UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Effect of Multiple Synaptic delays in Neural Plasticity

By Raul Adell Segarra

Google images: https://bujooeducation.com/author/andre/

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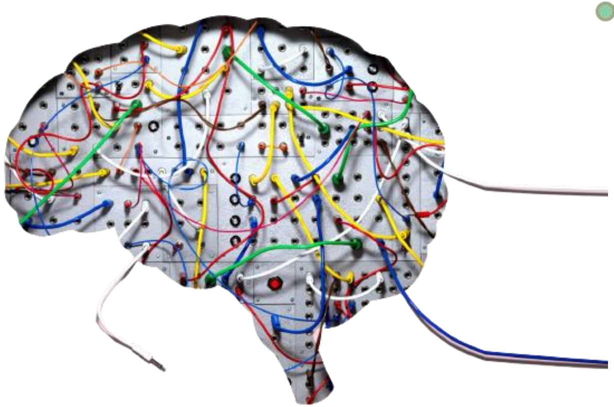
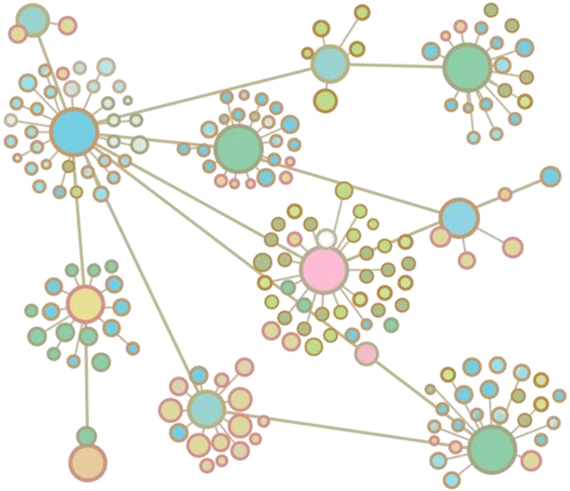
<u>Primitive motivation:</u>
Effect of neuron's spatial distributions in plasiticty



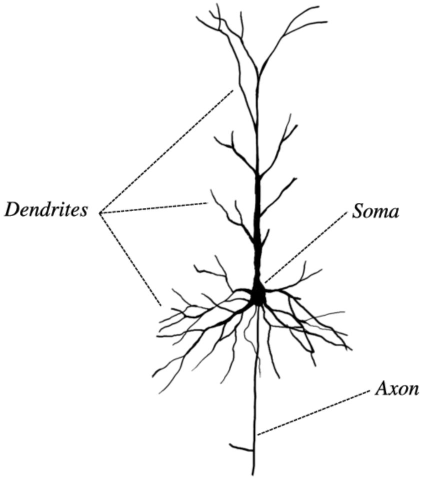


Motivation

References:
Google images: https://www.magisnet.com/2021/01/neurociencia-y-aprendizaje/
Google images : https://www.inc.com/christine-lagorio/your-brain-in-2050-according-to-neuroscience.html
Google images : https://pt.slideshare.net/JayVanBavel/the-neuroscience-of-cooperation?next_slideshow=true

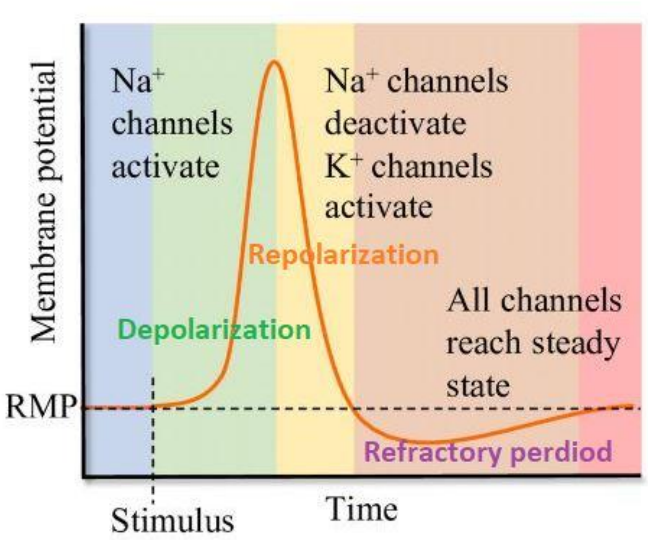
INTRODUCTION

Neuron structure



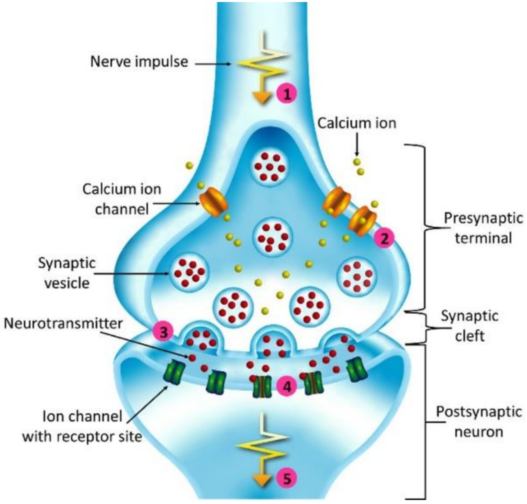
Marian C Diamond. “Response of the brain to enrichment”. In: Anais da Academia Brasileira de Cieencias 73.2 (2001), pp. 211–220.

Action potential



Parul Verma et al. “Using bifurcation theory for exploring pain”. In: Industrial & Engineering Chemistry Research 59.6 (2019), pp. 2524–2535.

Synapse



Okinawa Institute of Science and Technology Graduate University OIST. Diagram of synaptic transmission. 2020. url: https://www.oist.jp/news-center/photos/diagram-synaptic-transmission.

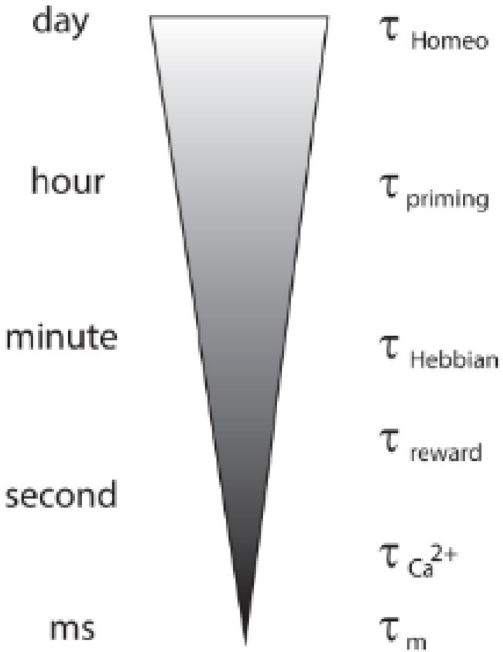
Introduction (I) : The Neuron

Classification depending on:

- Neuron part affected physiologically

- Time to induce a change

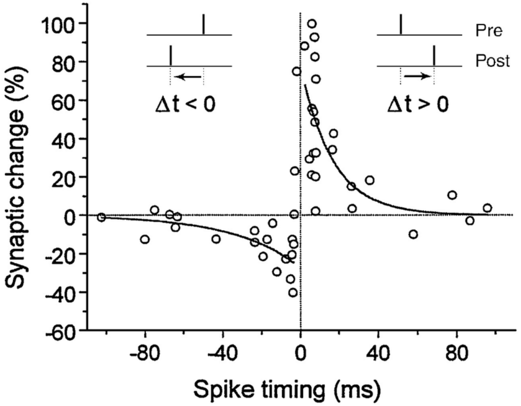
- Time scale of persistence



Yger, P., & Gilson, M. (2015). Models of Metaplasticity: A Review of Concepts. *Frontiers In Computational Neuroscience*, *9*

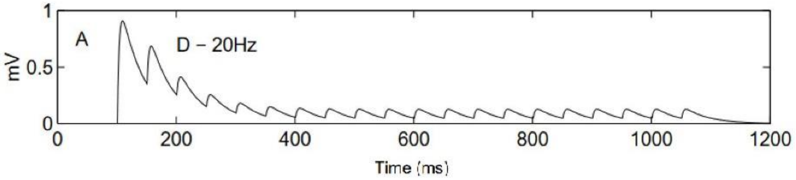
Introduction (II): Plasticity

- Spike Time-Dependent Plasticity



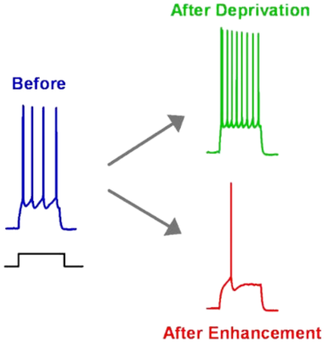
Guo-qiang Bi and Mu-ming Poo. “Synaptic modifications in cultured hippocampal neurons: dependence on spike timing, synaptic strength, and postsynaptic cell type”. In: Journal of neuroscience 18.24 (1998), pp. 10464–10472.

- Short term plasticity



Misha Tsodyks, Klaus Pawelzik, and Henry Markram. “Neural networks with dynamic synapses In: Neural computation 10.4 (1998), pp. 821–835.

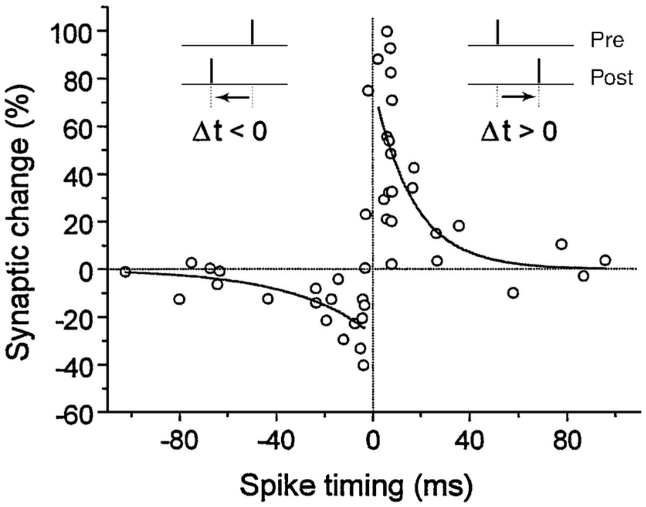
- Homeostatic or Metaplasticity



Watt, Alanna J., and Niraj S. Desai. "Homeostatic plasticity and STDP: keeping a neuron's cool in a fluctuating world." Frontiers in synaptic neuroscience (2010): 5.

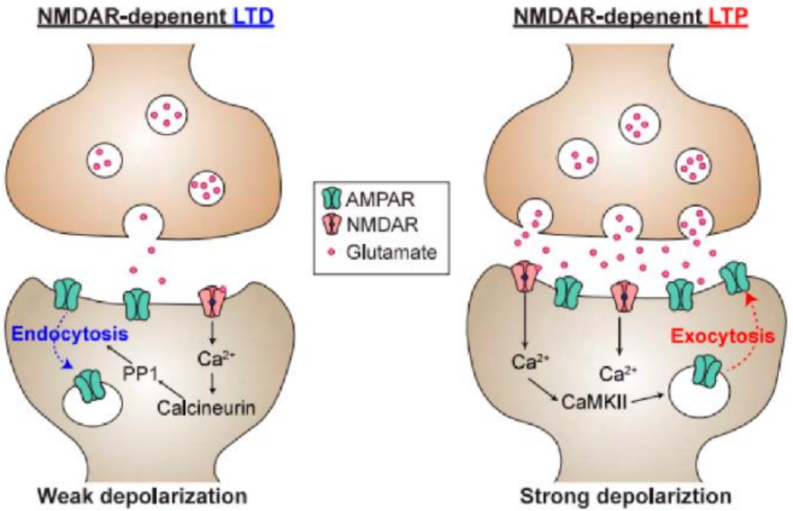
Introduction (II): Plasticity

Experimental evidence



Guo-qiang Bi and Mu-ming Poo. “Synaptic modifications in cultured hippocampal neurons: dependence on spike timing, synaptic strength, and postsynaptic cell type”. In: Journal of neuroscience 18.24 (1998), pp. 10464–10472.

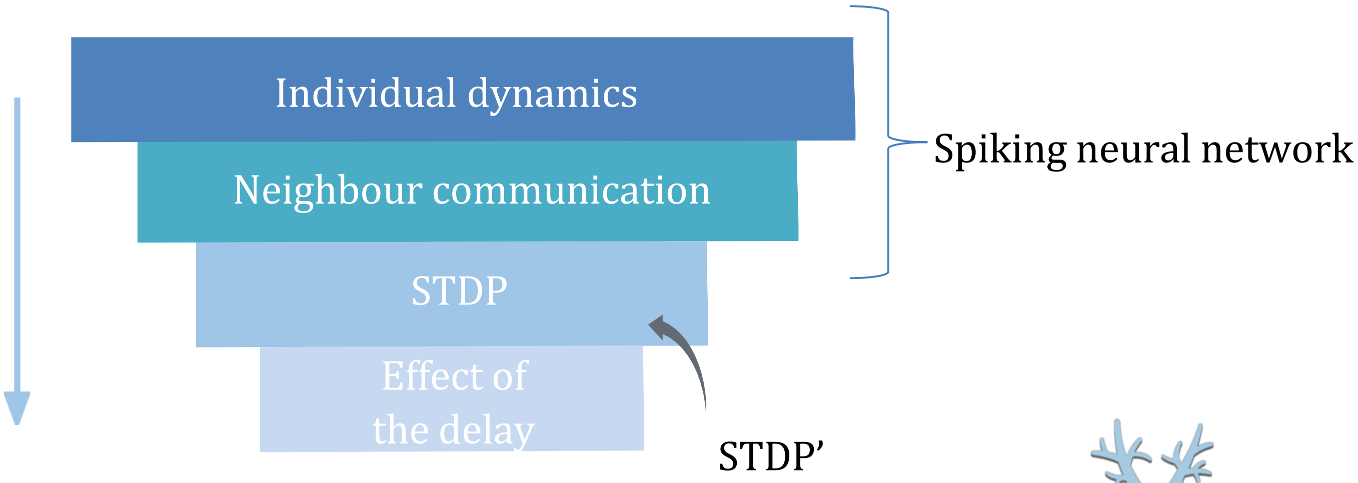
Biological mechanism

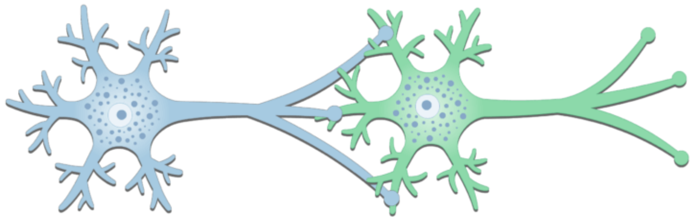


Jo Soo Hyun, Takafumi Inoue, and Akiko Hayashi-Takagi. “Multi-Scale Understanding of NMDA Receptor Function in Schizophrenia”. In: Biomolecules 10.8 (2020), p. 1172.

Introduction (III): STDP

METHODS

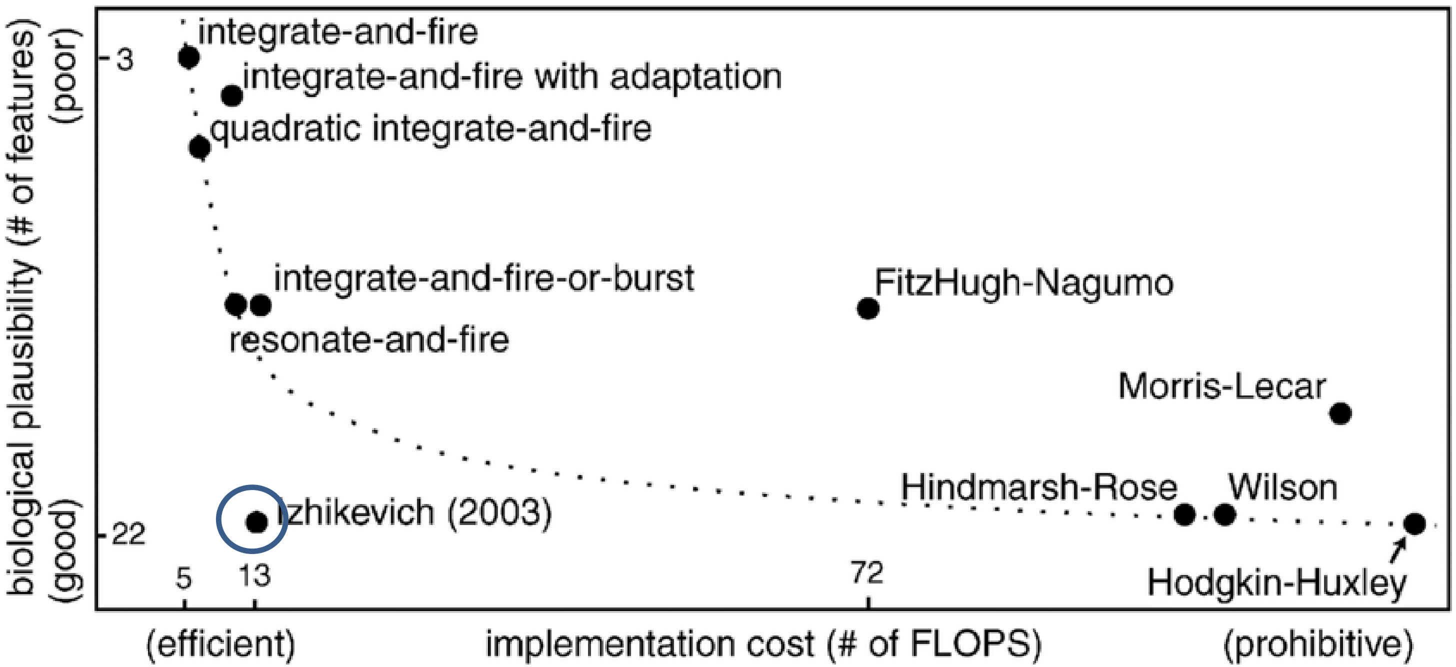




Google images: https://www.pngegg.com/es/png-pdqis

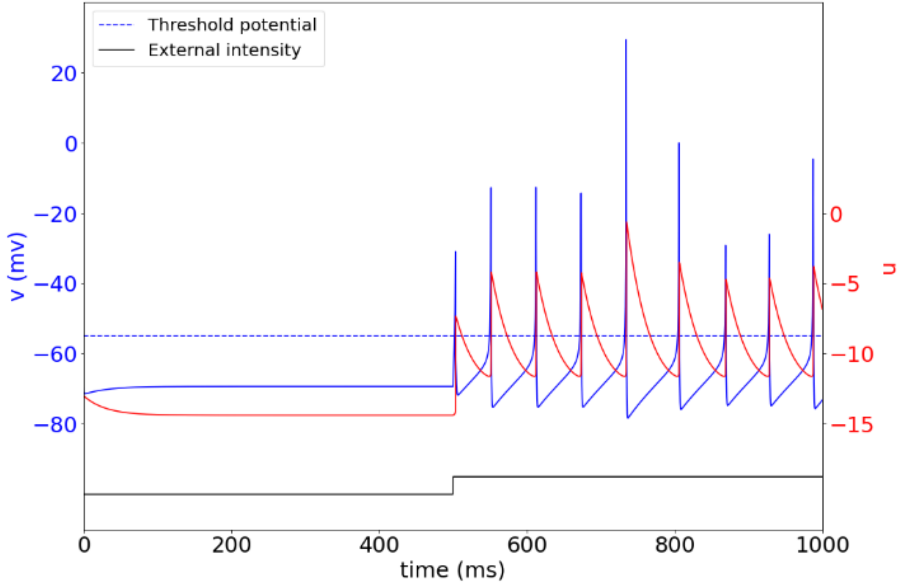
Structure and Objectives

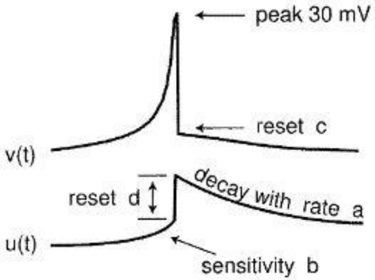
Comparison of different spiking models



Eugene M Izhikevich. “Which model to use for cortical spiking neurons?” In: IEEE transactions on neural networks 15.5 (2004), pp. 1063–1070.

$$\begin{cases} v' = 0.04v^2 + 5v + 140 - u + I_{ext} \\ u' = a(bv - u) \quad \text{if } v \geq 30\text{mV}, \text{ then } \begin{cases} v \leftarrow c \\ u \leftarrow u + d \end{cases} \end{cases}$$

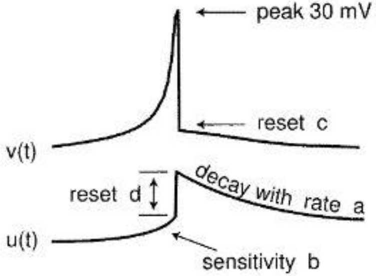




Eugene M Izhikevich. “Simple model of spiking neurons”. In: IEEE Transactions on neural networks 14.6 (2003), pp. 1569–1572.

Methods (I): Izhikevich model

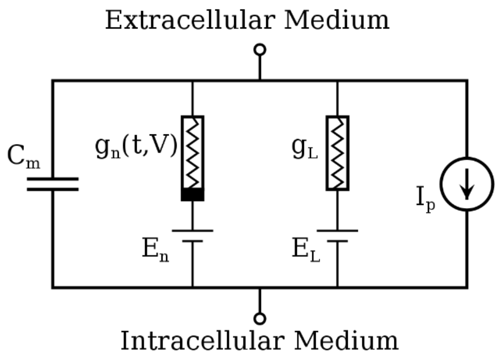
$$
\begin{cases}
v' = 0.04v^2 + 5v + 140 - u + I_{ext} \\
u' = a(bv - u) \quad \text{if } v \geq 30\text{mV}, \text{ then } \begin{cases} v \leftarrow c \\ u \leftarrow u + d \end{cases}
\end{cases}
$$



Models	biophysically meaningful	tonic spiking	phasic spiking	tonic bursting	phasic bursting	mixed mode	spike frequency adaptation	class 1 excitable	class 2 excitable	spike latency	subthreshold oscillations	resonator	integrator	rebound spike	rebound burst	threshold variability	bistability	DAP	accommodation	inhibition-indiced spiking	inhibition-induced bursting	chaos	# of FLOPS
integrate-and-fire	-	+	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	-	-	-	-	-	5
integrate-and-fire with adapt.	-	+	-	-	-	-	+	+	-	-	-	-	+	-	-	-	-	+	-	-	-	-	10
integrate-and-fire-or-burst	-	+	+		+	-	+	+	-	-	-	-	+	+	+	-	+	+	-	-	-		13
resonate-and-fire	-	+	+	-	-	-	-	+	+	-	+	+	+	+	-	-	+	+	+	-	-	+	10
quadratic integrate-and-fire	-	+	-	-	-	-	-	+	-	+	-	-	+	-	-	+	+	-	-	-	-	-	7
Izhikevich (2003)	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	13
FitzHugh-Nagumo	-	+	+	-		-	-	+	-	+	+	+	-	+	-	+	+	-	+	+	-	-	72
Hindmarsh-Rose	-	+	+	+			+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	120
Morris-Lecar	+	+	+	-		-	-	+	+	+	+	+	+	+		+	+	-	+	+	-	-	600
Wilson	-	+	+	+			+	+	+	+	+	+	+	+	+	+		+	+				180
Hodgkin-Huxley	+	+	+	+			+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	1200

Methods (I): Izhikevich model

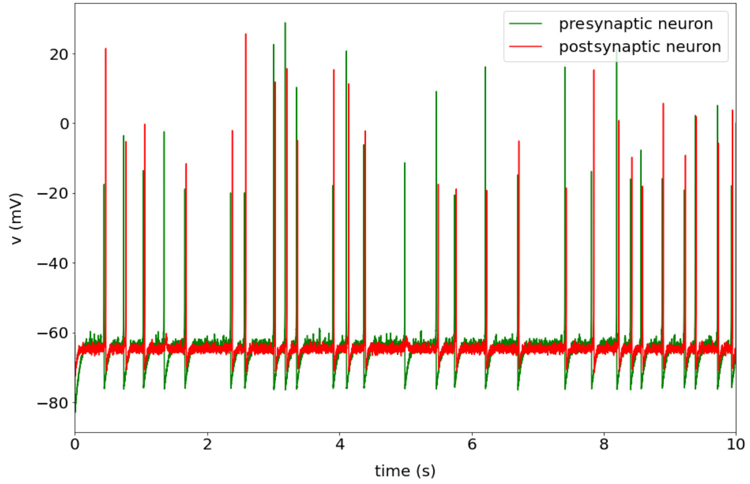
Eugene M Izhikevich. “Which model to use for cortical spiking neurons?” In: IEEE transactions on neural networks 15.5 (2004), pp. 1063–1070.

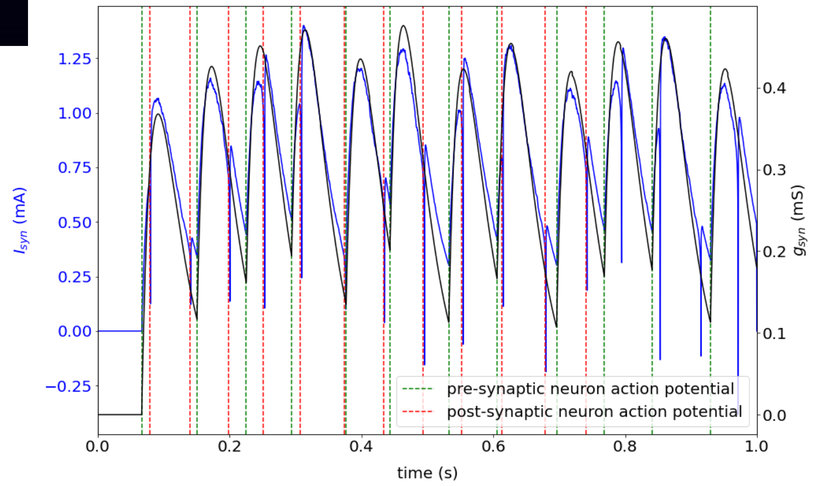


Chemical synapse equations

$$g_{syn}(t) = \bar{g}_{syn} \underbrace{\frac{t-t_s}{\pi_\alpha} \exp\left(-\frac{t-t_s}{\pi_\alpha}\right)}_{\alpha(t-t_s,\, \pi_\alpha)}$$

$$I_{syn}(t) = g_{syn}(t)\left(V(t) - E_{syn}\right)$$



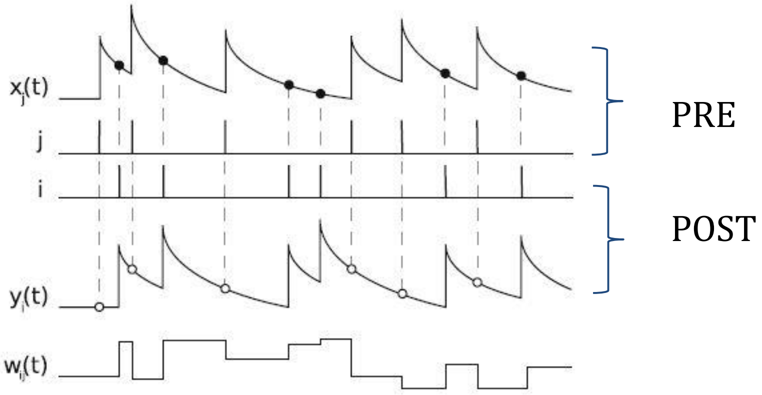


Methods (II): Synapse models

Huxley A. F. Hodgikin AL. “A quantitative description of mambrane current and its application to conduction and excitation in nerve”. In: J. Physiology 117 (1952), pp. 500–544.

Local trace

$$\frac{dx}{dt} = -\frac{x}{\tau} + \sum_{t^f} A\ (1 - x_-)\ \delta\left(t - t^f\right)$$

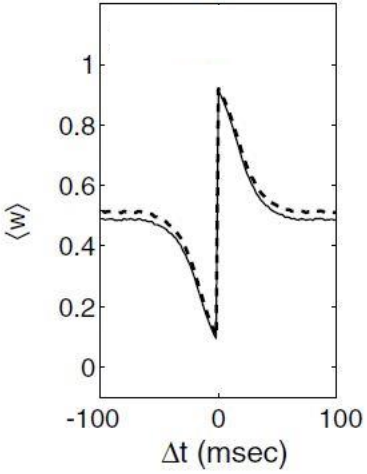


Abigail Morrison, Markus Diesmann, and Wulfram Gerstner. “Phenomenological modelsof synaptic plasticity based on spike timing”. In: Biological cybernetics 98.6 (2008),pp. 459–478.

Synaptic weight

$$I_{\text{syn}}\ (t) = -\sum_{pre}\sum_{i} \bar{g}_{\text{syn}}\ w_{syn}\ \alpha(t - t_{i_{pre}}, \pi_\alpha)\ (V_{post}(t) - E_{syn_{pre}})$$

$$\Delta w_{ij} = \begin{cases} -\lambda\ (1 - w_{ij})\ y_i(t_{pre\, spike}), & \text{when presynaptic neuron spikes} \\ \lambda\ w_{ij}\ x_j(_{post\, spike}), & \text{when postsynaptic neuron spikes} \end{cases}$$

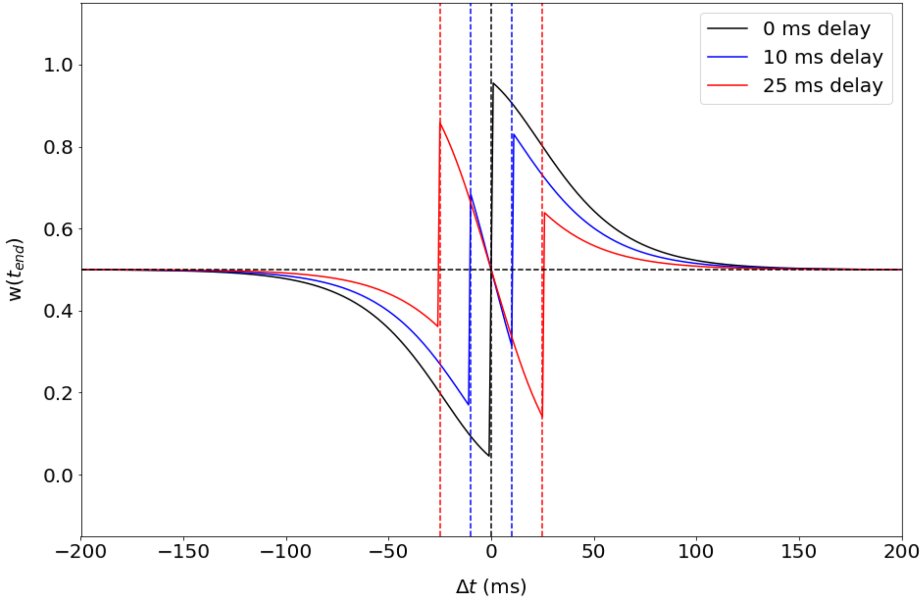


Jonathan Rubin, Daniel D Lee, and H Sompolinsky. “Equilibrium properties of temporally asymmetric Hebbian plasticity”. In: Physical review letters 86.2 (2001), p. 364.

Methods (III): Plasticity

Proposed model

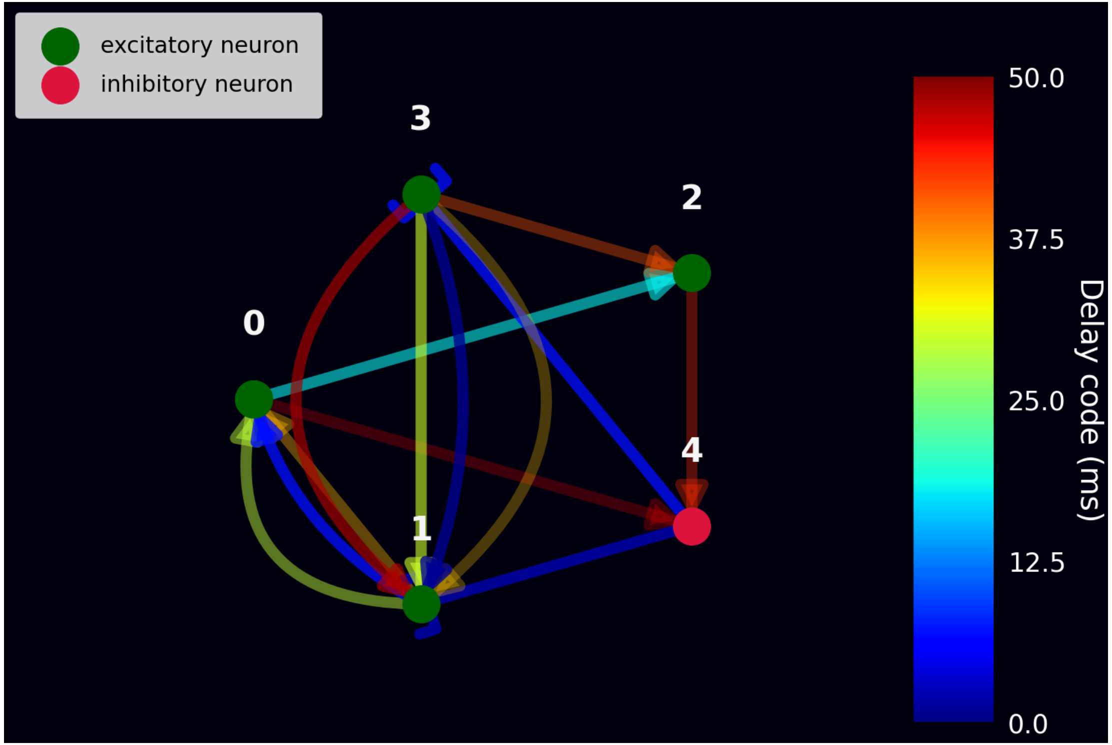
$$\Delta w_{ij} = \begin{cases} -\lambda\ (1 - w_{ij})\ y_i(t_{pre\,spike} + \tau), & \text{a time} = \tau \text{ after presynaptic neuron spikes.} \\ \lambda\ w_{ij}\ x_j(t_{post\,spike} + \tau), & \text{a time} = \tau \text{ after postsynaptic neuron spikes.} \end{cases}$$



Av. propagation speed ≈ $100\,\frac{m}{s}$

Delay range → $50\ ms$

Methods (IV): Delay implementation



- Edge colour
- Arrow shape & node colour
- Thickness & transparency

Methods (V): Network & Representation

- Resetting traces:

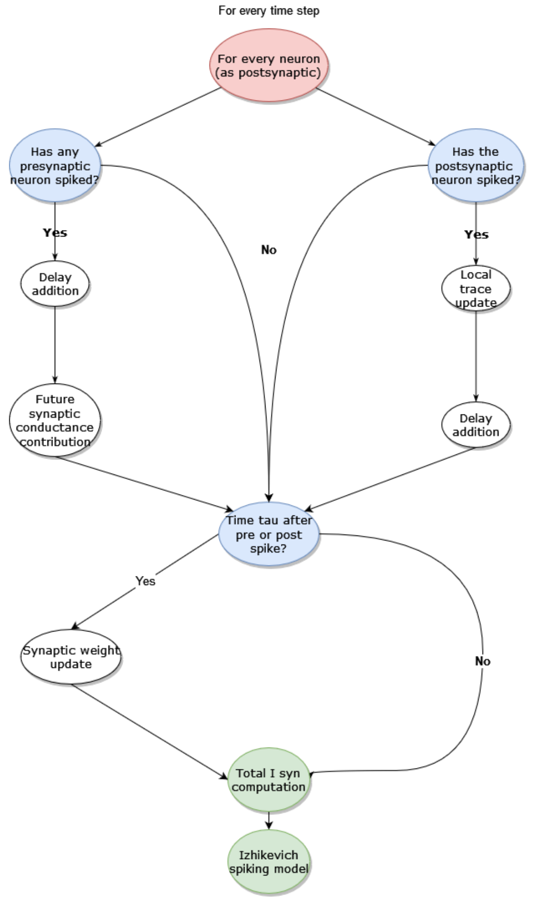
$$\frac{\mathrm{d}x}{\mathrm{d}t} = -\frac{x}{\tau} + \sum_{t^f} \cancel{A}^{\,1} \left(1 - x_-\right) \delta\left(t - t^f\right)$$

- Limiting negative exponential tails:

$$g_{\mathrm{syn}}(t) = \bar{g}_{\mathrm{syn}} \frac{t - t_s}{\pi_\alpha} \exp\left(-\frac{t - t_s}{\pi_\alpha}\right)$$

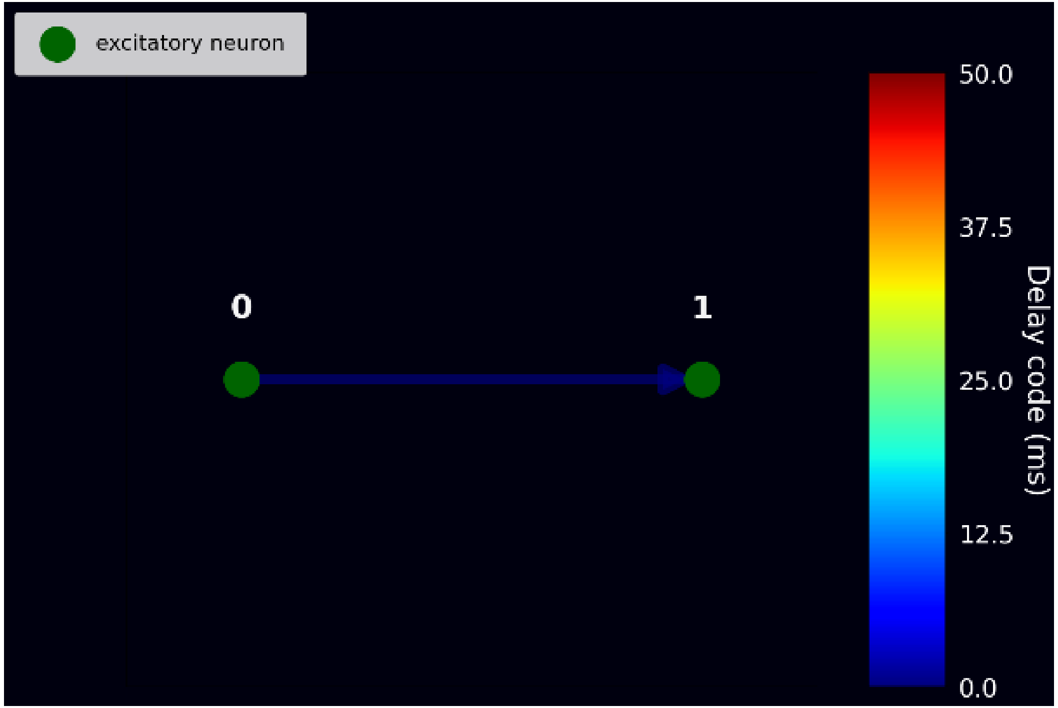
- JIT compiler

Google images: https://github.com/numba/numba

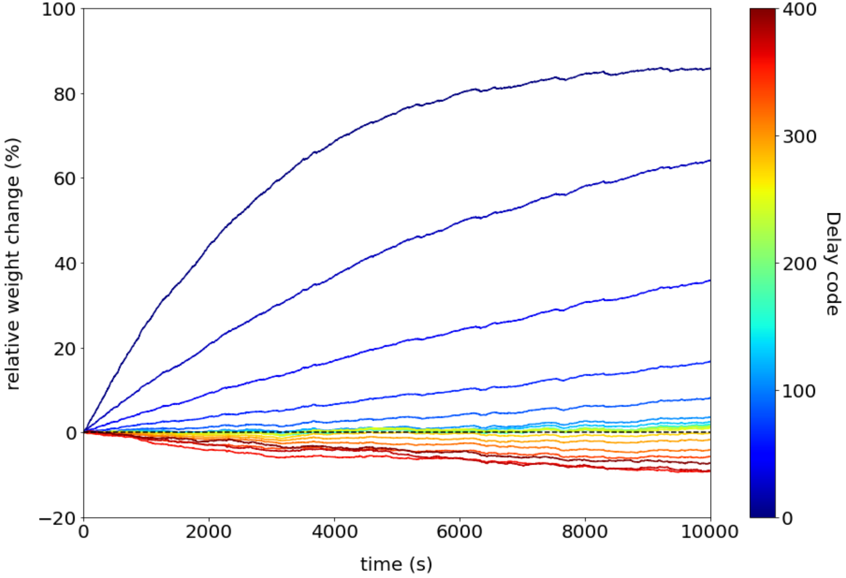


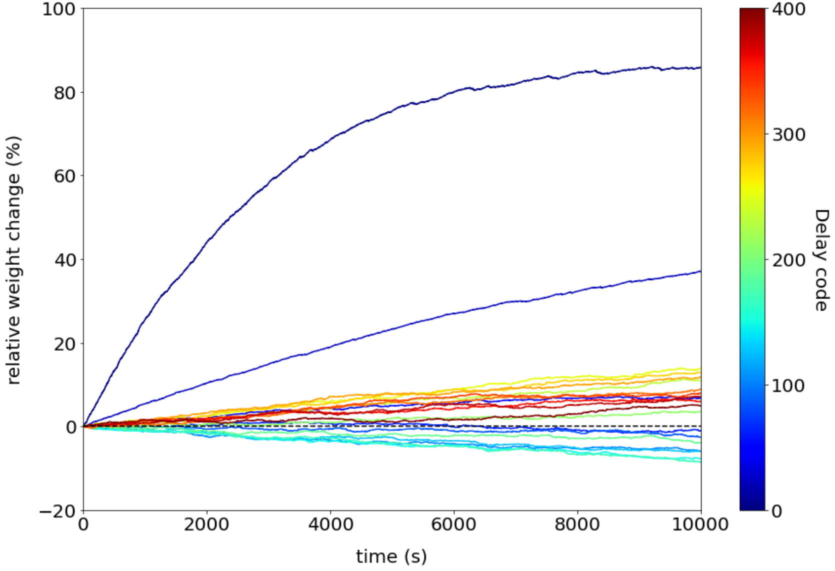
Methods (VI): Code structure & Optimization

RESULTS



Results: Model generalisation



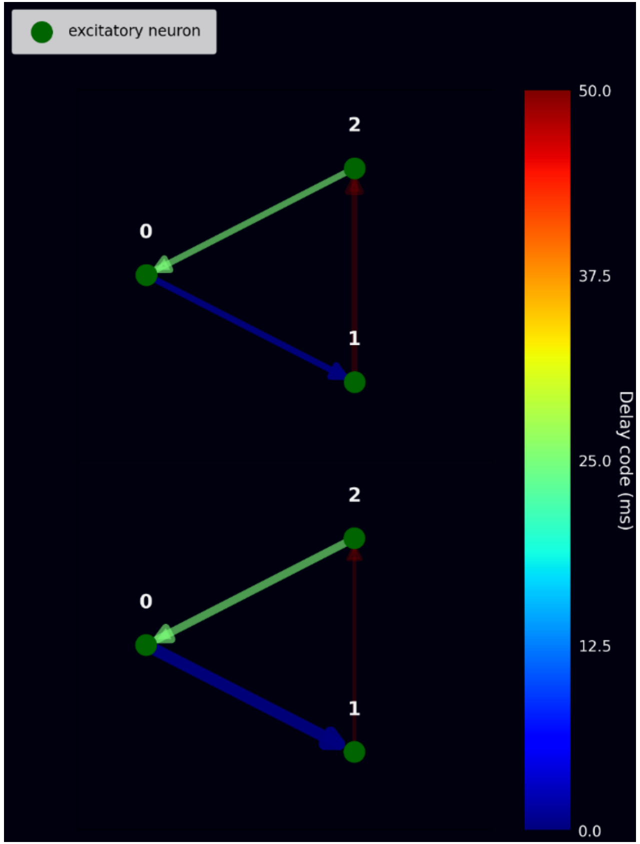


$$\Delta w_{ij} = \begin{cases} -\lambda\ (1 - w_{ij})\ y_i(t_{pre\,spike}), & \text{when presynaptic neuron spikes} \\ \lambda\ w_{ij}\ x_j(_{post\,spike}), & \text{when postsynaptic neuron spikes} \end{cases}$$

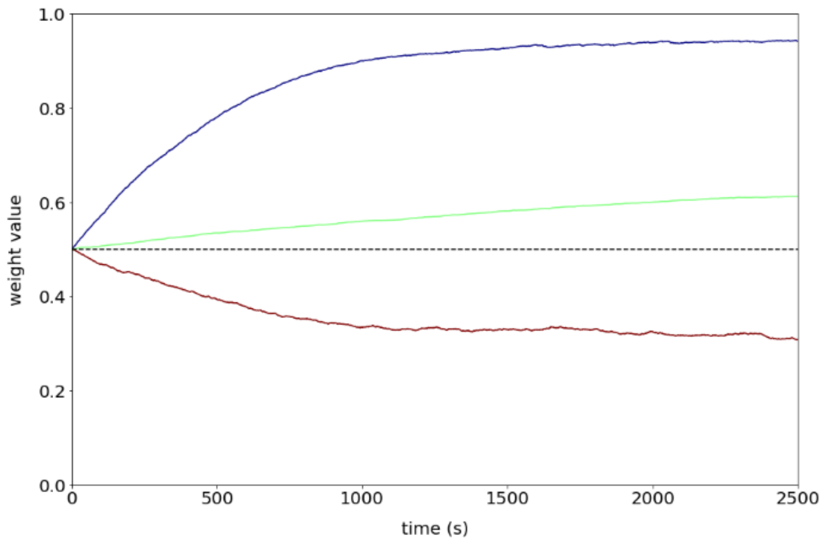
$$\Delta w_{ij} = \begin{cases} -\lambda\ (1 - w_{ij})\ y_i(t_{pre\,spike} + \tau), & \text{a time} = \tau \text{ after presynaptic neuron spikes.} \\ \lambda\ w_{ij}\ x_j(t_{post\,spike} + \tau), & \text{a time} = \tau \text{ after postsynaptic neuron spikes.} \end{cases}$$

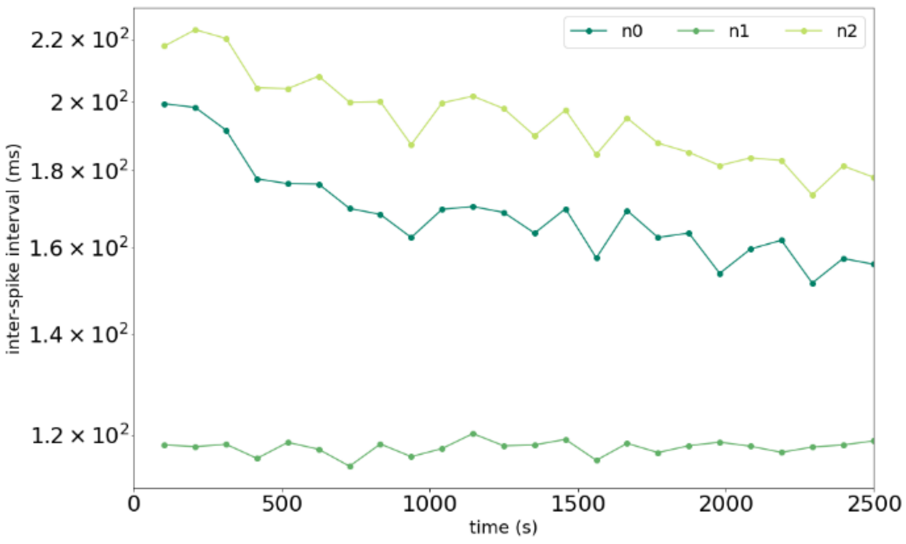
Results: Model generalisation

RESULTS: SMALL MOTIVES



Results: Small motives, Mono-Synapse Configuration





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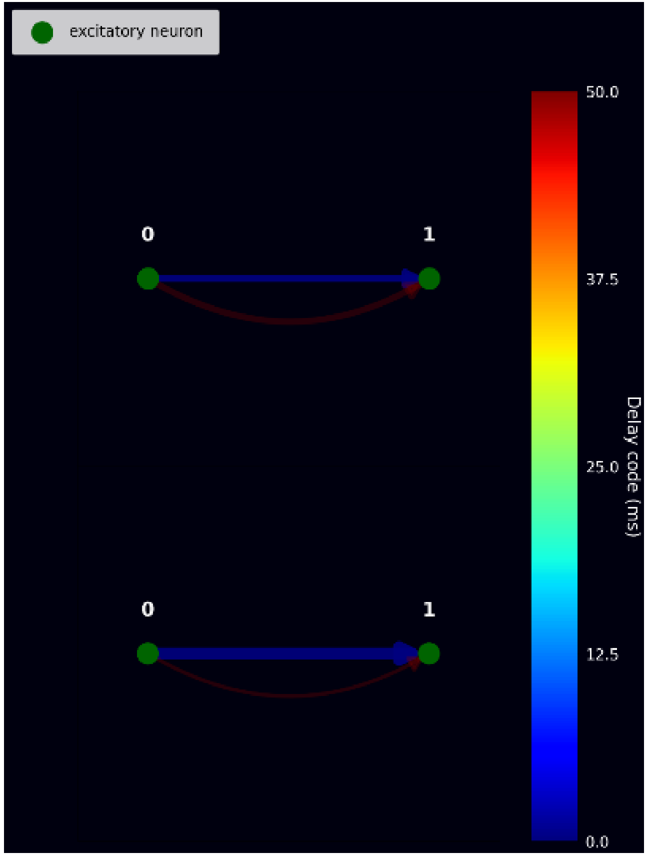
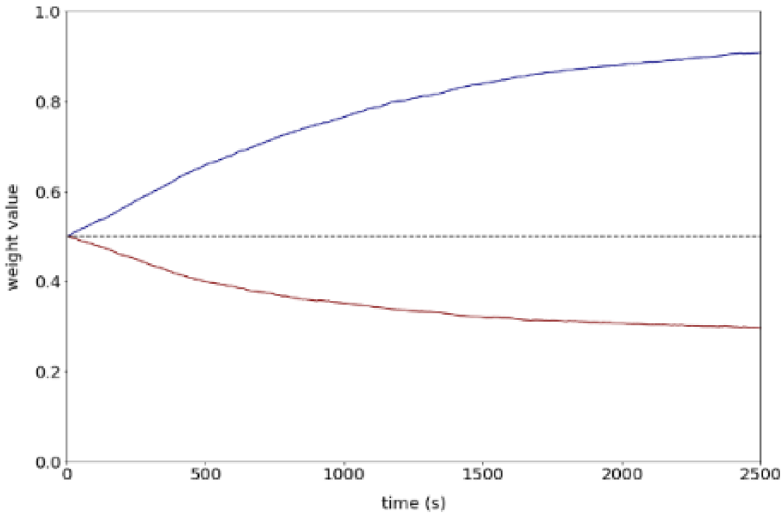
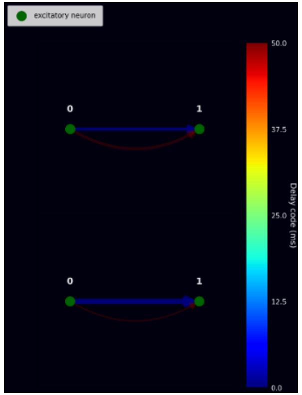
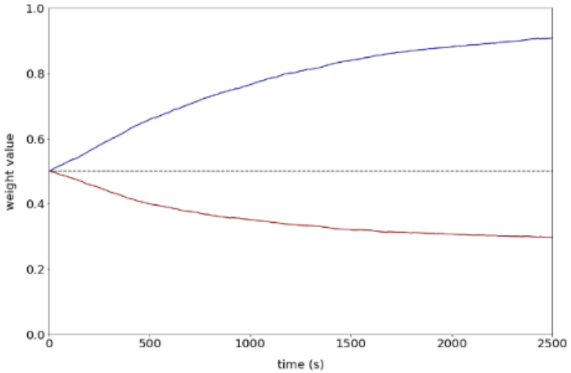


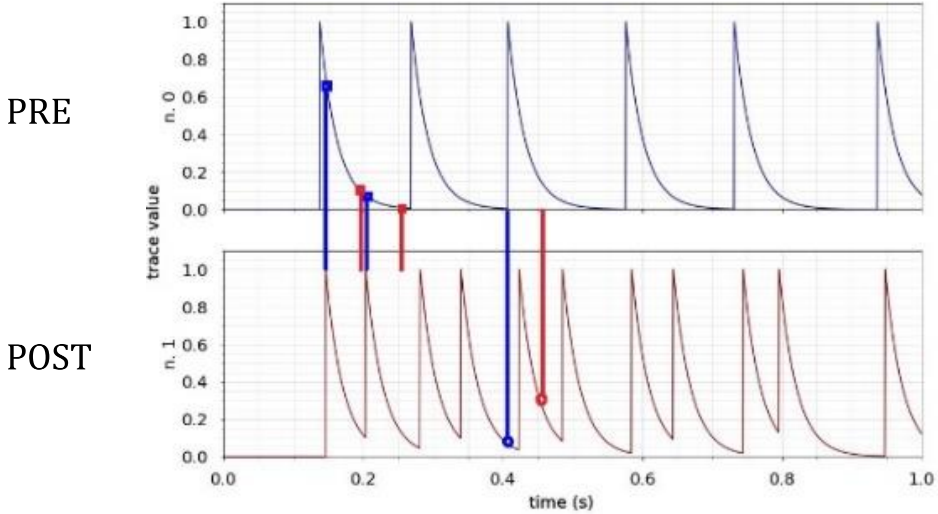


Results: Small motives, Multi-Synapse Configuration

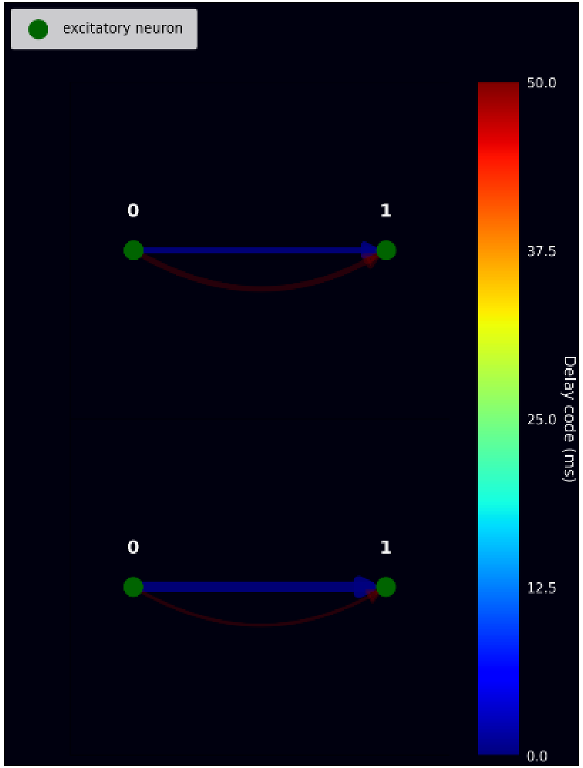


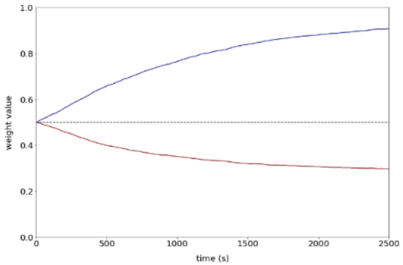


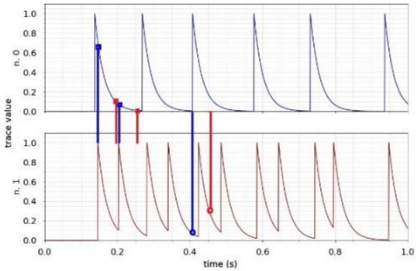
Update rule internals



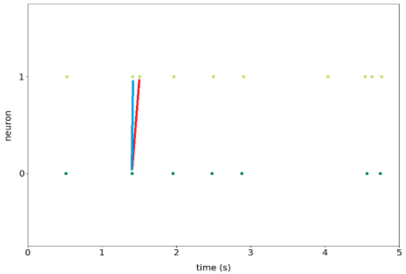
Results: Small motives, Multi-Synapse Configuration

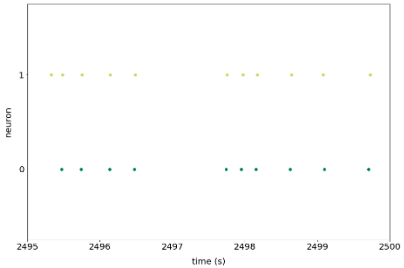


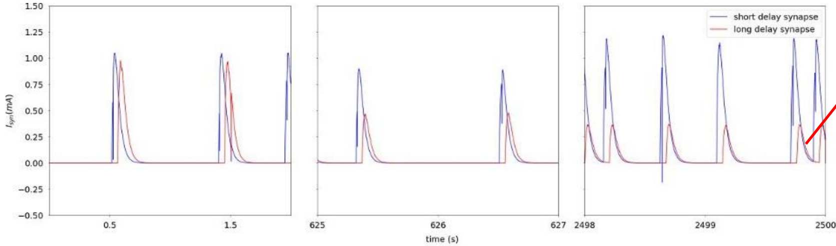




Update rule internals

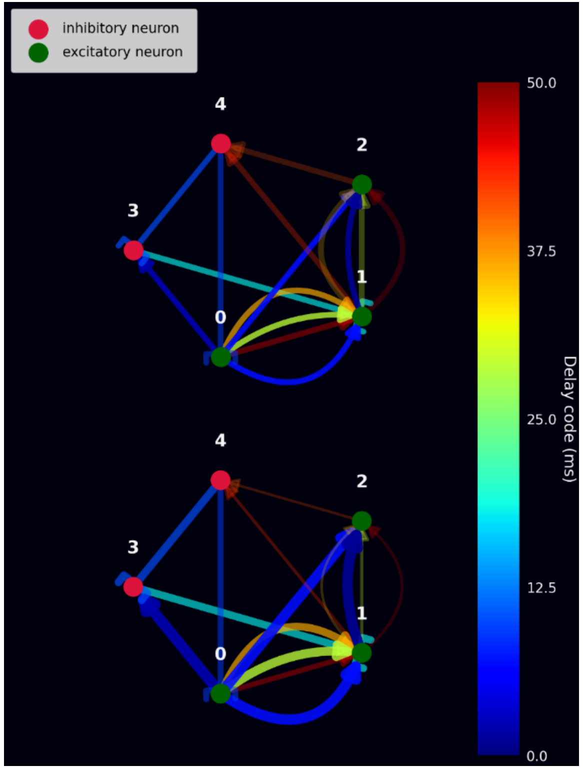


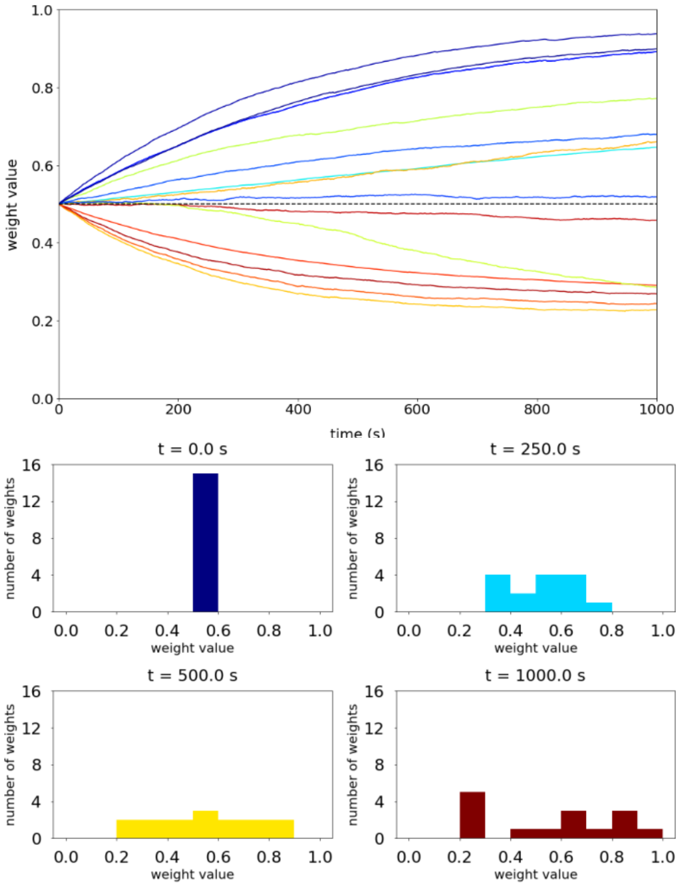




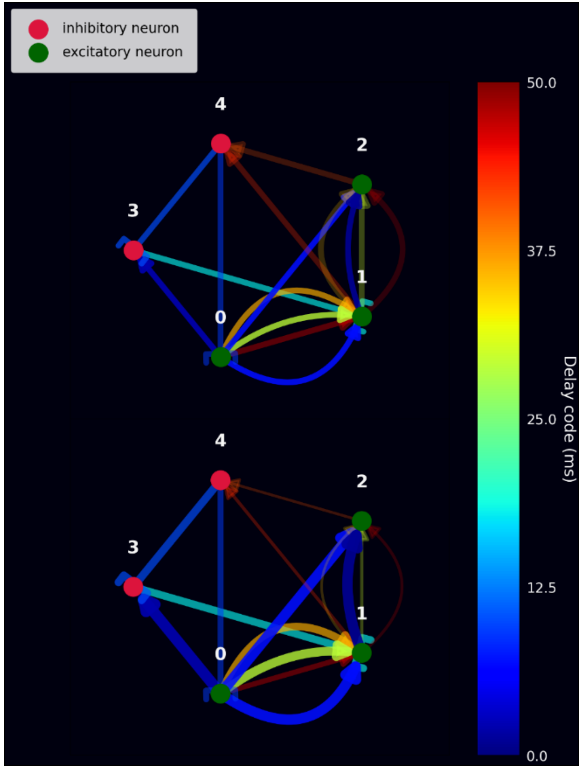
Transmission capability lost

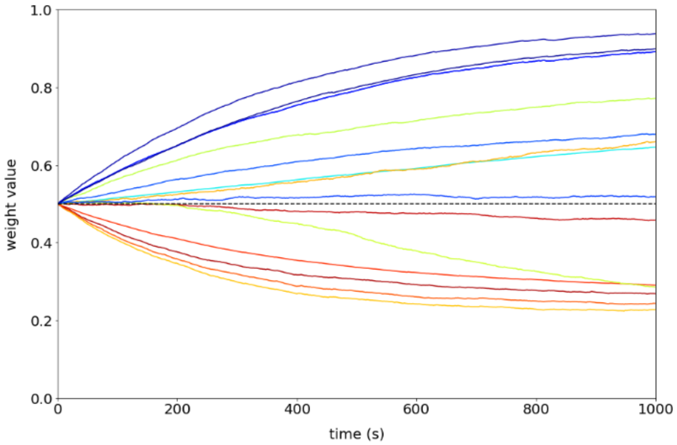
Results: Small motives, Multi-Synapse Configuration

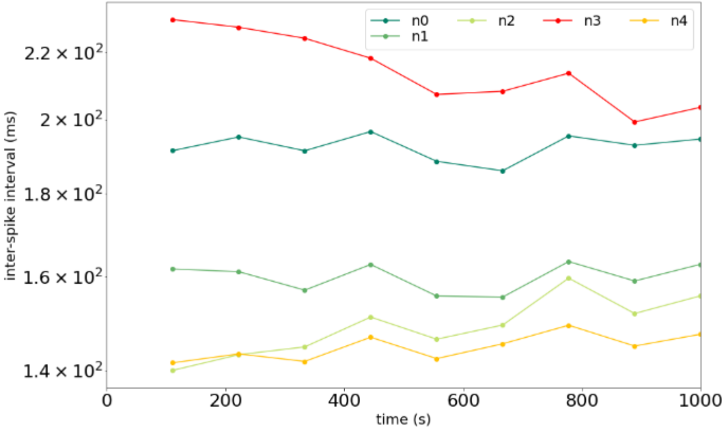




Results: Small motives, Network



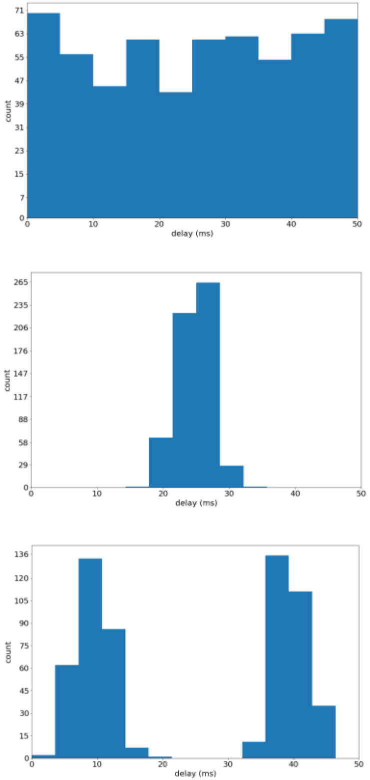




Results: Small motives, Network

RESULTS: LARGER NETWORKS

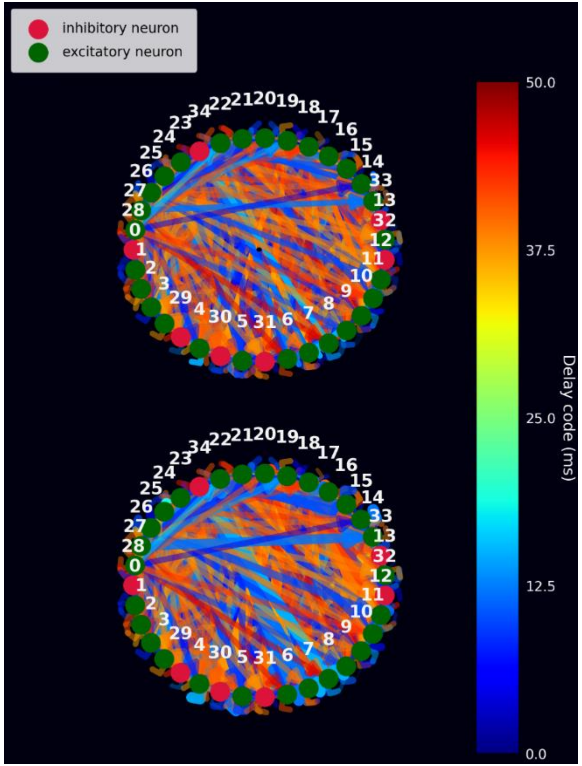
Network:
-35 neurons
-595 synapses

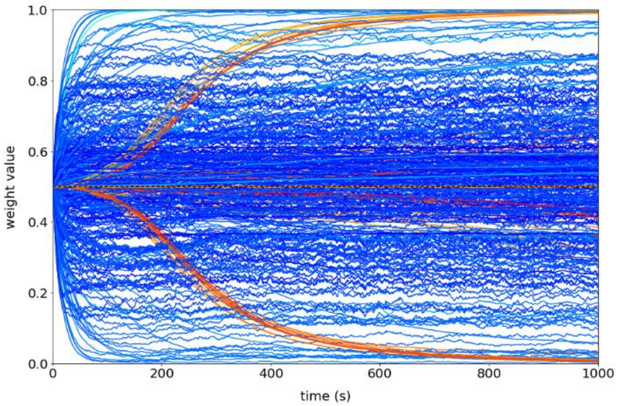


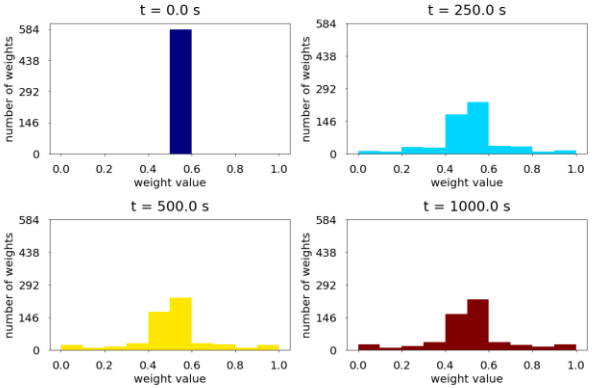
External Intensity Configuration:

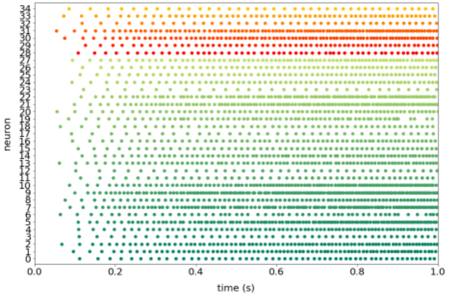
- Homogeneous
- Selected stimulation

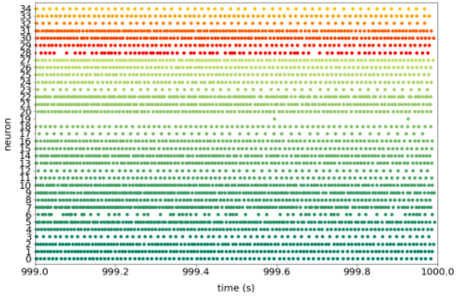
Results: Larger Networks (I)







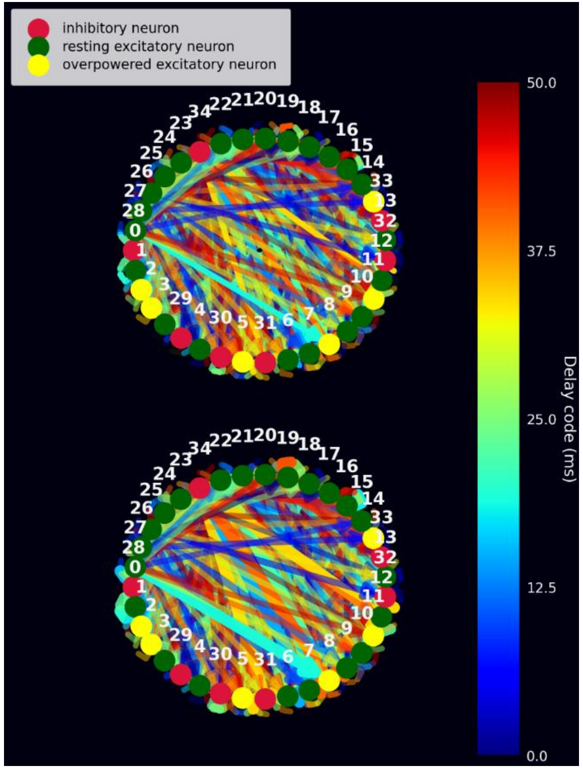


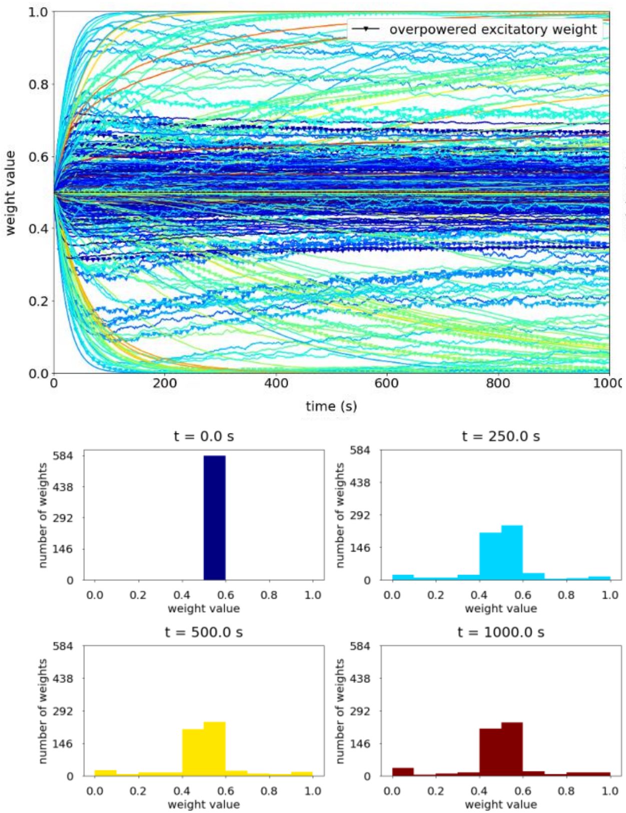


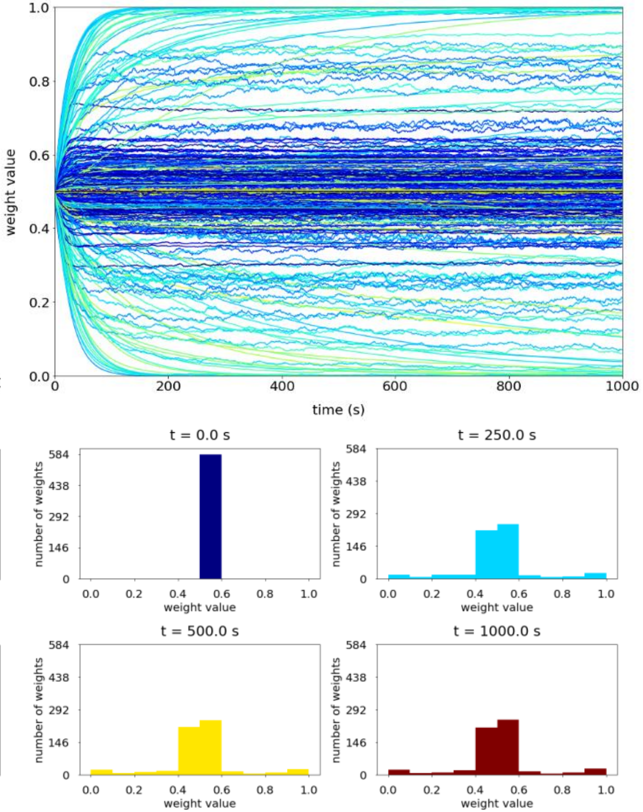
Results: Larger Networks (II)

Selected stimulation

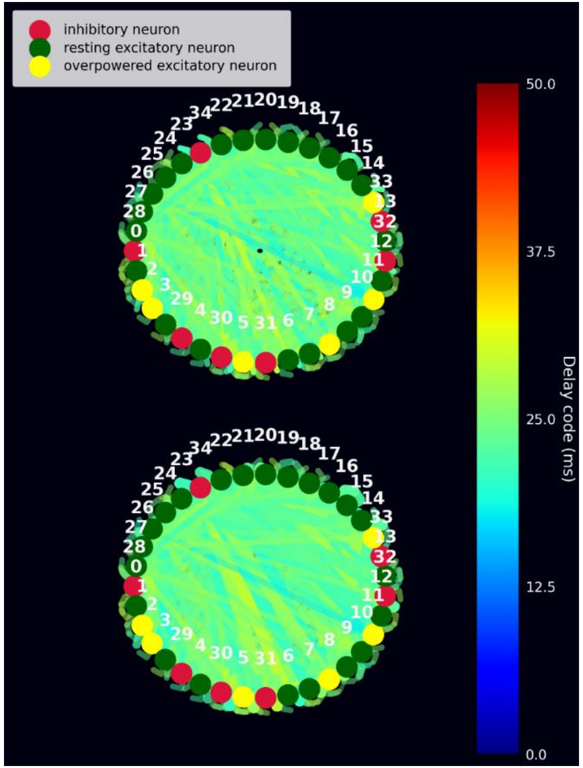
Homogeneous stimulation

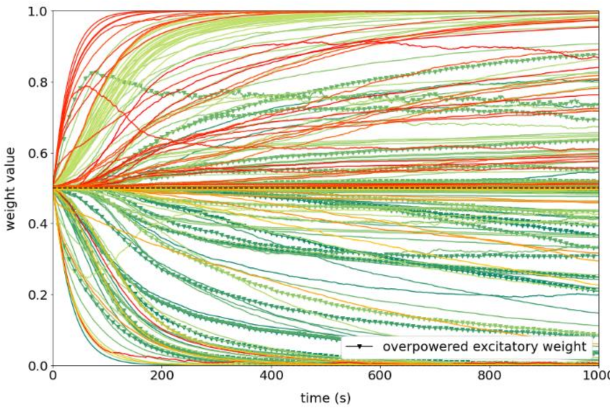


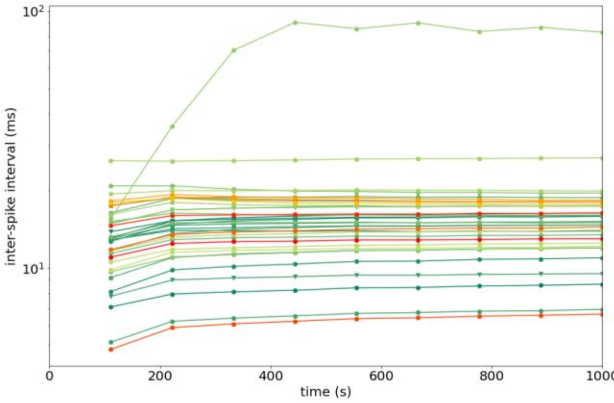


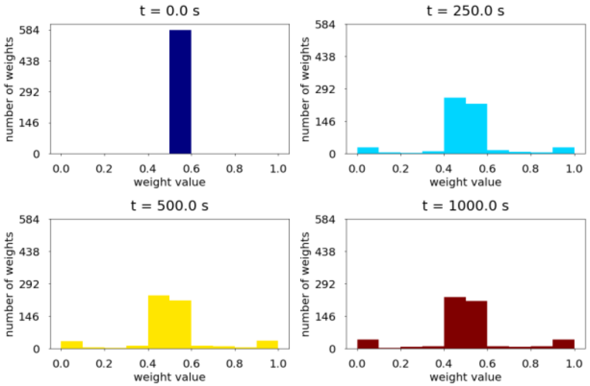


Results: Larger Networks (III)

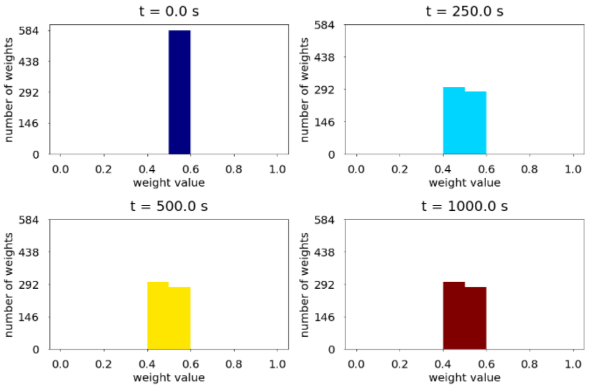




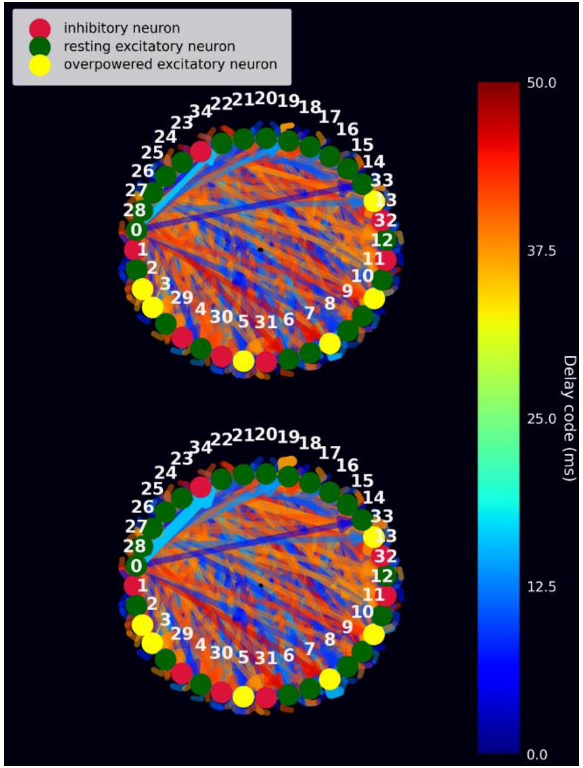




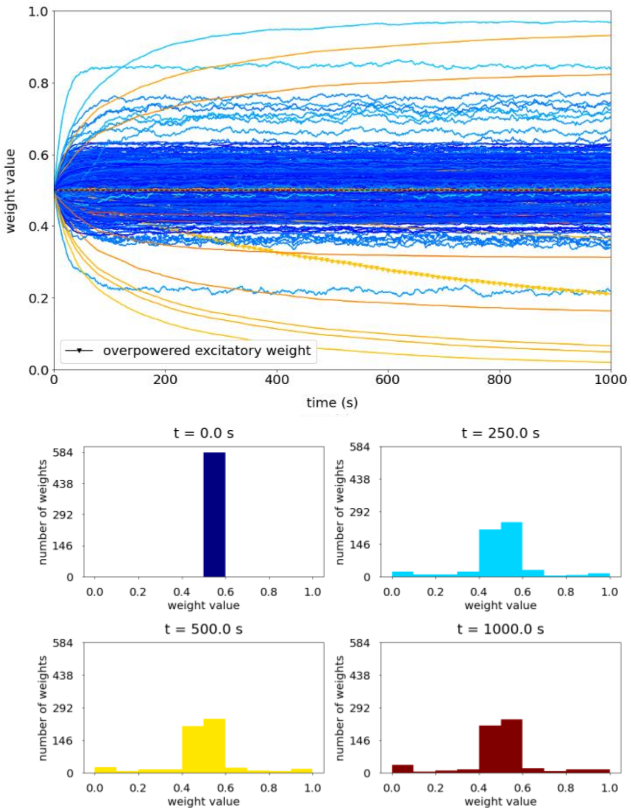
Homogeneous stimulation



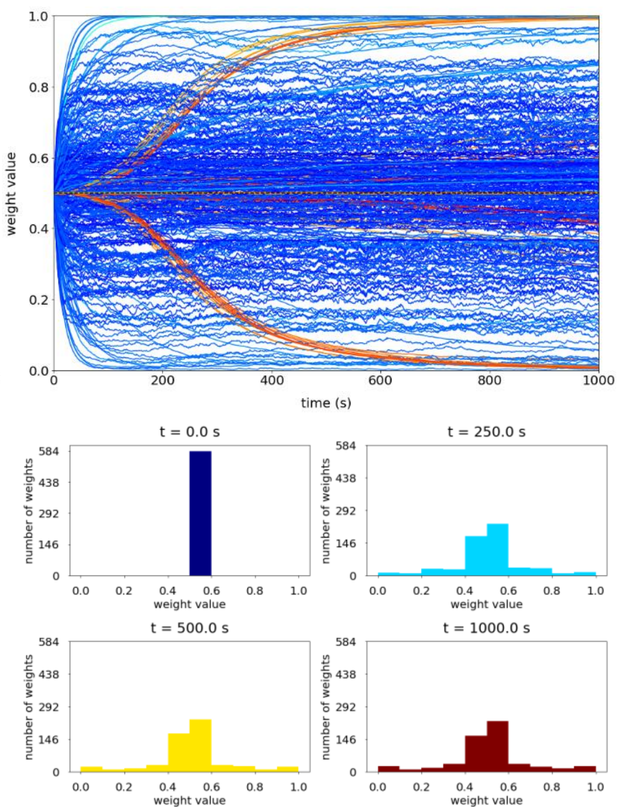
Results: Larger Networks (IV)



Selected stimulation



Homogeneous stimulation



Results: Larger Networks (V)

Conclusions

- Synaptic weight evolution according to it's associated delay.

- Delay distribution affects to the final state of the network.

- This happens with and without selected stimulation. Thus, the network learns this stimulation.

Future perspectives

- Quantification of the evolution of topological features of networks

- More realistic external stimulation

- Bigger networks with more realistic delay distributions

- Cooperation or competition interactions

- Interaction with other plasticity mechanisms

$$\Delta w_{ij} = \begin{cases} -\lambda\,(1 - w_{ij})\; y_i(t_{pre\,spike} + \tau), & \text{a time} = \tau \text{ after presynaptic neuron spikes.} \\ \lambda\; w_{ij}\; x_j(t_{post\,spike} + \tau), & \text{a time} = \tau \text{ after postsynaptic neuron spikes.} \end{cases}$$

Conclusion & Future perspectives