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# Neuromodulated STDP learning rule on SpiNNaker

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# Year 1 PhD projects

1. Hardware exponential function unit for SpiNNaker-2
2. Neuromodulated STDP learning rule (Initially a way to learn about STDP; Later part of BIMPC reinforcement learning project)

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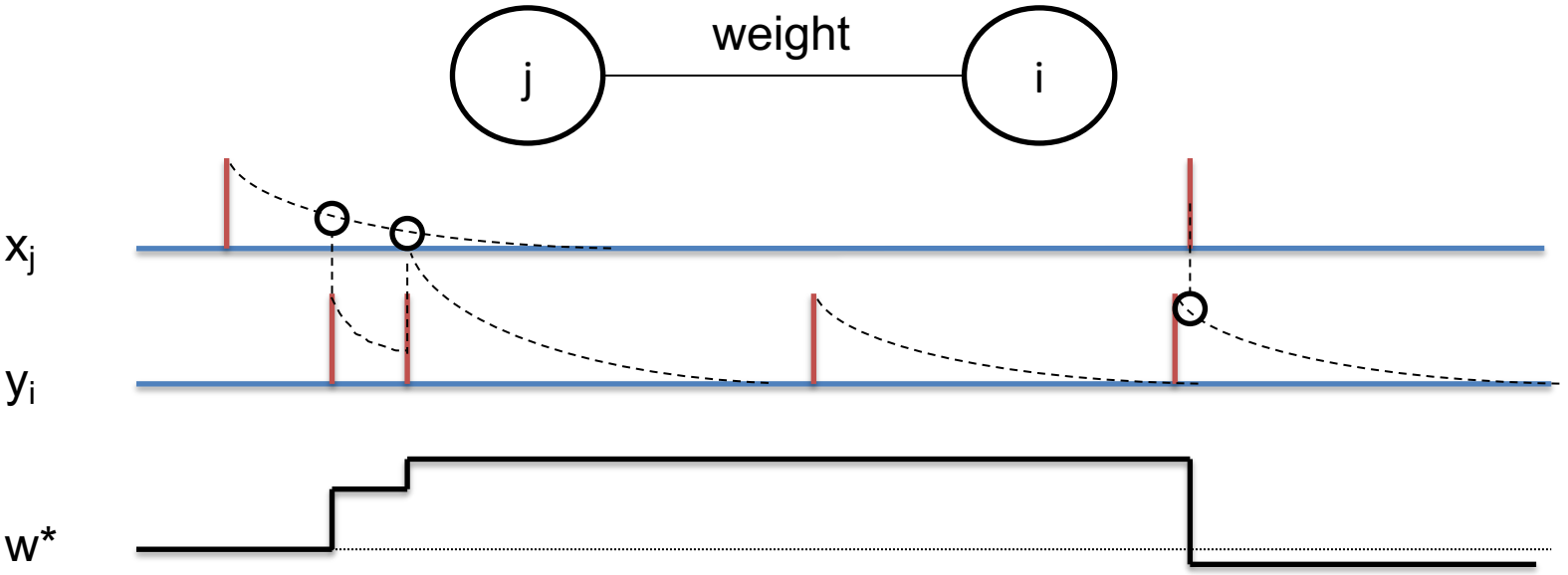
# What is STDP?

If a neuron repeatedly causes another neuron to fire, wire them together with a strong synapse. Otherwise, “disconnect” the synapse.

Make a decision by looking at spike times of both neurons and the current weight of the synapse.

Hebb 1949; Markram et al 1997; Bi and Poo 1998.

# Spike-Timing-Dependent-Plasticity (STDP)




$$\frac{dx_j}{dt} = -\frac{x_j}{\tau_x} + \sum_{t_j^f} \delta(t - t_j^f) \qquad \frac{dy_i}{dt} = -\frac{y_i}{\tau_y} + \sum_{t_i^f} \delta(t - t_i^f)$$

$$\Delta w_{ij}^{-}(t_j^f) = -F_{-}(w_{ij}) y_i(t_j^f)$$

$$\Delta w_{ij}^{+}(t_i^f) = F_{+}(w_{ij}) x_j(t_i^f)$$

Morrison A. Diesmann M. Gerstner W. 2008

* Example: additive weight dependence F

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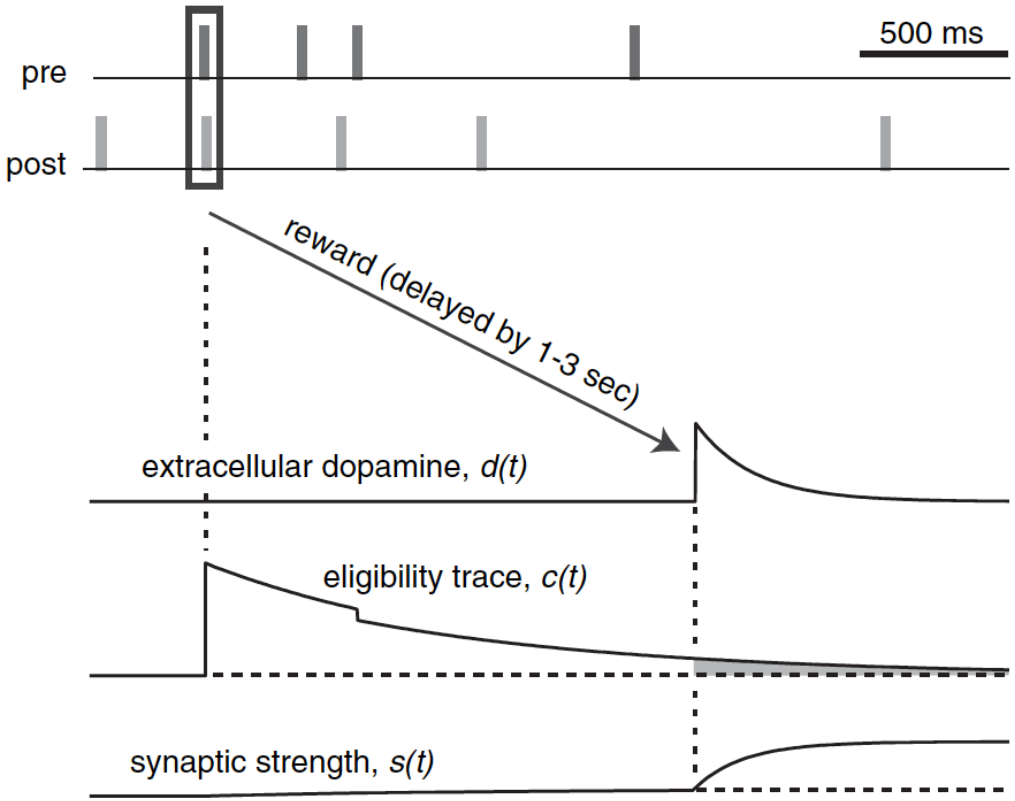
# What is neuromodulation?

- Classic Hebbian learning puts emphasis on pre- and postsynaptic activity.
- Neglects effect of neuromodulators, such as dopamine.
- Third-factor learning is a class of neo-Hebbian learning rules.
- Introduces a neuromodulator signal that conveys reward or novelty, which affects STDP.


Frémaux N. and Gerstner W. 2016

# Neuromodulated STDP – Izhikevich model

- In this model, dopamine signal 'gates' STDP – if there is no dopamine, there is no plasticity




New traces:

- D(t) - dopamine level per neuron
- c(t) – eligibility trace per synapse

$$\frac{dc}{dt} = -\frac{c}{\tau_c} + STDP(t_{post} - t_{pre})\delta(t - t_{pre/post})$$

$$\frac{dD}{dt} = -\frac{D}{\tau_D} + \sum_{t_d^f} \delta(t - t_d^f)$$

$$\frac{dW}{dt} = cD$$

Izhikevich E. 2007

"Evidence for eligibility traces in human learning", Lehmann M. et al, 2017

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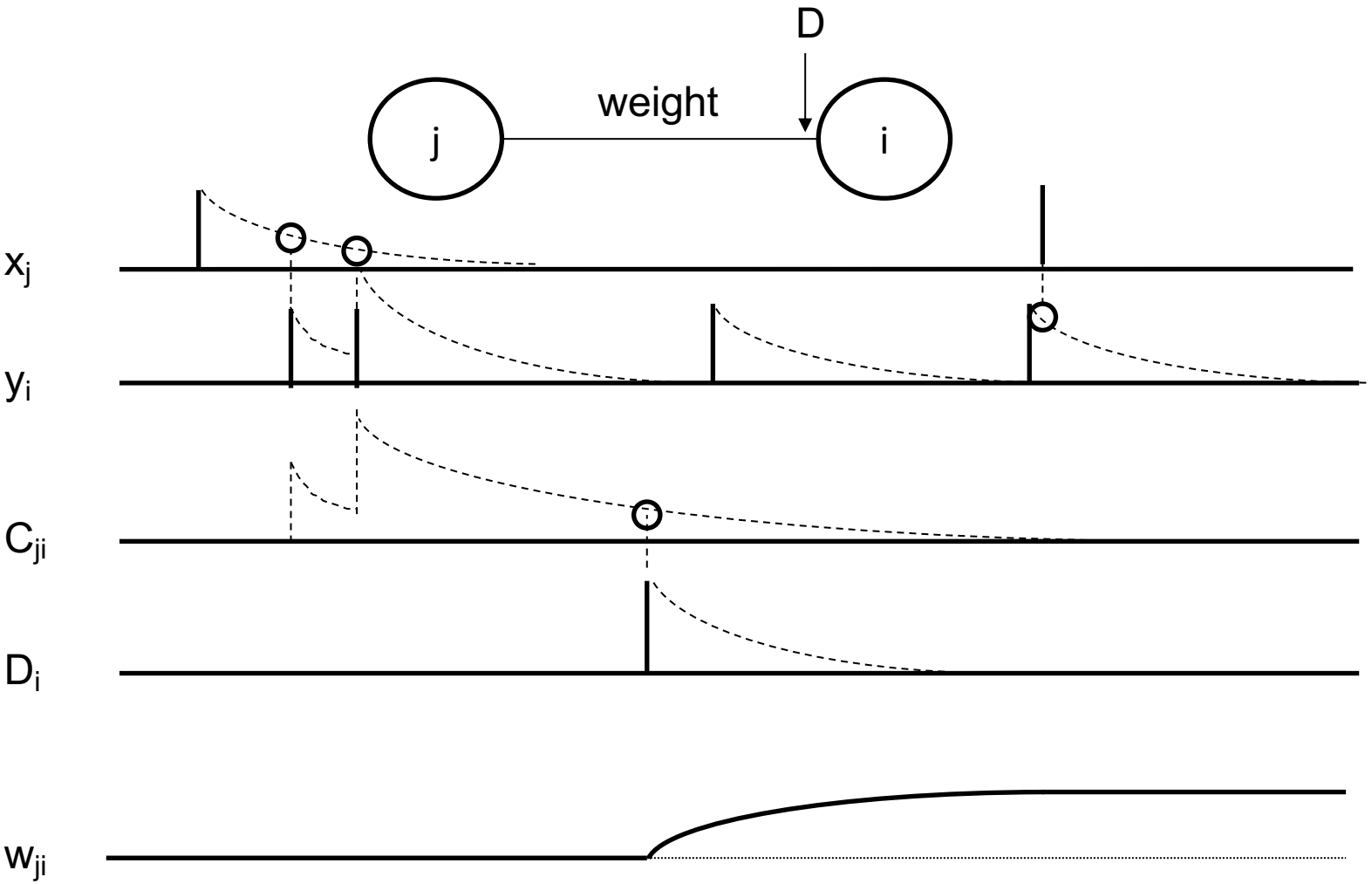
# Reward example



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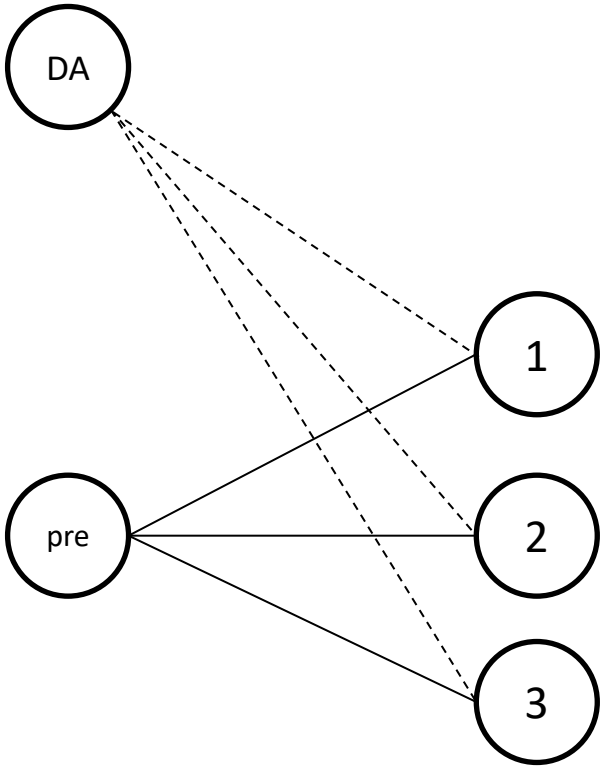
# Example PyNN Network




DA – Dopaminergic neuron

-------- neuromodulator (reward/punishment) connection

——— inh/exc. plastic connection

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# Using in sPyNNaker7

```
[…]
pre_pop = sim.Population(…)
post_pop = sim.Population(…)
dopaminergic_pop = sim.Population(…)

# Create synapse dynamics with neuromodulated STDP.
synapse_dynamics = sim.SynapseDynamics(slow=sim.STDPMechanism(
                timing_dependence=sim.SpikePairRule(tau_plus=15.0, tau_minus=30.0,
                tau_c=2.0, tau_d=200.0), # Eligibility trace and dopamine constants
                weight_dependence=sim.AdditiveWeightDependence(),
                neuromodulation=True))

# Create dopaminergic connection to post synaptic population
dopaminergic_projection = sim.Projection(dopaminergic_pop, post_pop,
                sim.AllToAllConnector(weights=1.0), # Weight in this case is level of dopamine
                target='reward', label='DA projection')
# Create a plastic connection between pre and post neurons
plastic_projection = sim.Projection(pre_pop, post_pop, sim.AllToAllConnector(weights=…),
                synapse_dynamics=synapse_dynamics,
                target='excitatory', label='Pre-post projection')
[…]
```

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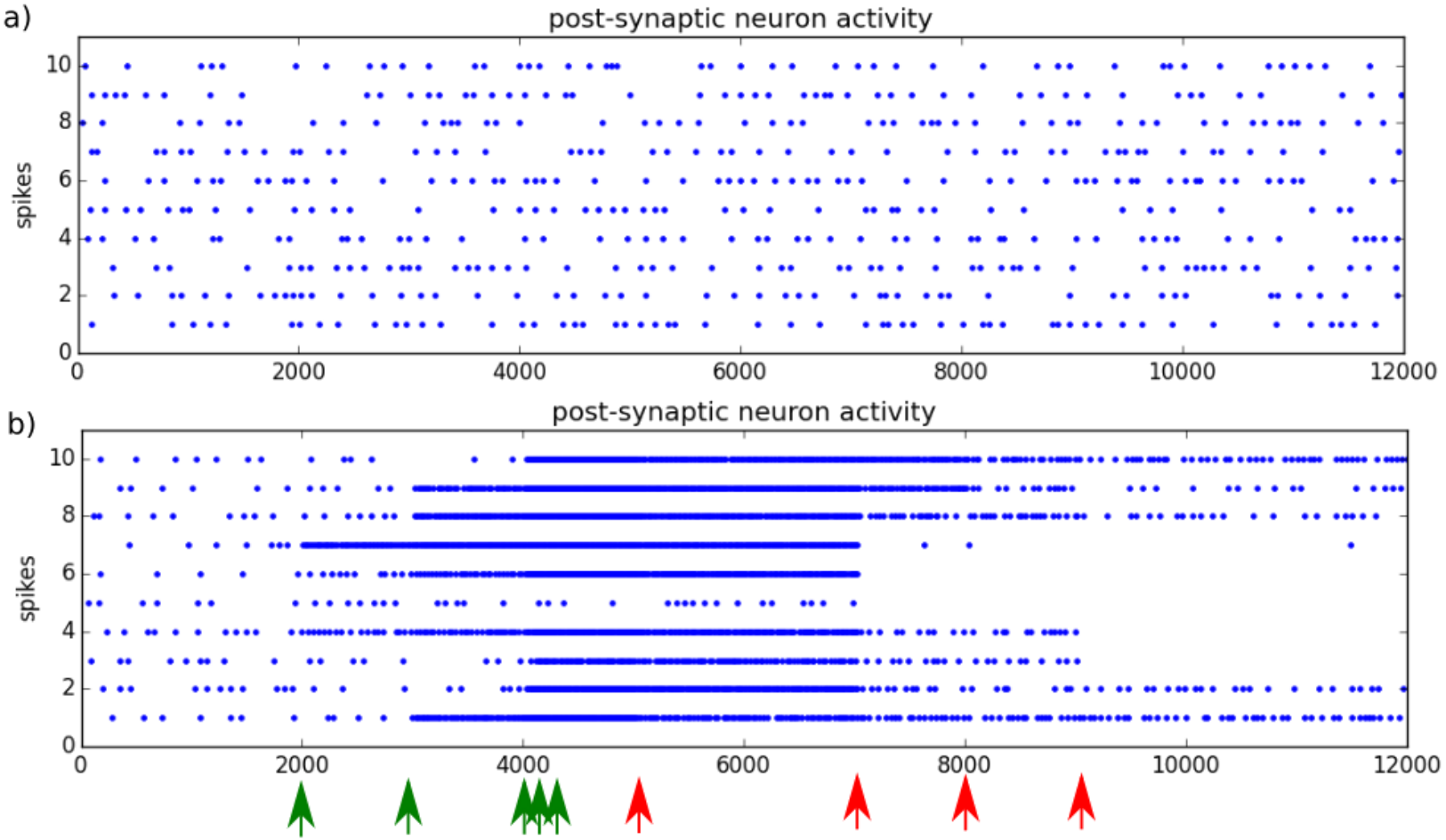
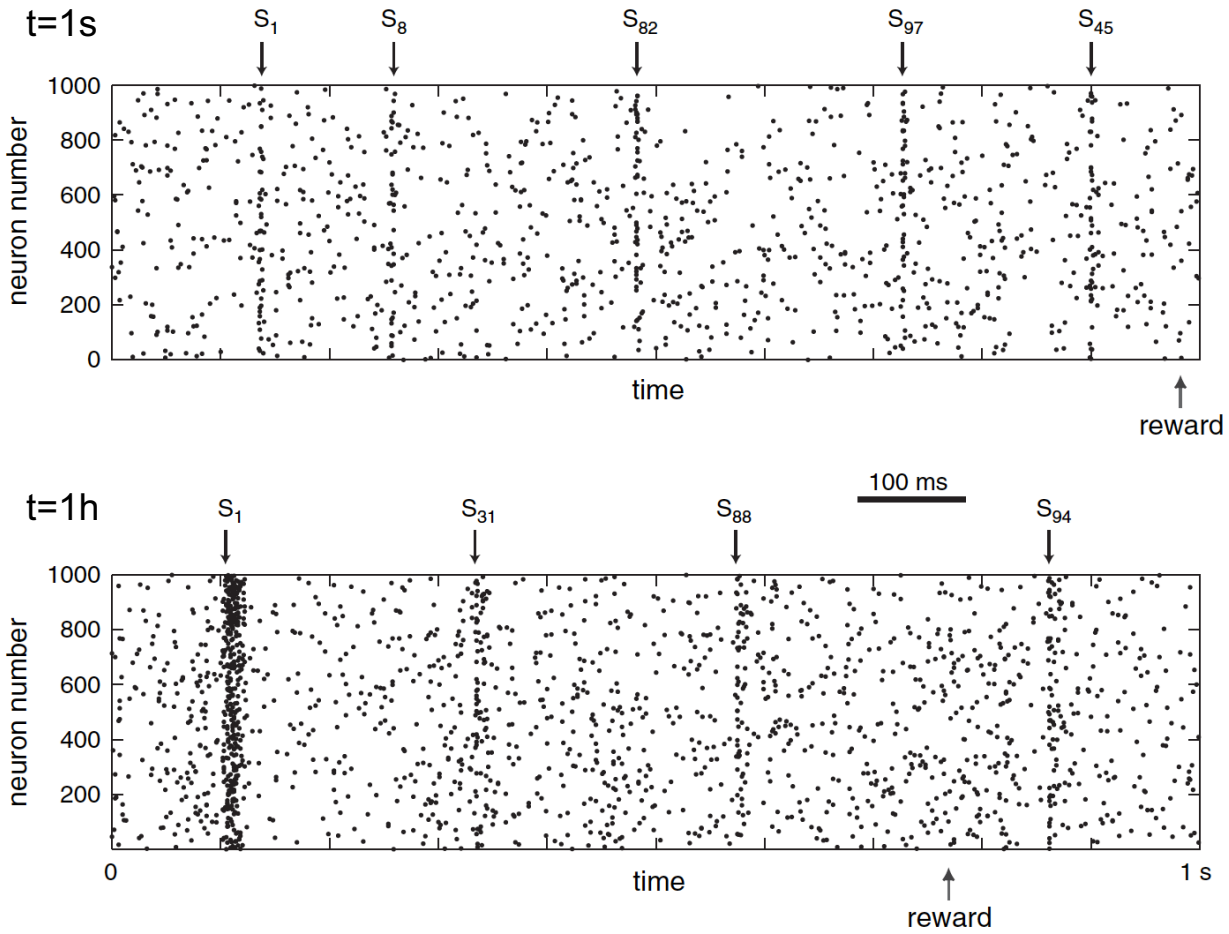
# Rewarding and punishing a synapse on SpiNNaker




200Hz fixed poisson stimulus. Example: Motor control – reward 10 neurons to turn left.

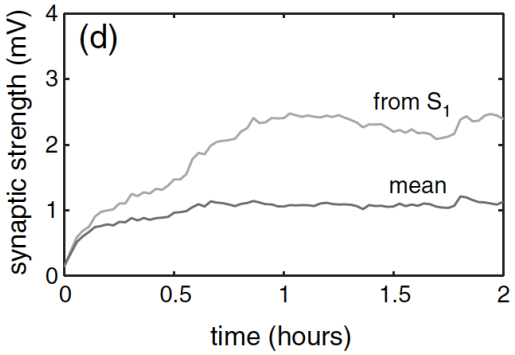
# Izhikevich's Pavlonian conditioning experiment



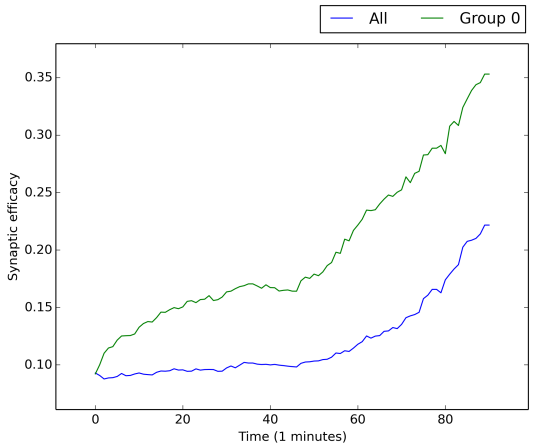

- $S_1 \ldots S_{100}$ groups each of 50 random neurons are chosen.
- Every 1s, 5 randomly chosen groups of neurons are stimulated to spike.
- When $S_1$ spikes, global DA signal arrives with a random delay up to 1s.
- After 1h (b to c), only synapses from $S_1$ strengthen.
- Network learns that $S_1$ brings reward. (Example: Monkey experiments)

Izhikevich E. 2007

# Izhikevich's Pavlonian conditioning experiment on SpiNNaker

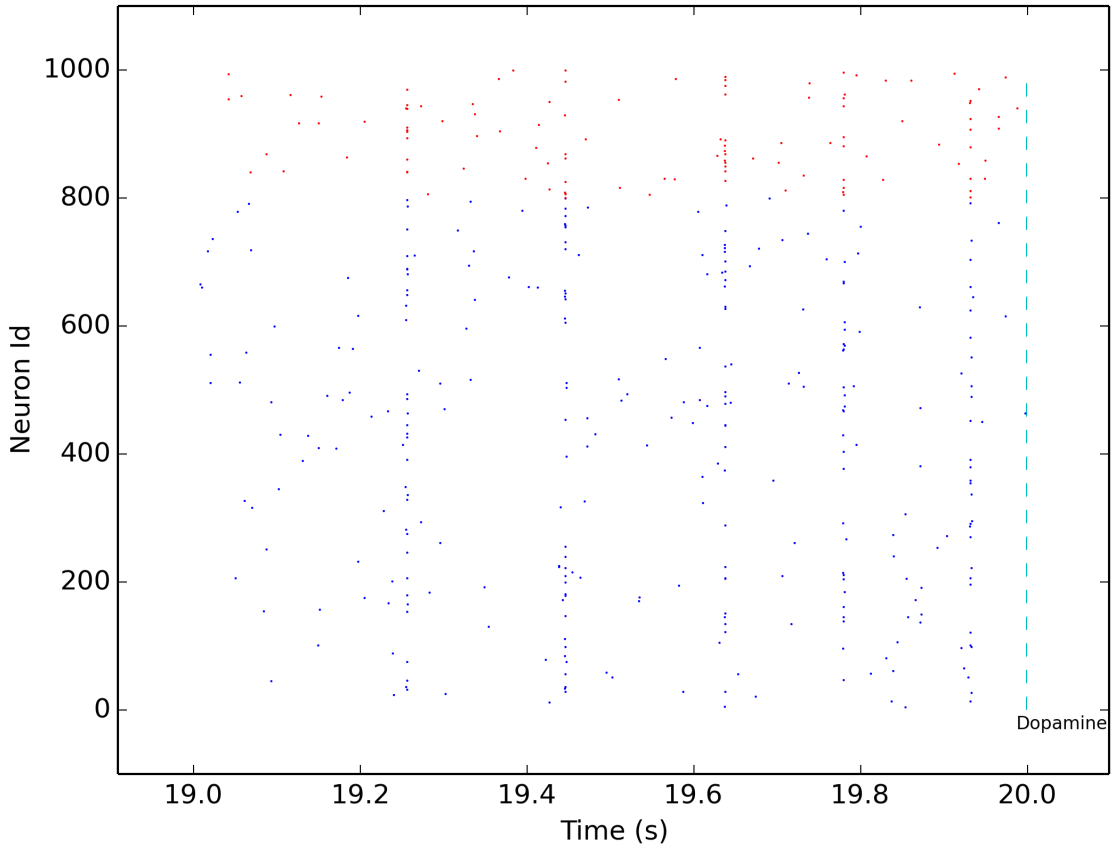



Izhikevich E. 2007

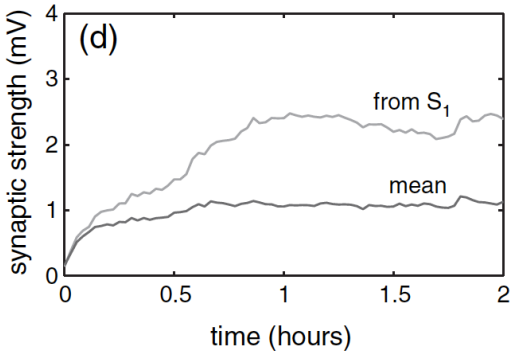



Experiment done by Gary

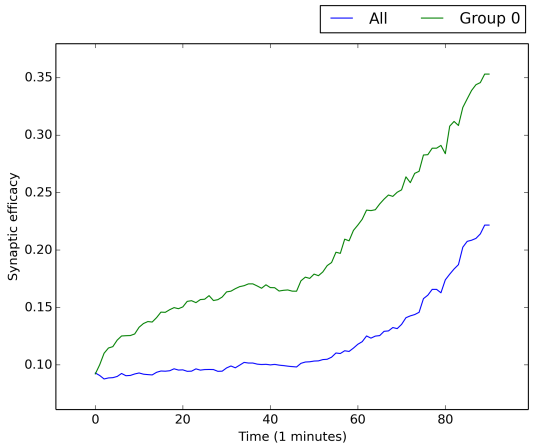
t=19s



# Izhikevich's Pavlonian conditioning experiment on SpiNNaker

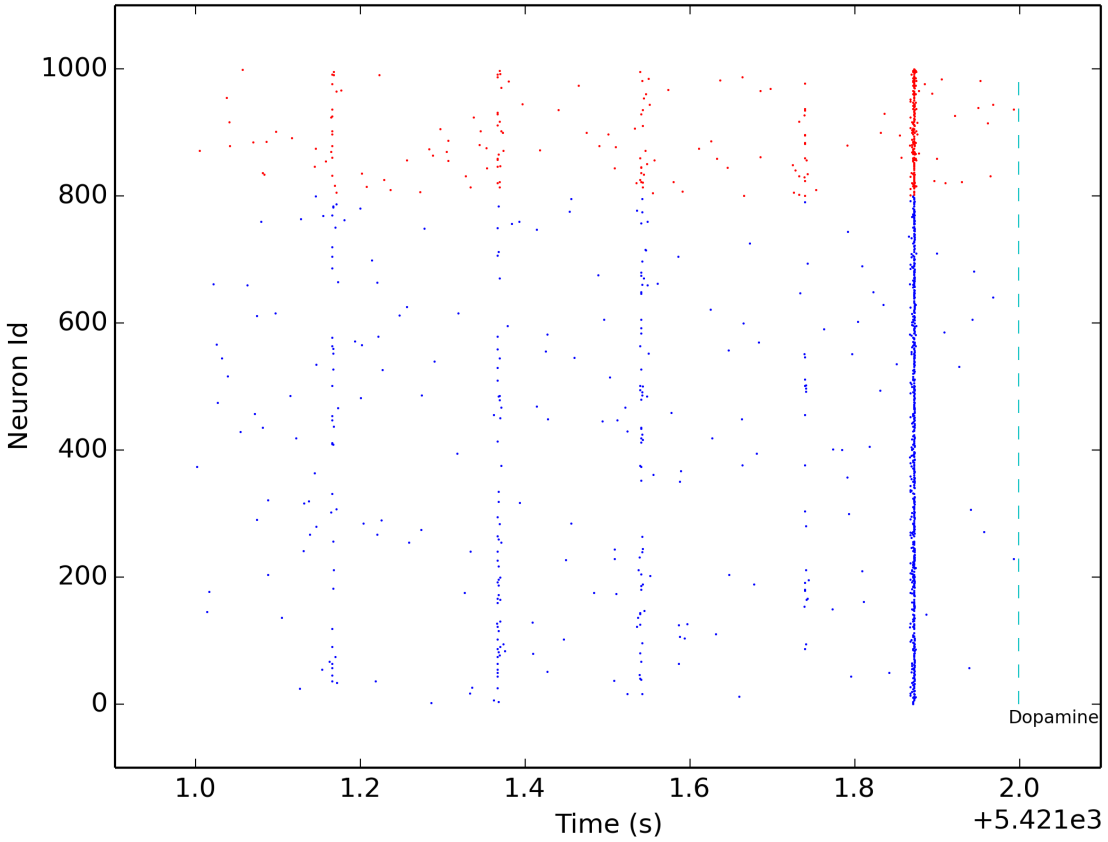



Izhikevich E. 2007




Experiment done by Gary

t=1.5h+



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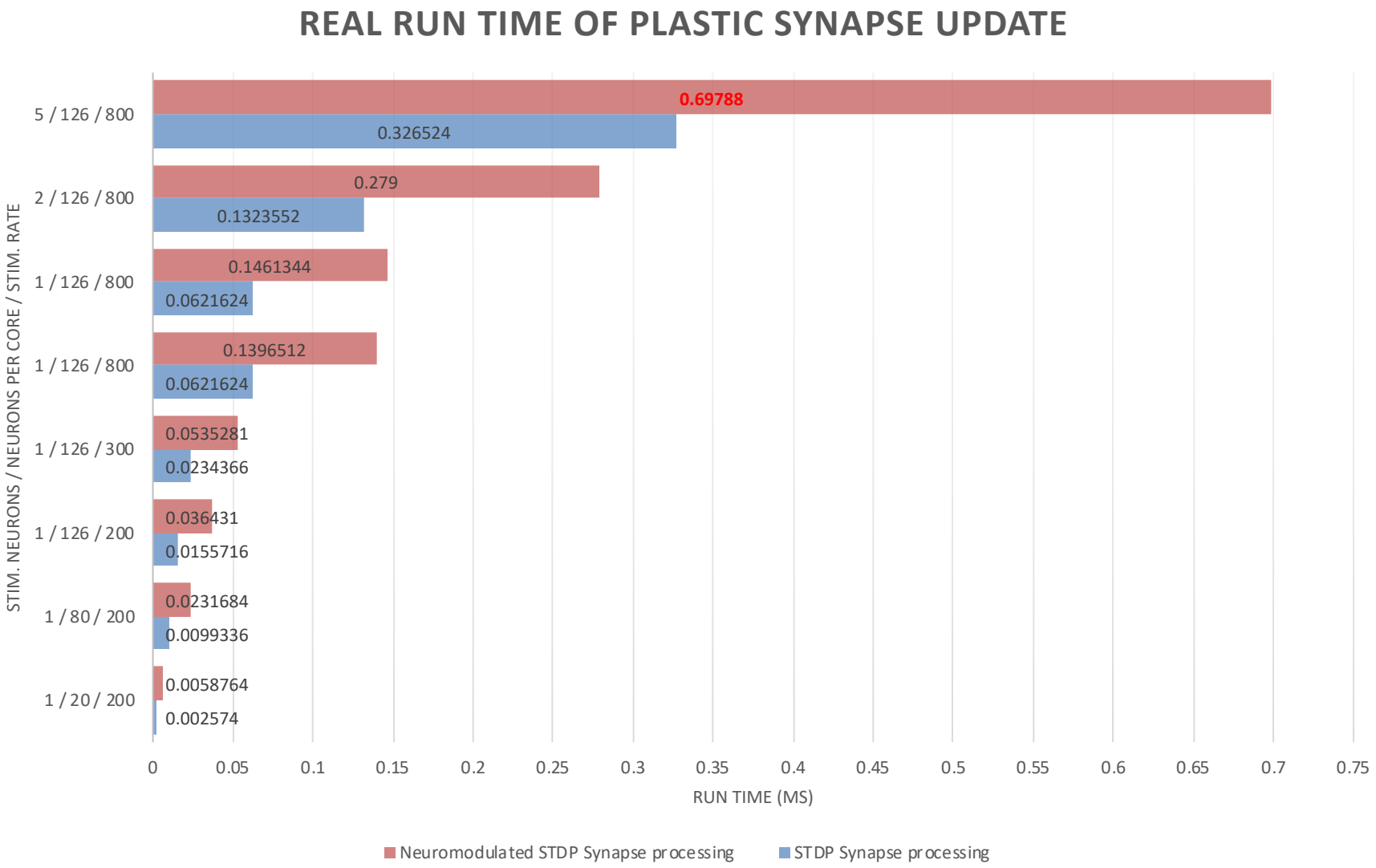
# Performance comparison to classical STDP



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# Future work

1. Volume transmitters – neuromodulators that affect area around release point (NEST; Potjans et al 2010)
2. Reinforcement learning (Both virtual and physical e.g. Mahadevuni et al 2017)
3. A general framework for Reward modulated STDP (Frémaux N. and Gerstner W. 2016)

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If you want to try it out, code is on SpiNNaker GitHub, package sPyNNaker, branch ”neuromodulation”.

Jamie Knight developed initial idea and math model; Mantas developed C code and tested the learning rule; Gary developed conditioning experiments.

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# References


- “Regulation of Synaptic Efficacy by Coincidence of Postsynaptic APs and EPSPs”, Henry Markram, Joachim Lübke, Michael Frotscher, Bert Sakmann, 1997
- “Synaptic Modifications in Cultured Hippocampal Neurons: Dependence on Spike Timing, Synaptic Strength, and Postsynaptic Cell Type”, Guo-qiang Bi and Mu-ming Poo, 1998
- “Neuromodulated Spike-Timing-Depedendent-Plasticity, and Theory of Three-Factor Learning Rules”, Nicolas Frémaux and Wulfram Gerstner, 2016
- “Phenomenological models of synaptic plasticity based on spike timing”, Abigail Morrison, Markus Diesmann, Wulfram Gerstner, 2008
- “Solving the Distal Reward Problem through Linkage of STDP and Dopamine Signalling”, Eugene M. Izhikevich, 2007
- “Enabling functional neural circuit simulations with distributed computing of neuromodulated plasticity”, Wiebke Potjans, Abigail Morrison, Markus Diesmann, 2010
- “Navigating Mobile Robots to Target in Near Shortest Time using Reinforcement Learning with Spiking Neural Networks ”, Amarnath Mahadevuni, Peng Li, 2017
- “Evidence for eligibility traces in human learning”, Lehmann et al, 2017, arXiv pre-print