Computational Neuroscience Course

An Introduction to Computational Neuroscience

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A brief pre-history

Theoretical Neurophysiology

1907 Lapique:
integrate-and-fire model

1952 Hodgkin-Huxley:
theory of action potential

1960's Rall:
cable theory of dendrites

1970's Wilson-Cowan:
firing-rate population models

1980’s: Biophysics of neurons &
synapses, network dynamics

Psychology & Computer Science

1949 Hebb:
learning rules

1960's Rosenblatt, Minsky:
perceptrons

1960's Rosenblatt, Minsky:
perceptrons

1970's signal detection theory

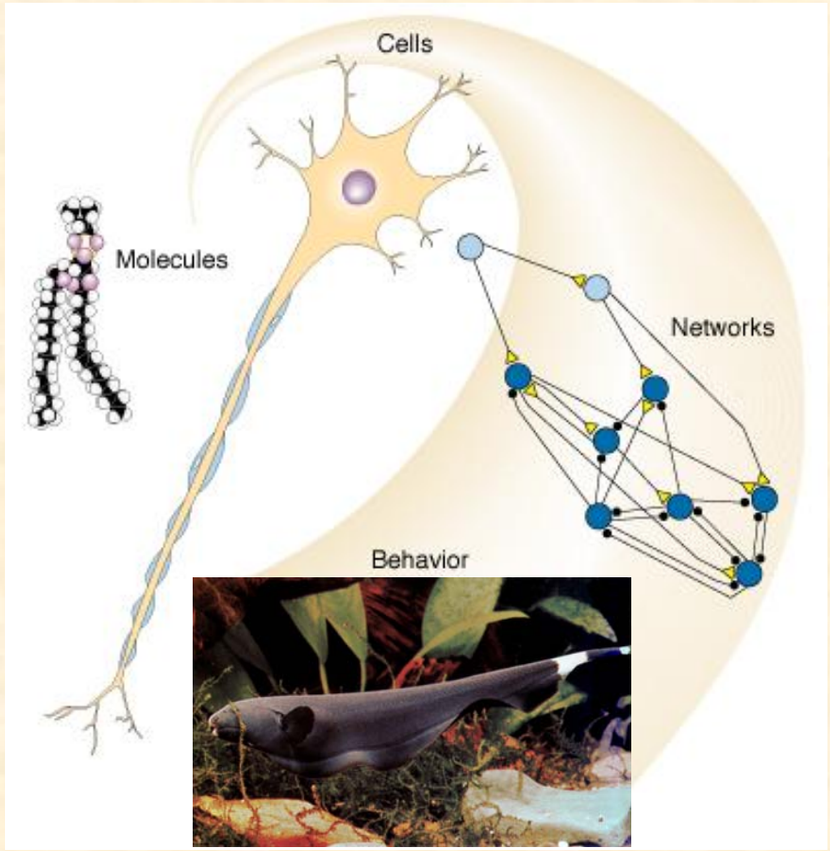
1980’s Hopfield:
associative memory model

Sejnowski, Koch, Churchland, Computational neuroscience. Science *1988* 241: 1299-1306
Methods in Computational Neuroscience Summer School, Marine Biological Laboratory

adapted from Xiaojing Wang’s slide

Principles of Neuroscience ?

Multiscale Organization of the Nervous System



Organism	1 m
System	10 cm
Map	1 cm
Column	1 mm
Neuron	10 μm
Synapse	1 μm
Molecule	10 Å

Delcomyn 1998

"To pile speculation on speculation, I would say that the next stage could be hierarchy or specialization of function, or both…. with increasing complication at each stage, we go on up the hierarchy of sciences. We expect to encounter fascinating and, I believe, very fundamental questions at each stage in fitting together less complicated pieces into the more complicated system and understanding the basically new types of behavior which can result."

P. W. Anderson, 1972
Nobel Laureate
condensed matter physicist

More is different

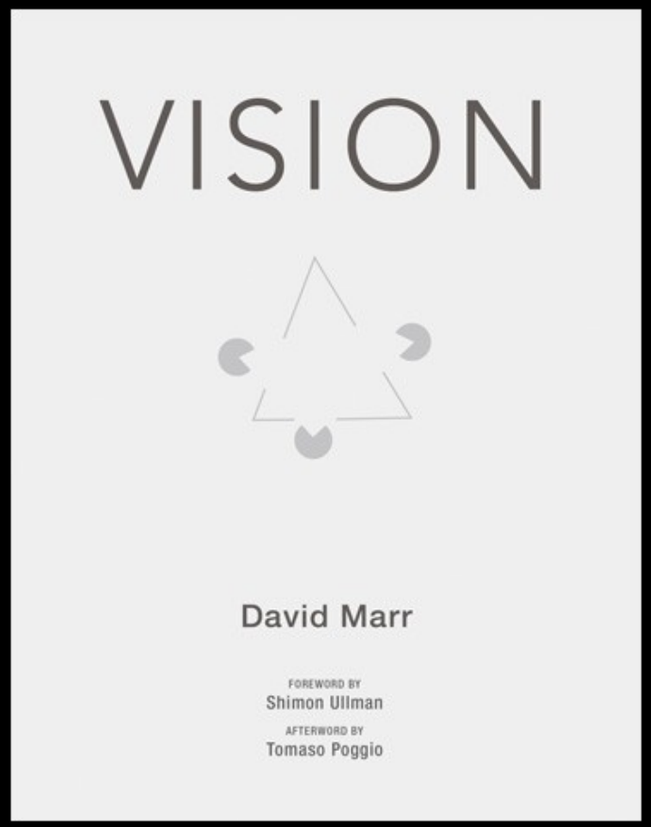
Fitzgerald: The rich are **different** from us.

Hemingway: Yes, they have **more** money.

a conversation somewhere in Paris in 1920s

David Marr
1945-1980

Henry Markram
1962 -



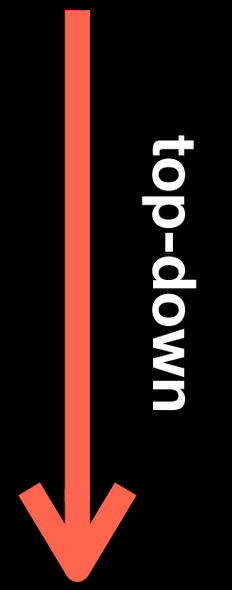
blue brain project

David Marr's three level theory

- **Computational level**: Identify the computational problem and task that the brain solves.

- **Algorithmic level**: Find the mathematical procedures that solve the problem.

- **Implementation level**: How the algorithms are realized by the nervous system.



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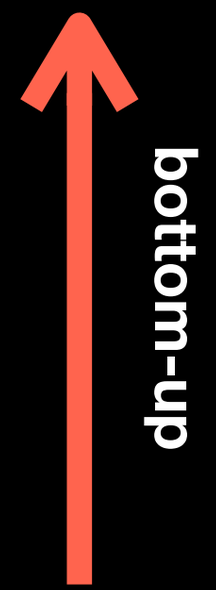
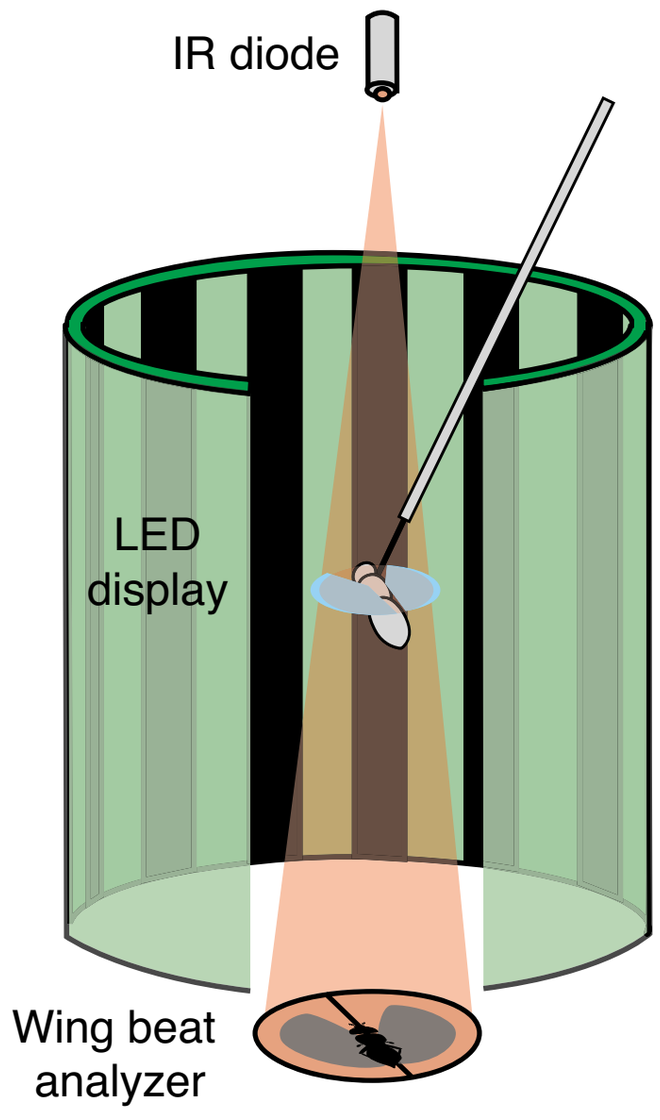


Motion detection, an example

Optomotor response in fly



Duistermars B et. al., Journal of Experimental Biology 2007

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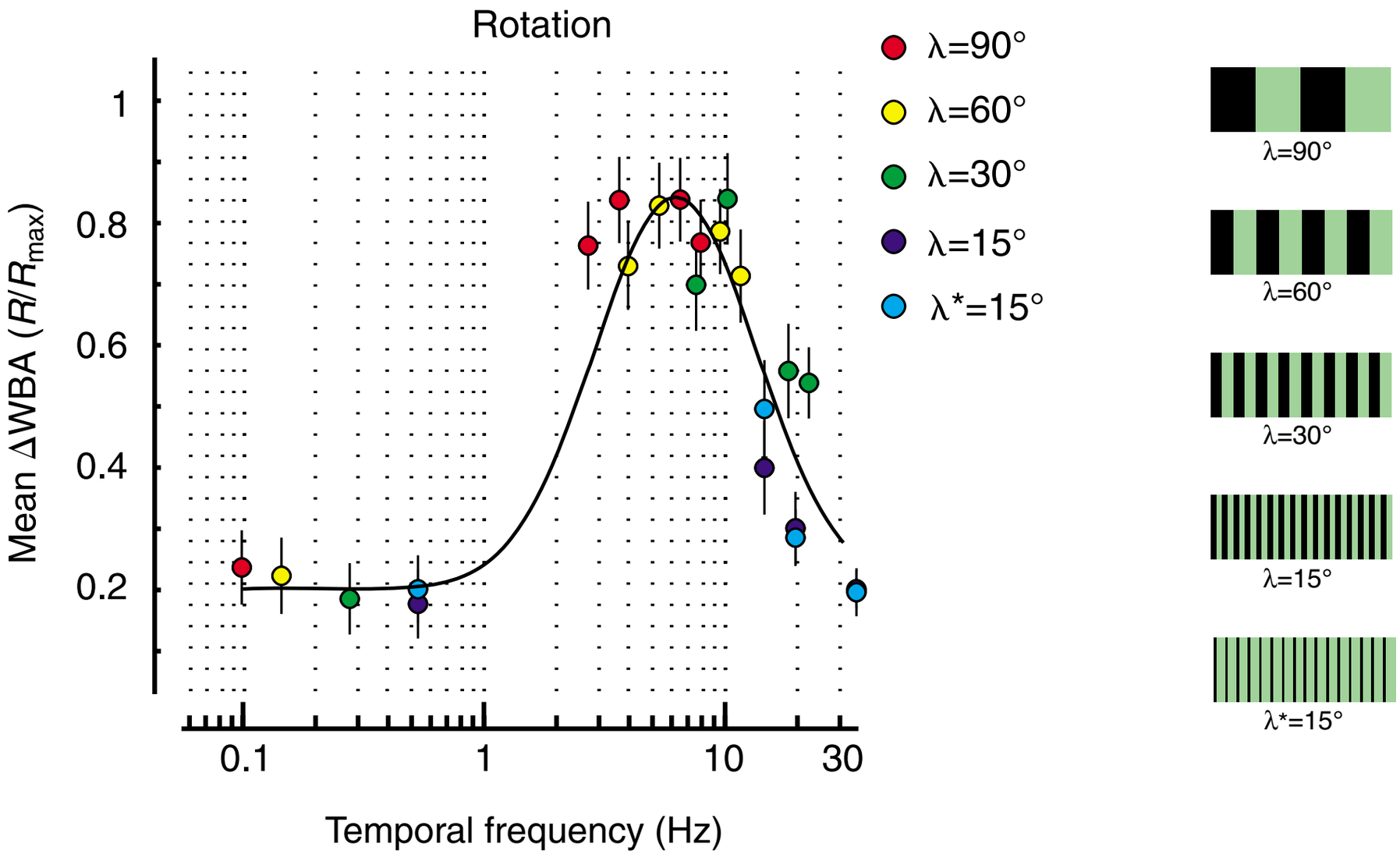
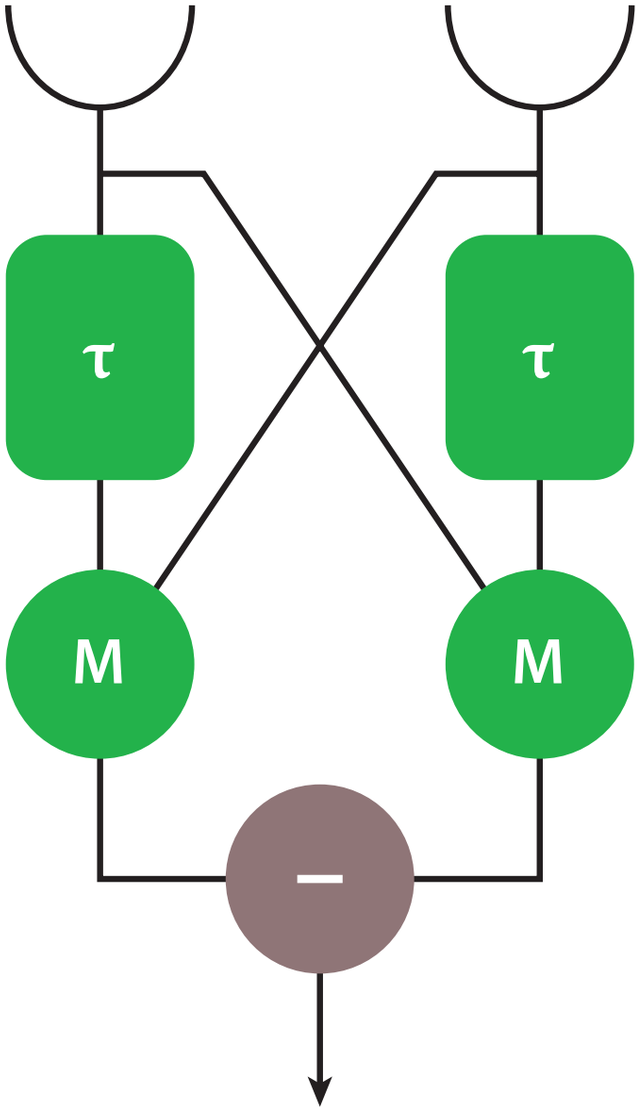


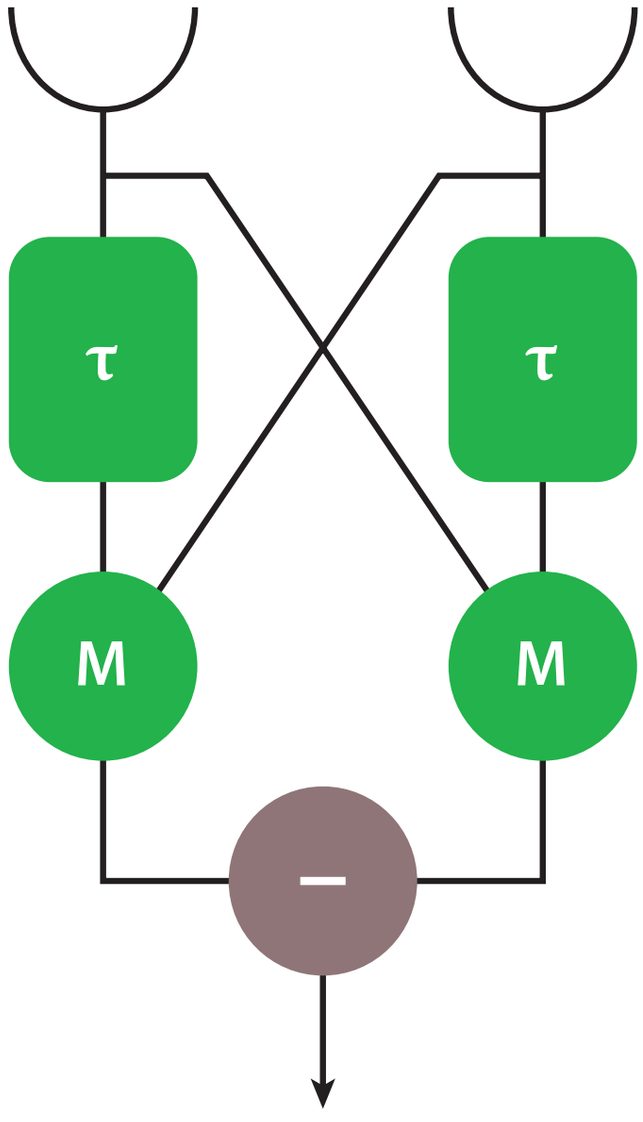
Duistermars B et. al., Journal of Experimental Biology 2007

Hassenstein-Reichardt Detector Model



Werner Reichardt

Hassenstein-Reichardt Detector Model



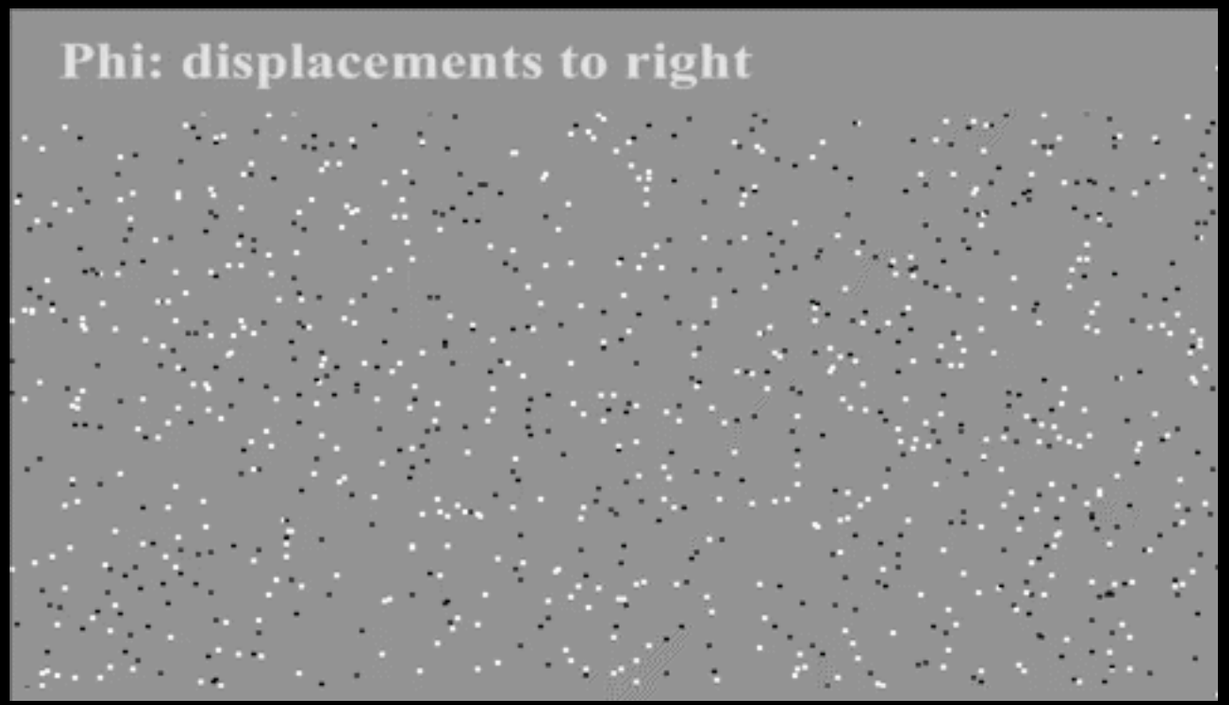
$$r_1(t) = \int_0^\infty s_1(t-\tau)D(\tau)d\tau;\ r_2(t) = \int_0^\infty s_1(t-\tau)\delta(\tau)d\tau$$

$$r_3(t) = \int_0^\infty s_2(t-\tau)\delta(\tau)d\tau;\ r_4(t) = \int_0^\infty s_2(t-\tau)D(\tau)d\tau;$$

$$R(t) = r_1(t)r_3(t) - r_2(t)r_4(t)$$

$$D(\tau) = \frac{1}{\tau_0}\exp(-\tau/\tau_0)$$

$$\langle R \rangle = \frac{\omega_0\tau_0}{\omega_0^2\tau_0^2 + 1}$$



adapted from Damon Clark's slide

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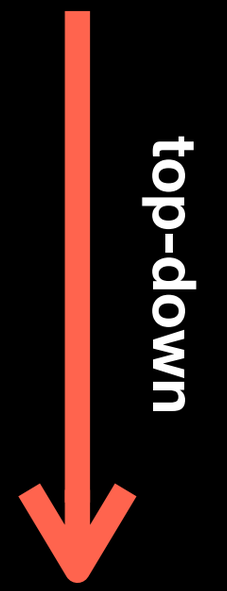
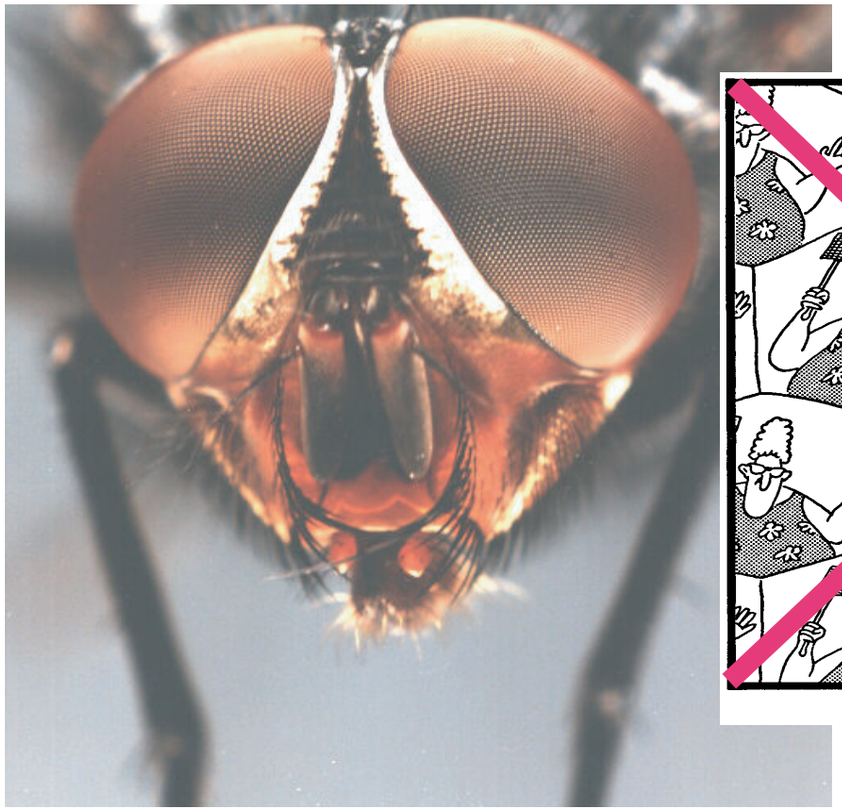
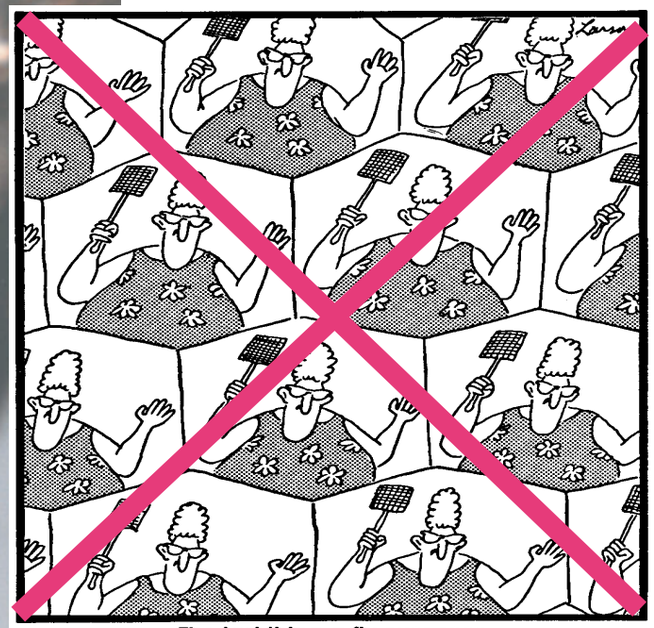


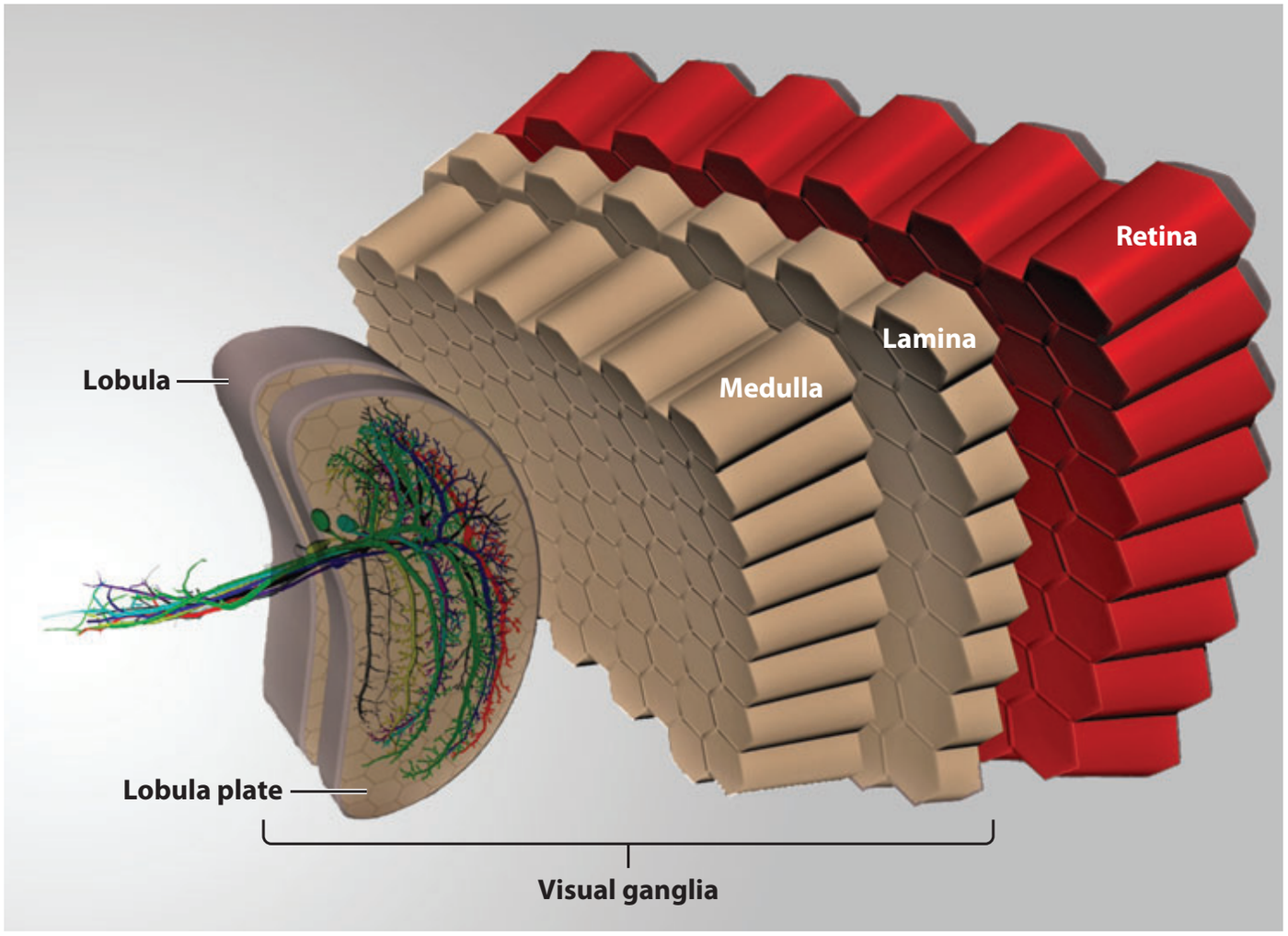
The Fly Visual System





The last thing a fly ever sees

The Fly Visual System



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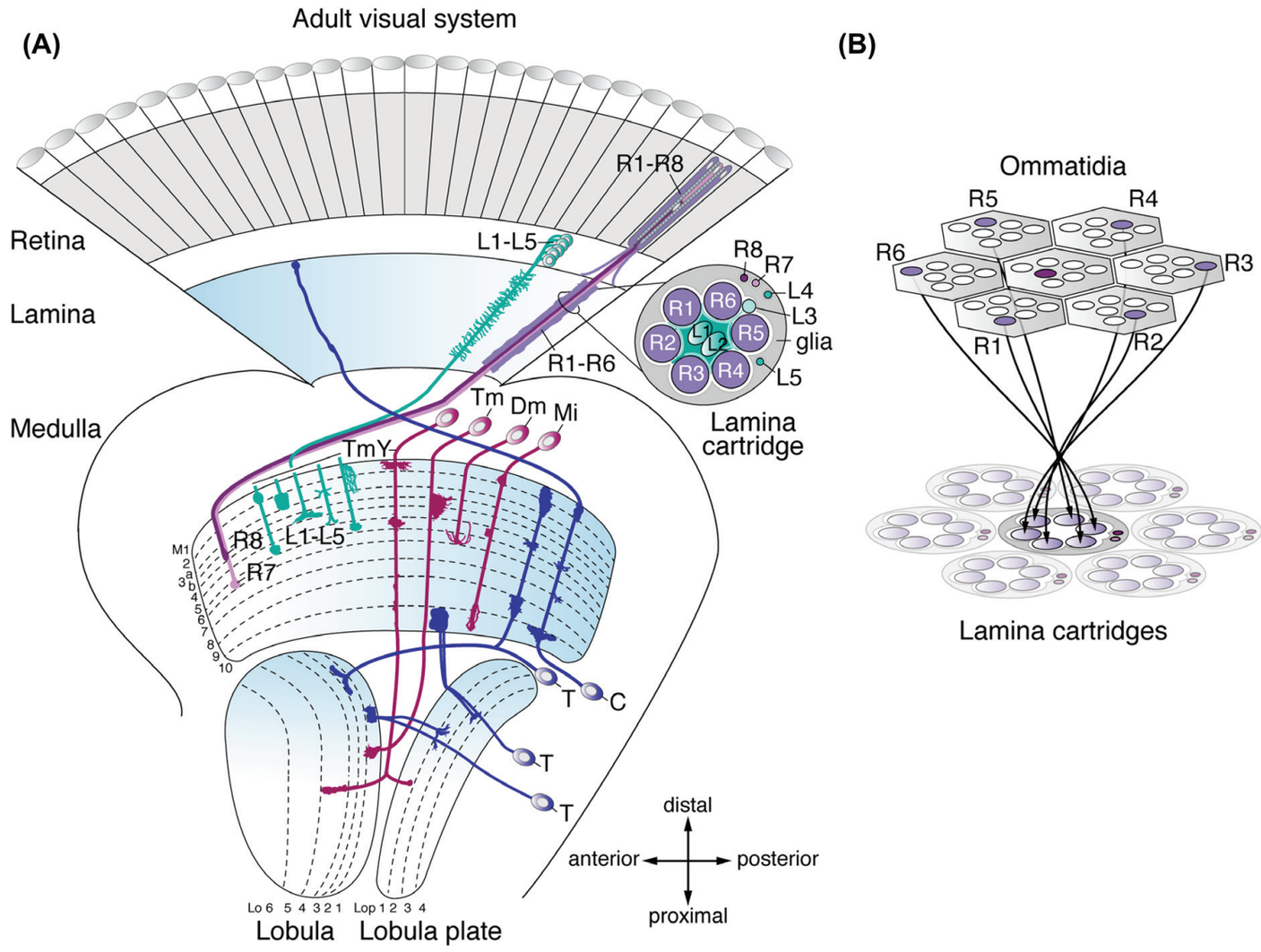
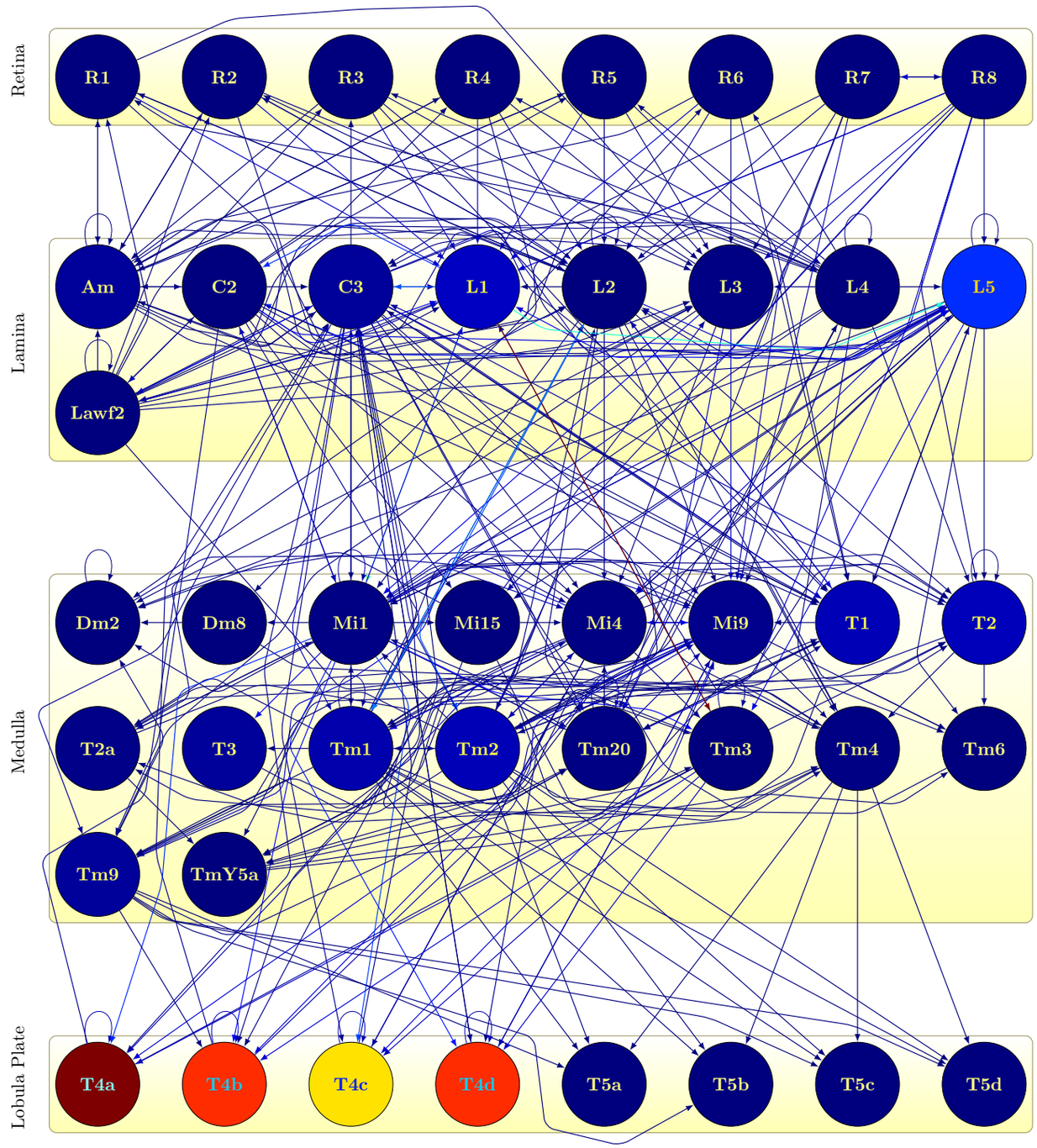
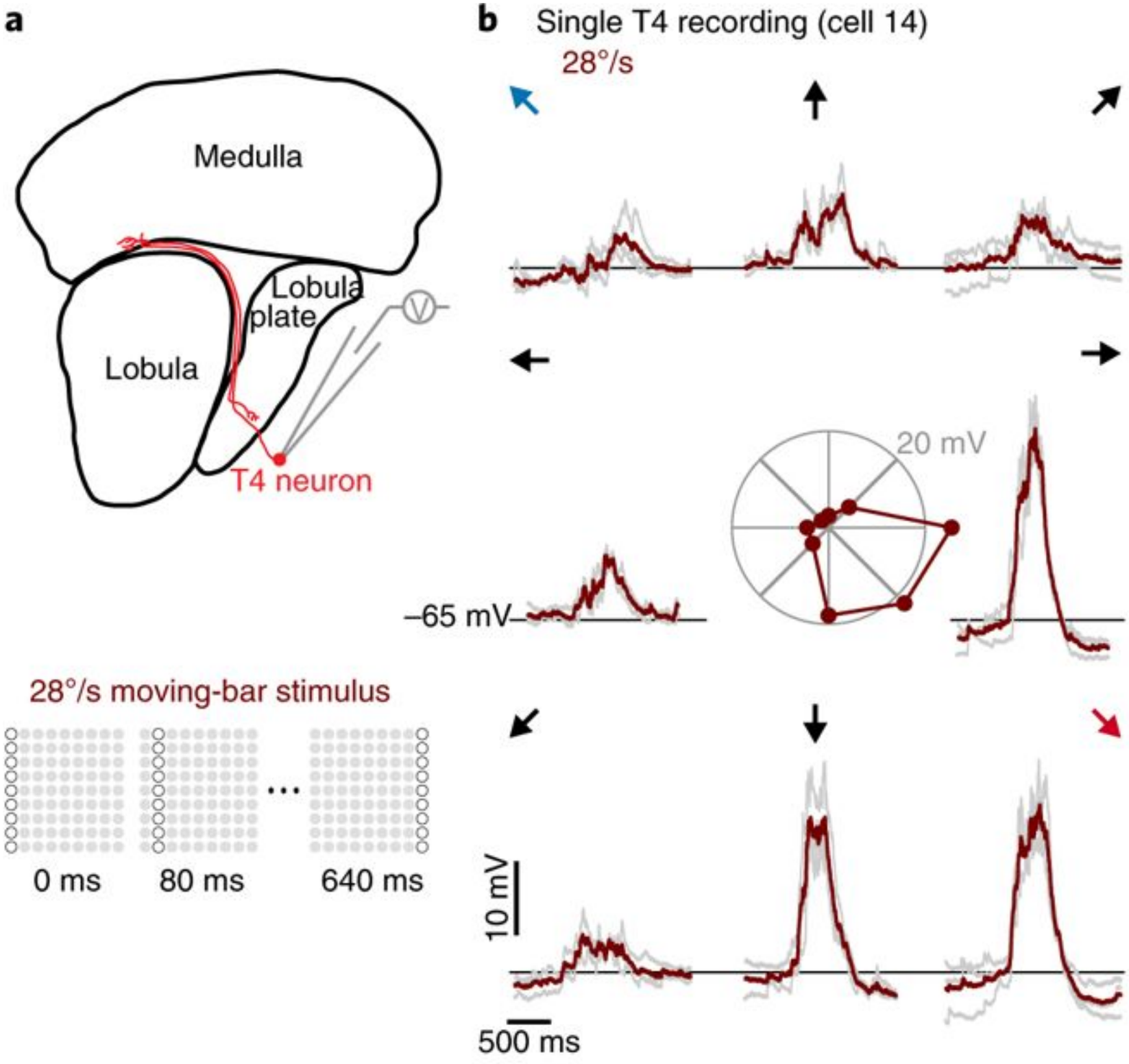
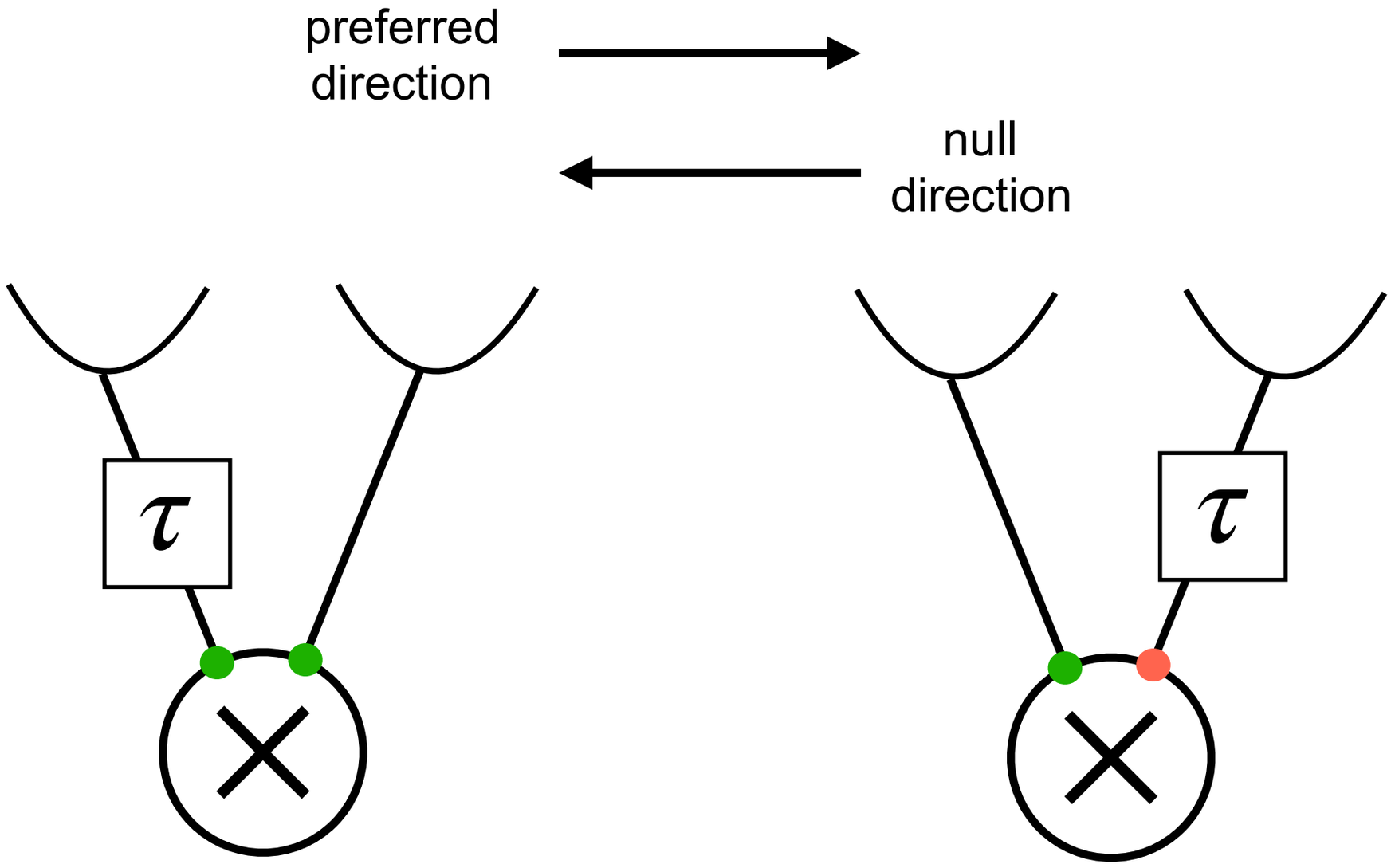




Takemura et. al., elife 2017



Gruntman, Romani and Reiser et. al., Nature Neuroscience 2018



Reichardt model

barlow-levick model

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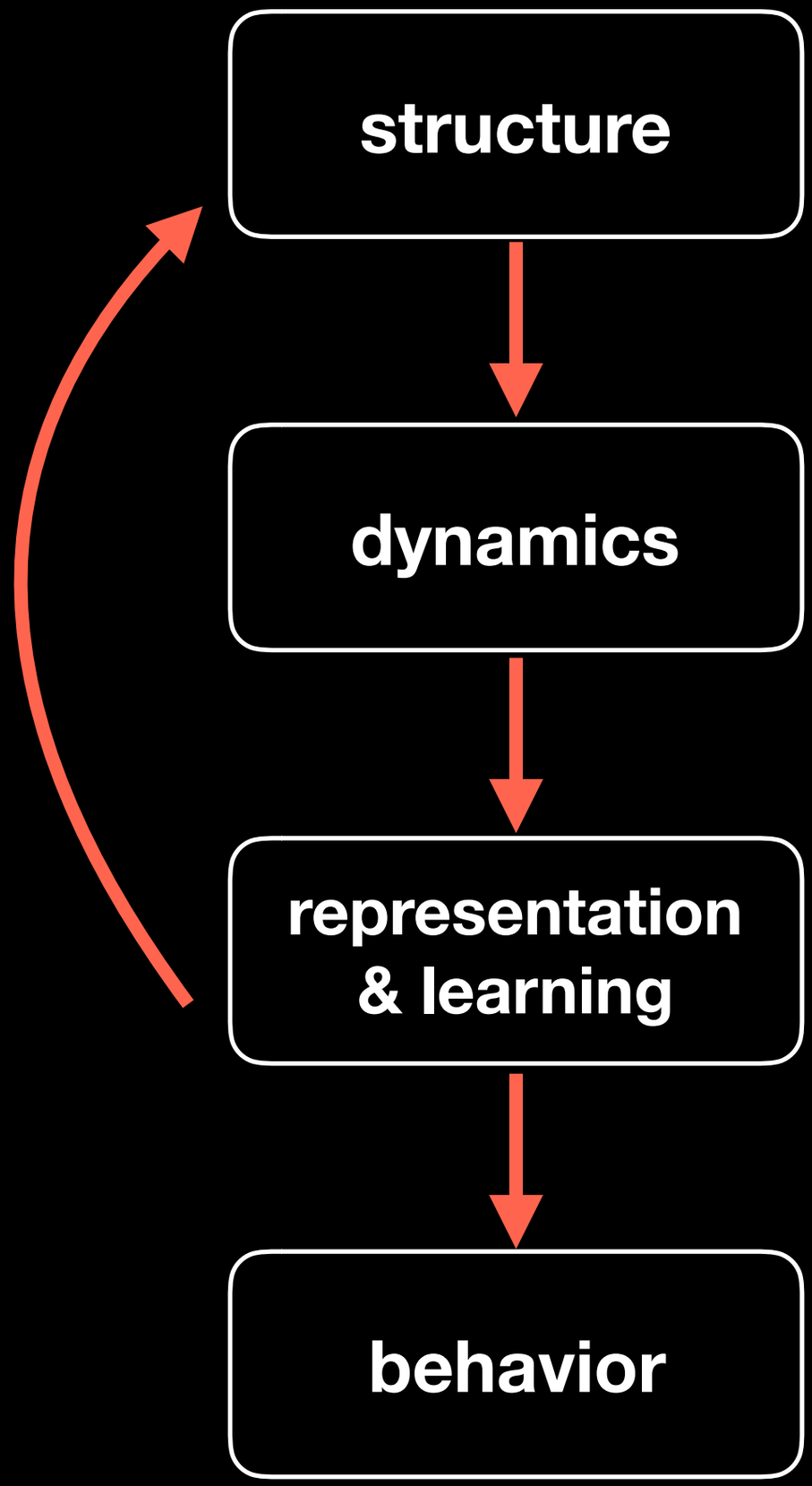
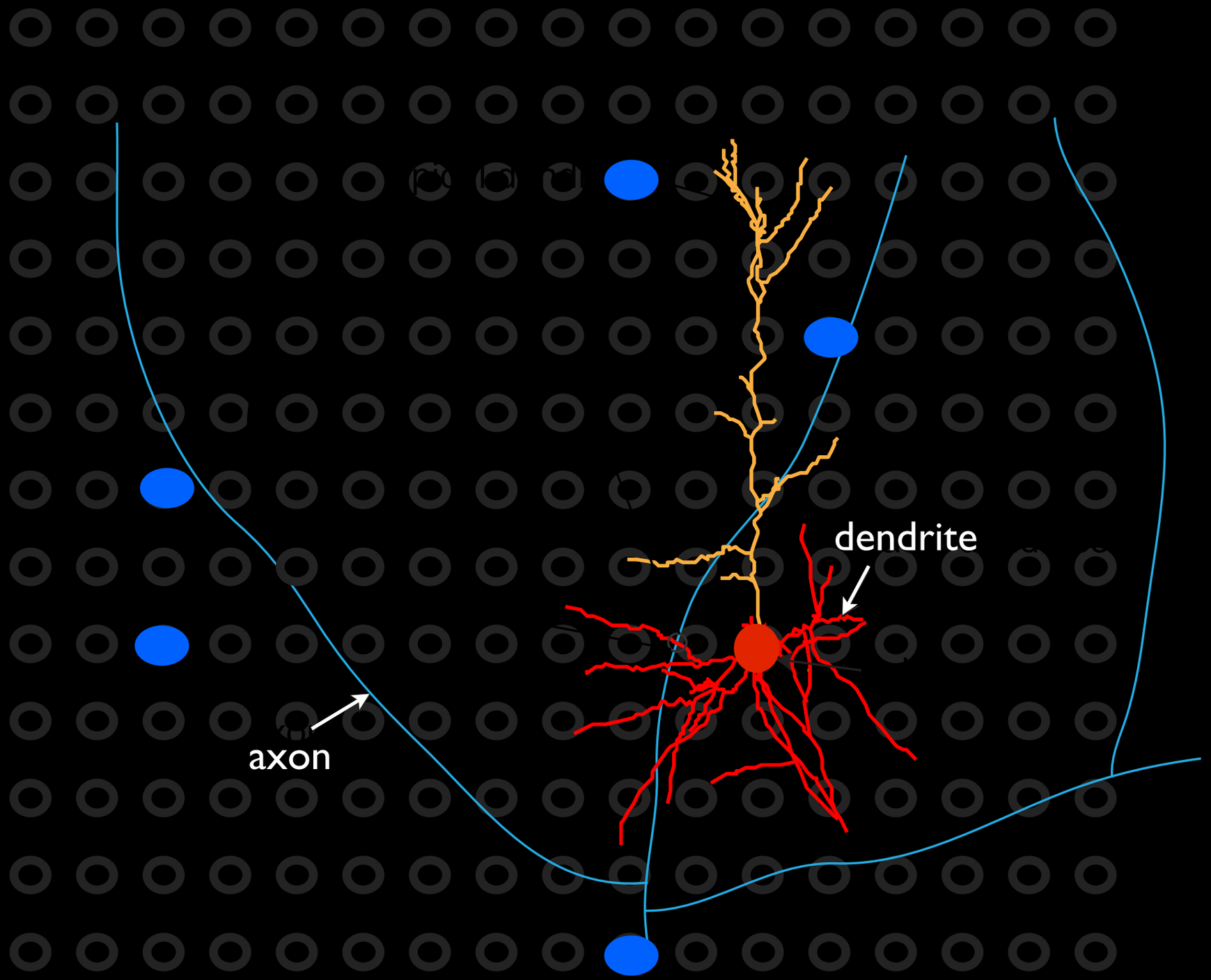
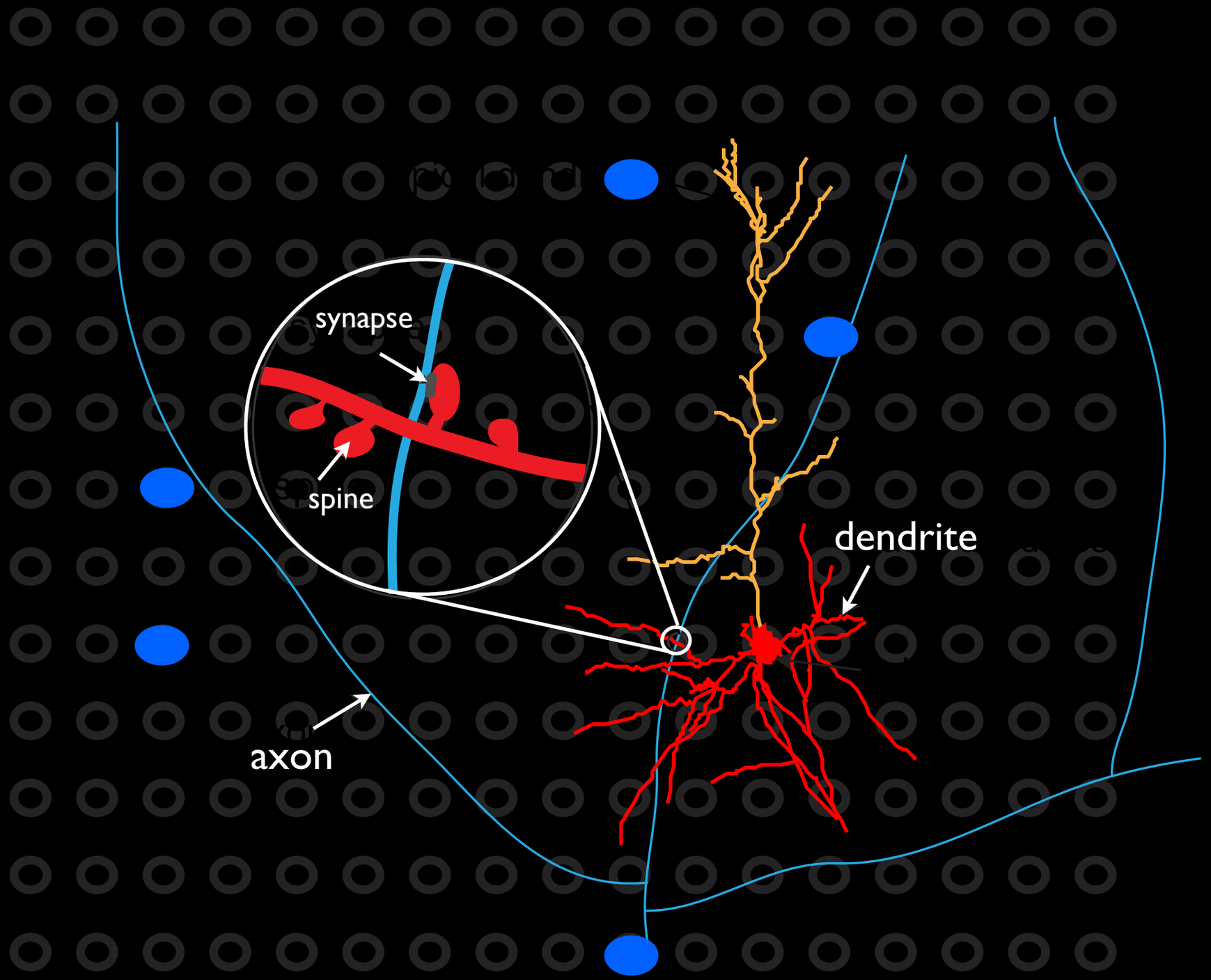
2019 *Fall Course Program*


structure
dynamics
representation
& learning
behavior

The Neuron Doctrine


dendrite
axon

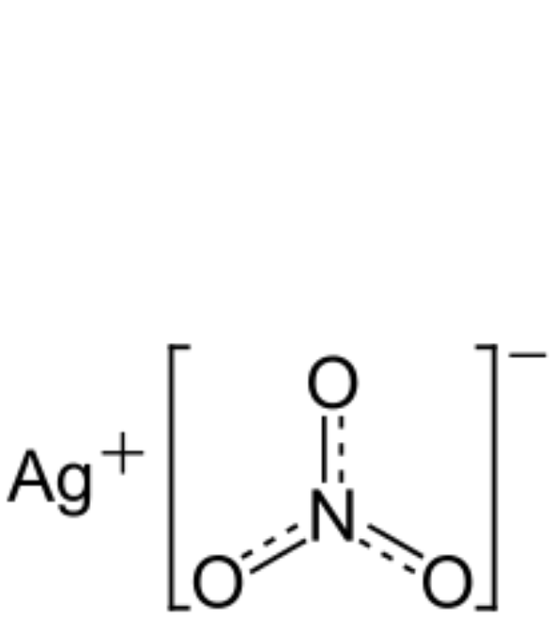

synapse
spine
dendrite
axon

The Debate between Cajal and Golgi

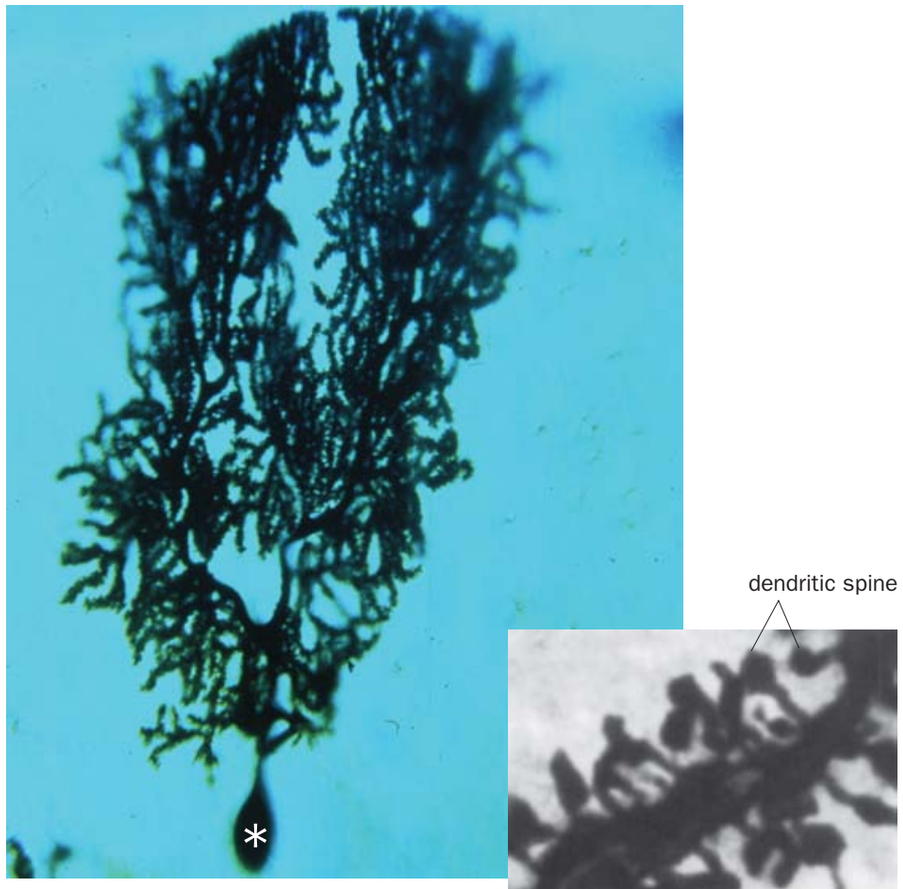
Ramon y Cajal

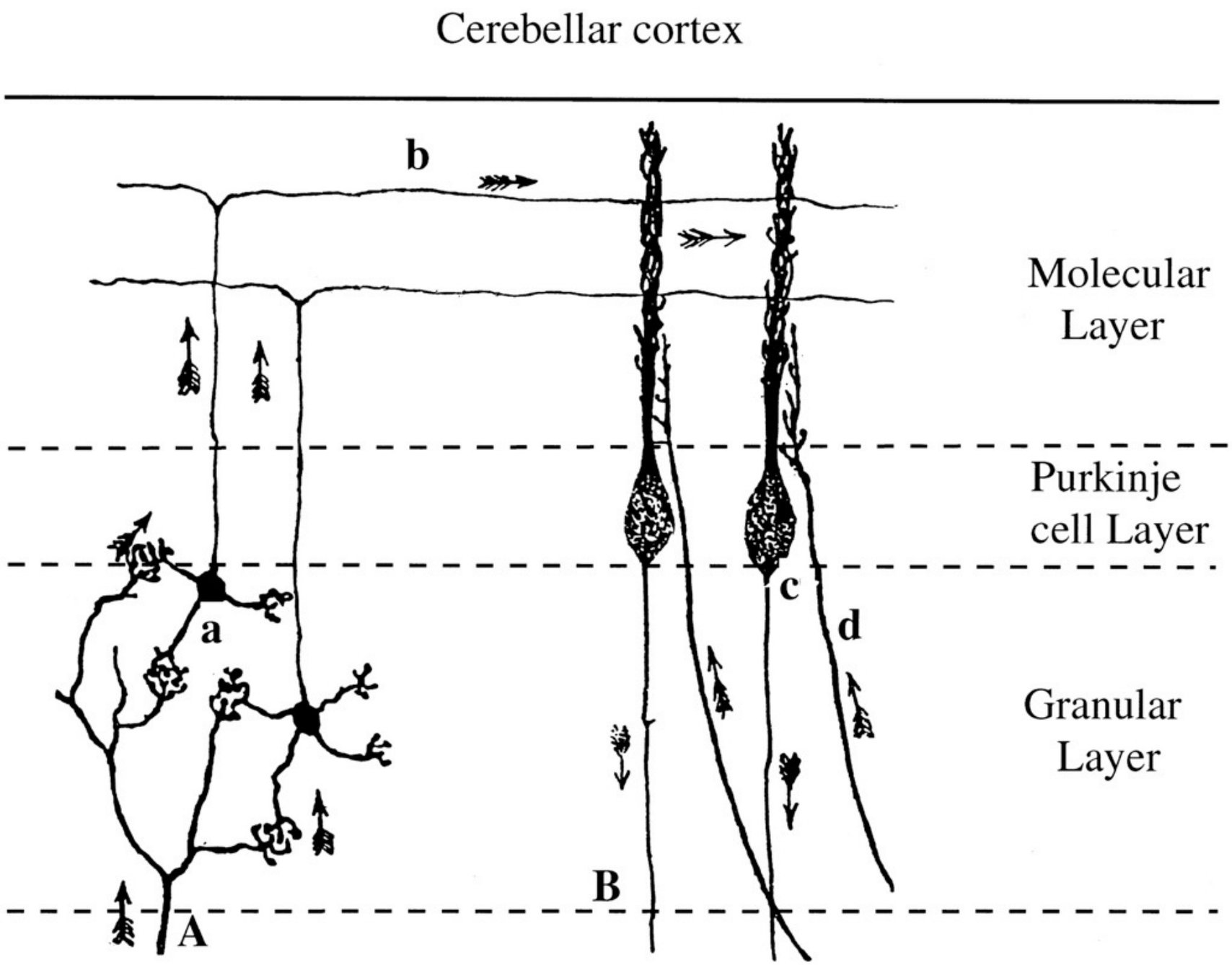
Camillo Golgi

Golgi Staining method



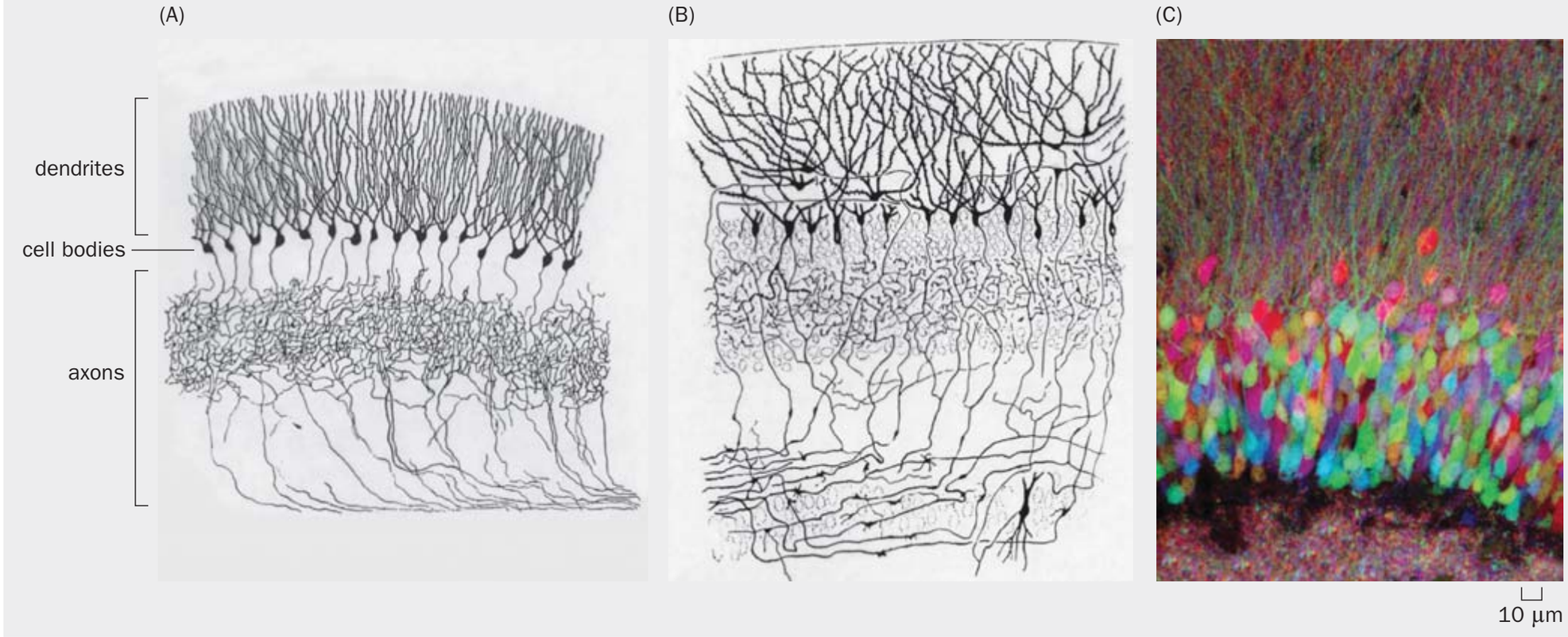
Silver nitrate





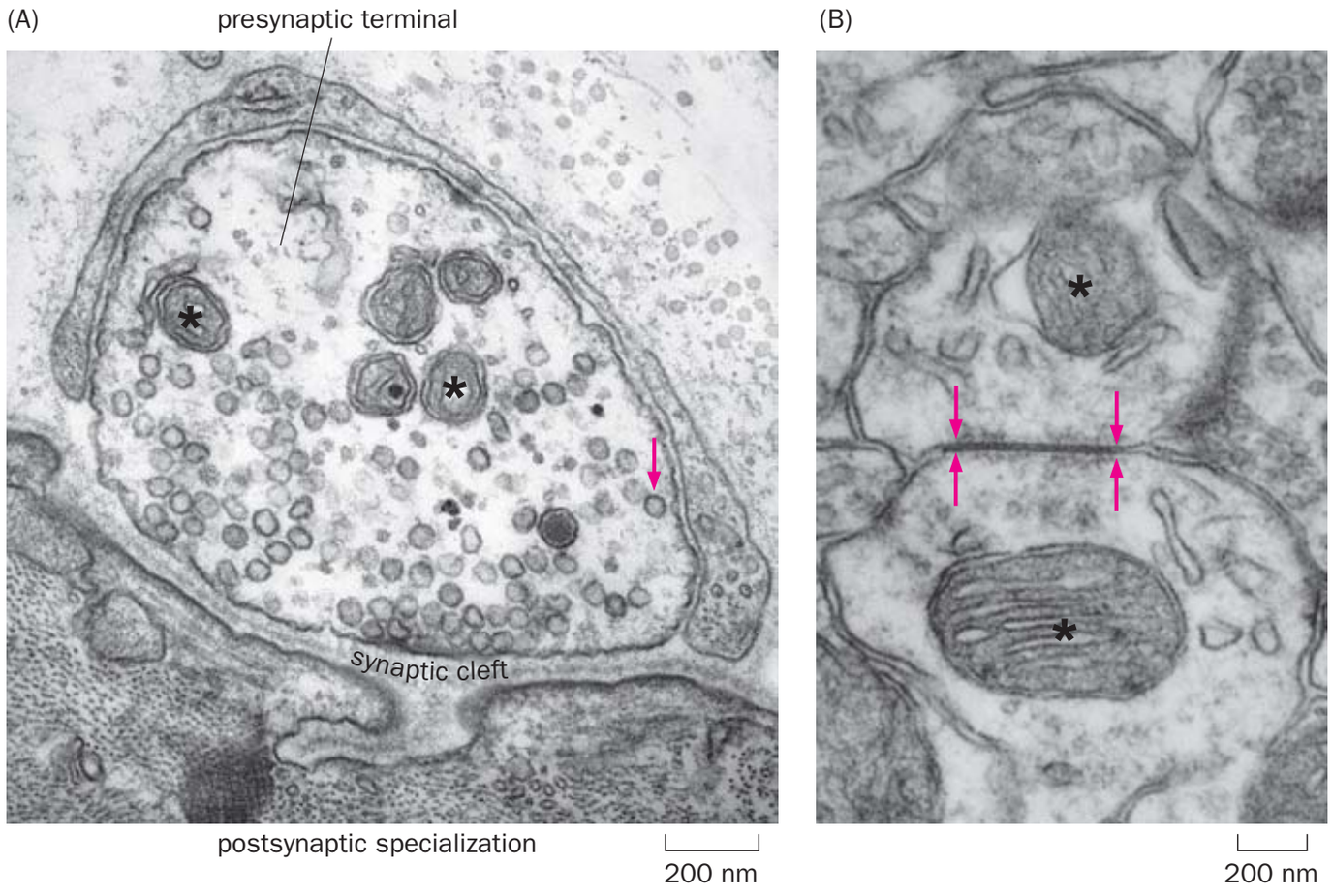
Cajal's drawing of the cerebellar cortex

Reticular Theory vs Neuron Doctrine



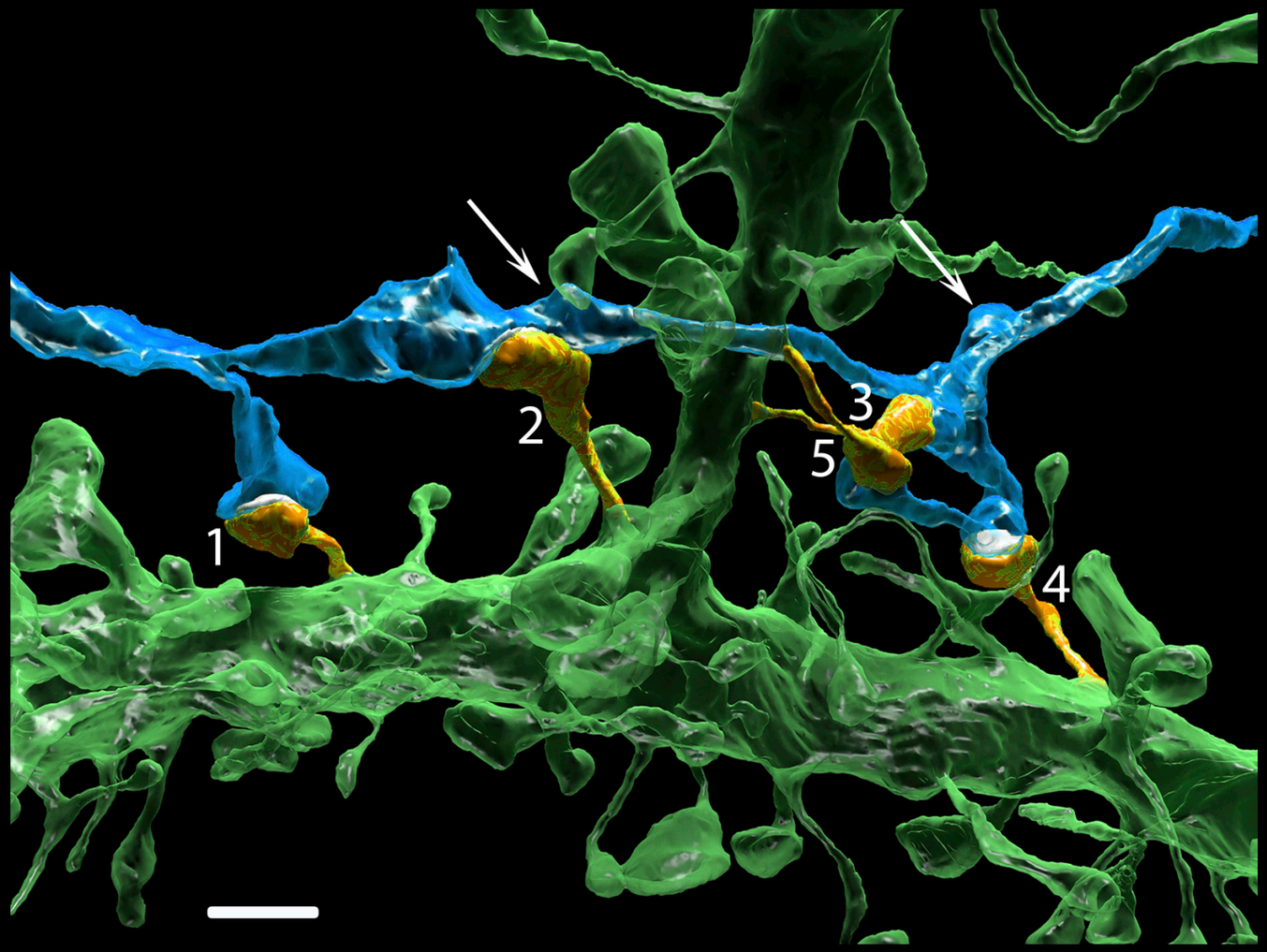
Synapse

How neurons communicate with each other?

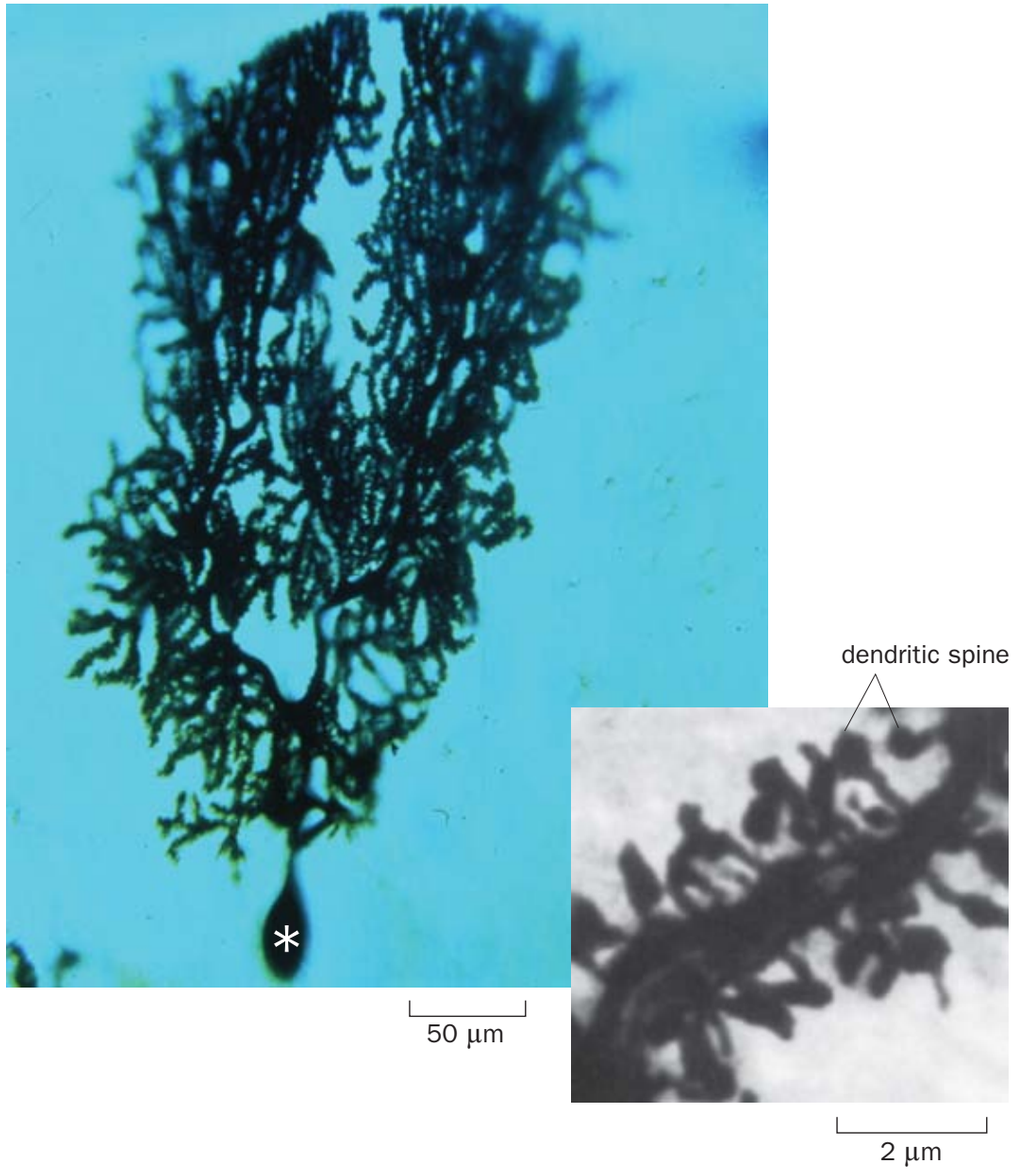


Chemical and electrical synapses

Synaptic Connectivity

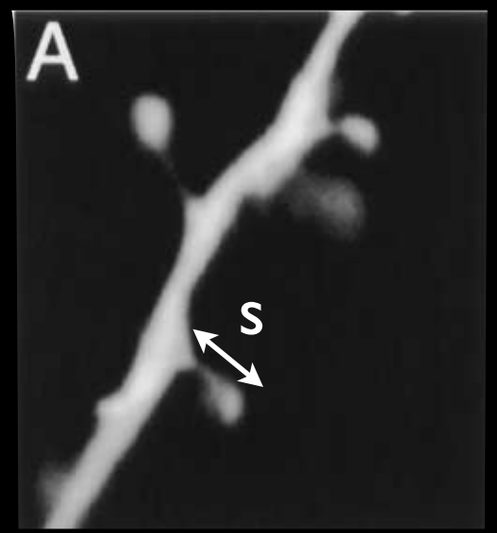


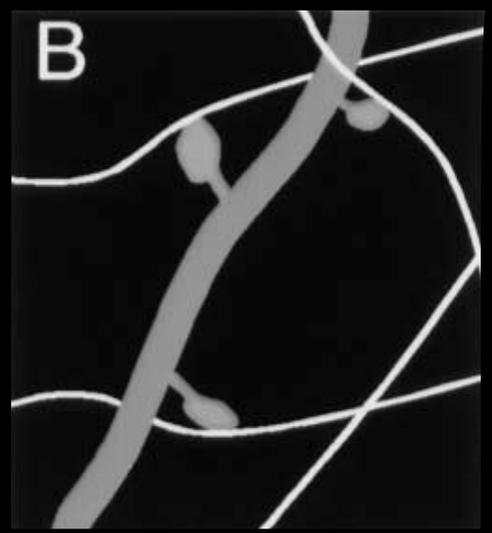
Kasthuri et. al, Cell 2015



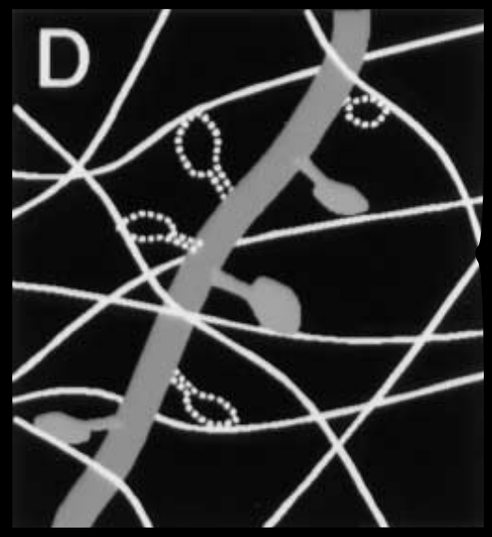
Purkinjie cell in the cerebellum has the highest spine density in the brain

Structural Plasticity of Synaptic Connectivity





$$f = \frac{2}{\pi s L_d b n}$$

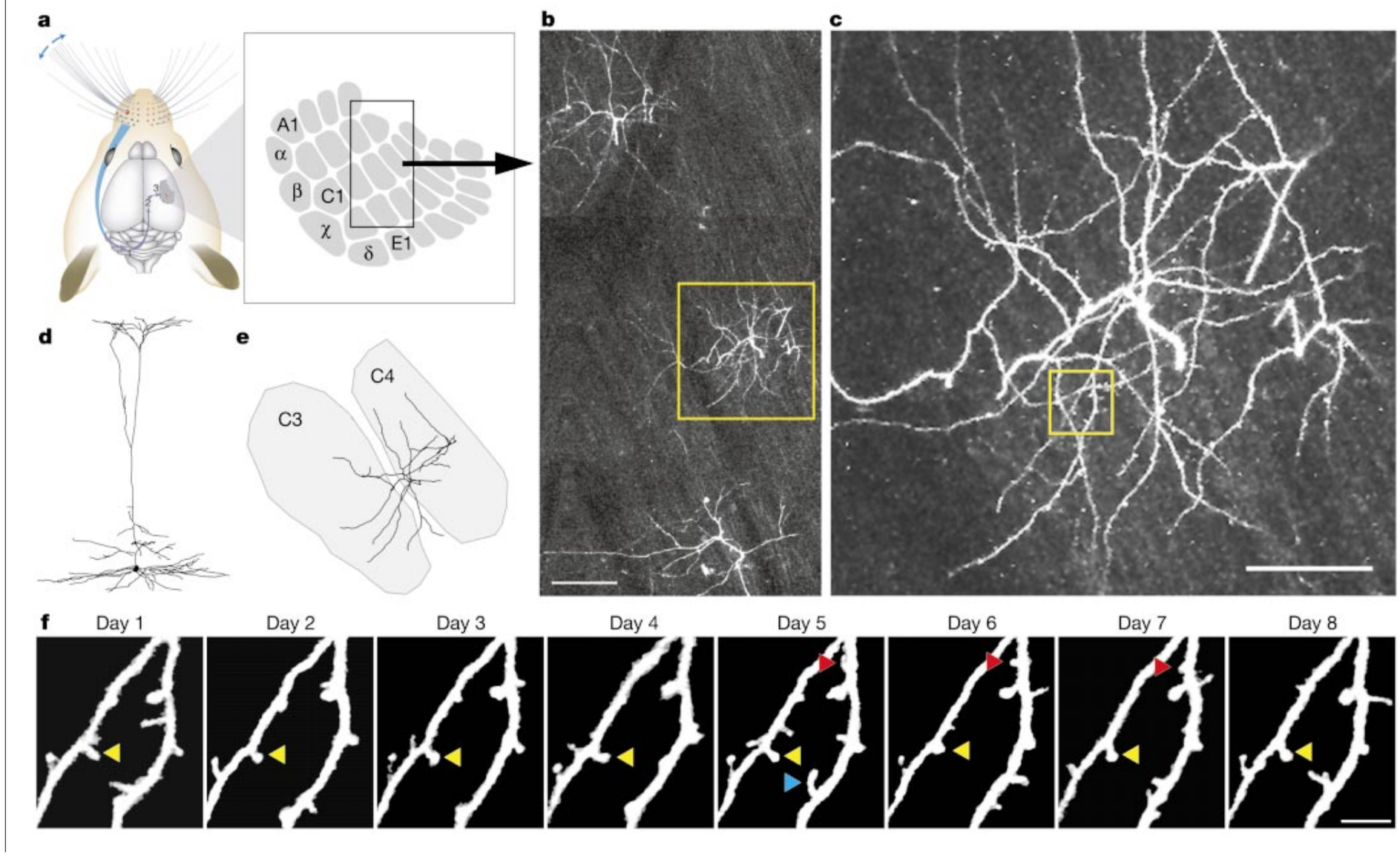


filling fraction = 3/7

s: spine length
L_d: total dendritic length per neuron
b: inter-bouton distance
n: neuronal density

Stepanyants et. al., *Neuron* 2001

Structural Plasticity of Synaptic Connectivity



Trachtenberg et., al. *Nature* 2002

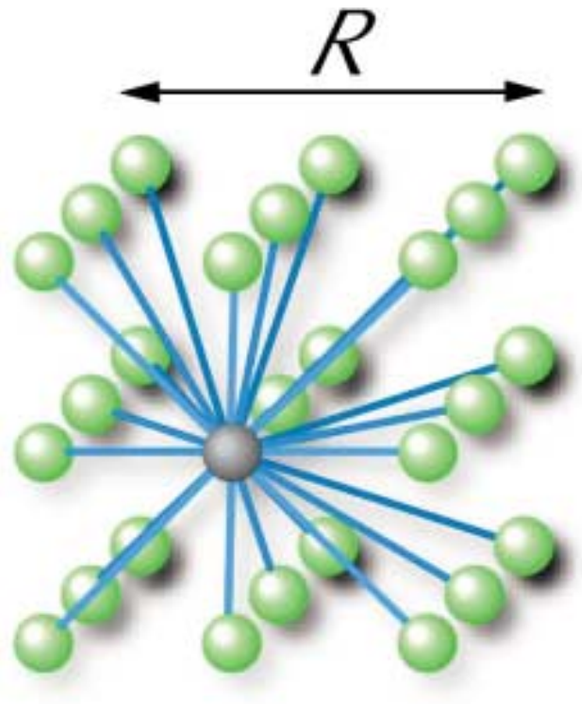
Why do we need axons and dendrites?

Wiring Optimization of Neural Circuit

"After the many shapes assumed by neurons, we are now in a position to ask whether this diversity ... has been left to chance and is insignificant, or whether it is tightly regulated and provides an advantage to the organism. ... we realized that all of the various conformations of the neuron and its various components are simply morphological adaptations governed by laws of conservation for time, space, and material."

Ramon y Cajal

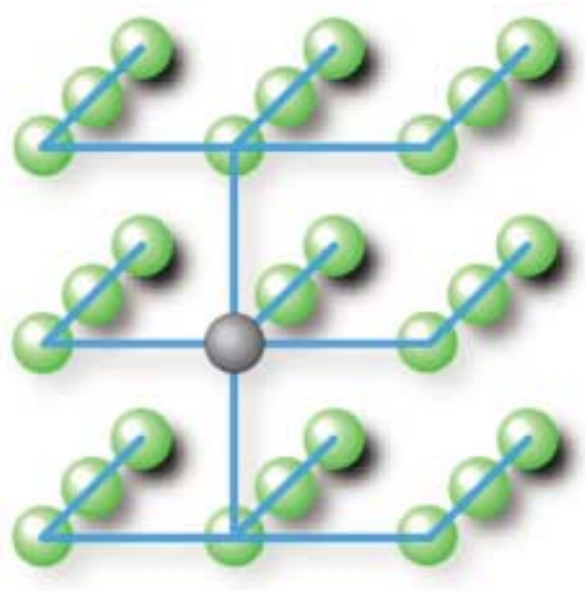
Why do we need axons and dendrites?



N: number of neurons
d: process diameter
R: network linear size

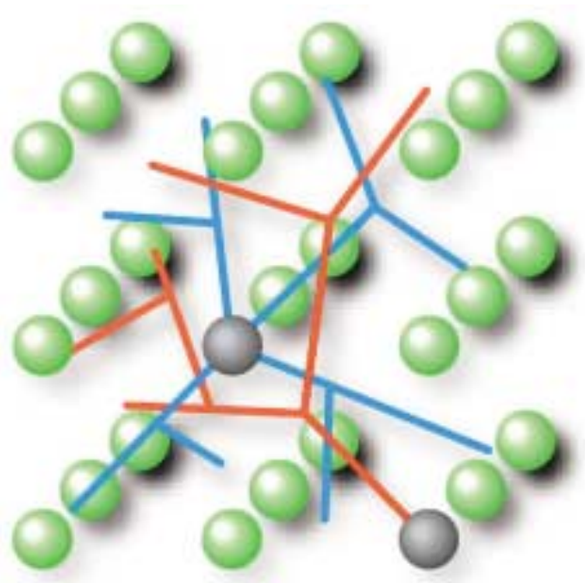
Design I

Why do we need axons and dendrites?



Design II

Why do we need axons and dendrites?



Design III

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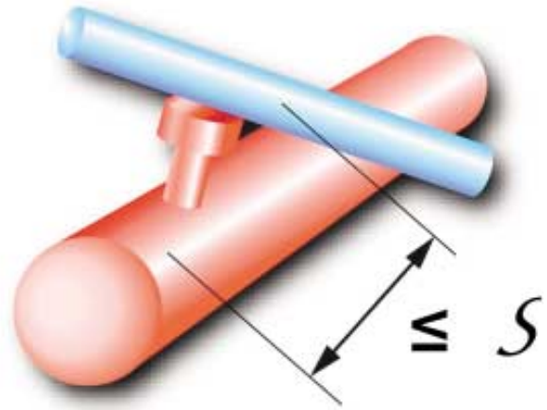
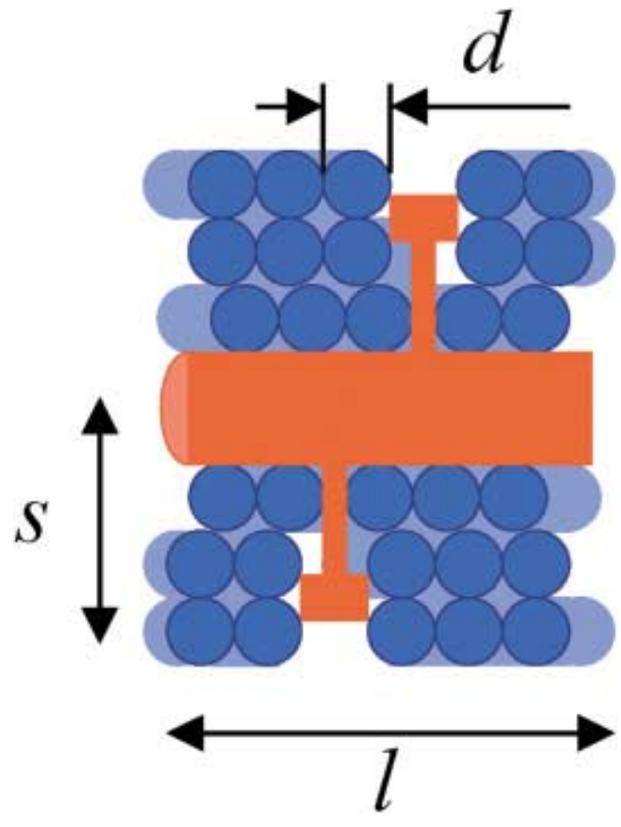


Design IV

Why do we need axons and dendrites?



The Optimality of the design

Chklovskii *Neuron* 2004

The cerebellar cortex