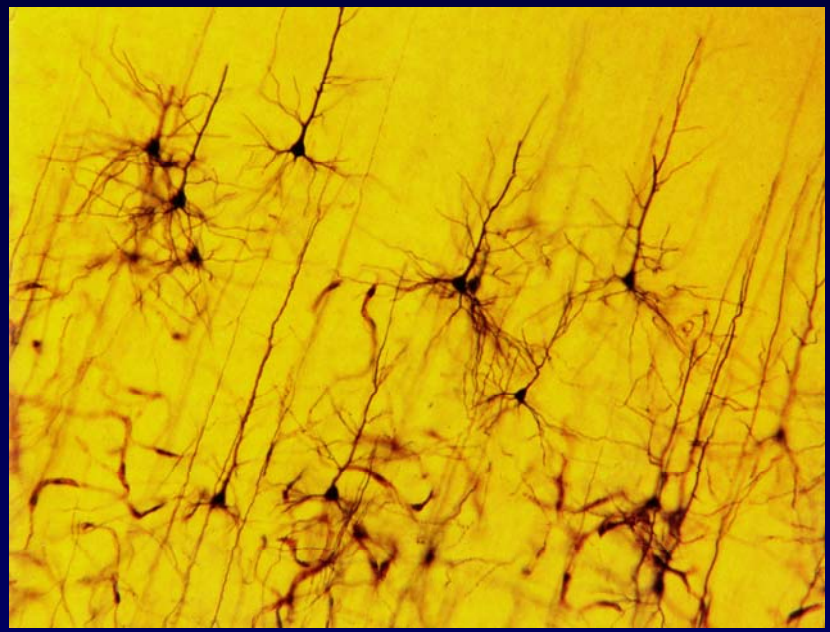
Measuring information flow in networks of ~100 cortical neurons



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Indiana University

Acknowledgements

- Aonan Tang
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Outline

- Neuroscience background
- Our question
- Measuring information flow
- Results
- Implications
- Final remarks

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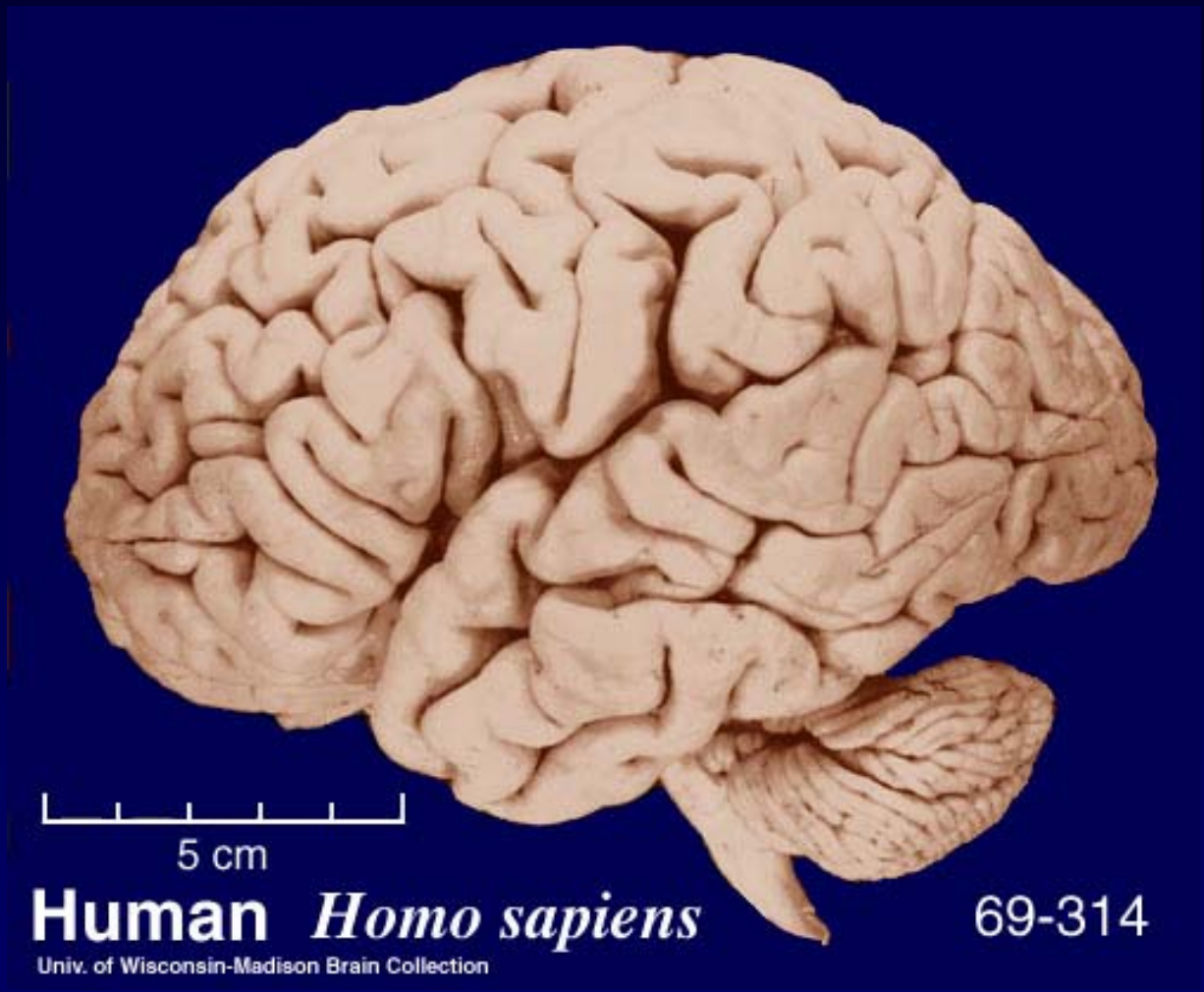
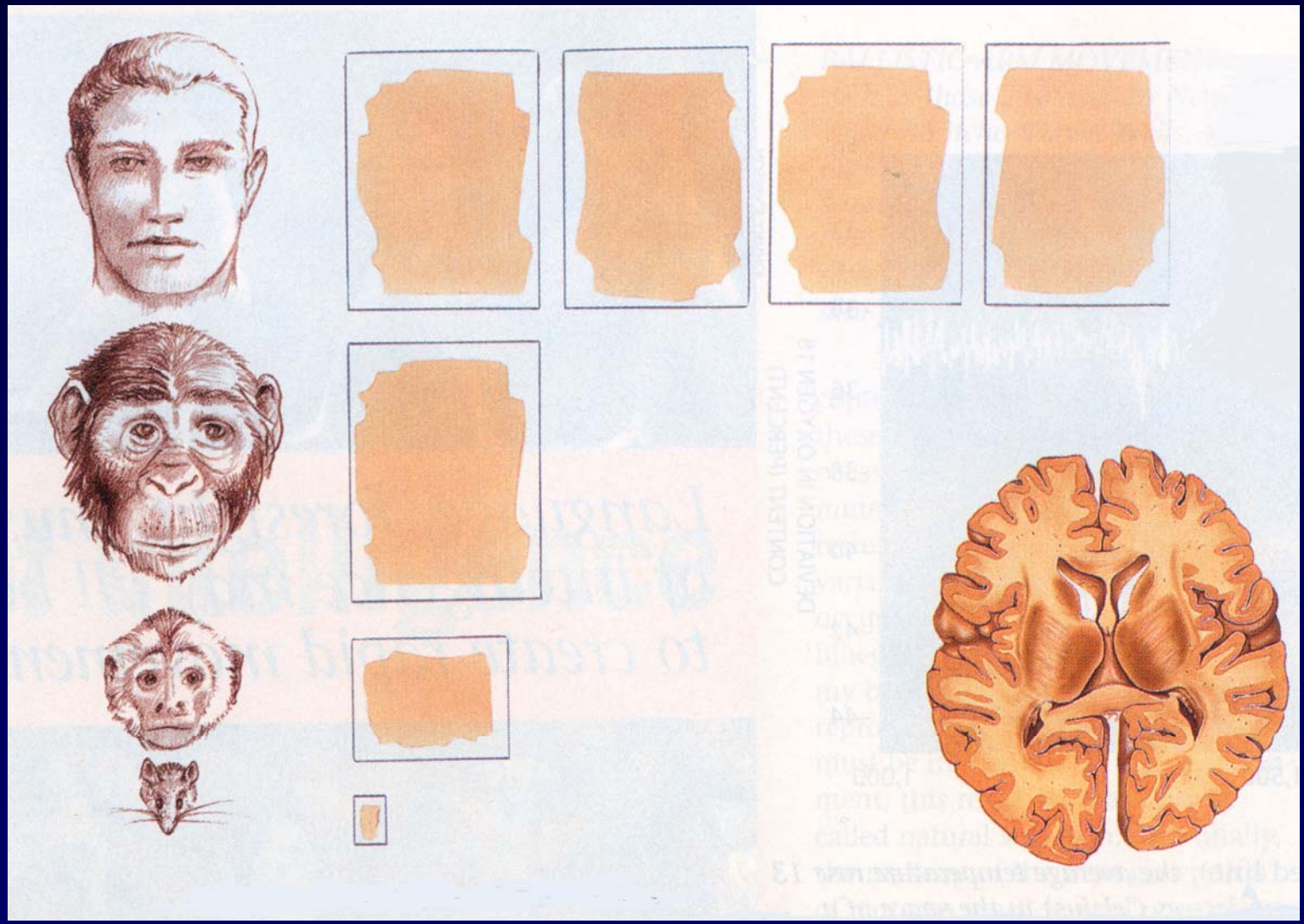
How does this work?

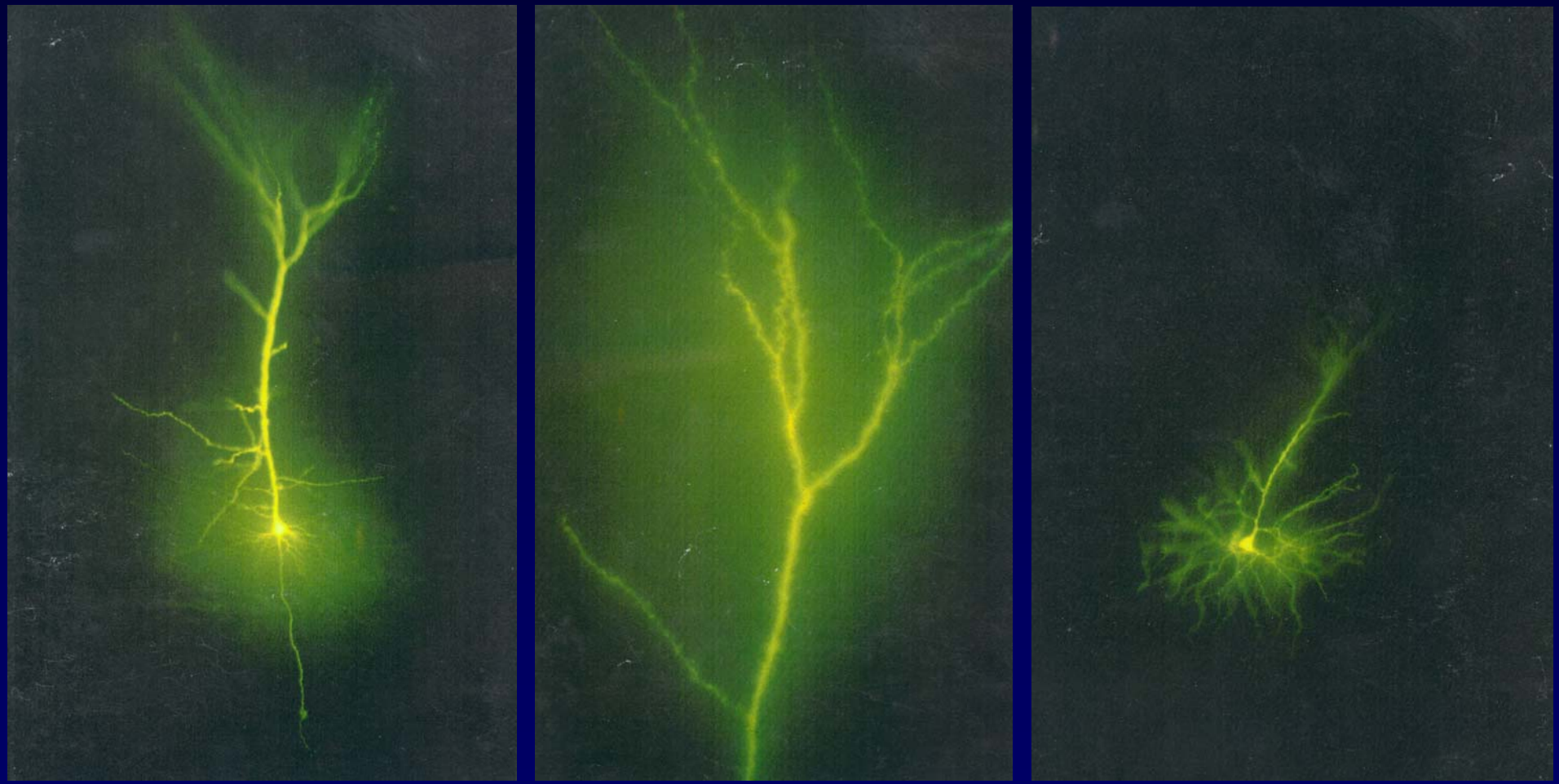


In other words, how does it process information?

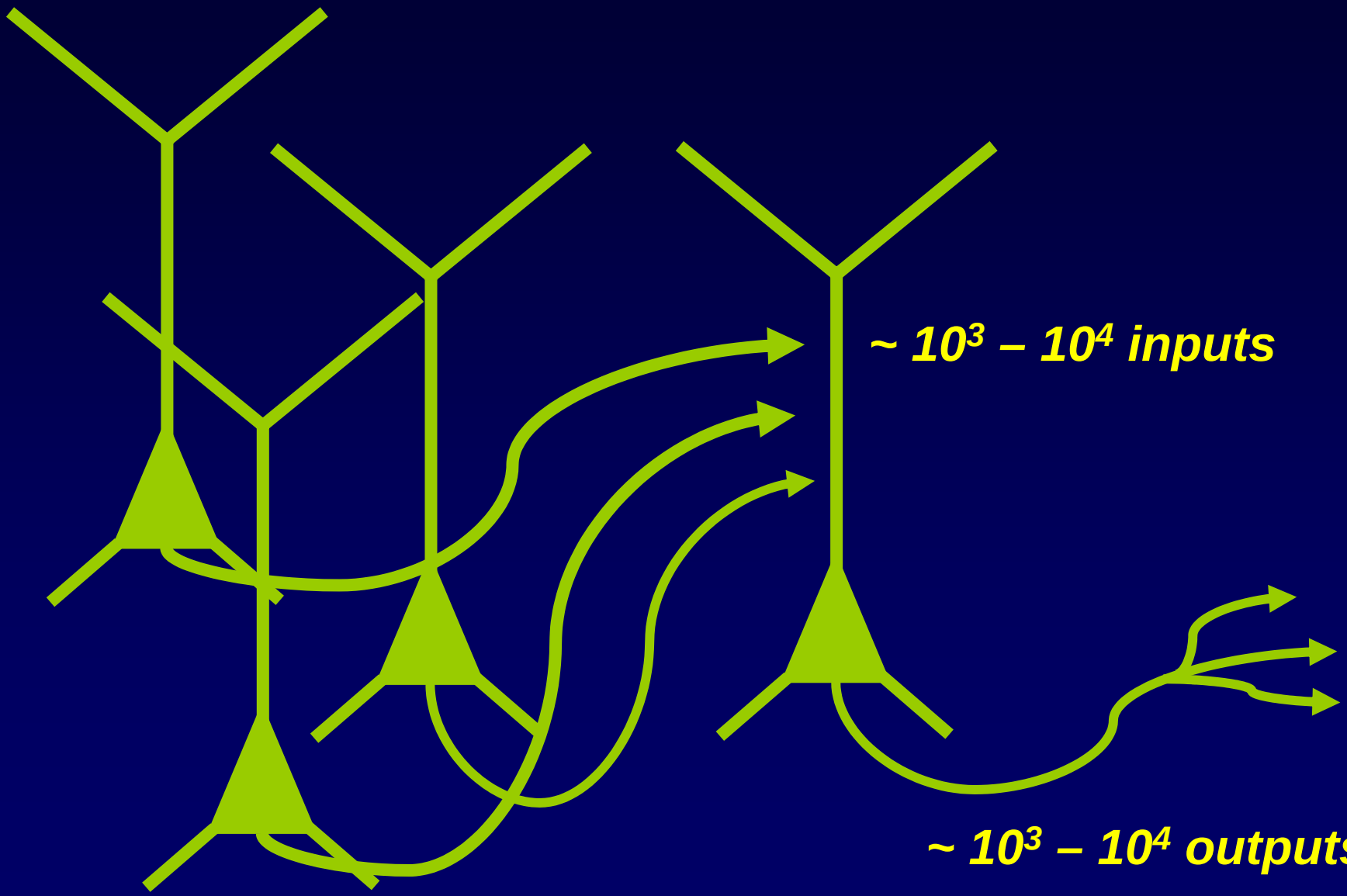
Cortex is essential for cognition



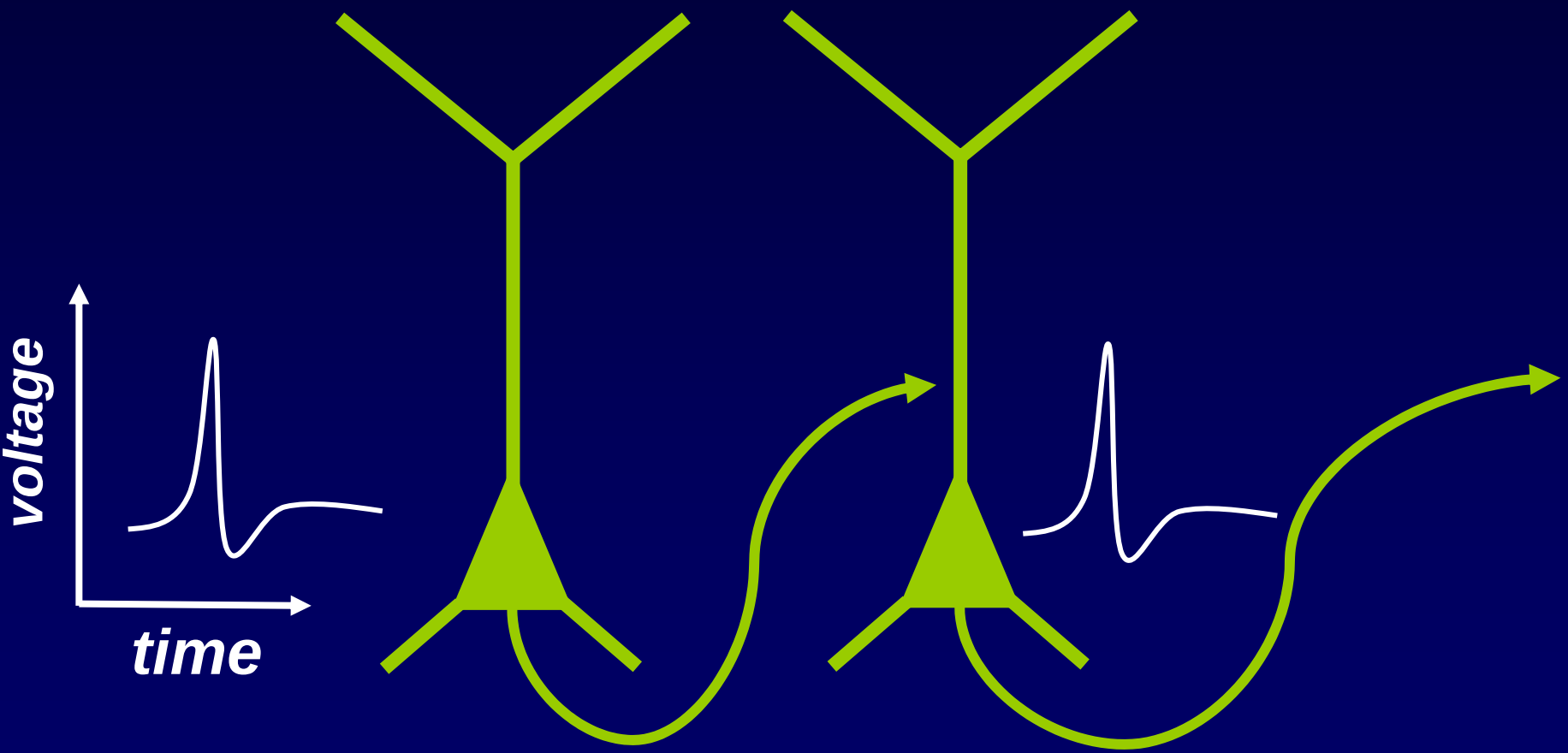
Neurons from rat cortex



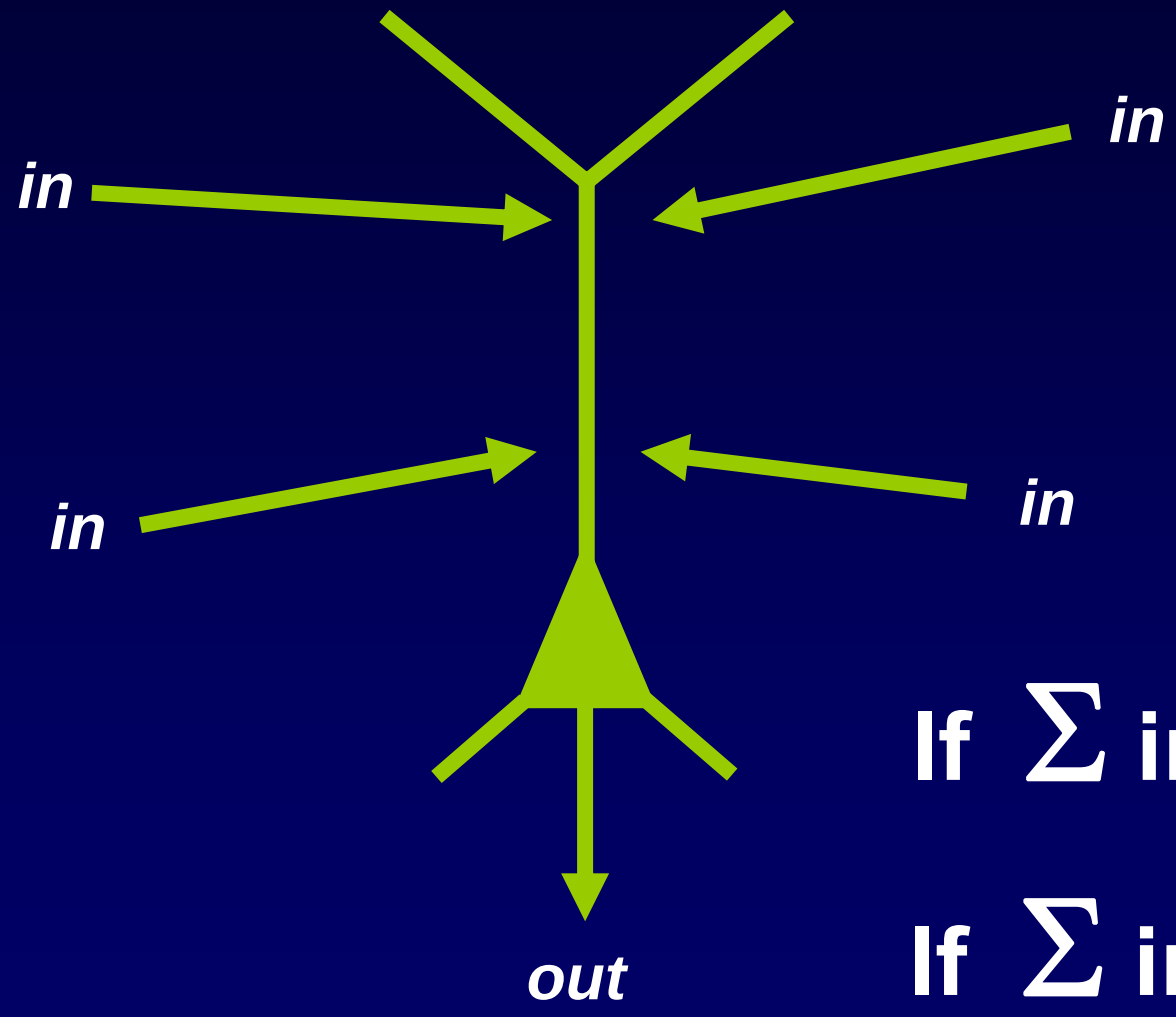
Each neuron makes and receives about the same number of synapses



Output is communicated by pulses

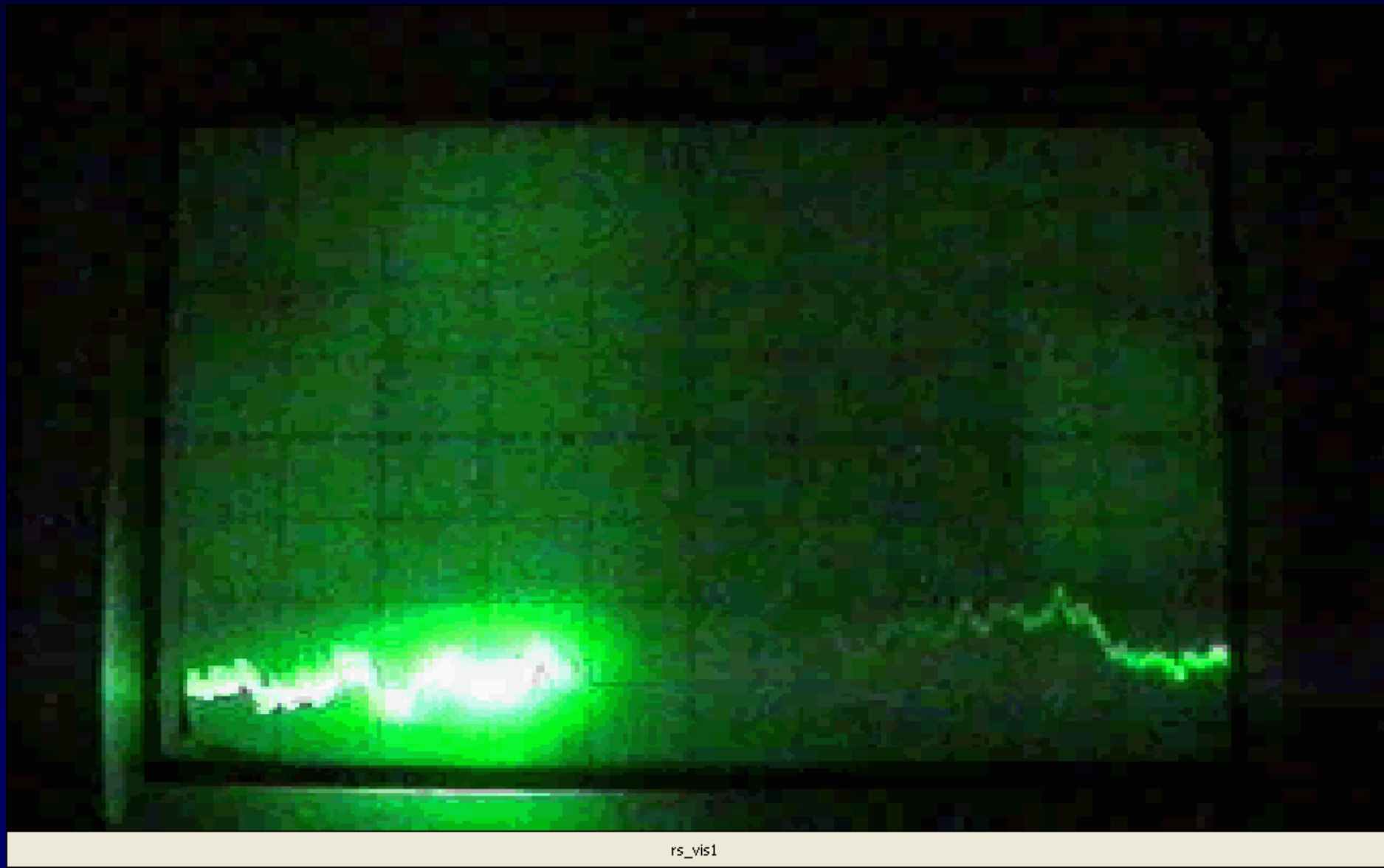


Neurons are similar to binary threshold devices



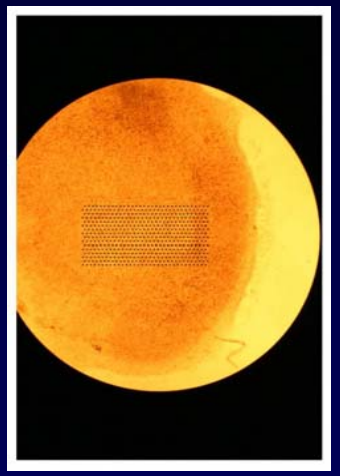
If $\sum$ in $\geq \theta$, out = 1

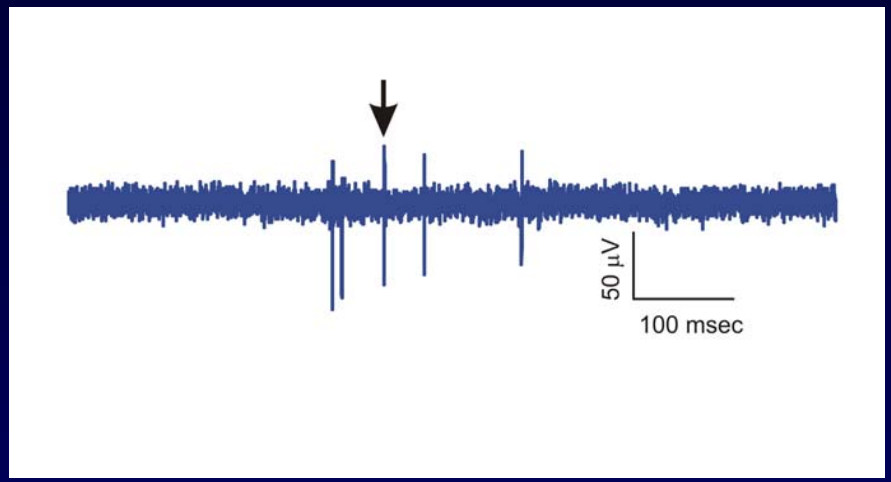
If $\sum$ in $< \theta$, out = 0

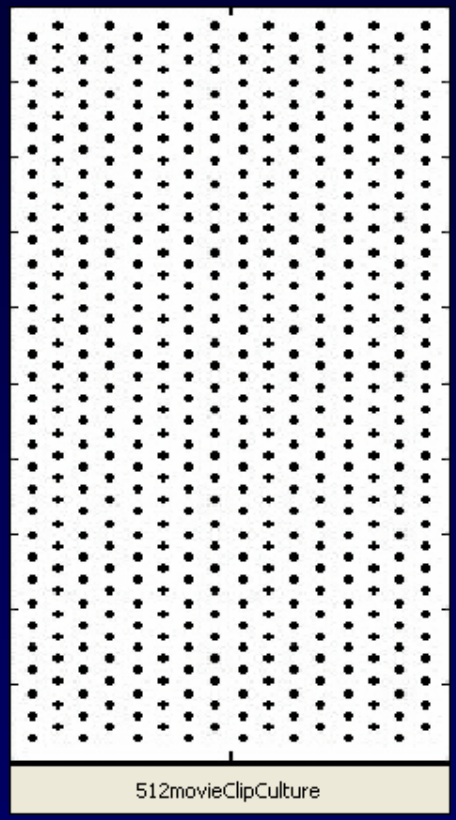


From the lab of David McCormick, Yale University

Network activity

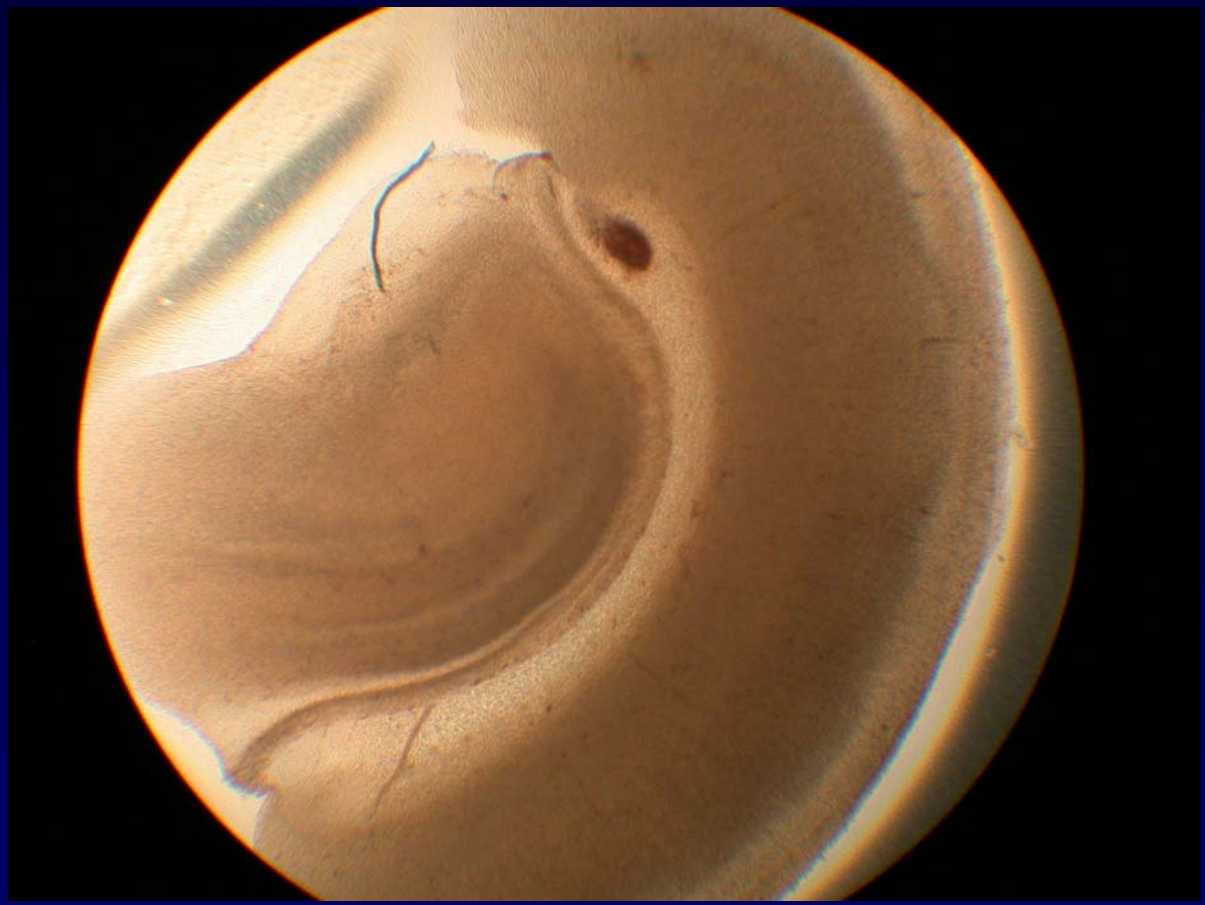






In collaboration with Alan Litke, UC Santa Cruz

Good recordings



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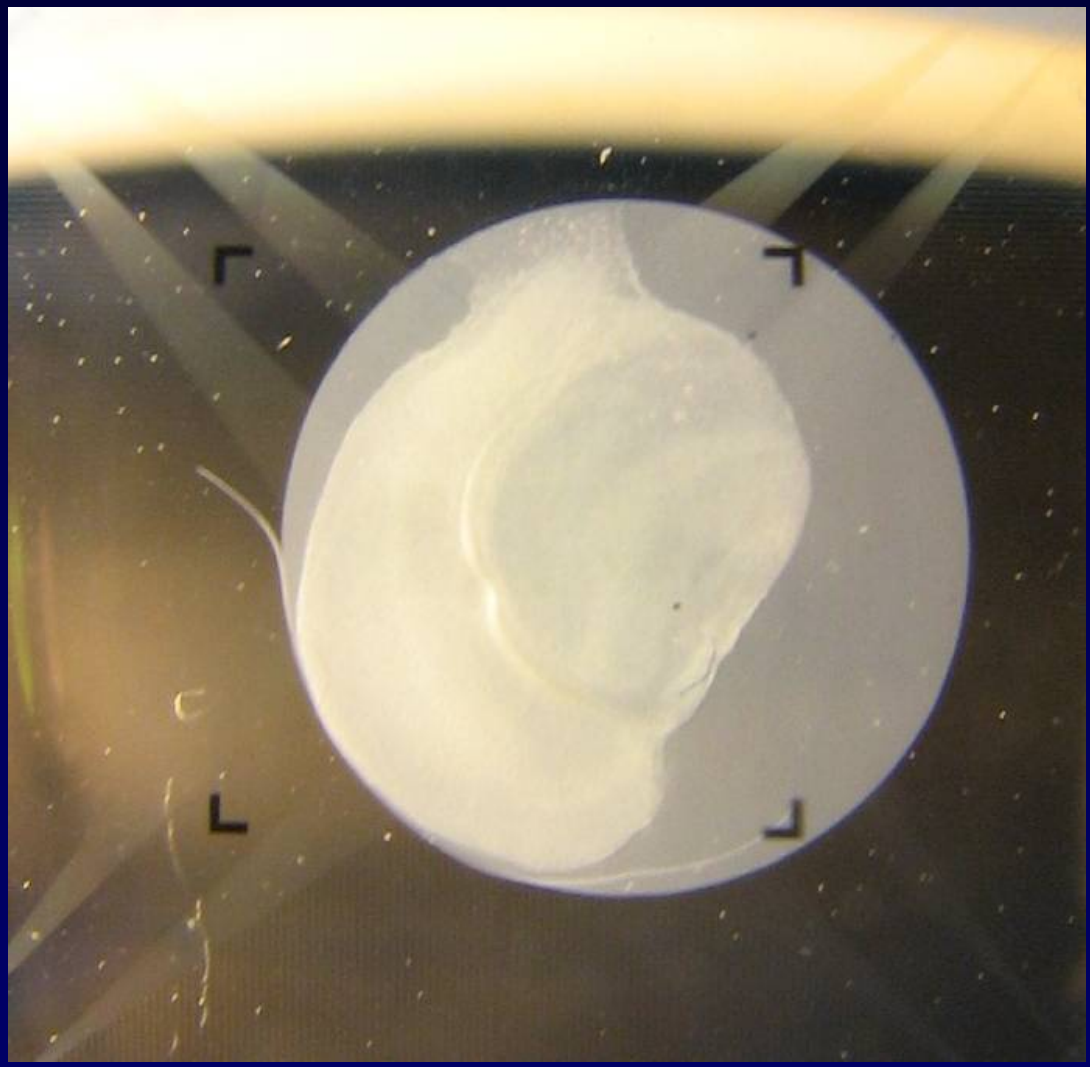
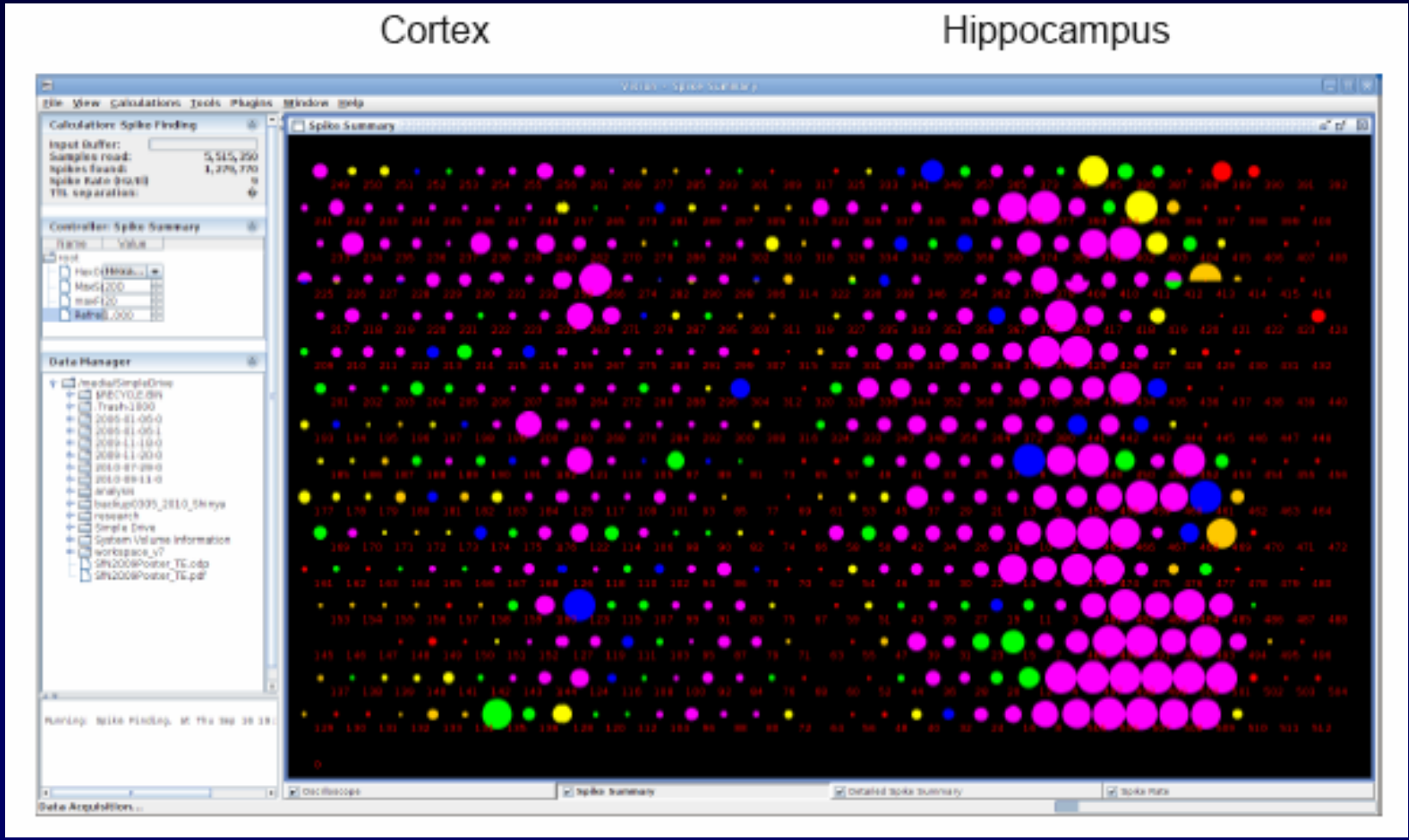
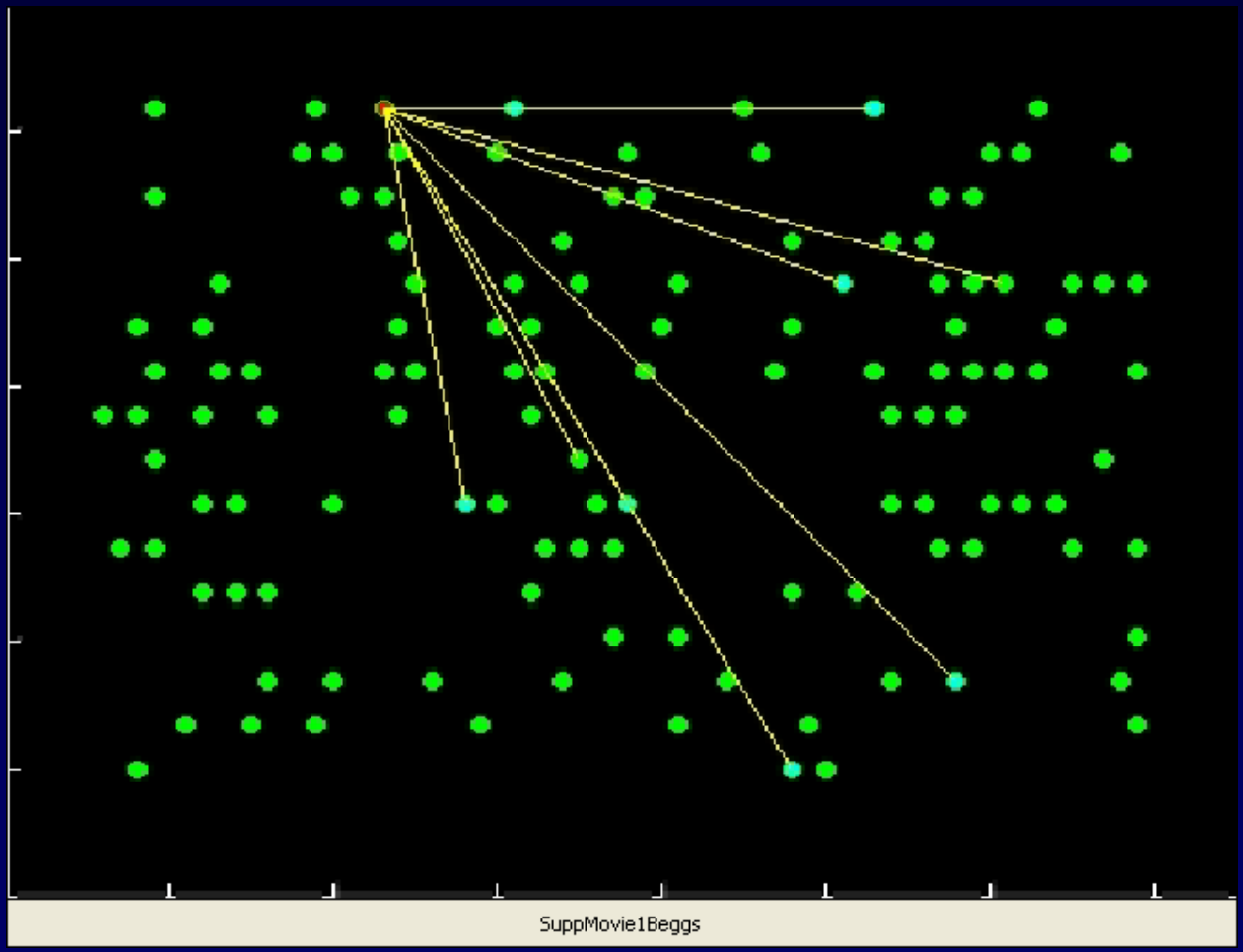


Good recordings



Time-lagged spikes



Outline

- Neuroscience background
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What is the pattern of information flow in local cortical networks?

What does it mean for two neurons to share a “connection”?

Different types of connections

- Physical: Is there a connection?

Different types of connections

- Physical: Is there a connection?
- Functional: Is there a correlation?

Different types of connections

- Physical: Is there a connection?
- Functional: Is there a correlation?
- Effective: Is there causation?

Different types of connections

- Physical: Is there a connection?
- Functional: Is there a correlation?
- Effective: Is there causation? Does knowing activity in one neuron help us to predict the activity of another?

What is the effective connectivity of a network of neurons in cortex?

We will pursue this by looking for information flow between neurons

Answering this will tell us if the brain has an efficient network

Answering this will tell us how the brain will respond to random cell loss (Alzheimer’s)

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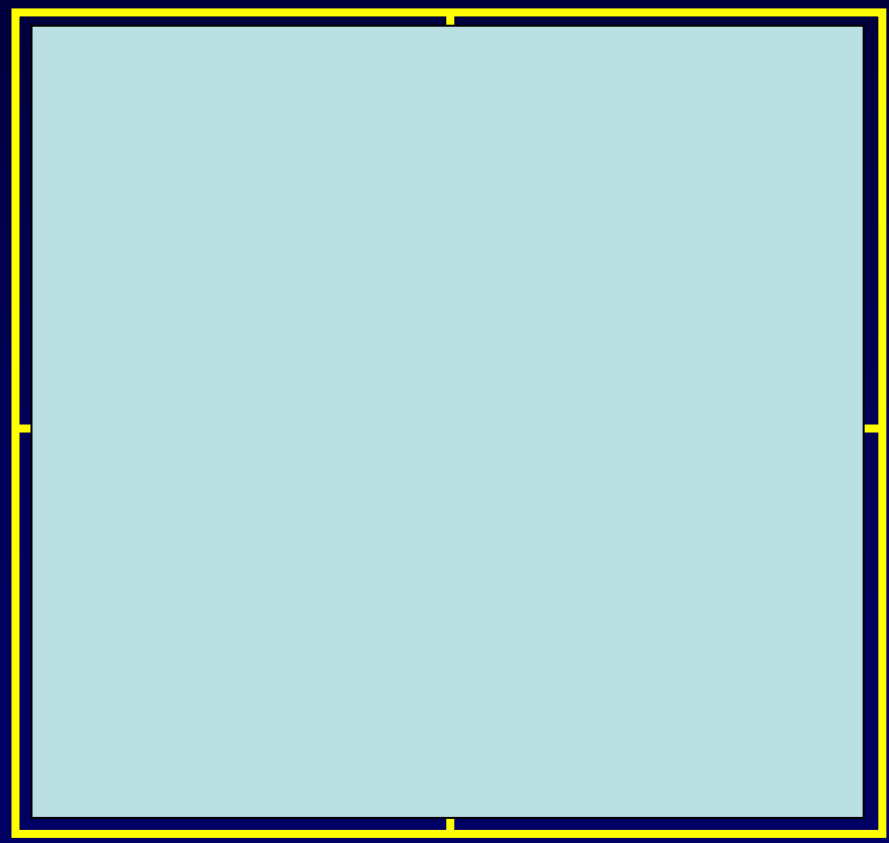
Information: a reduction in uncertainty

Information: a reduction in uncertainty

A ball is randomly placed in one of four quadrants

Is it in the upper half of the box?

No.



Information: a reduction in uncertainty

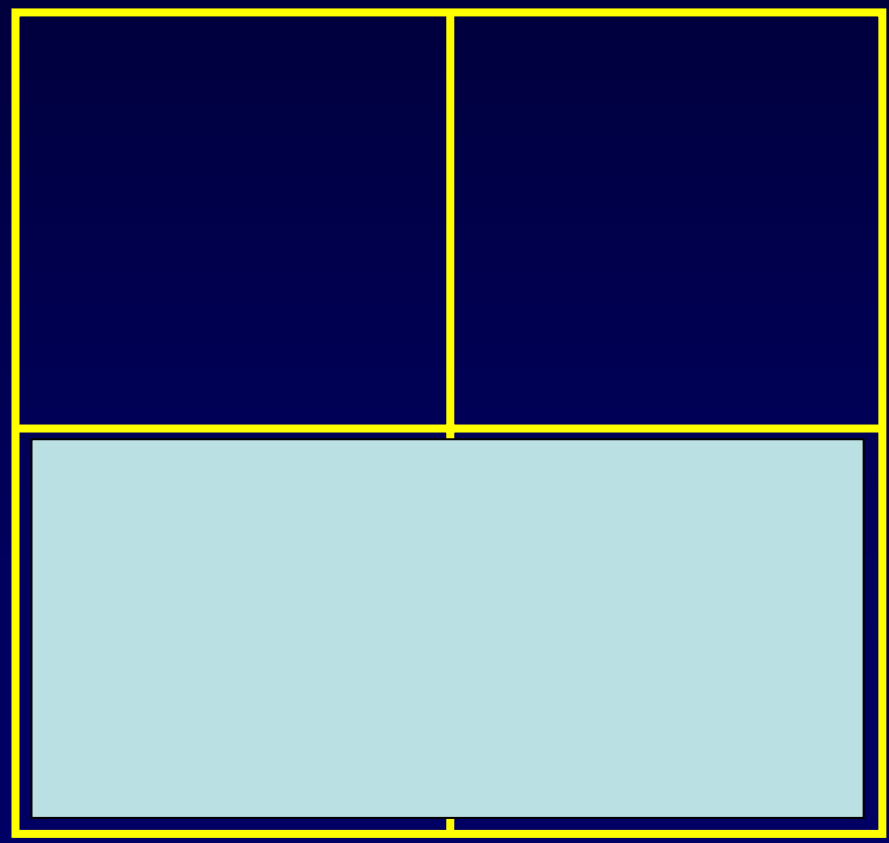
A ball is randomly placed in one of four quadrants

Is it in the upper half of the box?

No.

Is it in the left half of the box?

Yes.



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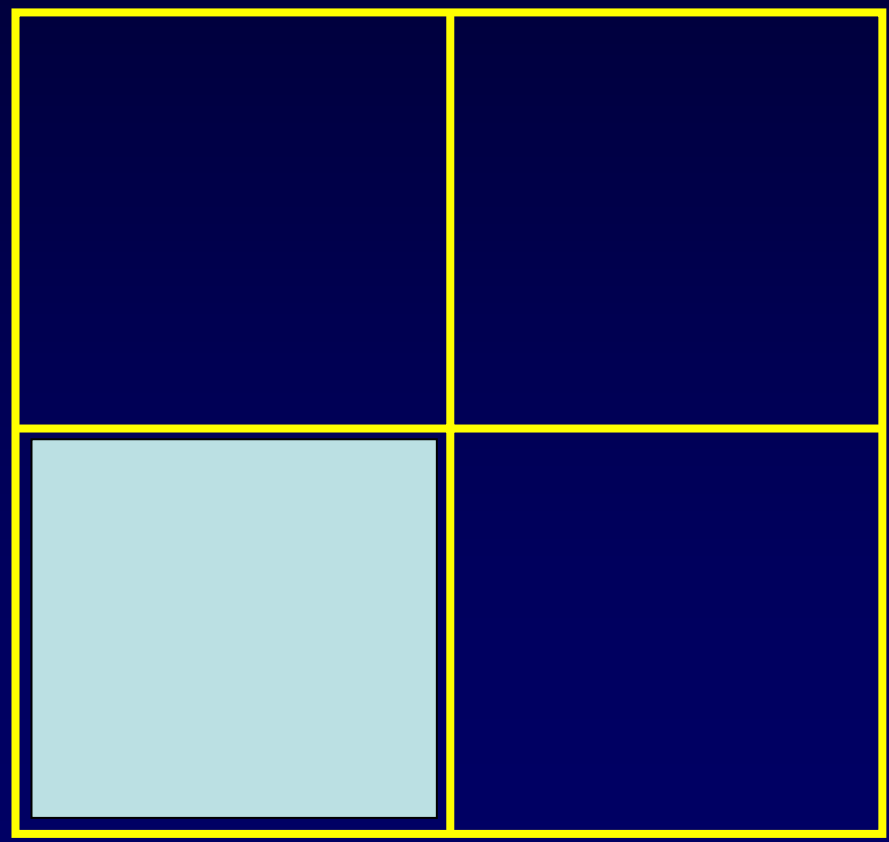

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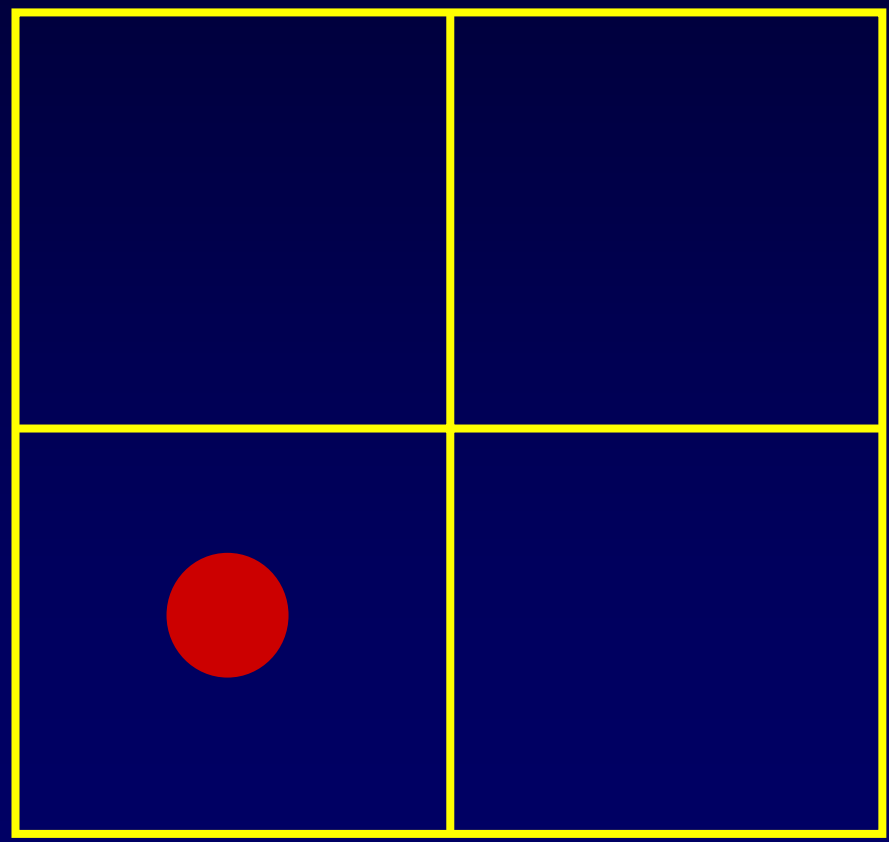

We can quantify this reduction in uncertainty

A ball is randomly placed in one of four quadrants

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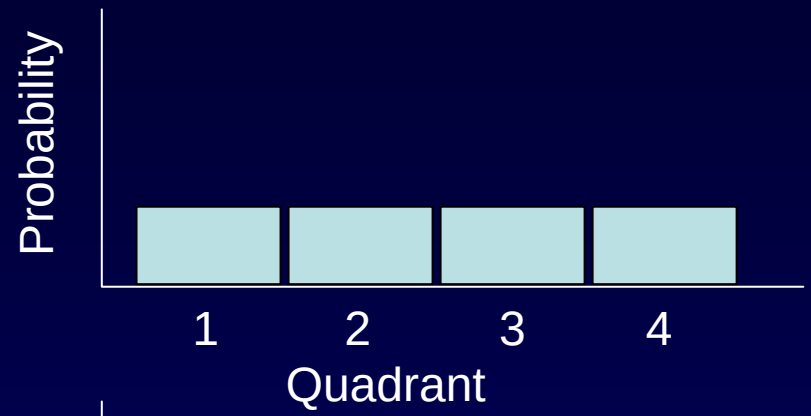
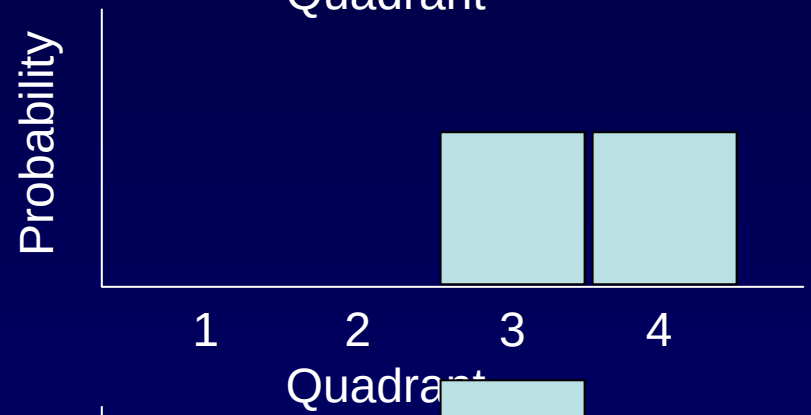
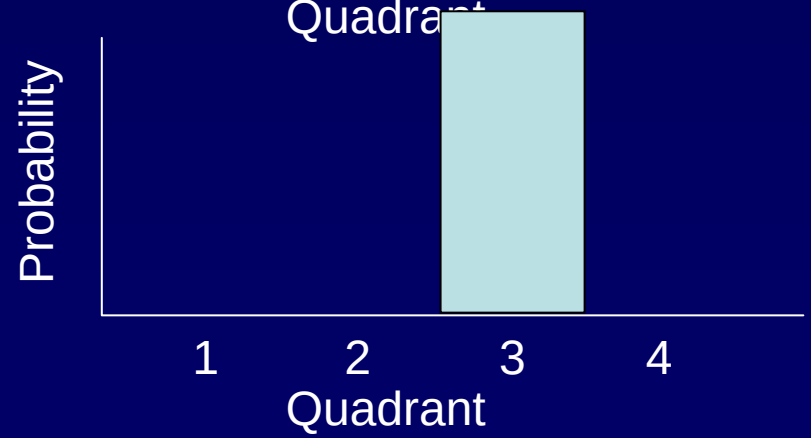
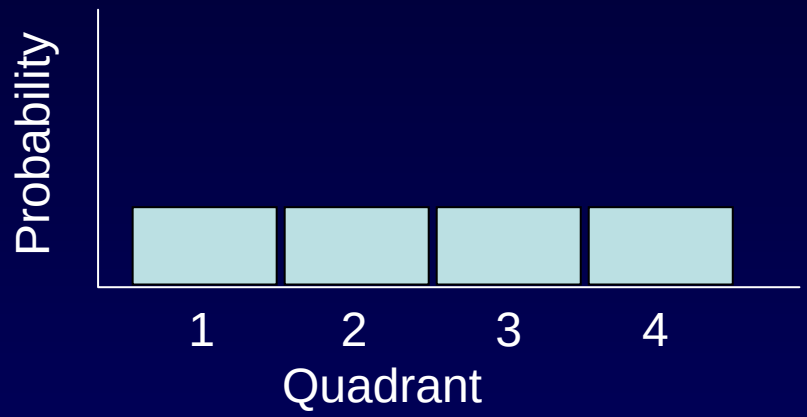






We can quantify uncertainty with entropy

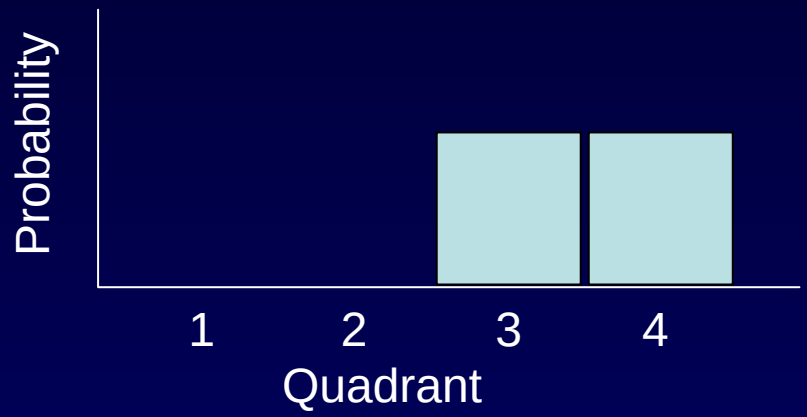


$$S = -\sum_{i=1}^{4} p_i \times \log_2(p_i)$$

$$S_1 = -\frac{1}{4} \times \log_2\left(\frac{1}{4}\right) - \frac{1}{4} \times \log_2\left(\frac{1}{4}\right) - \frac{1}{4} \times \log_2\left(\frac{1}{4}\right) - \frac{1}{4} \times \log_2\left(\frac{1}{4}\right)$$

$$S_1 = 2$$

We can quantify uncertainty with entropy

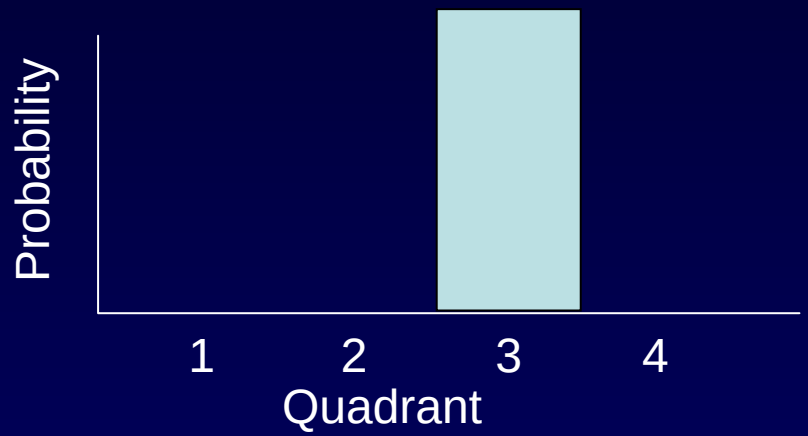


$$S = -\sum_{i=1}^{4} p_i \times \log_2(p_i)$$

$$S_2 = -\frac{1}{2} \times \log_2\left(\frac{1}{2}\right) - \frac{1}{2} \times \log_2\left(\frac{1}{2}\right)$$

$$S_2 = 1$$

We can quantify uncertainty with entropy



$$S = -\sum_{i=1}^{4} p_i \times \log_2(p_i)$$

$$S_3 = -\frac{1}{1} \times \log_2\left(\frac{1}{1}\right)$$

$$S_3 = 0$$

Information: a reduction in entropy

A ball is randomly placed in one of four quadrants

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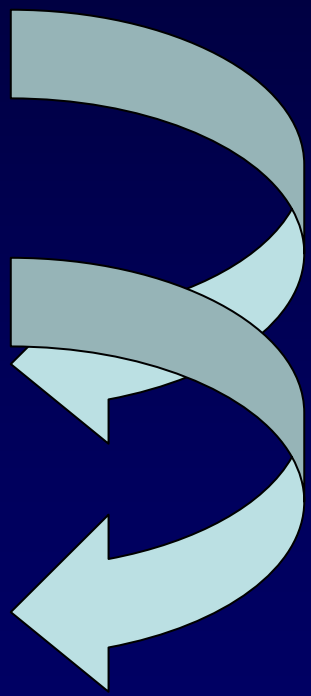
No.

Is it in the left half of the box?

Yes.



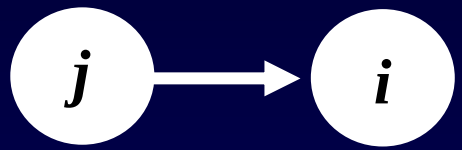
$$S_1 - S_2 = 2 - 1 = 1$$

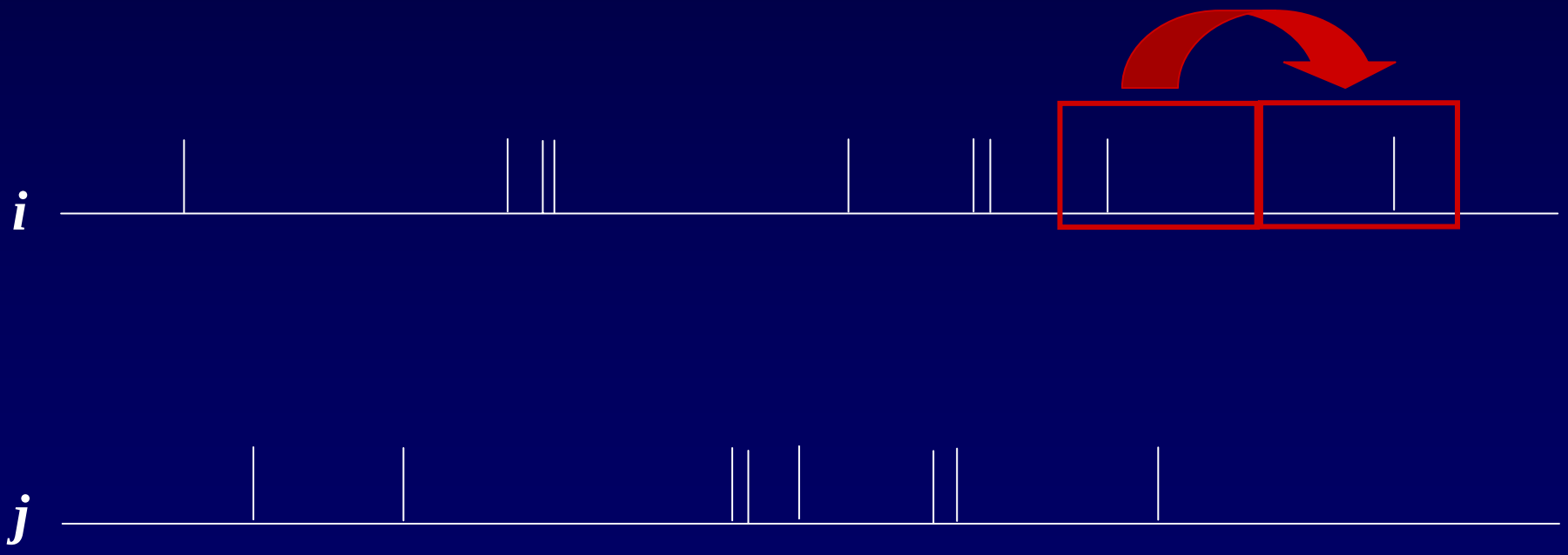
$$S_2 - S_3 = 1 - 0 = 1$$

Each time you cut the sample space in half, you gain 1 bit of information
Claude Shannon, Bell labs (1949)

How can we use this to tell if two neurons have effective connectivity?

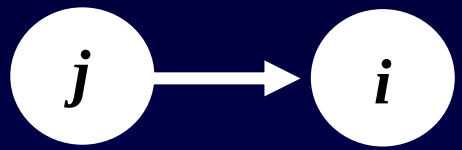
How well does i_n predict i_{n+1} ?

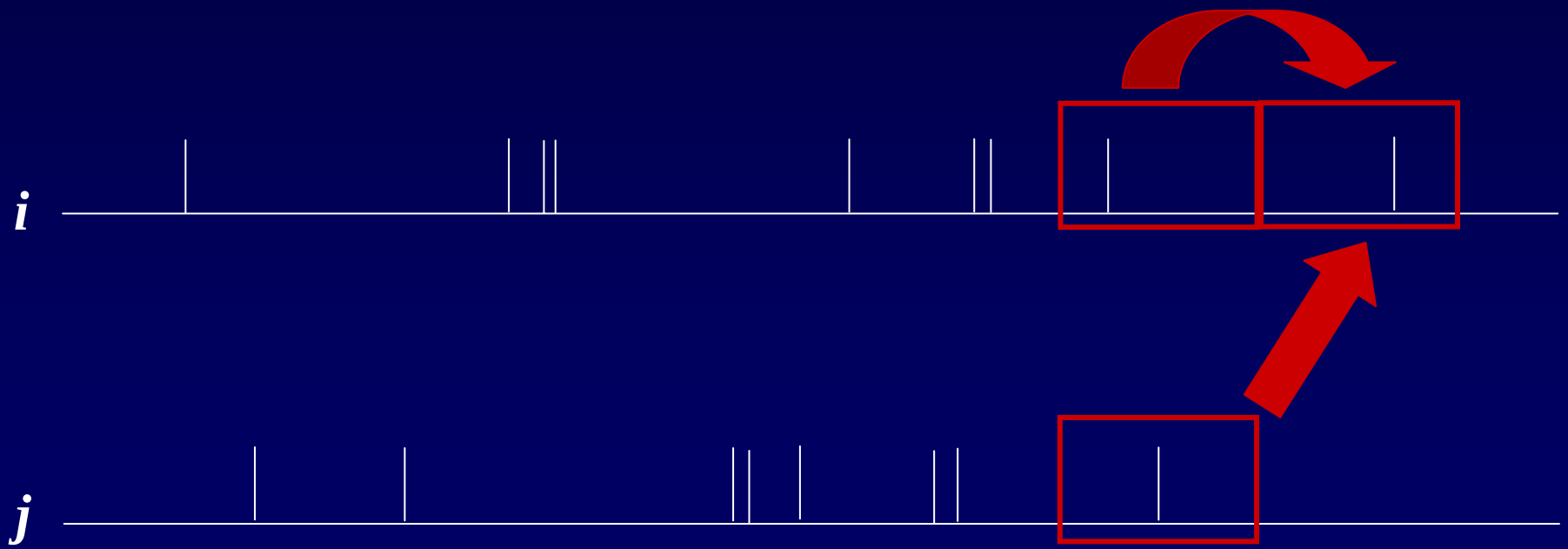




$$Info_{i_n \to i_{n+1}} = S(i_{n+1}) - S(i_{n+1} \mid i_n)$$

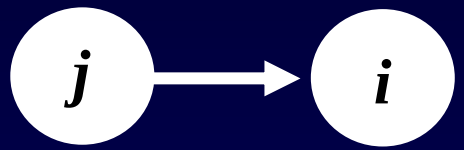
How well do i_n and j_n predict i_{n+1} ?

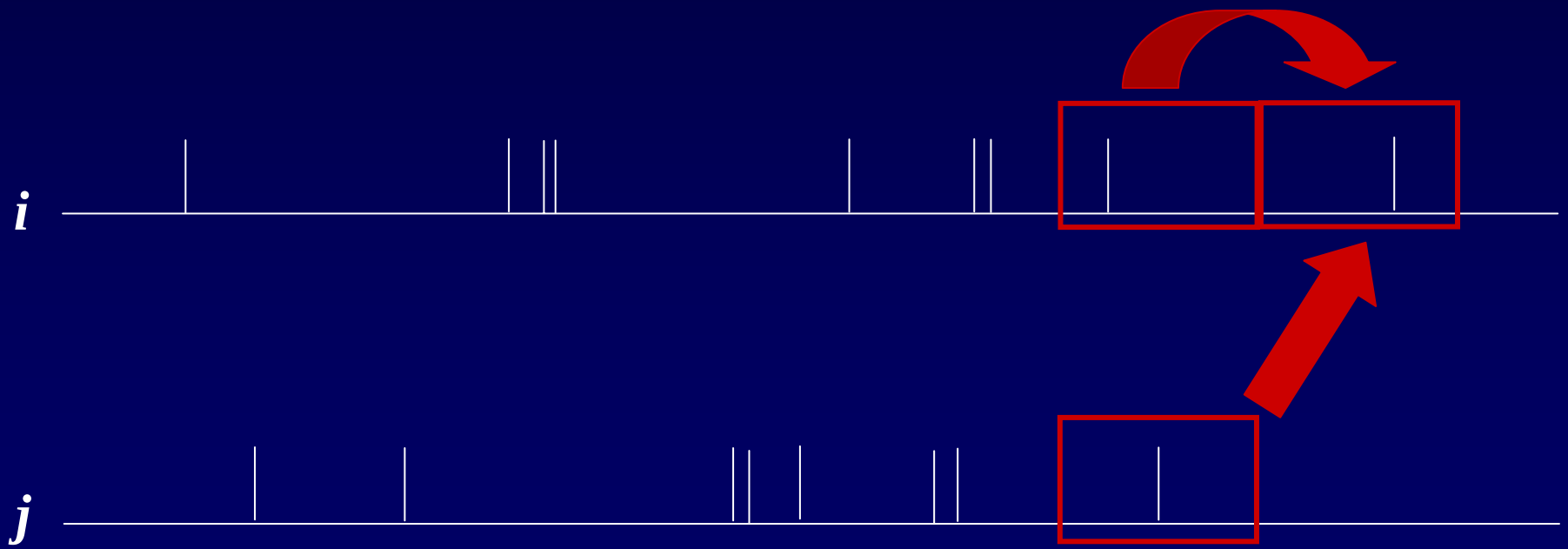




$$Info_{i_n, j_n \to i_{n+1}} = S(i_{n+1}) - S(i_{n+1} \mid i_n, j_n)$$

If including j_n improves the prediction, then there is effective connectivity





$$Info_{j_n \to i_{n+1}} = Info_{i_n, j_n \to i_{n+1}} - Info_{i_n \to i_{n+1}}$$

We are measuring “transfer entropy”

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Measuring Information Transfer

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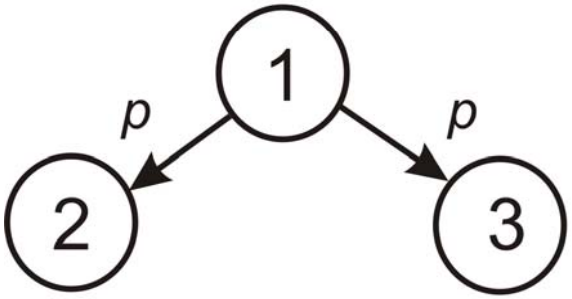
(Received 19 January 2000)

An information theoretic measure is derived that quantifies the statistical coherence between systems evolving in time. The standard time delayed mutual information fails to distinguish information that is actually exchanged from shared information due to common history and input signals. In our new approach, these influences are excluded by appropriate conditioning of transition probabilities. The resulting *transfer entropy* is able to distinguish effectively driving and responding elements and to detect asymmetry in the interaction of subsystems.

$$T_{J\to I} = \sum p(i_{n+1}, i_n^{(k)}, j_n^{(l)}) \log \frac{p(i_{n+1} \mid i_n^{(k)}, j_n^{(l)})}{p(i_{n+1} \mid i_n^{(k)})}$$

Why is transfer entropy better than correlation?

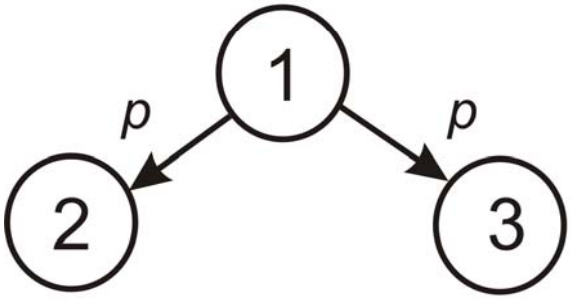
Lagged correlation



Network model

Correlation is not causation!

Transfer entropy



Network model

Transfer entropy is not fooled by a common source

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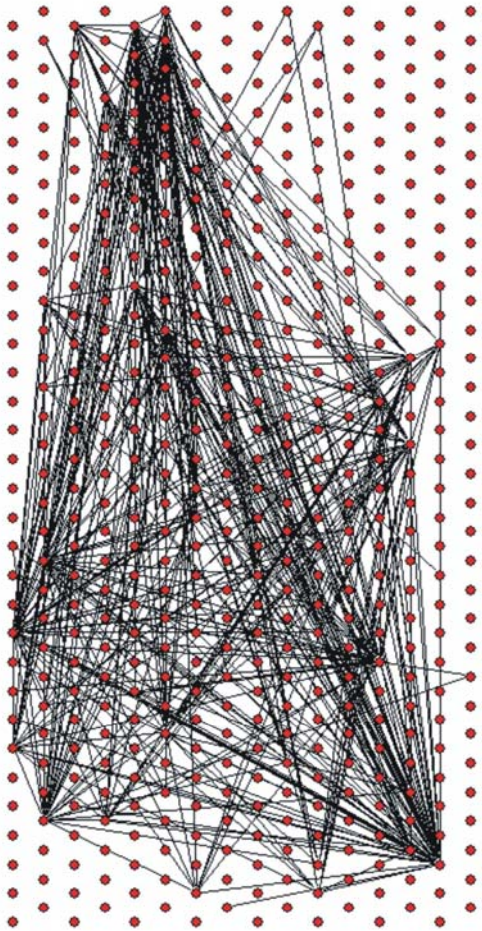
What should we expect?

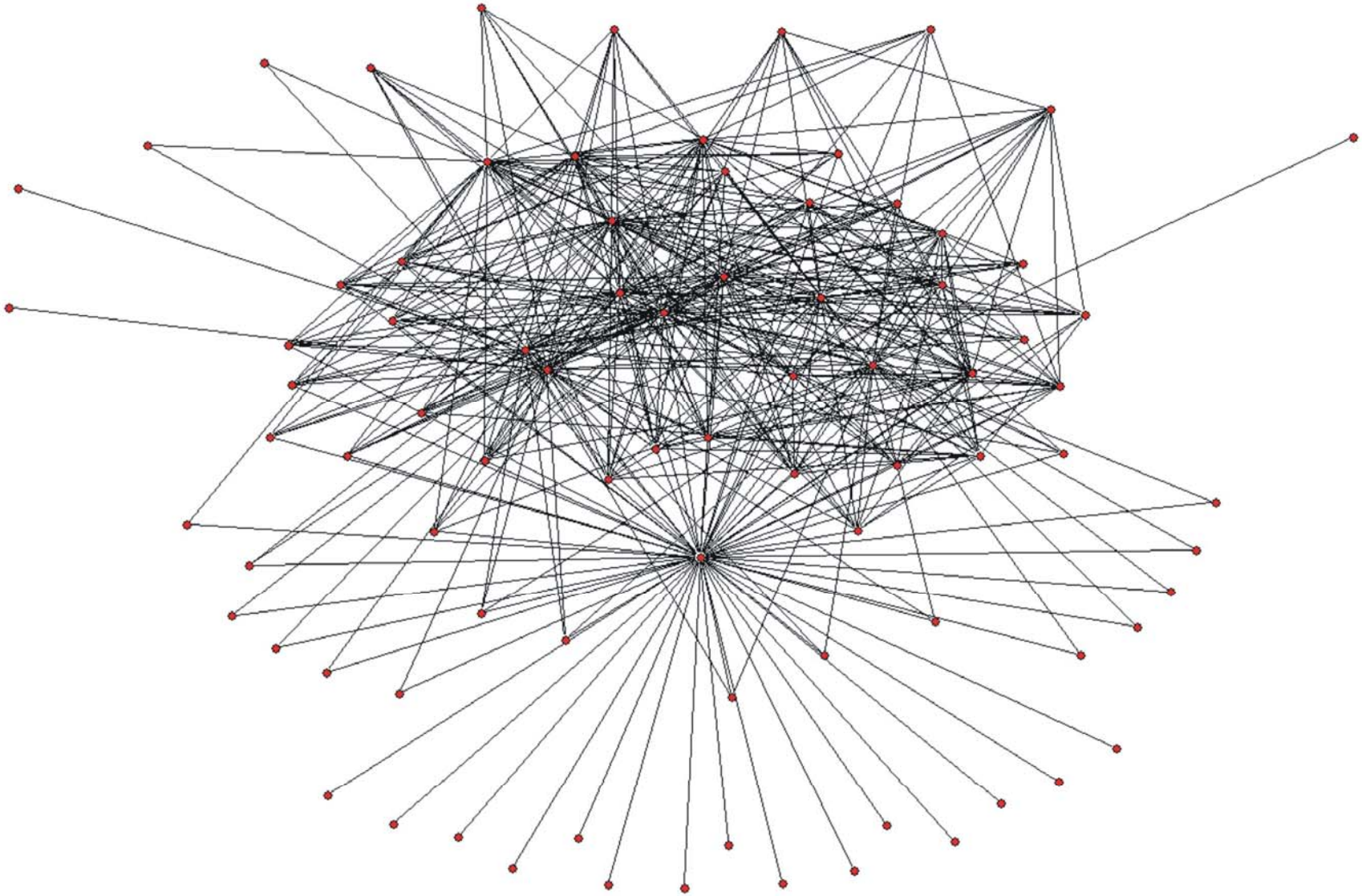
Hypothesis 1: Information load is carried by neurons *evenly* (all neurons have roughly the same number of synapses)

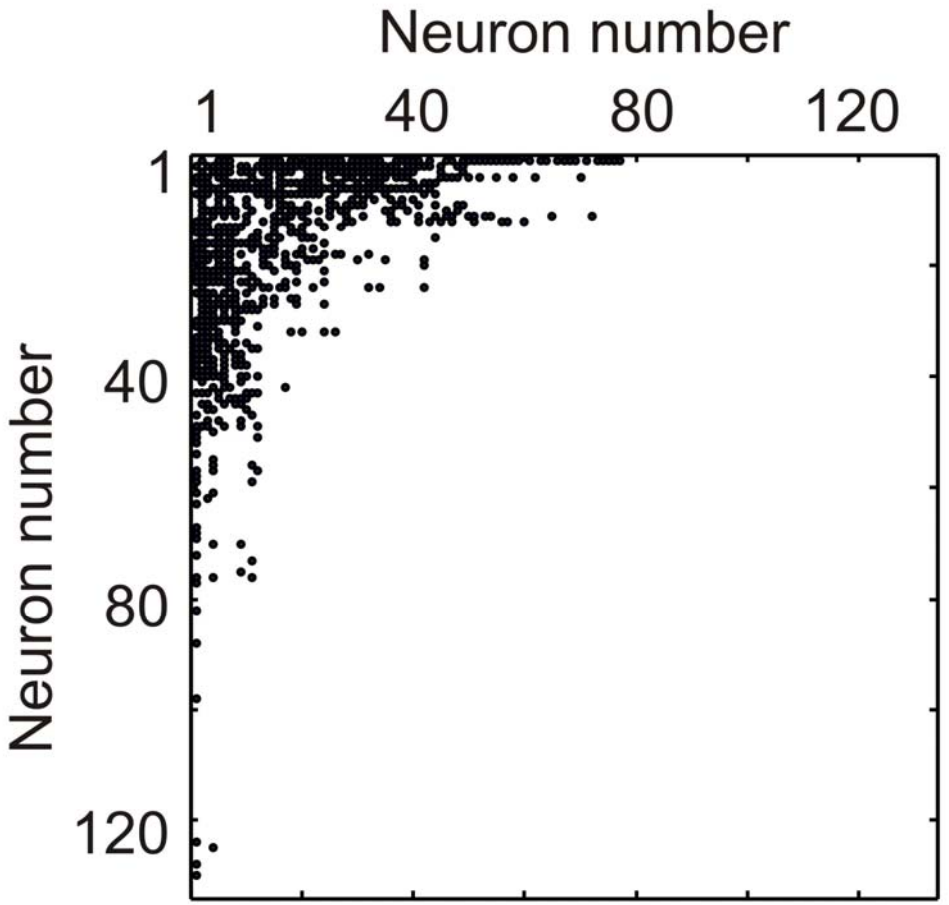
Hypothesis 2: Information load is carried by neurons *unevenly* (many natural networks contain hubs)

Physical map

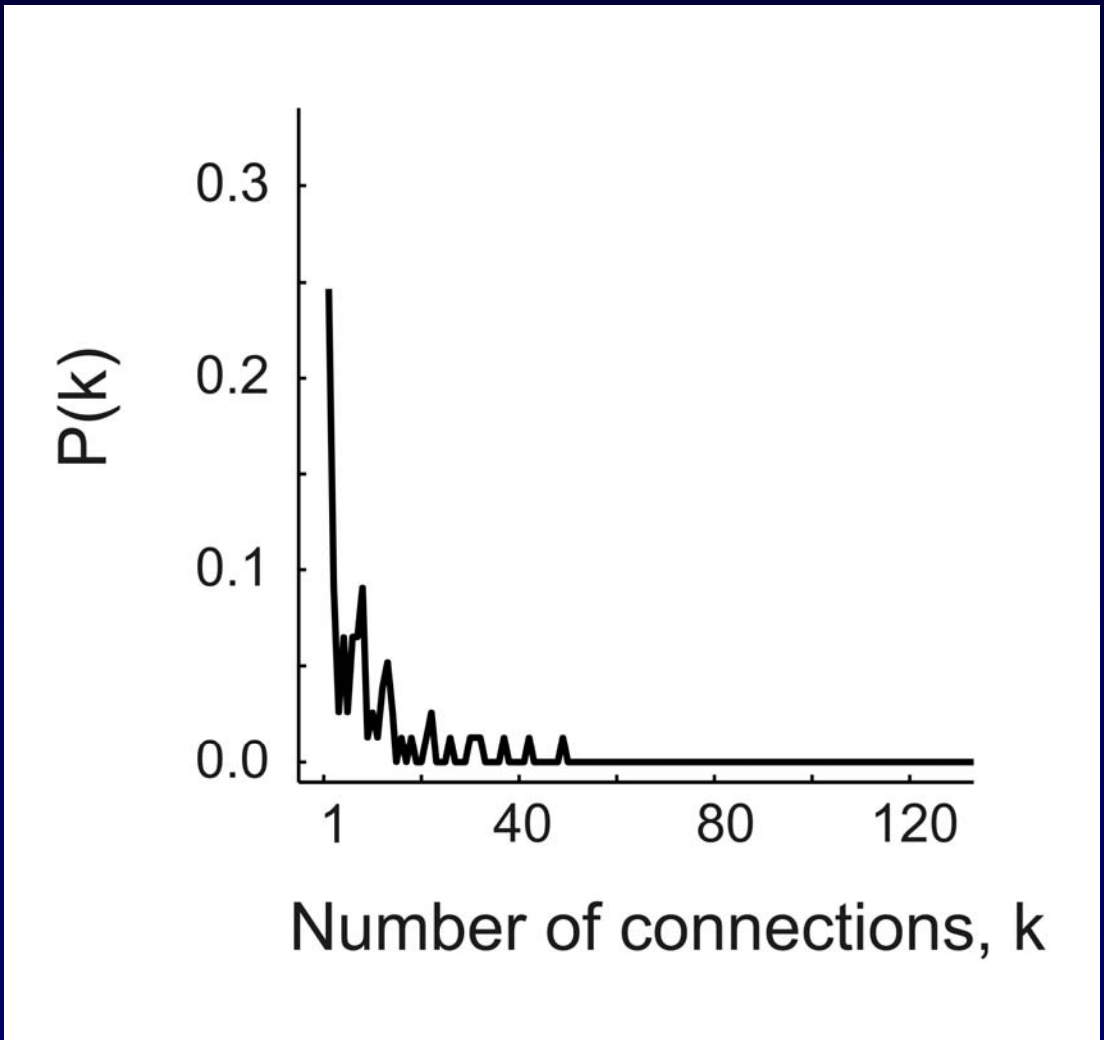


Topological map




Neuron number
1
40
80
120
Neuron number
1
40
80
120

(in)Degree distribution



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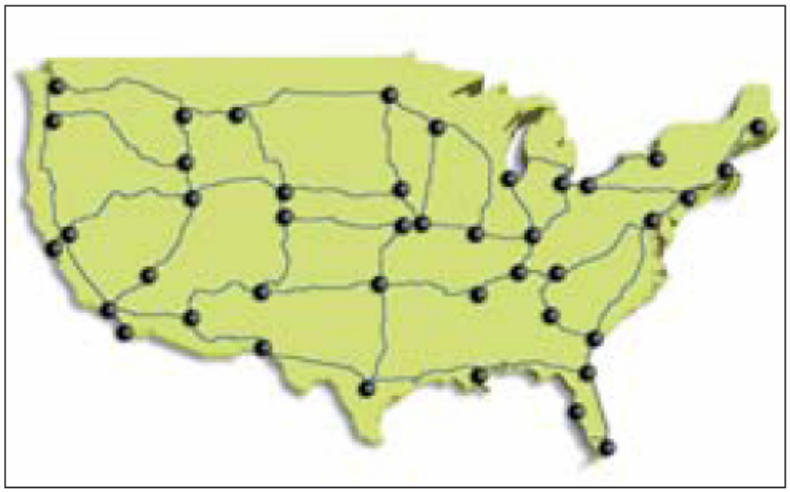
Why do some nodes have more connections than others?

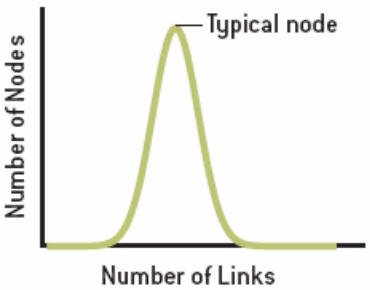
Do hubs improve the efficiency of the brain?

Different types of networks

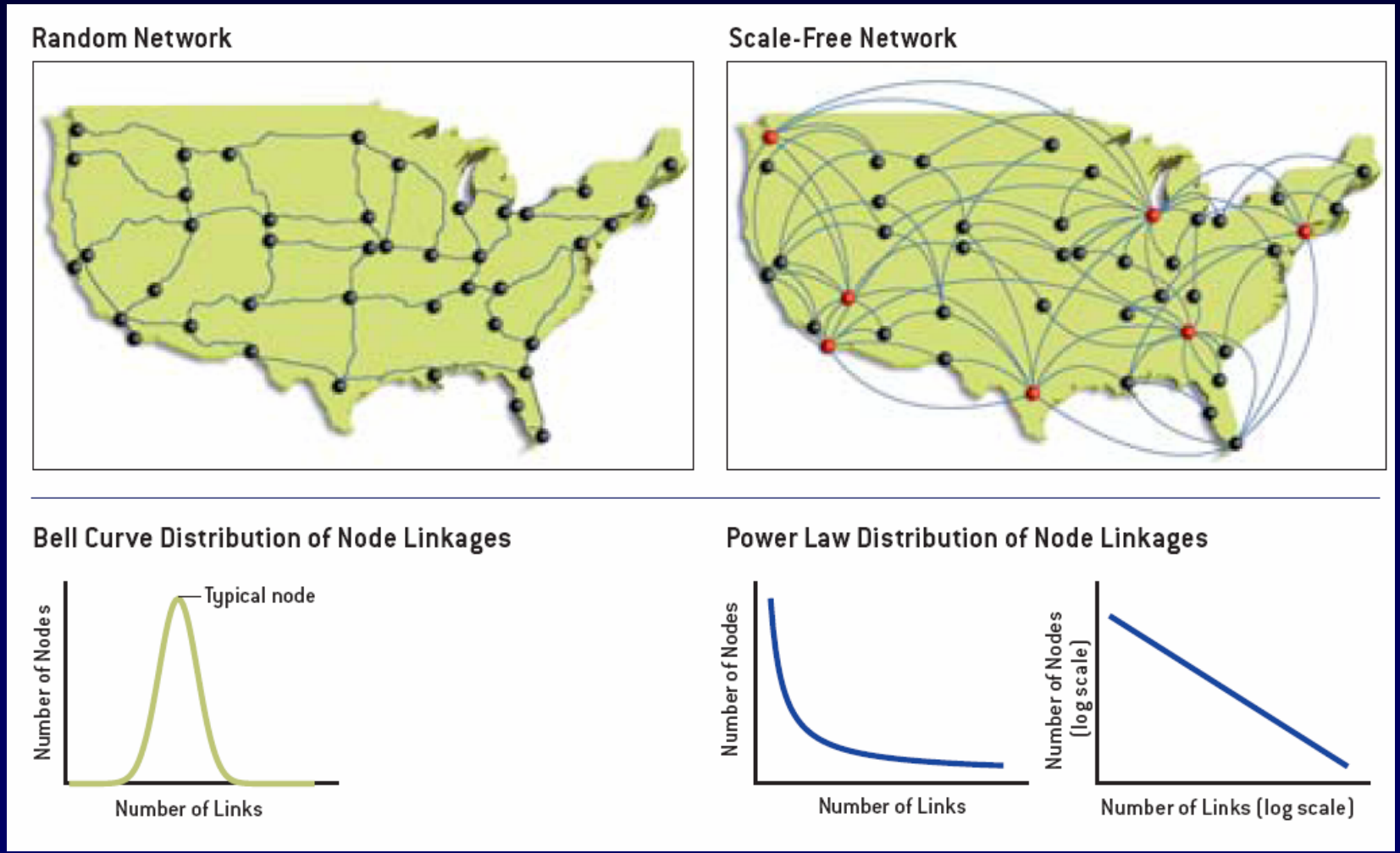
Random Network



Bell Curve Distribution of Node Linkages

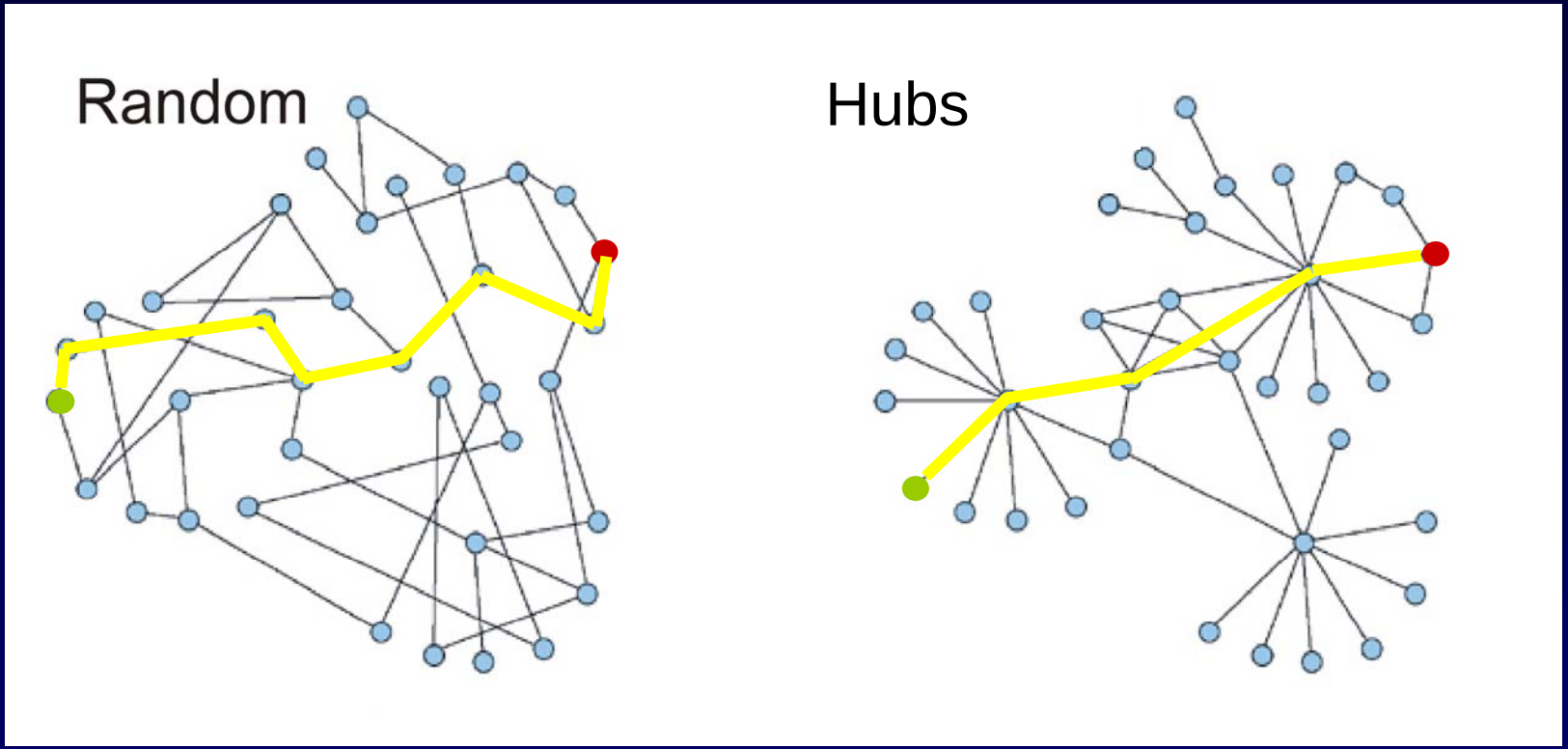


Different types of networks



Barabasi and Bonabeau, “Scale-free networks” Scientific American, May 2003.

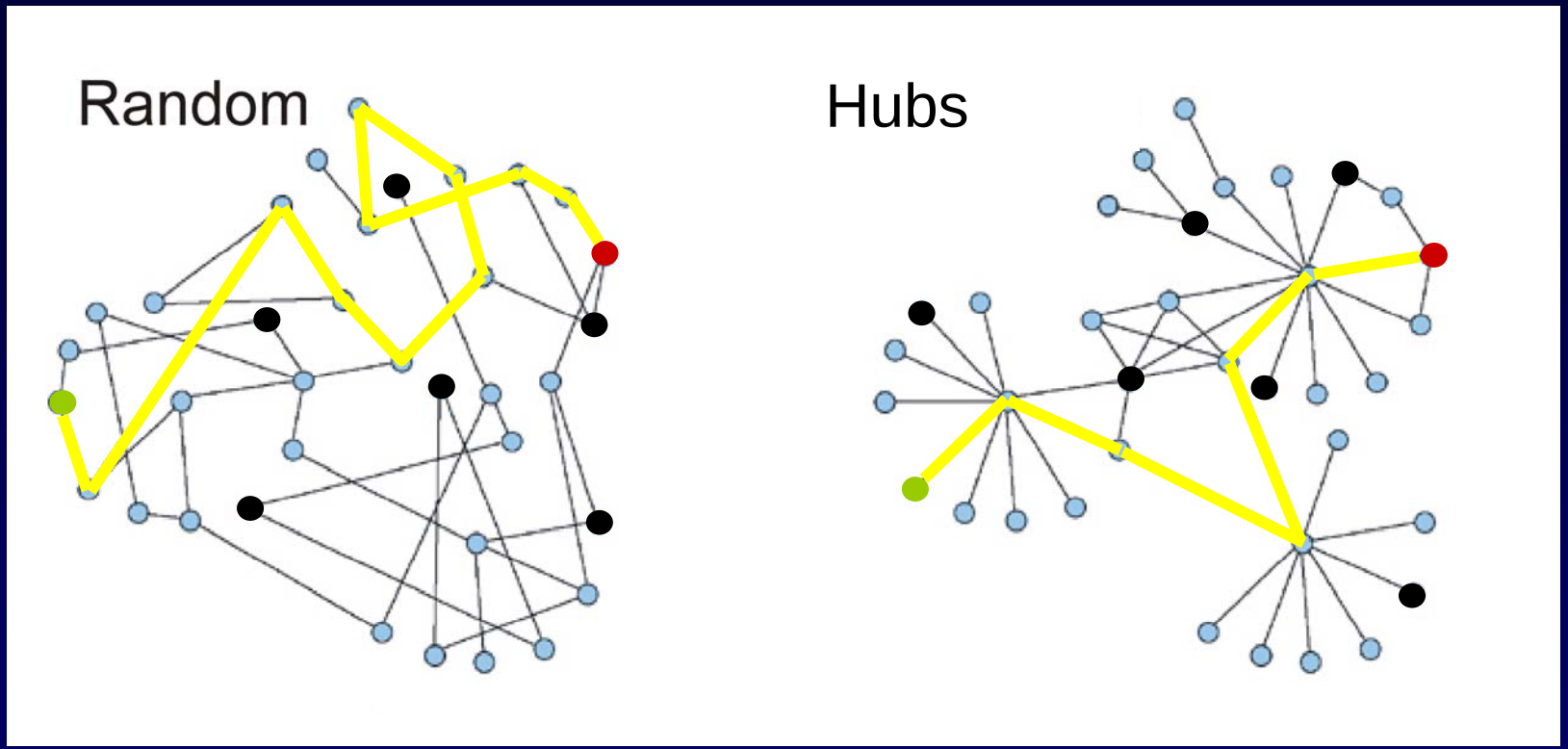
Consequences of network structure



Hubs: more efficient transport

Watts and Strogatz, 1998; Albert and Barabasi, 2002

Consequences of network structure



Hubs: more robust to random failure of nodes

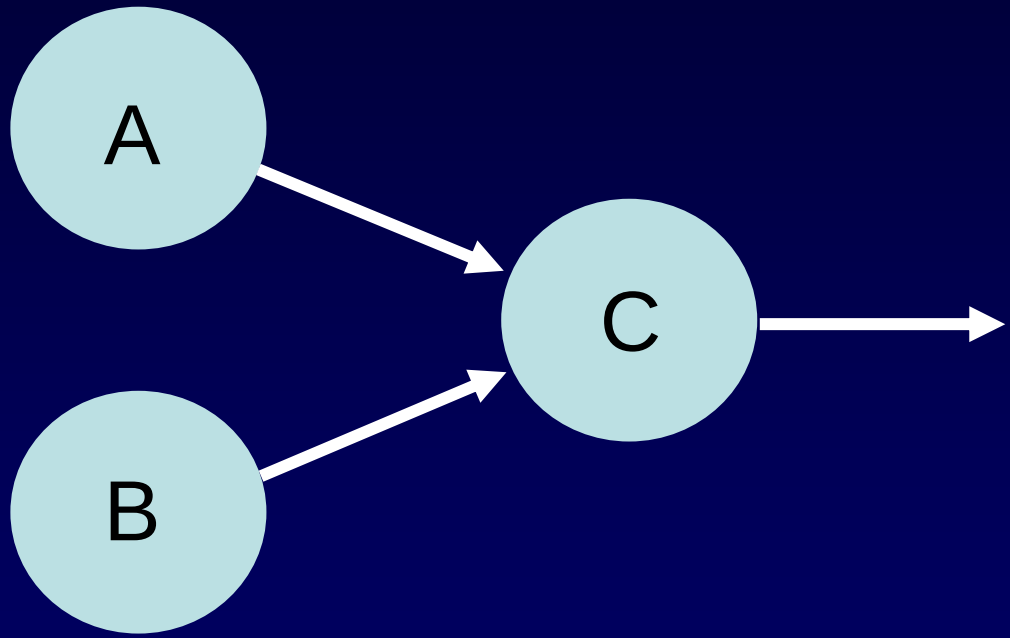
Albert, Jeong, Barabasi, 2000

Why do some nodes have more connections than others?

What if airlines were forced to have the same number of flights to Peoria as to Chicago?

Consequences of network structure

What happens at nodes where information flows converge?



$$Info_{A \to C} + Info_{B \to C} < Info_{A,B \to C} \; ?$$

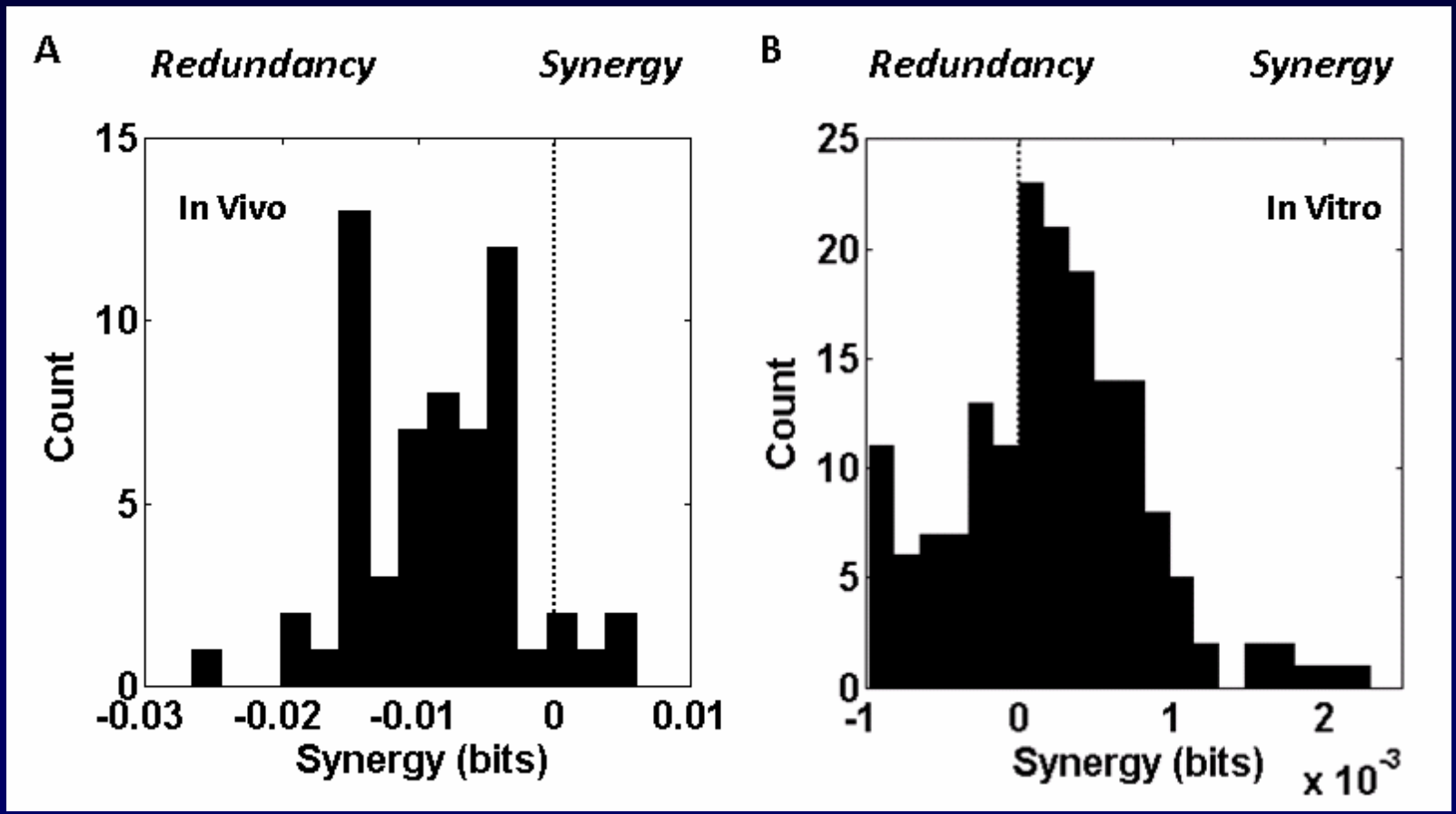
What happens at nodes where information flows converge?

A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

$$Info_{A\to C} = 0.3113$$
$$Info_{B\to C} = 0.3113$$
$$Info_{A,B\to C} = 0.8113$$
$$Info_{A,B\to C} - (Info_{A\to C} + Info_{B\to C}) = 0.1887$$

The “AND” gate is revealed by synergy

What happens at nodes where information flows converge?



Outline

- Neuroscience background
- Our question
- Measuring information flow
- Results
- Implications
- Final remarks

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- Information flow in cortical networks is unevenly distributed, with hubs: efficiency, robustness

Final remarks

- Information flow in cortical networks is unevenly distributed, with hubs: efficiency, robustness
- Converging information flows are usually redundant (error correction), but sometimes are synergistic (computations)

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