A very short introduction to neurons

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U2IS - ENSTA - IPParis

ecampus moodle: MI210 - Modèles neuro-computationnels de la vision (P4 - 2020-21)

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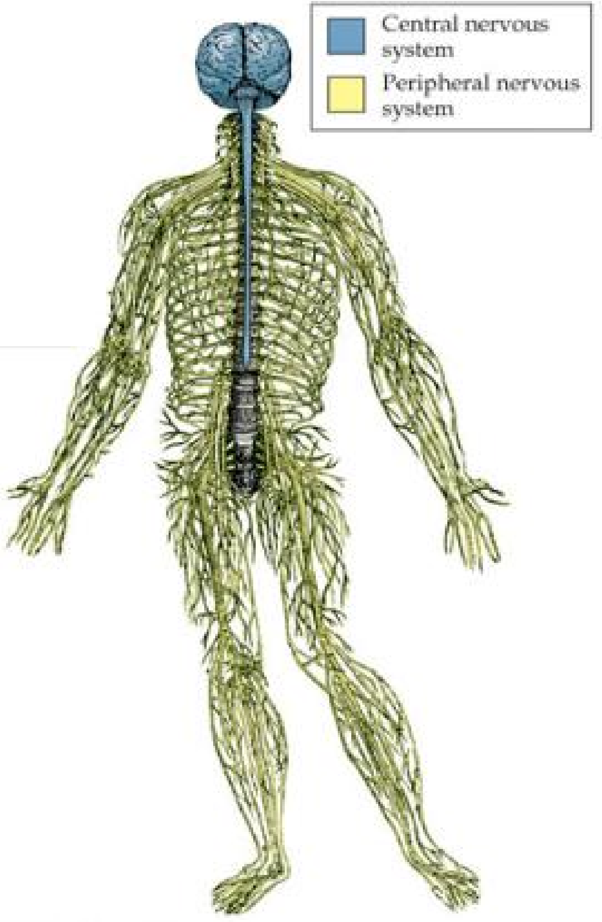
Nervous System Components



- Central: brain and spinal cord. Combines information and controls activity across the whole organism.

- **Peripheral:** cranial and spinal nervs. Relay between Central Nervous System and the rest of the body

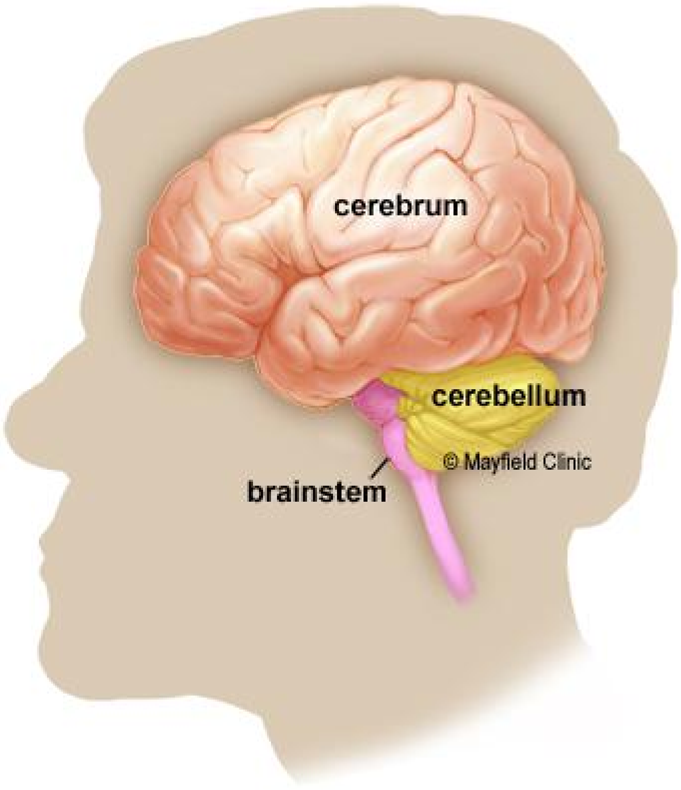
https://socratic.org/questions/whats-the-difference-between-the-central-nervous-system-the-peripheral-nervous-s
Crash course in neuroscience from British Neuroscience Association: https://youtu.be/qPix_X-9t7E

Brain regions classification methods

- **Anatomical**: Microscopy
- **Functional:** Functional/Diffusion Magnetic Resonance Imaging, Magnetoencephalography, neural recordings
- **Evolutionary:** Microscopy
- **Developmental:** Microscopy

Brain regions

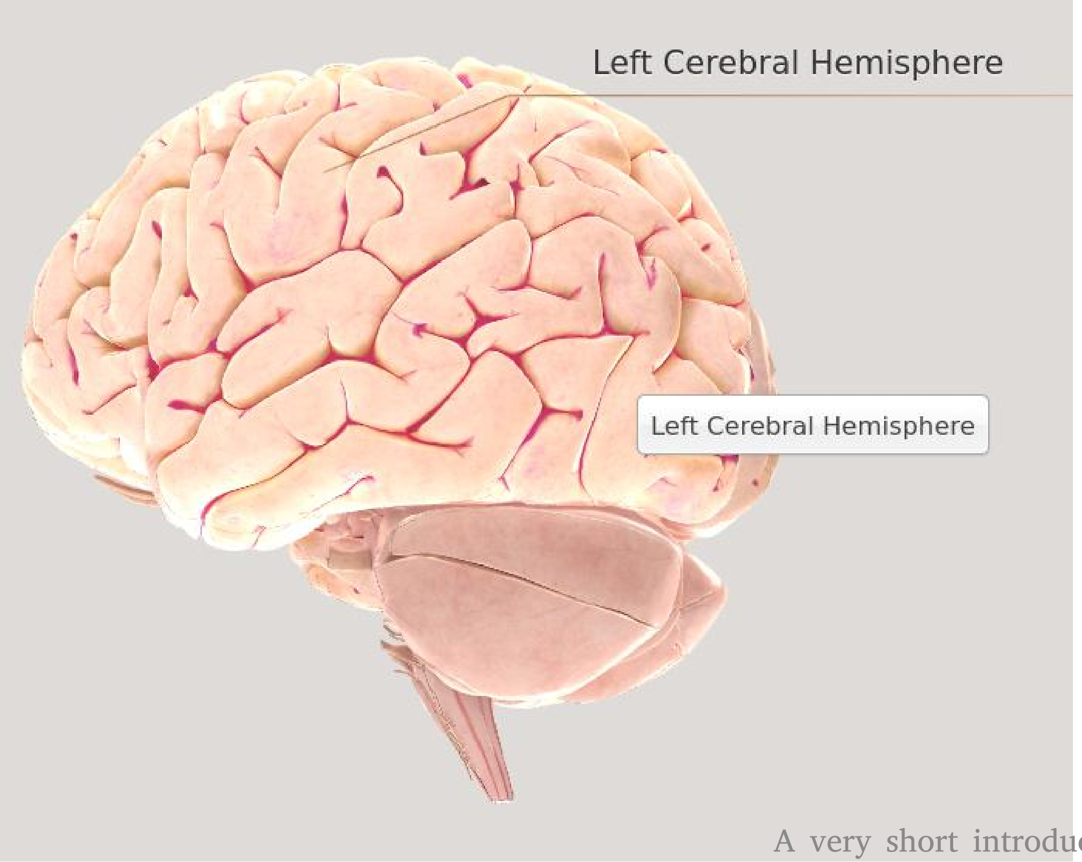
- **Cerebrum:** Performs higher functions: sensing, speech, reasoning, emotions, learning, and fine control of movement.
- **Cerebellum:** Coordinates muscle movements, maintain posture, and balance.
- **Diencephalon:** Relays sensory information and controls many PNS autonomic functions.
- **Brainstem:** CNS relay center. Performs automatic functions: breathing, heart rate, body temperature, cyrcadian cycles, digestion, sneezing…

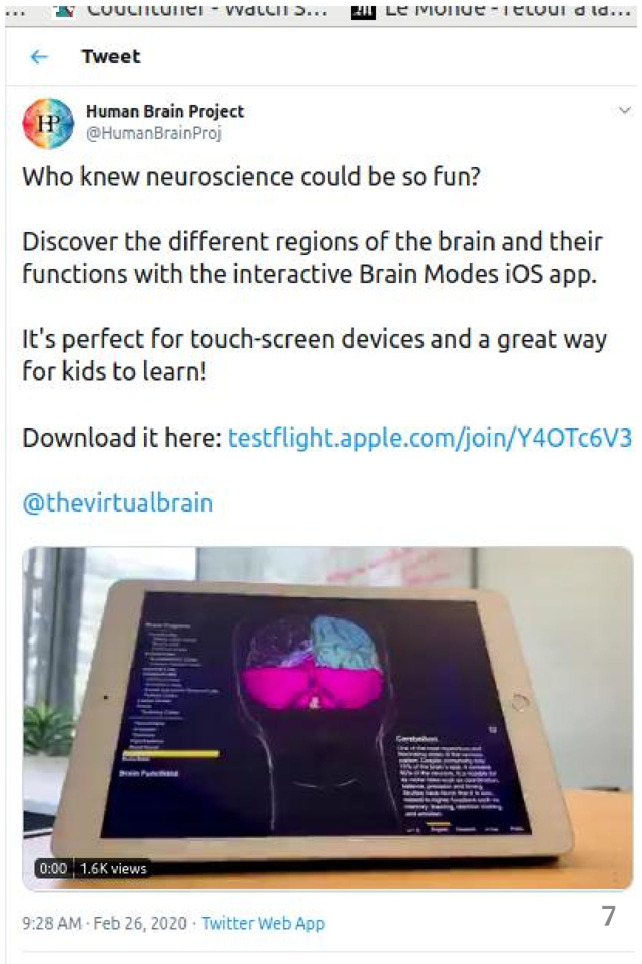


https://mayfieldclinic.com/pe-anatbrain.html
https://www.brainfacts.org/3D-Brain#intro=true

Visualization proposals

https://www.brainfacts.org/3D-Brain#intro=true




Tweet

Human Brain Project
@HumanBrainProj

Who knew neuroscience could be so fun?

Discover the different regions of the brain and their functions with the interactive Brain Modes iOS app.

It's perfect for touch-screen devices and a great way for kids to learn!

Download it here: testflight.apple.com/join/Y4OTc6V3

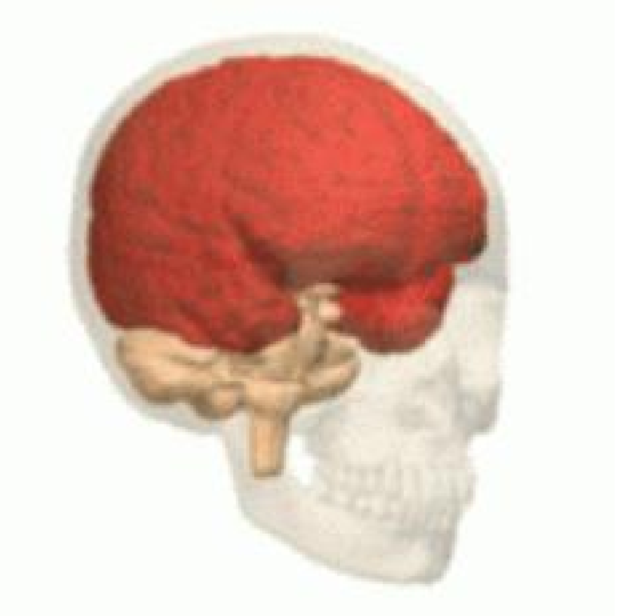
@thevirtualbrain

0:00 1.6K views

9:28 AM · Feb 26, 2020 · Twitter Web App

Cerebrum areas

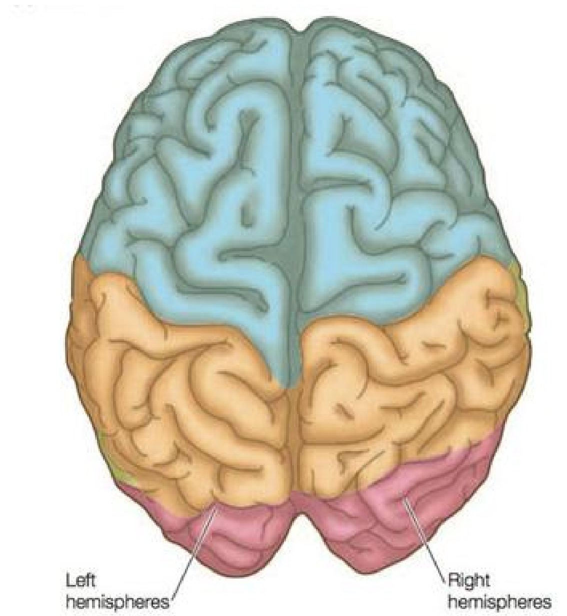
- **Cortex:** Perception, motor (planning, control and execution), language
- **Hippocampus:** Memory consolidation
- **Basal ganglia:** Control of voluntary motor movements, procedural learning, habit learning, eye movements, cognition and emotion
- **Olfactory bulb:** Olfactory processing

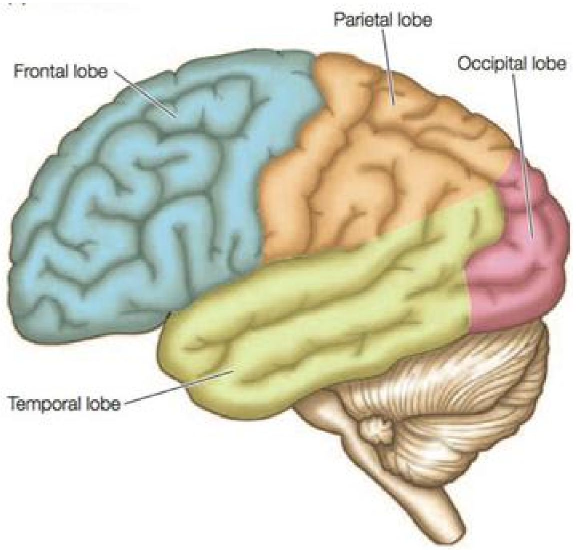


https://en.wikipedia.org/wiki/Cerebrum

Cortical areas

- **Hemispheres:** Right, left. The right receives information and controls the left part of the body and vice-versa. Mostly common functions, but also specialised
- **Lobes:**
  - Frontal: Reward, attention, short-term memory tasks, planning, and motivation
  - Parietal: Sensory information integration, visuospatial processing
  - Occipital: Vision (visual cortex)
  - Temporal lobe: Sensory processing, language recognition

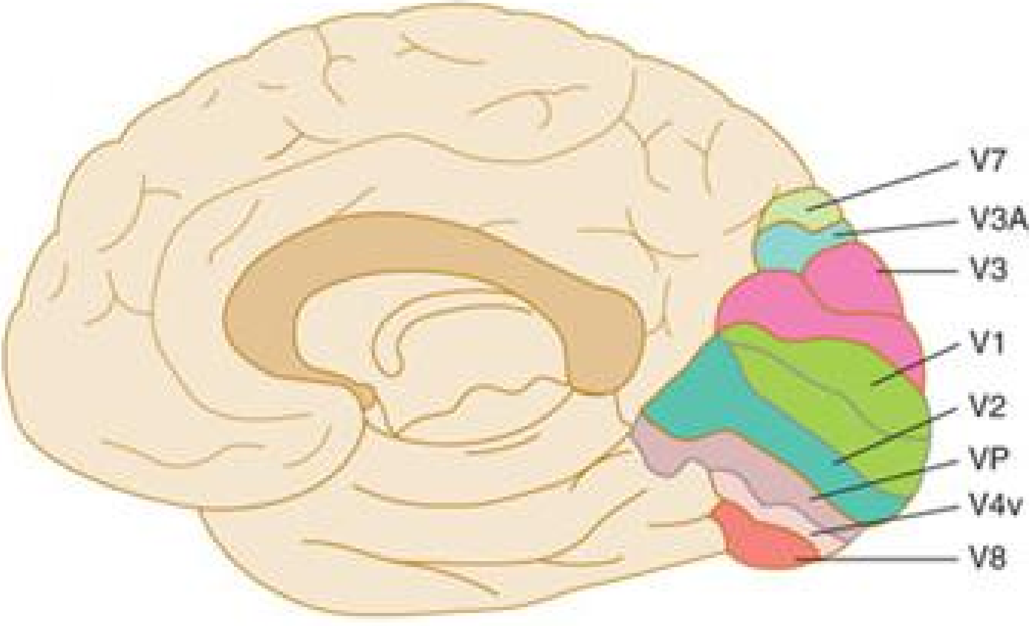




https://en.wikipedia.org/wiki/Cerebrum

Visual Cortex

1. Main center of visual processing, the larger area in the brain
2. The visual information arrives to V1 (striate cortex) that connects to V2-V6
3. Each area processes a specific feature: edge, color, shape, motion, depth of visual field…or control of eye movements
4. Each area has different neuronal properties



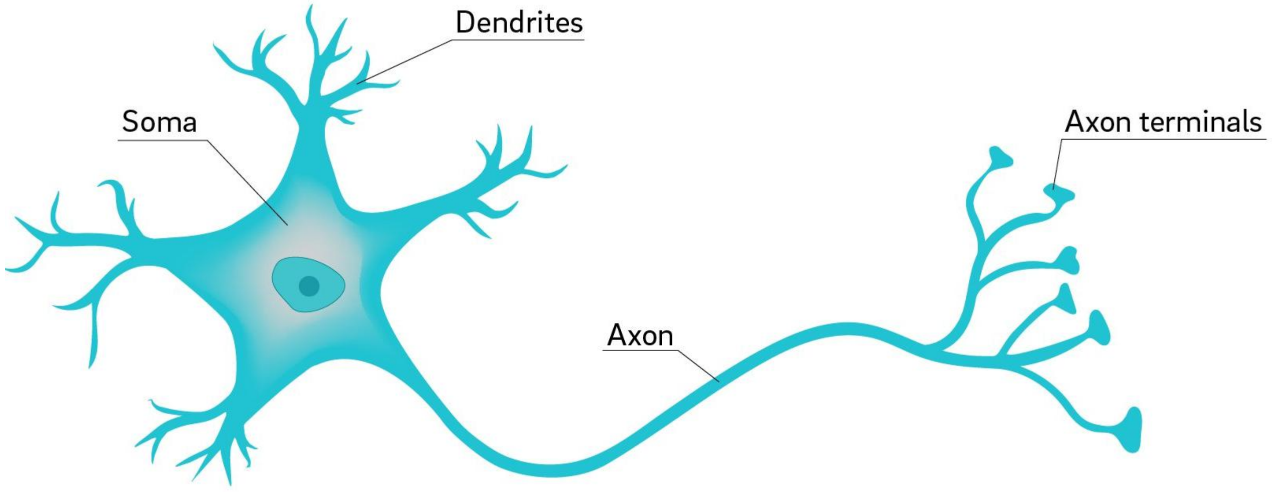
http://neurones.co.uk/Neurosciences/Tutorials/M4/M.4.2b%20Visual%20Pathway.html

Contents

Neurons

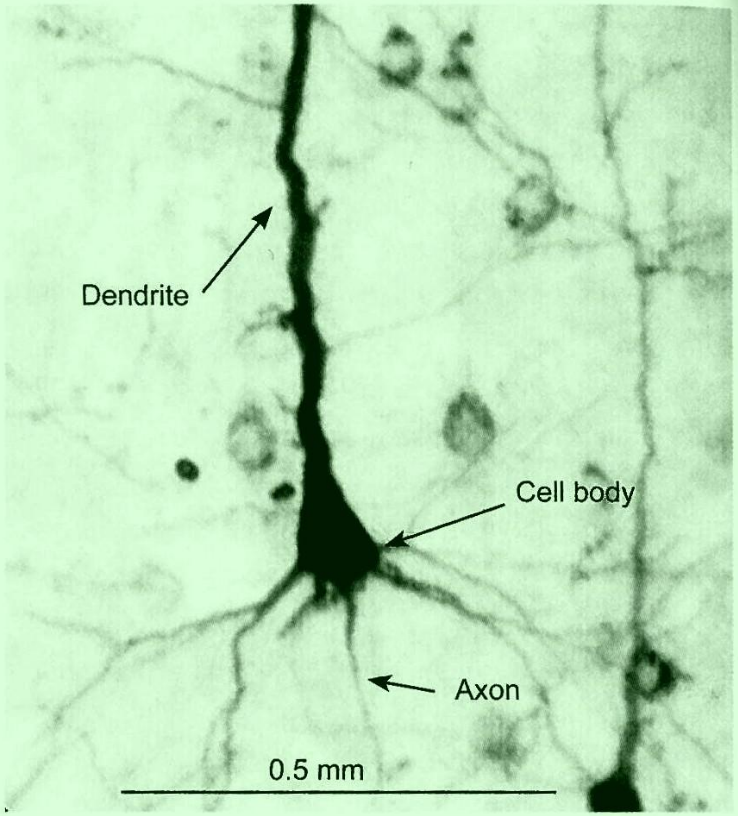
Neurons: primary components of the central nervous system

- **Dendrites:** receive informaton (also basic processing)
- **Soma:** (cell body) process information
- **axon:** send information



Neuron types

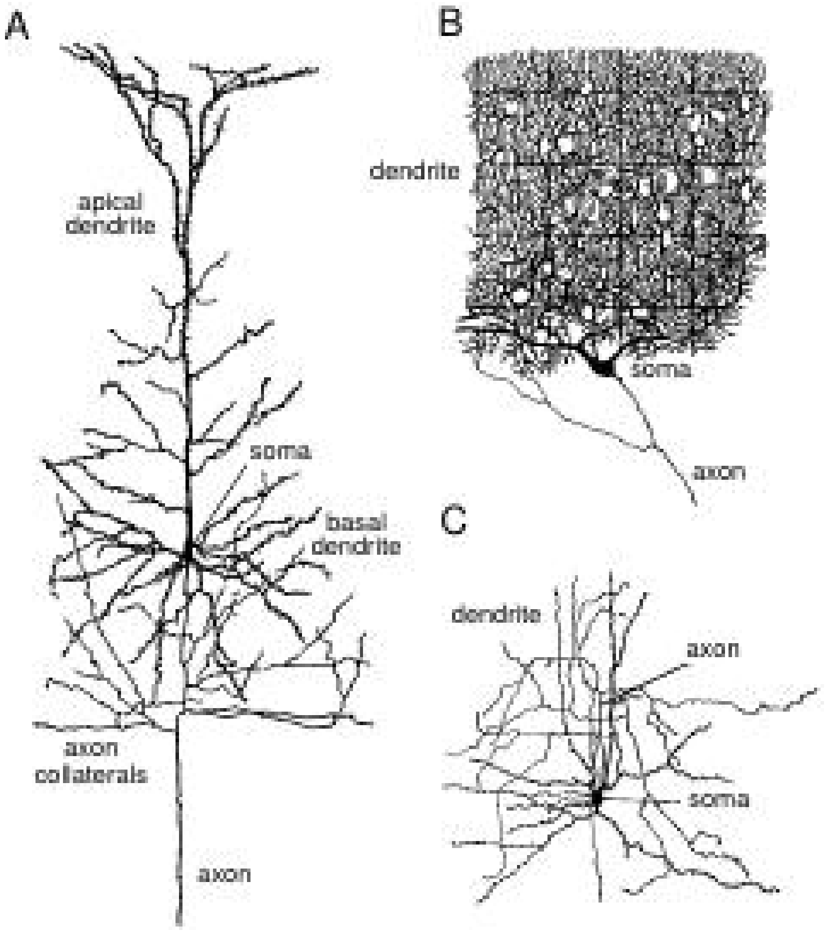
- Morphology (anatomy, microscope)
- Function (calcium imaging, recordings)



1.3 Pyramidal brain cell
Microscopic enlargement of a slice of rat brain stained to show a large neuron called a ***pyramidal cell.*** The long thick fiber is a dendrite that collects messages from other cells. The axon is the output fiber. (*Note* Some other types of neurons have thicker axons.) Brain neurons are highly interconnected: it has been estimated that there are more connections in the human brain than there are stars in the

Neuron types

- Morphology (anatomy, microscope)
  - Bipolar: 1 axon and 1 dendrite
  - Multipolar: 1 axon and 2 or more dendrites
  - Anaxonic: where the axon cannot be distinguished from the dendrite(s).
  - ...
- Function (calcium imaging, recordings)

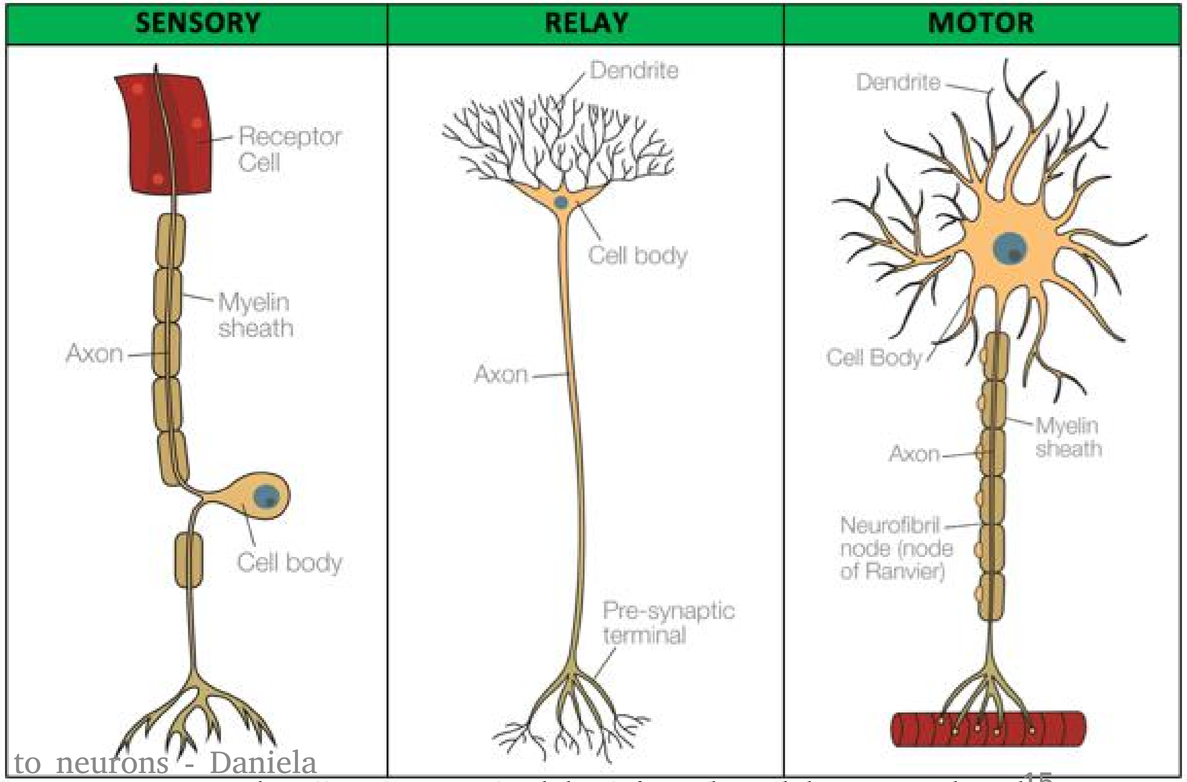


(A) Pyramidal cell from cortex.
(B) A Purking cell from cerebellum
(C) A Stellate cell from cortex

Dayan and Abbott,Theoretical Neuroscience Computational and Mathematical Modeling of Neural Systems

Neuron types

- Morphology (anatomy, microscope)
- Function (calcium imaging, recordings)
  - Direction
    - sensory neurons
    - motor neurons
    - Interneurons
  - Action on other neurons
    - Inhibitory
    - Excitatory
  - Discharge patterns
    - Tonic or regular spiking
    - Phasic or bursting spiking
    - Fast spiking



https://www.tutor2u.net/psychology/reference/biopsychology-sensory-relay-and-motor-neurons

Circuit Theory Review

- Potencial (difference)/ Voltage (V): measure of the work required to move a charge from one point to another in a electric field. Unit: Volt (V).
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  Ohm's Law $R = V/I$

- Capacitor (condenser or condensator): passive two-terminal electronic component that stores electrical energy in an electric field.
- Capacitance (C): measure of the storage capacity of a capacitor. Unit: Fahrad (F)

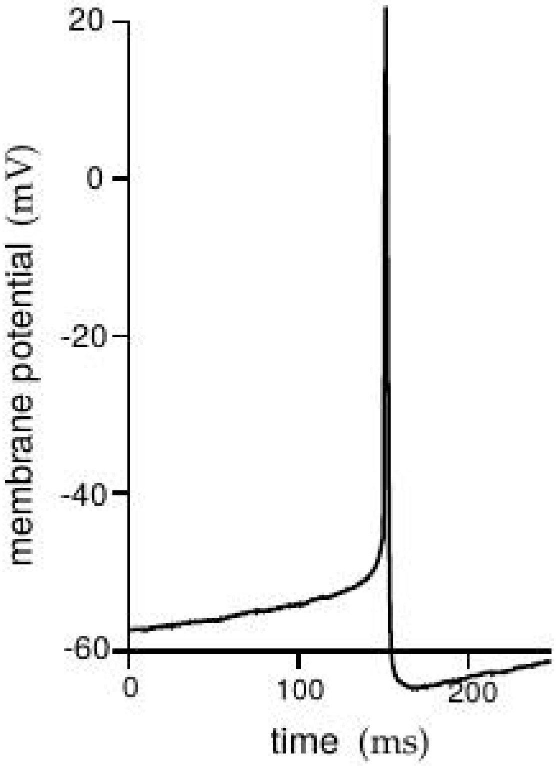
  $I(t) = C\, dV/dt$

Spiking neurons

- **Membrane Potential:** Voltage difference between the interior and exterior of a cell (most cells have it different of zero, but constant)

- **Action Potentia**l: Voltage fluctuation inside of the cell (only valid in electrically active cells like neurons and muscles)

- **Spike:** release of an action potential (because of the shape of the curve of the membrane potential)



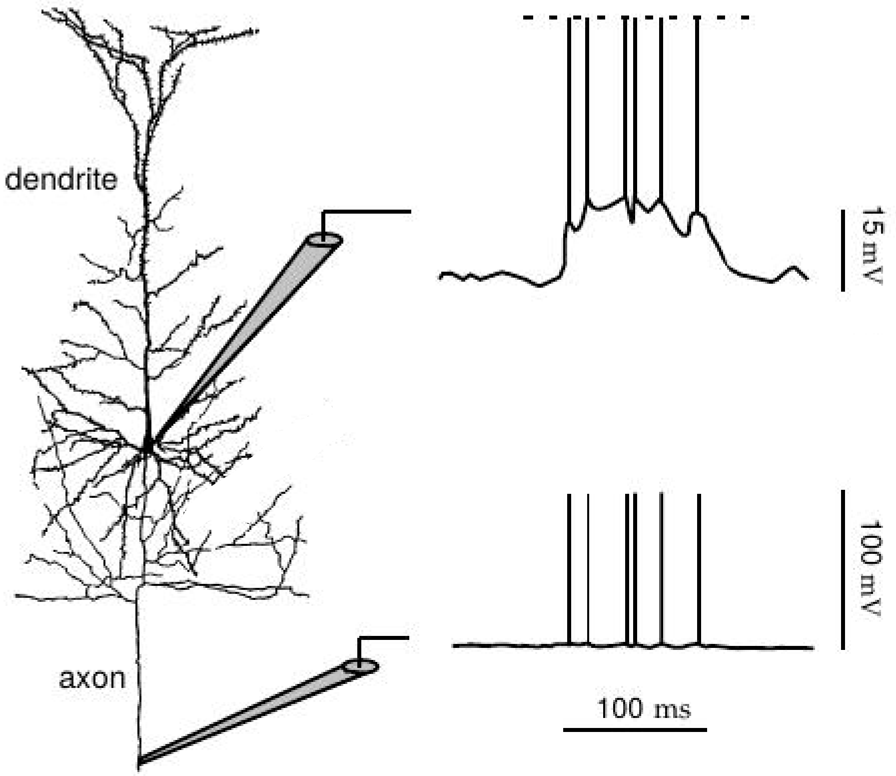
Membrane potential recorded intracellularly from a cultured rat cortical pyramidal cell.

How are spikes generated?

1. Chemical/Current input from dendrides

2. If membrane potential at soma is above a treshold an action potential is released

3. Spike goes trought the axon until the terminal



Two simulated recordings from a neuron.

Interesting videos

- The Cockroach Beatbox

https://www.youtube.com/watch?v=tr4gWi9Jf6k

- Recording Axon with a Multi-Electrode Array

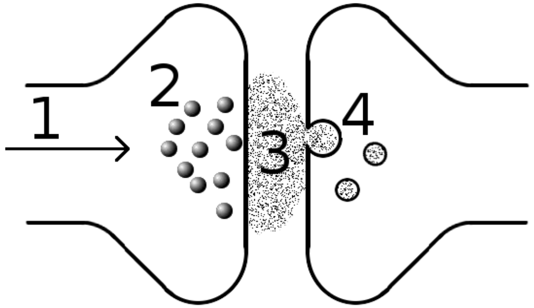
https://youtu.be/d4IE10zOM3U

How does the neurons comunicate? Synapses

Synapses: permit neurons to pass an electrical or chemical signal to other neurons

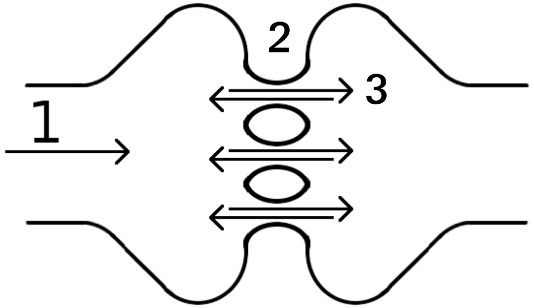
Chemical:

1. electrical activity in the presynaptic neuron
2. convertion into a chemical signal: the neurotransmitter
3. the neurotransmiter is released
4. the neurotransmister is recieved by receptors in the plasma membrane of the postsynaptic cell



Electrical:

1. electrical activity in the presynaptic neuron
2. special channels in both membranes, gap junctions, that are capable of passing electric current
3. electrical activity in the postsynaptic neuron



https://fr.wikibooks.org/wiki/Neurosciences/Les_synapses

Lets summarize

If you are curious, see part I, II, III of:

https://www.youtube.com/watch?v=qPix_X-9t7E

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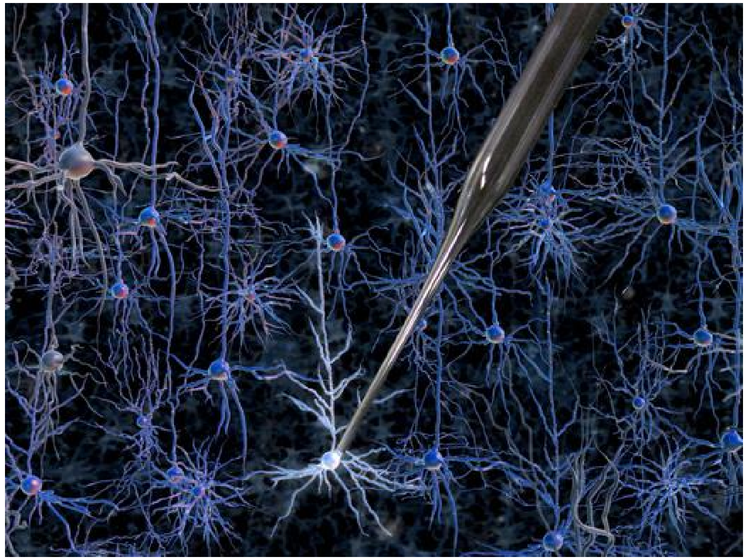
General Properties of Neuron Spike Trains



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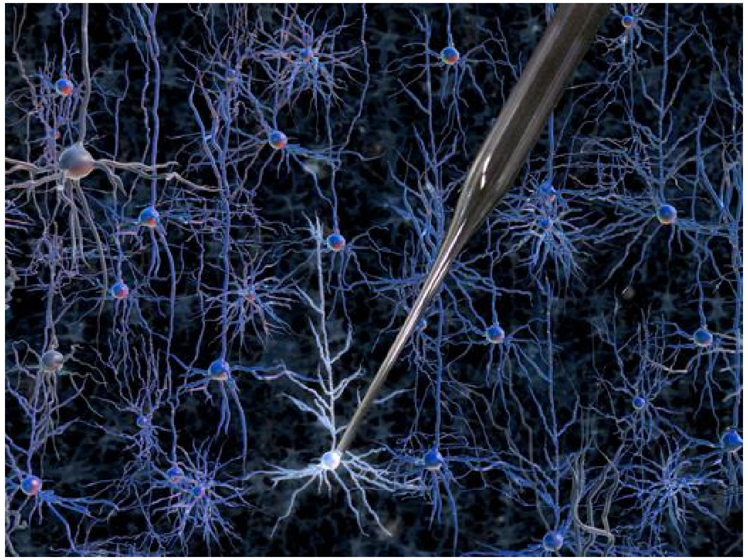

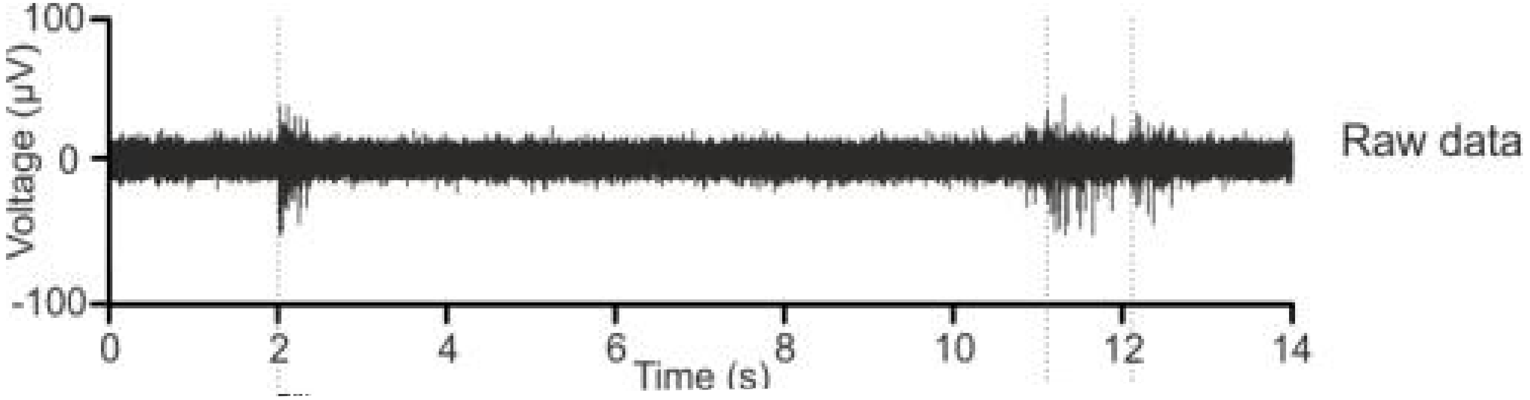

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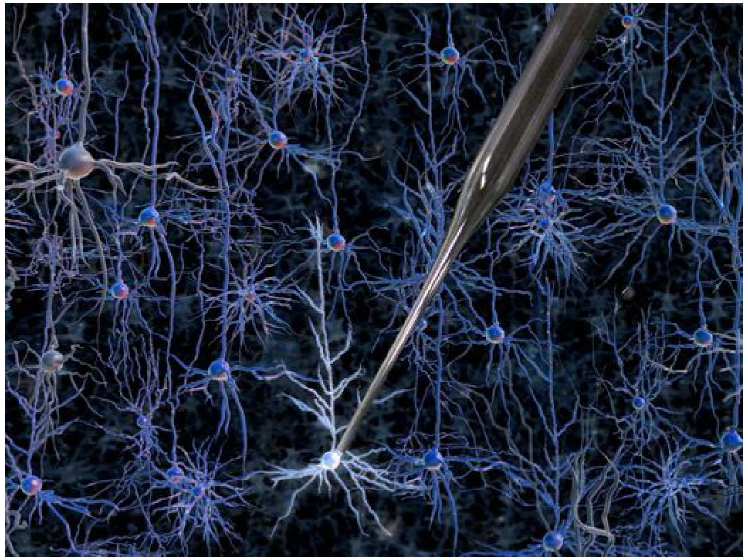

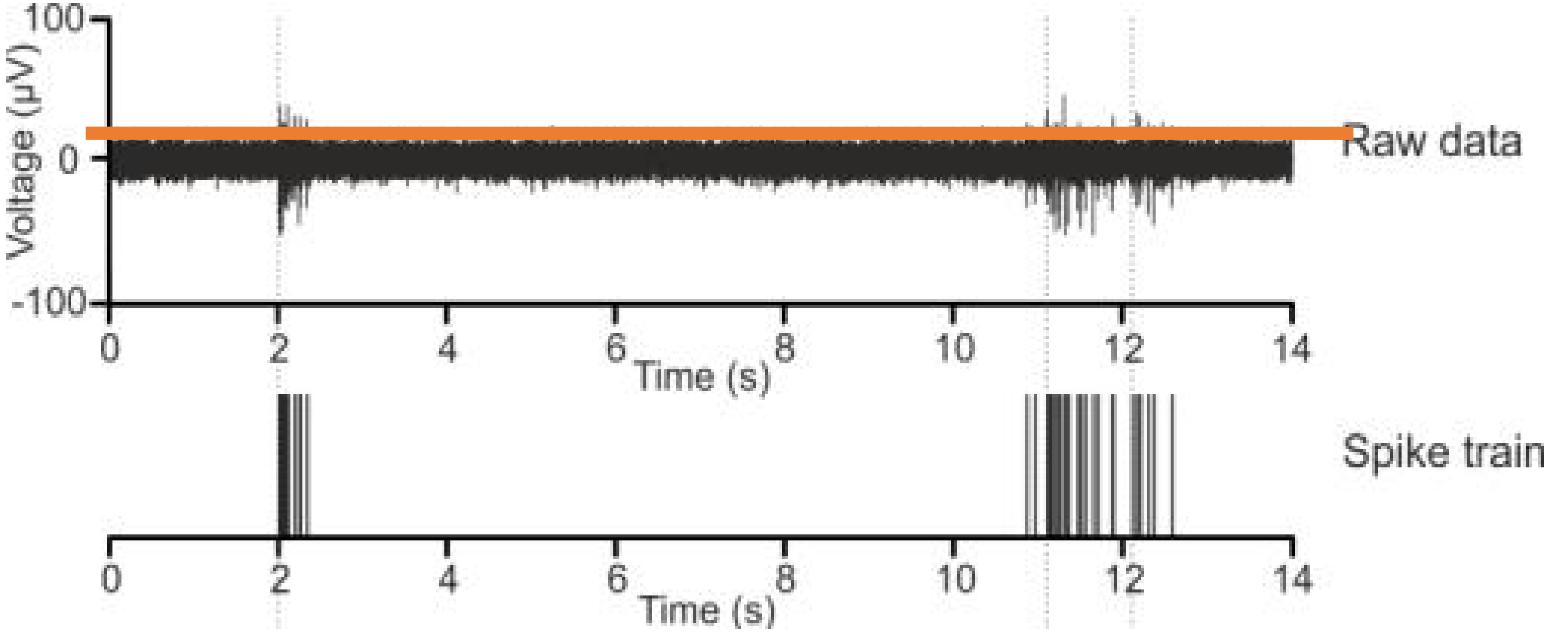

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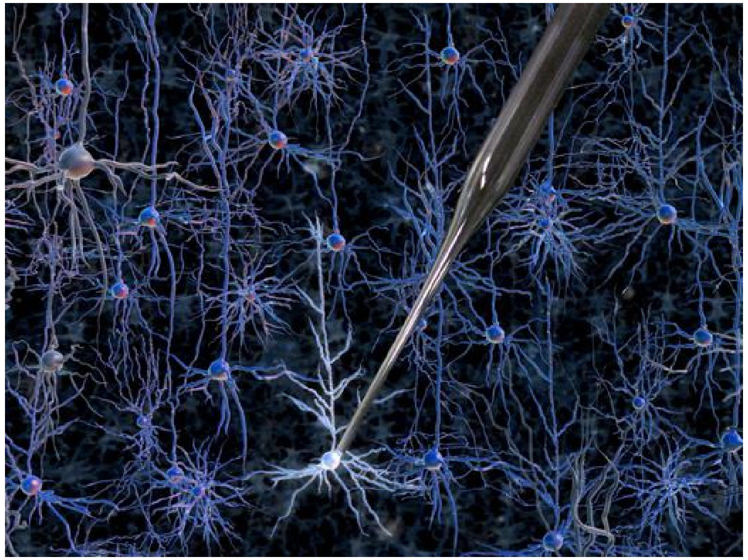
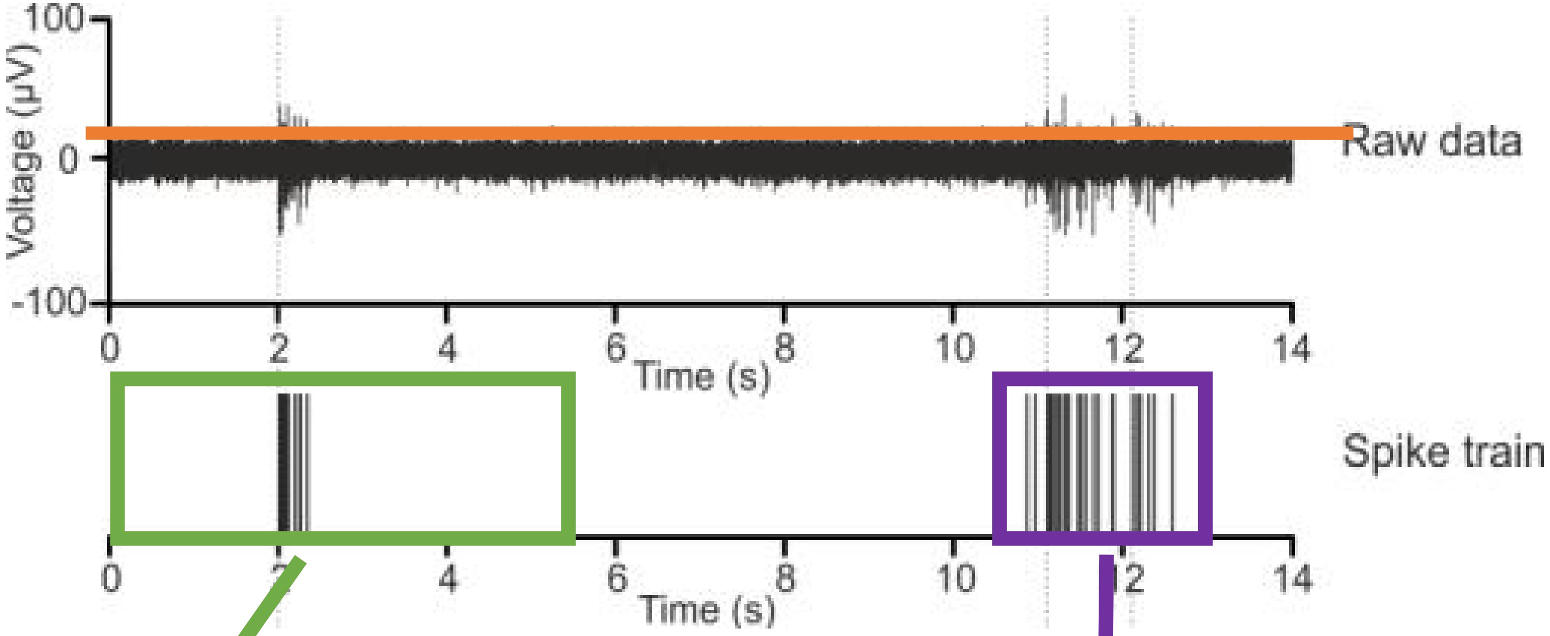




Temporal sparseness

Brusts of activity

Why bursts?

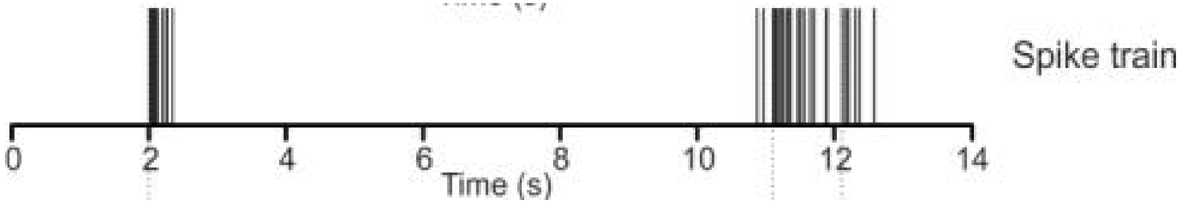
- Bursts are more reliable and have higher signal-to-noise ratio
- Bursts evoke long-term potentiation and hence affect synaptic plasticity much greater, or differently than single spikes (Lisman 1997).
- Bursts can resonate with short-term synaptic plasticity making a synapse a band-pass filter (Izhikevich et al. 2003).
- Bursts encode different features of sensory input than single spikes (Gabbiani et al. 1996, Oswald et al. 2004).

http://www.scholarpedia.org/article/Bursting

Why sparseness?

- To highlight bursts
- To save energy
- Others (population coding)

Neural data analysis

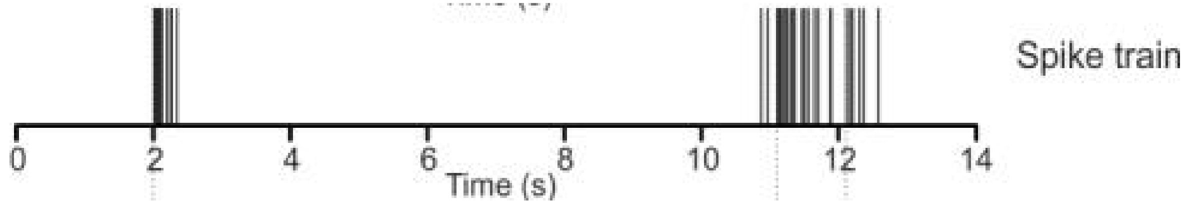


Simple tools:

- Average spike rate: Measure of neural activity
- Inter-spike interval: Measure the presence of brusts and sparseness
- Autocorrelation: Measure the presence of brusts, repetivite patterns, frequency analysis (if process is stationary)

Neuronal Dynamics. W. Gerstner, W. M. Kistler, R. Naud and L. Paninski

Neural data analysis



$$s(t) = \begin{cases} 1, & if\ spike \\ 0, & o.w. \end{cases}$$

$<f(t)>$ = average over time of f

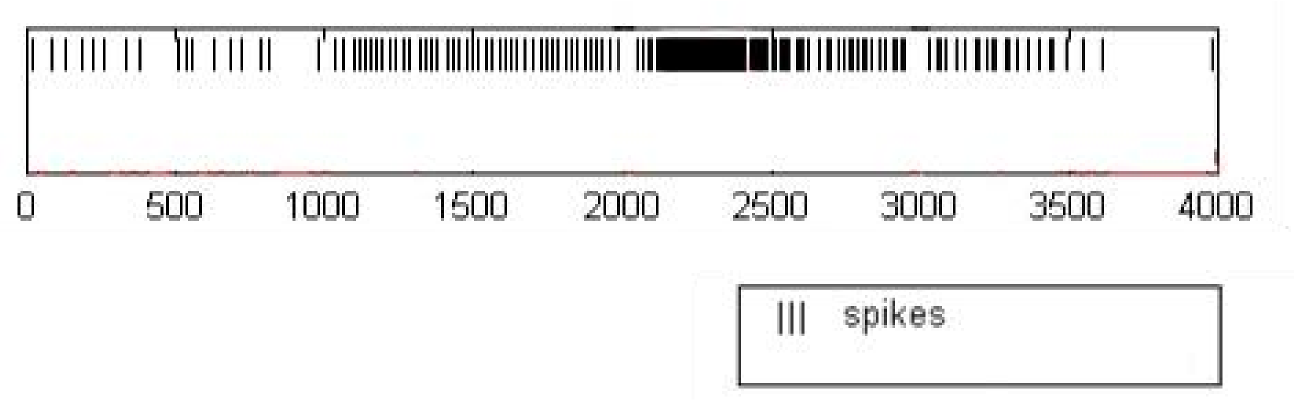
Possible measures

- Average spike rate (Hz): $\rho=<s(t)>=sum(s(t))/T$
- Inter-spike interval: $P(s(t_2) = 1 | s(t_1) =1; s(t_1+1) =0;\ldots, s(t_1+t_2-1) = 0)$
    1. spike_interval = $\{t_2-t_1 | s(t_2) = 1; s(t_1) = 1; s(t)=0, t_1<t<t_2\}$
    2. Hist(spike_interval)
- Autocorrelation: $C(\tau) = <s(t)s(t+\tau)> = sum(s(t)s(t+\tau))/T; \quad -\tau_{max}<\tau<\tau_{max}$

Neuronal Dynamics. W. Gerstner, W. M. Kistler, R. Naud and L. Paninski

Neural data analysis: average spike rate

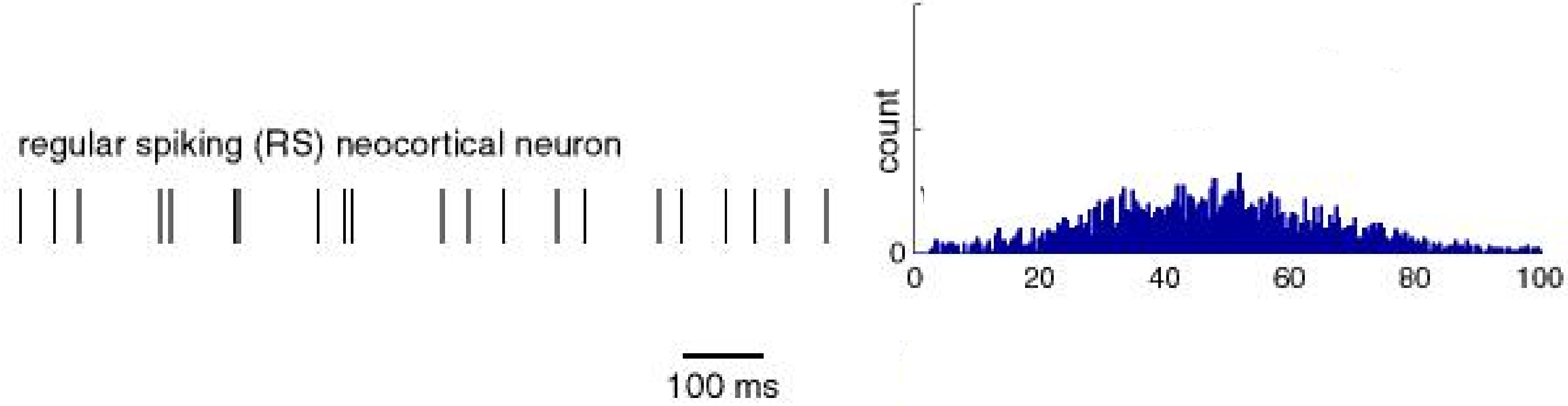
Average spike rate (Hz): 42.1053Hz



http://www.scholarpedia.org/article/Bursting
https://brainandmind.fandom.com/wiki/Automatic_Burst_Detection

Interspike interval detail

Inter-spike interval: $P(s(\tau) = 1 \mid s(t) = 1;\ s(t+1) = 0;\ldots,\ s(t+\tau-1) = 0)$



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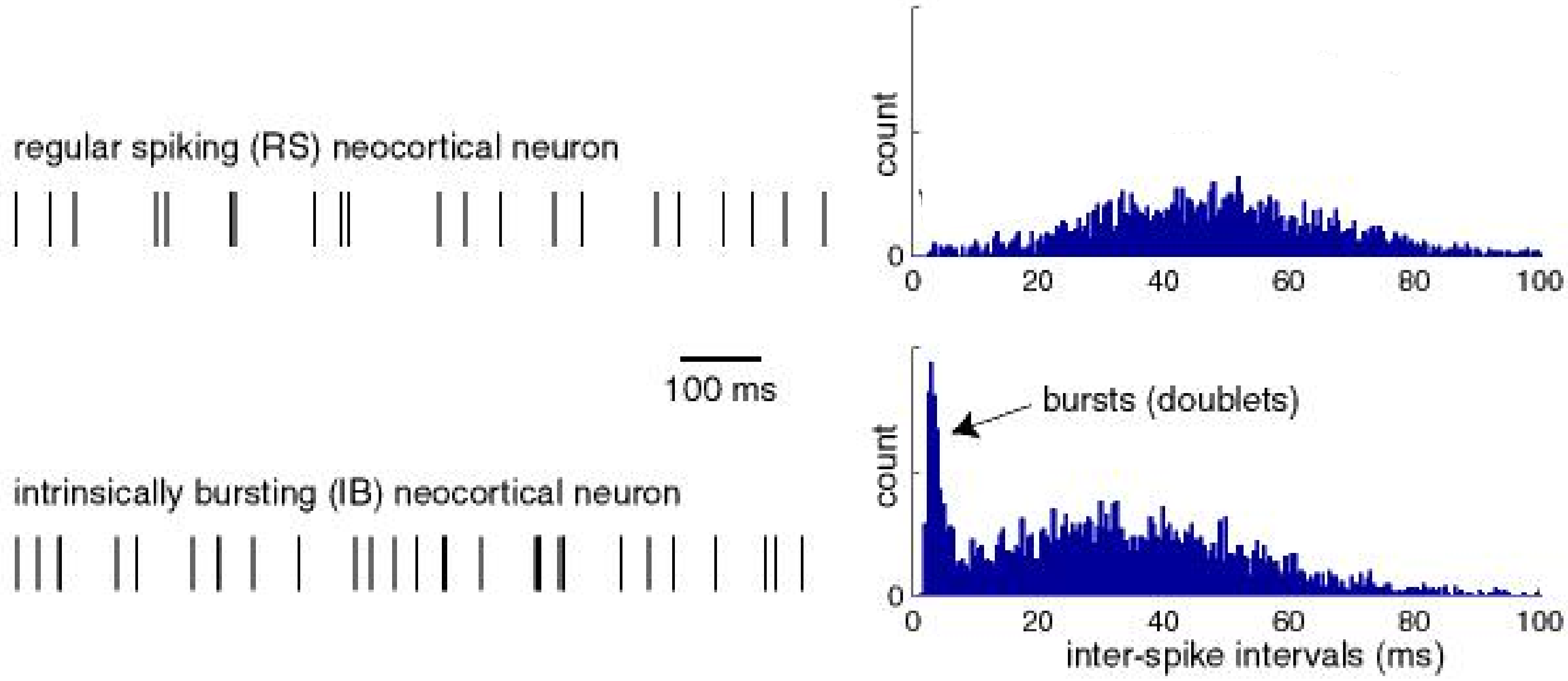

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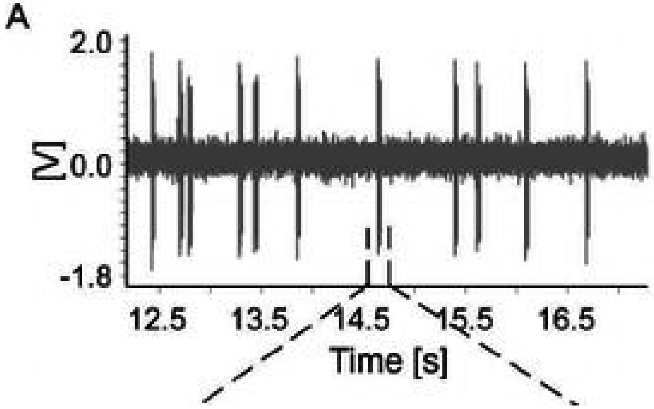
Autocorrelation detail

Autocorrelation: $C(\tau) = \langle s(t)s(t+\tau) \rangle$



Analysis of neural networks in subcortical visual structures using correlation methods, Andrzej Tomasz Foik et al

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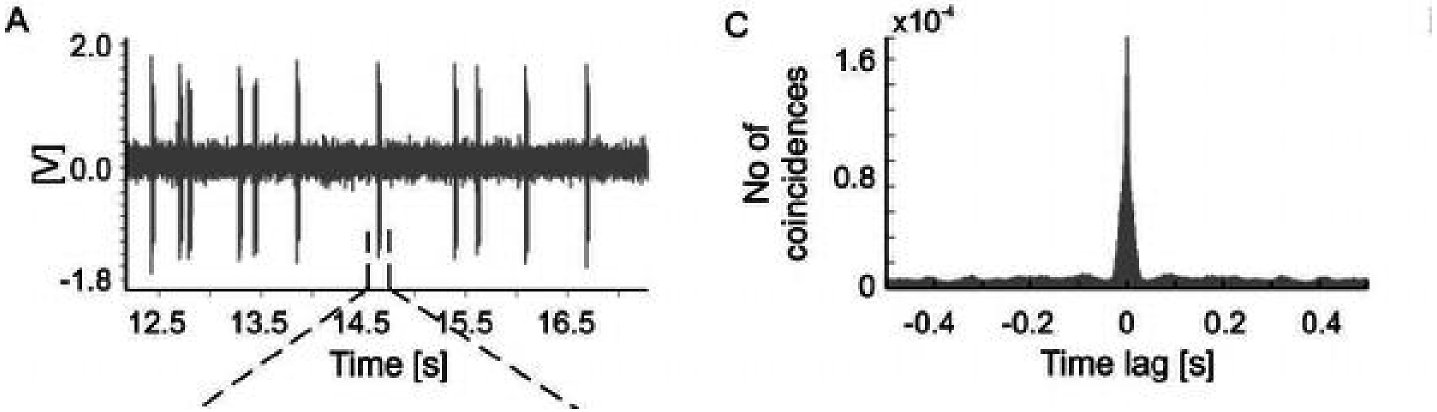

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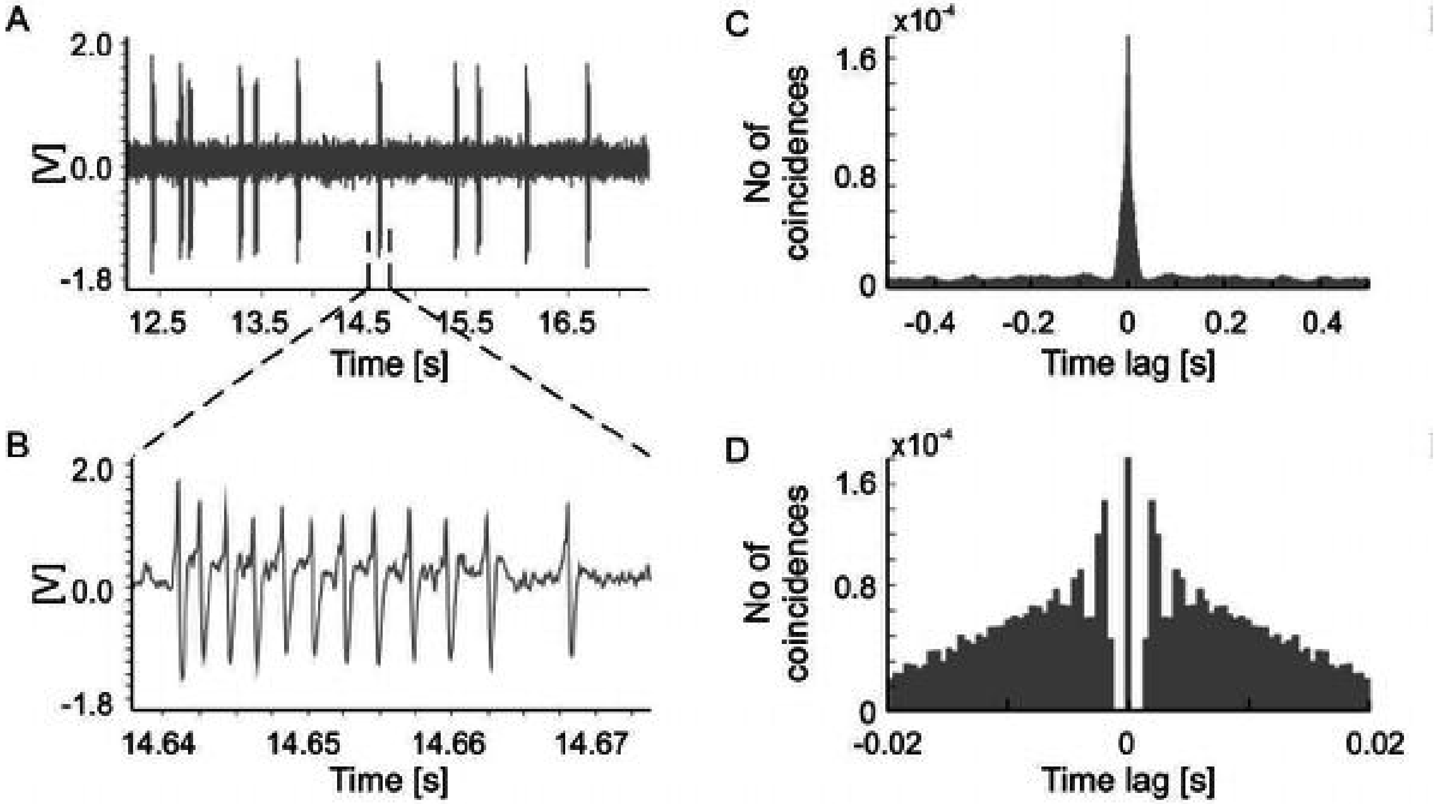

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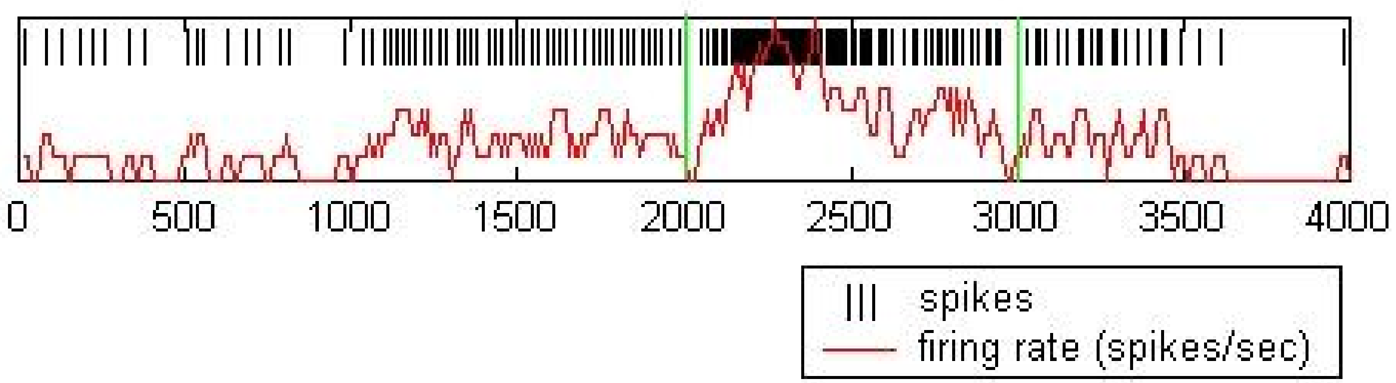
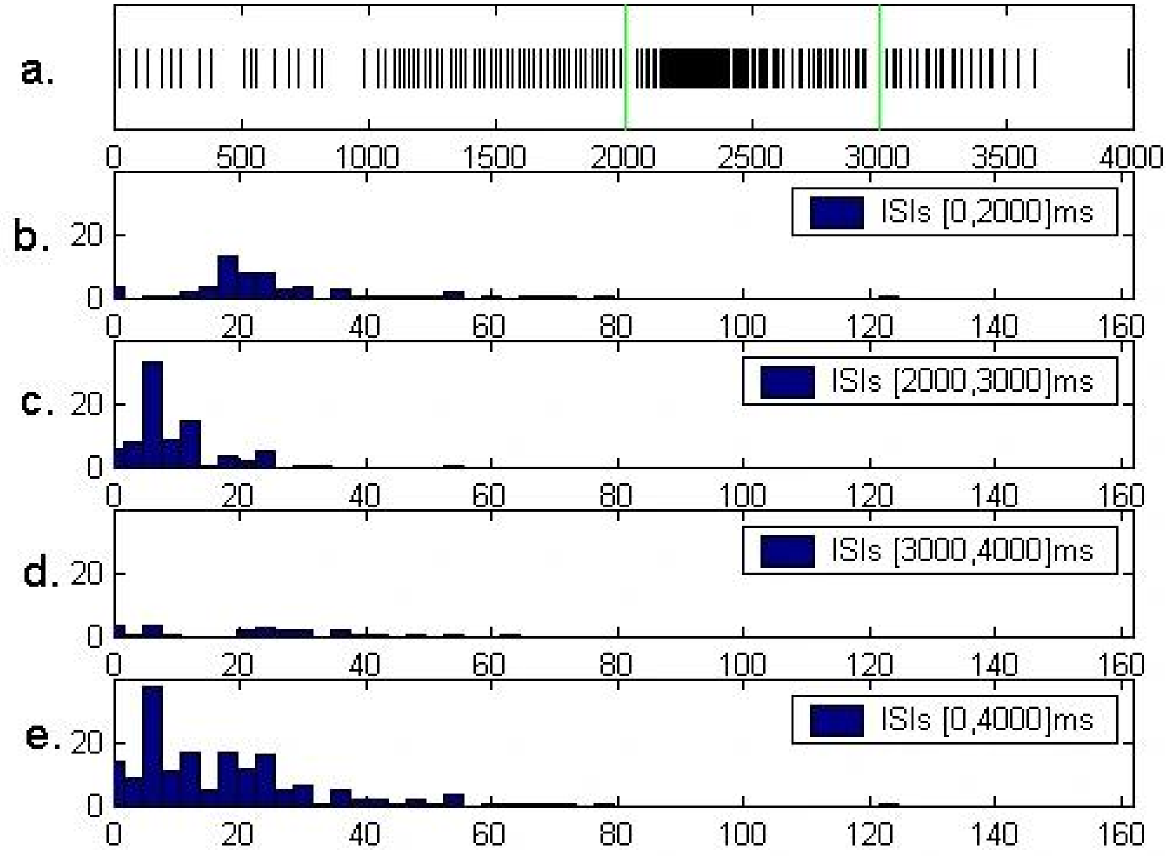
Neural data analysis
Global or local measurements



Time	Mean firing rate
0-2000	30.5556
2000-3000	82.3232
3000-4000	25.7576
0-4000	42.1053

http://www.scholarpedia.org/article/Bursting
https://brainandmind.fandom.com/wiki/Automatic_Burst_Detection

Neural data analysis
Global or local measurements



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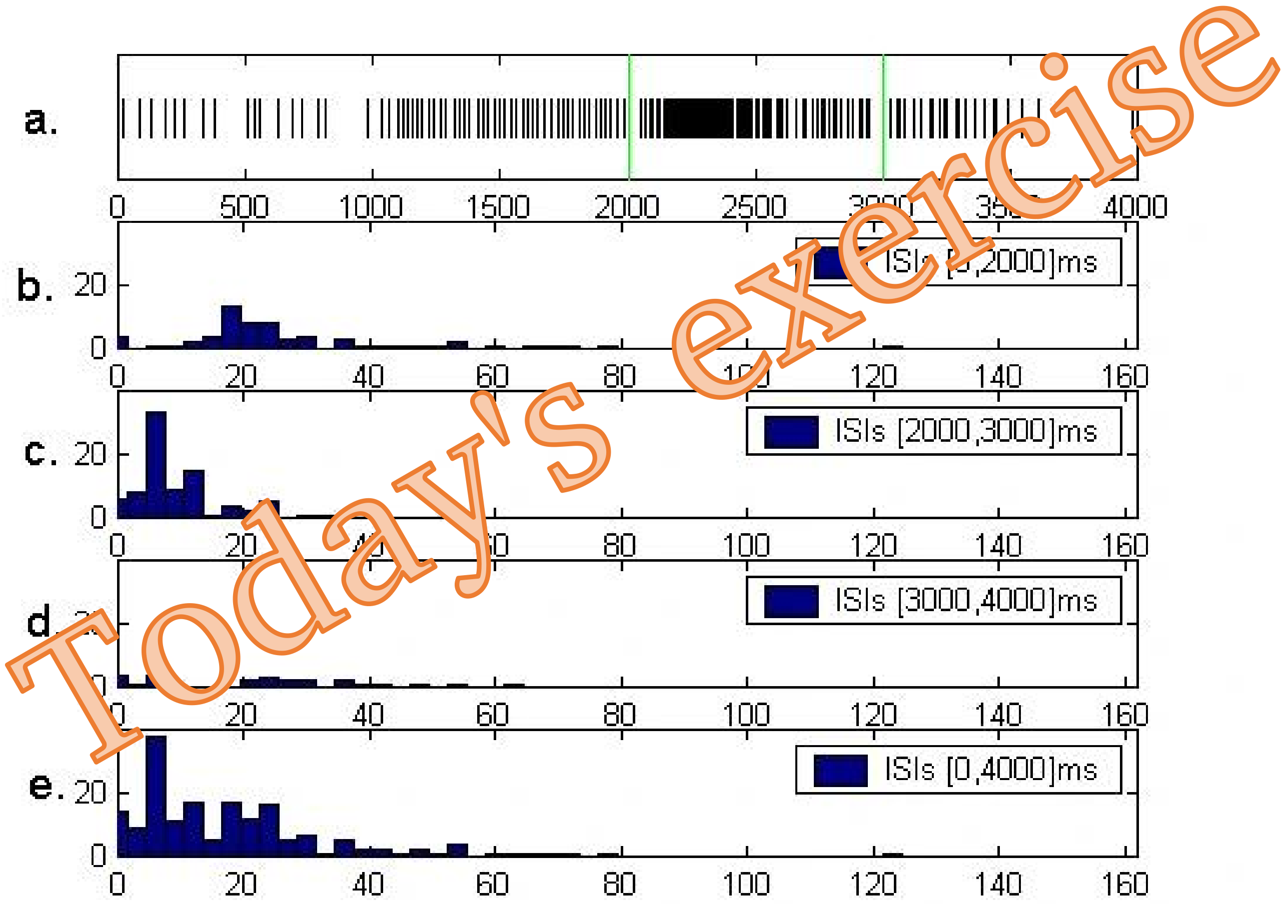

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Contents

Why do we build models?

Why do we build models?

Because it is fun!

To make simulators make predictions and prepare experiments: thus to save animal lives, test new drugs,

To inspire us for artificial systems

To understand how the brain works

To give a physical/chemical/data meaning to a biological experiment

Circuit Theory Review

- Potencial (difference)/ Voltage (V): measure of the work required to move a charge from one point to another in a electric field. Unit: Volt (V).
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  Ohm's Law

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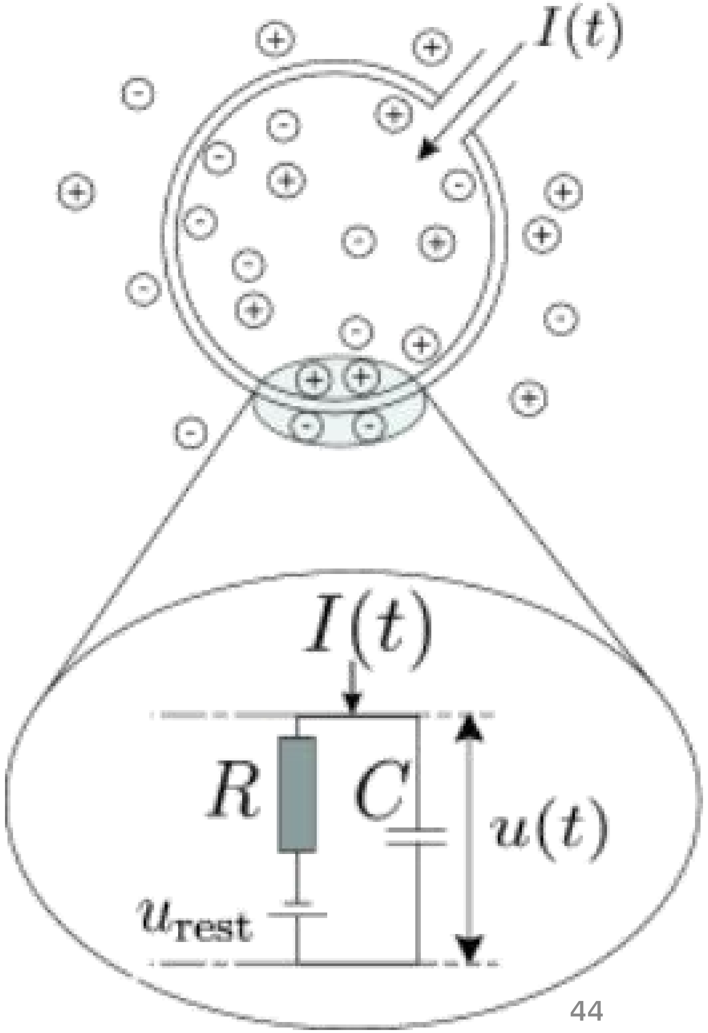
- Capacitor (condenser or condensator): passive two-terminal electronic component that stores electrical energy in an electric field.
- Capacitance (C): measure of the storage capacity of a capacitor. Unit: Fahrad (F)

$$I = C\frac{dV}{dt}$$

The Leaky Integrate and Fire Neuron

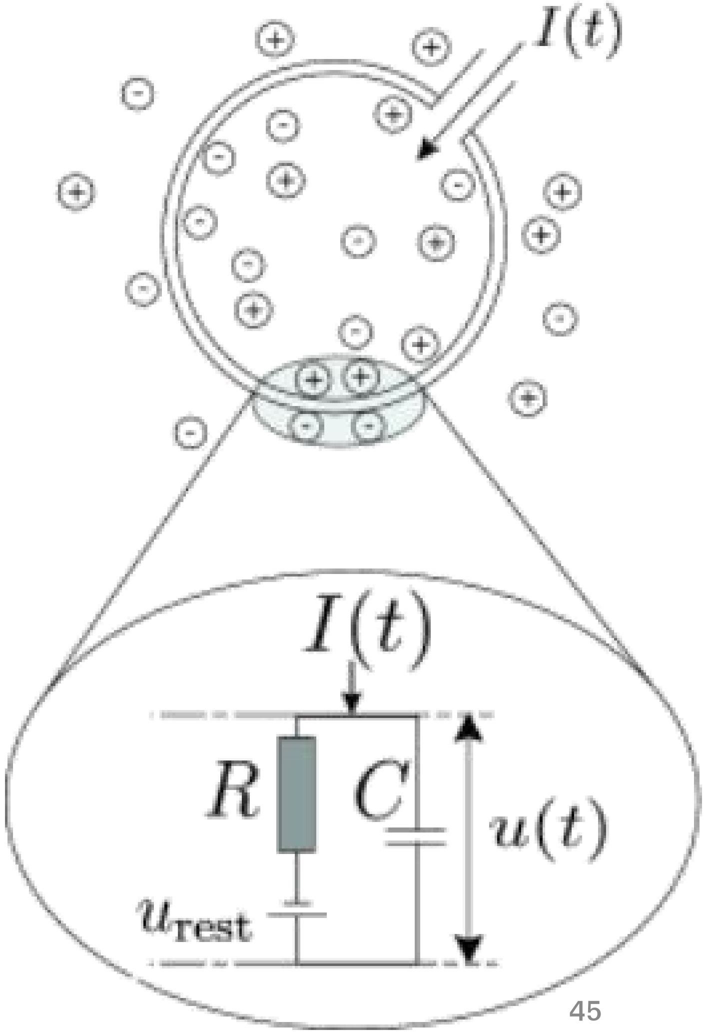
A passive membrane model:

1. The neuron receives a (positive) input current
2. The electrical charge inside the cell increases
3. The cell membrane acts like a capacitor in parallel with a resistor which in series with a battery of potential u_{rest}



The Leaky Integrate and Fire Neuron

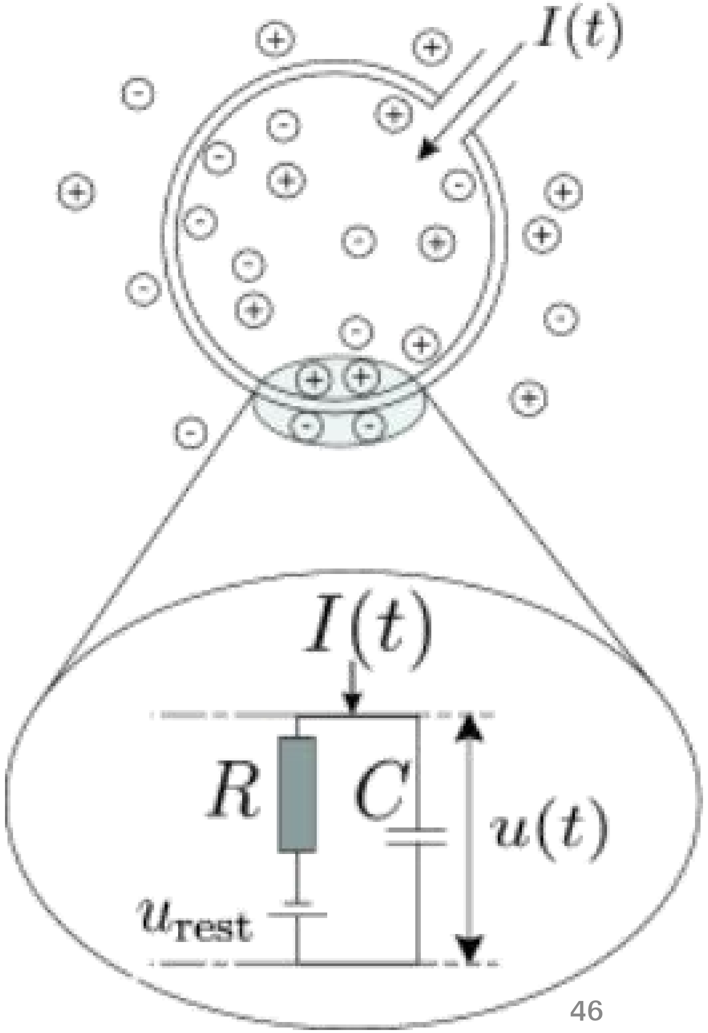
$$I(t) = I_R(t) + I_C(t) \text{ (parallel circuit)}$$



The Leaky Integrate and Fire Neuron

$$I(t) = I_R(t) + I_C(t) \text{ (parallel circuit)}$$

$$I_R(t) = \frac{V(t) - V_{rest}}{R} \text{ (Ohm's law)}$$



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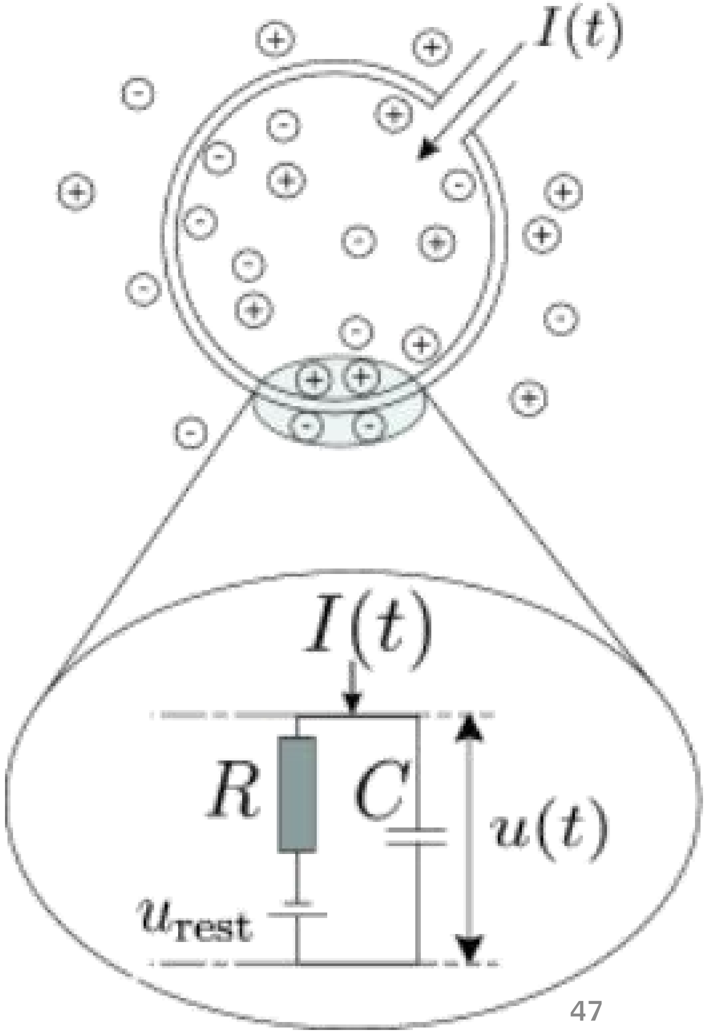
$$I_C(t) = C\frac{dV}{dt} \text{ (definition)}$$



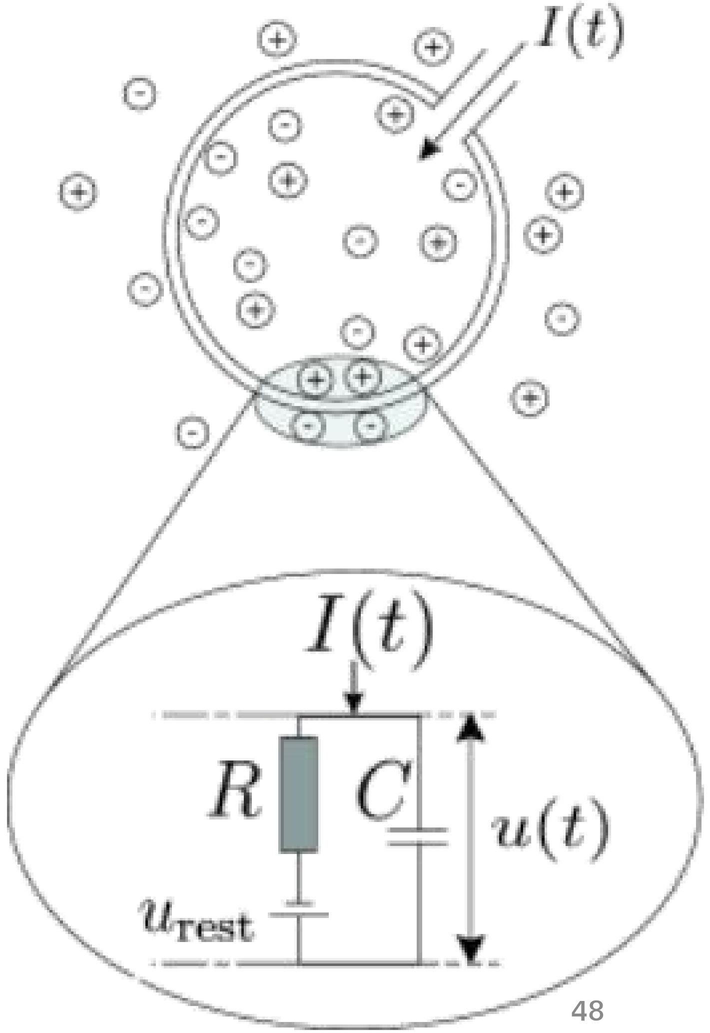
The Leaky Integrate and Fire Neuron

$$I(t) = I_R(t) + I_C(t) \text{ (parallel circuit)}$$

$$I_R(t) = \frac{V(t) - V_{rest}}{R} \text{ (Ohm's law)}$$

$$I_C(t) = C\frac{dV}{dt} \text{ (definition)}$$

$$I(t) = \frac{V(t) - V_{rest}}{R} + C\frac{dV}{dt}$$



The Leaky Integrate and Fire Neuron

$$I(t) = I_R(t) + I_C(t) \text{ (parallel circuit)}$$

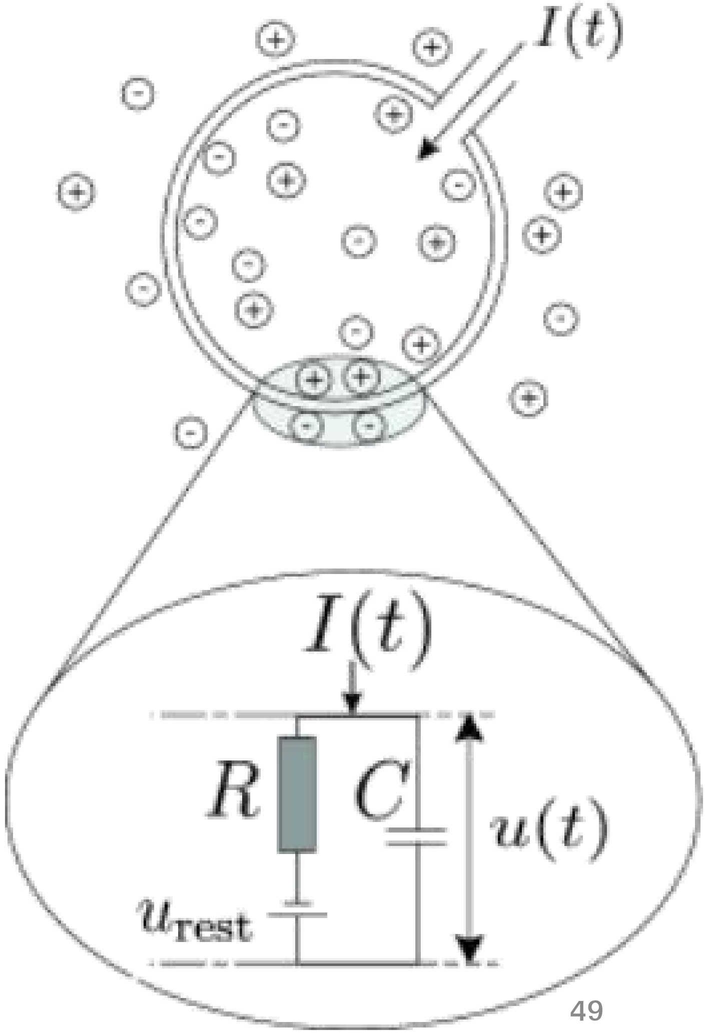
$$I_R(t) = \frac{V(t) - V_{rest}}{R} \text{ (Ohm's law)}$$

$$I_C(t) = C\frac{dV}{dt} \text{ (definition)}$$

$$I(t) = \frac{V(t) - V_{rest}}{R} + C\frac{dV}{dt}$$

$$\text{define } \tau = RC \text{ (membrane time scale)}$$

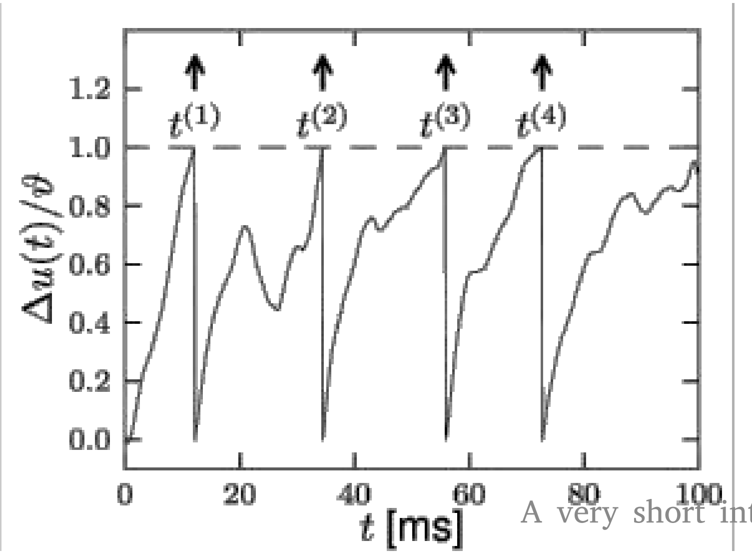
$$\tau\frac{dV}{dt} = -(V(t) - V_{rest}) + RI(t)$$

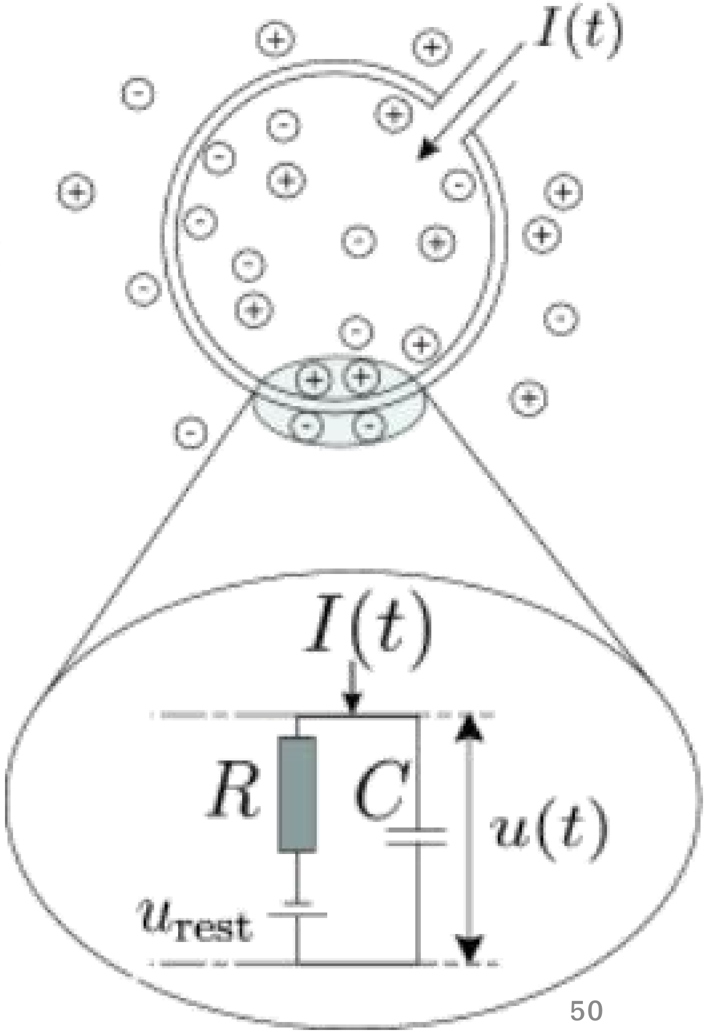


The Leaky Integrate and Fire Neuron

The final model

$$V(t) = \begin{cases} V_{rest} & \text{if } V(t) = v_{th} \\ V_{rest} - \tau \frac{dV}{dt} + RI(t) & \text{o.w.} \end{cases}$$





The Leaky Integrate and Fire Neuron

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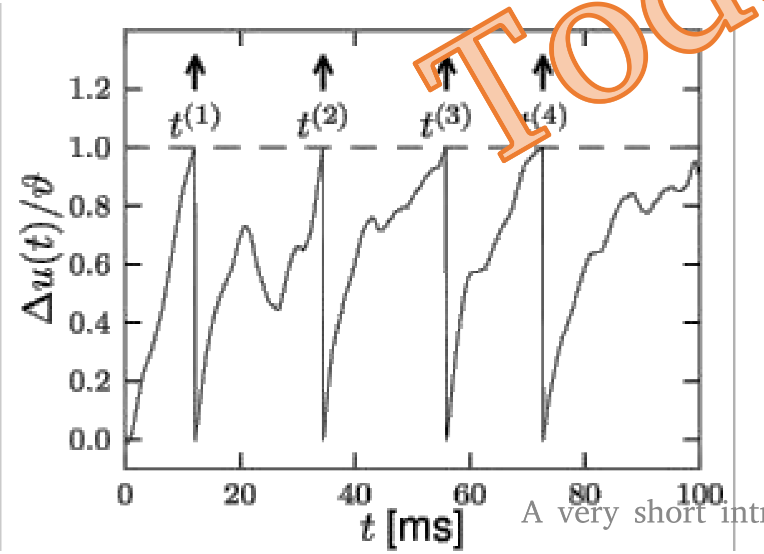
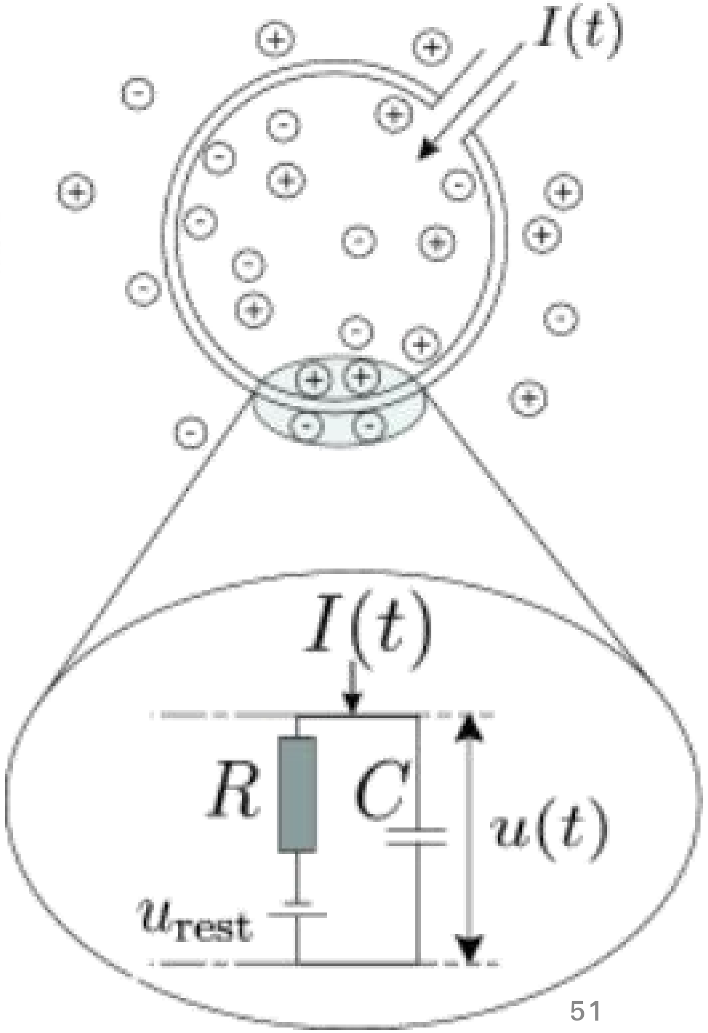
$$V(t) = \begin{cases} V_{rest} & \text{if } V(t) = v_{th} \\ V_{rest} - \tau \frac{dV}{dt} + RI(t) & \text{o.w.} \end{cases}$$

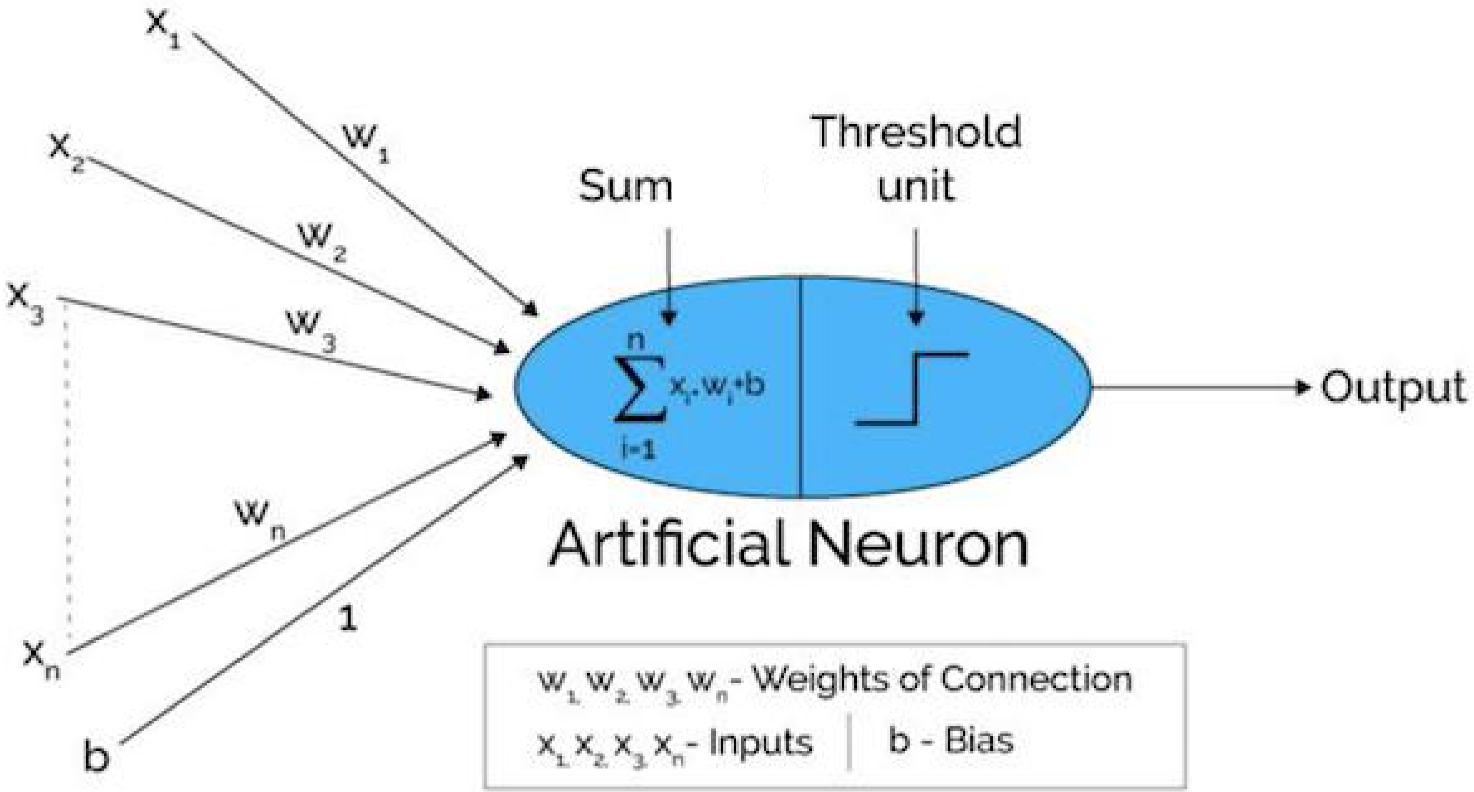
Today's TD



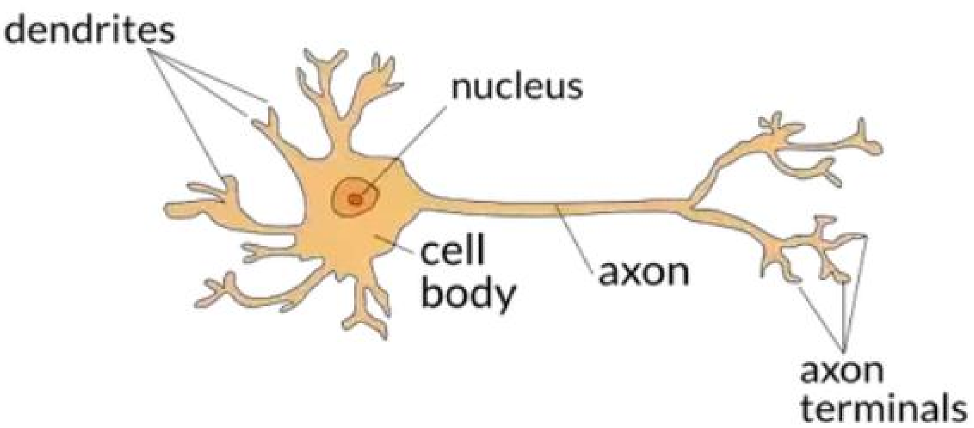


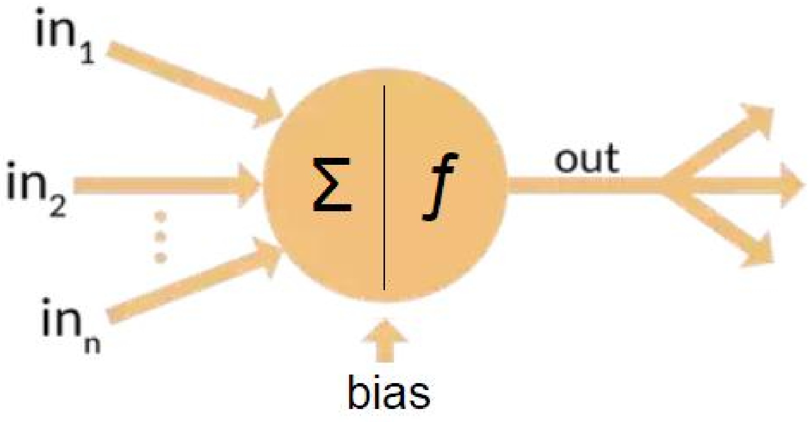
Contents

Artificial Neurons: perceptron



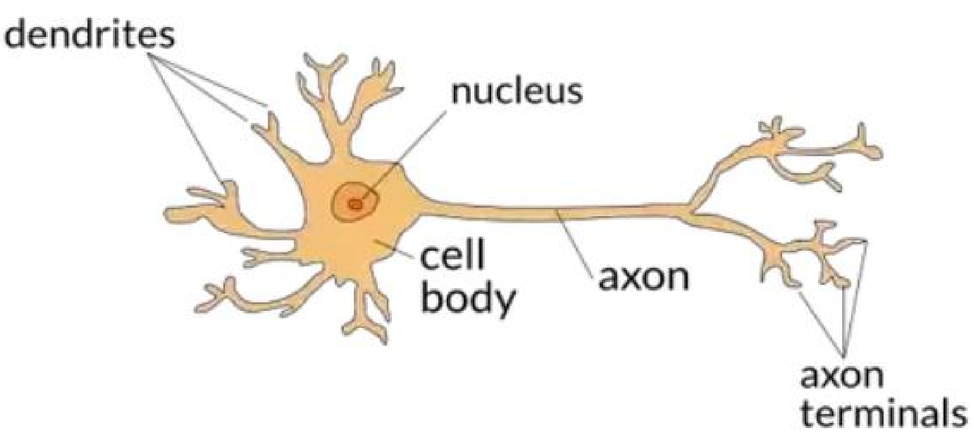
Neurons

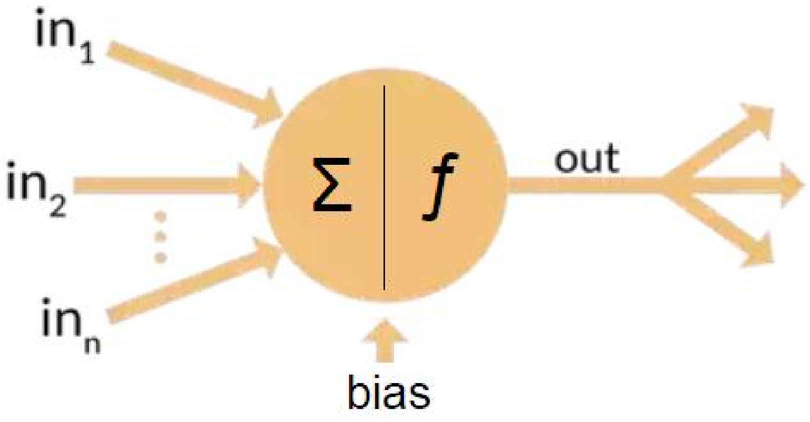




https://towardsdatascience.com/the-differences-between-artificial-and-biological-neural-networks-a8b46db828b7

Neurons

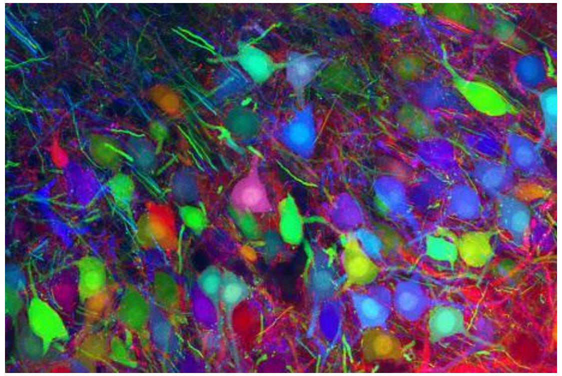


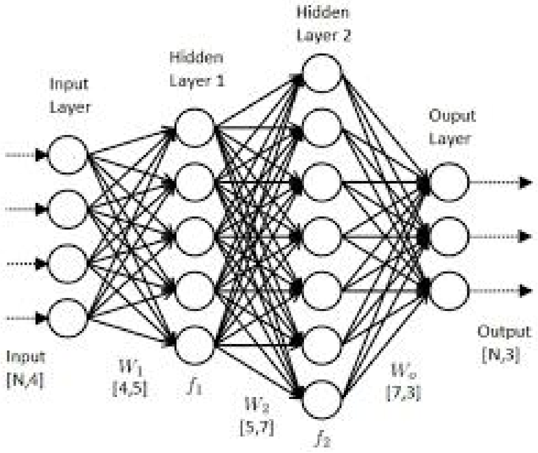


Biological Neural Neurons	Artificial Neural Neurons
continuous input, discret output	discret input and output
large functional variability	low functional variability
large anatomical variability	no anatomical variability
asyncronous	syncronous

https://towardsdatascience.com/the-differences-between-artificial-and-biological-neural-networks-a8b46db828b7

Networks

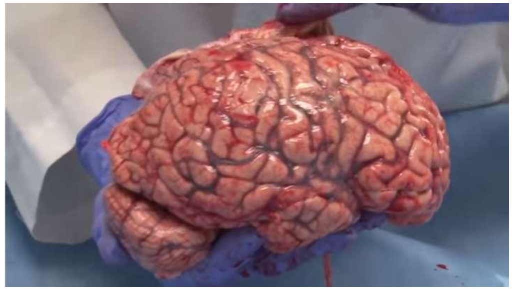


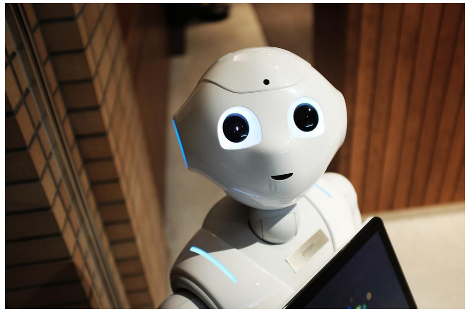


Biological Neural Networks	Artificial Neural Networks
Sparse connectivity	Not sparse connectivity
Preference for nearby neurons	Not defined spacial relations
Feedback connections	Feedfoward connections

http://www.institut-vision.org/fr/neurogenese-et-developpement-des-circuits-neuronaux.html

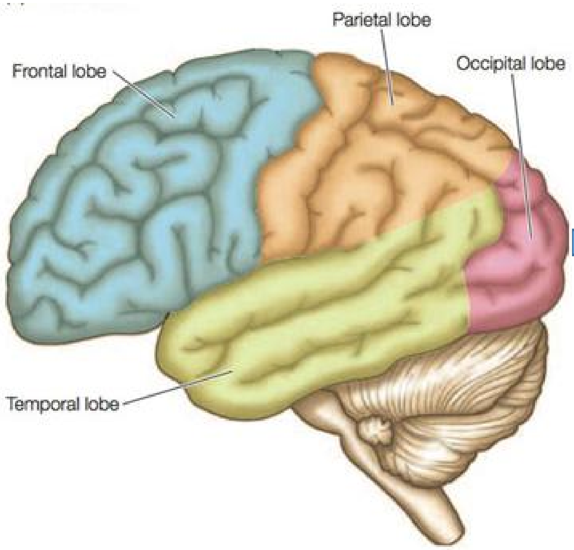
Brains



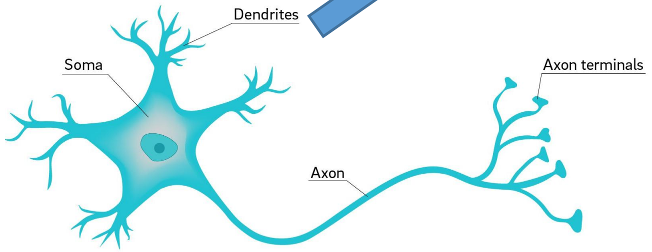


Biological Brains	Artificial Brains
hardware and software co-development	hardware and software developed separatelly
energetic savings	no energy concerns
multifunctions parts	each part has its own function
capability of generalization	not solved
capability of adaptation	not solved
missing parts can partially be substituted by existing parts	missing parts can be easely substituted by new parts

Summary

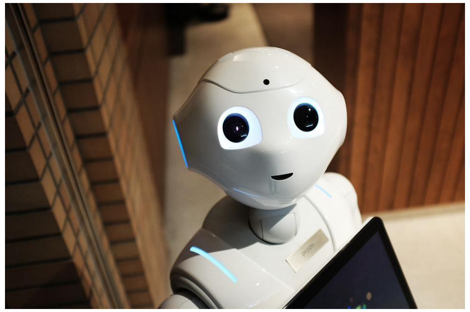


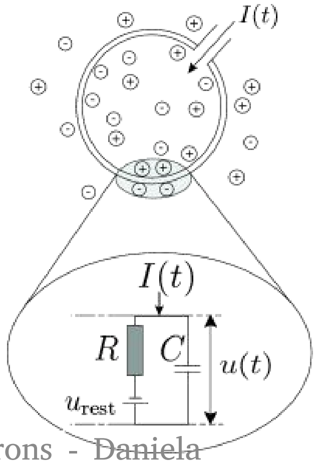
Parietal lobe
Frontal lobe
Occipital lobe
Temporal lobe



Dendrites
Soma
Axon terminals
Axon

0
500
1000
1500
2000
2500
3000
3500
4000



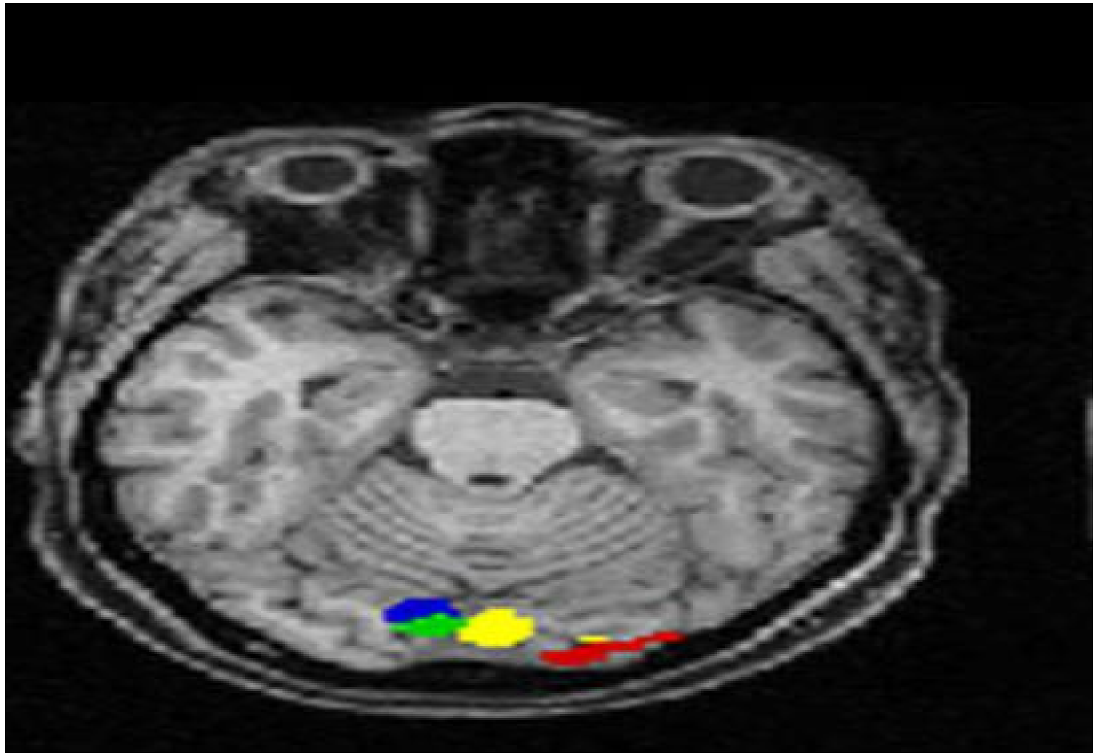


$I(t)$
$I(t)$
R
C
$u(t)$
u_{rest}

Extra-slides

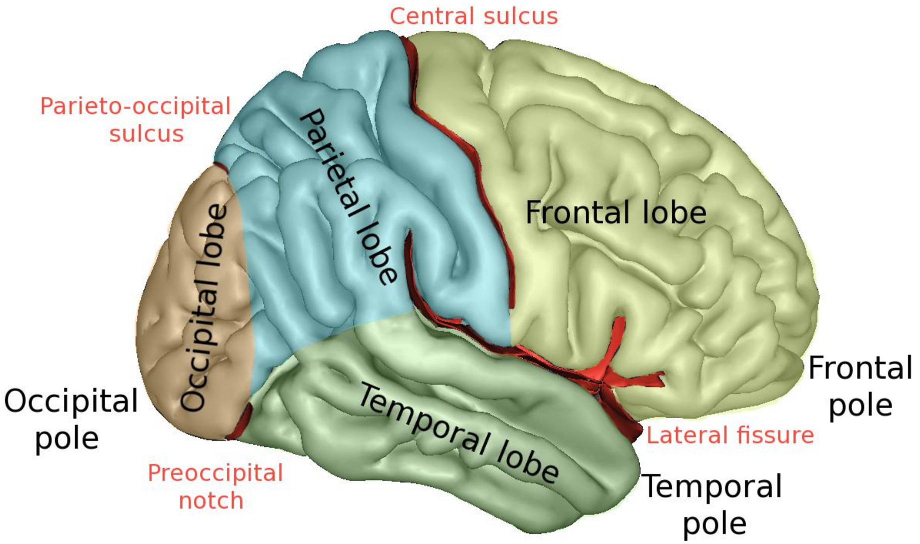
How can we separate the brain in areas?

- Cortical areas are defined by their function.
- Typically, they have different inputs and they project in different output
- They are defined by imaging: EEG, MEG, FMRI.



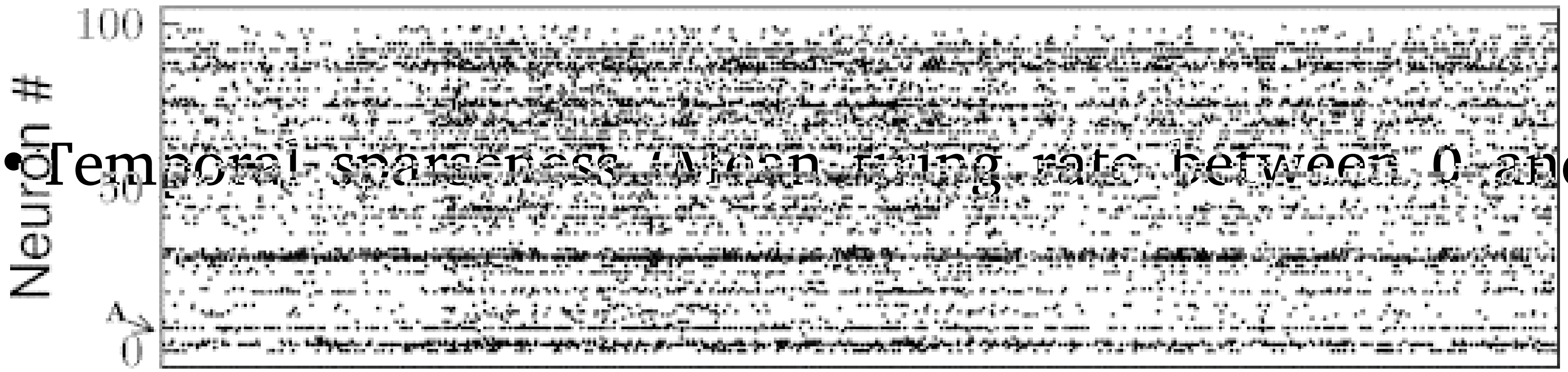
Layers of Visual Cortex

- Hemispheres: right, left (are they symmetric?)
- Lobes:
  - frontal: reward, attention, short-term memo motivation
  - parietal: integration sensory information, v
  - occipital: vision (visual cortex)
  - temporal lobe: sensory processing, language



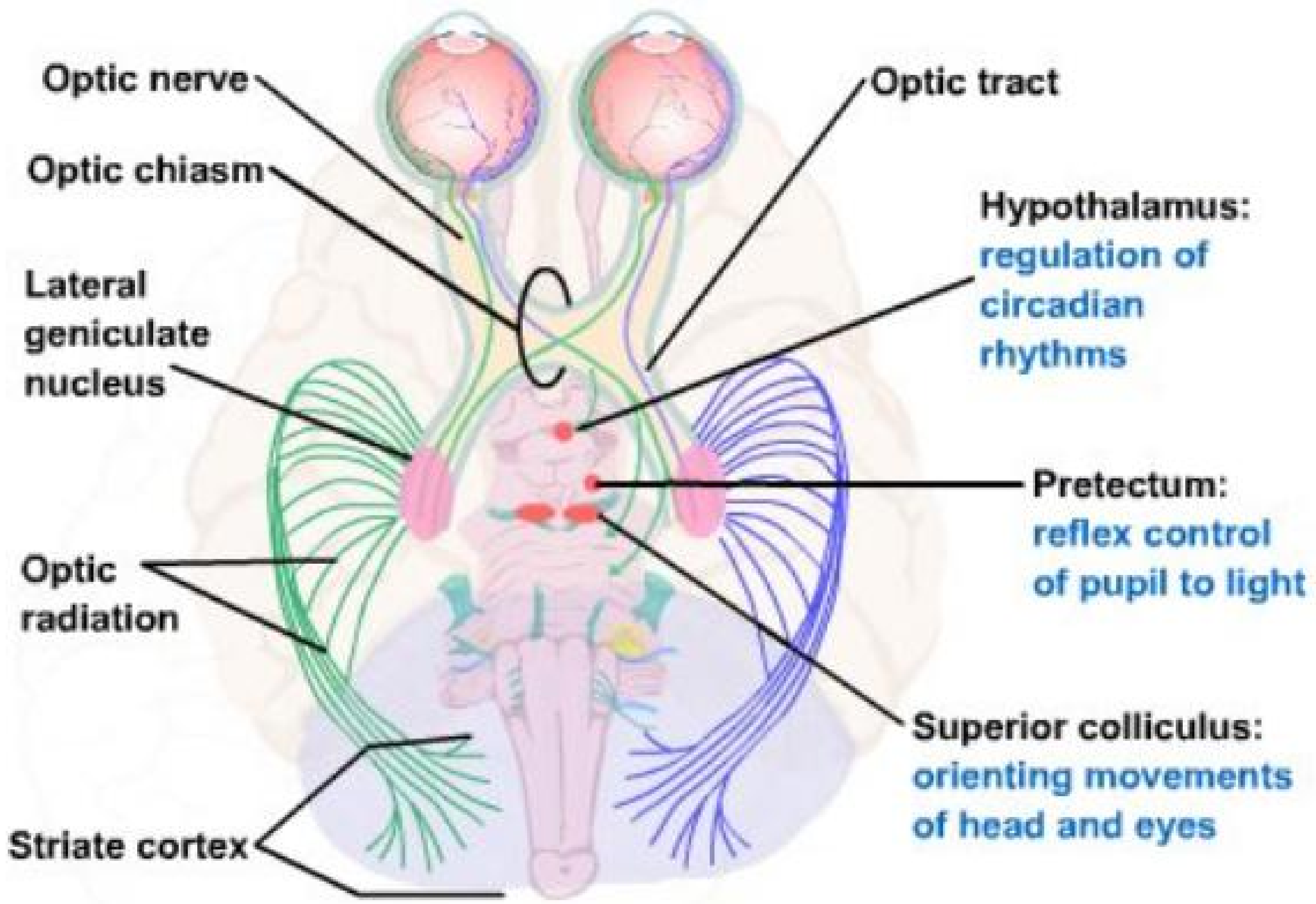
https://en.wikipedia.org/wiki/Cerebrum

General Properties of Spike Trains

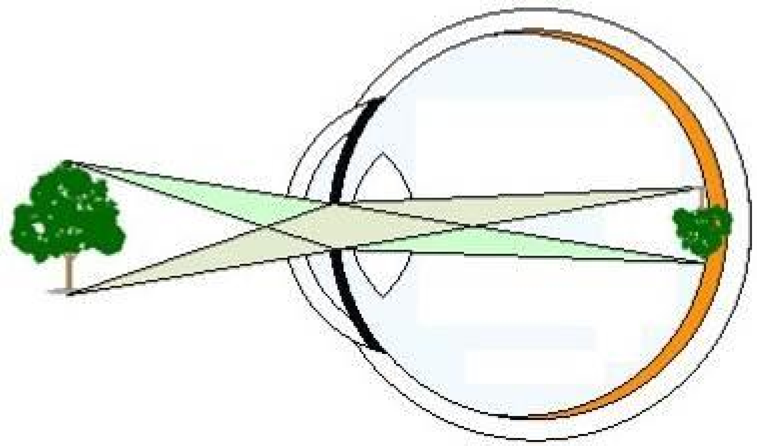


- Temporal sparseness (Mean firing rate between 0 and 20Hz)

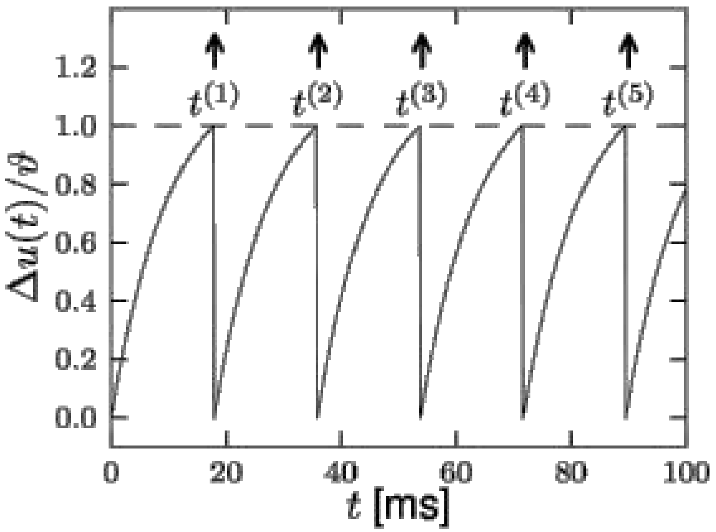
The visual information tour

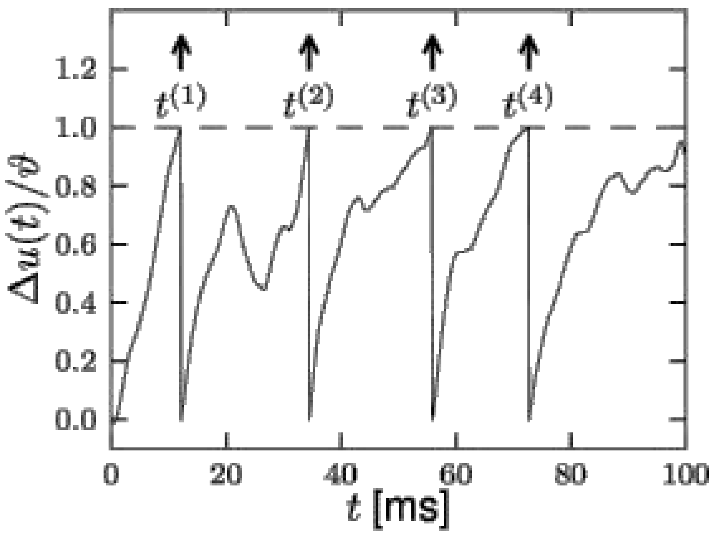


https://nba.uth.tmc.edu/neuroscience/m/s2/chapter15.html



The leaky integrate and fire neuron





A Time course of the membrane potential of an integrate-and-fire neuron driven by constant input current $I_0=1.5$. The voltage $\Delta u(t)=u-u_{rest}$ is normalized by the value of the threshold ϑ. Units of input current are chosen so that $I_0=1$ corresponds to a trajectory that reaches the threshold for $t\to\infty$. After a spike, the potential is reset to $u_r=u_{rest}$. B. Voltage response to a time-dependent input current.