Evolution as the blind engineer: wiring minimization and logic modules in the brain

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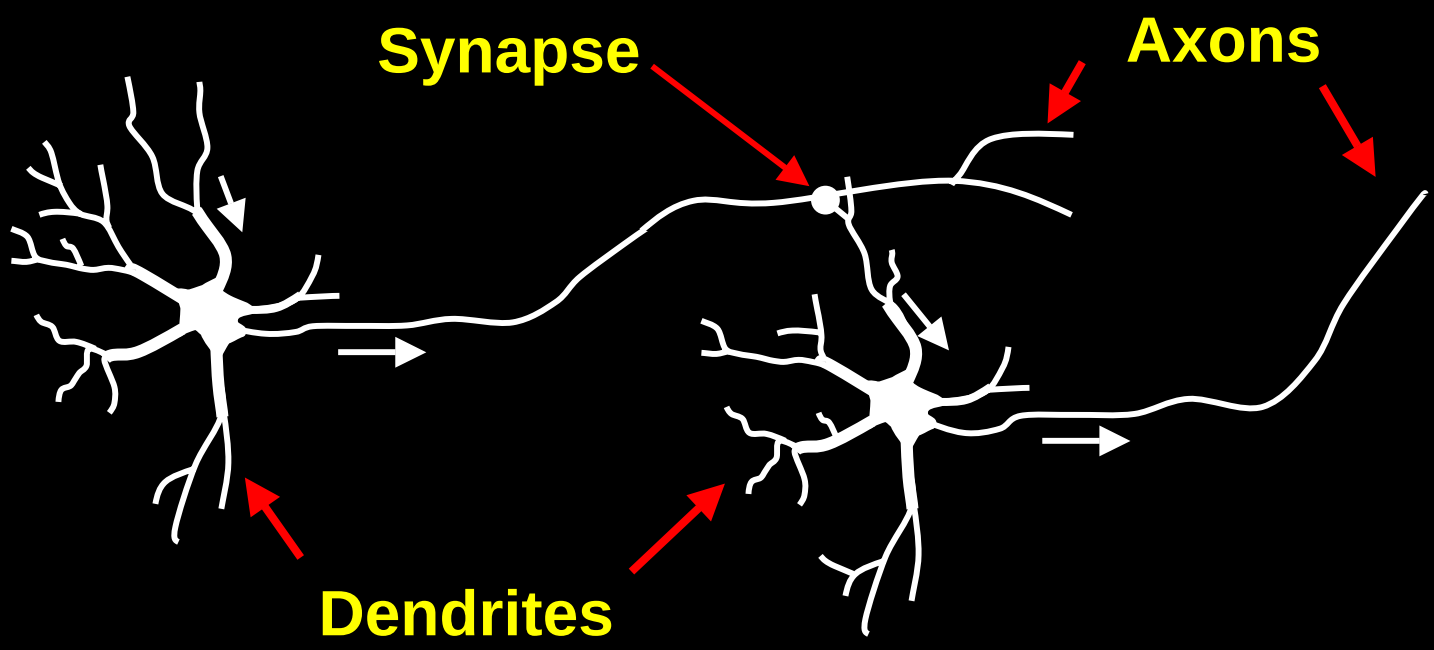
Foundations of theoretical neurobiology

Whole > Σ parts



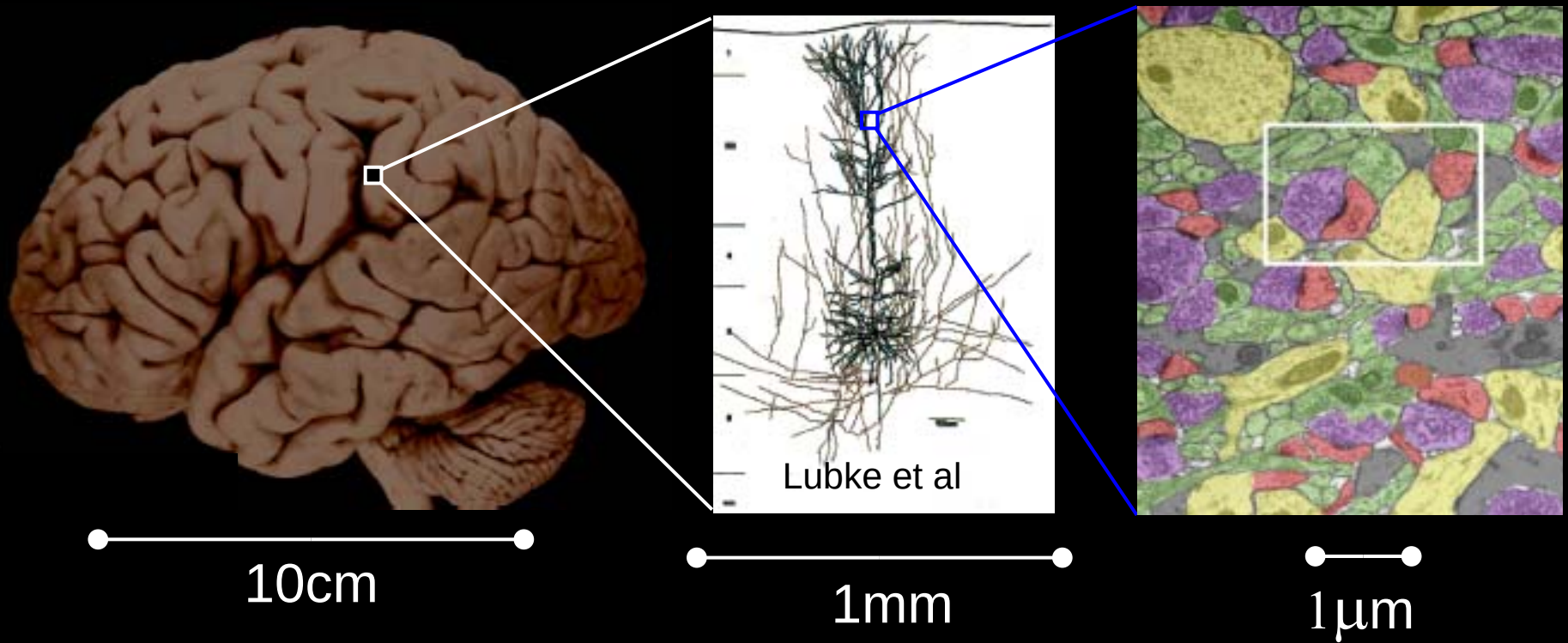
Neuron integrates incoming spikes and sends an outgoing spike when threshold is exceeded

Foundations of theoretical neurobiology II

More = different

Brain ~ 10^{11} neurons

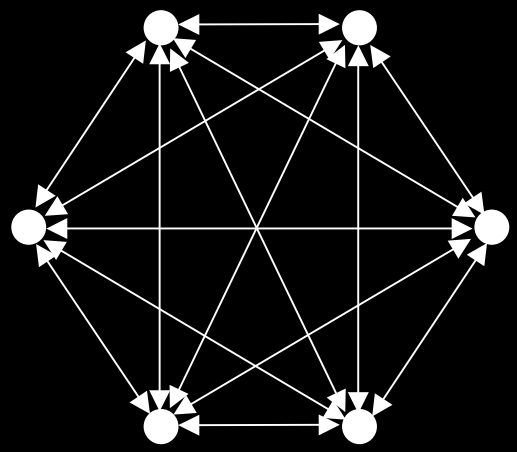
Synapse



Cortical column: ~ 1mm^3 containing ~10^5 neurons

Part I: Wiring problem

- Network of N neurons
- Fully connected (all-to-all)
- Fixed wire diameter, d



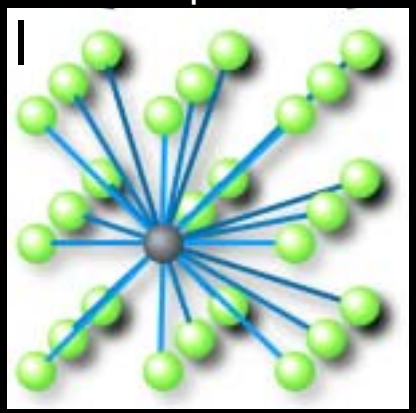
Find wiring design minimizing network volume

Network volume for different wiring designs

Cortical column: R=1mm, N=10^5,d=0.3μm;1μm, s=2.5μm

Point-to-point axons

I

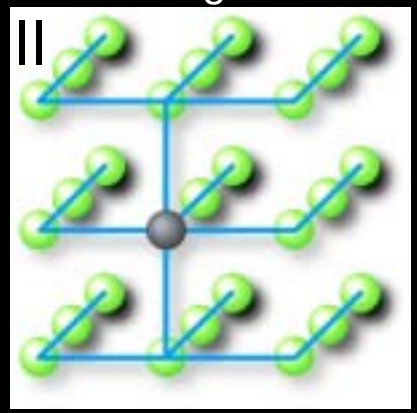


$R^3 \sim N^3 d^3$

30,000mm³

Branching axons

II

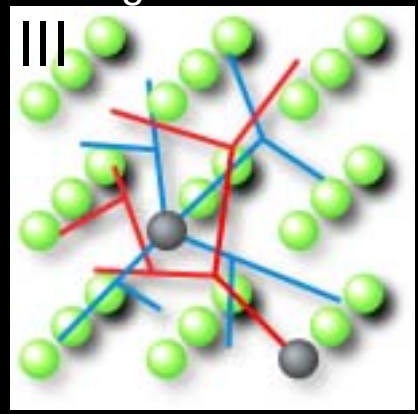


$R^3 \sim N^{5/2} d^3$

100mm³

Branching axons & dendrites

III

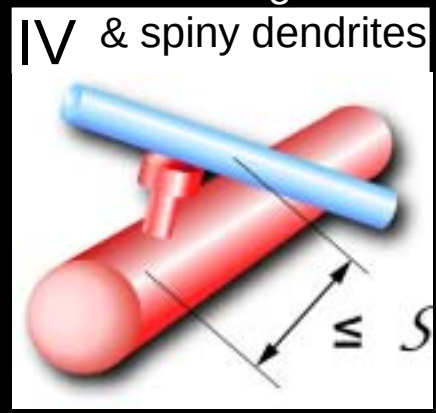


$R^3 \sim N^2 d^3$

2mm³

Branching axons & spiny dendrites

IV

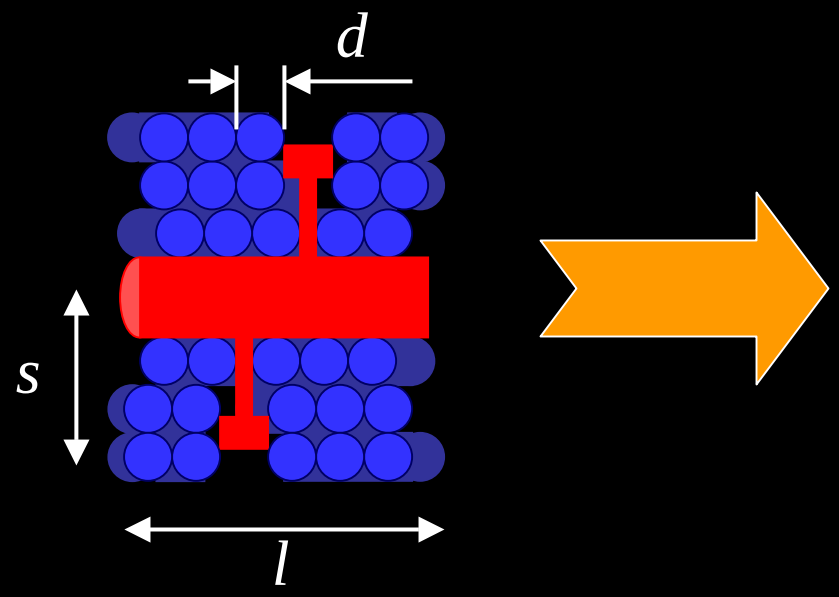


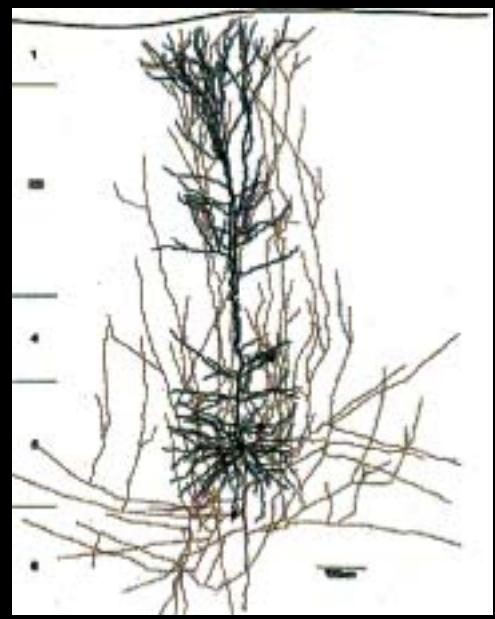
$R^3 \sim N^2 d^4/s$

0.6mm³

Chklovskii, 2004

Axons and dendrites are shortest possible for given diameters and inter-connectivity

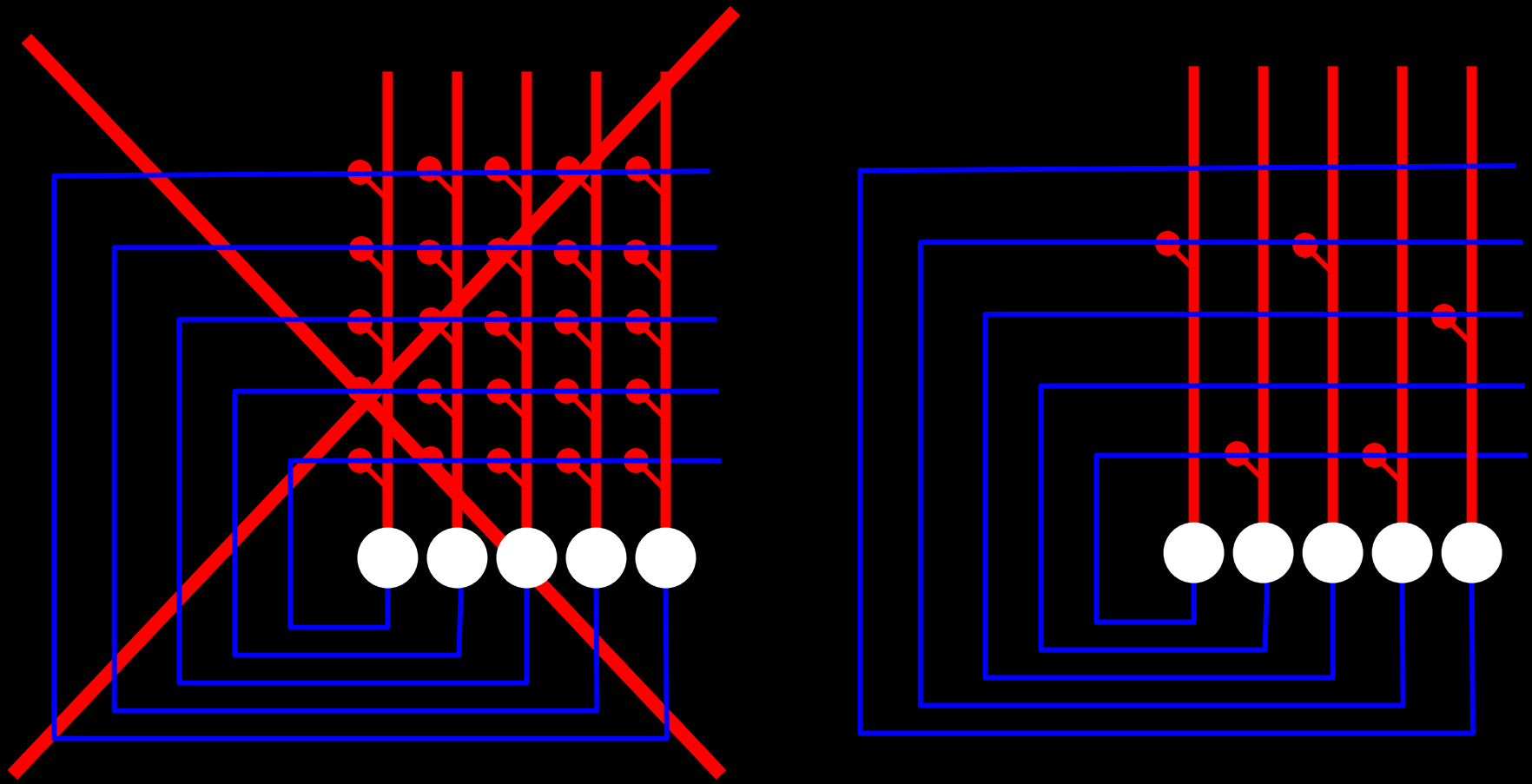




Minimal length of a dendrite with N potential synapses: $l \sim Nd^2/s$

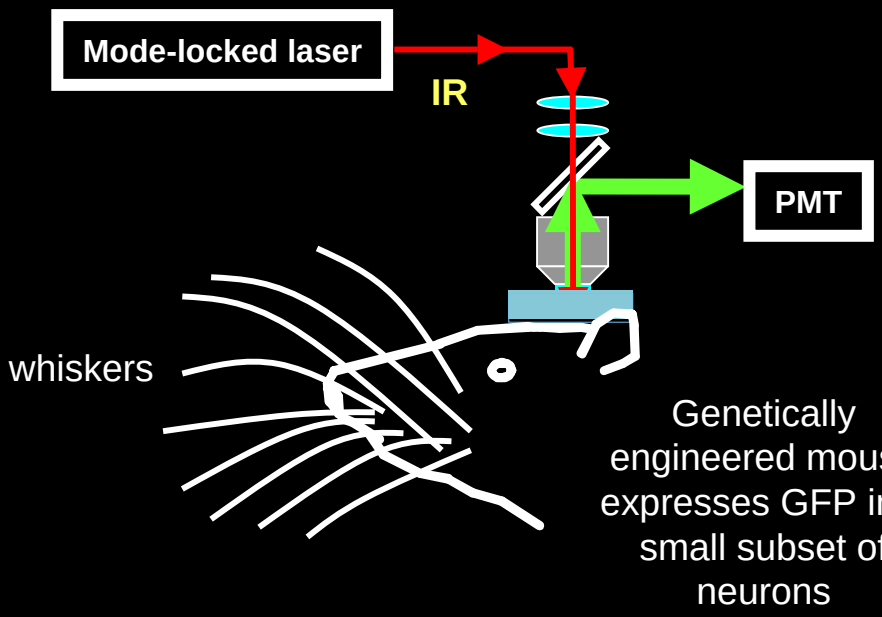
$N=10^5$ $d=0.3\mu m$ $s=2.5\mu m$ $\Rightarrow l=4mm$

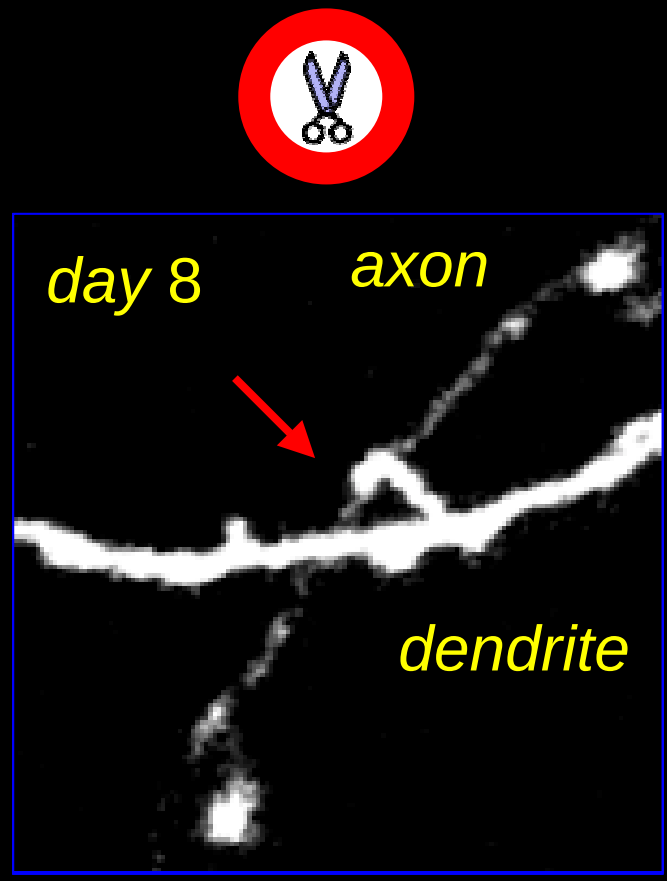
Cortical architecture is optimized for high inter-connectivity



Synapse re-arrangement is potential memory mechanism with high information storage capacity (Stepanyants, Hof, Chklovskii, 2002)

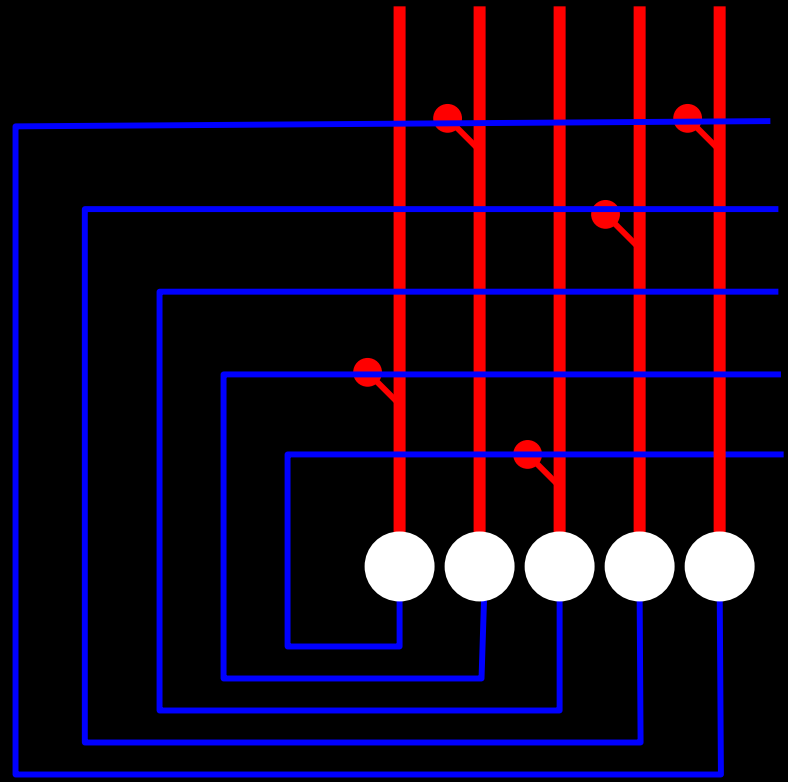
Two-photon imaging provides evidence of synapse re-arrangement *in vivo*





Trachtenberg, …, Svoboda, 2002

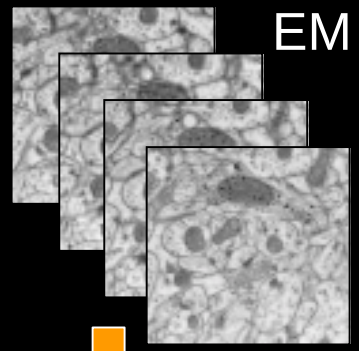
Part II: Search for logic modules

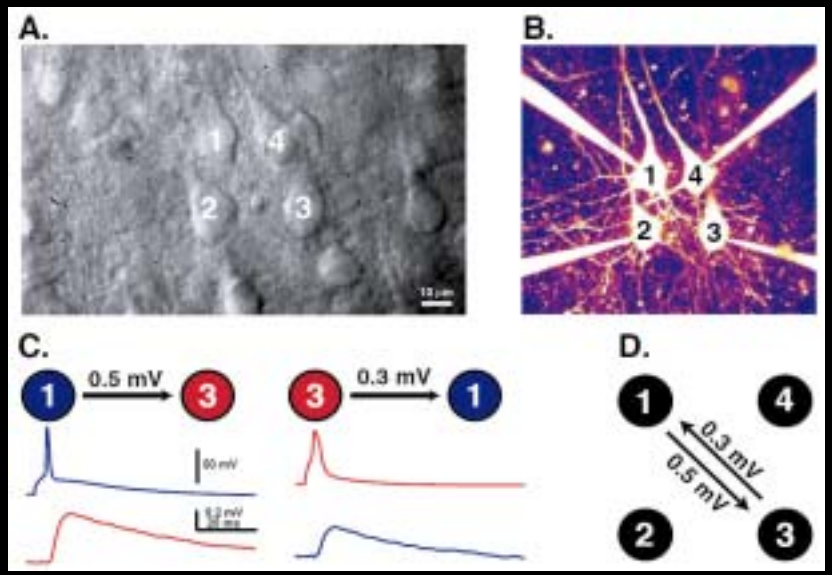


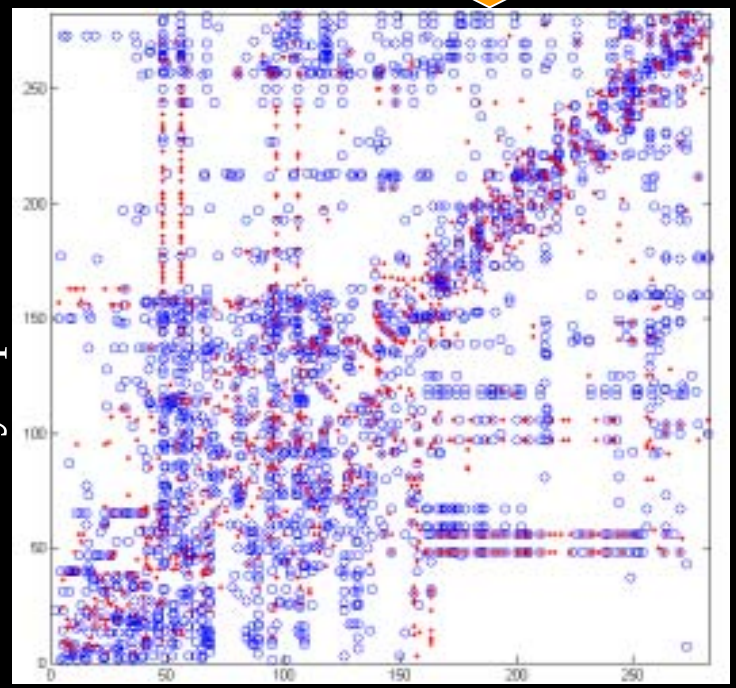
Hypothesis: Multi-neuronal modules performing stereotypical function may manifest themselves in recurring patterns of connectivity

Strategy: Discover modules by searching for over-represented multi-neuron connectivity patterns

Neuronal connectivity datasets





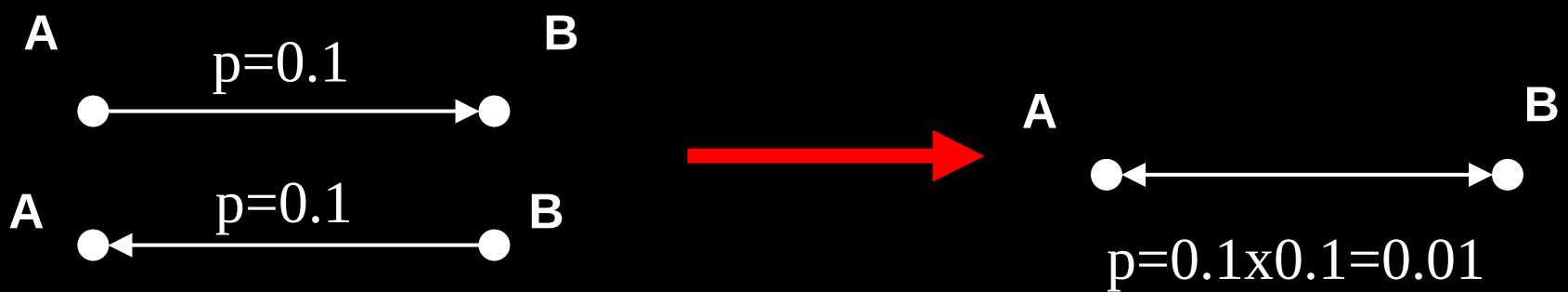


Sjöström & Nelson (Brandeis)

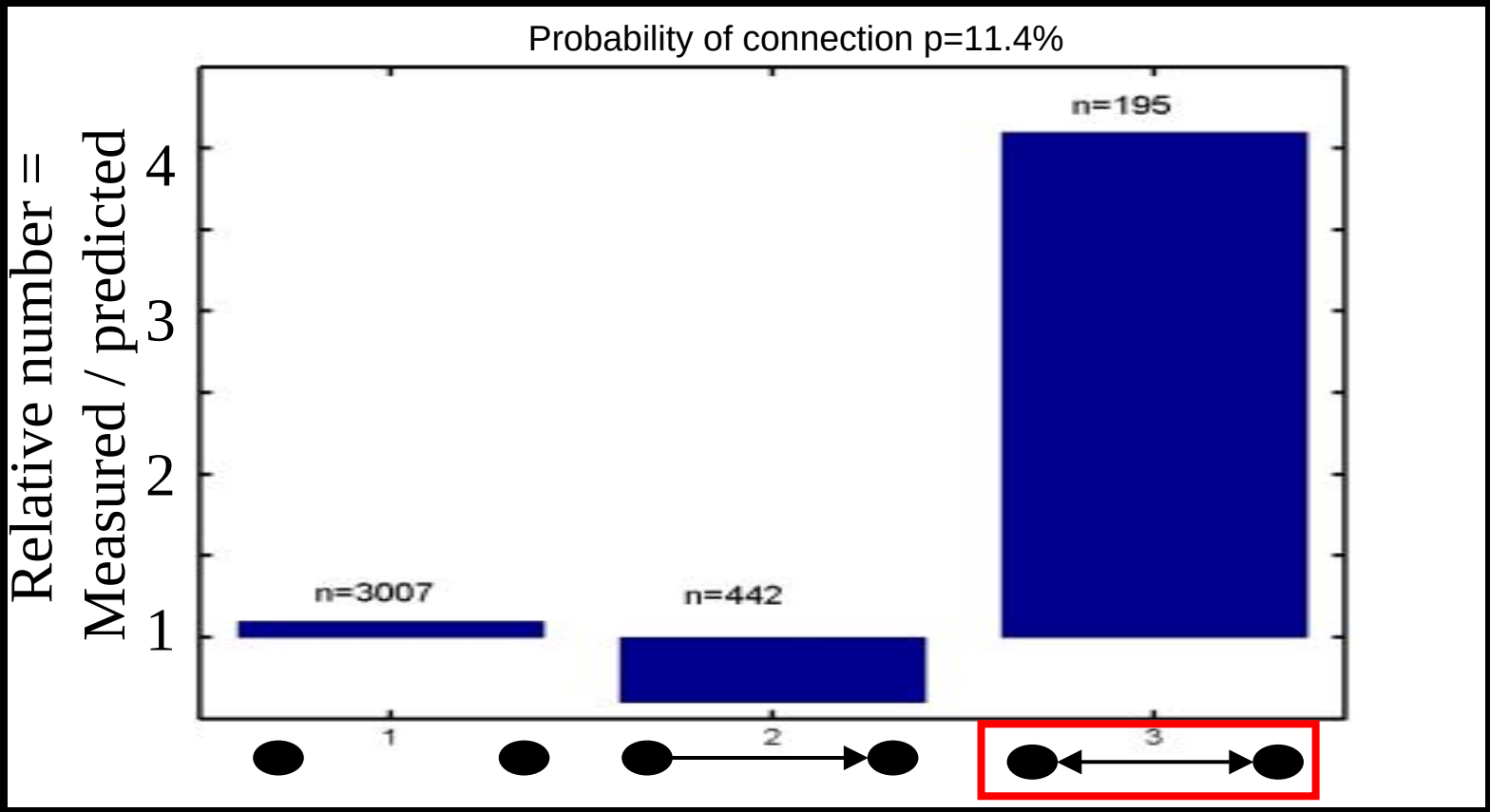
Null-hypothesis: network with Poisson connectivity statistics (Erdos-Renyi random graph)

Connection probabilities are independent

Example:

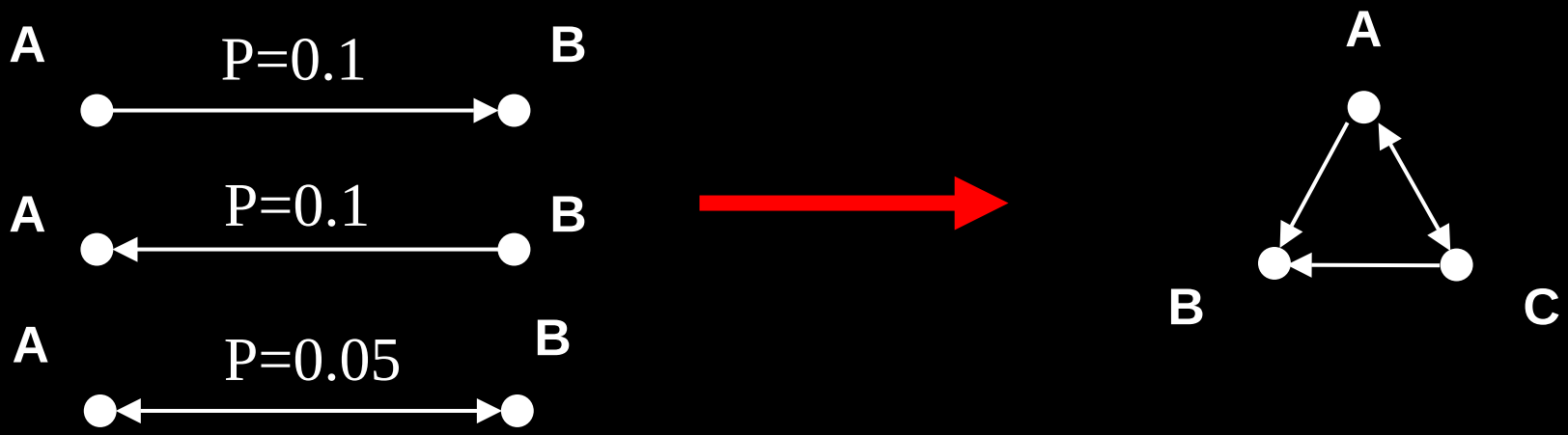


Two-neuron motifs



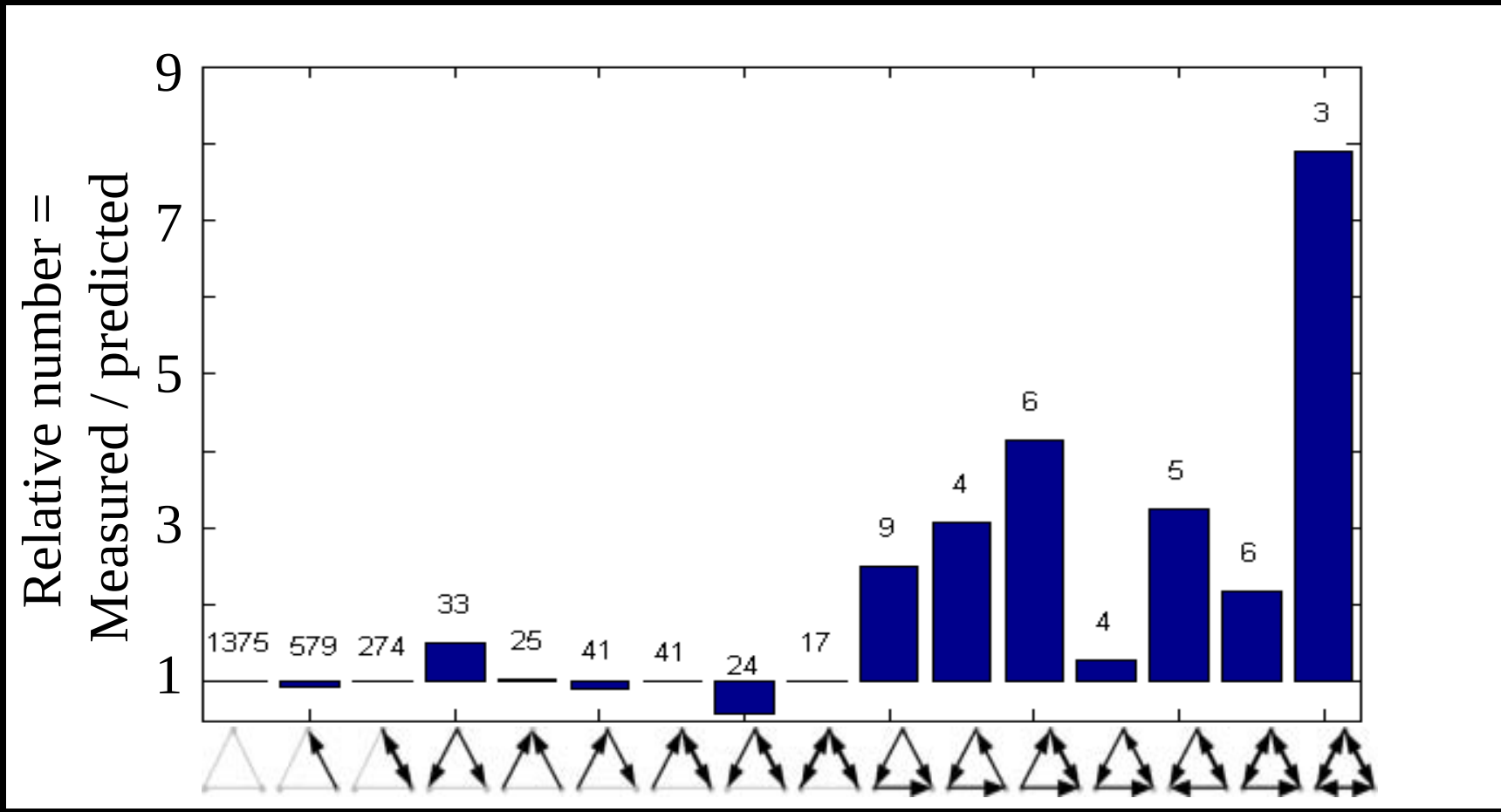
Reciprocal connections are over-represented both in rat cortex and in *C. elegans*

New null-hypothesis: network with three kinds of connections chosen independently



$P=C_3^1 x0.1x0.1x0.05=0.0015$

Three-neuron motifs

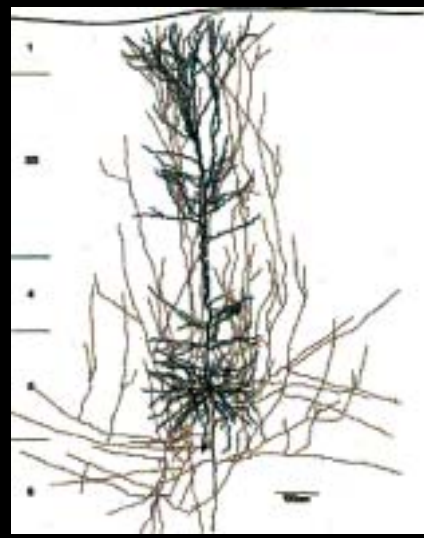


Actual numbers of triplets recorded are shown above the bars

Summary

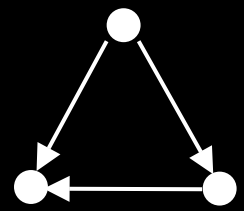
Wiring minimization is a key factor determining brain architecture.

Many challenging problems remain



Wiring diagram contains motifs, which are candidates for logic modules.

We need more ideas to decipher the wiring diagram of the brain



Acknowledgments

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