CISC 3250
Systems Neuroscience

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JMH 328A

Systems Neuroscience
• How groups of neurons work together to achieve intelligence
• How the nervous system performs computations
• Requirement for the Integrative Neuroscience major
• Elective in Computer and Information Science

Your instructor
• Prof. Daniel Leeds
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• Office hours: Tuesday and Thursday, 1-2pm
• Office: 328A

Objectives
To understand information processing in biological neural systems from computational and anatomical perspectives
• Understand the function of key components of the nervous system
• Understand how neurons interact with one another
• Understand how to use computational tools to examine neural data

Recommended student background
• Prerequisite: CISC 2500 Data and Information Management – not strict requirement this semester
  Math
  Some calculus
  Computer science
  Some programming

Textbook(s)
• Required
• We will focus on the ideas and study a relatively small set of equations

Lippincott’s Pocket Neuroanatomy, by Gould
• Optional, better anatomy diagrams
Website

http://storm.cis.fordham.edu/leeds/cisc3250/

Go online for
- Lecture slides
- Assignments
- Course materials/handouts
- Announcements

Requirements

- Attendance and participation
  - 1 unexcused absence allowed
  - Ask and answer questions in class
- Homework: Roughly 5 across the semester
- Exams
  - 2 midterms, in February and April
  - 1 final, in May
- Don’t cheat
  - You may discuss homeworks with other students, but your submitted work must be your own

Software

We will use Scilab – an environment for numeric analyses and computational modeling.

- Free
- Runs on all popular operating systems
- Similar to the very-popular Matlab®

http://www.scilab.org

Introducing systems and computational neuroscience

- How groups of neurons work together to achieve intelligence
- How the nervous system performs computations

Levels of organization

From a psychological perspective...

What are the elements of cognition?
Systems neuroscience

Regions of the central nervous system associated with particular elements of cognition

- Visual object recognition
- Motion planning and execution
- Learning and remembering

Computational neuroscience

Strategy used by the nervous system to solve problems

- Visual object perception through biological hierarchical model “HMAX”

Marr’s three levels for “HMAX” vision

- **Computational theory:** Goal is to recognize objects
- **Representation and algorithm:**
  - **Input:** Pixels of light and color
  - **Output:** Label of object identity
  - **Conversion:** Through combining local visual properties
- **Hardware implementation:**
  - Visual properties “computed” by networks of firing neurons in object recognition pathway

Levels of organization
Course outline

- Philosophy of neural modeling
- The neuron – biology and input/output behavior
- Learning in the neuron
- Neural systems and neuroanatomy
- Information representation with features in computer science
- Representations in the brain
- Perception
- Memory/learning
- Motor control

The neuron

- Building block of all the systems we will study
- Cell with special properties
  - **Soma** (cell body) can have 5-100 μm diameter, but **axon** can stretch over 10-1000 cm in length
  - Receives input from neurons through **dendrites**
  - Sends output to neurons through **axon**

Neuron membrane voltage

- Voltage difference across cell membrane
  - **Resting potential**: ~-65 mV
  - **Action potential**: quick positive spike in voltage

- Example neural signals

More on the action potential

- Action potential begins at axon hillock and travels down axon
- At each axon terminal, spike results in release of **neurotransmitters**
- **Neurotransmitters (NTs)** attach to dendrite of another neuron, causing voltage change in this second neuron

Inter-neuron communication

- Neuron receives input from 1000s of other neurons
- **Excitatory** input can increase spiking
- **Inhibitory** input can decrease spiking
- A **synapse** links neuron A with neuron B
  - Neuron A is **pre-synaptic**: axon terminal outputs NTs
  - Neuron B is **post-synaptic**: dendrite takes NTs as input

Modeling voltage over time

Equations focusing on change in voltage $v$

- Components:
  - Resting state potential (voltage) $E_L$
  - Input voltages $RI$
  - Time $t$

\[ \tau \frac{dv(t)}{dt} = -(v(t) - E_L) + RI(t) \]

- change towards resting state
- incorporate new input information
Voltage over time: reset

When voltage passes threshold $v_{\text{thresh}}$, voltage reset to $v_{\text{res}}$

$$v(t_f) = v_{\text{thresh}}$$

$$v(t_f + \delta) = v_{\text{res}}$$

$\delta$ is small positive number close to 0

**Coding in scilab:**

```scilab
dt=0.001 // ms time increment
vCurr=-50 // vCurr is current voltage
vRest=-70 // vRest is resting voltage
vThresh=20 // vThresh is reset threshold
tau=20 // tau is scaling factor
for time = 1:100
vCurr = vCurr+(input(time)-(vCurr-vRest))*dt/tau
if vCurr > vThresh,
vCurr = vRest // reset to vRest
end
end
```

Voltage over time

Simulated

Biological

Accumulating information over inputs
Positive and negative weighted inputs from dendrites $\alpha$ added together:

$$I(t) = \sum_j w_j \alpha_j(t)$$

$j$ is index over dendrites; first-pass model

Form of dendrite input

$$\tau \frac{dv(t)}{dt} = -(v(t) - E_L) + RI(t)$$

**“Leaky integrate-and-fire” neuron**

- Sum inputs from dendrites (“integral”)
  $$I(t) = \sum_j \sum_{t_j} w_j \alpha(t - t_j)$$

- Decrease voltage towards resting state (“leak”)
  $$\tau \frac{dv(t)}{dt} = -(v(t) - E_L) + RI(t)$$

- Reset after passing threshold (“fire”)
  $$v(t_f + \delta) = v_{\text{res}}$$
Tuning curves

Some single neurons fire in response to “perceiving” a quality in the world

Adrian, *J Physiol* 1926.


Neural coding

Perception, action, and other cognitive states represented by firing of neurons

- Coding by rate: high rate of pre-synaptic spiking causes post-synaptic spiking
- Coding by spike timing: multiple pre-synaptic neurons spiking together causes post-synaptic spiking

Computing spike rate

- Add spikes over a period of time
  \[ v(t) = \frac{\text{num spikes in } \Delta T}{\Delta T} \]
- Average spikes over a set of neurons
  \[ A(t) = \lim_{\Delta T \to 0} \frac{1}{\Delta T} \frac{\text{num spikes in } N \text{ neurons}}{N} \]

Activation function

Often non-linear relation between dendrite input and axon output

\[ \tau \frac{dv(t)}{dt} = -(v(t) - E_L) + RI(t) \]

Sum inputs

Multiply by \( R \)

Apply (non-linear?) transformation to input

Multiplying inputs

\[ h_l = \sum_{jk} w_{ljk} r_j^\text{in} r_k^\text{in} \]