John von Neumann and The Brain

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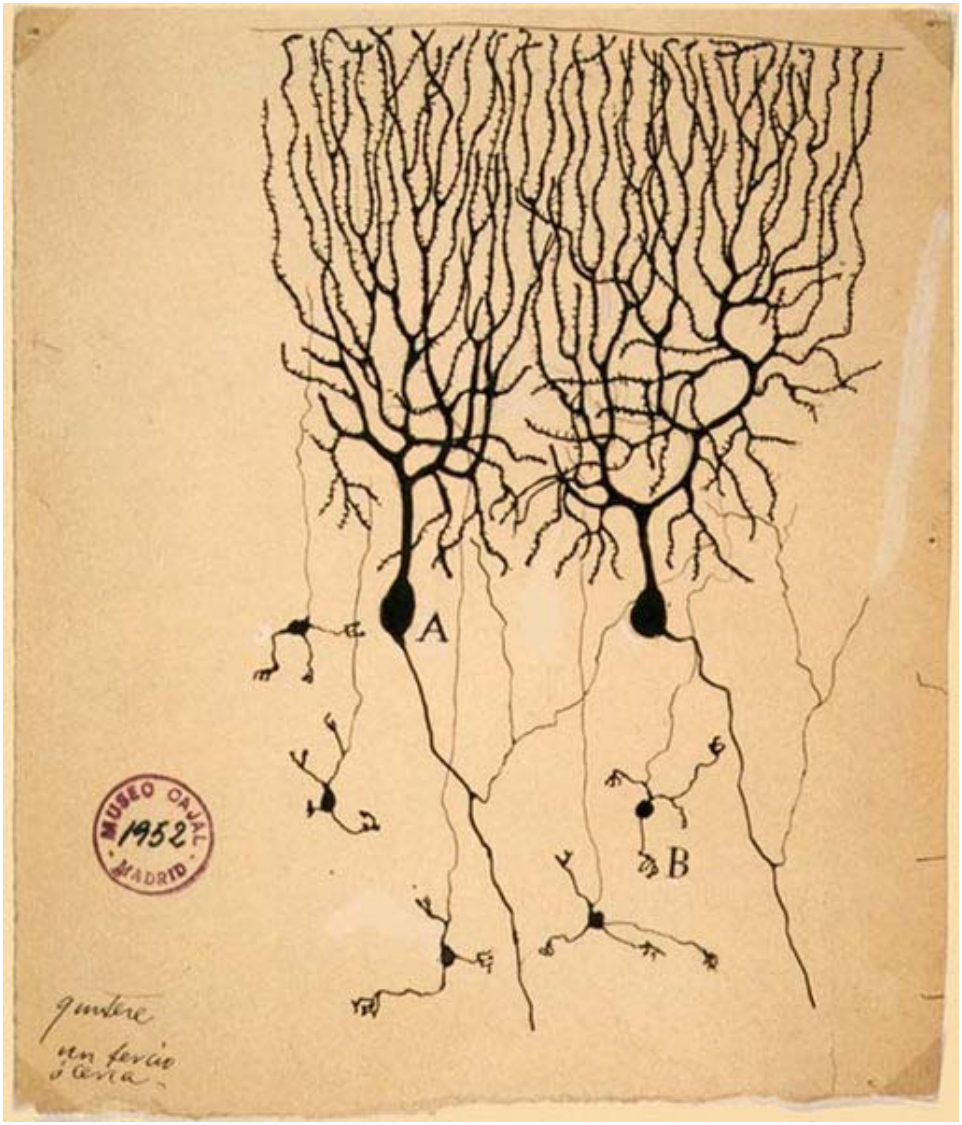
Nervous System – Digital?

- John von Neumann states that the functioning of the nervous system is prima facie (i.e., superficially, seemingly) digital. Why? Let's see…

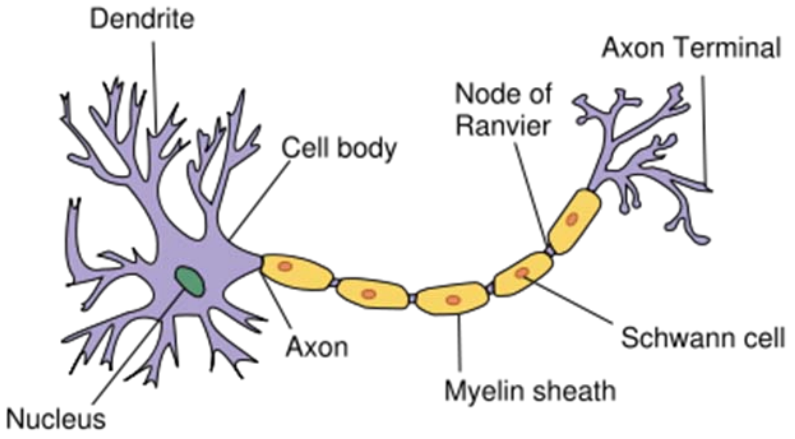
Neurons

- *Neurons* (also known as *nerve cells*) are electrically excitable cells in the nervous system that process and transmit information. The function of a neuron is to generate and propagate a nerve impulse.



Neuron Structure

- Neurons are typically composed of a *soma*, or cell body, a *dendritic tree* and an *axon*. The soma contains the *cell nucleus*. The majority of vertebrate neurons receive input on the cell body and dendritic tree, and transmit output via the axon.

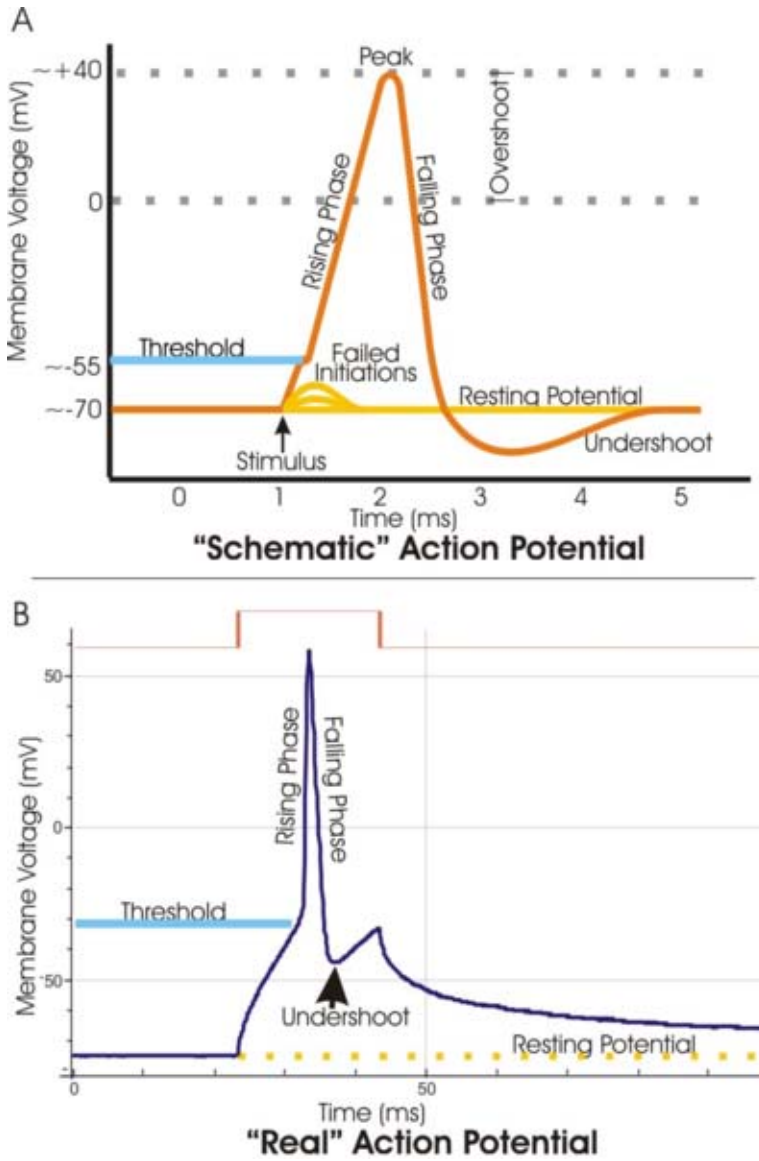


Nerve Impulse and Myelin

- The *nerve impulse* is a continuous change propagated along the axon
- Axons of many neurons are surrounded by *myelin*, an electrically-insulating phospholipid layer. The myelin layer increases the speed at which impulses propagate. It also helps prevent the electrical current from leaving the axon. Myelin is produced by *Schwann cells*.

Communication Between Neurons

- Neurons communicate via chemical and electrical *synapses*, in a process known as *synaptic transmission*. The fundamental process that triggers synaptic transmission is the *action potential*, a "spike" of positive and negative ionic discharge that travels along the *membrane* (i.e., the wall) of a cell. The height of the spike is ~50 millivolts, and its duration is 1-2 milliseconds.



Reversibility of The Change

- When the impulse has passed, the *resting potential* is restored. The term “resting” is somewhat misleading, as it takes a cell more energy to maintain the resting potential than to transmit nerve impulses. The establishment of this potential involves the *active transport* of potassium and sodium ions into and out of the cell accomplished by a number of *sodium-potassium pumps* scattered across the cell membrane. Each pump transports two ions of potassium into the cell for every three ions of sodium pumped out.

Stimulation

- *Stimulation* (*initiation*, induction) of a nerve pulse may or may not succeed. If it fails (see “Failed Initiations”), no disturbances propagate along the axon. If it succeeds, a nerve impulse will move along the axon.
- Let the resting potential mean ‘0’, and let the peak values above the threshold represent ‘1’. The process of pulse stimulation is… digital?
- The axon carries nerve signals away from the soma (and also carry some types of information back to it). Many neurons have only one axon, but this axon may - and usually will - undergo extensive branching, enabling communication with many target cells.

Synapses

- *Chemical synapses* are specialized junctions through which the cells of the nervous system signal to each other and to non-neuronal cells such as those in muscles or glands. The backflow of a nerve impulse is inhibited by the fact that an axon does not possess chemoreceptors and dendrites cannot secrete neurotransmitter chemicals.
- The human brain contains a huge number of chemical synapses; young children have about 10^{16} synapses (10 quadrillion). This number declines with age, stabilizing by adulthood. Estimates for adults vary from 10^{15} to 5×10^{15} (1-5 quadrillion) synapses.
- An *electrical synapse* is a mechanical and electrically conductive link between two abutting neurons that is formed at a narrow gap between the pre- and postsynaptic cells known as a gap junction. At gap junctions, cells approach within about 3.5 nm of each other, a much shorter distance than the 20 to 40 nm distance that separates cells at chemical synapses. As opposed to chemical synapses, the postsynaptic potential in electrical synapses is not caused by the opening of ion channels by chemical transmitters, but by direct electrical coupling between both neurons. Electrical synapses are faster and more reliable than chemical synapses. Electrical synapses are found throughout the nervous system, yet are less common than chemical synapses.

Synchronization of Neurons

- Recent results using multiple electrodes to record from several neurons at a time showed that neurons frequently fall into step with one another, forming *ensembles* that fire in relative synchrony for brief periods before some neurons drop out of synch. What's more, studies of such systems as the motor cortex of monkeys indicate that these changing patterns of synchrony correlate with specific behaviors. These findings suggest that the brain encodes information not just in the firing rates of individual neurons, but also in the patterns in which groups of neurons work together.

Summary of Comparisons

- Brain: More, but slower organs. (The firing rate of a neuron cannot exceed 100 Hz.)
- Computer: Fewer, but faster organs. More operations per second, but how much does one operation accomplish?
- Brain: **Highly** parallel