Workshop sul Calcolo nell'INFN

20 Maggio 2024

Computational neuroscience: simulation technology and study of the low-level correlates of high-level cognitive processes

UNICA UNIVERSITÀ DEGLI STUDI DI CAGLIARI

INFN CAGLIARI Istituto Nazionale di Fisica Nucleare Sezione di Cagliari

nest:: initiative

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How to simulate neuronal networks

How can we simulate a neuronal network?
Among the most popular we have:

Spiking neural networks (SNN), with point-like neurons having a time-dependent spike emission.

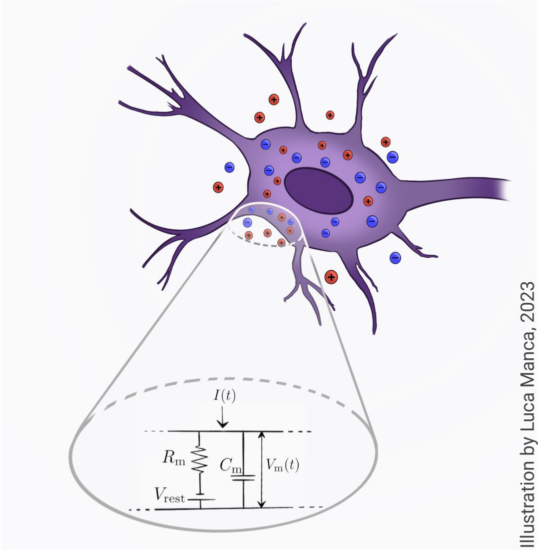
Neuron state variable: membrane electric potential.

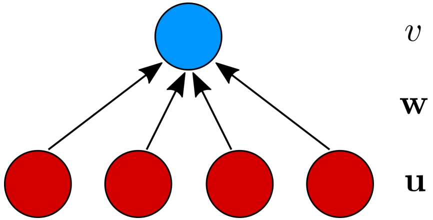
Example (spiking neuron): leaky integrate-and-fire neuron model (LIF)

Firing-rate-based networks, with point-like neurons. Higher level of abstraction wrt spiking networks, similarities with ANNs.

Neuron state variable: firing rate.

Example (network design): feed-forward network.





$$\tau_\nu \frac{d\nu}{dt} = -\nu + \mathcal{F}(\mathbf{w} \cdot \mathbf{u})$$

activation function

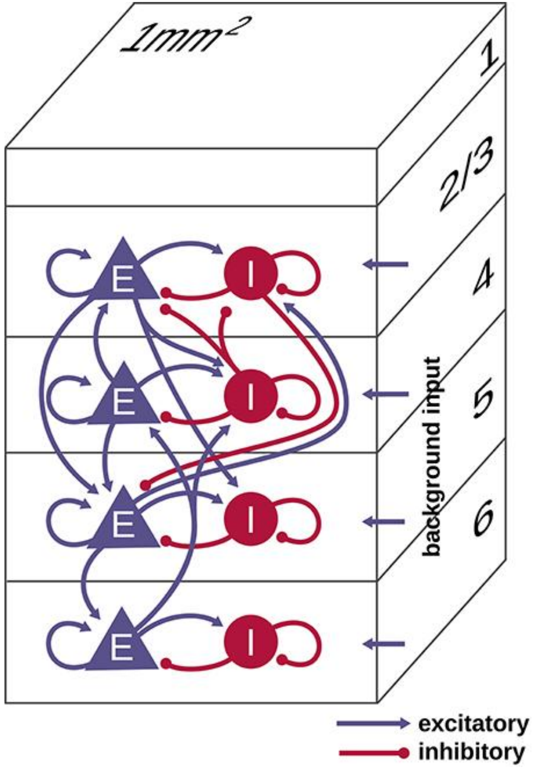
Large-scale SNN models: the cortical microcircuit

The cortical microcircuit model is made up of 77000 LIF neurons and $3 \cdot 10^8$ connections.

The model architecture lays on anatomical and physiological data and **represents 1mm² of cerebral cortex**.

It **reproduces the spiking activity of the brain cortex** according to electrophysiological observations.

This model is used to create larger networks representing different regions of the brain.



Potjans and Diesmann, *Cerebral Cortex*, 24(3), 2014

NEST GPU: a GPU-based simulator for SNN

NEST (NEural Simulation Tool) is one of the most reliable SNN simulators.
NEST GPU is the GPU-based simulator of the NEST Initiative.

We validated NEST GPU by performing simulations of models such as the cortical microcircuit.

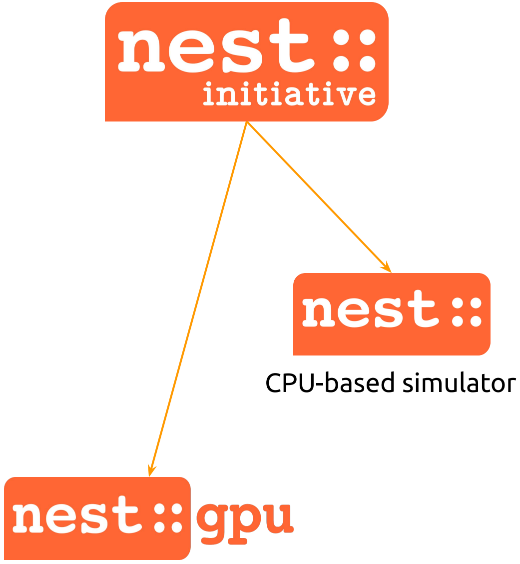
Golosio et al., ***Front. Comput. Neurosci.***, 15:627620, 2021

Golosio et al., ***Appl. Sci.***, *13*, 9598, 2023

Tiddia et al., ***Front. Neuroinform.***, 16:883333, 2022

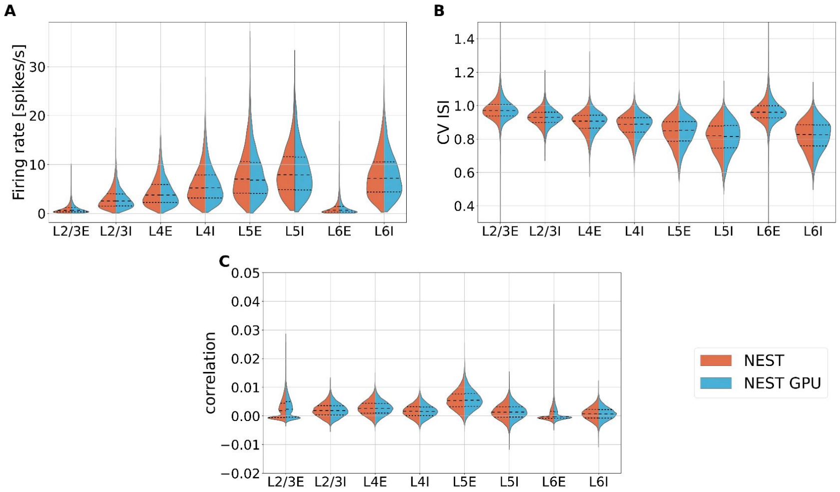
We are able to exploit multi-GPU systems, with the possibility of simulating millions of neurons and billions of synapses in a relatively low simulation time (spanning from <1 to ~10 times the biological time simulated).

Optimization in progress to take advantage of the modern supercomputers, like LEONARDO, with thousands of GPUs available.



NEST GPU is a result of active collaboration between:
Uni Cagliari & INFN, Sezione di Cagliari
INFN, Sezione di Roma 1 (APE Lab)
INM-6, Jülich Research Center

Validation and performance evaluation

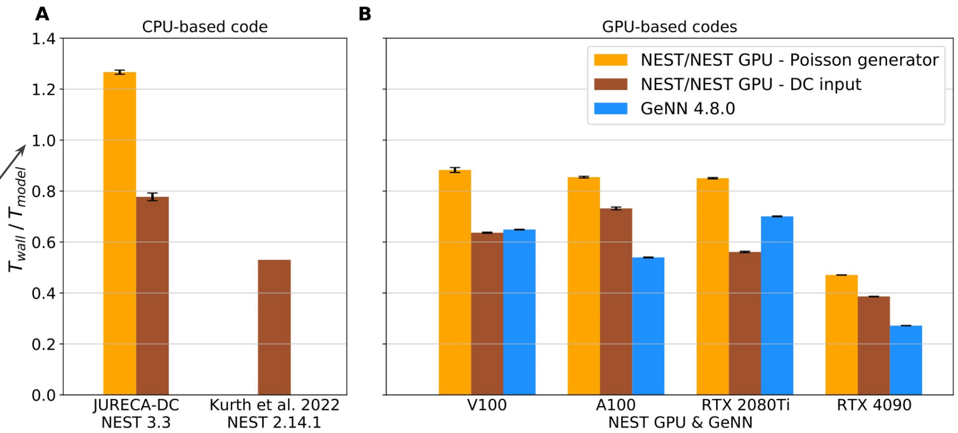


IMPORTANT

The simulation results are statistically compatible with the NEST (CPU) simulator.

NEST GPU performs below real-time simulations of the cortical microcircuit!

Real- time



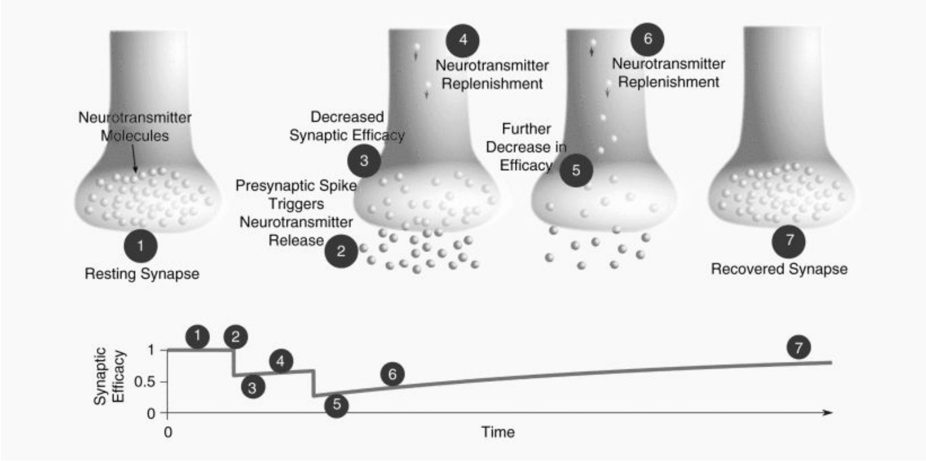
Tiddia, 10.5281/zenodo.10245798

How to model short-term plasticity

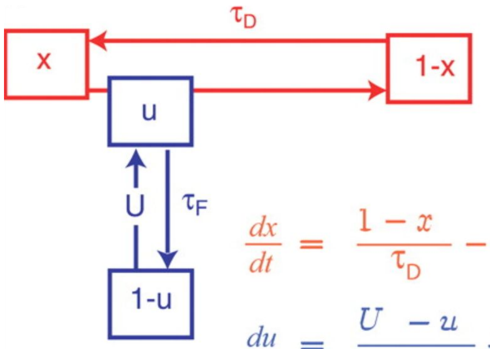
How can we model a synaptic mechanism?

An example we worked on: short-term plasticity

Short-term plasticity model modulated the synaptic efficacy taking into account the dynamics of neurotransmitters and presynaptic calcium.



© 2018 IEEE
Moraitis et al., ***IEEE Nanotechnol Mag***, 12(3), 2018



$$\frac{dx}{dt} = \frac{1-x}{\tau_D} - u\ x\ \delta(t-t_{sp})$$

$$\frac{du}{dt} = \frac{U - u}{\tau_F} + U\ (1-u\ )\ \delta(t-t_{sp})$$

x : (normalized) amount of neurotransmitters ready to be released from the synaptic vesicles

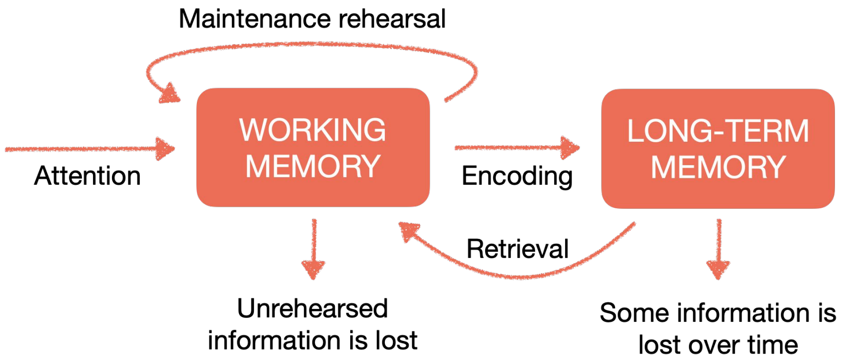
u : (normalized) presynaptic calcium concentration
U: baseline value of u

Synaptic efficacy modulated by u(t)x(t)

Synaptic theory of working memory

Working Memory (WM) is a cognitive process able to hold and manipulate information for a short time. It is fundamental for speech, visual and spatial processing.
It is observed in the prefrontal cortex (PFC) during *delay response tasks*.

The **Synaptic Theory of Working Memory** posits that a mechanism of short-term synaptic facilitation leads to information maintenance in both synaptic and spiking form, with spiking activity functional for synaptic facilitation upkeep. Mongillo et al., ***Science***, 319, 2008



Working Memory → spiking activity + activity-silent mechanism

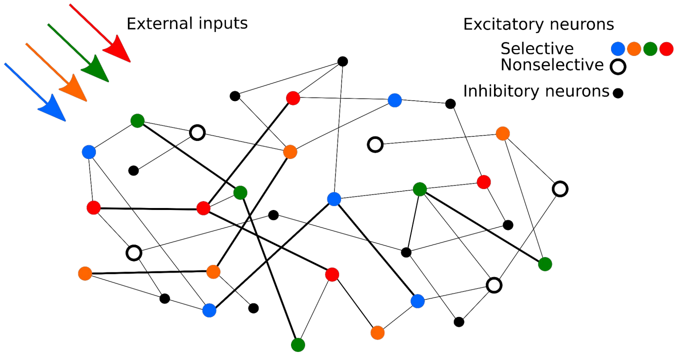
→ short-term plasticity?

Working memory spiking network model

Network of excitatory and inhibitory neurons.

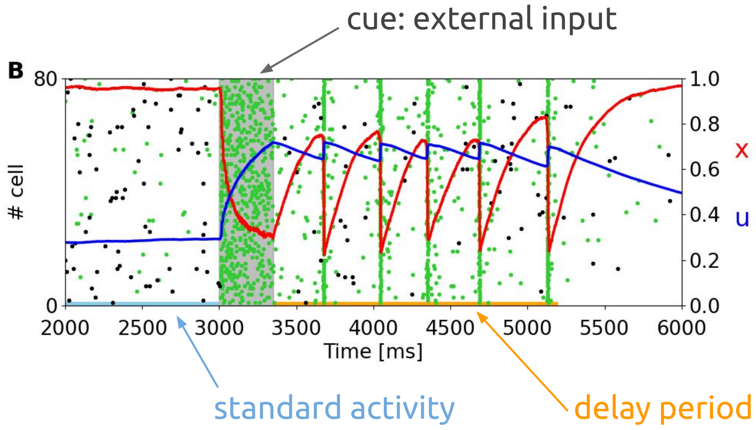
STP-modulated connectivity.

Excitatory neurons are organized in groups, and neurons belonging to the same group are connected with potentiated connections. Other excitatory connections have lower synaptic efficacy.



The model is able to describe many features related to working memory network dynamics.

It explains the activity-silent related observations and the measurements of average rate in the prefrontal cortex during WM tasks.



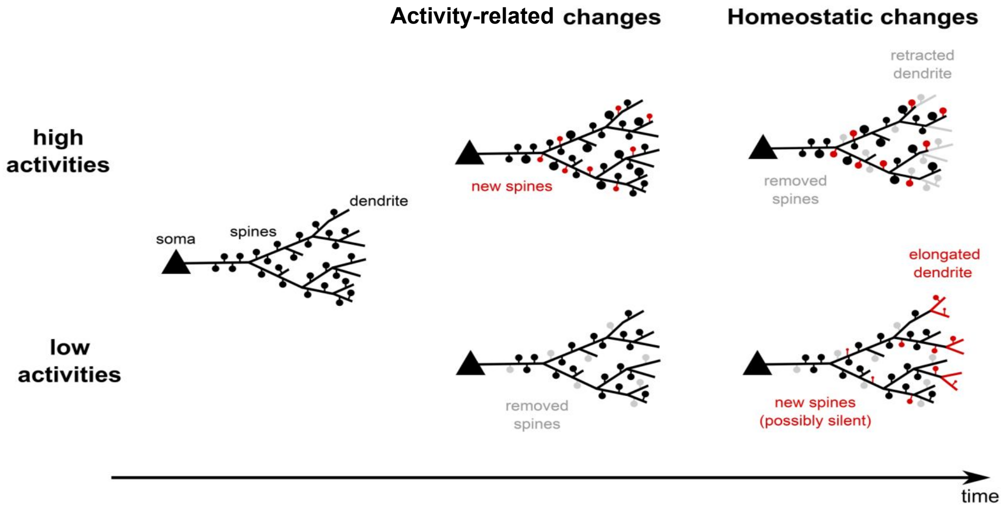
Structural synaptic plasticity

Structural plasticity describes the mechanisms of connection creation, consolidation and erasure (or pruning).

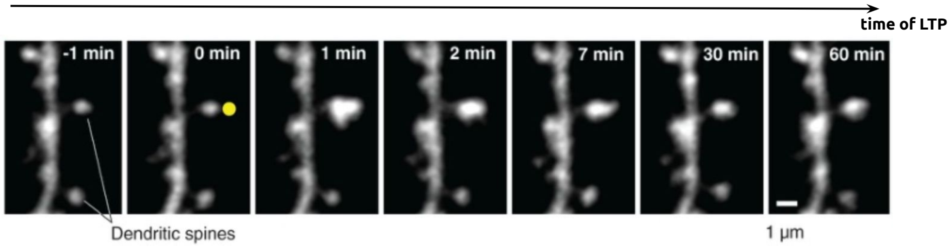
It can be activity-related or homeostatic. Fauth and Tetzlaff, ***Front. Neuroanat.***, 10:75, 2016

In particular, synaptic pruning and connection reorganization are fundamental mechanisms for learning and neural circuits optimization.

Question: can we estimate the impact of structural plasticity in learning?



Fauth and Tetzlaff, ***Front. Neuroanat.***, 10:75, 2016

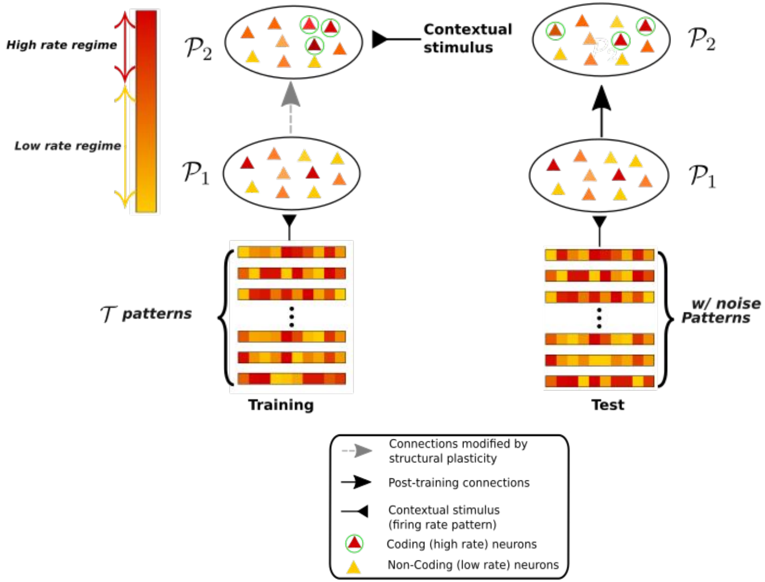


The firing rate model

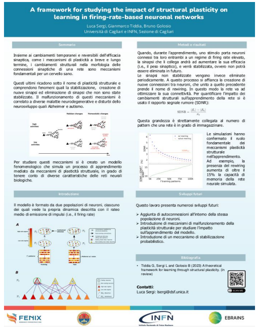
Feed-forward network with two neuron populations,

as described in Tiddia et al., arXiv:2307.11735 [q-bio.NC]

We developed a theoretical framework alongside simulations in C++, with which we estimated the impact of structural mechanisms in learning and the differences in memory capacity with and without these mechanisms.



Poster #adv



For more details about the model for learning through structural plasticity, you can find a poster!

A framework for studying the impact of structural plasticity on learning in firing-rate-based neuronal networks

Presenter: Luca Sergi

Outlook

- Simulation technology for neuroscience is advancing to fully exploit next era supercomputers to perform simulations of large networks of neurons and with higher level of detail
  - With NEST GPU, we aim to exploit MPI-GPU clusters such as LEONARDO to perform very-large-scale simulations
- Developing network models at single neuron resolution helps us to estimate the impact of low level processes in high-level cognitive mechanisms
  - Our aim is to provide reliable synapse and network models to study the impact of the synaptic correlates of high-level cognitive processes such as memory and learning

Thank you for your attention!

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