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425/525
Brain Inspired Computing

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Computational Brain Lab

Computer Science | Rutgers University | NJ, USA

Lecture 3 | NeuroBackground | Tuesday January 29th 2019

Course Syllabus

Brain Science

Biophysics of Brain Computation

Computational Modeling

Neurons as Spike Processing Machines

Neuroinspired AI

Integrating Neurons into SNNs

[Week 01] Overview of Brain Computation Handouts

[Week 02] Macro-Scale: Vision, Movement, Memory, Learning and Cognition Handouts

[Week 03] Micro- and Meso- Scales: Biological Neurons and Networks Handouts

[Week 04] Biophysically realistic Neuron Models Handouts + Downing Ch. 6

[Week 05] Phenomenological Neuron Models Gerstner Ch. 4

[Week 06] Probabilistic neuron models Gerstner Ch. 10

[Week 07] Evolving Neuronal Populations Downing Ch. 12

[Week 08] Brain as an optimization machine Sterling – Chs. 13/14

[Week 09] Learning via synaptic tuning Downing – Ch. 10

[Week 10] Memory and Attractor Dynamics Gerstner – Ch. 17

[Weeks 11-12] Students' presentations

[Week 13] Building functional SNNs Abbott Nature Neuroscience, 2015; Eliasmith Science, 2013

[Week 14] Synaptic Plasticity and Learning in SNNs Gerstner – Chs. 19/20

[Week 15] Computational elements of decision making, emotions and consciousness Ballard – Chs. 9/10/11

Please send us **1** email

Where: to Guangzhi Tang tangguangzhi.cs@gmail.com and *CC me*: konstantinos.michmizos@cs.rutgers.edu

Title: ***CS 425/525 - Team Project ***

Body:

a) names of your team members - with their NETIDs and their grad/undergrad status
e.g., John Point, jp123, graduate

b) Two titles for the best 2 ideas that you have:

c) Two possible 30 min slots for coming to discuss with us your ideas

These time slots should be between Monday and Thursday, the week after next (from 10 to 5)

What's next: You should receive from one of us a confirmation about your time slot

Please note that:

Note: 10% of your total course grade will be given on the presentation of your ideas - Please think about your project thoroughly and have an alternative idea

Potential Project ideas (1/2)

- Spike-based image encoding / decoding
- Spike-based image segmentation
- Spike-based image classification
- Linear Regression
- Spike-based bubble-sort algorithm
- Basic Logical Operations (AND, OR, X-OR etc.)
- Spike-based learning rules

Potential Project ideas (2/2) – Comp Vision

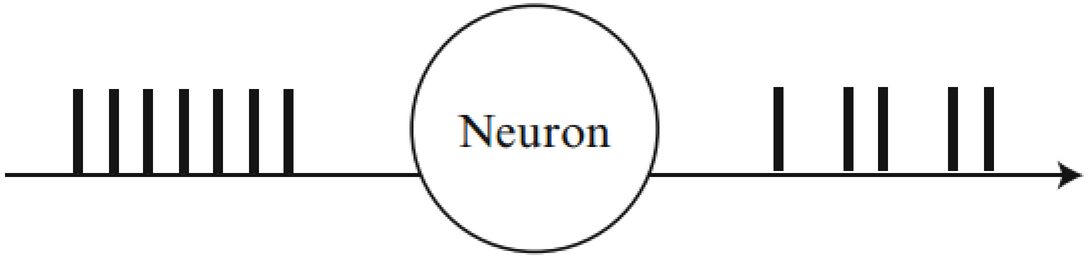
- Image encoding (neural representation)
- Image segmentation (edge detection via on center/off surround cells)
- Image binary classification (faces vs. houses, happy vs. sad people)
- Image recognition (0, 1, 2, …)

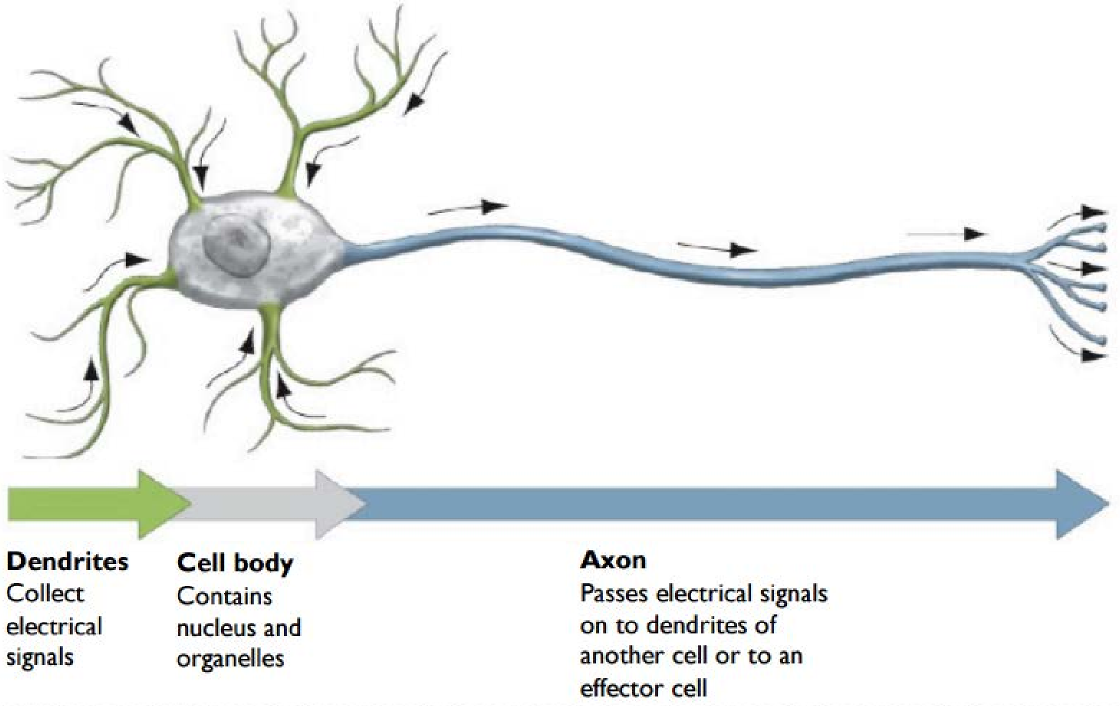
Outline

- The neuron anatomy
- The neuron physiology

Last Time

Neuron: Spikes in … Spikes out





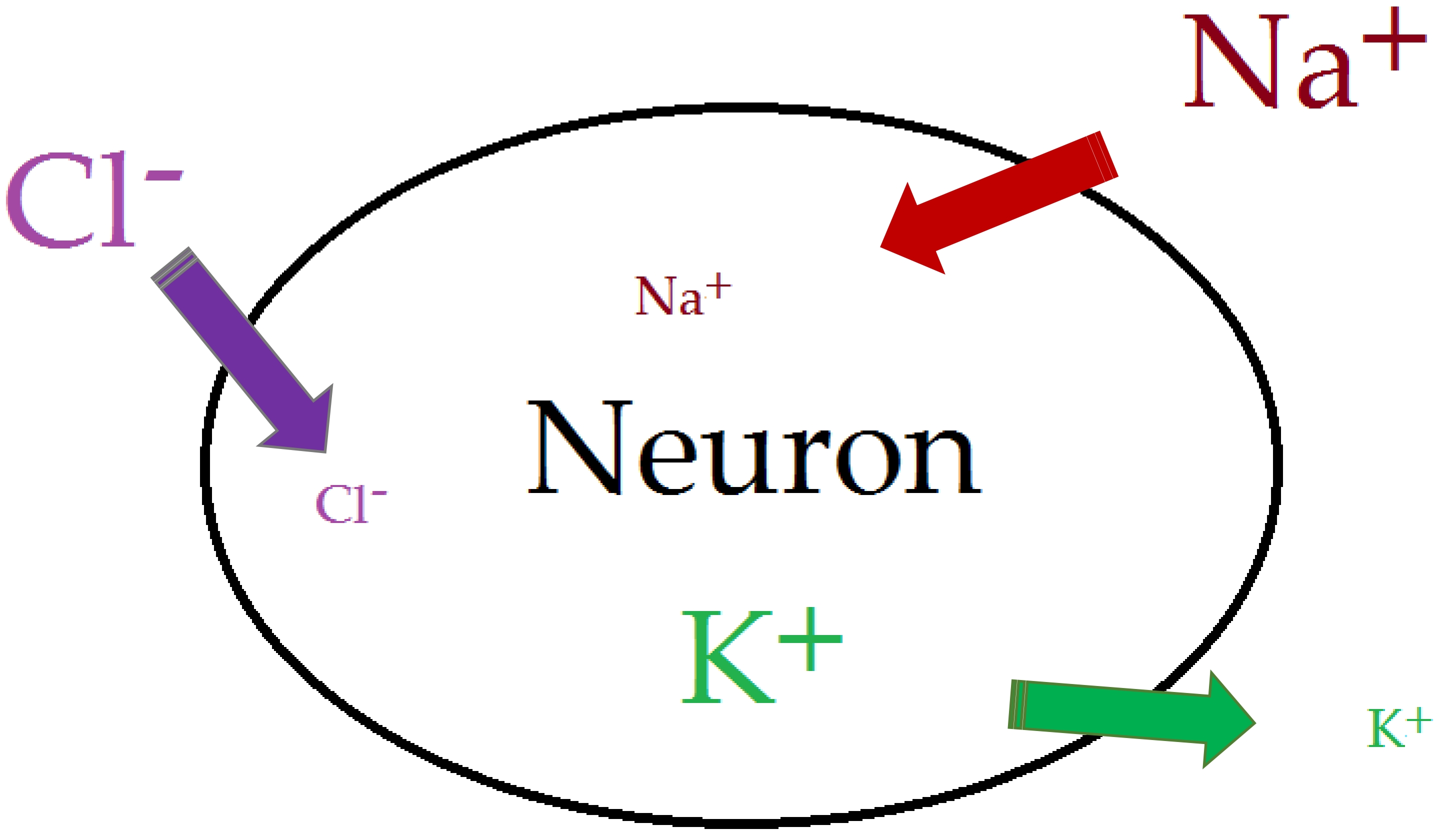
How spikes occur (1/2)

- The neuron is the basic cell that **processes** or **sends** information to/from the central nervous system from/to the periphery
- The neuron typically consists of a **soma**, the **dendrites** (input gateways) and an **axon** (output gateway)
- The neurons are bathed in the extracellular fluid, which contains **ions** (cations such as Na^+ and K^+ and anions such as Cl–)
- The concentrations of the ions between the two sides of the neuron’s membrane are different

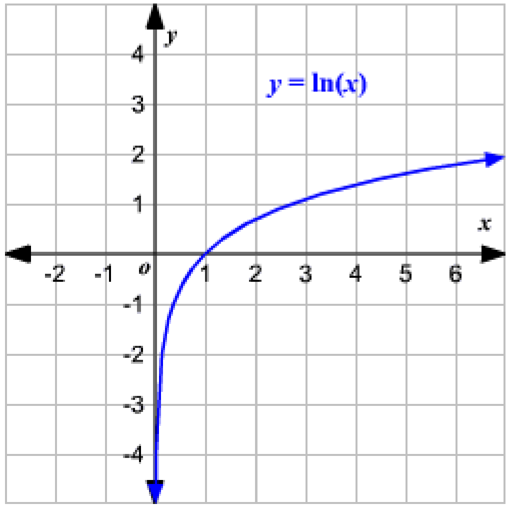
How spikes occur (2/2)

- This difference on ion concentrations creates the **membrane potential**, which is about -65 mV (i.e., there are more "negative" ions inside the neuron than outside)
- Ions can penetrate the neuron's membrane through **ion channels**, which are specialized openings in the membrane that allow certain ions to pass through them
- The movement of ions creates the change in the membrane potential: a larger concentration difference creates a larger flux of ions (Fick's Law of Diffusion) and, therefore, a larger current travelling in/out of the neuron

Membrane Potential



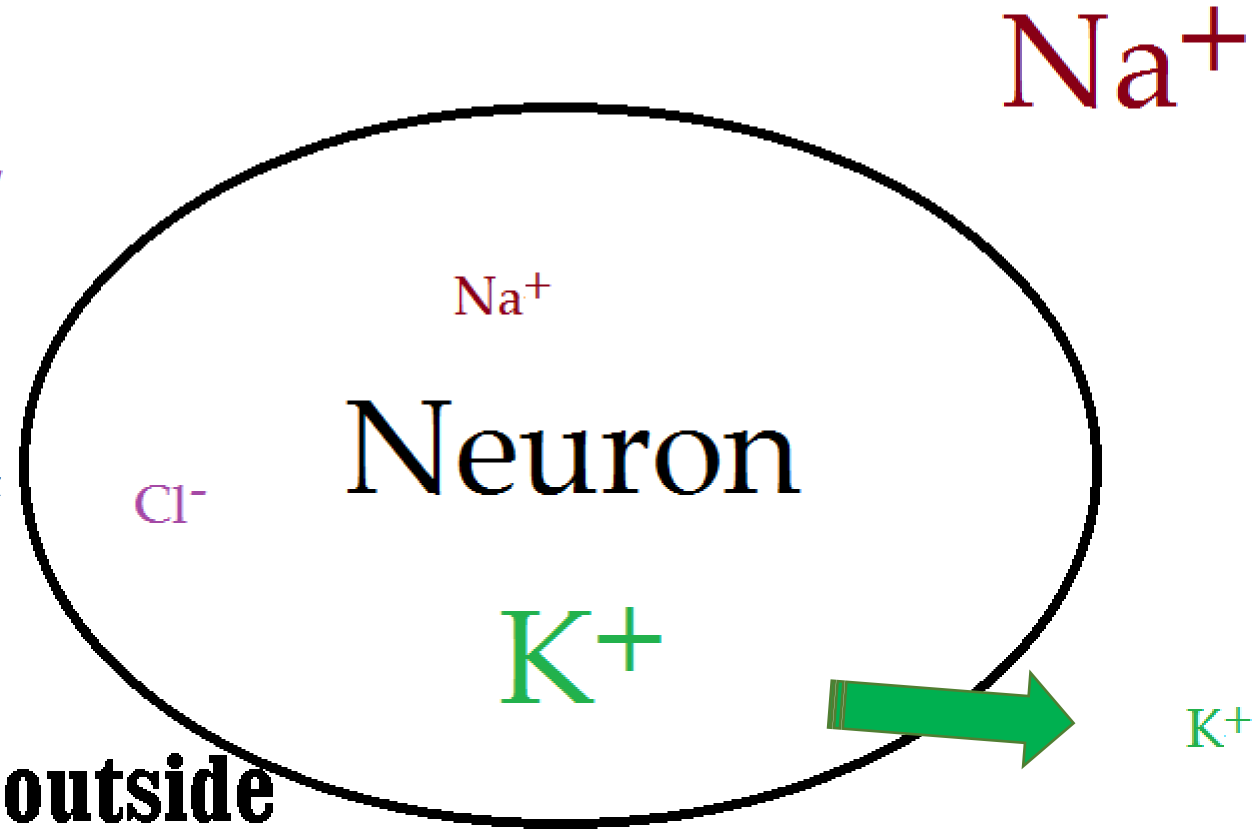
The Nerst Equation



Valence
(+1 for K+/Na+)

Cl^{-}

Temperature
(Kelvin)

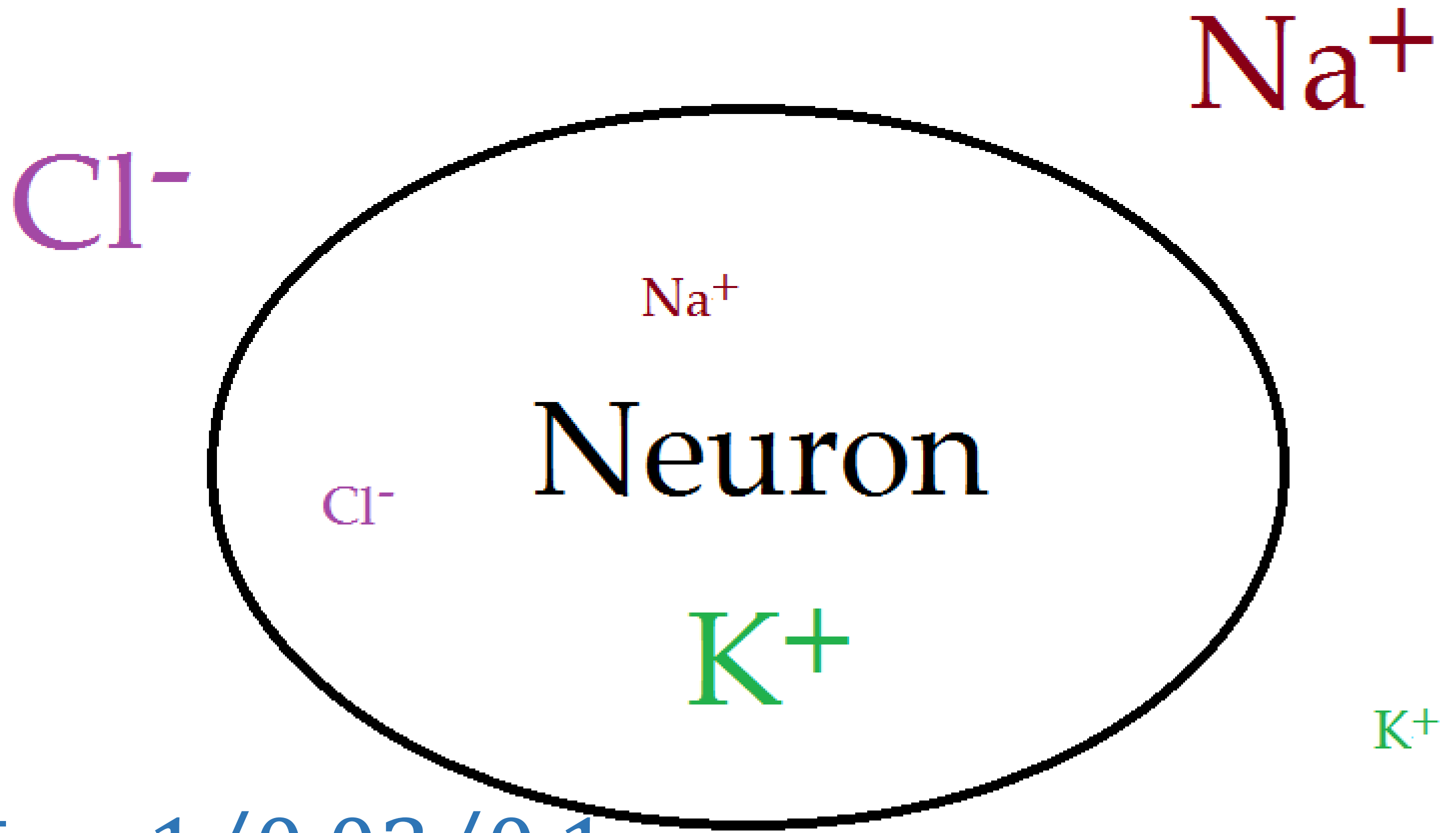


Gas
Constant

Faraday
Constant

$$E_x = \frac{RT}{zF} \ln \frac{[X]_{outside}}{[X]_{inside}}$$

The Goldman Equation



$$P_K^+/P_{Na}^+/P_{Cl}^- = 1/0.03/0.1$$

$$V = \frac{RT}{F} ln\left(\frac{P_{Na}^+[Na^+]outside + P_{Na}^+[K^+]outside + P_{Cl}^-[Cl^-]inside}{P_{Na}^+[Na^+]inside + P_K^+[K^+]inside + P_{Cl}^-[Cl^-]outside}\right)$$

Today

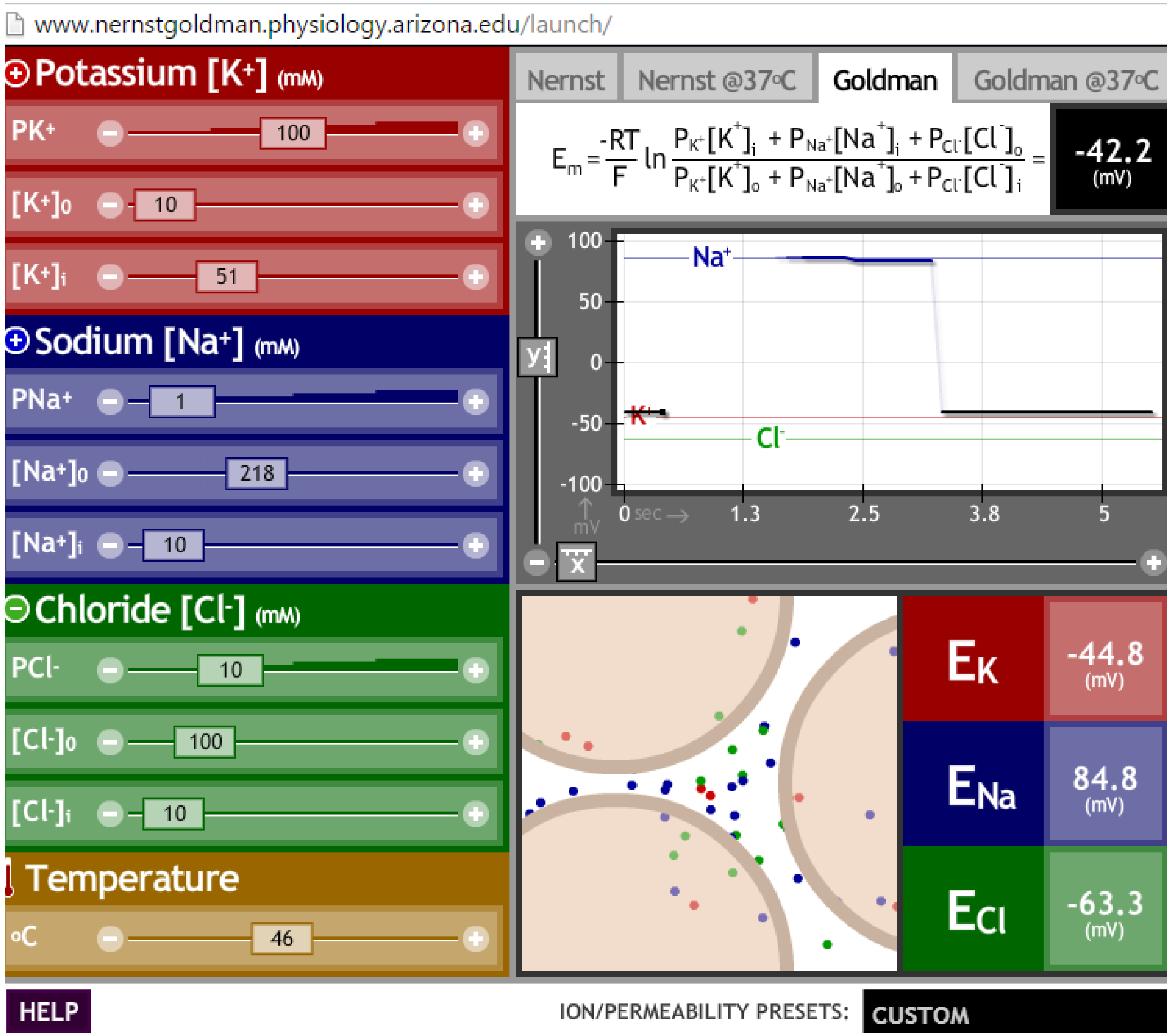
The Hodgkin-Huxley neuron model

- The **Hodgkin-Huxley model** of neuron (Hodgkin & Huxley, 1952) simulates **how a neuron generates an action potential**, which is a sharp change in the membrane potential that initiates in the soma and propagates all the way down the neuron's axon, until this potential difference reaches the synapse (the junction between two neurons that communicate)
- Qualitatively, the Hodgkin - Huxley model simulates the **opening/closing of three main ion channels** (Na^+, K^+, Cl^-) during the generation of an action potential

Example: a Hodgkin-Huxley model of a neuron and the administration of sedatives

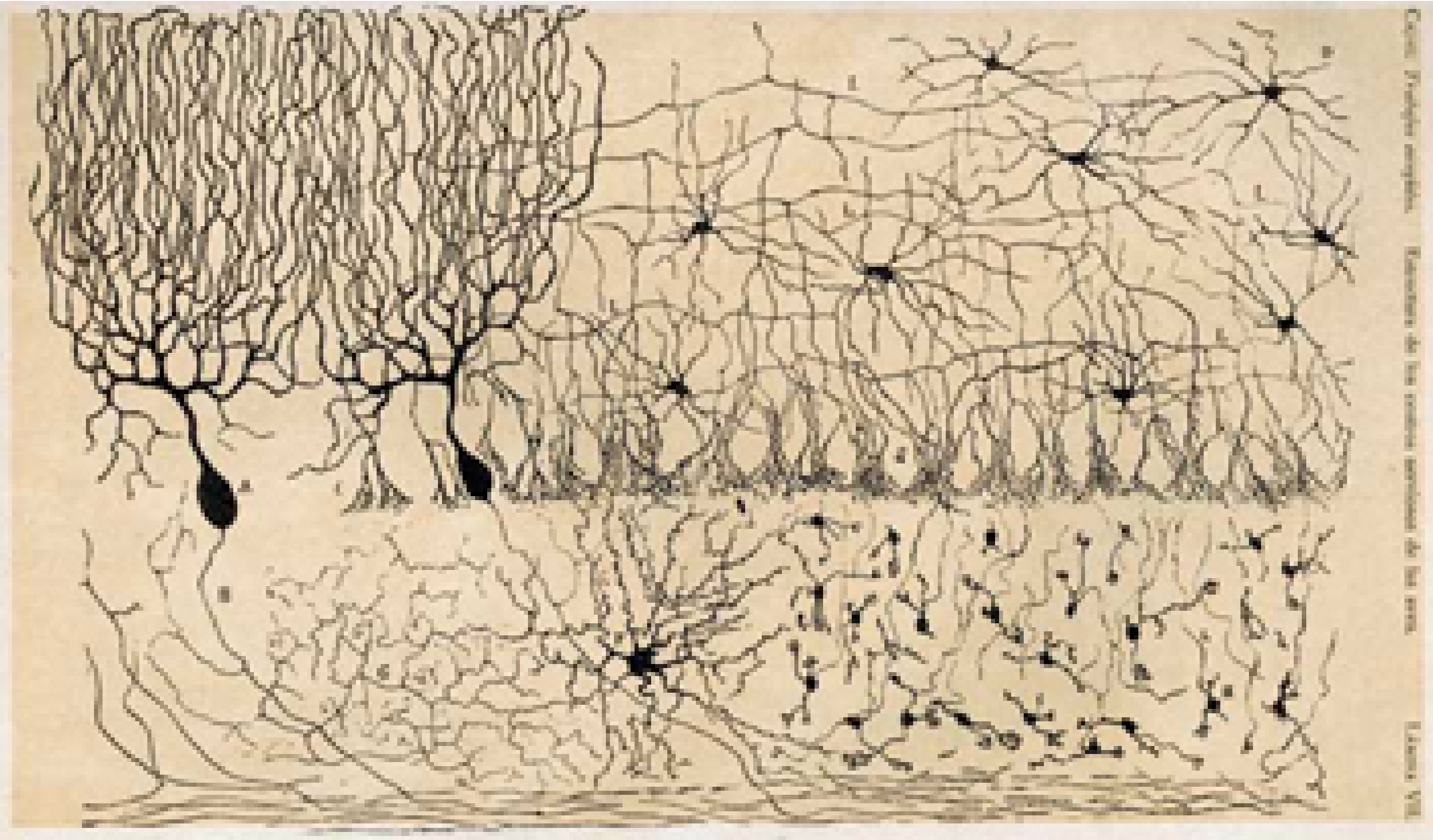
- [easy path]
  - I want to tweak the parameters of a Hodgkin-Huxley neuron model to simulate the effects of benzodiazepine administration
- [hard path]
  - I want to tweak the Hodgkin-Huxley neuron model to simulate the decreasing effect that benzodiazepines have after repeated administration
  - I want to create a network of Hodgkin-Huxley neuron models to simulate the effects of benzodiazepine administration on the network dynamics

The Nerst/Goldman Equation simulator



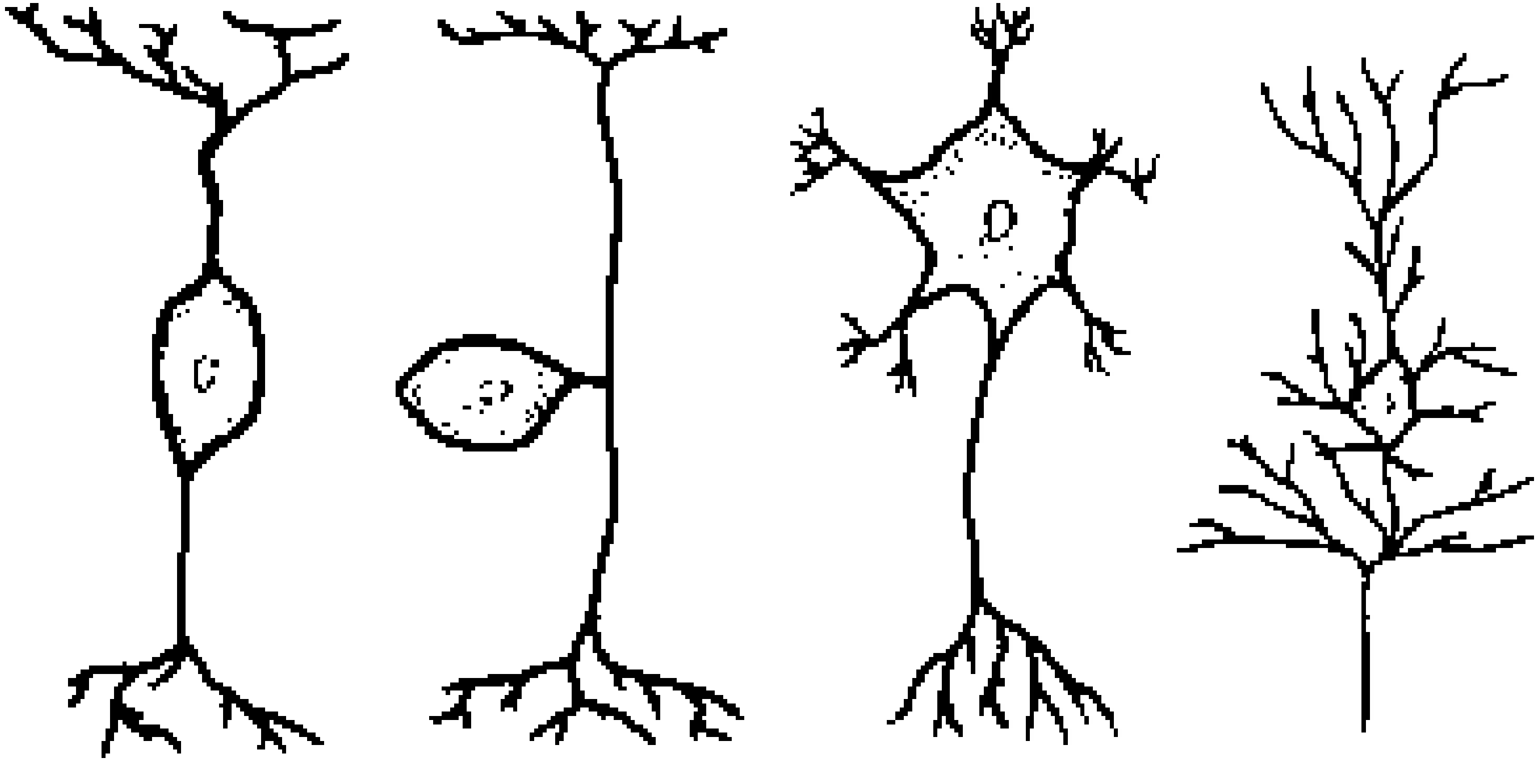
http://www.nernstgoldman.physiology.arizona.edu/

Ramon Y Cajal (1905)



Nobel Prize in Physiology of Medicine, 1906

Neuron Types



Bipolar
(interneuron)

Unipolar
(sensory neuron)

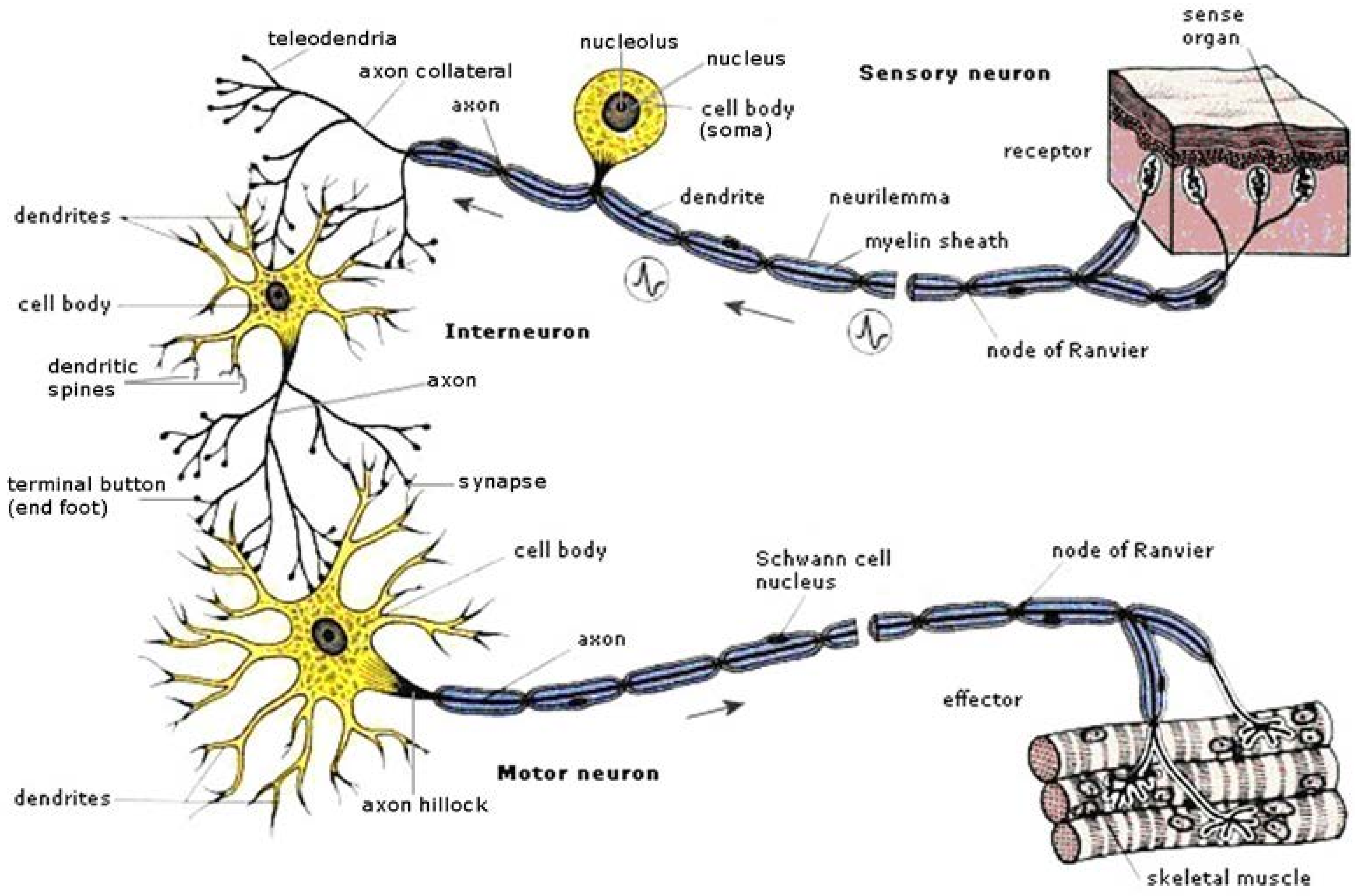
Multipolar
(motor neuron)

Pyramidal
(corticospinal tract)

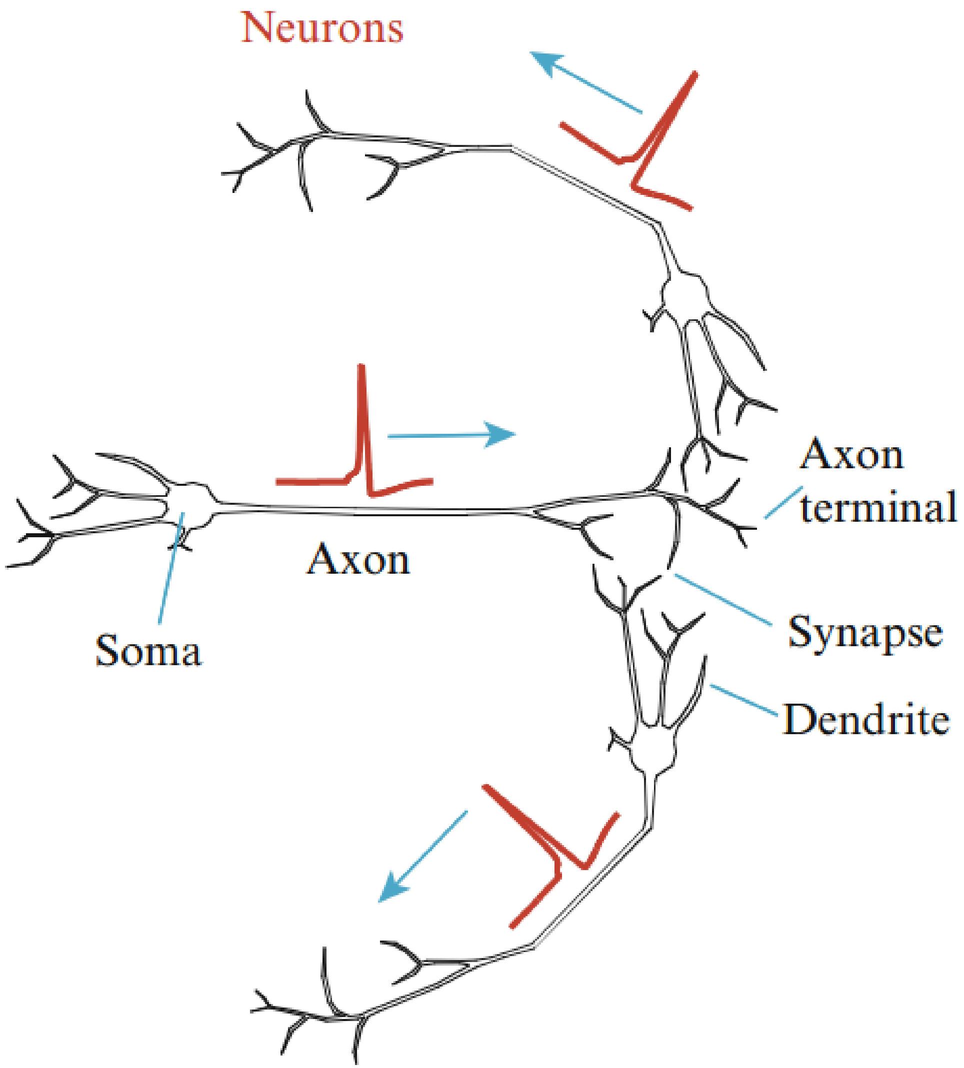
Can you find (the) differences across the neuron types?

Can you find a reason for them?

Connecting the 3 basic neuron types together



Summary: A network of 3 neurons sending/receiving spikes



Outline

- The neuron anatomy
- The neuron physiology

Course Goals – revisited

- To explore how computation in the human brain can be effectively modeled across different levels of abstraction
  - How does a neuron represent information?
  - How does a neuron change its connections strengths?
  - How does a neuron follow local rules of survival (homeostasis) while being part of one (or more) brain networks accomplishing specific tasks?

- To introduce a computational formalization of brain function based on the Spiking Neural Networks –SNNs

- To employ SNNs and solve a CS problem in a term-wide project

Neurons

- They accept input in the form of spikes and respond by sending spikes

- What kind of information neurons process?

Stroop Test

Stroop Test

Neural Representations

PURPLE YELLOW RED

BLACK RED GREEN

RED YELLOW ORANGE

BLUE PURPLE BLACK

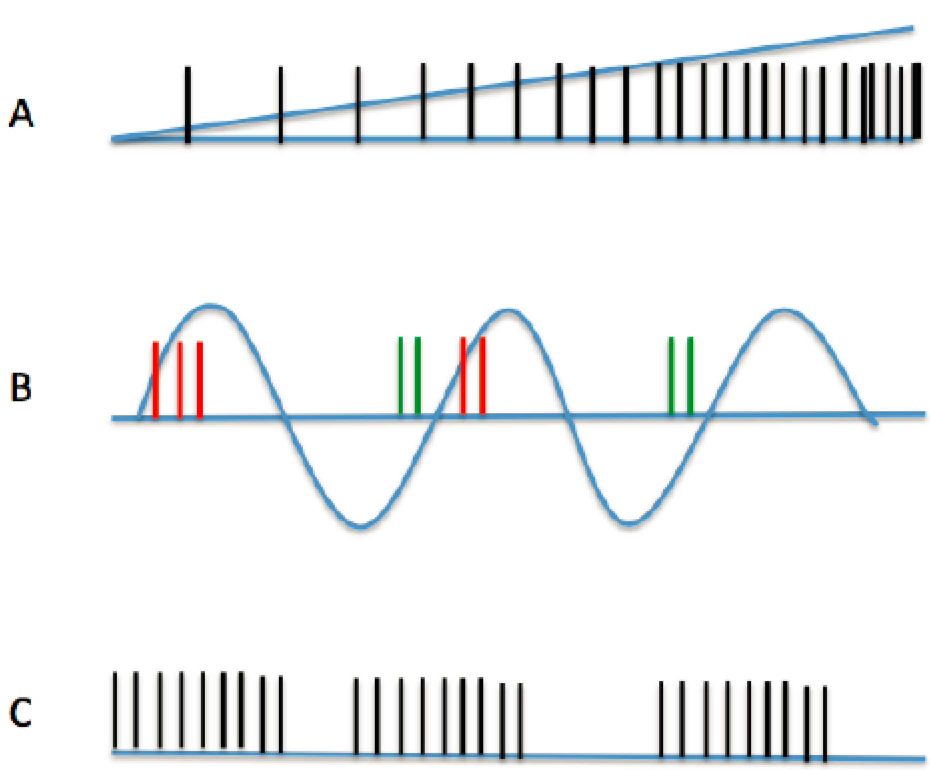
RED GREEN ORANGE

Cna Yuo Raed Tihs?

fi yuo cna raed tihs, yuo hvae a sgtrane mnid too. Cna yuo raed tihs? Olny 55 plepoe out of 100 can (kddiing).

i cdnuolt blveiee taht I cluod uesdnatnrd waht I was rdanieg. The phaonmneal pweor of the hmuan mind! It dseno’t mtaetr in waht oerdr the ltteres in a wrod are, the olny iproamtnt tihng is taht the frsit and lsat ltteer be in the rghit pclae. The rset can be a taotl mses and you can sitll raed it whotuit a pboerlm. Tihs is bcuseae the huamn mnid deos not raed ervey lteter by istlef, but the wrod as a wlohe. Azanmig huh? yaeh and I awlyas tghuhot slpeling was ipmorantt! if you can raed ti, you wlli gte an A.

Spike-based information encoding



Brainstem
Vestibulo-occular reflex:
Rate = number

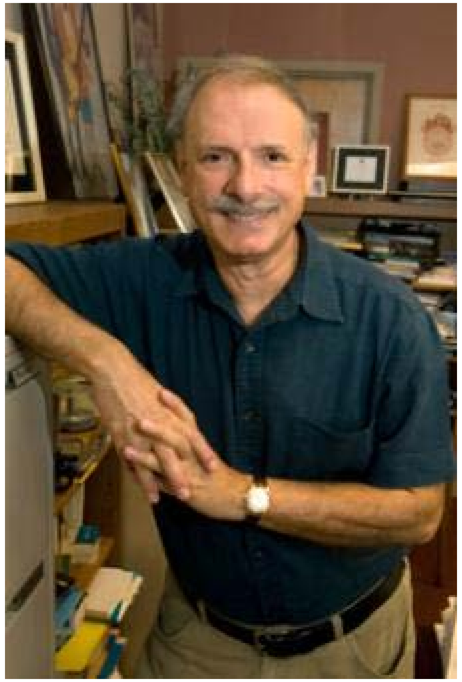
Hippocampus
Theta phase organizes the beginning and end of a task

Basal Ganglia
TANS cells indicate subtask breakpoints with silence

Computation with slow circuitry

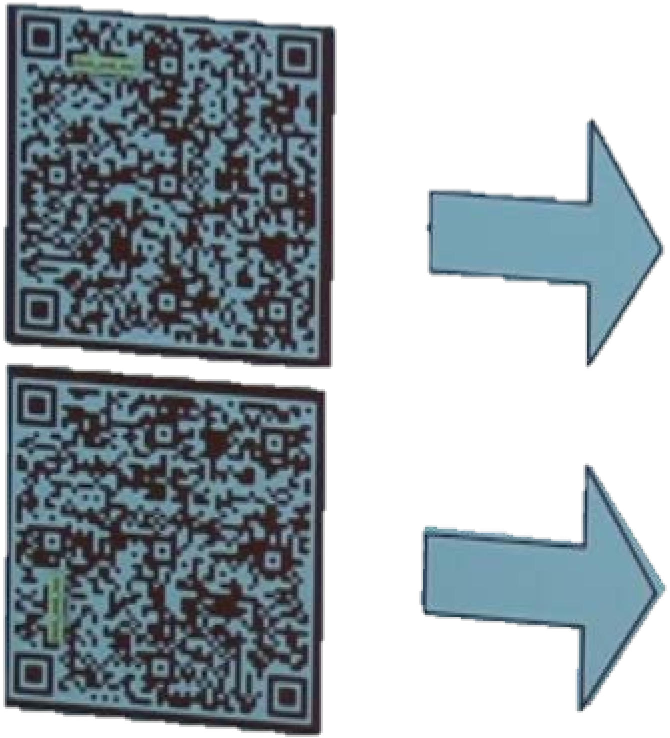
Feature	Value
Number of neurons	10^{11}
Ave. no. connections per neuron	10^{4}
Total connections	10^{15}
Speed of communication	10 meters/sec
Average signaling rate	10 voltage spikes/sec
Sum of all axonal lengths	10^{6} km

What kind of information neurons process?



Apostolos Georgopoulos, MD

Regents Professor of Neuroscience, University of Minnesotta
McKnight Presidential Chair in Cognitive Neuroscience
American Legion Brain Sciences Chair
Professor of Neuroscience, Neurology, and Psychiatry
Director, Center for Cognitive Sciences



LEFT

RIGHT

What kind of information neurons process?

Motor commands are the results of motor patterns

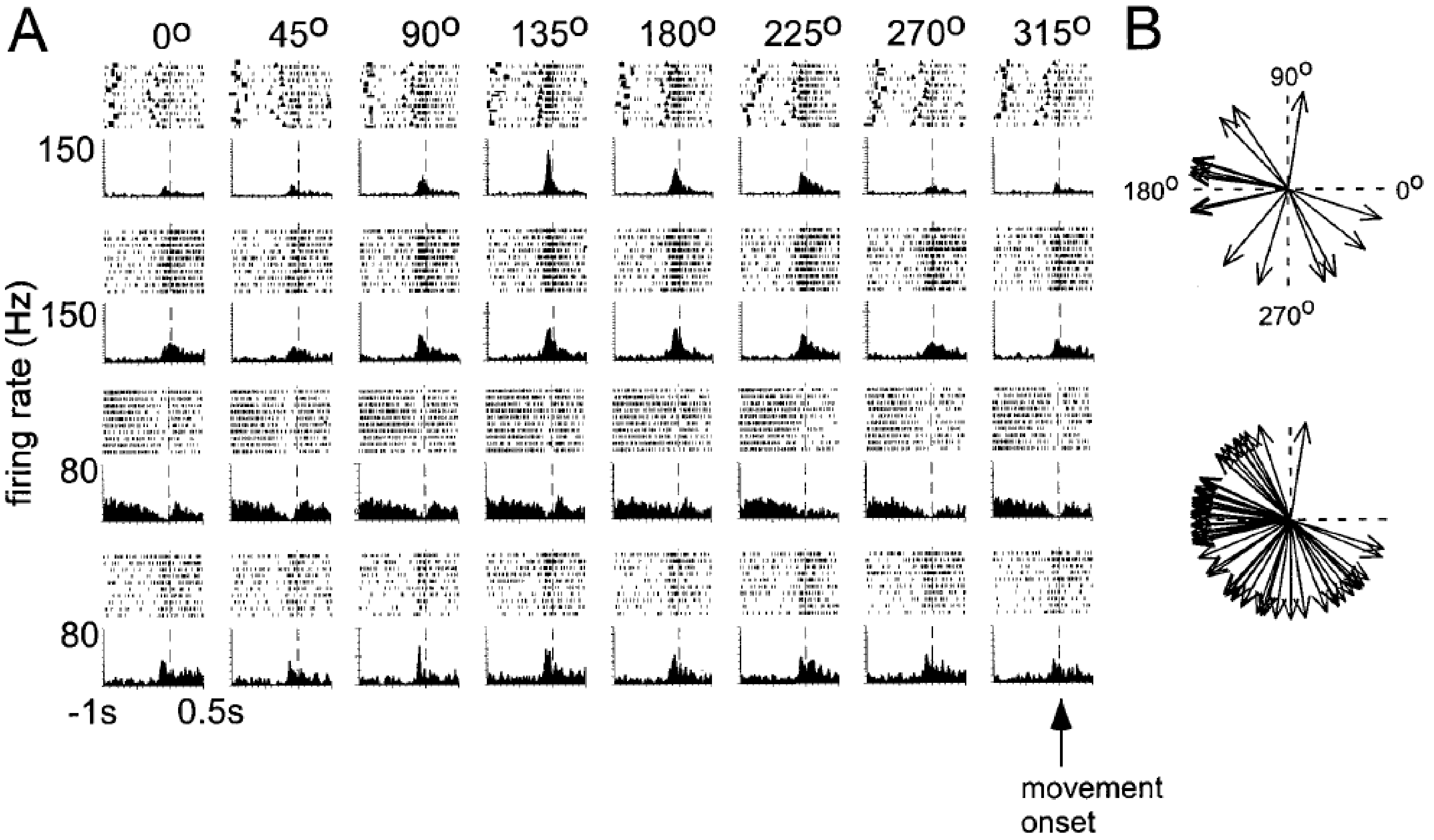
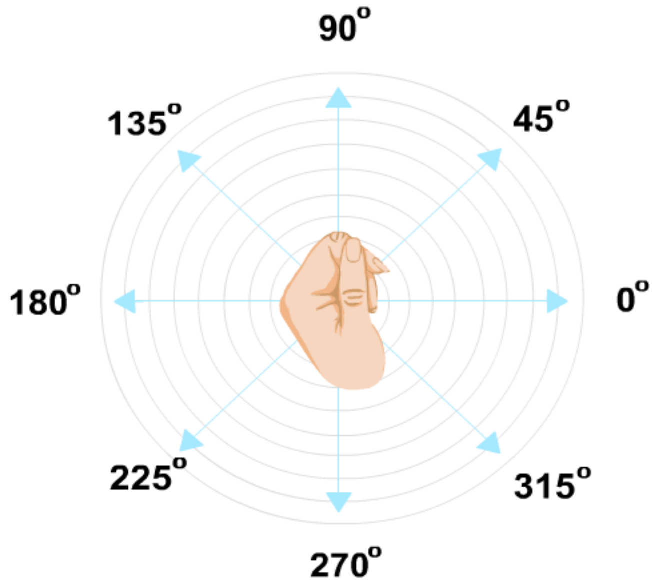


Figure 1. *A,* Raster plots and perievent histograms of four simultaneously recorded neurons in monkey MI for movements in all eight directions. Each *vertical mark* in the raster trace is a single action potential attributed to a single neuron. Each *row* of the raster is a single trial in which the monkey moved from a central hold position to a radially displaced target position. Rasters and histograms are aligned to the onset of movement (*dotted line*) and show the interval from 1 sec before to 500 msec after the onset of movement. The instruction signal (*solid square*), go cue (*solid triangle*), and reward (*solid circle*) are also shown in the rasters. Each perievent histogram was constructed with a bin width of 20 msec and then smoothed. *B,* Distributions of the preferred directions for neurons recorded from one data set (*top*) and from all data sets combined (*bottom*). The preferred direction of each unit was determined by fitting a cosine curve to the directional tuning function of the unit.

Directional tuning of motor cortex neurons

The cell fires maximally when the hand is moved in the 135º or 180º directions, moderately when the hand moves in the 90º and 225º directions, and is silent when the hand moves in the opposite directions (0º, 45º, 270º, and 315º)

Click on each directional coordinate



(Georgopoulos et al. 1982)