CISC 3250
Systems Neuroscience

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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

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

Recommended student background
Prerequisite:
- Officially: CISC 2500 Information and Data Management
  or CISC 1800/1810 Intro to Programming
- Math
- Computer science
- Some calculus
- Some programming
Textbook(s)


- **Suggested**
  - We will focus on the ideas and study a relatively *small set* of equations

Computational Cognitive Neuroscience, by O’Reilly et al.

- **Optional**, alternate perspective

Website

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

Go online for

- Announcements
- Lecture slides
- Course materials/handouts
- Assignments

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 course topics with other students, but you must answer homeworks yourself (and exams!) yourself

Matlab

Popular tool in scientific computing for:

- Finding patterns in data
- Plotting results
- Running simulations

Student license for $50 on Mathworks site
Available in computers at JMH 330 and LL 612
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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 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”

Computational neuroscience as “theory of the brain”

David Marr’s three levels of analysis (1982):
- **Computational theory**: What is the computational goal and the strategy to achieve it?
- **Representation and algorithm**: What are the input and output for the computation, and how do you mathematically convert input to output?
- **Hardware implementation**: How do the physical components perform the computation?
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

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Course outline

• Philosophy of neural modeling
• The neuron – biology and input/output behavior
• Learning in the neuron
• Neural systems and neuroanatomy
• Representations in the brain
• Perception
• Memory/learning
• Motor control

**Plus:** Matlab programming

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Levels of organization

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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 upward spike in voltage

![Example neural signals](image)

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

![Action potential diagram](image)

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

![Synapse diagram](image)

More on neuron membrane voltage

- Given no input, membrane stays at resting potential (~ -65 mV)

Inputs:

- Excitation temporarily increases potential
- Inhibition temporarily decreases potential

*Continual drive to remain at rest*
Patch clamp experiment

• Attach electrode to neuron
• Raise/drop voltage on electrode
• Measure nearby voltage (with another electrode)

More on the action potential

1. Accumulated excitation passes certain level
2. Non-linear increase in membrane voltage
3. Rapid reset

Modeling voltage over time

Equations focusing on change in voltage $v$

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

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

Simulation

• Initial voltage
• Time interval for update
• Input at each time

• Apply rule to compute new voltage at each time
Applying $\frac{dv}{dt}$ step-by-step

$E_L = -65\text{mV}$  \quad $v(0\text{ms}) = -65\text{mV}$  \quad $\tau = 1$

$R_I(t) = 20\text{mV}$ (from $t=0\text{ms}$ to $1000\text{ms}$)

time step: 10ms \quad \tau \frac{dv(t)}{dt} = -(v(t) - E_L) + R_I(t)$

Changing model terms

$\tau$ has inverse effect
- increase $\tau$ decreases update speed
- decrease $\tau$ increases update speed

$R_I(t)$ has linear effect
- increase $R_I(t)$ increases update speed
- decrease $R_I(t)$ decreases update speed

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

Voltage over time

Simulated

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

Biological
Below and above threshold

$E_L = -65 \text{mV}$

Accumulating information over inputs

Positive and negative weighted inputs from dendrites $w_\alpha$ added together:

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

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

Accumulating inputs

$w_1 = ?$

$w_2 = ?$
Chemical level: NT receptors

Pre-synaptic:
- Amount of NT released

Post-synaptic:
- Number of receptors in dendrite membrane
- Efficiency of receptors
  + or –
  - Reflect excitation or inhibition
- One NT type per synapse
- Fixed sign per NT

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

Pre-synaptic neuron spikes
Neurotransmitter (NT) released
NT received by post-synaptic dendrite at time t'
Post-synaptic voltage rises and then fades, α(t)

\[ RI(t) = \sum_j w_j \alpha_j(t) \]

"Leaky integrate-and-fire" neuron
- Sum inputs from dendrites ("integral")
- Decrease voltage towards resting state ("leak")
- Reset after passing threshold ("fire")

\[ v(t') + \delta = v_{res} \]