Neuromorphic computing with thermal interactions

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Neuromorphic computing

- Human Brain:
- $\sim 10^{11}$ neurons
- $\sim 10^{15}$ synapses
- Power consumption:

  ~ 20 W

- GPT-3:
- 1.75×10^{11} parameters
- $\sim 10^{4}$ J per query
- Training costs

  $\sim 10^{13}$ J

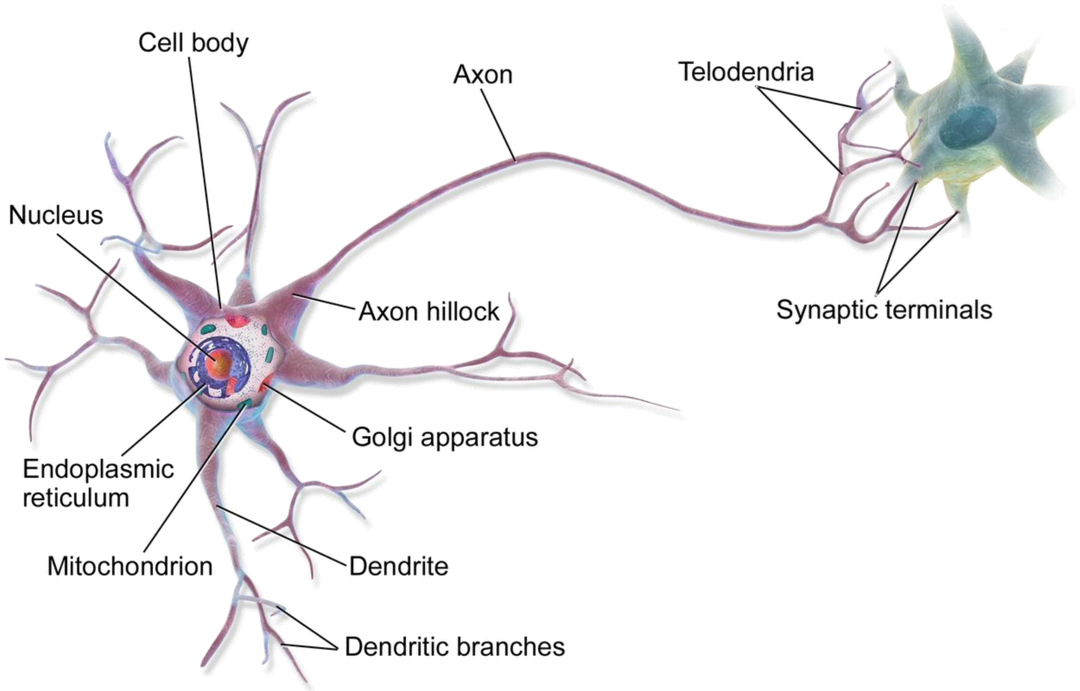
Marković, D., Mizrahi, A., Querlioz, D., & Grollier, J. (2020). Physics for neuromorphic computing. *Nature Reviews Physics*, *2*(9), 499-510.

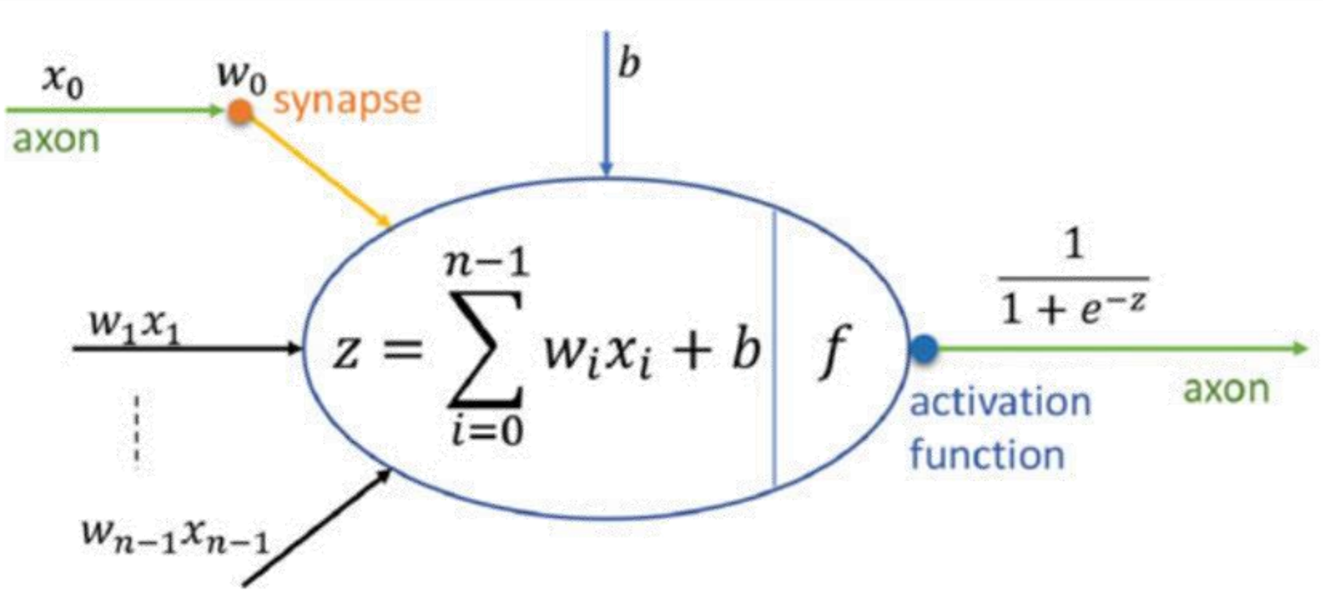
Patterson, David, et al. "Carbon emissions and large neural network training." *arXiv preprint arXiv:2104.10350* (2021).

Neuromorphic computing

- A query from ChatGPT $\leftrightarrow$ 10 minutes of brain activity
- Human brain is $\sim 10^4$ times larger than GPT-3
- We need energy efficient hardware!

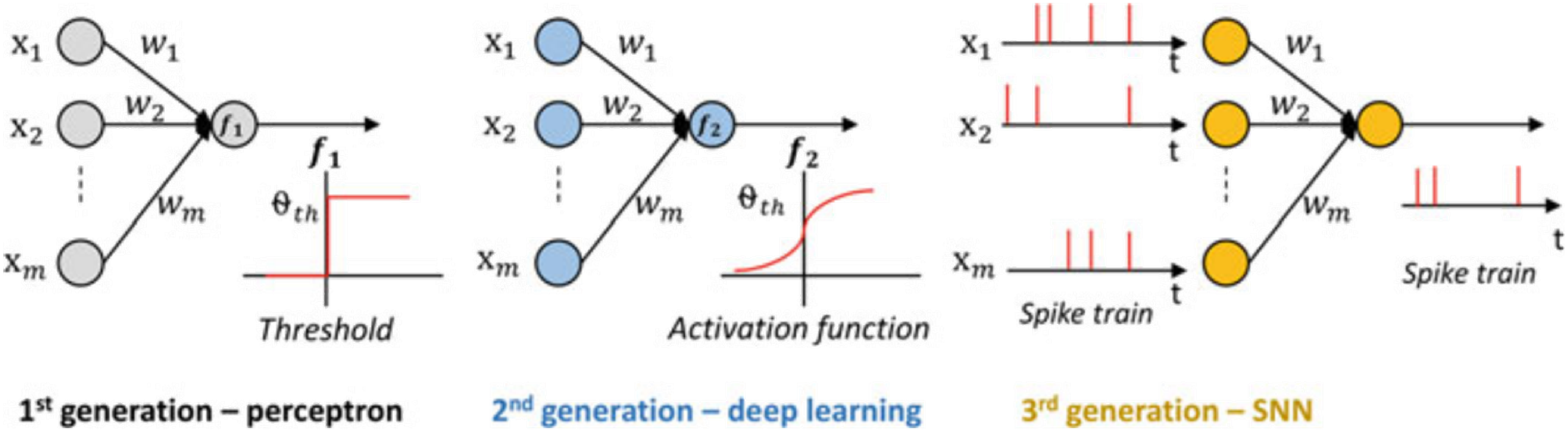
Neuromorphic computing





Abdallah, Abderazek Ben, and Khanh N. Dang. *Neuromorphic computing principles and organization*. Berlin: Springer, 2022.

Neuromorphic computing



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Vanadium dioxide

Insulator-to-metal transition: $T_c \approx 340K$

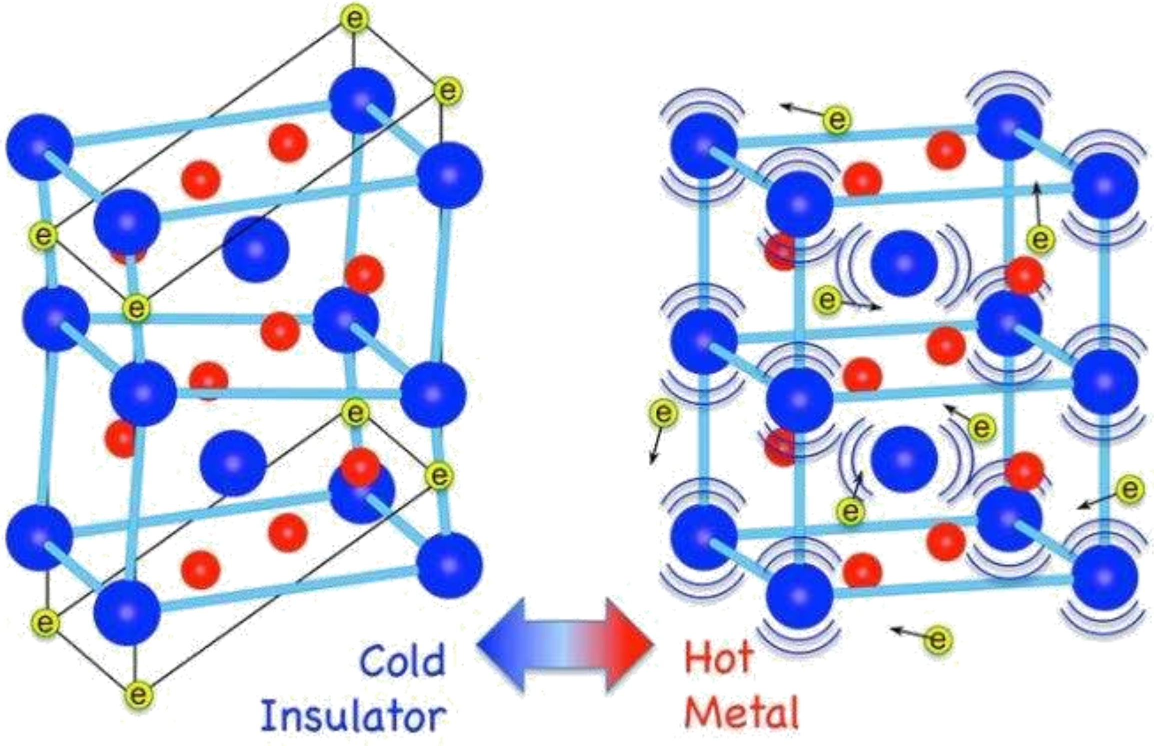
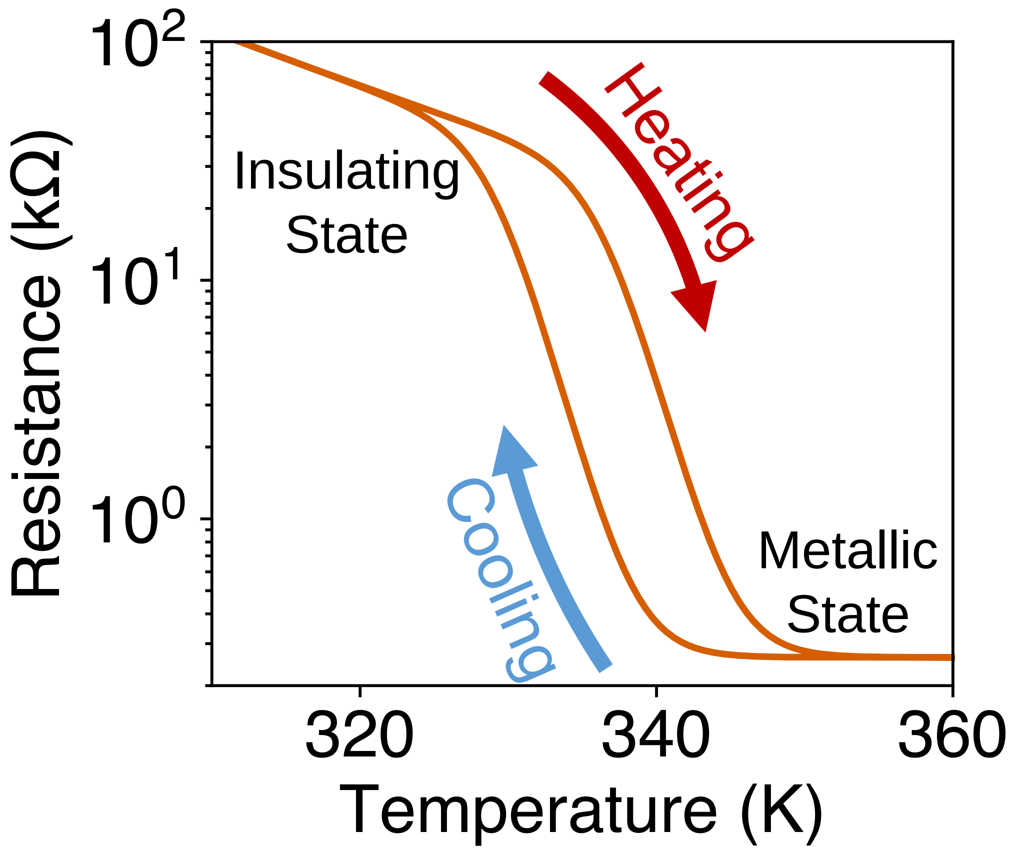
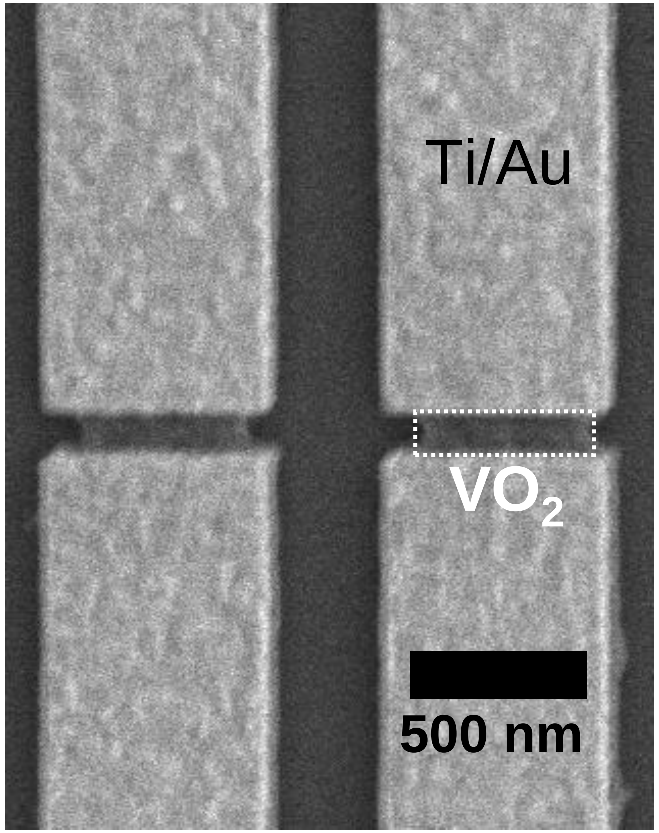


Image credit: https://phys.org/news/2015-04-insulator-to-metal-transition-vanadium-dioxide.html

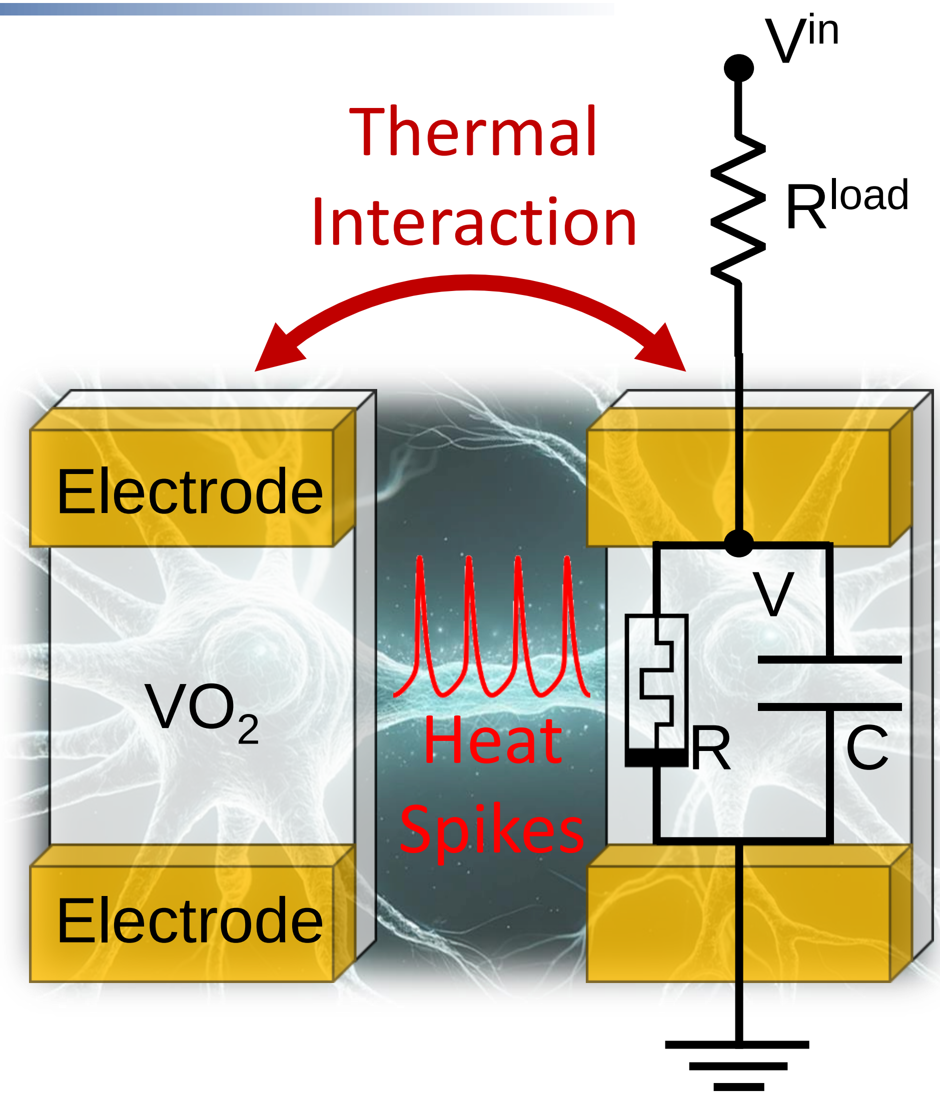


Budai, J. D., Hong, J., Manley, M. E., Specht, E. D., Li, C. W., Tischler, J. Z., ... & Delaire, O. (2014). Metallization of vanadium dioxide driven by large phonon entropy. Nature, 515(7528), 535-539.

Thermal Neuristor



Substrate: Al_2O_3



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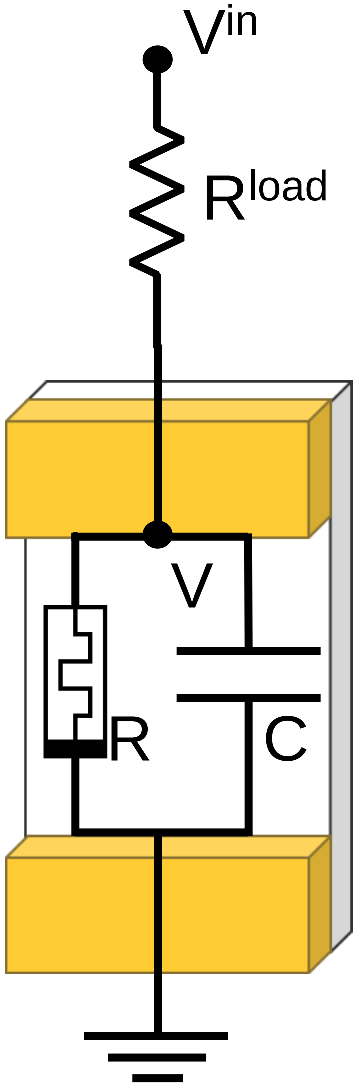
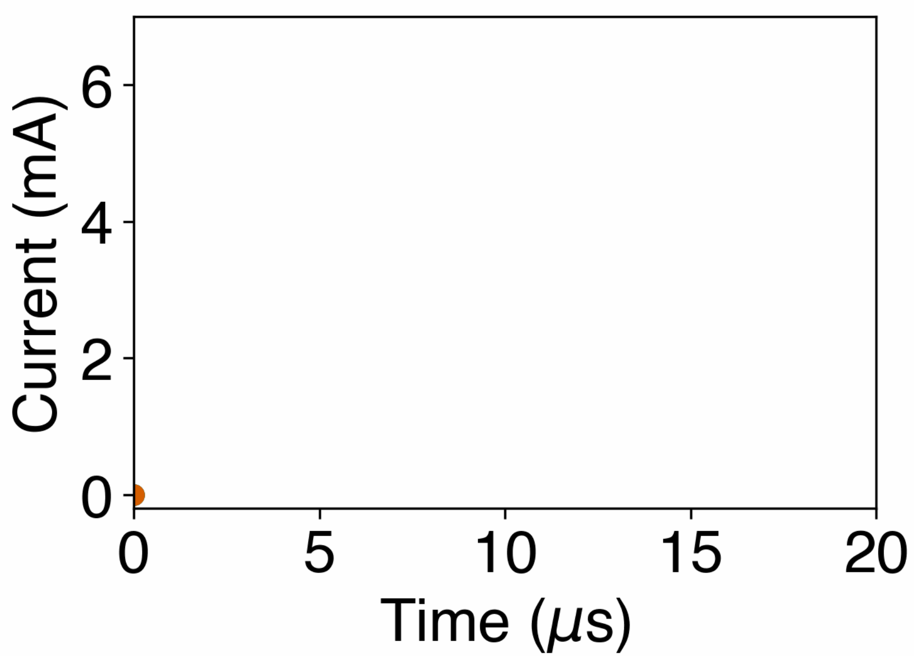
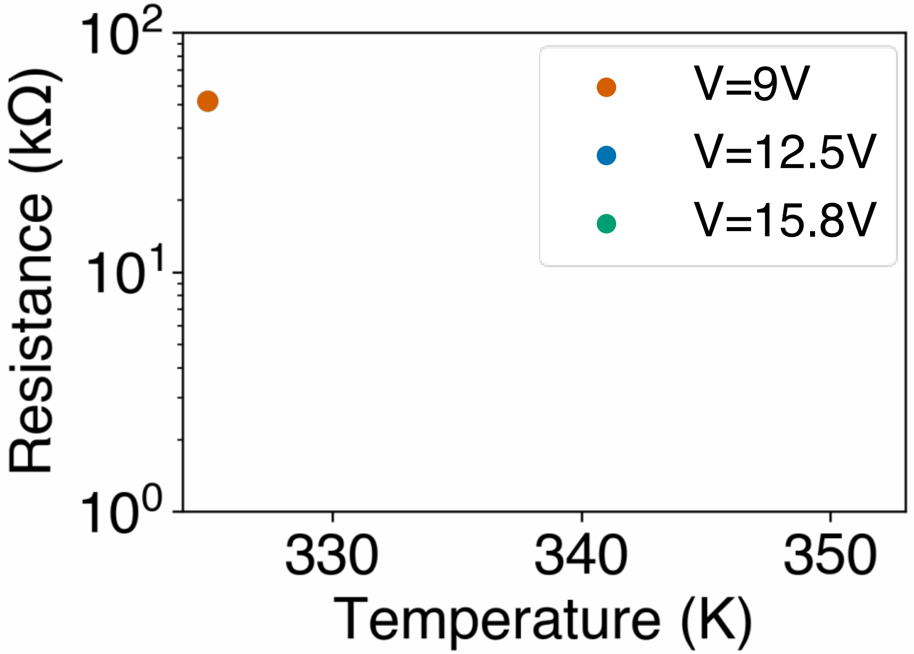
Single Neuristor Characteristics







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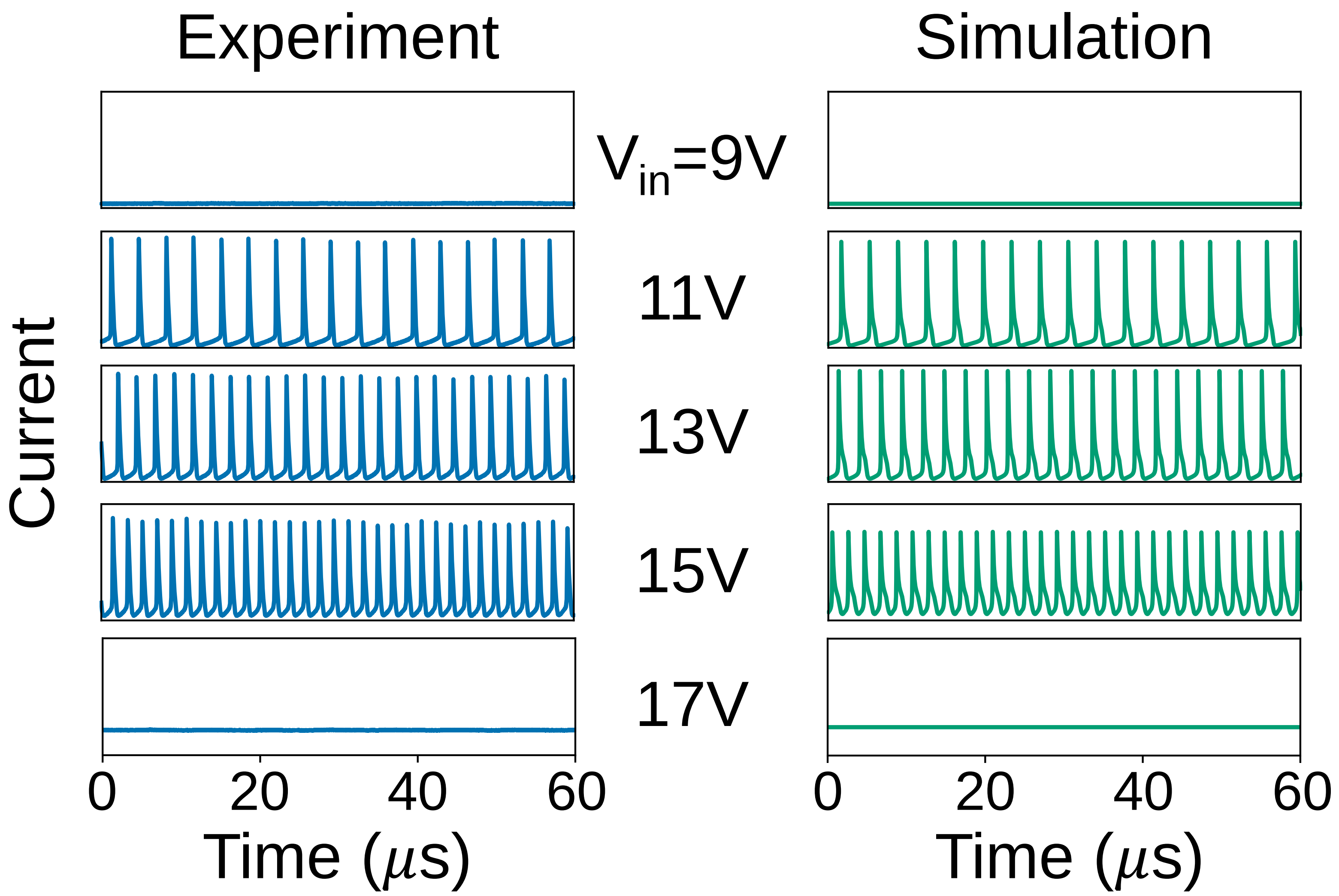

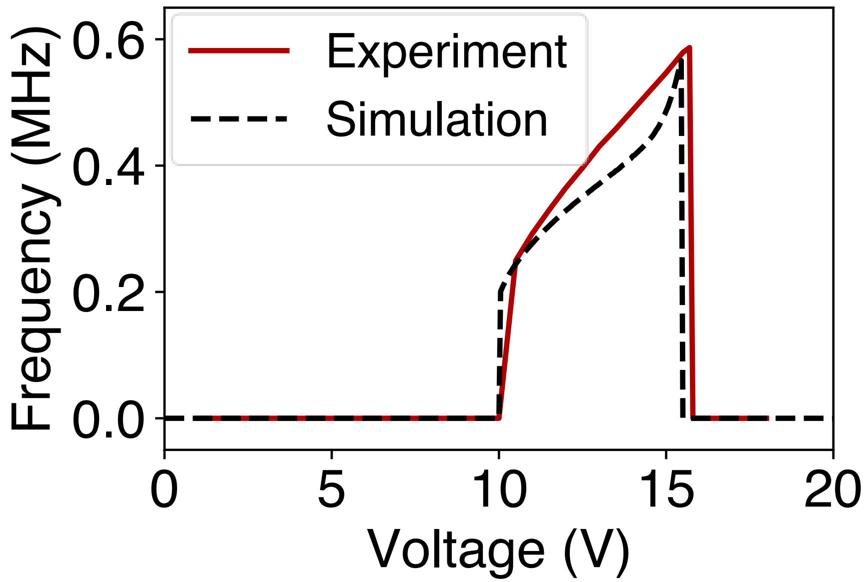

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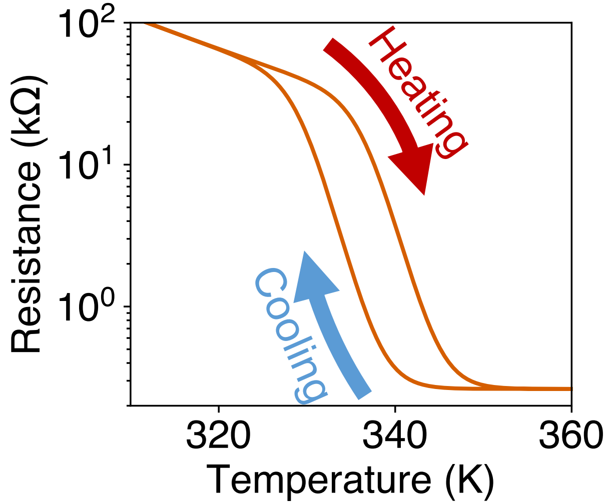
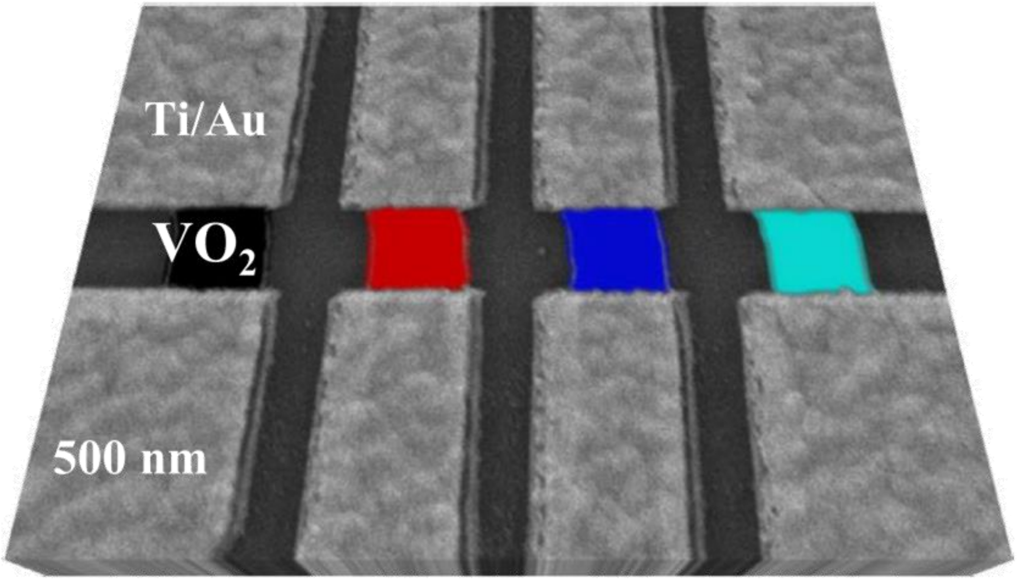
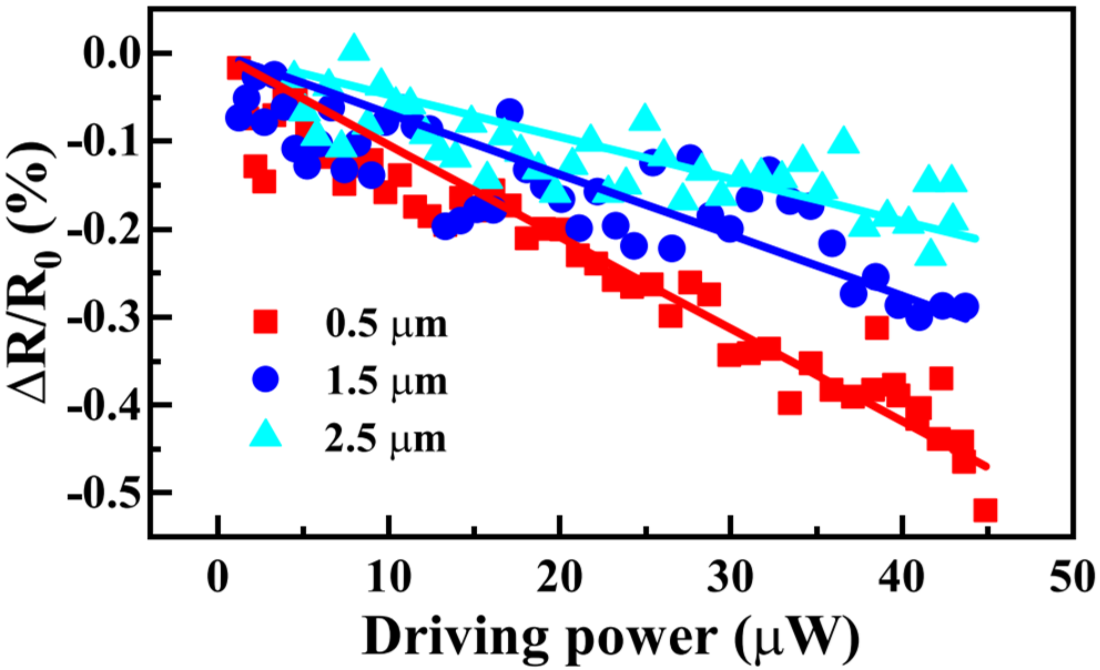
Thermal interactions

- Electrically isolated
- Heat propagation through Al_2O_3 substrate







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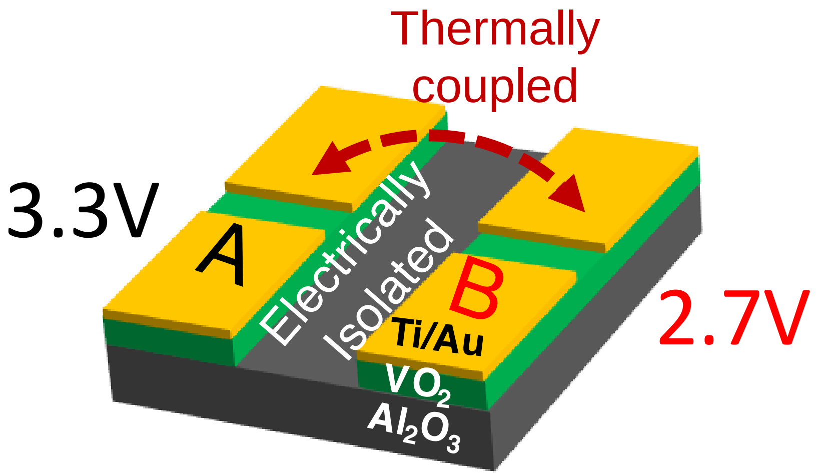
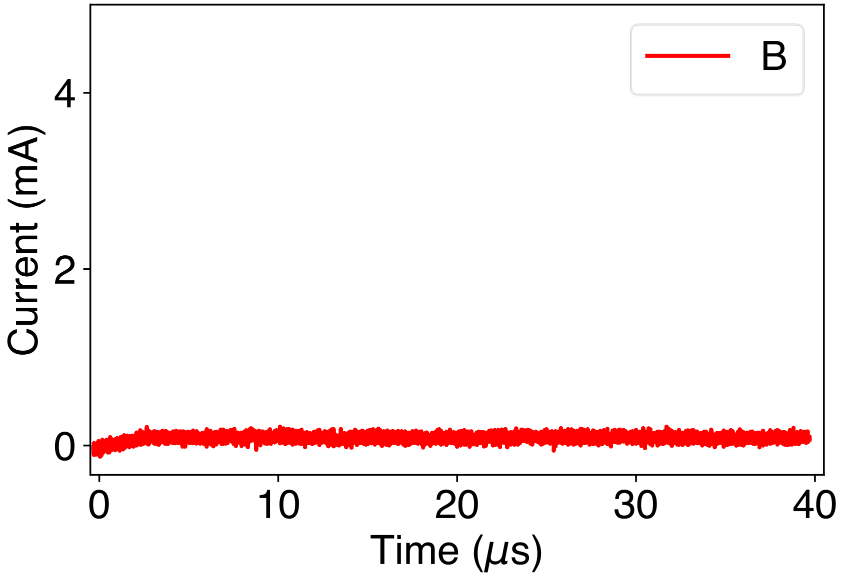
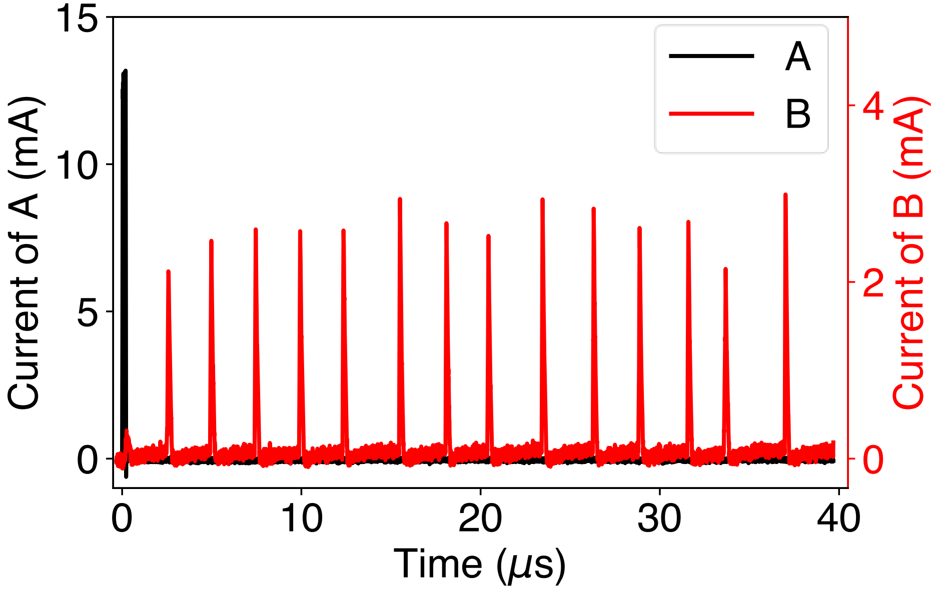
Thermal interactions







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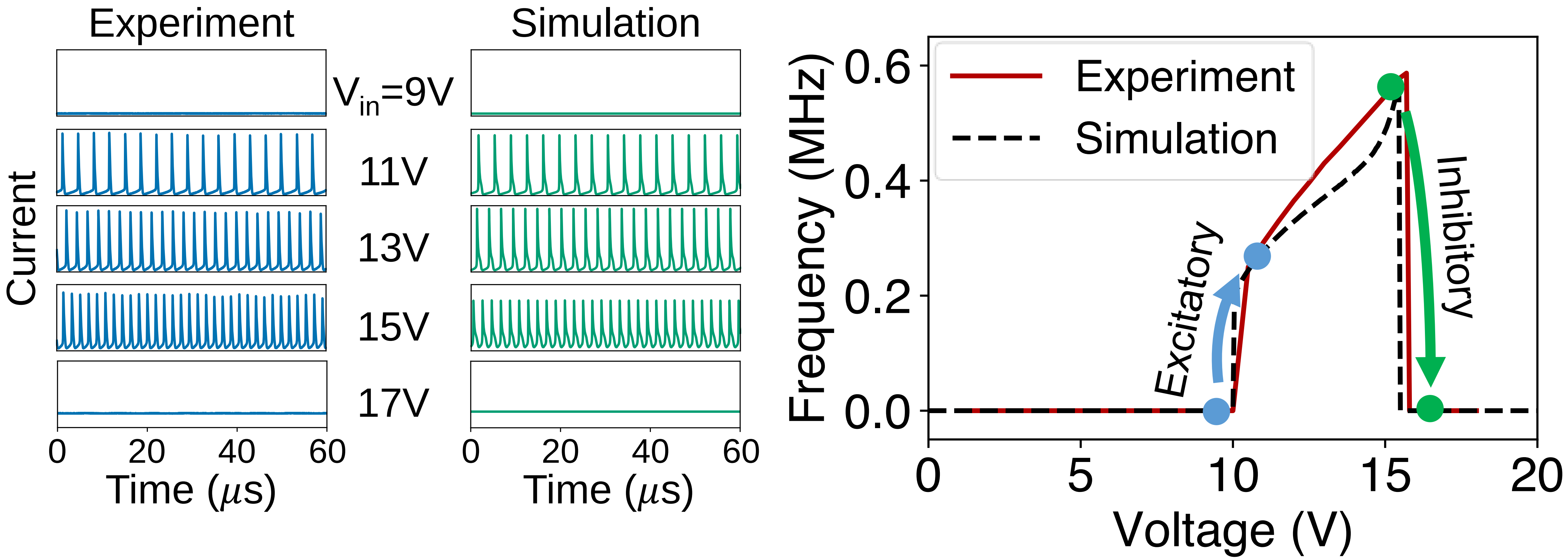
Excitatory and inhibitory interactions



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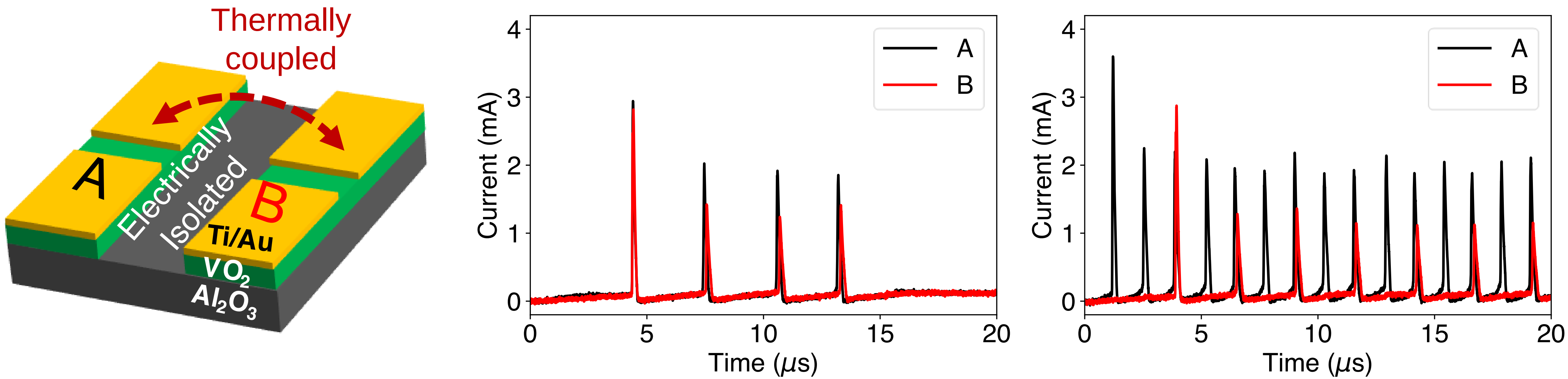
Excitatory interaction



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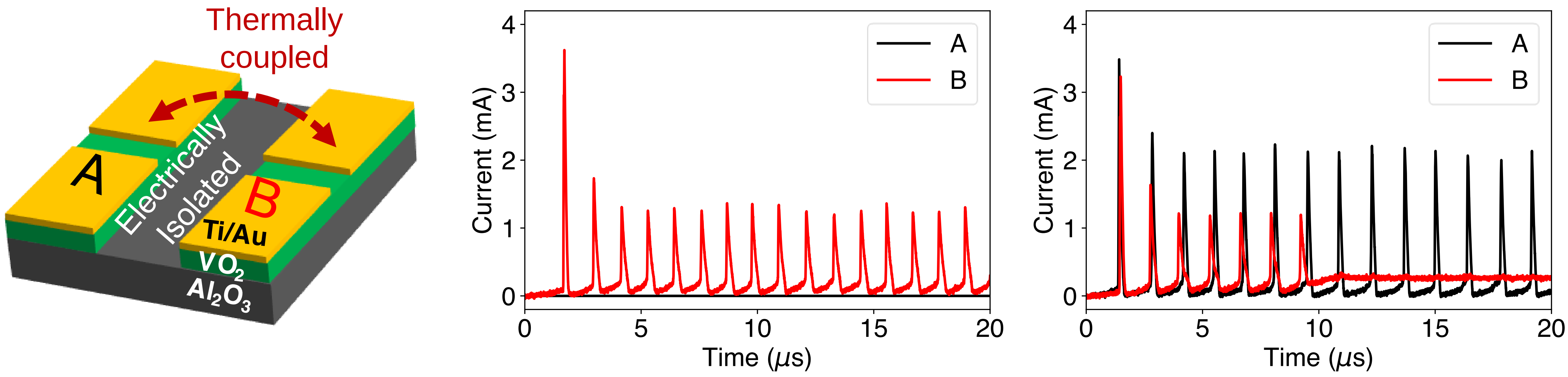
Inhibitory interaction



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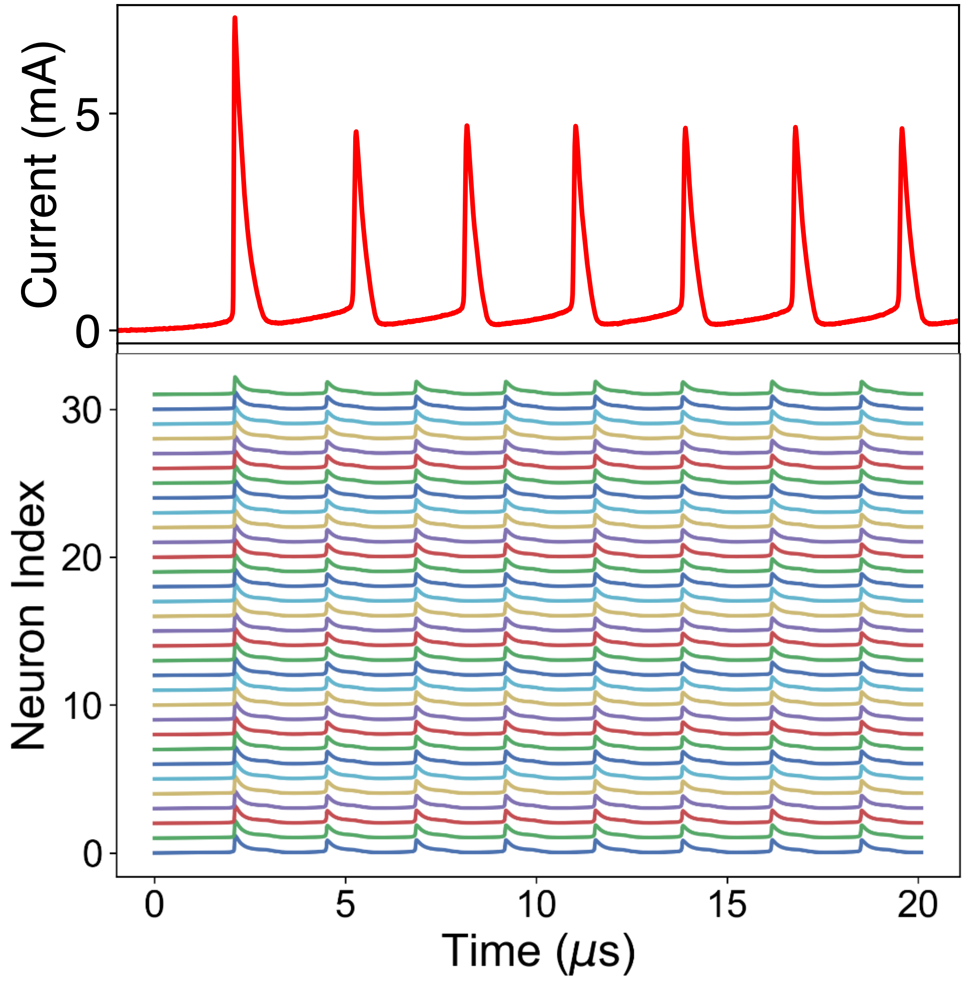
Thermal neuristor array

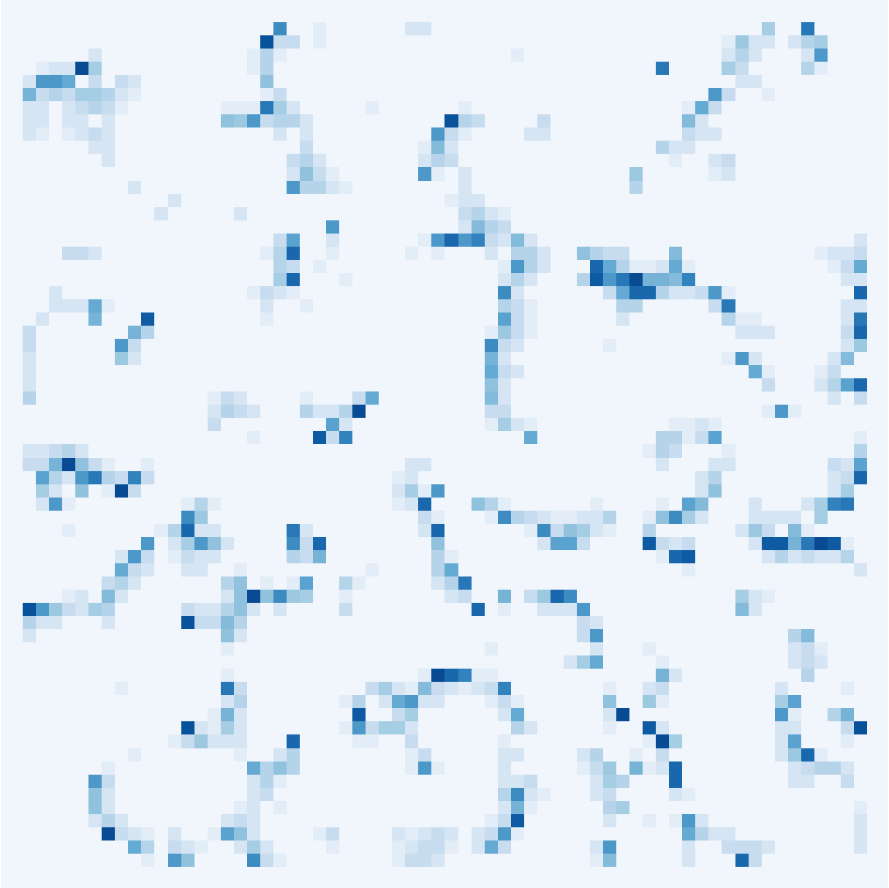
1 neuron
(experiment)

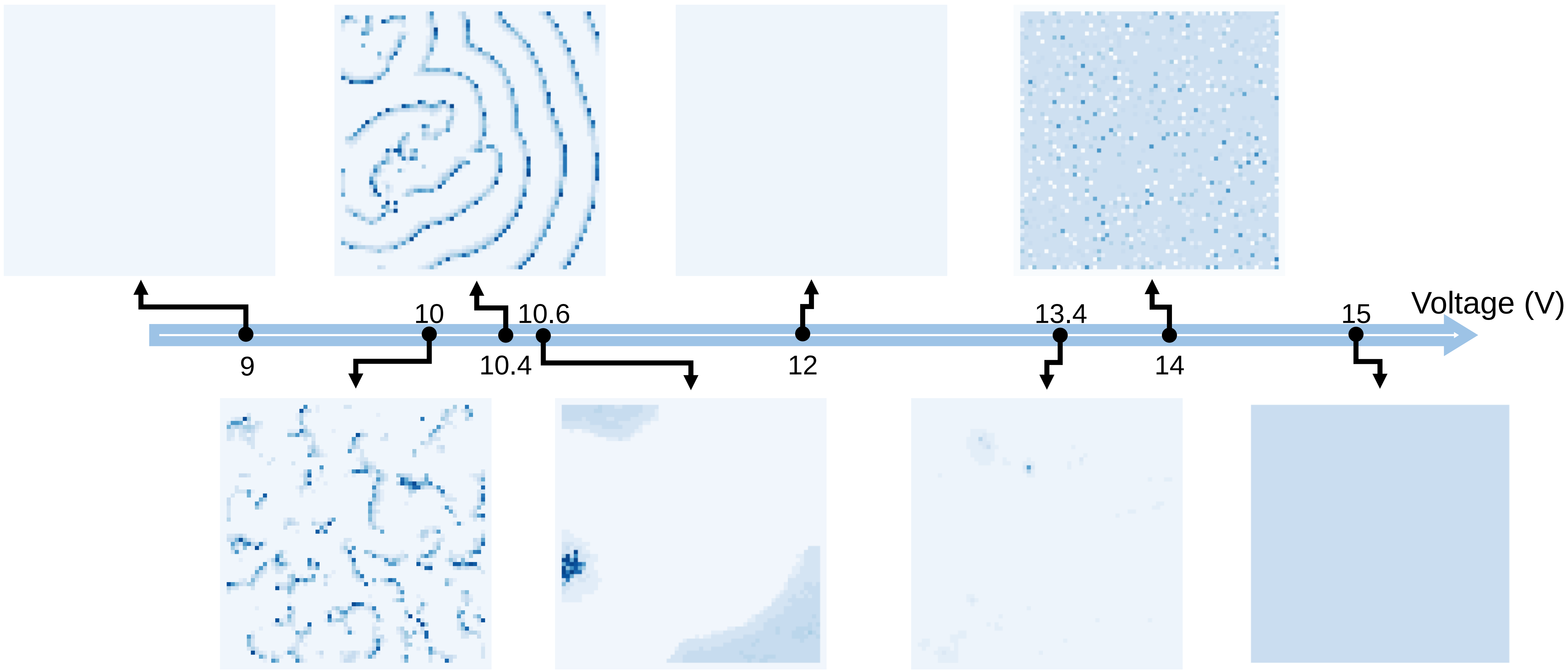
32 neurons
(simulation)



2D array

64x64
neurons





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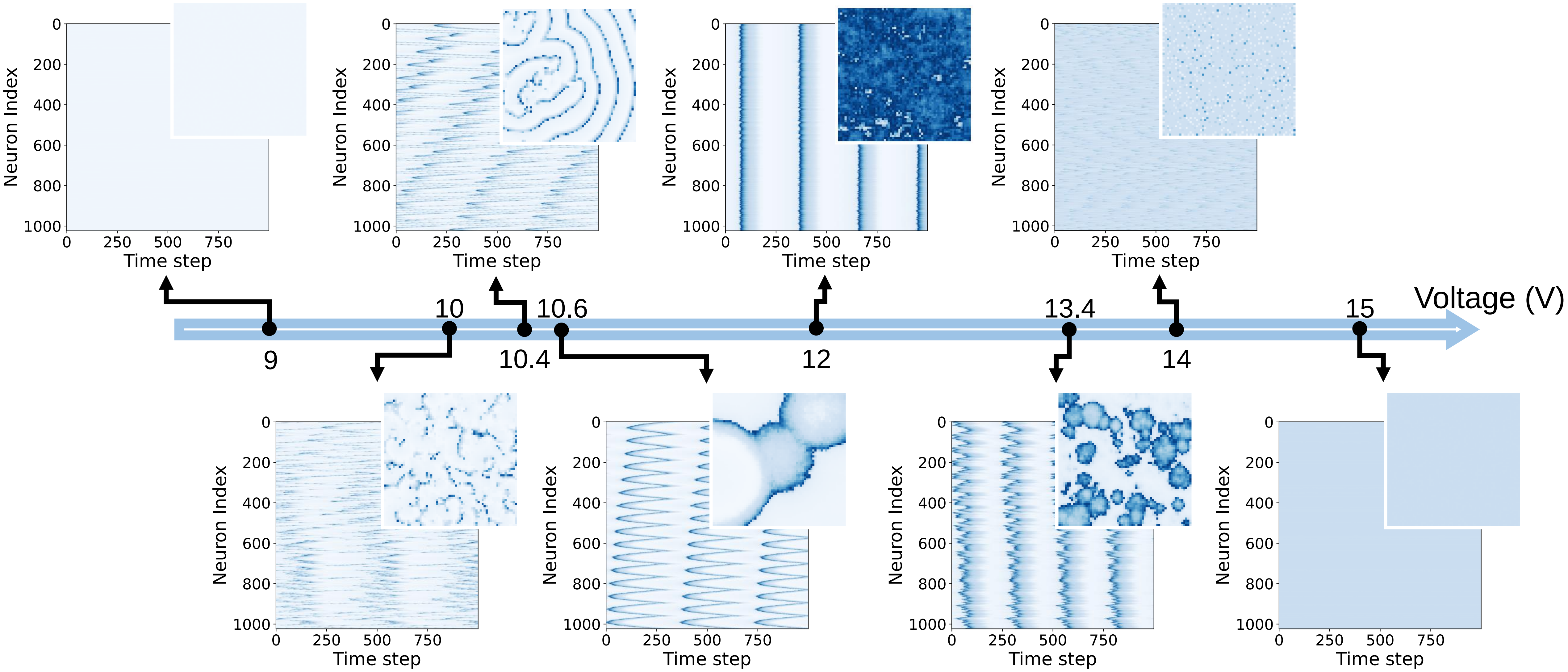

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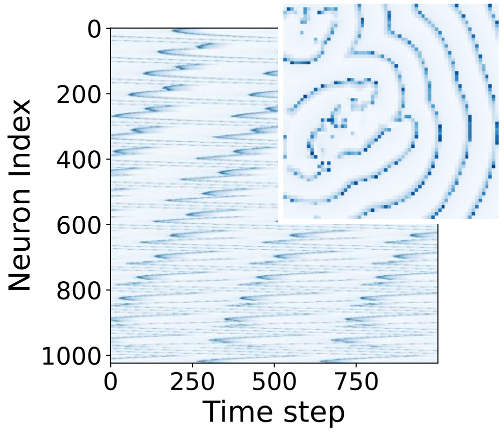
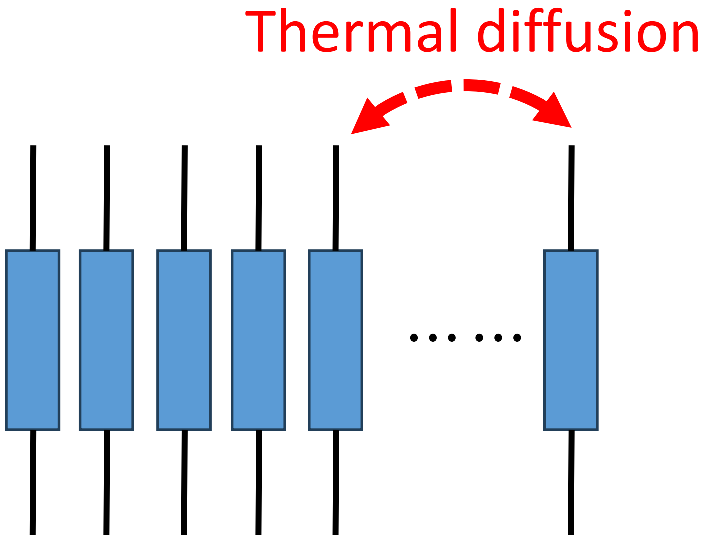
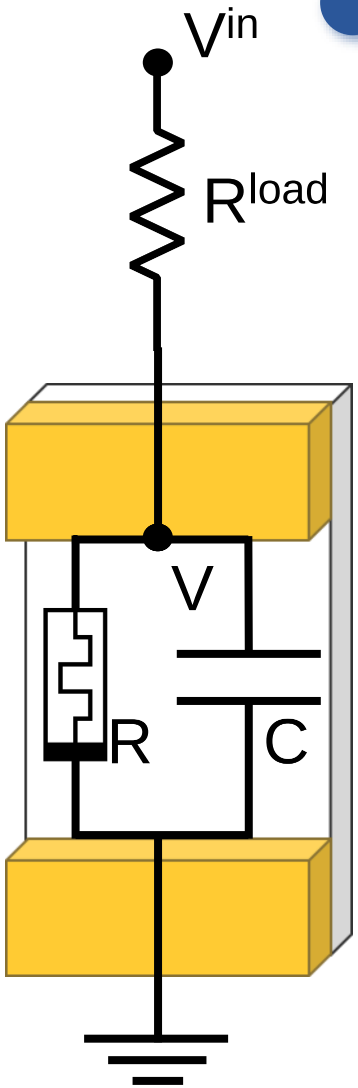
Long-range order?

$$C\frac{dV}{dt} = \frac{V_{in}}{R_{load}} - V\left(\frac{1}{R_{VO_2}} + \frac{1}{R_{load}}\right)$$

$$C_{th}\frac{dT}{dt} = \frac{V^2}{R_{VO_2}} - S_{env}(T - T_0) + S_{couple}\nabla^2 T + \eta(t)$$







Long-range order?

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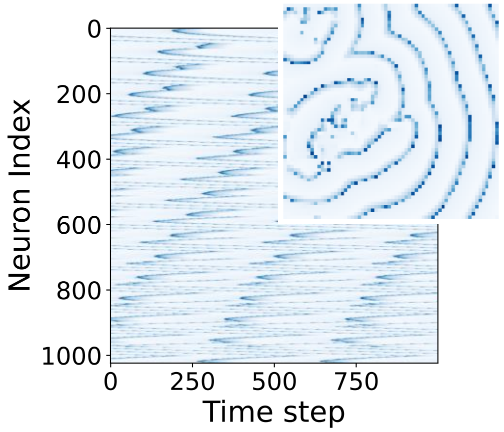
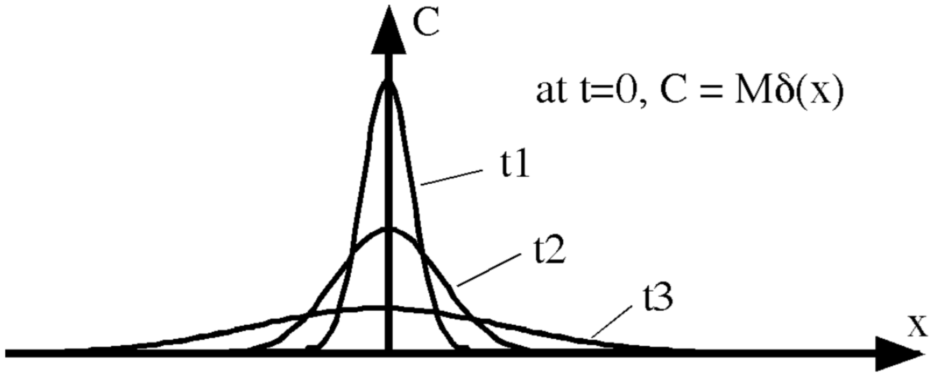
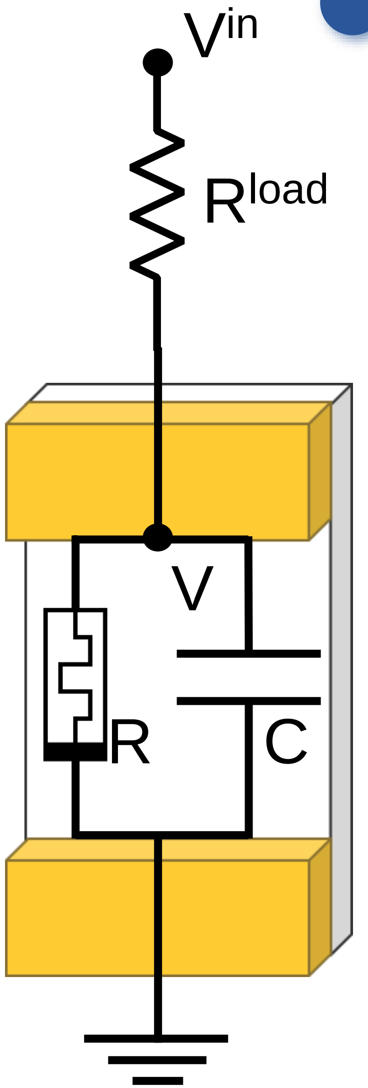
$$C_{th}\frac{dT}{dt} = \frac{V^2}{R_{VO_2}} - S_{env}(T - T_0) + S_{couple}\nabla^2 T + \eta(t)$$

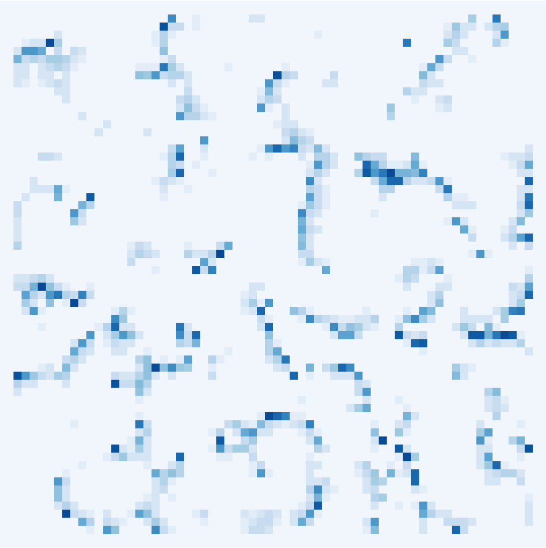






Self-organized criticality

Thermal neuristors



Sandpile model:
Self-organized criticality

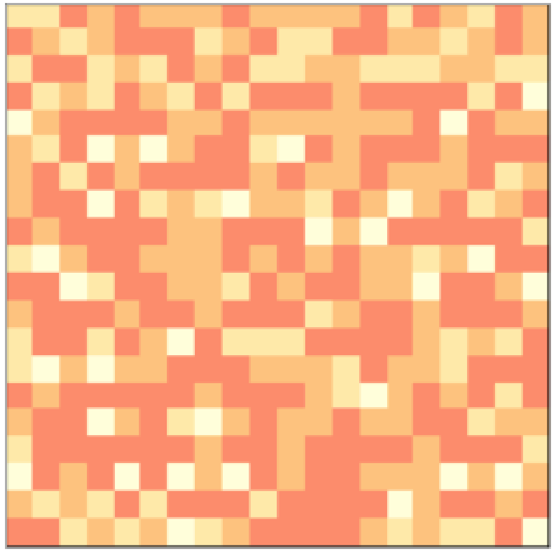


Image credit: https://runestone.academy/ns/books/published/complex/SelfOrganizedCriticality/ImplementingTheSandPile.html

Bak, Per, Chao Tang, and Kurt Wiesenfeld. "Self-organized criticality: An explanation of the 1/f noise." *Physical review letters* 59.4 (1987): 381.

Hesse, Janina, and Thilo Gross. "Self-organized criticality as a fundamental property of neural systems." *Frontiers in systems neuroscience* 8 (2014): 166.

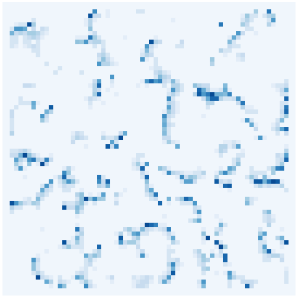
Long-range order?

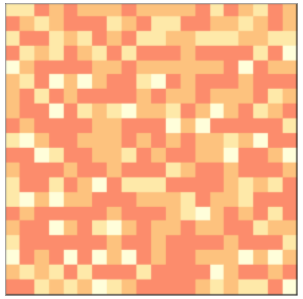
Fast spiking dynamics

$$C\frac{dV_1}{dt}=\frac{V_{in}}{R_{load}}-V_1\left(\frac{1}{R_{VO_2}}+\frac{1}{R_{load}}\right)$$

$$C_{th}\frac{dT}{dt}=\frac{V_1^2}{R_{VO_2}}-S_{env}(T-T_0)+S_{couple}\nabla^2 T+\eta(t)$$

Slow memory dynamics





Long-range order?

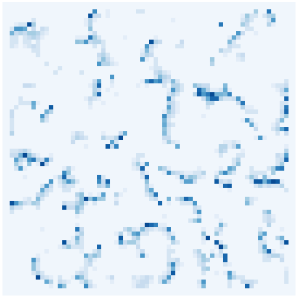
Fast spiking dynamics

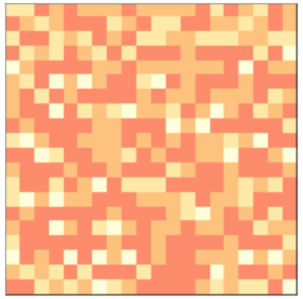
$$C\frac{dV_1}{dt} = \frac{V_{in}}{R_{load}} - V_1\left(\frac{1}{R_{VO_2}} + \frac{1}{R_{load}}\right)$$

Time scale

$$C_{th}\frac{dT}{dt} = \frac{V_1^2}{R_{VO_2}} - S_{env}(T - T_0) + S_{couple}\nabla^2 T + \eta(t)$$

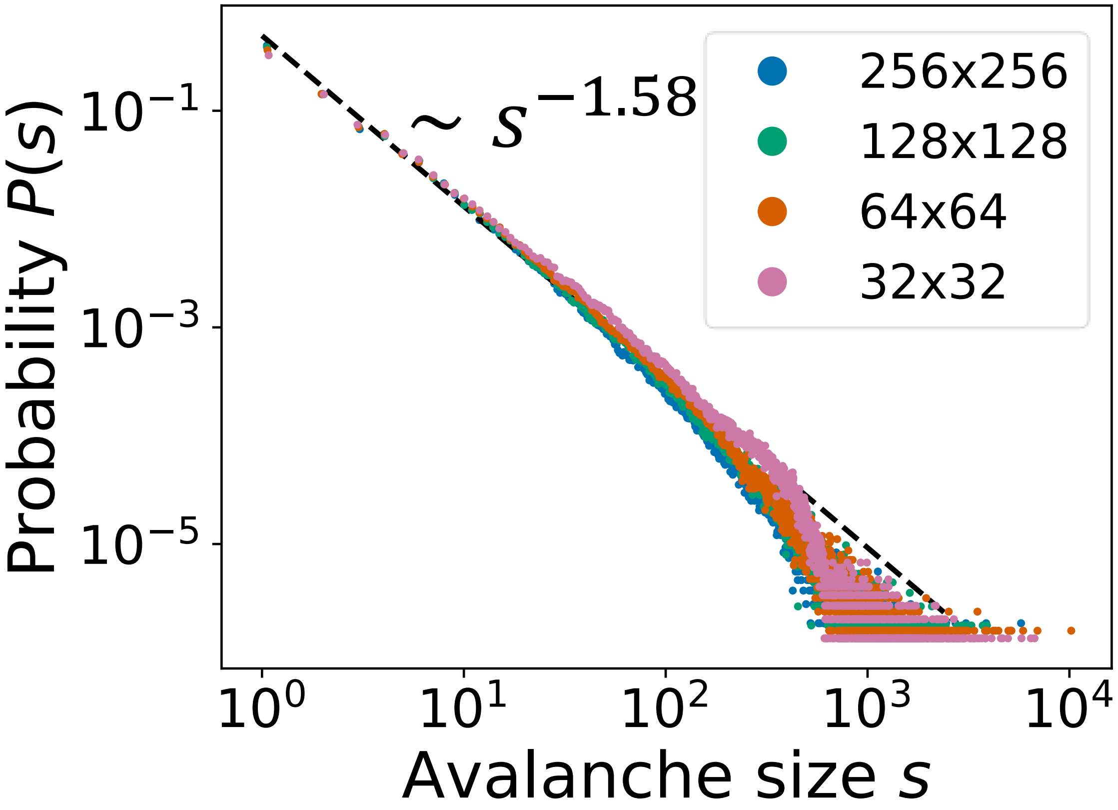
Slow memory dynamics

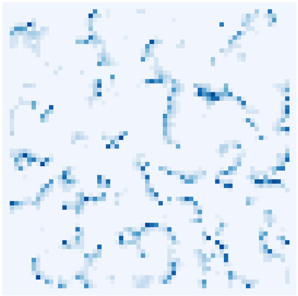


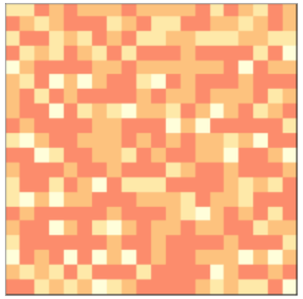


Avalanche size distribution

$V = 9.96\text{V}, C_{th} = 1$







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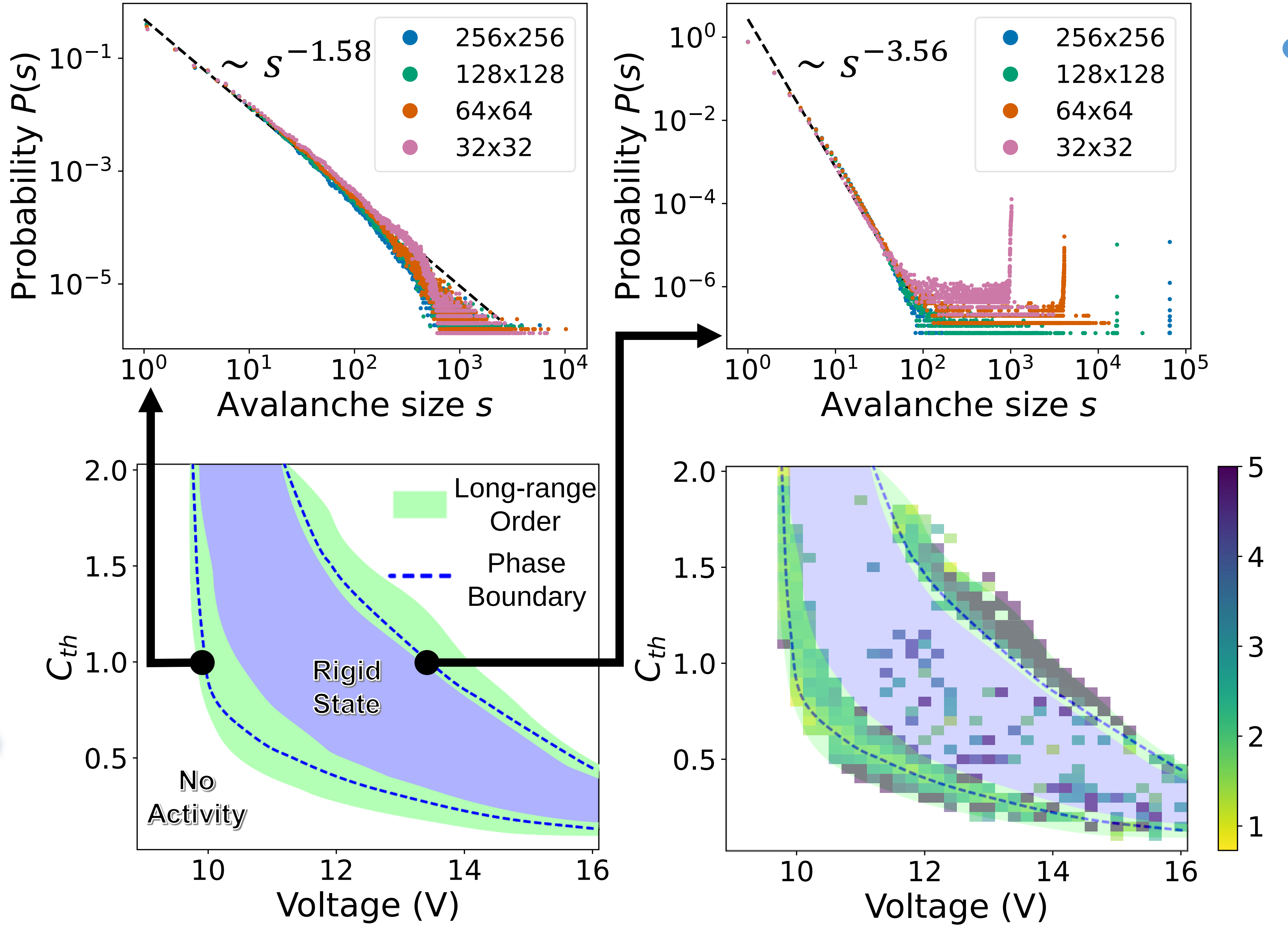
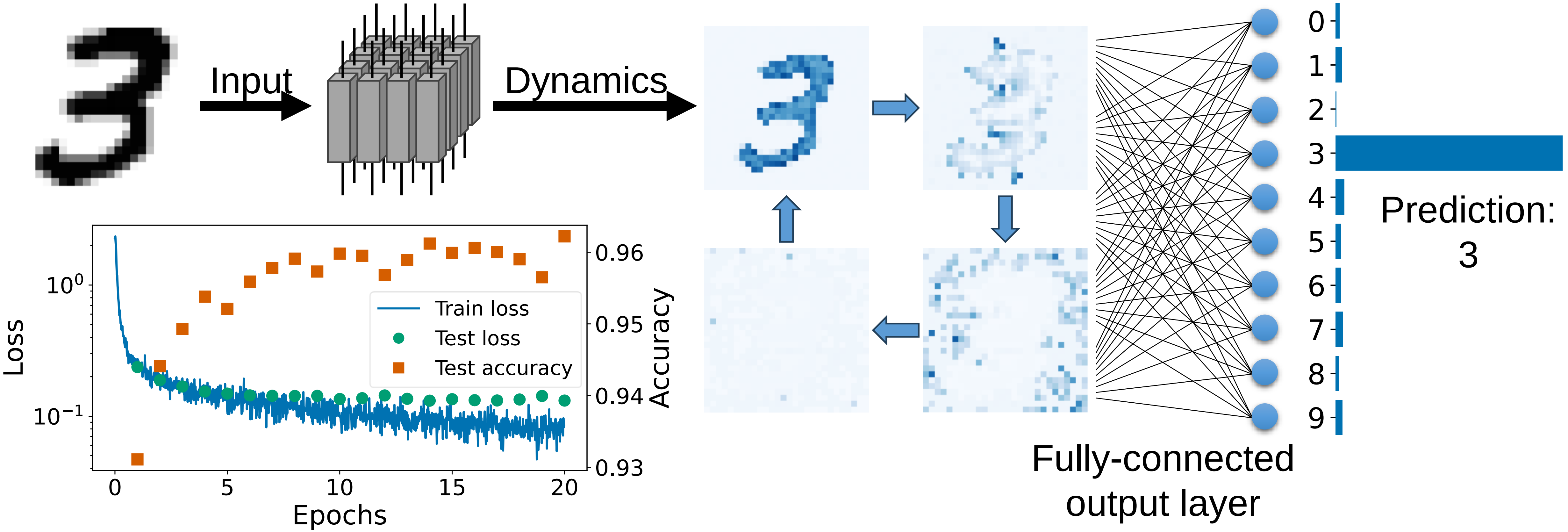


Probability $P(s)$
$\sim s^{-1.58}$
256x256
128x128
64x64
32x32
Avalanche size s
$\sim s^{-3.56}$
Long-range Order
Phase Boundary
Rigid State
No Activity
C_{th}
Voltage (V)

Application: MNIST



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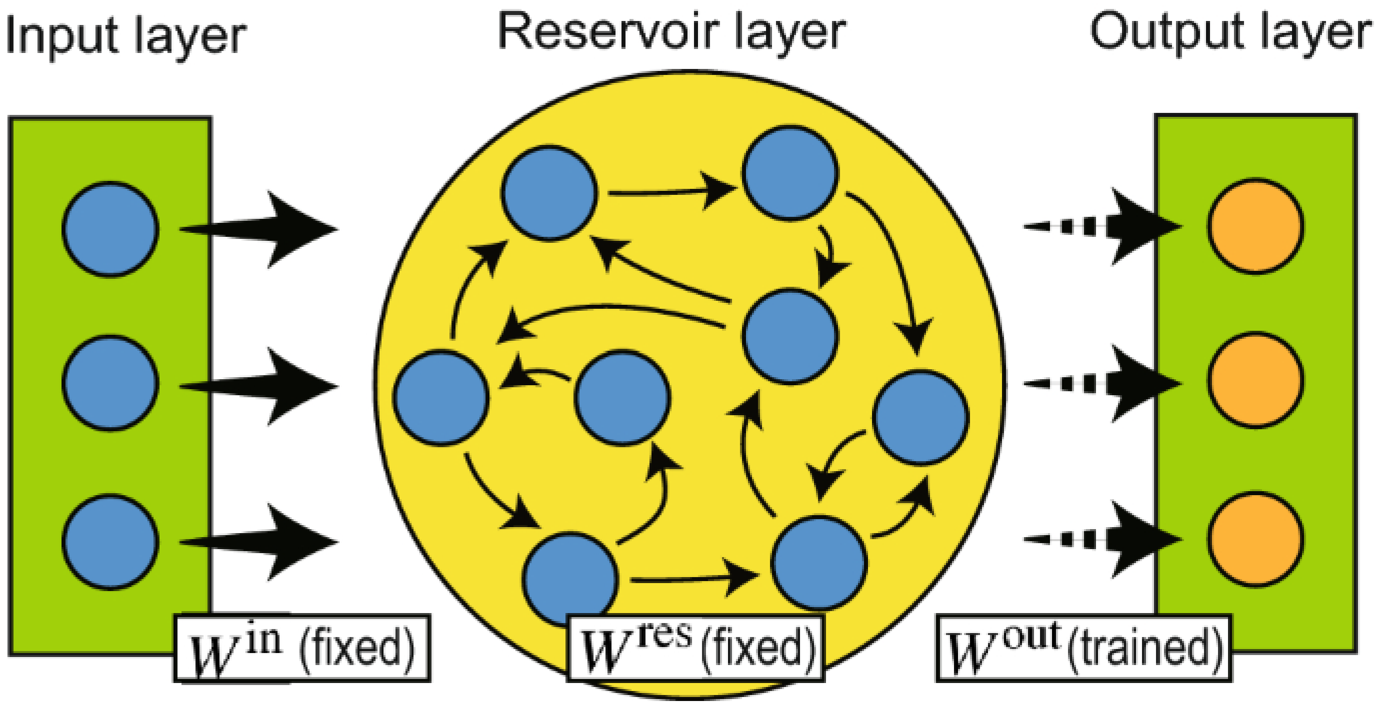
Reservoir Computing



Conclusions

- Spiking oscillators utilizing insulator-to-metal transition in VO_2
- Interactions mirroring biological neurons
- Phase of long-range order
- Application: reservoir computing

Thank you!

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