Neural Networks 1 – Synchronization in Spiking Neural Networks

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Synchronization in Spiking Neural Networks

1. Temporal Coding
2. Coupled Oscillators
3. Synfire Chains
Synchronization in Spiking Neural Networks

1. Temporal Coding
   • Neural networks
   • The neural code
   • Questions of representation

2. Coupled Oscillators

3. Synfire Chains
Synchronization in Spiking Neural Networks

1. Temporal Coding
   - Neural networks
     - Structure of neural networks
     - Structure of a neuron
     - Propagation of a “spike”
     - Model of neural network
   - The neural code
   - Questions of representation

2. Coupled Oscillators

3. Synfire Chains
**Neural networks**

**Structure of neural networks**

- Neurons together form... the brain! (and peripheral nervous system)
  - perception, cognition, action
  - emotions, consciousness
  - behavior, learning
  - autonomic regulation: organs, glands

- ~$10^{11}$ neurons in humans
- communicate with each other through (mostly) electrical potentials
- neural activity exhibits specific patterns of spatial and temporal synchronization ("temporal code")

**Medial surface of the brain**
(Virtual Hospital, University of Iowa)

**Pyramidal neurons and interneurons**
(Ramón y Cajal 1900)

**Cortical layers**
Neural networks
Structure of a neuron

Ionic channels opening and closing → depolarization of the membrane
(http://www.awa.com/norton/figures/fig0209.gif)

Pyramidal neurons and interneurons
(Ramón y Cajal 1900)

A typical neuron
(http://www.bio.brandeis.edu/biomath/mike/AP.html)
Neural networks
Propagation of a “spike”

Propagation of the depolarization along the axon → called “action potential”, or “spike”
(http://hypatia.ss.uci.edu/psych9a/lectures/lec4fig/n-action-potential.gif)
**Neural networks**

**Model of neural network**

**Schematic neurons**  
(adapted from CS 791S “Neural Networks”, Dr. George Bebis, UNR)

**Mechanism**

- each neuron receives signals from many other neurons through its **dendrites**
- the signals converge to the **soma** (cell body) and are integrated
- if the integration exceeds a threshold, the neuron fires a **spike** on its **axon**
Synchronization in Spiking Neural Networks

1. Temporal Coding
   - Neural networks
   - The neural code
     - Rate vs. temporal coding
     - Synchronization and correlations
     - Interest for temporal coding
   - Questions of representation

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The neural code
Rate vs. temporal coding

\[ x_i(t) \]

\[ \langle x_i(t) \rangle_T = \frac{1}{T} \int_0^T x_i(t) \, dt \]

- **Rate coding**: average firing rate (mean activity)

- **Temporal coding**: correlations, possibly delayed

\[ \langle x_i(t) \, x_j(t) \rangle \]
\[ \langle x_i(t) \, x_j(t - \tau_{ij}) \rangle \]
\[ \langle x_1(t) \, x_2(t - \tau_{1,2}) \ldots x_n(t - \tau_{1,n}) \rangle \]

The neural code
Synchronization and correlations

\[ x_1(t) \]
\[ x_2(t) \]
\[ x_3(t) \]
\[ x_4(t) \]
\[ x_5(t) \]
\[ x_6(t) \]

\[ \langle x_1(t) \rangle = \bullet \text{ high activity rate} \]
\[ \langle x_2(t) \rangle = \bullet \text{ high activity rate} \]
\[ \langle x_3(t) \rangle = \bullet \text{ high activity rate} \]
\[ \langle x_4(t) \rangle = \circ \text{ low activity rate} \]
\[ \langle x_5(t) \rangle = \circ \text{ low activity rate} \]
\[ \langle x_6(t) \rangle = \circ \text{ low activity rate} \]

\[ \langle x_1(t) x_2(t) \rangle \gg \langle x_1(t) x_3(t) \rangle \]
\[ \langle x_4(t) x_5(t - \tau_{4,5}) x_6(t - \tau_{4,6}) \rangle \]

- 1 and 2 more in sync than 1 and 3
- 4, 5 and 6 correlated through delays
The neural code
Interest for temporal coding

• **Historical motivation for rate coding**
  – Adrian (1926): the firing rate of mechanoreceptor neurons in frog leg is proportional to the stretch applied
  – Hubel & Wiesel (1959): selective response of visual cells; e.g., the firing rate is a function of edge orientation

  → rate coding is confirmed in sensory system and primary cortical areas, however increasingly considered insufficient for integrating the information

• **Recent temporal coding “boom”: a few milestones**
  – von der Malsburg (1981): theoretical proposal to consider correlations
  – Gray & Singer (1989): stimulus-dependent synchronization of oscillations in monkey visual cortex
  – O’Keefe & Recce (1993): phase coding in rat hippocampus supporting spatial location information
  – Bialek & Rieke (1996, 1997): in H1 neuron of fly, spike timing conveys information about time-dependent input
Synchronization in Spiking Neural Networks

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   • Neural networks
   • The neural code
     • Questions of representation
       – The “binding problem”
       – Feature binding in cell assemblies
       – “Grandmother” cells
       – Relational graph format
       – Solving the binding problem with temporal coding
       – A molecular metaphor

2. Coupled Oscillators

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Questions of representation
The “binding problem”

complex feature cells

input

\[
\begin{align*}
\text{red circle} & = \begin{array}{cccc}
\cdot & \cdot & \cdot & \cdot \\
\end{array} \\
\text{green triangle} & = \begin{array}{cccc}
\cdot & \cdot & \cdot & \cdot \\
\end{array} \\
\text{red circle + green triangle} & = \begin{array}{cccc}
\cdot & \cdot & \cdot & \cdot \\
\end{array} \\
\text{green triangle + red circle} & = \begin{array}{cccc}
\cdot & \cdot & \cdot & \cdot \\
\end{array}
\end{align*}
\]
Questions of representation
Feature binding in cell assemblies

→ unstructured lists of features lead to the “superposition catastrophe”
Questions of representation
“Grandmother” cells

→ one way to solve the confusion: introduce overarching complex detector cells
Questions of representation

“Grandmother” cells

... however, this soon leads to an unacceptable combinatorial explosion!
Questions of representation
Relational graph format

→ another way to solve the confusion: represent relational information
Questions of representation
Solving the binding problem with temporal coding

complex feature cells

→ another way to solve the confusion: represent relational information

Questions of representation
A molecular metaphor

C₃H₈O

1-propanol

2-propanol

“cognitive isomers” made of the same atomic features
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1. Temporal Coding

2. Coupled Oscillators
   - Temporal tagging
   - Group synchronization
   - Traveling waves

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1. Temporal Coding

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   - Temporal tagging
     - The binding problem in language
     - A model of semantic binding: SHRUTI
     - Using correlations to implement binding
   - Group synchronization
   - Traveling waves

3. Synfire Chains
Temporal tagging
The binding problem in language

(a) John gives a book to Mary.
(b) Mary gives a book to John.
(c)* Book John Mary give.

???
Temporal tagging
A model of semantic binding: SHRUTI

"John gives a book to Mary."

... therefore: “Mary can sell the book.”

Temporal tagging
Using correlations to implement binding

Binding by correlations, or “phase-locking”
Temporal tagging
Using correlations to implement binding

Inference by propagation of bindings
Synchronization in Spiking Neural Networks

1. Temporal Coding

2. Coupled Oscillators
   • Temporal tagging
   • Group synchronization
     – The scene segmentation problem
     – Excitatory-inhibitory relaxation oscillator
     – Van der Pol relaxation oscillator
     – Networks of coupled oscillators
     – A model of segmentation by sync: LEGION

   • Traveling waves

3. Synfire Chains
Group synchronization
The scene segmentation problem

- scene analysis and segmentation is a fundamental aspect of perception
- ability to group elements of a perceived scene or sensory field into coherent clusters or objects
- can be addressed with temporal correlations, especially:
  - dynamics of large networks of coupled neural oscillators
  - how does it work? . . .
Group synchronization

Excitatory-inhibitory relaxation oscillator

- relaxation oscillators exhibit discontinuous jumps
- different from sinusoidal or harmonic oscillations

Wang, DeLiang (http://www.cse.ohio-state.edu/~dwang/)
Group synchronization
Van der Pol relaxation oscillator

Van der Pol relaxation oscillator
Wang, DeLiang (http://www.cse.ohio-state.edu/~dwang/)

\[ \ddot{x} + x = c(1 - x^2)\dot{x} \quad \iff \quad \begin{cases} \dot{x} = c(y - f(x)) \\ \dot{y} = -x / c \end{cases} \]
Oscillators and excitable units
Bonhoeffer-Van der Pol (BVP) stochastic oscillator

\[
\begin{align*}
\dot{u}_i &= c \left( u_i - u_i^3 / 3 + v_i + z \right) + \eta + k \sum_j \left( u_j - u_i \right) + I_i \\
\dot{v}_i &= (a - u_i - bv_i) / c + \eta
\end{align*}
\]

- two activity regimes: (a) sparse stochastic and (b) quasi periodic
Group synchronization
Networks of coupled oscillators

Wang, DeLiang (http://www.cse.ohio-state.edu/~dwang/)
Group synchronization
A model of segmentation by sync: LEGION

indirectly coupled through central pacemaker
globally coupled
locally coupled

LEGION network: Locally Excitatory
Globally Inhibitory Oscillator Network
(http://www.cse.ohio-state.edu/~dwang/)
Group synchronization
A model of segmentation by sync: LEGION

- achieving fast synchronization with local, topological coupling only

Group synchronization 
A model of segmentation by sync: LEGION

Group synchronization
A model of segmentation by sync: LEGION

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   - Group synchronization
   - Traveling waves
     - Phase gradients, instead of plateaus
     - Wave propagation and collision

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Traveling waves
Phase gradients, instead of plateaus

\[ \phi = \pi - \pi \]
Traveling waves

Detail

“Grass-fire” wave on 16x16 network of coupled Bonhoeffer-van der Pol units
Traveling waves
Wave propagation and collision

64 x 64 lattice of locally coupled Bonhoeffer-van der Pol oscillators

Traveling waves
Wave propagation and collision

Two cross-coupled, mutually inhibiting lattices of coupled oscillators

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