CSE511 Brain & Memory Modeling

Lect05-6: Large-Scale Neuronal Structure Modeling

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Adapted from Research Proficiency Exam of Heraldo Memelli 8/31/2010
Outline

• Intro to neuroscience
• Modeling a neuron
• Modeling large-scale networks of neurons
• Examples of large-scale models
• Our work: BOSS
• Future directions
What is a neuron?

- Basic building block in the brain and nervous system
- Electrically excitable cell
- Forms synapses (connections) with other neurons
- Receives thousands of inputs (electrical signals) from its dendrites and sends output “spikes” through its axon
- Information is transmitted by synaptic communication of electro-chemical signals
Neuronal cell membrane

• Channels in the semi-permeable membrane control ion movements in and out of the cell
• Ion concentration gradients generate a voltage difference across the membrane
• At rest, there is too much extracellular Na\(^+\) and too much K\(^+\) inside the cell.

http://www.getbodysmart.com/ap/nervoussystem/neurophysiology/membranephys/menu/image.gif
Action potential (output spike)

- Action potential is an all-or-nothing positive spike in voltage across the axon’s cell wall membrane.
- Action potentials propagate constant-strength signals between neurons.
- The up slope comes from in-rushing Na\(^+\) and the drop from out-rushing K\(^+\) ions.
Neuron: passive & active electrical signals

Injecting current through the current-passing microelectrode alters the neuronal membrane potential. Hyperpolarizing current pulses produce only passive changes in potential. Small depolarizing currents also elicit only passive responses, but depolarizations that cause the membrane potential to meet or exceed threshold evoke action potentials. Action potentials are active responses in the sense that they are generated by changes in the permeability of the neuronal membrane.
Outline

• Intro to neuroscience
• Modeling a neuron
  – Hodgkin-Huxley
  – Integrate-and-Fire
  – Izhikevich
• Modeling large-scale networks of neurons
• Examples of large-scale models
• Our work: BOSS
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Hodgkin-Huxley model

- Model of a neuron as an electrical circuit
- Models three individual ion channels
- More biologically realistic

\[
C \frac{dV}{dt} = I_{\text{input}} + I_L + I_K + I_{Na}
\]

http://icwww.epfl.ch/~gerstner/SPNM/node14.html
Hodgkin-Huxley equations

\[ C \frac{dV}{dt} = I_{\text{input}} + g_{Na}(E_{Na} - V) + g_{K}(E_{K} - V) + g_{L}(E_{L} - V) \]

- Non-constant conductances \((g)\) for Na\(^+\) and K\(^+\) ions
- Non-linear gating variables \((m, n, h)\) for each ion channel & a fixed-rate L channel for slow “leaks”
- Computationally expensive! Seven differential equations and fourth power gating coefficients

\[ g = \frac{1}{R} \]

\[ g_{Na} = \overline{g}_{Na}m^{3}h \]
\[ g_{K} = \overline{g}_{K}n^{4} \]
\[ g_{L} = \overline{g}_{L} \]

\[ \frac{dx}{dt} = \frac{x_{\infty}(V) - x}{\tau_{x}(V)} \quad x = m,n,h \]
Leaky Integrate-and-Fire

• Much simpler model of a neuron

\[
\frac{dx}{dt} = -\frac{x}{\tau} + x_{\text{input}}
\]

\[if (x \geq x_{\text{threshold}}) \]

\[x = x_{\text{reset}}\]

• The \(-x/\tau\) voltage-decay term models ion leakage
• Spikes are generated artificially when the cell voltage exceeds the "threshold" and "resets"
• Lacks biophysical detail and it cannot display different complex spiking neuronal behaviors
Izhikevich model

- Combines simplicity of Leaky-Integrate-and-Fire with many easily achievable dynamic spiking patterns

\[
\begin{align*}
\frac{dv}{dt} &= 0.04v^2 + 5v + 140 - u + I_{ext} \\
\frac{du}{dt} &= a(bv - u)
\end{align*}
\]

if \((v \geq +30mV)\)\
\[
\begin{align*}
v &= c \\
u &= d
\end{align*}
\]
Other Izhikevich firing patterns

\[ v' = 0.04v^2 + 5v + 140 - u + I \]

\[ u' = a(bv - u) \]

If \( v = 30 \text{ mV} \),

then \( v \leftarrow c, \quad u \leftarrow u + d \)

- Regular spiking (RS)
- Intrinsically bursting (IB)
- Chattering (CH)
- Fast spiking (FS)
- Thalamo-cortical (TC)
- Resonator (RZ)
- Low-threshold spiking (LTS)

Izhikevich, 2003
Lect05-6 Large-Scale Neuronal Modeling

9/13,18/12
Outline

• Intro to neuroscience
• Modeling a neuron
• Modeling large-scale networks of neurons
  – Motivation and dynamic behaviors
  – Neuroscience challenges & questions
  – Computational methods
• Examples of large-scale models
• Our work: BOSS
• Future directions
Why large-scale neuronal networks?

- Improve understanding of brain functionality involving interactions of billions of neuronal and synaptic processes
- Perform experiments (on a computer) that are impossible (experimentally or ethically) to be done on humans or animals
- Eventually improve and test hypotheses about complex behaviors:
  - Perception
  - Attention
  - Learning
  - Memory
  - Consciousness
  - Sleep and wakefulness

http://www.scholarpedia.org/article/Cortical_memory
Large-scale neural network dynamics

- Large-scale network models can show complex dynamical patterns similar to brain firing activity
  - Response to external stimuli
  - Sustained intrinsic activity
  - Oscillations
  - Chaotic activity
  - Seizures
Neuroscience questions for large models

- What neuron model to use?
- How to obtain anatomically accurate neuron counts and connectivity patterns?
- How to handle synaptic plasticity (learning)?
Neuroscience questions:
What neuron model to use?

• Large models need simple neuron models:
  - Integrate-and-Fire types of models are obligatory because of their efficiency
  - Izhikevich model is a wise choice because it exhibits a wide range of spiking behaviors and allows about 100 times faster computation runs than Hodgkin-Huxley
How to have anatomically accurate neuron counts and connectivity patterns?

- Difficult to get accurate detailed anatomical information
- Strategies used: fMRI, DTI, in vivo measurements in animals
- Usually neuron types are approximated in models as a few simple types

http://www.hardenbergh.org/jch/volumes/fig1_1200.png
How to have anatomically accurate neuron counts and connectivity patterns?

- Very difficult to get accurate, detailed neuron-to-neuron connectivity information
- Apart from Diffusion Tensor Imaging (DTI), tedious multi-array spike-train recordings are sometimes used to get micro-circuitry information
- Approximate or probabilistic approaches are common
- Often random connections subject to a few constraints

Nuding, 2009
Neuroscience-related questions: How to handle synaptic plasticity?

- Synaptic plasticity is the main brain-learning mechanism.
- STDP (Spike-Timing Dependent Plasticity): a Hebb-style long term modification of synaptic strength that depends on timing of pre- and post-synaptic potentials.
- Main approach is to maintain bounded but dynamically changing synaptic weights.
- Only the most repeatedly effective synapses survive.
Computational methods: modeling tools

NEURON

• Complete simulation environment for biophysically detailed neurons and networks of neurons
• Has a built-in GUI and is widely used by neuroscientists
• More suitable for small to medium size networks
NEURON - Screenshot

Lect05-6 Large-Scale Neuronal Modeling
Other modeling systems

GENESIS
• Similar to NEURON in targeting Hodgkin-Huxley types of models.
• Size of large models = order of $10^4$ neurons

NEST
• Focused towards larger-scale networks with quite realistic connectivity
• Size of large models = order of $10^5$ neurons

SPLIT
• A C++ library (not a full system) that helps modeling large-scale networks of HH-type
• Size of large models = order of $10^6$ neurons
Super-computing

• All large-scale neural simulations need super-computers with thousands of processors.
• All the modeling tools/platforms are now adding parallelization libraries/mechanisms.
• The MPI (Message Passing Interface) library is often used for inter-processor communication.
• Efficient scaling to thousands of processors is not an easy task.
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• **Examples of large-scale models**
• Our work: BOSS
• Future directions
Examples of large network simulations

• Blue Brain project (2007)
• Djurfeldt brain cortex model (2008)
• Izhikevich thalamo-cortical model (2007)
• IBM “Cat-Brain” model (2009)
Examples of large-scale models

• Blue Brain
  – Most biologically detailed and accurate model based on thousands of microanatomy experiments
  – One neo-cortical column of 10,000 neurons

• Djurfeldt brain cortex model
  – Hodgkin-Huxley type of neurons
  – Models few cortical layers with approximate connectivity detail
  – 22 millions of neurons and 11 billion synapses

Lect05-6 Large-Scale Neuronal Modeling

Djurfeldt, 2008
Izhikevich model

- Izhikevich-type neurons with 22 different basic types
- Thalamo-cortical anatomy based on human DTI, plus other experimental data
- 1 million neurons (tens of millions compartments), 0.5 billion synapses
IBM “Cat-Brain” model

- Simpler single-compartment I&F neurons
- Anatomical approximation of thalamo-cortical brain tissue
- Ran on a Blue Gene/P supercomputer with 147,456 CPUs with 1 GB of memory each
- Won the ACM Gordon Bell “Parallel Speedup” Prize in 2009
- 1.6 billion ($10^9$) neurons
- 8.87 trillion ($10^{12}$) synapses
<table>
<thead>
<tr>
<th>Neuron Type</th>
<th>Neuron Type</th>
<th># of Neurons</th>
<th># of Synapses</th>
<th>Runtime (seconds)</th>
<th>Supercomputer</th>
<th>Biophysical Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue-Brain</td>
<td>Hodgkin-Huxley (+)</td>
<td>10,000</td>
<td>$1 \times 10^8$</td>
<td>~100</td>
<td>BlueGene (8192 CPUs)</td>
<td>Extremely detailed</td>
</tr>
<tr>
<td>Djurfeldt Cortex</td>
<td>Hodgkin-Huxley</td>
<td>22 million</td>
<td>$1.1 \times 10^{10}$</td>
<td>Not reported</td>
<td>BlueGene (4096 CPUs)</td>
<td>Good approx.</td>
</tr>
<tr>
<td>Izhikevich thalam-cor.</td>
<td>Izhikevich model</td>
<td>1 million</td>
<td>$0.5 \times 10^9$</td>
<td>660</td>
<td>Beowulf (60 CPUs)</td>
<td>“Mixed” approx.</td>
</tr>
<tr>
<td>IBM Cat-Brain</td>
<td>Simple I&amp;F</td>
<td>1.6 billion</td>
<td>$8.9 \times 10^{12}$</td>
<td>683</td>
<td>BlueGene (147,456 CPUs)</td>
<td>Rough approx.</td>
</tr>
</tbody>
</table>
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BOSS: Intro and goal

• Brain Organization Simulation System
• Attempt to create a tool for neuroscientists to simulate huge-scale networks of neuronal structures
• Test hypotheses about memory, learning, and other complex emergent behaviors that require simulation of networks of millions or billions of neurons
BOSS – Simulator details

• Quantitized-time discrete-event simulator
• Circular header array of unsorted (thus faster) queues of future events for every future time cycle.
• Each firing of a neuron creates an event for every output synapse of that neuron and is placed in the appropriate future queue
• Summing events that target the same neuron can save memory.
BOSS: Discrete event queues

TimeUp[ ] Array of Event Queue Headers
BOSS V1-V6: First simple neuron model

• Neuron model: Simple threshold element that sums square-wave pulses propagating along output links (axons) from many inputs
BOSS: Improvements through V7

- V1: coded by Slava Akhmechet for 4 Sun T1000s
- V2: ported to Bluegene by Ryan Welsch
- V3: Summed pre-synaptic potential changes for the same local neuron to run bigger models
- V5: Decreased memory bits per synapse to double sizes of largest achievable models
- V6: Implemented remote future-event summing potentials allowing for higher synapses/neuron
- V7: Replaced threshold element with Izhikevich neuron models by Heraldo Memelli
Neuronal features of first BOSS models

- Threshold-based action potentials
- Refractory period
- Axonal delays
- Balanced excitation and inhibition
- Periodic external stimulation
- Uniform neuron connectivity topologies
BOSS V1-V7: Initial network model

- **Topology:** The first BOSS simulator versions implemented a simple one-layer square topology with end-around links (torus)
- E-cells at each grid point strongly excited a few nearby cells
- I-cells weakly inhibited many surrounding cells
- The simple torus topology was chosen for easier supercomputer code development & debugging
BOSS-First Grid Topology
BOSS : Parallel computing

- Runs are performed on NY-Blue: an IBM Blue Gene/L supercomputer sited at Brookhaven National Laboratory (BNL) but owned by Stony Brook University for joint use by BNL & SBU computational scientists.
- Currently BOSS uses up to 4,096 processor nodes out of the 18,432 processors in total.
- Inter-processor communication is handled by MPI calls to pass messages about firing events.
BOSS V2-7: Maximum Sizes of Grid Model

- A temporary maximum of 131 billion synapses
- Number of neurons ranges from dozens of millions to up to a billion (depending on the average number of synapses per neuron)
- Uses 1 TeraByte (TB) of memory on 1,024 Bluegene processors
- For size of human brain, we would need about 8,000 TBs of computer main memory (Jaguar, the fastest 2010 super-computer has 360 TB)
BOSS – memory needs of big models

- Future-event storage limited model sizes in BOSS V1-5
- Since version 6 (V6), memory needs for synapse data structures determines maximum model sizes
- Each synapse needs only 8 bytes, allowing up to 131 billion per model in 1 TB of NY-Blue memory
- Runtime is not critical on NY-Blue for BOSS models
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Upcoming BOSS improvements

- Completed (2012) front-end initializer (INIT) for more anatomically accurate models of brain tissues
- Add learning mechanisms – synaptic plasticity
- Let widely separated neurons interact across very distant NY-Blue computing nodes (in process ‘12).
- Let INIT use all cores in each computing node
- Consistently optimize the BOSS simulator for fast runtimes and efficient use of NY-Blue memory
INIT

• Front-end initializer to create realistic brain tissue models
• INIT takes dozens of parameters for:
  – Number of neuron types
  – Density and placement of neurons in the tissue
  – Definitions for axonal and dendritic fields
  – Density and placement of synapses
  – Other connection details
• Automatically places all neurons to match distributions
• Finds all synapses with an efficient staggered walk (N logN) algorithm (N^2 and N^{3/2} in the first INIT implementations)
• Creates details of specific network models that can run fast
Many neuron types

• Dozens of neuronal types in our nervous systems
• They differ by size, shape and electrical behavior.

http://www.mind.ilstu.edu/curriculum/neurons_intro/imgs/neuron_types.gif
INIT: Sample details from cerebellar model
Future Directions

• Finish building a full BOSS system, a flexible tool for creating large-scale brain structure models.
• Use models created by BOSS to tackle questions related to many complex brain behaviors.
• Show formation, interaction, and regeneration of Hebb-style distributed memories: demonstrate “memories in motion”
• Collaborate with the group at Dept. of Physiology & Biophysics to address their large-scale modeling needs.
Thank you

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