Josephson Junction Simulation of Neurons

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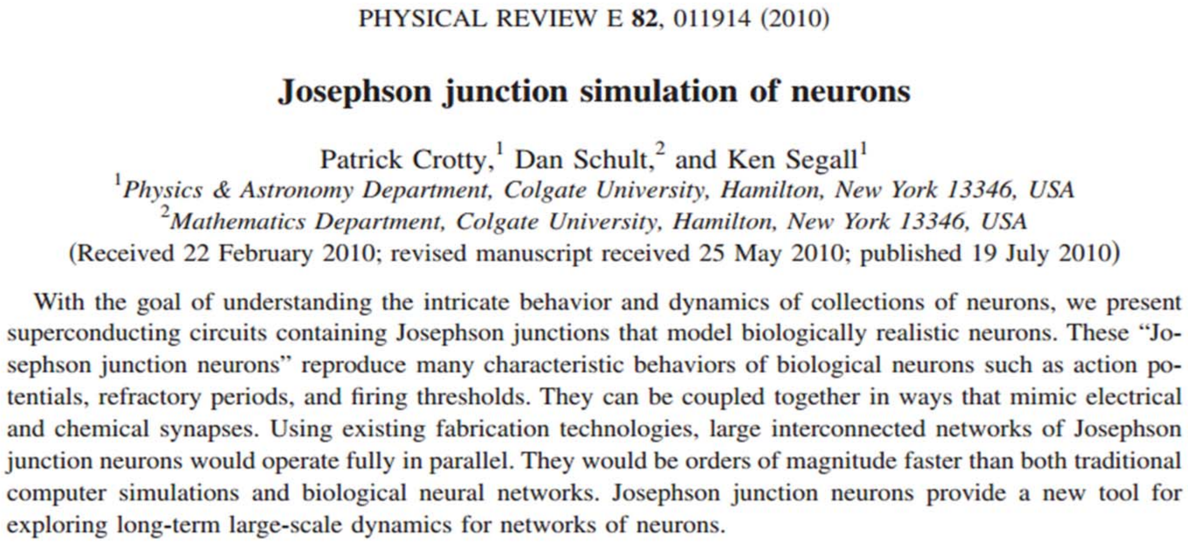

PHYSICAL REVIEW E **82**, 011914 (2010)

Josephson junction simulation of neurons

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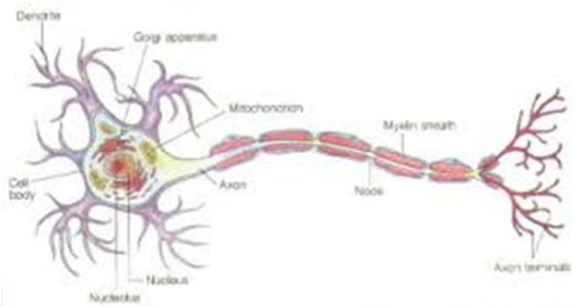
(Received 22 February 2010; revised manuscript received 25 May 2010; published 19 July 2010)

With the goal of understanding the intricate behavior and dynamics of collections of neurons, we present superconducting circuits containing Josephson junctions that model biologically realistic neurons. These “Josephson junction neurons” reproduce many characteristic behaviors of biological neurons such as action potentials, refractory periods, and firing thresholds. They can be coupled together in ways that mimic electrical and chemical synapses. Using existing fabrication technologies, large interconnected networks of Josephson junction neurons would operate fully in parallel. They would be orders of magnitude faster than both traditional computer simulations and biological neural networks. Josephson junction neurons provide a new tool for exploring long-term large-scale dynamics for networks of neurons.

Outline



- Motivation for the paper.
- What is a Josephson Junction?
- What is the JJ-Neuron model?
- A comparison of different models for the simulation of neurons’ function.
- Results of the JJ simulation presented in this paper.
- A look at the impact of this paper and the future of the field.

Motivation of the paper

- We want to understand how the collective behaviour of large networks of neurons gives rise to the intrinsic dynamics of the brain.
- Typical size of a neocortical column- 10,000 neurons.
- Large scale digital simulation projects (Blue Brain, Peta Vision etc.) are difficult to make biologically realistic due to large simulation times.
- Analog simulations (VLSI circuits) are limited by complexity and power consumption.
- Alternative proposed by authors-JJ Neurons: superconducting Josephson Junctions used to model neuron and synapses, which allows us to explore neural network dynamics orders of magnitude faster than these other techniques.

Josephson Junctions

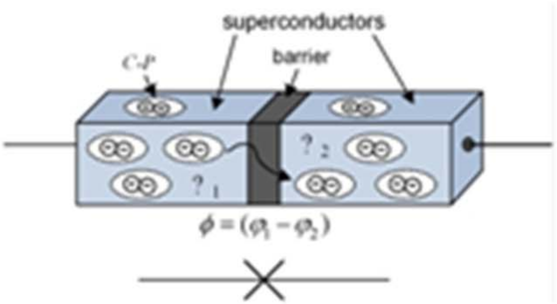
- Two superconductors separated by thin insulating barrier.
- Phase difference of electrons across the barrier (Josephson phase), ϕ, controls electrical properties including voltage and current across junction.
- Voltage develops above critical current I_0 ,

$$V = \left(\frac{\Phi_0}{2\pi}\right)\frac{d\phi}{dt} \qquad ; \Phi_0 = \frac{h}{e}$$

- Current through the circuit

$$i = \ddot{\phi} + \Gamma\dot{\phi} + \sin\phi$$

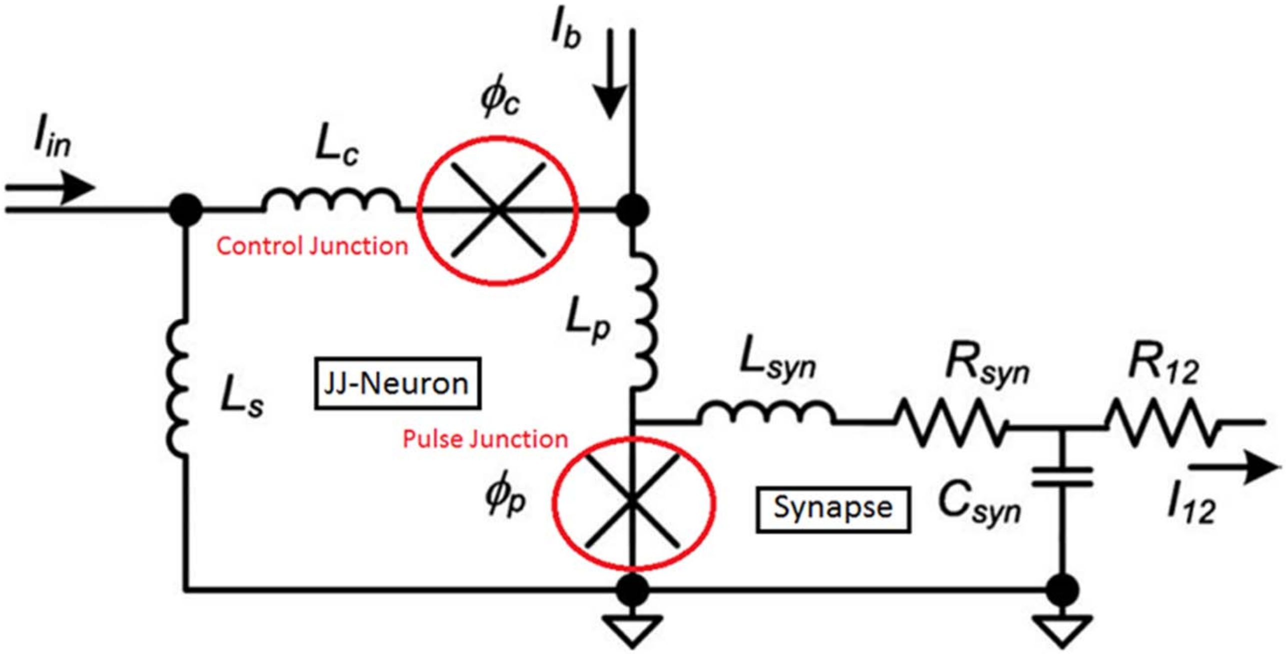
where Γ is a damping parameter which depends on R and C.



JJ-Neuron Model

- Biologically realistic features that this model captures:
  - Action Potential (AP or ‘firing’): A voltage pulse across the neuron membrane in response to input currents/pulses. Two ion currents involved- an inward Na^+ current produces the rising phase and an outward K^+ the falling phase of the pulse.
  - Firing threshold: Level of external stimulus below which there is negligible response, above which an AP is triggered.
  - Refractory period: Period of time after firing during which it is difficult to evoke a second firing.

Circuit diagram for the JJ-Neuron model



Biological equivalents of the model

JJ-Neuron	Biological equivalent
Flux, $\Phi=\lambda(\phi_p+\phi_c)$	Membrane Potential, V_m
Pulse voltage, v_p	Na^+ current, I_{Na}
Control voltage, v_c	K^+ current, I_K
Input current, i_{in}	Synapse current, I_{syn}

Pros and Cons of the JJ Neuron

Pro / Con	**Why?**
Low power consumption	Superconductivity of JJ
Takes less time to execute commands than in digital models	Parallel connections possible using analog components
Signal time scales 10-20 ps (typical neuron 5ms)	Superconductivity of JJ
Costly experiment. Circuit works around 4 Kelvin	Superconductivity of JJ

Other Key Players in the Game

Hodgkin Huxley Model

Mathematical model based on experimental measurements of ion movements into and out of a giant squid neuron.

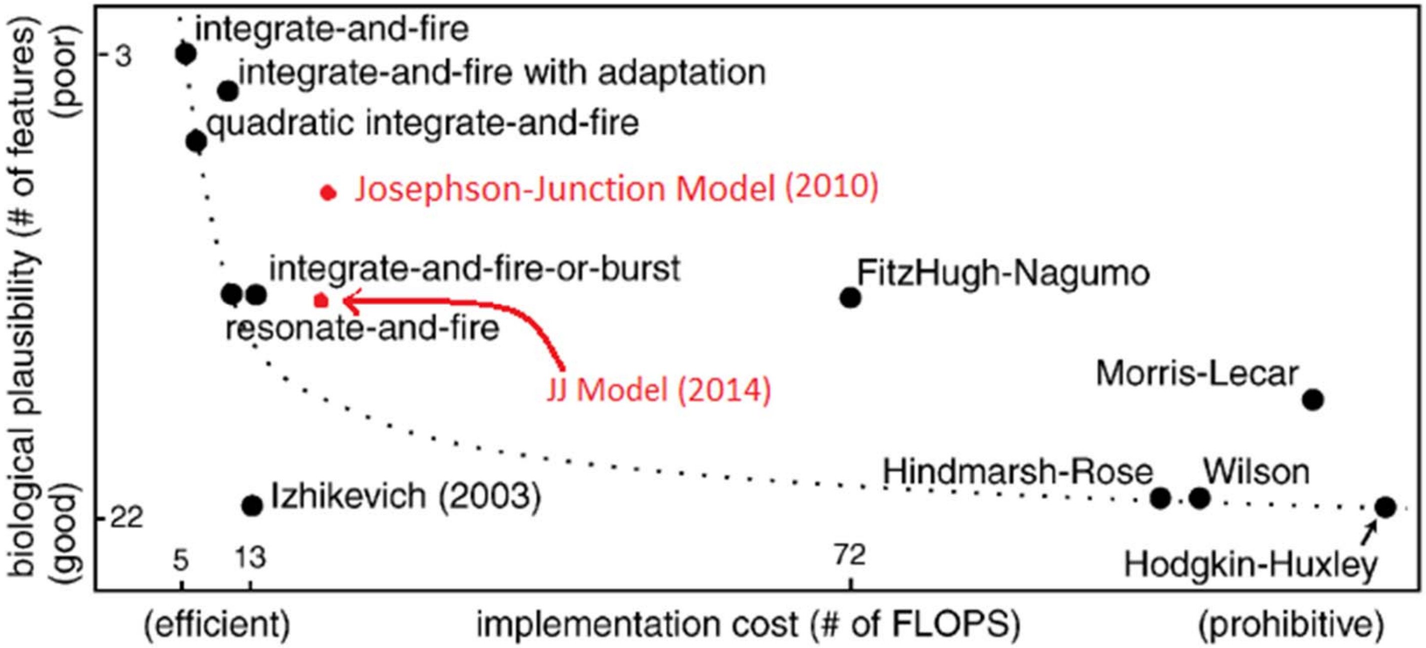
Most accurate there is.

Izhikevich

Phenomenological model based on classical nonlinear dynamics

Most successful model that is not based on experiments

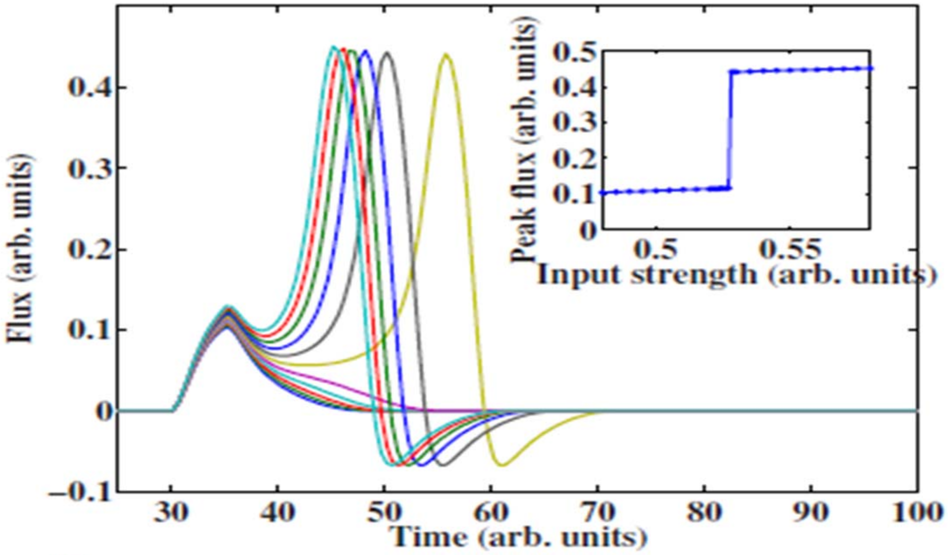
JJ Neuron model captures more biological features at higher efficiency



Izhikevich et. al

Result 1

Action Potentials Only Occur above a Threshold Input Strength

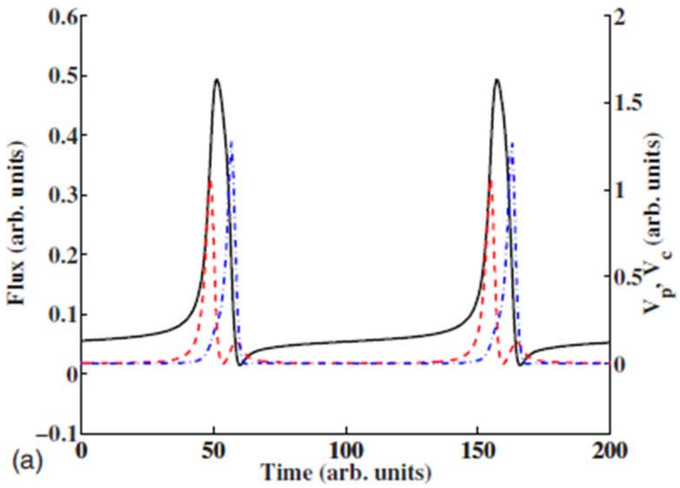


(c)

- Stronger inputs lead to Action Potentials.
- Peak response depends on the strength of the input (inset graph).

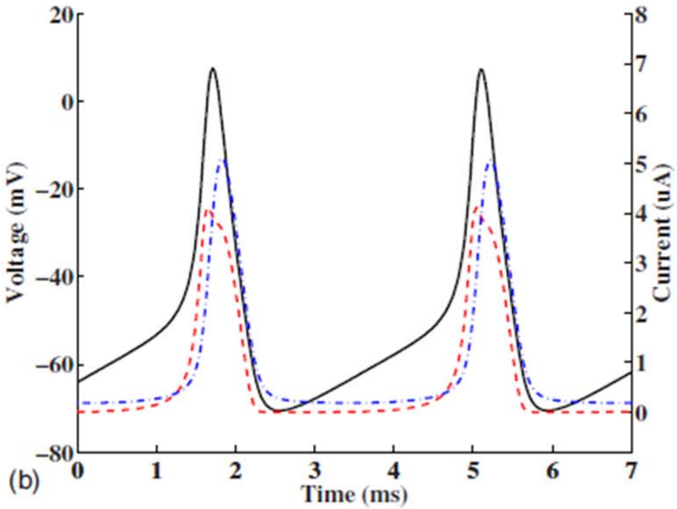
Result 2

Action Potentials in JJ Neuron match those in Hodgkin-Huxley Neuron (most accurate neuron model)



Action Potentials in JJ Neuron

Black-Solid: Flux through Neuron
Red-Dashed: Pulse Junction Voltage
Blue-Dashed: Control Junction Voltage

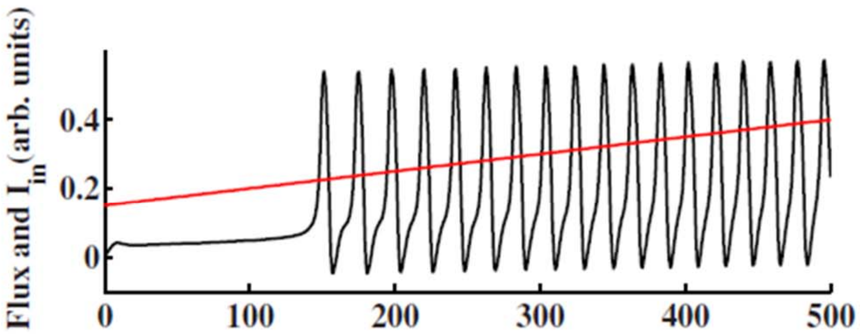


Action Potentials in HH Neuron

Black-Solid: Membrane Potential
Red-Dashed: Sodium Current
Blue-Dashed: Potassium Current

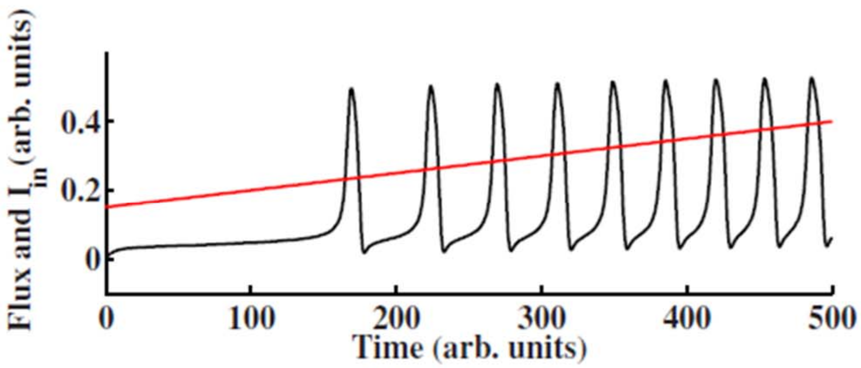
Result 3

JJ Neuron changes from a Class 2 Neuron to a Class 1 Neuron at Gamma=1



Gamma = 0.9

Class 2 Neuron: Frequency independent of Input Strength

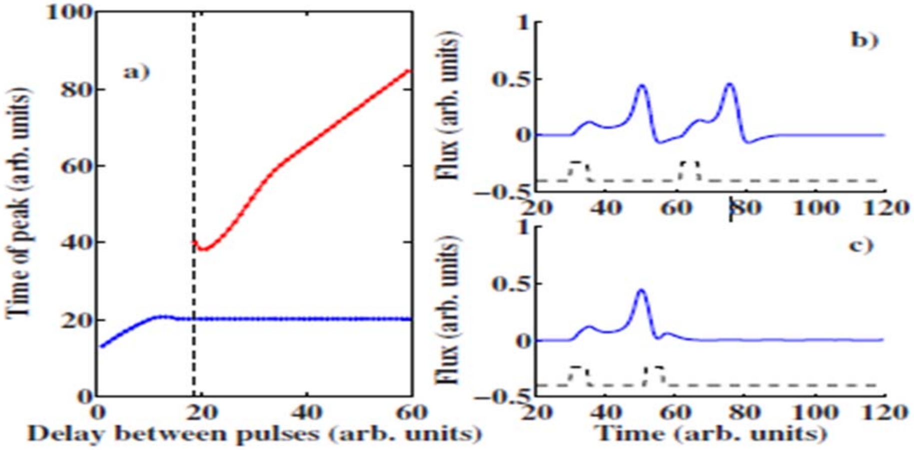


Gamma = 1.5

Class 1 Neuron: Frequency increases with input Strength

Result 4

A subsequent Action Potential can only be induced after a certain critical time delay (Refractory Period)



- If the twin pulse inputs are injected with a delay less than 20 s, a second response peak is not observed (left plot).
- If the delay between the two input currents (green dashed) is smaller than the refractory period, the second response pulse (blue solid) is not generated (right plot).

What do we learn?

- Basic features in neurons have been demonstrated
  - Action potentials
  - Refractory Period
  - Firing threshold
- Results in good agreement with mainstream models
- Extensions via available integrated circuits is possible
  - e.g. Josephson Transmission Line has been added to simulate the neural axon

Impact of this paper and the future of the field

This paper has been cited 12 times according to Scopus (as of 11/16/15). It was published in summer of 2010.

Of the 12 citations, only one is by the authors on a follow-up paper titled
“Phase-flip bifurcation in a coupled Josephson junction neuron system”

Of the remaining 11 citations, 10 publications were directly related to either
1) neuron electrical activity simulation via Josephson Junction or other models
2) Chaotic emergent behavior motivated by or related to Josephson Junctions

☐ Josephson junction simulation of neurons
1

Crotty, P., Schult, D., Segall, K.

2010 Physical Review E - Statistical, Nonlinear, and Soft Matter Physics
82 (1), 011914

12
Cited
by

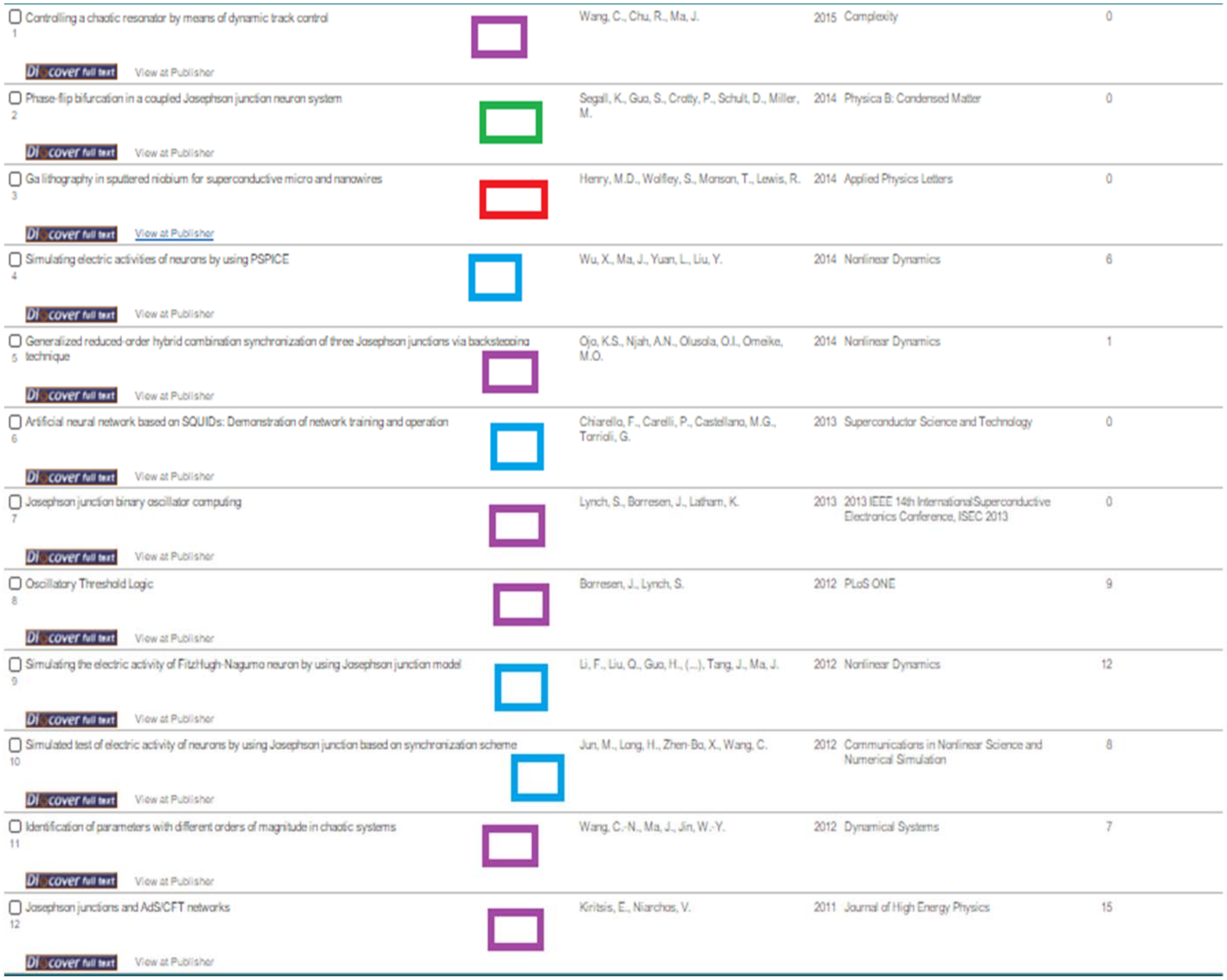
Citation breakdown

Purple: Josephson Junction and related dynamics

Blue: Neural Modelling via Josephson Junction or other methods

Green: Authors’ follow-up paper

Red: Cited this paper as motivation for new experimental methods



☐ 1	Controlling a chaotic resonator by means of dynamic track control	🟪	Wang, C., Chu, R., Ma, J.	2015	Complexity	0
☐ 2	Phase-flip bifurcation in a coupled Josephson junction neuron system	🟩	Segall, K., Guo, S., Crotty, P., Schult, D., Miller, M.	2014	Physica B: Condensed Matter	0
☐ 3	Ga lithography in sputtered niobium for superconductive micro and nanowires	🟥	Henry, M.D., Wolfley, S., Monson, T., Lewis, R.	2014	Applied Physics Letters	0
☐ 4	Simulating electric activities of neurons by using PSPICE	🟦	Wu, X., Ma, J., Yuan, L., Liu, Y.	2014	Nonlinear Dynamics	6
☐ 5	Generalized reduced-order hybrid combination synchronization of three Josephson junctions via backstepping technique	🟪	Ojo, K.S., Njah, A.N., Olusola, O.I., Omeike, M.O.	2014	Nonlinear Dynamics	1
☐ 6	Artificial neural network based on SQUIDs: Demonstration of network training and operation	🟦	Chiarello, F., Carelli, P., Castellano, M.G., Torrioli, G.	2013	Superconductor Science and Technology	0
☐ 7	Josephson junction binary oscillator computing	🟪	Lynch, S., Borresen, J., Latham, K.	2013	2013 IEEE 14th International Superconductive Electronics Conference, ISEC 2013	0
☐ 8	Oscillatory Threshold Logic	🟪	Borresen, J., Lynch, S.	2012	PLoS ONE	9
☐ 9	Simulating the electric activity of FitzHugh-Nagumo neuron by using Josephson junction model	🟦	Li, F., Liu, Q., Guo, H., (...), Tang, J., Ma, J.	2012	Nonlinear Dynamics	12
☐ 10	Simulated test of electric activity of neurons by using Josephson junction based on synchronization scheme	🟦	Jun, M., Long, H., Zhen-Bo, X., Wang, C.	2012	Communications in Nonlinear Science and Numerical Simulation	8
☐ 11	Identification of parameters with different orders of magnitude in chaotic systems	🟪	Wang, C.-N., Ma, J., Jin, W.-Y.	2012	Dynamical Systems	7
☐ 12	Josephson junctions and AdS/CFT networks	🟪	Kiritsis, E., Niarchos, V.	2011	Journal of High Energy Physics	15

Follow-up Paper (published Fall 2014)

- The group (Crotty, Schult, Segall) + new collaborators (S. Guo, M. Miller) follow-up paper focuses largely on extending ideas from the previous work

- Analysis of two coupled JJ neurons

- Investigated varying levels of coupling between them: strong, intermediate, weak

- In the intermediate phase, two stable regimes → phase-flip bifurcation observed
  - Emergent property in neural networks, documented property

Phase-flip bifurcation in a coupled Josephson junction neuron system

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Current state of the field: Optimistic

- (**Summer 2012**) *Linking synchronization to self-assembly using magnetic Janus colloids* by J. Yan et al
    - Independently linked coupled JJ circuits with neuron-firing networks
    - Highly cited paper in *Nature*--added interest to the field
- (**Summer 2012**) *Simulated test of electric activity of neurons by using Josephson junction based on synchronization scheme* by M. Jun et al
    - Found JJ circuit scheme capable of completely modelling Hindmarsh-Rose neurons
    - Verified this model can be implemented physically--other models too much heat/power
- (**Fall 2014**) *Simulating electric activities of neurons by using PSPICE*, X. Wu et al
    - Operated with equivalent nonlinear circuit
    - Came to similar conclusions--encourages further numerical simulations of larger circuits
- (**Fall 2014**) *Phase-flip bifurcation in a coupled Josephson junction neuron system*
    - (group paper, last page)

Thank You!!