SAND2011-6069 C

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Neuron Simulations for Emerging Brain Maps

Principal Investigator: Richard Schiek

Program Manager: John Wagner

Team Members: Christy Warrender, Heidi Thornquist, Steve Verzi, Ting Mei, Mike Bernard, Alex Duda (student)

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

LDRD Laboratory Directed Research & Development

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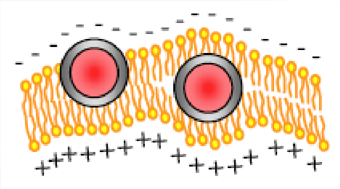
Position in CS&T Roadmap



10^{-10} 10^{-5} 10^{-3} 1 meter 10^{7}

1 neuron 10^{11} 10^{20}

1st order 2nd 3rd 4+

James - Engineered Neural Circuits

Schiek - Emerging Brain Maps

Rothganger – Neurons to Algorithms

Matzen - Sensing to Enhancing Brain Processes

Outline

- Motivation
- Project Goals
- Status of current work
  - Modeling hierarchy
  - Biological complexity
  - Computational map
- Publications / Presentations
- New directions

Motivation

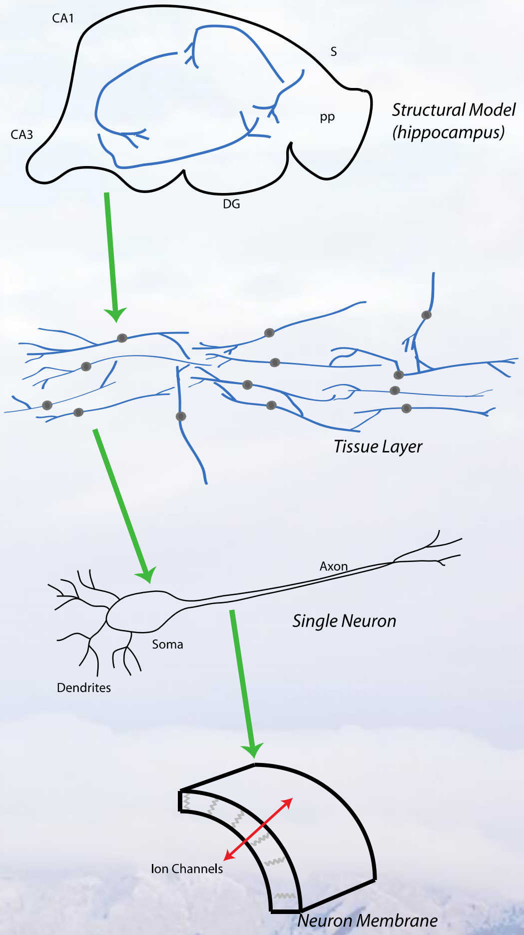
- Network problems
  - Common motif in cognitive science
    - Information flow
    - Relational influence
  - Sandia experience in electrical networks – Xyce
    - Mathematical formulation (parallel, modular physics)
    - Topological functionality (parallel, analytic)
  - Applying Xyce to cognitive and neuroscience benefits both communities (CS&T and electrical modeling)

Project Goal

- Develop a cognitive and neuron simulation framework that can address complex, multi-scale networks.
- Requires:
  - Share with the neuroscience & cognitive community
  - Interoperable with existing tools
  - Can address
    - multiple problem scales
    - multiple scientific applications.

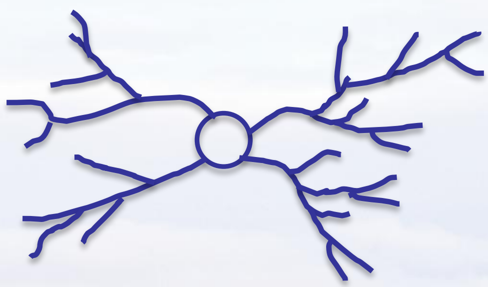
Multi-scale Rational

- Multiple, hierarchical structures in the brain.
  - Maintaining fine scale for macro modeling may not be feasible.
  - Allow building & simulating macro-model with varying fidelity of fine scale.

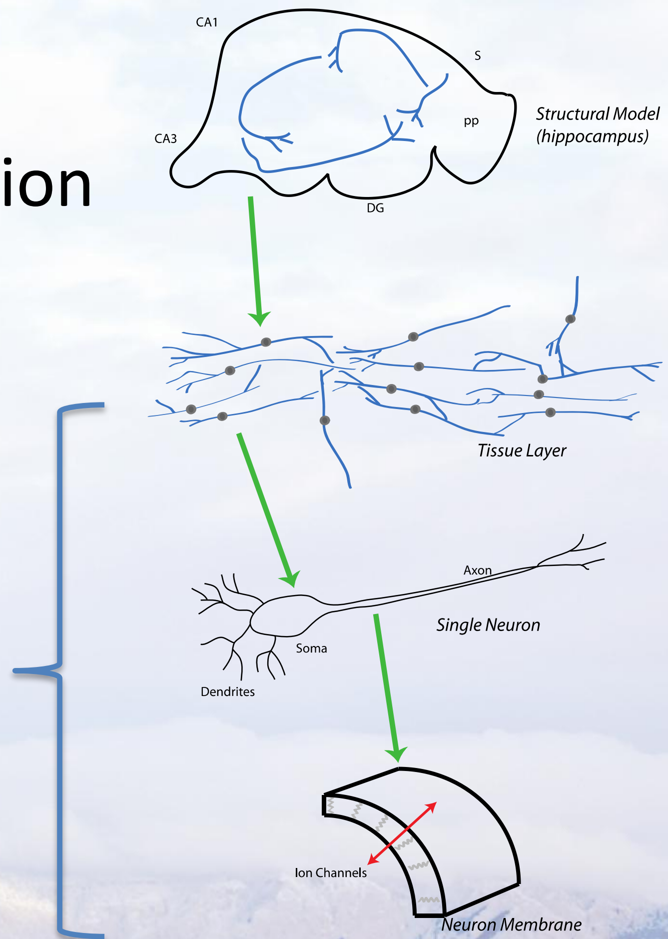


Multi-scale modeling targets

- Micro-scale:
  - ion channel & cable equation



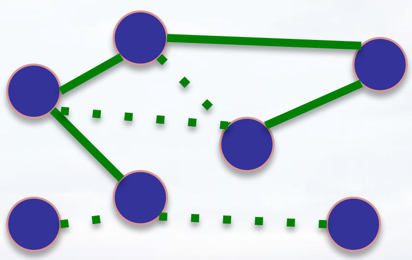
$$C_m \frac{dV_i}{dt} = -i_i^m + \frac{I_i^E}{A_i} + g_{i,i+1}\left(V_{i+1} - V_i\right) + g_{i,i-1}\left(V_{i-1} - V_i\right)$$



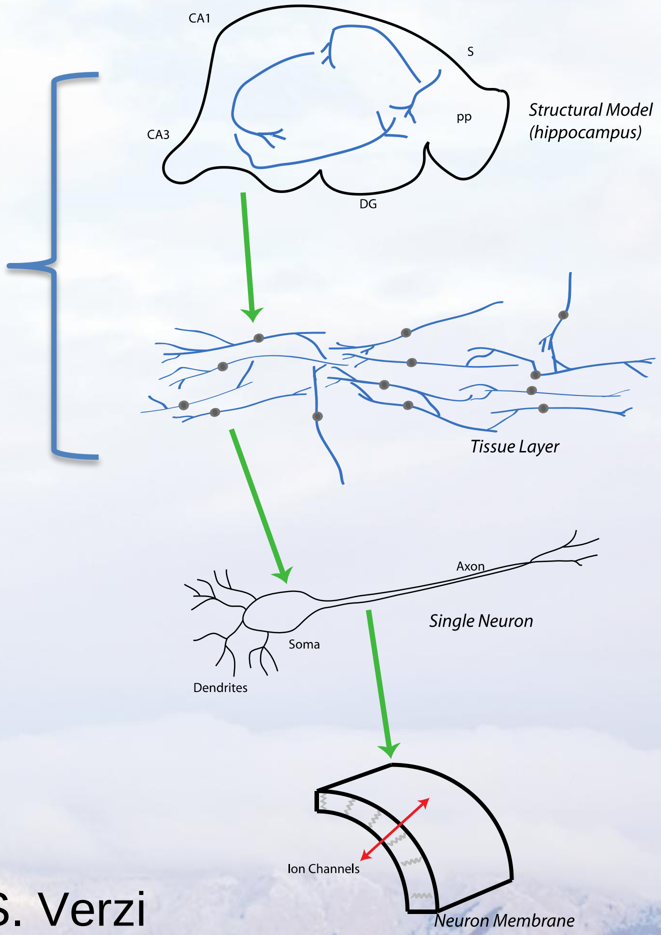
C. Warrender, H. Thornquist, T. Mei, R. Schiek

Multi-scale modeling targets

- Macro-scale:
  - Population model



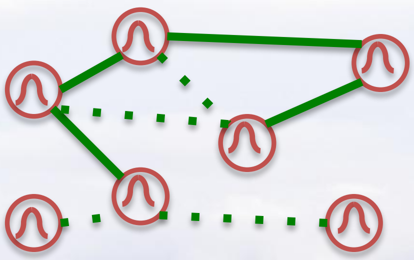
$$N_i \leftarrow \sum_{H(t)} N_j(t) + \sum_{Int} N_j \times S_j + \sum_{Ext} N_j \times S_j$$



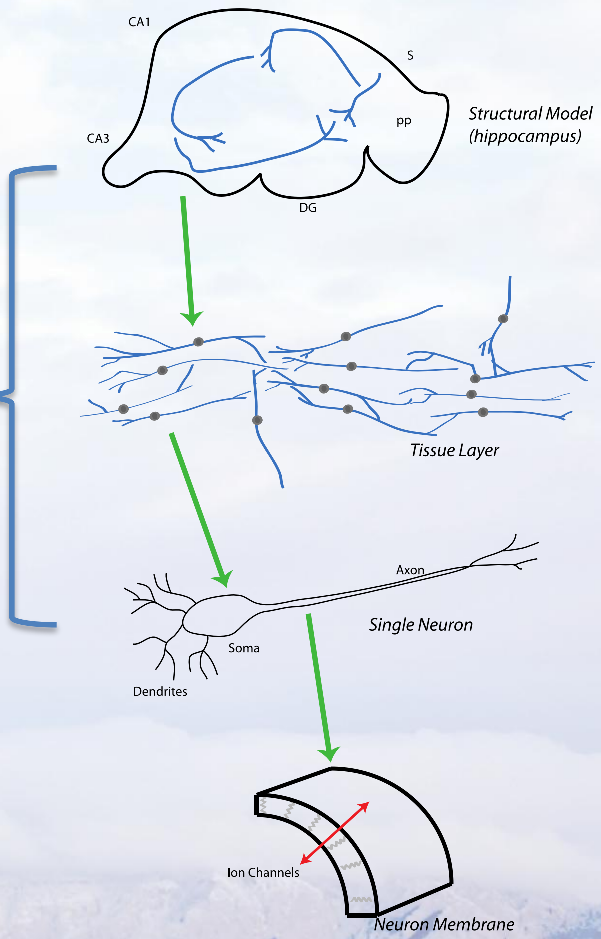
N. Cohen, H. Eichenbaum, M. Bernard, S. Verzi

Multi-scale modeling targets

- Meso-scale:
  - Limiting biophysics
    - ion channel & cable equation
  - Want to understand what's lost when fidelity is lost

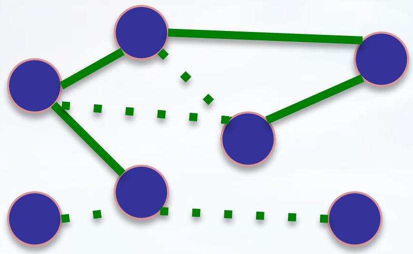


$$C_m \frac{dV_i}{dt} = - i_i^m + \frac{I_i^E}{A_i}$$



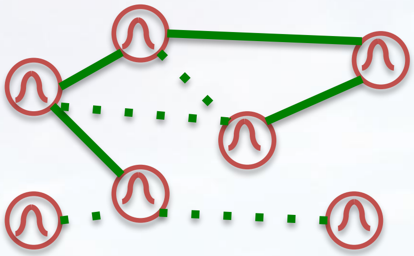
S. Levenson, A. Duda at Univ. of Illinois, Romero & Mei, SNL

Population Modeling



- Implemented device to model a population of neurons
  - Intra-population dynamic connectivity
  - Age dependent plasticity
  - Population dynamics (neurogenesis & cell death)
  - Fully resolved time dependent population state.
  - Modeled after Gage Model
- Mike Bernard has taken lead on new LDRD proposal:
  - Using High Performance Computing to Examine the Processes of Neurogenesis Underlying Pattern Separation/Completion of Episodic Information
    Proposal # 12-0274
    accepted for FY12 LDRD

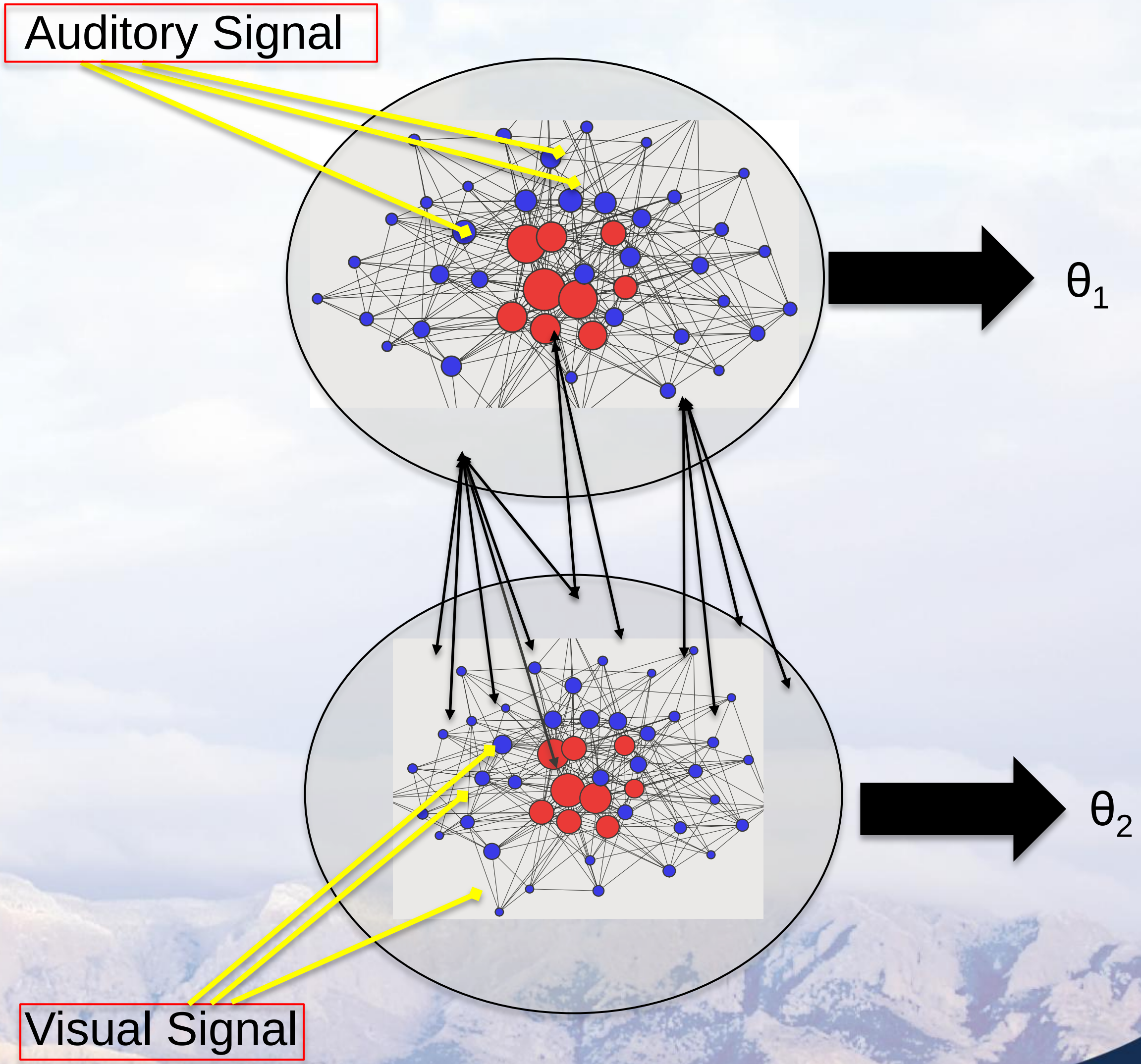
Meso-scale Modeling



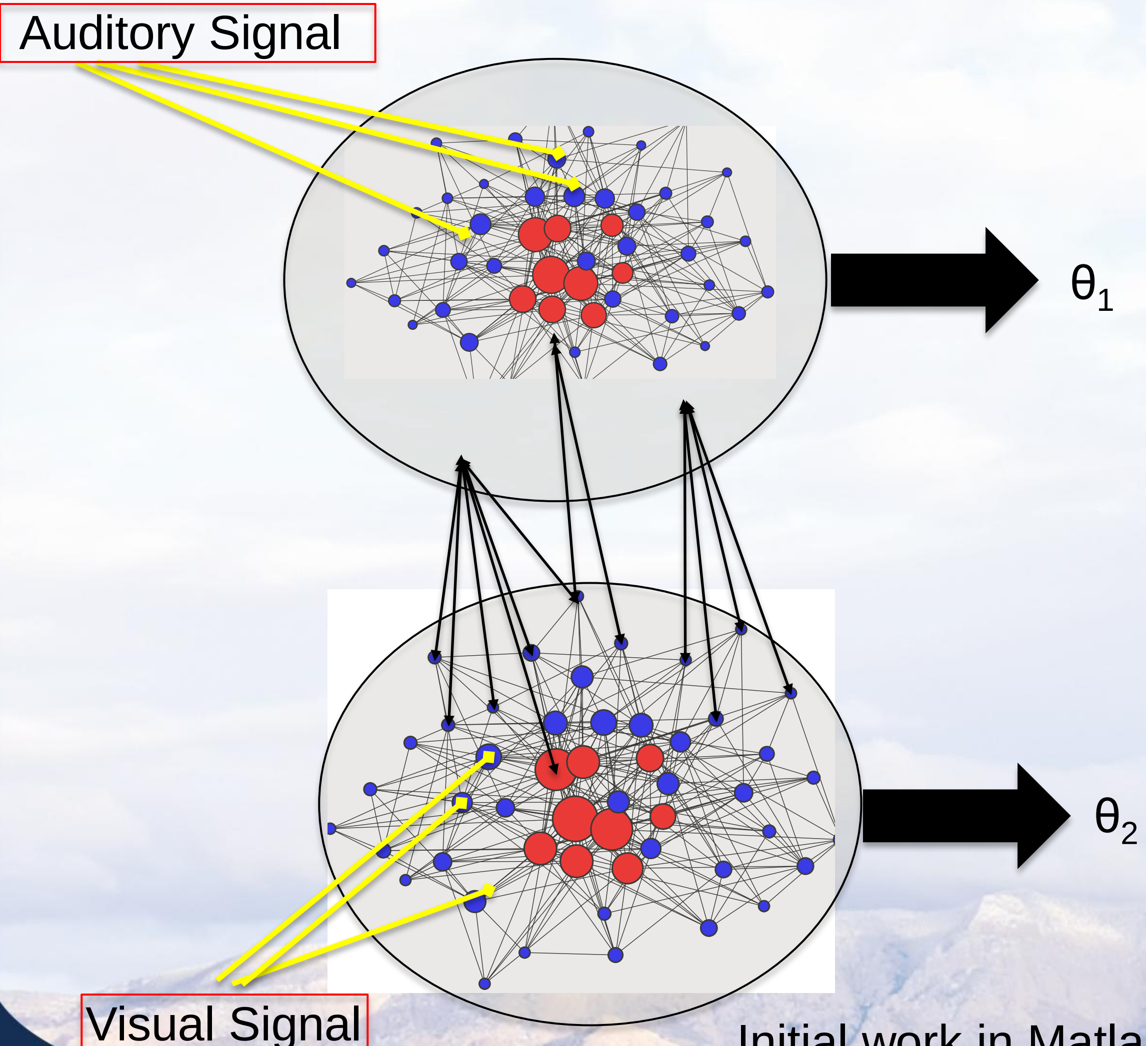
- Collective Behavior Characterization
  - Alex Duda and Steve Levenson at the University of Illinois
  - Basis for a multi-modal associative memory for language acquisition and motor control.
  - Used with an embodied cognitive robotics platform (the humanoid robot, iCub).
- L. Romero & Mei Ting, SNL:
  - Networks of coupled oscillators
  - Central pattern generators, circadian rhythms
  - New technique for implicitly generating basis functions.

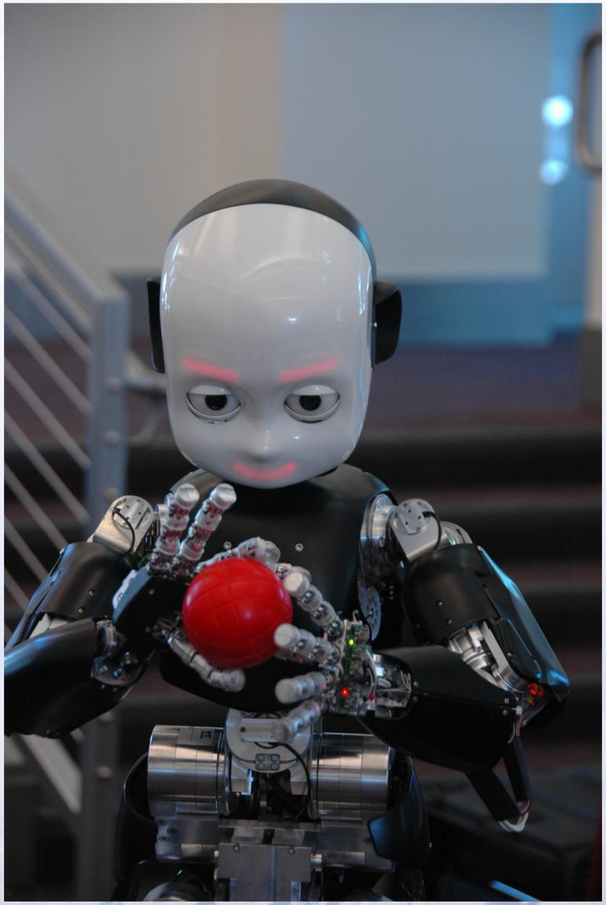
Neocortical Model

- Large populations of canonical Hodgkin-Huxley neuron model.
- Synaptic connections evolve according to a spike-timing dependent plasticity (inspired) scheme.
- Excitatory and inhibitory neurons present with proportions, spatial location, and topological connectivity that are experimentally inspired.



Neocortical Model





Initial work in Matlab.
Prototyping larger calculations in Xyce.

Objectives

1. Understanding/identifying population-level features that could be considered the "information-bearing signal" in the neocortex

2. Discovering robust ways to encode real-world, multi-modal objects/concepts (visual, auditory, etc.) in a population of spiking neurons.
   - Phase synchrony
   - Graph Theoretic / Network Analysis
     – Weighted Degree distribution
     – Network flow metrics

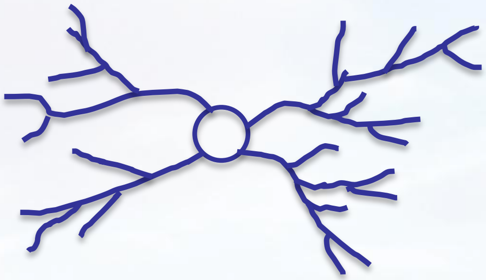
3. Use encodings as part of an inverse model for language production and motor control (to "close-the-loop" in the sensorimotor integration problem).

4. Use (1-3) as the basis for a multi-modal associative memory implemented in a humanoid robot (iCub) to acquire basic language and motor control expertise by interacting with the environment.

5. Note: Differs from Jeff Krichmar & Gerald Edelman work:
   - Looking for minimal system that can produce function
   - Discover information bearing signal to make superordinate decision.
   - Neuron populations start uncorrelated and synaptic weights change via learning.

Award for Scientific Achievement and Outstanding Presentation at *International Conference on Complex Systems*, Boston, June 2011. Alexander M. Duda and Stephen E. Levinson: *Complex Networks of Spiking Neurons: Collective Behavior Characterization*

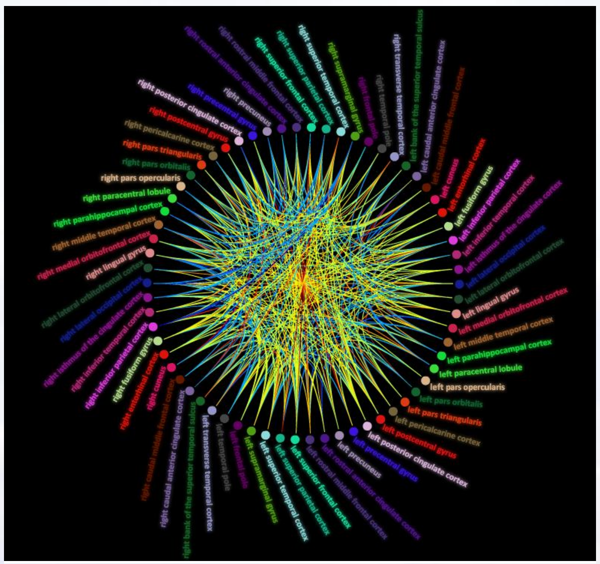
Micro-Scale Modeling



- Detailed Neuron Models
- What?
  - Full ordinary differential equation description
  - Cable equation solved for dynamics
- Why?
  - Detailed biophysics are needed to fully describe natural systems
  - Coupling between systems requires detailed modeling
- Status
  - Multiple neuron and synapse models in place (more under development).
  - Goal is to demonstrate how Xyce performs on complex systems.

Biological Complexity

- Challenge:
  - How do Xyce & Neuron perform on real problems?
    - Extracting circuits from existing projects (i.e. Human connectome, Retina connectome)
      - Proceeding, but difficult to get complete circuits
      - DAPRA SyNAPSE – evolved graphs
    - Generate synthetic graphs using external data
      - Higher level organisms have neuron/synapse densities approaching 10,000 synapses per neuron
      - Use synaptic density to scale circuit complexity.



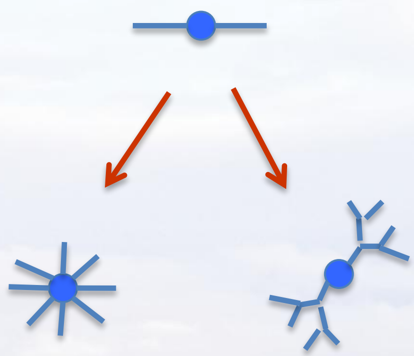
Human Connectome Project
www.humanconnectomeproject.org

Biological Complexity

- Increasing synaptic density – multiple meanings:

1 neuron,
2 synapse

1 neuron,
8 synapse



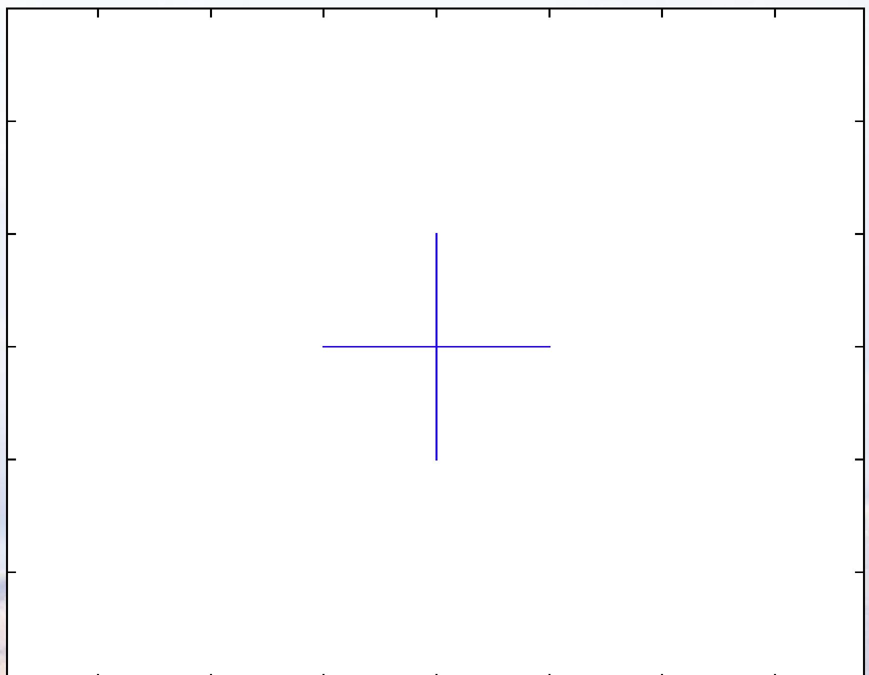
Point neuron
- Ignores neuron details
- Easier to implement

Extended neuron
- Full branching details
- Bigger simulations

Biological Complexity

Going from 1 to 10,000 synapses per neuron requires

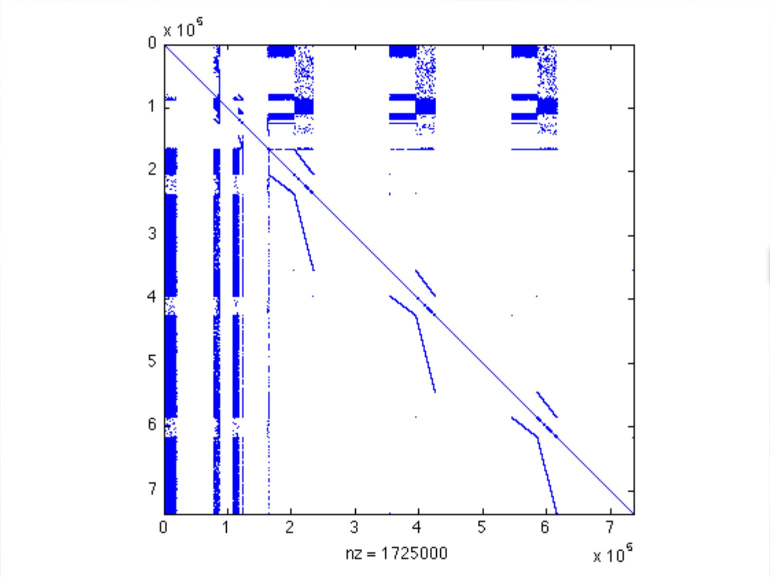
- More memory
- Parallel Strategies
  - Parsing / Loading
  - Solver preconditioning



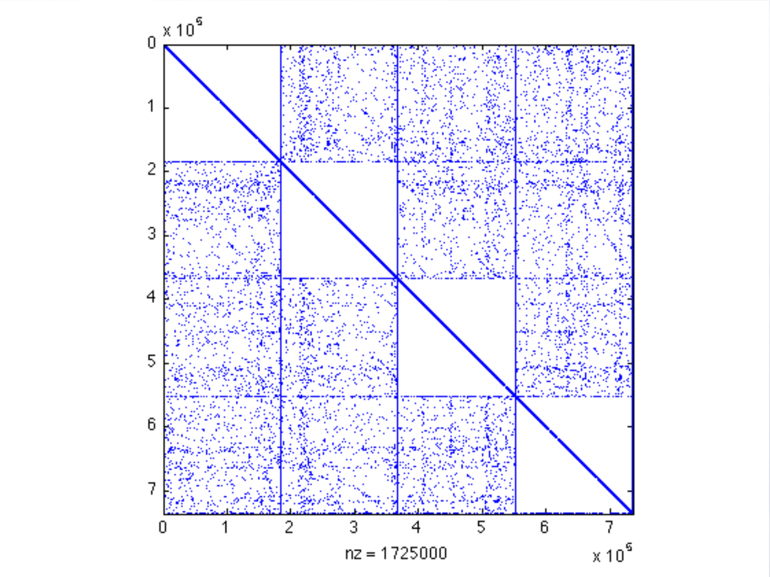
Synapses per Neuron	Num. Unknowns
10	86,000
50	366,000
100	736,000
1000	6,116,000
10,000	60,498,000

Improving solution performance

- Preconditioning of the matrix makes the work-per-time step faster



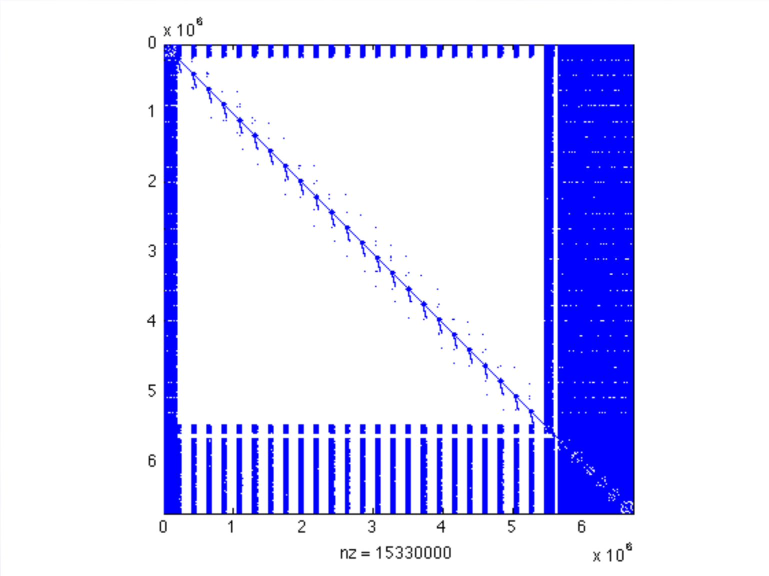
Original matrix

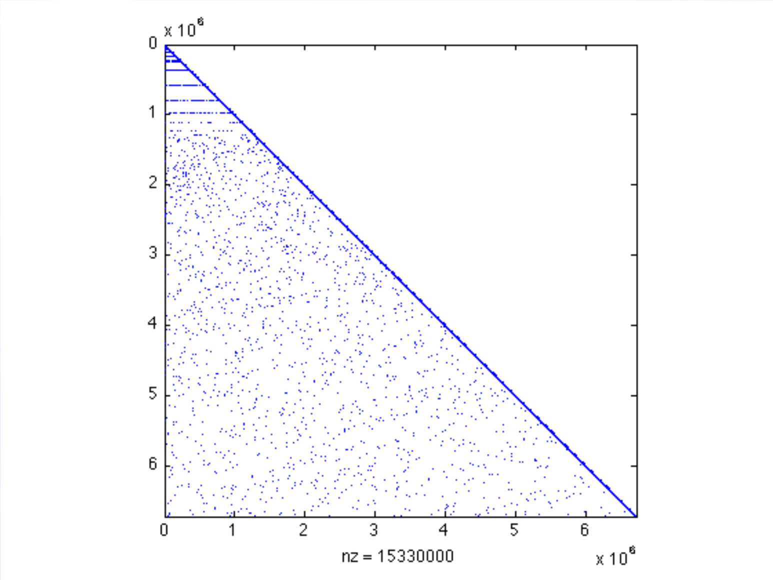


Graph / Hypergraph partitioning

Improving solution performance

- Further research has improved this (Thornquist)



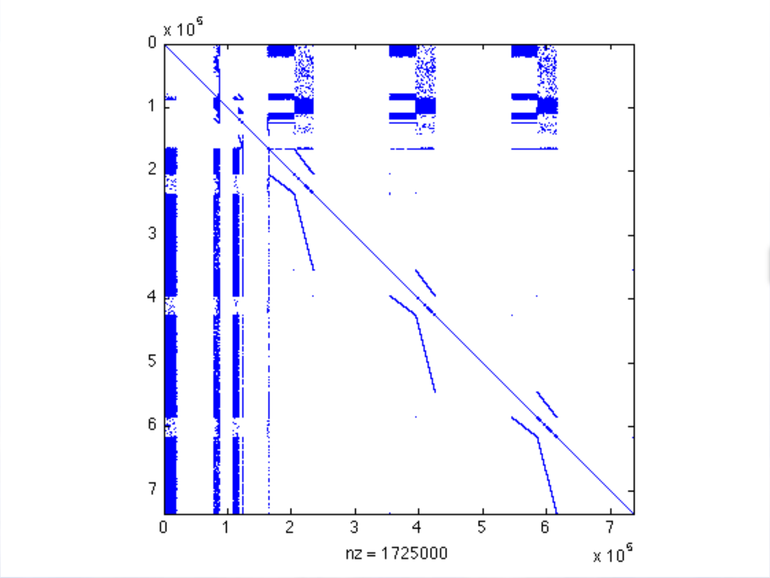


Original matrix

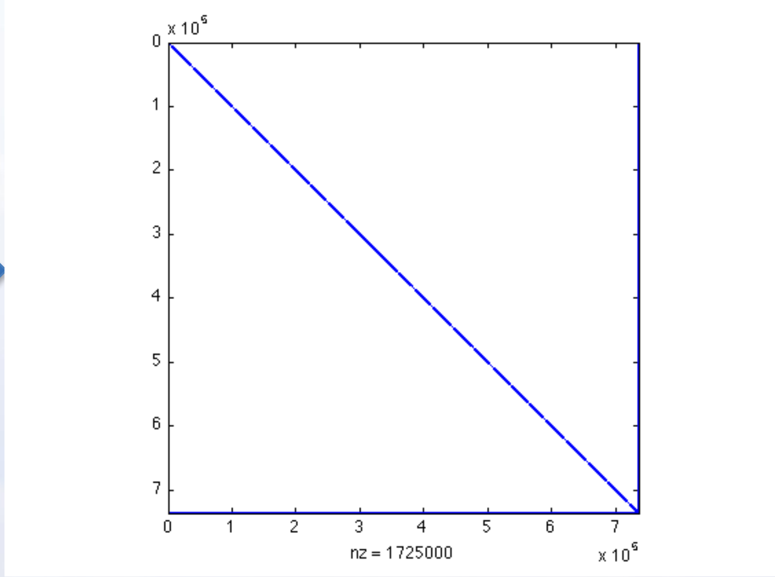
Graph / Hypergraph partitioning

Improving solution performance

- Schur-complement techniques in prototype

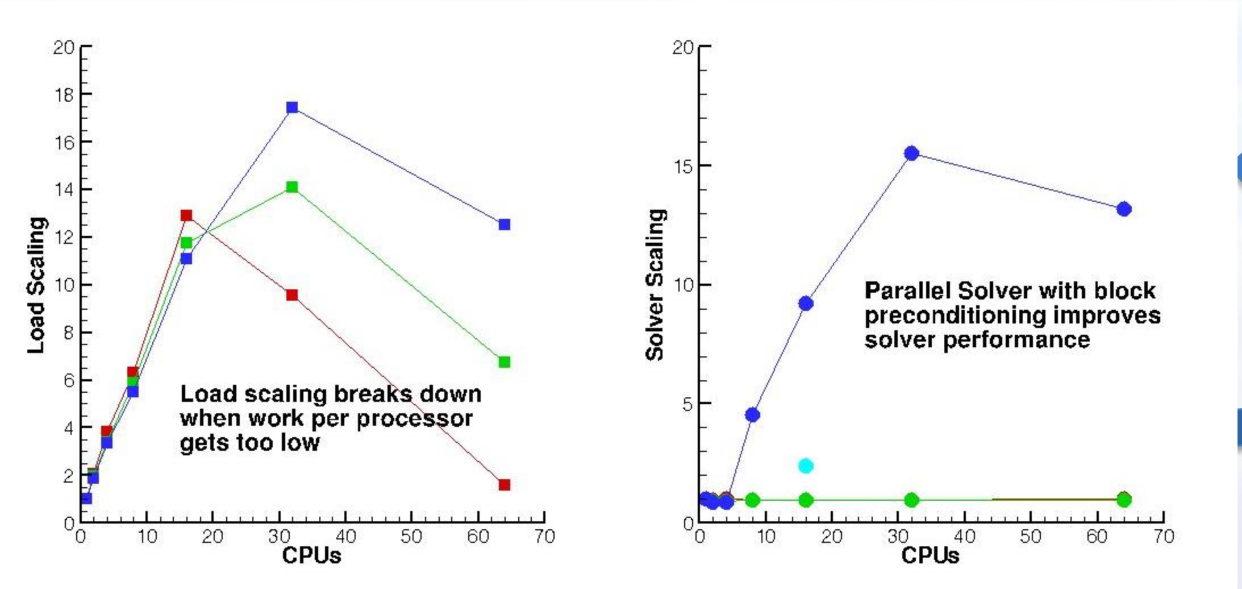


Original matrix



ShyLU (a generalized Schur-complement framework for hybrid linear solvers)
Erik Boman and Siva Rajamanickam, H. Thornquist

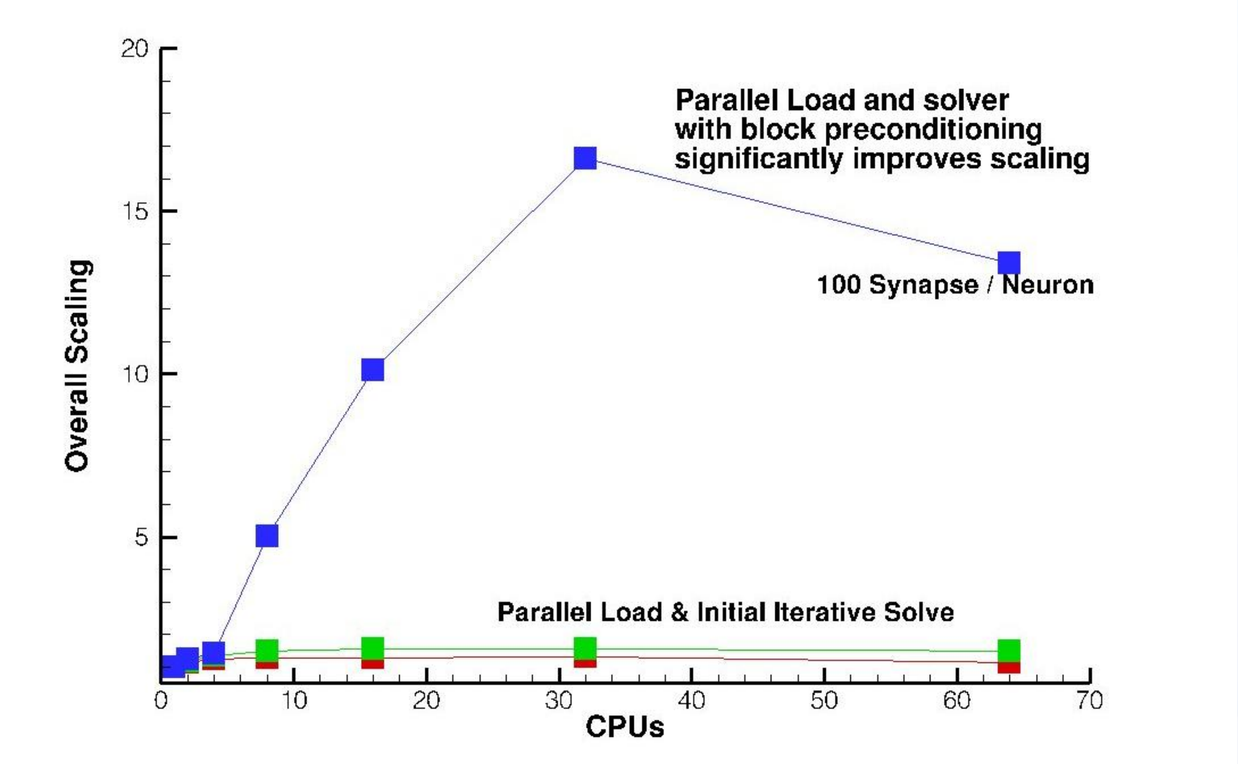
First Scaling results



Improvement from parallel solver preconditioning

- Problem loading scales as expected
- Larger problems will plateau out at higher CPU numbers
- Preconditioning for parallel, iterative solvers helps, but need more!

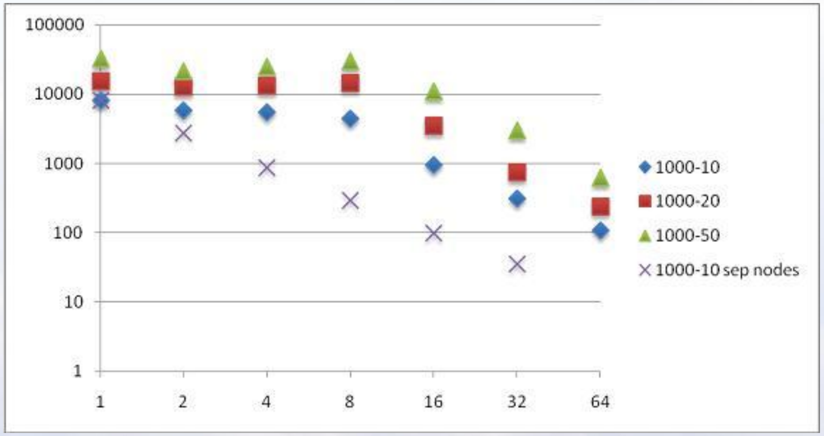
First Scaling results

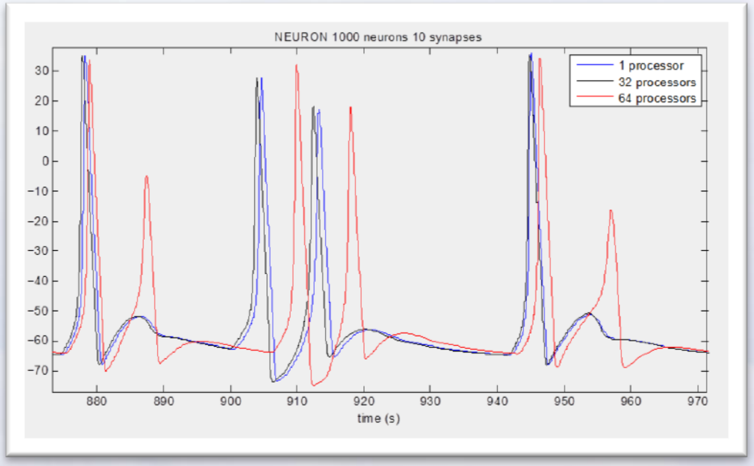


Overall scaling tops out when work per processor drops

Comparing to other simulators

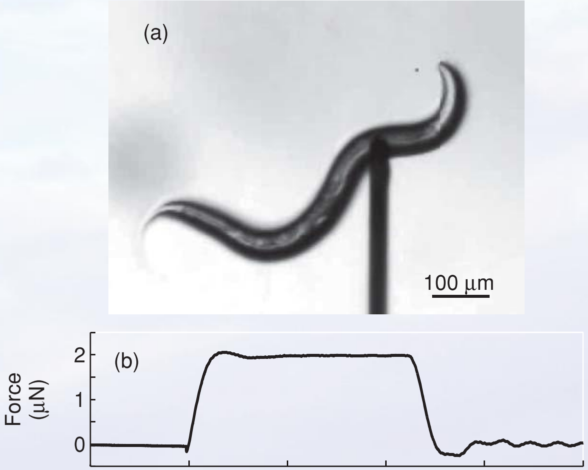
- Neuron
  - On average Xyce's timestep was 10x larger.
  - Parallel scale up changes underlying problem





Future Work

- Release Xyce neuron work as Open source release.
- Joint NSF Funding from work with
  - Stanford and/or Berkeley
- Publications Opportunities
  - Alex Duda's adaptive learning work
  - Scaling of densely connected networks. (JCNS)
- Post-doc starting in fall.
  - Guide a specific application in neuroscience



Park et. al, 2011

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Publications / Presentations

- Publications
  - Relational Memory Implemented
    Patrick D.K. Watson, Shawn Taylor, Craig Vineyard, Steven Verzi, Tom Caudell, Howard Eichenbaum, Neal J. Cohen.
  - Alexander M. Duda and Stephen E. Levinson: Complex Networks of Spiking Neurons: Collective Behavior Characterization, *International Conference on Complex Systems*, Boston, June 2011
- Presentations
  - Grand Challenges in Neural Computation II: Neuromimetic Processing and Synthetic Cognition, Feb 21, 2011, Santa Fe, NM
  - Design Automation Conference, June 4, 2011, San Diego, Ca
  - "Understanding Model, Experimental and Population Level Variance in Cognitive and Neuron Simulations", Schiek, Warrender, DARPA Neural Restoration Workshop, SNL, Albuquerque 11-2010
  - R. Schiek and C. Warrender, "Using uncertainty quantification to constrain dynamic neuron modeling parameters," International Workshop on Bio-Inspired Design at DAC, Anaheim, CA, June 2010.
  - R. Schiek, C. Warrender, Thornquist, Mei, Keiter, Russo, "Parallel design simulation for neurologically inspired systems" DAC, San Diego, CA, June 2011.
  - R. Schiek, Warrender, Thronquist, Mei, Keiter, Russo, "Advanced partitioning and integration techniques to improve parallel performance of densely connected neuron simulations." Society for Neuroscience, October 2011.