Simulation technology for brain-scale neuronal networks at single neuron resolution – Part 1

Geilo Winter School 2020

Susanne Kunkel

nest::

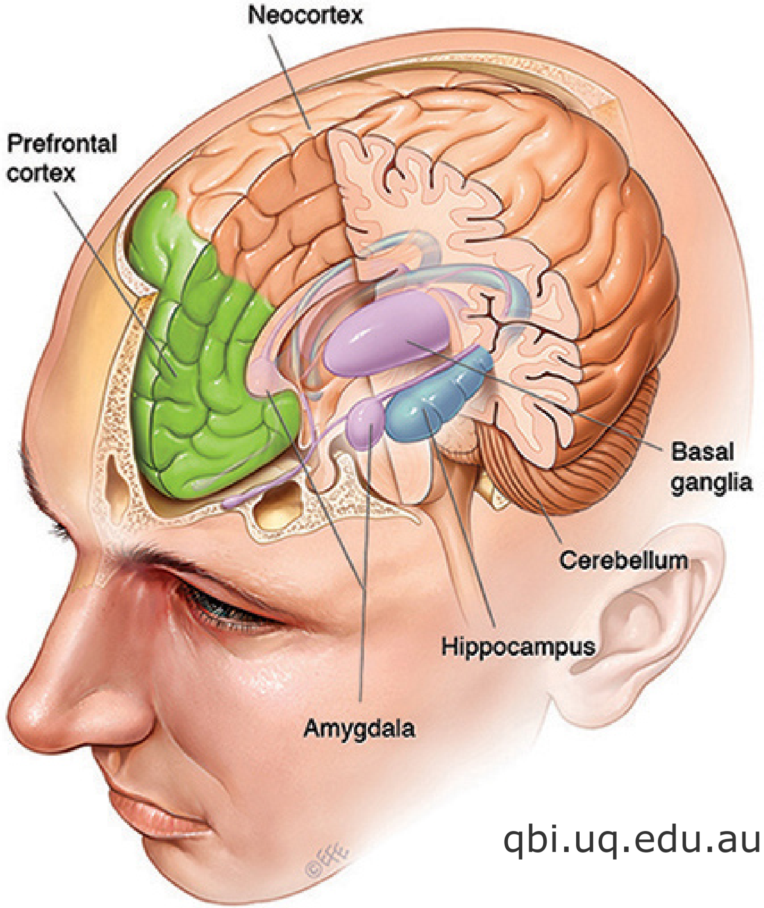
Human Brain Project

DEEP Projects

Norwegian University of Life Sciences

Terminology

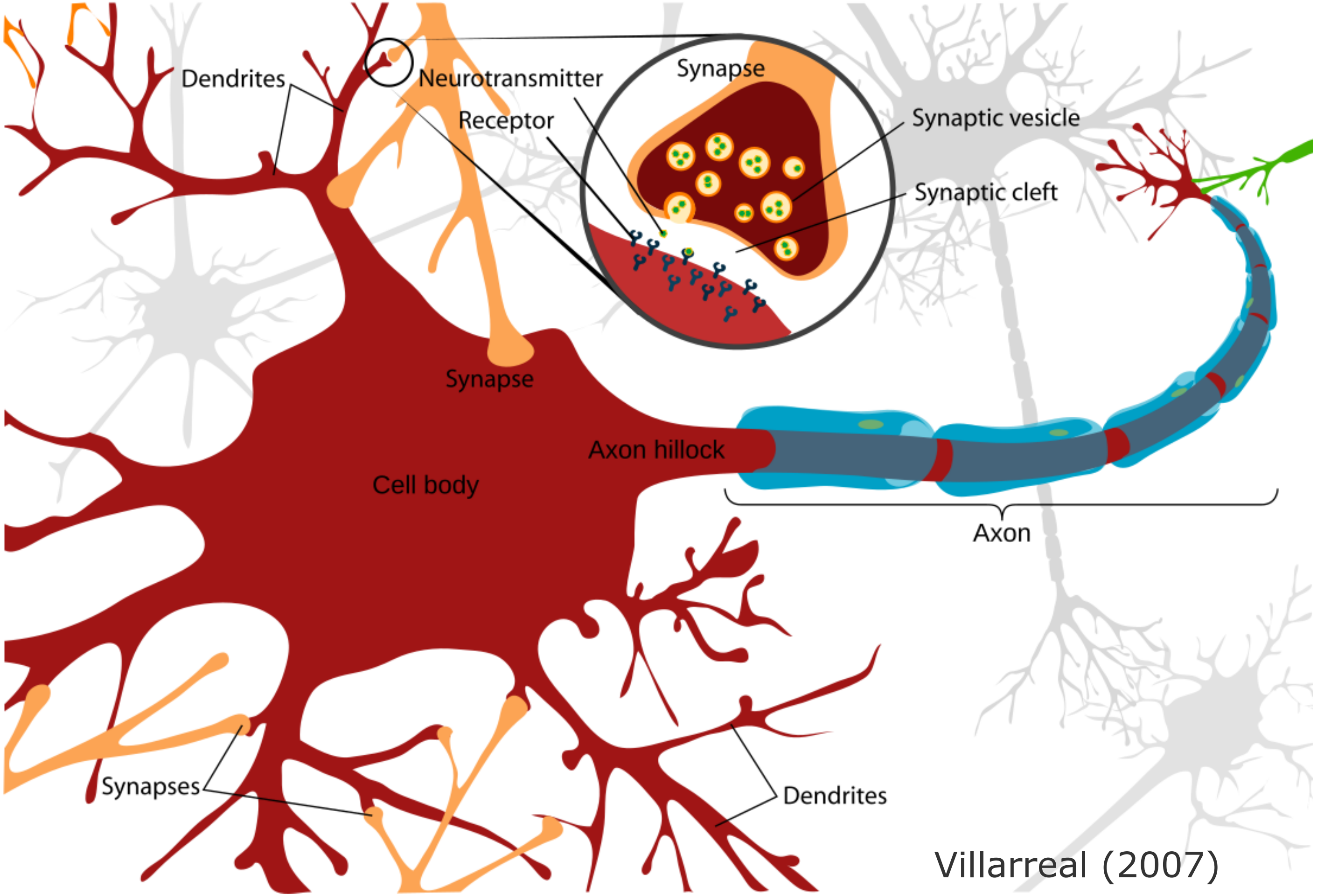
- Cortex
  - Higher brain functions
- Amygdala
  - Fear conditioning
- Hippocampus
  - Episodic memory
- Cerebellum
  - Fine tuning
- Basal ganglia
  - Action selection



qbi.uq.edu.au

Terminology

- Neuron
  - Microscopic building block of the brain
- Synapse
  - Connection from one neuron onto another neuron
- Spike
  - Neuronal signal
  - Electrical pulse

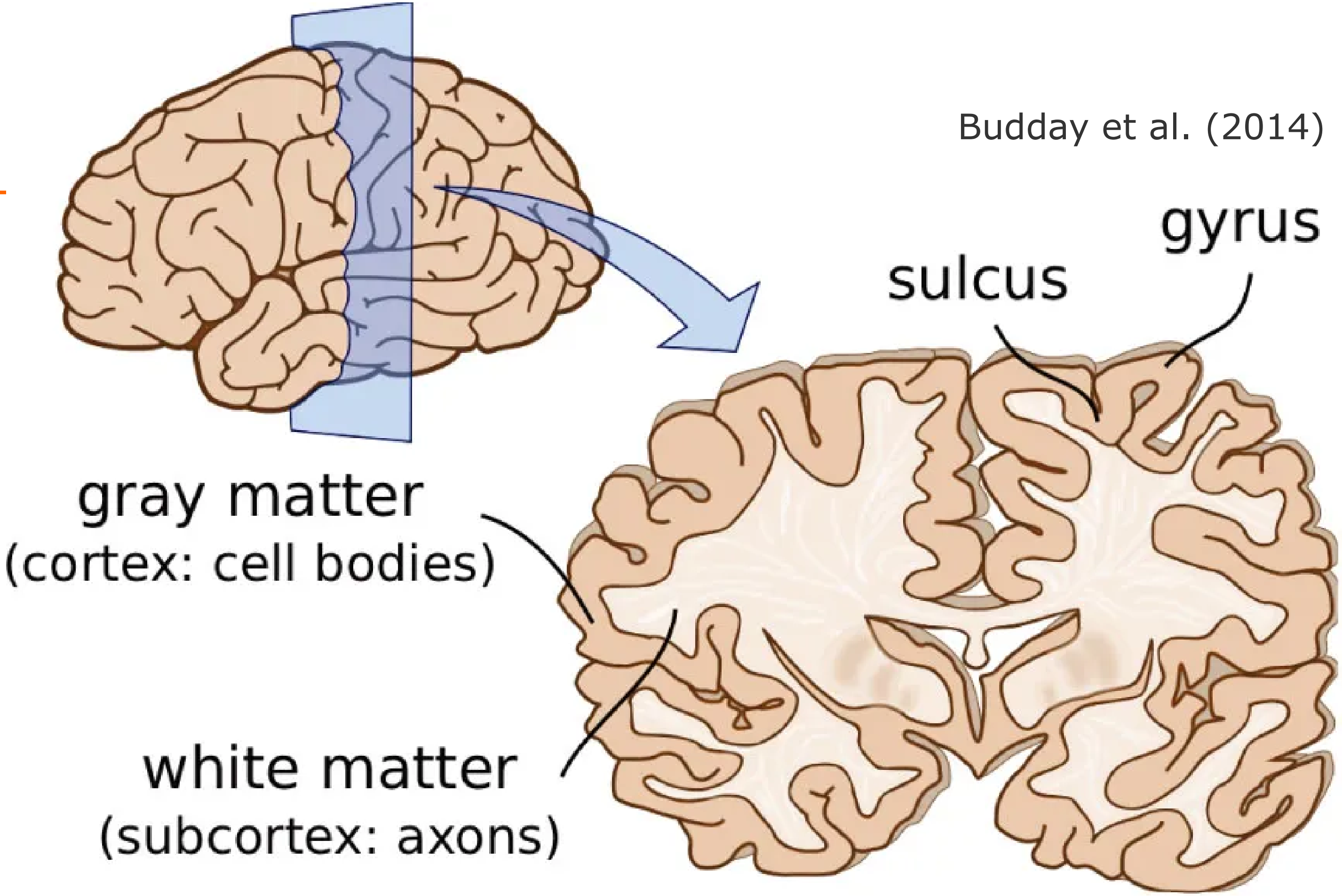


Villarreal (2007)

Terminology

- Cortex
  - Higher brain functions

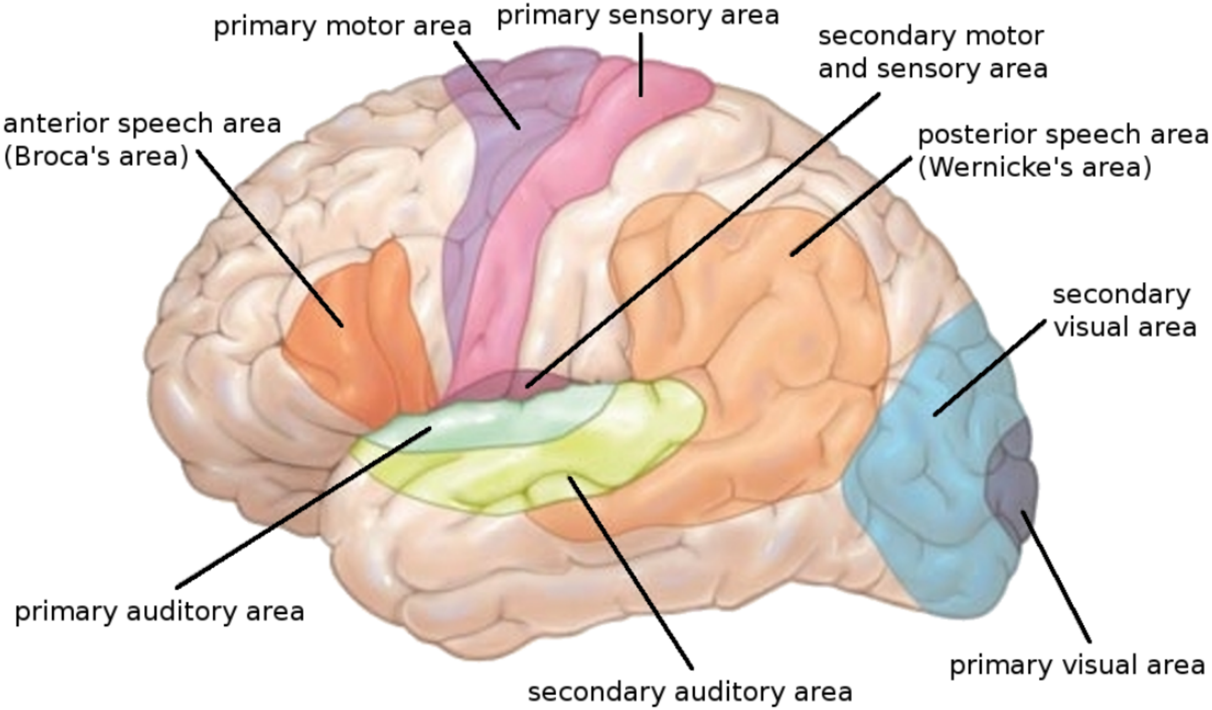
Budday et al. (2014)



Why brain-scale models?

Encyclopaedia Britannica (2007)

- Brain function involves the interaction of different brain areas

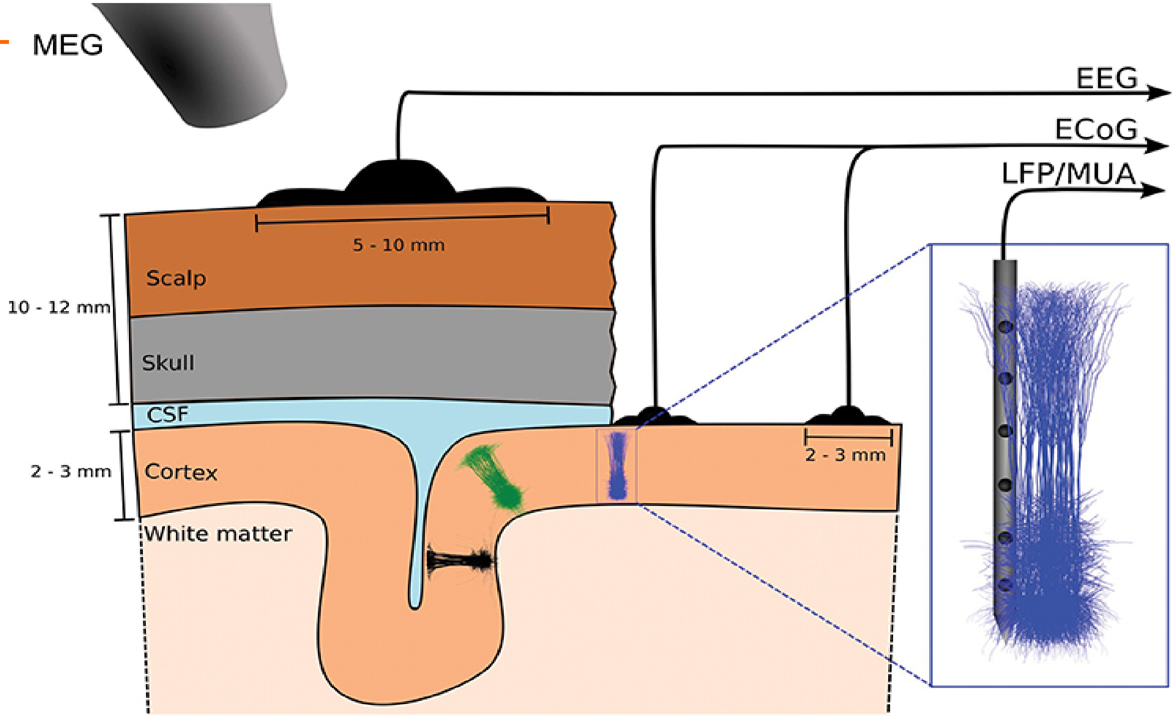


Why brain-scale models?

- Meso-scale and macro-scale measures to investigate brain function and dysfunction

  Examples:

  - Macro scale: EEG
  - Meso scale: local field potentials (LFP)

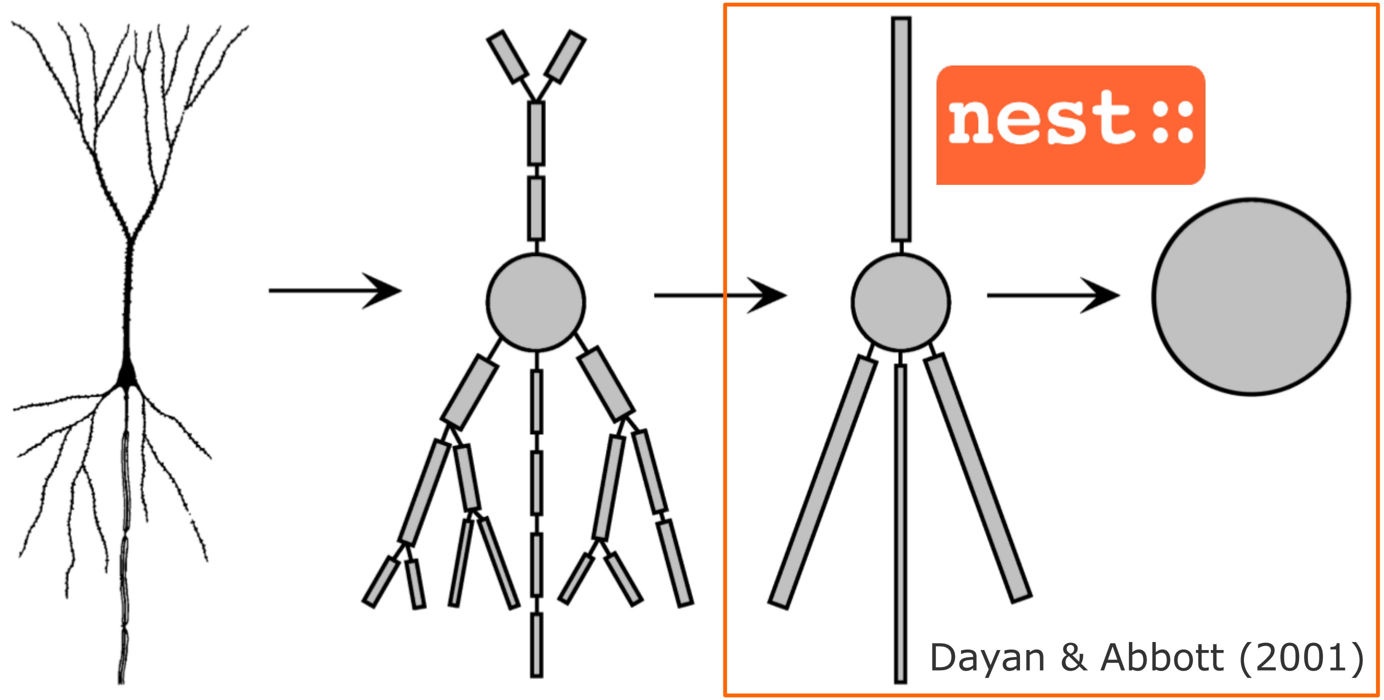


Hagen et al. (2018)

Level of abstraction

- Point-neuron models
  - Abstract away neuronal morphology

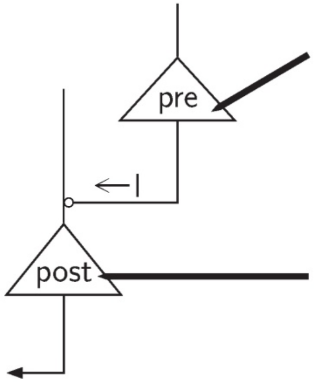
    (no dendrites or axon)
- Few-compartment neuron models
- Enable large-scale simulation

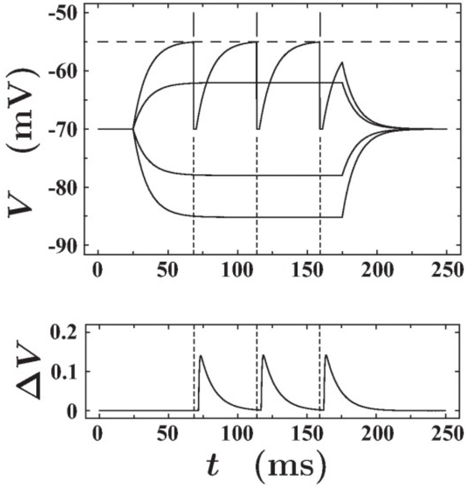


Dayan & Abbott (2001)

Fundamental interactions

- Simple neuron models
  - Exact integration





Spike of presynaptic neuron causes small excursions of postsynaptic membrane potential

$$\dot{I}_{\mathrm{x}} = 0$$

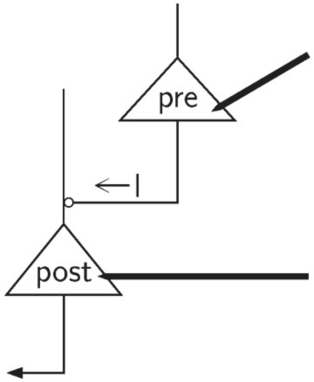
$$\dot{I}_{\mathrm{syn}} = -\frac{1}{\tau} I_{\mathrm{syn}} + \xi$$

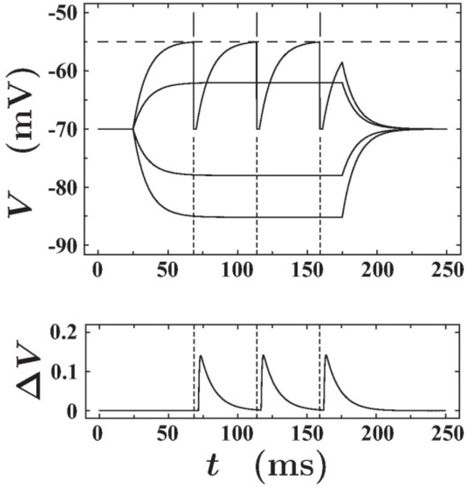
$$\dot{V} = -\frac{1}{\tau_{\mathrm{m}}} V + \frac{1}{C_{\mathrm{m}}} I_{\mathrm{syn}} + \frac{1}{C_{\mathrm{m}}} I_{\mathrm{x}}$$

Leaky integrate-and-fire neuron model with exponential postsynaptic currents

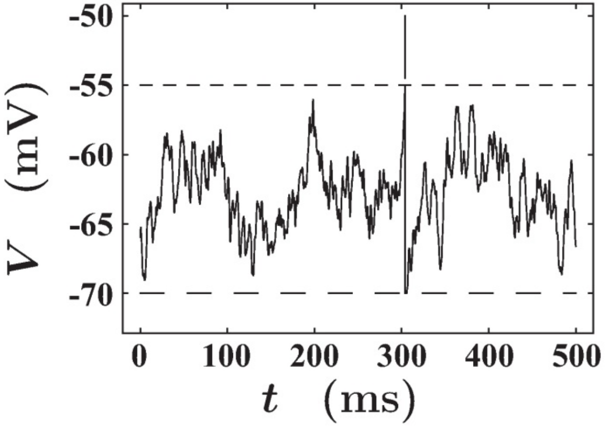
NEST: `iaf_psc_exp`

Fundamental interactions





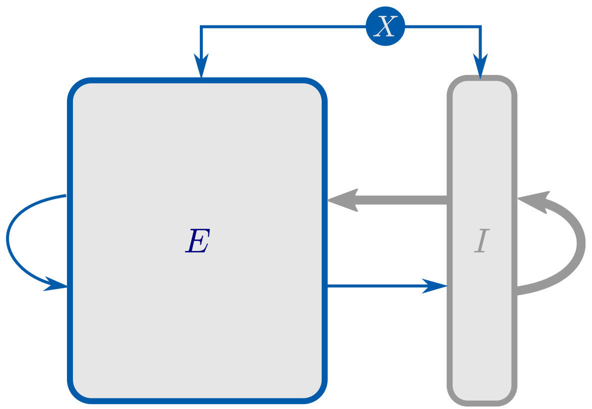
Spike of presynaptic neuron causes small excursions of postsynaptic membrane potential



Each neuron receives input from several thousands of other neurons, which causes fluctuations of membrane potential

Balanced random network

- Two populations: more excitatory than inhibitory neurons
- Stronger inhibitory than excitatory synaptic weights



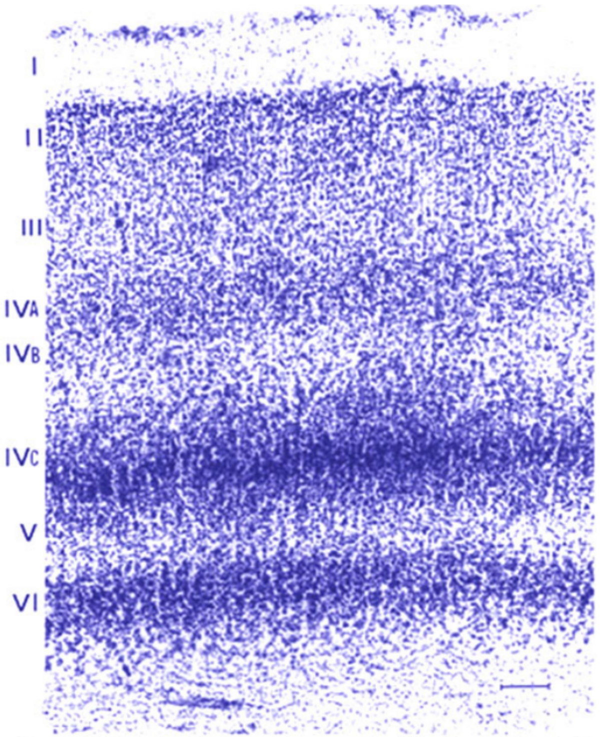
- Asynchronous irregular firing as a result of excitation-inhibition balance

(Brunel, 2000)

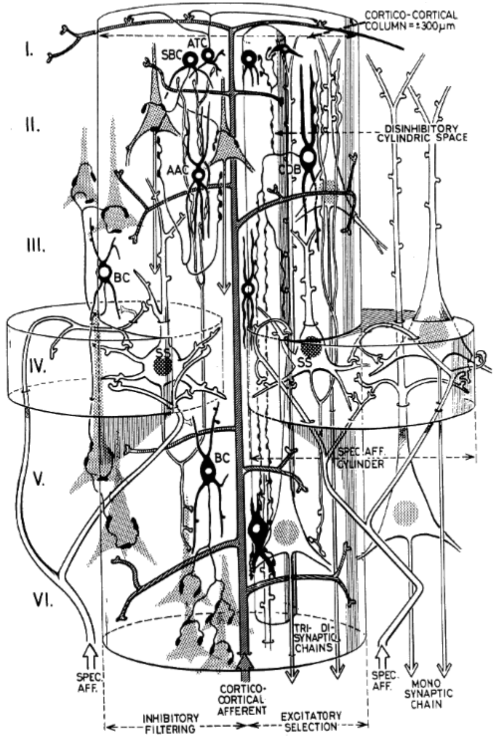
Layers of the cortex

- Up to six distinct vertical layers visible in stained cortical slices
- Differences in number of neurons and connectivity
  - Input layer IV
  - Layers II/III project to other areas
  - Layers V/VI project out of the cortex (e.g. thalamus)

Schmolesky (2000)

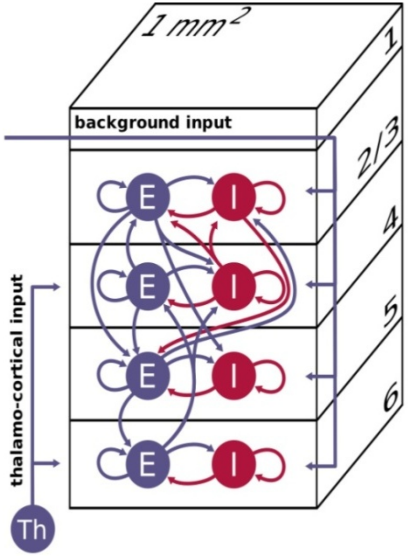


Szentágothai (1978)

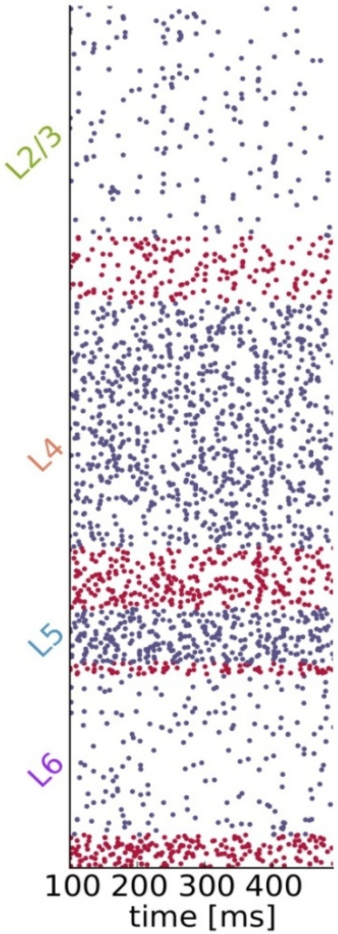


Microcircuit model

- Each layer represented by a balanced random network
- Connectivity between layers based on experimental data
- Different firing rates in different populations as a result of connectivity (and not of different neuron types)



Potjans & Diesmann (2012)

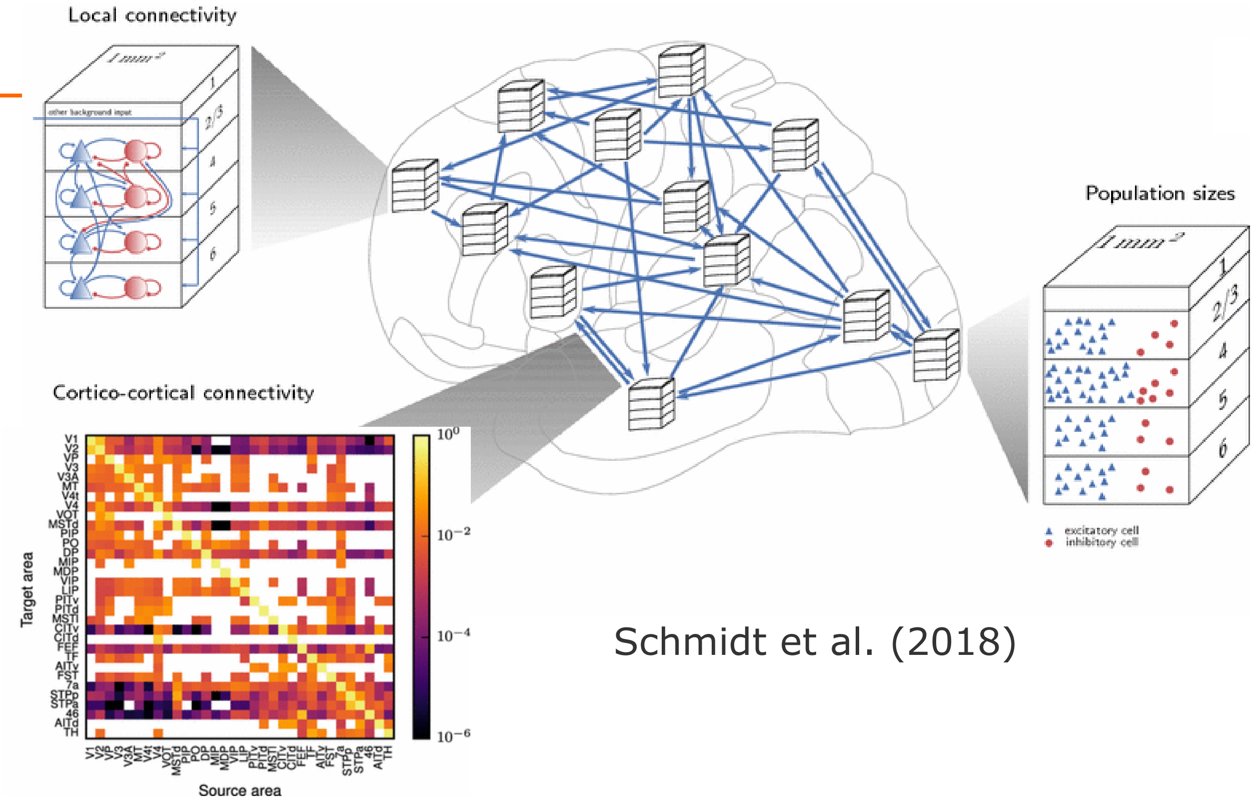


nest:: Human Brain Project DEEP Projects Norwegian University of Life Sciences

Multi-area model

- Early brain-scale model at a resolution of single neurons and synapses
- Each area modeled by microcircuit model

- 4 million neurons
- 6000 synapses per neuron

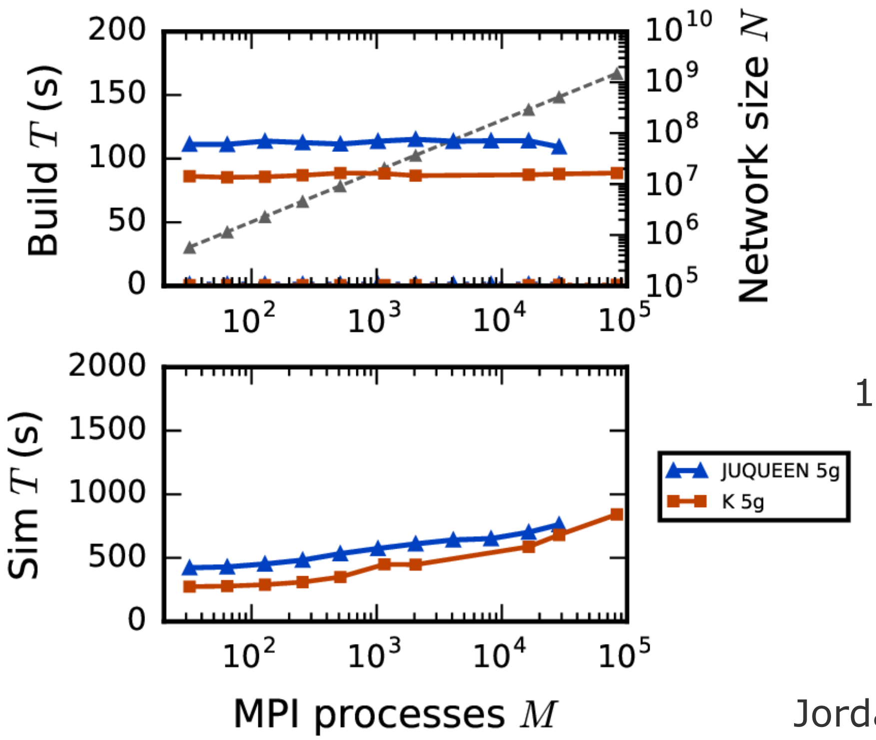


Schmidt et al. (2018)

Multi-area model

Simulation technology ready for much larger networks

- 4 million neurons
- 6000 synapses per neuron



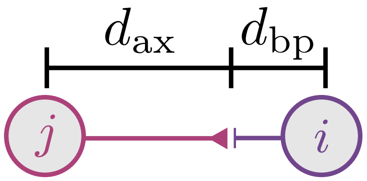
18,000 neurons per process
11,250 synapses per neuron

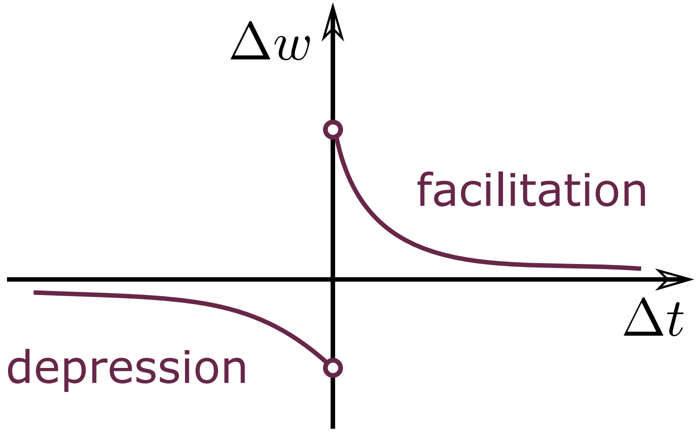
Jordan et al. (2018)

Synaptic plasticity

Spike-timing dependent plasticity (STDP)

- Synaptic weight increases/decreases in response to pre- and postsynaptic spikes occurring within a few milliseconds



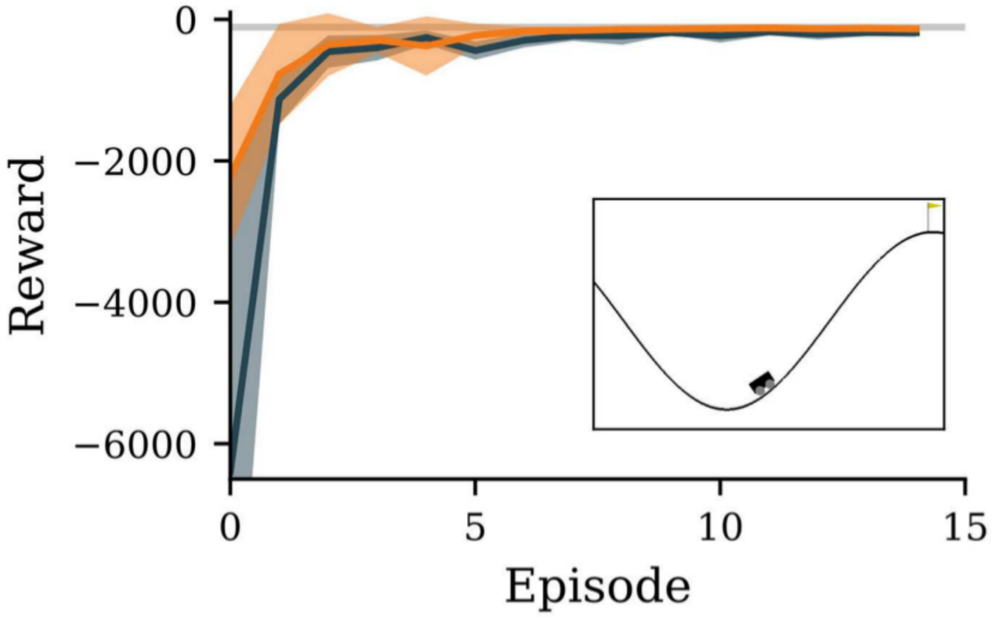


Top-down modeling

Neuronal networks solving problems

- Actor-critic architecture for reinforcement learning simulated with NEST
- Training on different environments from the OpenAI Gym
  - e.g. mountain car

Jordan et al. (2019)



NEST Conference 2020

Where?

NMBU campus at Ås

When?

June 29/30, 2020

July 1–3, 2020 (Hackathon)

www.nest-simulator.org

Norwegian University of Life Sciences