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?

Tree
no neurons

C. elegans
302 neurons

brains generate motion
( = behavior)
What’s the brain good for?

<table>
<thead>
<tr>
<th>Tree</th>
<th>no neurons</th>
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<tbody>
<tr>
<td>C. elegans</td>
<td>302 neurons</td>
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<tr>
<td>Fly</td>
<td>1 000 000</td>
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more complex brains generate a greater variety of behaviors
What’s the brain good for?

<table>
<thead>
<tr>
<th>Species</th>
<th>Neurons</th>
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<td>Tree</td>
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<tr>
<td>Fly</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Rat</td>
<td>10,000,000,000</td>
</tr>
<tr>
<td>Human</td>
<td>100,000,000,000</td>
</tr>
</tbody>
</table>

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
- Neurons
- Synapses
- Molecules

1 cm
1 mm
100 μm
1 μm
1 nm
What’s the brain made of?

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

1 m, 10 cm, 1 cm, 1 mm, 100 μm, 1 μm, 1 nm
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

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

1 m
10 cm
1 cm
1 mm
100 μm
1 μm
1 nm
Biophysics of the membrane voltage: The Hodgkin-Huxley Model
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
- Networks
- Neurons
- Synapses
- Molecules

1 m
10 cm
1 cm
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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 \rightarrow 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
- ...

\( r_1 \quad r_2 \quad r_3 \quad r_N \)
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>
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<tbody>
<tr>
<td>XXIII</td>
<td>23</td>
<td>00010111</td>
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Representations make information explicit

Example numbers:

XXIII mixed decomposition
23 powers of 10
00010111 powers of 2

Can you divide this number by 10?

100 Decimal System
Representations make information explicit

Example numbers:

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Can you divide this number by 10?

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<td>100</td>
<td>01100100</td>
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Representations allow for easier algorithms

Example numbers:

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

Can you add these numbers?

29  00011101  XXIX
+ 33  + 00100001  + XXXIII
--------  -----------  ---------
Representations allow for easier algorithms

Example numbers:

\[
\begin{align*}
\text{XXIII} & \quad \text{in } \ldots? \\
23 & \quad \text{in multiples of 10} \\
00010111 & \quad \text{in multiples of 2}
\end{align*}
\]

Can you add these numbers?

\[
\begin{align*}
29 & \quad 00011101 & \quad \text{XXIX} \\
+ 33 & \quad + 00100001 & \quad + \text{XXXIII} \\
---- & \quad \text{---------} & \quad \text{----------}
\end{align*}
\]

62
Representations allow for easier algorithms

Example numbers:

XXIII
23
00010111

in ...

in multiples of 10

in multiples of 2

Can you add these numbers?

29
+ 33
---
62

000111101
+ 00100001
--------
001111110

XXIX
+ XXXIII
---------
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
easy

00011101 + 00100001 ---------- 00111110
easy
difficult
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.

\[
\begin{align*}
\dot{r}_1 &= -r_1 + f\left( \sum_{j=1}^{N} w_{1j} r_j + E_1 \right) \\
\dot{r}_2 &= -r_2 + f\left( \sum_{j=1}^{N} w_{2j} r_j + E_2 \right)
\end{align*}
\]

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

Computational Neuroscience
# Core Classes

<table>
<thead>
<tr>
<th>Term</th>
<th>Course Code</th>
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<tbody>
<tr>
<td>M1/S1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1/S2</td>
<td>CO6</td>
<td>Introduction to Comput. Neuroscience</td>
</tr>
<tr>
<td></td>
<td>AT2</td>
<td>Atelier Comput. Neuroscience</td>
</tr>
<tr>
<td>M2/S1</td>
<td>CA6</td>
<td>Theoretical Neuroscience</td>
</tr>
<tr>
<td></td>
<td>XXX</td>
<td>Seminar in Quantitative Neuroscience</td>
</tr>
<tr>
<td>M2/S2</td>
<td>YYY</td>
<td>Research Seminar</td>
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Introduction aux neurosciences computationnels

Christian Machens

S2, Wed, 17-19

Neurons
- Membrane voltage
- Action potentials
- Computations

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

Behavior
- Psychophysics
- Reinforcement Learning
- Neuroeconomics
\[ \dot{r}_1 = -r_1 + f \left( \sum_{j=1}^{N} w_1 j r_j + E_1 \right) \]

\[ \dot{r}_2 = -r_2 + f \left( \sum_{j=1}^{N} w_2 j r_j + E_2 \right) \]

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
Atelier théorique
neuromodélisation

Christian Machens

What you need

- Basic math skills
- High School Level

What you get

- Putting models into the computer!
- 4 ECTS

Validation

- 100% course exercises

S2, Tue, 10-12
Seminar / Journal Club
Quantitative Neuroscience

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

S3, Tue, 15.30-17
Start: Sep 30th

Talks in French or English
CA6

Theoretical Neuroscience

Rava da Silveira, Vincent Hakim, Nicolas Brunel, Jean-Pierre Nadal
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.)