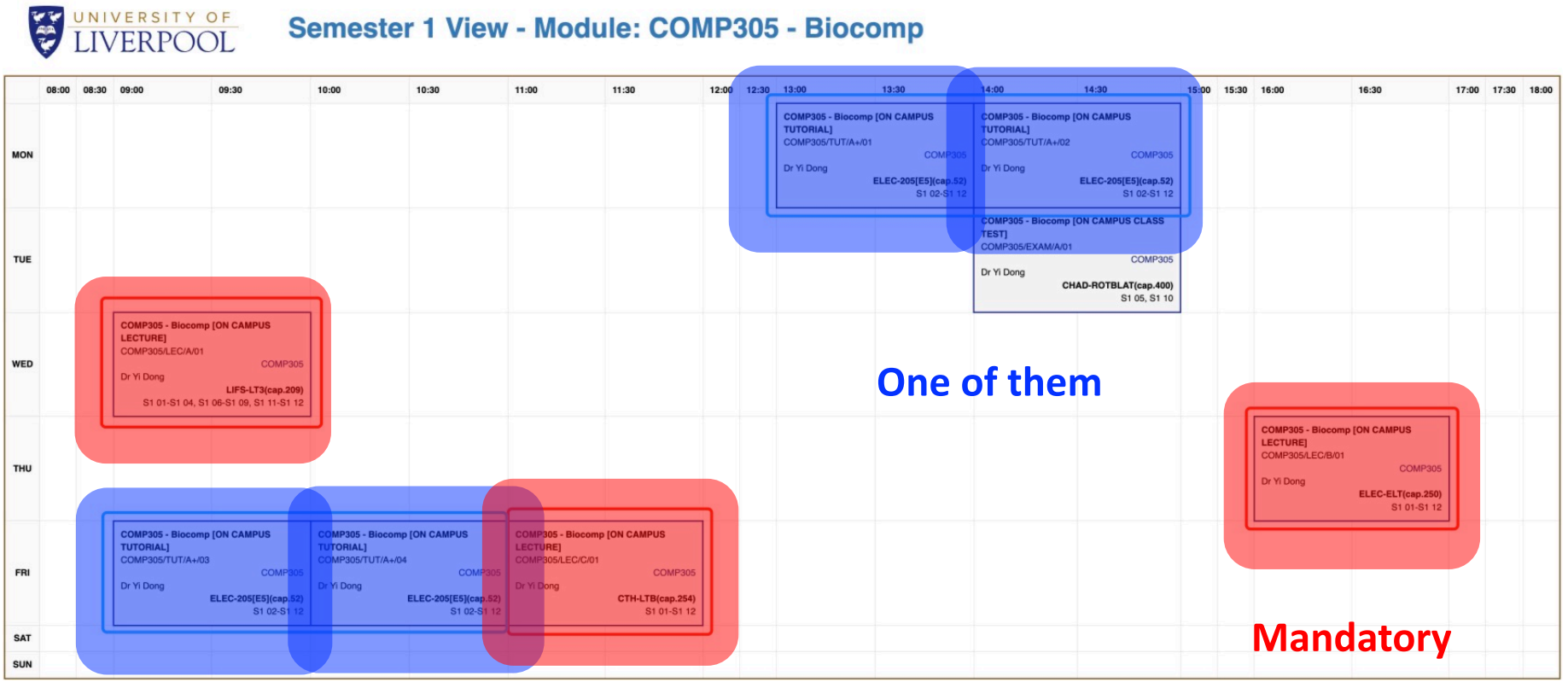
Comp305

Biocomputation

Lecturer: Yi Dong

Comp305 Module Timetable



There will be **26-30** lectures, thee per week. The lecture slides will appear on Canvas. Please use Canvas to access the lecture information. There will be **9** tutorials, one per week.

Lecture/Tutorial Rules

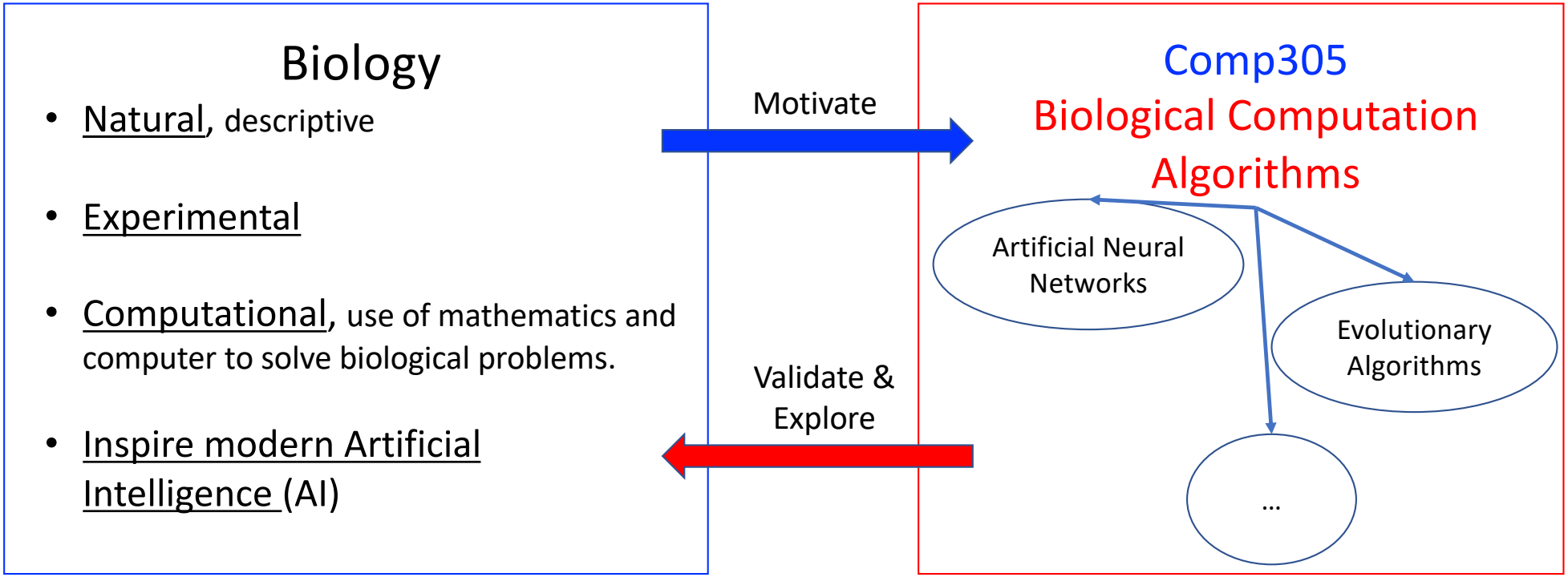
Questions are welcome as soon as they arise, because

1. Questions give feedback to the lecturer;

2. Questions help your understanding;

3. Your questions help your classmates, who might experience difficulties with formulating the same problems/doubts in the form of a question.

Overview & Structure



Comp305 Part I.

Artificial Neural Networks

Objective of Part I

- The Artificial Neural Networks (ANN) constitute
  - A part of computer science
  - Based on some neuroscience ideas.

- ANNs claim to be the last *6^{th} generation of computing technology*.

- The aim of the part I is to introduce students to the Artificial Neural Networks and some of their applications.

Topic 1.

Historical/Biological Introduction

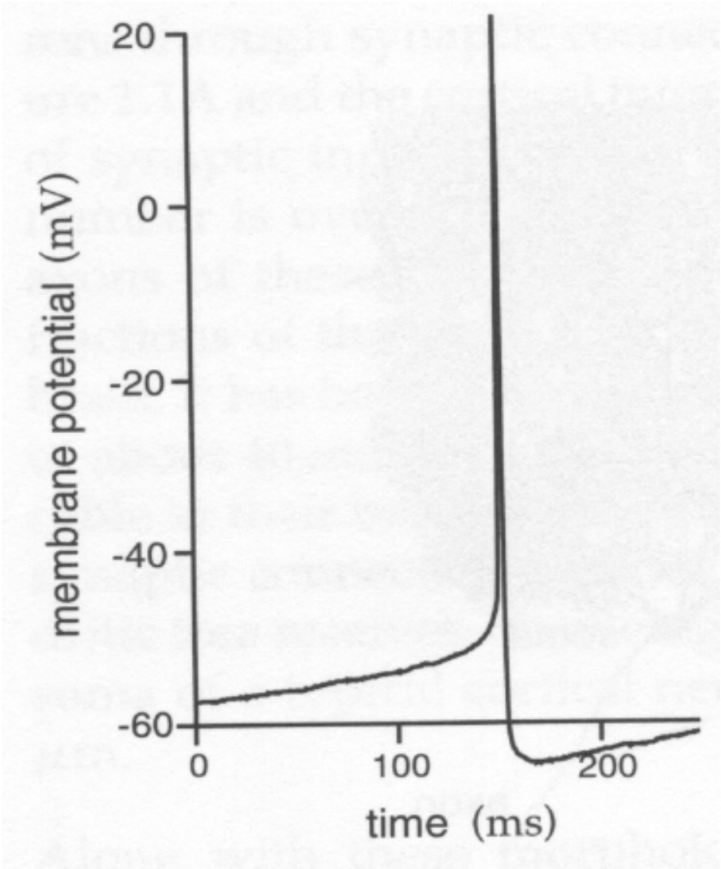
Topic of This Lecture

How does a biological neuron propagate information?

Outline

- A brief introduction of the information propagation mechanism of neurons.
  - Key words: potentials, spikes, excitation, propagation
- What is biological excitation?
  - Internal mechanism
- The components of a neuron that enable the propagation.
  - External mechanism
- What are really propagated by a neuron?
  - Spikes, rather than all the potentials.

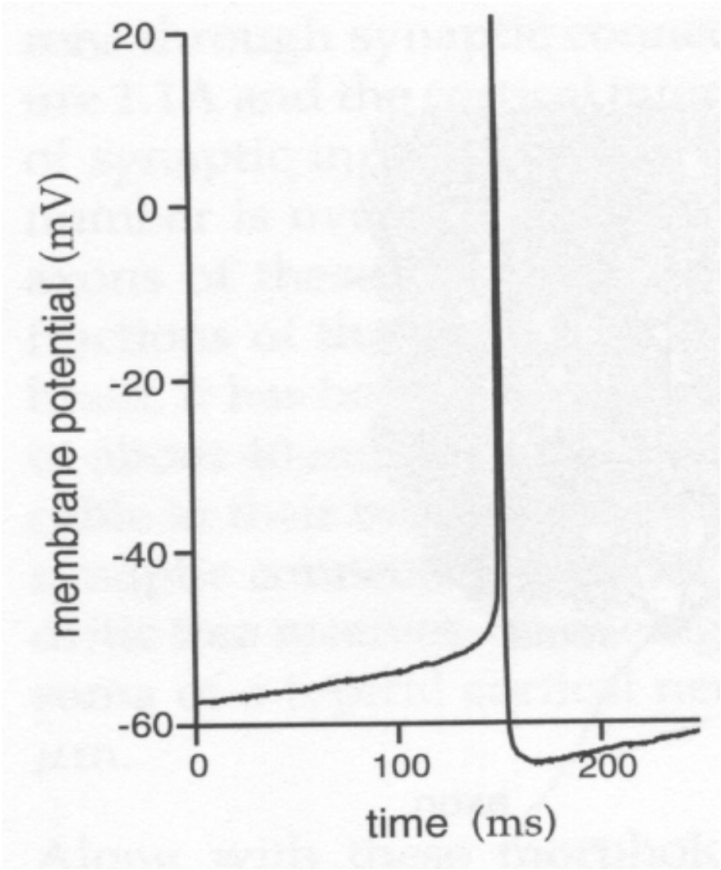
Overview: Nerve fibers. Trains of Spikes.



Neurons

- are remarkable among the cells of the body in their ability to propagate signals rapidly over large distances.
- propagate information by generating characteristic electrical pulses called *action potentials* or *spikes* that can travel down nerve fibers.
- are highly specialized for generating electrical signals in response to chemical and other inputs and transmitting them to other cells.
- represent and transmit information by firing sequence of spikes in various temporal patterns.

Overview: Nerve fibers. Trains of Spikes.



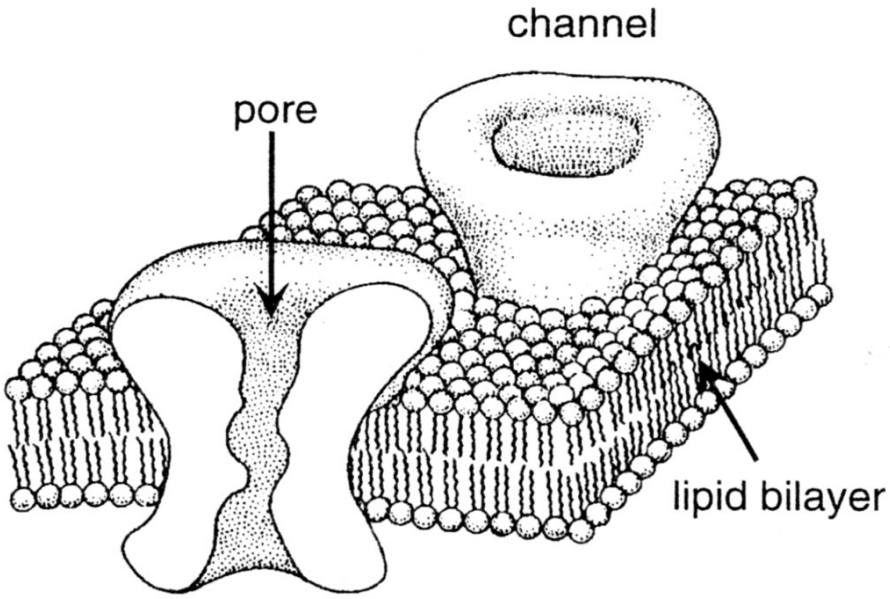
The electrical nature of nerve impulses was established in the middle of 19th century.
In 1852, Herman von Helmholtz measured the velocity of nerve impulses and showed that it was not as fast as was previously thought, just about 27 m/s.

Biological Excitability

- Virtually all living cells maintain an electrical potential difference between their interiors and the environment (exteriors).

- The membrane potential is one of the factors determining the energy barriers encountered by charged substances (ions) entering or leaving the cell.

Biological Excitability



Within the cell membrane there are ion channels – proteins with the central pore through which ions can cross the membrane.

A cell membrane acts as a barrier for ions.

Biological Excitability

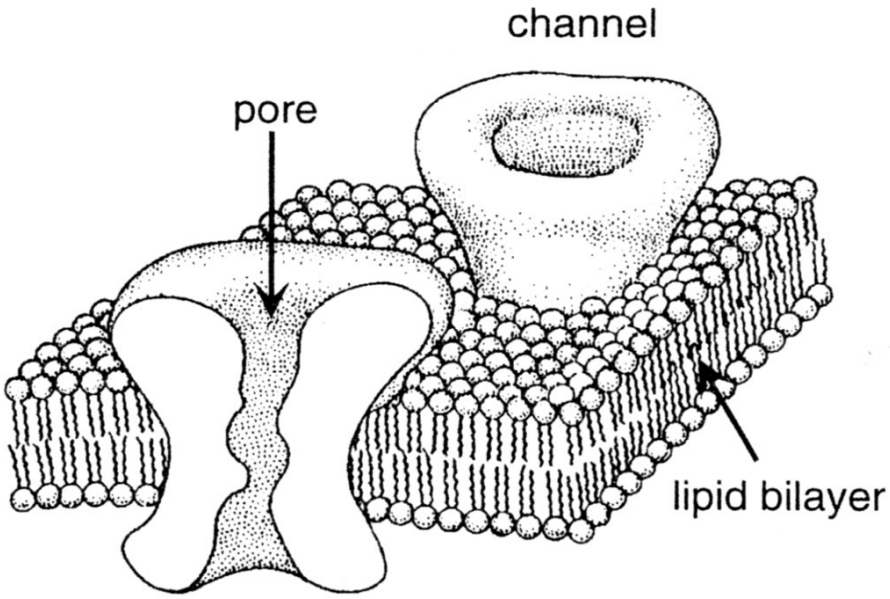
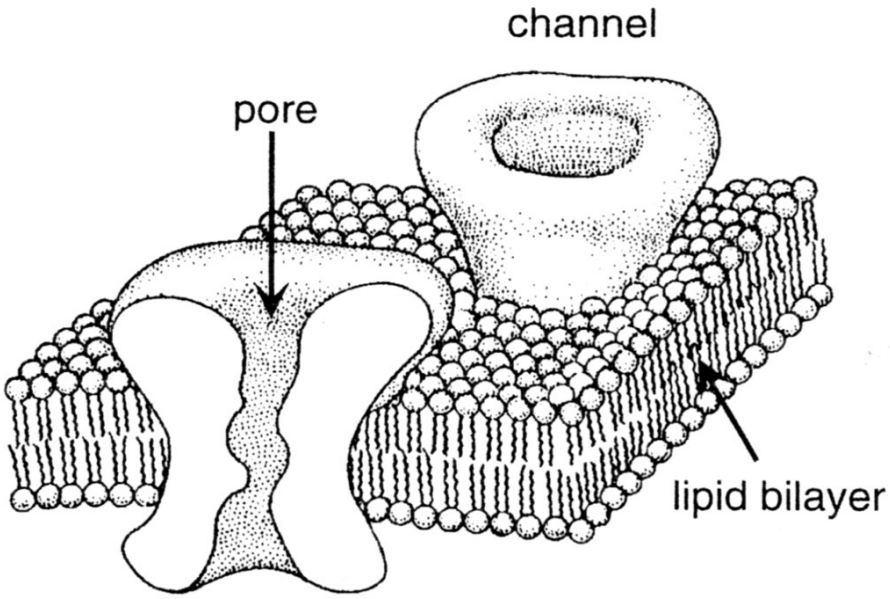


Figure. A schematic diagram of a **section of the lipid bilayer** that forms the cell membrane with two ion channels embedded in it. The membrane is 3 to 4 nm thick, and the ion channels are about 10 nm long.

A cell membrane acts as a barrier for iron.

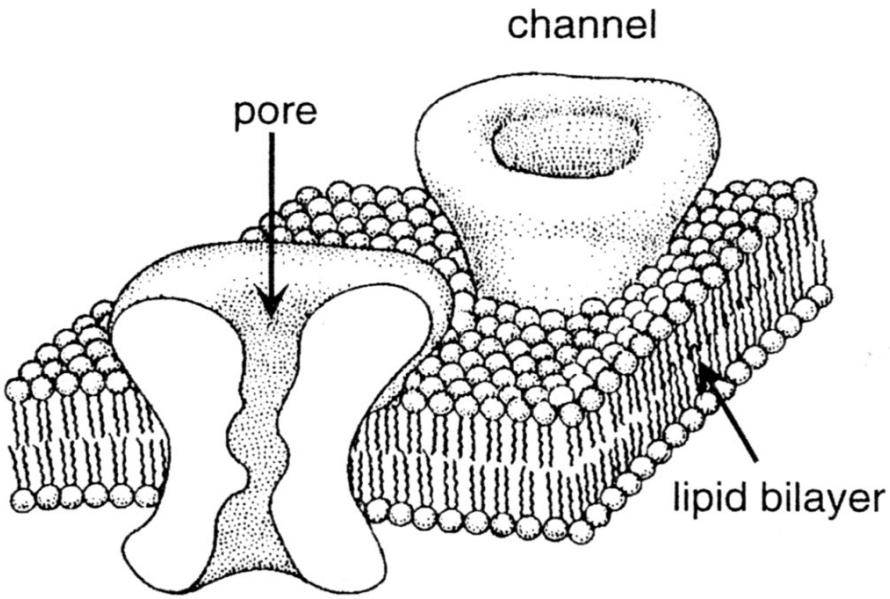
Biological Excitability



- A wide variety of membrane-spanning ion channels allow ions, predominantly sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and chloride (Cl^-), to move in and out of the cell.
- Ion channels control the flow of ions across the cell membrane by opening and closing in response to voltage changes and to both internal and external signals.

A cell membrane acts as a barrier for iron.

Biological Excitability



- Under *resting* conditions (normal, inactive, not sending a signal), the potential inside neuron membrane is from -30 mV to -90 mV relative to that of the surrounding bath, conventionally defined to be 0 mV, and the cell is said to be ***polarized***.

- **The electrical signal** of a living cell is change of the membrane potential.

Biological Excitability

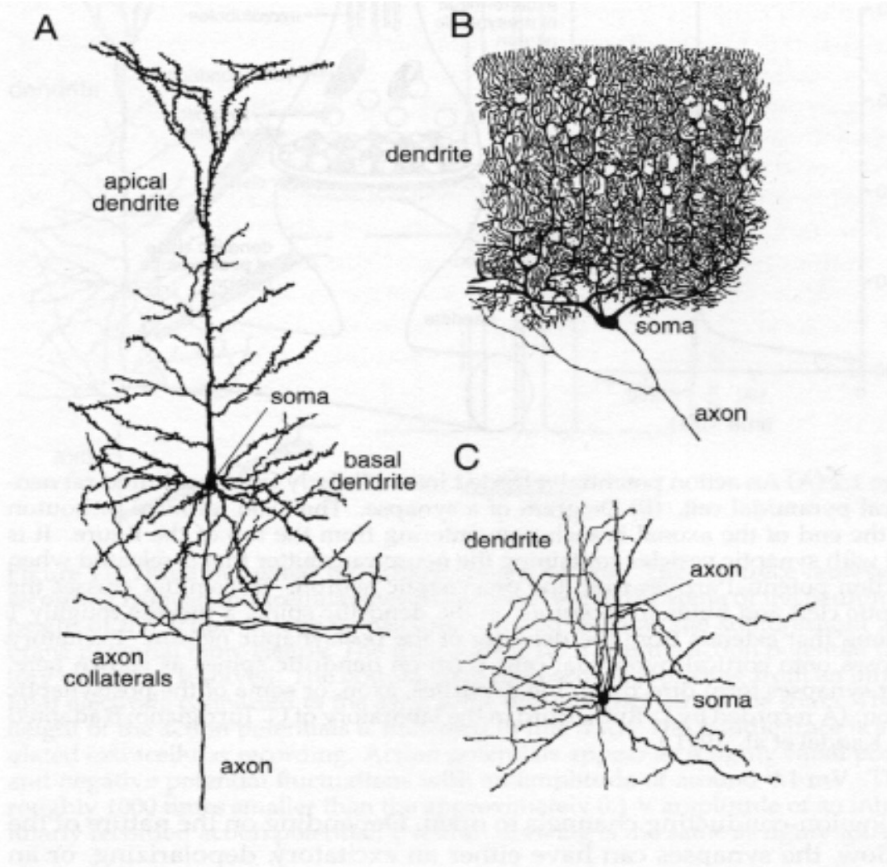
- The membrane potential may change in response to electrical perturbation from other neurons.

- If the perturbation is sufficiently large, **above a threshold** in intensity and duration, the response is a large amplitude electrical wave, propagating from the stimulated points to the rest of the tissue.

Biological Excitation. Wave Propagation.

- The wave travels with a nearly **uniform velocity**.
- The excitation and transmission are **all-or-none** and do not allow varying degree of strength.
- Excitation is followed by **an unexcitable period of definite duration**, called the absolute refractory period; which is followed in turn by a relative refractory period when the cell has subnormal excitability.

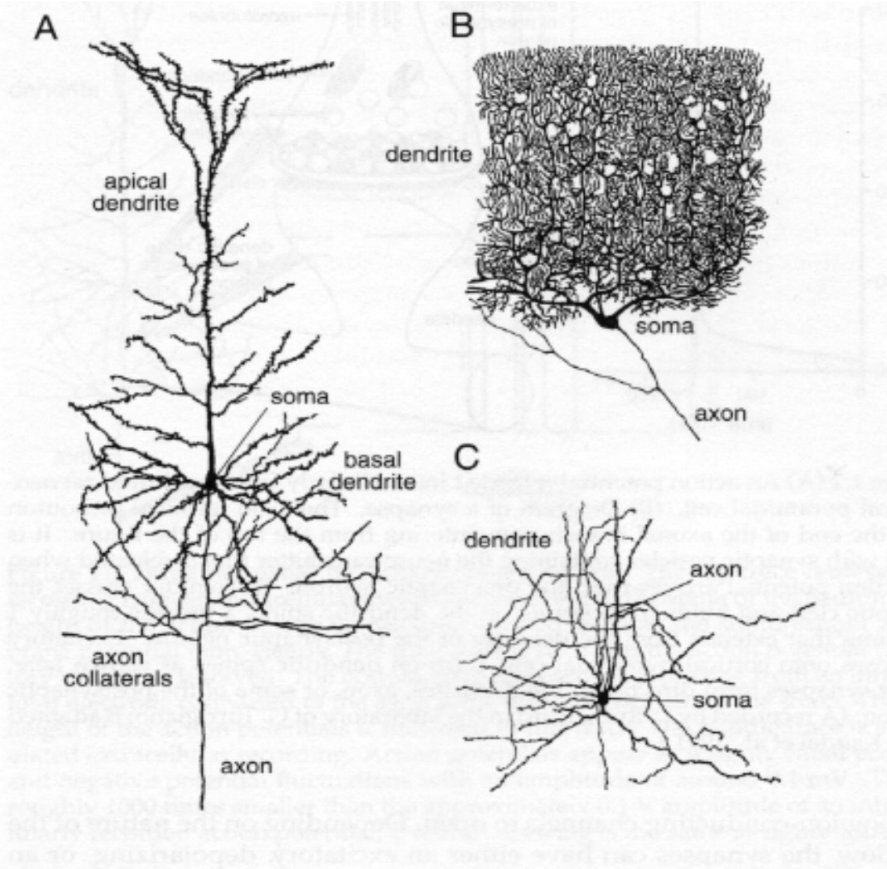
Neuron Components



- Important morphological specializations of neurons are the dendrites that receive inputs from other neurons, soma (the cell body), and the axon that carries the neuronal output to other cells.

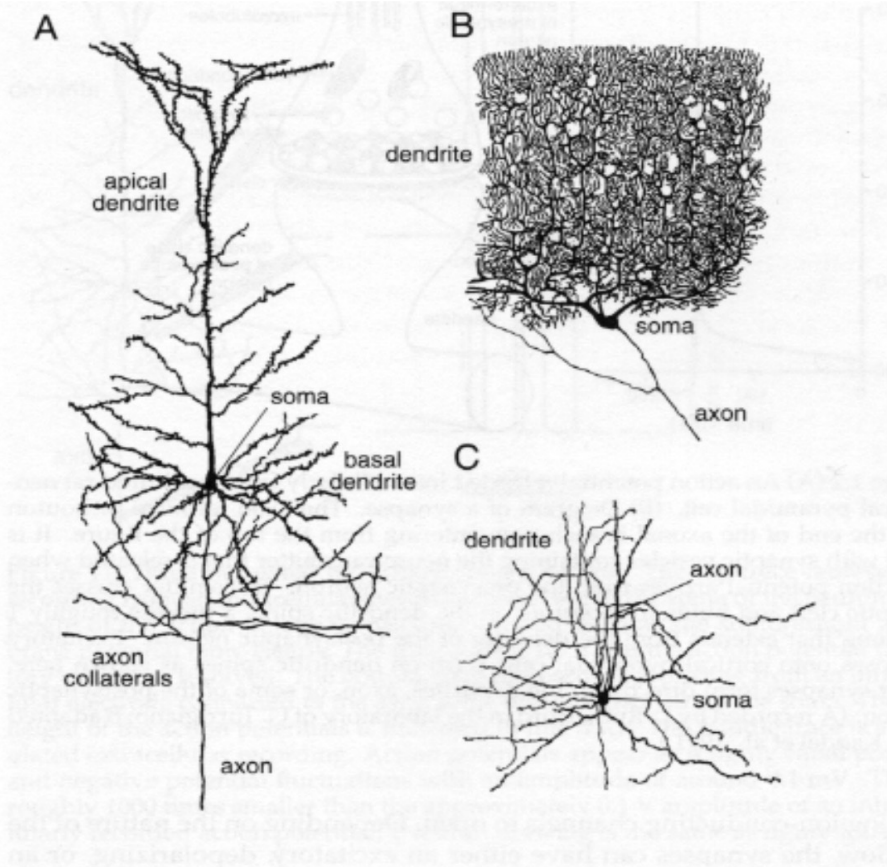
- The elaborate branching structure of the dendritic tree allows a neuron to receive inputs from many other neurons through synaptic connections.

Neuron Components



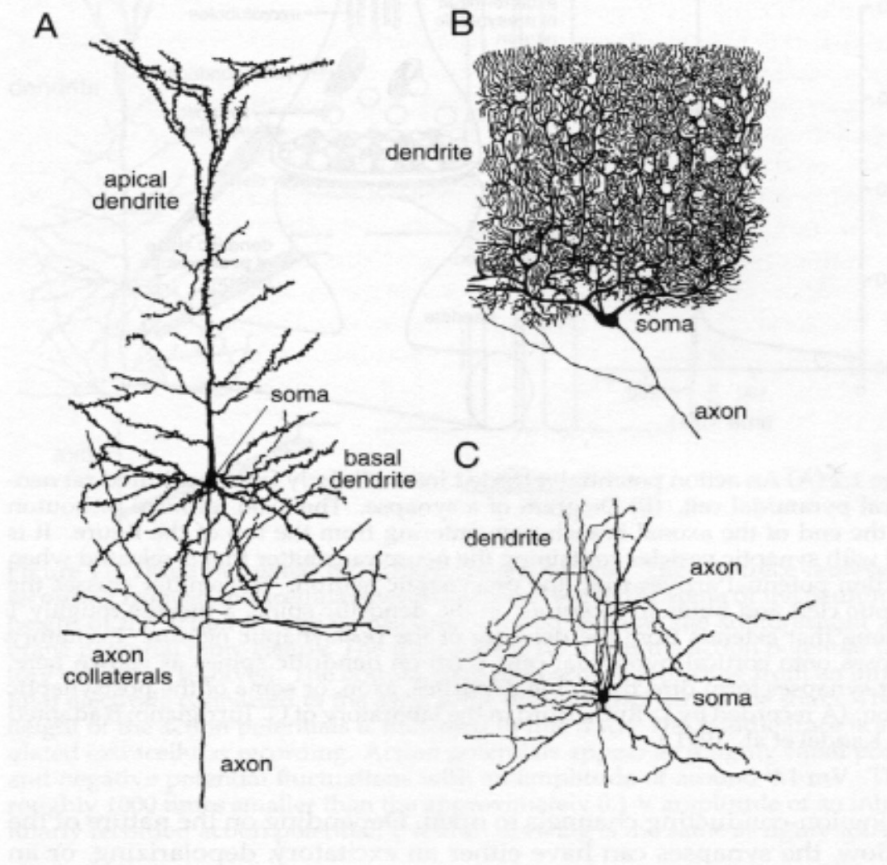
- The dendrites and soma act as input surface for signals from other neurons and/or receptors.
- The axon carries signals from the neuron to other neurons and/or effectors (e.g., muscle fibers or glands).

Some Examples – Neurons in Cerebral Cortex



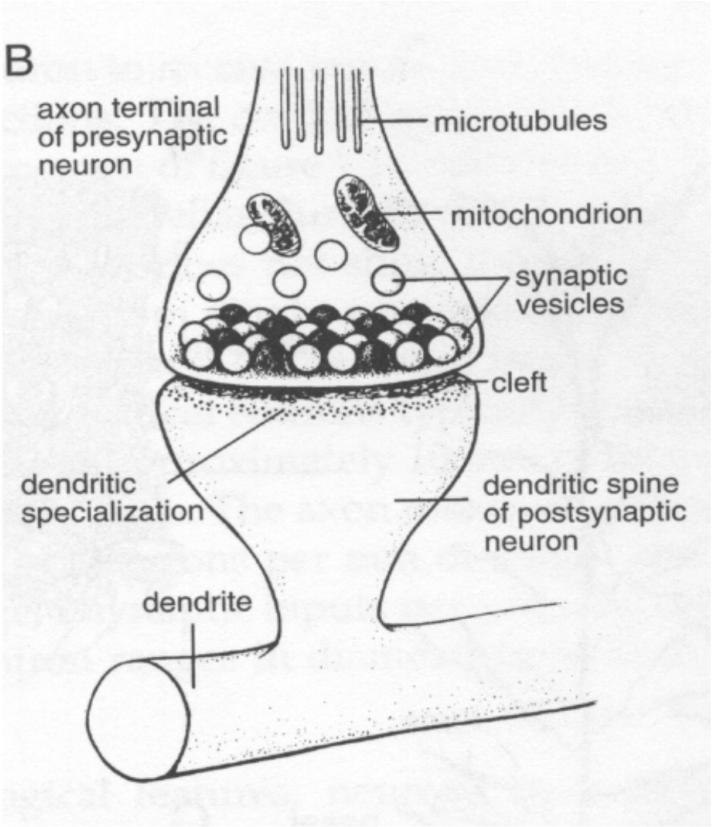
- (A): cortical pyramidal cell. These are the primary excitatory neurons of the cerebral cortex. Pyramidal cell axons branch locally, sending signals to synapse with nearby neurons, and also more distally to other parts of the brain and nervous system.
- (B): Purkinje cell. Purkinje cell axons transmit the output of the cerebral cortex.
- (C): stellate cell. Stellate cells are one of a large class of interneurons that provide inhibitory input to the neurons of the cerebral cortex.

Some Examples – Neurons in Cerebral Cortex



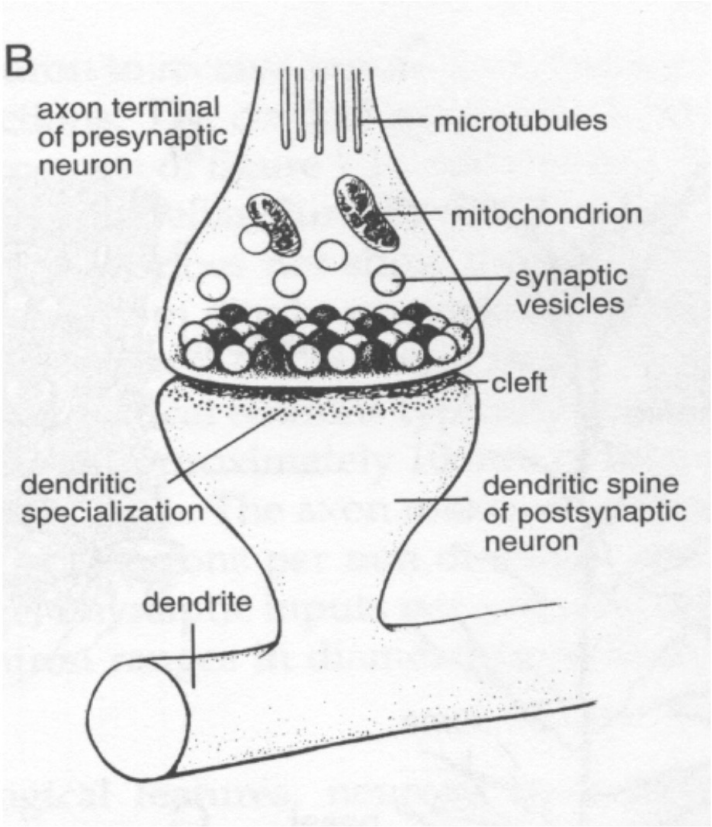
- The cortical pyramidal neuron A and the cortical interneuron C each receive **thousands of synaptic** inputs, and for the Purkinje cell B, the number is over 100,000.
- Axons from single neurons can traverse large fractions of the brain or, in some cases, of the entire body.
- Axons can also connect with multiple targets.

Trans-synaptic stimulation – External Mechanism



- The tips of the axon branches are called nerve terminals or boutons.
- The location of interaction between a terminal and the cell upon is called a synapse.
- A synapse shown in the left figure illustrates the presynaptic bouton at the end of the axon and a spine on the dendrite.

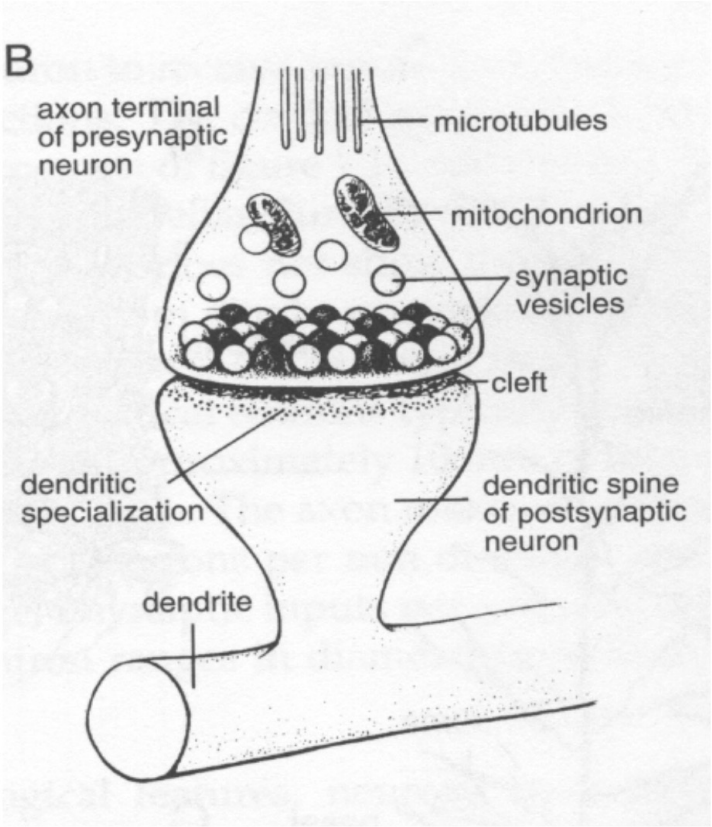
Trans-synaptic stimulation – External Mechanism



- The terminology of presynaptic and postsynaptic defines the direction of signal flow.

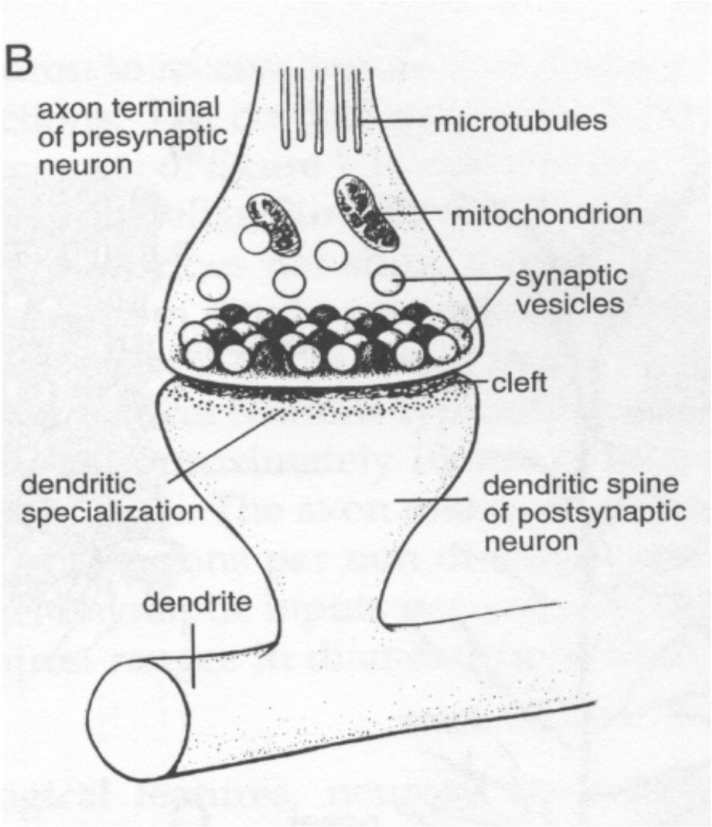
- Santiago Ramon y Cajal, ~1901, supposed that the specific networking of the nervous cells determines *direction of transmission of information*. This discovery made clear that the coupling of the neurons constitutes a **hierarchical system**.

Trans-synaptic stimulation – External Mechanism



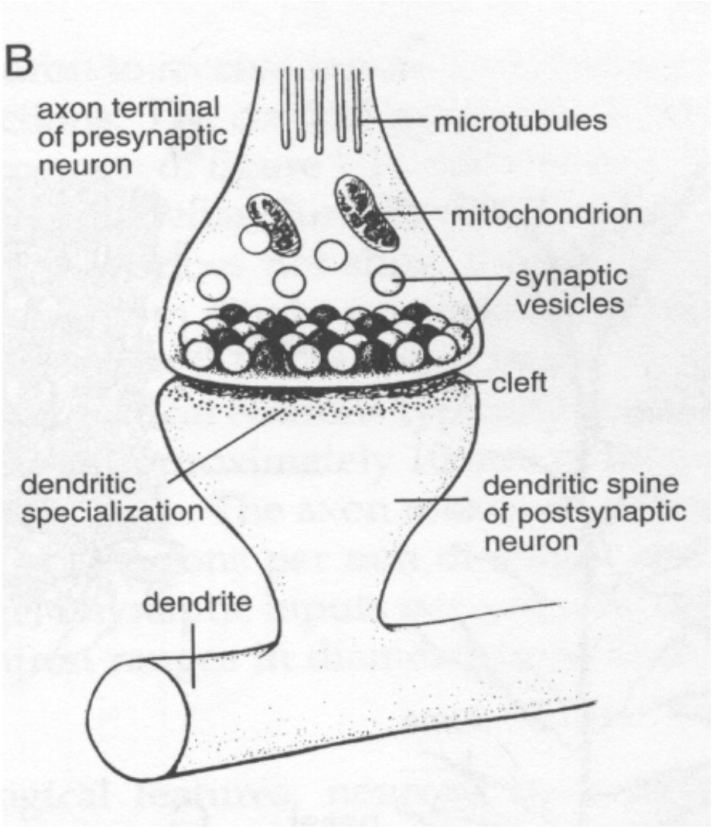
- The chemical transmission of information at the synapses was mostly studied from 1920 to 1940.
- The two neurons are not directly connected but communicate via the cleft.

Trans-synaptic stimulation – External Mechanism



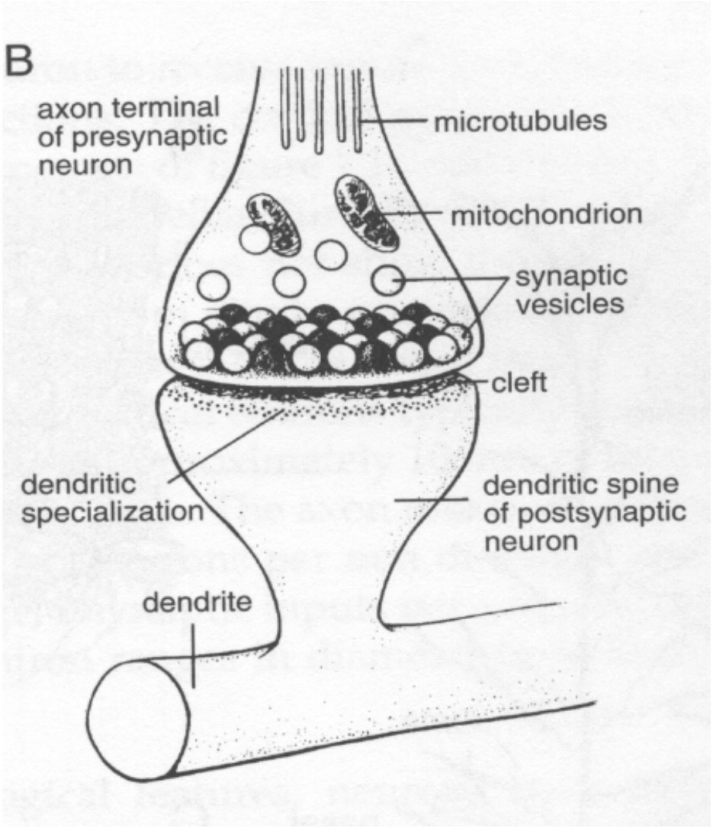
- The axon terminal or bouton is filled with synaptic vesicles containing neurotransmitter.
- The neurotransmitter is released when a spike arrives from the presynaptic neuron.

Trans-synaptic stimulation – External Mechanism



- Transmitter crosses the synaptic cleft and binds to receptors on the dendritic spine.
- Excitatory synapses on cortical pyramidal cells form on dendritic spines as shown here. Synapses can form on the dendrites, or axon.

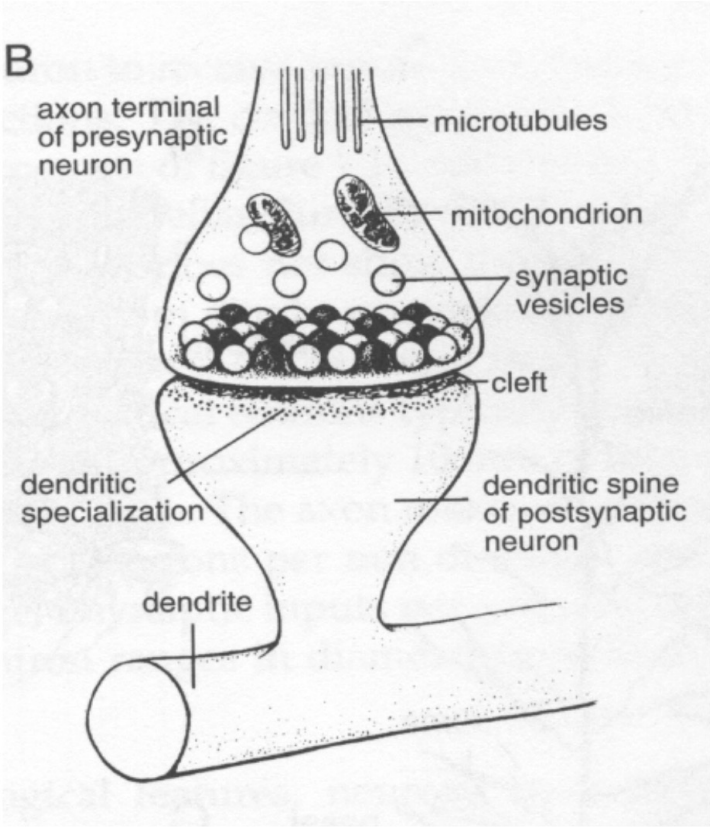
Trans-synaptic stimulation – External Mechanism



- Although impulses spread uniformly along axons, there is ***no physiological continuity from neuron to neuron***.

- When an impulse (perturbation) reaches a synapse, it does not necessarily stimulate the following neuron.

Trans-synaptic stimulation – External Mechanism

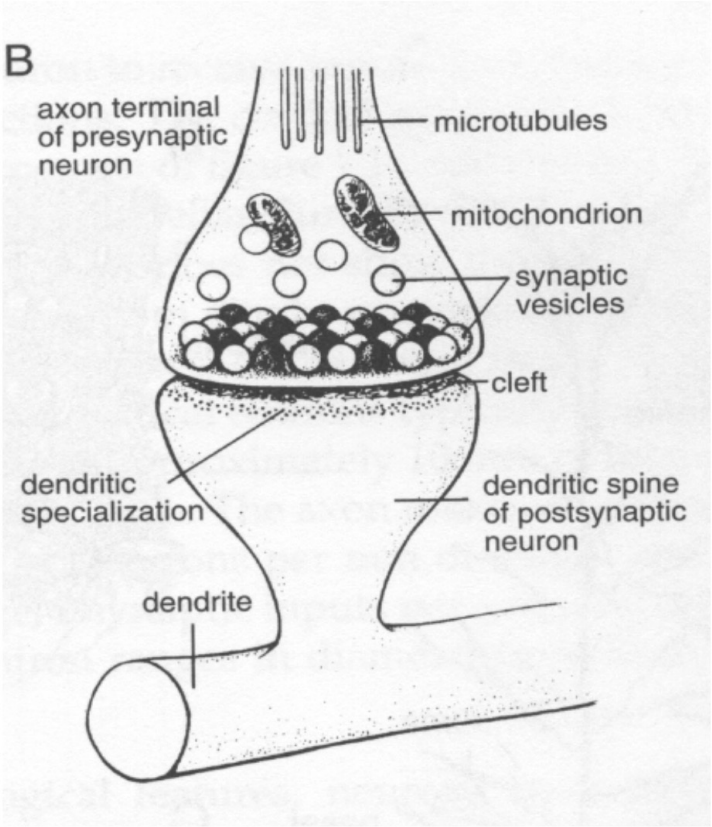


Trans-synaptic stimulation of a neuron requires usually

- either a repetition of impulses in time at the same synapse (*temporal summation*).
- or the simultaneous arrival of impulses at a sufficient number of adjacent synapses (*spatial summation*)

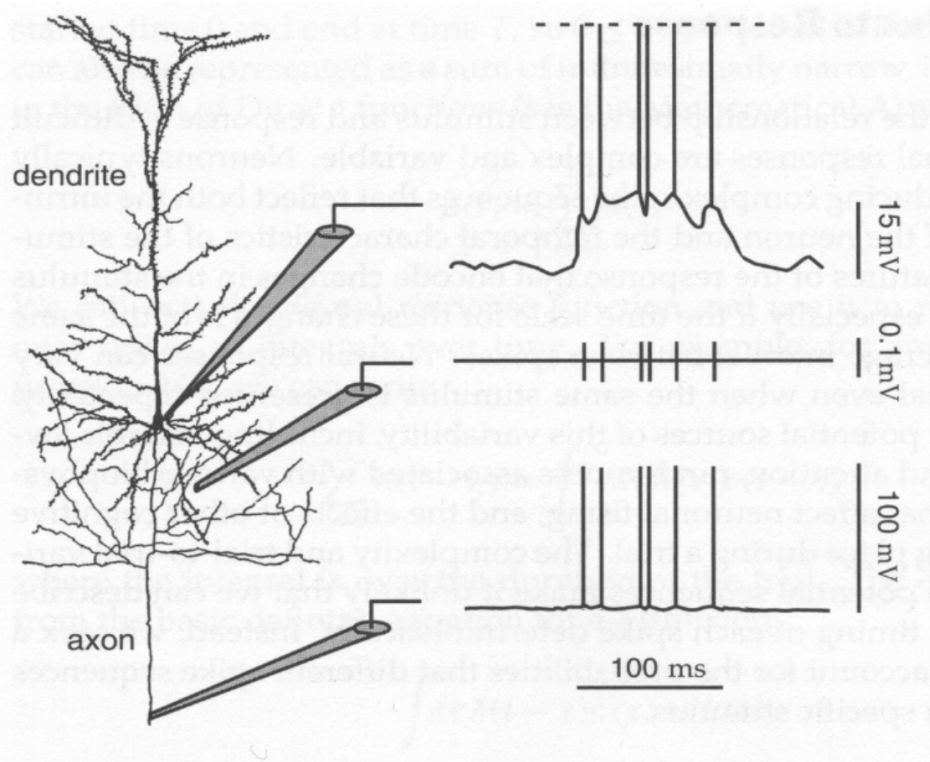
to make the “density” of excitation high enough at some region of the neuron.

Trans-synaptic stimulation – External Mechanism



- The arrival of impulses at synapses may have opposite to excitation effect, i.e., it may render the element less excitable to other stimuli. This decrease of excitability is called *inhibition*.

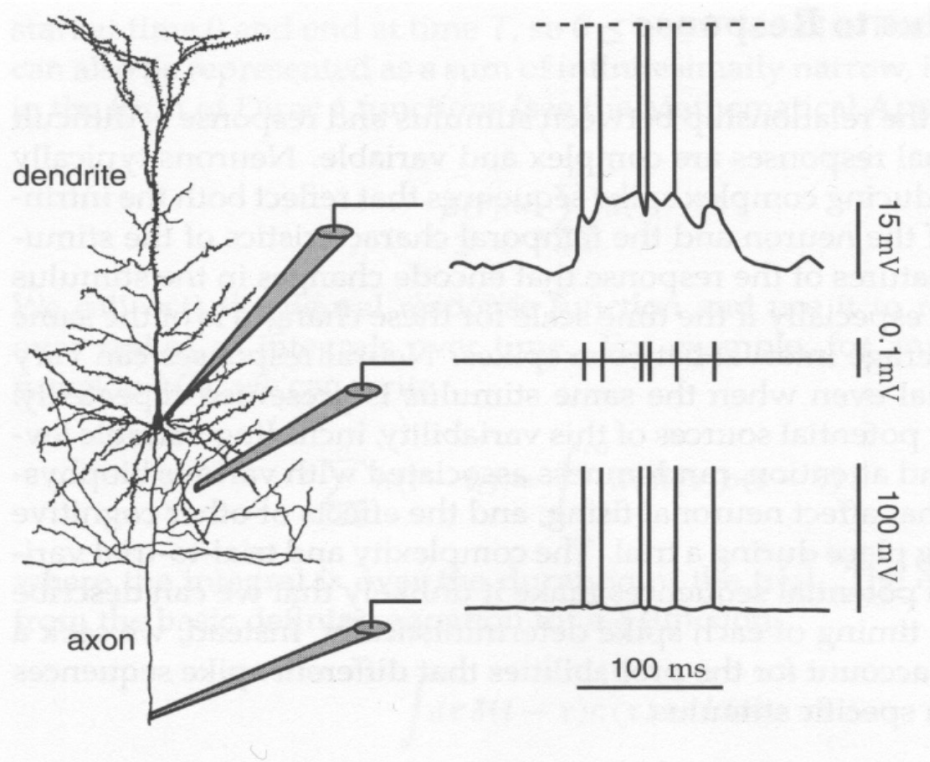
Neuronal Excitation



- The excitatory or inhibitory effect of the transmitter generally causes a ***potential change*** in the postsynaptic membrane.

- The ***cooperative effect*** of many potential changes may yield a synthesized potential change in the soma that **exceeds the threshold** – and if this occurs at a time when the neuron has passed the refractory period of its previous firing, then a new impulse is fired down the axon.

Records from a Neuron -- Cortical Pyramidal Neuron

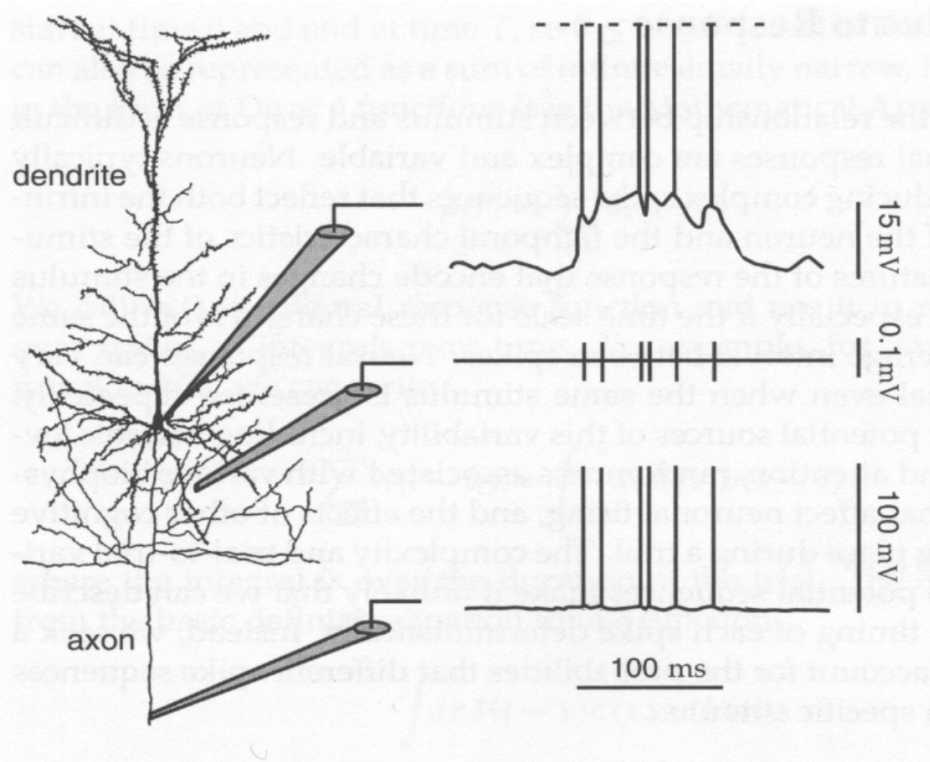


- ***The top trace*** represents a recording from an ***intracellular*** electrode connected to the ***soma*** of the neuron. The height of the action potentials has been clipped to show the subthreshold membrane potential more clearly.

- ***The middle trace*** is a simulated ***extracellular recording***. Action potentials appear as roughly equal positive and negative potential fluctuations with an amplitude of ~0.1mV, which is ~1000 times smaller than the approximately 0.1V amplitude of an intracellularly recorded action potential.

- ***The bottom trace*** represents a recording from an ***intracellular*** electrode connected to the ***axon*** some distance away from the soma. The full height of the action potentials is indicated in this trace.

Records from a Neuron -- Cortical Pyramidal Neuron



- **The top recording from soma** shows rapid spikes riding on top of a more slowly varying subthreshold potential.
- **The bottom trace** shows intracellular recording from axon some distance out of soma. The subthreshold membrane potential waveform, apparent in the soma recording, is completely absent on the axon due to attenuation, while the action potential sequence in the two recordings is the same.
- The difference in records from soma and from the axon illustrates the important point that

spikes, but not subthreshold potentials, propagate regeneratively down the axons.

Summary: Neuron Signal Processing

Neuron	Input	Dendrites: From huge number of neurons, sometimes very distant ones
	Excitation	From a repetition of impulses in time at the same synapse (***temporal summation***) or from the simultaneous arrival of impulses at a sufficient number of adjacent synapses (***spatial summation***) to make the "density" of signal high enough at some region of the neuron to overcome ***the excitation threshold***. There are ***refractory periods.***
	Output	Axon: To huge number of neurons, sometimes very distance ones
Neuron-to-Neuron	Propagation	**spikes, but not subthreshold potentials, propagate regeneratively down the axons.**