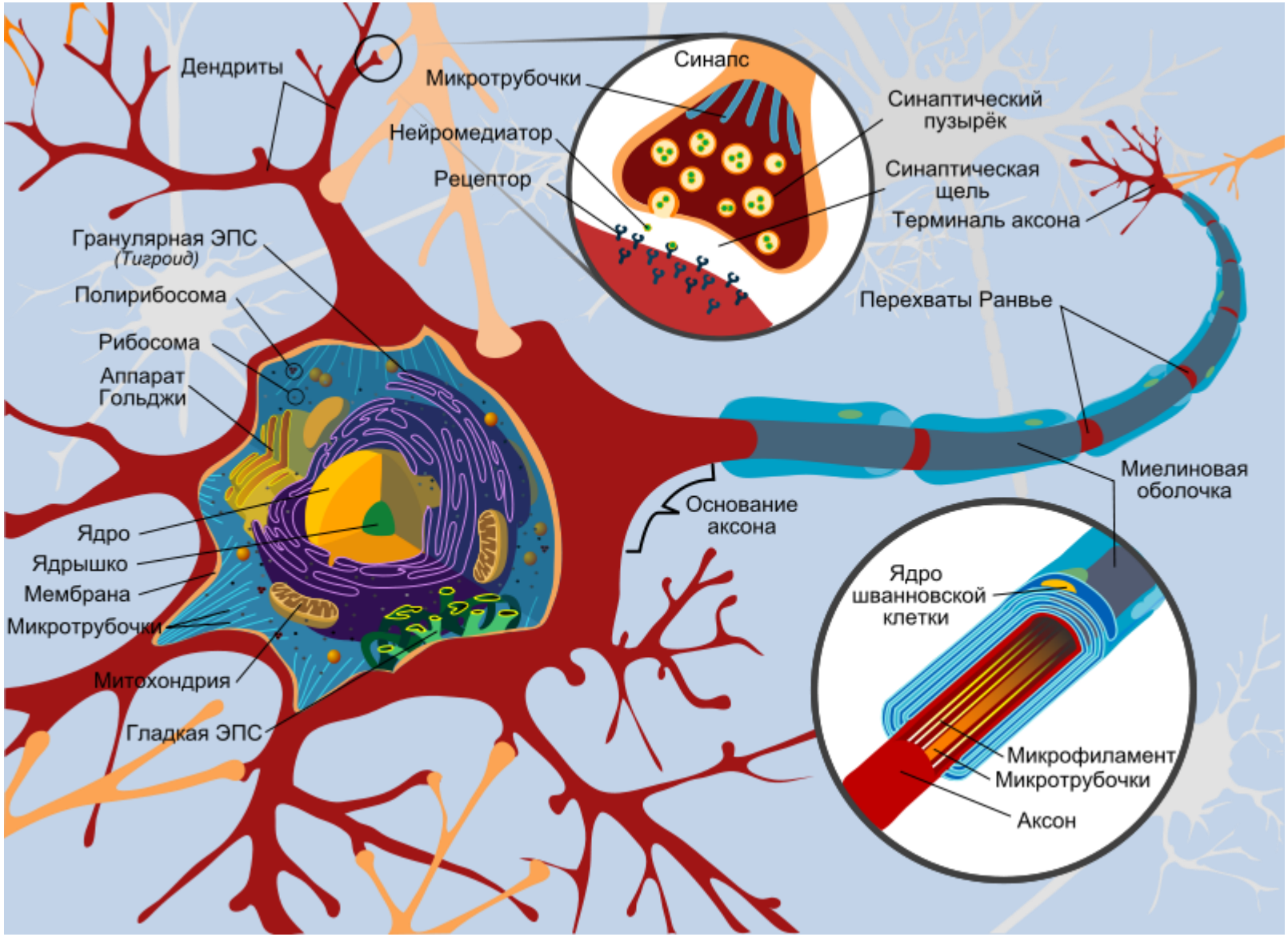
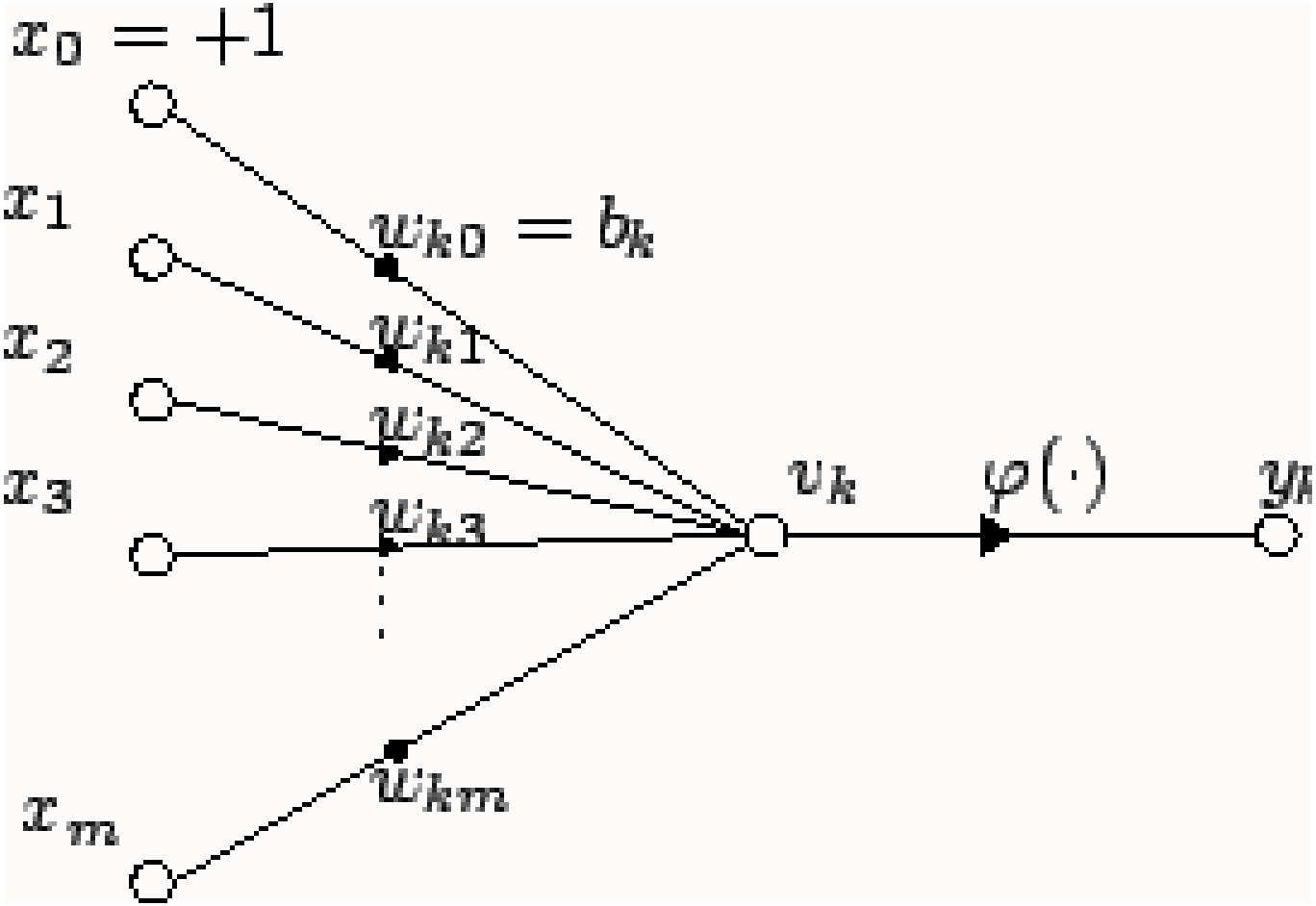
Спайковые и бионические нейронные сети, нейроморфные системы

Dmitry Nowicki

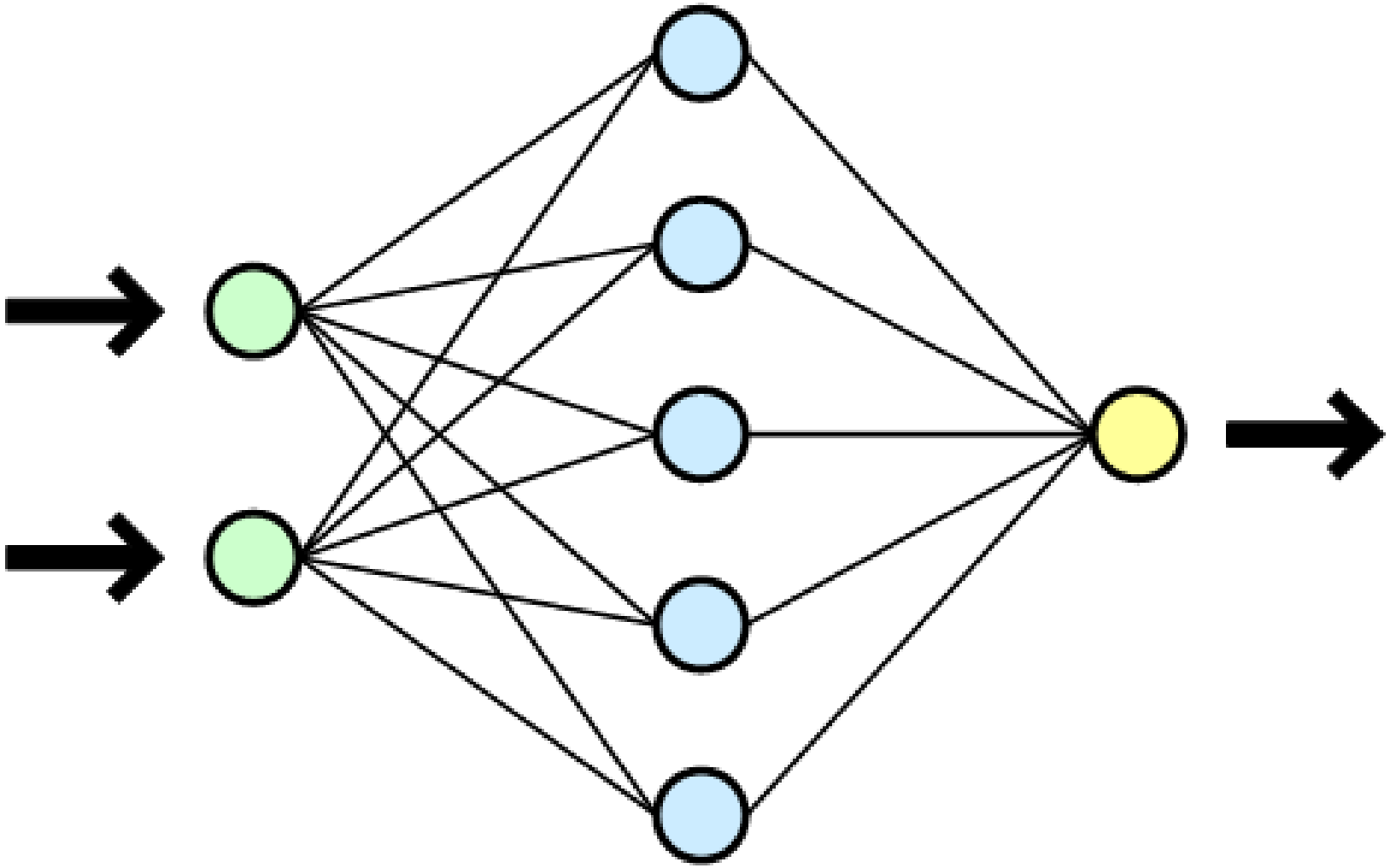
Биологический нейрон



Нейрон МакКаллока-Питтса (не похож !?)

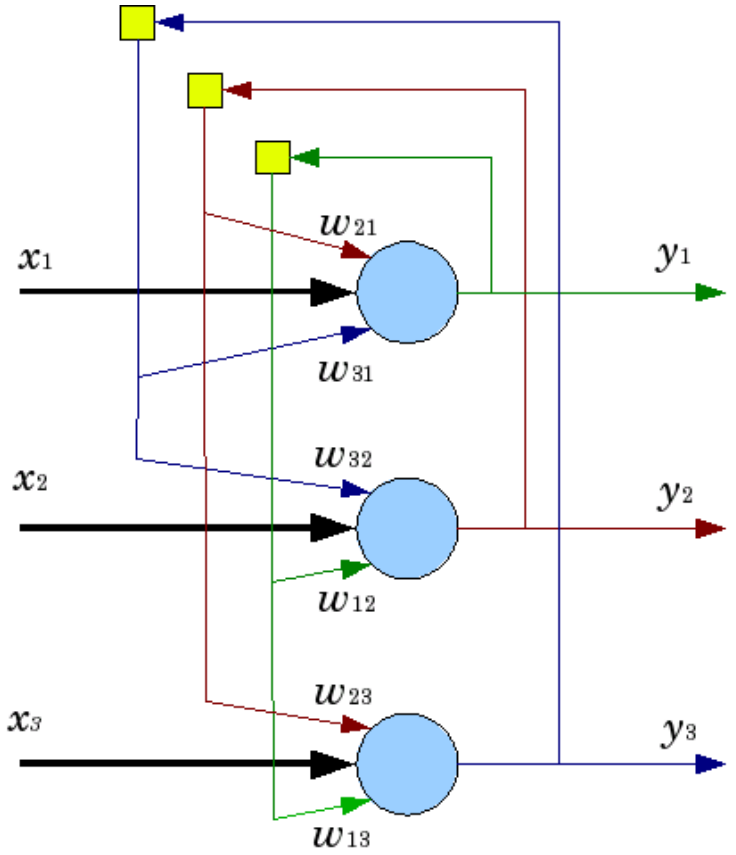


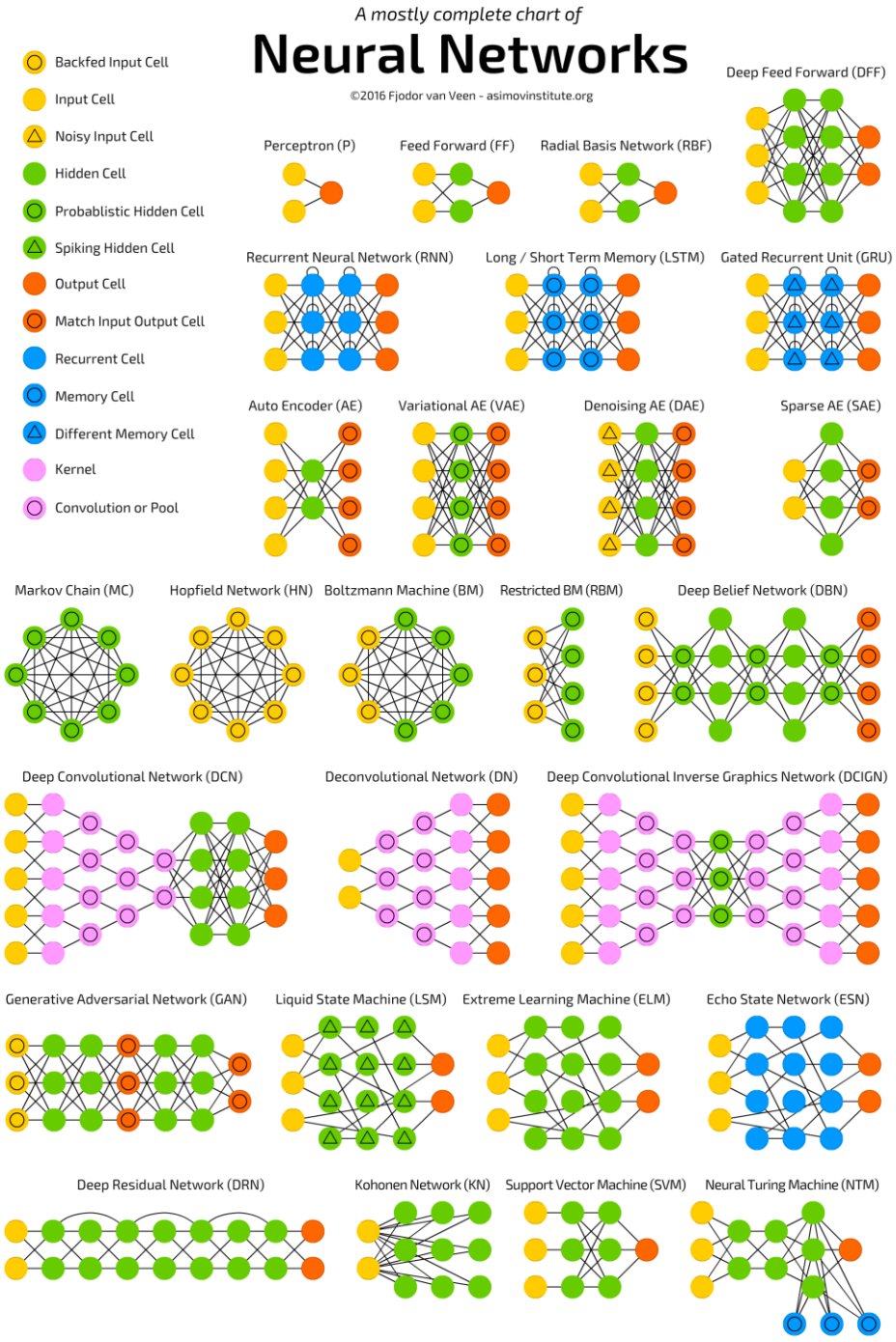
Сеть прямого распространения



Сеть Хопфилда: простейшая ассоциативная память

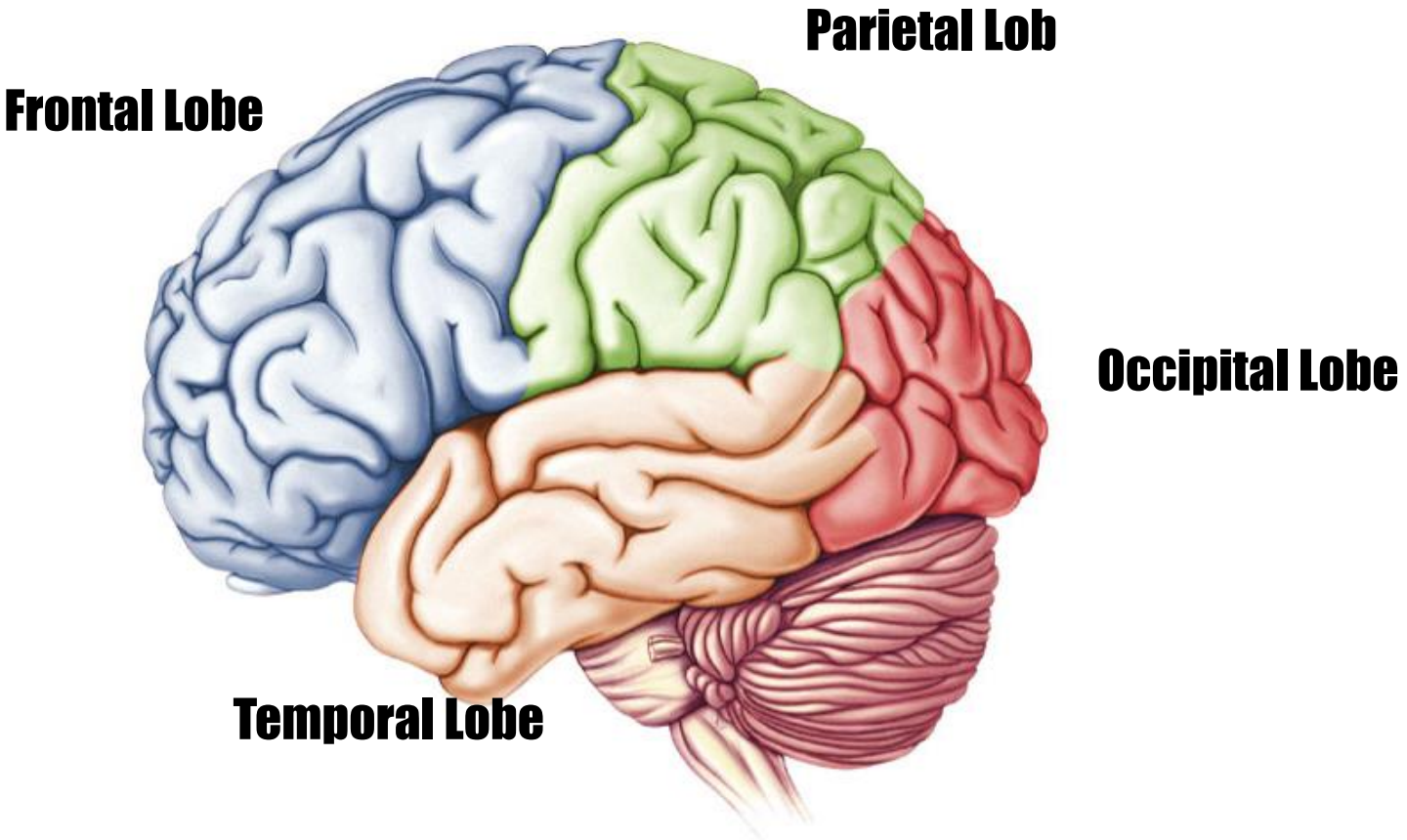
Работает как динамическая система с аттракторами





The Neural Network zoo

Our “meat machine” what does it consists of?



Historical perspective for “brain ingredients”

Key players

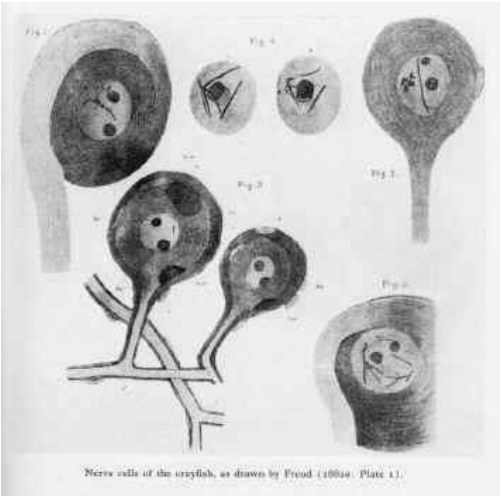
1665 – First use of simple microscope to view living cells (Robert Hooke) 1839 – “Cell theory” (Theodor Schwann) – but is it true for the brain?

1870 – Camilo Golgi develops his silver-based method, for randomly staining nerve cells

1887 – S. Ramon Y. Cajal uses Golgi technique – proposes the “neuron doctrine”

1891 – Hienrich Waldeyer – coined the word “Neuron”

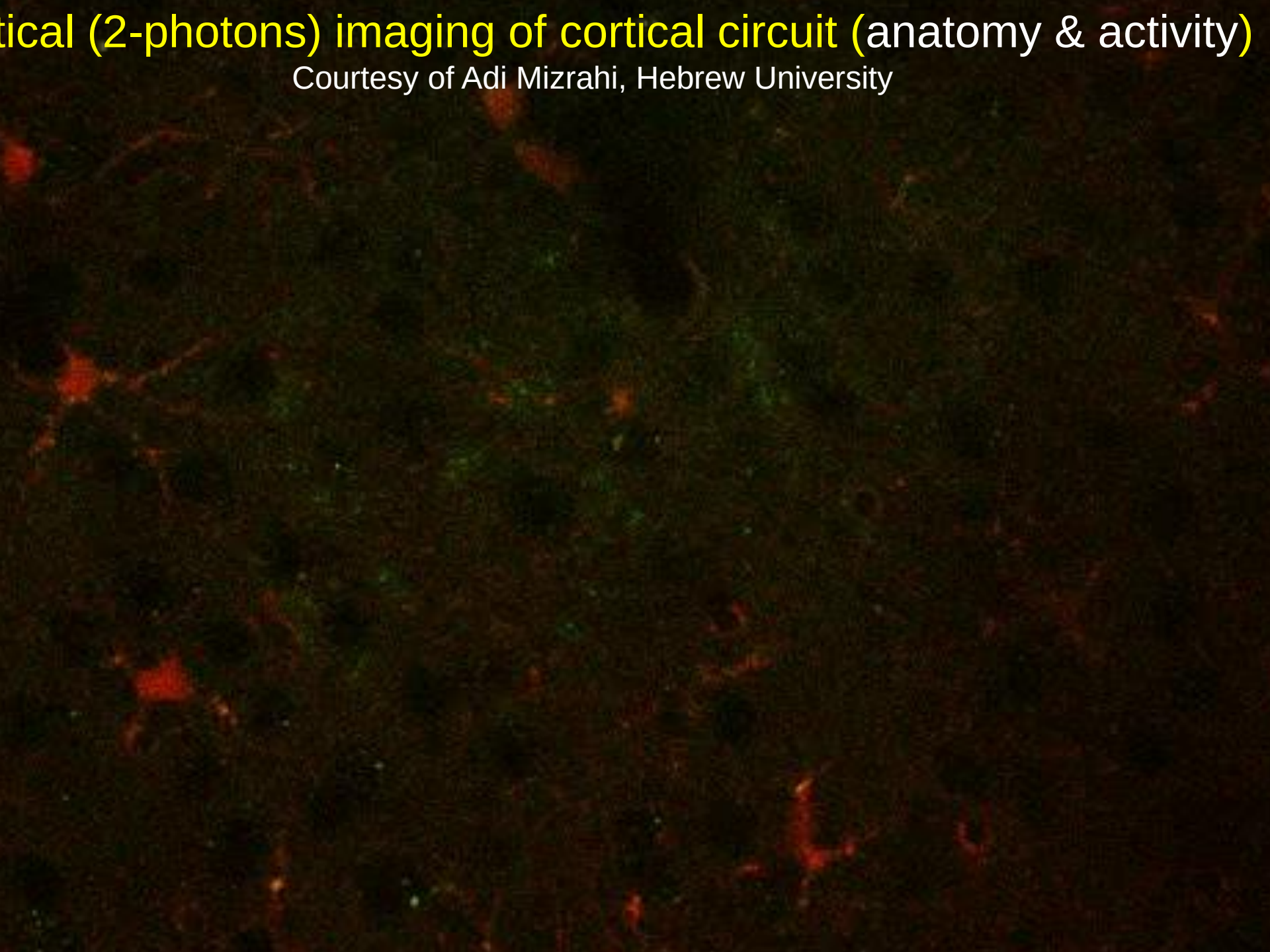
1897 - Charles Sherrington coined the word “synapse”



Sigmund Freud drawing crayfish neurons, 1882

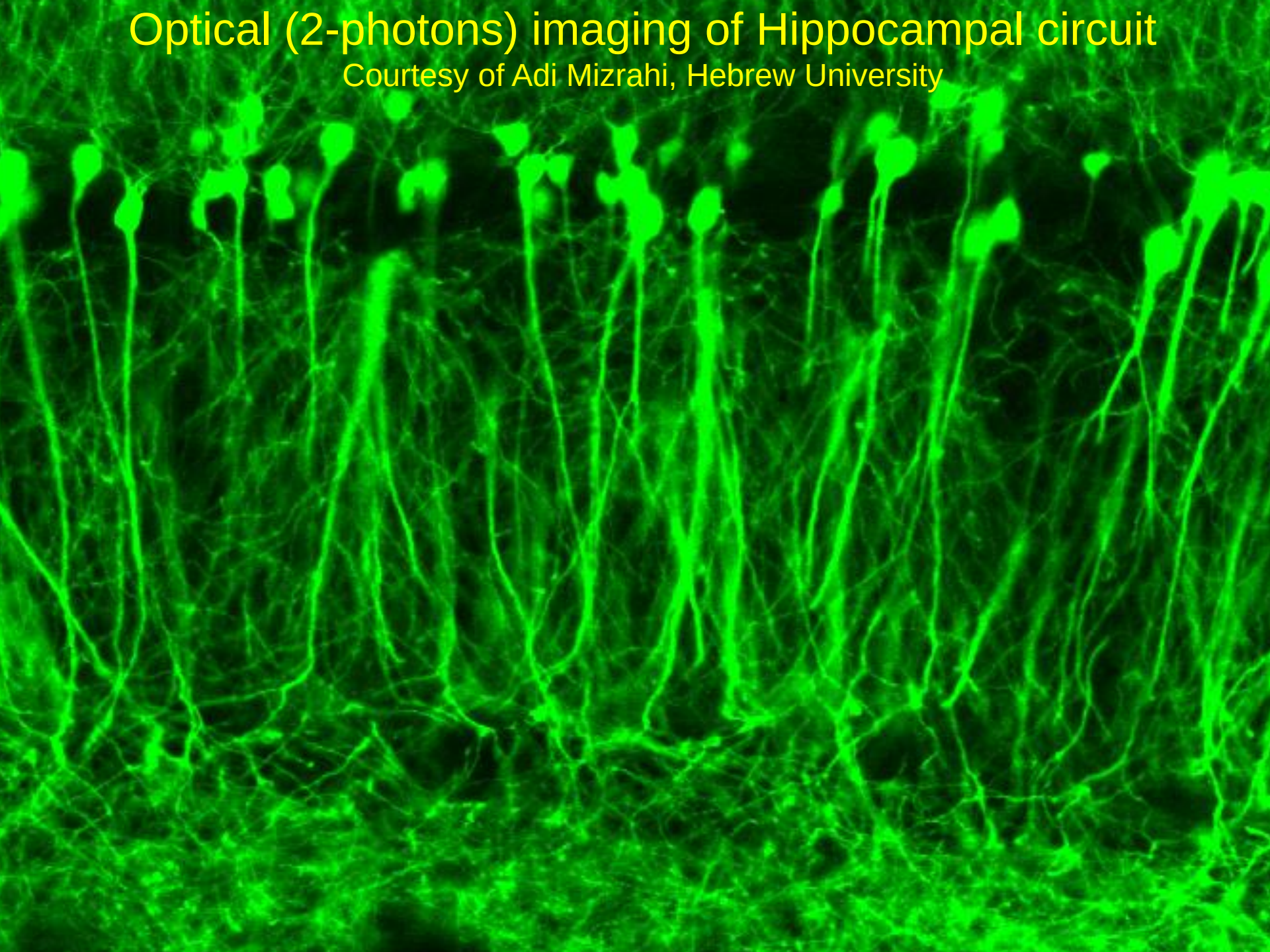
tical (2-photons) imaging of cortical circuit (anatomy & activity)

Courtesy of Adi Mizrahi, Hebrew University



Optical (2-photons) imaging of Hippocampal circuit

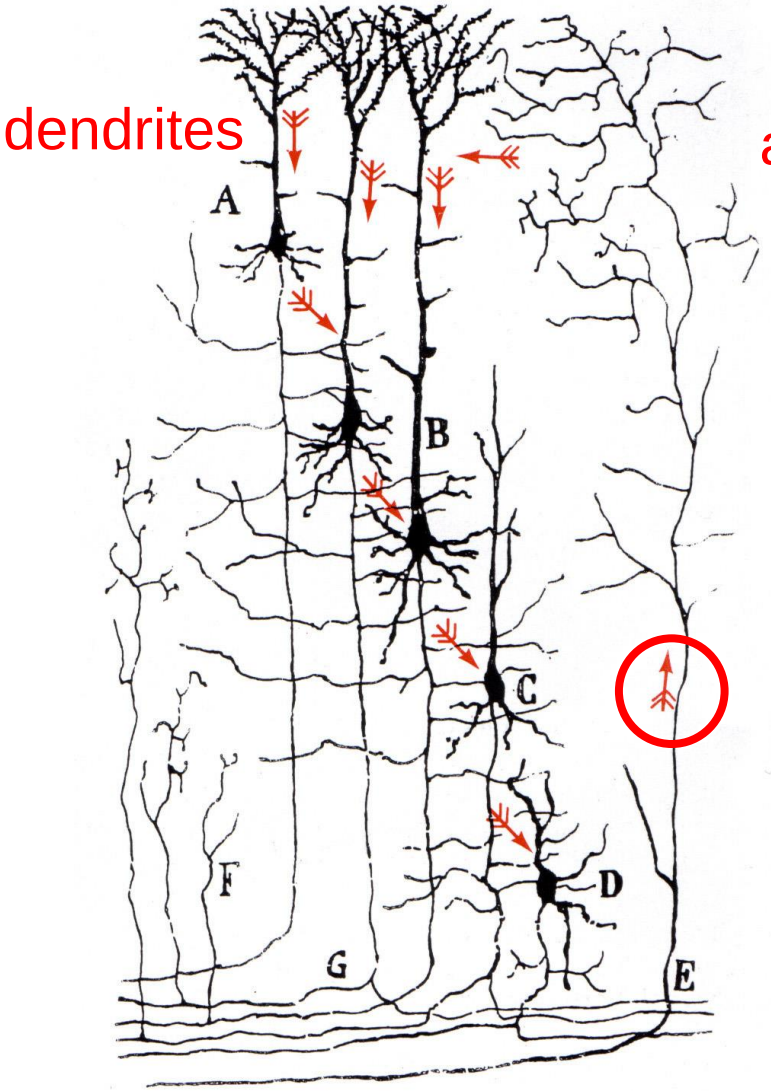
Courtesy of Adi Mizrahi, Hebrew University



S. Ramon Y Cajal

Possible direction of current flow and pattern of axo-dendritic connection

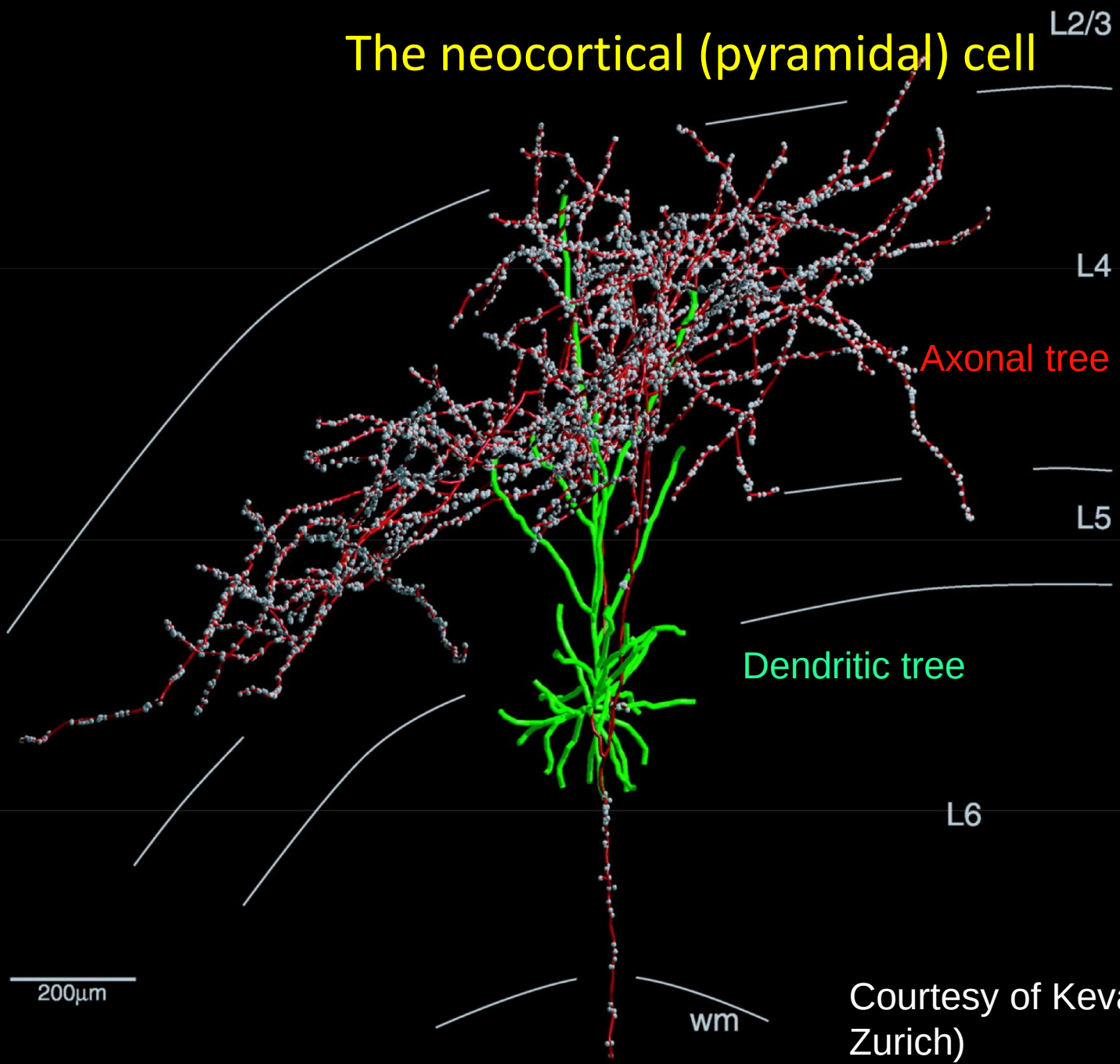
The "Neuron Doctrine" and the "Theory of dynamic polarization"



Dendrites are receptive (input) devices

Axon are the sending (output) devices

The neocortical (pyramidal) cell



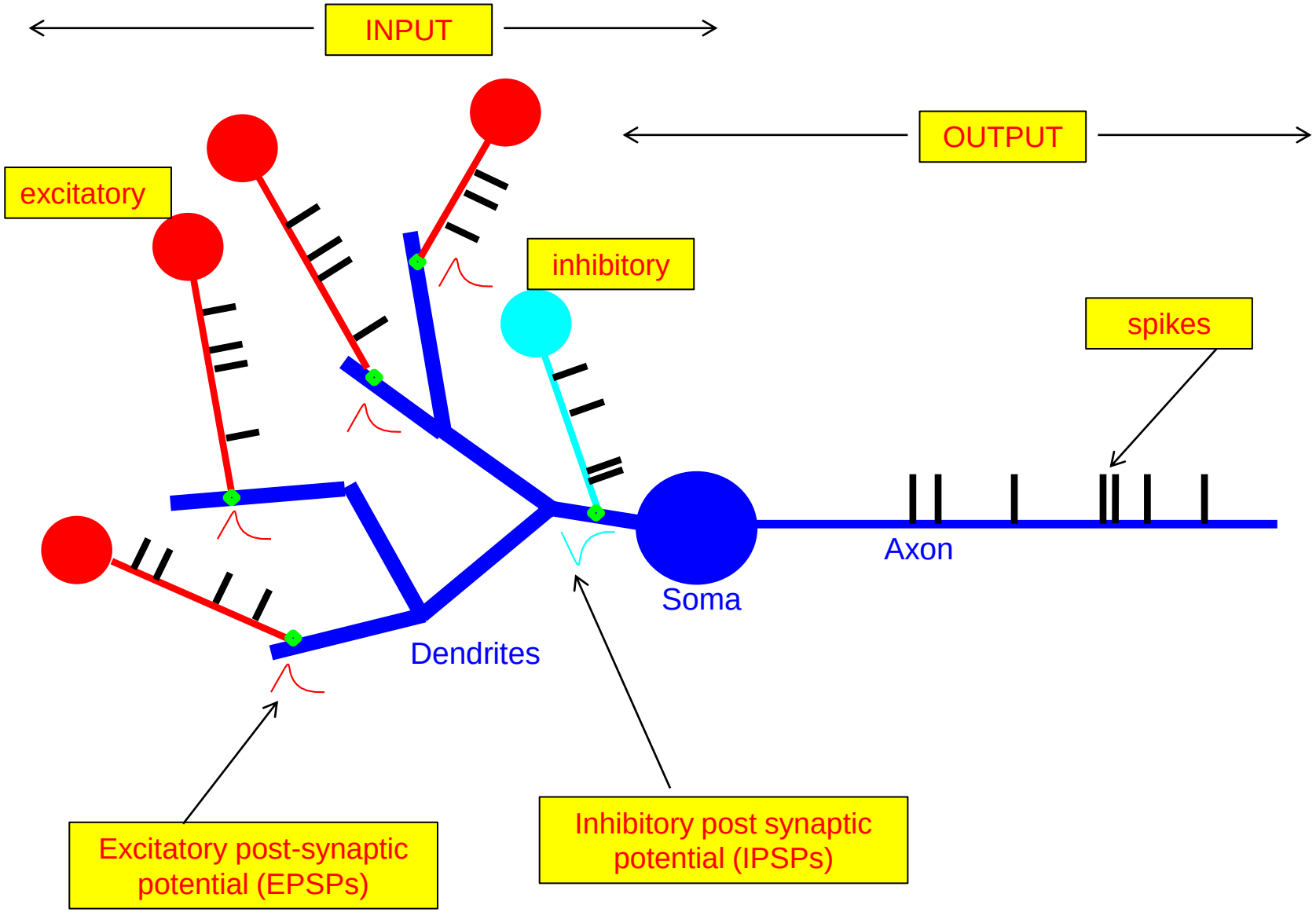
Axonal tree + varicosities

Dendritic tree

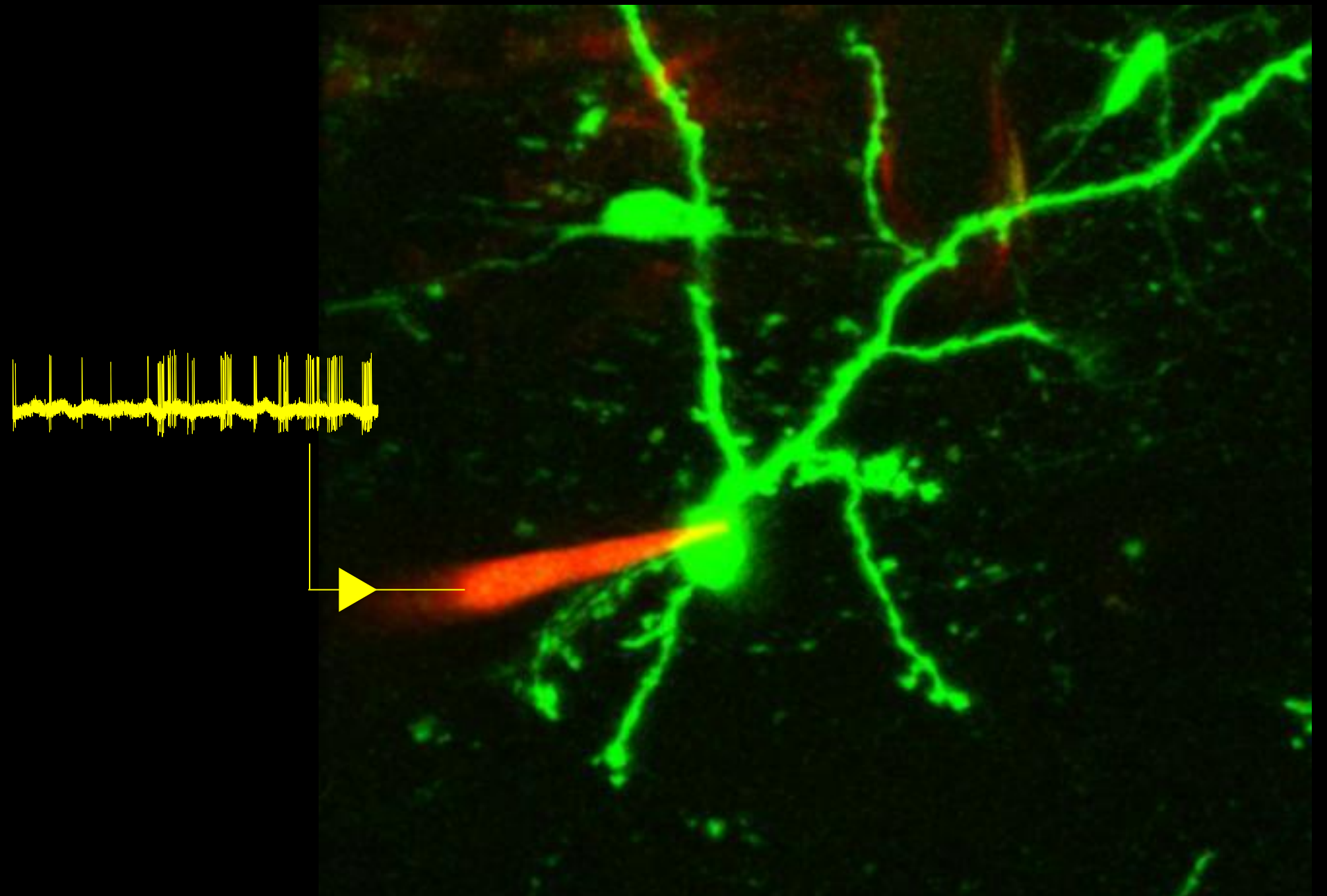
Courtesy of Kevan Martin, Univ. Zurich)

The neuron as an input-output electrical device

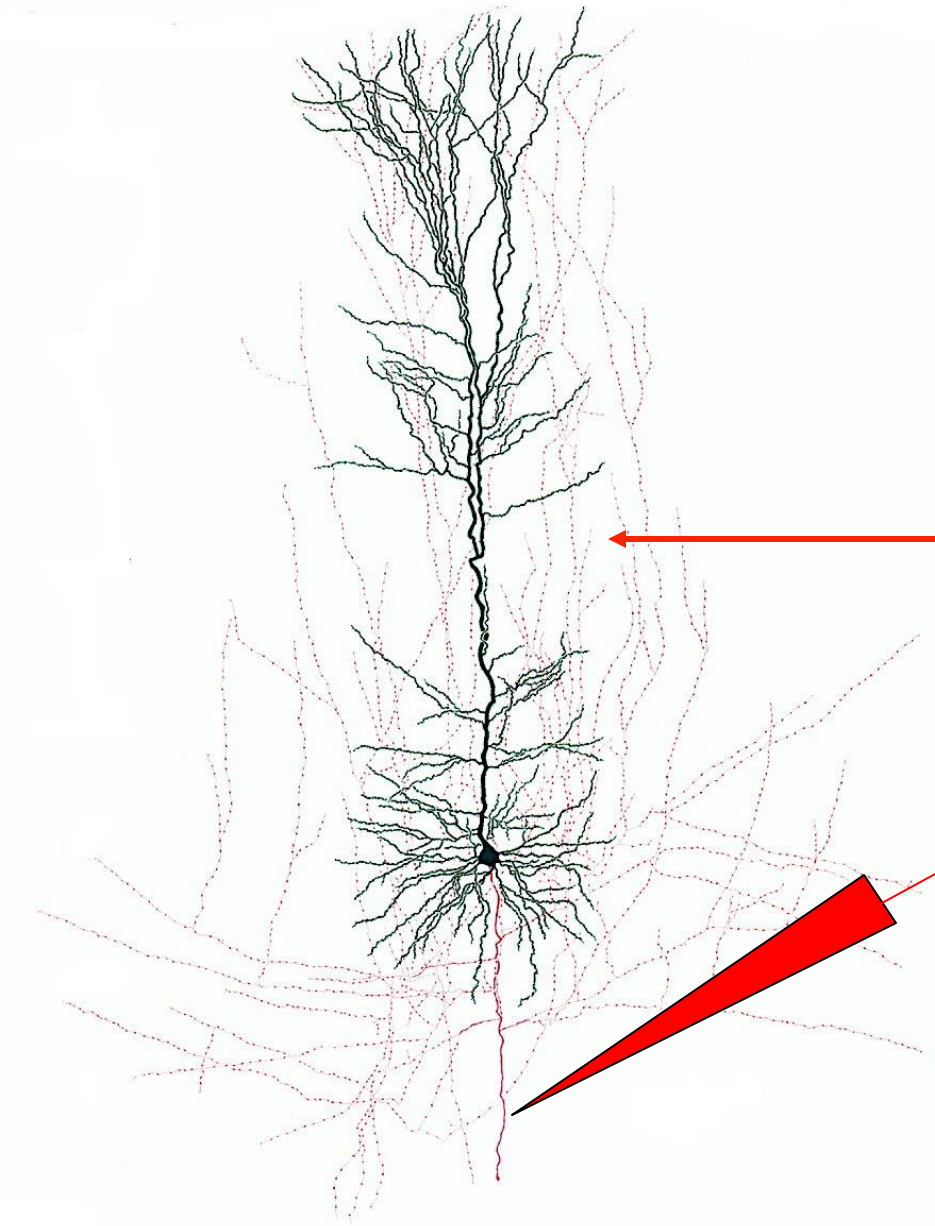
(conceptual, details will follow)



Spiking activity of a neuron

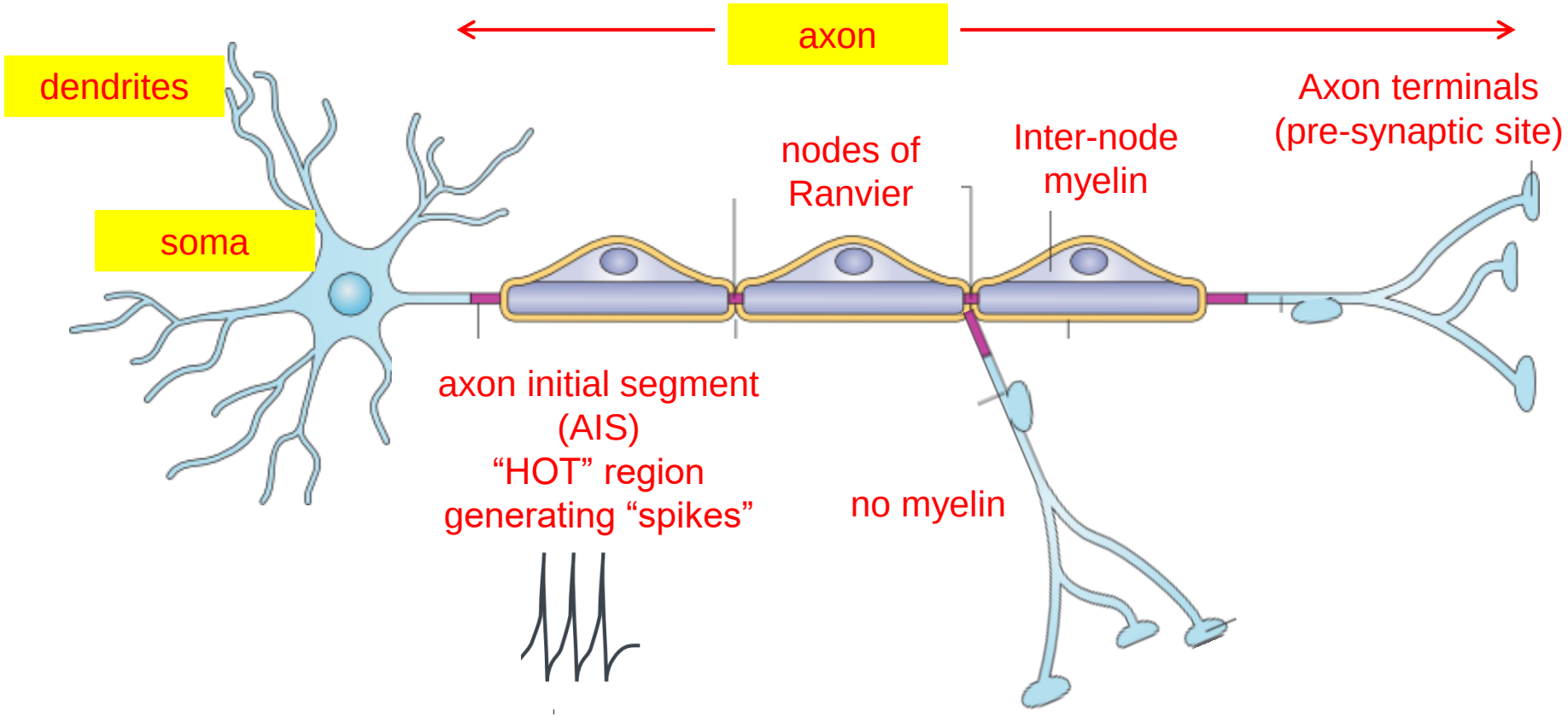


Axons "fire" spikes (carrying the brain code)



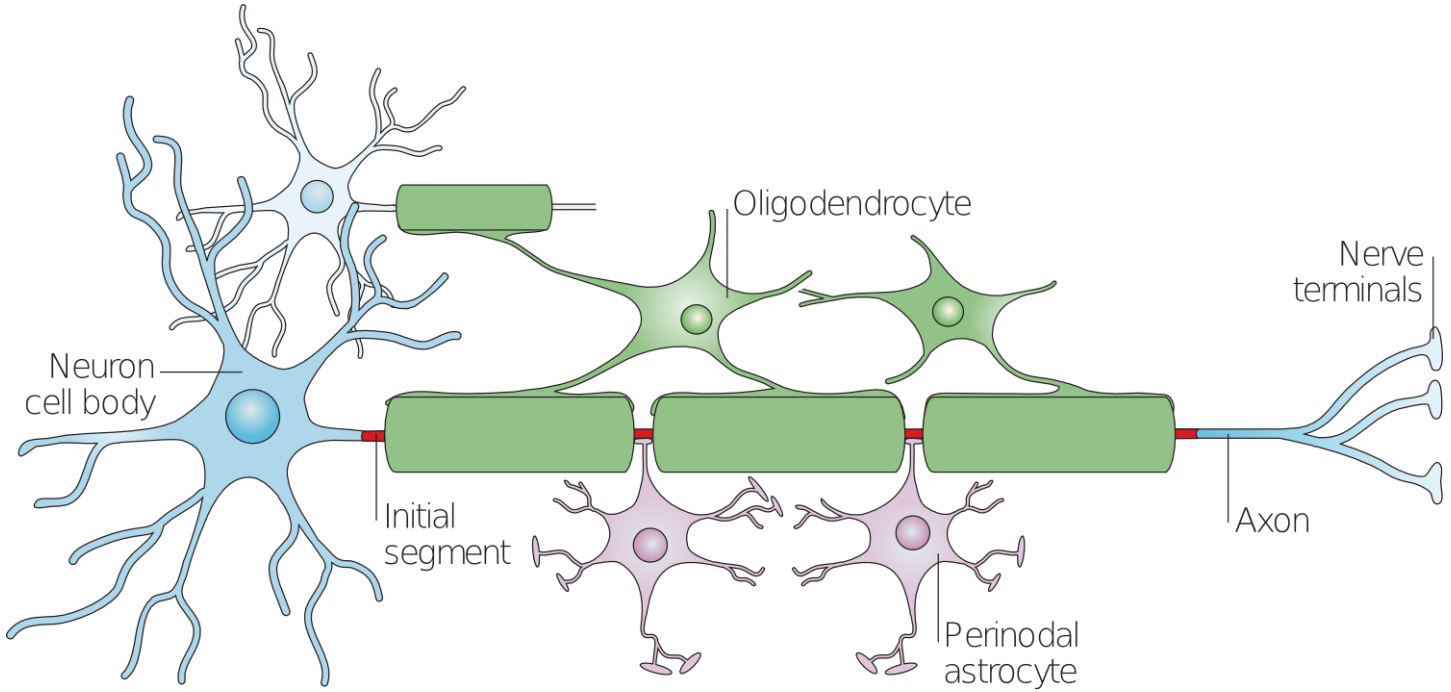
Axonal tree sending output - Spikes

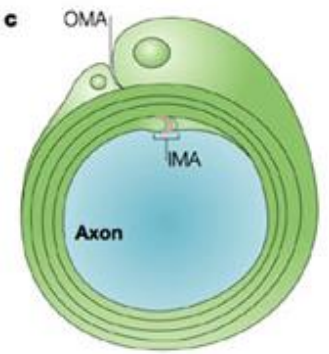
Typical morphology of a neuron



Poliak & Peles
Nature Reviews Neuroscience 4, 968-980 (December 2003)

The myelin of axons



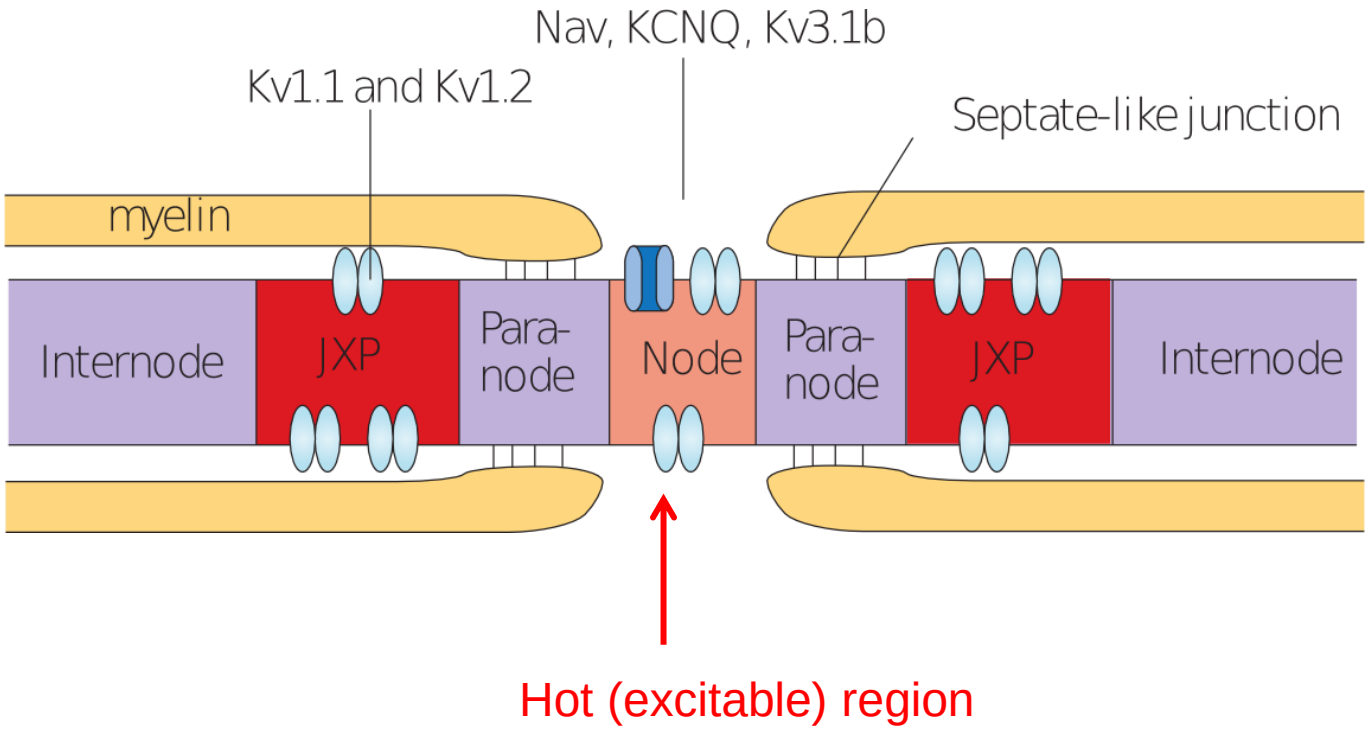


0.3 - 4μm

Myelinating glial cells, oligodendrocytes in the central nervous system (CNS) or Schwann cells in the peripheral nervous system (PNS), form the myelin sheath by enwrapping their membrane several times around the axon.

Poliak & Peles
Nature Reviews Neuroscience 4, 968-980 (December 2003)

The node of Ranvier in axons



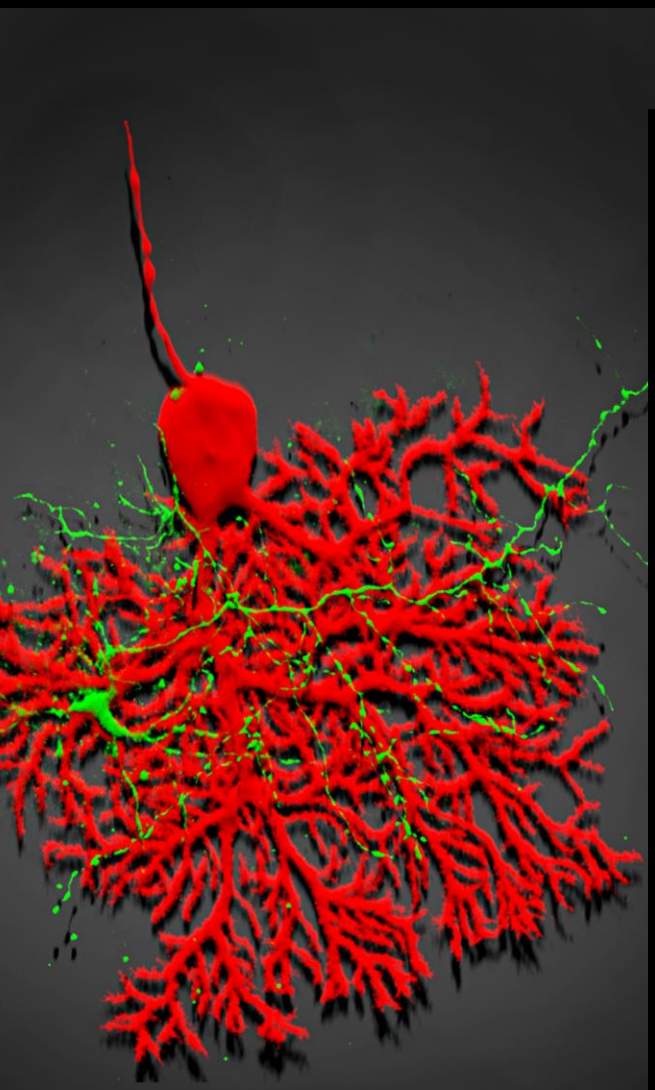
Helen C. Lai and Lily Y. Jan
Nature Reviews Neuroscience 7, 548-562 (July 2006)

A typical axon in the central nervous system (CNS summary

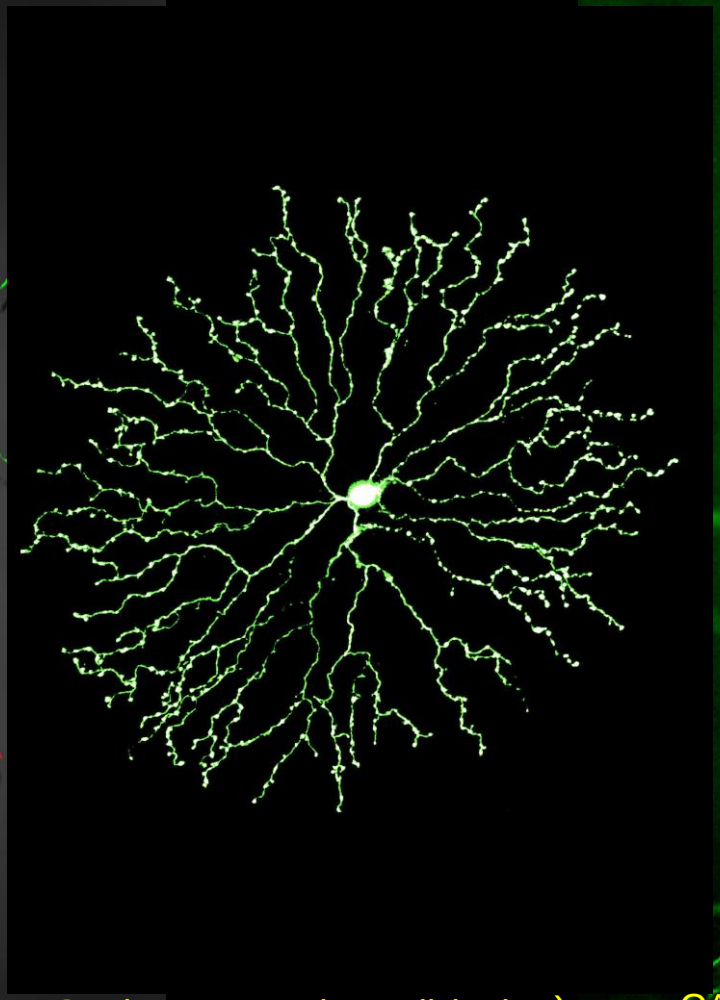
1. A single, highly branched, thin (μm) process emerging from the soma. Branched locally but may extend far (many centimeters and even meters) away from the soma
2. At the "hot" axon initial segment (AIS) the spike ("action potential") is initiated and then propagates along the axon
3. Covered with myelin (isolating) lipid sheath, with intermittent small gaps – the nodes of Ranvier (where "hot" – excitable ion channels reside)
4. Decorated with frequent swellings (axonal boutons) – where the neurotransmitter "hides" (the pre-synaptic site)

The axon is the output electrical device of neurons,
It generates and carries electrical signals called spikes

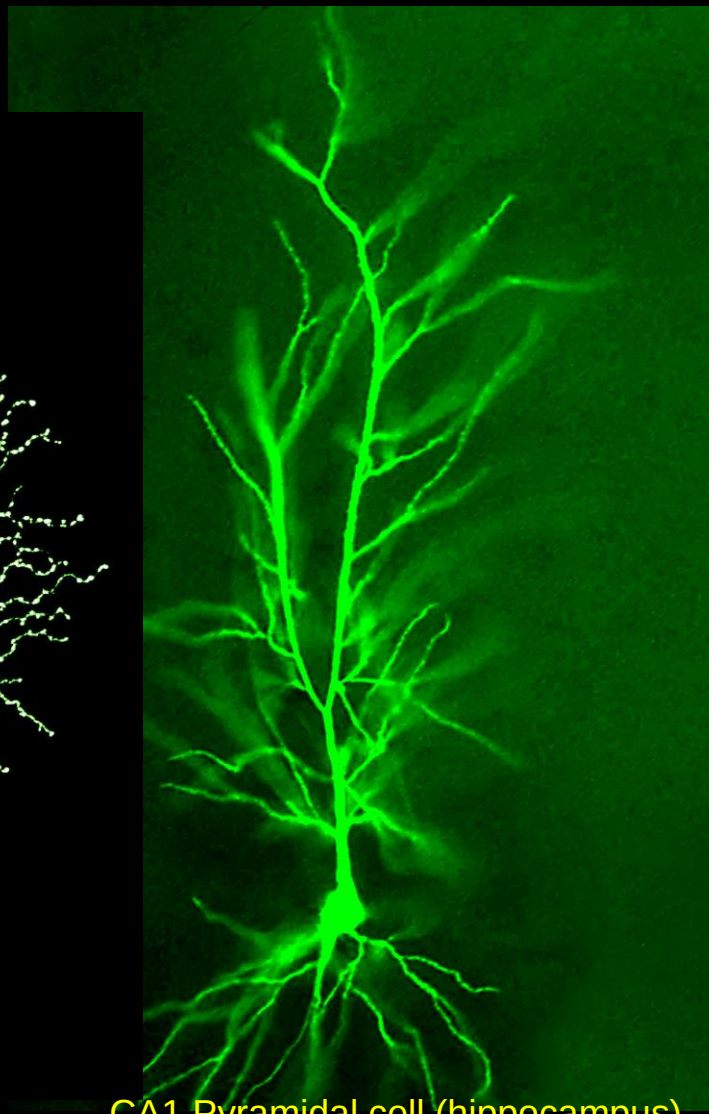
Dendrites



Purkinje cell (cerebellum)
(Courtesy of M. Hausser)

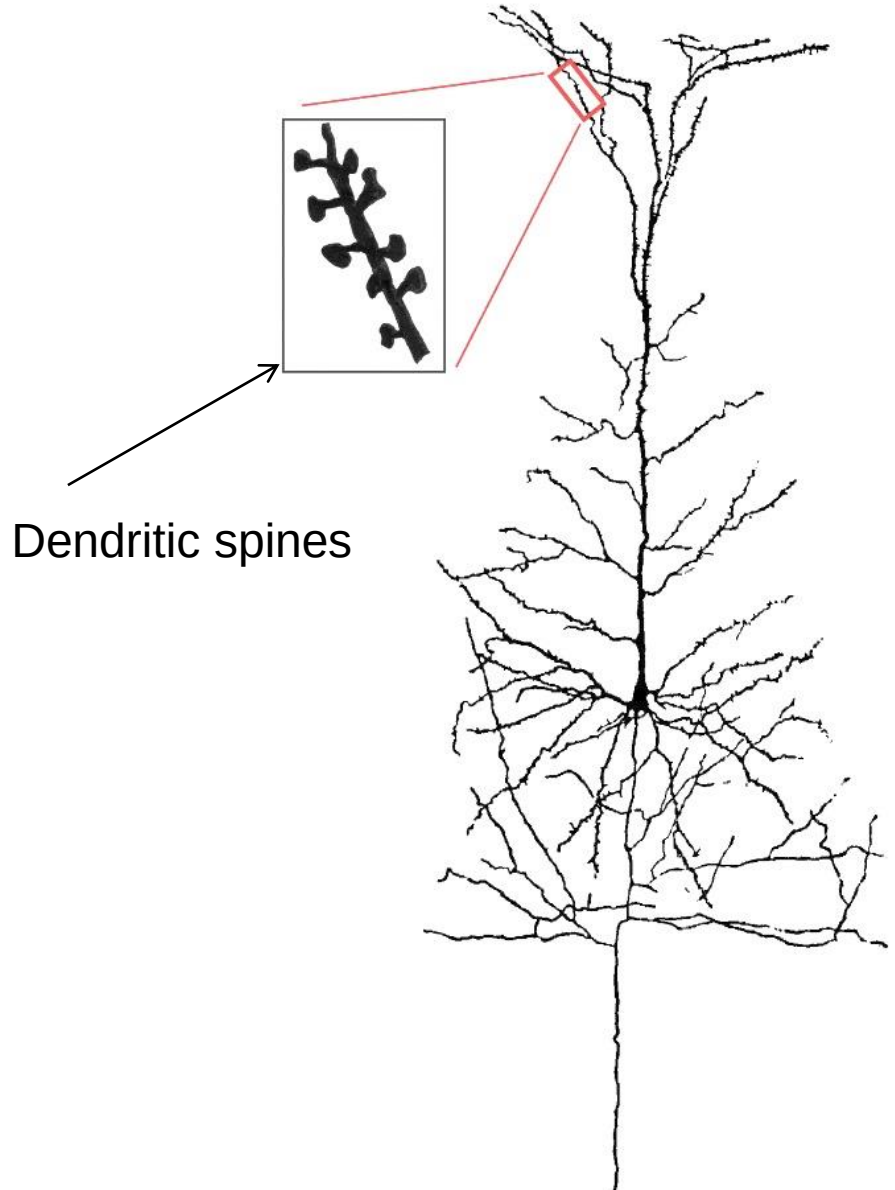


Starburst amacrine cell (retina)
(Courtesy of W. Denk)



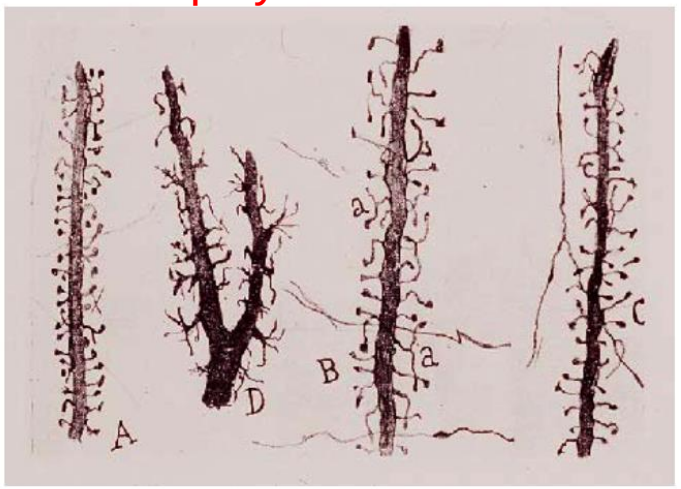
CA1 Pyramidal cell (hippocampus)
(Courtesy of D. Johnston)

An example: The layer 5 cortical pyramidal cell
(the "psychic" cell by Cajal)



Dendrites with spines

Spiny neurons



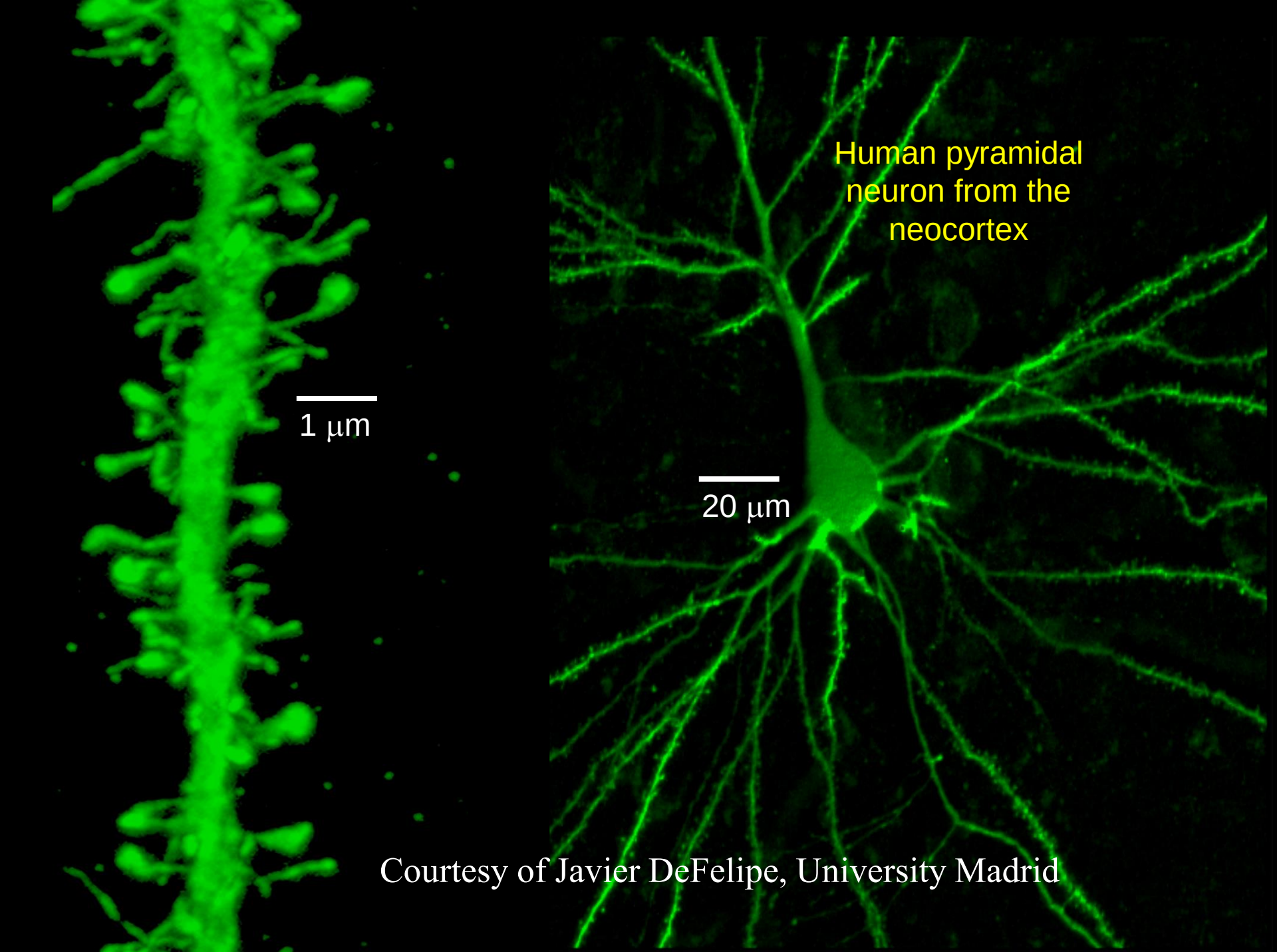
Typical numbers

Total dendritic area – **20,000 μm^2**

Number of dendritic spines/cell – **8,000**

Spine area – ~**1 μm^2**

Number of converging inputs (synapses/cell) – **10,000**

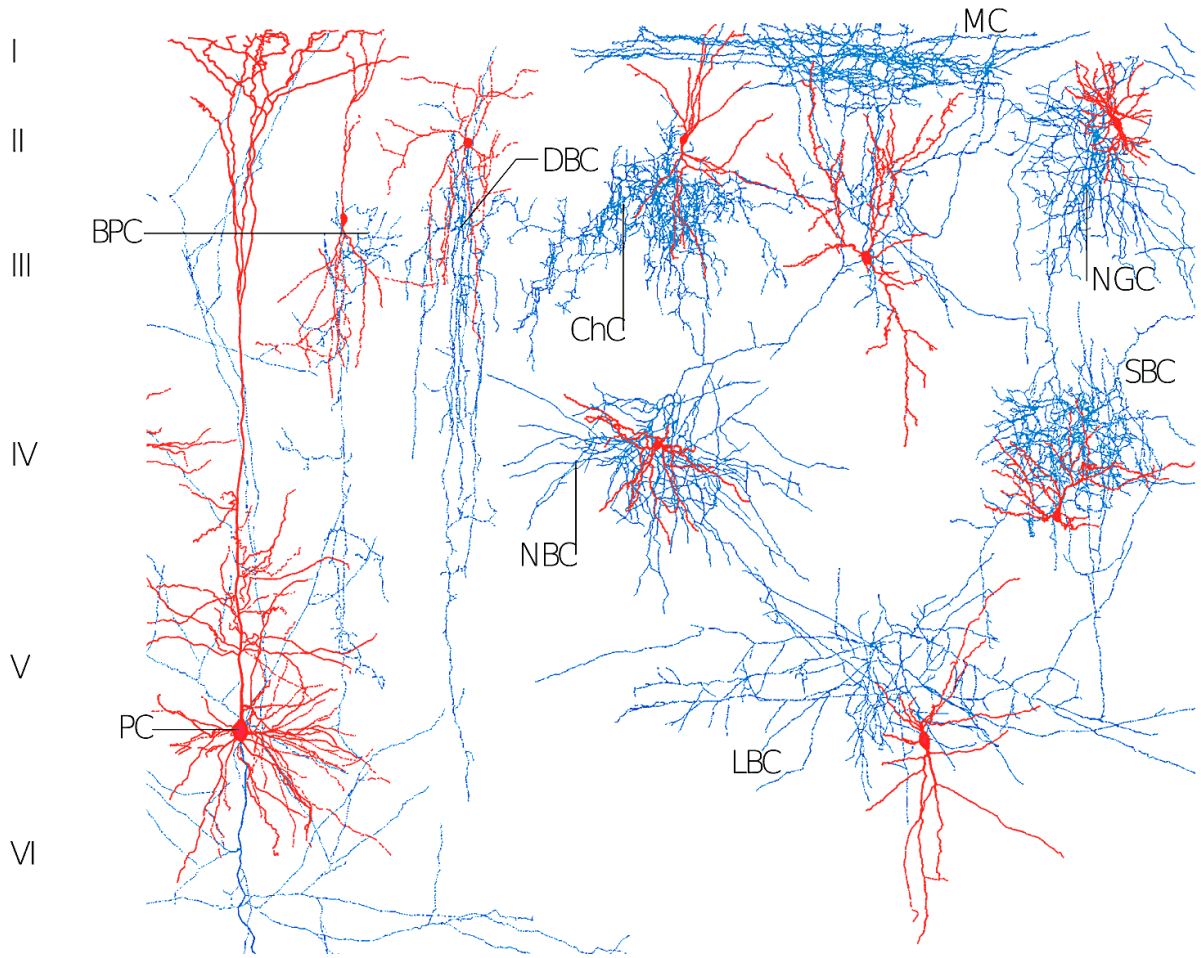


Courtesy of Javier DeFelipe, University Madrid

Neuron types

- Classification by anatomical features (“the face” of dendrites and axons)
- Classification – functional (e.g., Excitatory (principal) vs. Inhibitory (inter) neurons)
- Classification using electrical/spiking activity pattern
- Classification using chemical characteristics
- Classification using gene expression

Microcircuit of the Neocortex

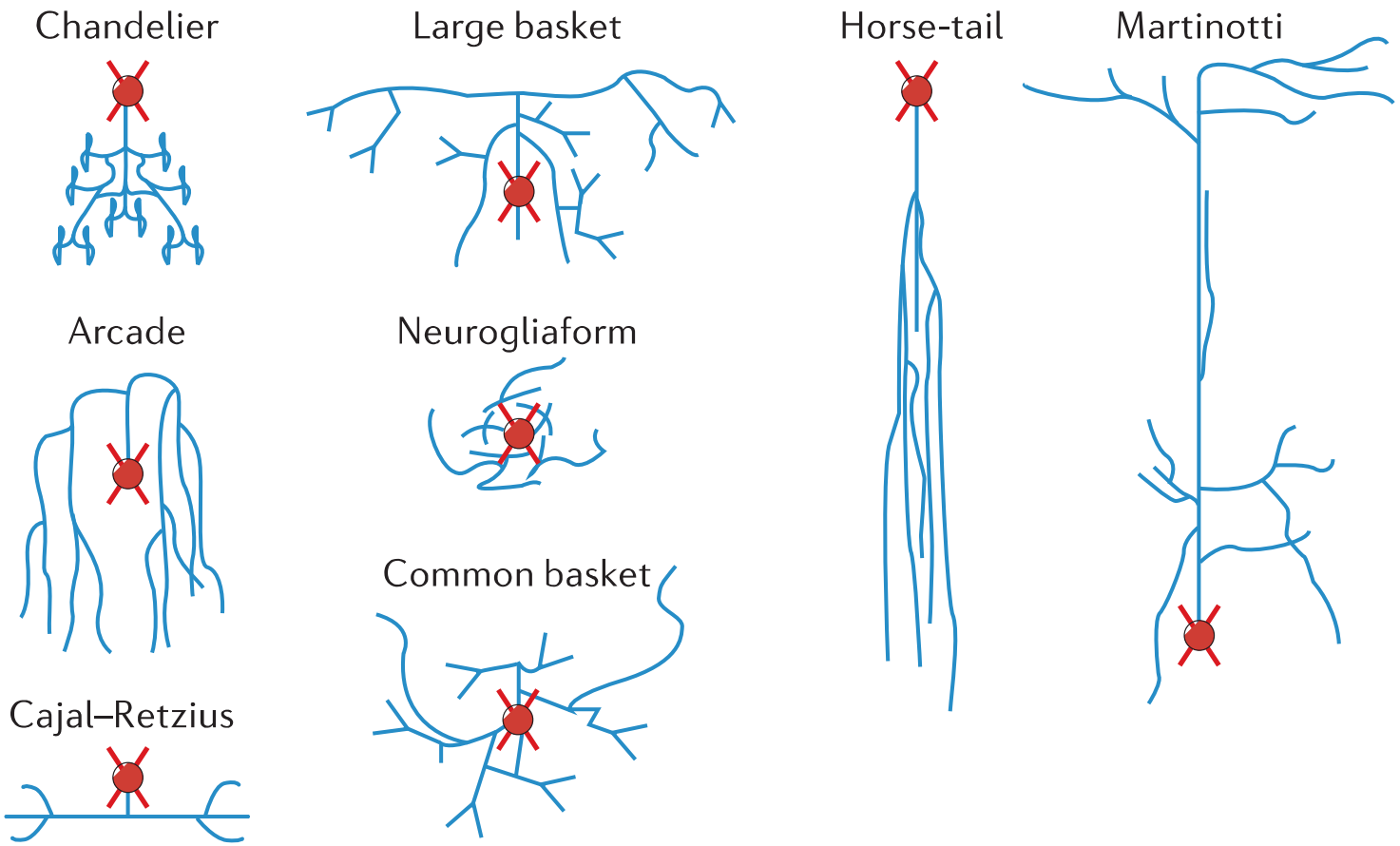


Principal neurons (excitatory) - axon projects to other brain regions

Interneurons (inhibitory) – local axonal projection

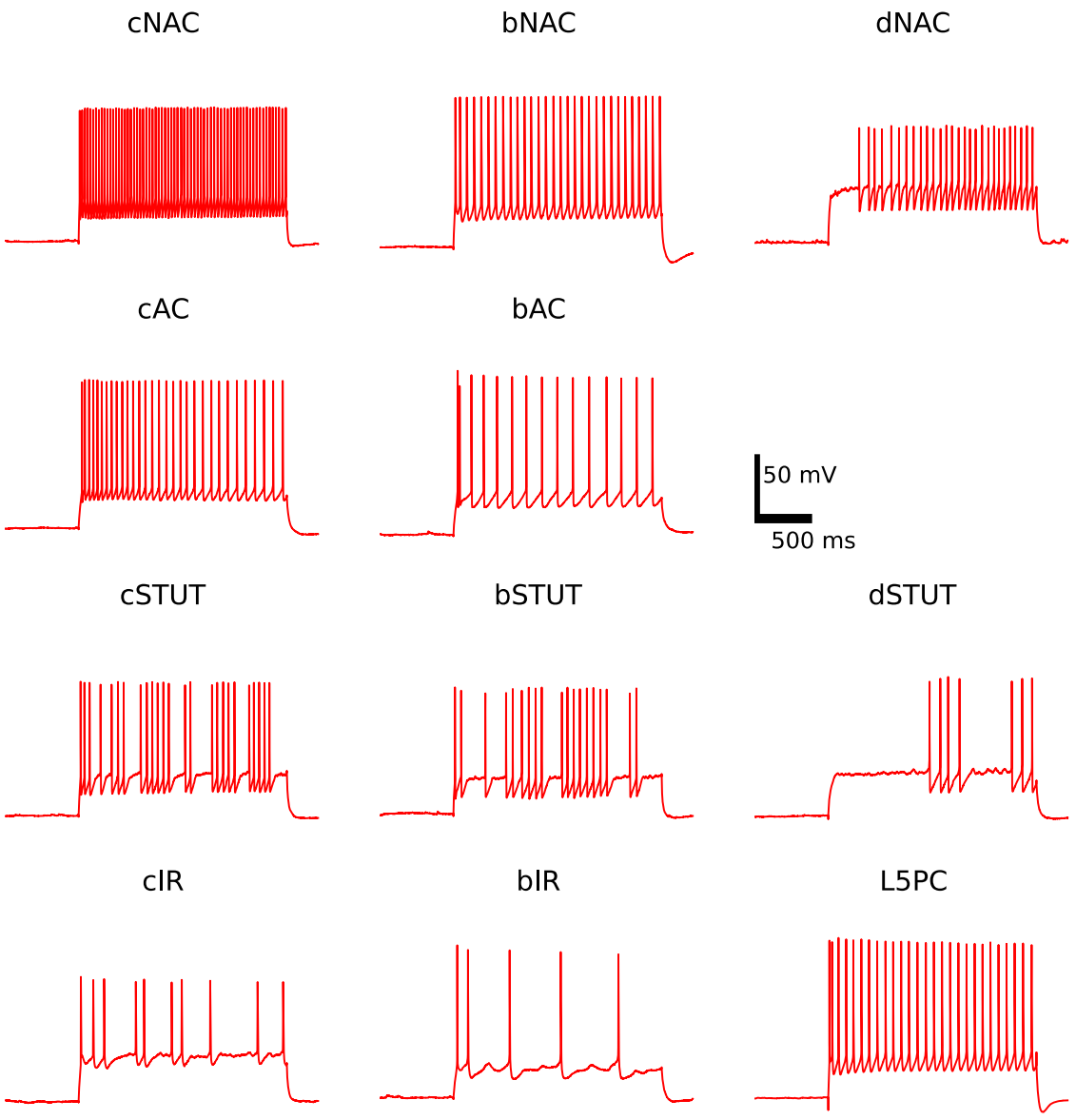
Z. J. Huang, G. Di Cristo & F. Ango
Nature Reviews Neuroscience 8, 673-686 (September 2007)

Morphometric-based classification of (inhibitory) *interneurons*



DeFelipe et al., Nature Review neuroscience, 2013

Electrically-based neuron classification
(based of spiking patterns)

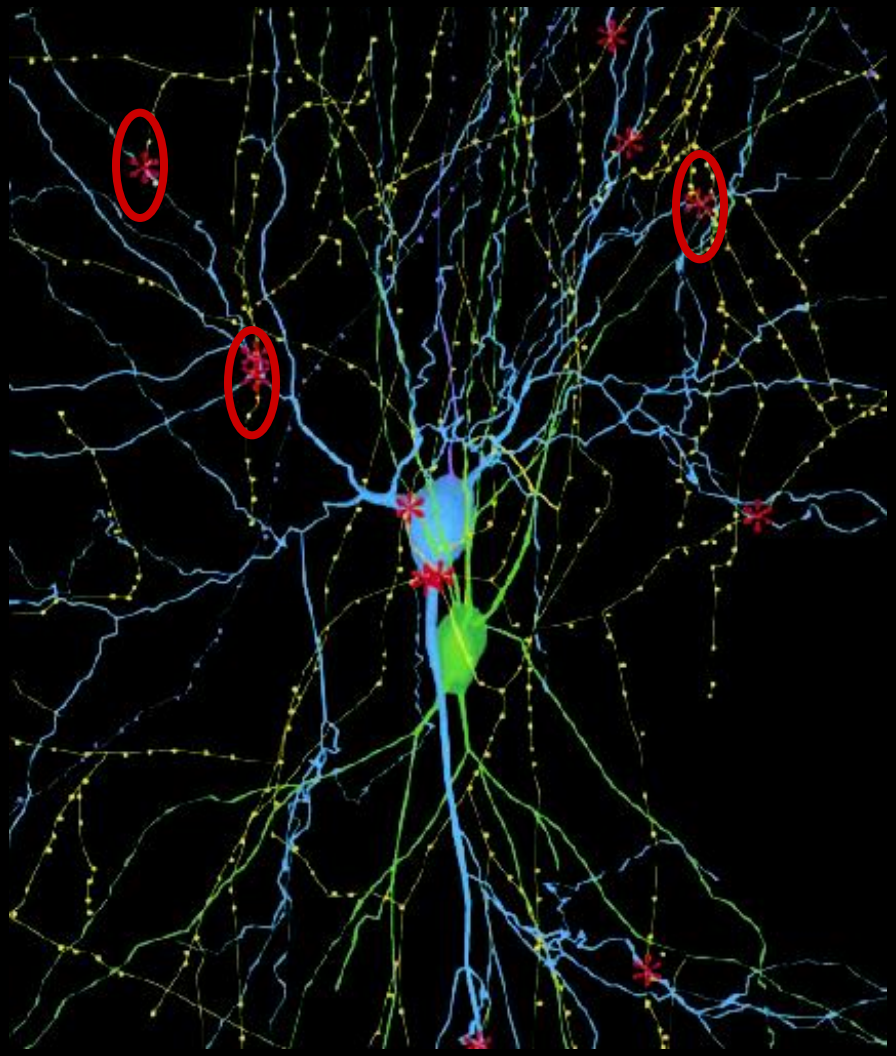


Courtesy of the Blue Brain data-base

The Chemical Synapse

A (chemical/electrical) device that connects

axon of neuron A to dendrites of neuron B

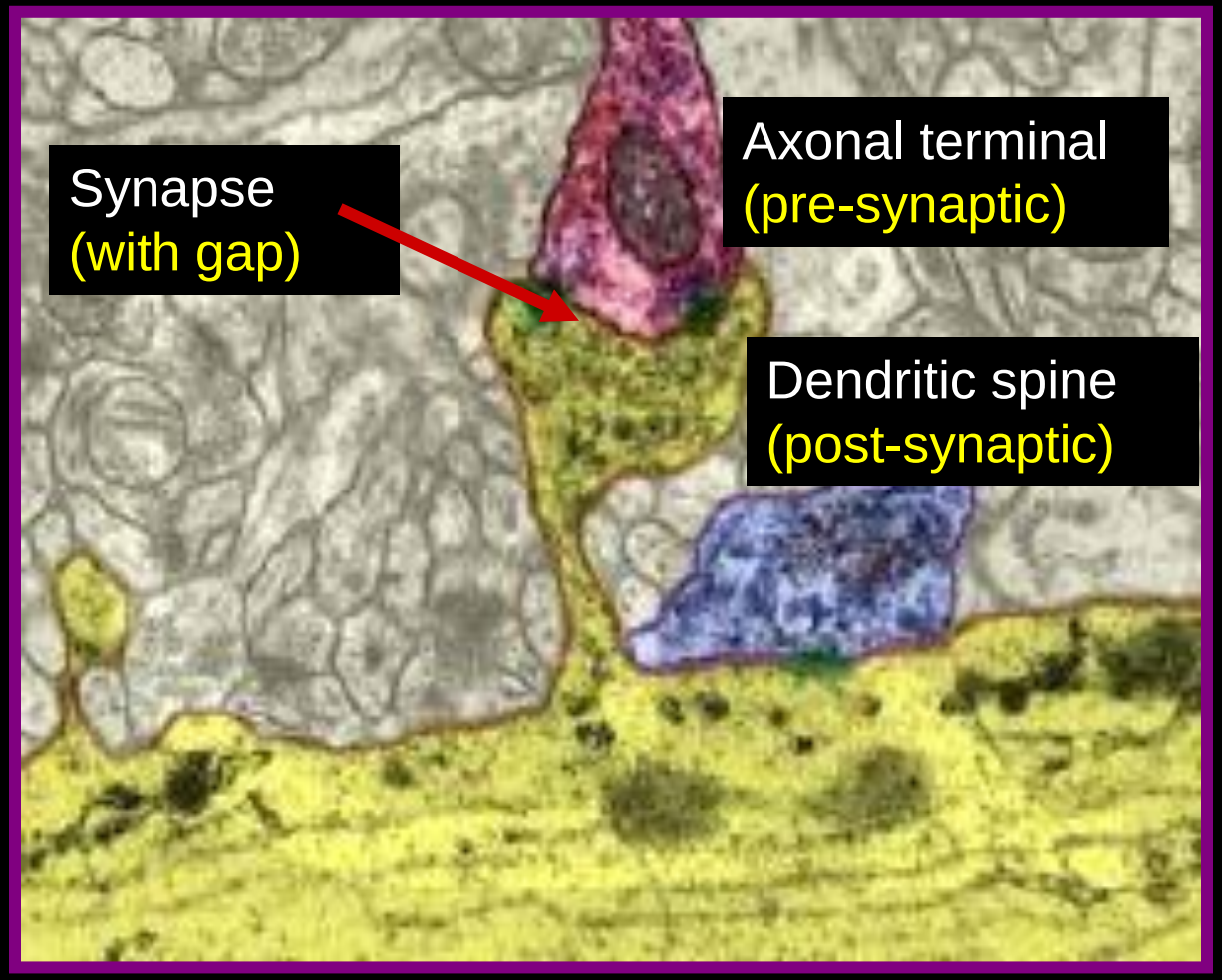


Dendrites of neuron B

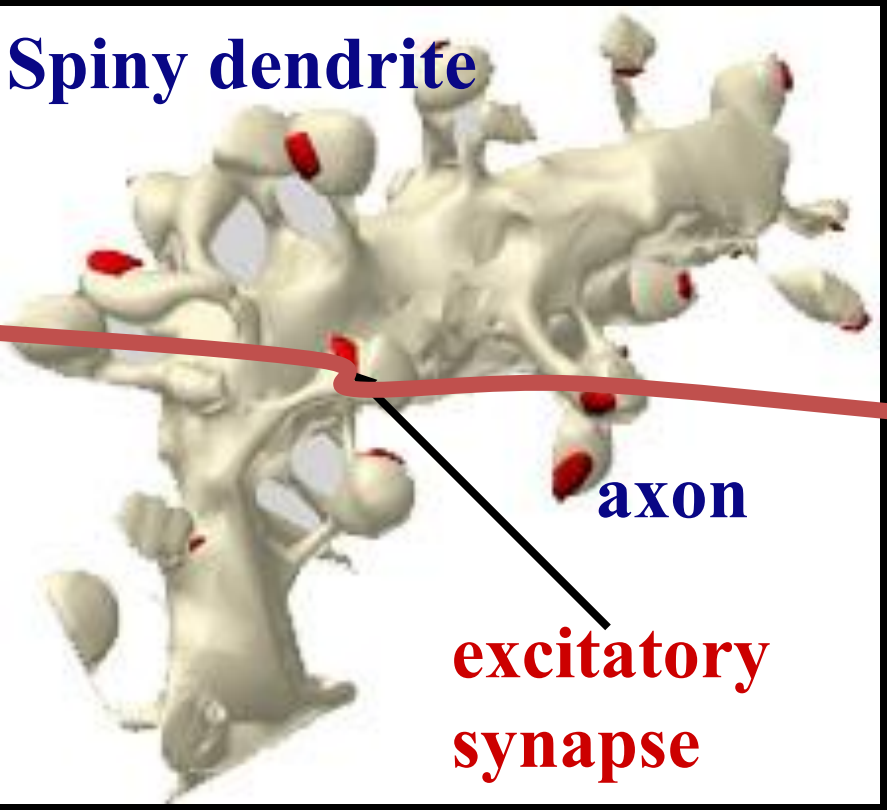
Axon of neuron A
(note varicosities)

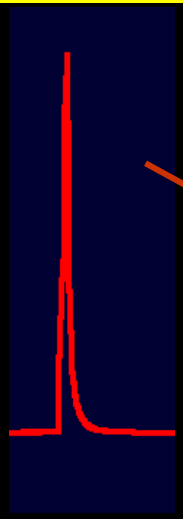
A chemical synapse

formed between axons and dendrites

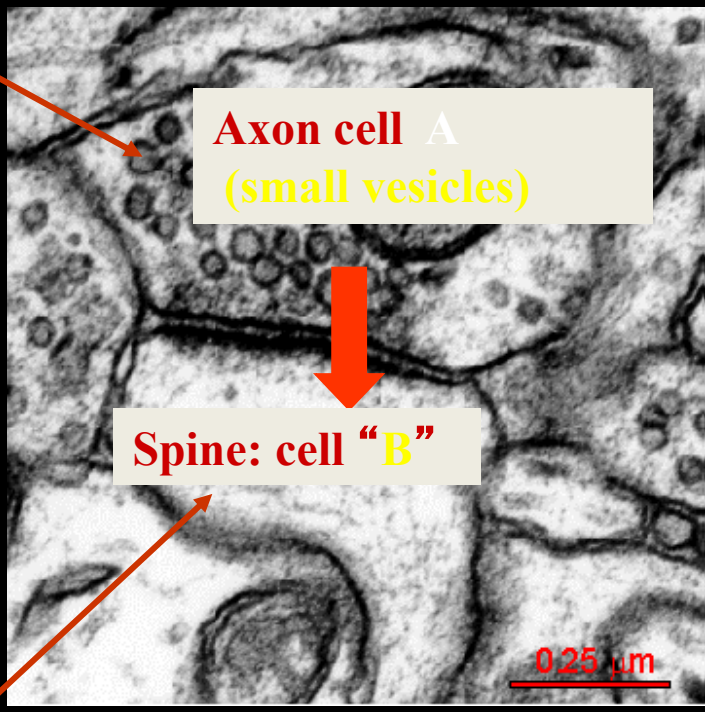


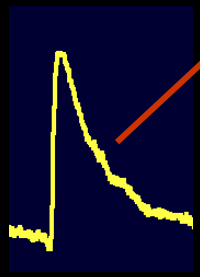
The chemical synapse





SPIKE at axon (digital - "all or none)



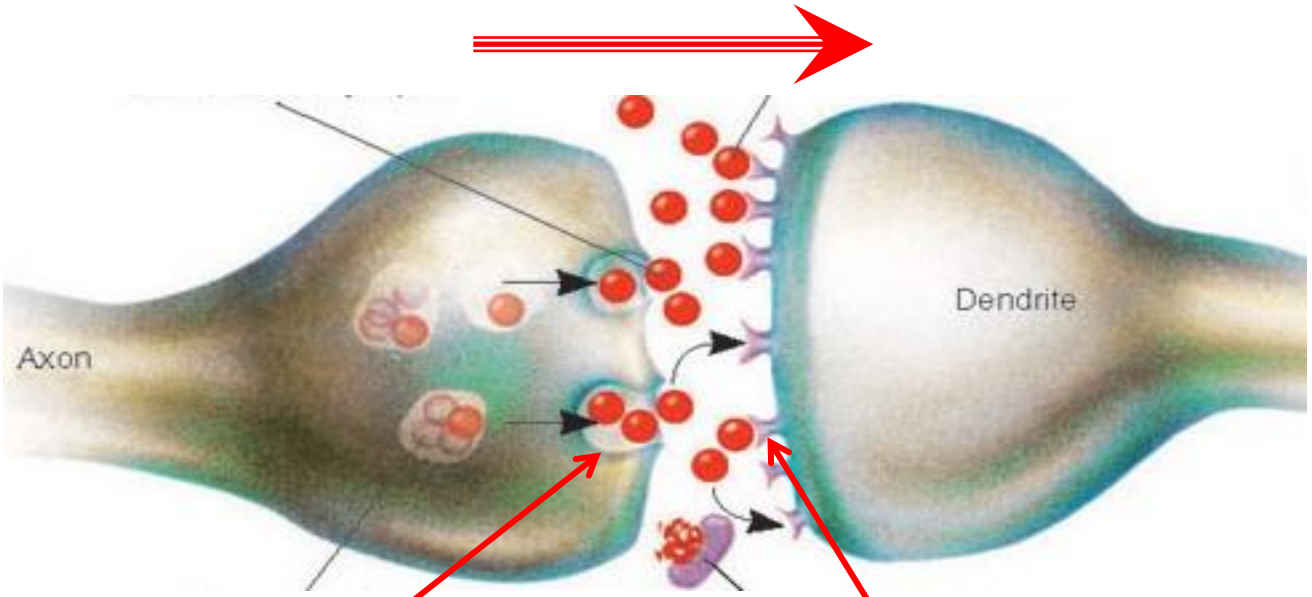


Excitatory synaptic potential
(analog/graded)

The Chemical Synapse

Axon of Cell A

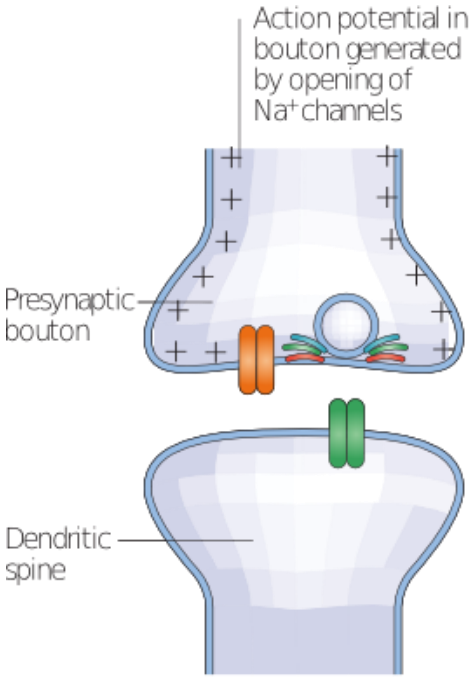
Dendrite of Cell B



Vesicles containing neurotransmitter molecules

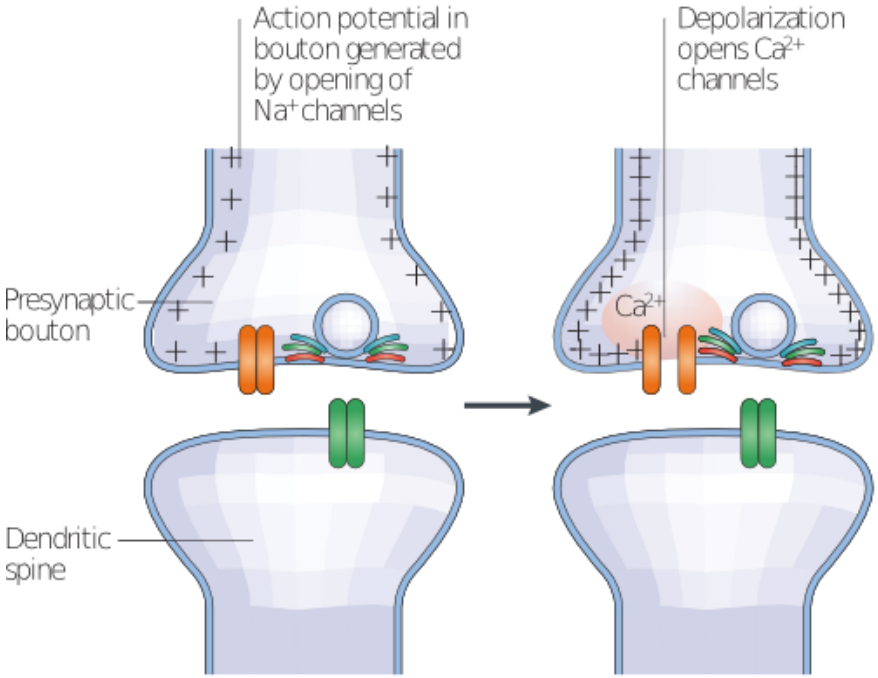
Receptors binding neurotransmitter

Chemical synapse



E. Lisman, Sridhar Raghavachari & Richard W. Tsien
Nature Reviews Neuroscience 8, 597-609 (August 2007)

Vesicle quantal release



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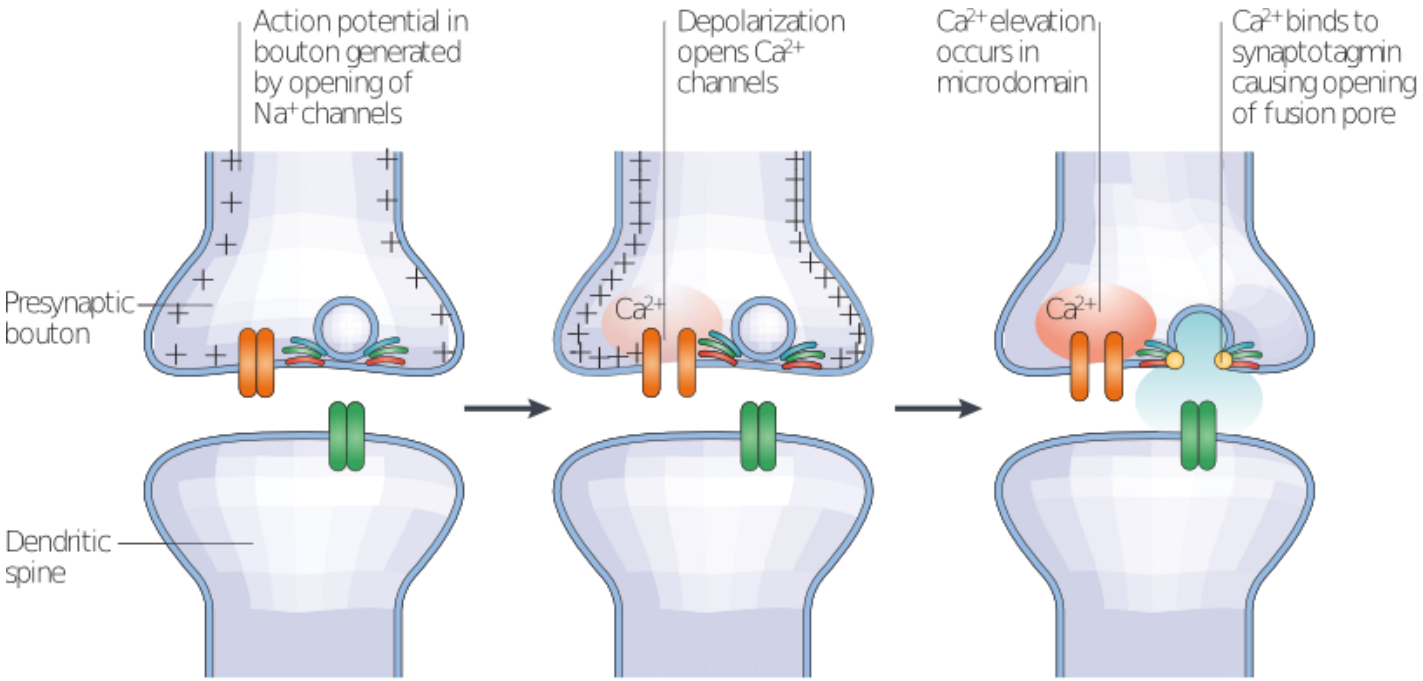

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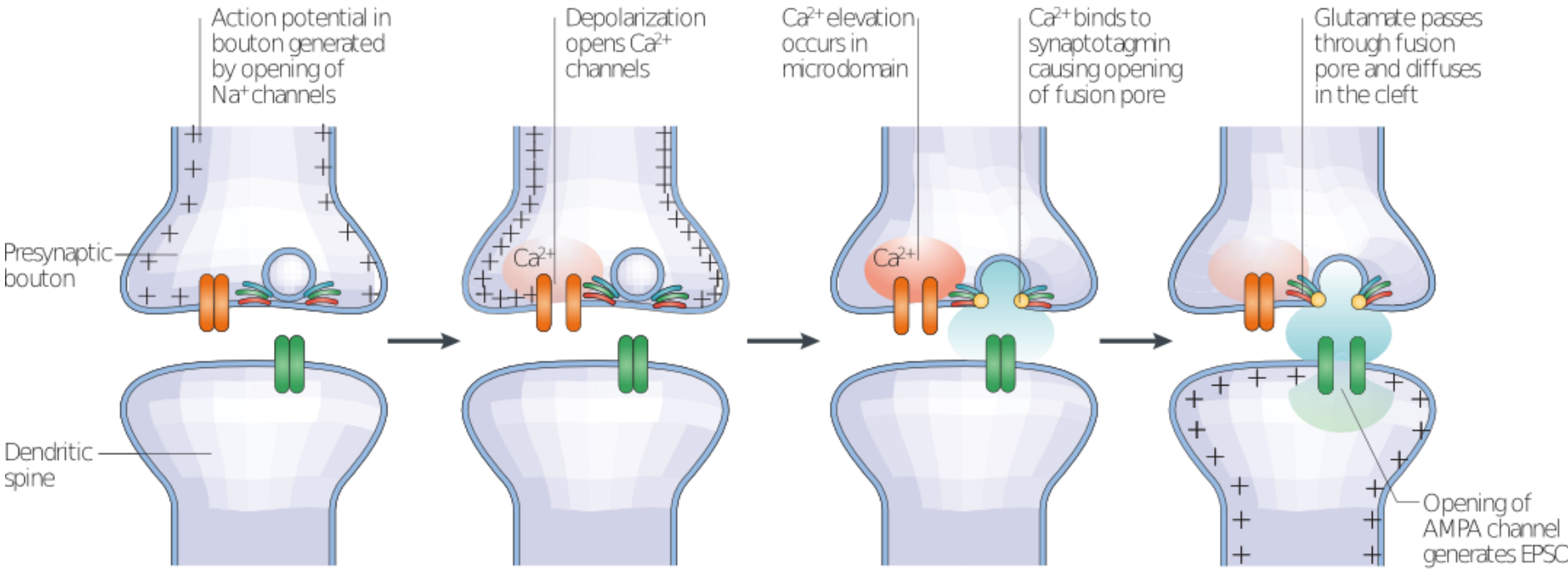

E. Lisman, Sridhar Raghavachari & Richard W. Tsien
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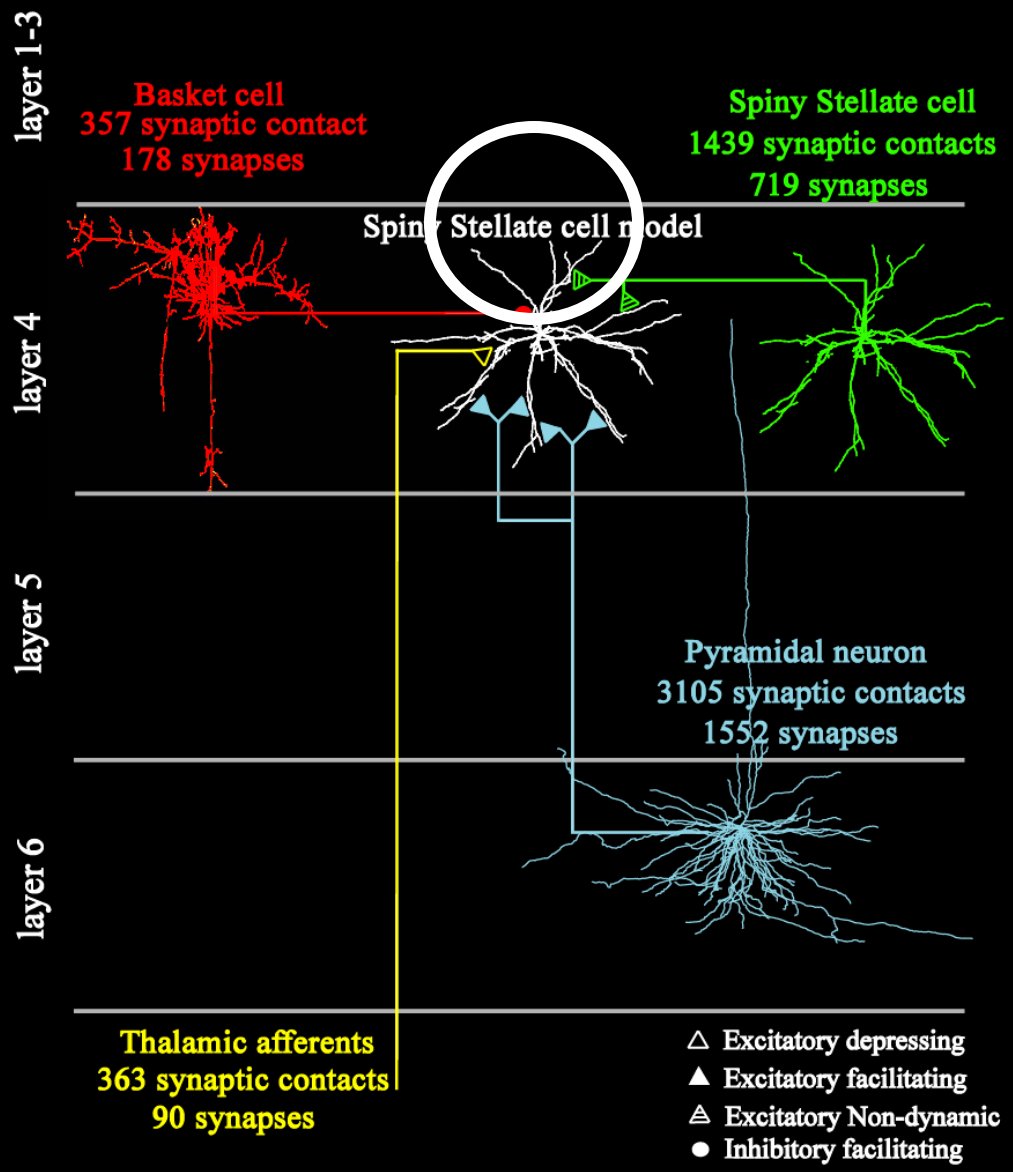
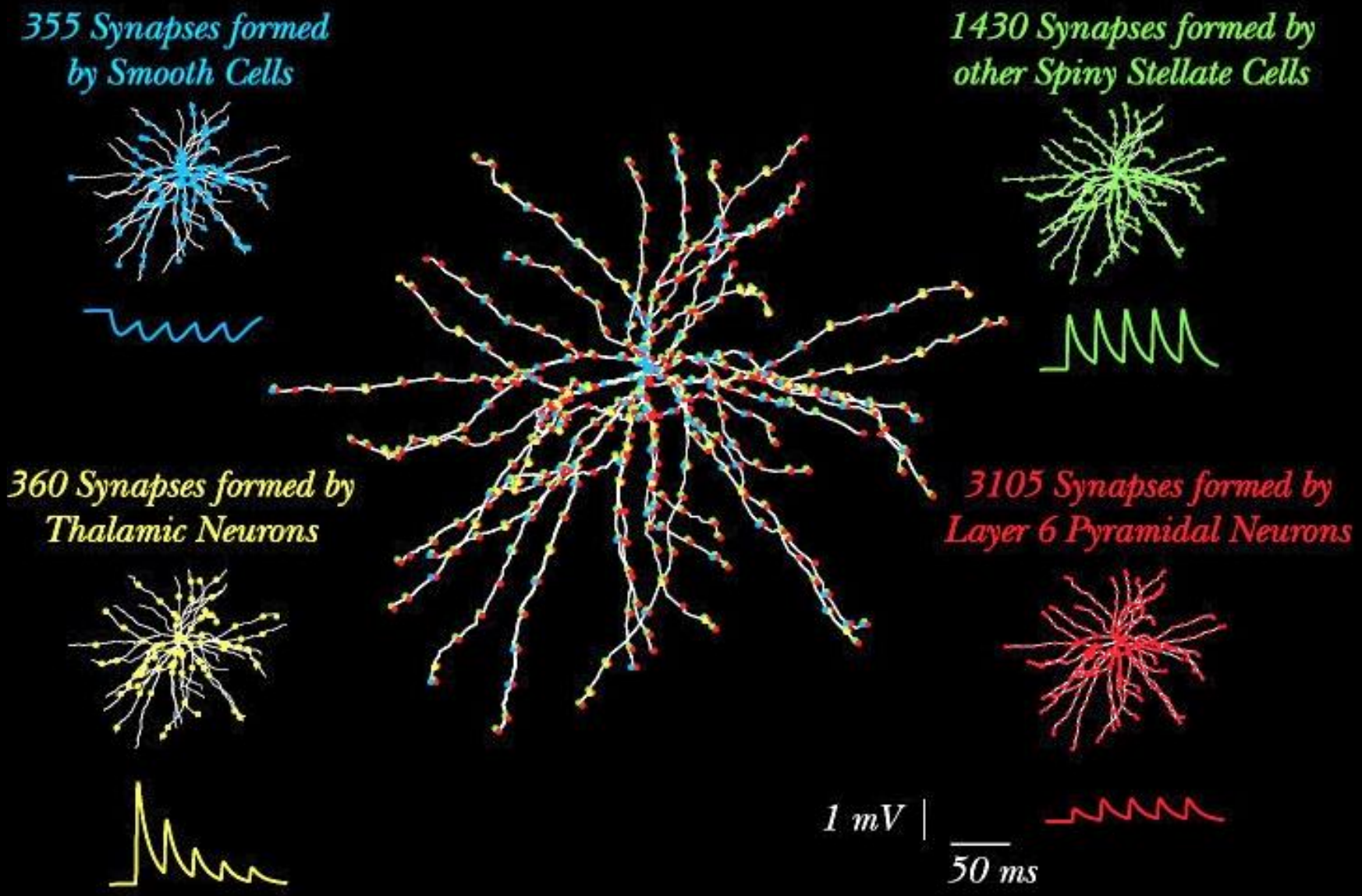
What neurons "see" when embedded in the (cortical) circuit



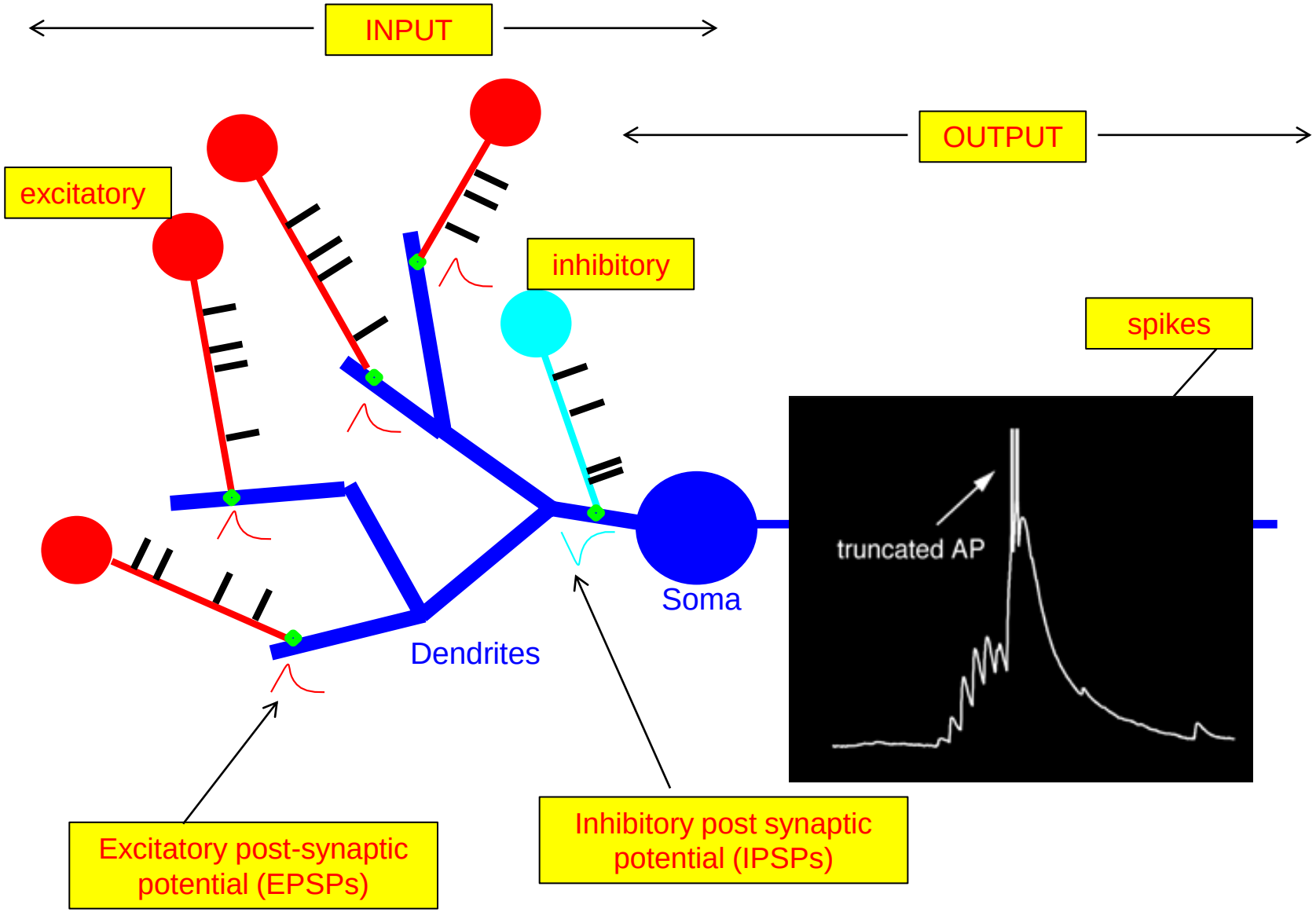
L4 Spiny Stellate Cell

covered with (excitatory and inhibotory synapses)

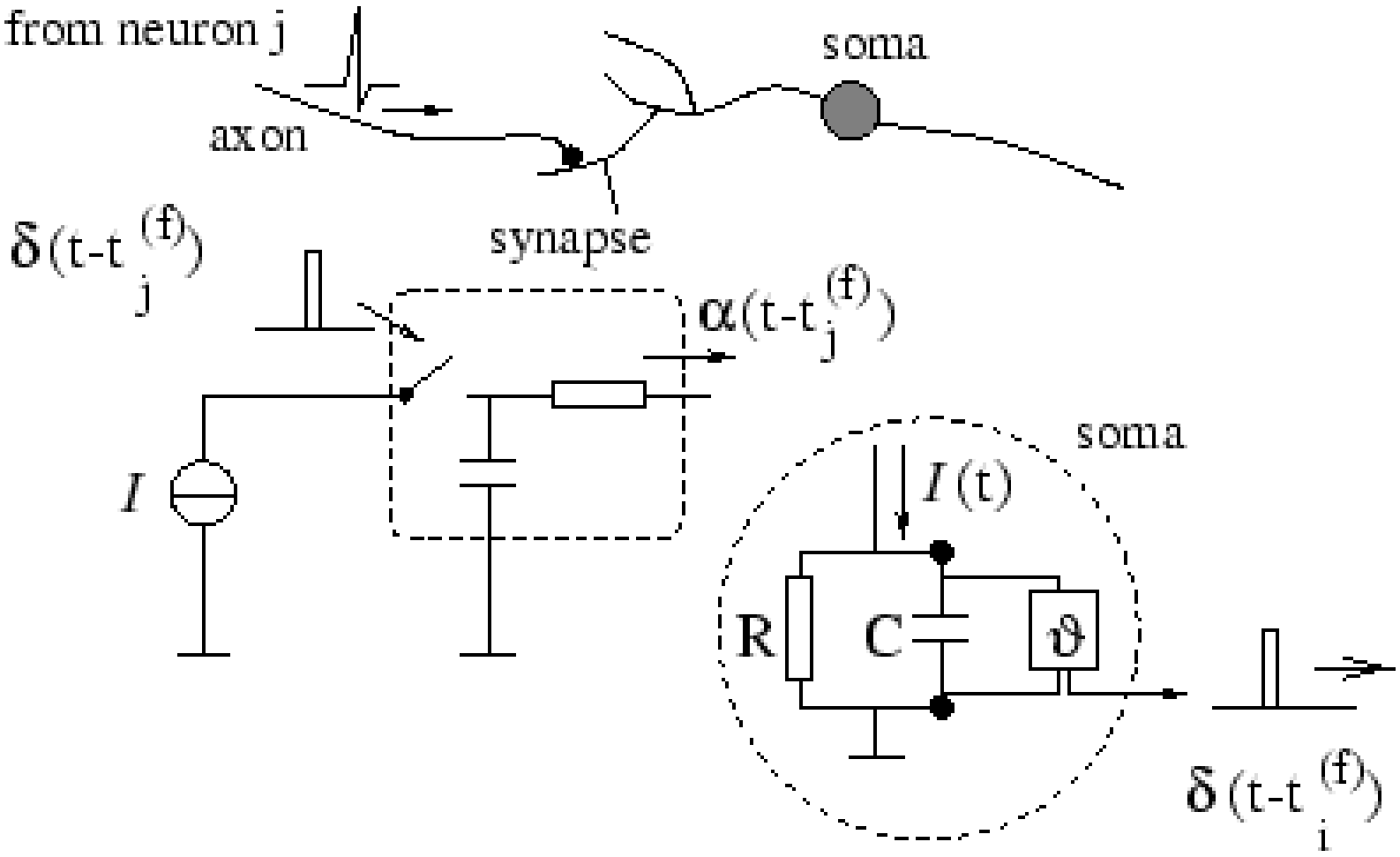


The neuron as an input-output electrical device

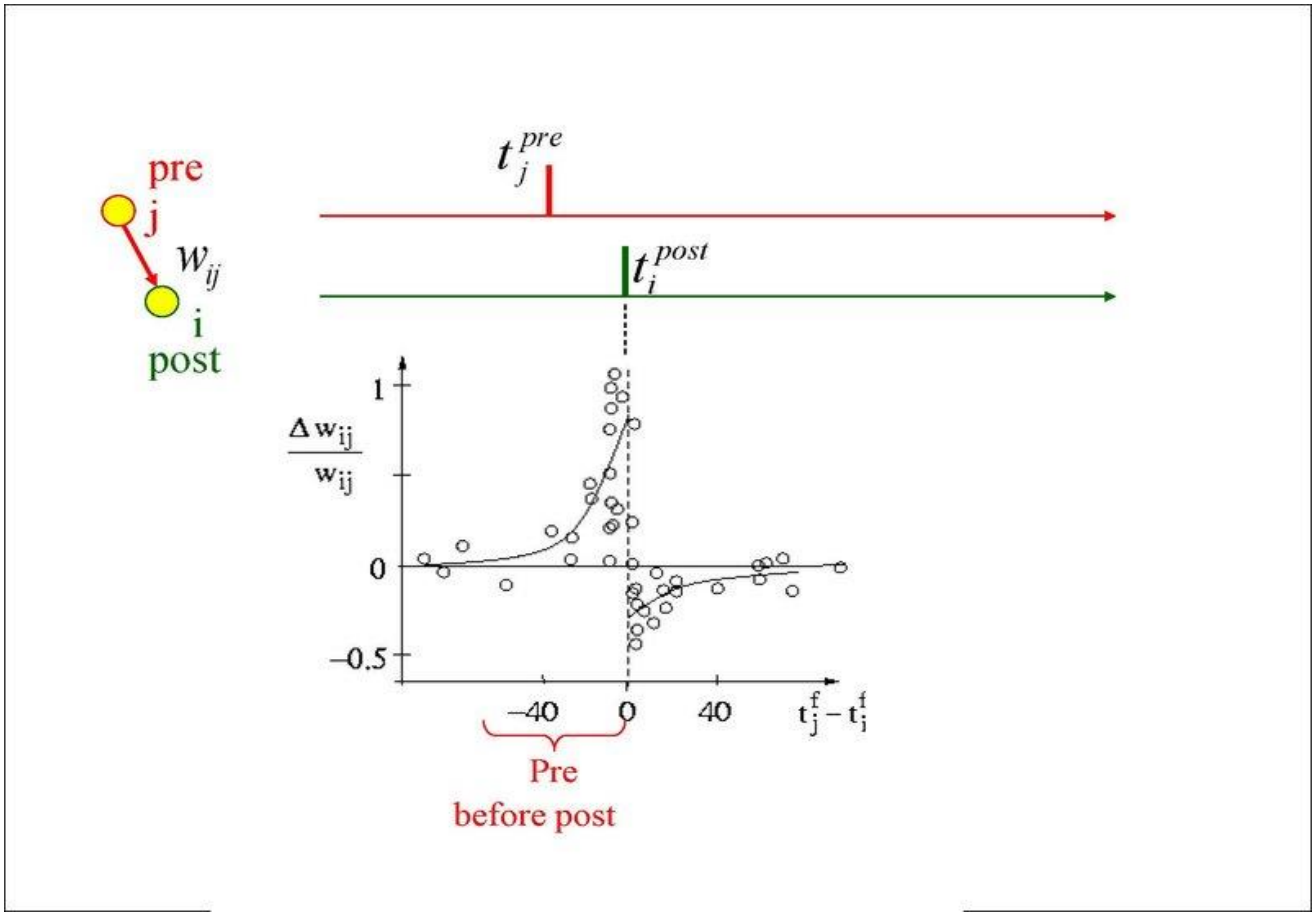
(SUMMARY after you've been learning)



Integrate and Fire



Spike-Time Dependent Plasticity (STPD)



- Spike-Timing Dependent Plasticity (schematic): The STDP function shows the change of synaptic connections as a function of the relative timing of pre- and postsynaptic spikes after 60 spike pairings.

STPD (Continued)

- **Basic STDP Model**
- The weight change Δ*wj* of a synapse from a presynaptic neuron *j* depends on the relative timing between presynaptic spike arrivals and postsynaptic spikes. Let us name the presynaptic spike arrival times at synapse *j* by *tfj* where *f*=1,2,3,... counts the presynaptic spikes. Similarly, *tn* with *n*=1,2,3,... labels the firing times of the postsynaptic neuron. The total weight change Δ*wj* induced by a stimulation protocol with pairs of pre- and postsynaptic spikes is then (Gerstner and al. 1996, Kempter et al. 1999)
- Δ*wj*=∑*f*=1*N*∑*n*=1*NW*(*tni*−*tfj*)(1)
- where *W*(dt)=F(dt) denotes one of the STDP functions (also called learning window)

$$F(\Delta t) = \begin{cases} A_+ \exp(\Delta t/\tau_+) & \text{if } \Delta t < 0 \\ -A_- \exp(-\Delta t/\tau_-) & \text{if } \Delta t > 0\,, \end{cases}$$

- (Song et al. 2000). The parameters $A+$ and $A-$ may depend on the current value of the synaptic weight wj. The time constants are on the order of $\tau+=10ms$ and $\tau-=10ms$

The STDP can control this robot

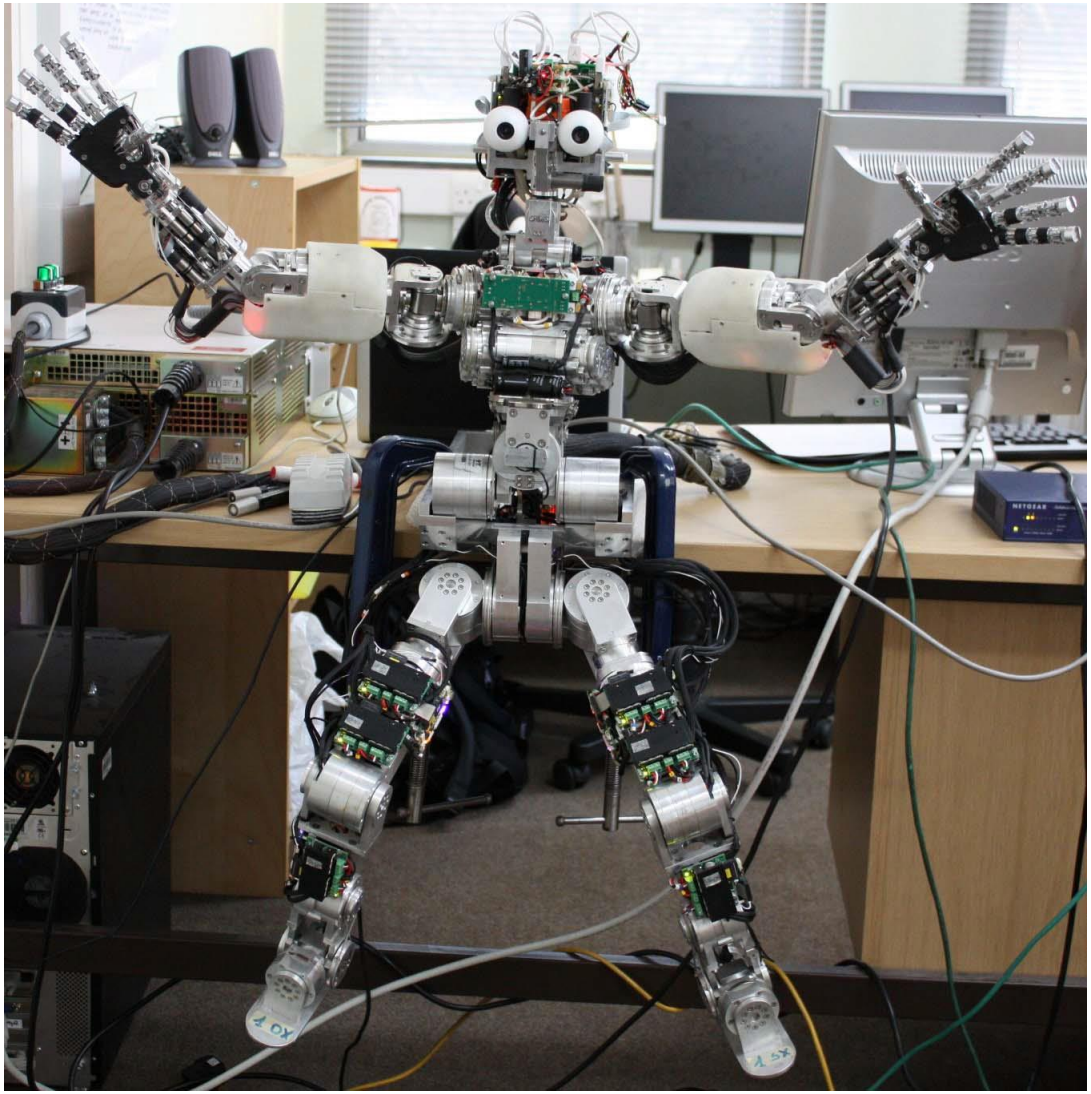
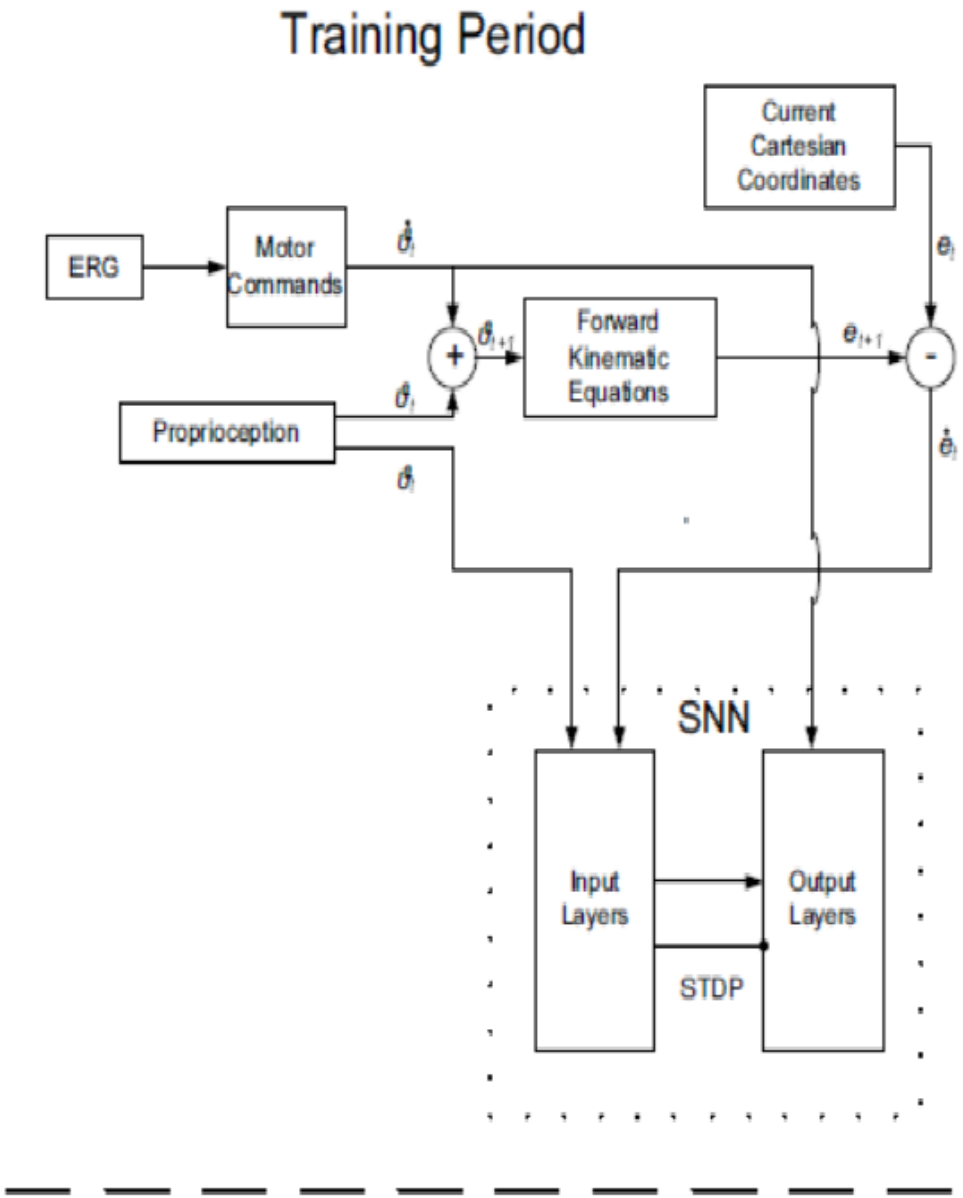
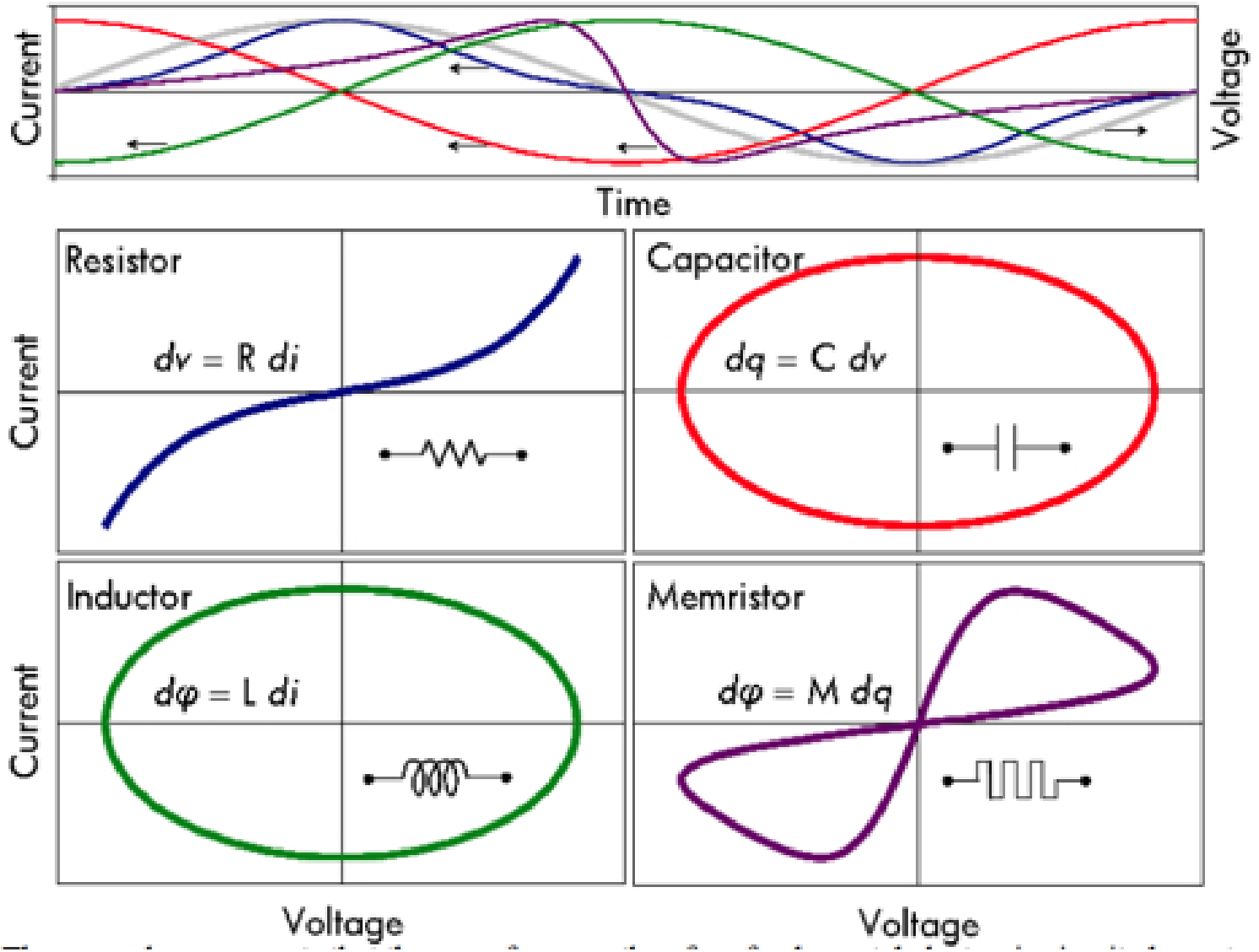
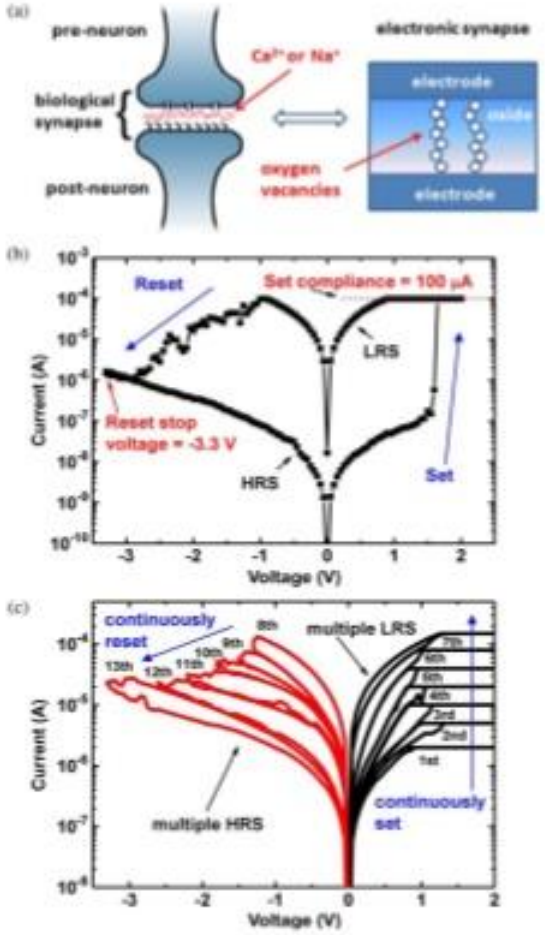


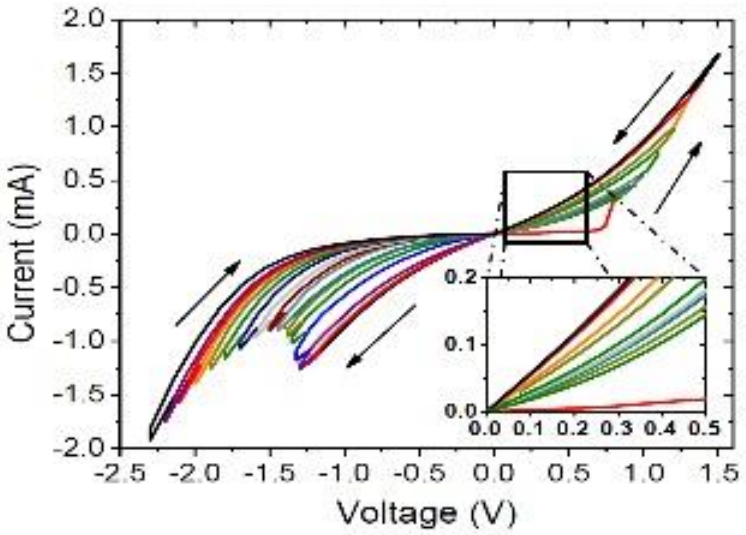
Схема сети


Training Period
Current Cartesian Coordinates
ERG
Motor Commands
Forward Kinematic Equations
Proprioception
SNN
Input Layers
Output Layers
STDP
Performance Period


Current
Voltage
Time
Resistor
dv = R di
Capacitor
dq = C dv
Inductor
dφ = L di
Memristor
dφ = M dq
Current
Current
Voltage
Voltage

Мемристор = «электронный синапс»



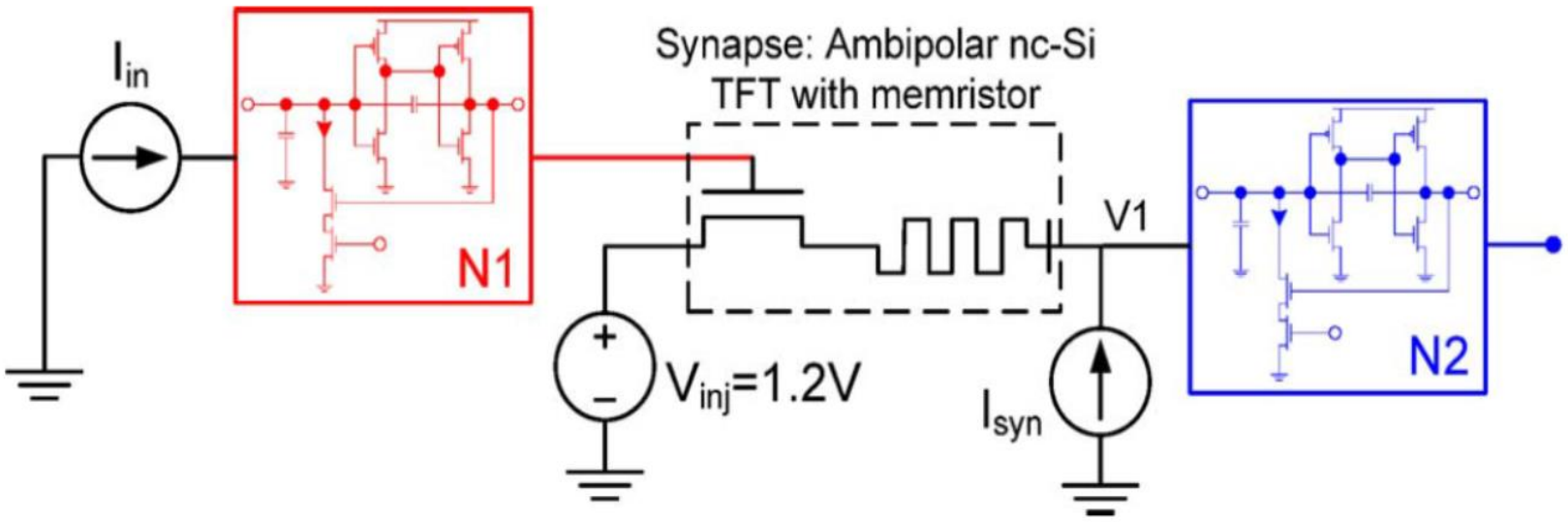


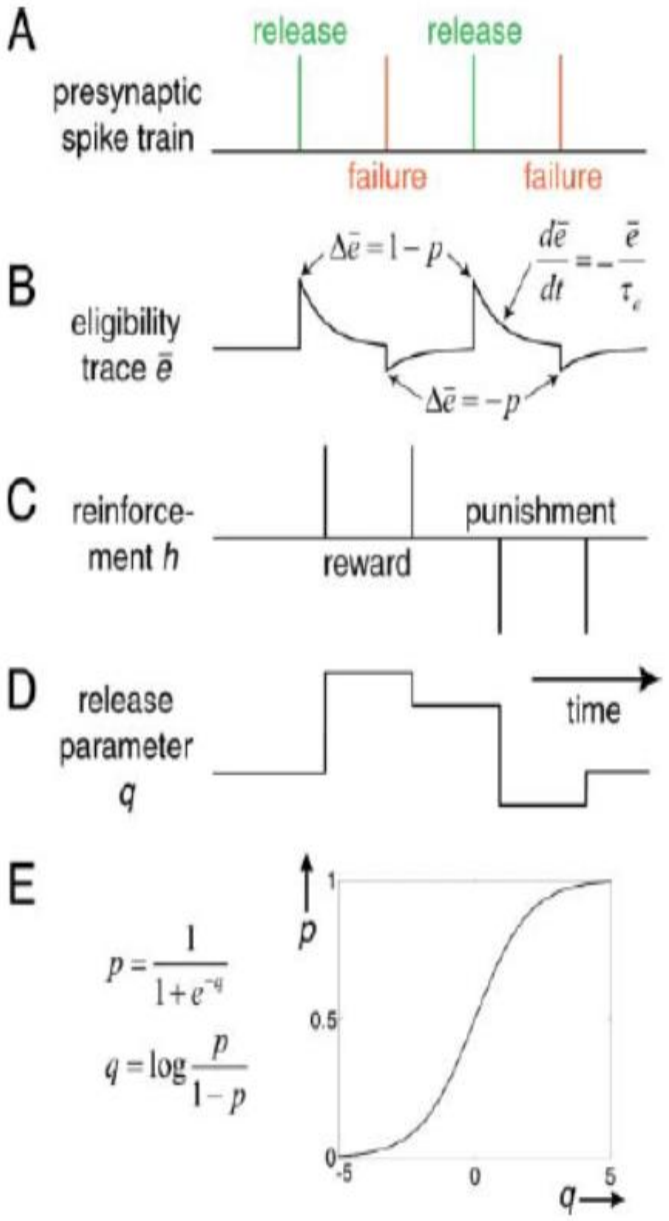
$HfO_{x-1}AlO_x$ memristor ***(МФТИ)***

Наноструктуры с «мемристорным» поведением функционально аналогичны синапсам мозга млекопитающих

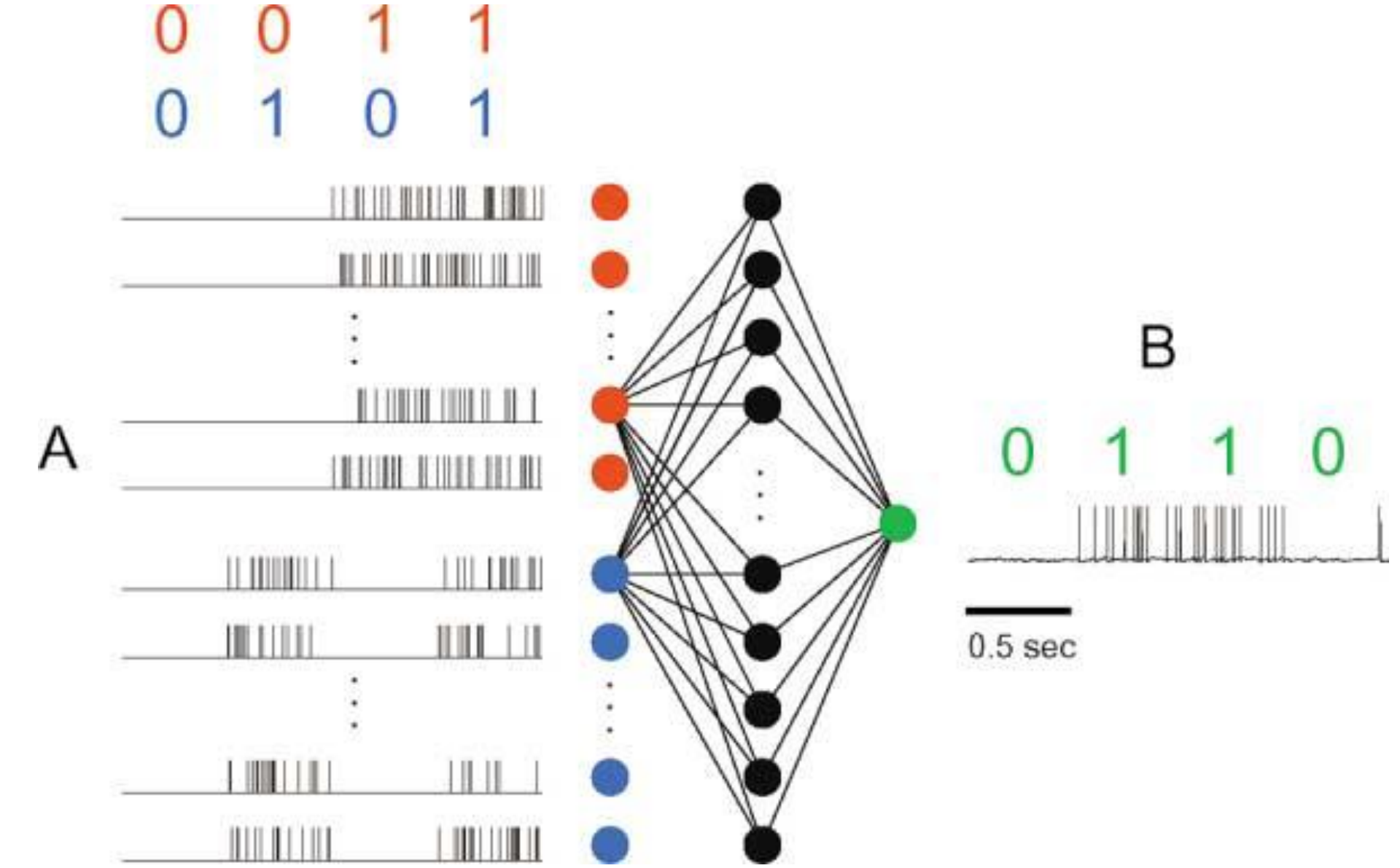
Мемристоры, хеббовское обучени

1069





Synaptic transmission reinforcement


0 0 1 1
0 1 0 1
A
B
0 1 1 0
0.5 sec

Thank you for attention!