The Basic Organization of the Brain

summary.

SUMMARY

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

$$P = \text{probability},$$
$$\phi = \text{probability amplitude},$$
$$P = |\phi|^2.$$

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

$$\phi = \phi_1 + \phi_2,$$
$$P = |\phi_1 + \phi_2|^2.$$

(3) If an experiment is performed which is capable of determining whether one or 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 "explain" 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.

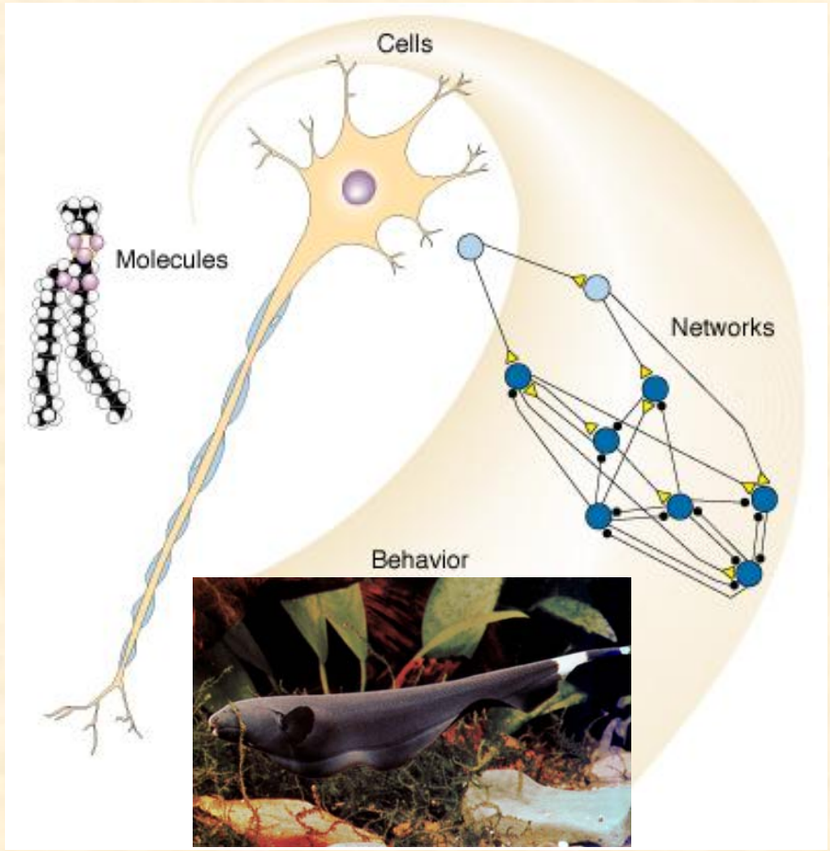
First Principle of Quantum Mechanics

The Feymann Lectures on Physics Volume III page 10

?

First Principle of Neurobiology

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.

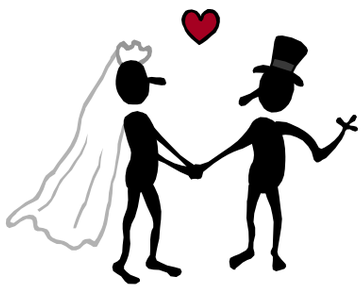
Hemingway: Yes, they have **more** money.

a conversation somewhere in Paris in 1920s

Practical Rules

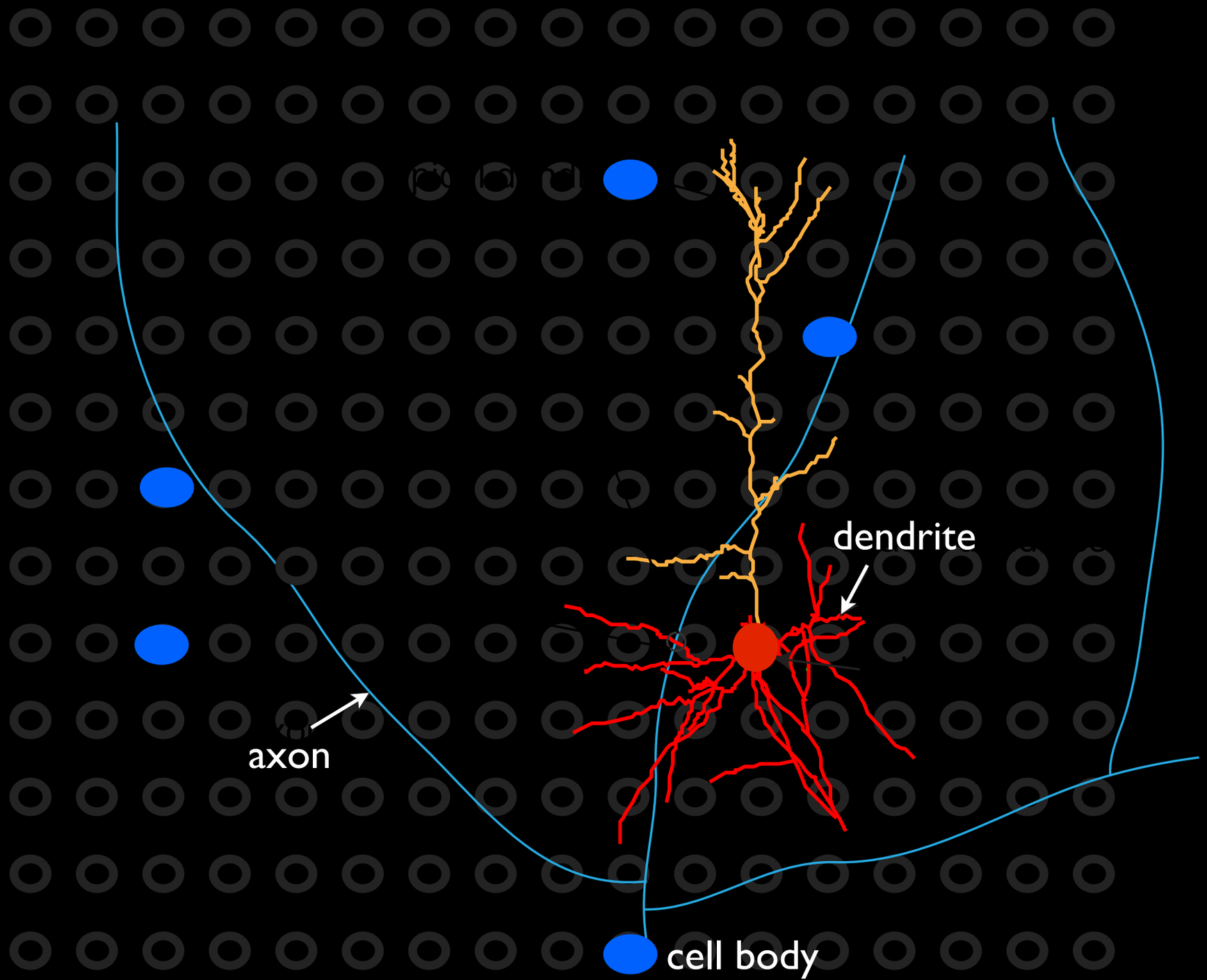
Identify levels of
organization in the brain

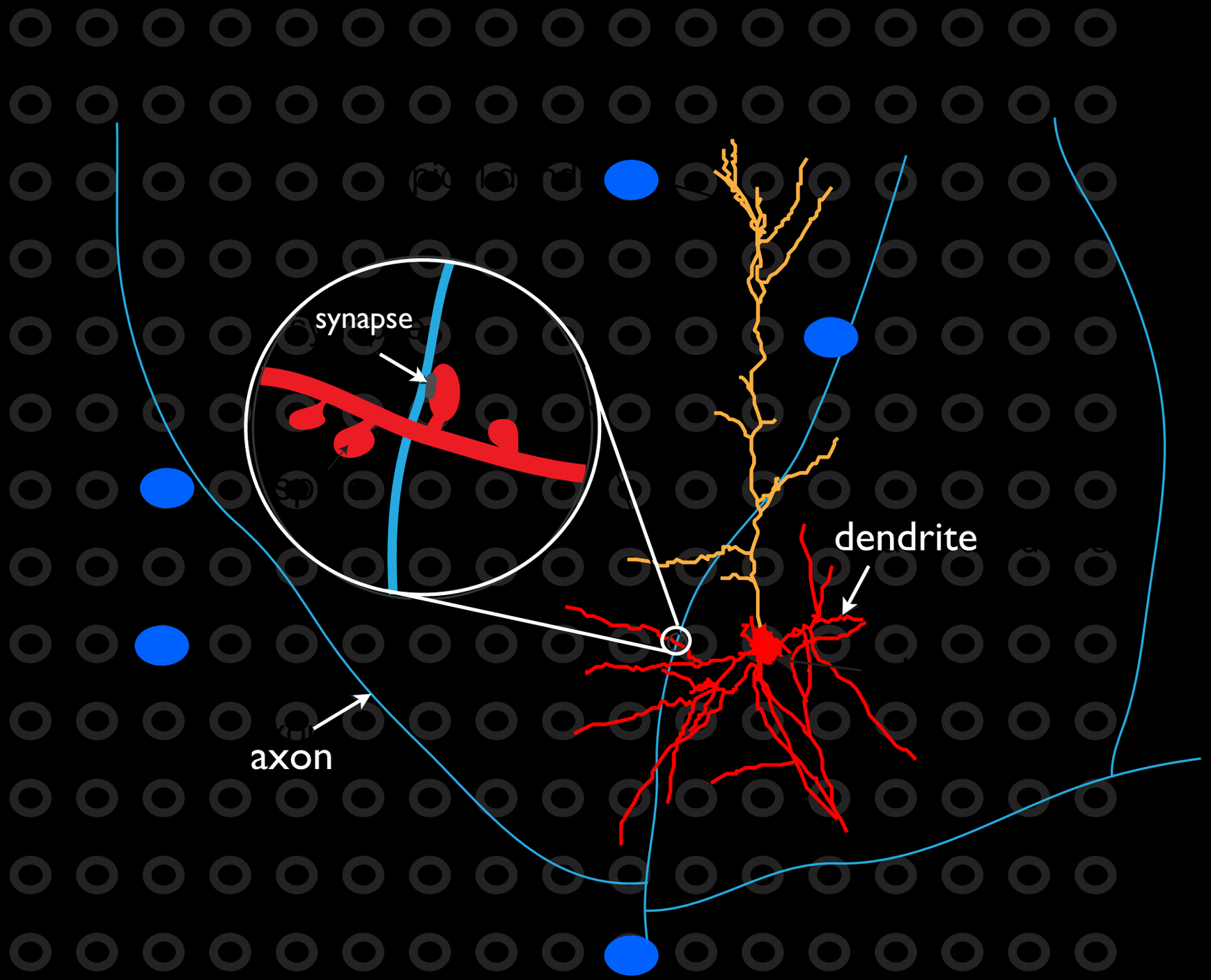
Accept different levels of
description for the different scales
“with natural piety”



Interact closely with experiment

Neuron Doctrine


dendrite
axon
cell body

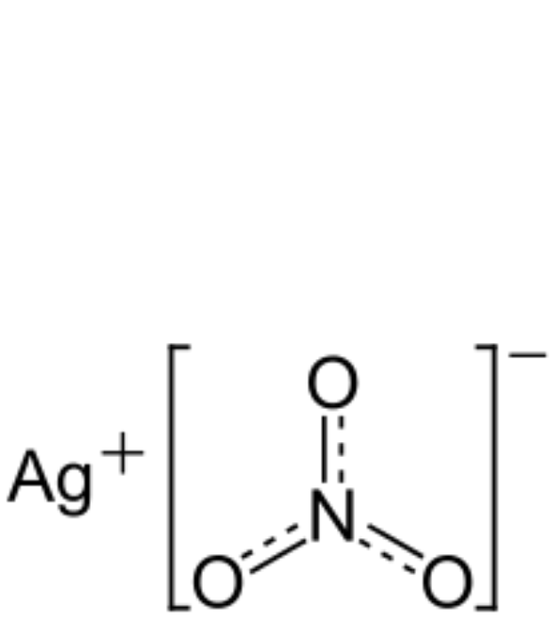

synapse
dendrite
axon

The Debate between Cajal and Golgi

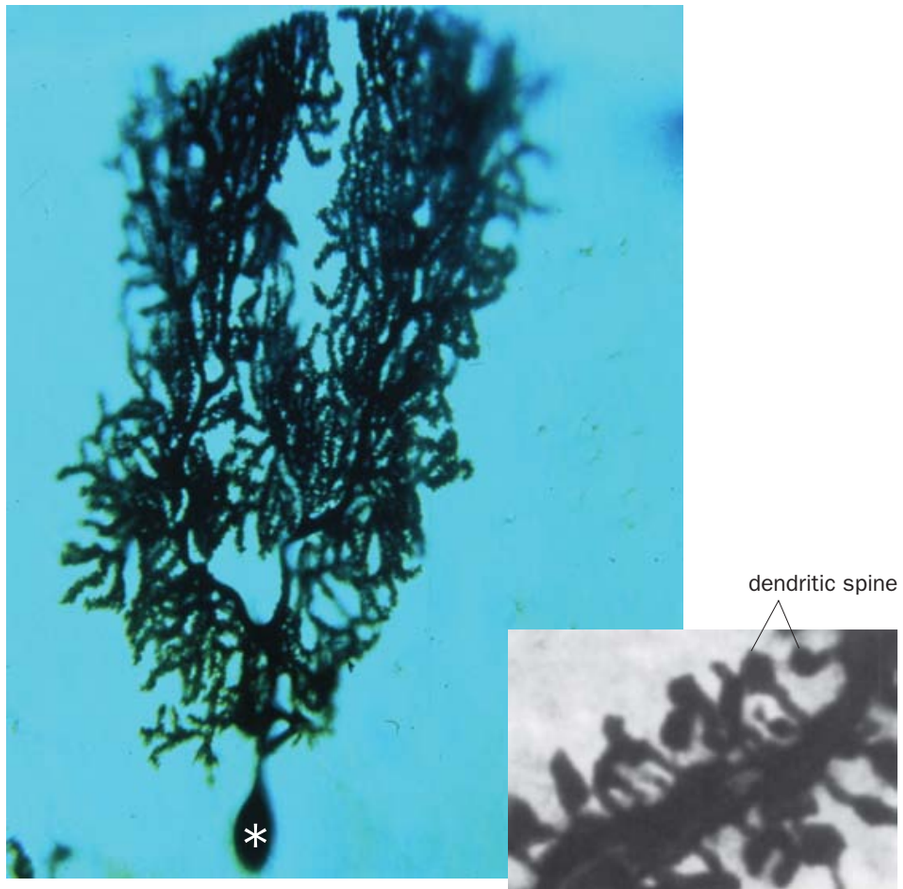
Ramon y Cajal

Camillo Golgi

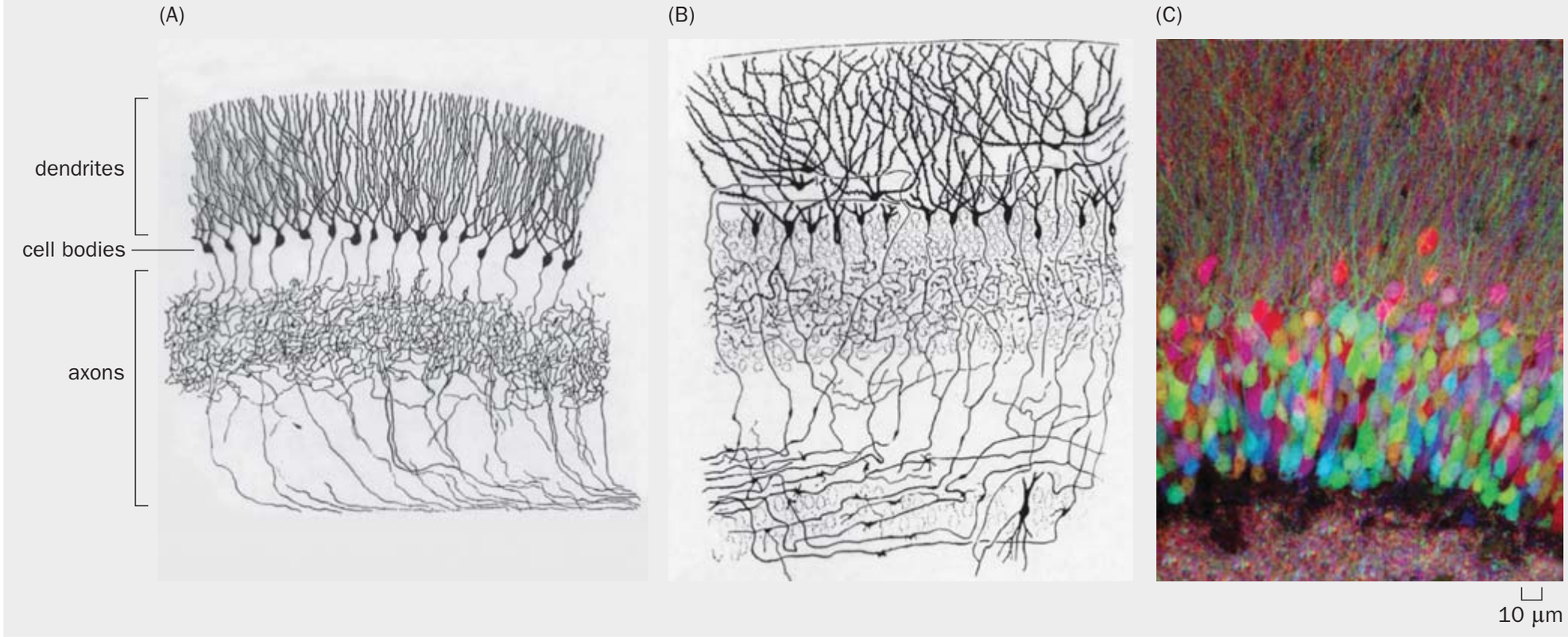
Golgi Staining method



Silver nitrate

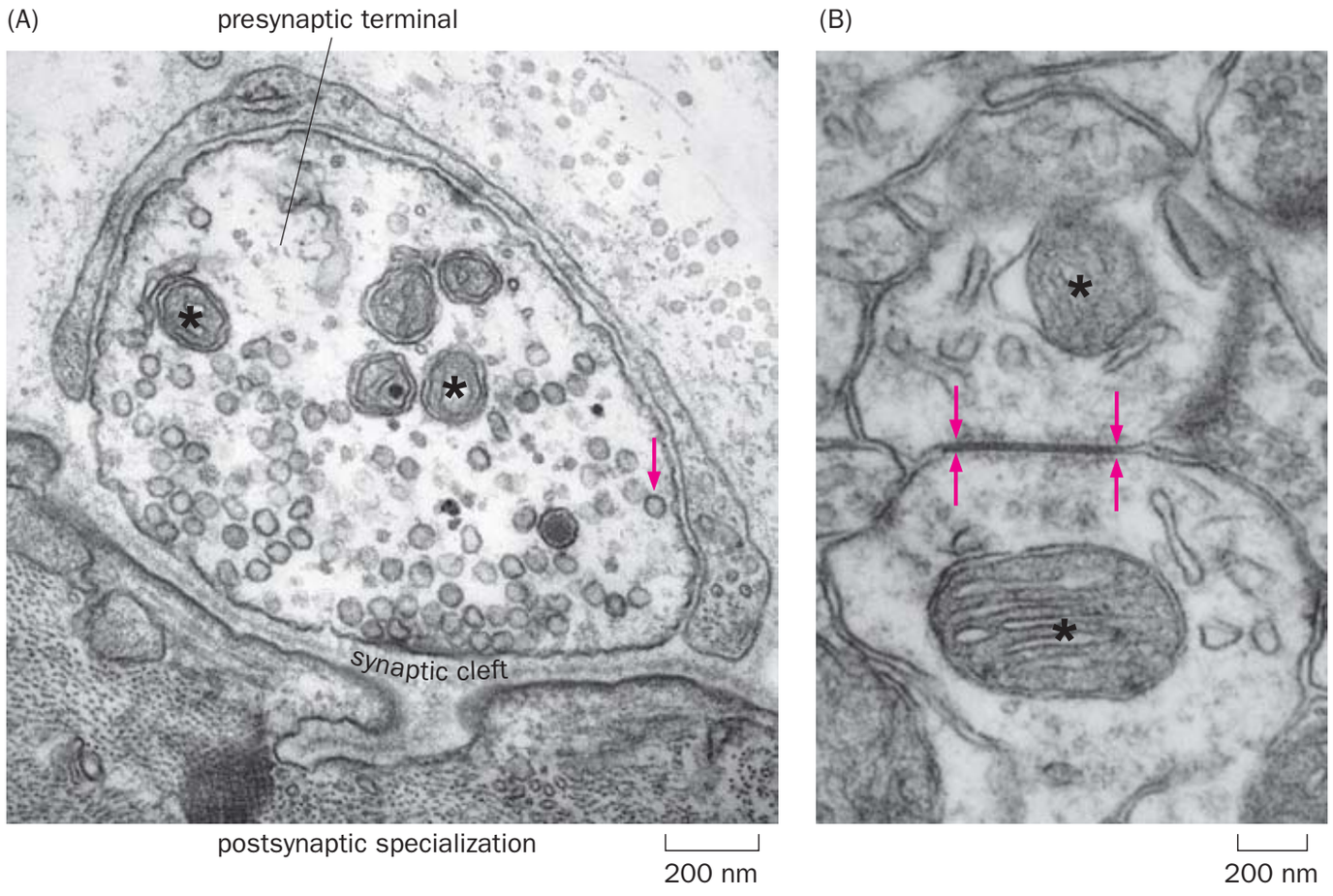


Reticular Theory vs Neuron Doctrine



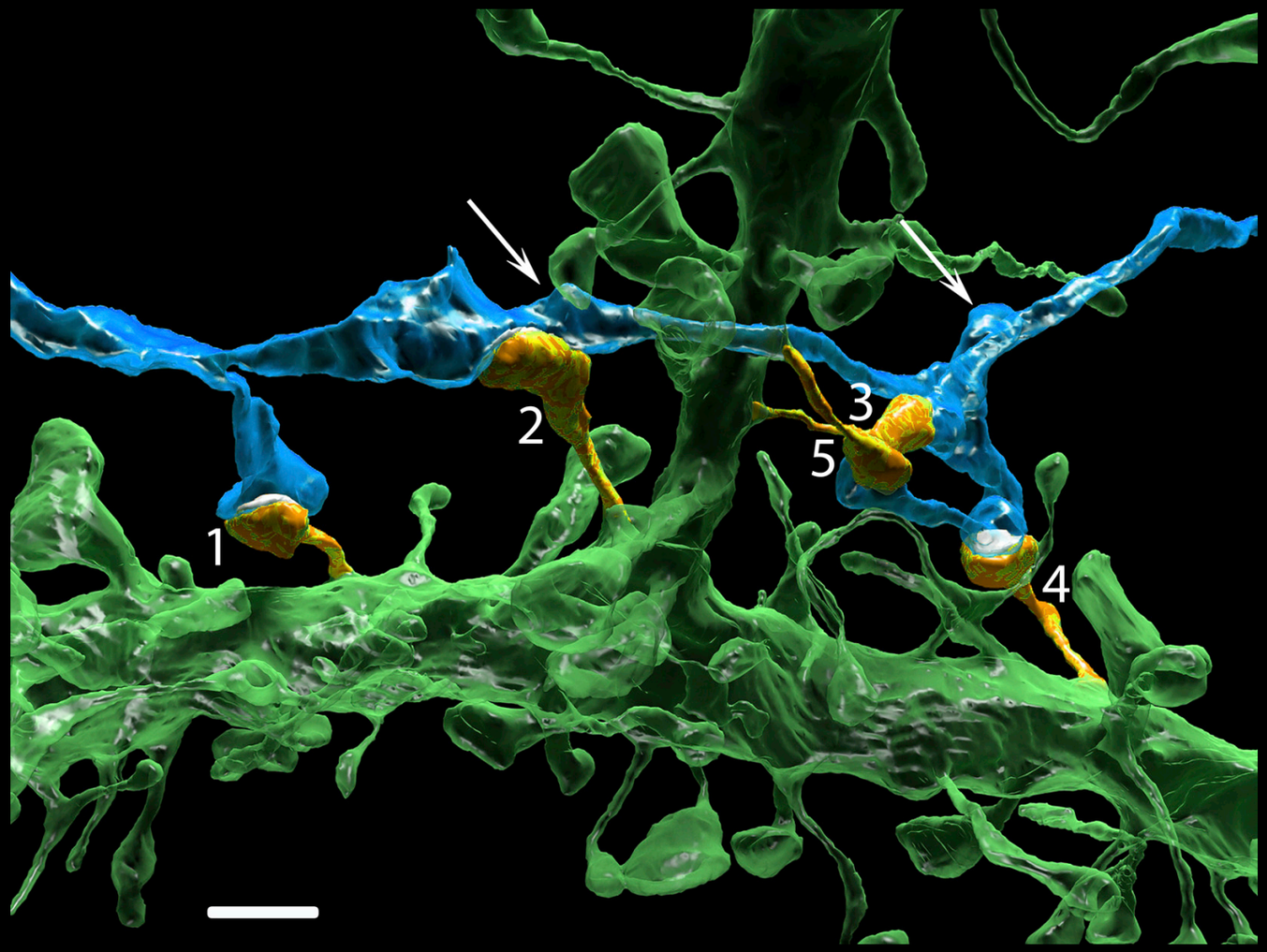
Synapse

How neurons communicate with each other?

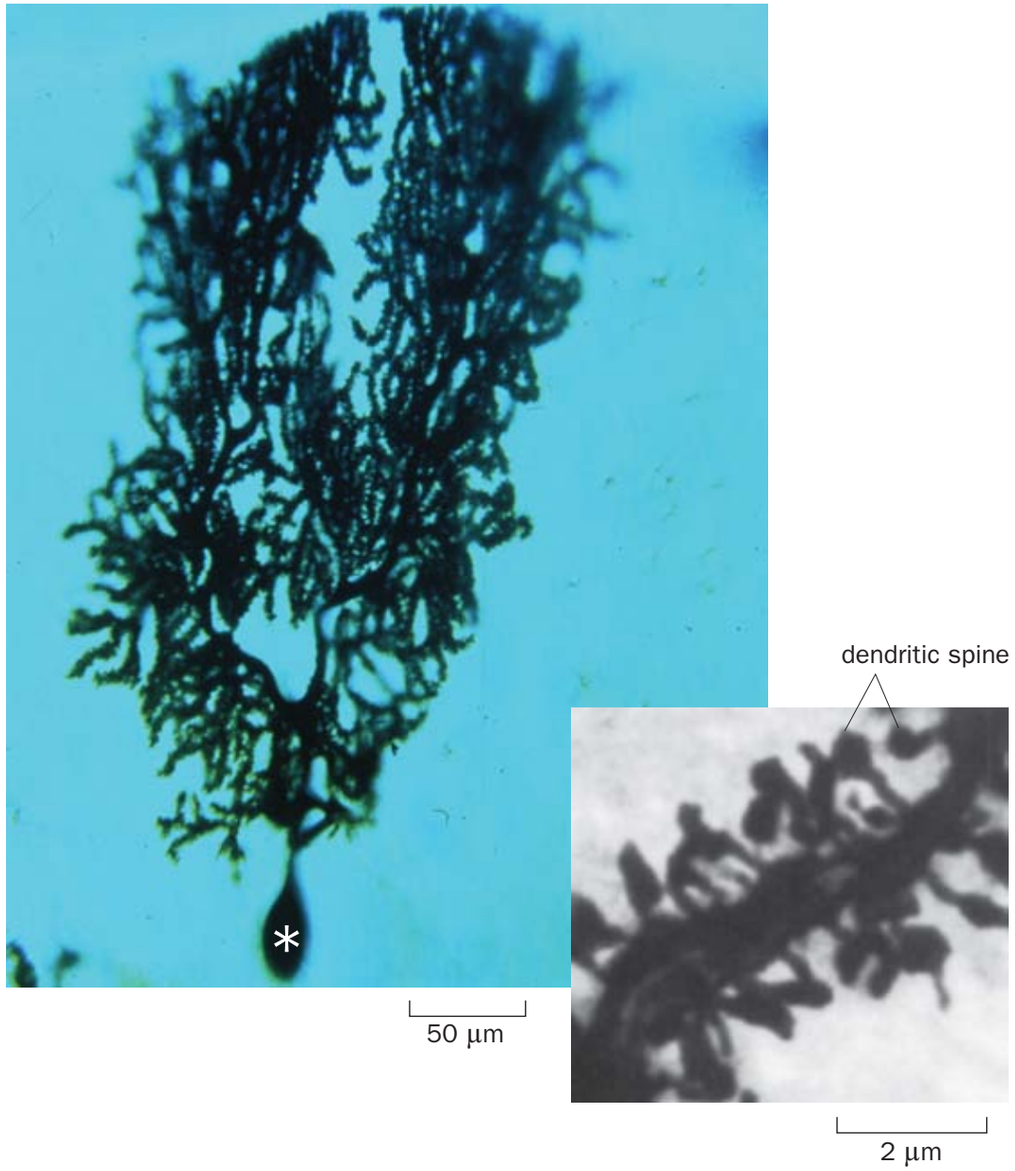


Chemical and electrical synapses

Synaptic Connectivity

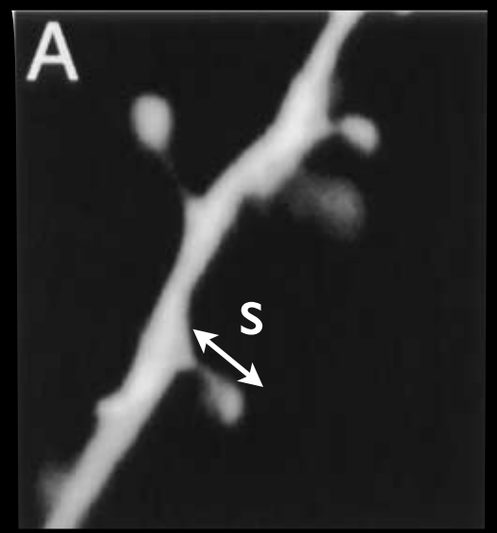


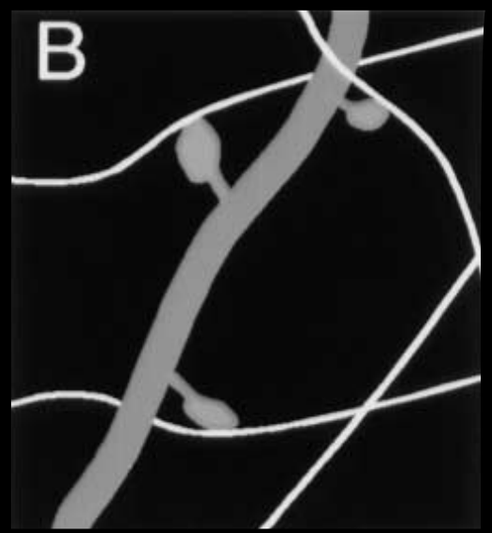
Kasthuri et. al, Cell 2015



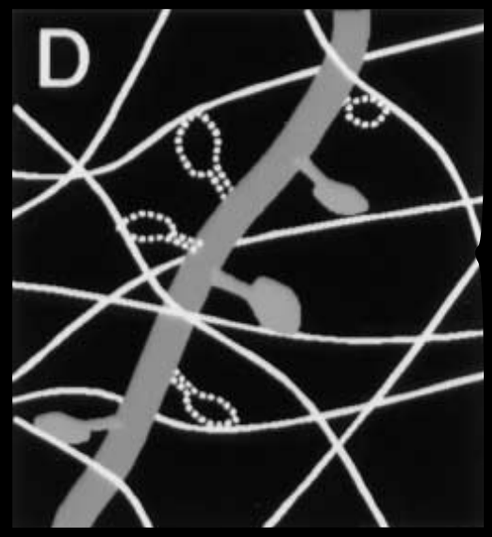
Purkinjie cell in the cerebellum has the highest spine density in the brain

Structural Plasticity of Synaptic Connectivity





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

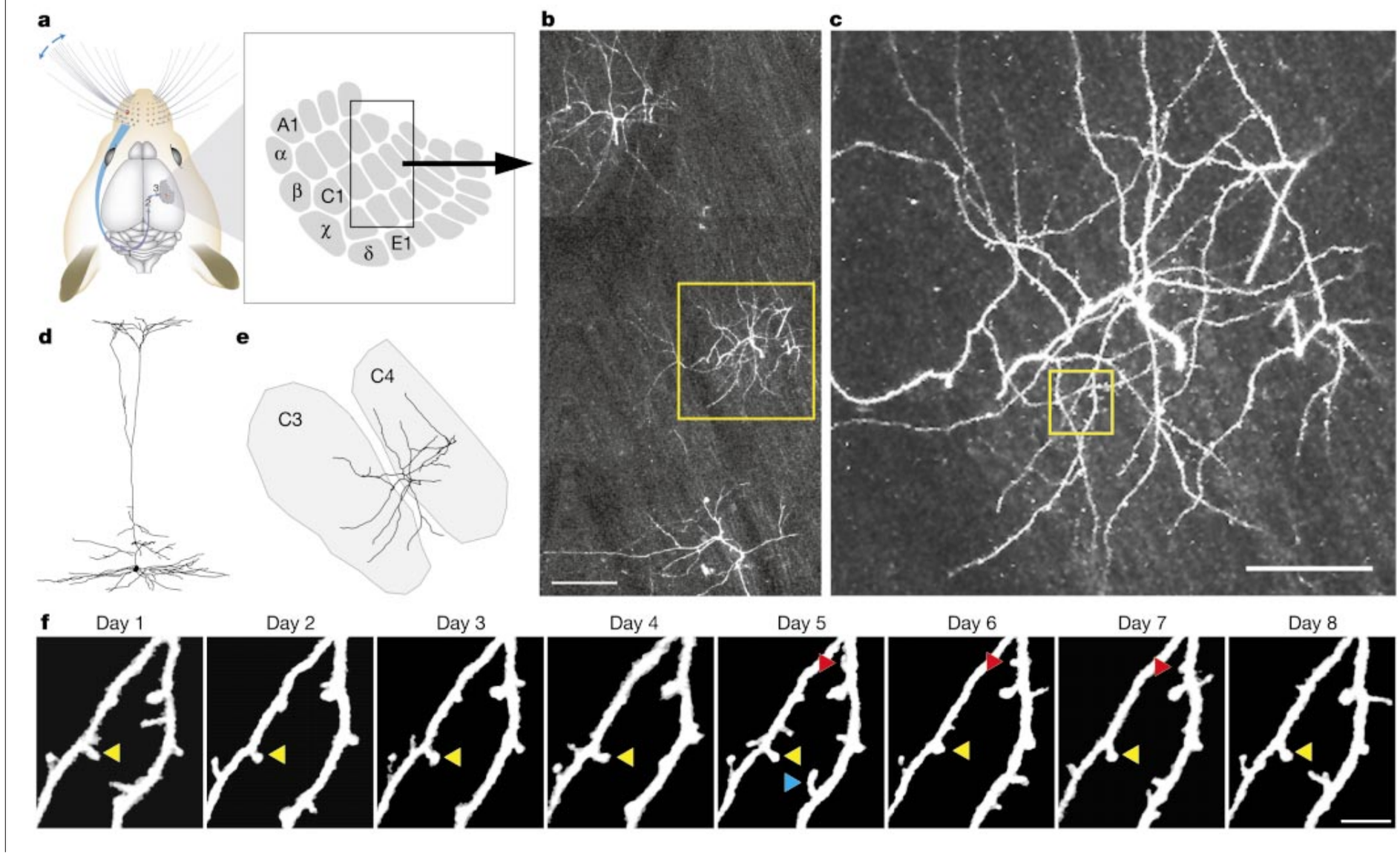


filling fraction = 3/7

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

Stepanyants et. al., *Neuron* 2001

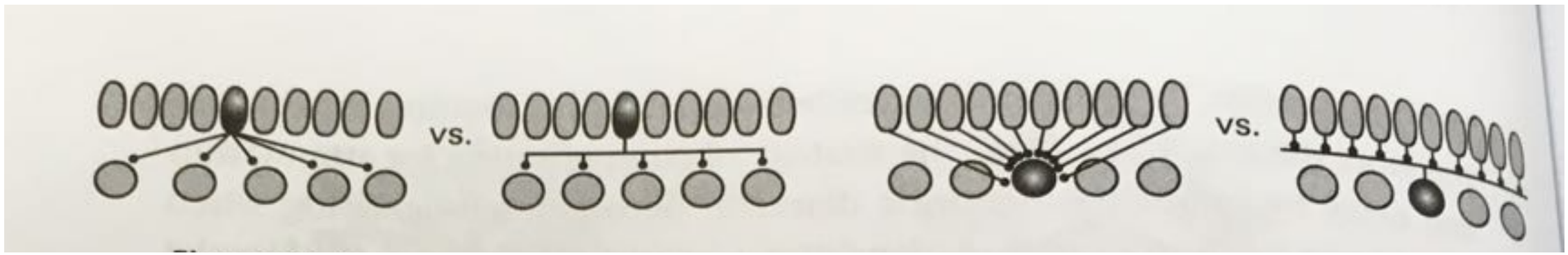
Structural Plasticity of Synaptic Connectivity



Trachtenberg et., al. *Nature* 2002

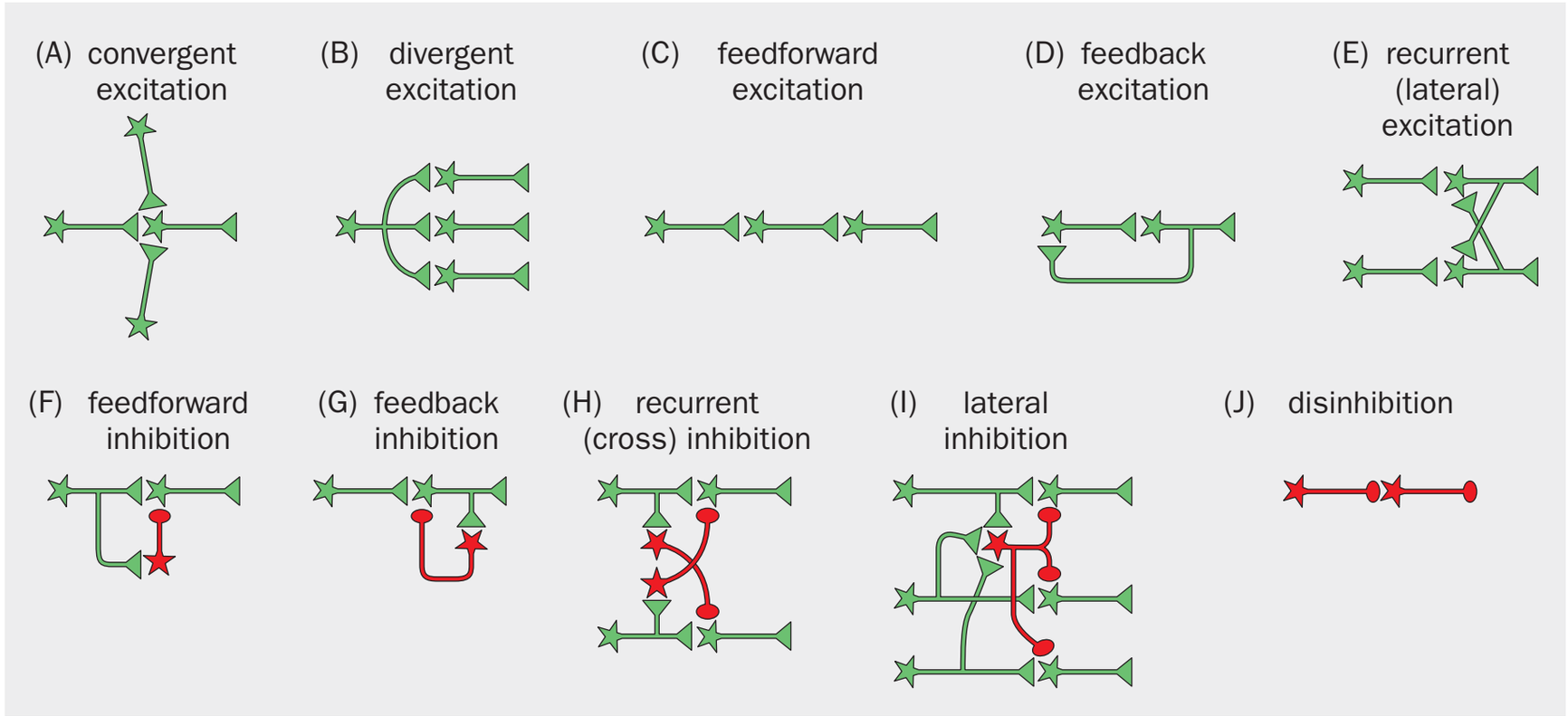
Circuit motif

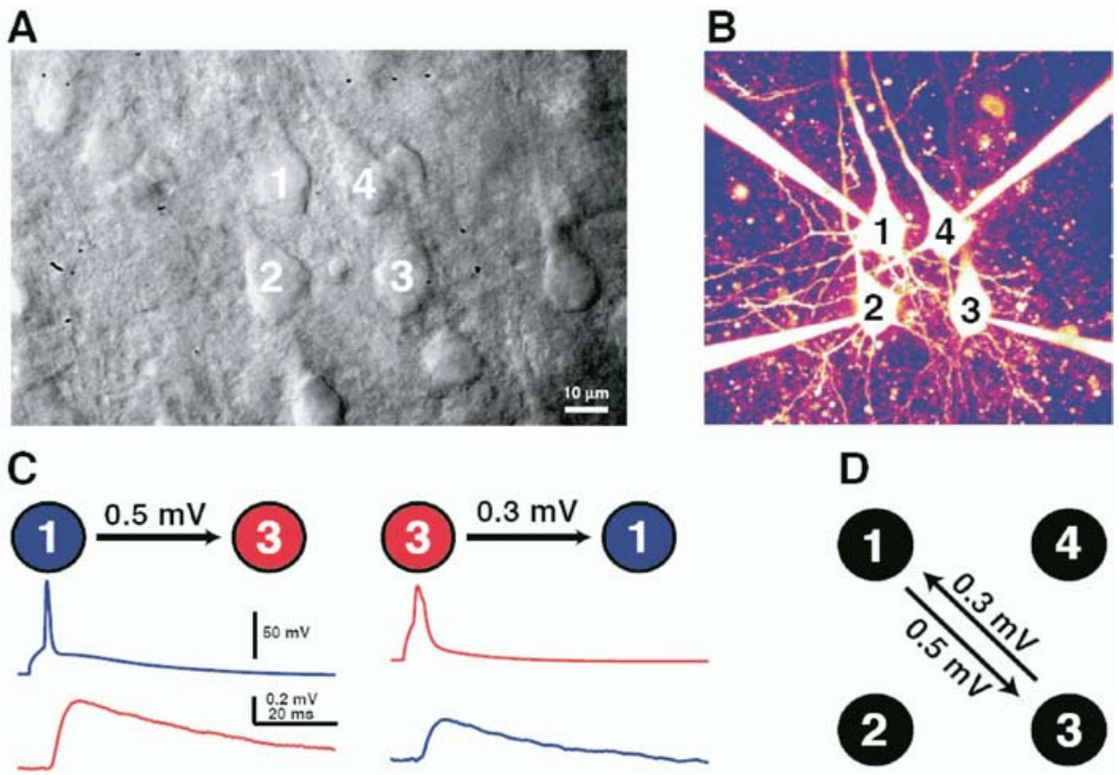
Convergence and divergence



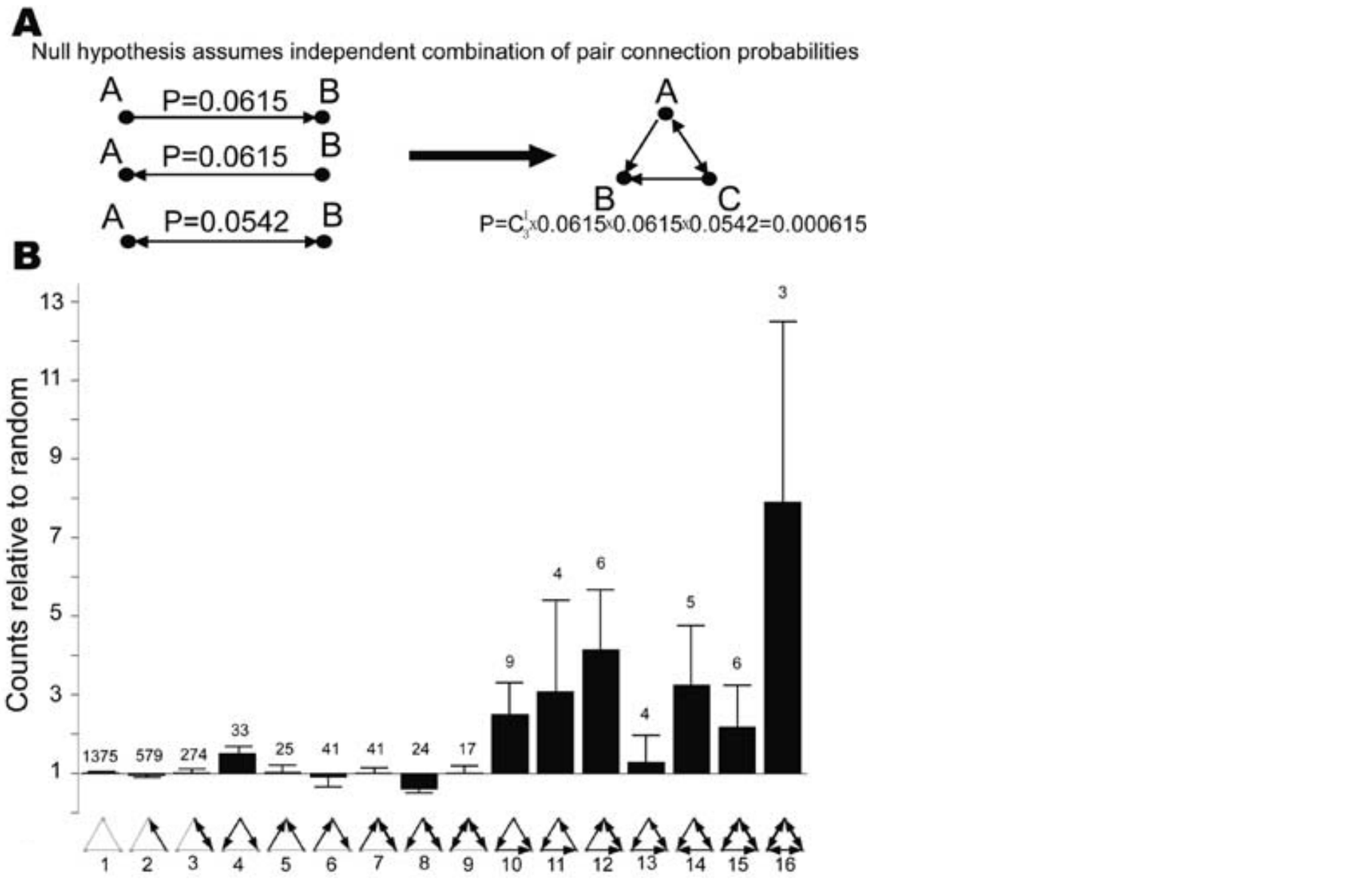
Why do we have branching axons and dendrites?

Motifs


(A) convergent excitation
(B) divergent excitation
(C) feedforward excitation
(D) feedback excitation
(E) recurrent (lateral) excitation
(F) feedforward inhibition
(G) feedback inhibition
(H) recurrent (cross) inhibition
(I) lateral inhibition
(J) disinhibition

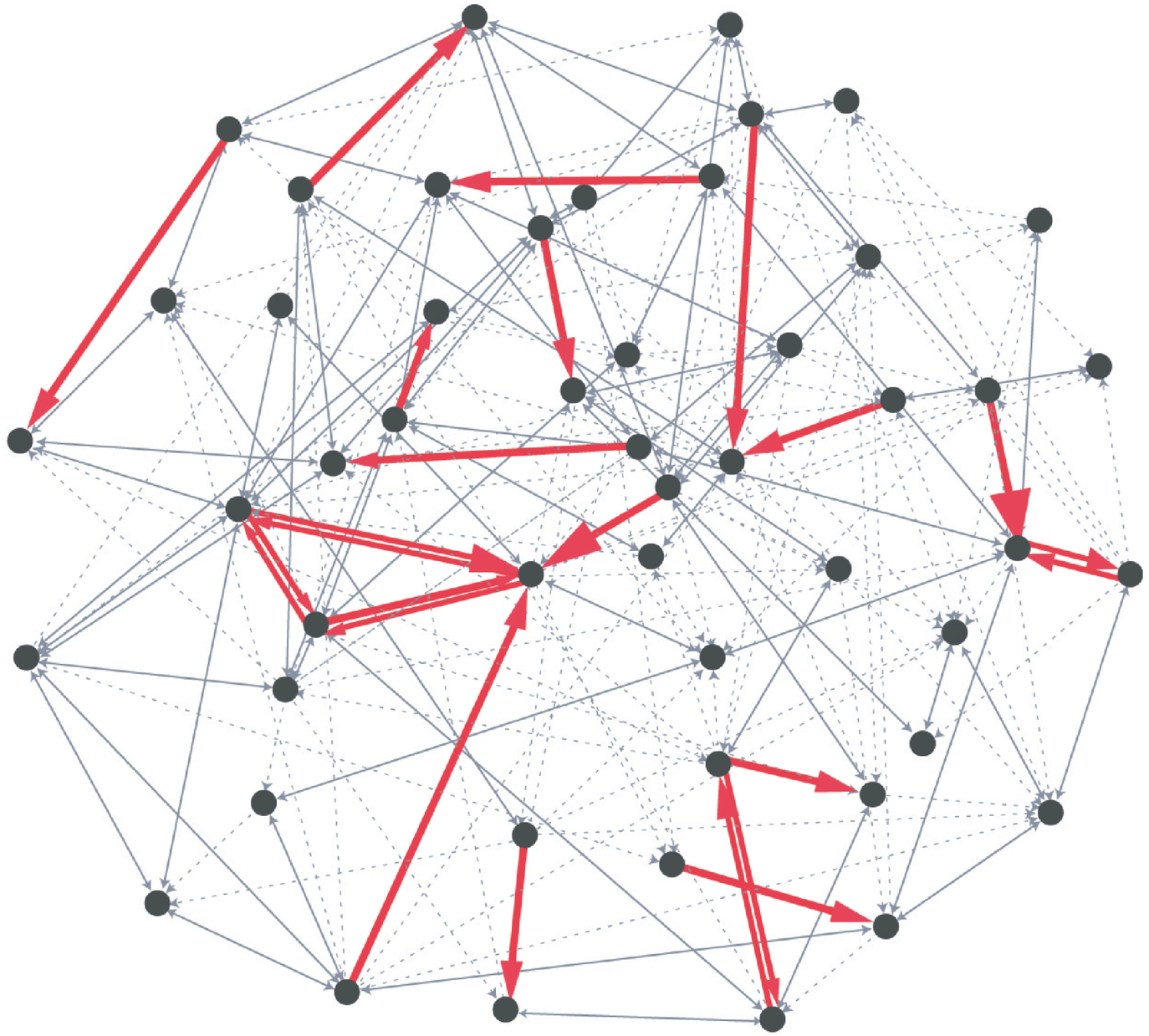

A
1
4
2
3
10 µm
B
1
4
2
3
C
1
0.5 mV
3
50 mV
0.2 mV
20 ms
3
0.3 mV
1
D
1
4
0.3 mV
0.5 mV
2
3

Some circuit motifs are over-represented in the brain



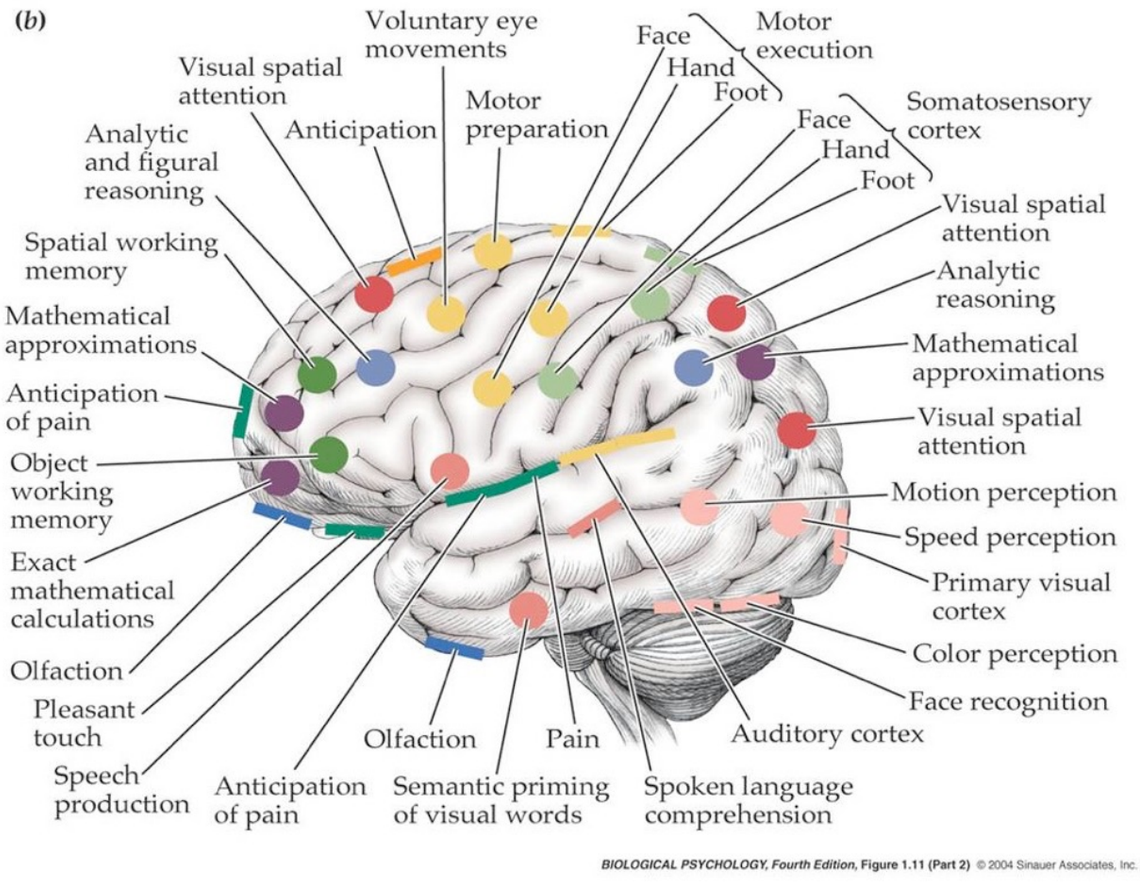
Song S, et.al, PloS Biology 2005

A skeleton of strong connections are immersed in the sea of weaker ones

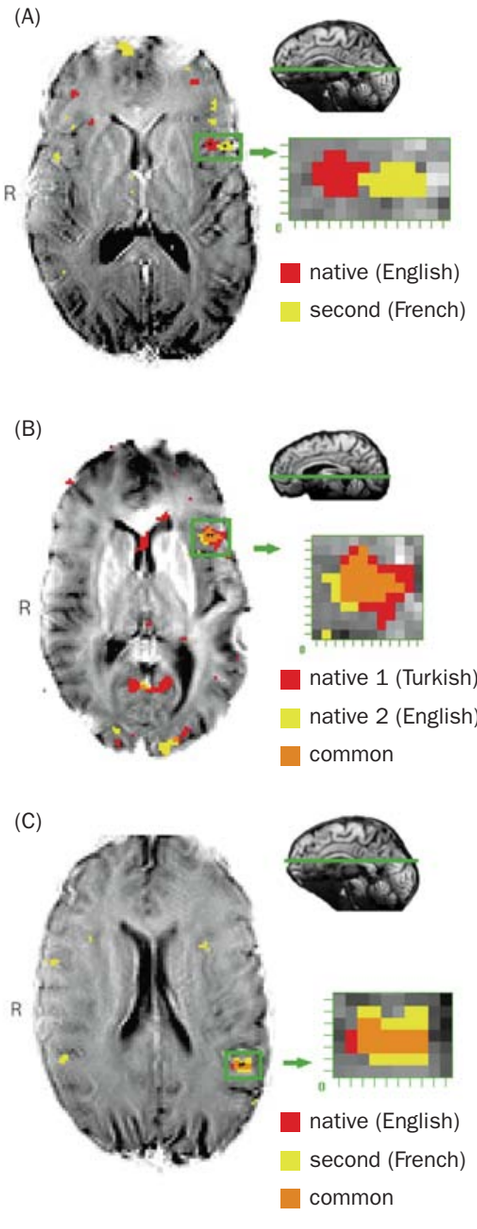


Cortical map and column

Specific brain regions (columns) perform specialized brain functions

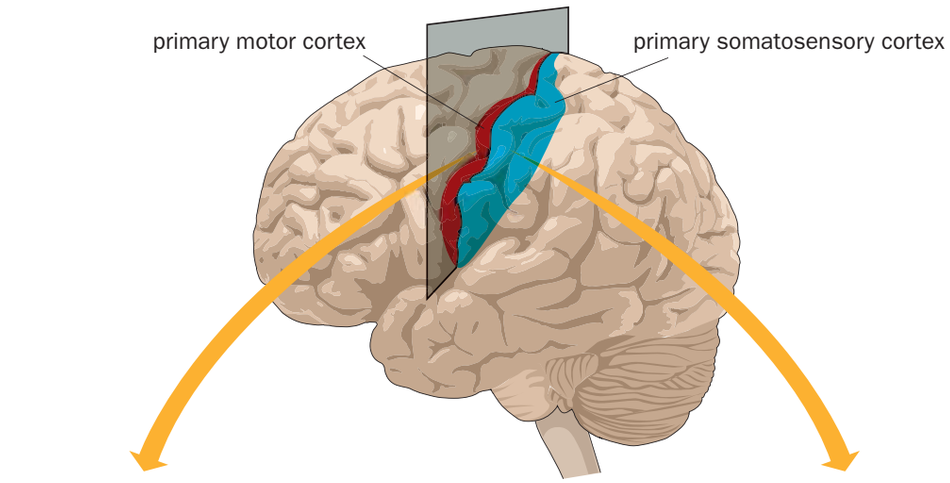


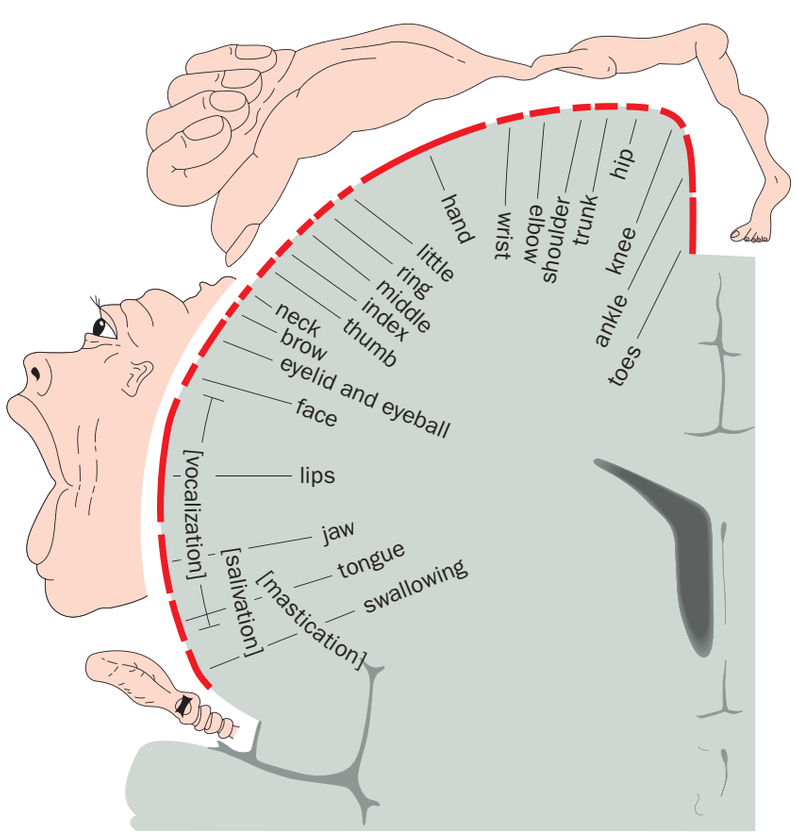
BIOLOGICAL PSYCHOLOGY, Fourth Edition, Figure 1.11 (Part 2) © 2004 Sinauer Associates, Inc.

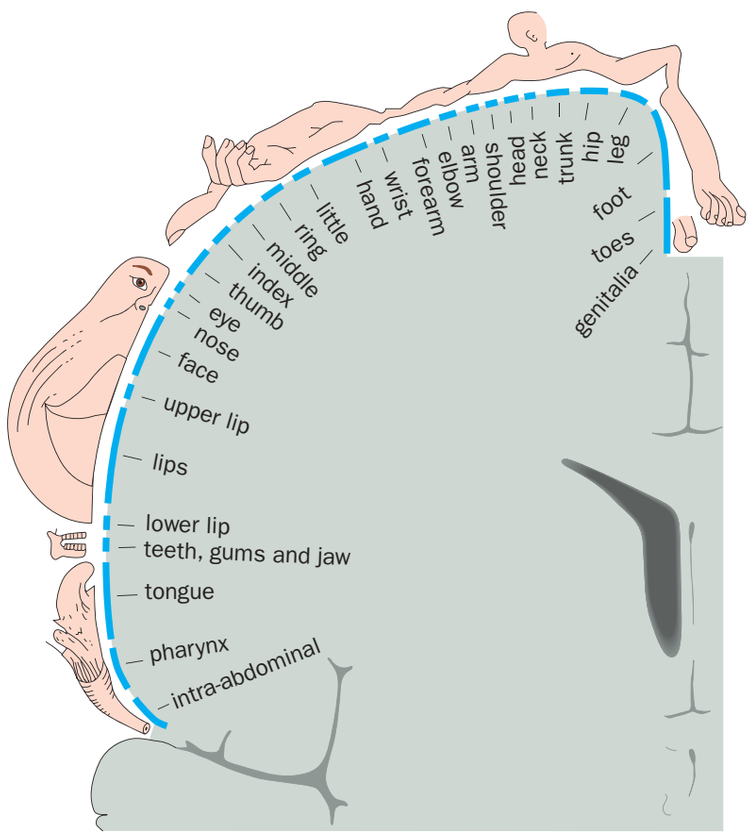


fMRI (functional magnetic resonance imaging)

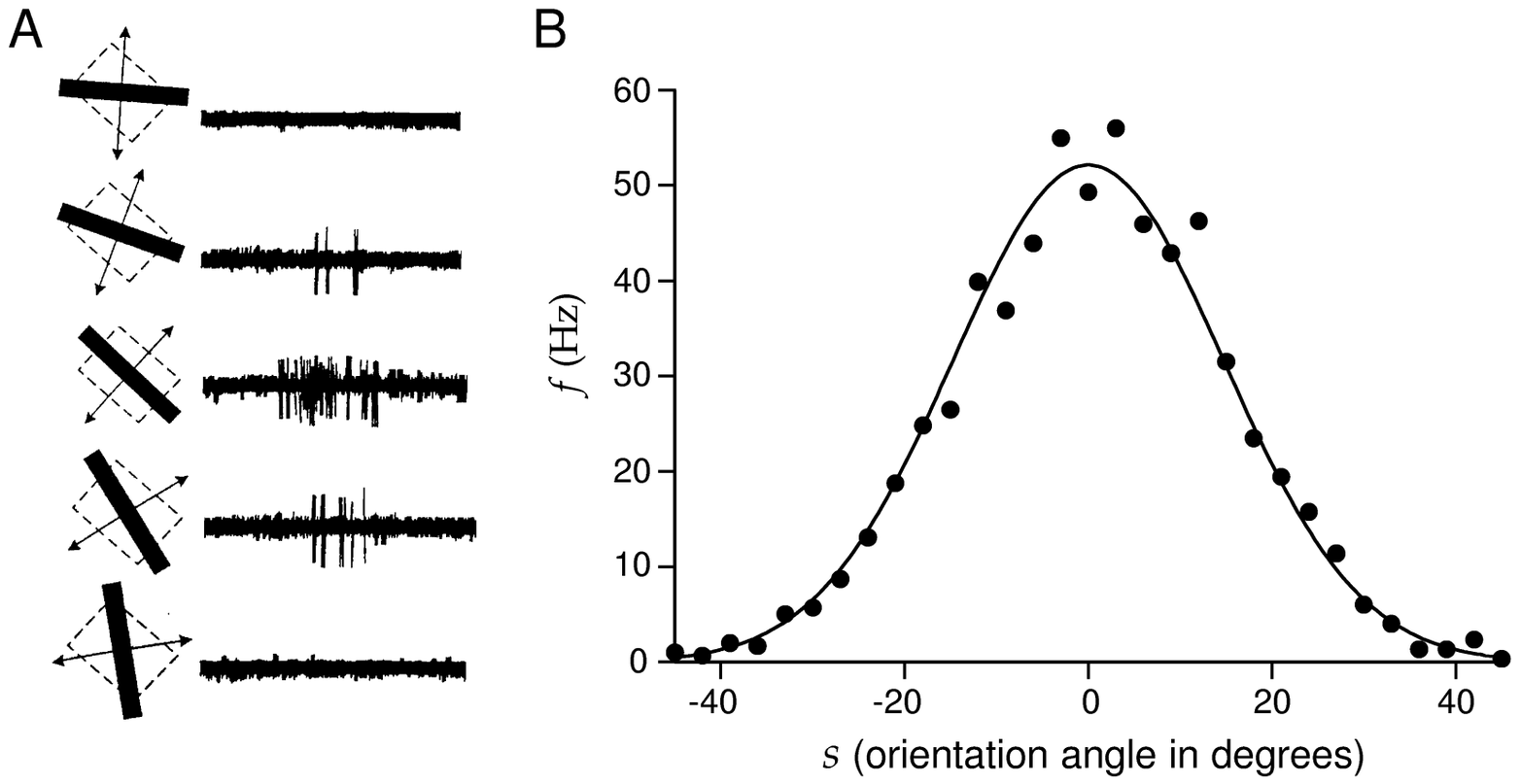
The cortex uses maps to organize information



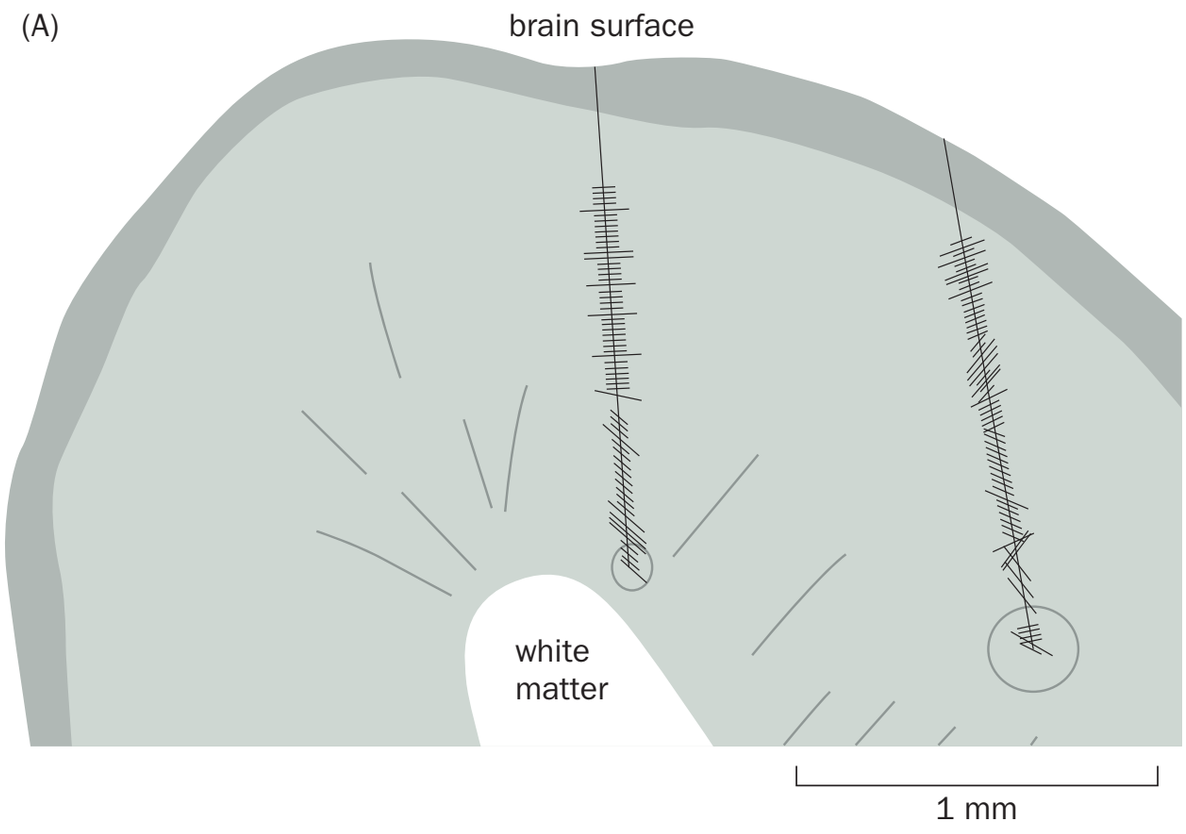




The cortex uses maps to organize information

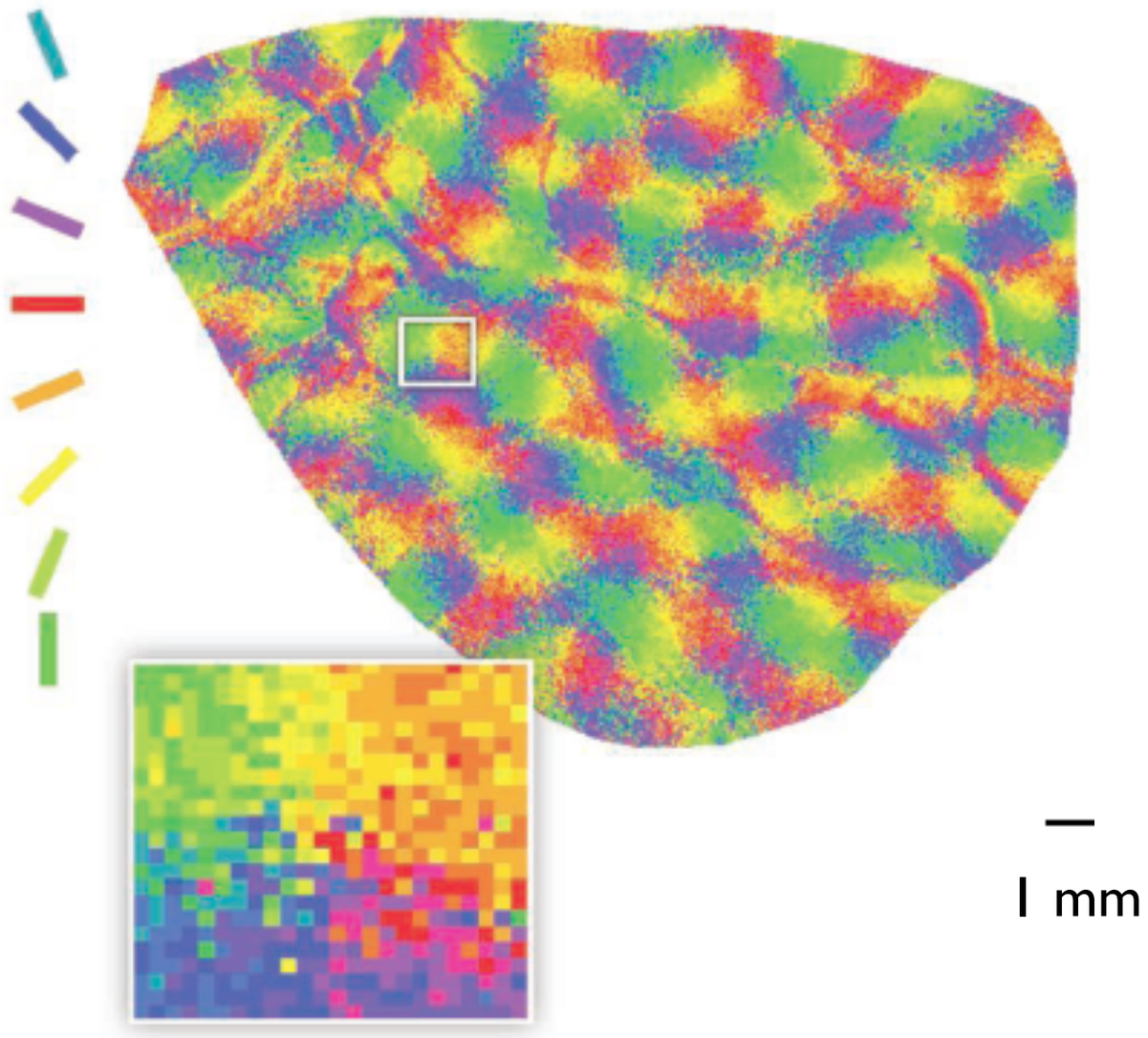


The Cortical Column

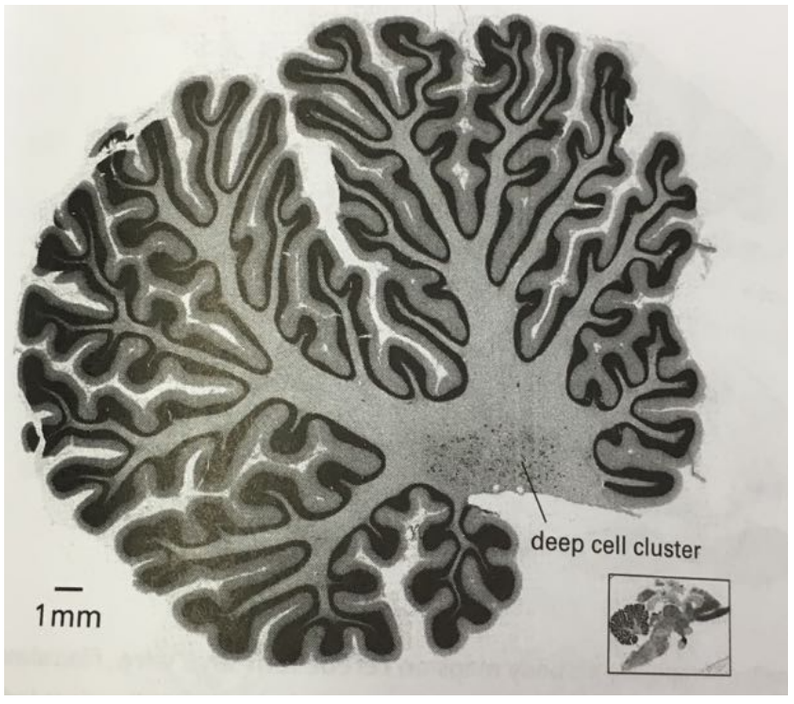


Hubel DH & Wiesel TN (1962) J Physiology 160: 106-154

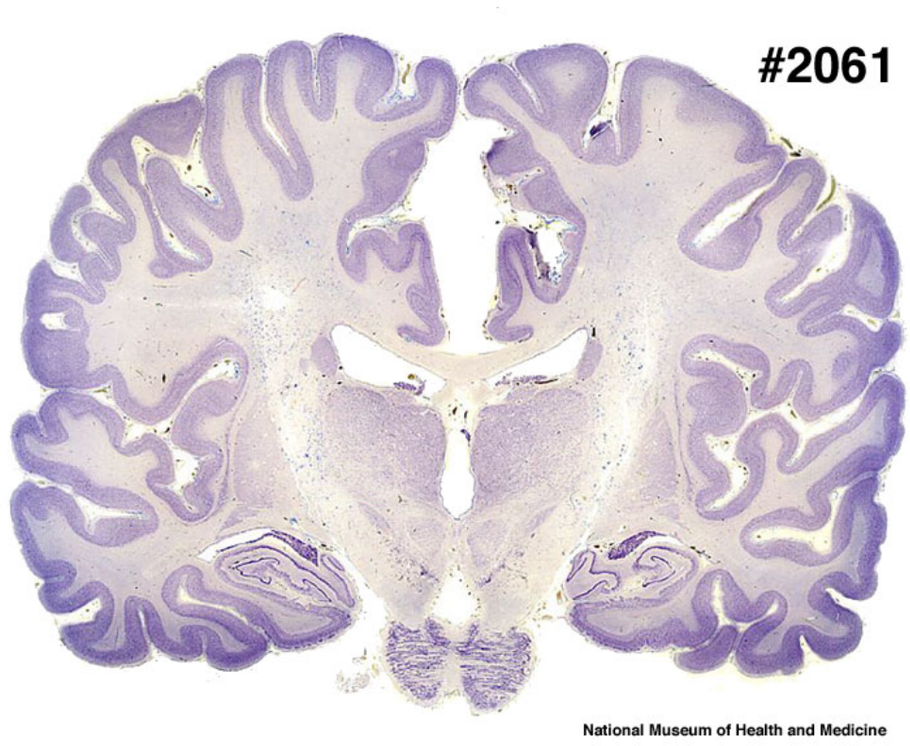
The cortex uses maps to organize information



cerebral cortex vs. cerebellar cortex

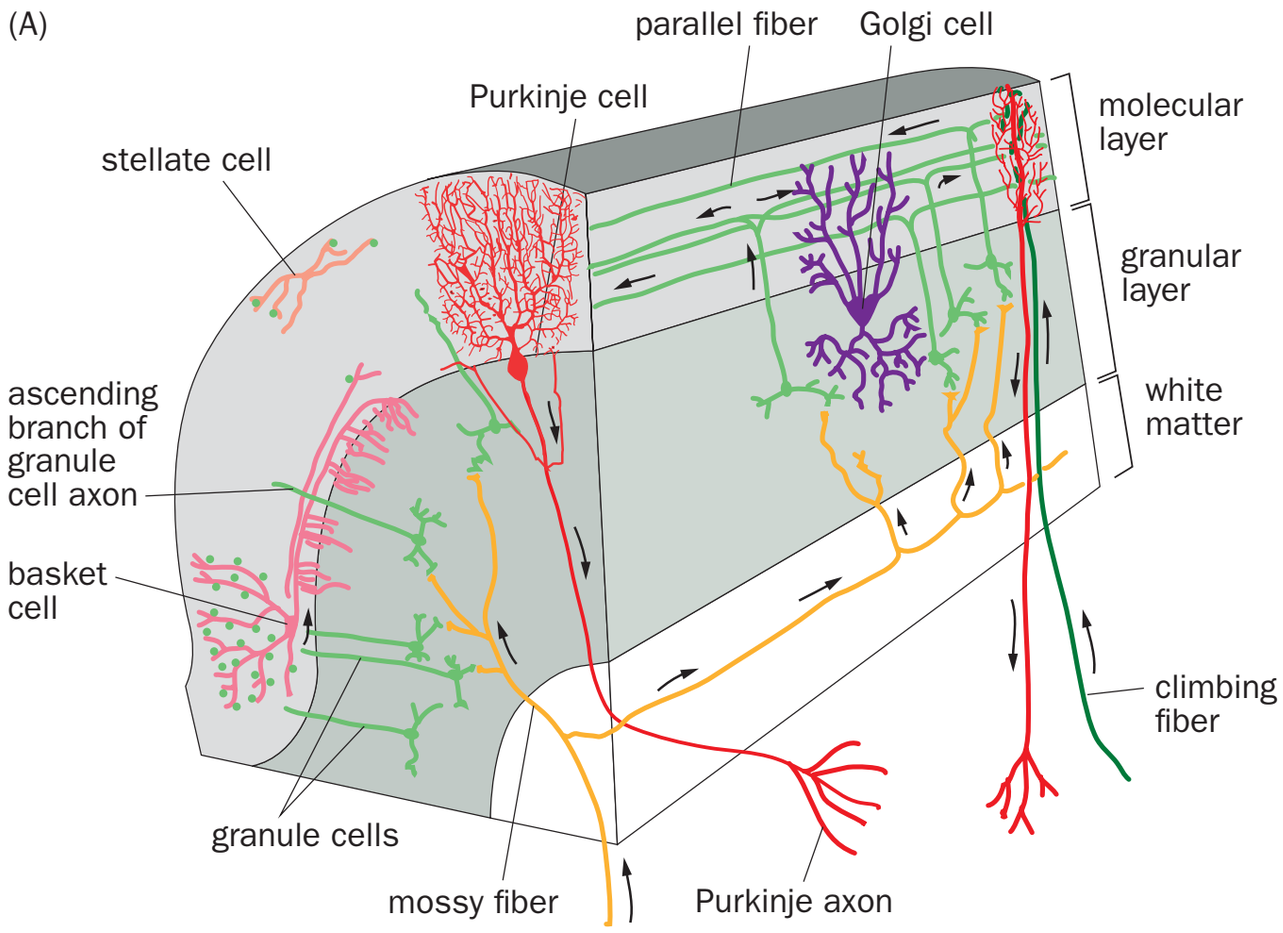


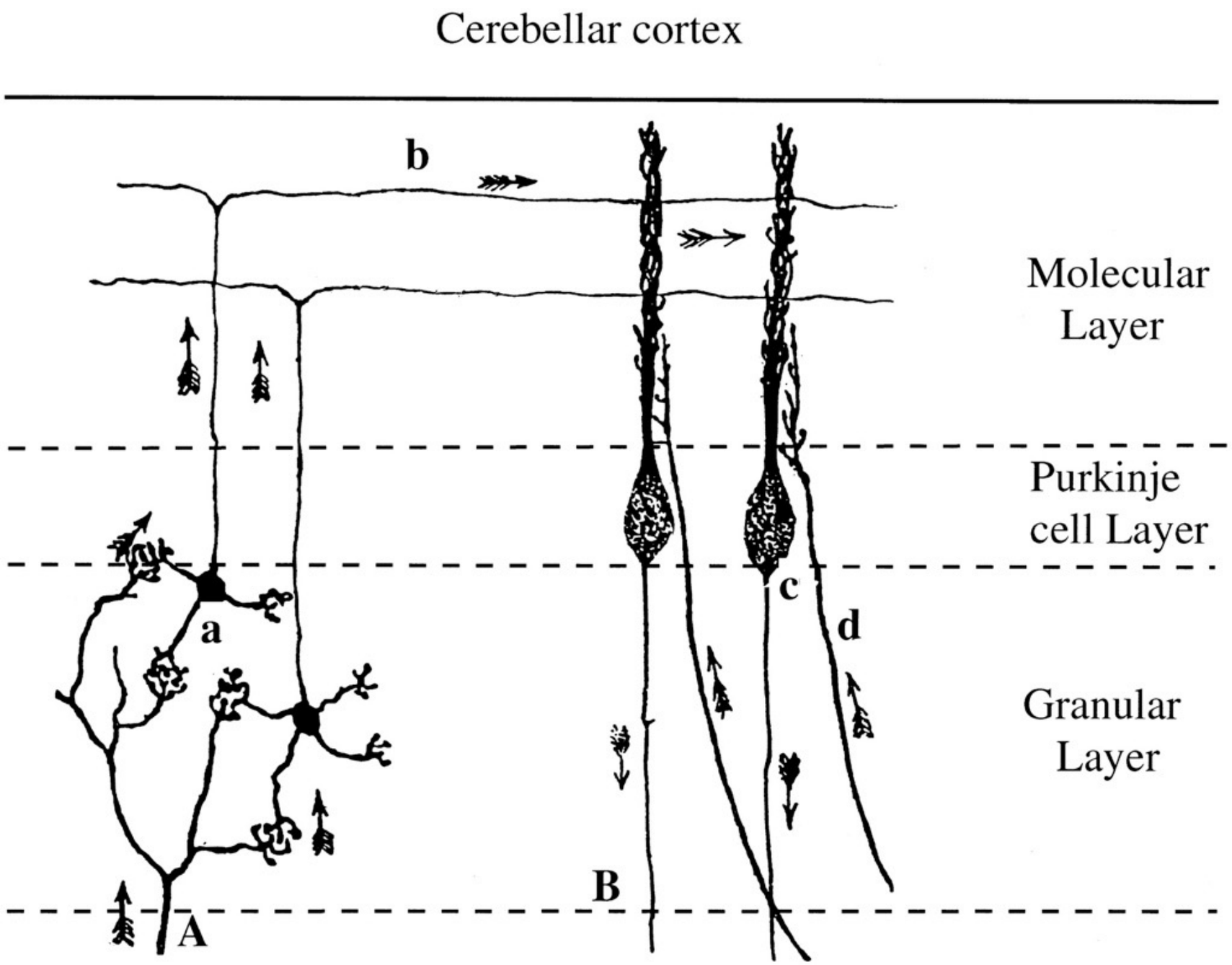
cerebellum



cerebral cortex

The organization of cerebellar cortex





Cajal's drawing of the cerebellar cortex

Connecting dense array to sparse array with extreme convergence and divergence

The organization of the cortical column

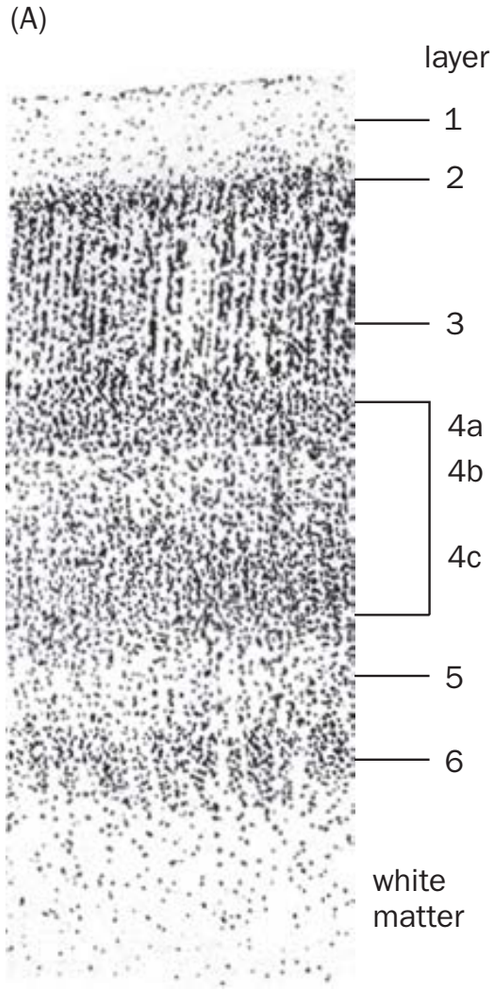
85% excitatory cells

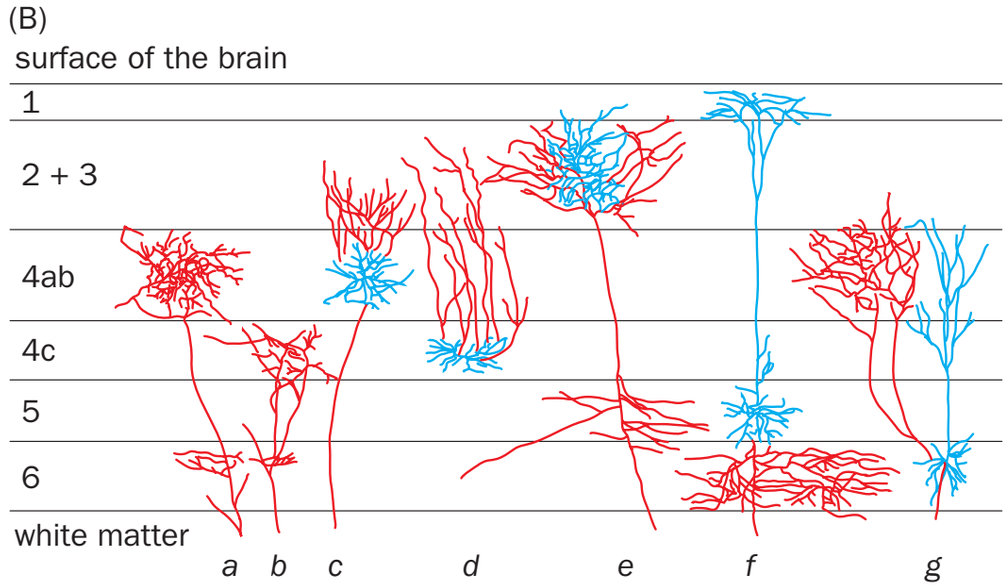
15% inhibitory cells

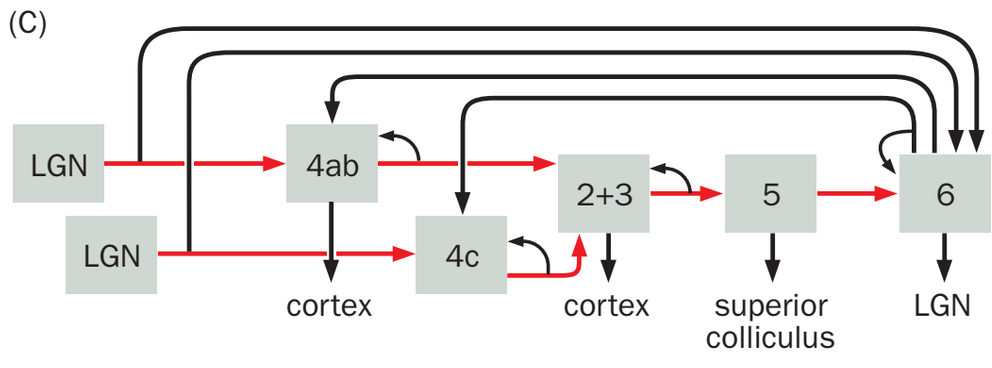
10^5 neurons

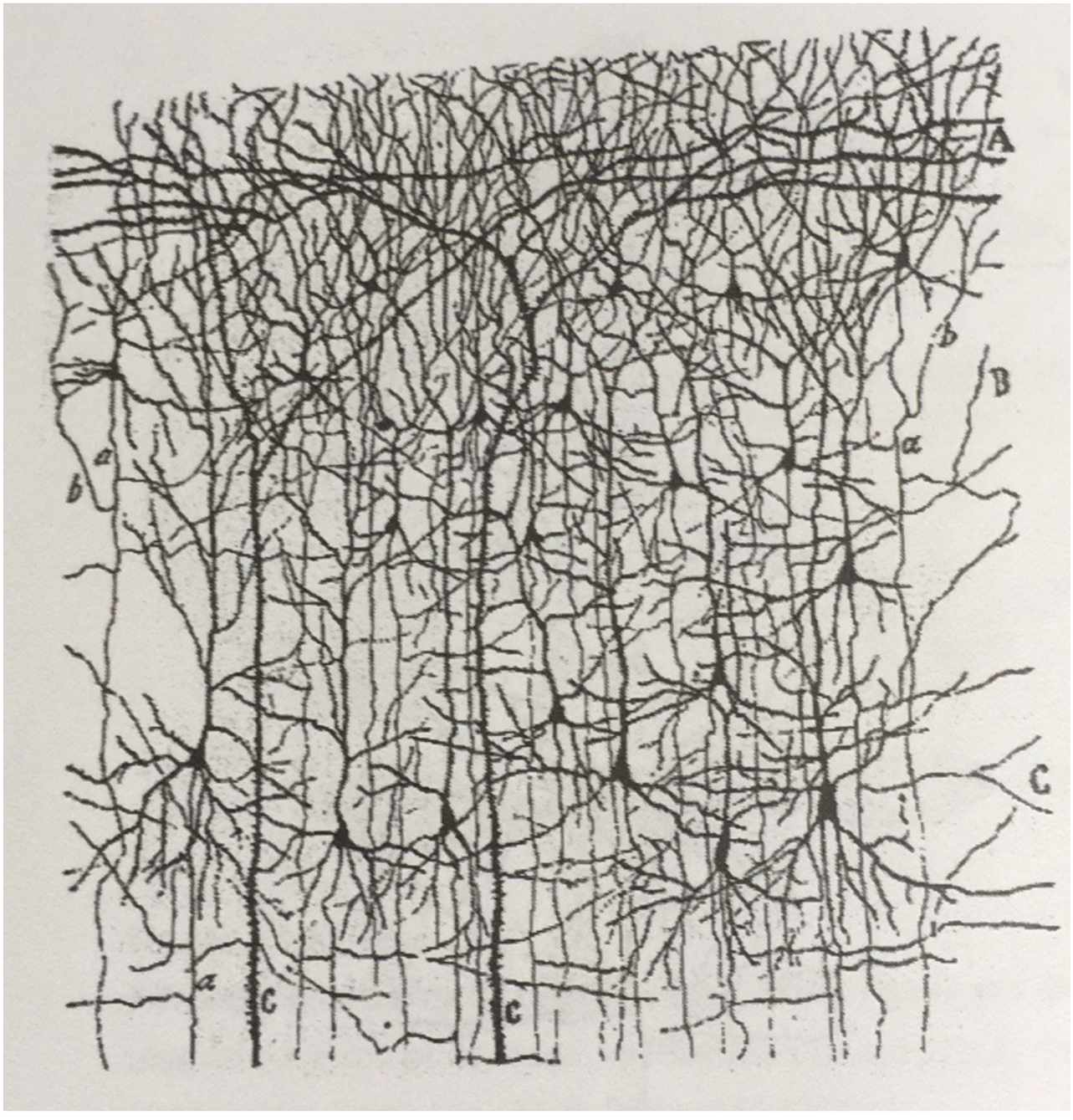
10^9 synapses

5000 m wires



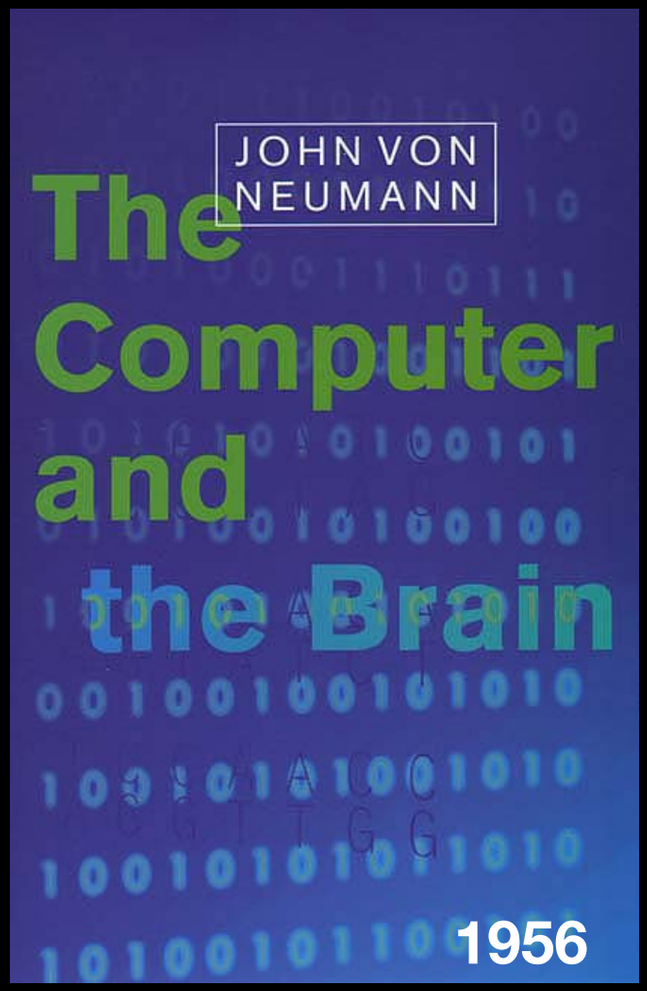






Cajal's drawing of the cerebral cortex

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



an unfinished book

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*

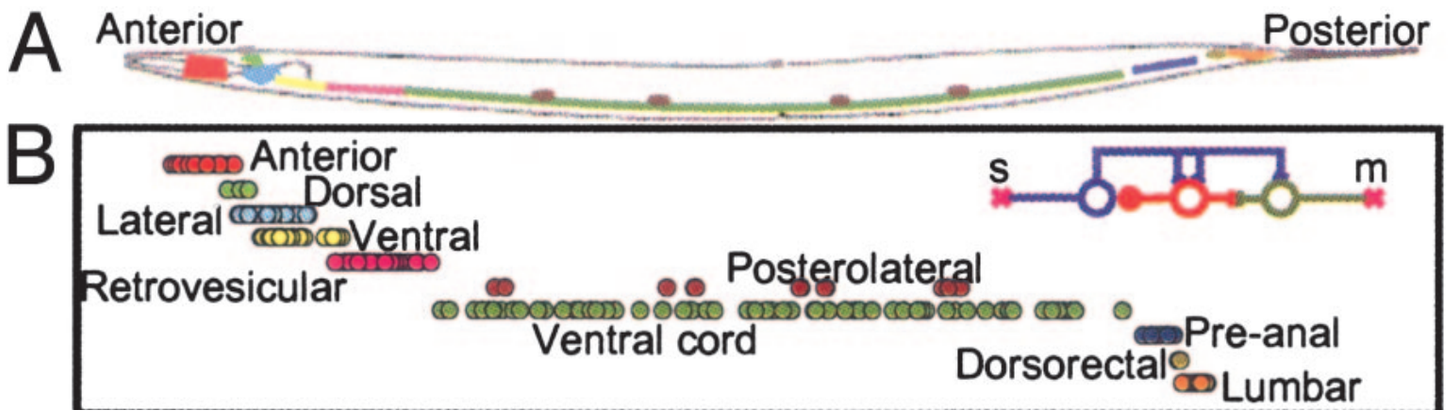
- *Synapses are far more complex than electrical logical gate*
- *Unlike computers, processing and memory are performed by the same components in the brain*
- *The brain is a self-organizing system*
- *Brain has bodies*

Wiring Optimization of Neural Circuit

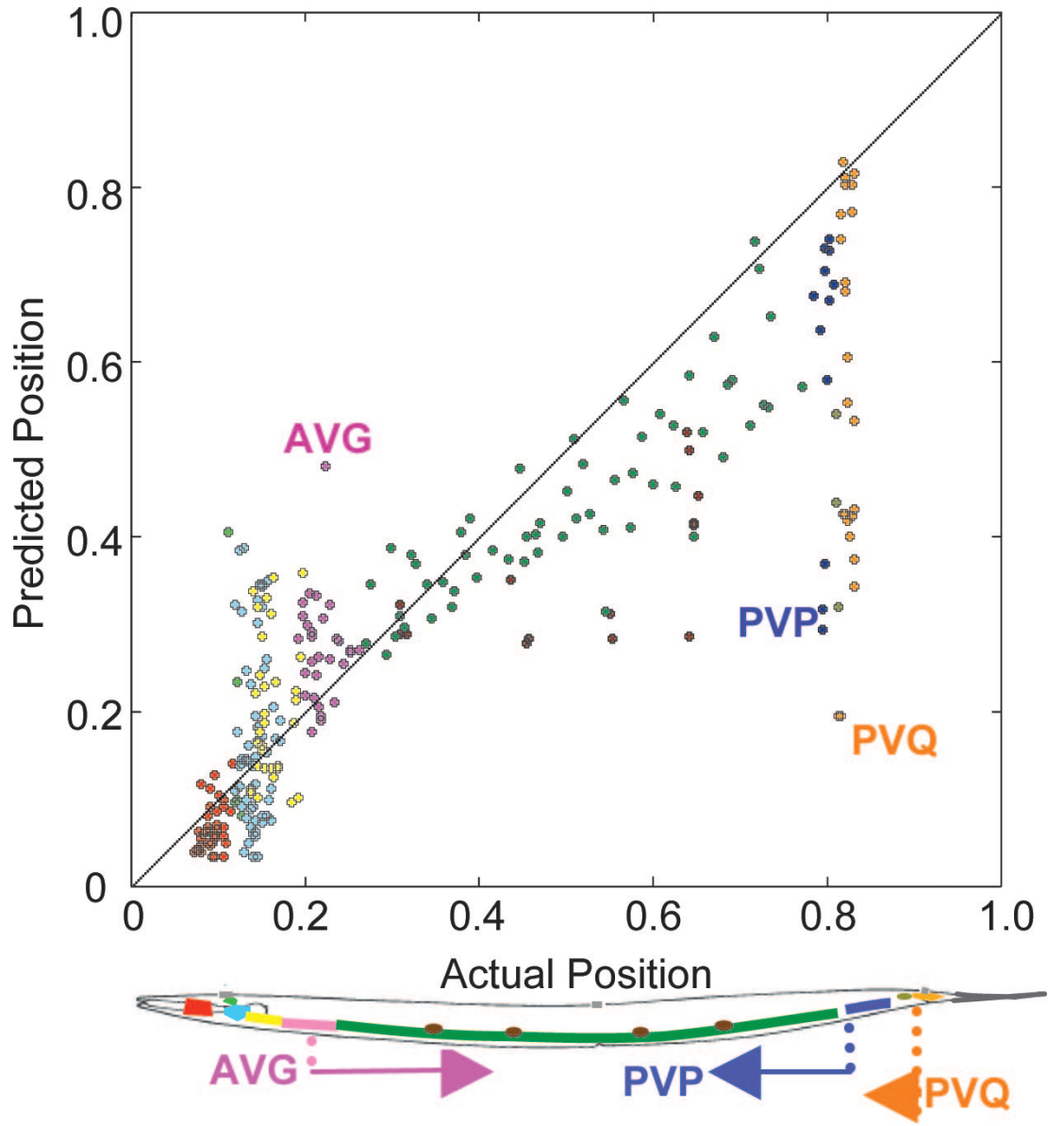
"After the many shapes assumed by neurons, we are now in a position to ask whether this diversity ... has been left to chance and is insignificant, or whether it is tightly regulated and provides an advantage to the organism. ... we realized that all of the various conformations of the neuron and its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

Ramon y Cajal

Neuronal layout in *C. elegans*

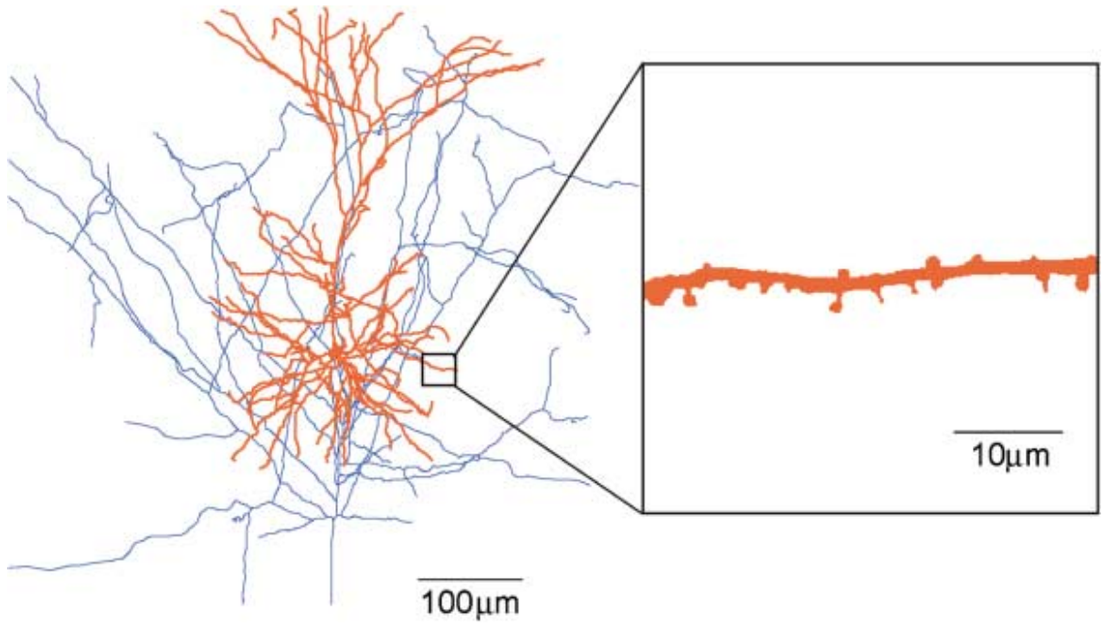


Neuronal layout in *C. elegans*

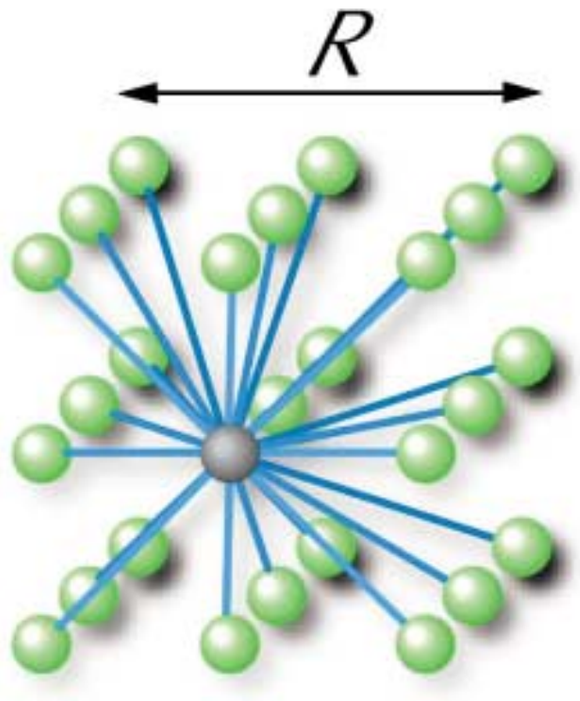


Beth Chen et. al., PNAS 2006

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

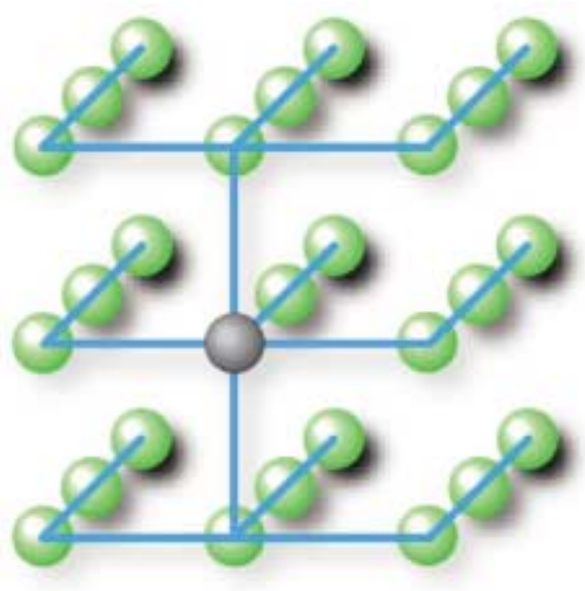


A toy problem: why do we need axons and dendrites?



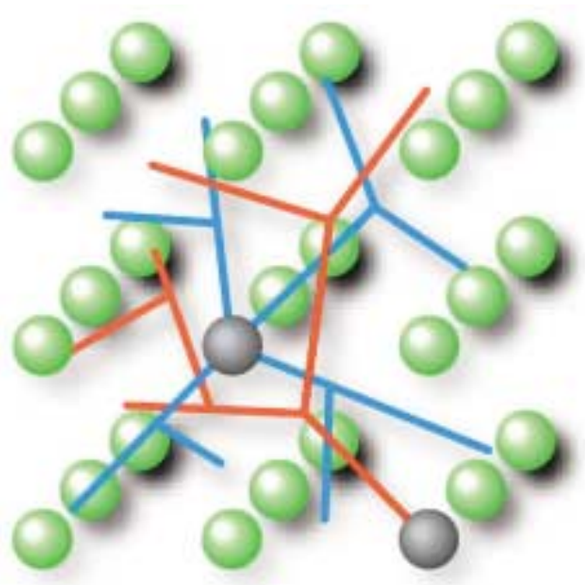
Design 1

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



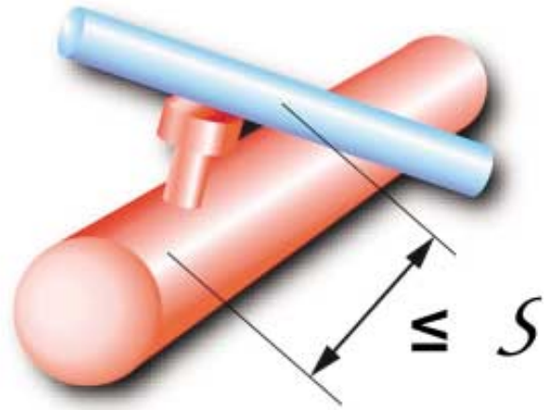
Design II

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



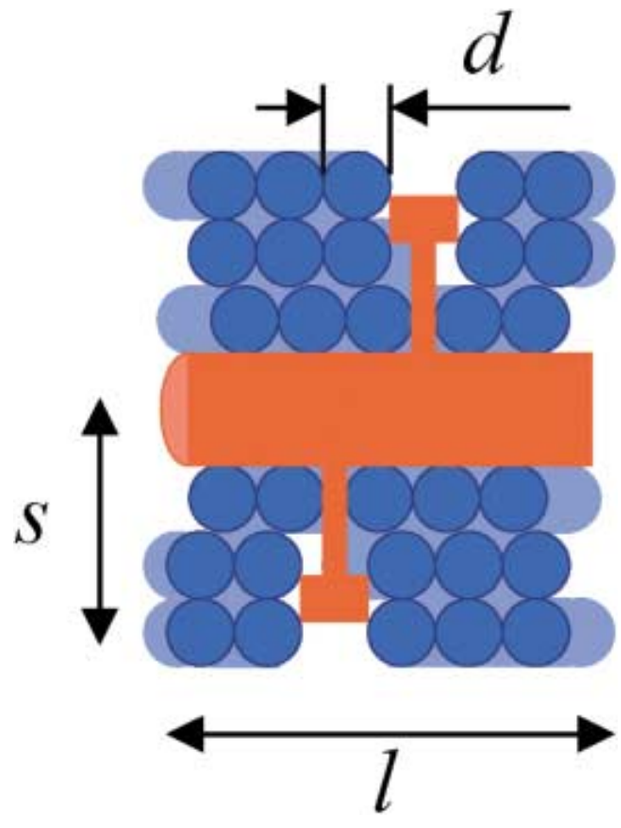
Design III

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