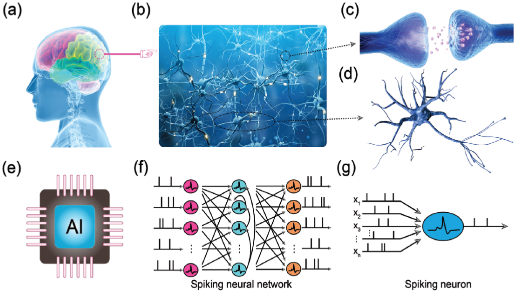
Lecture 1: Motivation and Basic Biological Background of Neurons

Objectives

- To briefly recall the role of ML/AI in Neuroscience and vice versa.
- To present the biological background of neurons necessary to understand the anatomy of neurons and mechanisms behind the generation and propagation of an action potential (spike).
- REMARK: We do not intend to provide an all-inclusive introduction to the intricate subject of neurobiology. Instead, we opt to present a basic and highly selective overview of the biological background of neurons, emphasizing only aspects crucial for comprehending the theoretical work that will be expounded in this course. For an in-depth discussion of neurobiology, please refer to the existing literature, e.g., Luo, Liqun. *Principles of neurobiology*. Garland Science, 2015.

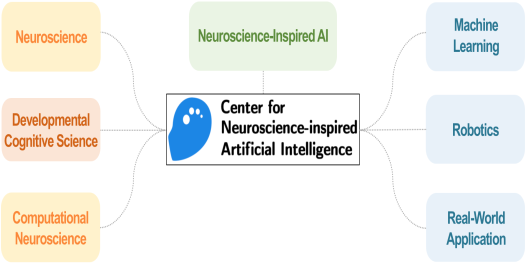
- What is Intelligence? Could it be (in a nutshell) the ability to perceive and adapt to the environment and take actions that maximize success?
- How does it work? One way to understand it is to (try) replicate Human Cognition, including reasoning, problem-solving, abstract thinking, learning from experience, understanding natural language, creativity, memory, perceiving the environment, adaptability, and control of objects.
- Cognitive Science exists at the intersection of computational neuroscience and machine learning (ML), encompassing both biological intelligence (BI) and artificial intelligence (AI).



Schematic diagram of biological and artificial computing systems. a) The human brain. b) The biological neural network. c) A biological synapse. d) A biological neuron. e) An AI chip. f) Spiking neural networks. g) An artificial spiking neuron..

1 Introduction and Motivation

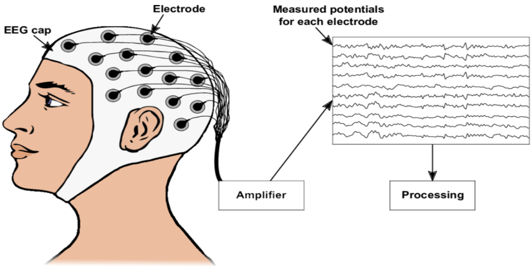
- Neuroscience offers two benefits to ML and AI.
  - It is a rich source of inspiration for developing a better understanding of novel ML algorithms, regardless of the mathematical methods that have conventionally dominated AI and ML, such as artificial neural networks and deep learning.
  - Neuroscience can validate AI techniques, with a neuron-based implementation being strong evidence for its integration into a comprehensive artificial intelligence system.



https://cnai.kaist.ac.kr/

1 Introduction and Motivation

- On the other hand, ML and AI could retroactively benefit neuroscience. ML algorithms are enhancing neuroscience research by improving the analysis of neurophysiological datasets, e.g., Electroencephalography (EEG), forecasting epileptic seizures, etc



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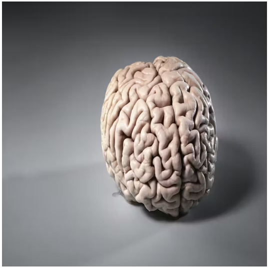
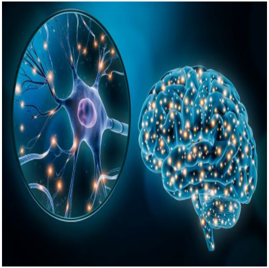
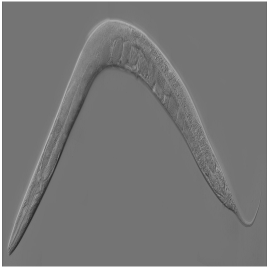
- Thus, understanding the fundamental biology and mathematical modeling — chiefly using dynamical system theory — of biological neural networks and their influence on information processing efficiency is crucial for developing and optimizing neuroscience-inspired ML algorithms.

This is the strategy in the course.

1.1 Elements of neuronal systems



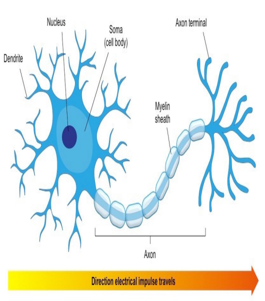


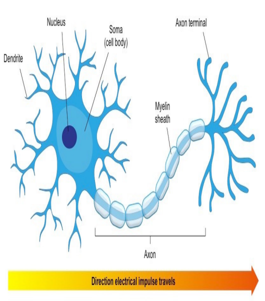


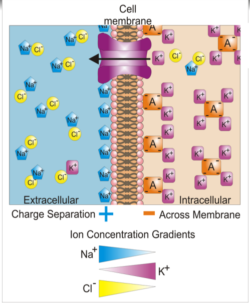
Sunny/Stone via Getty Images
Biologydictionary.net Editors. “Organ” Biologydictionary.net. 2014
https://en.wikipedia.org/wiki/Caenorhabditis_elegans.

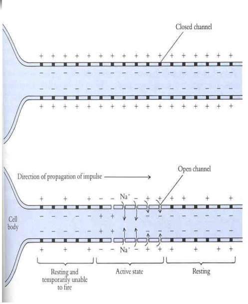
- An adult human brain made up of about 86 billion neurons
- 100 trillion (10^{14}) synapses ($\simeq$ 850000 km of wiring)
- C. elegans has exactly 302 neurons and only 9000 synapses

1.1.1 Structure of a biological neuron and action potential

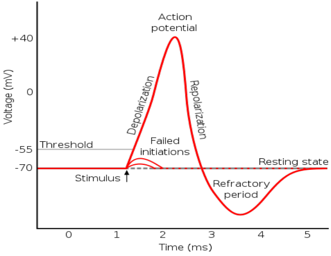


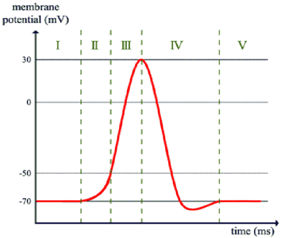






https://en.wikipedia.org/wiki/Membrane_potential.





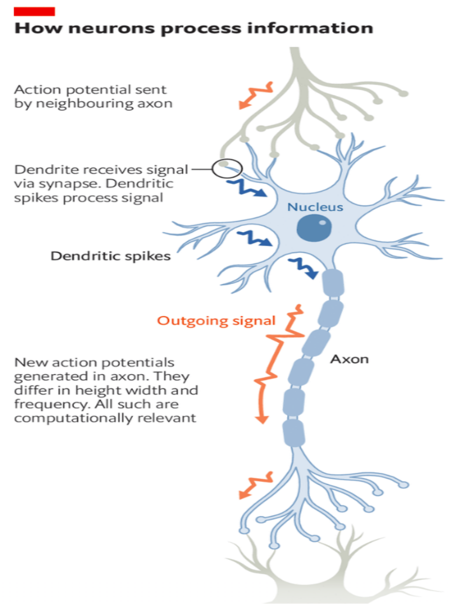
ACTION POTENTIAL :

- I : Resting state
- I-II : Stimulation
- II&III : Depolarization
- IV : Repolarization & hyperpolarization
- V : Resting state

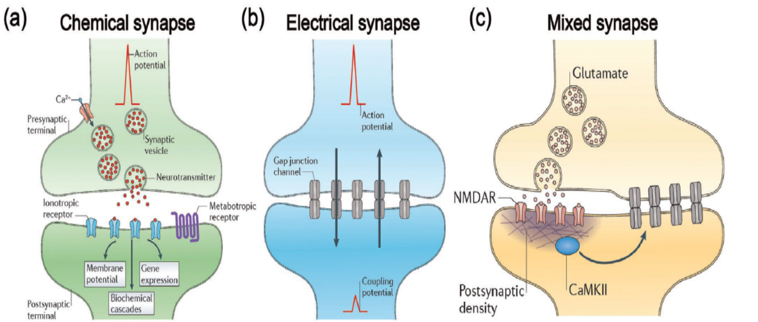
IONIC SCALE :

- II : Sodium channels open
- III : More sodium channels open
- III-IV : Sodium channels close
- III-IV : Potassium channels open
- IV-V : Potassium channels close

Time evolution of membrane potential during the emission of an action potential



The Economist.



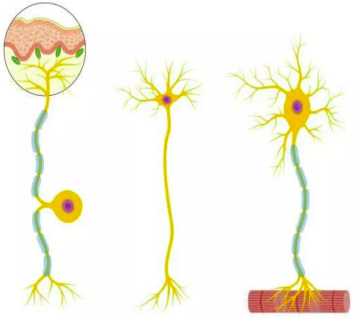
A. E. Pereda, Nat. Rev. Neurosci. 2014, 15, 250..

- a) Chemical synapses are by far the most prevalent and are the main player involved in excitatory synapses. The transfer of neurotransmitters from a presynaptic axon to a postsynaptic dendrite. Unlike an electrical synapse, chemical synapses are separated by a space called the synaptic cleft, typically measured between 15 and 25 nm. In the figure, the arrival of action potential results in the activation of voltage-gated $Ca+$ channels, promoting the probabilistic release of neurotransmitters by exocytosis from presynaptic membrane. The ionotropic and metabotropic receptors on the postsynaptic membrane can detect and translate the information carried by neurotransmitters into different postsynaptic behaviors, varying from changes in membrane potential to gene expression.
- b) Electrical synapses allow direct, virtually instantaneous, and passive flow of electric current through special intercellular connections called gap junctions. Electrical transmission is conducted by gap junctions (some clusters of intercellular channels) between two adjacent cells. The transmission is bidirectional: when an action potential is transmitted from pre-synapse to postsynapse, the postsynaptic resting potential propagates concurrently to the pre-synapse.

1.1.3 Types of synapses and their main modalities of synaptic transmissions.

- c) Mixed synapse. Chemical and electrical transmission coexist at mixed synapses. Chemical synapses (such as glutamate-based) influence the connective strength of electrical synapses by activating the NMDA receptors and CaMKII.
- An excitatory synapse is a synapse in which an action potential in a presynaptic neuron increases the probability of an action potential occurring in a postsynaptic neuron.
- An inhibitory synapse is a synapse in which an action potential in a presynaptic neuron decreases the probability of an action potential occurring in a postsynaptic neuron.

1.1.4 Types of neurons



- Sensory neurons detect stimuli in the external environment. They are activated by sensory input such as light, sound, heat, or pressure and carry information from the sense organs (like the eyes and ears) to the brain. E.g., a pain signal will be sent to the brain if a bee stings you.
- Interneurons connect other nerve cells and help to relay messages between the brain and the rest of the body. They allow impulses to pass from the sensory neurons to the brain, and from the brain to the motor neurons.
- Motor neurons carry impulses from the brain to the muscles and control all of our voluntary movements. This allows us to react to stimuli in our environment. For example, if a bee stings you, the motor neurons will transmit messages from the brain to the muscles of your arm and cause you to swat at the insect.