x]_{out}\, p_y[y]_{out}}\right)$$

A,B **are cations**

x,y **are anions**

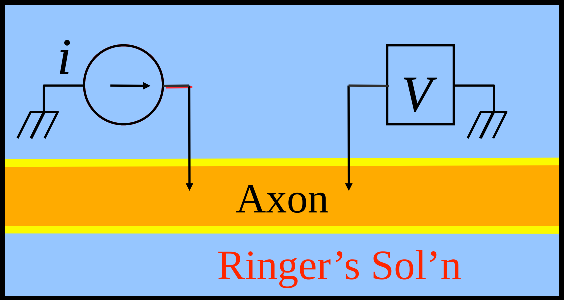
STRUCTURE OF THE CELL MEMBRANE

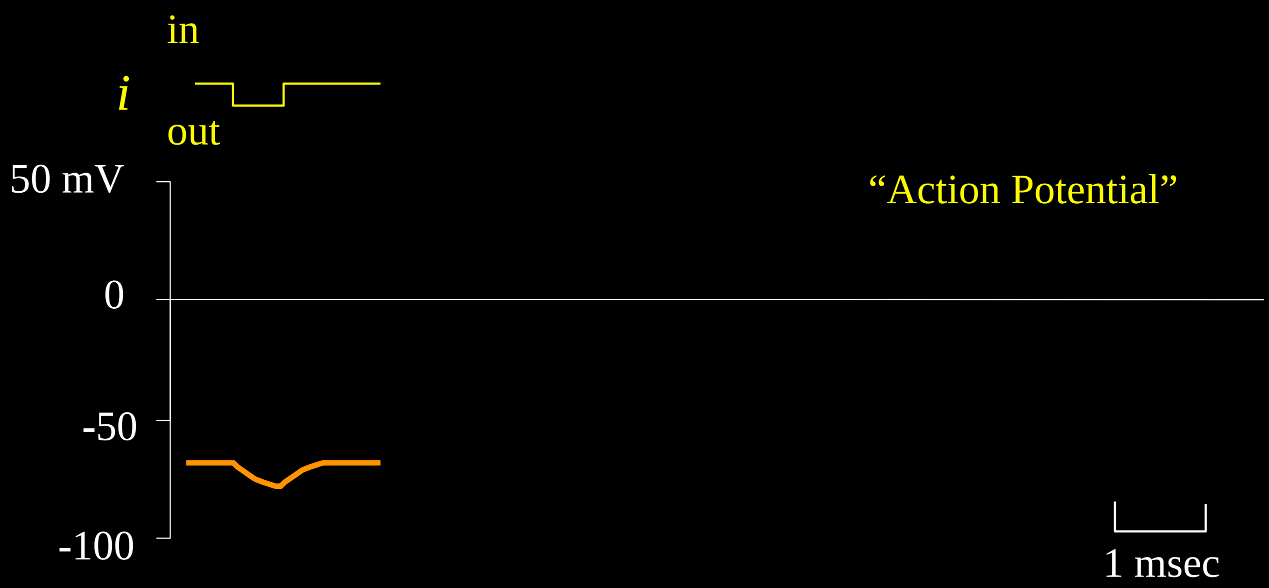


Note: E-field is >10 MV/m!

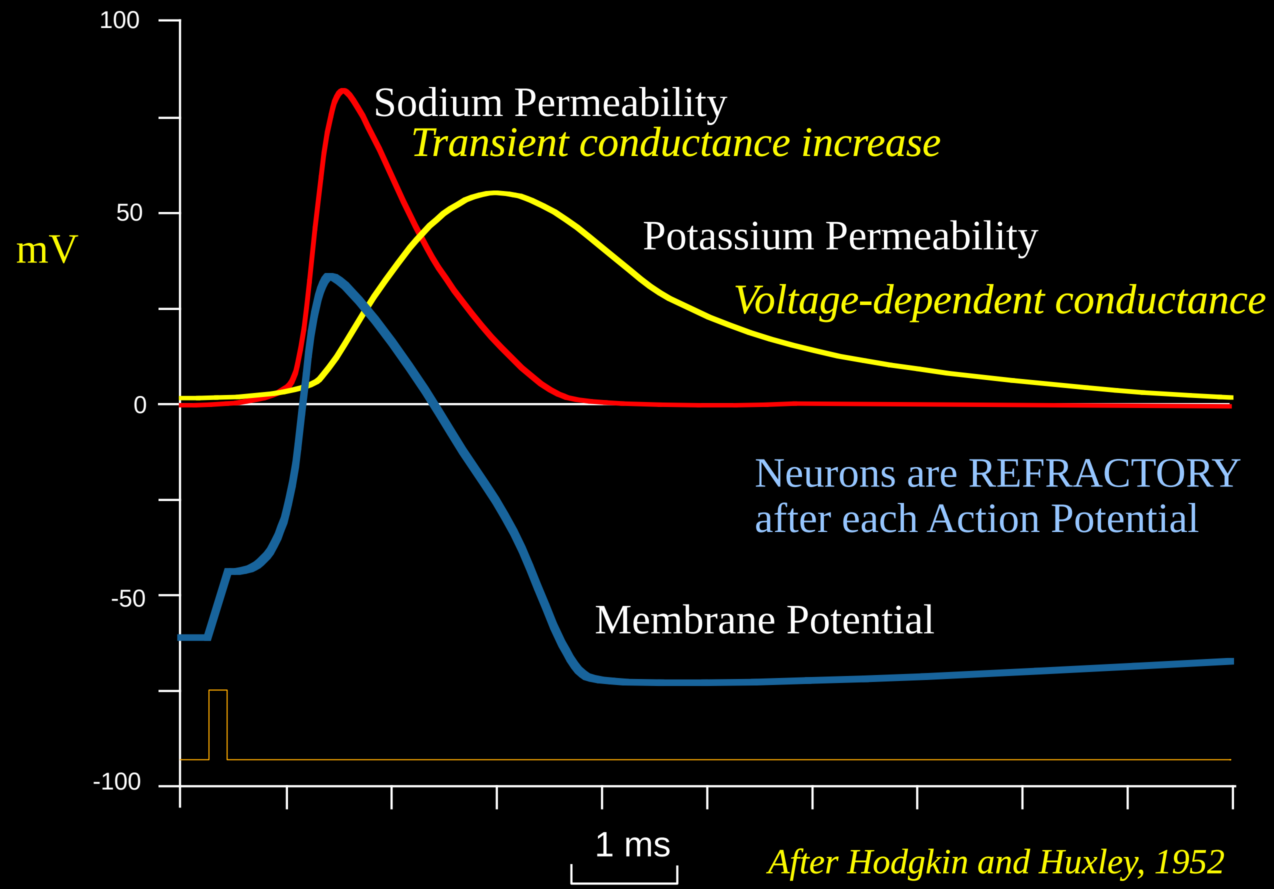
Taken from *Human Biology* by Daniel Chiras

Electrical Behavior of Neurons



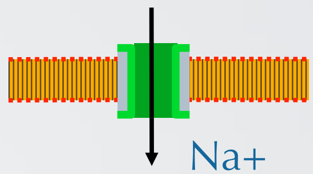


Current and Voltage



After Hodgkin and Huxley, 1952

Sodium Leakage with Action Potentials

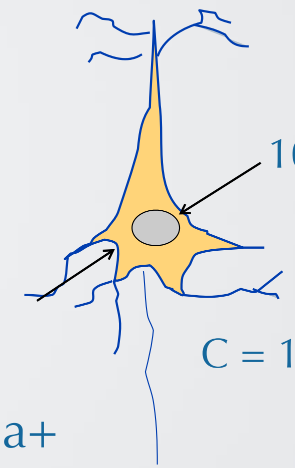


Cell Volume = 9 x 10 $^{-13}$ liters,
about half of which is liquid.

At 40 mM Sodium:
= 4.0 x 10^{-14} Moles Sodium/cell

With Each Action Potential:

$\Delta V = 0.13$ Volt
Q = CV = 1.3 x 10^{-7} Coulombs /cm^2
= 1.4 x 10^{-12} Moles/cm^2



Surface Area = 2.8 x 10^{-5} cm^2

Each AP passes 3.7 x 10^{-17} Moles of Na+

[Na+] is increased by 0.1% with each Action Potential!

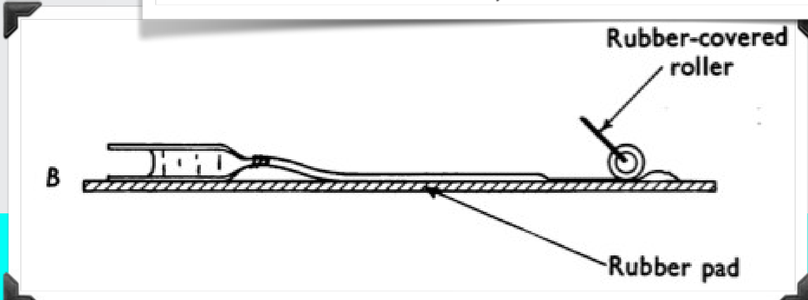
Cohen. IEEE, 2009

PASSIVE FIRING OF ACTION POTENTIALS

J. Physiol. (1962), **164**, *pp.* 330–354
With 5 plates and 12 text-figures
Printed in Great Britain

REPLACEMENT OF THE AXOPLASM OF GIANT NERVE FIBRES WITH ARTIFICIAL SOLUTIONS

BY P. F. BAKER, A. L. HODGKIN AND T. I. SHAW

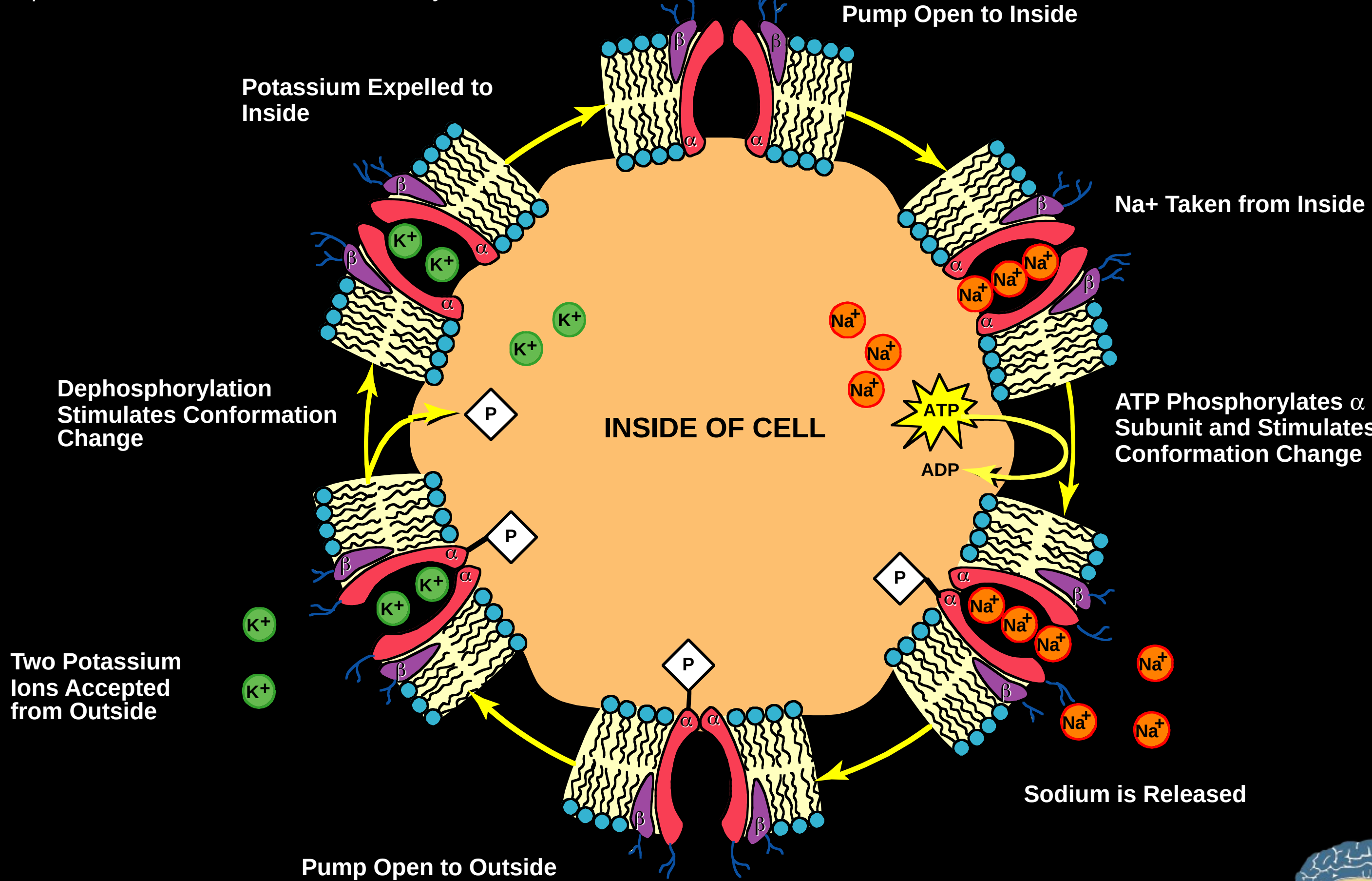


Row	Axon	Diameter (μ)	Temperature (° C)	Condition	Internal solution	Period of stimulation (min)	Main stimulation frequency (shocks/sec)	Number of impulses
1	59	770	15	Fully inflated	K- isethionate	120	50	$3{\cdot}6 \times 10^5$
2	101	720	21	40 % inflated	K_2SO_4	80	50	$2{\cdot}3 \times 10^5$
3	114	880	18	60 % inflated	K_2SO_4	120	50	$4{\cdot}1 \times 10^5$
4	115	810	18	Intact	Axoplasm	107	50	$3{\cdot}9 \times 10^5$
5	118	750	19·5	Intact	Axoplasm	186	125	$1{\cdot}1 \times 10^6$

 mscohen@g.ucla.edu

Sodium Potassium Pump

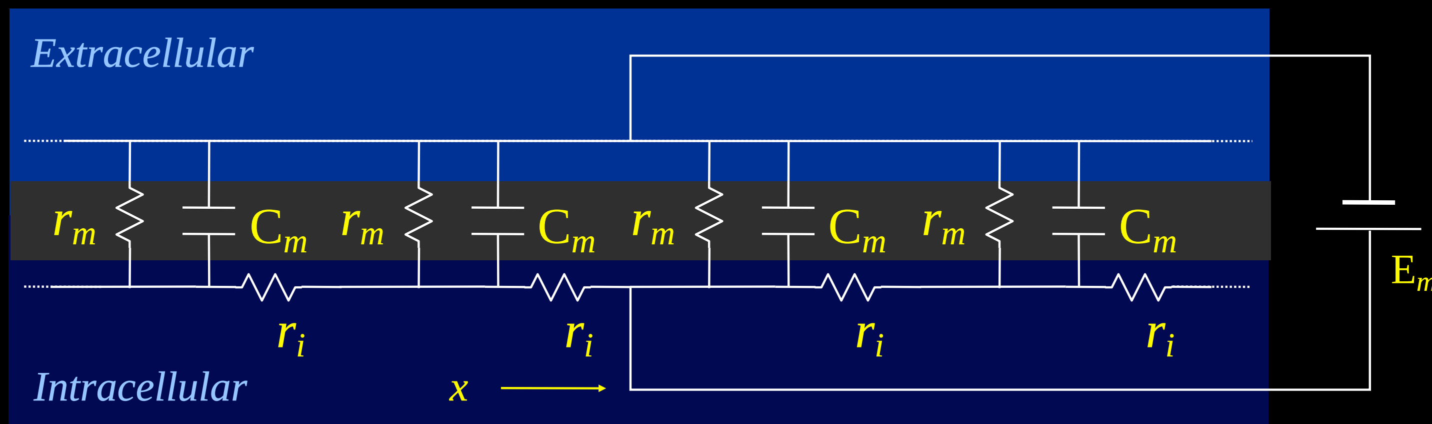
After Matthews and van Holde: Biochemistry 2/e

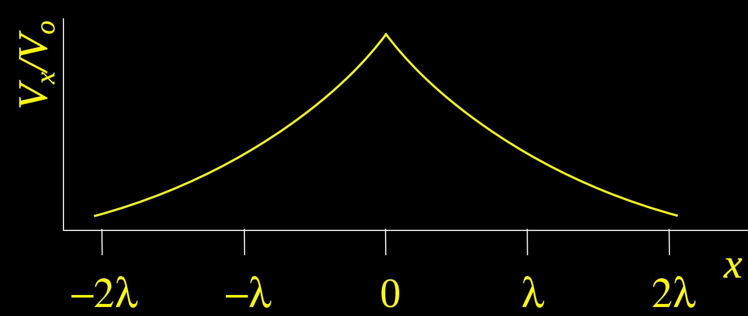


www.brainmapping.org

Center for Cognitive Neuroscience

Cable Properties



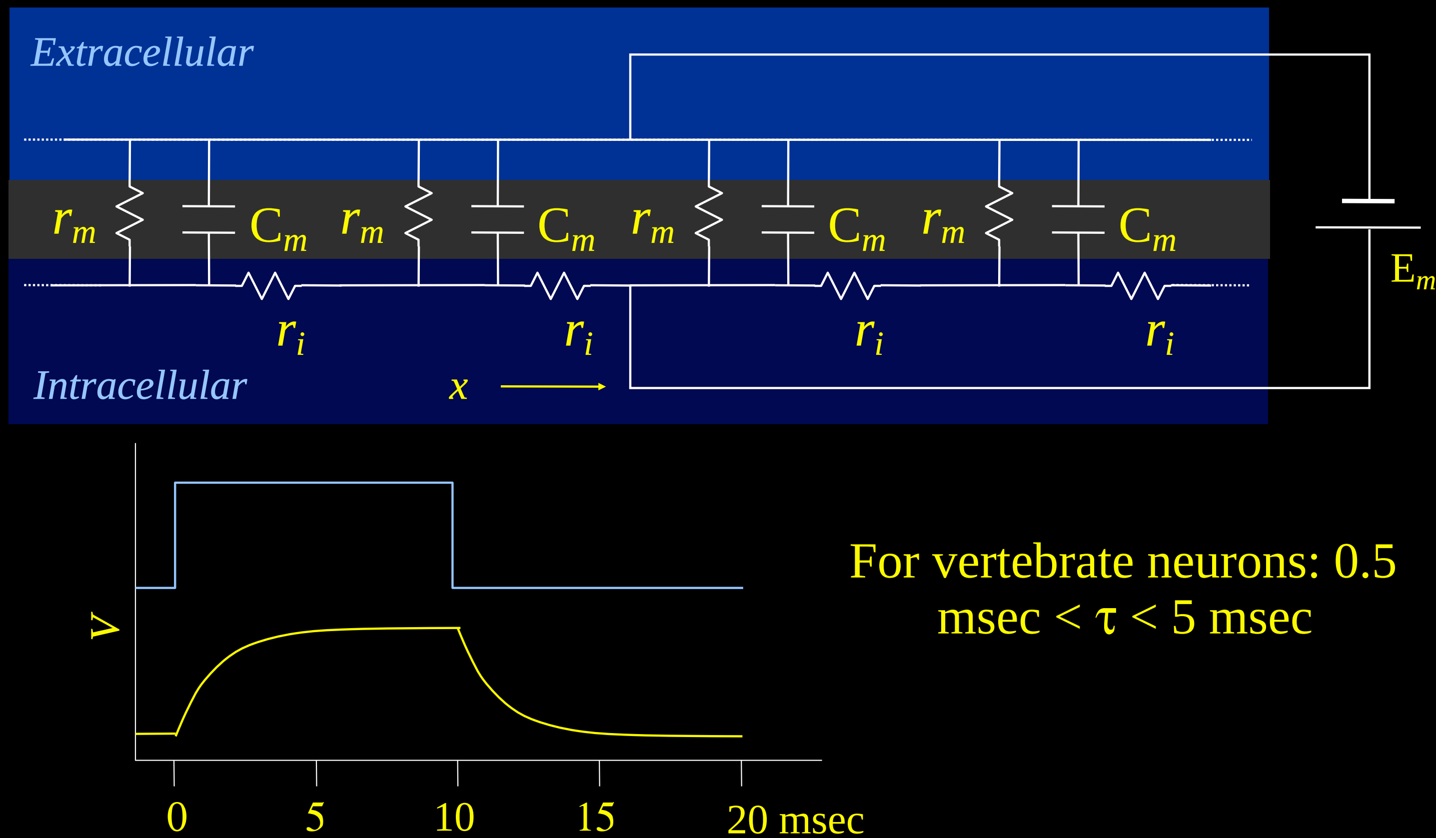


$$\frac{V_x}{V_0} = e^{-x/\lambda}$$

$$\lambda = \sqrt{r_m / r_i}$$

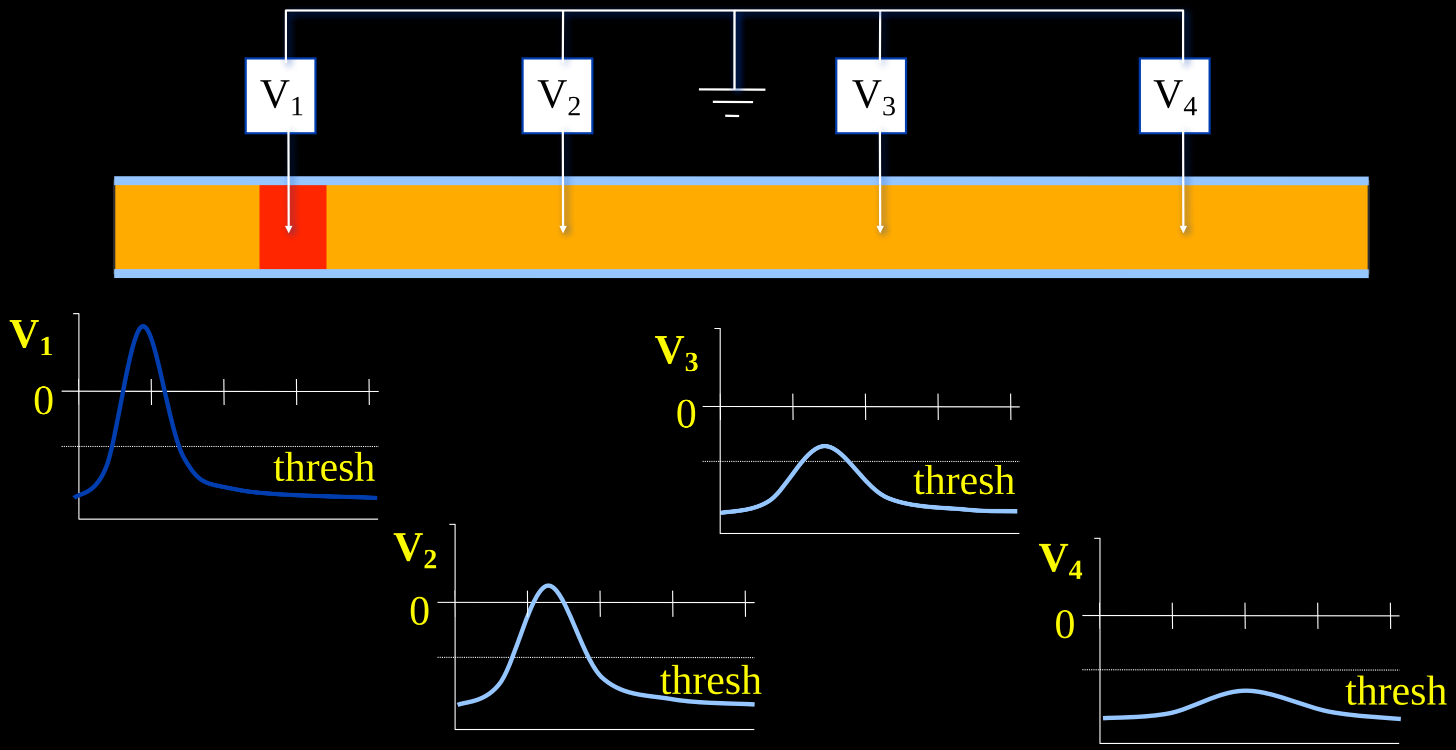
For vertebrate neurons: µm < λ < mm

Cable Properties



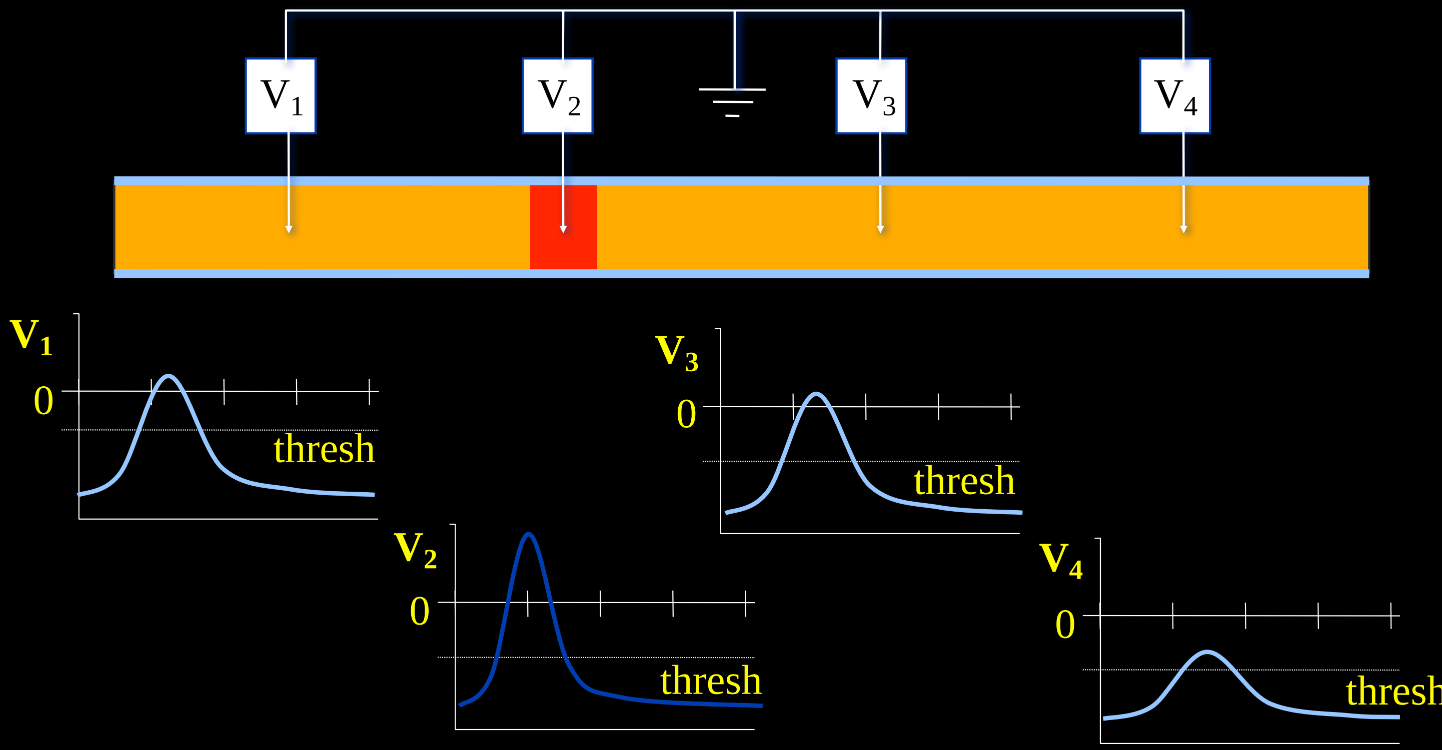
For vertebrate neurons: $0.5\ \text{msec} < \tau < 5\ \text{msec}$

Propagation of the Action Potential



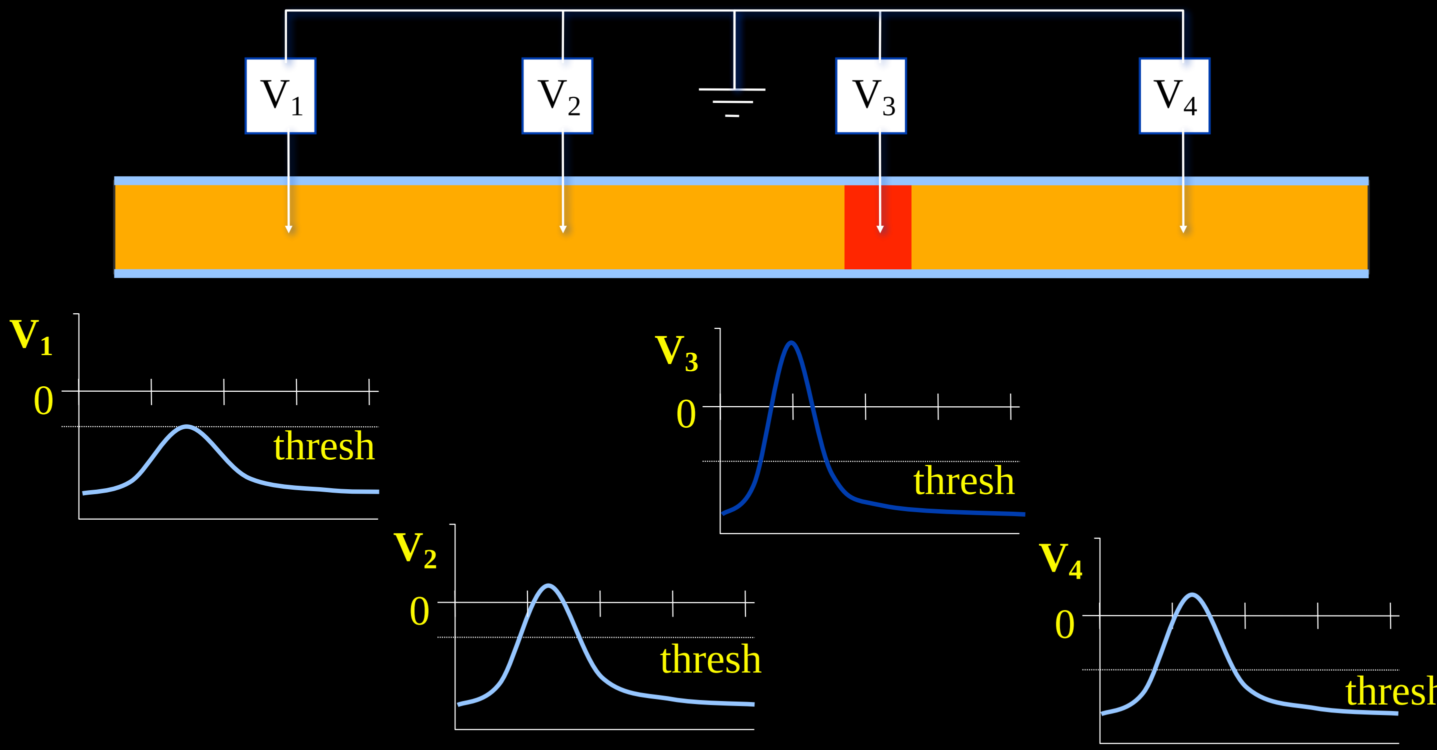
Resulting Velocity ~1-3m/sec

Propagation of the Action Potential



Resulting Velocity ~1-3m/sec

Propagation of the Action Potential



Resulting Velocity ~1-3m/sec

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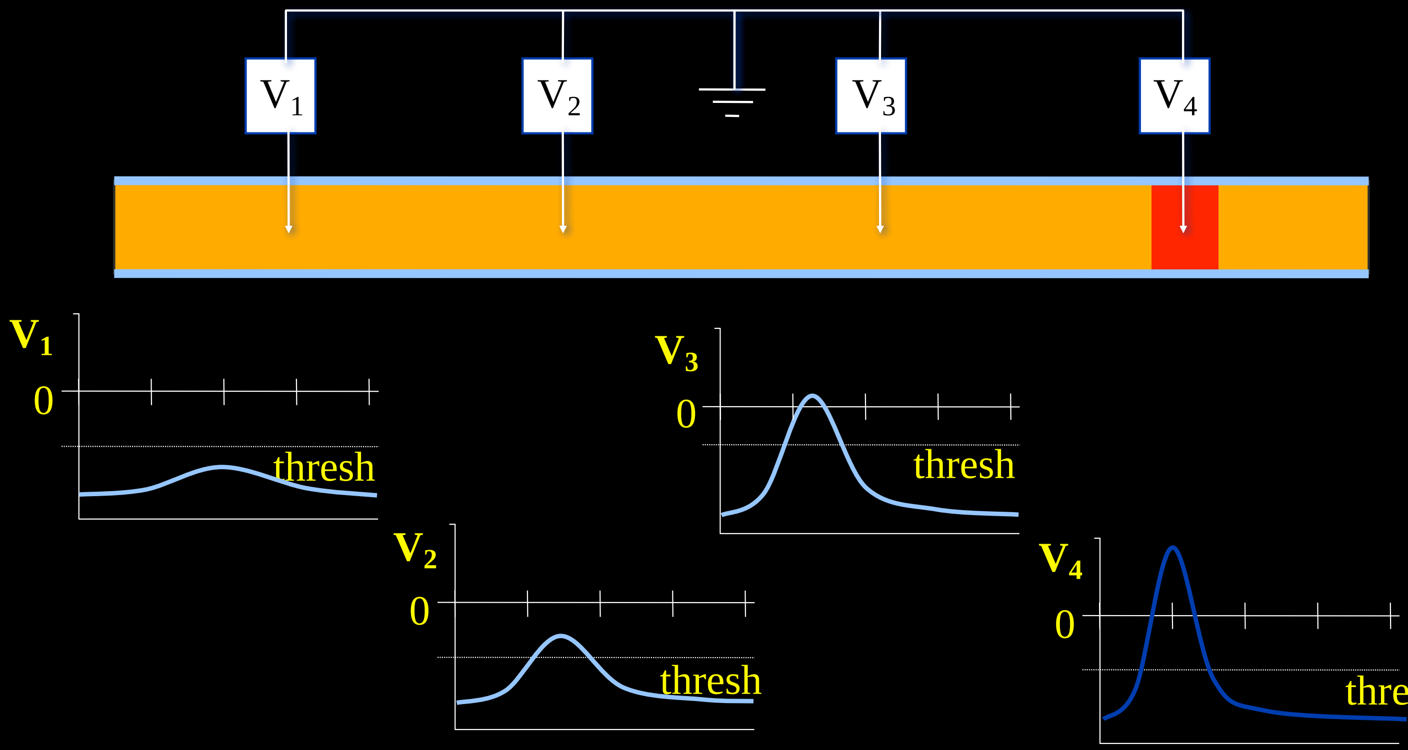

Resulting Velocity ~1-3m/sec

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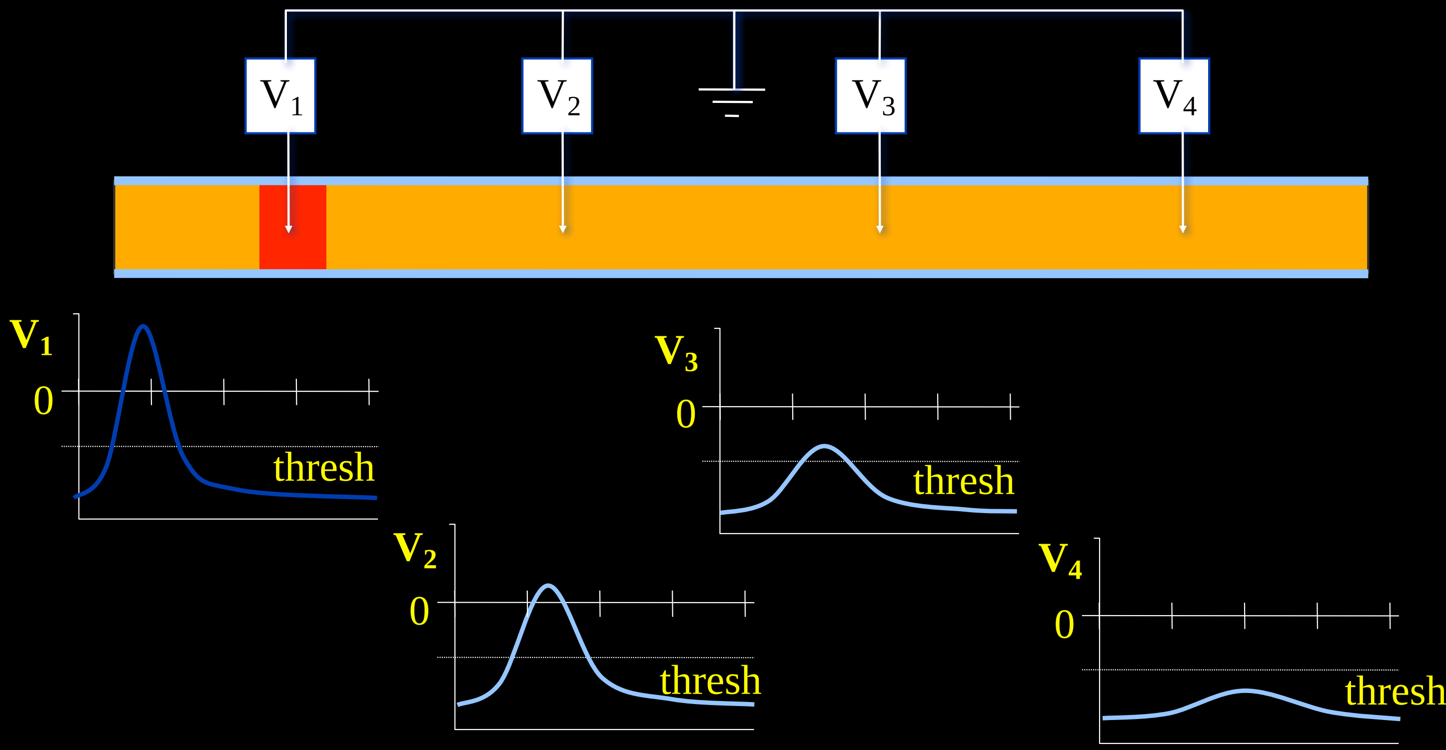

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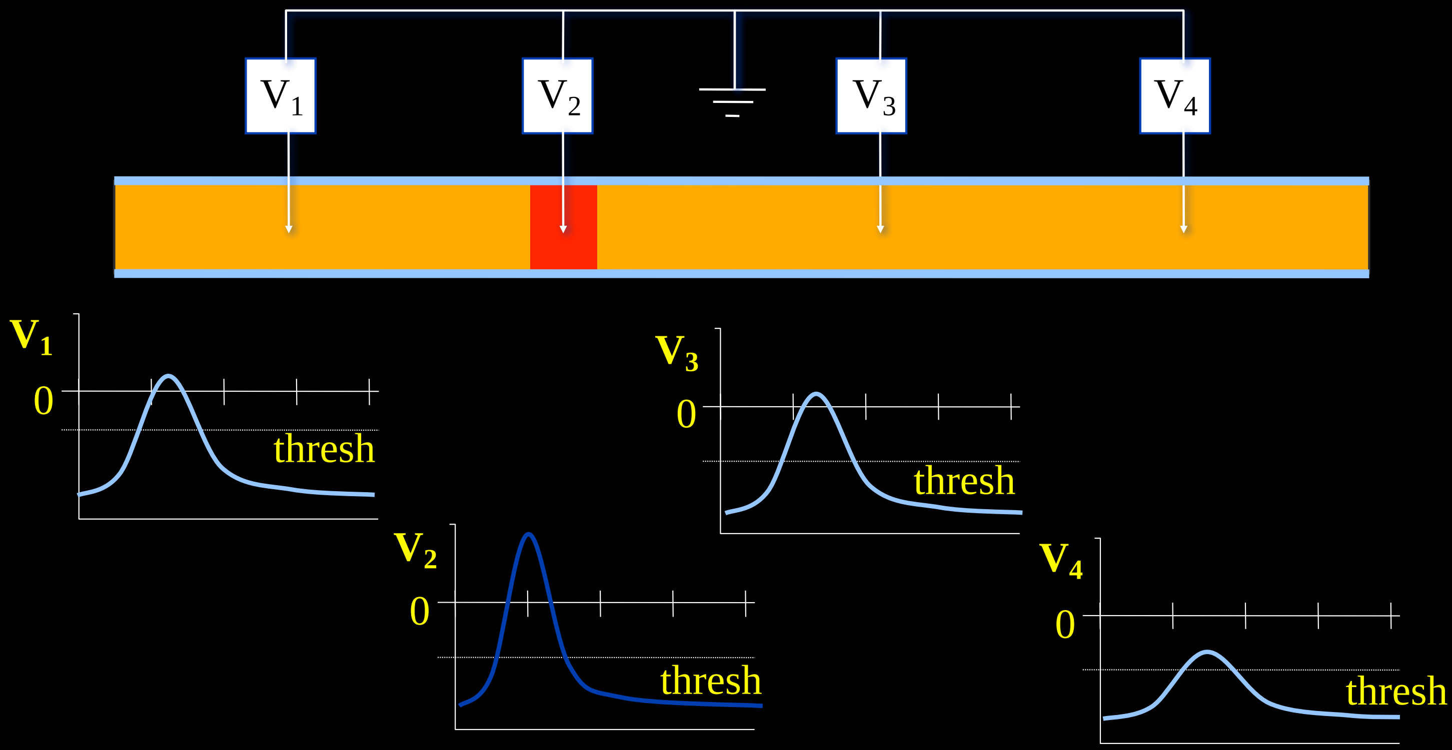
Propagation of the Action Potential



Resulting Velocity ~1-3m/sec

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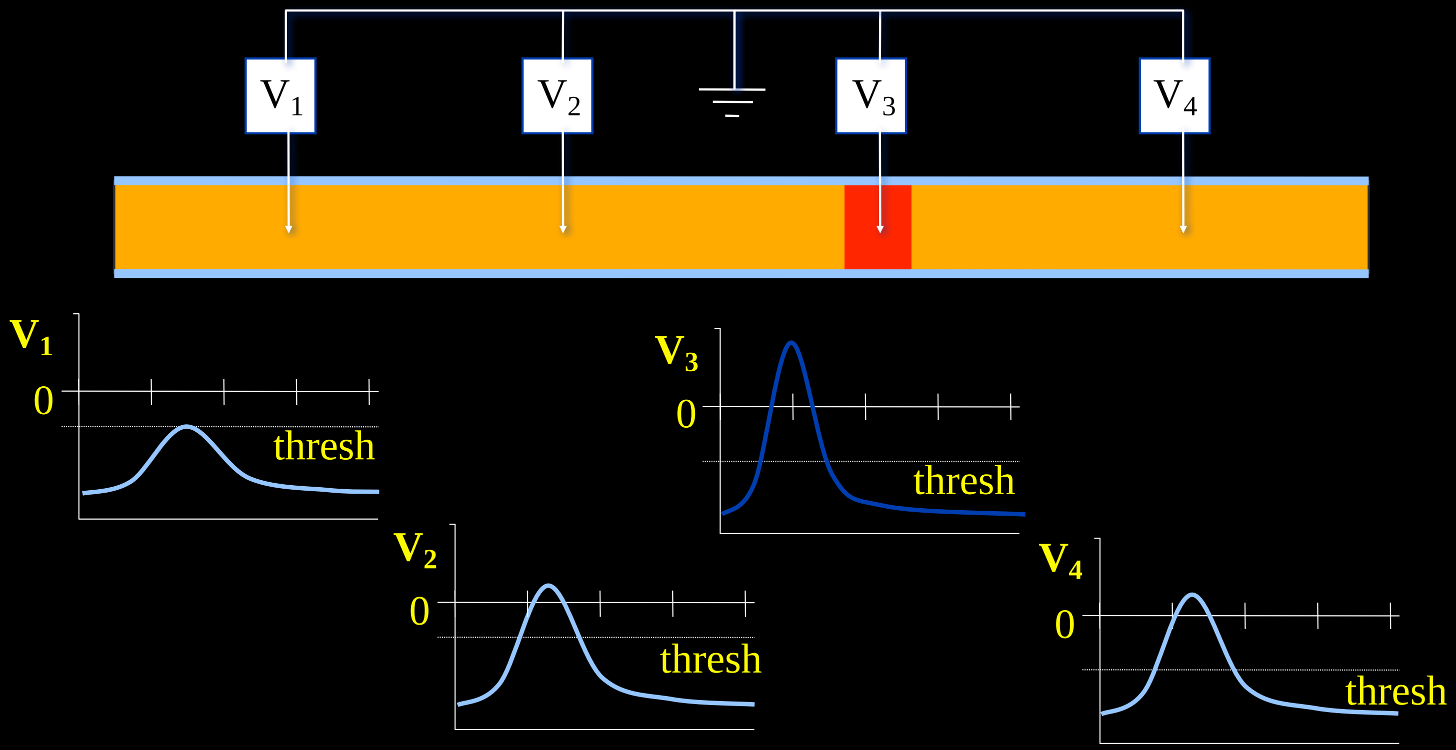
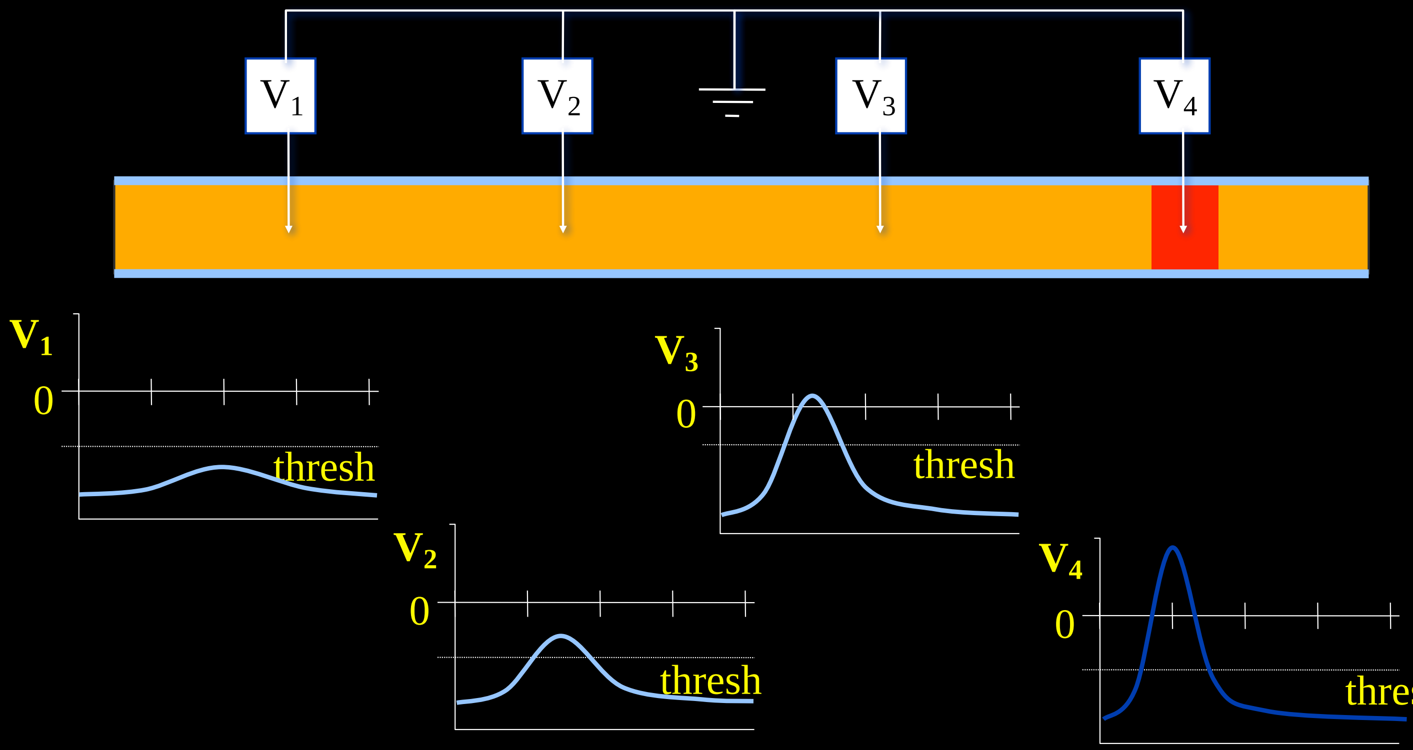


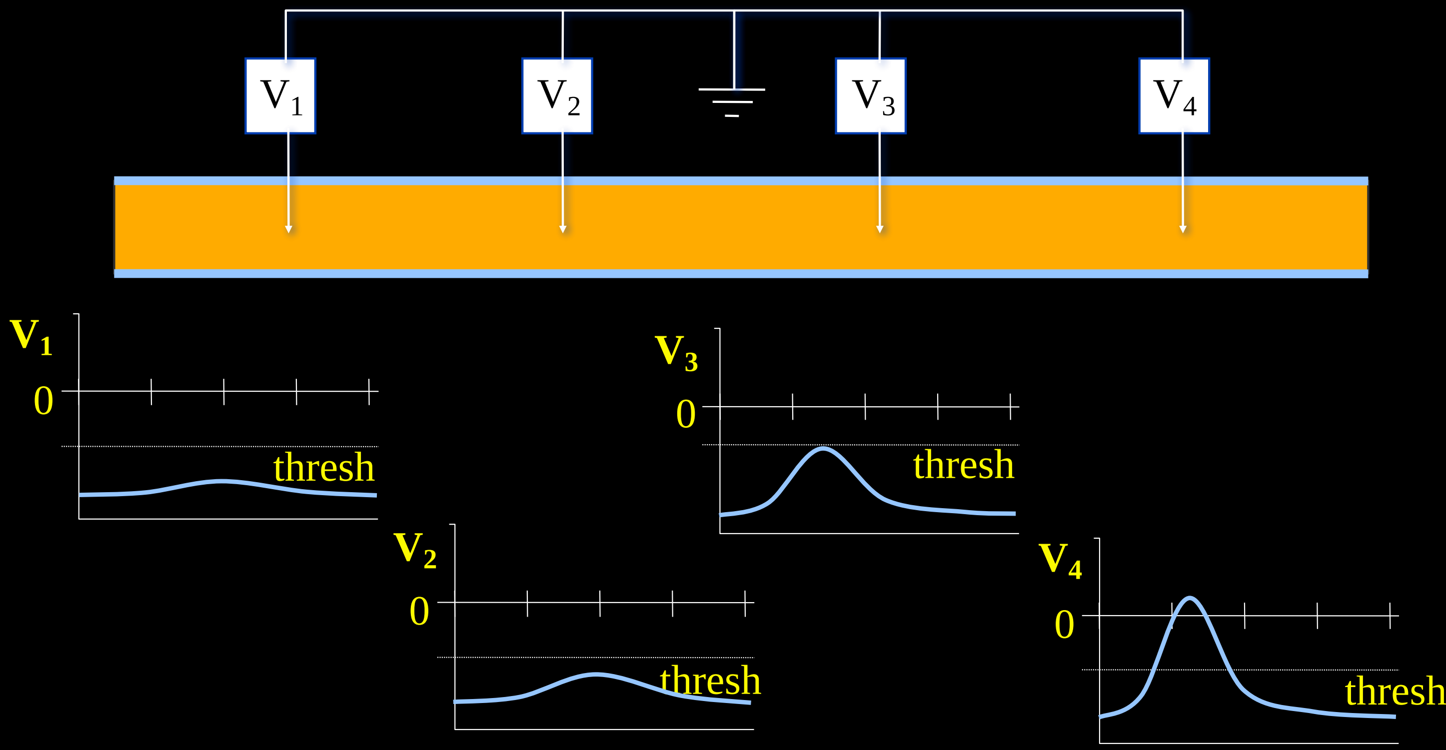
Resulting Velocity ~1-3m/sec

Propagation of the Action Potential



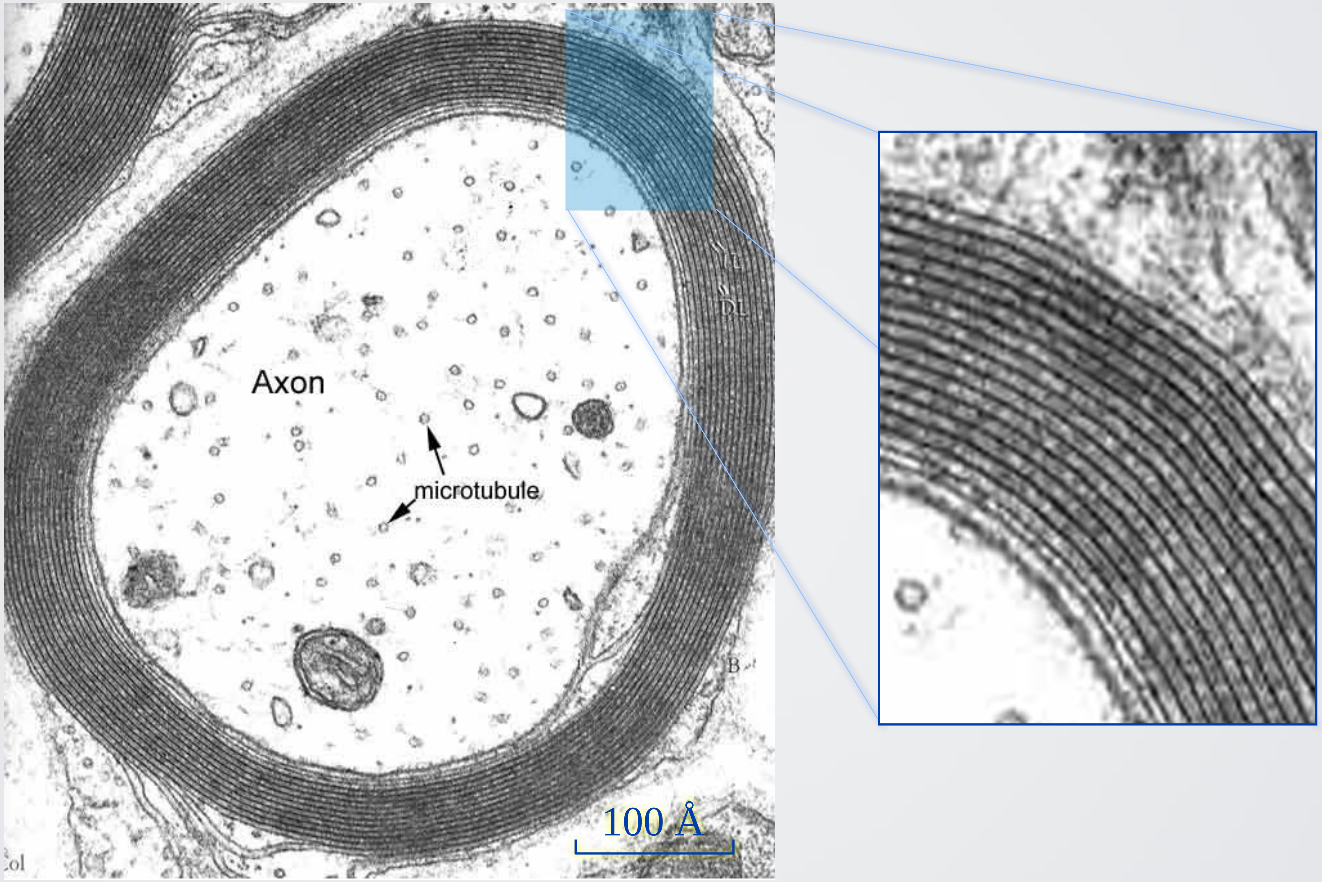
Resulting Velocity ~1-3m/sec

Propagation of the Action Potential

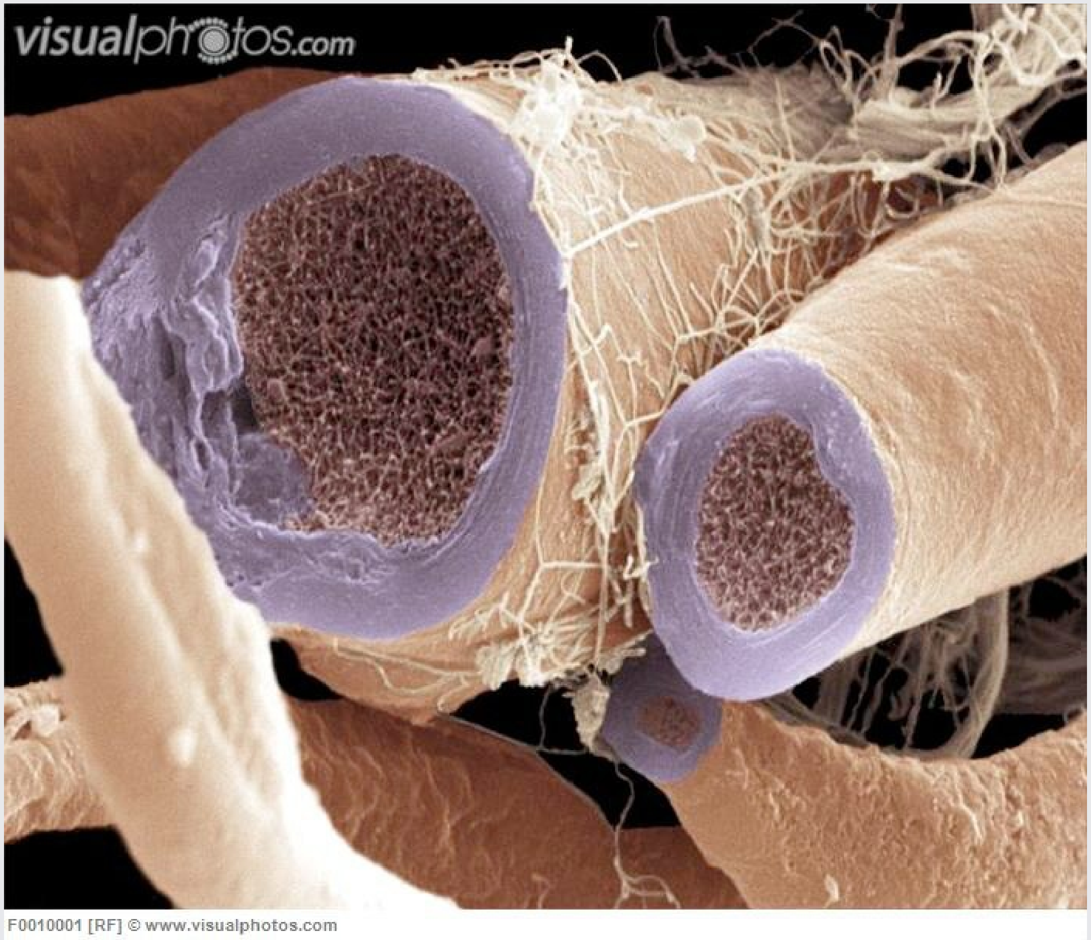


Resulting Velocity ~1-3m/sec

Myelin Sheath



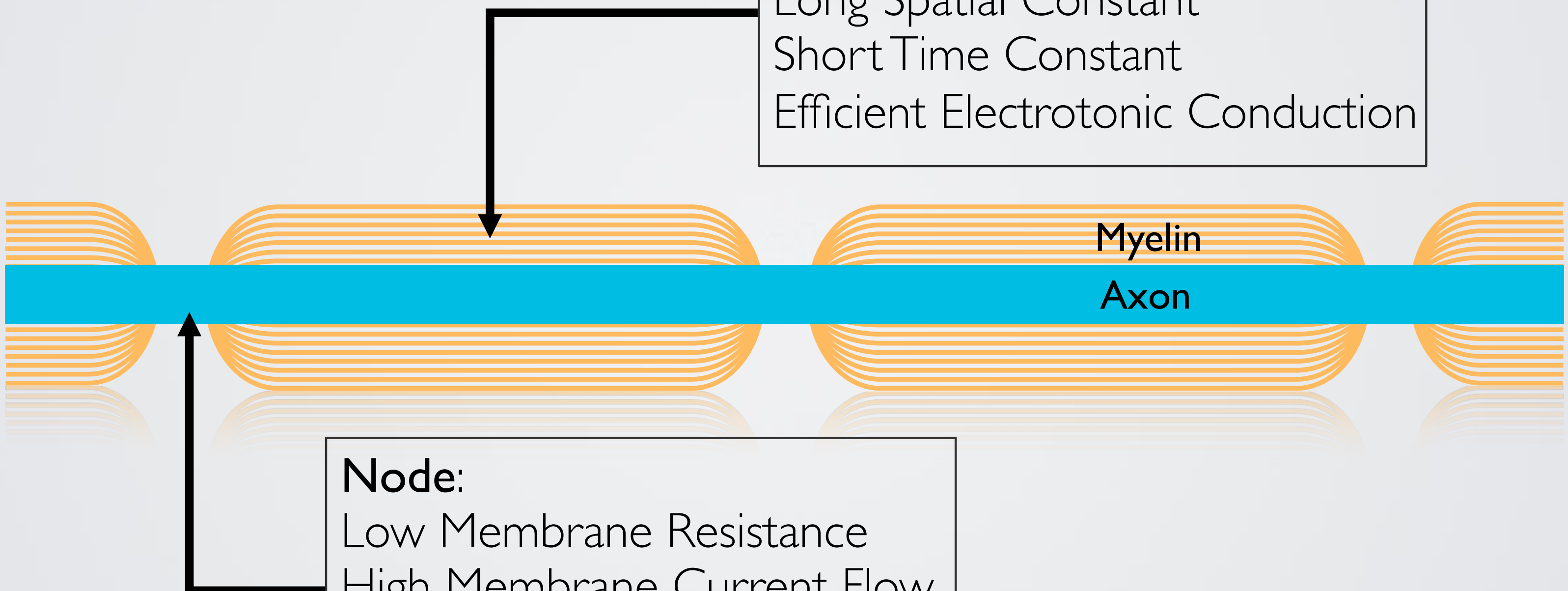
MYELIN SHEATH



Nodes of Ranvier

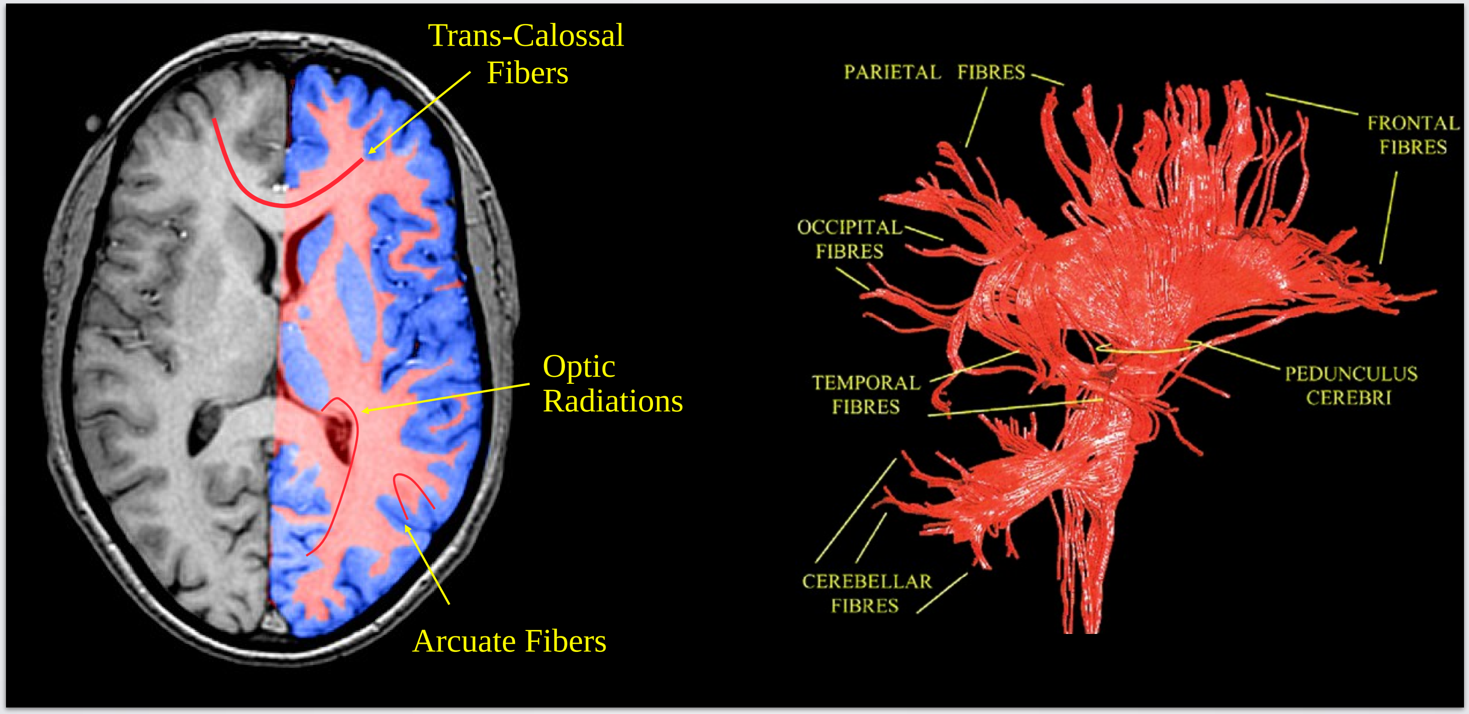
SALTATORY CONDUCTION

Internode:
High Membrane Resistance
Long Spatial Constant
Short Time Constant
Efficient Electrotonic Conduction



Node:
Low Membrane Resistance
High Membrane Current Flow
Fires Action Potential
Action Potential Regeneration

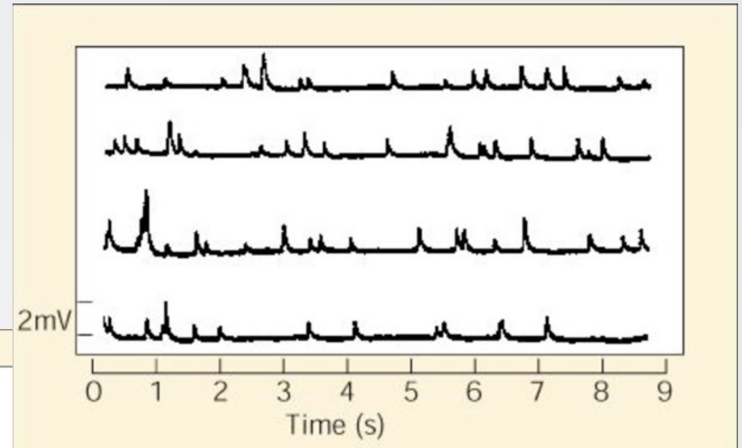
White and Gray Matter

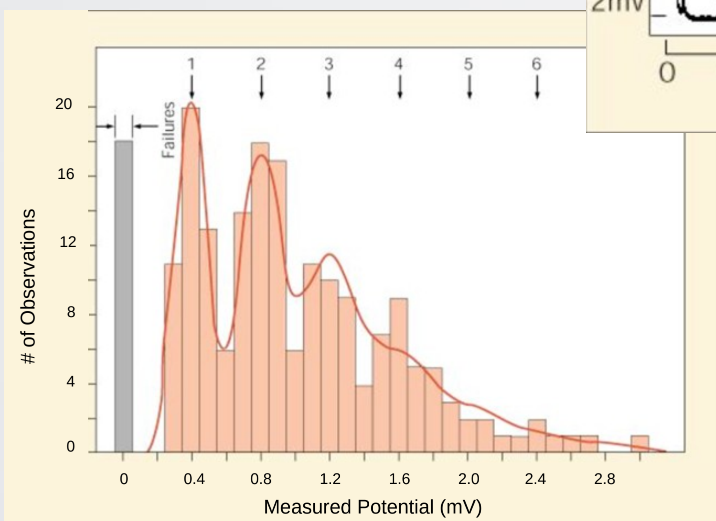


After: Catani, et al., NeuroImage **17**:77, 2002

EPSP'S: *EXCITATORY POST-SYNAPTIC POTENTIALS*

Muscle end plate potentials
Recorded in low Ca^{2+} / high Mg^{2+}

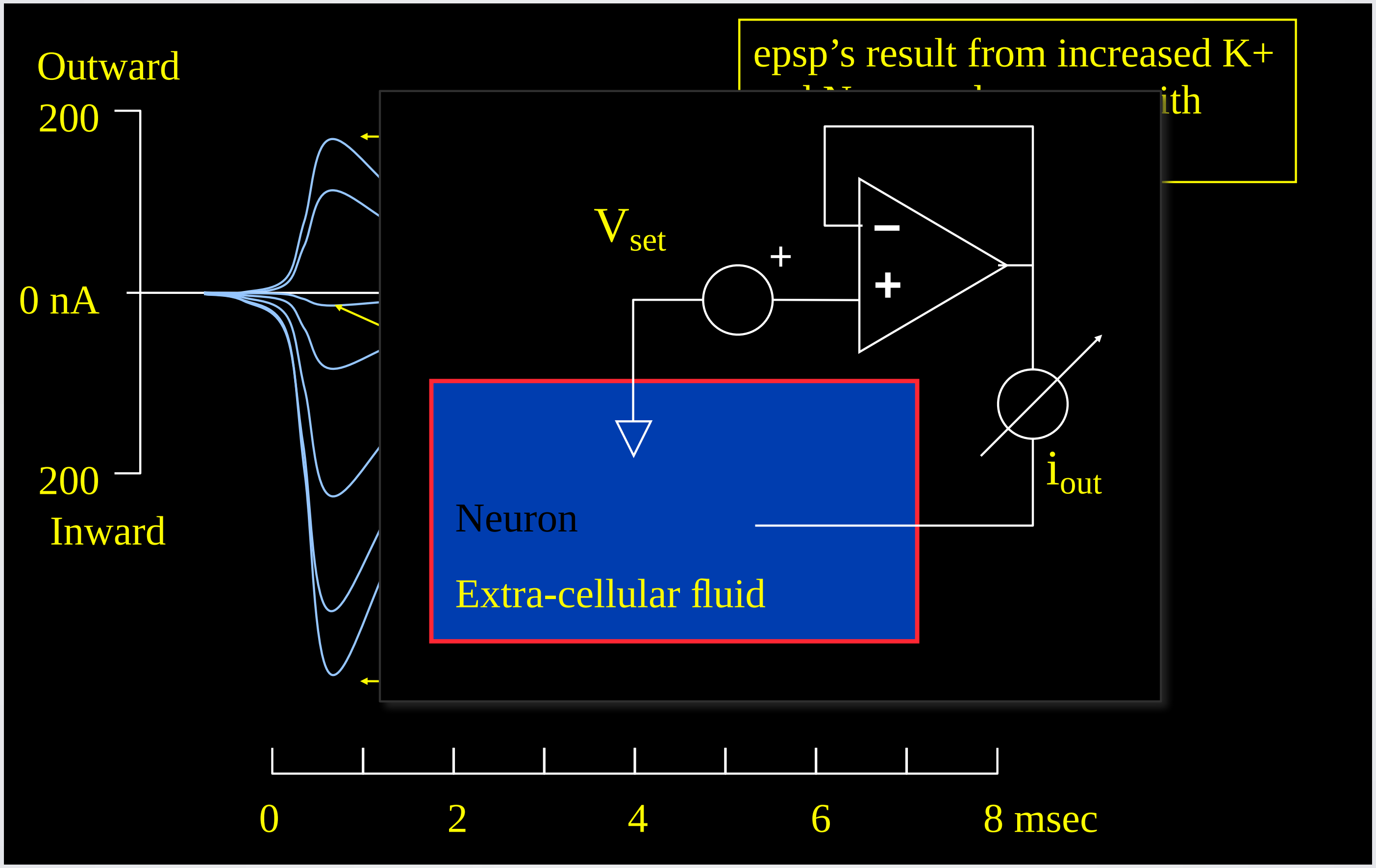




Amplitudes are *quantized* and display a Poisson distribution

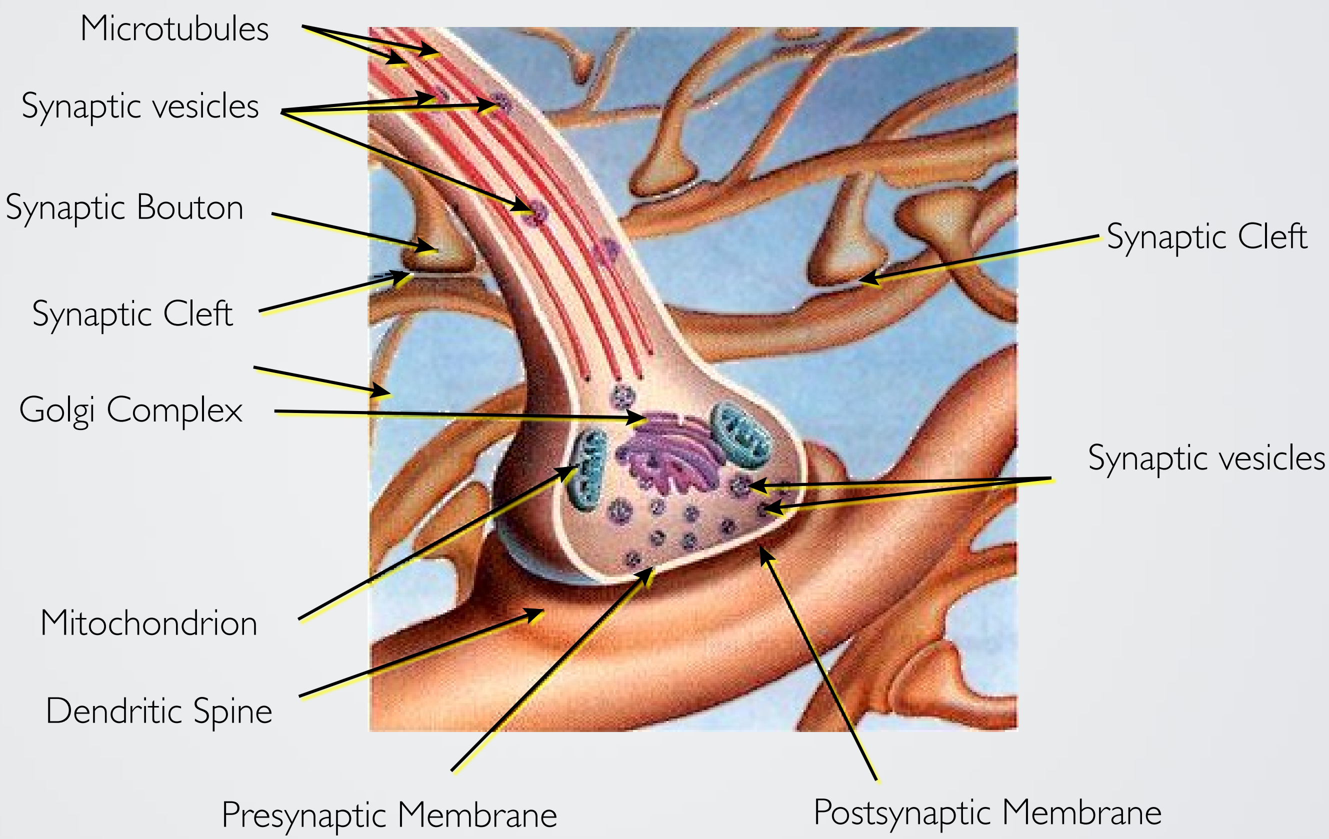
Boyd and Martin. J Physiol, **132**. 1956

Reversal Potential



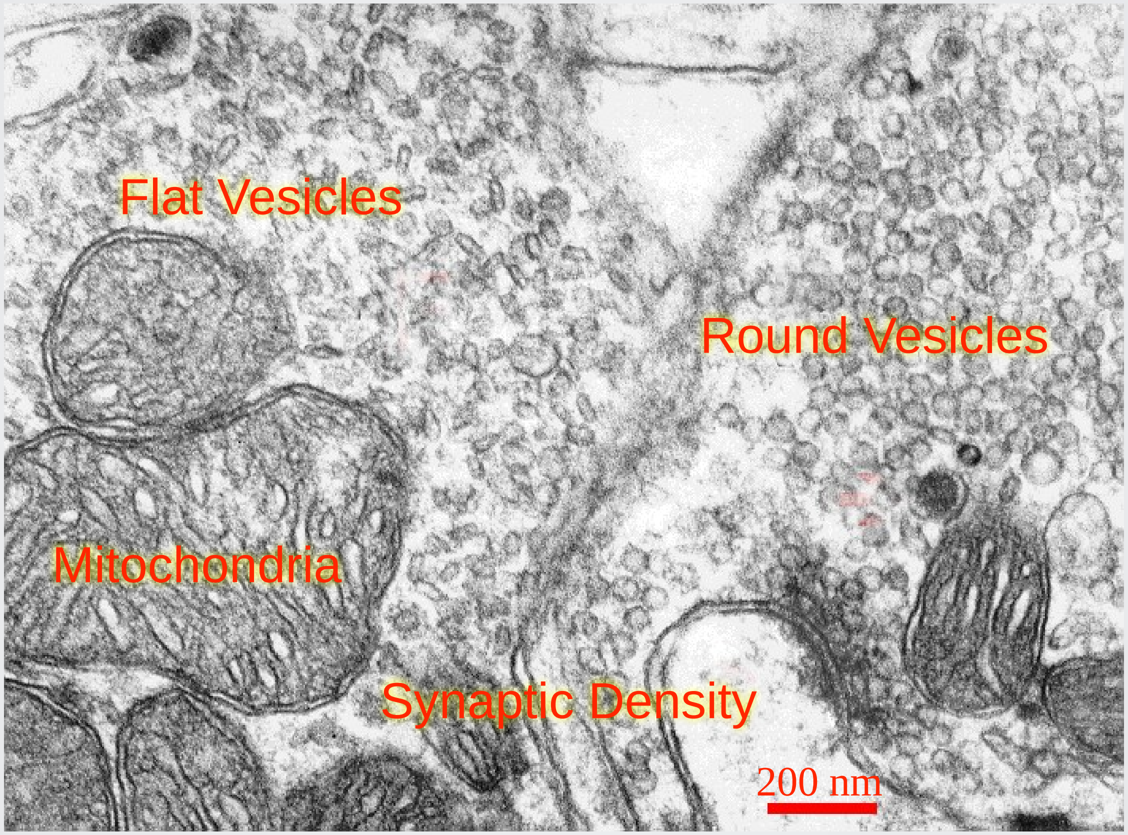
After Magleby and Stevens. J Physiol. **223**, 1972

Neural Synapse



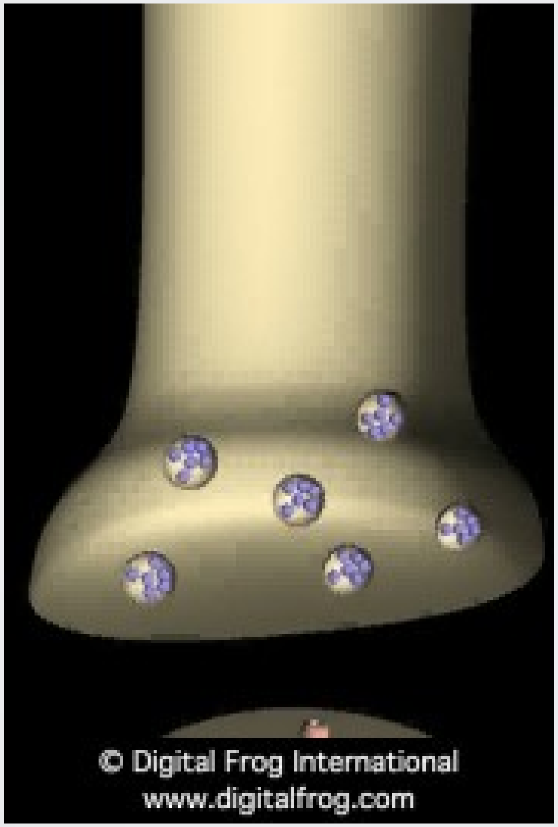
http://www.driesen.com/synapse.htm

Synapses by EM



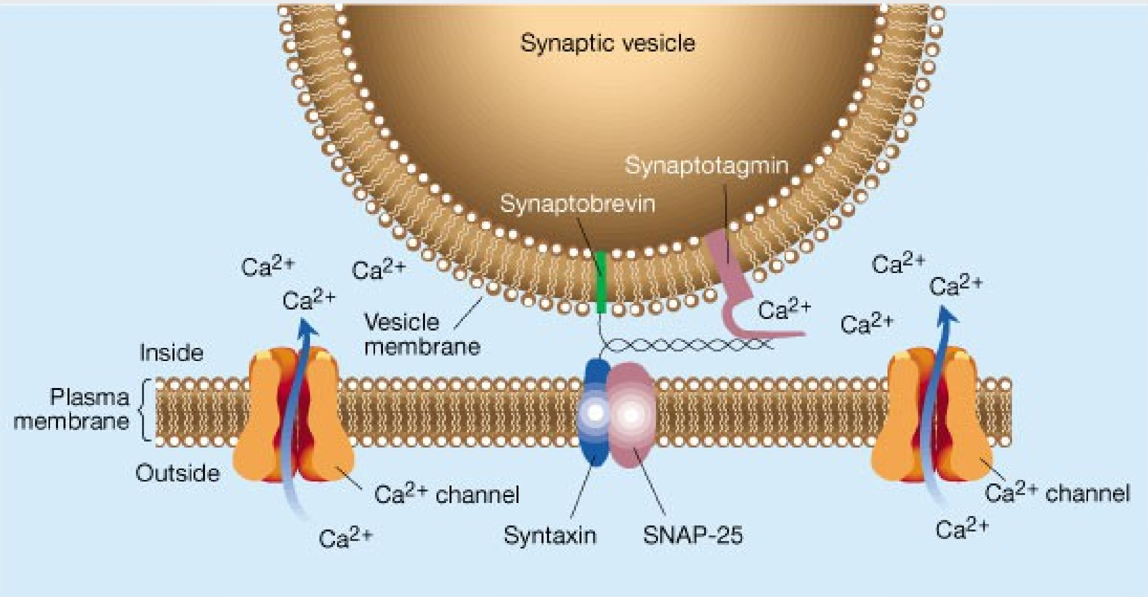
Atlas of Ultrastructural Neurocytology
http://synapses.mcg.edu/atlas/1_6_1.stm

SYNAPTIC MECHANISM (MOVIE)



Delay from Presynaptic Action Potential to Post-synaptic Voltage Change is ≈ 0.5 msec

SYNAPTIC VESICLES



Exocytosis of Transmitter requires Ca^{2+}

Matthews, G. Neurobiology: Molecules, Cells and Systems 2nd ed

NEUROTRANSMITTERS

Small Molecules

- Acetylcholine
- Serotonin
- Histamine
- Epinephrine
- Norepinephrine
- Dopamine
- Adenosine
- ATP
- Nitric Oxide

Amino Acids

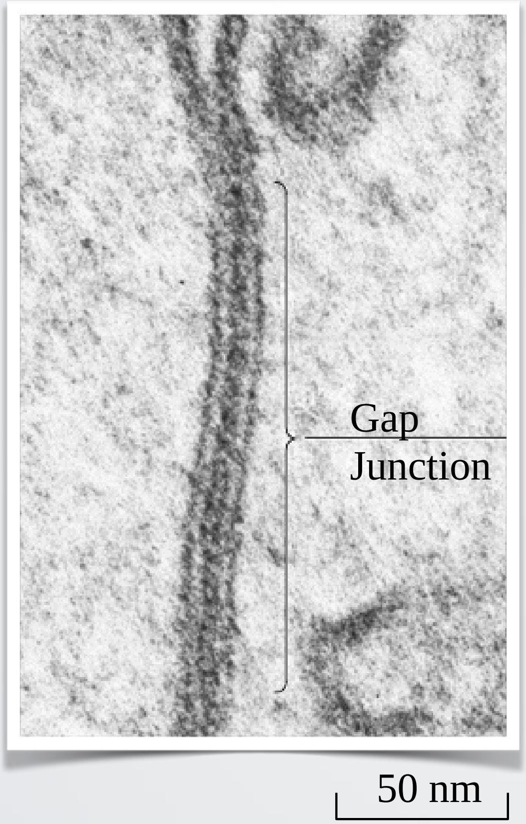
- Aspartate
- Gamma-aminobutyric Acid
- Glutamate
- Glycine

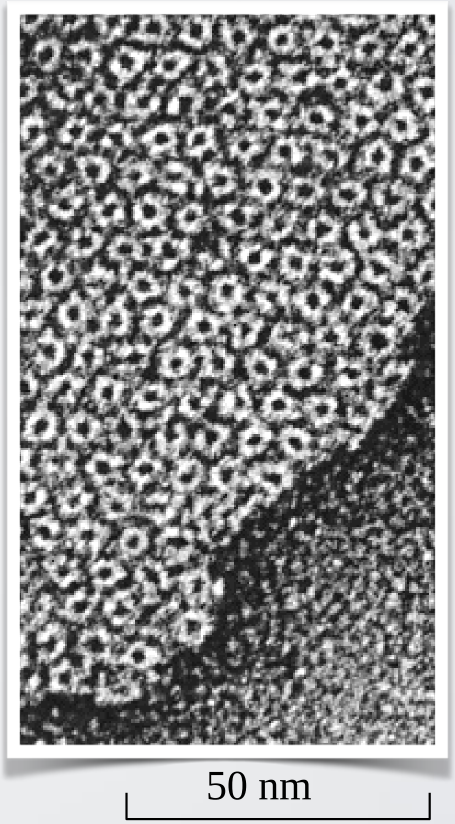
Peptides

- Angiotensin II
- Bradykinin
- Beta-endorphin
- Bombesin
- Calcitonin
- Cholecystokinin
- Enkephalin
- Dynorphin
- Insulin
- Galanin
- Gastrin
- Glucagon
- GRH
- GHRH
- Motilin
- Neurotensin
- Neuropeptide Y
- Substance P
- Secretin
- Somatostatin
- Vasopressin
- Oxytocin
- Prolactin
- Thyrotropin
- THRH
- Luteinizing Hormone
- Vasoactive Intestinal Peptide

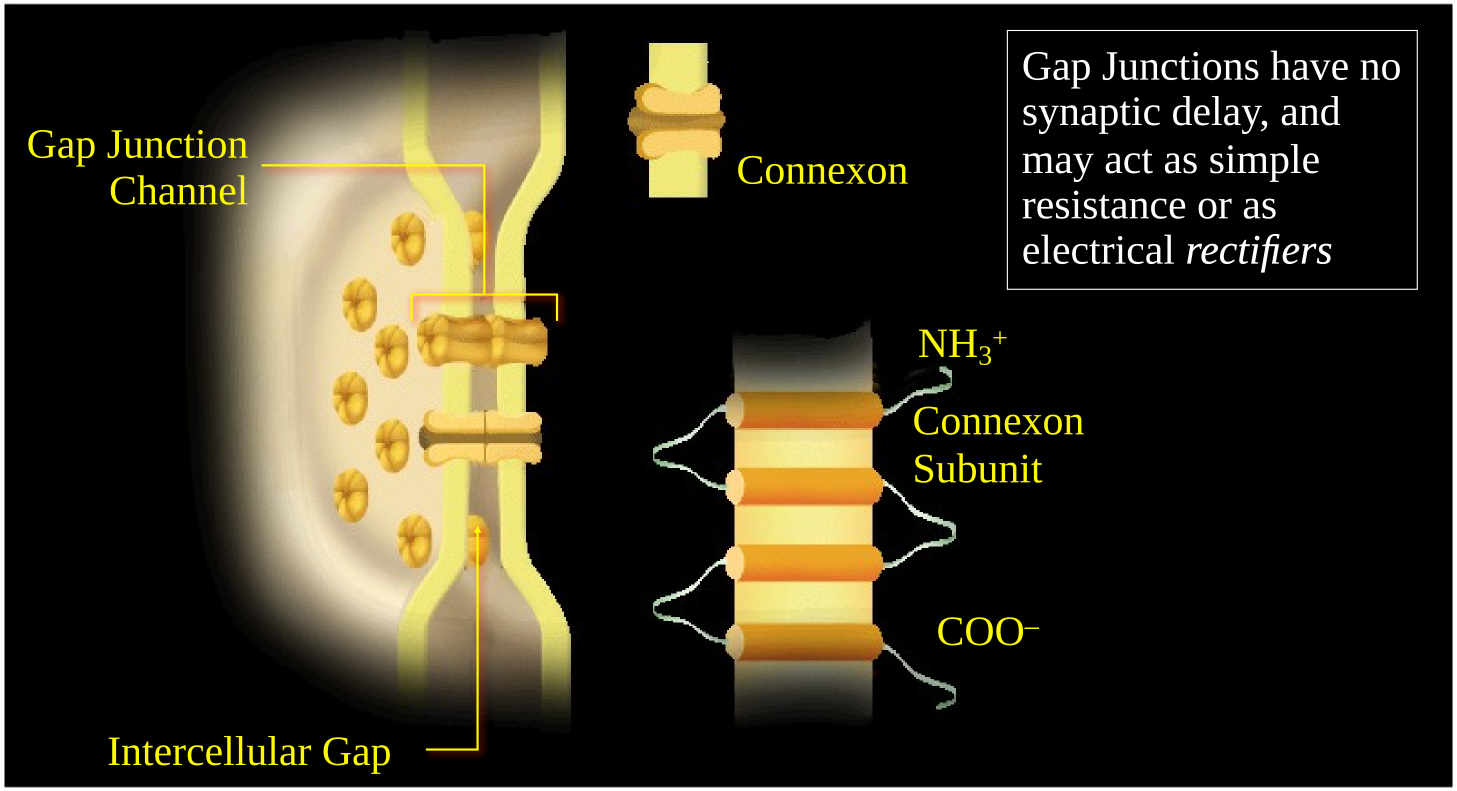
…and many others

ELECTRICAL SYNAPSES



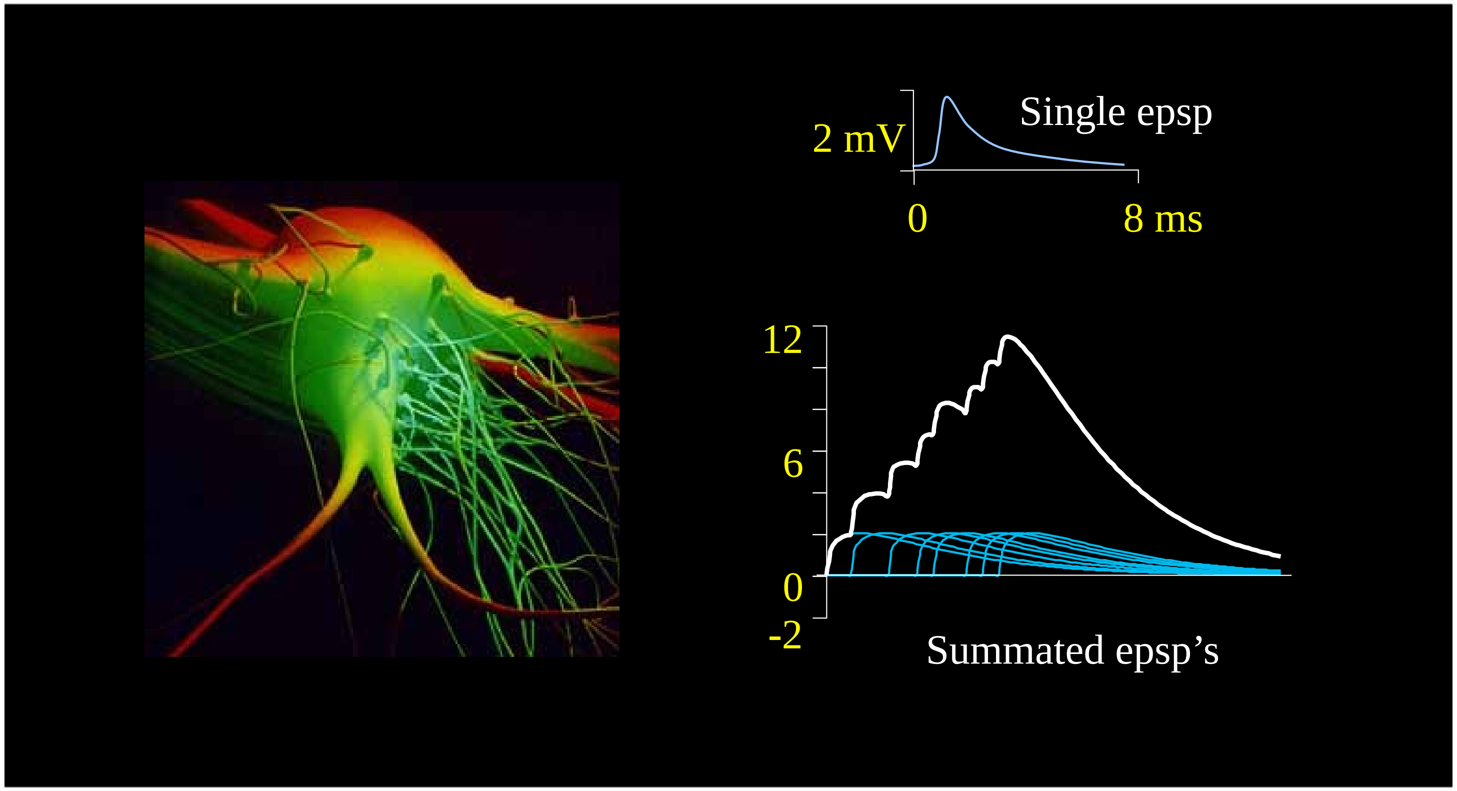


GAP JUNCTION MICROSTRUCTURE



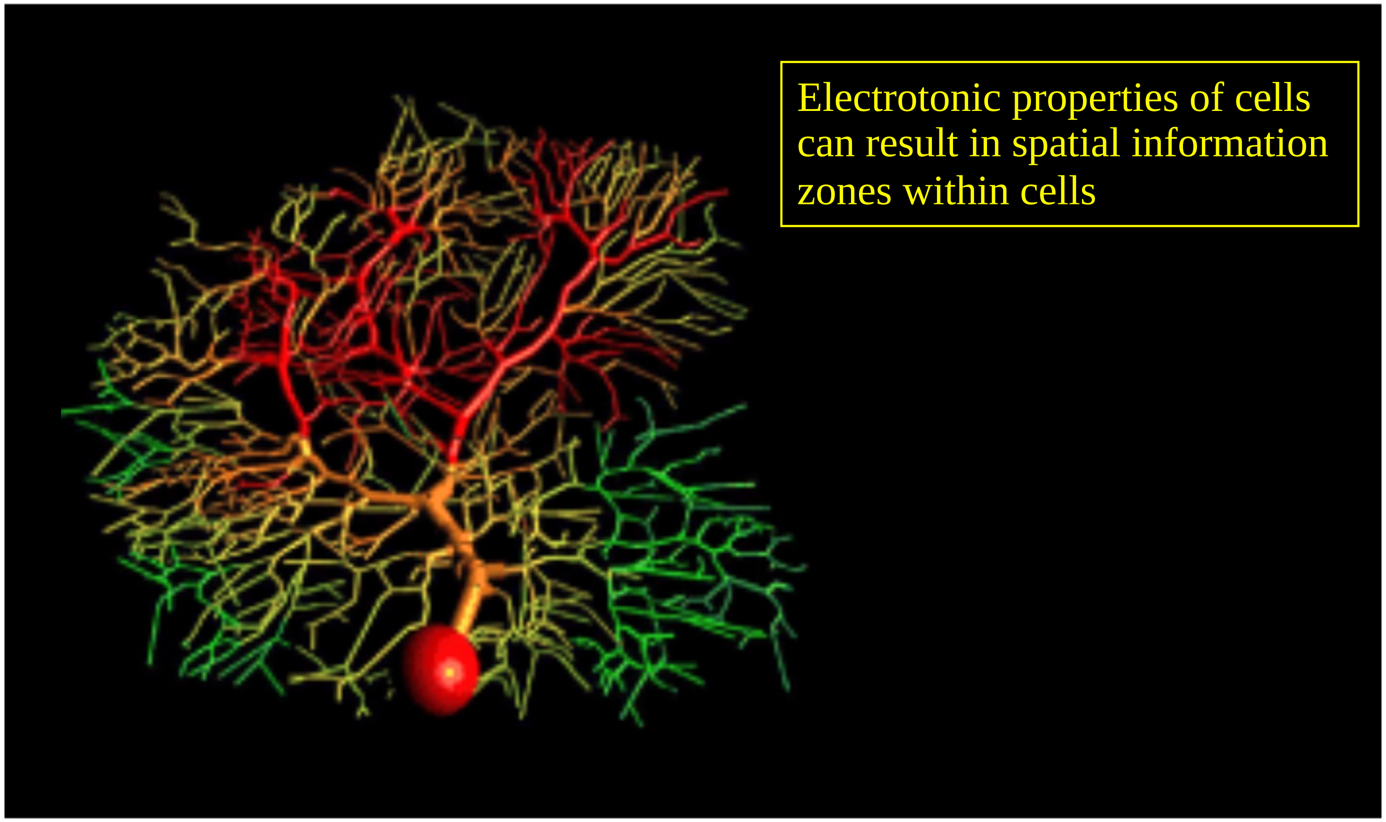
Modified from: http://aids.hallym.ac.kr

SpatioTemporal Summation of PSP's

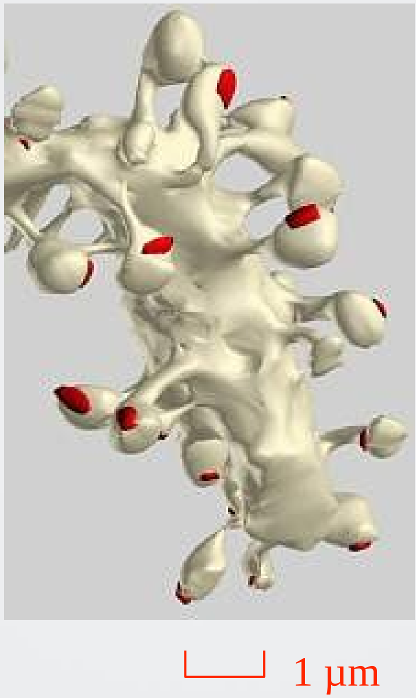


http://www.oseplus.de/Images/jpg/Synapse1.jpg

Integration of Inputs

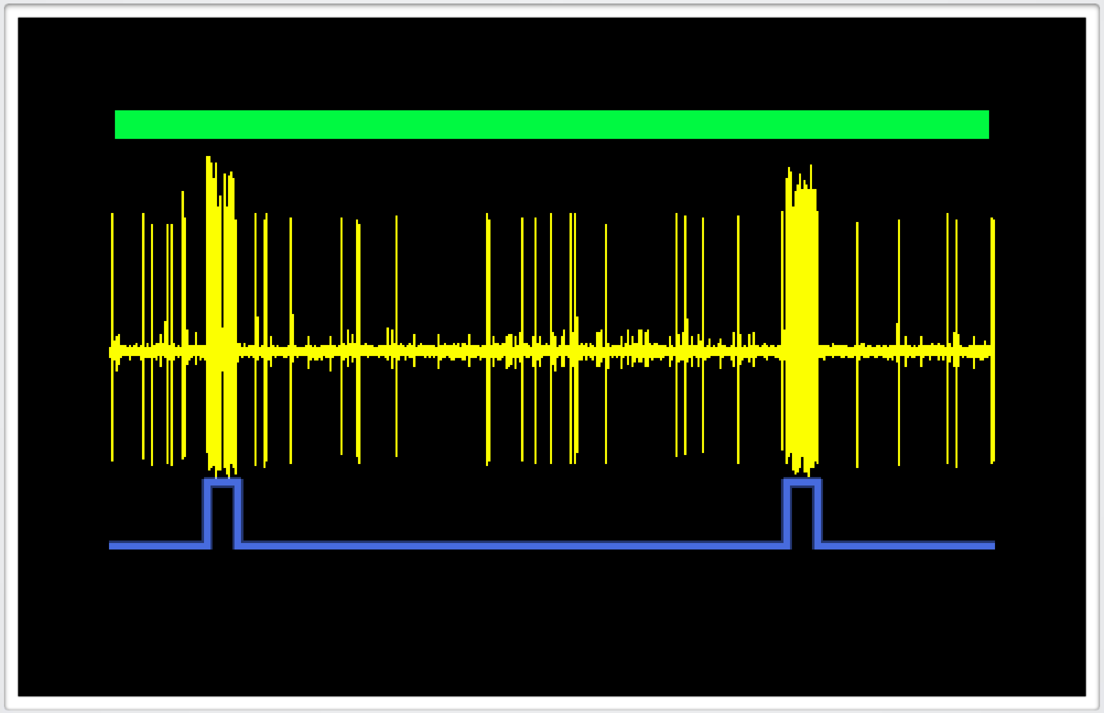


Dendritic Spines



Atlas of Ultrastructural Neurocytology

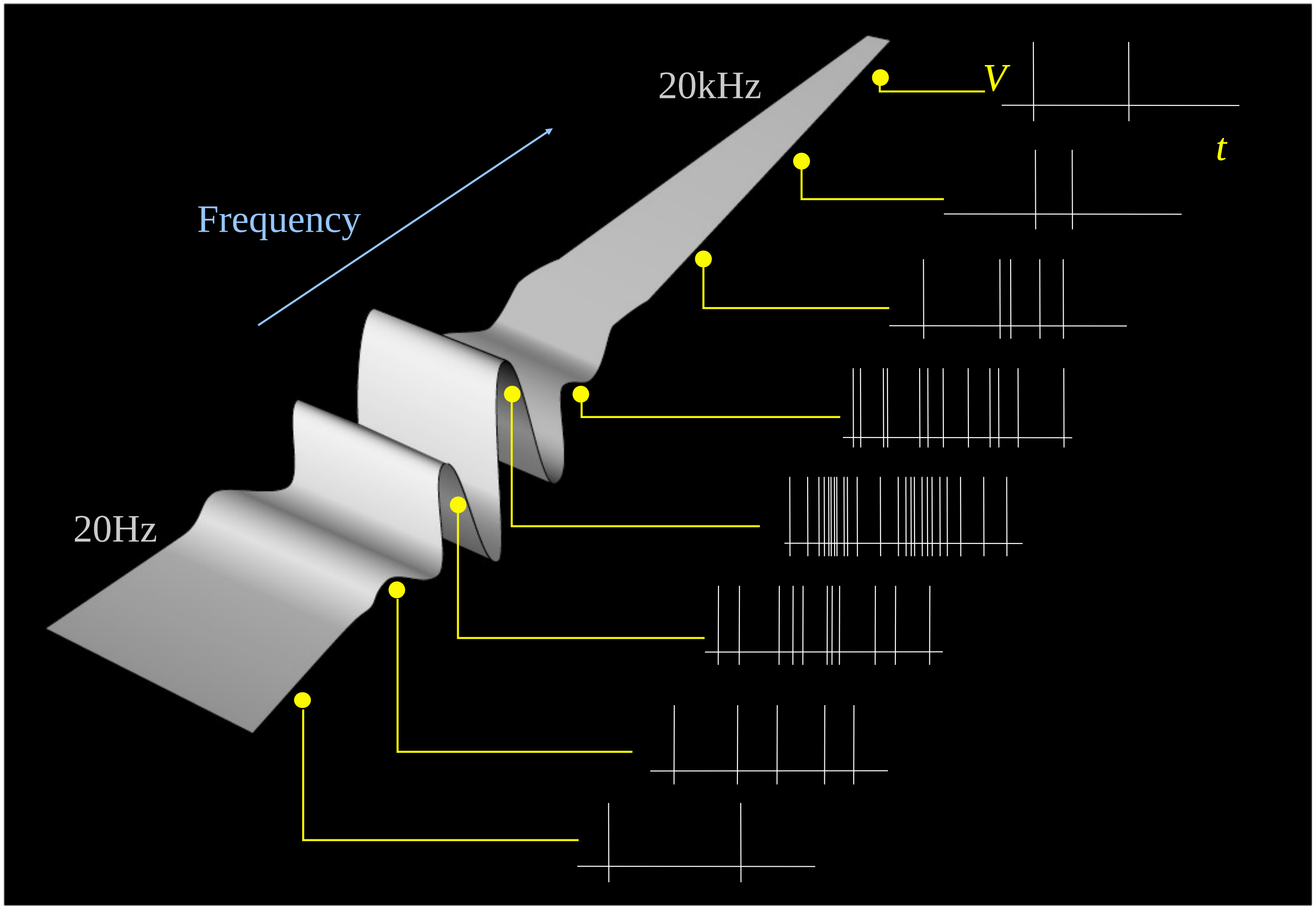
How Do Neurons Encode Information?



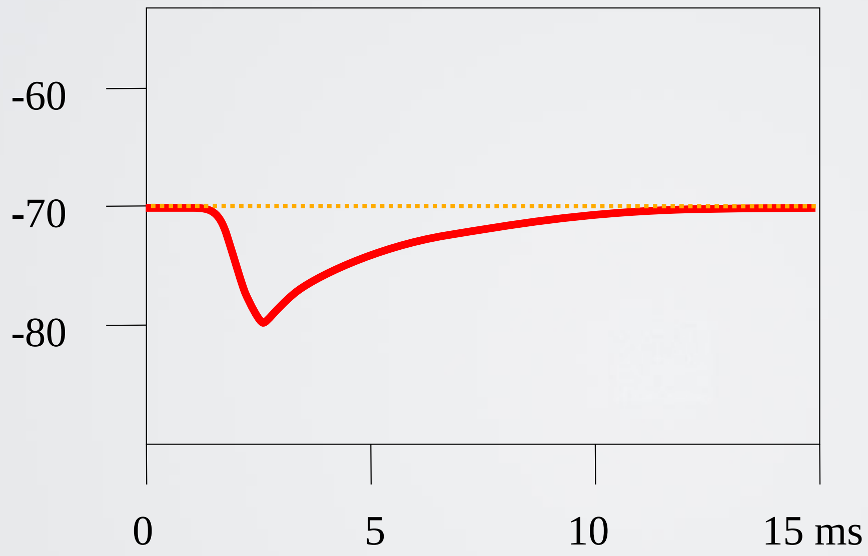
How Do Neurons Encode Information?

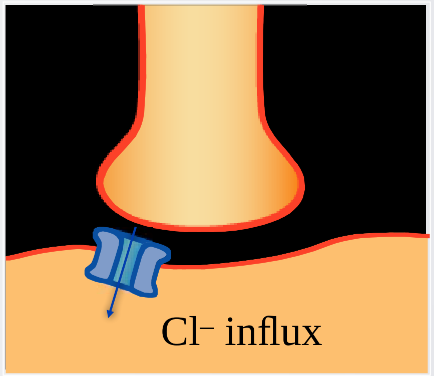
- Firing Rate: Ranges up to 1000 spikes/second
- Labeled Channels: Each neuron has different information content
- Modification of Synaptic Efficacy
- Firing Synchrony
- Transmitter Identity

Place Encoding - Basilar Membrane



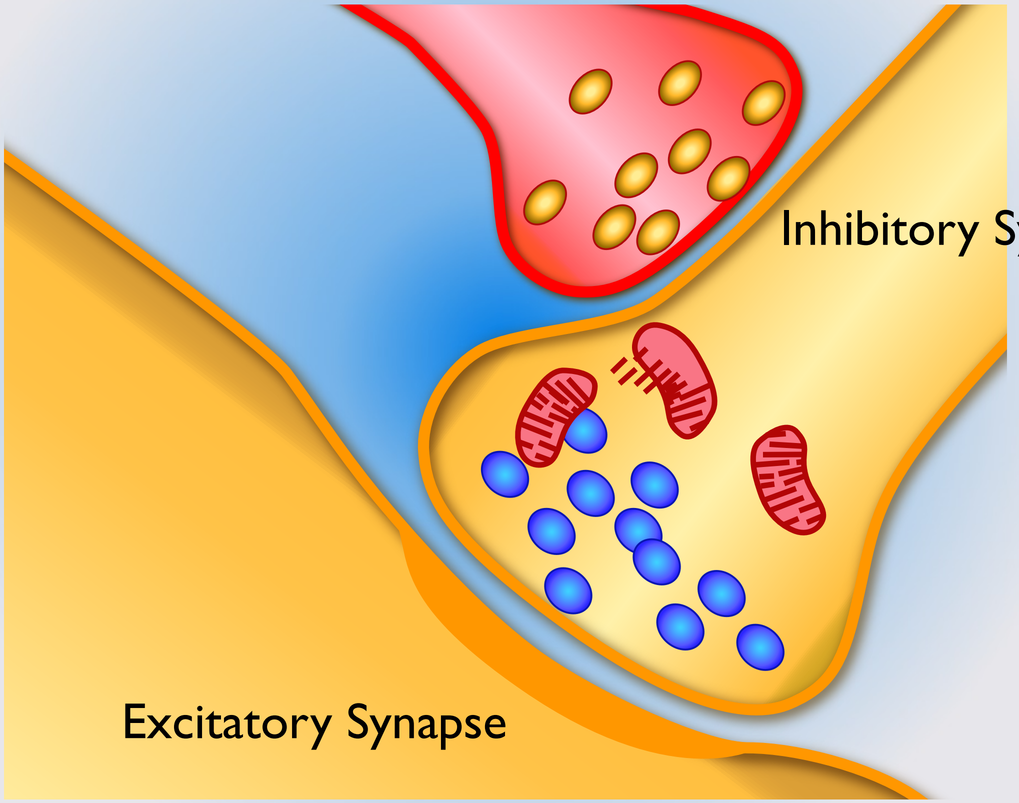
Inhibition





Reversal potential of Cl^- is near the resting potential. Therefore, its inhibition may be silent.

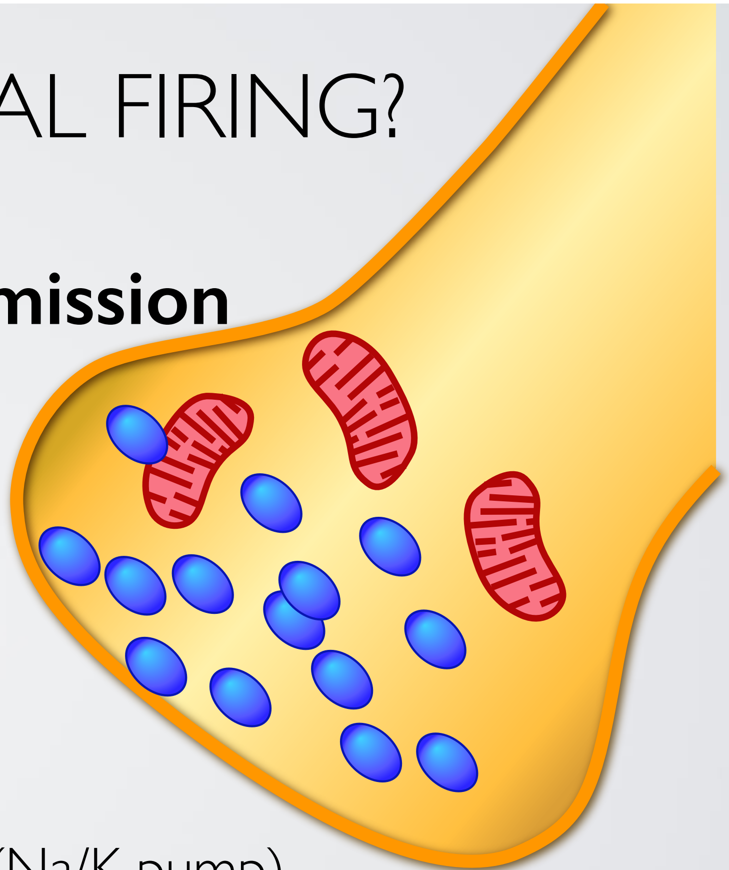
PRE-SYNAPTIC INHIBITION



WHAT MIGHT WE DETECT?

- Energy Demand
- Direct Electrical Signaling
- Morphological Differences
- Chemical Concentrations
- Tissue Density
- Fat/Water
- etc...

BOLD AND NEURAL FIRING?



Energy Demands in Transmission

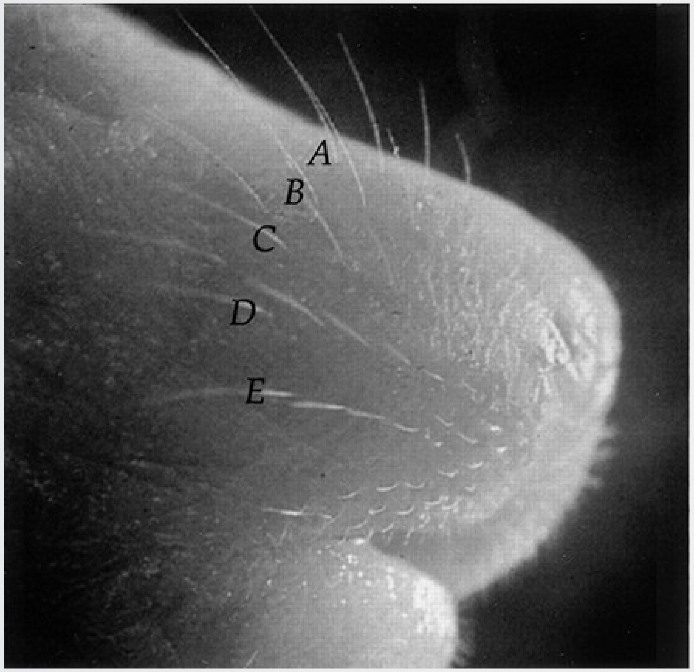
Pre-synaptic:

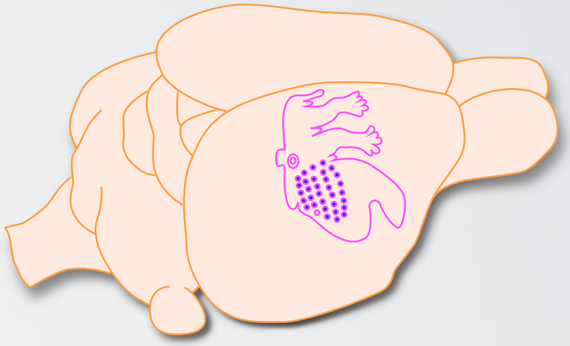
- Transmitter Synthesis
- Exocytosis
- Transmitter re-uptake

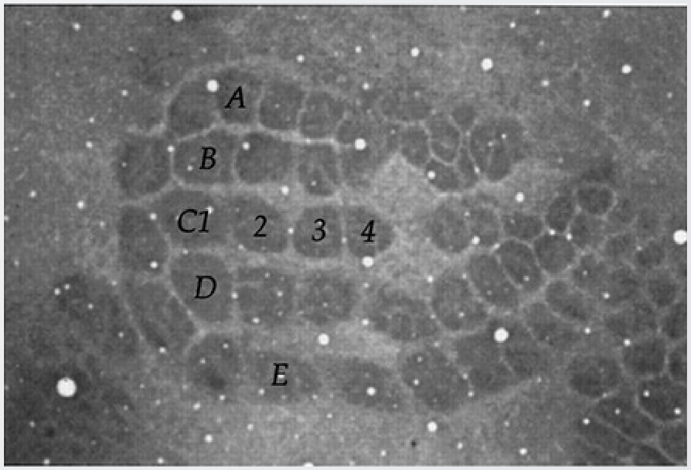
Post-Synaptic

- Excitatory: Removal of Sodium (Na/K pump)
- Maintenance of membrane potential after ion leakage
- Inhibitory: ???

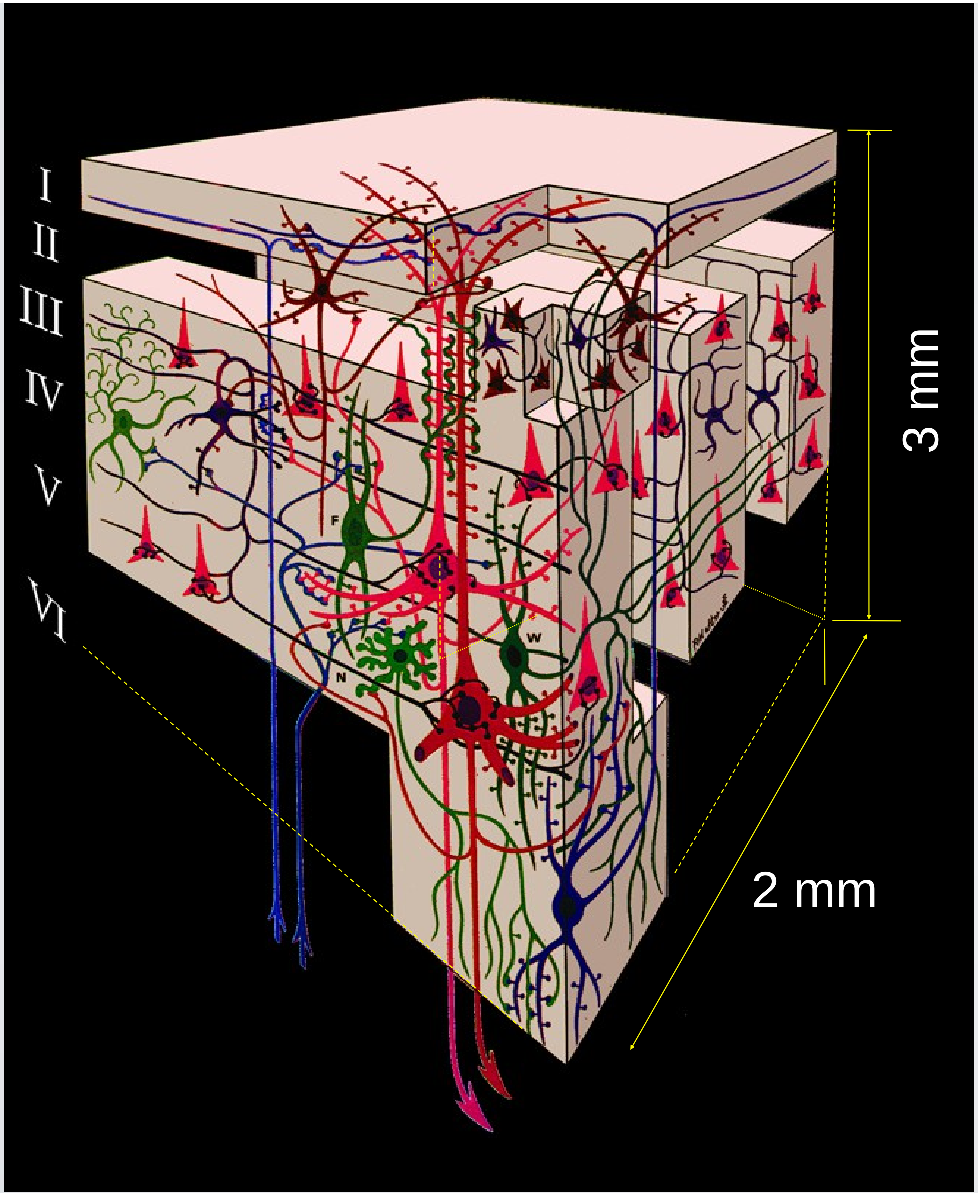
Cortical Column





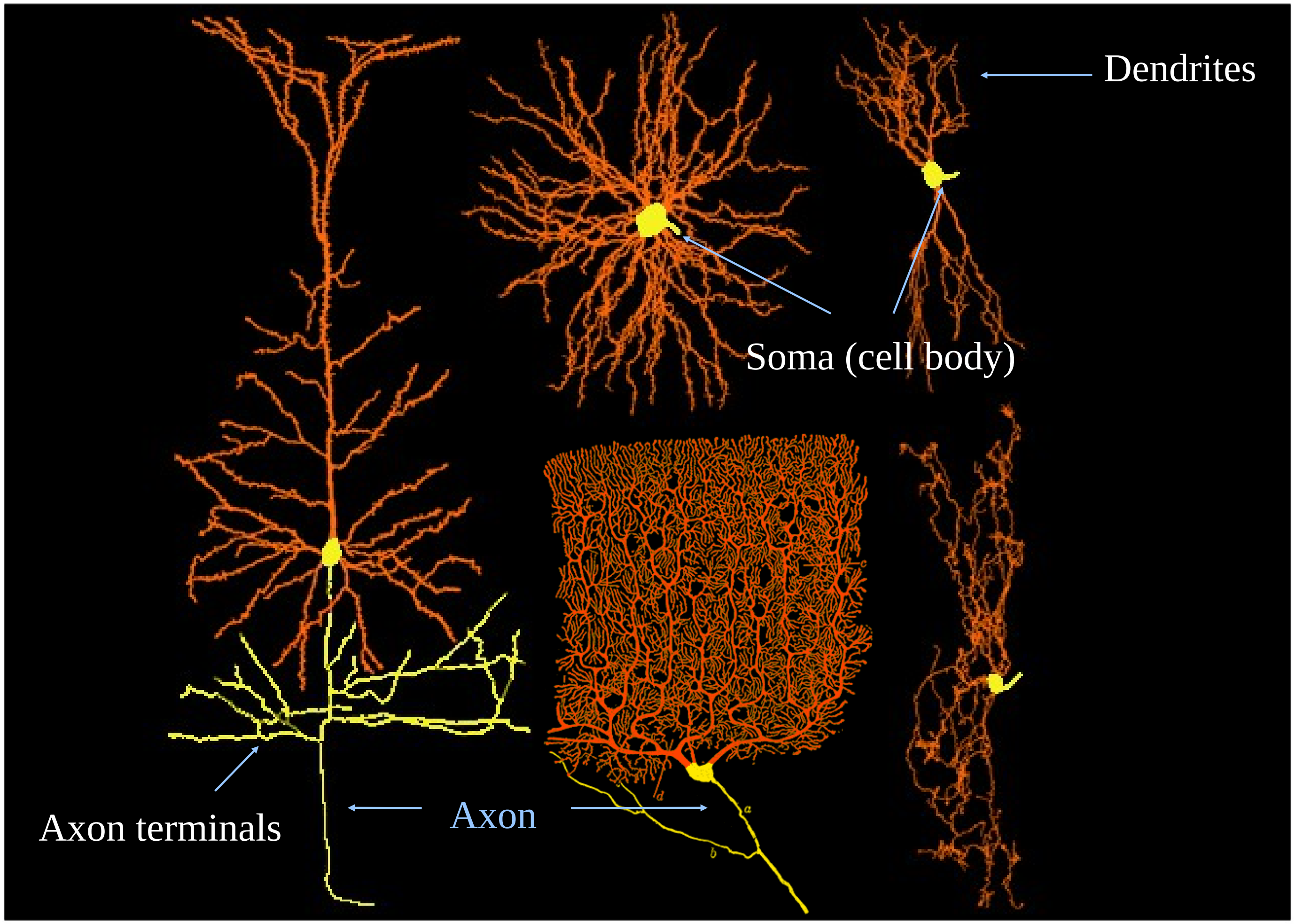


Wilson. PNAS **97**, 2000

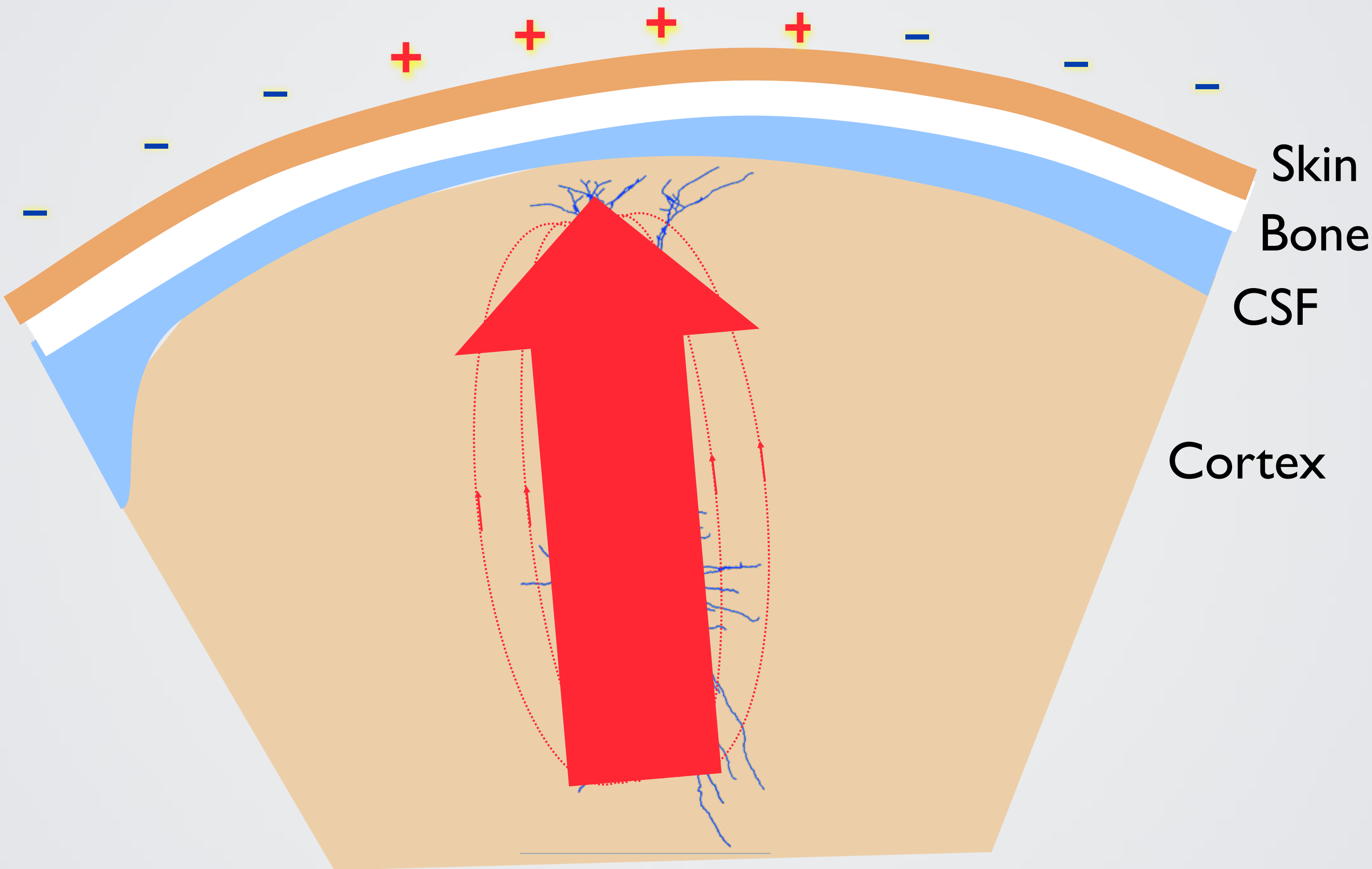


Imaging voxels and Neuropil

Types of Neurons



Presumed Origin of the EEG

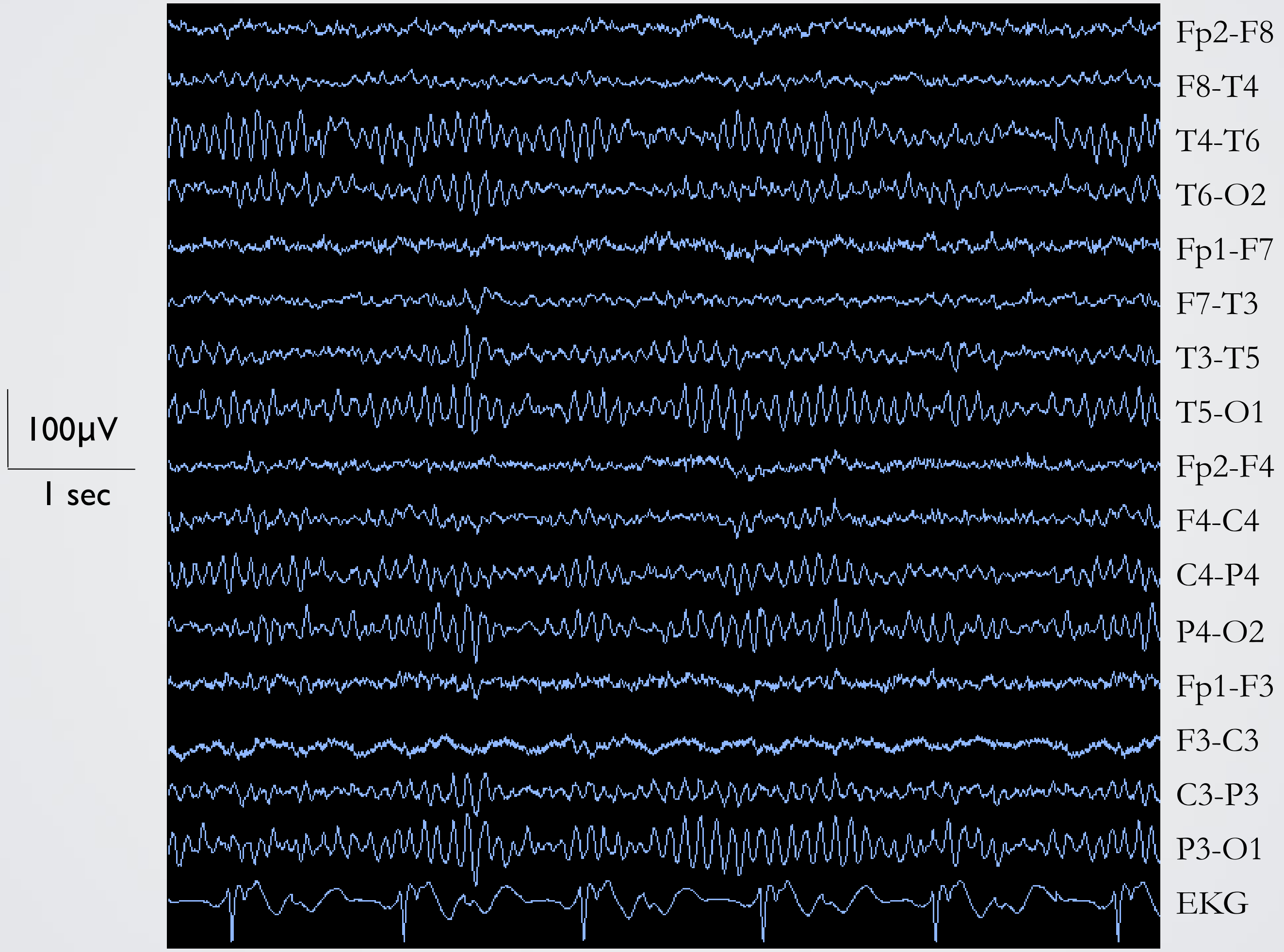


Many Neurons are Not "Seen" by EEG

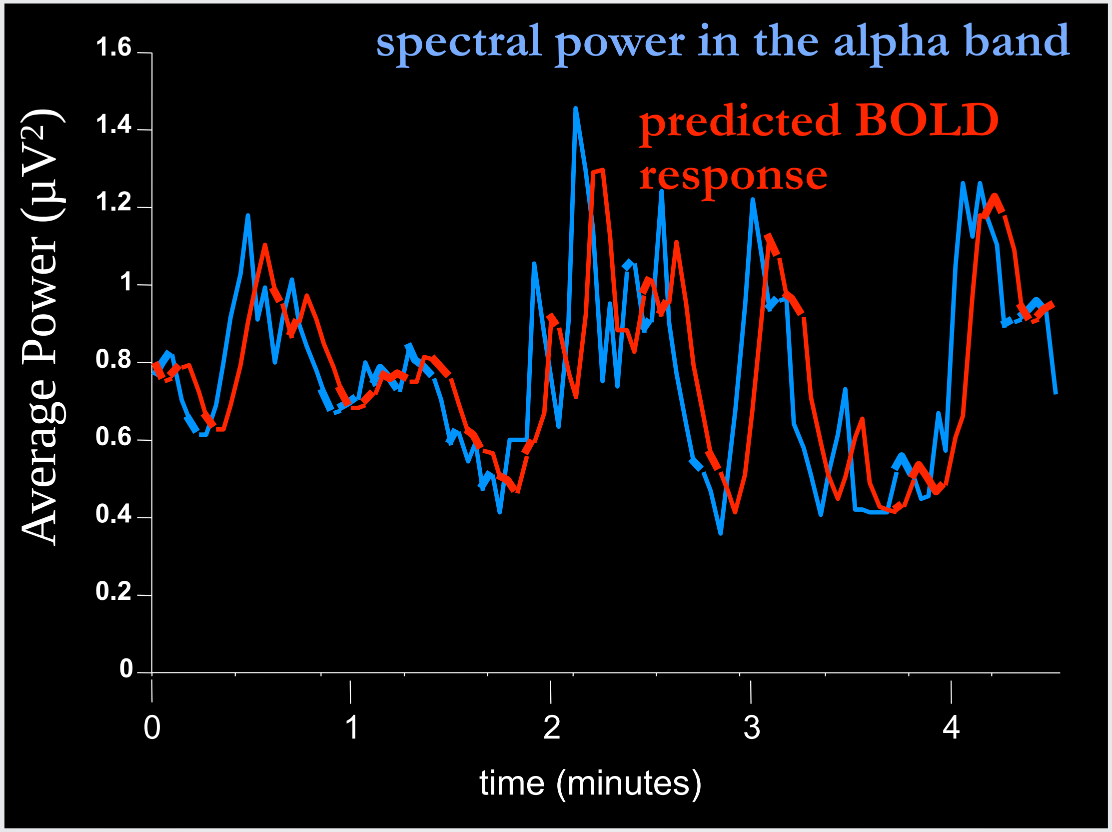
General Limitations in EEG Localization

- Deeper Sources Show Weaker Signals
- Magnitude Depends on Dipole Orientation
- Magnitude Depends on Temporal Synchrony
- Magnitude Depends on Spatial Coherence
- Conductivity of Body Tissues (CSF, scalp) Blur the Scalp Potentials

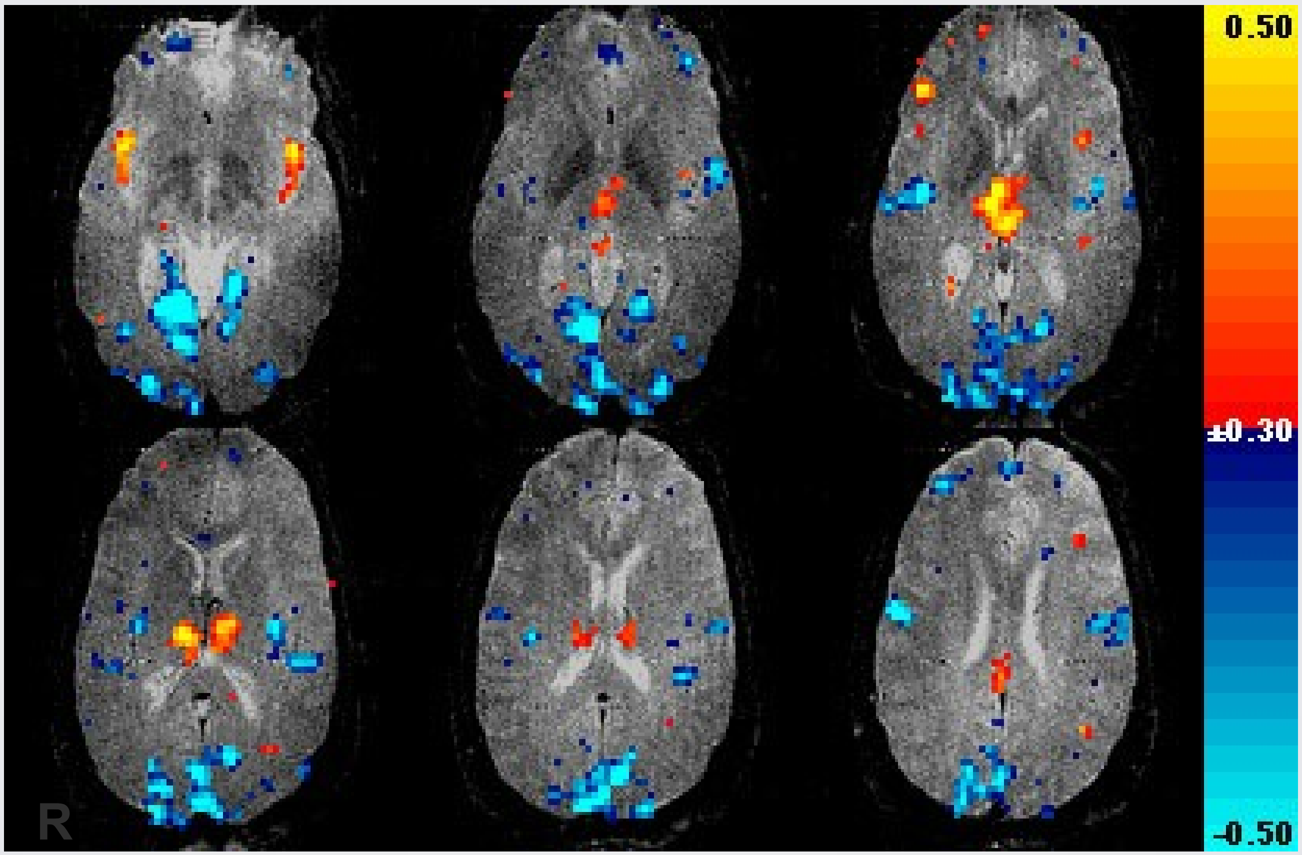
EEG at Rest


100μV
1 sec
Fp2-F8
F8-T4
T4-T6
T6-O2
Fp1-F7
F7-T3
T3-T5
T5-O1
Fp2-F4
F4-C4
C4-P4
P4-O2
Fp1-F3
F3-C3
C3-P3
P3-O1
EKG

Alpha Mapping



SITE OF RESTING ALPHA



Reference

Goldman (2002) 3(18):2487

EEG-fMRI Issues

- Scalp Potentials are Proportional to the **Derivative** of the Voltage, whereas fMRI is Proportional to the **Integral** of the Firing
- The Action Potential, *per se*, Is Probably **Invisible** to BOLD
- The Rhythmic Structures in the EEG May Depend More on **Synchronous** Firing than on **High Firing Rate**
- The BOLD Signal is Likely Associated with the **Post**-Synaptic Neurons

Cohen, IEEE, 2009

MR-Lucent Neurophysiology

Energetic Demands .... *(BOLD, ASL)*

Transmitter Synthesis, Exocytosis, Metabolism

Na+/K+ Pump

[Na+] .... *Imaging*

Glucose Metabolism .... *Spectroscopy*

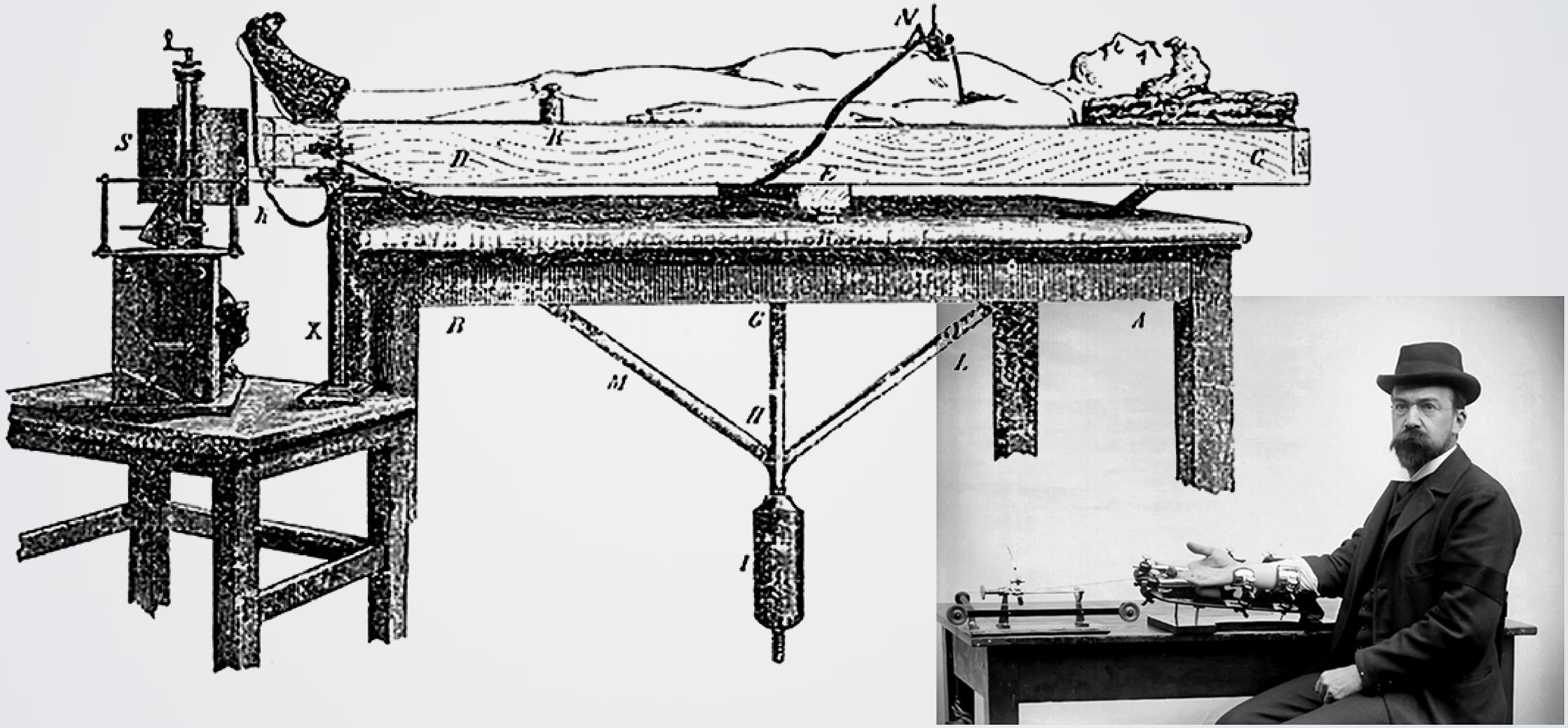
Extracellular Currents (?) .... *Phase Disturbance*

Anisotropic Diffusion .... *DTI, etc…*

Neural Constituents (NAA) .... *Spectroscopy*

BOLD

A Delicate Balance

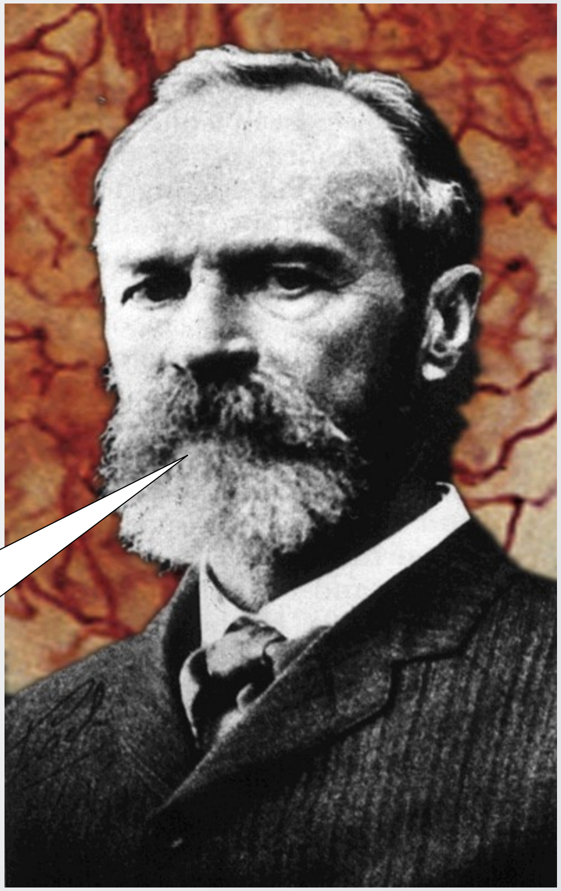


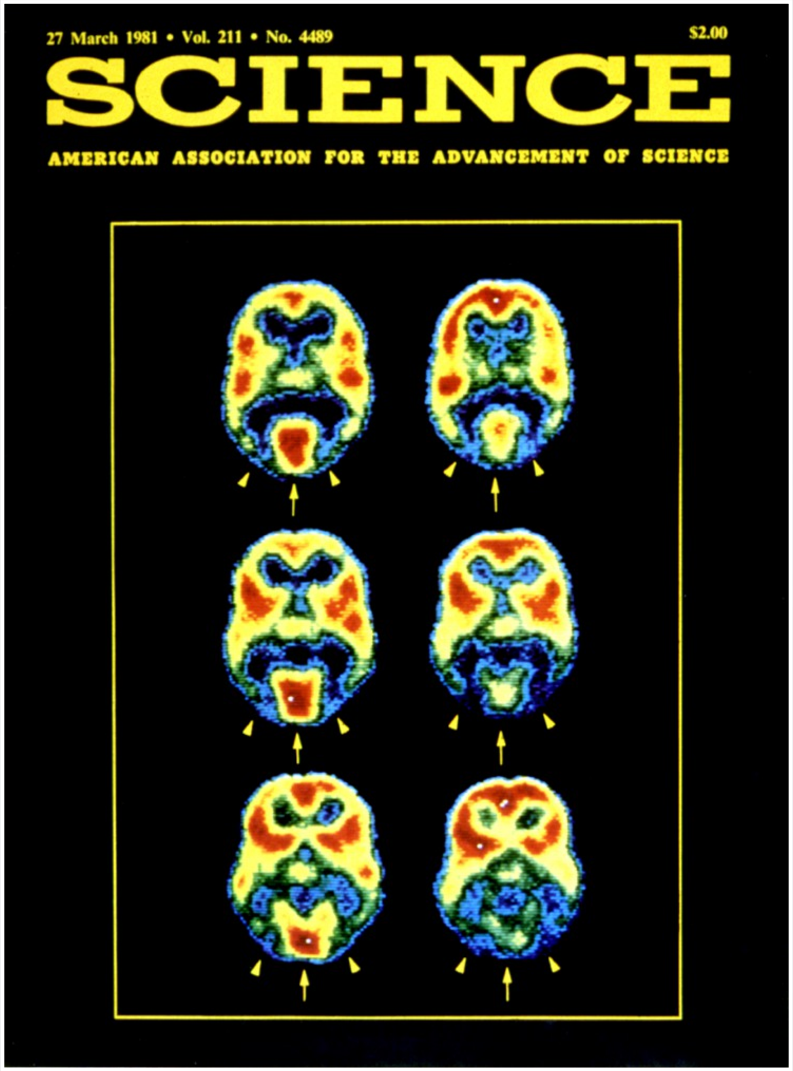
Angelo Mosso. *Atti R Accad Lincei Mem Cl Sci Fis Mat Nat*, **1884** ;XIX:531-43

WILLIAM JAMES (1890)

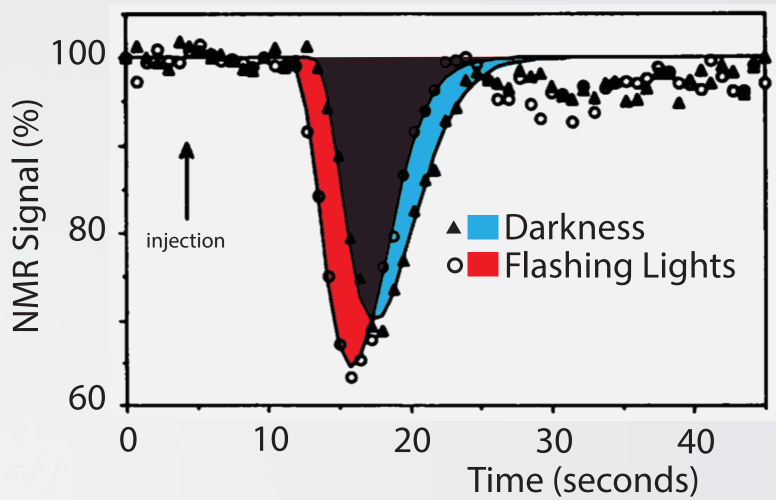
"*We must suppose a very delicate adjustment whereby the circulation follows the needs of the cerebral activity.*

Blood very likely may rush to each region of the cortex according as it is most active, but of this we know nothing."





27 March 1981 • Vol. 211 • No. 4489
$2.00
SCIENCE
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE



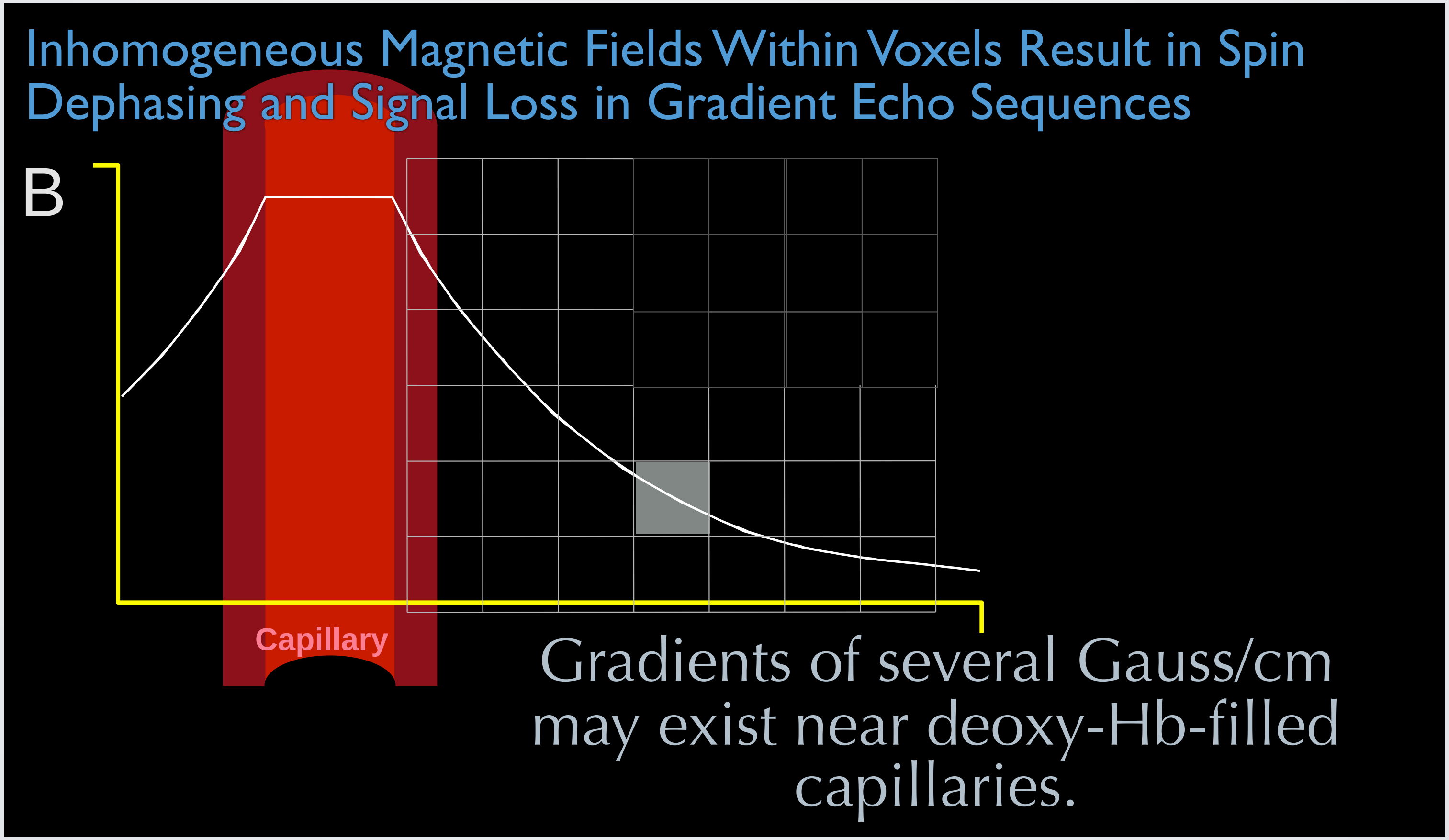
Jack Belliveau 1959-2014

http://www.nmr.mgh.harvard.edu/in-memoriam-jack-belliveau

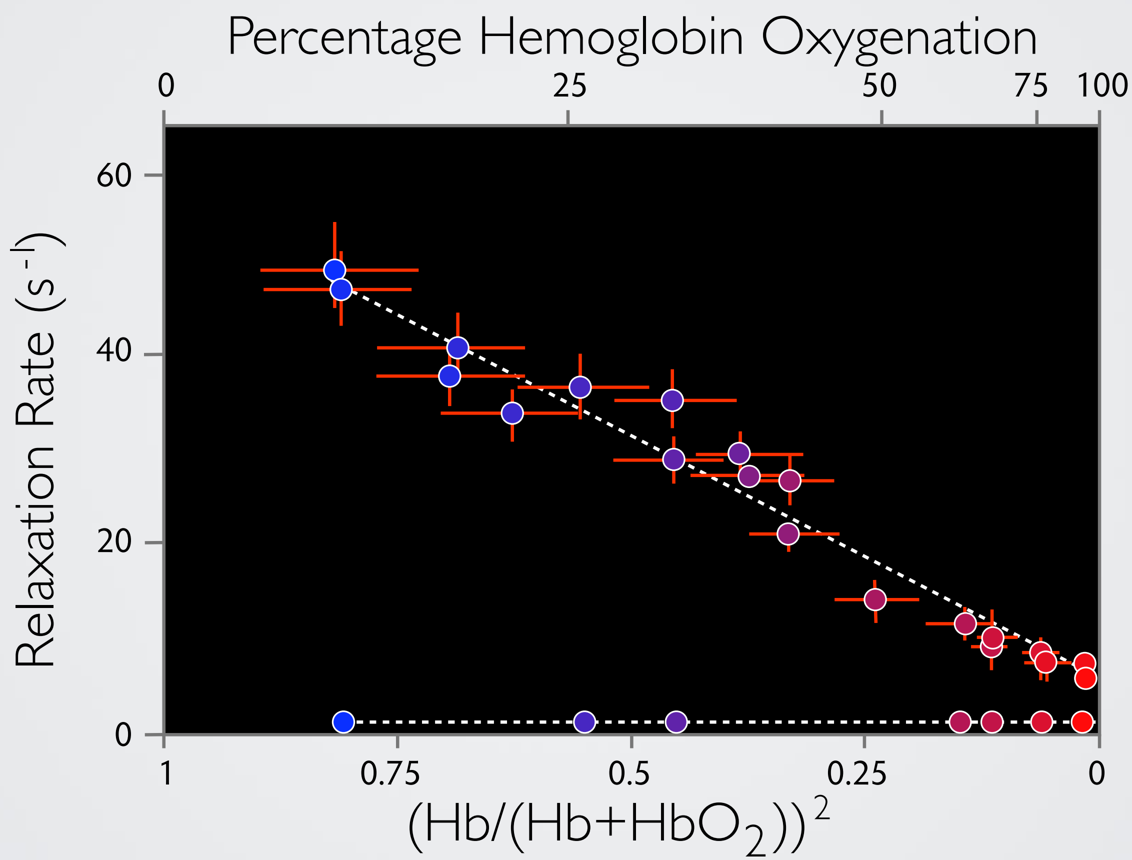
A DELICATE BALANCE: *REPRISE*

Pauling and Coryell. PNAS **22**, 1936

SIGNAL LOSSES FROM SPIN DEPHASING

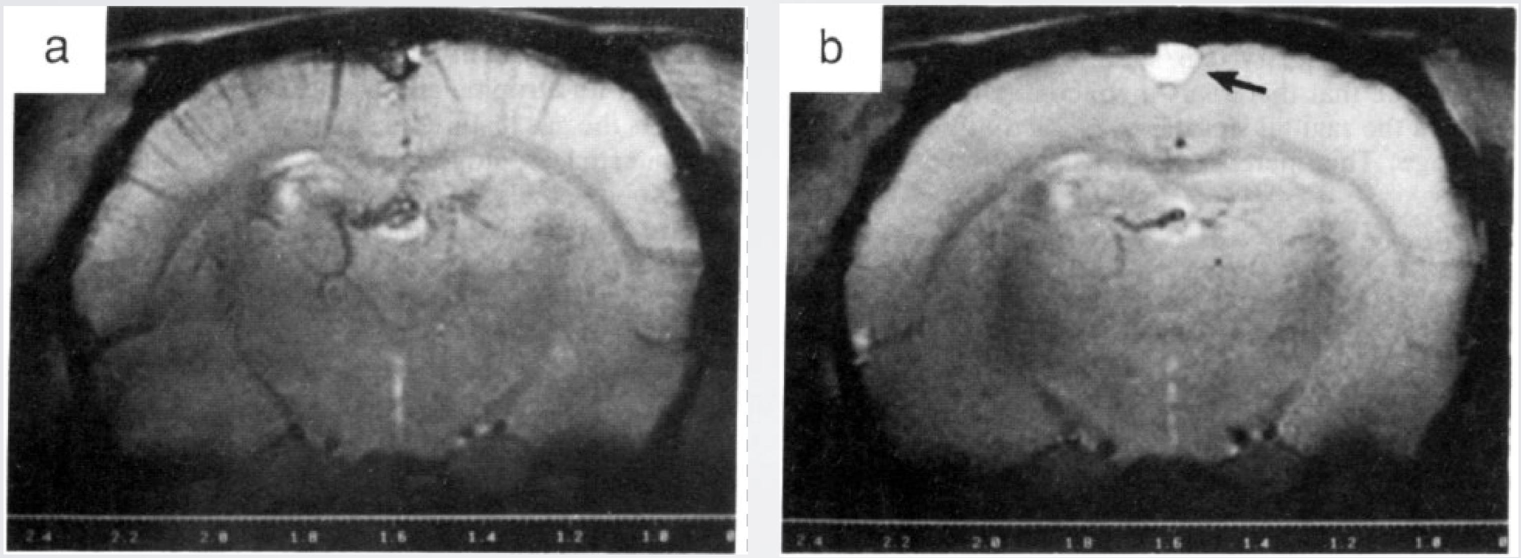


MRI Relaxation Rate and HbO2



Thulborn, et al., Biochimica et Biophysica Acta **714**, 1982

BOLD



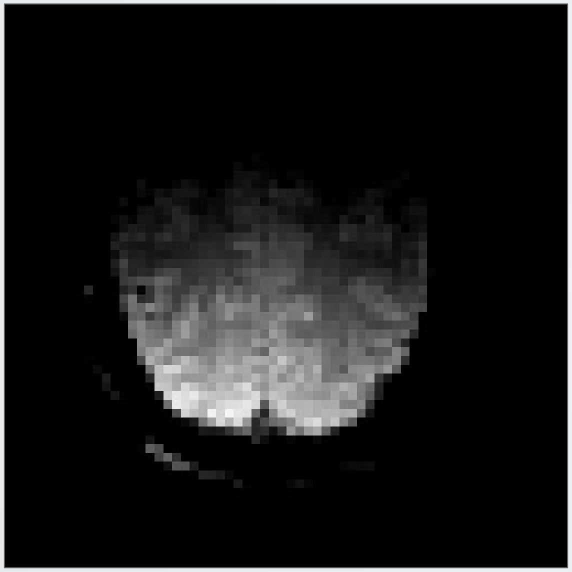
Effect of blood CO_2 level on BOLD contrast.
(*a*) Coronal slice brain image showing BOLD contrast from a rat anesthetized with urethane. The gas inspired was 100% O_2.

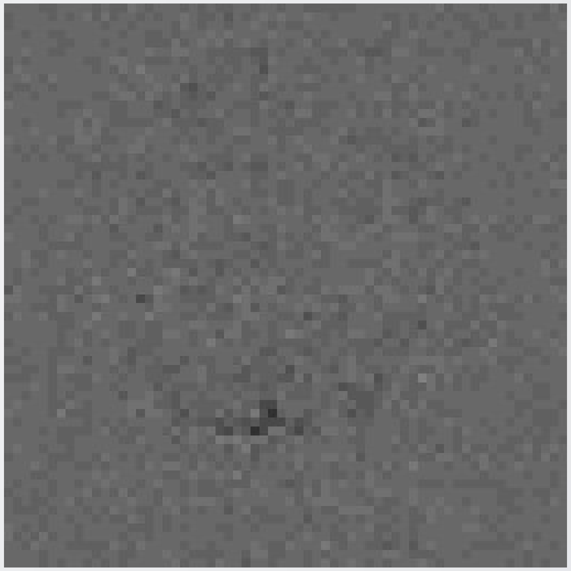
(*b*) The same brain but with 90% O_2/10%CO_2 as the gas inspired. BOLD contrast is greatly reduced.

S Ogawa, *et al.*,
PNAS, **87**(24):9868,1990

fMRI

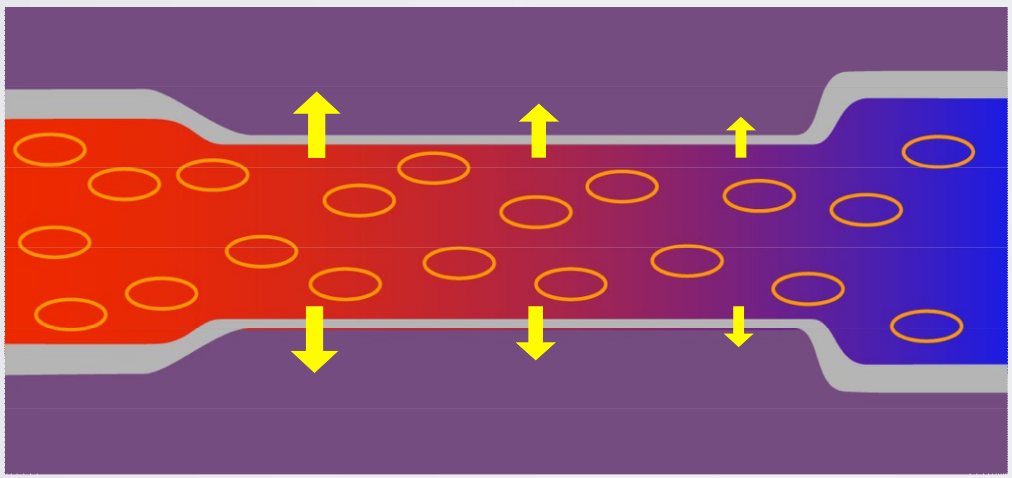
explores intensity variations in MR signal

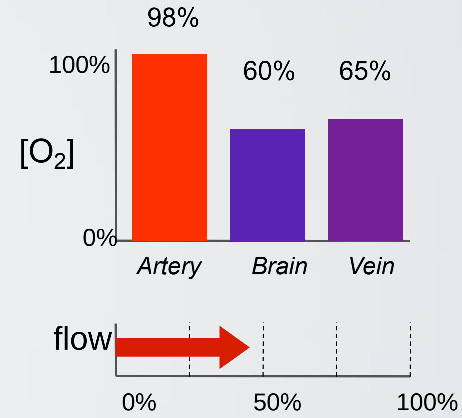




intensity variations reflect venous [O2]

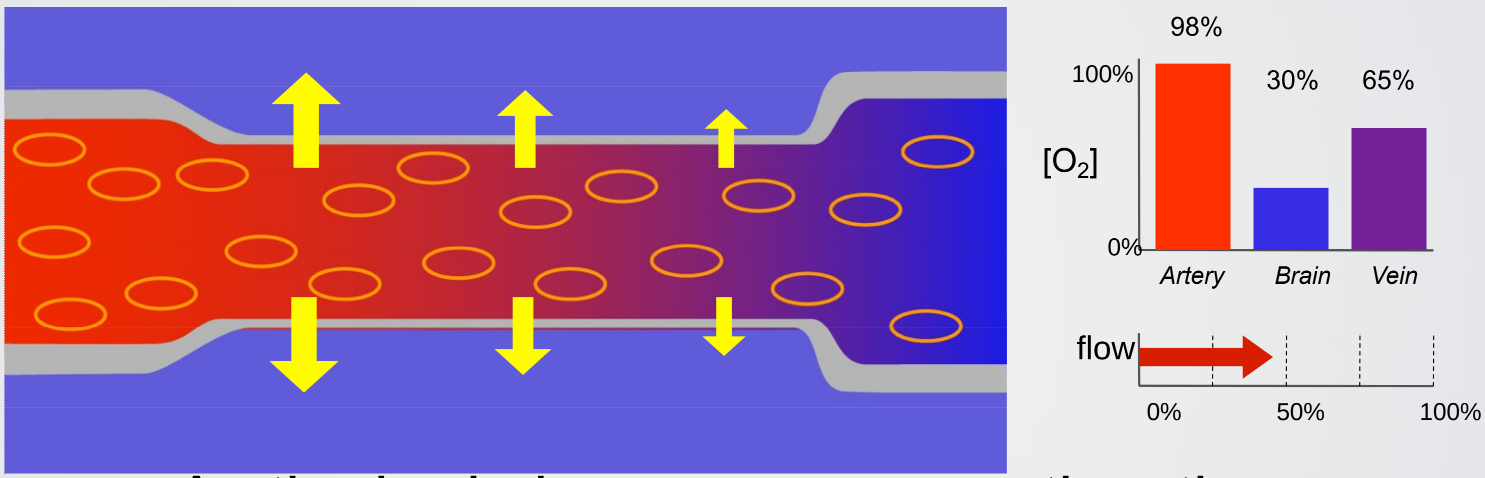
Why Does Venous O_2 Increase? (1)





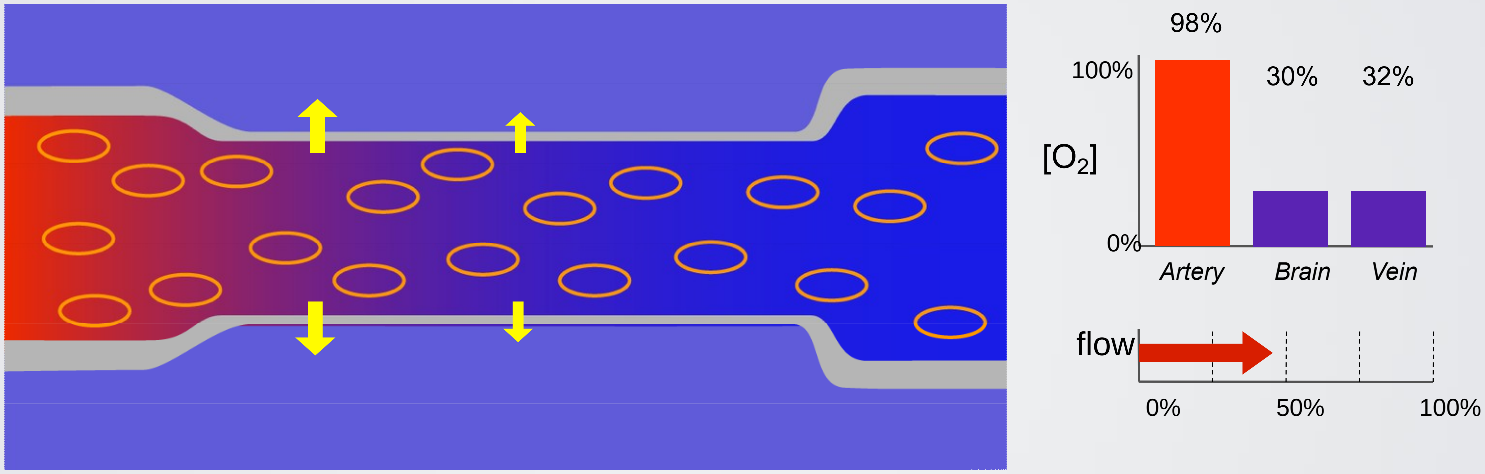
Under normal conditions oxygen diffuses down its concentration gradient from the capillary to the brain parenchyma

WHY DOES VENOUS O_2 INCREASE? (2)



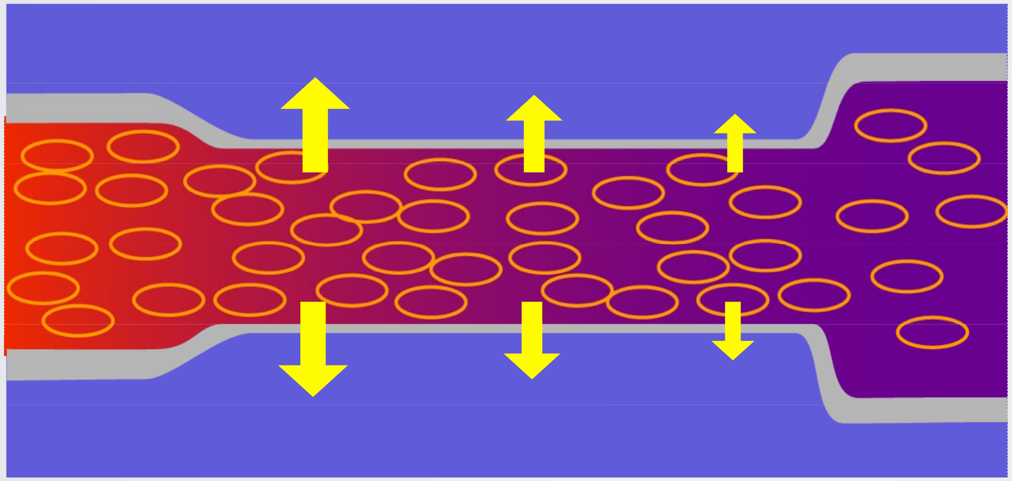
As the brain becomes more active, the oxygen consumption increases, increasing the transluminal oxygen gradient.

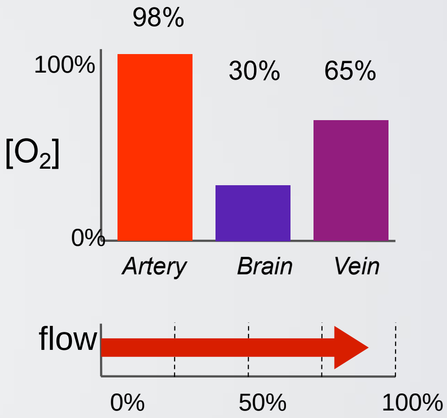
Why Does Venous O_2 Increase? (3)



As oxygen flows across the capillary lumen it is depleted in the capillary and no further oxygen can be delivered

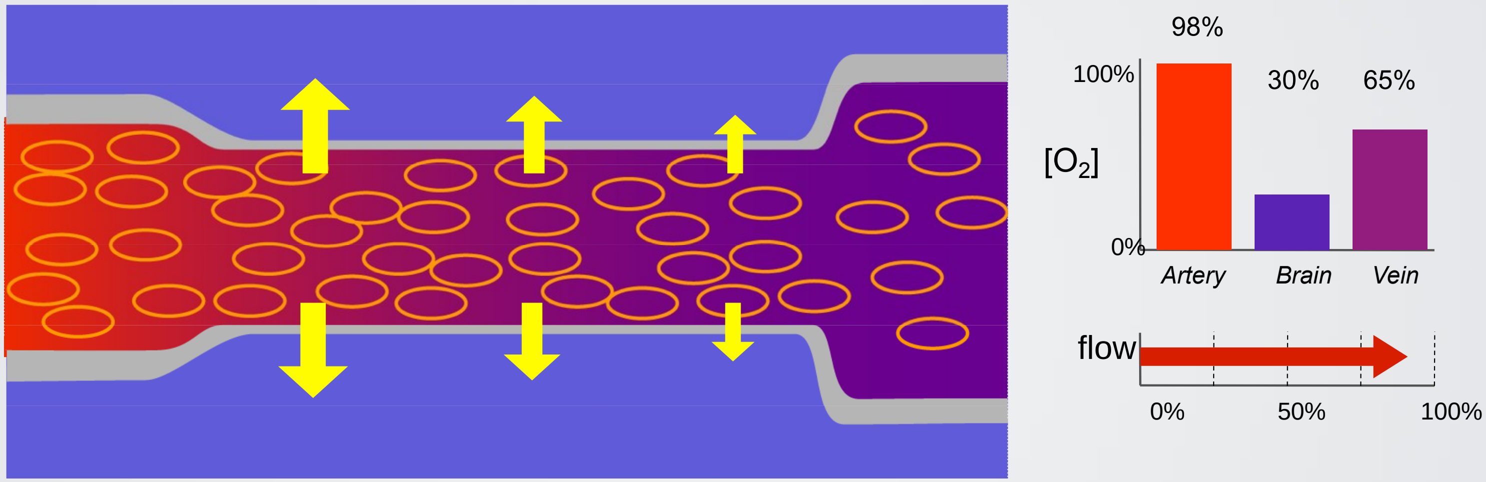
Why Does Venous O_2 Increase? (4)





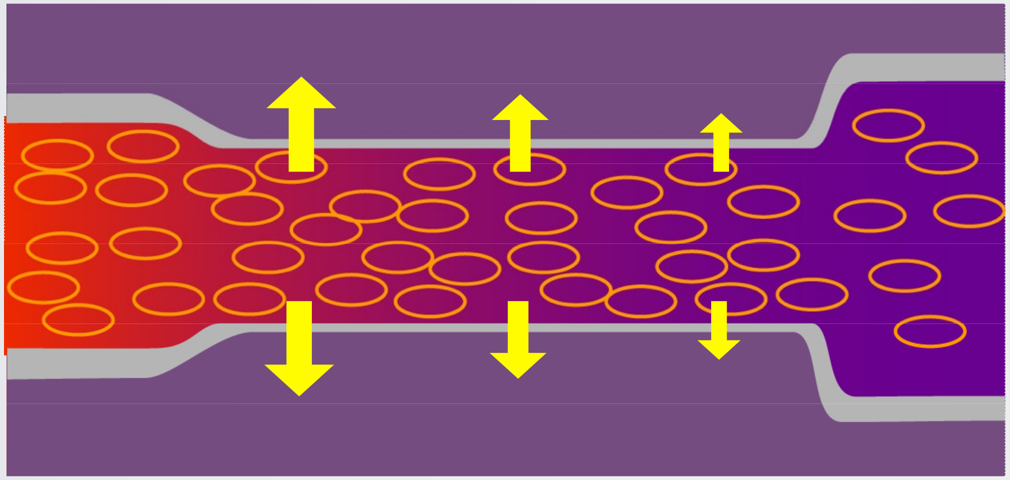
The vascular system responds by increasing blood flow so that more oxygenated blood is available throughout the capillary

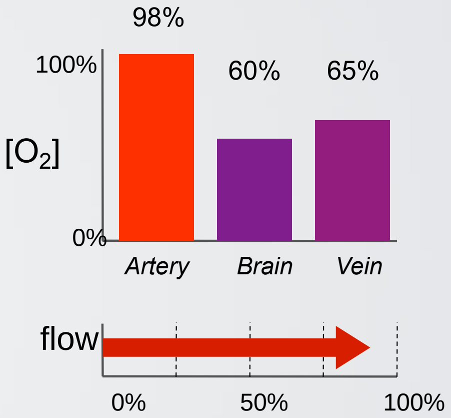
WHY DOES VENOUS O_2 INCREASE? (5)



Because the blood flow is increased more oxygenated blood passes into the venous end of the capillary

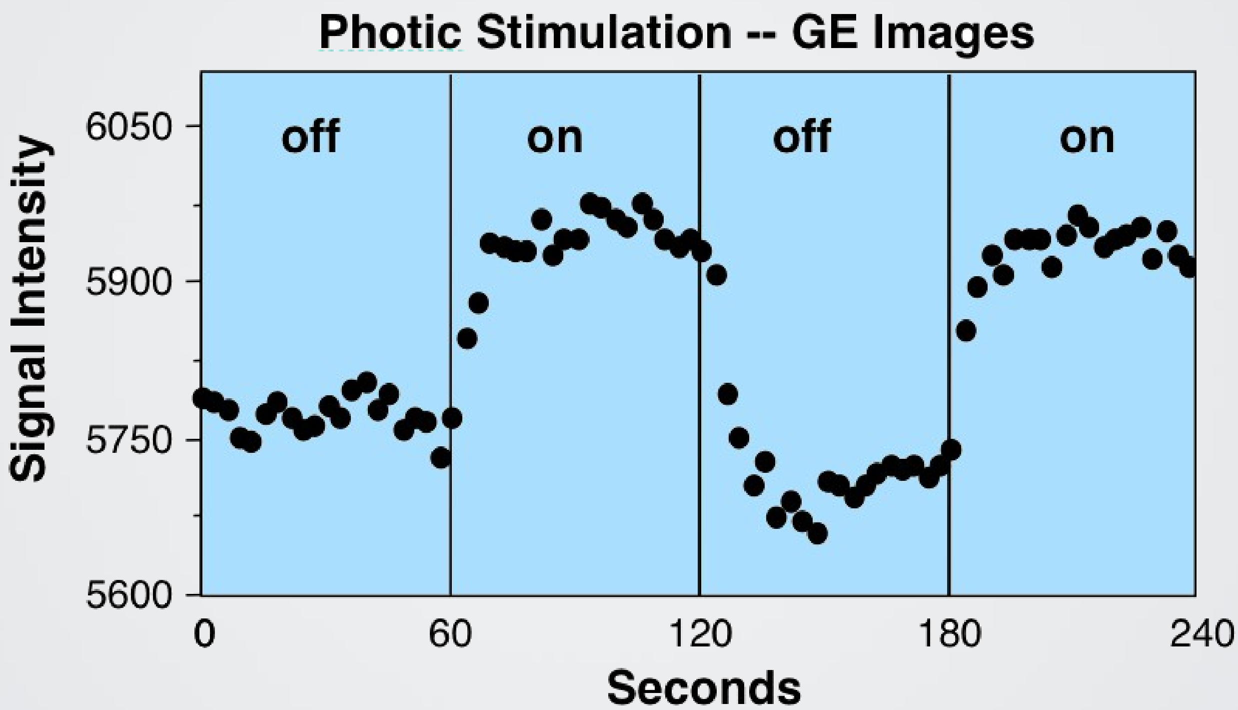
WHY DOES VENOUS O_2 INCREASE? (6)





With the Concentration Gradient Maintained Oxygen is Delivered to the Brain Parenchyma

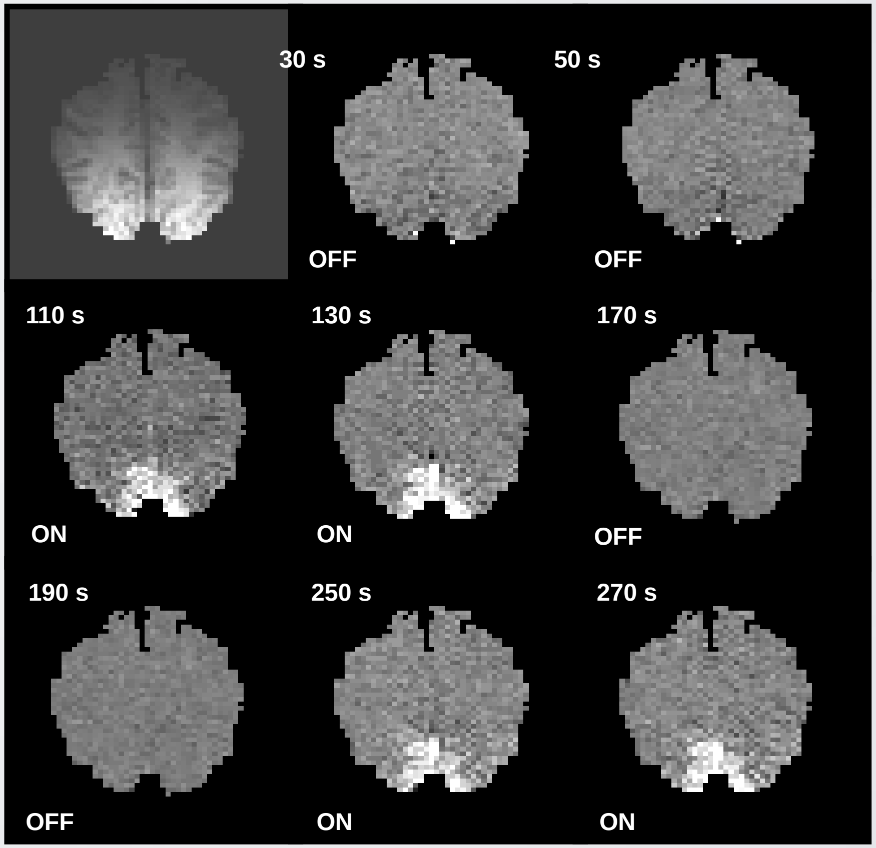
GRADIENT-RECALLED ECHO



Ken Kwong

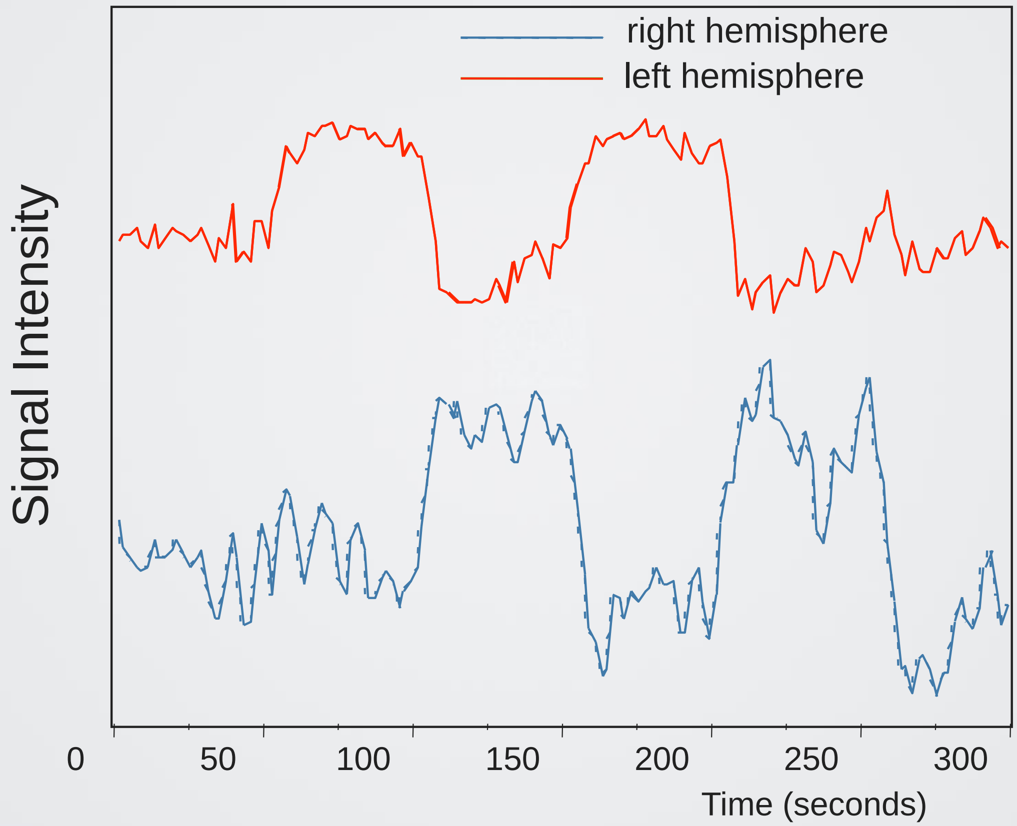
Ken Kwong

INVERSION RECOVERY
TE=42 TR=3000
TI = 1100
THICKNESS=10



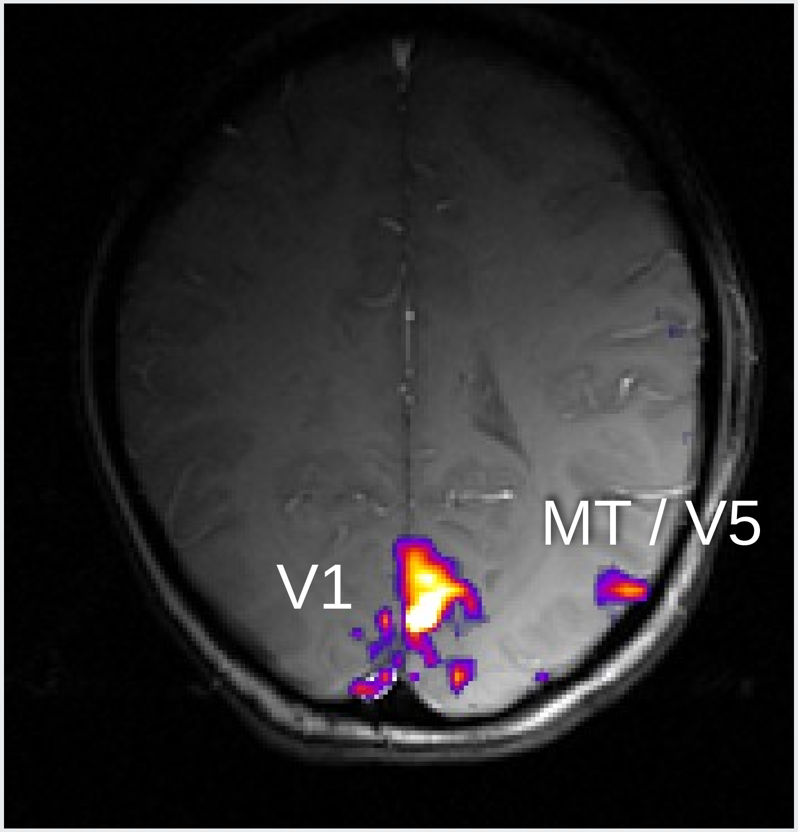
Seiji Ogawa   Ken Kwong

Brain Mapping - hemifield alternation

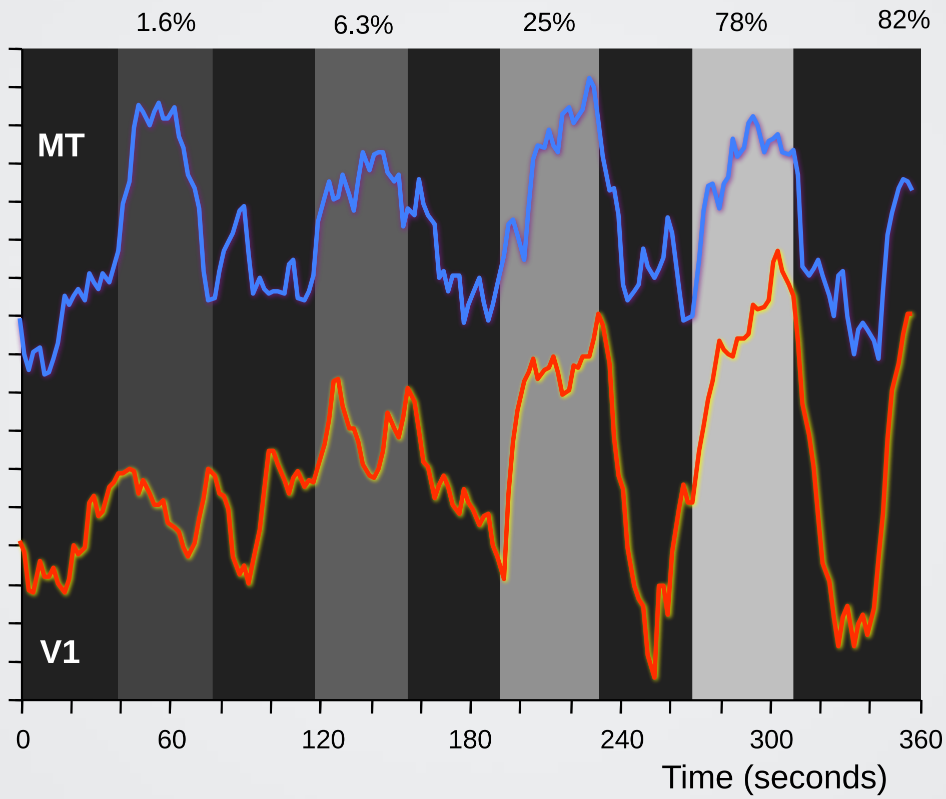


 www.brainmapping.org

Activation with Moving Visual Stimuli

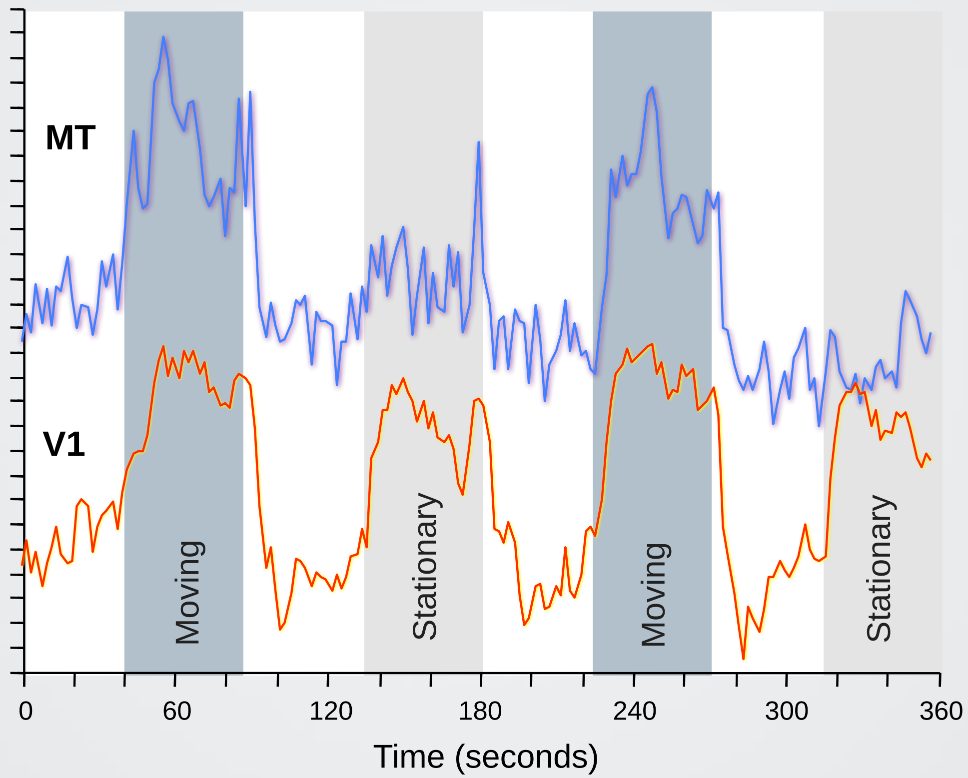


Contrast Response Test



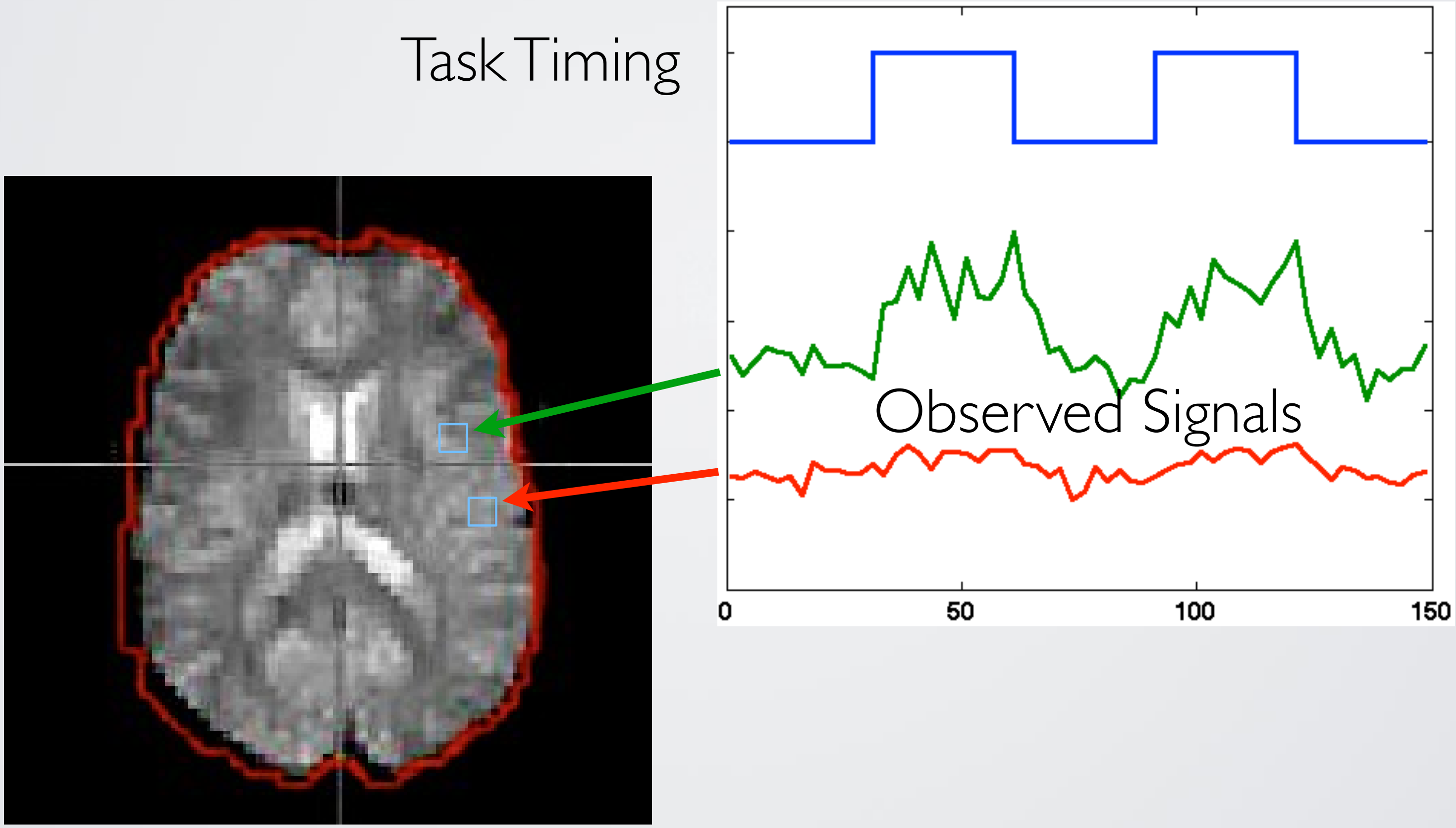
From R. Tootell

Motion Sensitivity Test



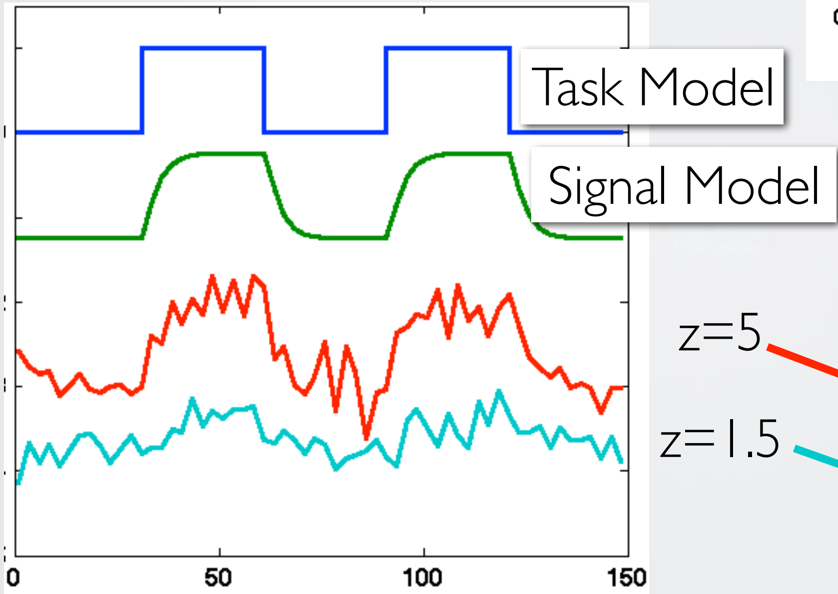
From R. Tootell

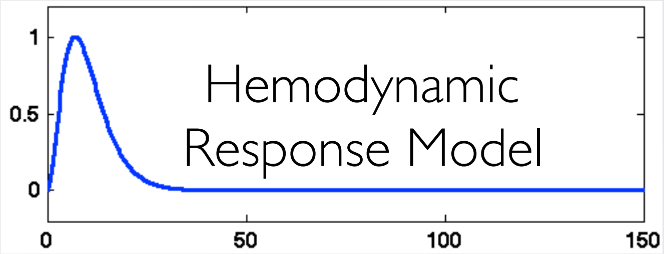
TRADITIONAL MRI ANALYSIS

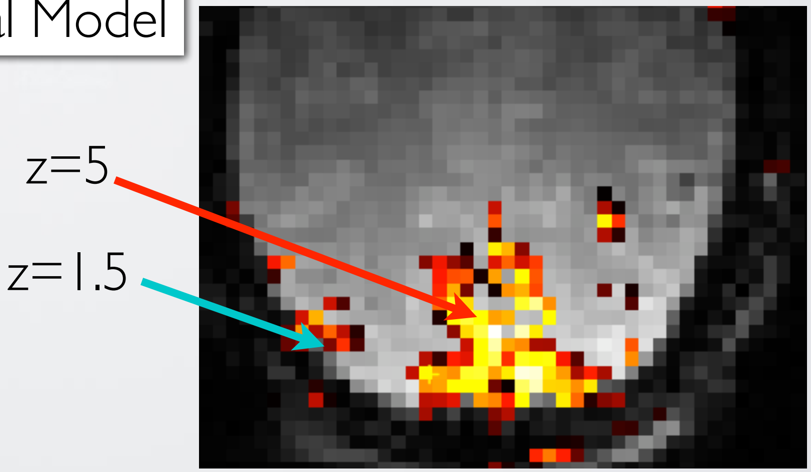


 www.brainmapping.org

Parametric MRI Analysis - Model Driven

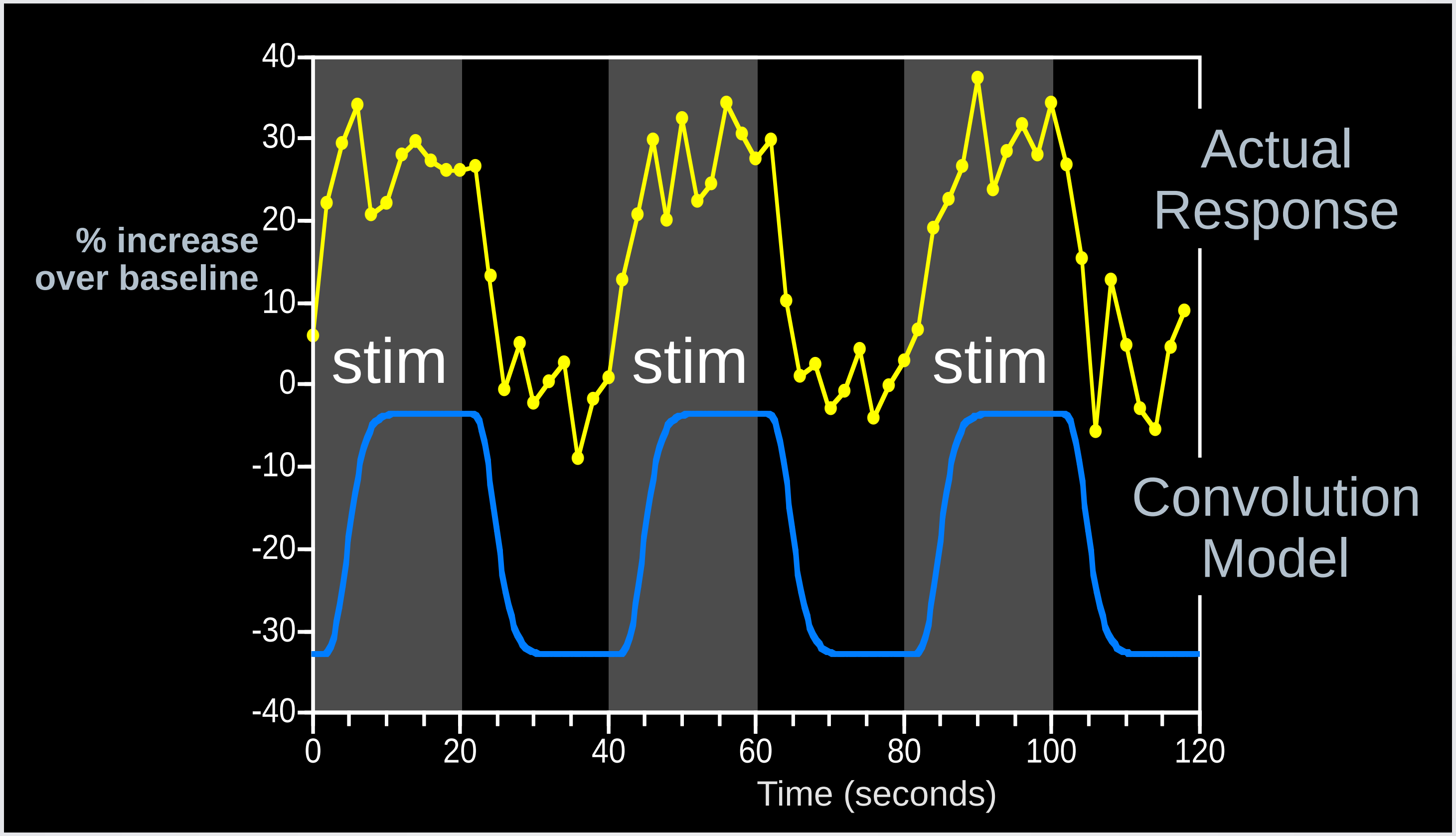






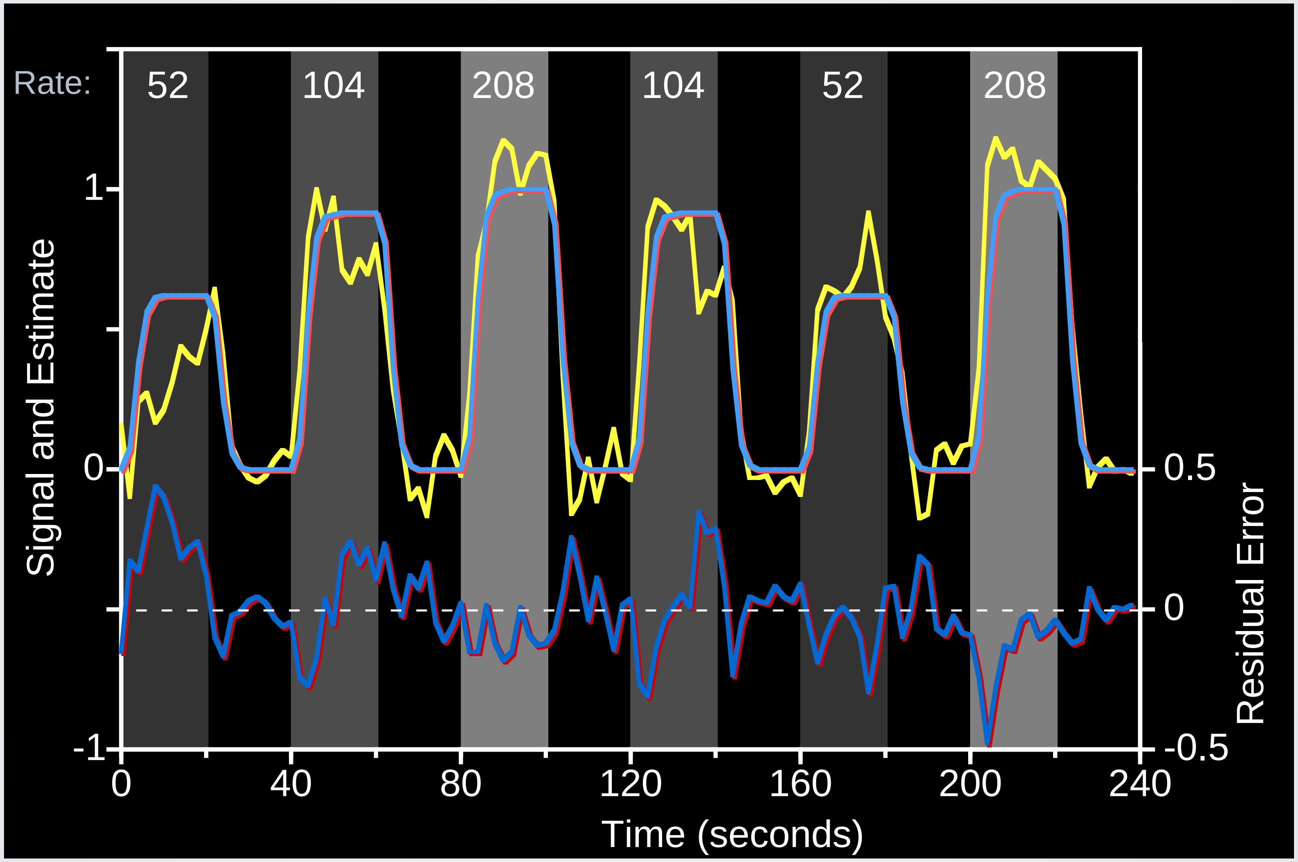
Cohen, NeuroImage **6**, 1997

Stimulus - HRF Convolution



Cohen, NeuroImage **6**, 1997

AMPLITUDE-WEIGHTED LINEAR ESTIMATE



Cohen, NeuroImage **6**, 1997

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