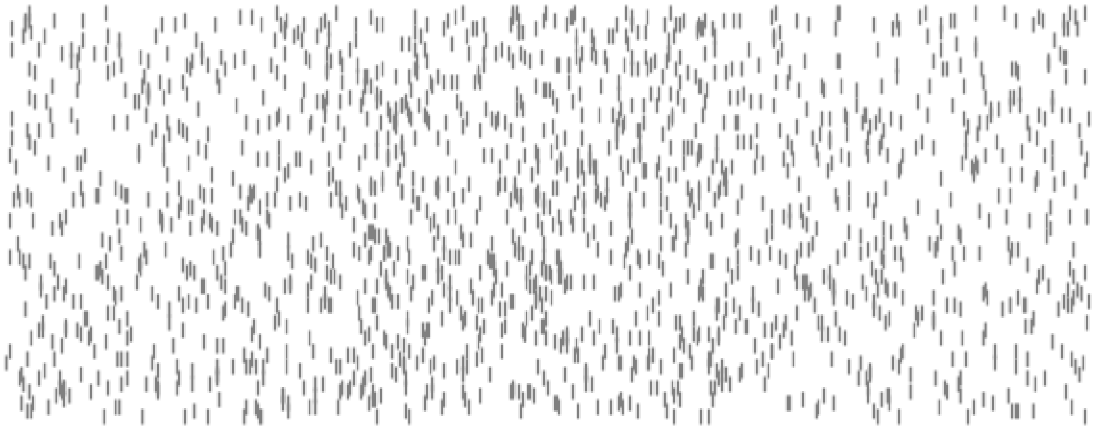

Spiking neural network simulation with Brian

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Why study networks of neurons?

- Studying neurons in isolation has its limits
  - the brain is **highly recurrent**, the output of a neuron affects the network and therefore its input
- Everything we perceive, think, or do results from the **activity of many neurons**
- **Memories** (short and long-term) are stored on the network level, not in individual neurons
- **Dynamics of the network** (and not just of individual neurons) are important for healthy brains ("brain rhythms") as well as in disease (e.g. epilepsy)

Modelling networks of neurons

Three main components:

1) Individual neurons

How is a single neuron modeled?

2) Synaptic connectivity

Which neurons connect to each other?

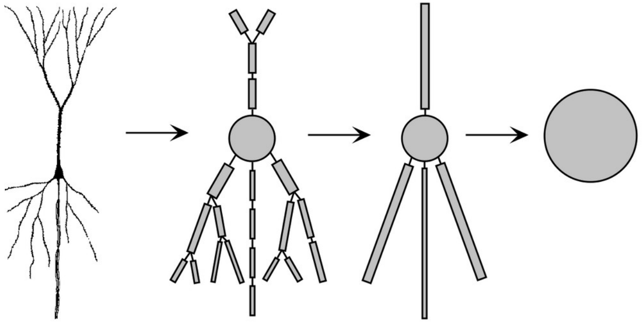
3) Synaptic models

What is the effect of a spike arriving at the synapse?

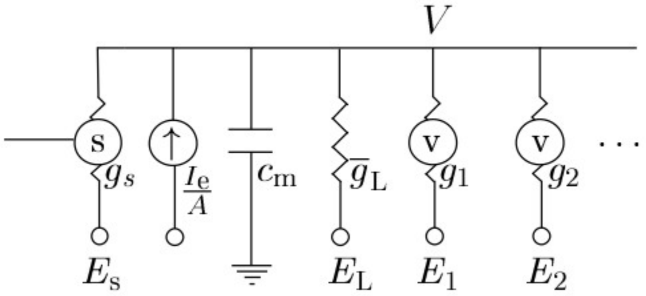
Also: how does this effect change over time (plasticity)

Individual neurons

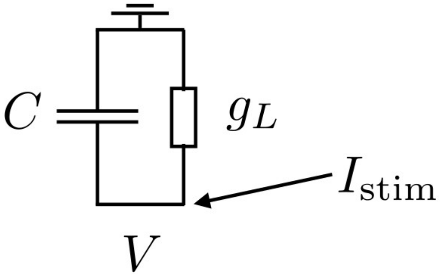
Spatially extended model



Point-neuron model



Hodgkin-Huxley formalism

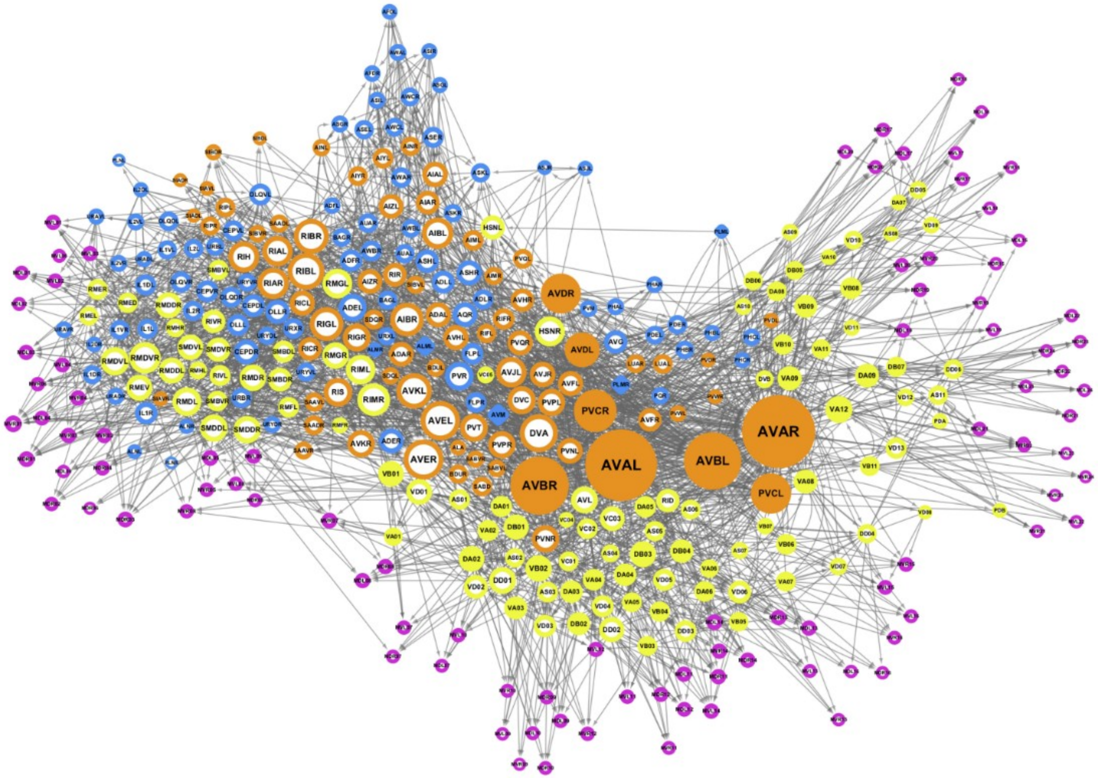


integrate-and-fire model

→ see lecture/tutorial 8

Synaptic connectivity

- Structured connectivity

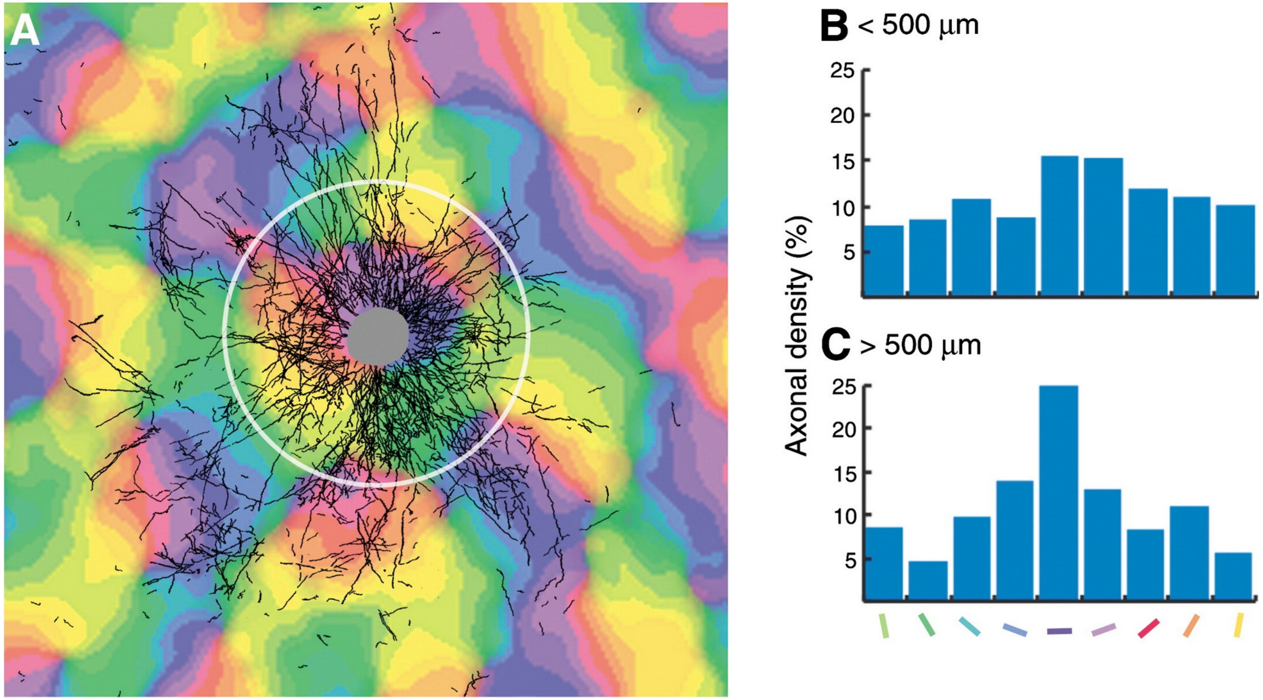


C. elegans connectome

Yan et al., Nature (2017)

Synaptic connectivity

- Structured connectivity



Superficial layers of V1
in Macaque monkeys

Stettler et al., Neuron (2002)

Synaptic connectivity

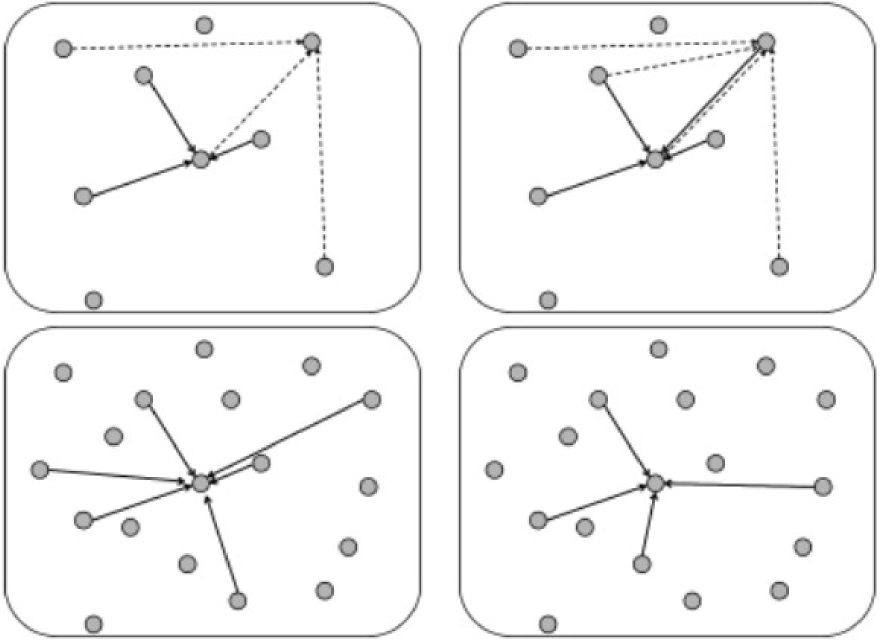
- Unstructured (random) connectivity

Fixed probability

Fixed number of inputs

N = 9

N = 18



Gerstner et al., Neuronal Dynamics , chapter 12

Synaptic models

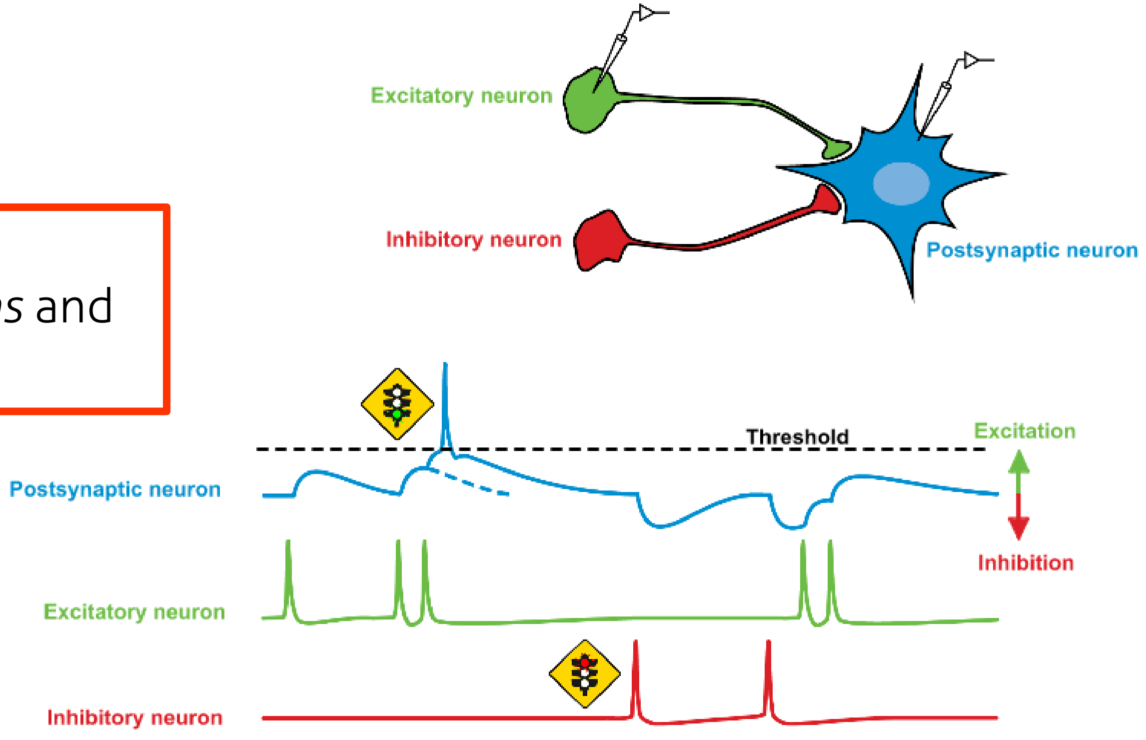
Synapses

?

Why can we talk about excitatory/inhibitory *neurons* and not just synapses?

!

→ "Dale's law"
Neurons release the same neurotransmitter(s) on every synapse



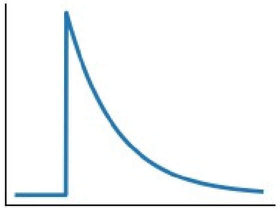
Synaptic models

Synapses

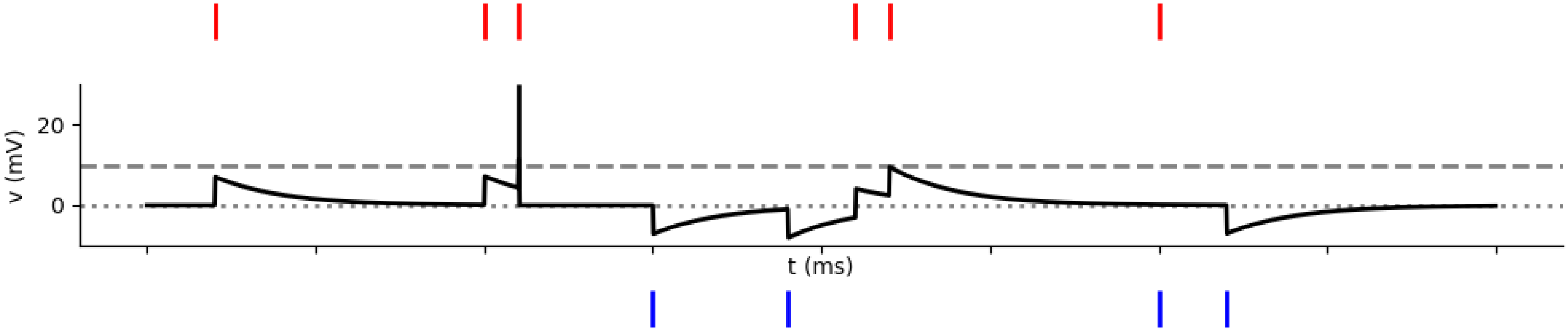
weight from j to i

For each spike: increase V_m by J_{ij}

membrane potential



"delta synapse"

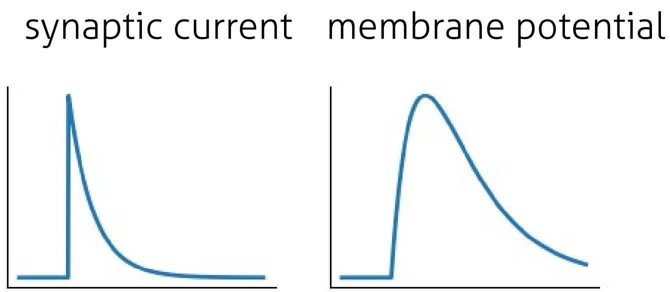


Synaptic models

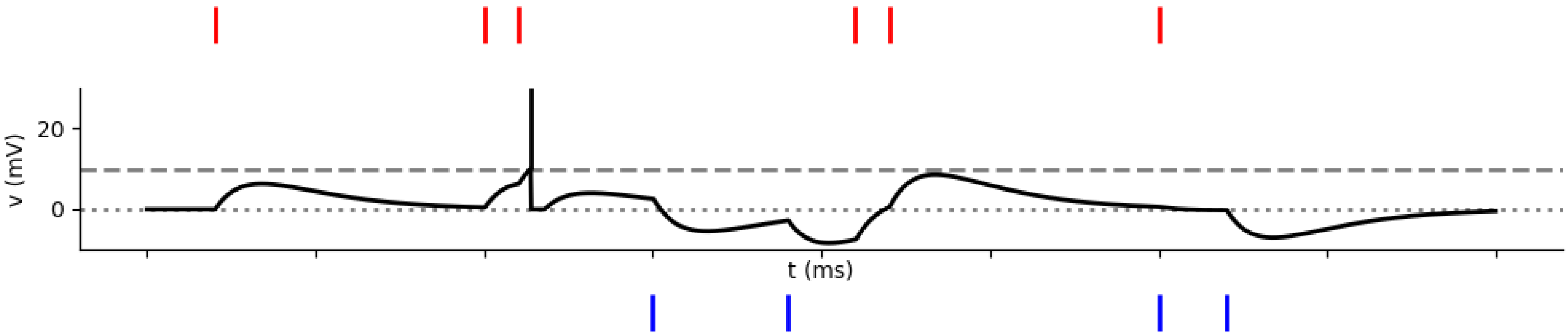
Synapses

For each spike: increase I_{syn} by J_{ij}

Between spikes: I_{syn} exponentially decays to 0



Current-based synapse



Synaptic models

Synapses

$I_{syn} = g_{syn} (E_{syn} - V_m)$

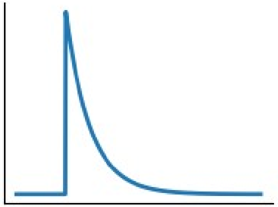
For each spike:

increase g_{syn} by J_{ij}

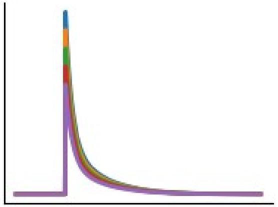
Between spikes:

g_{syn} exponentially decays to 0

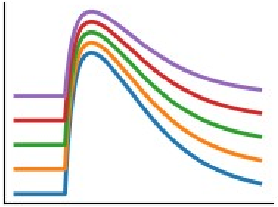
synaptic conductance



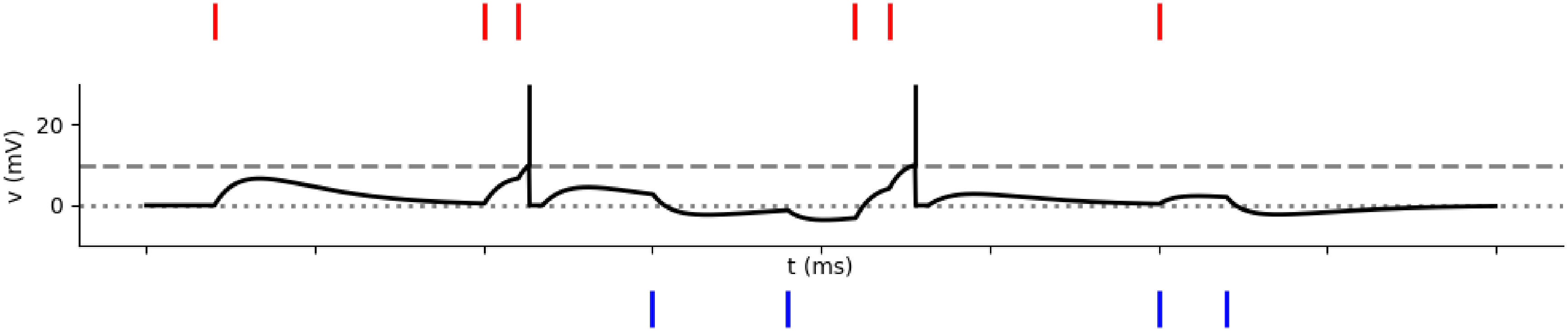
synaptic current



membrane potential



exponential conductance-based



Neurons in a network

In the mouse cortex

- **Neurons:** ~90 000/mm³
  Synapses: ~8000 per neuron
  ~270 000 000 synapses/mm³
- **Fewer inhibitory neurons**
  (~20% of all neurons)

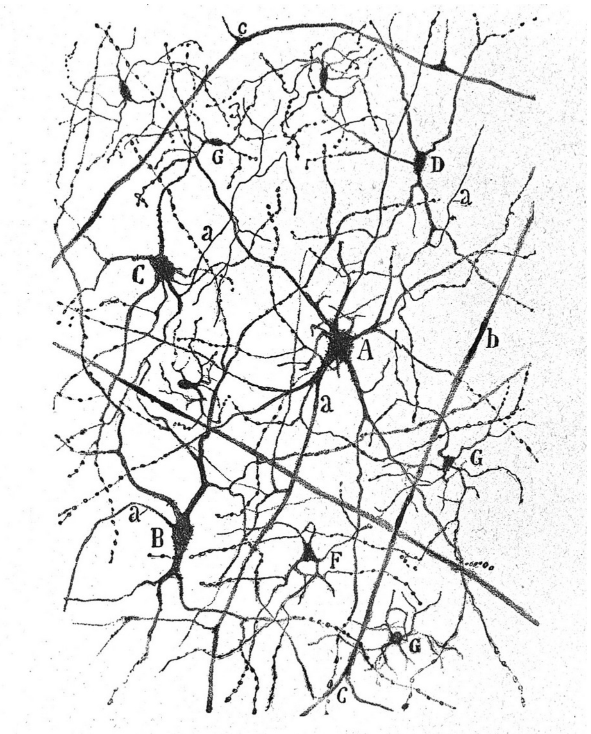


Fig. 339. — Coupe tangentielle de la couche plexiforme; chat adulte. Méthode d'Ehrlich.

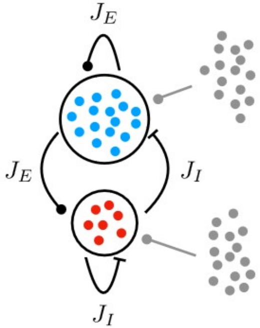
Network models: approaches

With thousands of neurons and millions of synapses (even in a very small part of the brain), how can we decide on the parameters? How can we get closer to an understanding of the system?

Roughly, two opposing approaches:

Try to gather as much data as possible
Use complex models and supercomputers

Simplify everything as much as possible
Use mathematics to gain insights



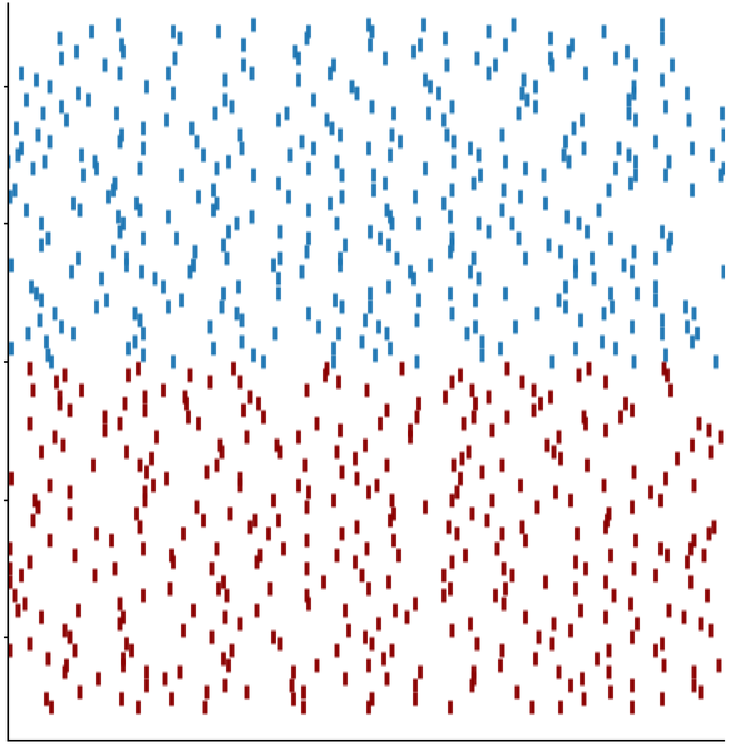
Network models: approaches

Today, we'll simplify things a lot

- **Leaky integrate-and-fire** point neuron model
  (no Hodgkin-Huxley dynamics, no neuronal morphology, …)
- **Homogeneous population**, all neurons are "the same"
  (no neuron types, no heterogeneity, …)
- **Simple synapse** model ("delta synapses")
  (no synaptic dynamics, no adaptation, no plasticity…)
- **Random connectivity** between neurons
  (no structure, no position in space, …)

Network dynamics

How can we characterize network activity?



Individual neurons:
Weakly or strongly active?
Firing regularly or irregularly?

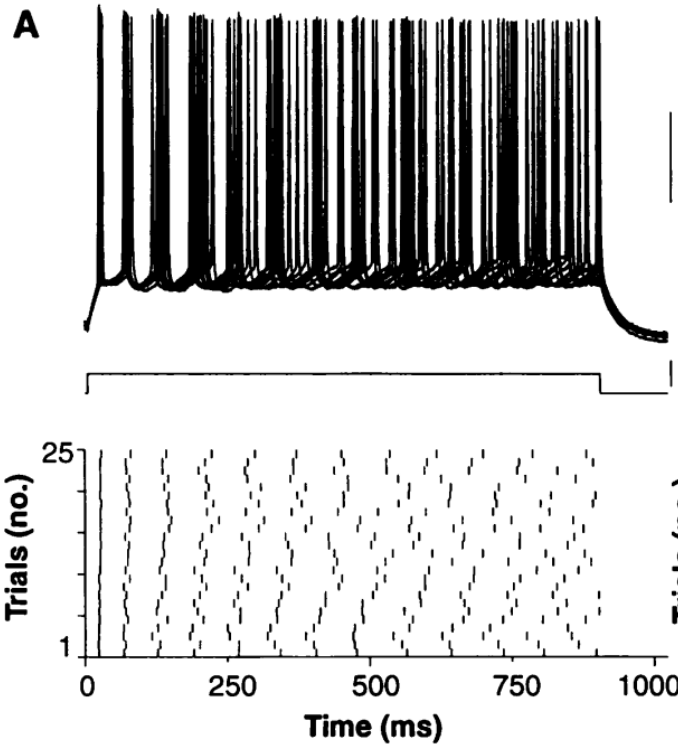
Firing rate,
ISI distribution → CV

Network:
Synchronized or unsynchronized?
Oscillating?

e.g. spectral analysis
(auto)correlation

Computing with spikes

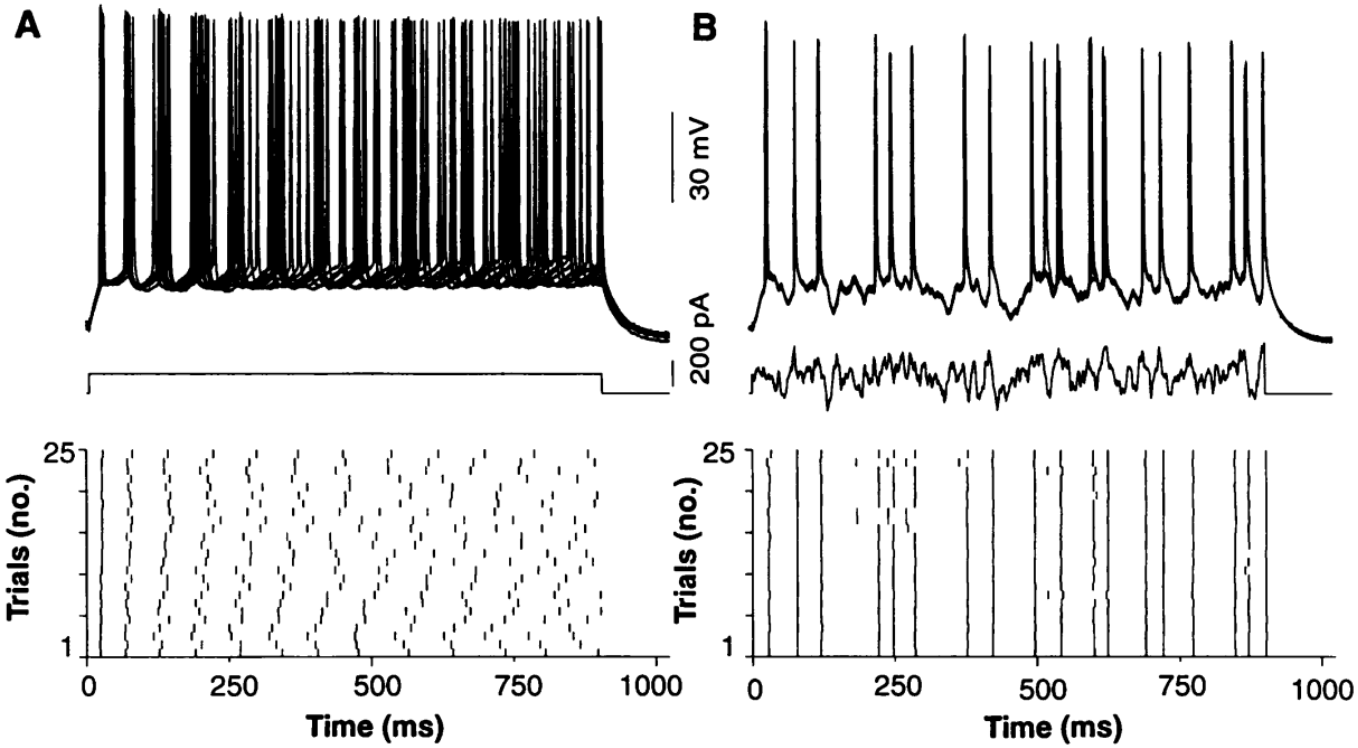
Constant current injection = **unreliable** spike times



Mainen & Sejnowski, Science (1995)

Computing with spikes

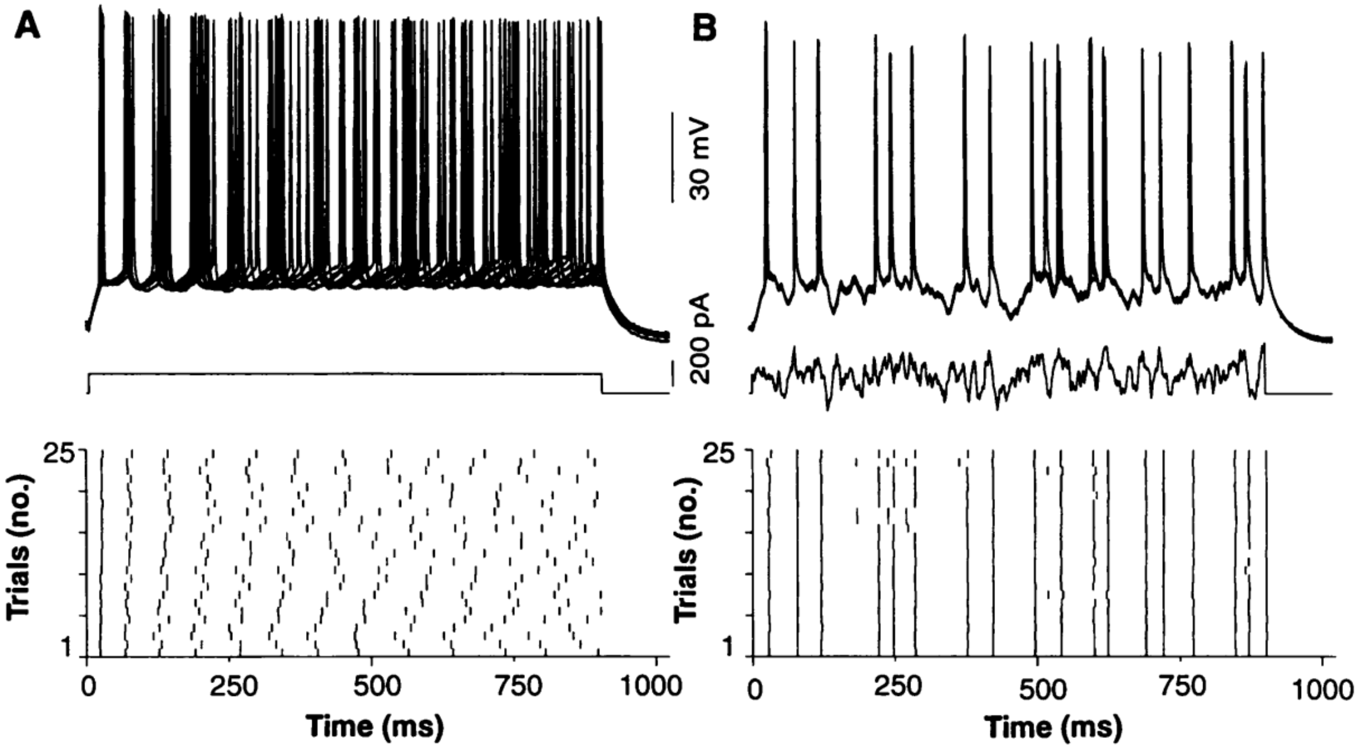
Constant current injection = **unreliable** spike times
Fluctuating current injection = **reliable** spike times



Mainen & Sejnowski, Science (1995)

Computing with spikes

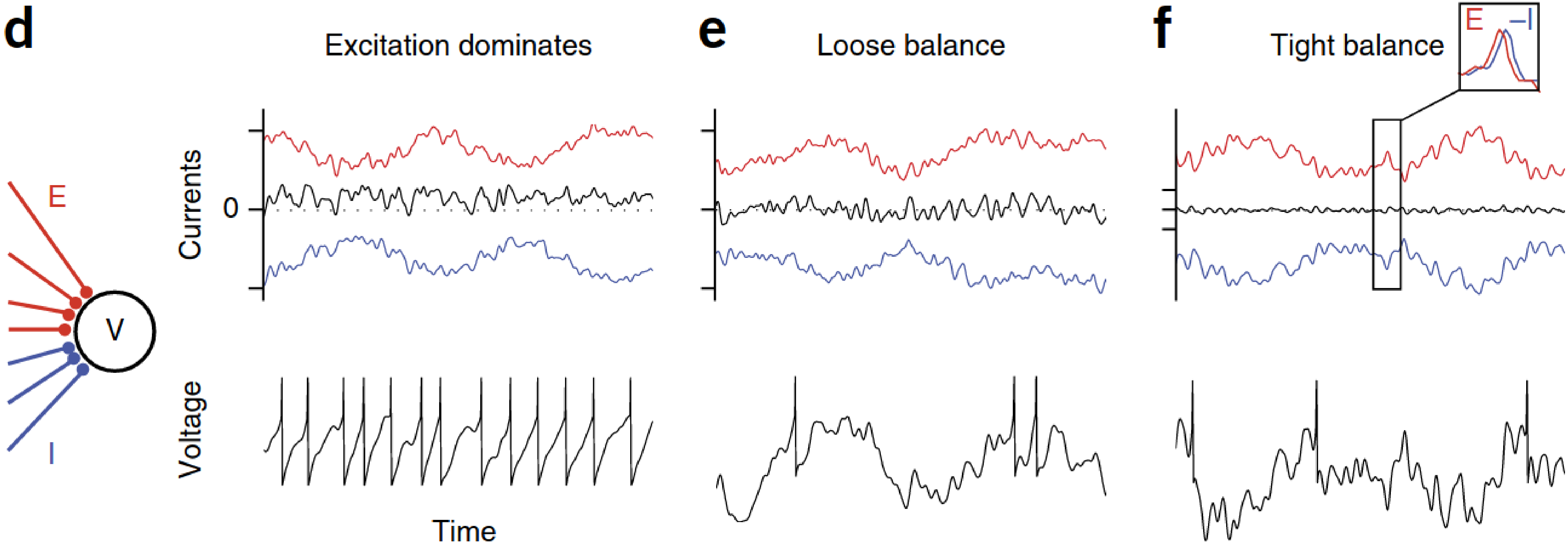
Constant current injection = **unreliable** spike times
Fluctuating current injection = **reliable** spike times



If the neuron receives *many* inputs – shouldn't the total current be rather constant (law of large numbers)?

Mainen & Sejnowski, Science (1995)

Balanced excitation/inhibition



Denève & Machens, Nat Neurosci (2016)

Tutorial

Deepnote notebook

http://tiny.cc/2025-T09