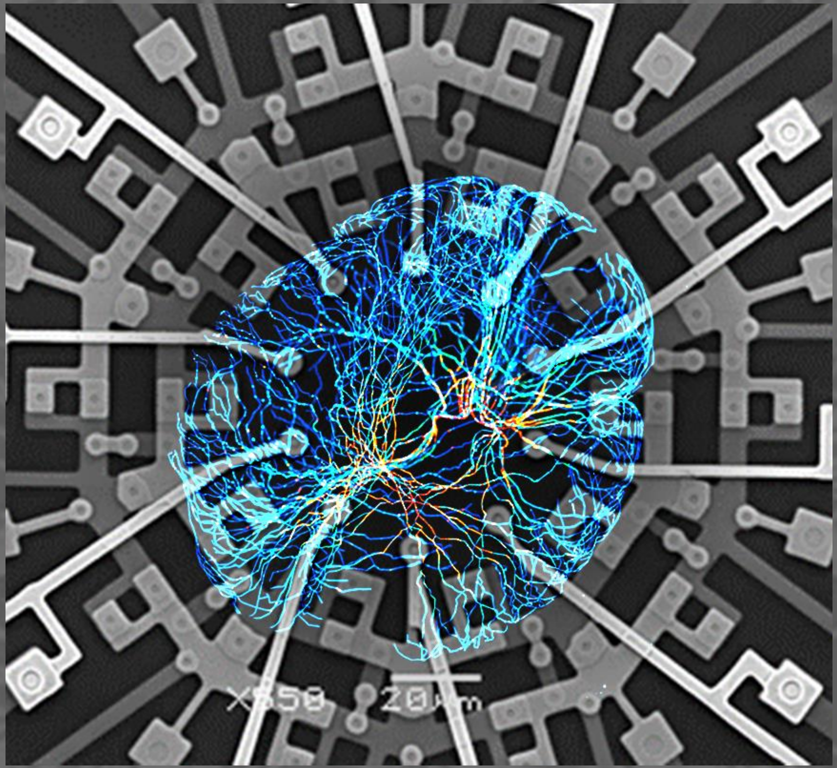
Neuromorphic Computing Using Superconducting Electronics



Ken Segall, Colgate University

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Outline

I. Introduction: What is neuromorphic computing? Why are computers starting to look like the brain? What can superconductors offer?

II. What does the brain do? Can superconductors do the same thing?
   1. Synaptic weighting → **Today's A.I.**
   2. Spiking
   3. Learning
   4. Optimization
   5. Connecting and networking

III. Projections, applications, outlook - can we make a superconducting brain?

Takeaway: Time to get in the game, and go big!

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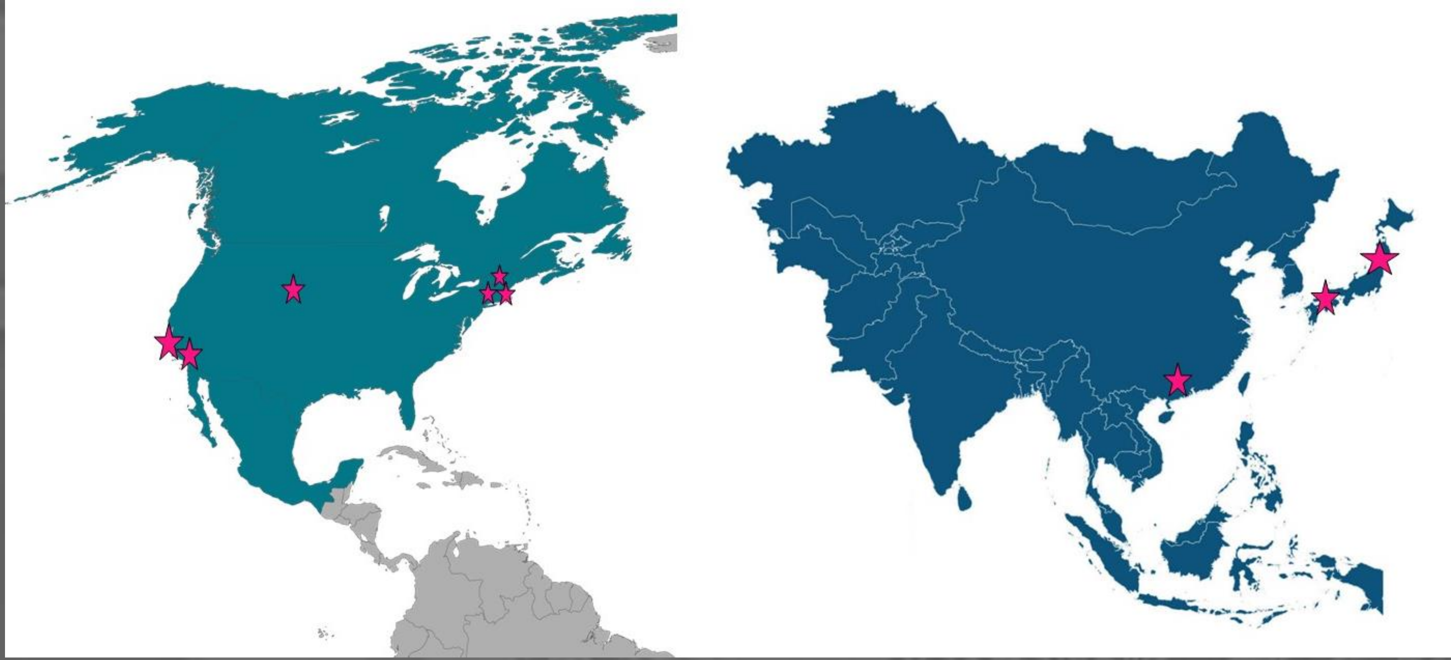
Superconducting Neuromorphic Community

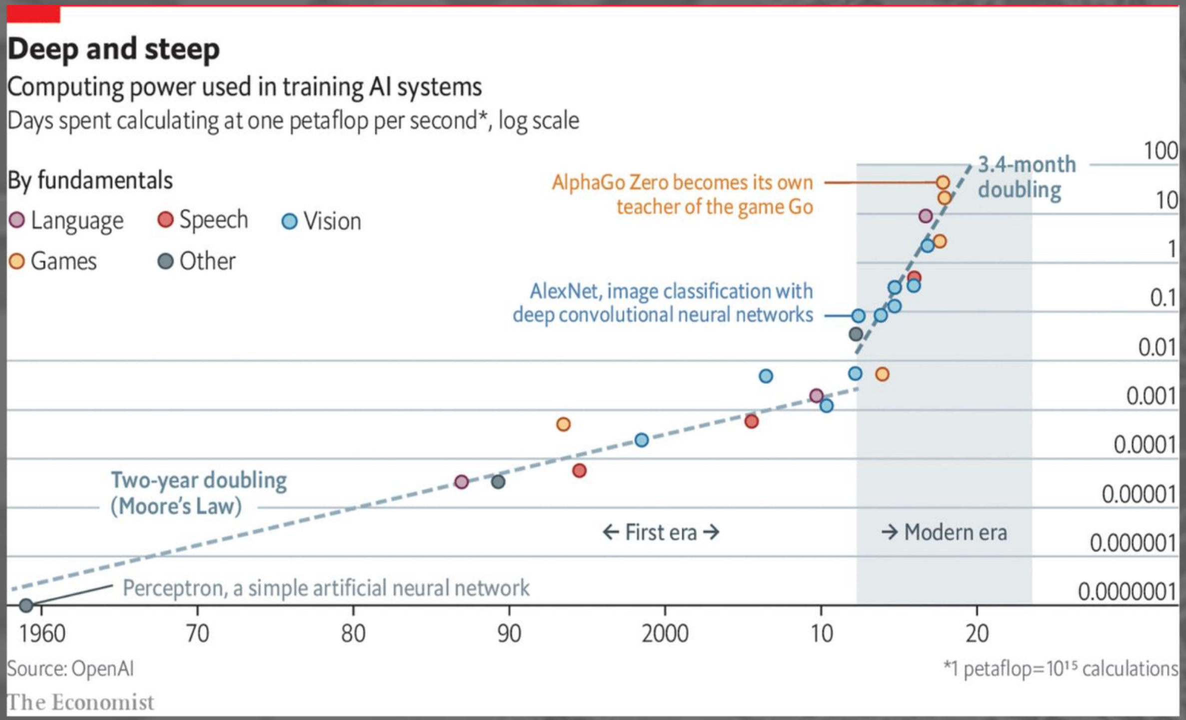


- Colgate University, Hamlton, NY
- MIT and MIT LL, Boston, MA
- NIST, Boulder, CO
- UCSD, San Diego, CA
- USC, Los Angeles, CA
- SUNY Stony Brook, Stony Brook NY
- Yokohama University, Yokohama, Japan
- Tohoku University, Sendai, Japan
- University of Chinese Academy of Sciences, Bejing, China

Others: Moscow State University, Auburn University, Raytheon/BBN, Ankara University, Lawrence Berkley Lab, IFN-CNR Rome

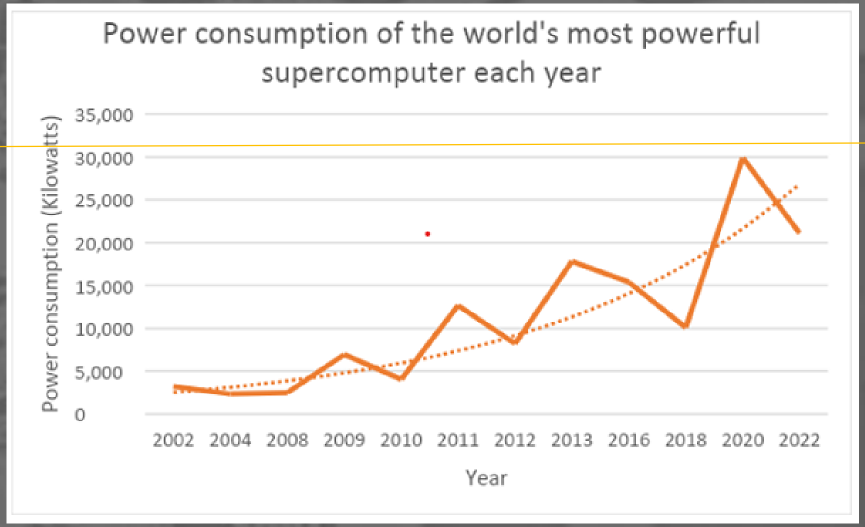
INTRODUCTION

Training A.I. : A lot of time and energy!



Days of training (at 10^{15} FLOPs)

Electrical consumption of Utica, NY



Source: insidehpc.com

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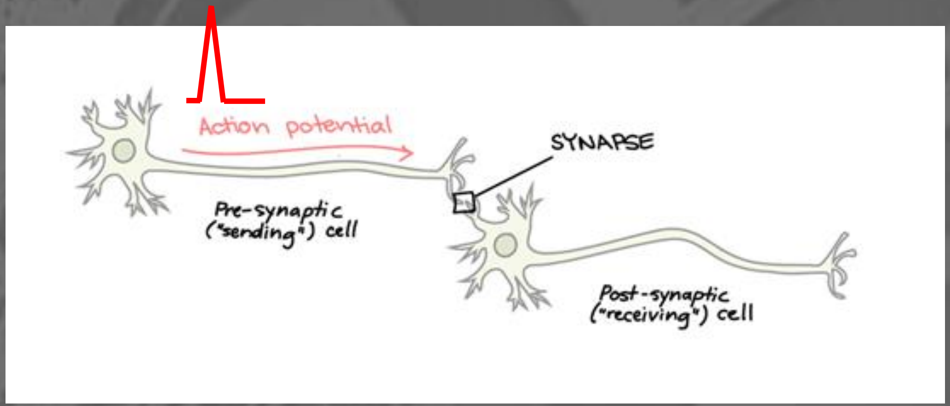
Enter: The brain!



- 86 billion neurons
- 100 trillion synapses
- 20 W of power

- The low power consumption of the brain makes it a good candidate for a computer

- Terminology: Neurons (somas), synapses, axons and dendrites

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Neuromorphic Computing

- Focuses on building hardware whose operating principles are based on the human brain
- Mostly utilizing semiconductor components (for now..)
- A key goal is energy efficiency, but it also aims to enable new computational capabilities
- Working platforms exist
- Applications: Replacing deep learning, Event-driven image processing, robotics, optimization, brain simulation, and others to be determined!

	True North	Loihi	SpiNNaker
# Neurons	$1.0\text{x}10^6$	$4\text{x}10^5$	$1.8\text{x}10^4$
Energy/Syn. Op.	26 pJ	78 pJ	11.3 nJ
SOPS/watt	$3.8\text{x}10^{10}$	$1.3\text{x}10^{10}$	$9\text{x}10^7$

Frenkel et al. arxiv 2106.01288 (2023)

Related work: Accelerating AI training with SCE (see work by IMEC), Processing In Memory approach (see Zhu et al. *Super. Sci. & Tech.* **37**, 095022, 2024)

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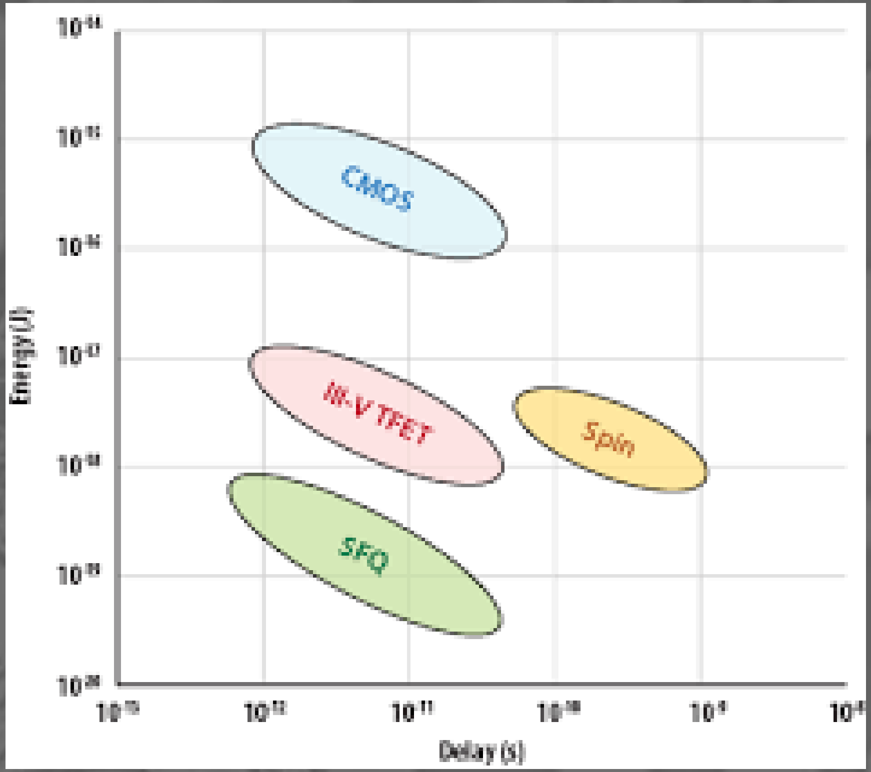
Why Superconductors?

- Energy efficiency (even with the cooling…)
- Speed (more spikes in a shorter time)
- Biological realism
- Better scaling properties (if we go big!)

Lower Power



Faster

Underappreciated!

*MIT Lincoln Laboratory, "Forcasting superconductive electronics technology," The Next Wave, vol.20, no.3, 2014

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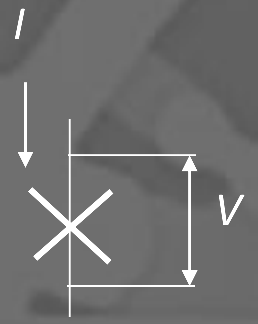
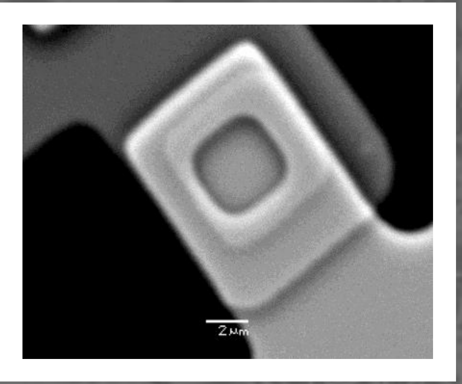
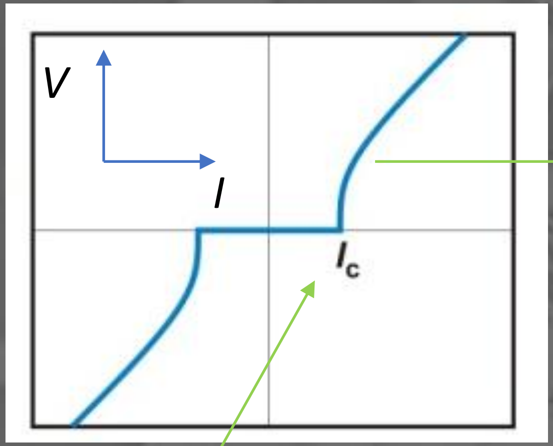
Superconducting Electronics for Neuroscientists



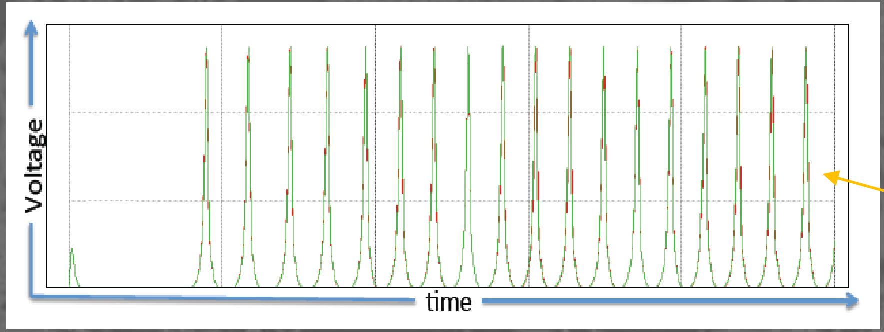




Threshold

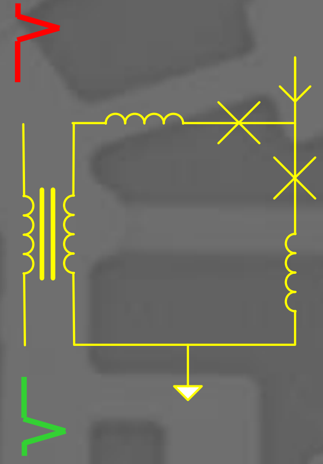
(with inductive shunt)

Single-flux quantum (SFQ) pluses



Area = Φ_0 = h/2e

Excitatory



Inhibitory

- Spiking and thresholding – similar to neurons, except very fast!
- Coupling through mutual inductance
- Circuit simulations (WR-SPICE) are very accurate

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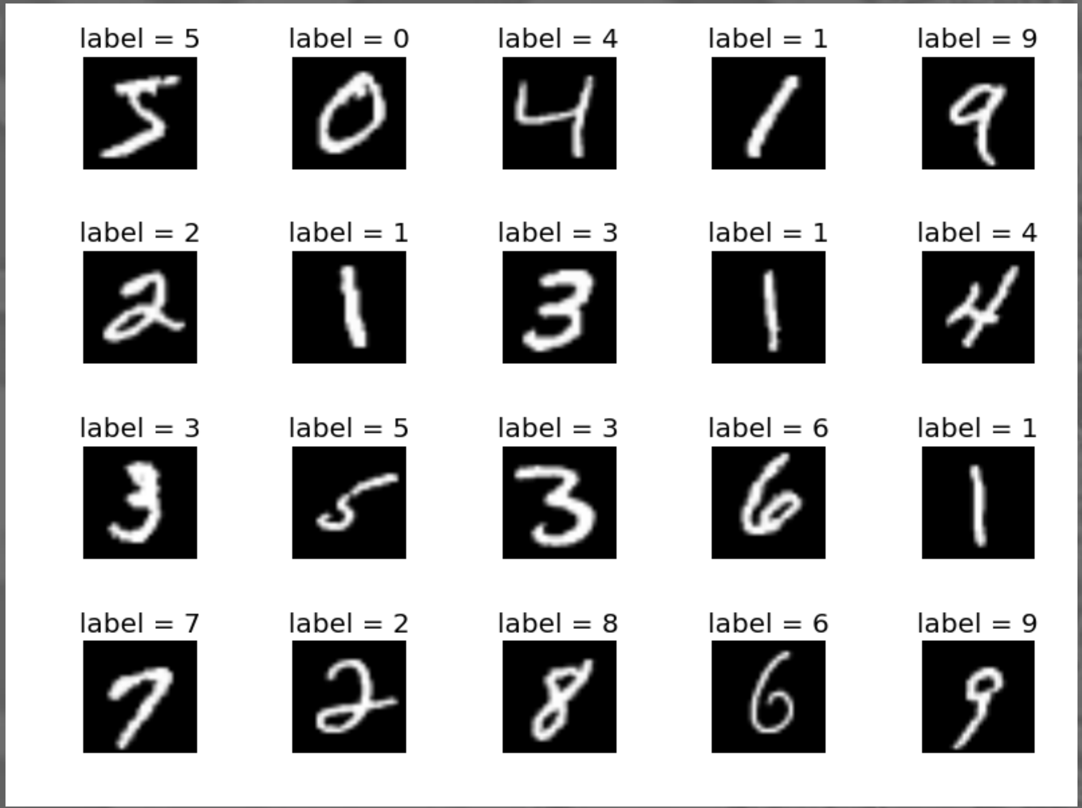
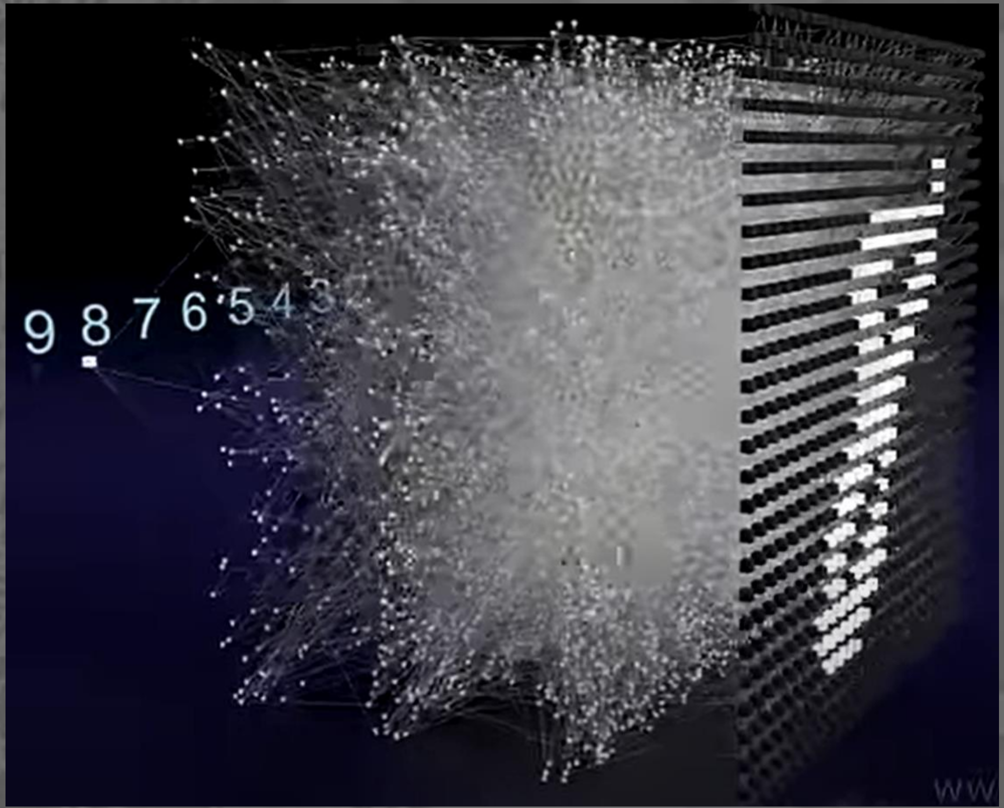
Benchmarking Neuromorphic Systems





- MNIST data set
- Deep learning systems (software!) regularly attain ~ 95% with ~ 10^{-2} J/inference

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THE BRAIN DOES…SYNAPTIC WEIGHTING

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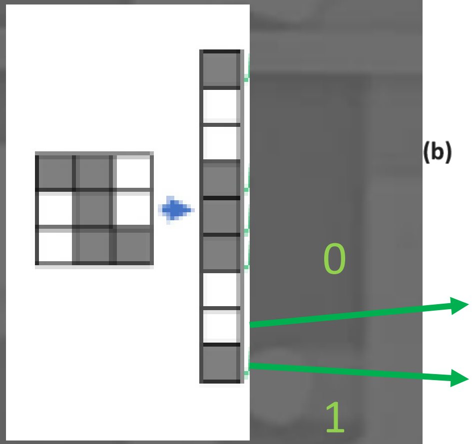
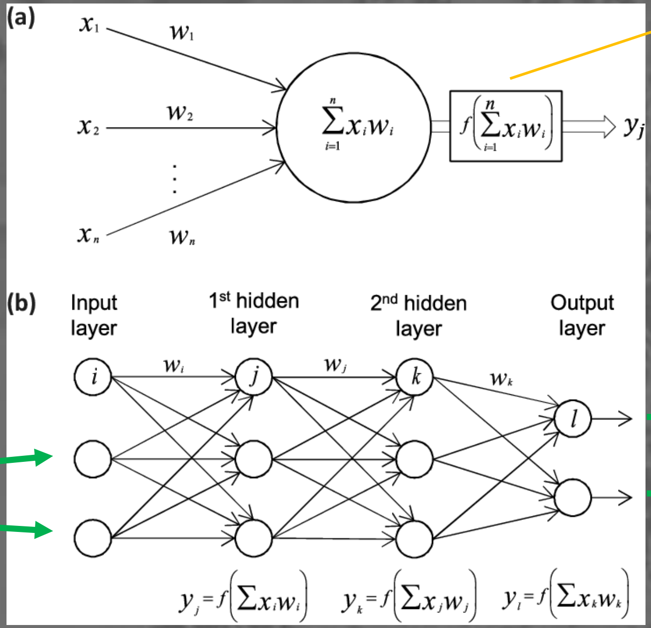
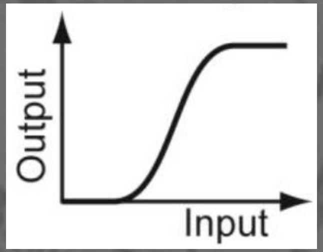
Neural networks and training

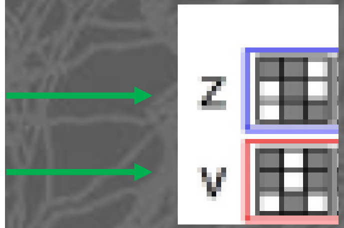


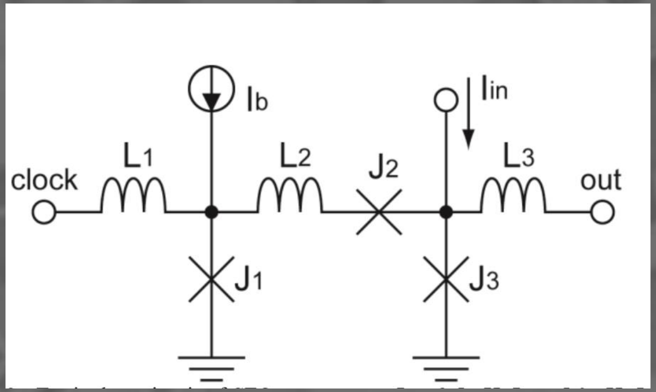


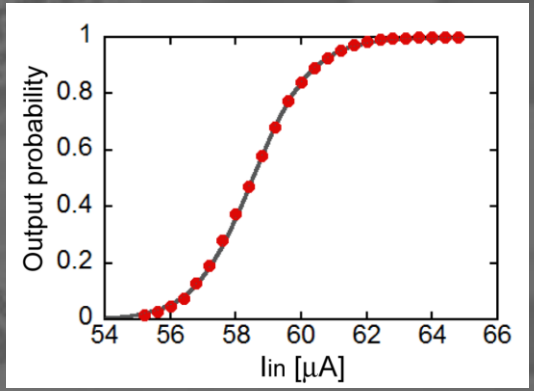
Researchgate.net



Sigmoid function







Yamanashi and Yoshikawa IEEE TAS **23** 1701004 (2013)

- Large neural networks ("Deep Learning") can learn to recognize complex patterns
- Training utilizes a backpropagation algorithm with requires a differentiable function

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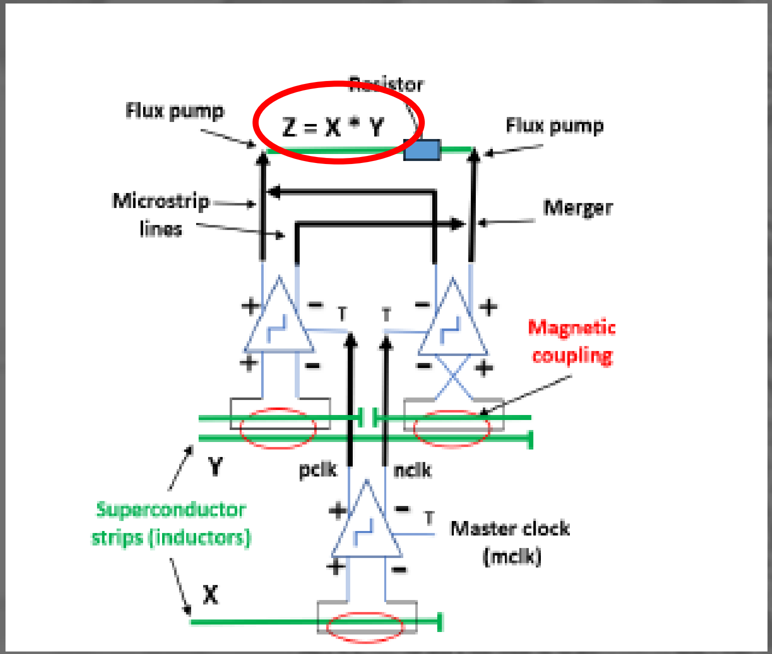
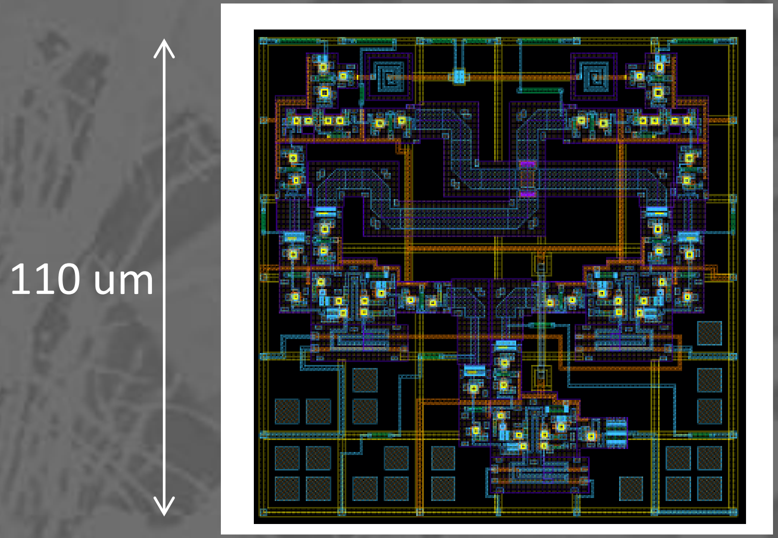
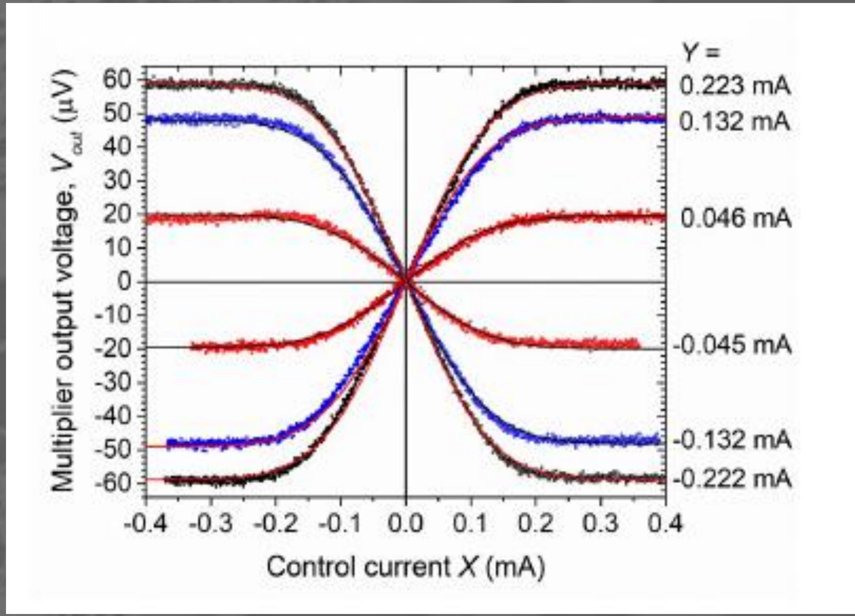
Just Multiply and Add!



Semenov et al. IEEE TAS **33**, 5 p.1-8 (2023)

2EPo1B-01





- “BioSFQ” logic family includes multiplication, division, addition and other operations with both signs
- Converts back and forth between frequency and current

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THE BRAIN DOES…SPIKING

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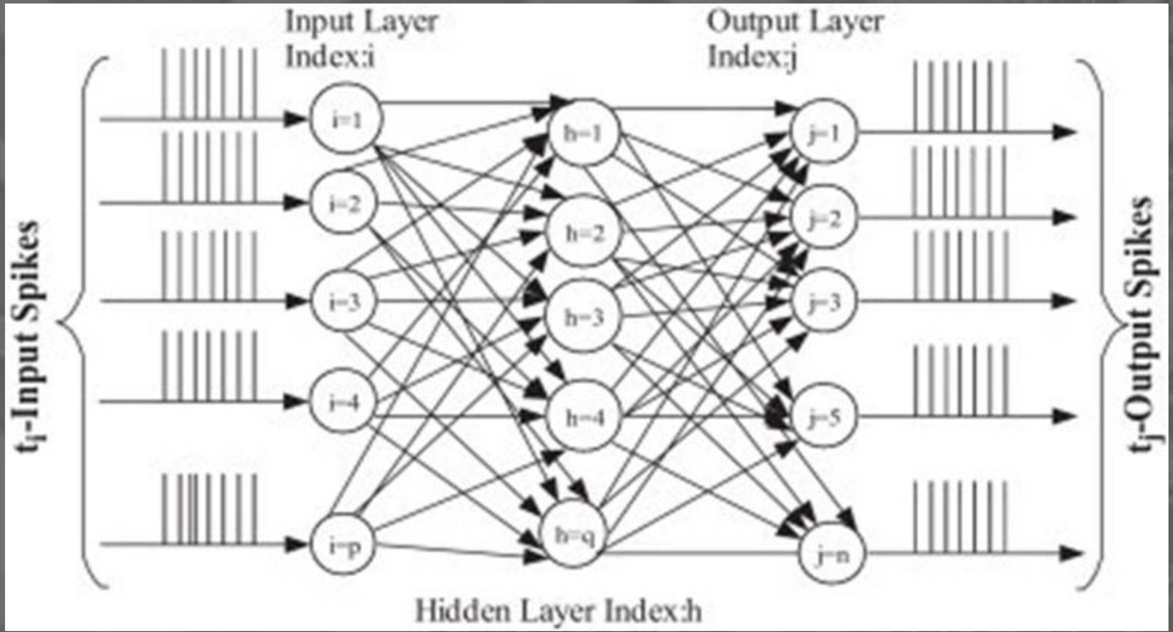
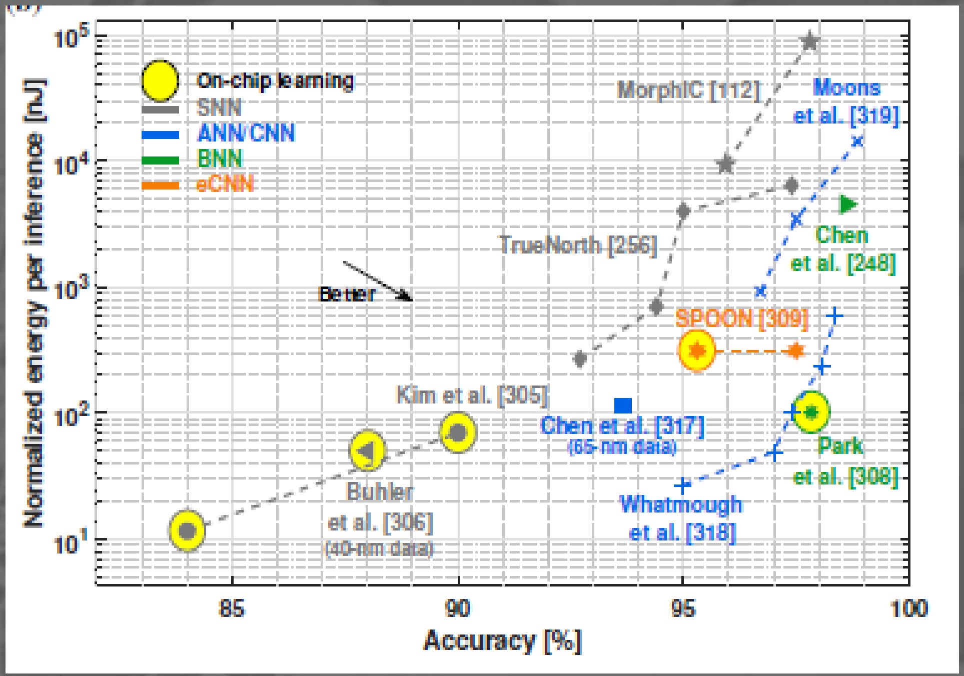
Spiking Neural Networks (SNNs)



Towardsdatascience.com

(Deep Learning ~ 10^7 nJ)



Energy

Accuracy

Frenkel et al. arxiv 2106.01288 (2023)

MNIST Classification

- Event driven – more energy efficient!
- Better for spatial-temporal data

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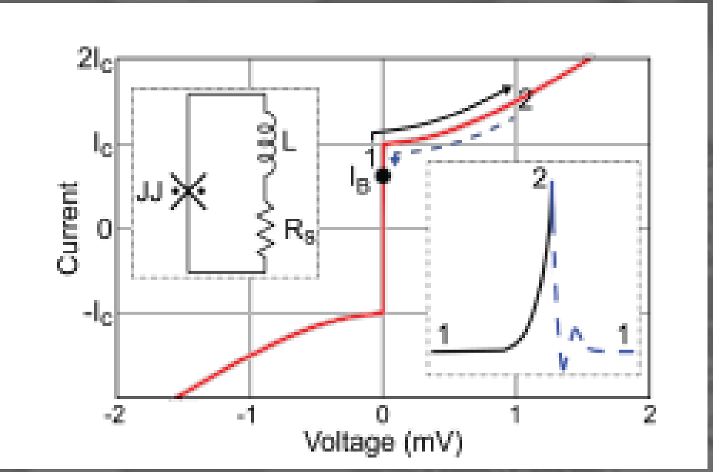
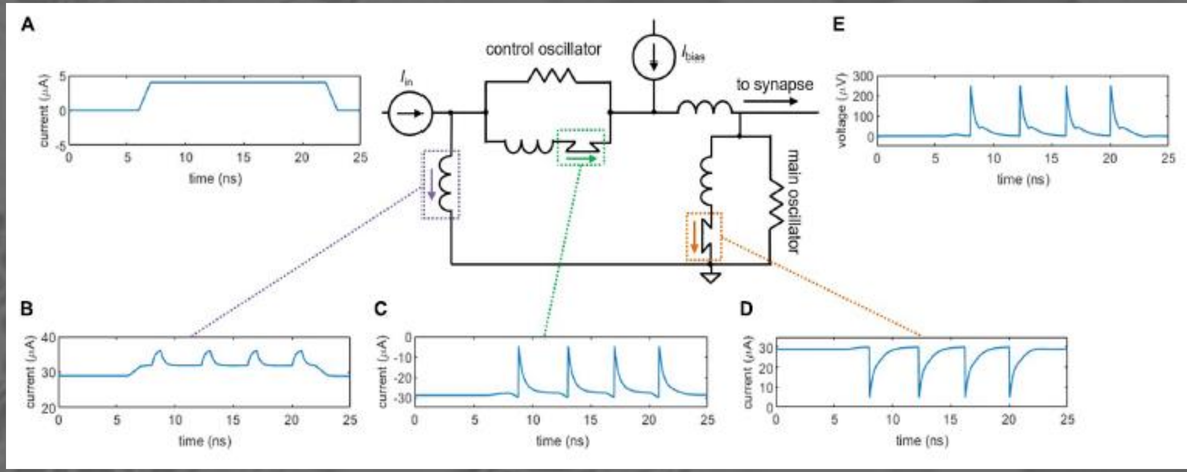
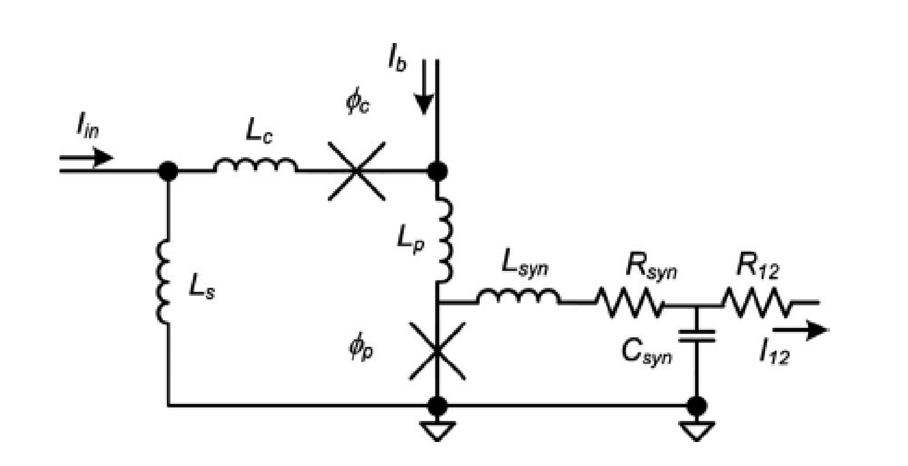
Superconducting spiking neurons



Single junction neurons
Karamuftuoglu et al. arxiv 2402.16384 (2024)



Nanowire neurons
Toomey et al. *Frontiers of Neuro.* **13**, 933 (2019)



Josephson Junction neurons
Crotty, Schult and Segall *Phys. Rev.* **E82**, 011914 (2010)

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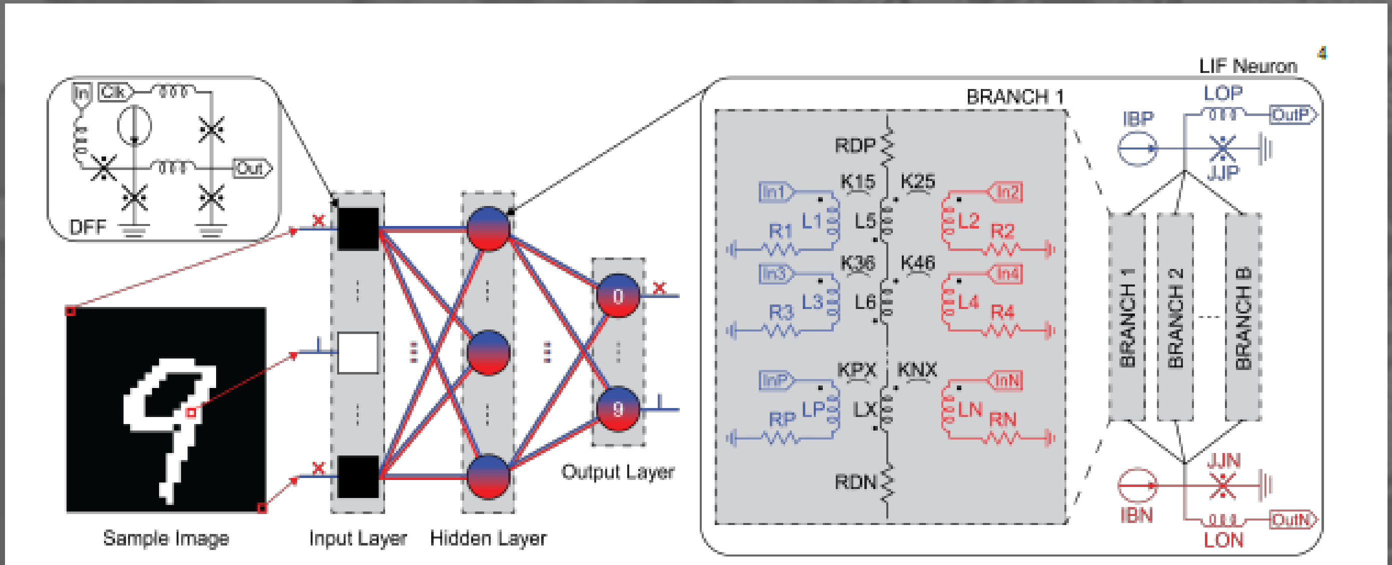
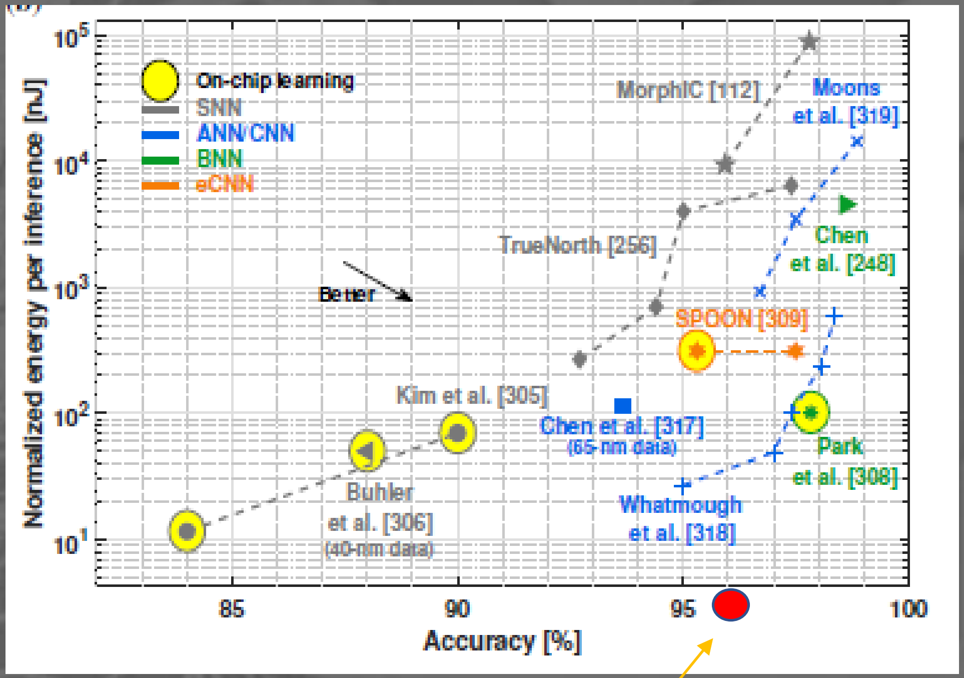
SNN Inference

Simulation

MNIST classification





Karamuftuoglu et al. arxiv 2402.16384 (2024)

4EPo1C-06

96.1 % accuracy
1.5 nJ per inference

- 32-synapse fan-in
- 5-layer network (3 hidden layers) with over 1000 total neurons

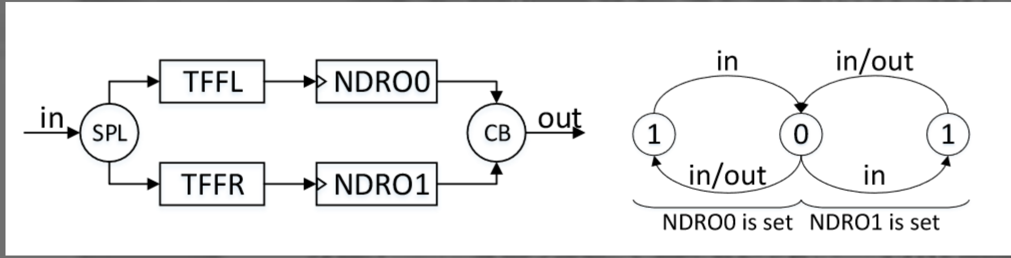
Experiment

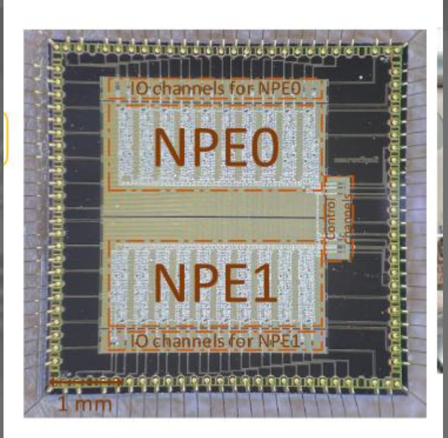
Experimental SNN

First fully superconducting SNN!

SUSHI: Ultra-High-Speed and Ultra-Low-Power Neuromorphic Chip Using Superconducting Single-Flux-Quantum Circuits

Liu et al. *MICRO '23 proceedings* (2023)

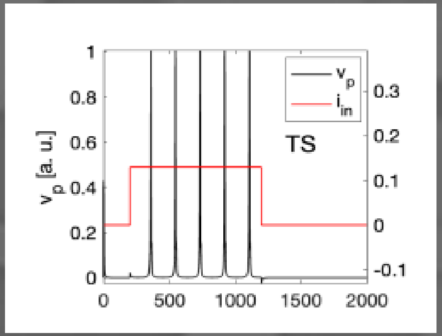


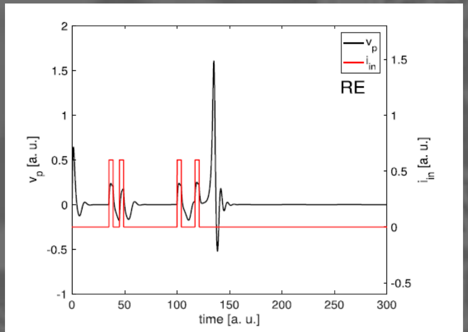


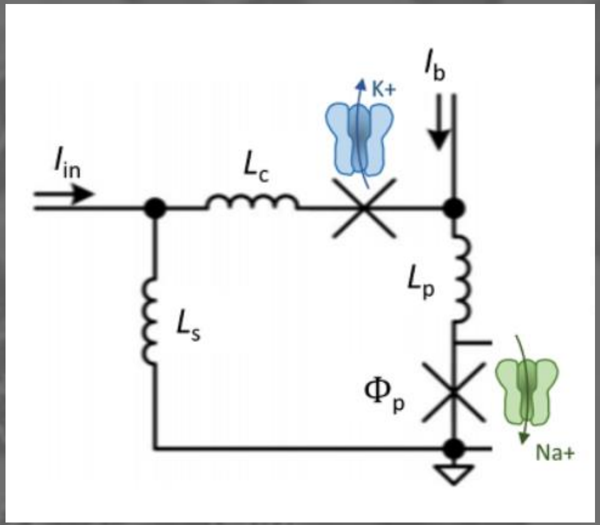
- 4x4 Fully-connected network
- Spiking neuron achieved with SFQ gates, Weighting achieved with nested NDROs
- $8\text{x}10^{10}$ SOPS/watt (with cooling), better than True North

Biological Realism

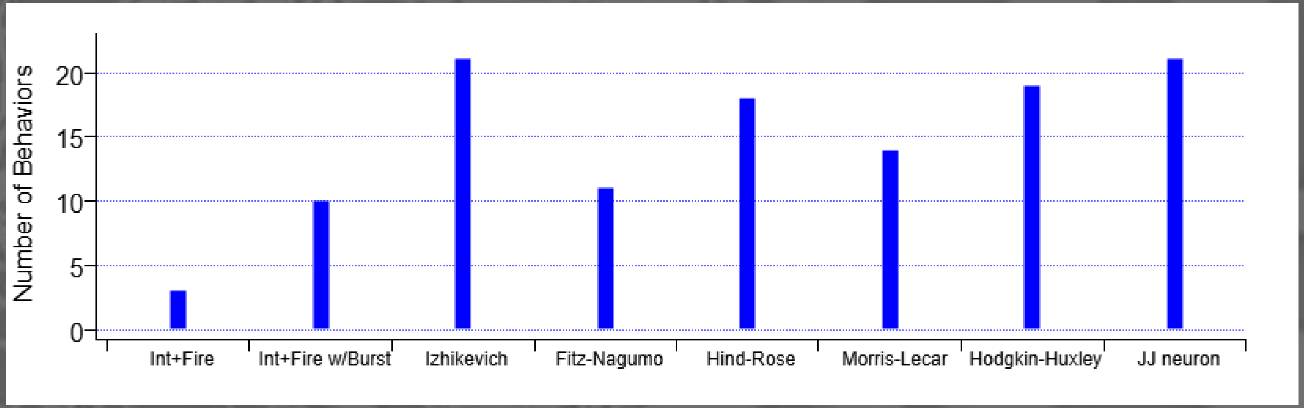
Simulation







behavior	η	Γ	λ	Λ_s	Λ_p	i_b
TS	1.2	1.53	0.16	0.35	0.55	2.19
TB	0.95	1.81	0.11	0.44	0.46	(sin)
IIS	1.2	1.53	0.16	0.35	0.55	2.19
IIB	0.95	1.81	0.11	0.44	0.46	(sin)
PS	1.71	1.55	0.13	0.49	0.48	2.085
PB	1.58	1.64	0.09	0.61	0.1	0.95
RS	1.708	1.55	0.13	0.51	0.48	2.14
RB	0.95	0.758	0.11	0.44	0.46	(sin)
C1	0.96	1.55	0.26	0.49	0.48	1.93
C2	0.96	1.04	0.26	0.46	0.46	1.93
MM	0.941	1.683	0.03	0.49	0.48	1.928
SFA	1.79	2.67	0.001	0.52	0.48	1.9
DAP	1.26	1.593	0.183	0.54	0.46	2.017
STO	1.71	0.649	0.13	0.49	0.48	1.9
SL	1.71	1.55	0.13	0.49	0.48	2.143
IN	1.115	2.114	0.1	0.5	0.5	2.053
BI	1.0	0.93	0.064	0.5	0.46	1.906
RE	1.71	0.649	0.13	0.49	0.48	(sin)
TV	1.1	1.5	0.1	0.5	0.5	1.96

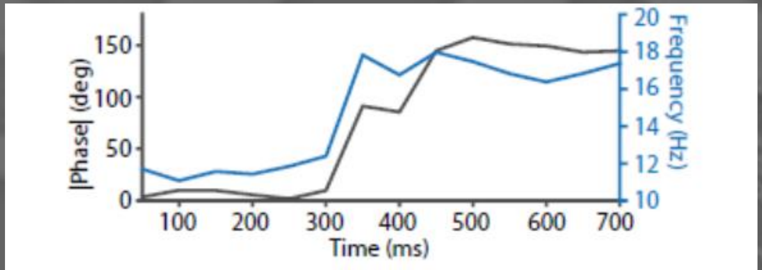


Crotty, Schult and Segall, *IEEE TAS* ***33***, 1800806 (2023)

Izhikevich Behaviors

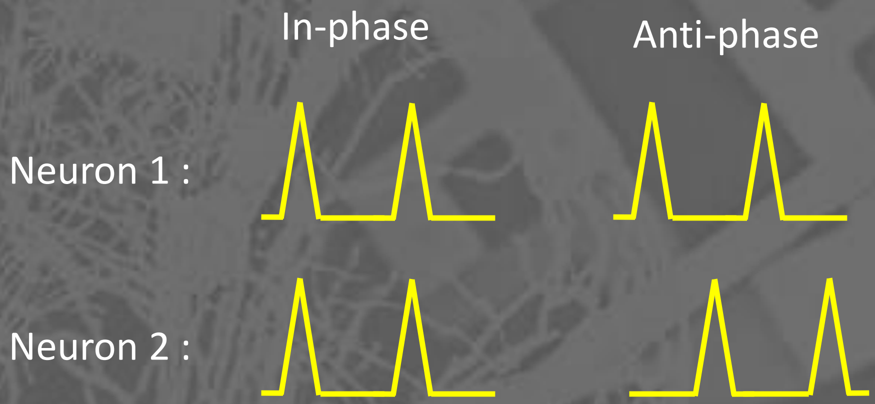
Experiment

Flipping the phase

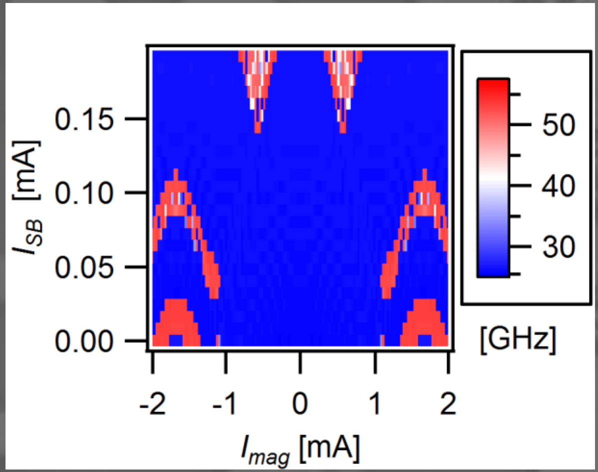


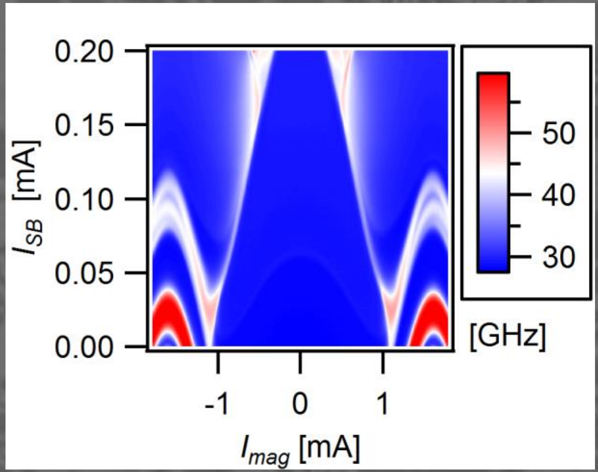
Dotson et al.

Phase-flip bifurcation in primates



Mutually-coupled JJ neurons





Blue = in-phase
Red = antiphase

Simulation
10^3 pts in 60 h

Experiment
10^6 pts in 51 m

Segall et al. *Physical Review* E **95**, 032220 (2017)

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THE BRAIN DOES…LEARNING

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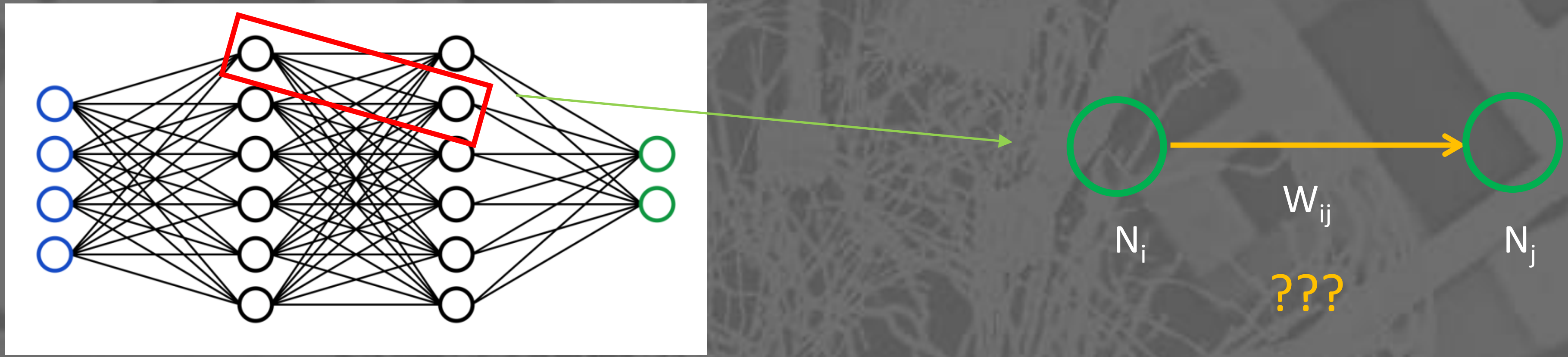
Types of Learning



- <u>Supervised learning</u>: Updated weights calculated with a numerical formula
- <u>Reinforcement learning</u>: Weights are nudged up and down with local rules based only on the global output
- <u>Reservoir computing</u>: Only a small fraction of the weights are adjustable, the rest are fixed in a "reservoir"
- <u>Unsupervised learning</u>: The weights *adjust themselves* according to the coincident firing of the two neurons

More biological

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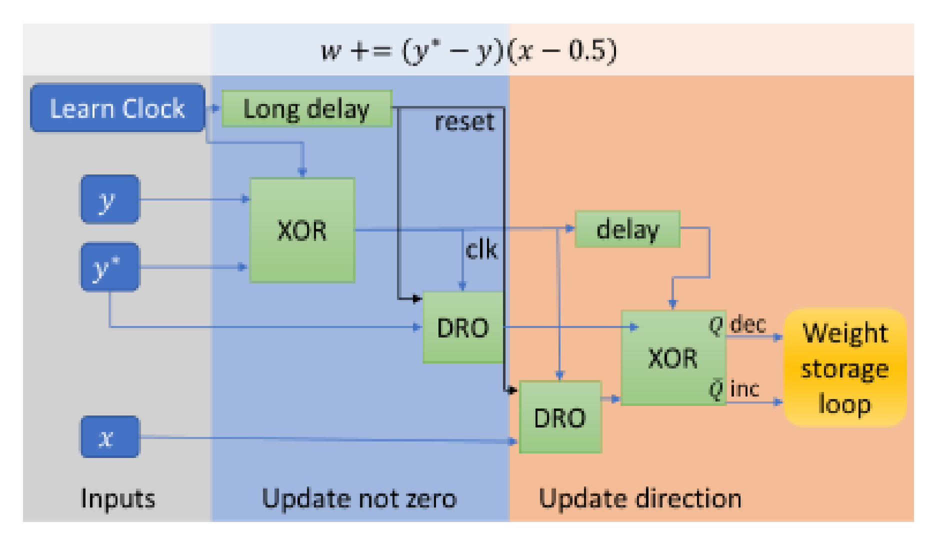
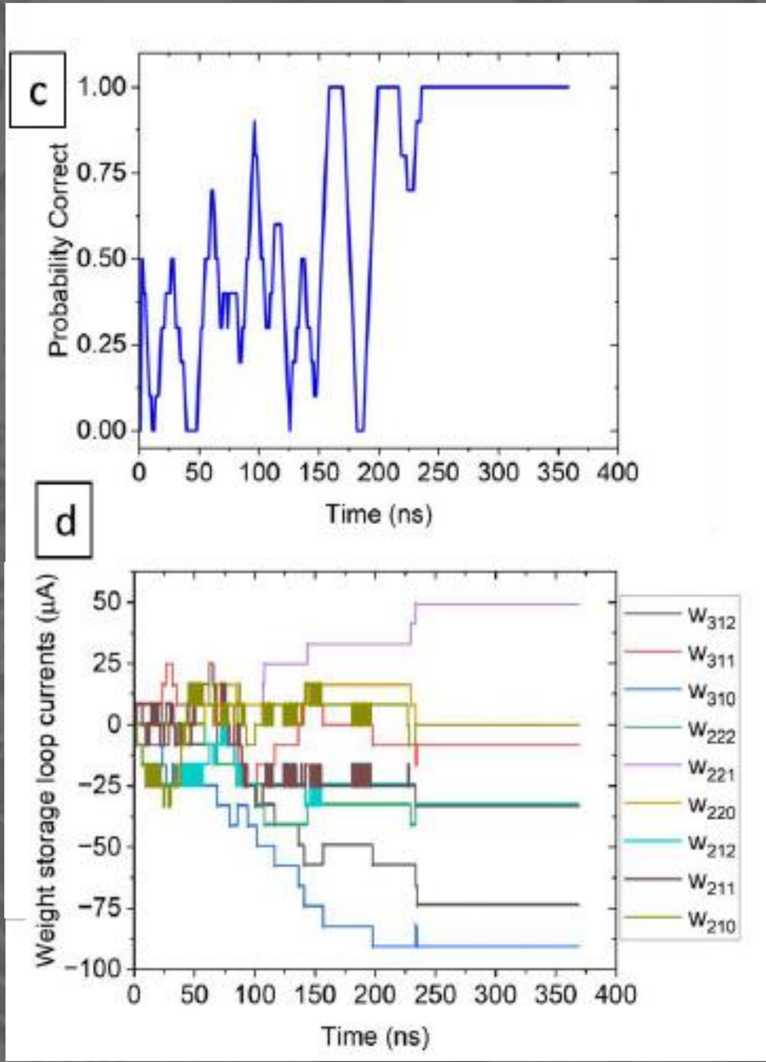
Reinforcement Learning

Simulation



Schneider et al. arxiv 2404.18774 (2024)



Could lead to really fast training!!

5EOr1B

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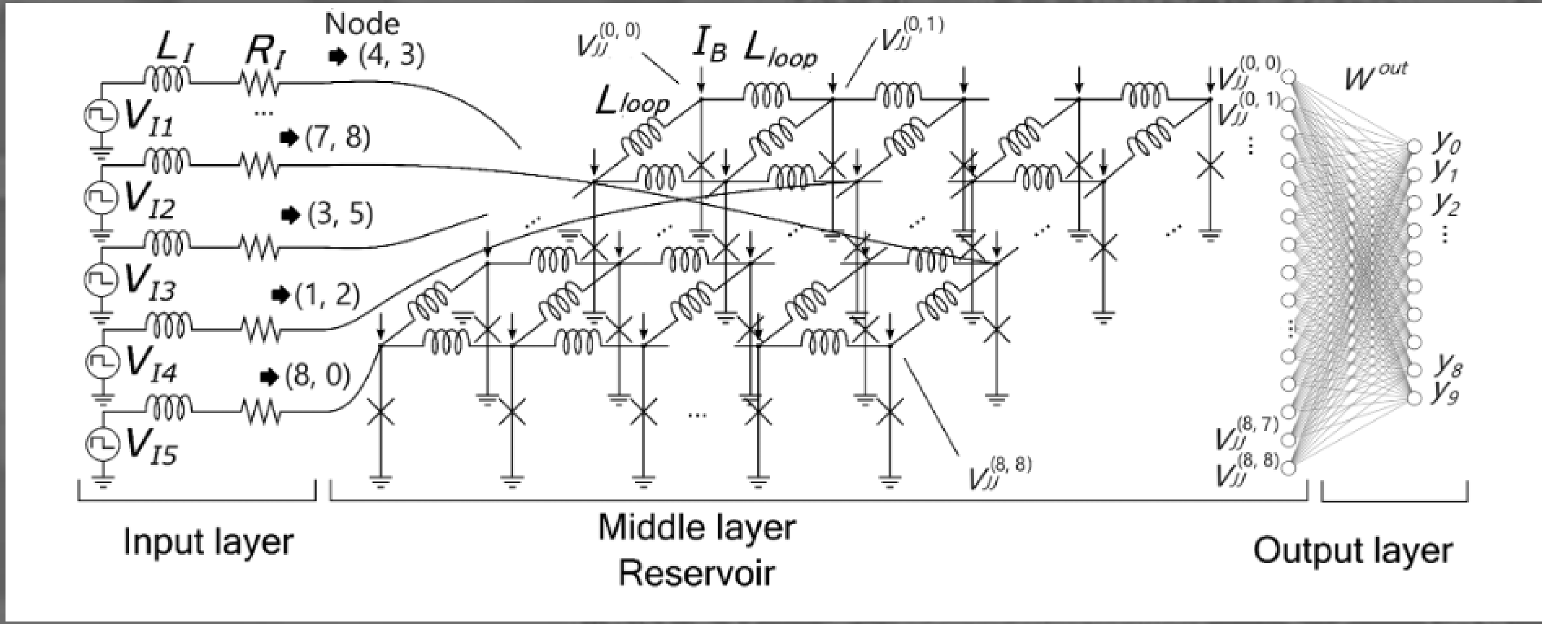
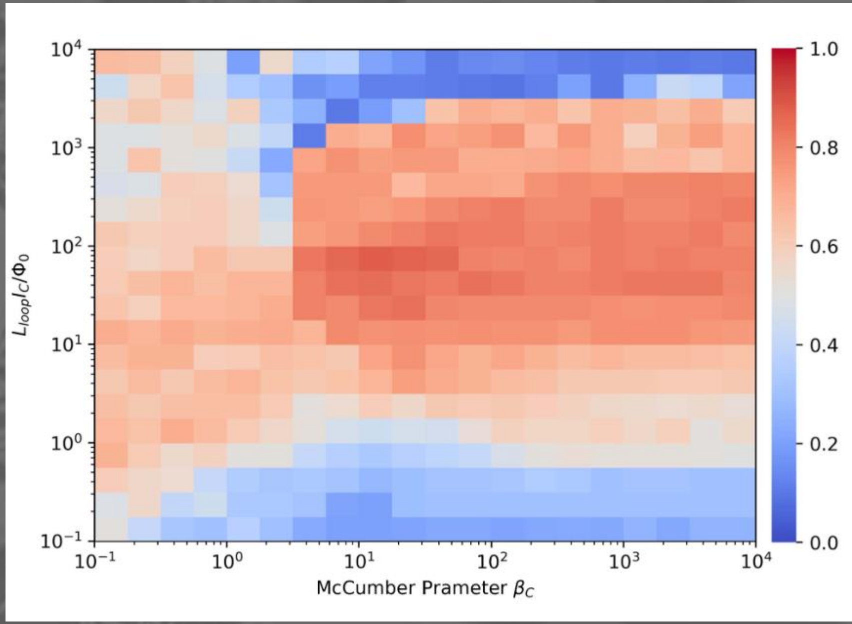
Simulation

Reservoir Computing





Watanabe et al. *IEEE TAS* **34**, 1700204 (2024)

MNIST Data set

Peak accuracy = 88%

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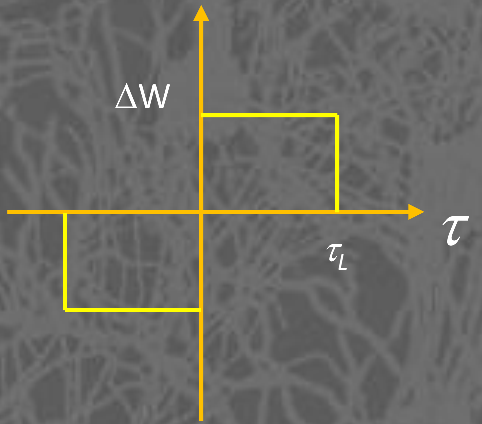
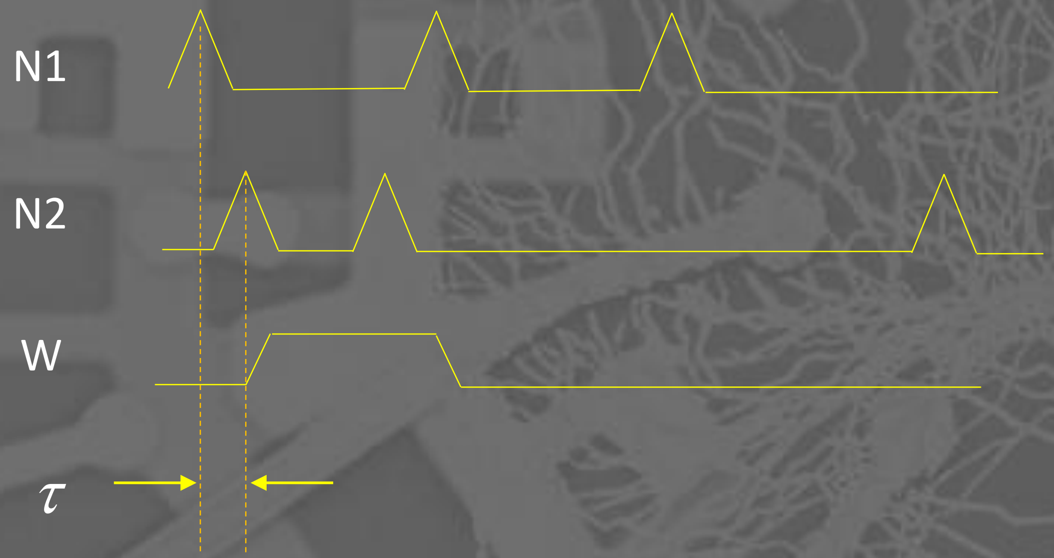
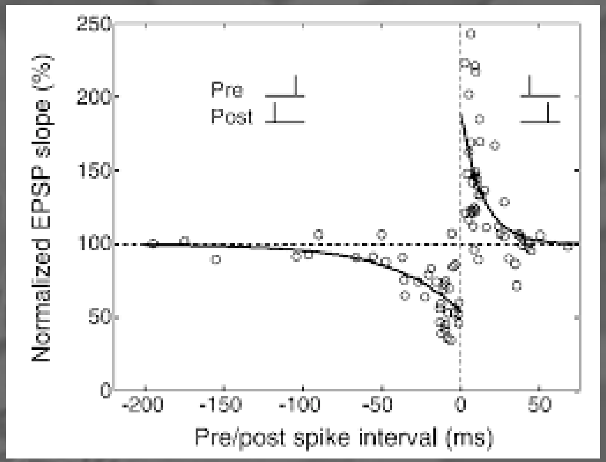
Unsupervised Learning







Froemke et al, 2006

- “Things that fire together wire together”
- Called “Spike Timing Dependent Plasticity” (STDP)

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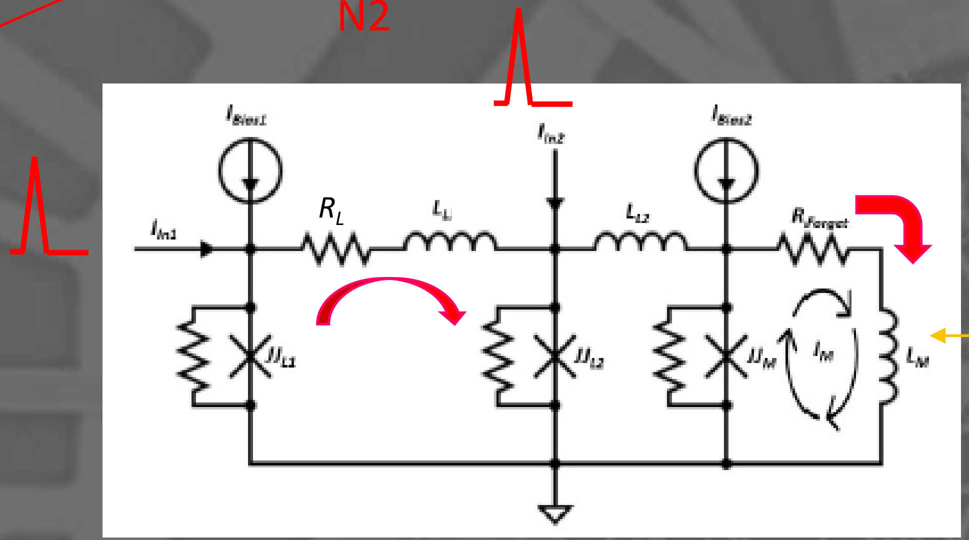
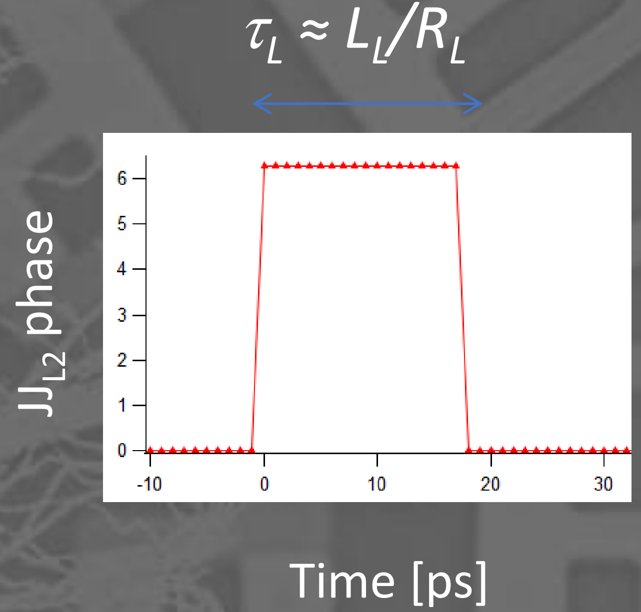
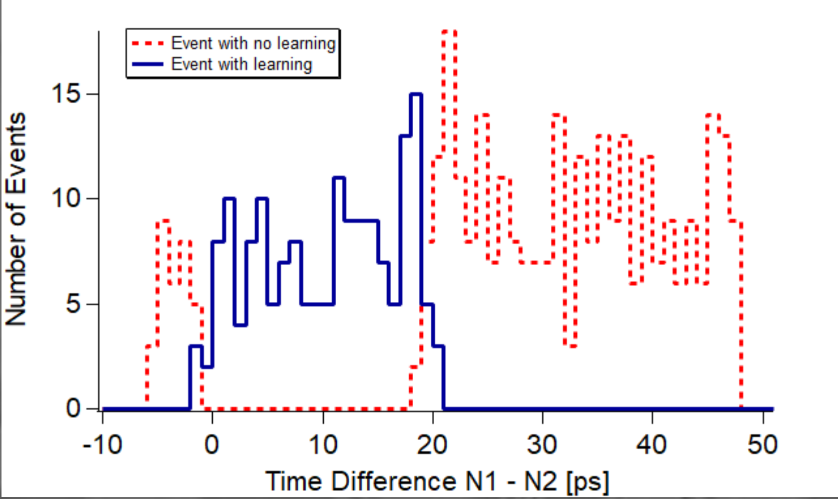
Superconducting STDP

Simulation



Flux = Weight





Segall et al. *Appl. Phys. Lett.* 122, 242601 (2023).

(Measurement in preparation)

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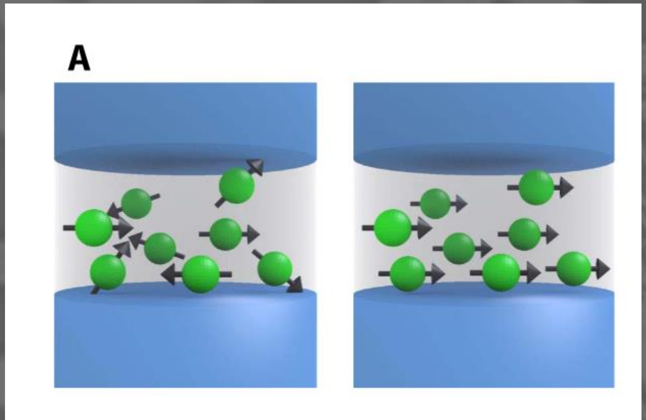
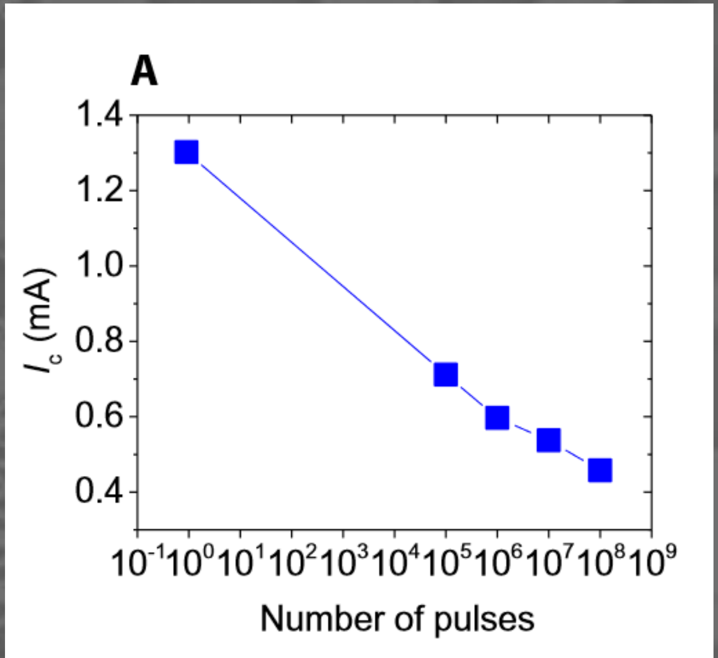
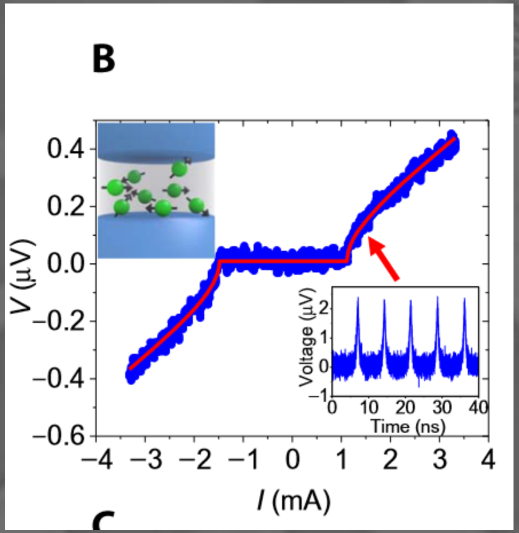
Learning to align..

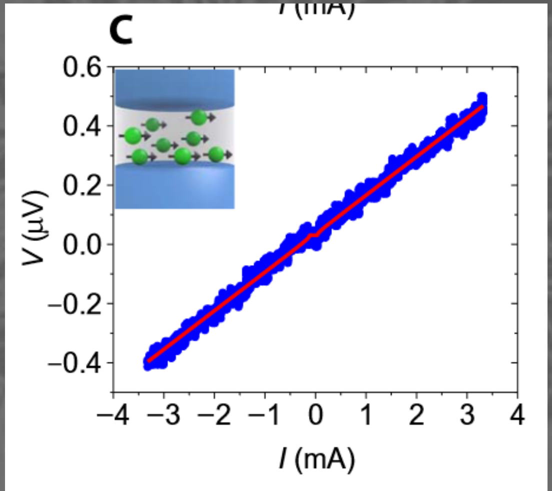
Experiment



Magnetic Josephson Junction
(MJJ)







Schneider et al. Sci. Adv. 4, 1701329 (2018)

- Device “trains” itself as current pulses are applied!

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I. Introduction
II. Brain activities:
   1. Synaptic Weighting
   2. Spiking
   3. Learning
   4. Optimization ←
   5. Networking
III. Looking forward

THE BRAIN DOES…OPTIMIZATION

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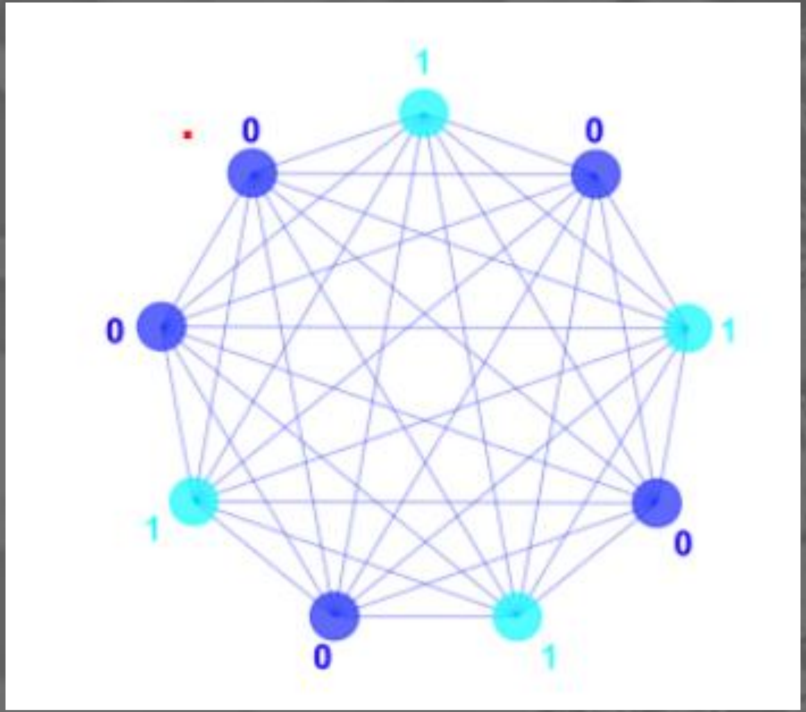
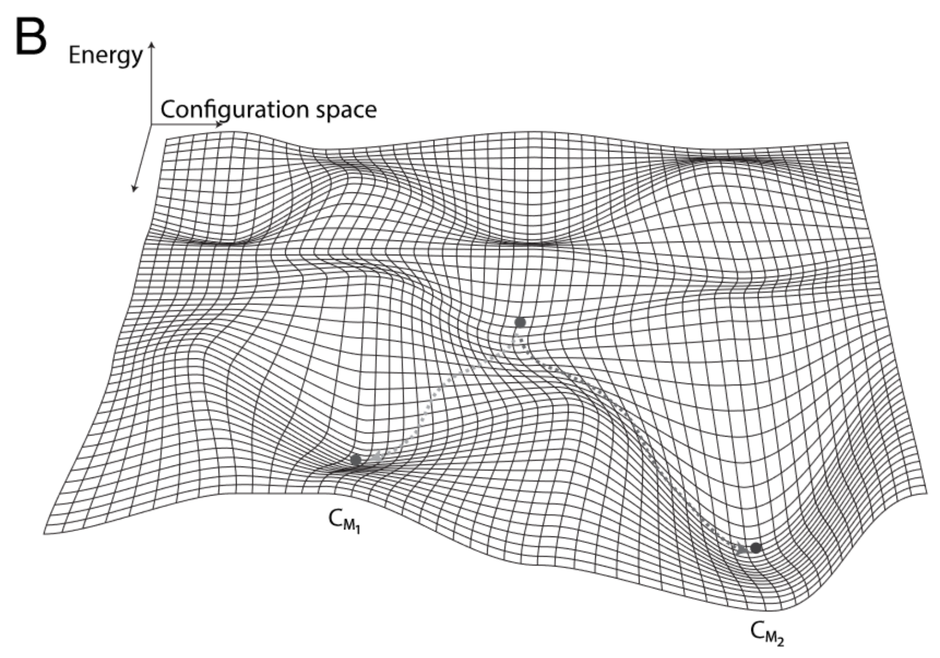
Hopfield Networks





$$U = -(1/2)x^t W x - b^t x$$

Lyapunov Function: $\frac{dU}{dt} \leq 0$

Can be used to:

1. Solve optimization problems
2. Model associative memory

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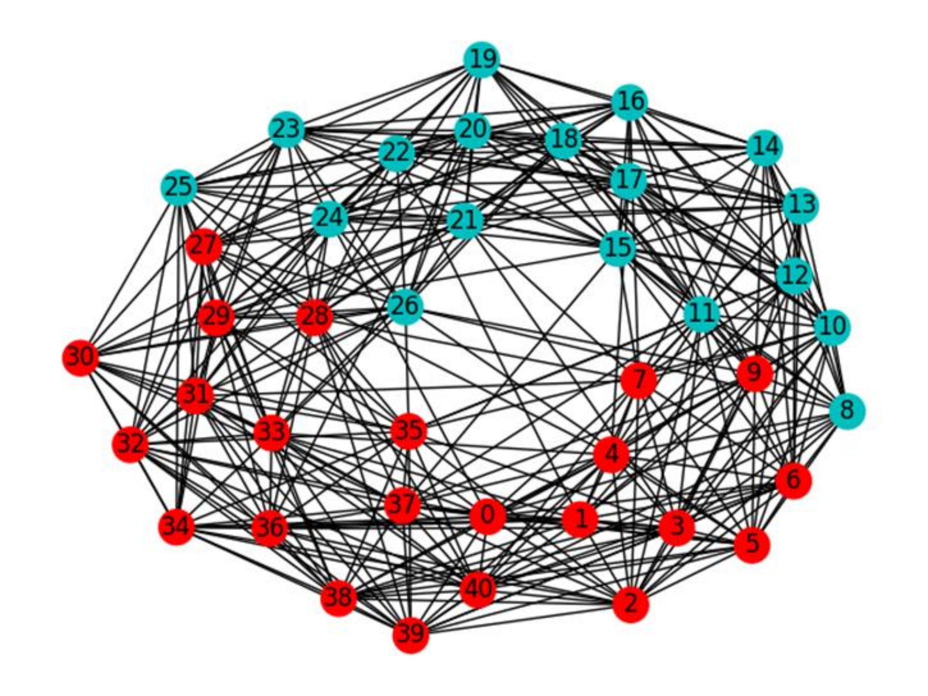
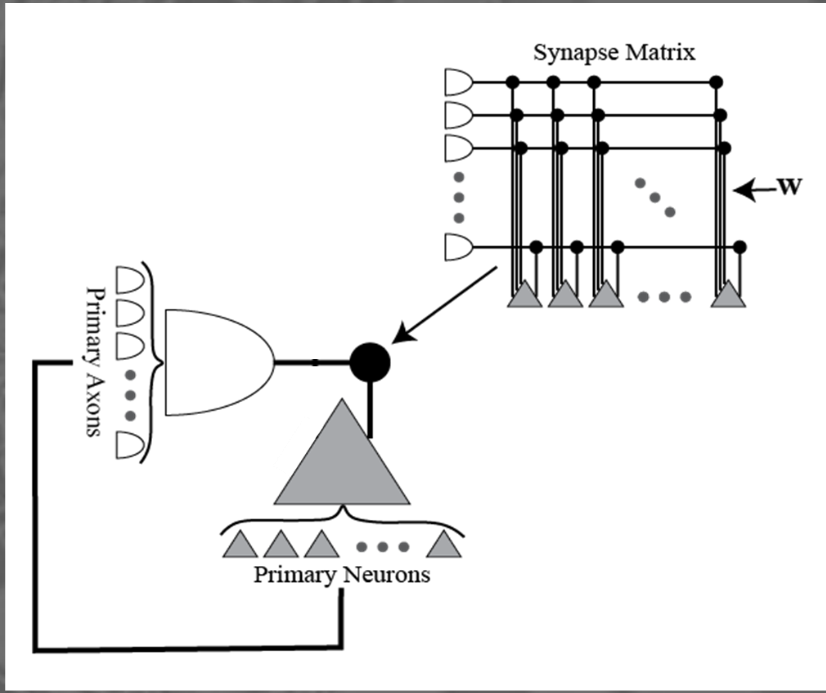
QUBO and Graph partitioning

Simulation

$U = -x^t W x - b^t x$ → Maps onto NP-complete problems like Traveling Salesman and Graph Partitioning (GP)!





JJ network to solve GP: 5EOr1B-05 (Adler)

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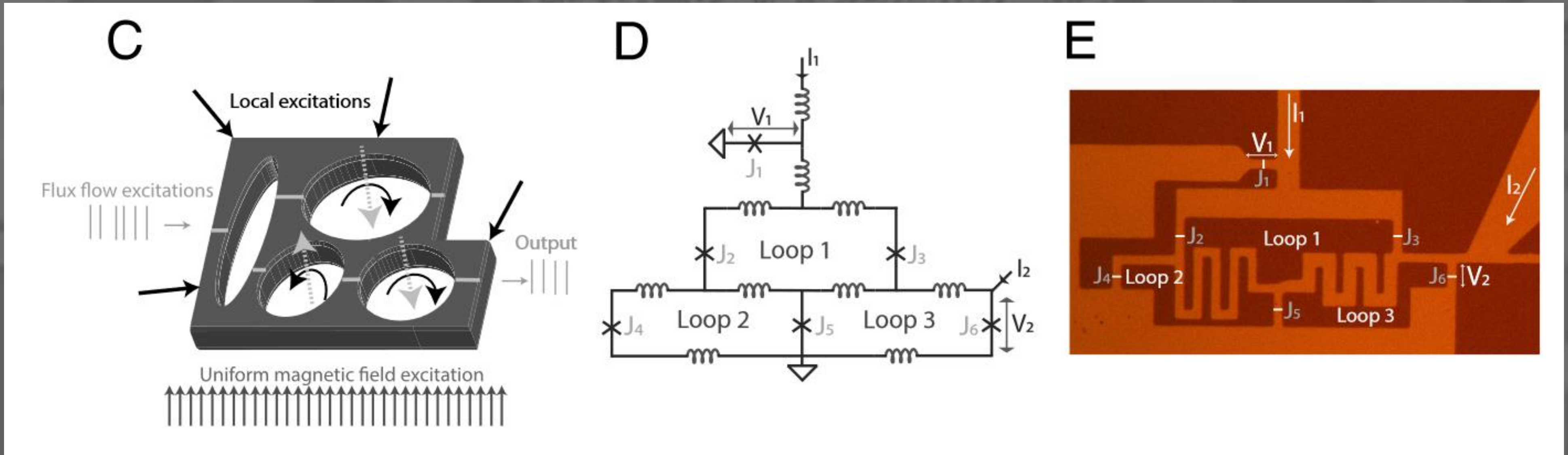
Associative Memories and Categorization

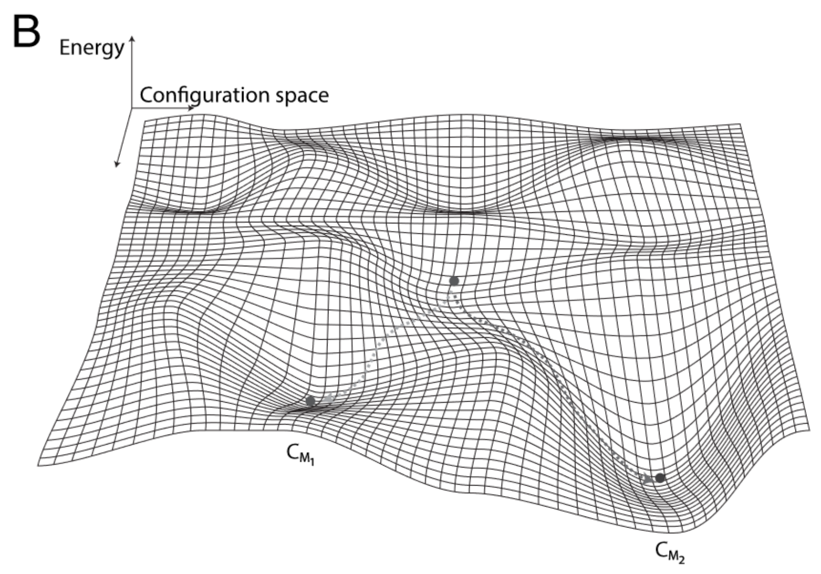
Experiment

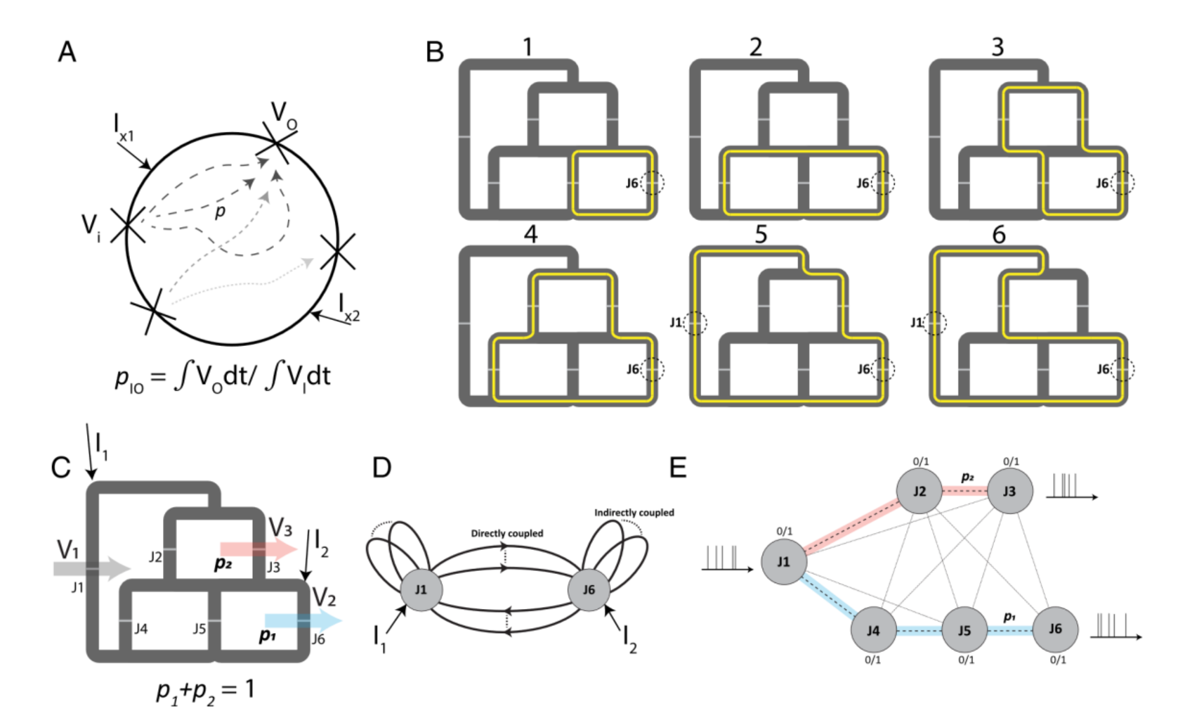


Goeti et al. PNAS **212** 2314995121 (2024)

- Four loops with JJs in a high-Tc material
- Fluxons can be added by pulsing the junctions

Coupling neurons into networks





- With a large number of fluxons you get a large configuration space
- JJs act like neurons, closed loops act like connections
- Neural behavior observed!

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THE BRAIN DOES…COMMUNICATION AND NETWORKING

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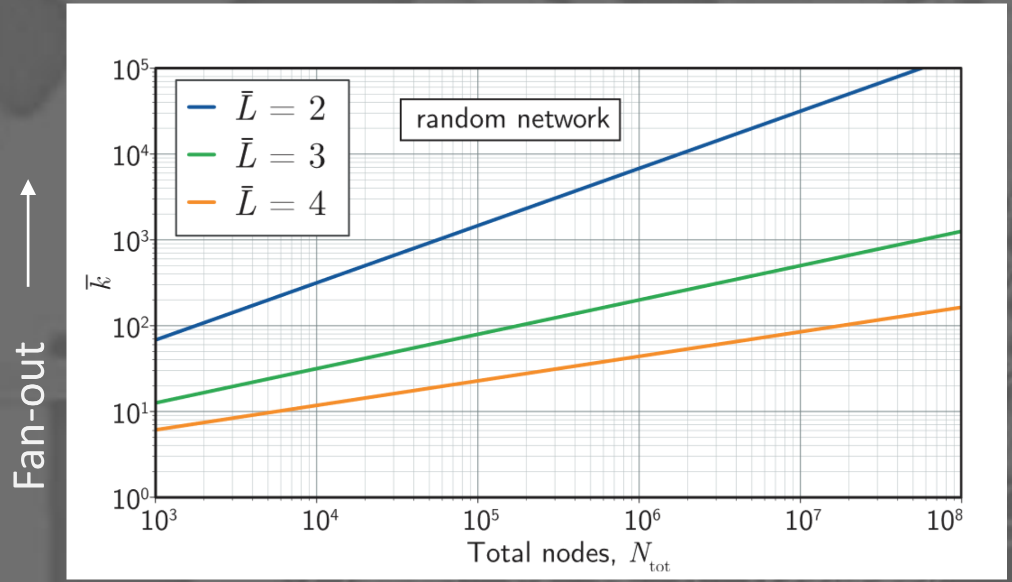
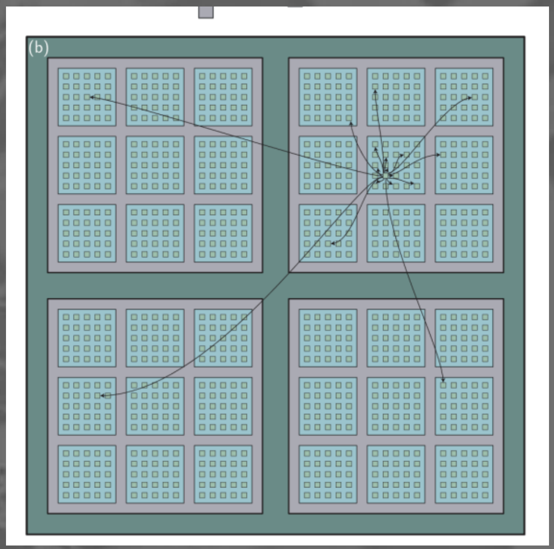
Communication across different brain regions





J. Shainline *Appl. Phys. Lett.* 118, 160501 (2021)

- Each neuron in the brain connects to ~ 5000 other neurons
- Will be challenging to realize this level of fan-in/fan-out with only superconducting electronics
- Can we do better? Is human-level AI possible?

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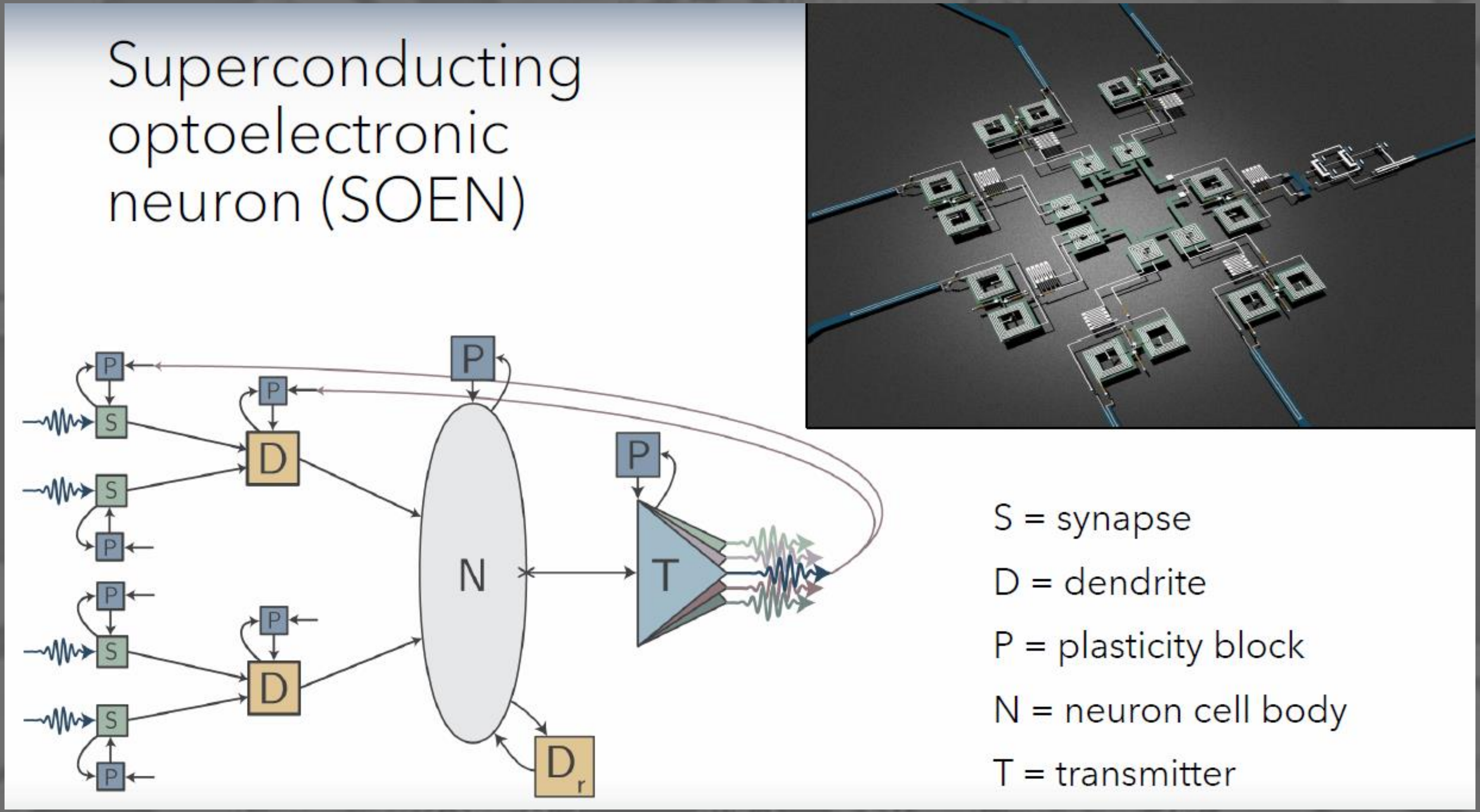
Superconductors for computation, light for communication



J. Shainline *Appl. Phys. Lett.* 118, 160501 (2021)

5EOr1B

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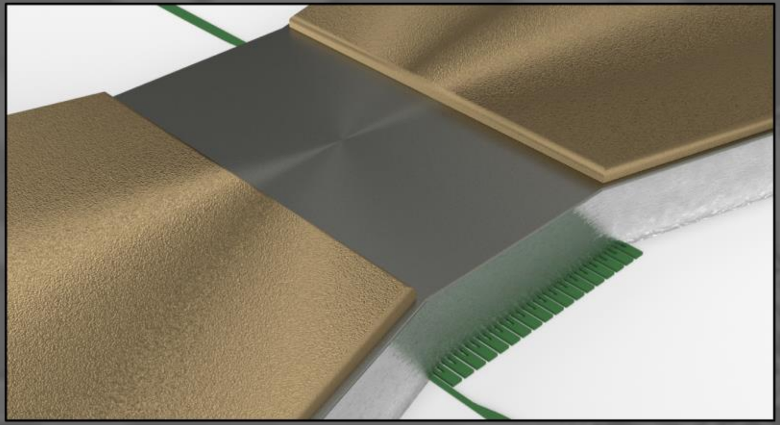
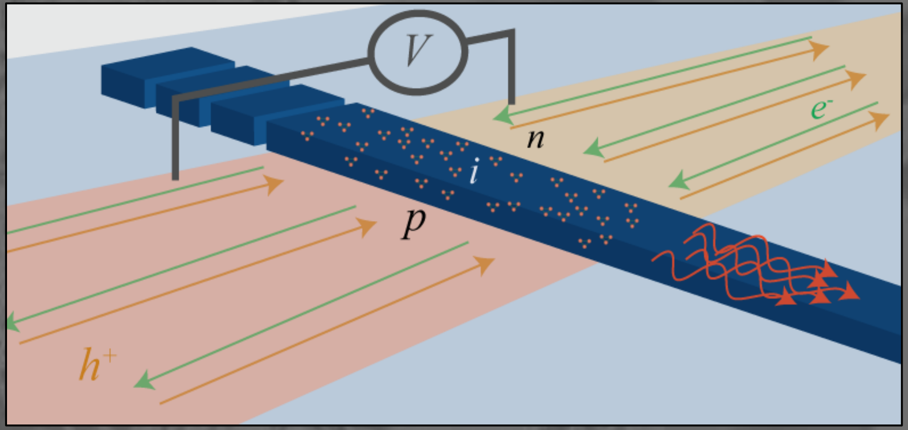
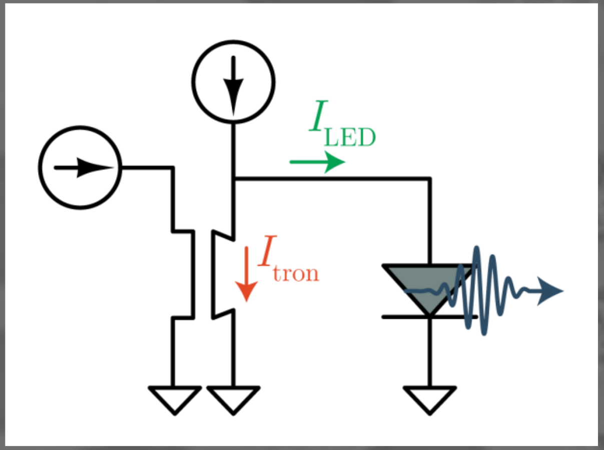
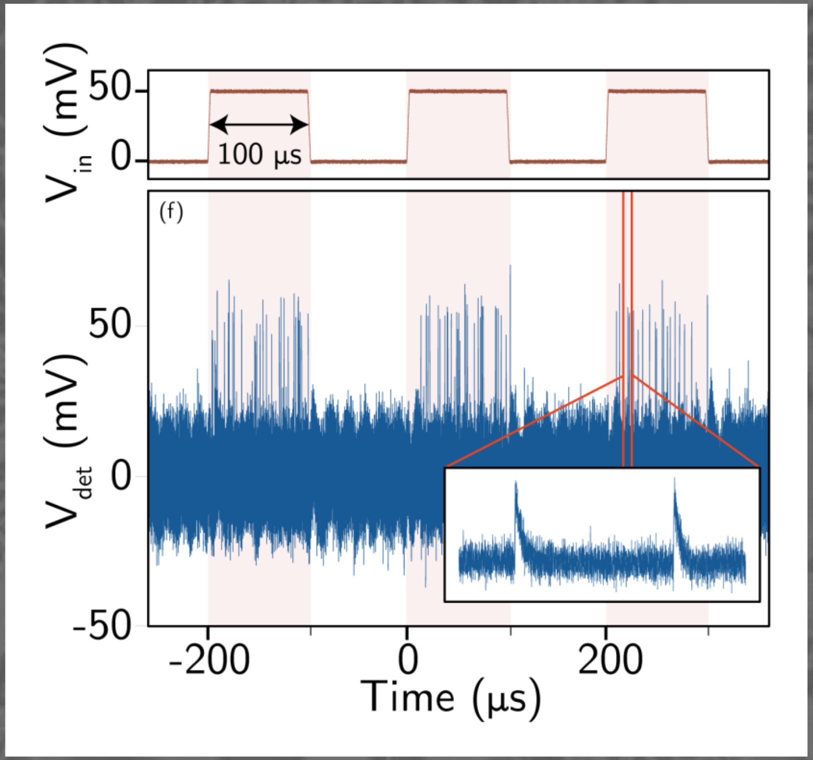
From SFQ to light…







McCaughan et al., Nat. Electron., 2, 451 (2019)



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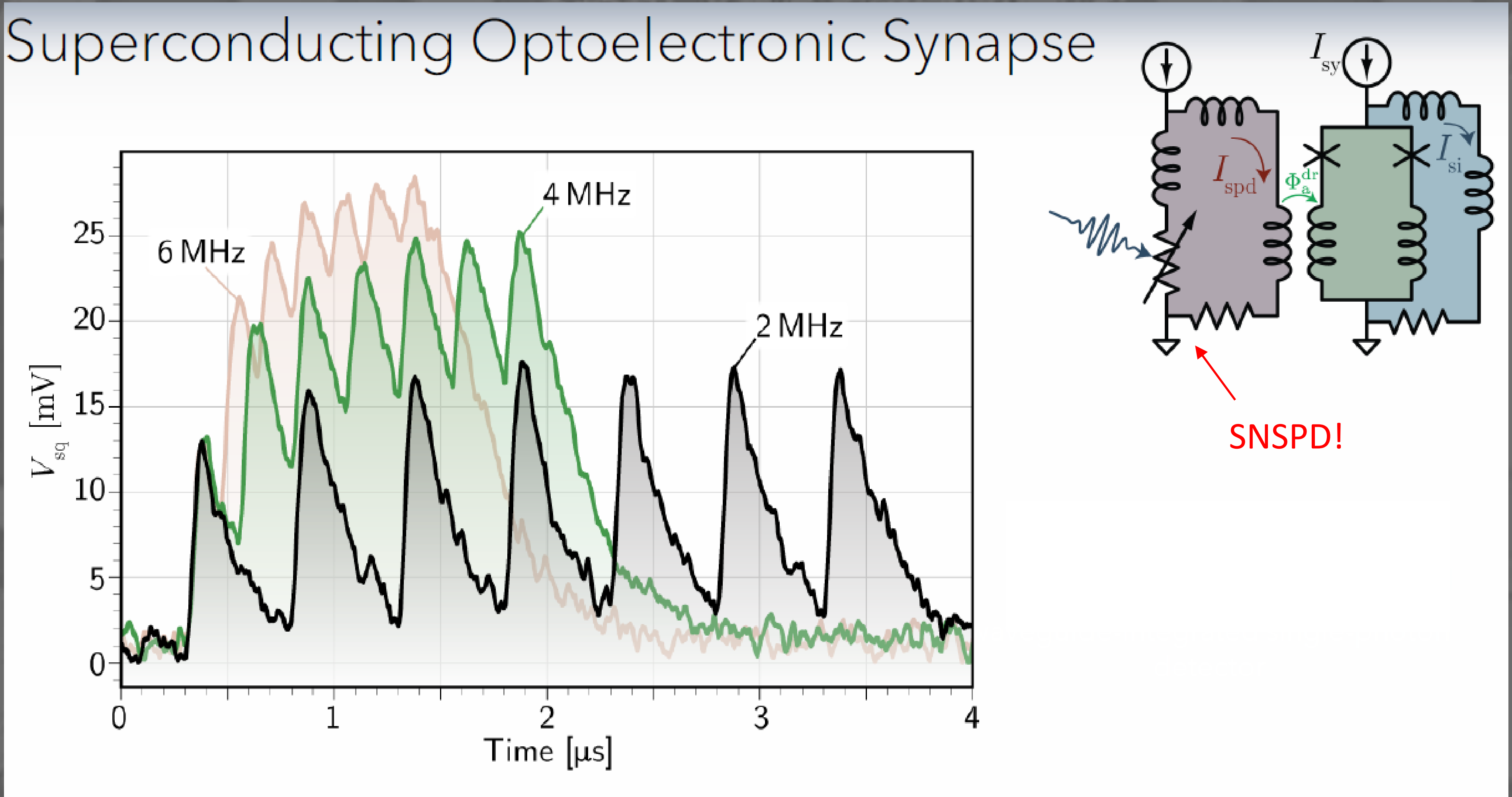
And from light back to SFQ!

Experiment



Khan, Primavera et al. Nature Electronics (2022)

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LOOKING FORWARD…

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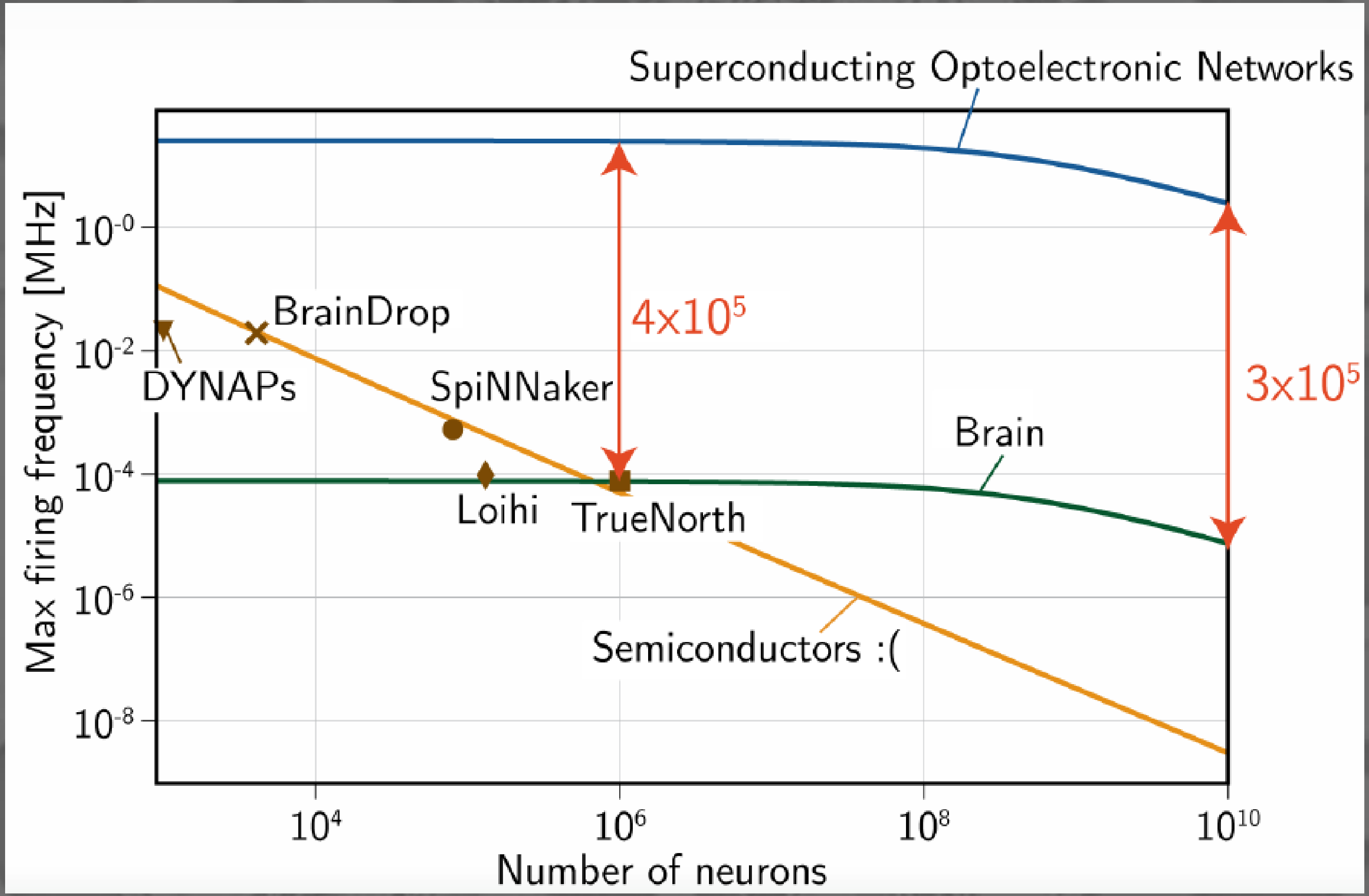
More bandwidth....



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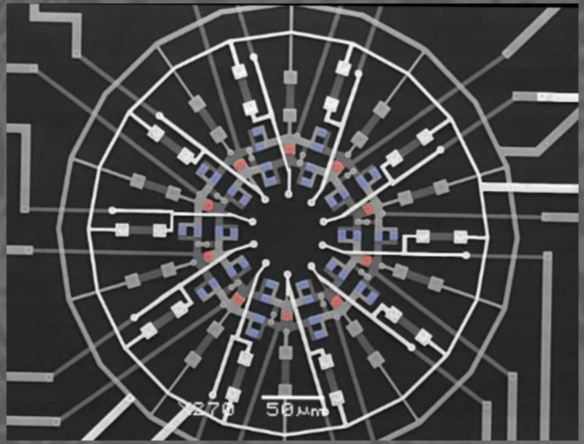
With more spikes…

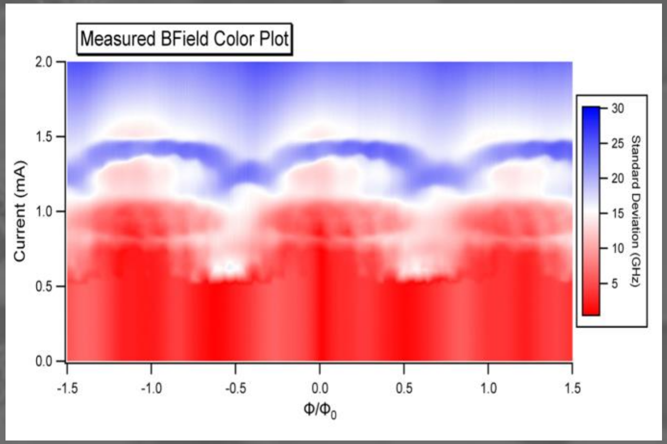
N Neurons: AP/Neuron/sec (w/ sparse connections)

Assume
10^9 FLOPS →

Model	N=100	N=10,000	$N=1x10^6$
Hodgkin-Huxley Model	8.3 $x10^3$	83	0.83
Mammalian CNS	1 $x10^3$	1 $x10^3$	1 $x10^3$
JJ Neuron	1 $x10^{10}$	1 $x10^{10}$	1 $x10^{10}$

Best for long term dynamics:
A lifetime (90 years) of learning in
5 *minutes* of lab time!!





Voltage measurements to predict epileptic seizures
(5EOr-1B tomorrow)

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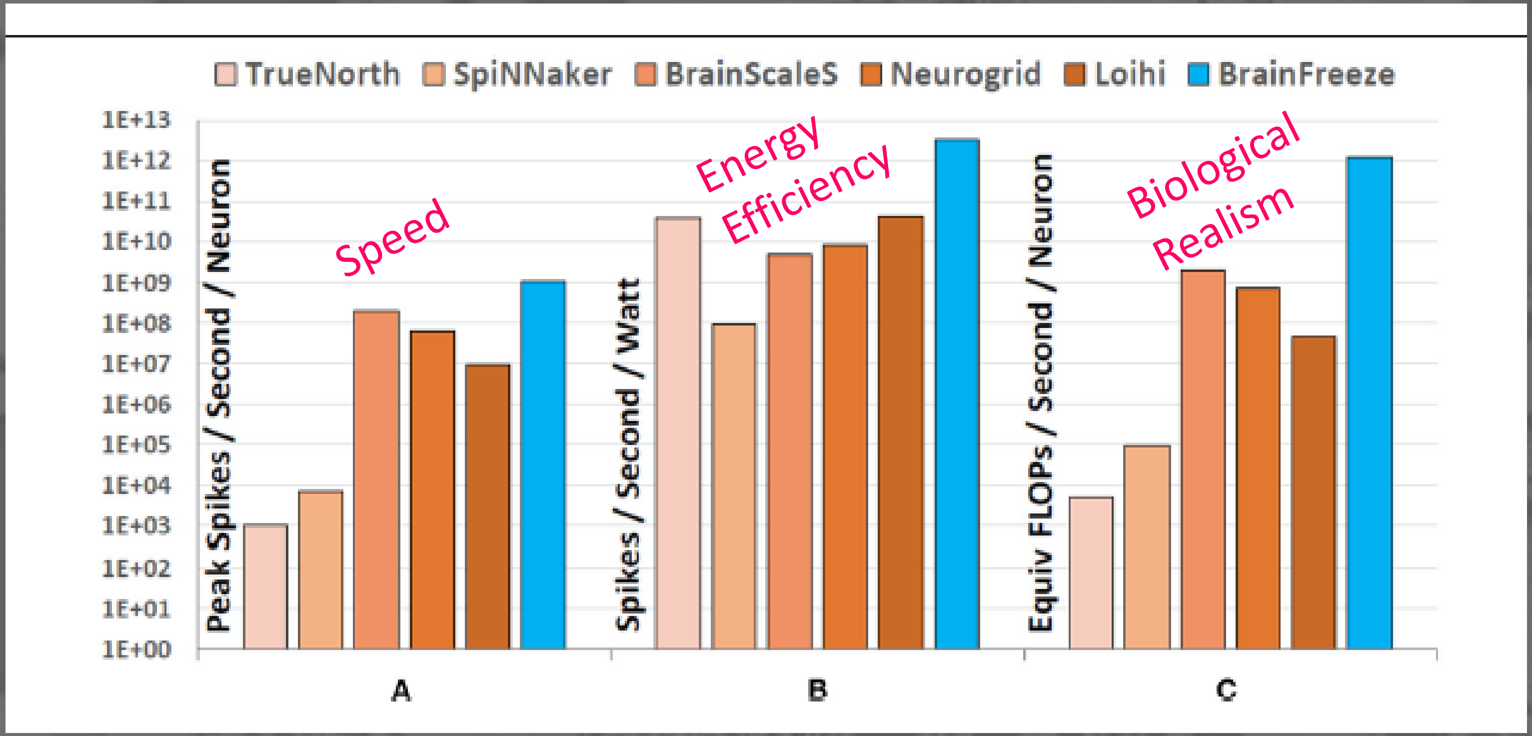
And more efficiency and biological realism…



Tshirhart and Segall, *Frontiers of Neuroscience* (2021)

- Mixed-signal architecture (analog neurons, digital connections)
- Assumes only available published superconducting technology
- Utilizes Multi-Chip Modules (MCMs)

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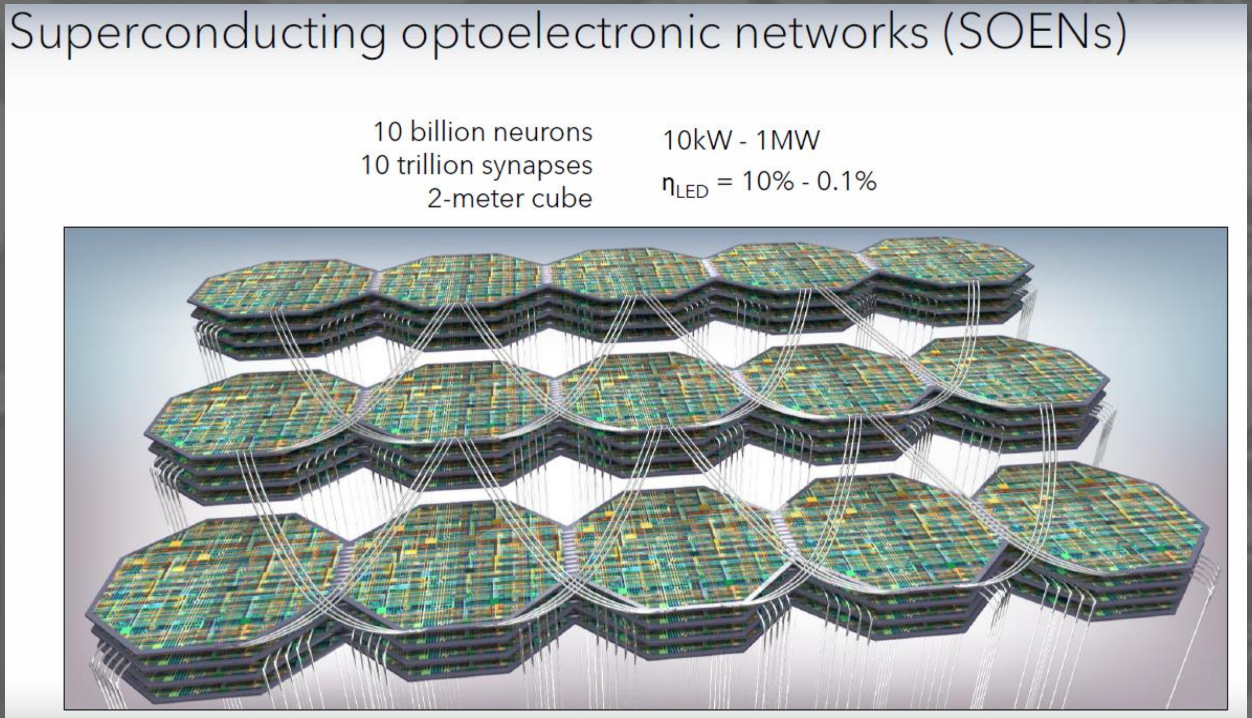
So let's go big!



Superconducting Brain Conception (courtesy J. Shainline)

- Energy efficiency advantage comes mostly from interconnects – win more with a bigger system!

- Fast inference (real-time malware detection?)
- Whole brain simulation (Artificial General Intelligence?)
- Fast computation (mediate plasma instabilities in fusion?)
- Large-scale optimization (planet-scale sustainability trade-offs?)

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Conclusions

- Neuromorphic computing aims to make computer hardware that works according to principles of the human brain
- The brain's activities of synaptic weighting, spiking, learning, optimization and networking can all be made with superconducting electronics
- The field is expanding, and now is the time to go big!

Acknowledgements:

- Talk preparation: Mike Schneider, Jeff Shainline, Elie Track, Timur Filippov
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- Colgate Students: Matt LeGro, Sam Adler, Sarah Miller, Shreeya Khadka (and many others!)