Large-scale neural modeling

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Goal: Link structure to function by developing multi-level computational models of neural systems.
We're acquiring brain data at an unprecedented rate.

- **Dendritic recording**
  - Hausser et al. 1997

- **Serial Scanning EM**
  - Denk et al. 2005

- **Ca++ imaging**
  - Reid et al. 2005

Now all we have to is connect the dots...

**Computational primitives** + **Microcircuitry** = **Functional behavior**
Multi-level simulations can link structure to function

The problem is one of scale

- 7 levels of investigation
- 10 orders of magnitude

Option 1: Dissect experimentally

- System properties are lost

Option 2: Analyze theoretically

- Stochastic, heterogeneous, recurrent, nonlinear

Option 3: Simulate directly

- Include all the details
  - Complements theory
- Control all the parameters
  - Complements experiment

Churchland & Sejnowski 1992
The fastest supercomputers available are not up to the task

- 8M neurons connected by 4B synapses
  - 9° visual field in V1

- 1sec of activity took 1hr 20mins to simulate
  - 4750× slower then real-time

- Had to perform 38 trillion evaluations
  - 8M neurons × 6 comp. × 8 eq. × 10^5 steps/sec

Lansner et al. used one 2048-processor rack (3Tflops, $2M).

\[
\begin{align*}
1 - u & \quad \overset{\alpha(v)}{\longrightarrow} \quad u \\
\tau(V) & = \frac{1}{\alpha(V) + \beta(V)} \\
\sigma(V) & = \frac{\alpha(V)}{\alpha(V) + \beta(V)} \\
\frac{du}{dt} & = \frac{\sigma(V) - u}{\tau(V)} \\
\end{align*}
\]
Don’t evaluate equations—emulate physics

Emulate ionic currents with electronic currents

- Exploit physical *analogy*
  - Including stochastic behavior
- Analog VLSI
  - Very Large Scale Integration
- Runs in real-time
  - Takes 1sec instead of 1hr and 20mins

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Physicists revolutionized astrophysics by building their own supercomputer

Two spiral galaxies

Hubble Telescope 1999

Univ. of Tokyo astrophysicist Jun Makino

Point mass approx.

Law of gravity

$F_j = G m_j \sum \frac{m_i}{r_{ij}^2}$

● Hardwired to calculate gravitational force
● A third as fast as Blue Gene rack (1Tflop)
● Sixteen times more cost-effective ($42K$)
  - First to show gravothermal oscillations
  - Resulted in 40 papers in 2000 alone
Neurogrid—an affordable supercomputer for neuroscientists

- **Neurogrid**: Board with grid of chips
  - Programmable connections
  - One chip per cortical cell-layer or type
- **Neurocore**: Chip with array of neurons
  - Programmable ion-channel properties
  - Multiple compartments per neuron

<table>
<thead>
<tr>
<th></th>
<th>2 years</th>
<th>5 years</th>
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<tbody>
<tr>
<td><strong>Neurogrid</strong></td>
<td>4×4</td>
<td>8×8</td>
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<tr>
<td><strong>Neurocore</strong></td>
<td>256×256</td>
<td>1K×1K</td>
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<td><strong>Total</strong></td>
<td>1M</td>
<td>64M</td>
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<tr>
<td><strong>Speedup</strong></td>
<td>280</td>
<td>18,200</td>
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Feedforward view of motion

- V1: Parts
- MT: Object

Anatomy has feedback

- MT projects to V1

Hypotheses about feedback:

- Aggregates parts into coherent object
- Composes cues into unambiguous percept
BioE332's thousand-neuron baby

Computer

USB

CPLD

RAM Chip

USB Chip

STDP Chip

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The chip: Spike-timing dependent plasticity

- 1024 excitatory principle cells
  - 21 plastic synapses each
- 256 inhibitory interneurons
- ~750,000 transistors
- 10.2mm² in 0.25µm CMOS
The GUI: Memorizing patterns

Before learning
- Neuron array
- Spike trains

After learning
- Neuron array
- Spike trains

Synaptic strengths
- LTP
- LTD

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Lab 1: Synapse Model

Temporal Integration

Axon

Dendrite

Q

G

T

Sum

Synaptic current (nA)

Time (ms)
Lab 2: Neuron Model

\[ E_{Na} \]
\[ E_{K} \]
\[ g_{Na} \]
\[ g_{K} \]
\[ g_{l_k} \]
\[ V_{m} \]

Current Clamp

![Graph showing somatic potential over time with current clamp](image-url)
Lab 3: Adaptation and Bursting

Current Clamp

- Soma
- Dendrite
- Potassium
- Calcium

Time (s)

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Lab 4: Phase Response

Effect of Inhibition

![Graph showing the effect of inhibition on membrane response over time. The graph plots delay (ms) on the y-axis and time (ms) on the x-axis. Several curves represent different inhibition levels, with one curve showing a pronounced effect around 40 ms.]
Lab 5: Synchrony

Inhibitory Network

Count

Neuron #

Time (ms)

Rate (Hz)

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Lab 6: Binding

Excitatory-Inhibitory Network

- Neuron #
- Count
- Time (ms)
- Rate (Hz)
Lab 7: Potentiation & Depression

Spike-timing dependent plasticity

- Potentiation
- Depression

Spike timing: $t_{pre} - t_{post}$ (ms) vs. Inverse number of pairings

- Presynaptic spike
- Postsynaptic spike

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Lab 8: Plasticity and Synchrony

Plasticity enhanced phase-coding

Before STDP

After STDP

Raster

Spike probability

Time (s)
Lab 9: Associative memory

Memory recall

Before learning

After learning