Neuroinformatics 2017

February 23, 2017

Introduction
What is Computational Neuroscience?

Computational Neuroscience is the theoretical study of the brain to uncover the principles and mechanisms that guide the development, organization, information processing and mental abilities of the nervous system.
What is Neuroscience?

- How does the brain work?
- What are the biological mechanism involved?
- How is organised?
- How did evolve?
- How does it change during lifetime?
- What are the origins of the degenerative diseases and the possible rehabilitation?
Brain r-evolution

Modern Humans ~ 200,000 years & Cultural Evolution

Understanding/repairing our brain
Today

Cell Phones, ICT
Today

Modern Computers
70 years

Science
3,000 years

Language/Math
5,000 years

Art
(60,000 - 30,000 ago)

Culture explosion of Homo sapiens sapiens
Tools in Neuroscience?

- Genetic manipulations
- Brain slices
- Optical imaging
- Functional brain imaging
- Psychophysiological measurement
- Computational simulations (analytic solutions & Numeric simulations)
Computational/theoretical tools in context

- Psychology
- Neurophysiology
- Neurobiology
- Neuroanatomy

- Quantitative knowledge
  - Non-linear dynamics
  - Information theory

- Experimental facts
- Experimental predictions
- Applications

- Refinement feedback
- New questions

- Computational neuroscience

Applications

Refinement feedback

New questions
Levels of organizations in the nervous system

<table>
<thead>
<tr>
<th>Scale</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m</td>
<td>People</td>
</tr>
<tr>
<td>1 m</td>
<td>CNS</td>
</tr>
<tr>
<td>10 cm</td>
<td>System</td>
</tr>
<tr>
<td>1 cm</td>
<td>Maps</td>
</tr>
<tr>
<td>1 mm</td>
<td>Networks</td>
</tr>
<tr>
<td>100 mm</td>
<td>Neurons</td>
</tr>
<tr>
<td>1 μm</td>
<td>Synapses</td>
</tr>
<tr>
<td>1 Å</td>
<td>Molecules</td>
</tr>
</tbody>
</table>

**Examples**
- People
- CNS
- System
- Maps
- Networks
- Neurons
- Synapses
- Molecules

**Diagrams**
- Self-organizing map
- Compartimental model
- Amino acid

**Complementary memory system**
- Edge detector
- Vesicles and ion channels
Brain blossom

The Jerusalem Brain (Norman Foster)
Perspective: Some new dramatic ($ billions) projects for the brain

1. Allen Institute – Seattle, USA (Mouse/Human brain atlas – recently new focus on mouse vision)

2. Janelia farm – DC, USA (Industrial scale Inst. for connecting network level anatomy and physiology to specific behavior)

3. EU Human Brain Project - EPFL, Lausanne Switzerland (ICT-based brain research platform, integrating data and knowledge from different disciplines, and catalyzing world-wide effort to achieve understanding of the brain, propose new treatments for brain diseases and new brain-like computing technologies) - Lesson #7.

4. President Obama’s “Brain Activity Map” initiative (Creating revolutionary tools to measure/stimulate millions or even billions or neurons simultaneously)
The BIG - difficult question:
What does it mean “To Understand the brain?”

Clearly - A THEORY is required to
explain how the brain ingredients
(its anatomical units; its electro-chemical signals)
generate “high level” phenomena
(perception, action, emotions)
New-breaking methods

Recent Brain-Excitements

1. Connectomics – Complete 3D road-map for the brain
2. Brainbow – Colorful, genetically-designed, brains
3. Brain-machine/computer interface (BMI)
4. Optogenetics – Light-activated brain circuits
5. Computer simulation of the brain - “Blue Brain Project”
Beginning of Modern Neuroscience – Cellular Anatomy

**The two giants:** Camillo Golgi (Italy) & S. Ramon Y Cajal (Spain) – Nobel Prize 1906

Using Golgi staining method
- Very small % of cells stained
- Connections (synapses) - not seen

**The neuron doctrine (Cajal)**
- Our brain is built from individual cells (neurons)
Frontiers 1: Connectomics - modern brain anatomy

Electron microscope (EM) reconstruction of a whole piece of brain (nanometers resolution). All neurons (and other cell types) and all connections (synapses)

Courtesy of Mitya Chklovskii (Janelia Farm)
Based on hippocampus data from Kristen Harris (U. Texas, Austin)
Brainbow

Frontiers 2. “Brainbow” technology

Genetic staining of neurons in vivo (light microscope – micrometer resolution)

Courtesy of Jeff Lichtman, Jean Livet and Joshua R. Sanes
Brainbow
Brain Computer interface
Brain-activated robot arm

*Courtesy of Miguel Nicolelis (Duke University)*
From machine (pulses generated by a battery) to brain
(the amazing success of BMI for ameliorating Parkinson’s)

Normal

The Basal Ganglia

Parkinson

Parkinson’s disease (MPTP)

0.5 s
Optogenetics

Optical stimulation (and recording) from single neurons in the living brain

Channel Rhodopsin opens with blue light
Causes spikes

Natronomonas pharaonis activated with yellow light
Prevents spikes

Hausser and Smith, Nature 2007
Blue Brain Project

The Blue Brain Project

Using the powerful “Blue-Gene” IBM Computer for realistic simulation of the cortical circuits

Courtesy of Henry Markram and the Blue Brain team (EPFL, Switzerland)
Modelling
Further Readings


Jeff Hawkins with Sandra Blakeslee 2004, *On Intelligence*, Henry Holt and Company


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Basic physiology and conductance-based model
Biological background

A. Schematic neuron

- Dendrites
- Nucleus
- Soma
- Axon
- Axon hillock
- Ranvier node
- Myelin sheath
- Synaptic cleft
- Postsynaptic neurons

B. Pyramidal cell

C. Granule cell

D. Spiny cell

E. Purkinje cell
Gliall cells

Figure 2-1 The principal types of glial cells in the central nervous system are astrocytes and oligodendrocytes and in the peripheral nervous system, Schwann cells.
Four components of neurons
Microscopical features of neurons

(A) Mitochondrion
(B) Axon
(C) Synaptic endings (terminal boutons)
(D) Myelinated axons
(E) Dendrites
(F) Neuronal cell body (soma)
(G) Myelinated axon and node of Ranvier
Nerst potential

(A) Voltmeter $V = 0$

1 mM KCl 1 mM KCl
Permeable to K$^+$

No net flux of K$^+$

(B) Initially $V = 0$

10 mM KCl 1 mM KCl

Net flux of K$^+$ from 1 to 2 balanced by opposing membrane potential

(C) $V_{1-2} = -58$ mV

Membrane potential

$[K^+]_1$ (mM)

Slope = 58 mV per tenfold change in K$^+$ gradient
Calculation of Nerst potential

- Nerst calculation for Cl ion!,$ V = \frac{kT}{ze} \log \frac{c_{out}}{c_{in}} $
Membrane simulation

- Simulation of membrane

\[ I_C(t) = C_m \frac{dV}{dt}(t) \]

\[ \tau \frac{dV}{dt} = V_{Cl} - V(t) + \frac{I_{stim}(t)}{A_{g_{Cl}}} \]

\[ \tau = \frac{C_m}{g_{Cl}} \]
Further Readings


Christof Koch (1999), *Biophysics of computation; information processing in single neurons*, Oxford University Press.

