Large-Scale Biologically Realistic Models of Cortical Mesocircuit Dynamics

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Large-Scale Cortical Mesocircuit Dynamics

1. Scope of Work

2. Neurodynamics & Mesocircuit Theory

3. RAIN Concepts & Progress to Date

4. Future Directions
1. Scope of Work

- Assumptions:
  - The brain is an analog system (with some digital-like features)
  - The brain obeys classical, non-quantum physics, operating in biological time
  - The brain can be reverse-engineered

- Obstacles to understanding relevant brain processing:
  - No consensus on algorithmic basis of cognition, memory, or consciousness
  - Biological brain models have an extreme no. of unconstrained parameters
  - Extracting biological parameters from behaving brains is very difficult
  - Emulating genetic/developmental neural cell biology doesn't “explain” it

- Hypotheses:
  - Phenomenologically-detailed brain mesocircuit models (to be described) could bridge this gap in our understanding (and give rise to novel hybrid analog-digital “AI”)
  - Robots based on mesocircuit theory and through social interaction can provide strong behavioral constraints on the cortical modeling (and result in immediate applications)
1. Scope of Work

- Simulation Software and Cluster Development
  - 200-CPU cluster (Xeon/Opteron), Myrinet, 2 TB memory
  - NCS software written in C/C++ with MPI architecture

- 100 columns x 10,000 cells = 1 million multicompartmental neurons, massively interconnected through 1 billion synapses
1. Scope of Work

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4. Future Directions
2. Neurodynamics

- **AI**: symbols, syntax → production rules
  - *logical systems* define high-level *symbols* that can be *composed* together in a generative way
  - → they are lacking a “microstructure” needed to explain the fuzzy complexity of perception, categorization, motor control, learning

- **Neural networks**: neurons, links → activation rules
  - in neurally inspired *dynamical systems*, the *nodes* of a network *activate* each other by association
  - → they are lacking a “macrostructure” needed to explain the systematic compositionality of language, reasoning, cognition

- **Missing link**: “mesoscopic” level of description
  - cognitive phenomena emerge as *complex systems* from the underlying neurodynamics, via intermediary *spatiotemporal patterns*
2. Neurodynamics

macrolevel: genetics

mesolevel: molec. biology

microlevel: atoms

TT × Tt → Tt × Tt → TT, Tt, tT, tt
2. Neurodynamics

**macrolevel:** symbols

“John gives a book to Mary” → “Mary is the owner of the book”

**mesolevel:**

“molec. cognition”

**microlevel:**

neurons

2. Neurodynamics

- **Laws of neurodynamics: from rate to temporal coding**
  - more than mean rates → *temporal correlations* among spikes

  ![Diagram showing temporal coding and rate coding]

  - **Rate coding**
    - $\langle x_1(t) \rangle = \bullet$ high activity rate
    - $\langle x_2(t) \rangle = \bullet$ high activity rate
    - $\langle x_3(t) \rangle = \bullet$ high activity rate
    - $\langle x_4(t) \rangle = \circ$ low activity rate
    - $\langle x_5(t) \rangle = \circ$ low activity rate
    - $\langle x_6(t) \rangle = \circ$ low activity rate

  - **Temporal coding**
    - $\langle x_1(t) x_2(t) \rangle \gg \langle x_1(t) x_3(t) \rangle$
    - $\langle x_4(t) x_5(t - \tau_{4,5}) x_6(t - \tau_{4,6}) \rangle$

  - **Zero-delays: synchrony**
    - (1 and 2 more in sync than 1 and 3)

  - **Nonzero delays: rhythms**
    - (4, 5 and 6 correlated through delays)
2. Neurodynamics

- From digital to analog temporal coding
  - more than discrete spikes $\rightarrow$ continuous \textit{membrane potential}
  - neurons receive a great amount of \textit{background activity} from close or remote cortical areas
  - this activity is \textit{irregular but somewhat rhythmic} and has a critical influence on the neurons’ \textit{responsiveness}
  - $\rightarrow$ this suggests a new form of \textit{analog binding}, instead of spike synchrony
2. Neurodynamics

- Cognitive Neurodynamics
  - Springer journal: “CN is a trend to study cognition from a dynamic view that has emerged as a result of the rapid developments taking place in nonlinear dynamics and cognitive science.”
    - focus on the spatiotemporal dynamics of neural activity in describing brain function
    - contemporary theoretical neurobiology that integrates recent and rapid advances in nonlinear dynamics, complex systems and statistical physics
    - often contrasted with computational and modular approaches of cognitive neurosciences
2. Neurodynamics

- Cognitive Neurodynamics... and beyond

  - CN also distinguishes three levels of organization (W. Freeman):
    - microscopic – multiple spike activity (MSA)
    - “mesoscopic” – local field potentials (LFP), electrocorticograms (ECoG)
    - macroscopic – electroencephalograms (EEG)

  - however, in the CN view, upper levels are generally based on neural fields:
    - continuum approximation of discrete neural activity by spatial and temporal integration of lower levels → loss of spatial and temporal resolution

  → in our view, the mesoscopic level of description should retain the fine details of spiking (and subthreshold) patterns: what truly matters are the spatiotemporal “shapes” of mesoscopic objects
2. Neurodynamics

- **Mesoscopic entities are spatiotemporal patterns (STPs)**
  - large-scale, localized dynamic cell assemblies that display complex, *reproducible* digital-analog regimes of neuronal activity
  - these regimes of activity are supported by specific, *ordered* patterns of recurrent synaptic connectivity
  - paradigm shift: construing the brain as a *pattern formation machine*
2. Neurodynamics

- Theories populating the mesolevel: a zoology of STPs
  - synfire chains & braids
  - polychronous groups
  - BlueColumn
  - RAIN & mesocircuits

- Izhikevich (2006)
- Markram (2006)
2. Neurodynamics

- A building-block game of mental representations

  - STPs can bind, interact and/or assemble at several levels, forming complex structures from simpler ones in a hierarchy.

  - binding by temporal correlations and fast synaptic plasticity
    - synchronization
    - delayed correlations, waves
    - analog induction, resonance, etc.
2. Mesocircuit Theory

- Inter-pattern perturbation and coherence induction
  - cell assemblies can interact through weak coupling contacts and influence each other’s dynamical activity modes
  - an input “key” stimulating a “lock” pattern induces a transient regime change and a greater or lesser response in the lock

- the lock has key-specific recognition/representation abilities; it is
  - similar to a “template”, except not a copy of, or analogous to the key
  - similar to an “attractor”, except does not need the key to be active
2. Mesocircuit Theory

- New neural dynamics: perturbation by coupling
  - subtle but fundamental distinction between activating and perturbing/influencing
  - old paradigms (input/output processing chain): a lower area literally activates a higher area, initially silent

- New paradigm: subnetworks already possess endogenous modes of activity, perturbed by coupling interactions, possibly two-way
2. Mesocircuit Theory

“Molding” locks by Hebbian learning

- A lock’s ability to respond more to certain types of keys relies on its specific distribution of synaptic contacts.
- These contacts could be learned through Hebbian modification, for example by presenting certain types of keys repeatedly.
- During the training phase, undifferentiated locks are transformed into specialized locks.
2. Mesocircuit Theory

- Lock diversification and inter-lock competition
  - both training and functional phases could be carried out on multiple locks in parallel
  - inter-lock competition by inhibitory feedback could create diversification and specialization in the context of a “society of locks”
2. Mesocircuit Theory

- Preliminary lock & key experiments
  - lock $L$: 100 neurons ($R$) driven by 20 source cells ($S$) via different combinations of synaptic weights ($W$), which make $L$’s specificity
  - $S$ cells are bursting at various frequencies and phases, creating complex potential landscapes in $R$ cells with low spike frequency
  - key $K$ is a random train of spikes: when $L$ is stimulated by $K$, the $R$ cells’ firing rates increase more or less, depending on the match between their endogenous temporal structure and $K$’s structure
2. Mesocircuit Theory

- **Lock excited by key**
  - example of strongly resonant $L$-cell $\rightarrow$ 6 extra spikes when stimulated by $K$:
    - blue signal = intrinsic $L$ potential
    - red signal = potential when excited by $K$

- example of nonresonant $L$-cell $\rightarrow$ 0 extra spikes when stimulated by $K$: 
2. Mesocircuit Theory

- Lock excited by key
- other examples of $L$-cells strongly excited by the $K$ spikes
2. Mesocircuit Theory

➢ Next stages in the model

✓ driven mode – $L$ modeled as a subthreshold SNN driven by source cells, and $K$ as spike trains

– endogenous mode – add to $L$ recurrent connections (possibly delayed) and inhibitory neurons → RAIN Concepts

– Hebbian learning – add STDP synaptic plasticity and devise training procedure, so that lock $L$ “molds” around specific keys $K$

– brain module – integrate a society of $L$ networks into the association module (AS) of the brain architecture
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3. RAIN Concepts

- Evoked vs. ongoing activity


(Tsodyks et al. Science 1999; 286, 1943 -1946)
3. RAIN Concepts

- **Ongoing activity** - transient coherence

3. RAIN Concepts

- *in vivo awake spiking* (identical cell, repeated trials)

**Rat Thalamus LGN** (Erik Flister, Pam Reinagel): 2006, UCSD online course

**Monkey Lateral Prefrontal Cortex** (Shima et al. Nature 2007; 445:315-318)
3. RAIN Concepts

- First, we stimulate a recurrently connected excitatory network...
3. RAIN Concepts

- Next, we add recurrent inhibition via E:I and I:E synapses...

![Diagram showing 800 excitatory neurons connected to 200 inhibitory neurons with recurrent inhibition via E:I and I:E synapses.](image)
3. RAIN Concepts

How could we get sustained firing?

- 800 excitatory neurons
- 200 inhibitory neurons

Parameters:
- $P_{\text{connect}}$
- $G_{\text{exc}}$
- $G_{\text{inh}}$
- Rand Noise

Equations:
- $G_{\text{exc}}$
- $G_{\text{inh}}$
- $P_{\text{connect}}$

Graphical representation showing the dynamics of excitatory and inhibitory neurons with parameters $P_{\text{connect}}$, $G_{\text{exc}}$, and $G_{\text{inh}}$.
3. RAIN Concepts

But what if we instead add recurrent inhibition of inhibition?
3. RAIN Concepts

- Work of others
3. RAIN Concepts

✔ Work of others (cont’d)


3. RAIN Concepts

- “Negative-pulse ignited” firing phase diagram: $G_{\text{exc}}$ vs. $G_{\text{inh}}$
  - based on a combination of firing statistics, 4 consistent domains are discovered as excitatory and inhibitory conductances are covaried in separate experiments.
3. RAIN Concepts

Effect of Membrane Ion Channels

Figure 1: Excit [Base no K+] and Inhib [Base no K+] [Km=0.025] [Ka=1.0] [KaHp=0.007]

Figure 2: Excit [Km=0.015] and Inhib [Base no K+] [Km=0.025] [Ka=1.0] [KaHp=0.007]

Figure 3: Excit [Ka=6.000] and Inhib [Base no K+] [Km=0.025] [Ka=1.0] [KaHp=0.007]

Figure 4: Excit [KaHp=0.003] and Inhib [Base no K+] [Km=0.025] [Ka=1.0] [KaHp=0.007]
3. RAIN Concepts

➢ Firing characteristics
3. Progress to Date

Subthreshold correlation complexity (eigenvalue distribution):

“Hello World” @ 200-700 ms into 4 of 800 exc cells
3. Progress to Date

- Multi-RAIN “Transient Winner-Take-Most”

[Diagrams and graphs related to the topic]
3. Progress to Date

- Multi-RAIN Discriminate Hebbian Learning: clustering

![Diagram showing 2 distinct sensory patterns and their connection to RAIN A and RAIN B.]

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3. Progress to Date

- Multi-RAIN Discriminate Hebbian Learning: clustering

Science 315: 973–976
3. Progress to Date

- Multi-RAIN Discriminate Hebbian STDP Learning

Rate Diffs (Hz) with 95% Confidence Intervals

No Pattern Injection

Baseline RAIN A & B activity:

Patterns into RAIN A & B, pre-STDP:

Patterns into RAIN A & B, post-STDP:

Response to Patt X

-1.81 [-1.85 -1.77]

Response to Patt Y

-1.67 [-1.71 -1.63]

0.054 [0.027 0.081]
3. Progress to Date

- **Robot’s visual input**
  - coarse Gabor filters transduced into raster of spikes
3. Progress to Date

At the core: visual-association-motor triad

- **Key**
  - The visual cortex (VC) provides the stimulus patterns, or “keys.”

- **Locks**
  - The association area (AS) holds the complex neurodynamics in “locks.”

- **MC**
  - The motor cortex (MC) is the AS “readout”: it coalesces the activity into winner-take-all.

- **PFC buffer**
  - The SC reward buffer.
3. Progress to Date

- **RAIN drives Robot’s behavioral output**

![Diagram showing RAIN drives behavioral output]

- Raster of spikes transduced into stereotyped actions:
  - bark
  - stand up
  - present paw
  - step back
  - growl
  - lie down
3. Progress to Date

- Completed sensorimotor loop between cluster and robot
  - Initial attempt to implement a real-time, embedded neural robot
  - A robot (military sentry, industrial assistant, etc.) interacts with environment and humans via sensors & actuators
    - NeoCortical Simulator (NCS) software runs on computer cluster; contains the brain architecture for decision-making and learning
    - "Brainstem" laptop brokers WiFi connection: transmits multimodal sensory signals to NCS; sends actuator commands to robot
3. Progress to Date

- Social robotics paradigm
  - Typical robot/human interaction and learning scenario

- a. resting
- b. alerted, observing
- c. reacting by offering a paw
- d. receiving reward (stroking)
- e. angry barking and walking (no reward!)
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Remote-RAIN Brain control of MDS (Mobile/Dexterous/Social) Robot

Developed by a collaboration of:
1. Cynthia Breazeal (MIT Media Lab)
2. Xitome (MIT spinoff)
3. Rod Grupen (U Mass Amherst)

Expressive face design to support the robot’s social function (Xitome)

2 DoF hands with tactile sensing developed at MIT (based on SDM technique developed by Aaron Dollar and Rob Howe at Harvard)

uBot-5 chassis from U Mass—1/2 meter tall
- 11 DoF inverted pendulum mobility base
- Trunk rotation and two 4 DoF arms
- 11-channel embedded FPGA controller
- Force and position feedback & series-elastic actuators
- API in C++
4. Future Directions

NCS development & robotics
- optimization of RAIN mesocircuit network design and STDP
- addition of realistic dopamine-reward basal ganglion (subcortical SC) module for reinforcement learning & planning
- humanoid social interactive robotics
- mesocircuit application to other domains (eg, speech & threat recognition)
4. Future Directions

DURIP 2007: optimizing architecture for neural simulation

Additional CPUs:
1. Distributed, inexpensive cluster
2. New “less expensive” shared-memory architectures

Faster inter-CPU communication options:
1. Infiniband (switched, theoretically up to 96 Gbit/s throughput)
2. LightFleet’s “Corowave” direct optical interconnect (32-cpu this summer)
4. Future Directions

Collaboration with Mind Brain Institute, EPFL, Lausanne

- **Basic science:** ongoing biological extraction of neural parameters

- **Computer science:**
  1. Use of IBM BlueGene L: 8096-CPU cluster, 22 Trillion Flops
  2. Runs NCS and NEURON (and a hybrid)
  3. Plan to run remote-brain AIBO this summer
  4. & MDS robot by summer 2008
Q & A