Computational Neuroscience Introduction Day

• 9.30am Introduction (C. Machens)
• 10am M1 (C. Machens)
• 10.15am M2 (V. Hakim)
• 10.40 break
• 11.00 Matching Law (S. Deneve)
• 11.20 Rescorla-Wagner Learning (C. Machens)
• 11.40 Reinforcement Learning (J.-P. Nadal)
• 12.00-14.00 Lunch break + paper reading
• 14.00 Student presentations
Computational Neuroscience: How does the brain work?

Christian Machens
Group for Neural Theory
Ecole normale supérieure Paris
What’s the brain good for?

Tree
no neurons
What’s the brain good for?

<table>
<thead>
<tr>
<th>Tree</th>
<th>no neurons</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. elegans</td>
<td>302 neurons</td>
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Brains generate motion (= behavior)
What’s the brain good for?

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<tr>
<td>Fly</td>
<td>1 000 000</td>
</tr>
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more complex brains generate a greater variety of behaviors
What's the brain good for?

- Tree
  - No neurons

- C. elegans
  - 302 neurons

- Fly
  - 1,000,000

- Rat
  - 1,000,000,000

- Human
  - 100,000,000,000

More complex brains generate a greater variety of behaviors.

More complex brains can learn more behaviors.
What’s the brain made of?

Molecules

1 nm
What’s the brain made of?

- Neurons
- Synapses
- Molecules

100 μm
1 μm
1 nm
What's the brain made of?

Maps

Networks

1 cm

1 mm

100 μm

1 μm

1 nm

Neurons

Synapses

Molecules
What’s the brain made of?

<table>
<thead>
<tr>
<th>Layer</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecules</td>
<td>1 nm</td>
</tr>
<tr>
<td>Synapses</td>
<td>1 μm</td>
</tr>
<tr>
<td>Neurons</td>
<td>100 μm</td>
</tr>
<tr>
<td>Networks</td>
<td>1 mm</td>
</tr>
<tr>
<td>Maps</td>
<td>1 cm</td>
</tr>
<tr>
<td>Systems</td>
<td>10 cm</td>
</tr>
<tr>
<td>CNS</td>
<td>1 m</td>
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</table>
A physics/engineering approach

Just rebuild the whole thing
The quest for mechanisms: Constructing systems from parts

- CNS
- Systems
- Maps
- Networks
- Neurons
- Synapses
- Molecules

1 m
10 cm
1 cm
1 mm
100 μm
1 μm
1 nm
The quest for mechanisms: Constructing systems from parts
Biophysics of the membrane voltage: The Hodgkin-Huxley Model

The Hodgkin-Huxley model is a mathematical model for how action potentials are generated in neurons. It describes the changes in membrane potential over time due to the opening and closing of ion channels. The model includes the following key components:

- **Ion Channels:**
  - Sodium channels ($g_{Na}$) open in response to a decrease in membrane potential, allowing sodium ions to flow into the cell.
  - Potassium channels ($g_{K}$) open in response to an increase in membrane potential, allowing potassium ions to flow out of the cell.
  - Chloride channels ($g_{Cl}$) also open in response to changes in membrane potential, allowing chloride ions to flow into or out of the cell.

- **Membrane Potential ($V_m$):** Changes over time due to the flow of ions through the channels.

- **Membrane Capacitance ($C$):** Represents the electrical capacity of the membrane to store charge.

- **Gating Variables ($m$, $h$, $n$):** These variables control the opening and closing of the ion channels. They are influenced by the membrane potential and change over time according to specific equations.

The model equations describe how these variables and currents interact to produce the action potential and allow neurons to transmit information efficiently.
Reconstructing neurons:
Ralls’ cable theory and compartmental modeling

Detailed compartmental models of single neurons:
Large-scale differential equation models
Reconstructing neurons
Simulating the membrane potential

Llinas & Sugimori (1980)
The quest for mechanisms: Constructing systems from parts

- CNS
- Systems
- Maps
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- Molecules

1 m
10 cm
1 cm
1 mm
100 μm
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1 nm
Reconstructing circuits
Electron microscopy and brute-force simulations
courtesy of W.Denk
Reconstructing circuits
Electron microscopy and brute-force simulations

Scan brain slices and reconstruct the circuit...“connectonomics”

H. Markram (Lausanne):
“blue-brain project”
B. Sakmann/ W. Denk (Heidelberg)
J. Lichtman (Harvard)
H.S. Seung (MIT)

but: the devil is in the details and when it comes to connectivity, details matter!
Theory of neural networks

Neurons, synapses → network activity

\[ \dot{r}_i = -r_i + f\left(\sum_{j=1}^{N} w_{ij} r_j + I_i\right) \]
Network dynamics largely determined by connectivity

\[ \dot{r}_i = -r_i + f \left( \sum_{j=1}^{N} w_{ij} r_j + I_i \right) \]

Possible dynamics:
- stable/unstable fixed points
- limit cycles
- chaotic attractors

Note: different attractors can co-exist in different parts of the state space!

For \( N \to \infty \)
- neural networks can compute anything
(Statistical) theory of neural networks

Neurons, synapses → network activity

Under what conditions do you get

- only fixed points
- synchronous activity
- asynchronous activity
- Poisson spike trains
- oscillations
- spatial patterns
- ...

$r_1$ $r_2$ $r_3$ $r_N$
The quest for mechanisms:
Constructing systems from parts

- CNS
- Systems
- Maps
- Networks
- Neurons
- Synapses
- Molecules

1 m
10 cm
1 cm
1 mm
100 μm
1 μm
1 nm
Connectionist models: From networks to behavior
A computer science approach

Study the computational problems
Computation: manipulating information

sound pressure wave

cochleogram (time-frequency representation of sound)
Representation of information, more or less lossy

Example music:

- Sheet notes

- Sound

- CD

Language: The other day, I heard this cool jazz CD with this drummer...
Why represent information differently?

Example numbers:

<table>
<thead>
<tr>
<th>Roman System</th>
<th>Decimal System</th>
<th>Binary System</th>
</tr>
</thead>
<tbody>
<tr>
<td>XXIII</td>
<td>23</td>
<td>00010111</td>
</tr>
</tbody>
</table>
Representations make information explicit

Example numbers:

- XXIII
- 23
- 00010111

mixed decomposition
powers of 10
powers of 2

Can you divide this number by 10?

- 100
- Decimal System
Representations make information explicit

Example numbers:

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<td>powers of 2</td>
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</table>

Can you divide this number by 10?

<table>
<thead>
<tr>
<th>Roman System</th>
<th>Decimal System</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>01100100</td>
</tr>
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</table>
Representations allow for easier algorithms

Example numbers:

<p>| | | | |</p>
<table>
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<tr>
<td>XXIII</td>
<td>in ...?</td>
<td>in multiples of 10</td>
<td>in multiples of 2</td>
</tr>
<tr>
<td>23</td>
<td>000101111</td>
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Can you add these numbers?

<p>| | | | |</p>
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<tr>
<td>29</td>
<td>00011101</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ 33</td>
<td>+ 00100001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>---------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XXIX</td>
<td>XXXIII</td>
<td></td>
<td></td>
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Representations allow for easier algorithms

Example numbers:

\[
\begin{array}{c}
\text{XXIII} \\
\text{23} \\
00010111
\end{array}
\quad \text{in ...?}
\quad \begin{array}{c}
in \text{multiples of 10} \\
in \text{multiples of 2}
\end{array}
\]

Can you add these numbers?

\[
\begin{array}{c}
29 \\
+ \text{33}
\end{array}
\quad \begin{array}{c}
00011101 \\
+ 00100001
\end{array}
\quad \begin{array}{c}
\text{XXIX} \\
+ \text{XXXIII}
\end{array}
\]

\[
\begin{array}{c}
\text{62}
\end{array}
\quad \begin{array}{c}
\text{---------}
\end{array}
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\end{array}
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Representations allow for easier algorithms

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<td>+00100001</td>
<td>+XXXIII</td>
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<tr>
<td>62</td>
<td>00111110</td>
<td>------</td>
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Representations can ease certain computations

Example numbers:

XXIII  
23  
00010111  in ...?  in multiples of 10  in multiples of 2

Can you add these numbers?

29
+ 33
---
62

00011101
+ 00100001
----------
00111110

easy
easy
difficult

XXIX
+ XXXII
--------
Most famous example: “edge detectors” in visual system

Stimulus: black bar

Activity of a neuron in V1
Another famous example: Place cells in the hippocampus
Studying representations in the brain

Experimental work

- perceptual representations: vision, audition, olfaction, etc.
- representation of motor variables
- “higher-order” representations: decisions
  short-term memory
  rewards
  dreams
  uncertainty
  ... you name it ...

Theoretical work

- Quantifying information content quest for the neural code, information theory, discriminability, ...
- Understanding the computational problems: object recognition, sound recognition, reward maximization
What we understand now

very little
What we understand now

very little
What we need

- biologists
- psychologists

- to probe the brains of animals and humans
- to design and carry out clever experiments
- to investigate and quantify human and animal behavior
What we need

- physicists, computer scientists, engineers, etc.

- to formulate mathematical theories of information processing
- to create biophysical models of neural networks
Teaching in the Cogmaster

Computational Neuroscience
Core Classes

M1/S1

M1/S2  CO6 Introduction to Comput. Neuroscience
       AT2 Atelier Comput. Neuroscience

M2/S1  CA6 Theoretical Neuroscience
       XXX Seminar in Quantitative Neuroscience

M2/S2  YYY Research Seminar
Introduction aux neurosciences computationnels

Christian Machens

- Neurons
  - Membrane voltage
  - Action potentials
  - Computations

- Networks
  - Attractors
  - Associative memory
  - Decision-making
  - Sensory processing

- Behavior
  - Psychophysics
  - Reinforcement Learning
  - Neuroeconomics

L3/M1 CO6 S2, Wed, 17-19
\[ \dot{r}_1 = -r_1 + f \left( \sum_{j=1}^{N} w_{1j}r_j + E_1 \right) \]
\[ \dot{r}_2 = -r_2 + f \left( \sum_{j=1}^{N} w_{2j}r_j + E_2 \right) \]

What you need

- Basic math skills, High-School Level
  (ask if you are uncertain!)

What you get

- Foundations of Comp Neurosci
- 4 ECTS

Validation

- 100% exam
What you need

- Basic math skills
- High School Level

What you get

- Putting models into the computer!
- 4 ECTS

Validation

- 100% course exercises
Rava da Silveira, Vincent Hakim, Christian Machens

What you need

• Basic knowledge of computational neuroscience
  (ask if you are uncertain!)

What you get

• Learn about recent research
• Learn how to give a talk
• 3 ECTS

Validation

• 50% talk
• 50% course participation

Talks in French or English

S3, Tue, 15:30-17
Start: Sep 30th

Seminar / Journal Club
Quantitative Neuroscience
If you are looking for more classes with a computational twist, contact us!

- CO8 Rational Decision Theory

- Computational Neuroscience (Single Cell Modeling) Romain Brette

- Statistical Learning Theory (Gerard Dreyfus)

etc. etc.
Computational Neuroscience Research in the Cogmaster and Beyond

ENS: Group for Neural Theory
(Sophie Deneve, Christian Machens, ...)
ENS: Laboratoire de Physique Statistique
(Jean-Pierre Nadal, Vincent Hakim ...)
Paris V: Laboratoire de Neurophysique et Physiologie
(Nicolas Brunel, ...)

you can find more labs under:

http://cogmaster.net
http://neurocomp.risc.cnrs.fr

for internship / stages / Master’s thesis: contact the faculty! (email etc.)