Waves and Delay in Modeling the Neuron Potential

Ann Motl

Dee Prioleau

Natasha Wright

Advisors: Dr. Shvartsman, Dr. Bělík

Acknowledgments

- National Science Foundation (Grant DMS-0802959)

Outline

I. The Problem
II. Introduction
III. Cable Equation
IV. Simulations and Delay
    I. Simple Network
    II. Polychronization
V. Results
VI. Analysis and Conclusion
VII. Future Work
VIII. References

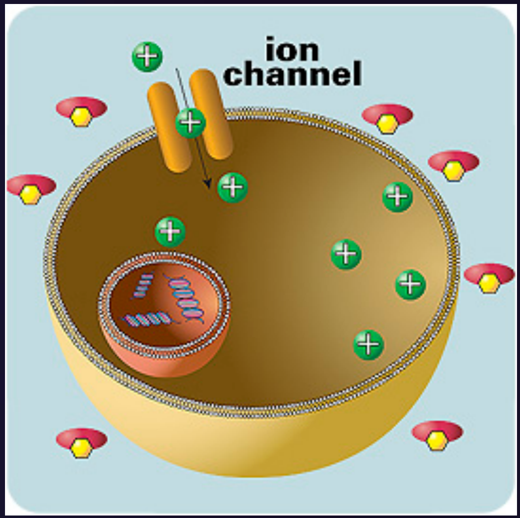
The Problem

- Neurons are important specialized cells of the central nervous system.
- There are still questions as to how neurons communicate, leaving mechanisms of some neurological disorders unknown.
- In our work we look at how conduction delay influences communication between a network of interconnected neurons and a specific neuron.
- A lot of research has been done in this area – in particular, mathematical modeling of electric potential in neuronal membranes.
- We use previously done experimental and theoretical work to develop a numerical delay model of axonal membrane potential.

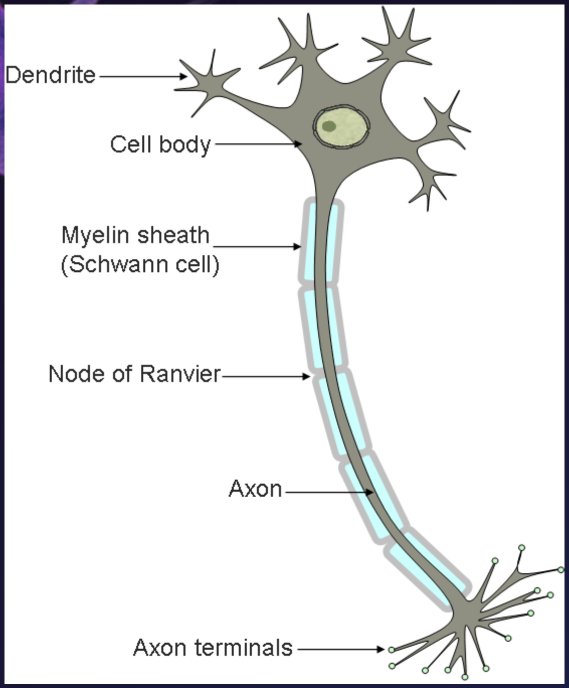
Electric Potential

Difference in voltage between the interior and exterior of a cell

- Membrane potential
- Differences in the concentrations of ions
- Is measurable, therefore we can model it



http://www.moleculardevices.com/media2/mdc_reagents/membrane_potential_270.jpg

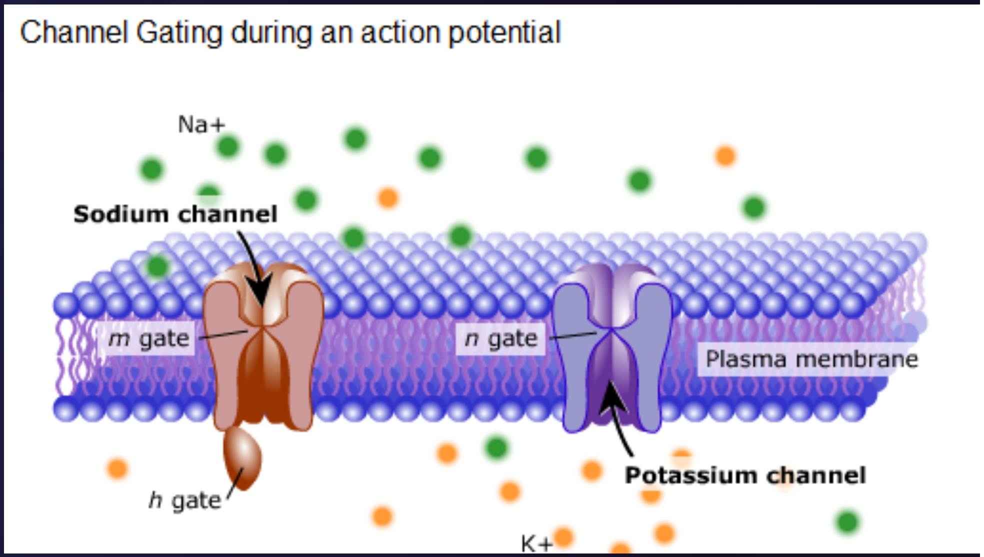


http://scienceblogs.com/neurotopia/upload/2006/07/neuron.png

Introduction: Neurons vs. Other Cells

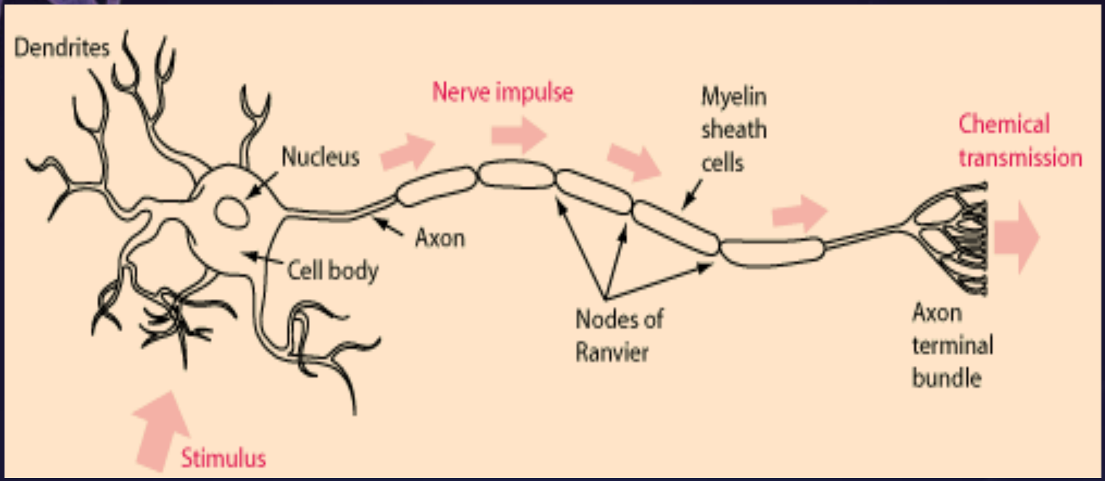
-Electrically excitable cell that processes and transmits information by electrochemical signaling.

-Voltage gradients on membranes are maintained using ion channels. If voltage change is large enough an electrochemical pulse called an action potential is generated.

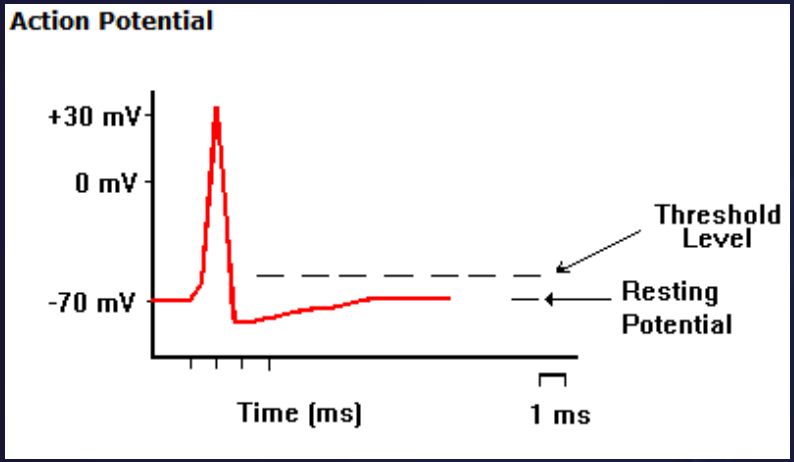


http://www.blackwellpublishing.com/matthews/channel.html

Action Potential



http://hyperphysics.phy-astr.gsu.edu/hbase/biology/nervecell.html#c2



http://faculty.washington.edu/chudler/ap.html

Action potential occurs when there is a momentary change in the electrical potential difference across the axon.

Potential propagates along the length of the cell and away from the cell body.

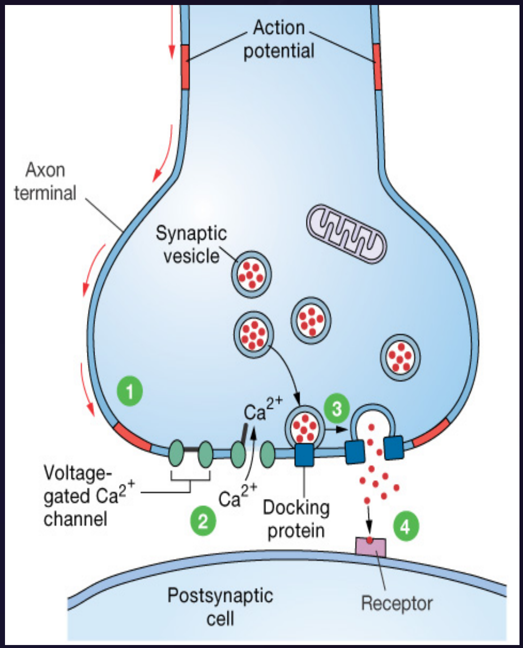
Main Questions

- 10^{11} Neurons and 10^{15} Synapses

Need to Know:

- How a specific neuron works
- How neurons communicate with each other (networks)

In our work we address how a specific neuron reacts to signals from its network



http://74.125.95.132/search?q=cache:2nByWBi3Cq4J:lpc1.clpccd.cc.ca.us/lpc/jgallagher/Physio/Chapter%25208%2520Neurons,%2520Part%25202.ppt+synaptic+delay+animation&cd=3&hl=en&ct=clnk&gl=us

Cable Equation

Axon = Cylinder

$$\frac{1}{2\pi a r_i}\frac{\partial^2 V_m}{\partial x^2} = C_m \frac{\partial V_m}{\partial t} + \sum_k (V_m - E_k) G_k(x, t, V_m)$$

Hodgkin-Huxley -> The Cable Equation

a = axonal inner radius (10^{-5}m)

r_i= intracellular resistance per unit length (100.0/(Pi*a^2) Ω/m)

V_m = trans-membrane voltage (mV)

C_m = membrane capacitance per unit area (1.0 F/m^2)

k = ion type (K, Ca)

E_k = equilibrium potential (-80 mV)

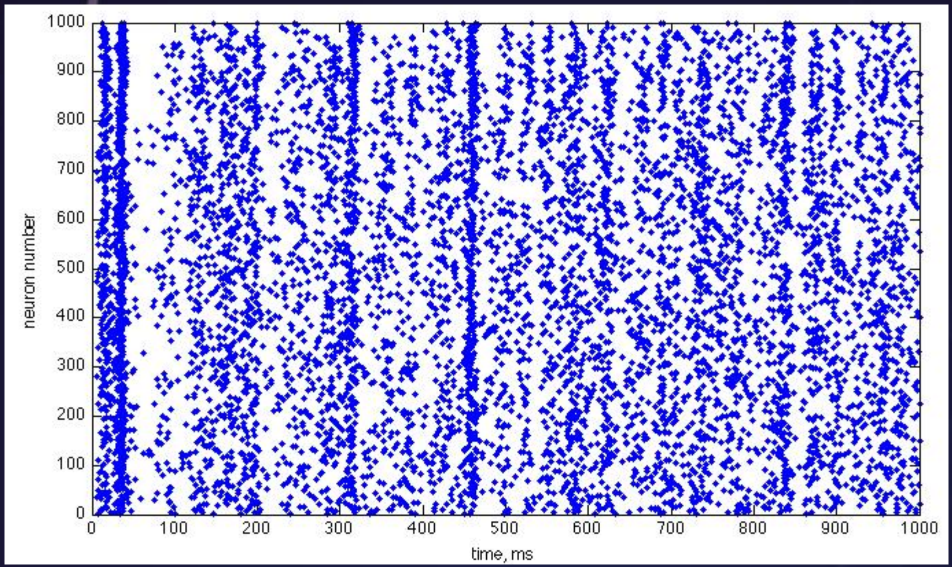
G_k = conductance per unit area

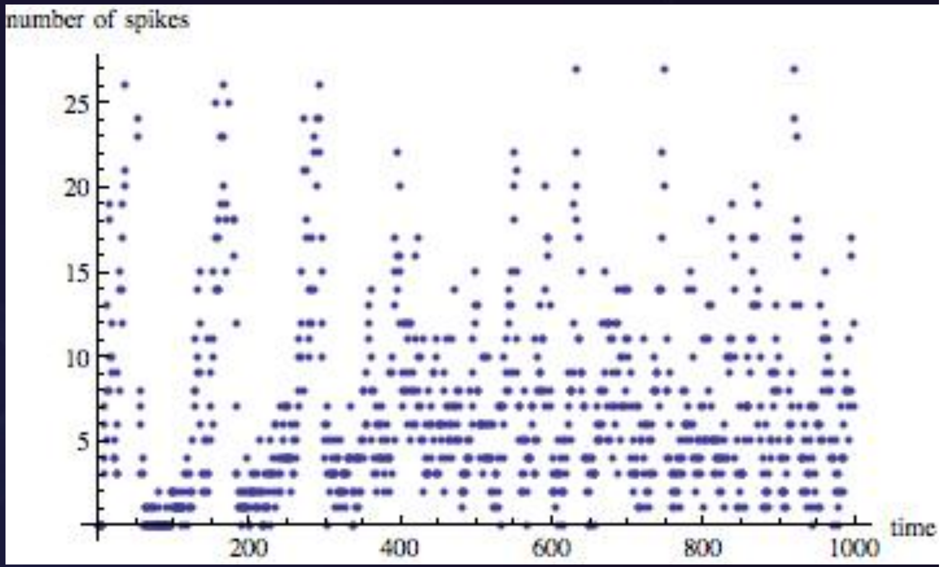
Types of Delay

- Modeled within the Network:
  - STDP: Spike-Timing Dependent Plasticity
  - Conduction Delay: Delay in the signal itself
- Modeled within the Cable Equation:
  - Boundary Condition
  - Within the PDE model itself (discrete)

Simple Network Simulation

Without Delay

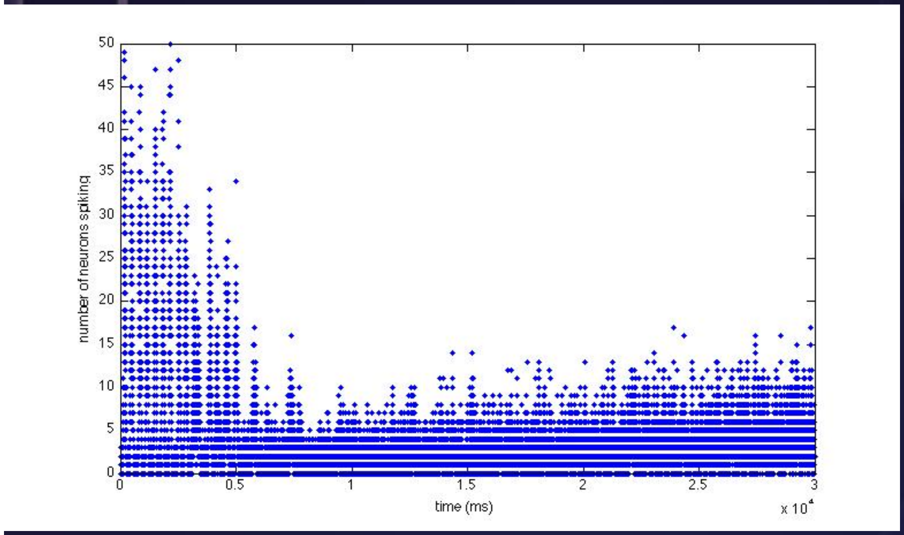


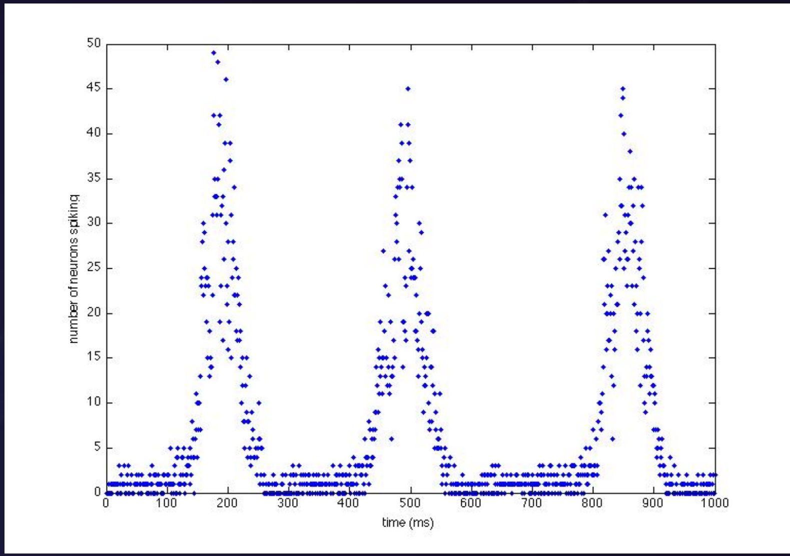


Simulation of randomly connected 1000 coupled spiking neurons

Number of neuronal spikes for each millisecond

Polychronization Simulation
With Delay





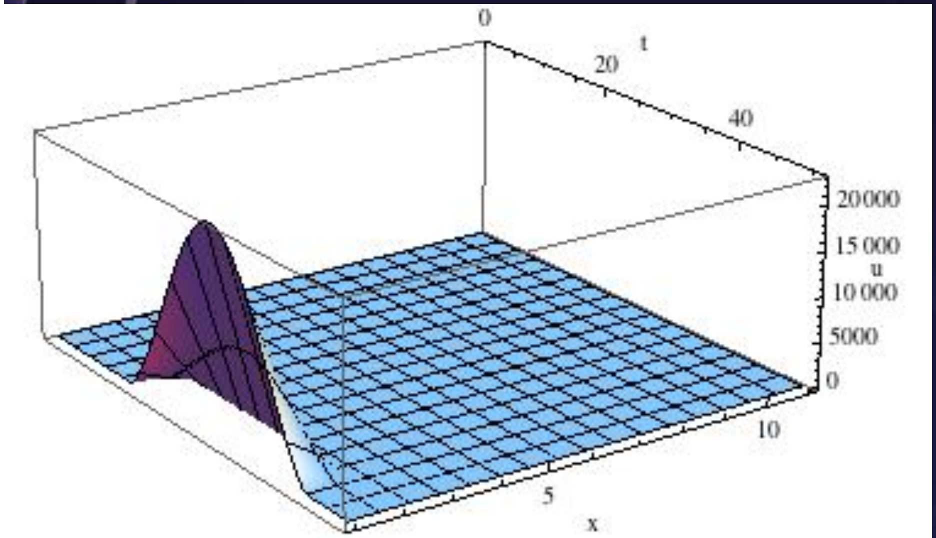
Simulation of 1000 polychronized neurons with delay = 20ms for a duration of 30 sec

Simulation of 1000 polychronized neurons with delay = 20ms zoomed in at one second

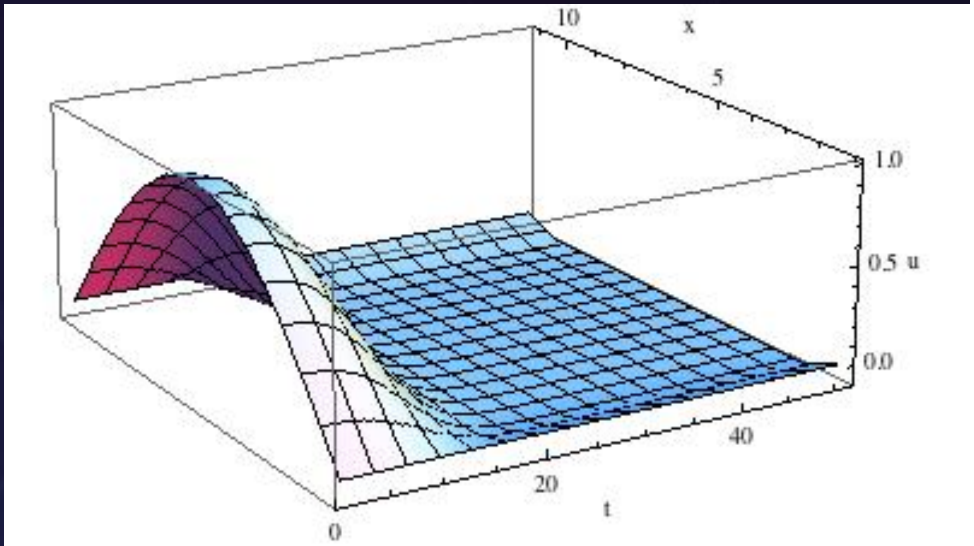
Types of Delay

- Modeled within the Network:
  - STDP : Spike-Timing Dependent Plasticity
  - Conduction Delay: Delay in the signal itself
- Modeled within the Cable Equation:
  - Boundary Condition: from Polychronization
  - Within the PDE model itself: (discrete)

Results



No Delay Cable 3D Graph



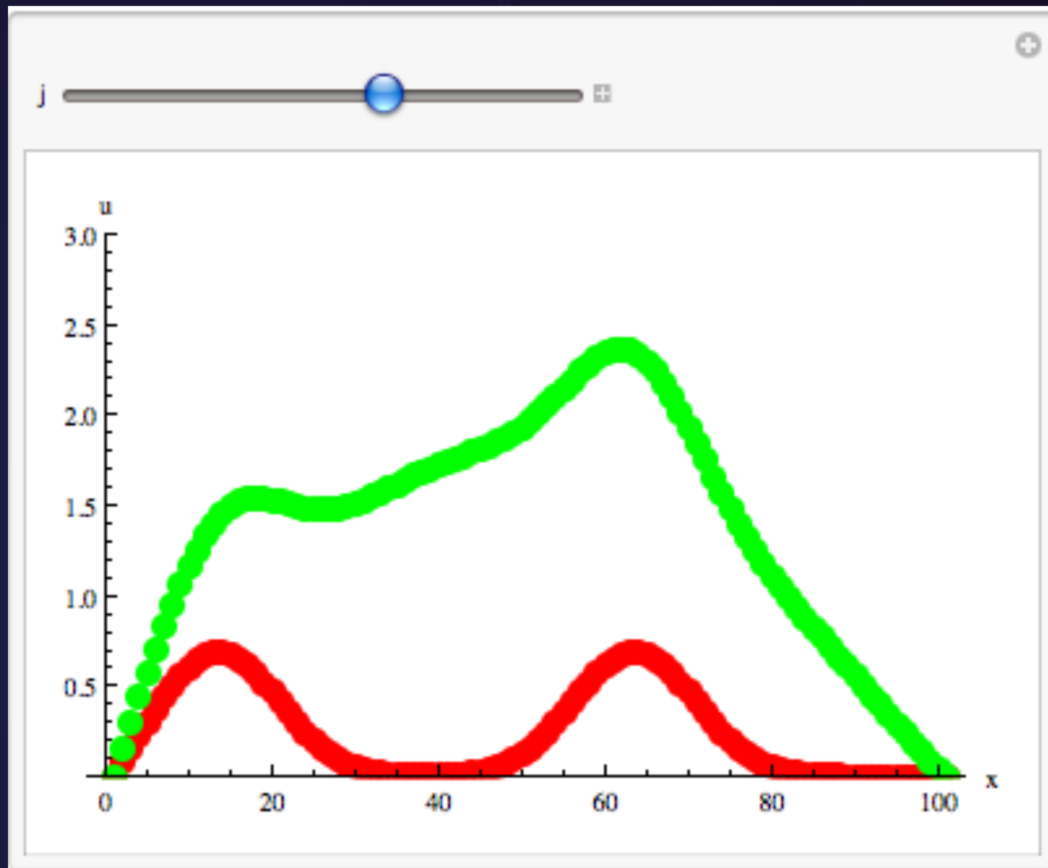
Delay Cable 3D Graph

Cable Equation with initial boundary condition created off of Simple Network Simulation

Cable Equation with initial boundary condition created off of Polychronization Simulation

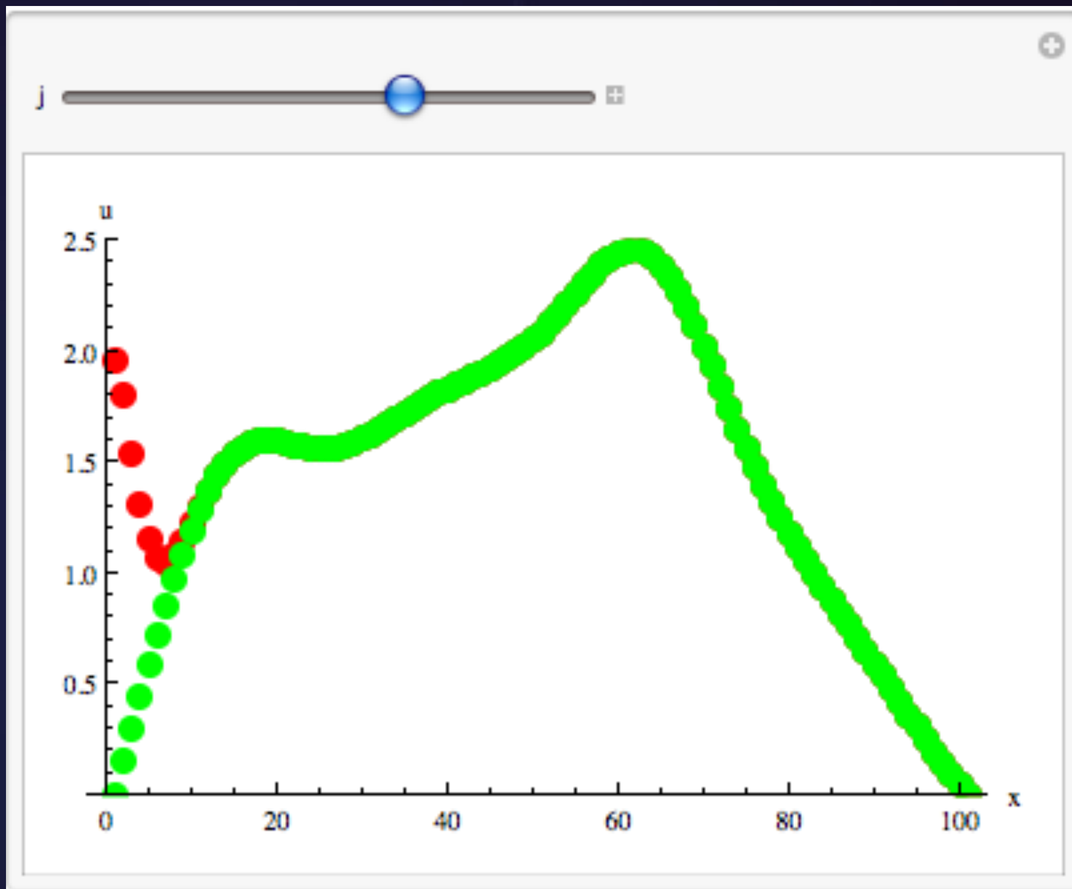
Analysis

Passive without PDE delay
G = 0 (Red) vs G < 0



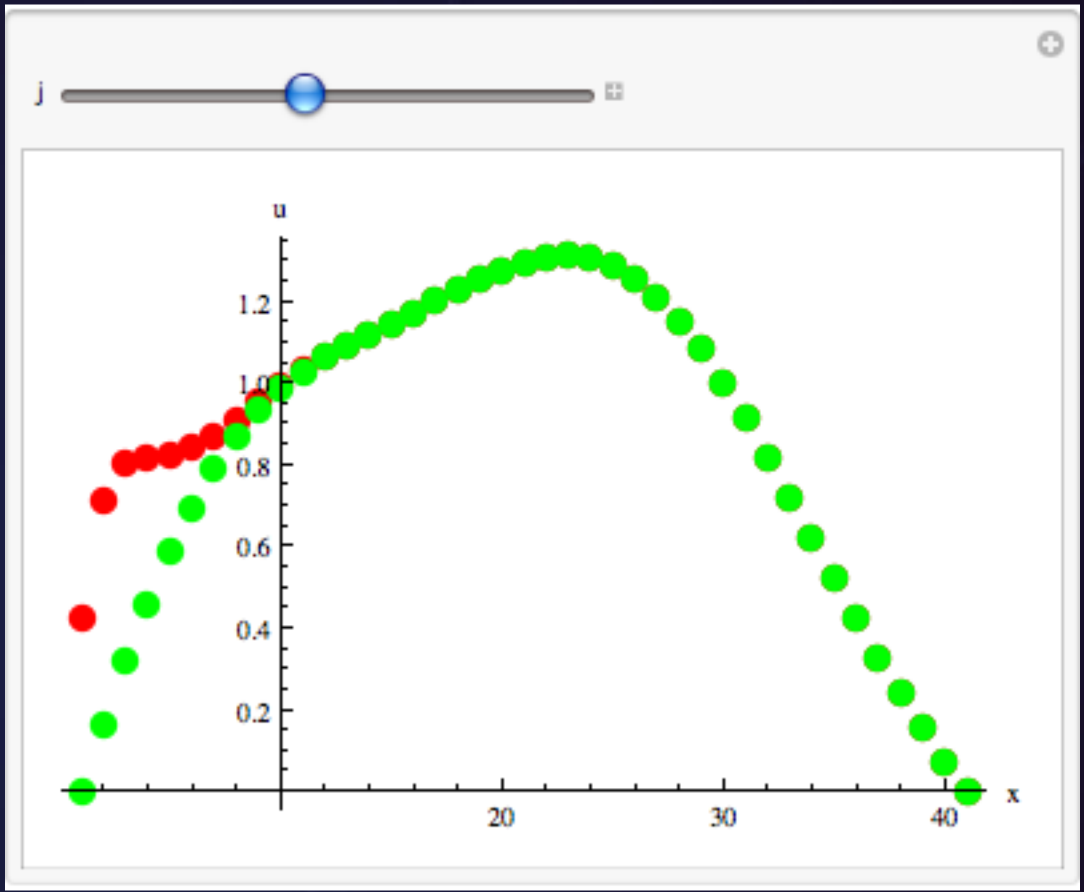
Analysis

Passive without PDE delay
STDP (Red) vs No STDP



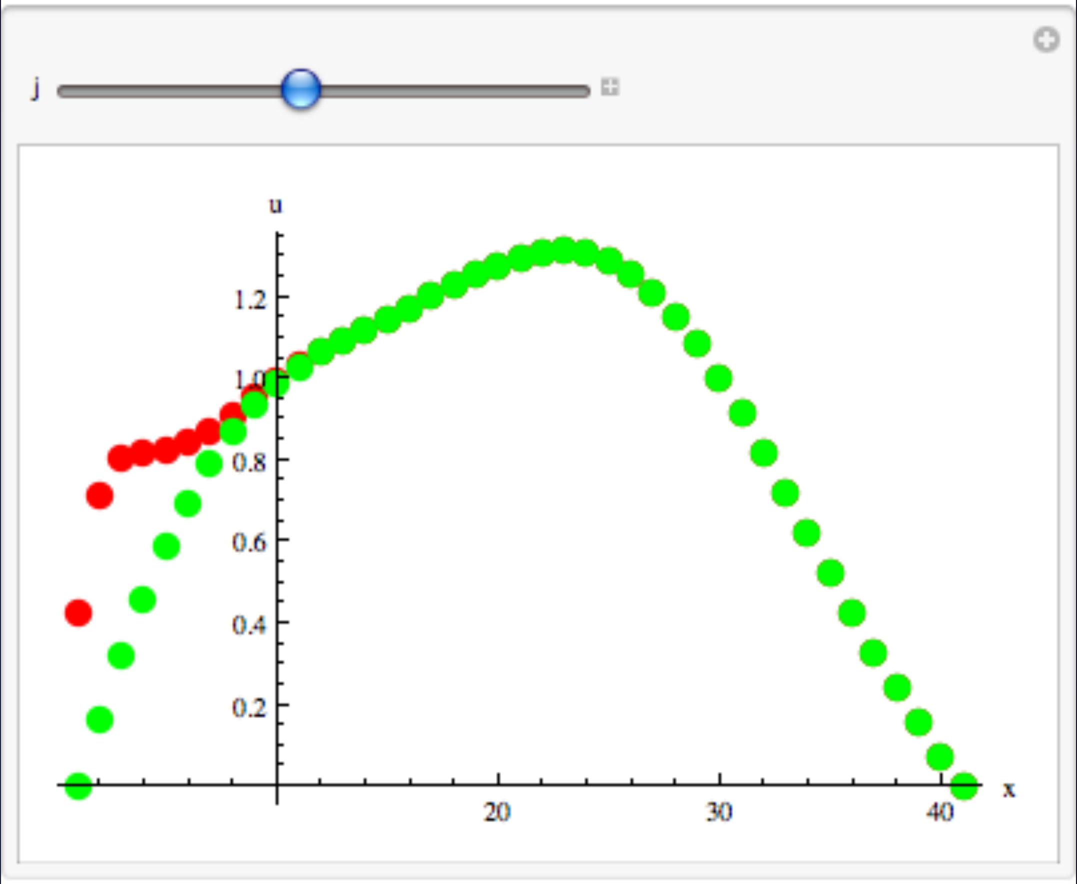
Analysis

Passive without PDE delay
Polychronization (Red) vs No STDP



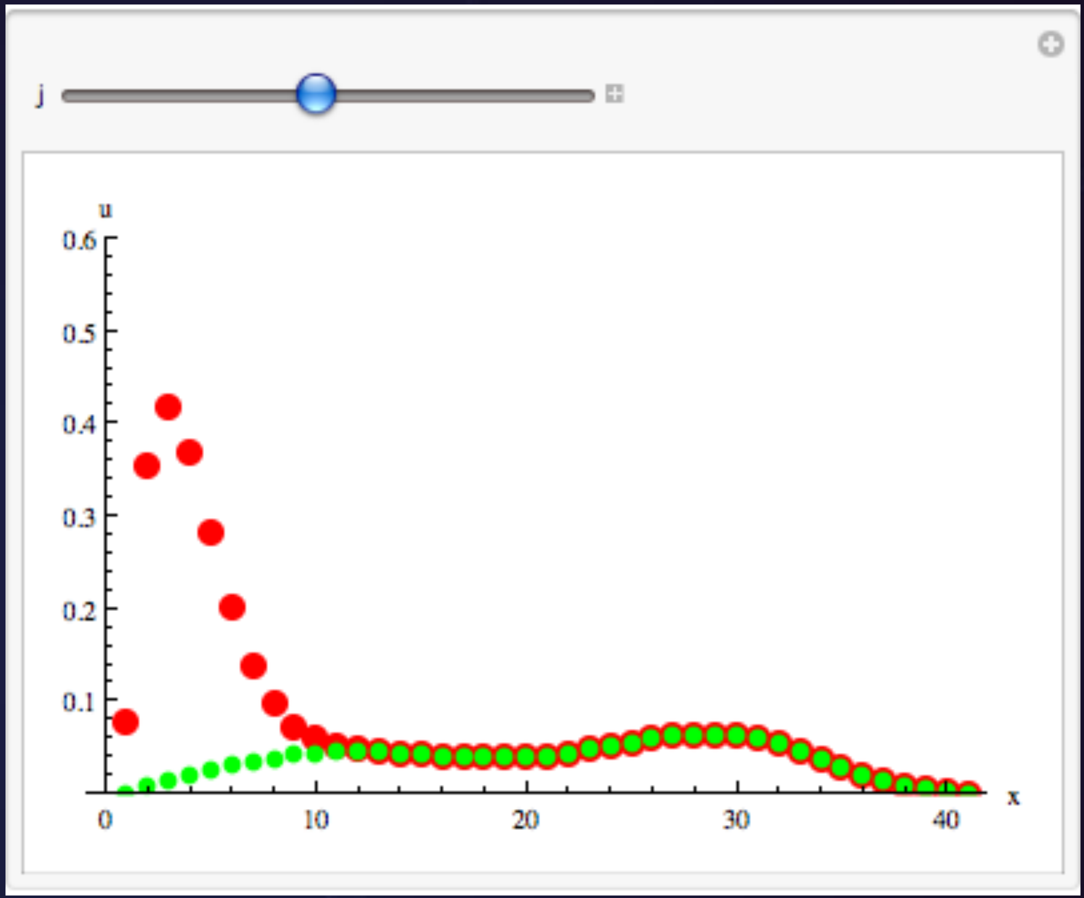
Analysis

Propagating without PDE delay
STDP (Red) vs No STDP



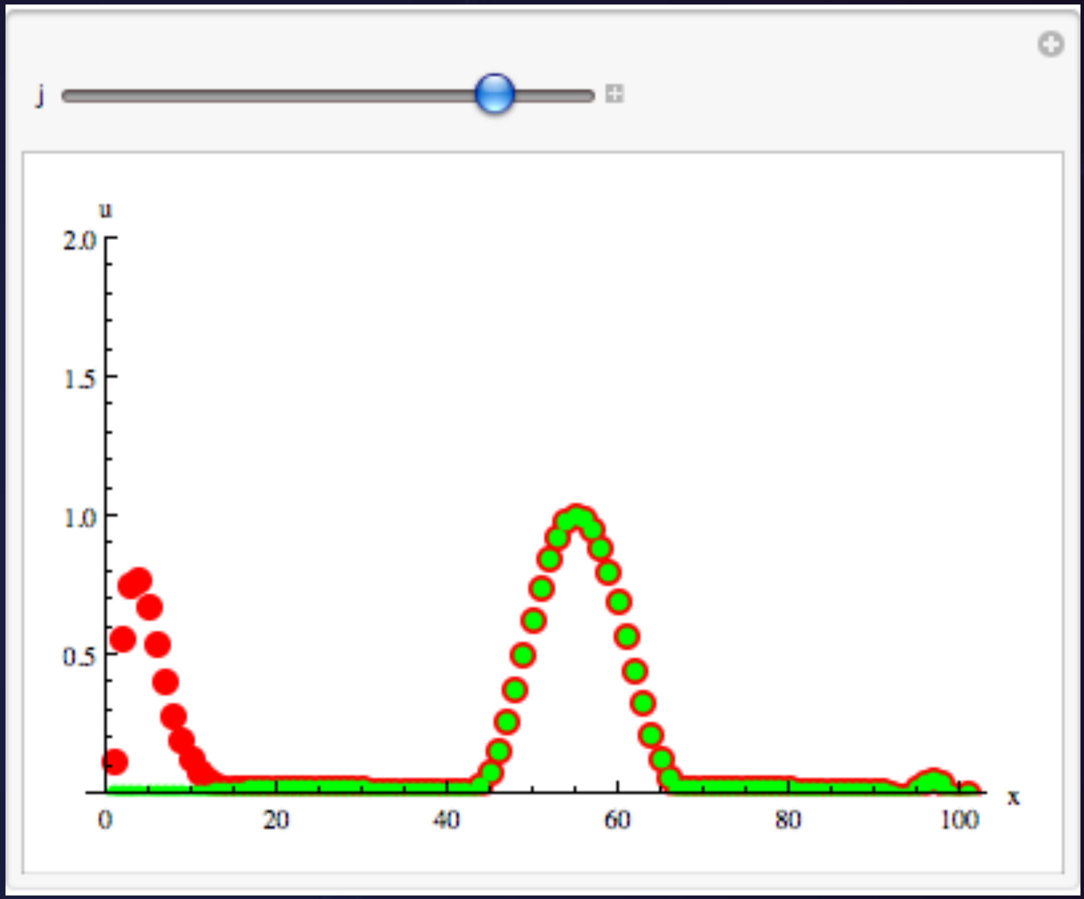
Analysis

Propagating without PDE delay
Polychronization (Red) vs No STDP



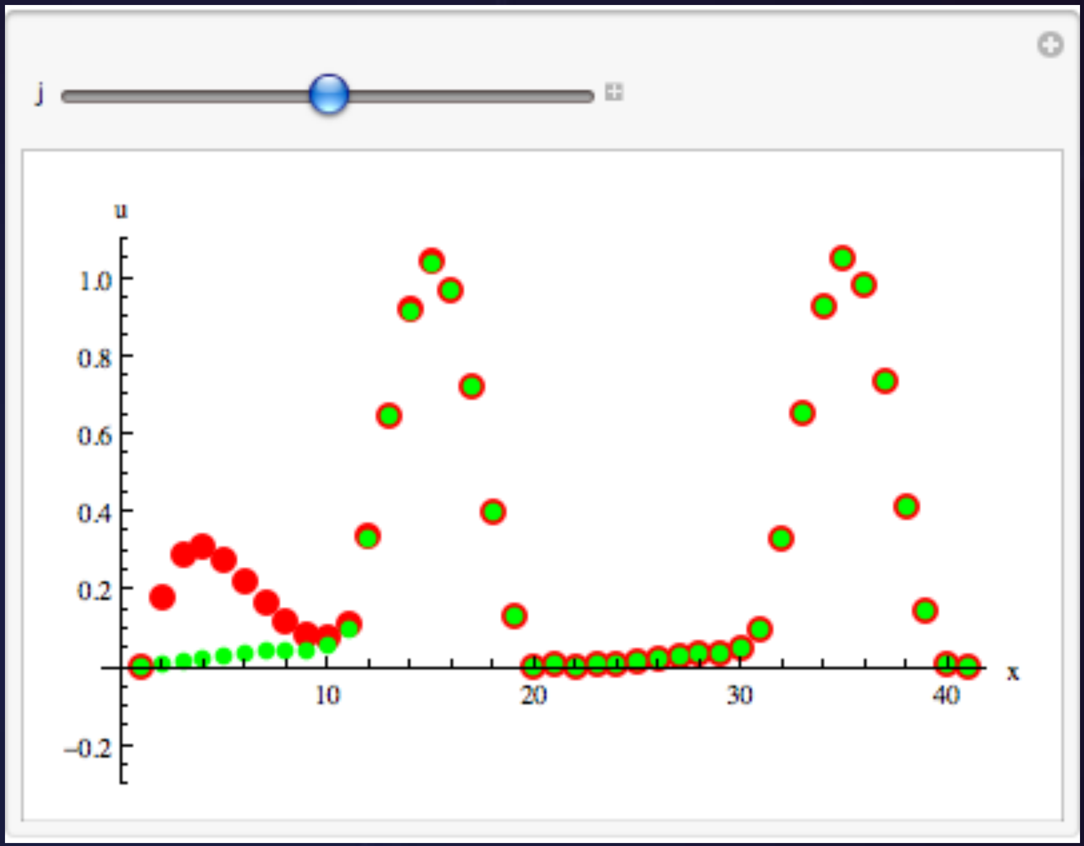
Analysis

Propagating with PDE delay
STDP (Red) vs No STDP



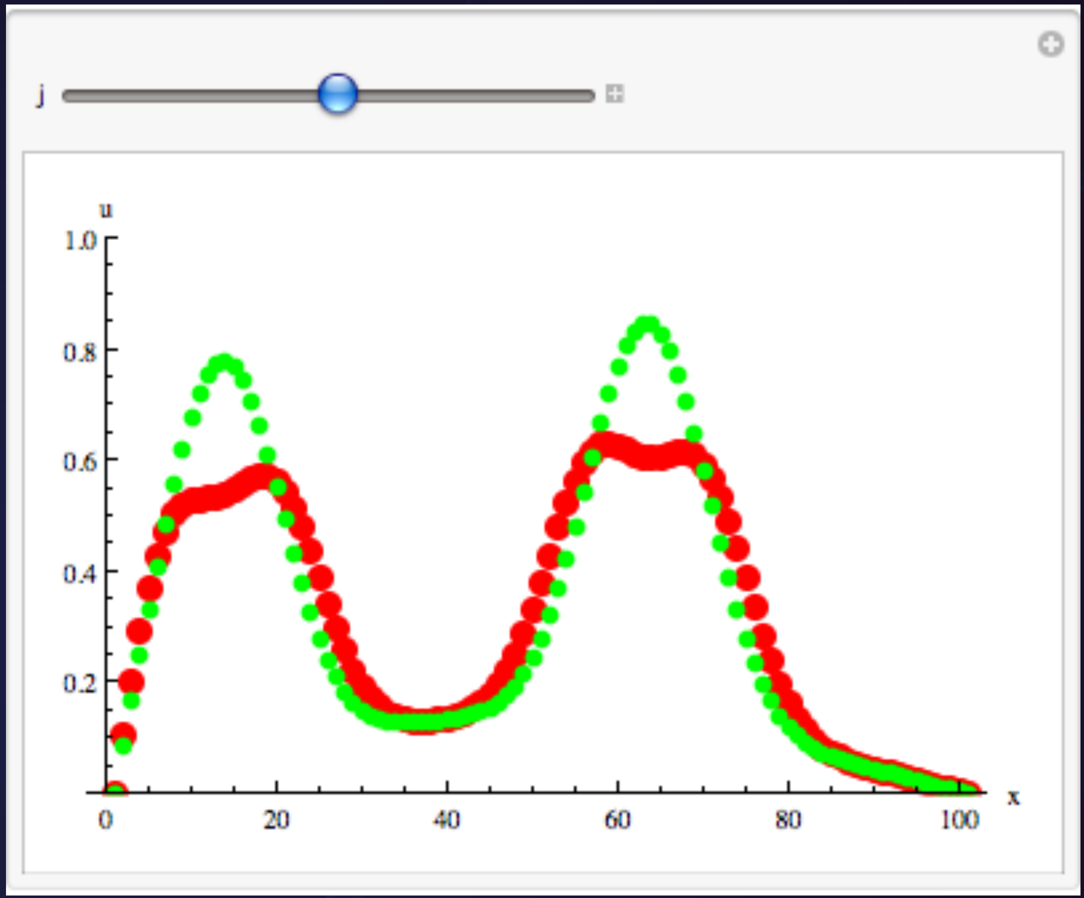
Analysis

Propagating with PDE delay
Polychronization (Red) vs No STDP



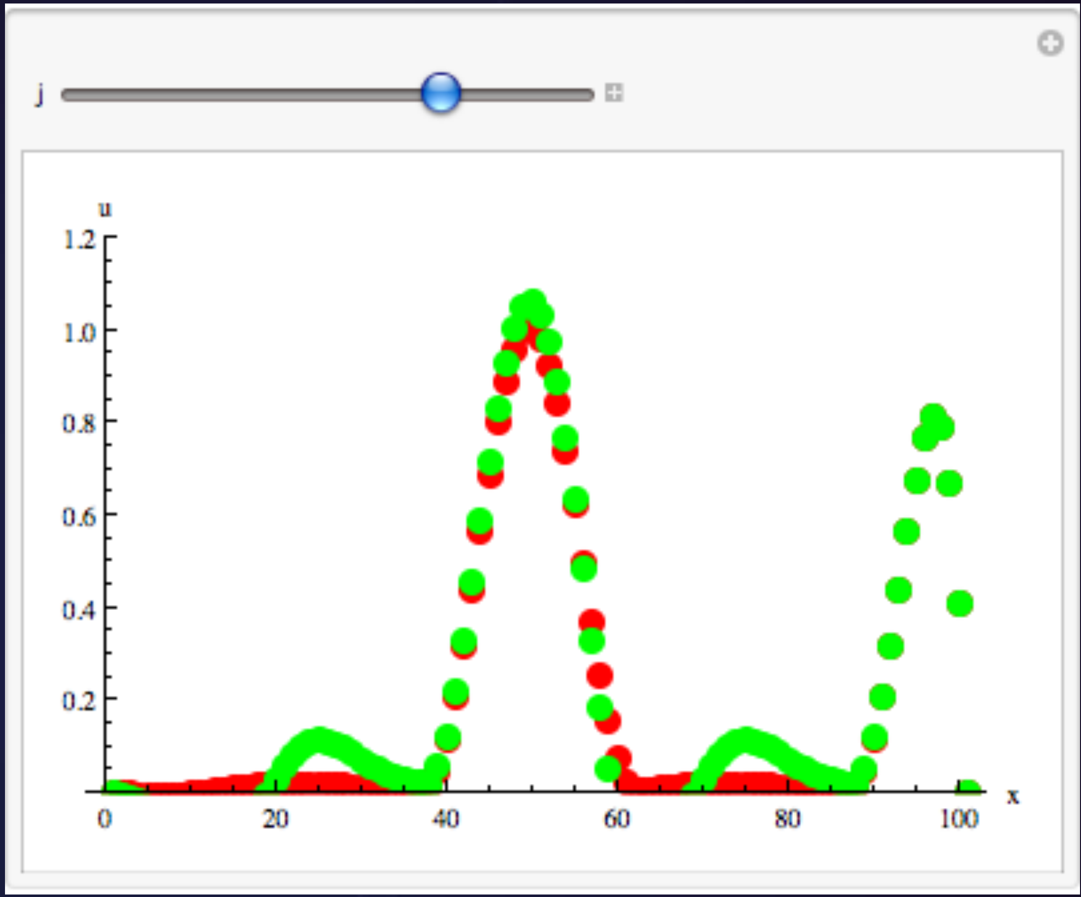
Analysis

Passive Cable
PDE delay (Red) No PDE Delay



Analysis

Propagating Potential
PDE delay (Red) vs No PDE Delay



Future Work

1. Add nonlinear waves (soliton) for initial conditions

2. To extend Discrete Time Delay to a larger number of steps

3. Investigate other Spiking Models to emulate the Network

4. Investigate other modes of modeling conduction delay induced by the network (delay as a function vs. delay as a discrete number)

5. To use Implicit Methods for Polychronized Network

6. Compare STDP to Polychronization with the same time scale

References

- Friedman, A. (2004). *Introduction to Neurons.* Heidelberg: Springer Berlin.
- Izhikevich, E. (2006). Polychronization: Computation With Spikes. *Neural Computation* , 245-281.
- Izhikevich, E. (2003). Simple Model of Spiking Neurons. *IEEE Transactions on Neural Networks* , 1569-1572.
- *SlideWorld*. (n.d.). Retrieved June 29, 2010, from http://www.slideworld.com/ppt_templates/Download-free-powerpoint-templates.aspx/Neuron-721
- *Swinburne University of Technology*. (2001). Retrieved January 5, 2010, from Physiological Modeling HET419 : http://opax.swin.edu.au/~dliley/lectures/het419/het419.html

References

- Friedman, A. (2004). *Introduction to Neurons.* Heidelberg: Springer Berlin.
- Izhikevich, E. (2006). Polychronization: Computation With Spikes. *Neural Computation* , 245-281.
- Izhikevich, E. (2003). Simple Model of Spiking Neurons. *IEEE Transactions on Neural Networks* , 1569-1572.
- *SlideWorld*. (n.d.). Retrieved June 29, 2010, from http://www.slideworld.com/ppt_templates/Download-free-powerpoint-templates.aspx/Neuron-721
- *Swinburne University of Technology*. (2001). Retrieved January 5, 2010, from Physiological Modeling HET419 : http://opax.swin.edu.au/~dliley/lectures/het419/het419.html