

The Basic Organization of the Brain

SUMMARY

- (1) The probability of an event in an ideal experiment is given by the absolute value of a complex number ϕ which is called the probability amplitude:

$$\begin{aligned} P &= \text{probability,} \\ \phi &= \text{probability amplitude,} \\ P &= |\phi|^2. \end{aligned}$$

- (2) When an event can occur in several alternative ways, the probability for the event is the sum of the probability amplitudes for each considered separately. There is interference:

$$\begin{aligned} \phi &= \phi_1 + \phi_2, \\ P &= |\phi_1 + \phi_2|^2. \end{aligned}$$

- (3) If an experiment is performed which is capable of determining whether another alternative is actually taken, the probability of the event is the sum of the probabilities for each alternative. The interference is lost:

$$P = P_1 + P_2.$$

One might still like to ask: "How does it work? What is the machinery behind the law?" No one has found any machinery behind the law. No one can tell you any more than we have just "explained." No one will give you any deeper representation of the situation. We have no ideas about a more basic mechanism from which these results can be deduced.

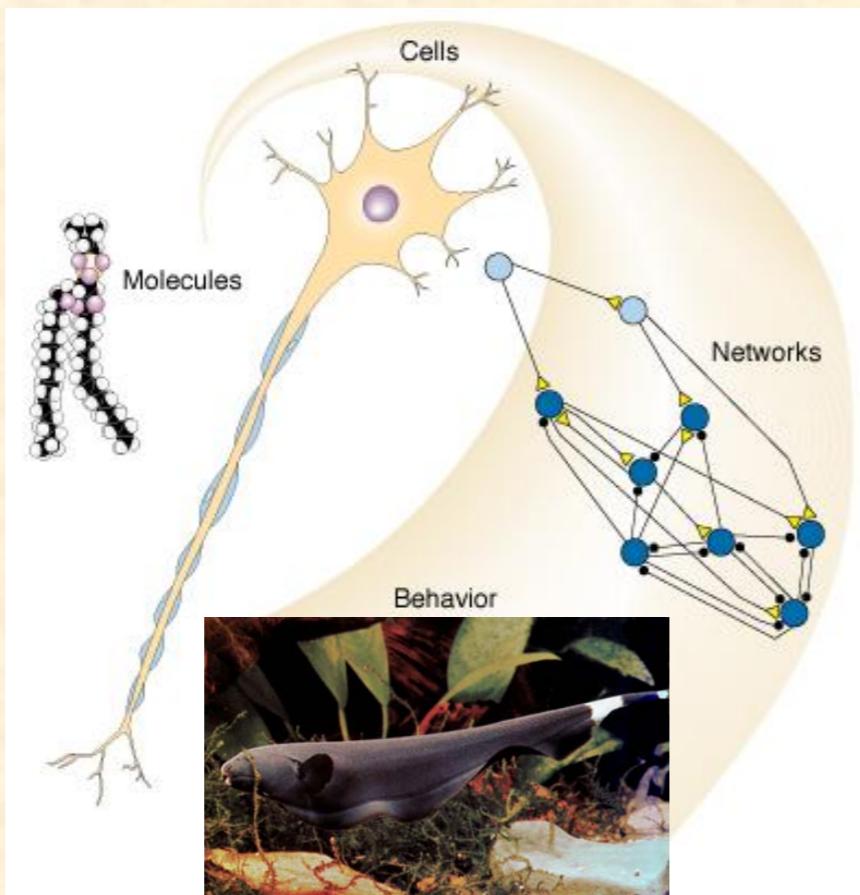
First Principle of Quantum Mechanics

The Feynman Lectures on Physics Volume III page 10

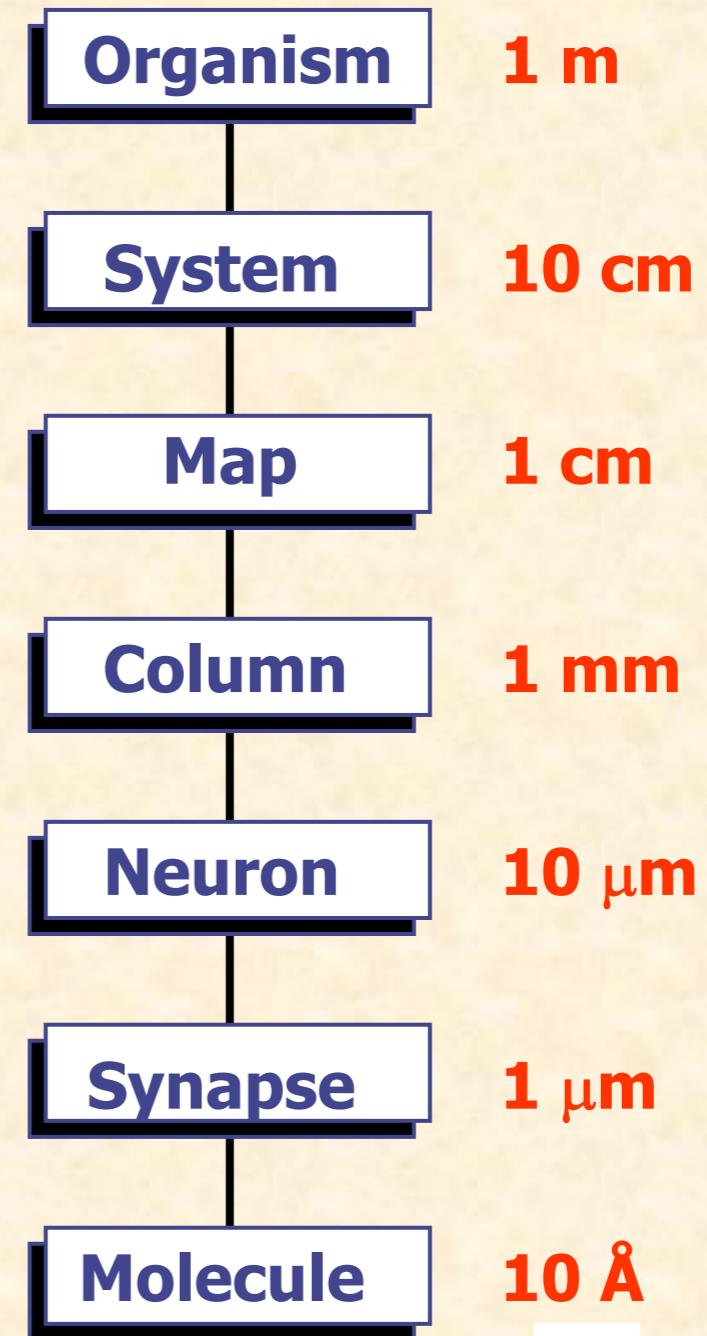


First Principle of Neurobiology

Multiscale Organization of the Nervous System



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

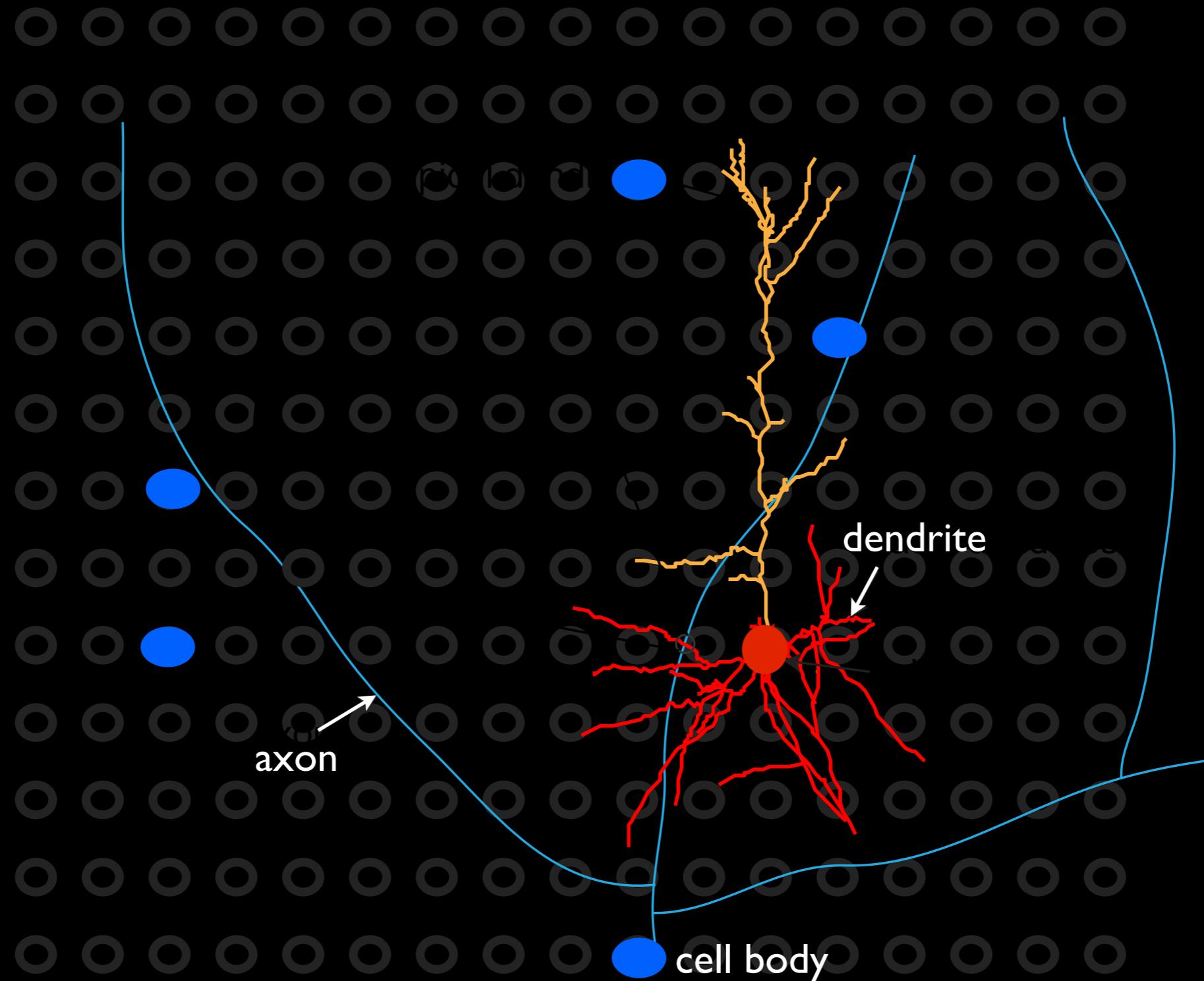
More is different

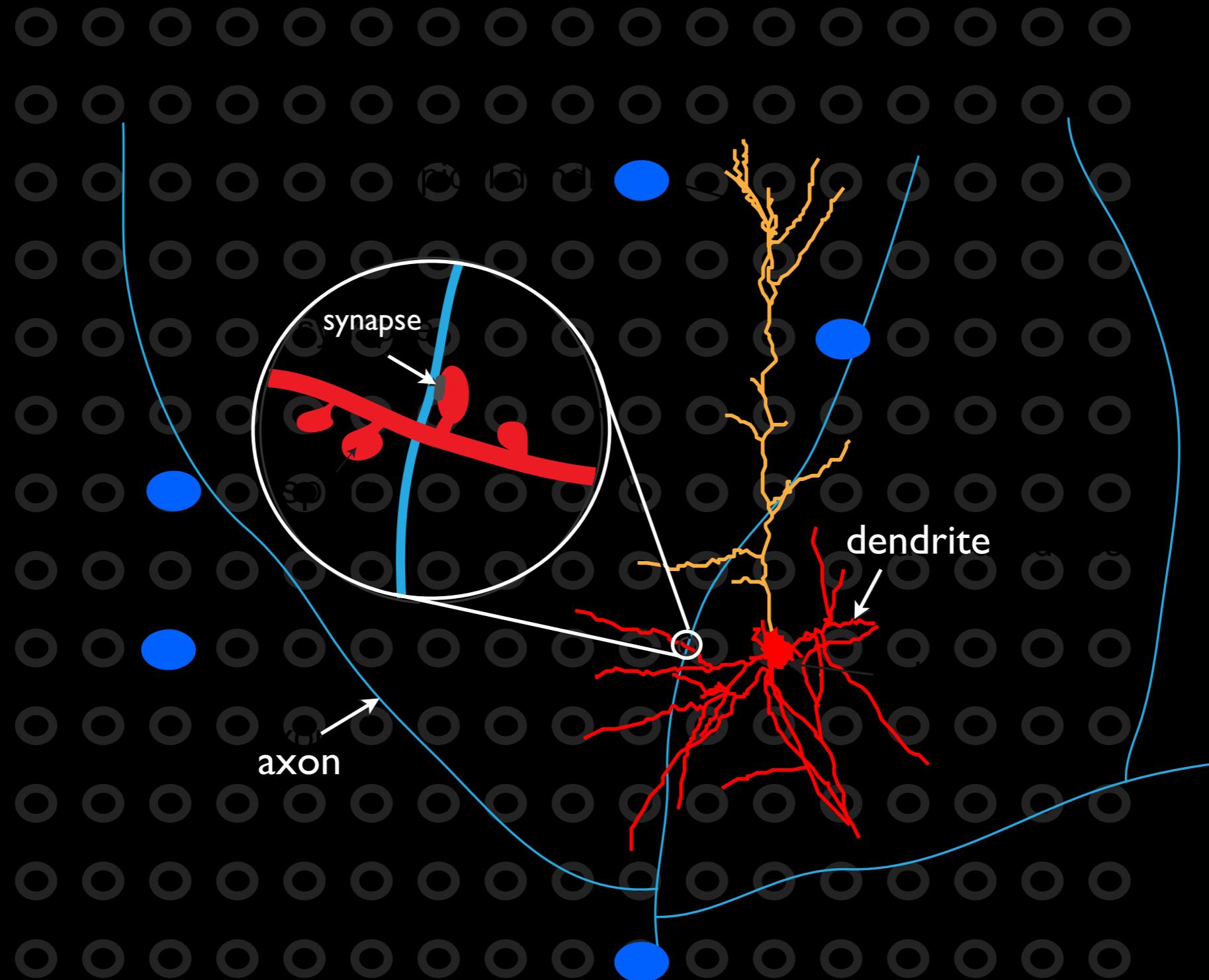
Fitzgerald: The rich are **different** from us.

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

a conversation somewhere in Paris in 1920s

The Neuron Doctrine





The Debate between Cajal and Golgi

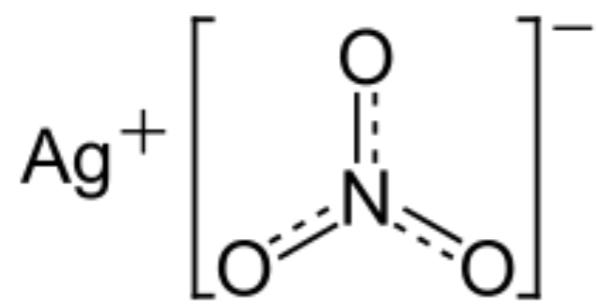


Ramon y Cajal

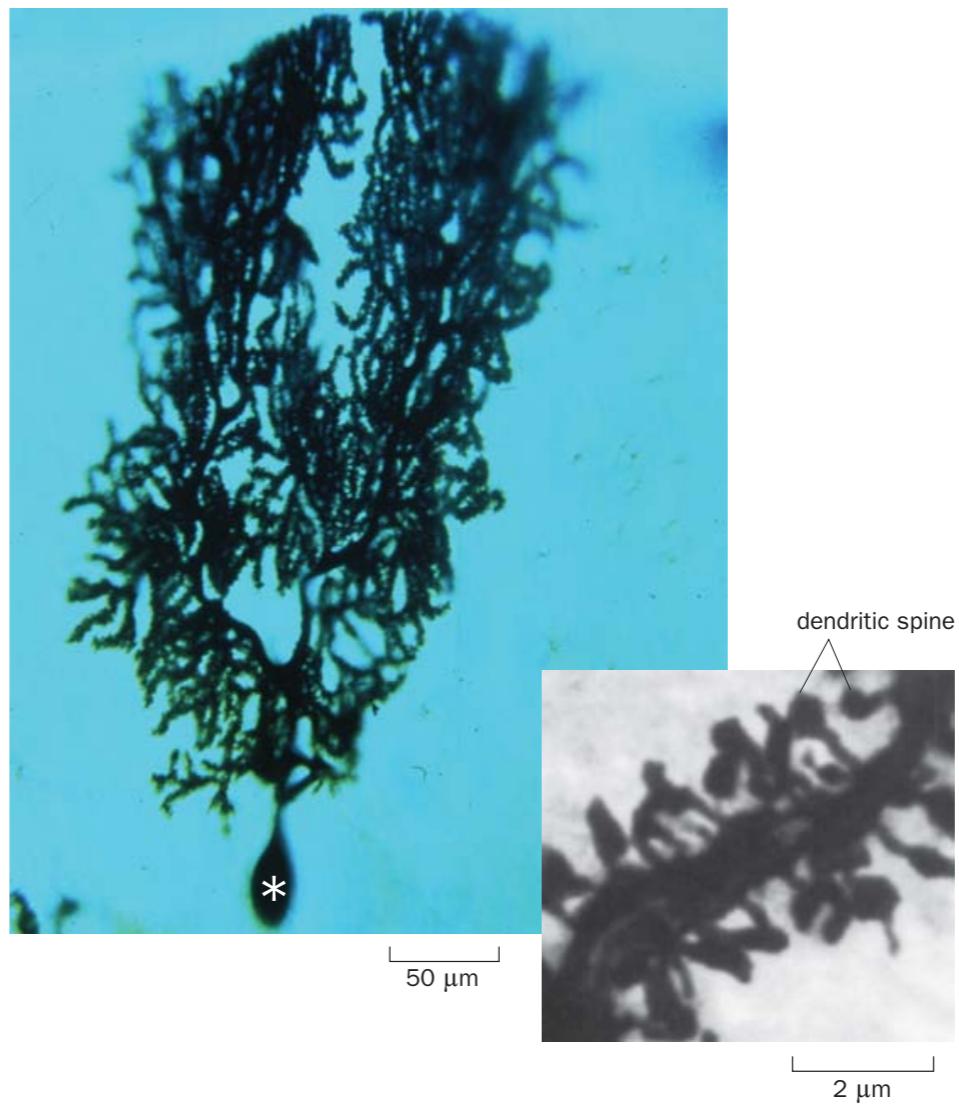


Camillo Golgi

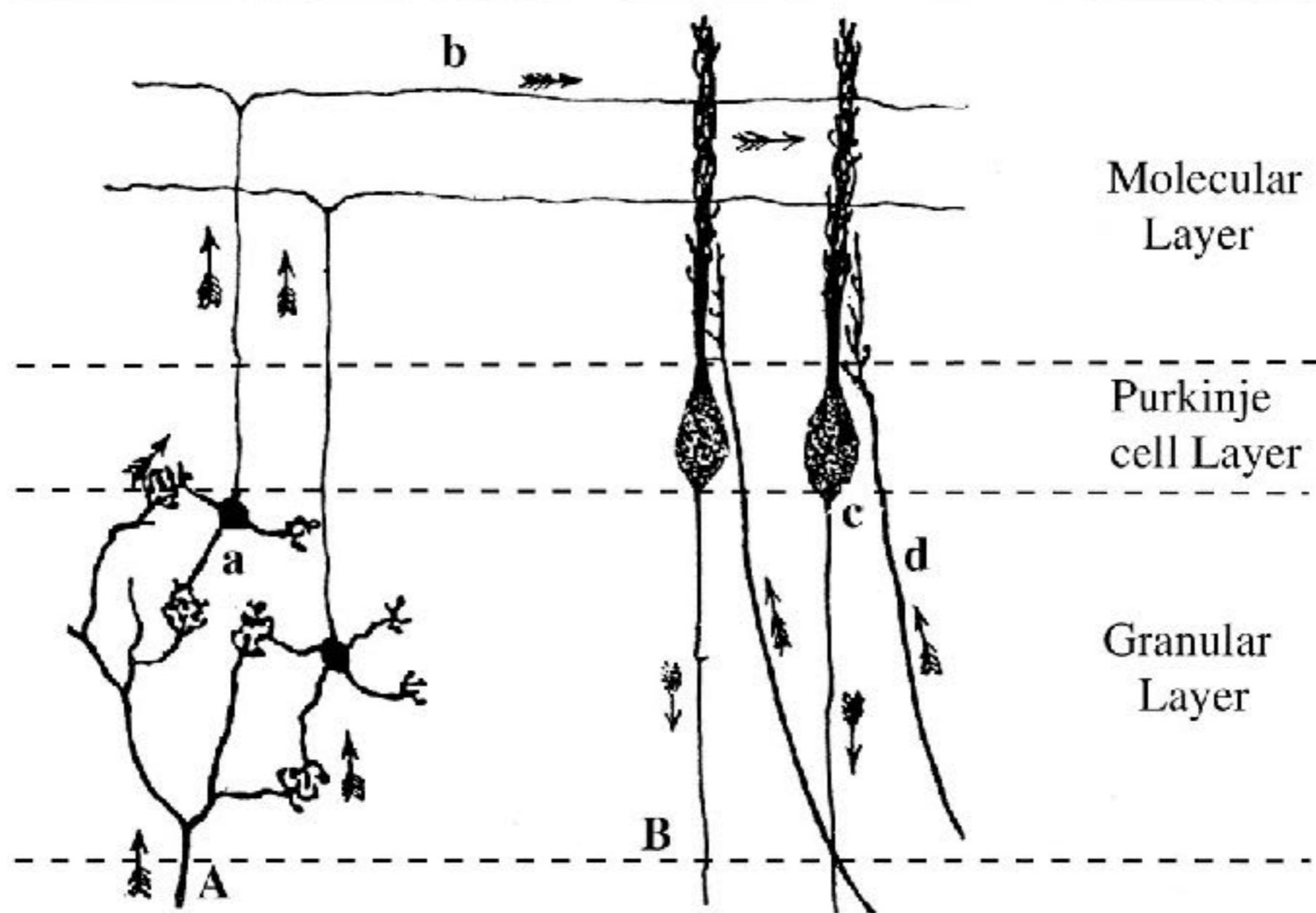
Golgi Staining method



Silver nitrate

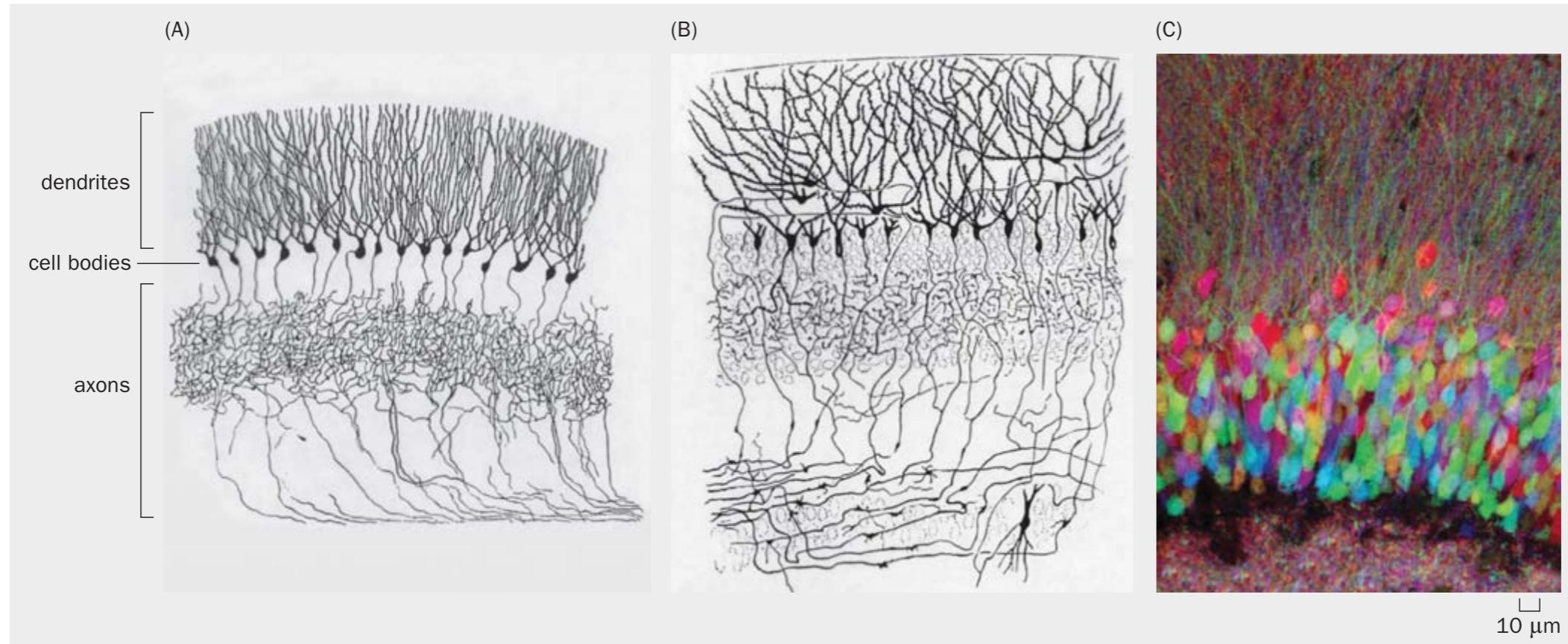


Cerebellar cortex



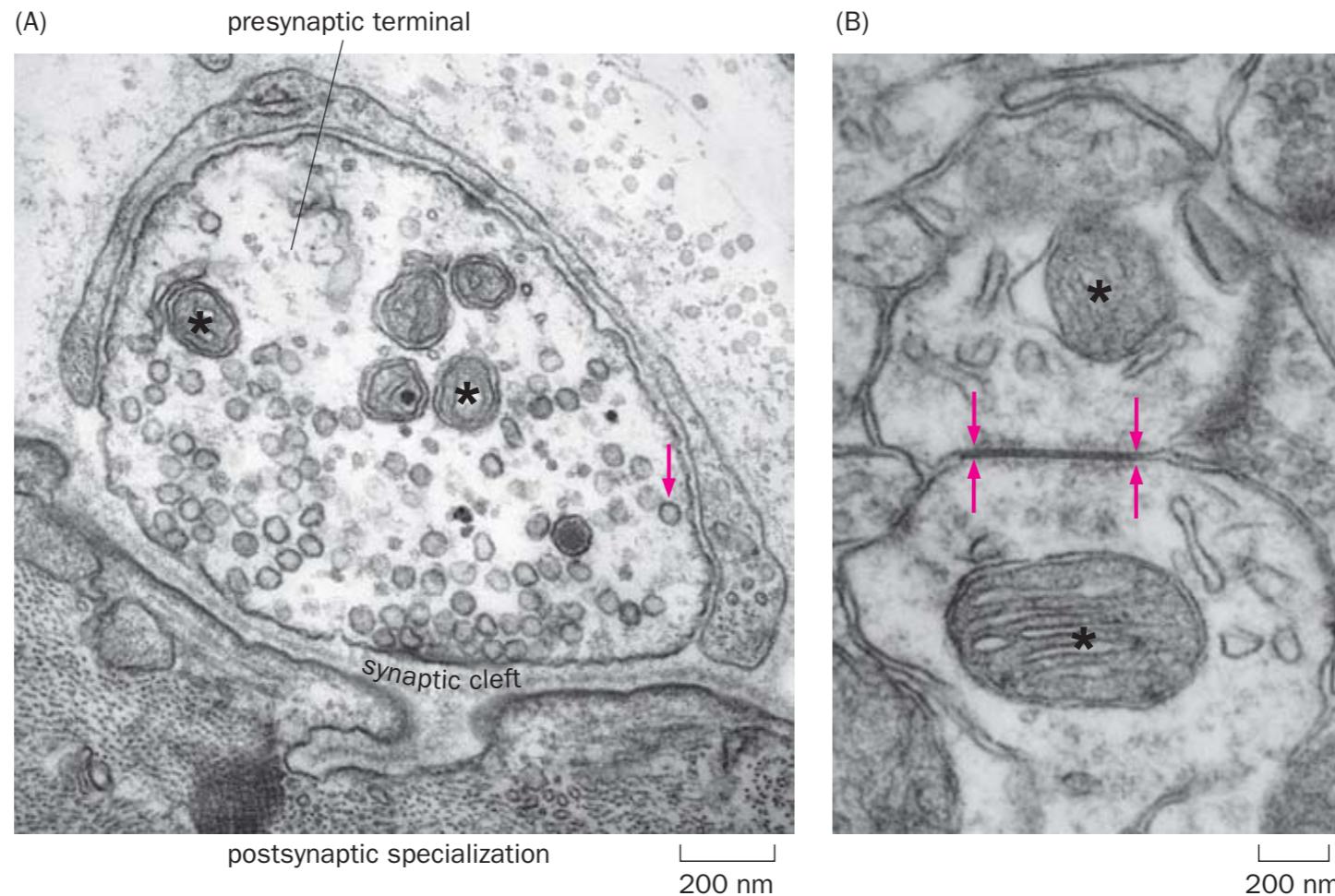
Cajal's drawing of the cerebellar cortex

Reticular Theory vs Neuron Doctrine



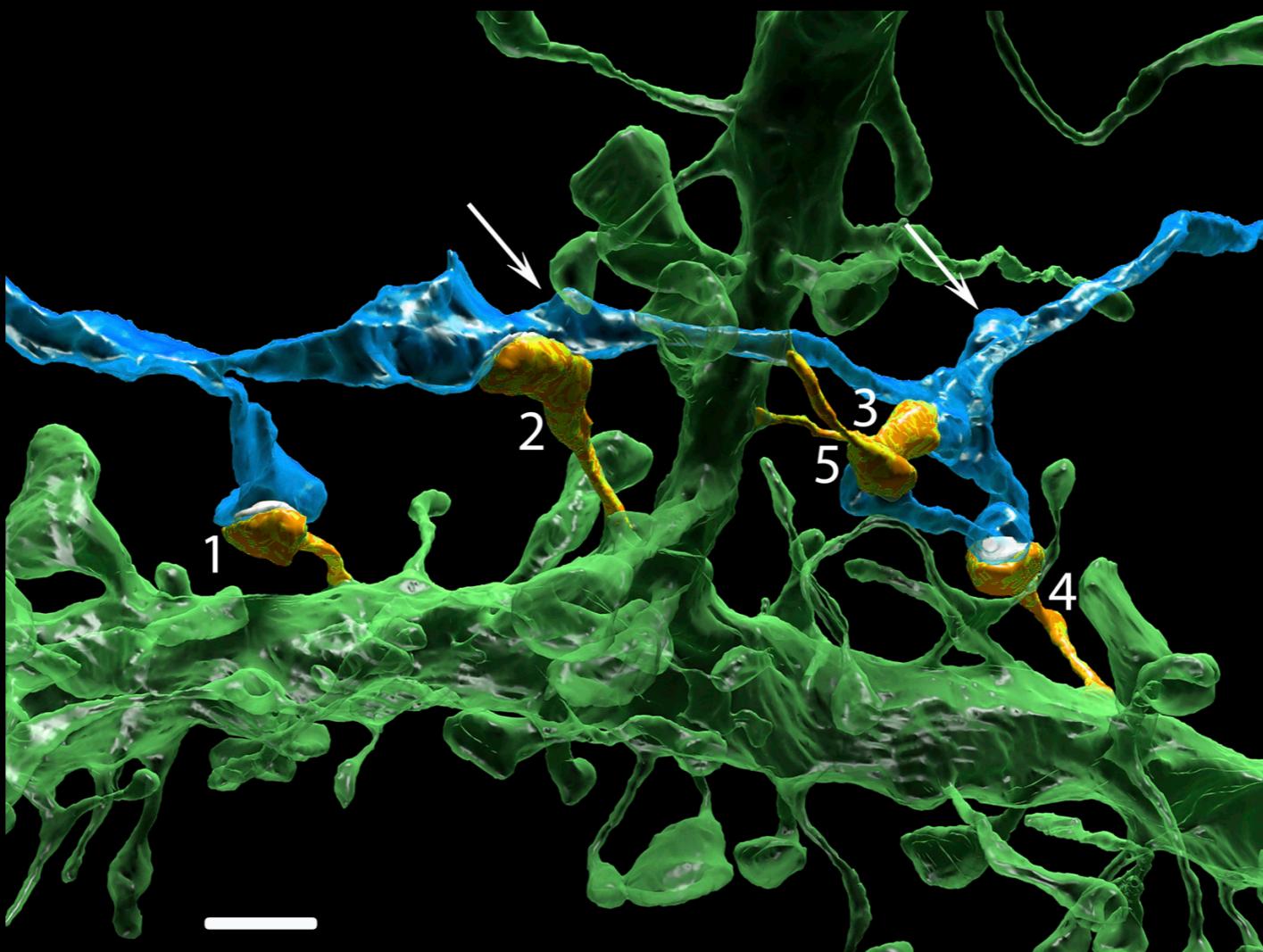
Synapse

How neurons communicate with each other?

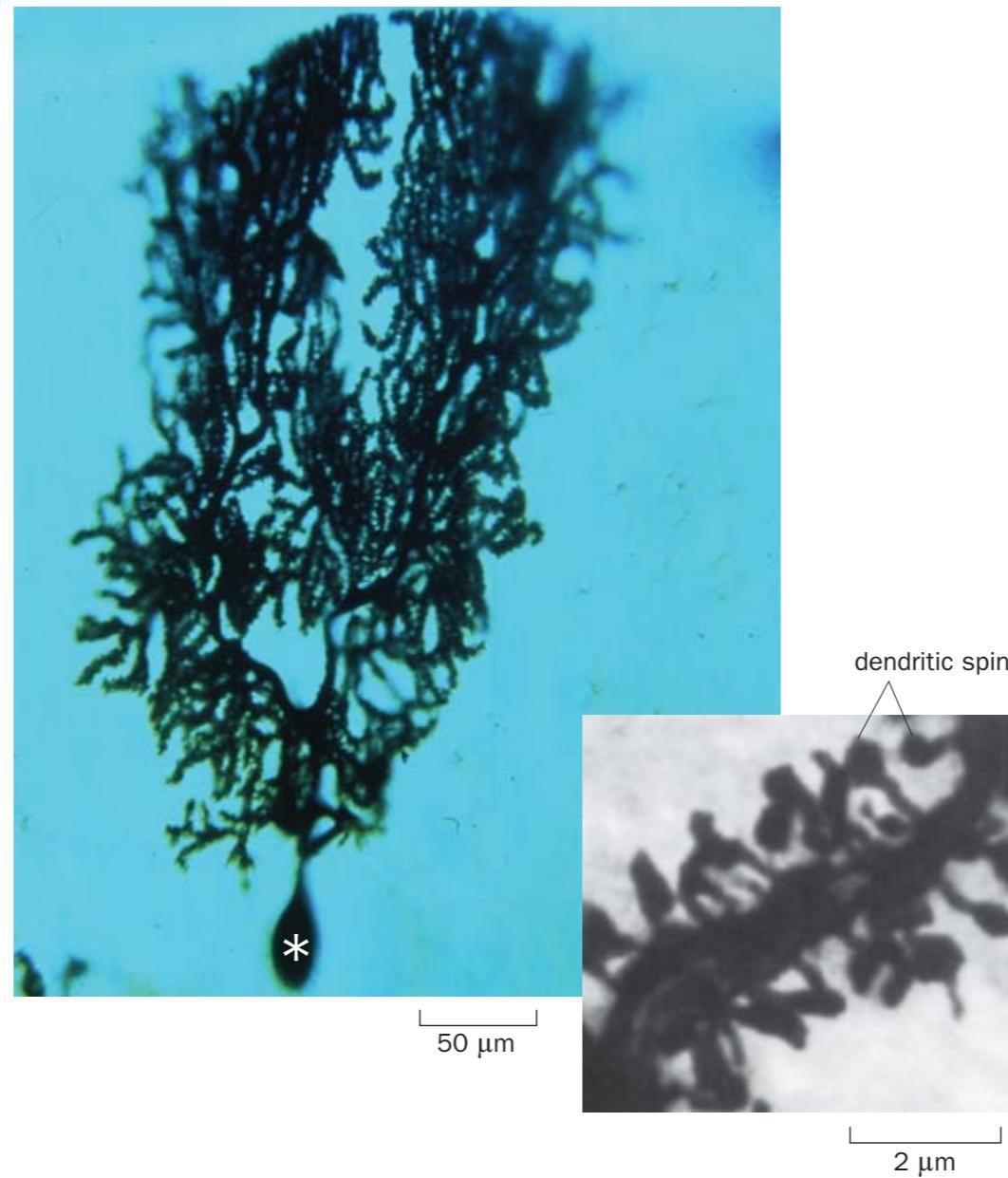


Chemical and electrical synapses

Synaptic Connectivity

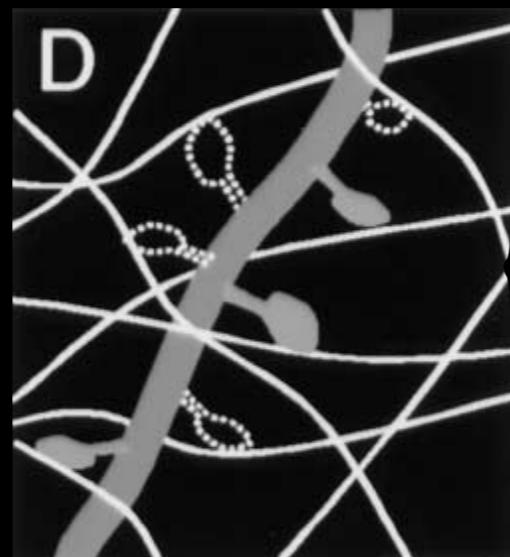
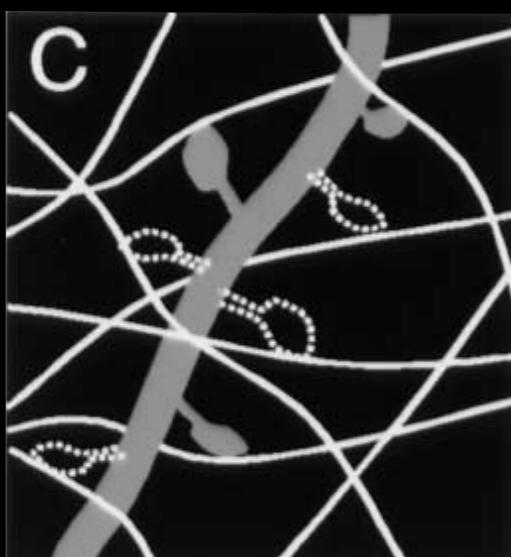
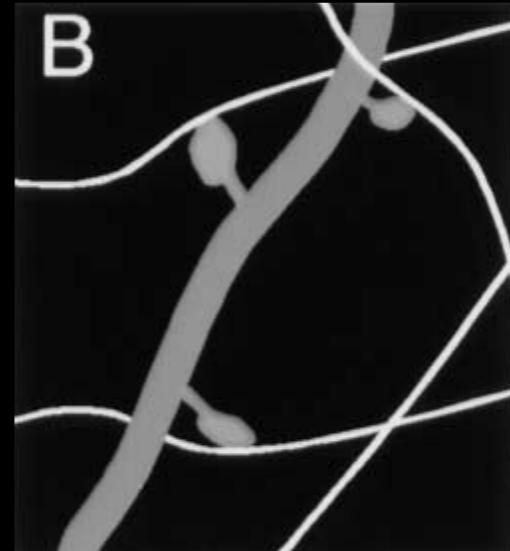
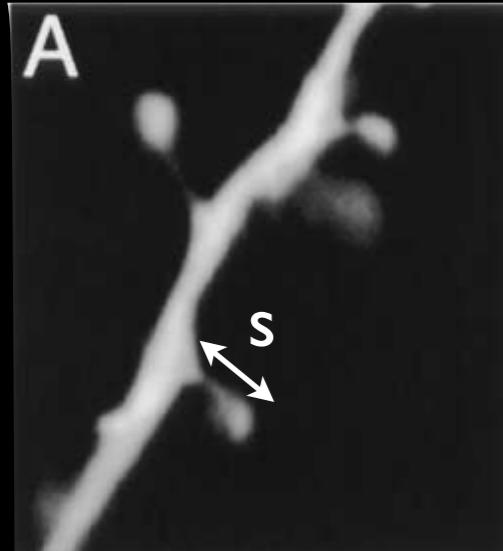


Kasthuri et. al, Cell 2015



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

Structural Plasticity of Synaptic Connectivity



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

s: spine length

L_d: total dendritic length per neuron

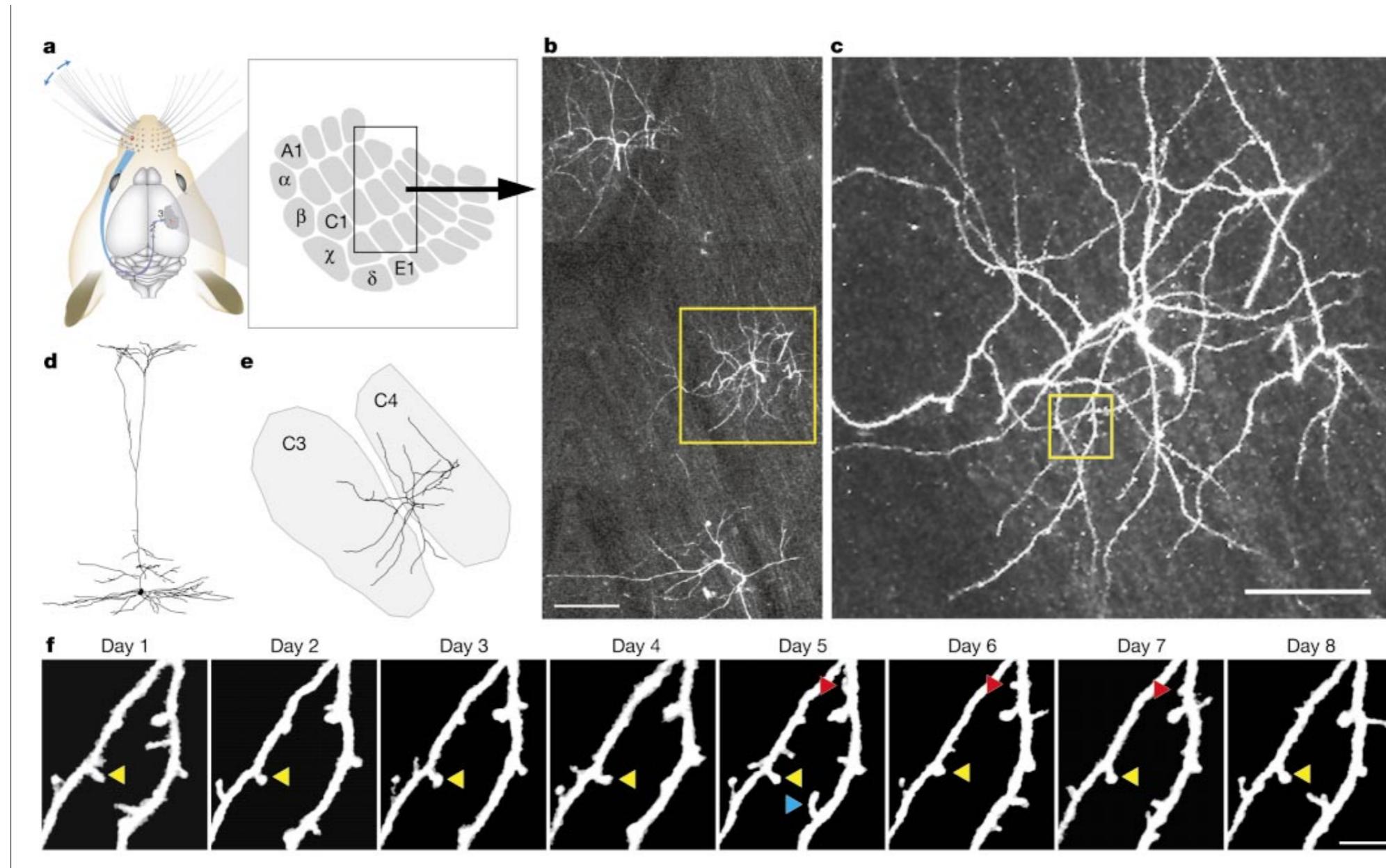
b: inter-bouton distance

n: neuronal density

filling fraction = 3/7

Stepanyants et. al., *Neuron* 2001

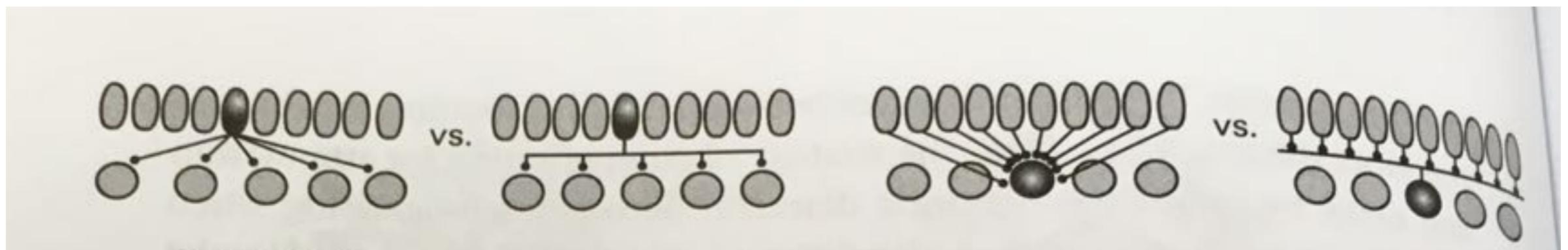
Structural Plasticity of Synaptic Connectivity



Trachtenberg et., al. *Nature* 2002

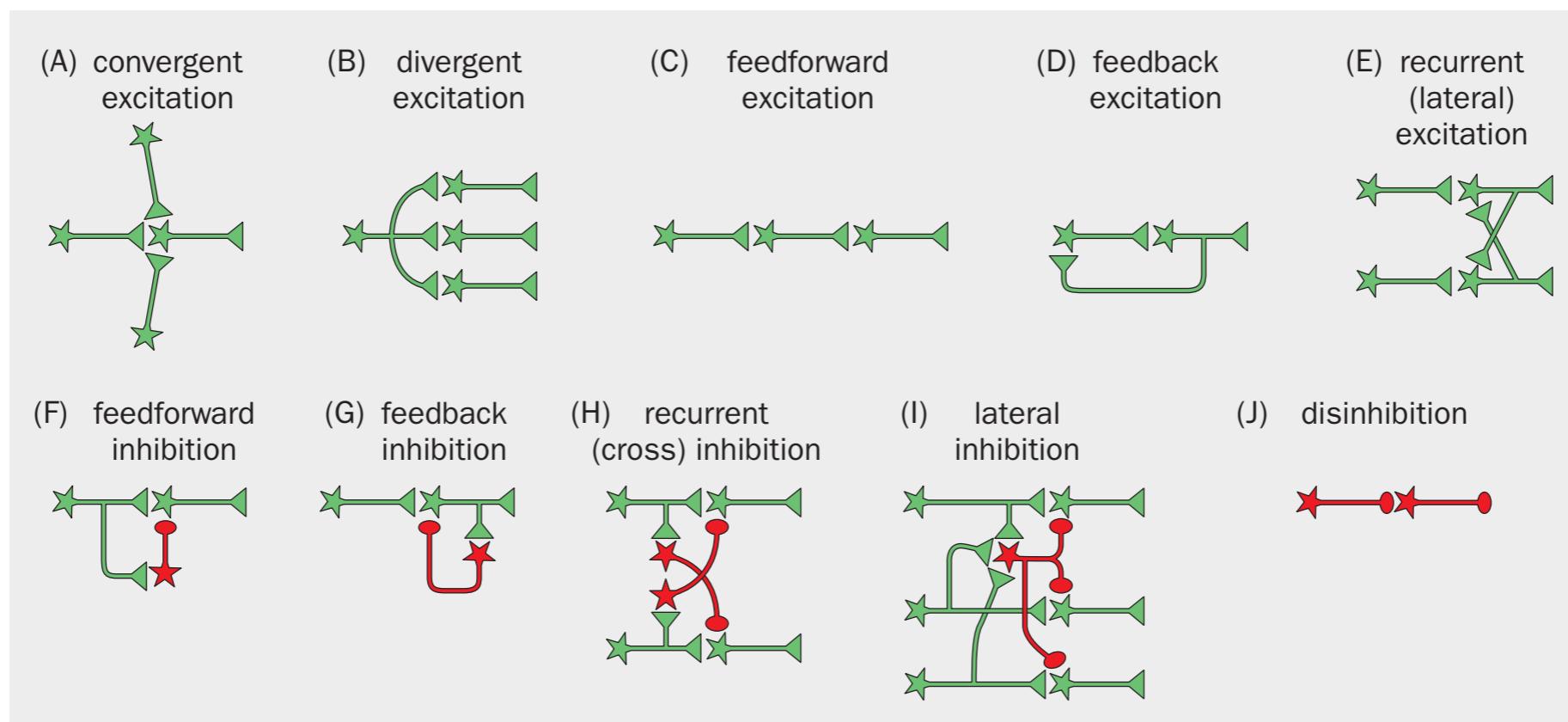
Circuit motif

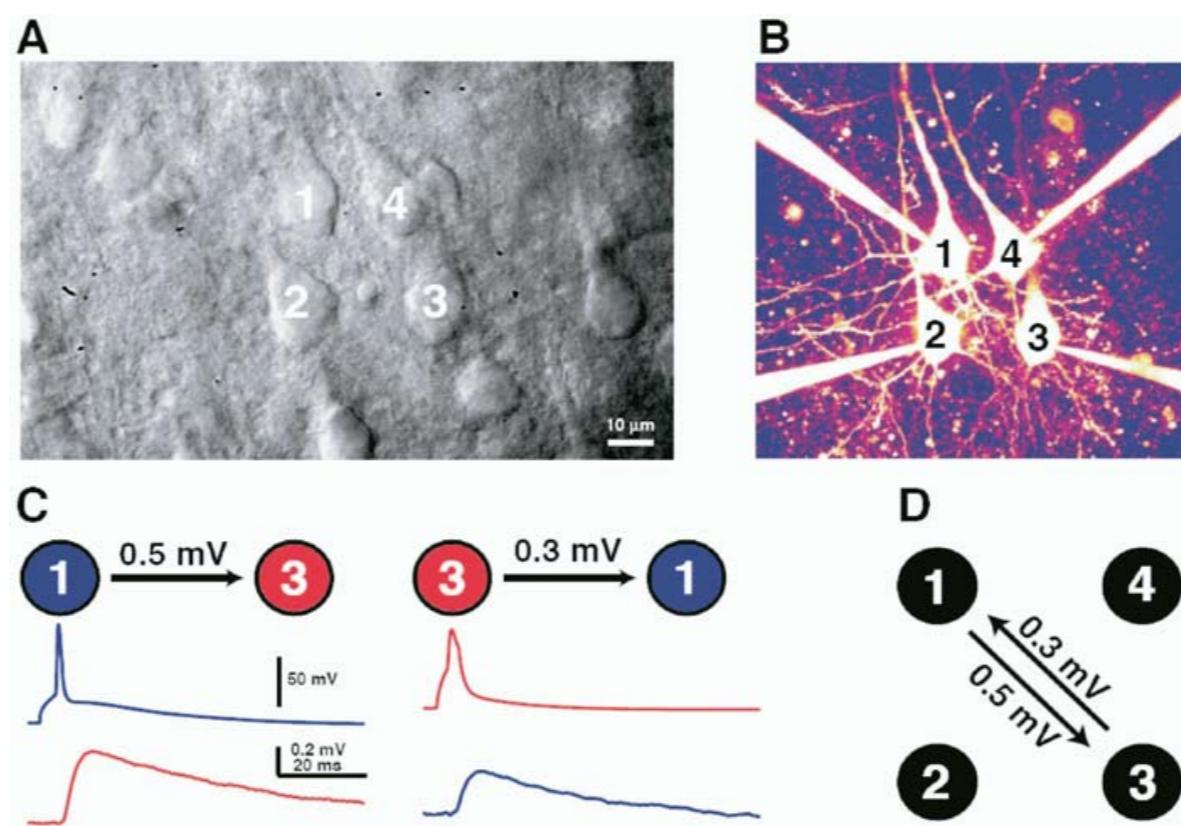
Convergence and divergence



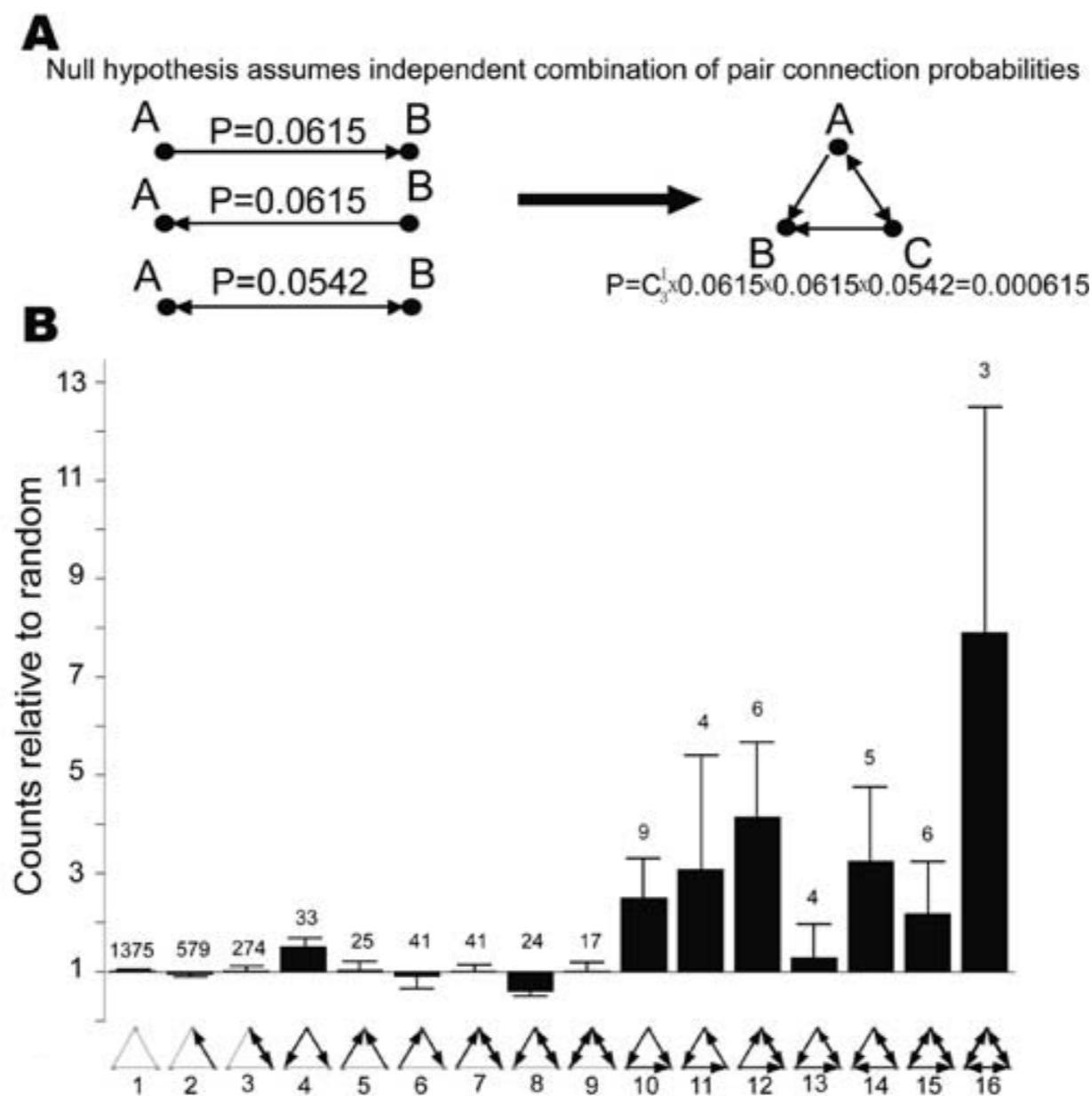
Why do we have branching axons and dendrites?

Circuit motifs



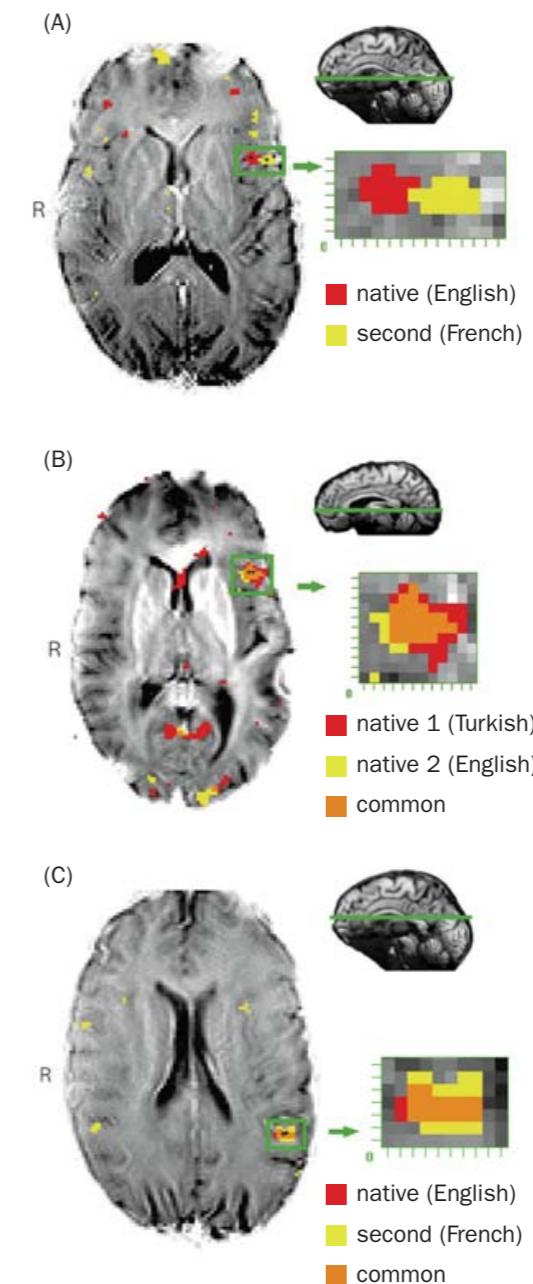
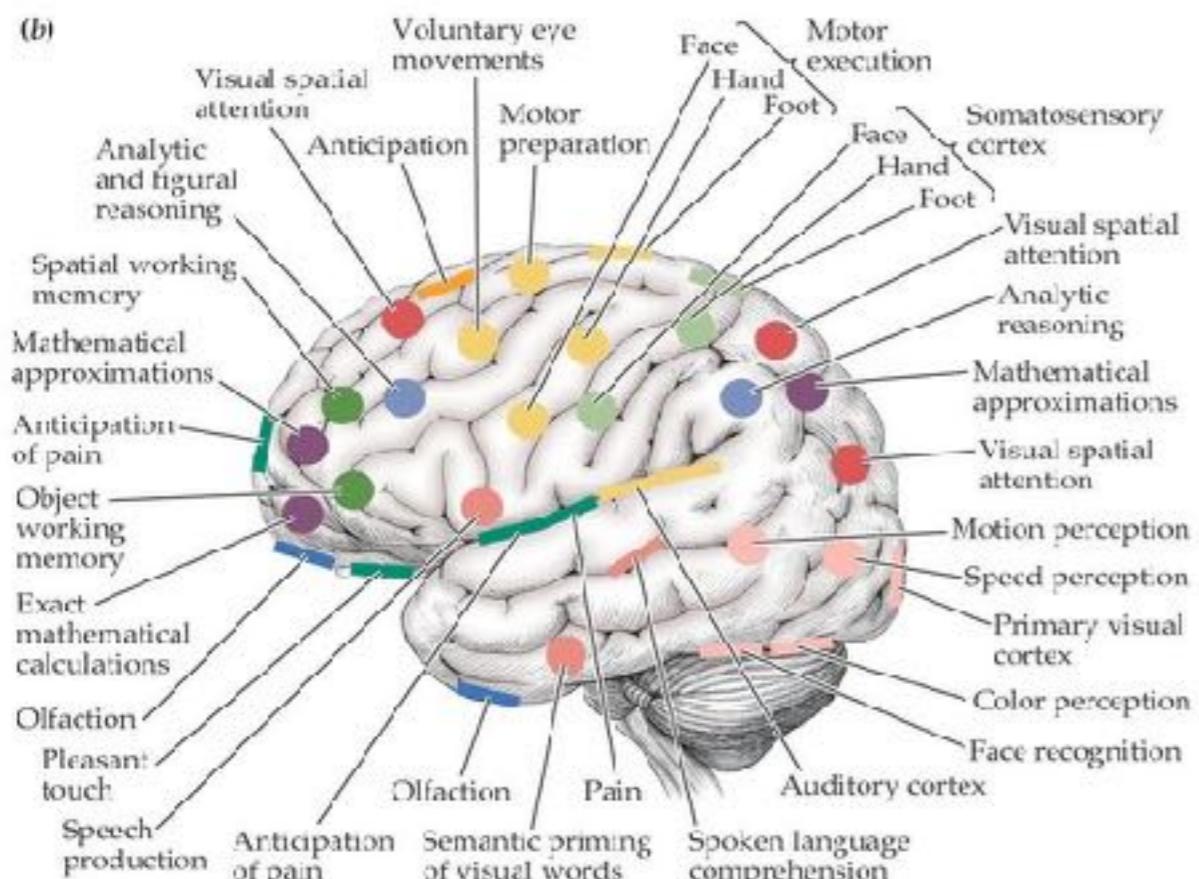


Some circuit motifs are over-represented



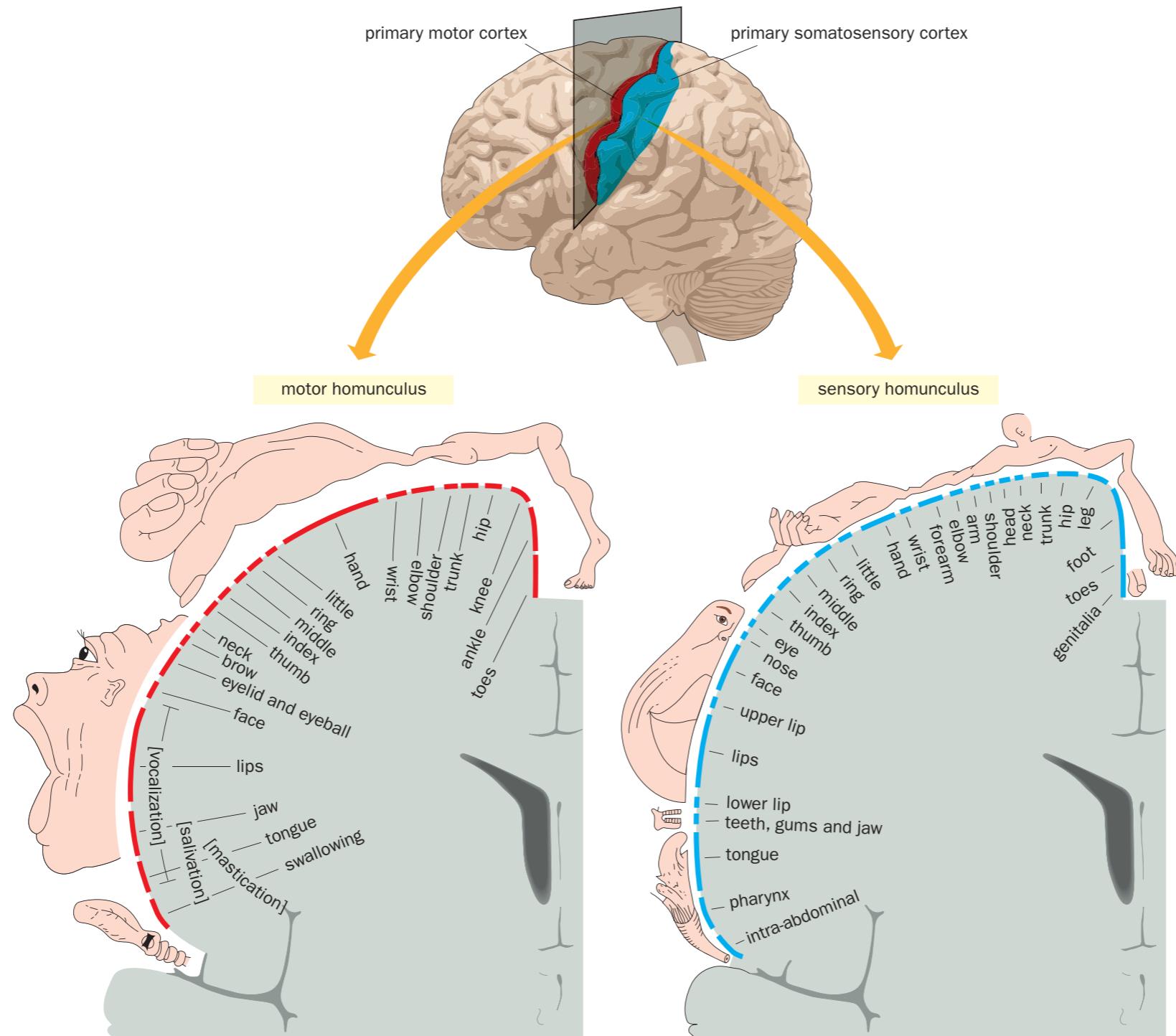
Cortical map and column

Specific brain regions (columns) perform specialized brain functions

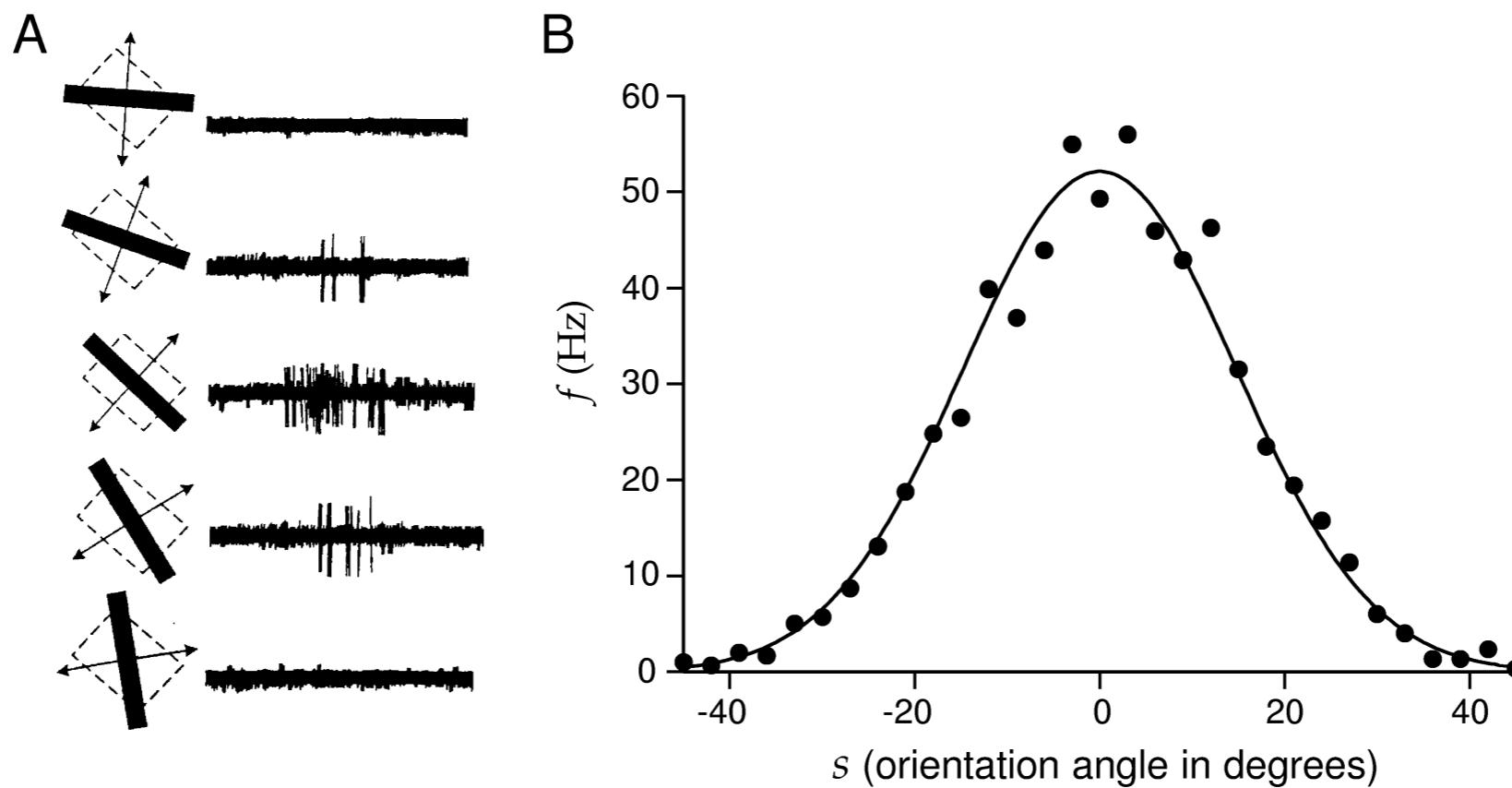


fMRI (functional magnetic resonance imaging)

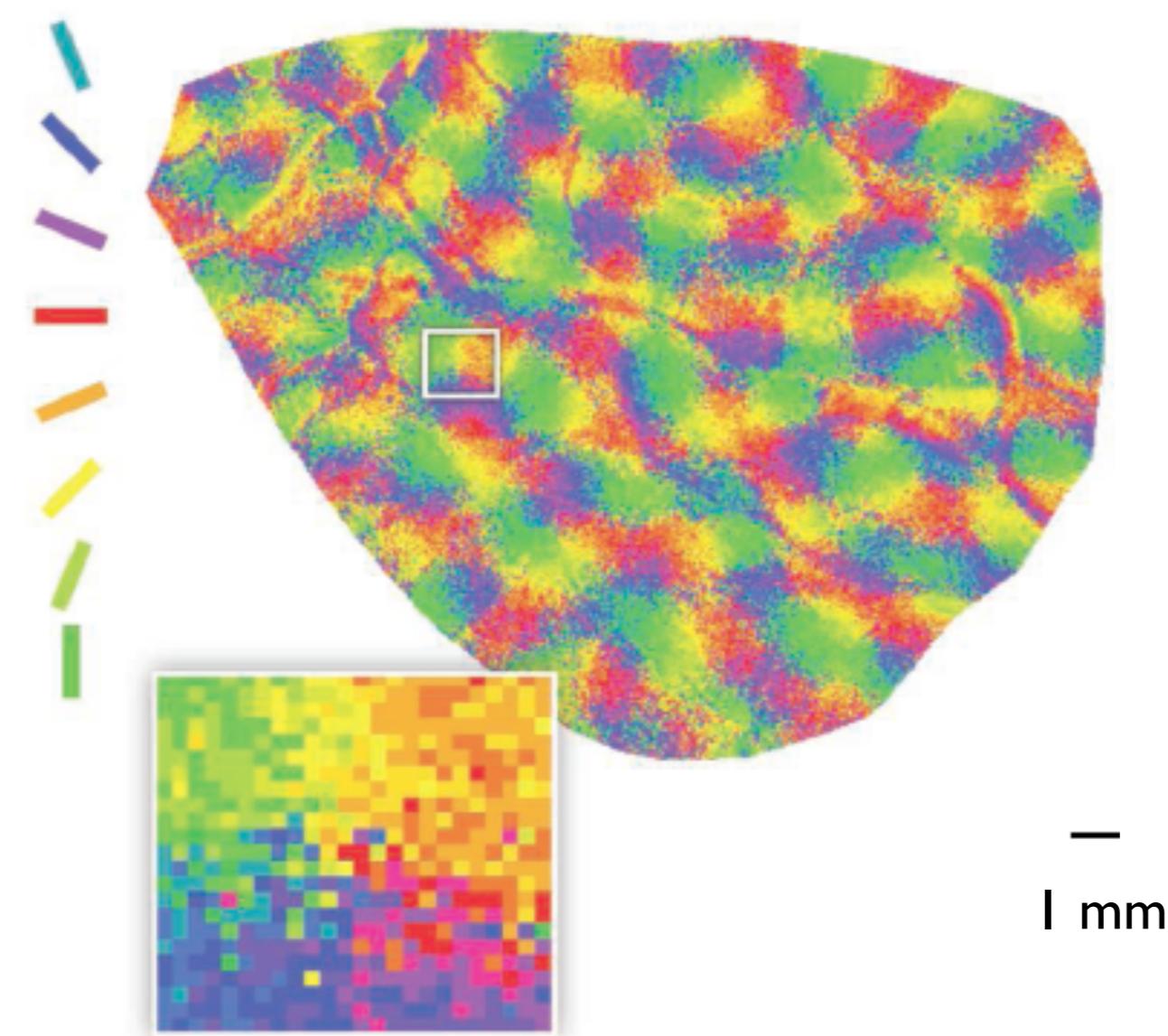
The cortex uses maps to organize information



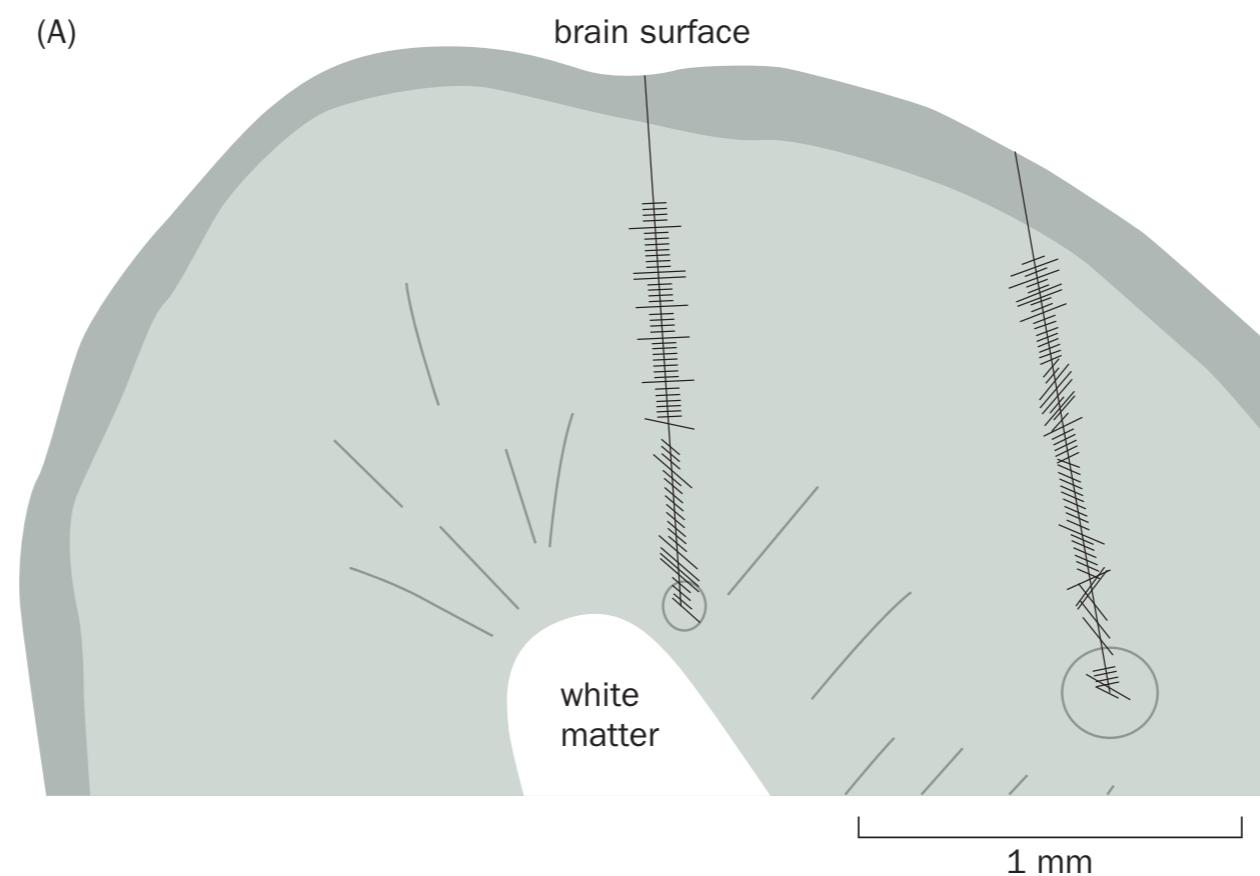
The cortex uses maps to organize information



The cortex uses maps to organize information

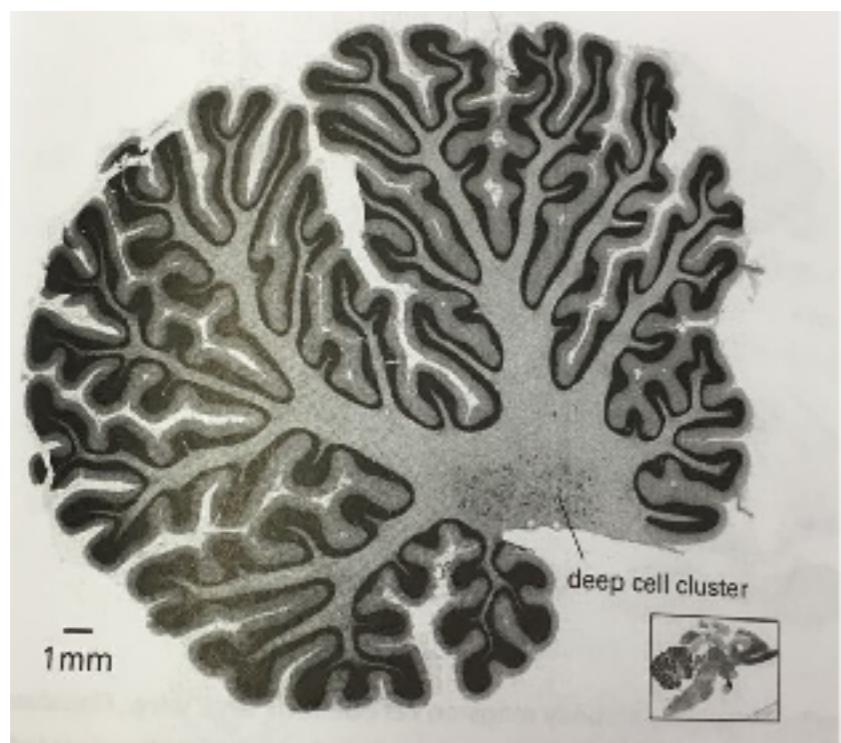


The Cortical Column

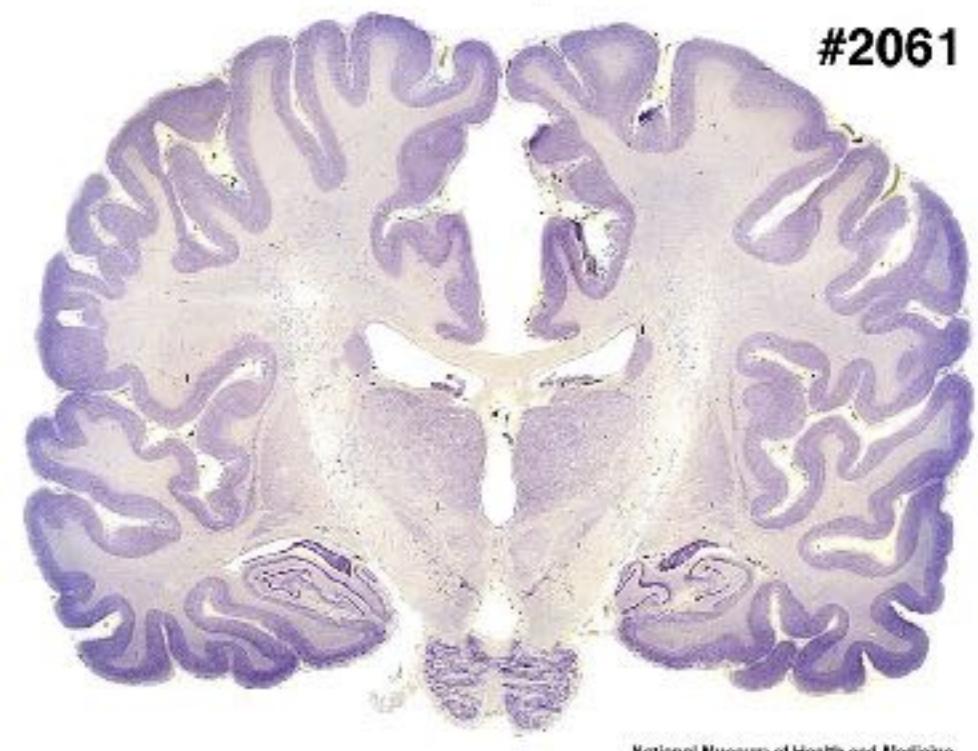


Hubel DH & Wiesel TN (1962) J Physiology 160: 106-154

cerebral cortex vs. cerebellar cortex



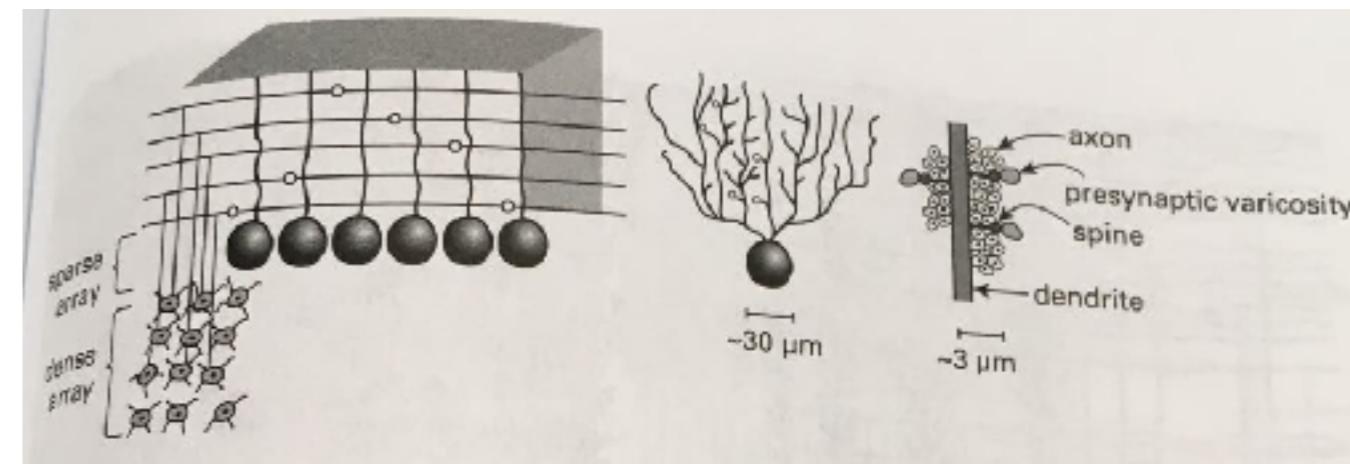
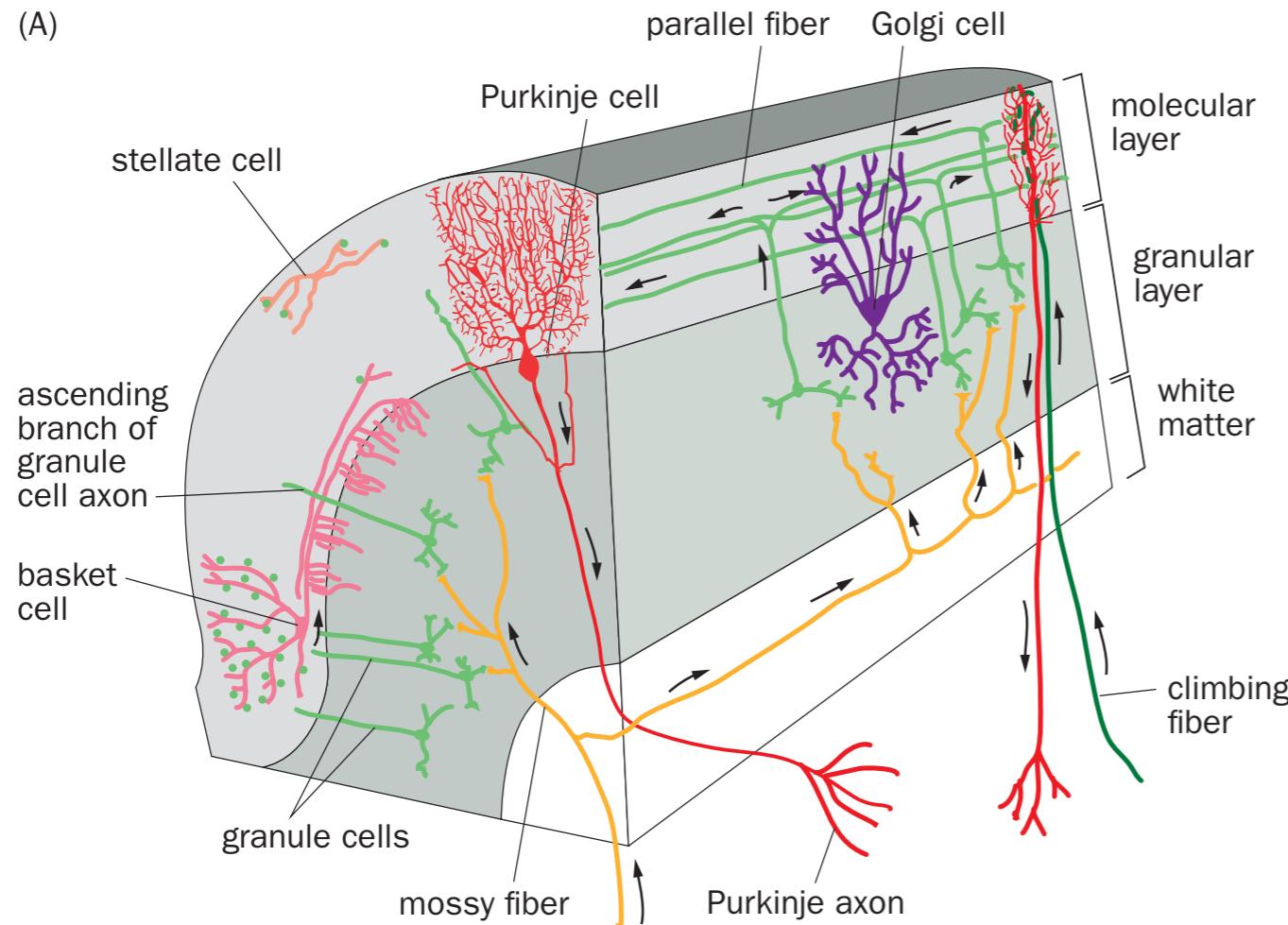
cerebellum



cerebral cortex

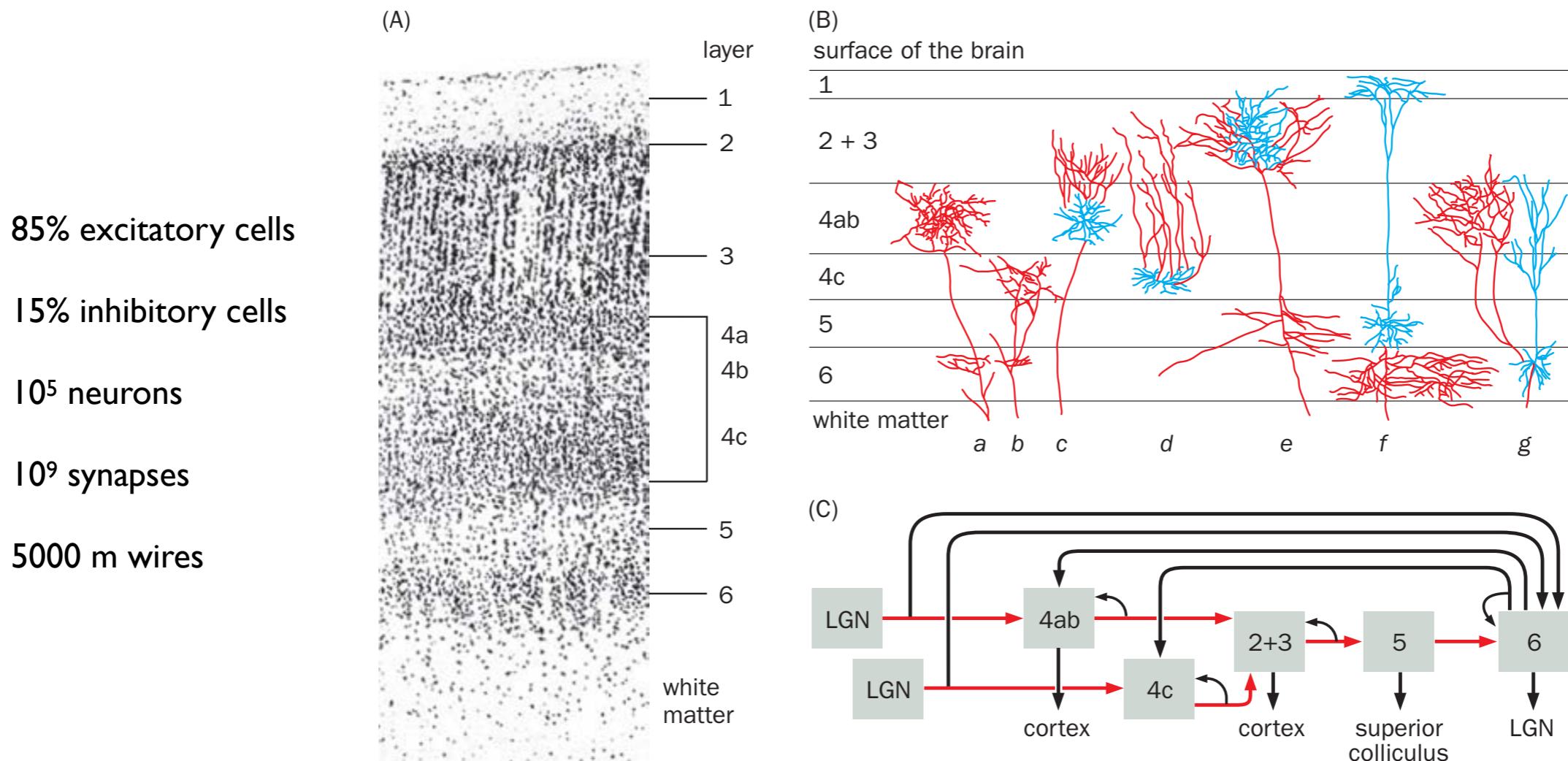
The organization cerebellar cortex

(A)



**Connecting dense array to sparse array with
extreme convergence and divergence**

The organization of the cortical column



Connecting many dense arrays to many other dense arrays with moderate convergence and divergence

Differences between a computer and a brain

- *Brain is analogue; computer is digital*
- *Brain uses content-addressable memory*
- *Brain is a massively parallel machine; computer is modular and serial*
- *Processing speed is not fixed in the brain; there is no central clock*
- *Short-term “working” memory is not like RAM*

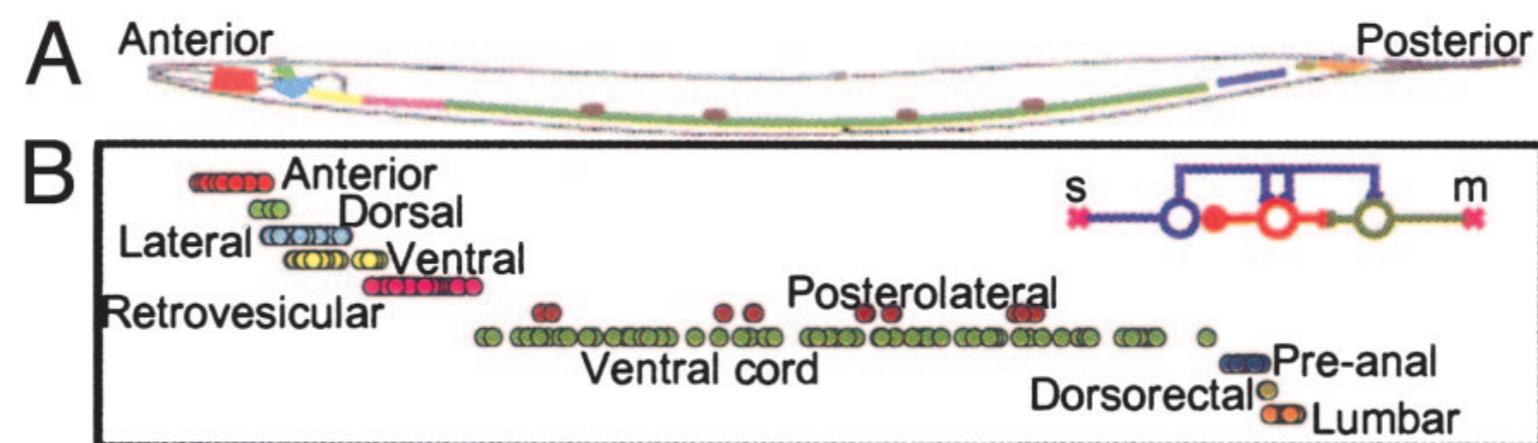
- *Synapses are far more complex than electrical logical gate*
- *Unlike computers, processing and memory are performed by the same components in the brain*
- *The brain is a self-organizing system*
- *Brain has bodies*

Wiring Optimization of Neural Circuit

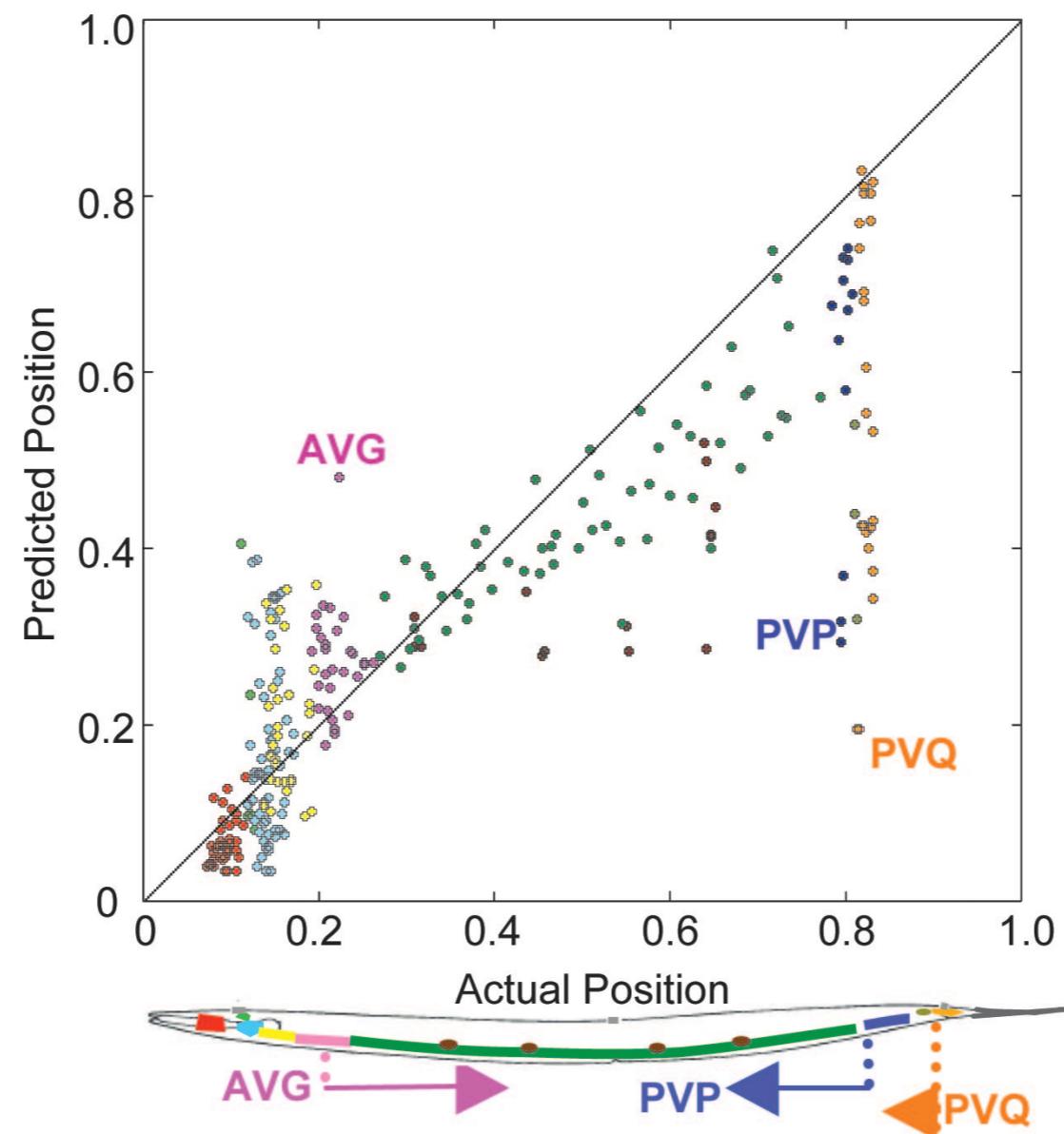
“After the many shapes assumed by neurons, we are now in a position to ask whether this diversity ... has been left to chance and is insignificant, or whether it is tightly regulated and provides an advantage to the organism. ... we realized that all of the various conformations of the neuron and its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

Ramon y Cajal

Neuronal layout in *C. elegans*

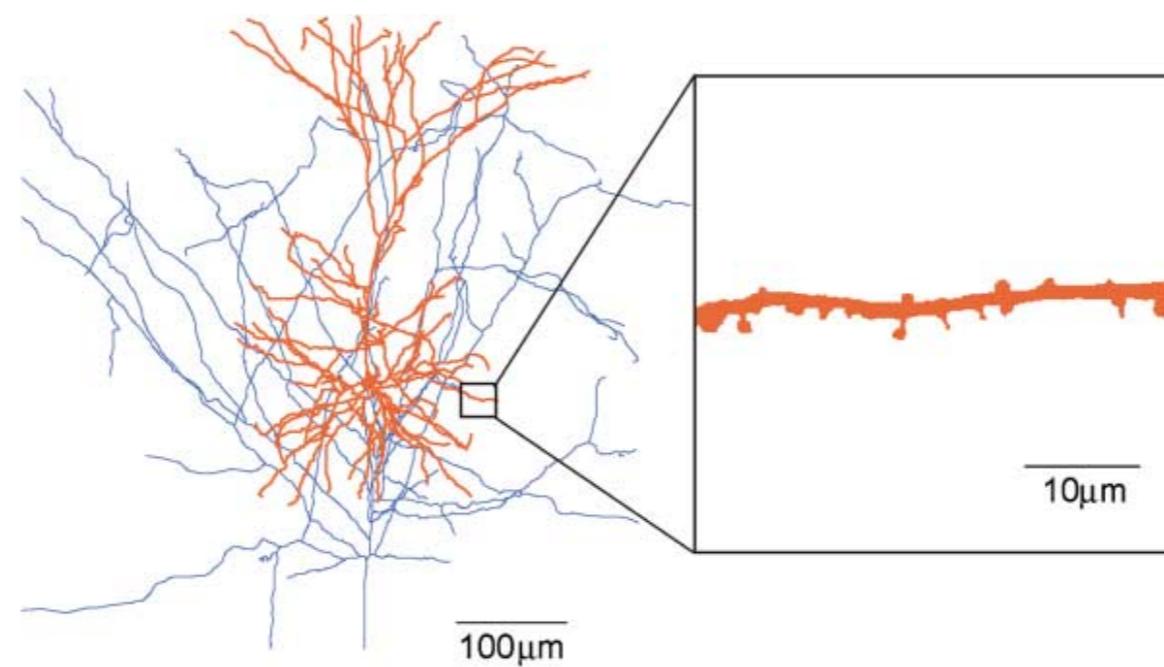


Neuronal layout in *C. elegans*

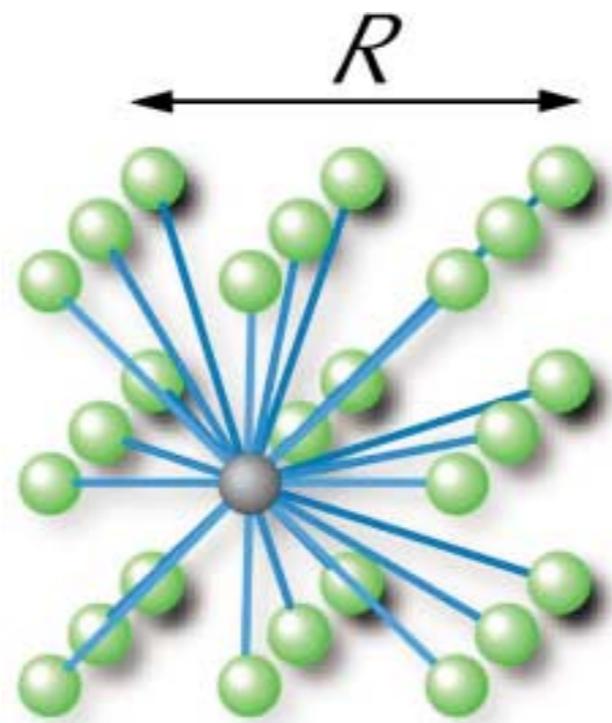


Beth Chen et. al., PNAS 2006

A toy problem: why do we need axons and dendrites?

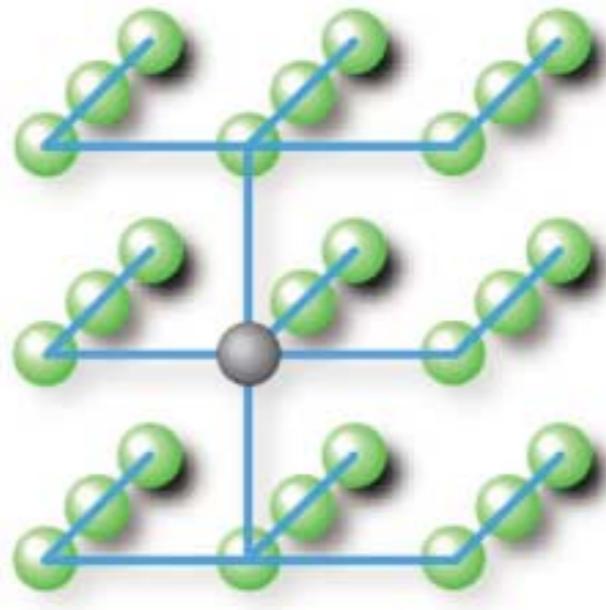


A toy problem: why do we need axons and dendrites?



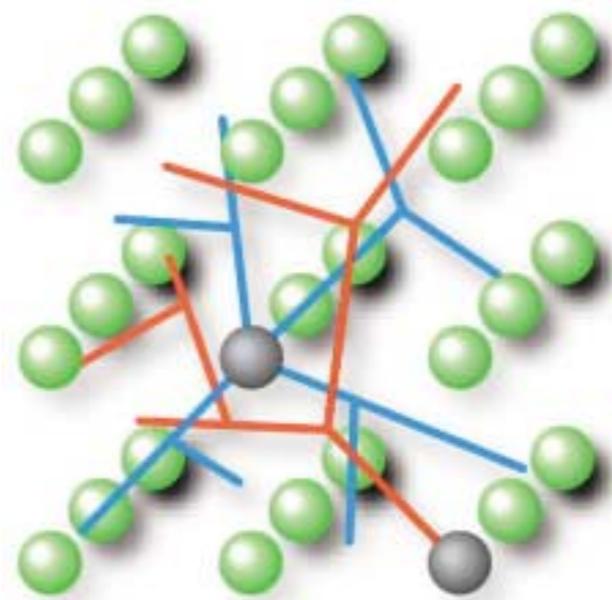
Design I

A toy problem: why do we need axons and dendrites?



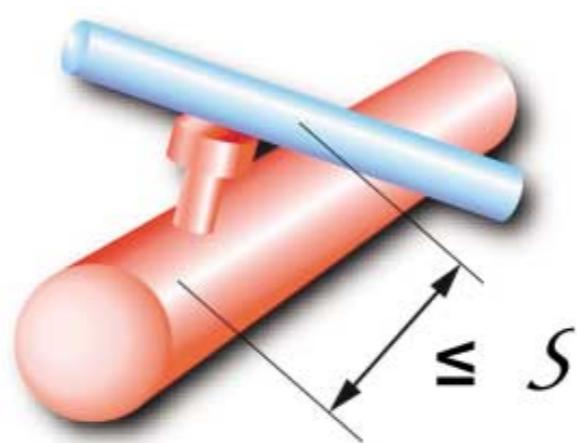
Design II

A toy problem: why do we need axons and dendrites?



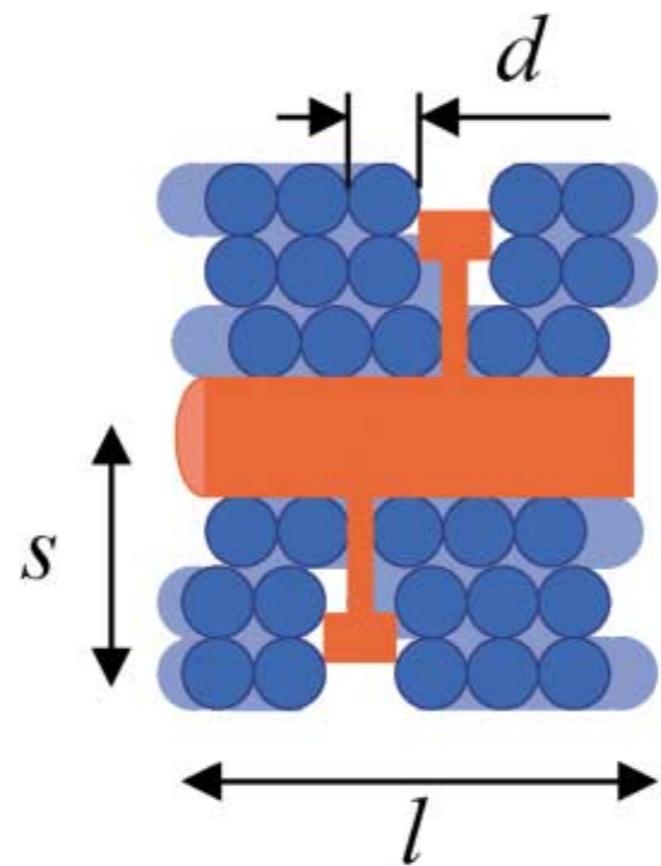
Design III

A toy problem: why do we need axons and dendrites?



Design IV

A toy problem: why do we need axons and dendrites?



The Optimality of the design