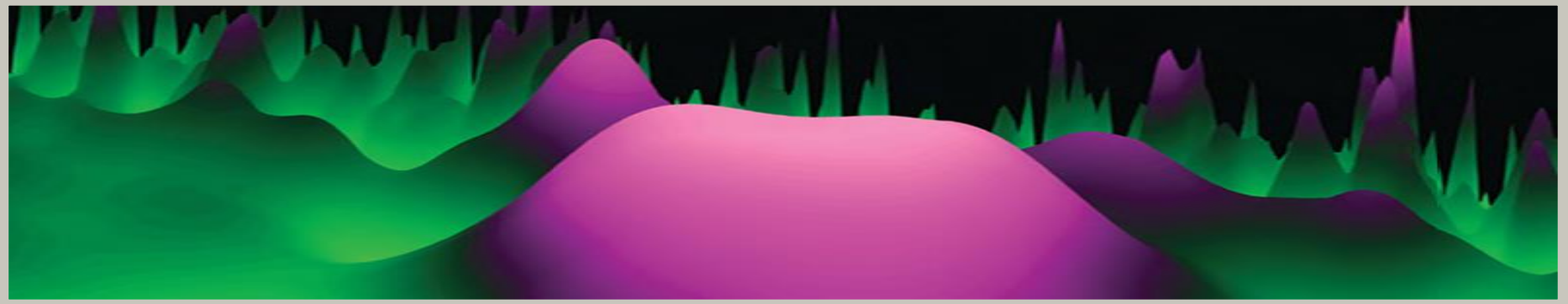
Introduction to neural signal analysis

Brandenburg University of Technology

Summer Winter Semester 2025/2026



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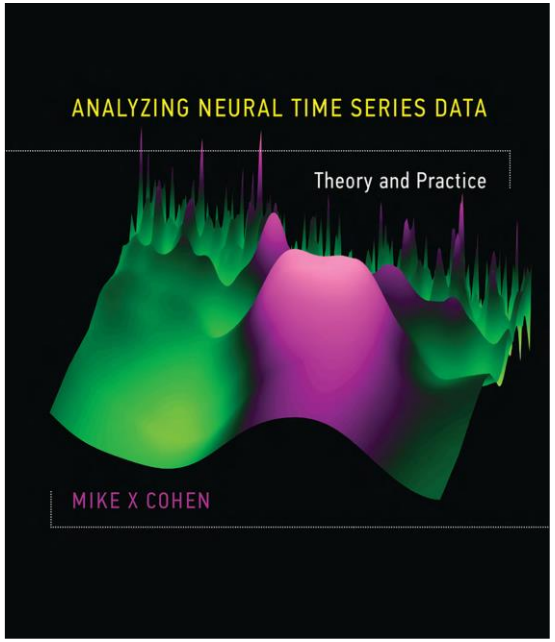
ANALYZING NEURAL TIME SERIES DATA
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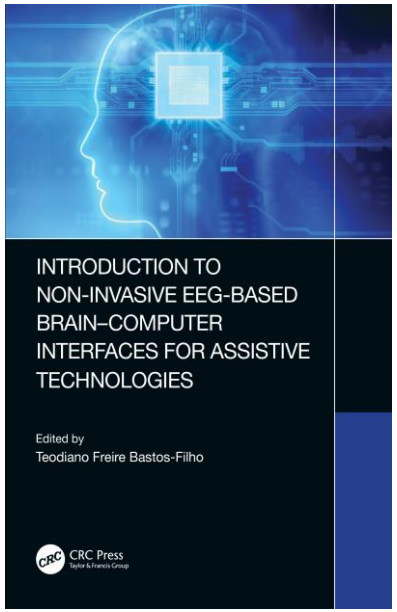
INTRODUCTION TO NON-INVASIVE EEG-BASED BRAIN–COMPUTER INTERFACES FOR ASSISTIVE TECHNOLOGIES
Edited by
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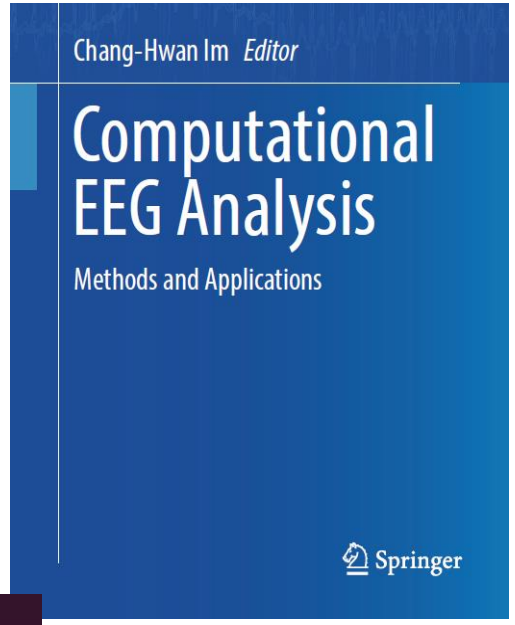
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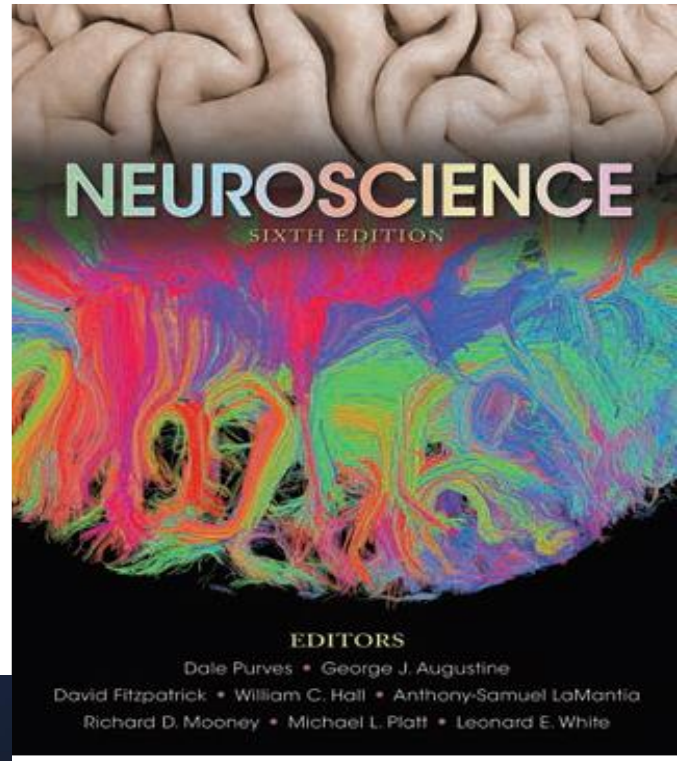
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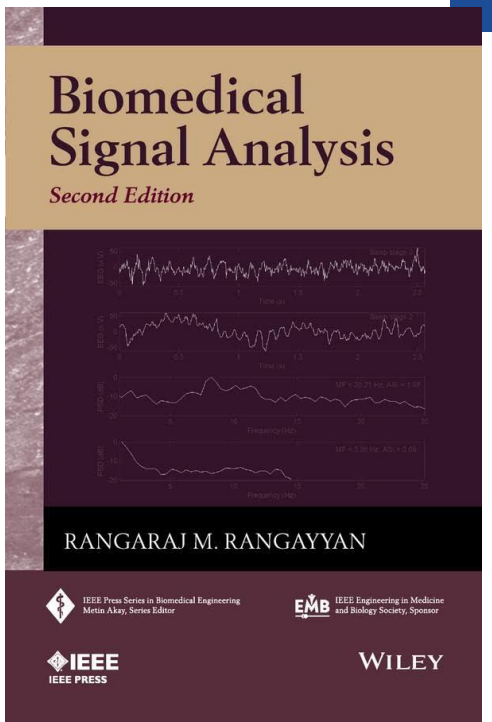
Biomedical Signal Analysis
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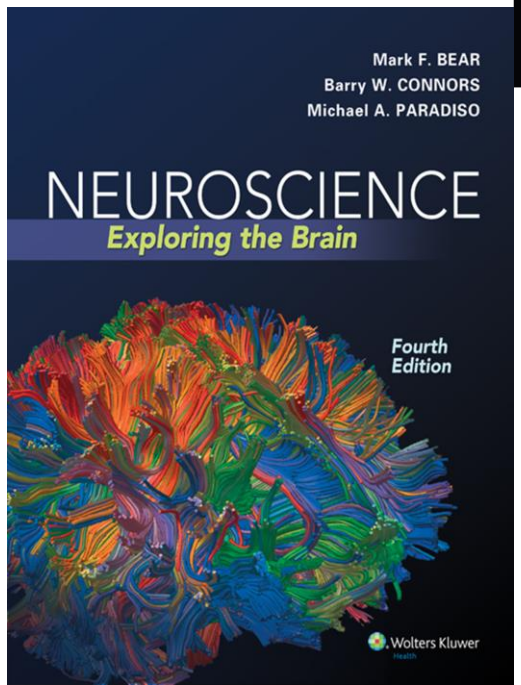
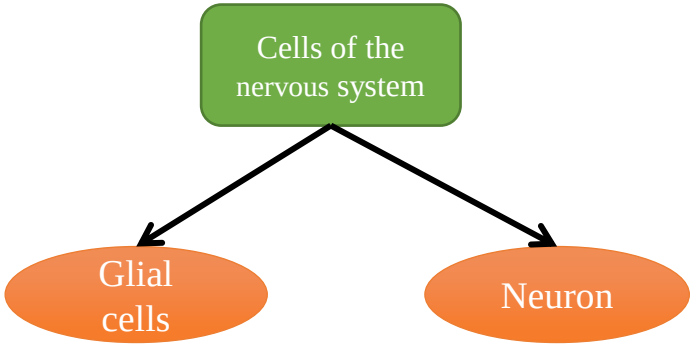

Mark F. BEAR
Barry W. CONNORS
Michael A. PARADISO
NEUROSCIENCE
Exploring the Brain
Fourth Edition
Wolters Kluwer

Goals of the course

- To understand
  - Basic knowledge of neural signals and specifically EEG signal, their origin and generation
  - What problems and needs are related to the acquisition and processing of EEG
  - What kind of methods are available and get an idea of they are applied and which kind of problem
- To get to know how we can analysis the EEG signals appropriately to get reliable results.

Neuron



- support the signaling functions of nerve cells.
- repairing nervous system Damage.
- Acting as stem cells in some brain areas .
- In other regions, they prevent regeneration where uncontrolled regrowth might do more

electrical signaling over long distances

Cell body (soma): spherical central part of the neuron (diameter : 20 μm), contains nucleus, cytoplasm (organelles, cytosol,..).

***dendrites*:** receive signals from neighboring neurons (like a radio antenna).

***axon*:** transmit signals over a distance (like telephone wires)

***axon terminal*:** transmit signals to other neuron dendrites or tissues (like a radio transmitter)

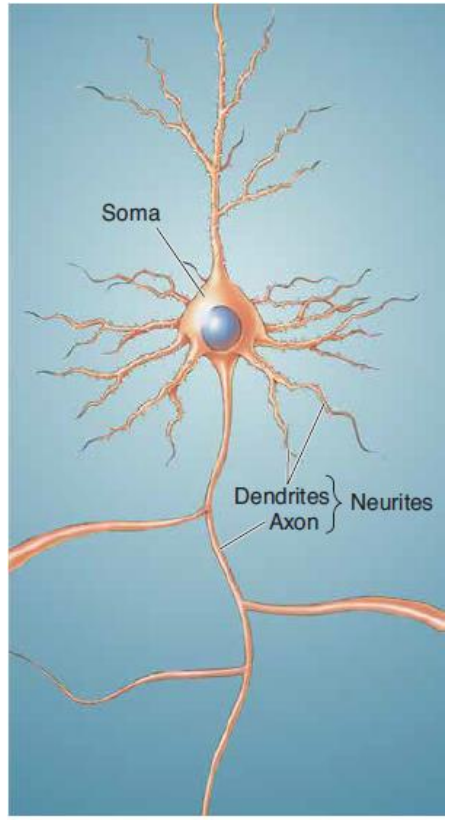
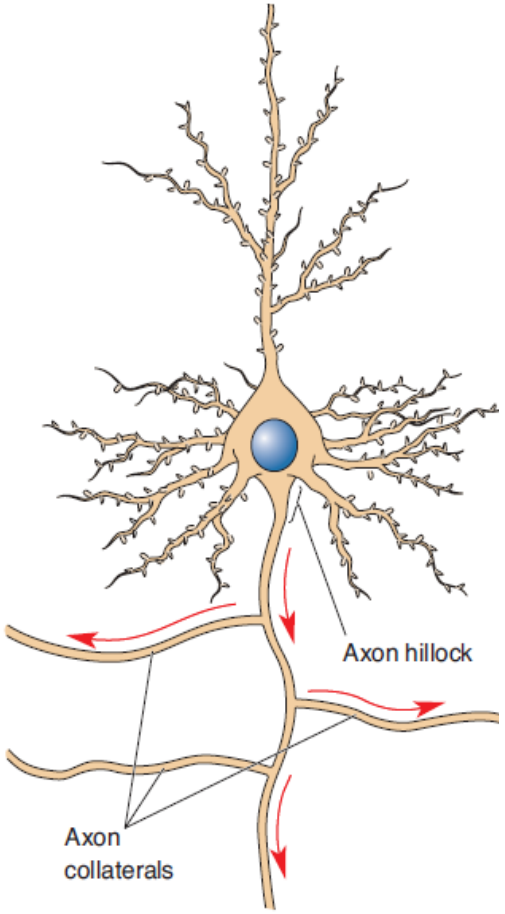
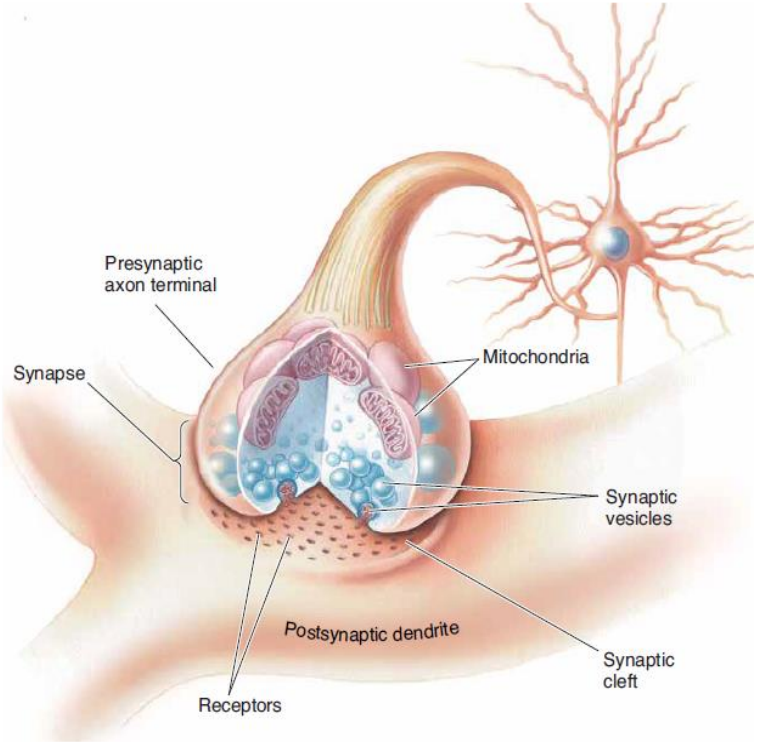


FIGURE 2. 4, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

The axon and axon collaterals.

The axon functions like a telegraph wire to send electrical impulses to distant sites in the nervous system. The arrows indicate the direction of information flow.





The process by which the information encoded by action potentials is passed on at synaptic contacts to a target cell is called **synaptic transmission.**

The axon terminal and the synapse. Axon terminals form synapses with the dendrites or somata of other neurons. When a nerve impulse arrives in the presynaptic axon terminal, neurotransmitter molecules are released from synaptic vesicles into the synaptic cleft. Neurotransmitter then binds to specific receptor proteins, causing the generation of electrical or chemical signals in the postsynaptic cell.

FIGURE 2.15 and 2.16 , Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

Some of the diverse nerve cell morphologies

The variation in the **size** and **branching** of **dendrites** is cause to different **information-processing** capacity of individual neurons.

The number of inputs to a single neuron reflects the degree of **convergence**, while the number of targets innervated by any one neuron represents its **divergence**.

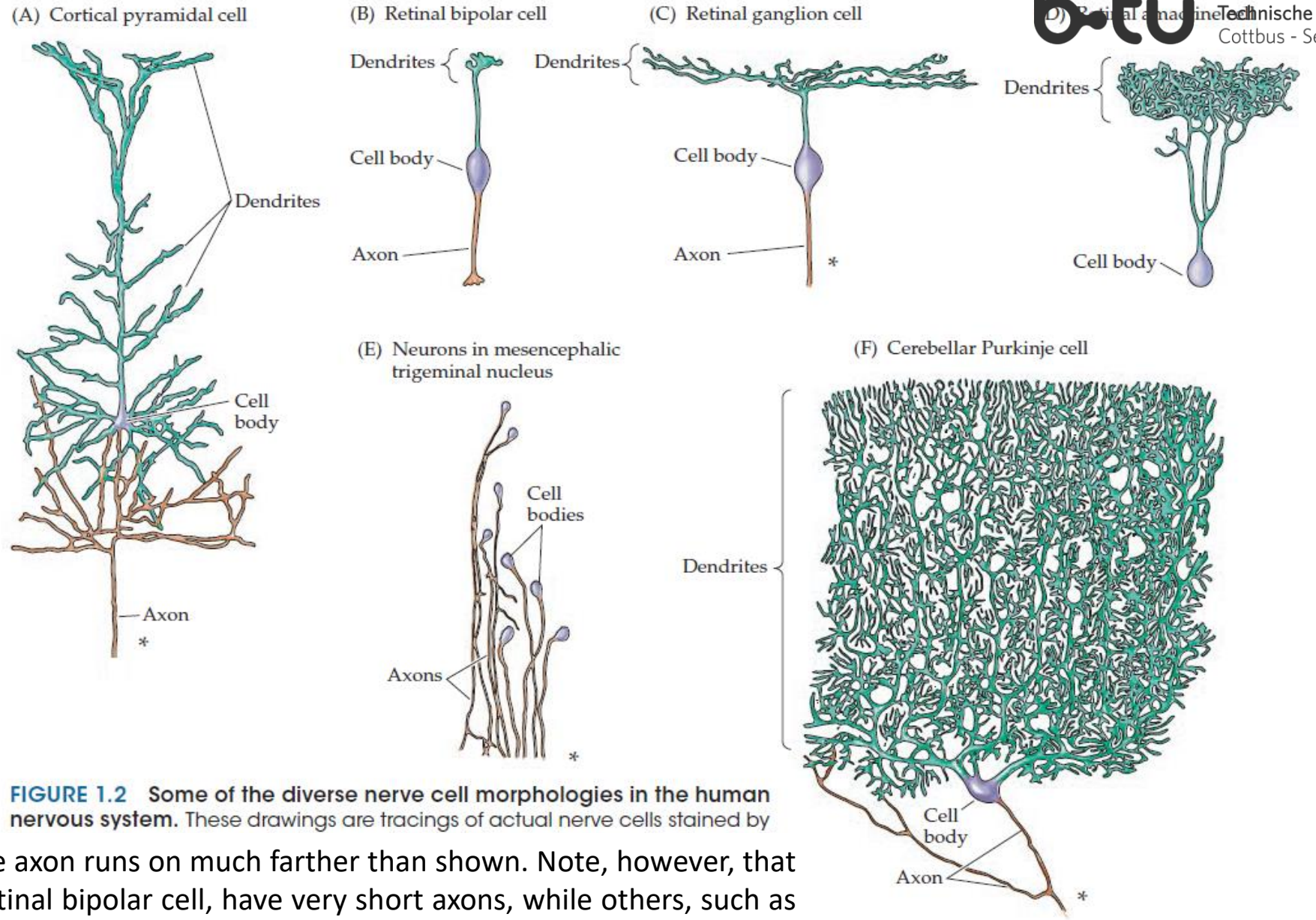


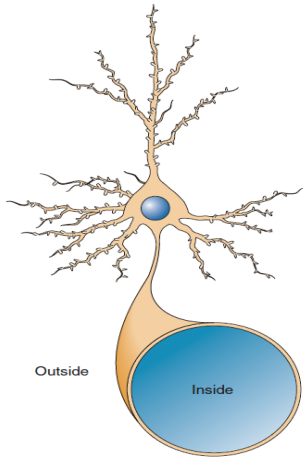
FIGURE 1.2 Some of the diverse nerve cell morphologies in the human nervous system. These drawings are tracings of actual nerve cells stained by

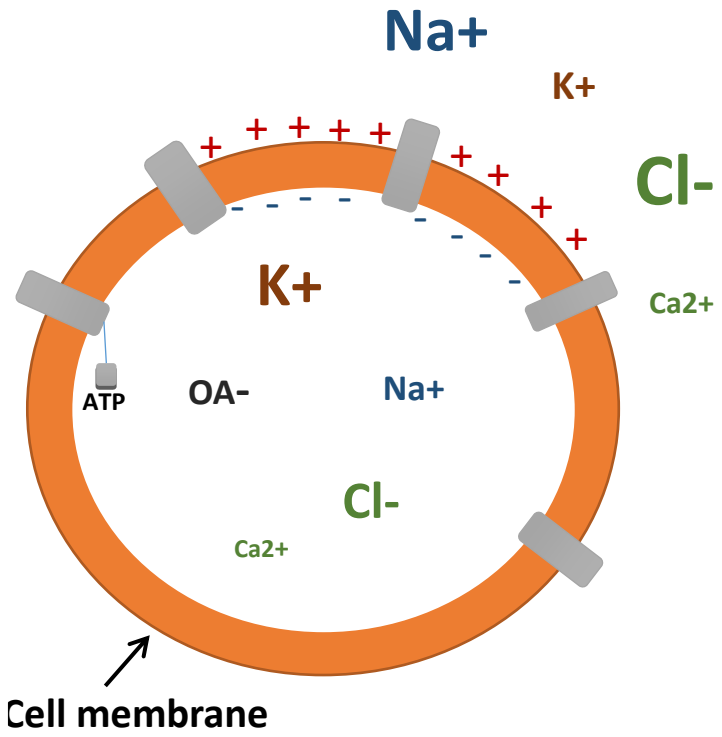
Asterisks indicate that the axon runs on much farther than shown. Note, however, that some cells, such as the retinal bipolar cell, have very short axons, while others, such as the retinal amacrine cell, have no axon at all. The drawings are not all at the same scale.

Fig1.2, Neuroscience, six edition ,Edited by Dale Purves

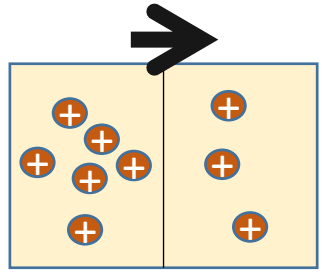
Distribution of ions across the membrane

Membrane potentials :
Electrical charge difference across the cell membrane



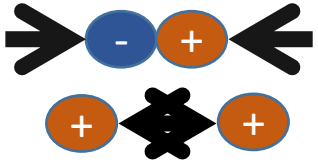


Basic rules for Ion movements:

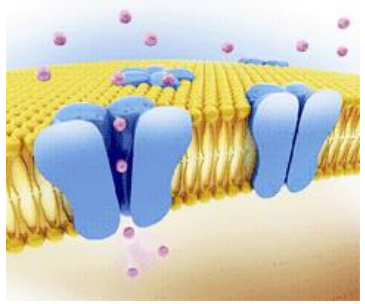


- From Higher to Lower concentration.

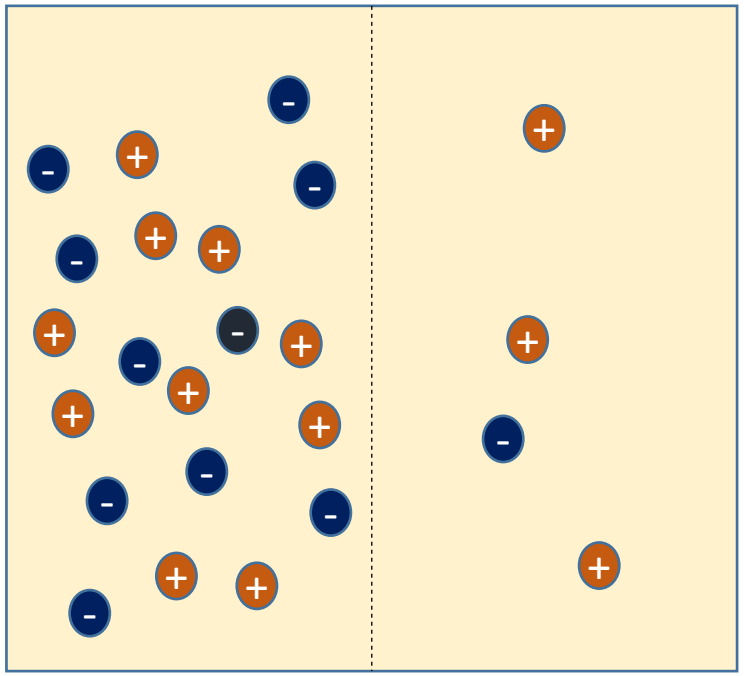
- Away from like charge and toward to opposite charges.

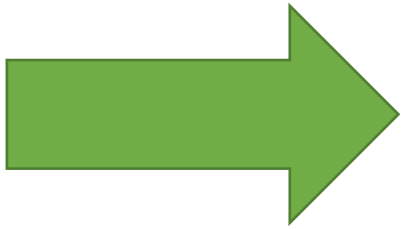


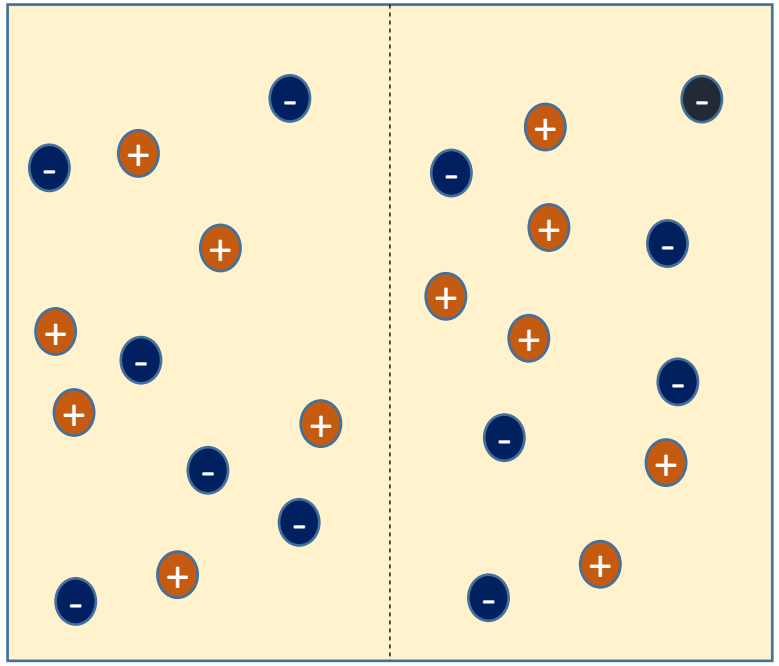
- Membrane permeability (ion channels).



EXAMPLE : If the membrane is equally permeable to both ions





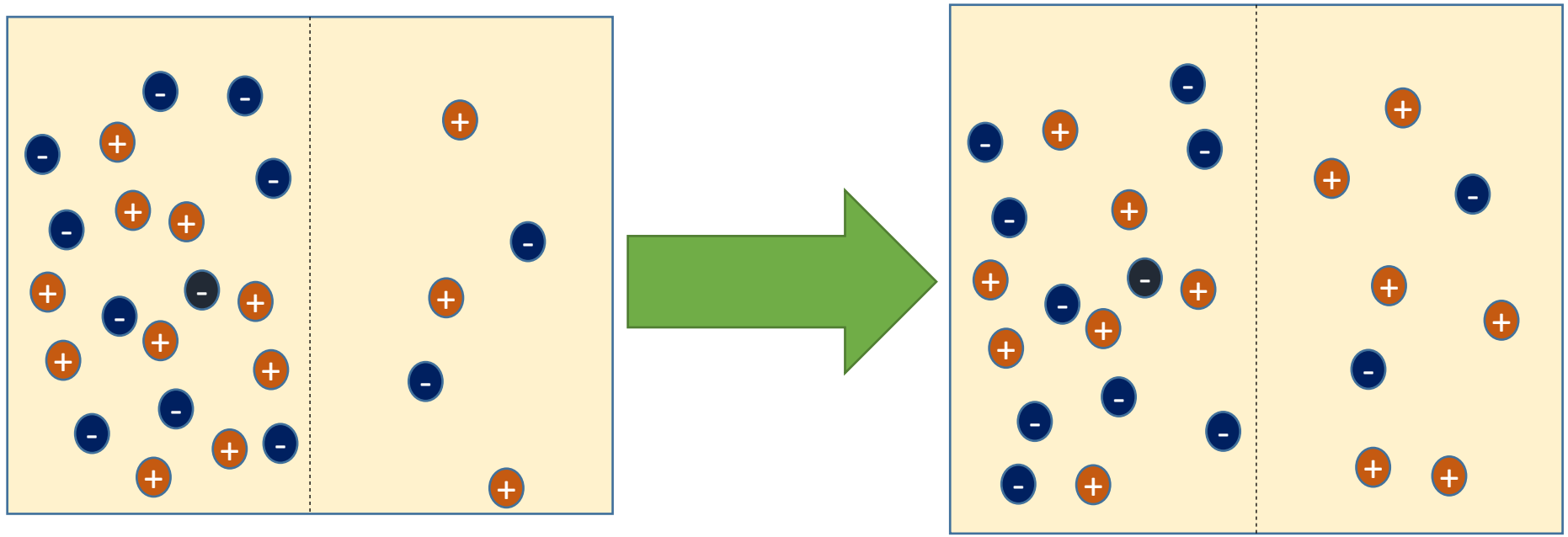


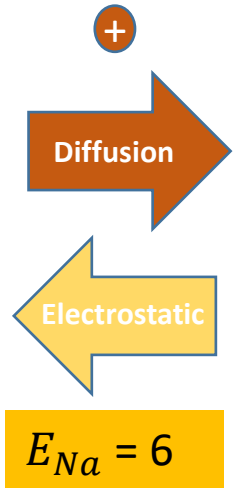
	Na+	Cl-	Na+	Cl-
Concentration	10	10	2	2
Electric charges	0		0	

	Na+	Cl-	Na+	Cl-
	6	6	6	6
	0		0	

Membrane potential = 0

If the membrane is only permeable to Na ions



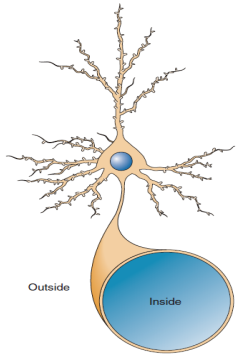


No net current for Na

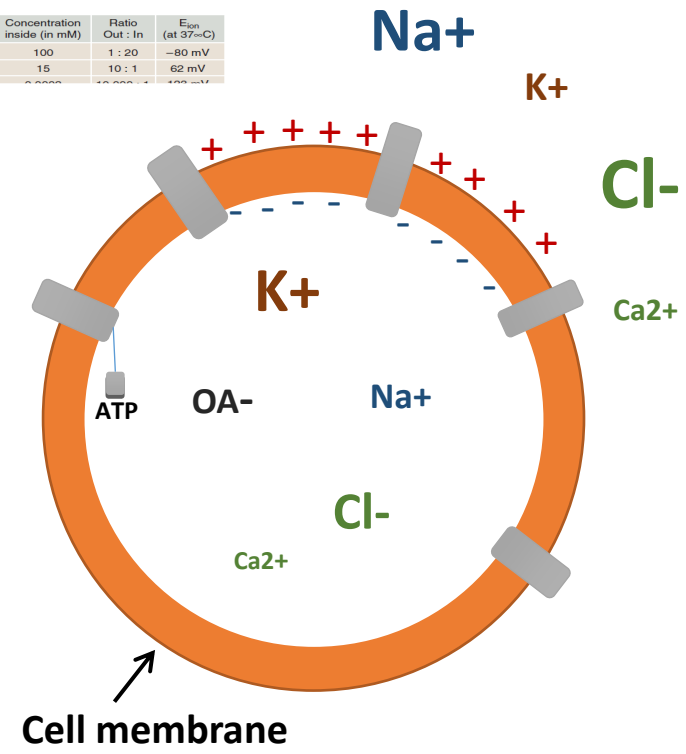
	Na+	Cl-	Na+	Cl-
Concentration	10	10	2	2
Electric charges	0		0	

	Na+	Cl-	Na+	Cl-
	7	10	5	2
	-3		+3	

Equilibrium potential



Ion	Concentration outside (in mM)	Concentration inside (in mM)	Ratio Out : In	E_{ion} (at 37°C)
K^+	5	100	1 : 20	−80 mV
Na^+	150	15	10 : 1	62 mV



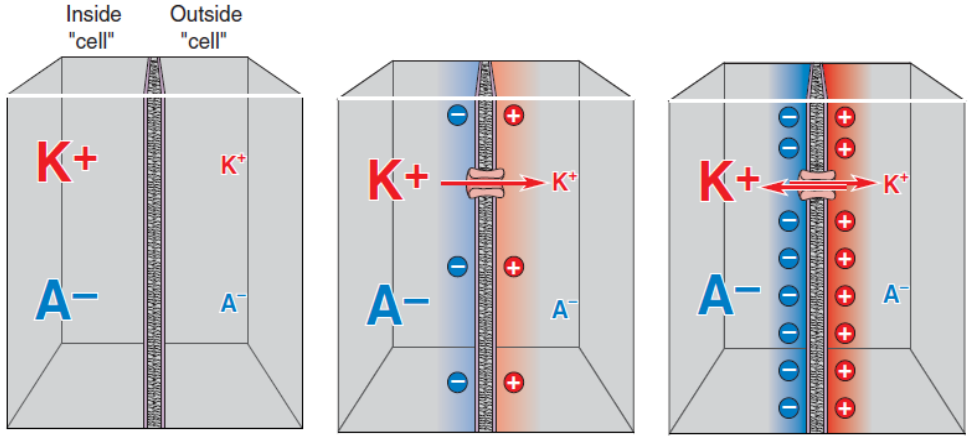


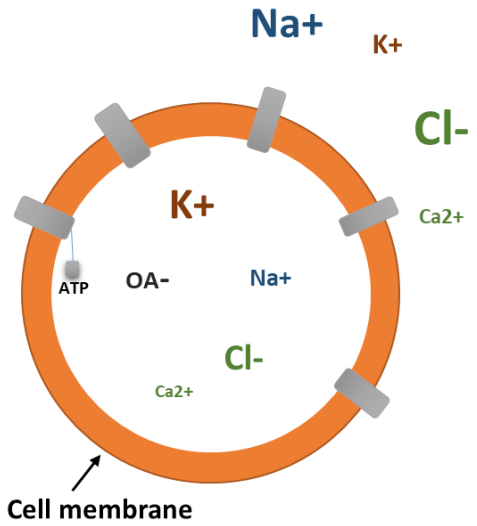
FIGURE 3.14, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

The electrical potential difference that exactly balances an ionic concentration gradient is called an **ionic equilibrium potential** (E_{ion})

$$E_{ion} = {}^{2,0303\ RT}/_{zF} \log \frac{[ion]0ut}{[ion]inside}$$

E_{ion} = ionic equillibrium potential
R =gas constant
T= absolute temperature
Z=charge of the ion
F= Faradays constant
[ion]out = ionic concentration outside the cell
[ion]inside = ionic concentration inside the cell

Equilibrium potential



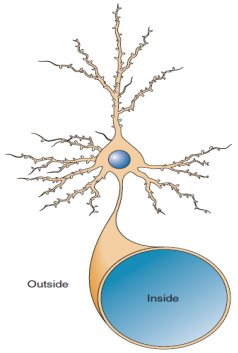
$$E_{ion} = {}^{2{,}0303\ \mathrm{RT}}/_{\mathrm{zF}} \log \frac{[ion]0out}{[ion]inside}$$

$$E_K = 61.54\ \mathrm{mV} \log \frac{[K^+]0}{[K^+]i}$$

$$E_{Na} = 61.54\ \mathrm{mV} \log \frac{[Na^+]0}{[Na^+]i}$$

$$E_{Cl} = 61.54\ \mathrm{mV} \log \frac{[Cl^-]0}{[Cl^-]i}$$

$$E_{Ca} = 30.77\ \mathrm{mV} \log \frac{[Ca^{2+}]0}{[Ca^{2+}]i}$$



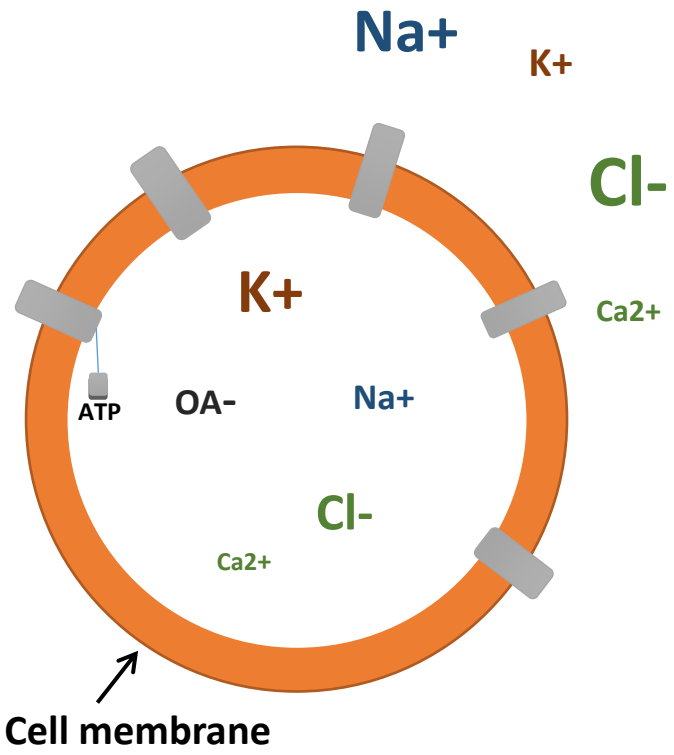
Ion	Concentration outside (in mM)	Concentration inside (in mM)	Ratio Out : In	E_{ion} (at 37∞C)
K^+	5	100	1 : 20	−80 mV
Na^+	150	15	10 : 1	62 mV

If $\frac{[K^+]0}{[K^+]i} = \frac{1}{20}$ **Then** $E_K = -80\ \mathrm{mV}$

If $\frac{[Na^+]0}{[Na^+]i} = 10$ **Then** $E_{Na} = 61.54\ \mathrm{mV}$

Ion	[ion]out In mM	[ion]in In mM	Ratio	E_ion At 37 C
K^+	5	100	1:20	-80 mv
Na^+	150	15	10:1	62 mv
Ca^{2+}	2	0.0002	10,000:1	123 mv
Cl^-	150	13	11.5 :1	65 mv

Resting membrane potential



If the membrane of a real neuron were c iv only to K, the resting membrane potential would equal EK, about 80 mV. But it does not; the measured resting membrane potential of a typical neuron is about 65 mV.

This discrepancy is explained because real neurons at rest **are not exclusively permeable to K**; there is also **some Na permeability**. Stated another way, the *relative permeability* of the resting neuronal membrane is quite **high to K** and **low to Na**.

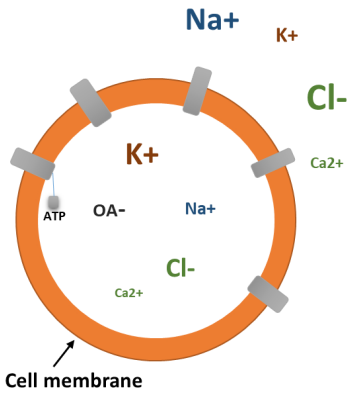
The resting membrane ion permeability to K is 40 times greater than it is to Na

Goldman Equation

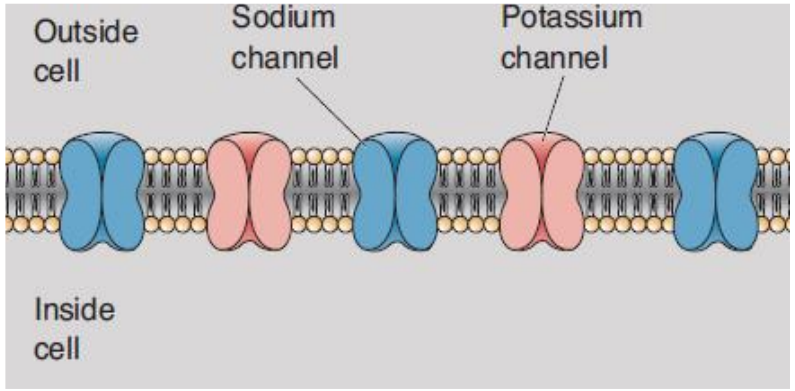
$$V_m = 61.54\ mV\ log\ \frac{P_k\,[K^+]o + P_{Na}\,[Na^+]o}{P_k\,[K^+]i + P_{Na}\,[Na^+]i}$$

Vm : membrane potential relative
Pk: permeability to K
PNa: permeability to Na

Membrane channels

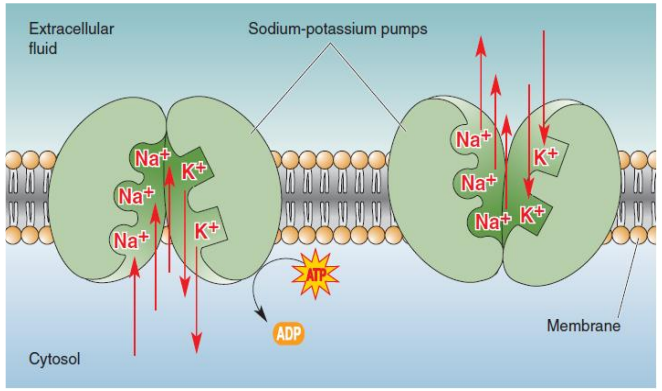


Leak Channels



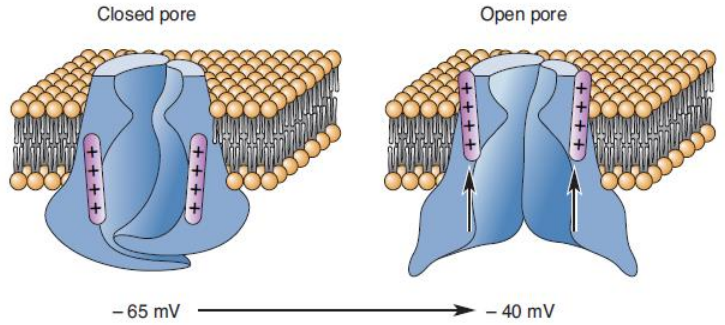
The leak channels are normally opened but they have **different permeability** for different ions.

Sodium-potassium pump



This ion pump is a membrane-associated protein that transports ions across the membrane against their **concentration gradients** at the expense of **metabolic energy**.

Voltage gated channels

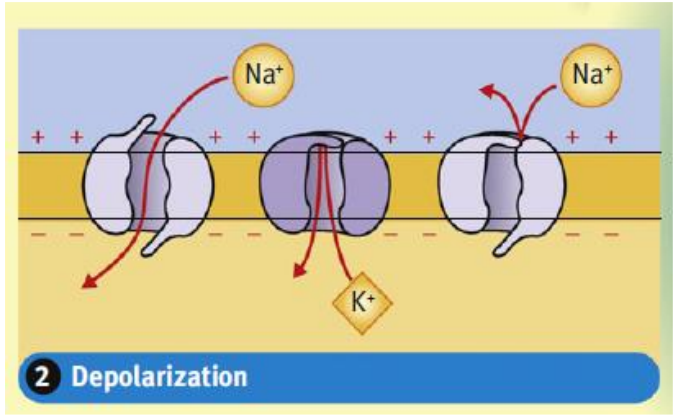


The voltage gated channel gated by a change in voltage across the membrane. Thus, the entire segment can be forced to move by changing the membrane potential.

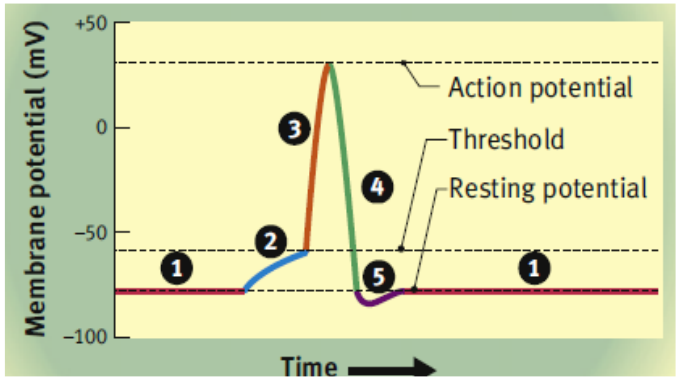
FIGURE 4.5, FIGURE 4.8 and FIGURE 4.8, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

Action potential (AP)

2

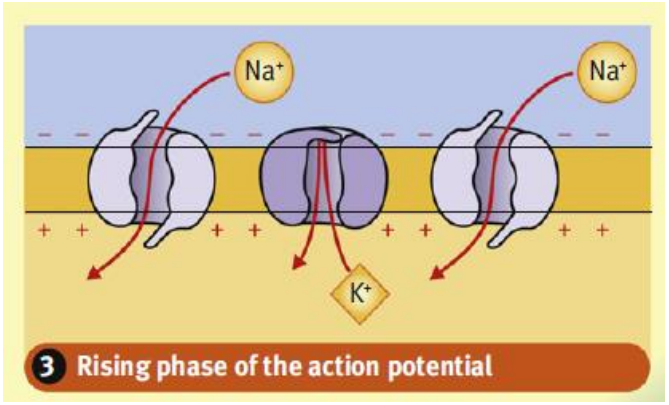


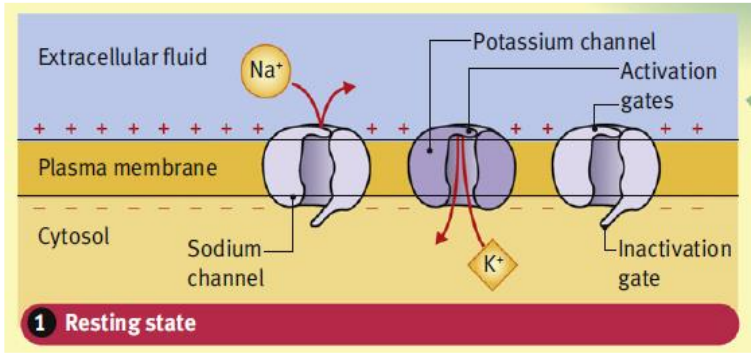
some sodium channels open, followed by many other channels when the depolarization **attains threshold** for **triggering** the action potential .



At this stage, **Na+ ions flood down their concentration gradient** into the cell . Then, the membrane potential rapidly moves towards the equilibrium potential for Na+ (~ +60 mV). However, the membrane potential does become positive, **it does not attain the Na+ equilibrium potential because the sodium channels quickly close.**

3





1

The initial resting potential is approximately –65 mV, at which time **both the voltage-gated sodium and potassium channels are closed.**

There are two separate mechanisms controlling the gating of the sodium channel:

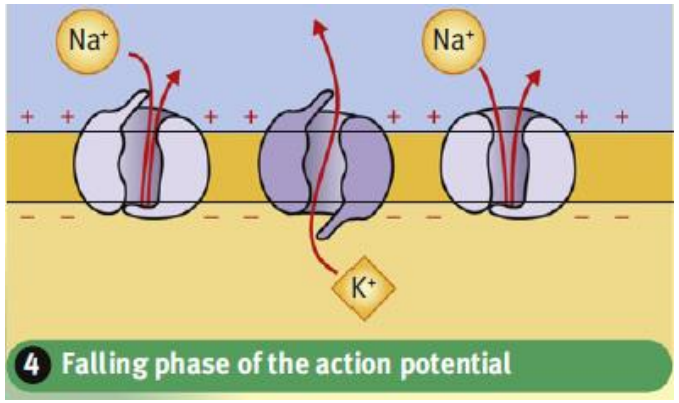
1. 'Activation' gate, which opens in response to a depolarizing stimulus.
2. Inactivation gate, which gate closed approximately **1 ms** after the activation gate opens

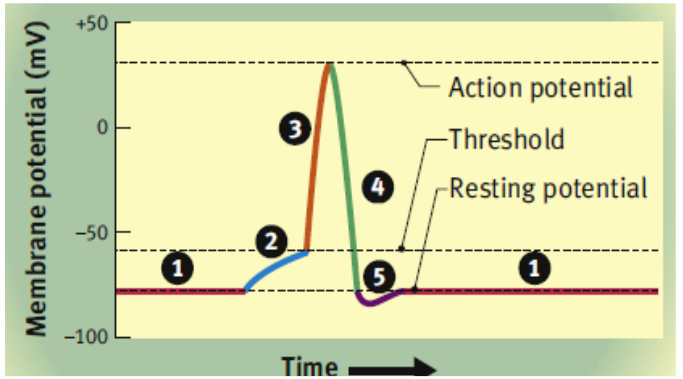
Allan Fletcher, Action potential: generation and propagation, Anaesthesia & Intensive Care Medicine,Volume 12, Issue 6,2011,

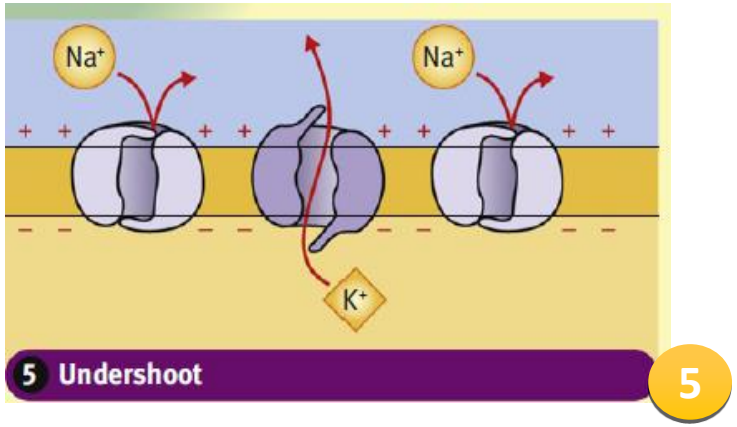
Action potential …

4

Approximately 1 ms after opening, the voltage-gated sodium channels close. At this time, the voltage-gated **potassium channels open, allowing K+ ions to 'flood' out** of the cell to rapidly repolarize the membrane.







The voltage-gated potassium channels actually remain open long enough for the membrane potential to 'undershoot' the resting value transiently .
(the relative refractory period), the sodium channels are again responsive but a larger depolarizing stimulus is required to trigger an action potential.

The **all**-or-none **law** is a principle that states that the strength of a AP is not dependent upon the strength of the stimulus.

Allan Fletcher, Action potential: generation and propagation, Anaesthesia & Intensive Care Medicine,Volume 12, Issue 6,2011,

(a) The membrane potential as it changes in time during an action potential.
(b) The inward currents through three representative voltage gated sodium channels. Each channel opens with little delay when the membrane is depolarized to threshold. The channels stay open for no more than 1 ms and then inactivate.
(c) The summed Na current flowing through all the sodium channels.
(d) The outward currents through three representative voltage gated potassium channels. The high potassium permeability causes the membrane to hyperpolarize briefly. When the voltage-gated potassium channels close, the membrane potential relaxes back to the resting value, around 65 mV.
(e) The summed K current flowing through all the potassium channels.
(f) The net transmembrane current during the action potential.

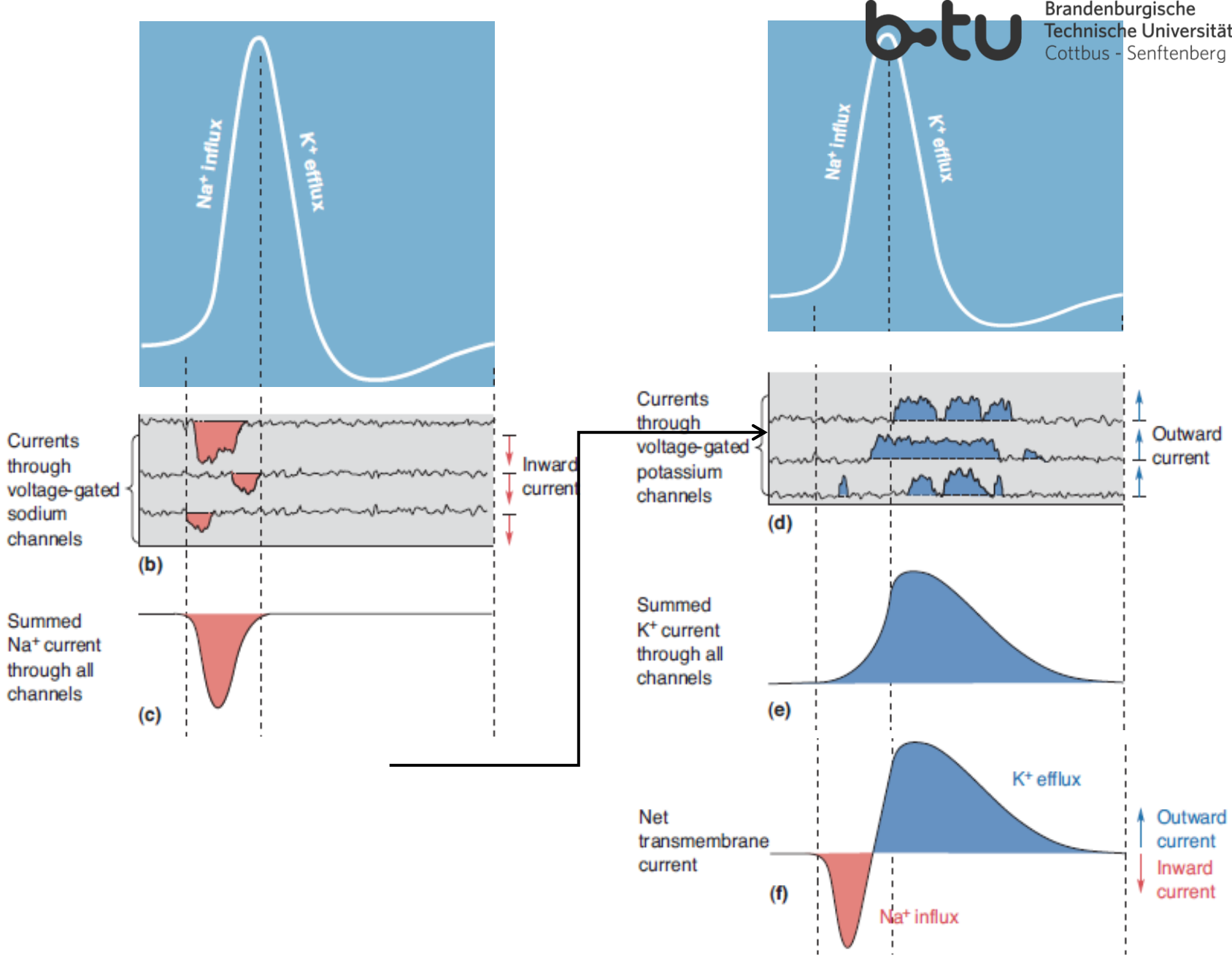
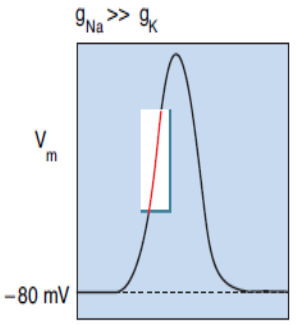
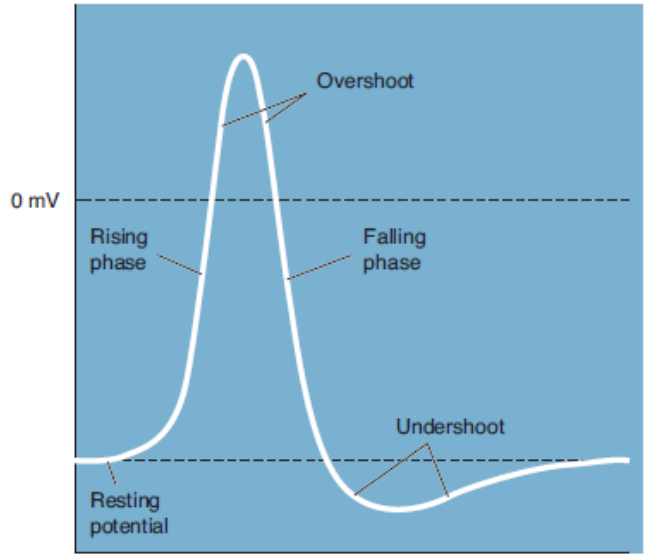


FIGURE 4.12, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

Action potential

Review





***Threshold* :**

Threshold is the membrane potential at which enough voltage-gated sodium channels open so that the relative ionic permeability of the membrane (g) favors sodium over potassium.

Rising phase:

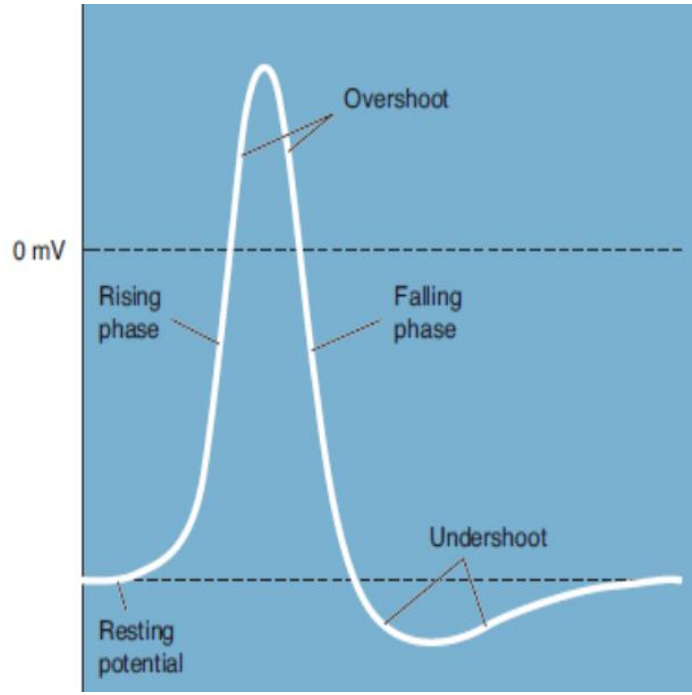
When the inside of the membrane has a negative electrical potential, there is a large driving force on Na. Therefore, Na rushes into the cell through the open sodium channels, causing the membrane to rapidly depolarize.

***Overshoot* :**

Because the relative permeability of the membrane greatly favors sodium, the membrane potential goes to a value close to **E Na** which is greater than 0 mV.

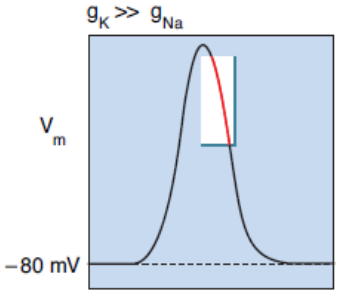
Action potential

Review …



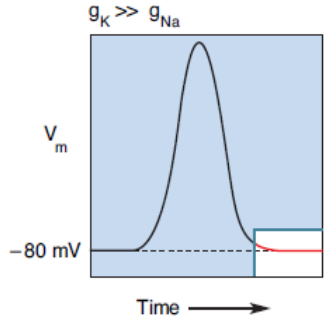
Falling phase :

The behavior of two types of channels contributes to the falling phase. **First**, the voltage-gated **sodium channels inactivate**. **Second**, the voltage-gated **potassium channels finally open** (triggered to do so 1 ms earlier by the depolarization of the membrane). There is a great driving force on K when the membrane is strongly depolarized. Therefore, K rushes out of the cell through the open channels, causing the membrane potential to become negative again.

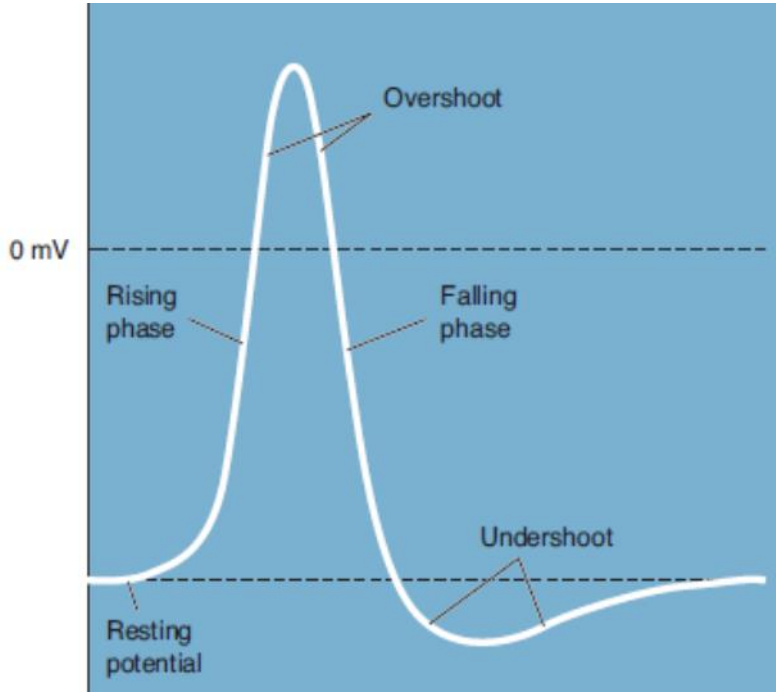


Undershoot:

The open voltage-gated potassium channels add to the resting potassium membrane permeability. Because there is very **little sodium permeability,** the membrane potential goes **toward EK** , causing a **hyperpolarization** relative to the resting membrane potential until the voltage-gated potassium channels close again.



Action potential …



***Absolute refractory period* :**

Sodium channels inactivate when the membrane becomes **strongly depolarized**. They cannot be activated again, and another action potential cannot be generated, until the membrane potential becomes sufficiently negative to deactivate the channels.

***Relative refractory period* :**

The membrane potential **stays hyperpolarized until the voltage-gated potassium channels close**. Therefore, more depolarizing current is required to bring the membrane potential to threshold.

The effect of injecting positive charge into a neuron

(a) The axon hillock is impaled by two electrodes, one for recording the membrane potential relative to ground and the other for stimulating the neuron with electrical current.
(b) When electrical current is injected into the neuron(top trace), the membrane is depolarized sufficiently to fire action potentials (bottom trace).

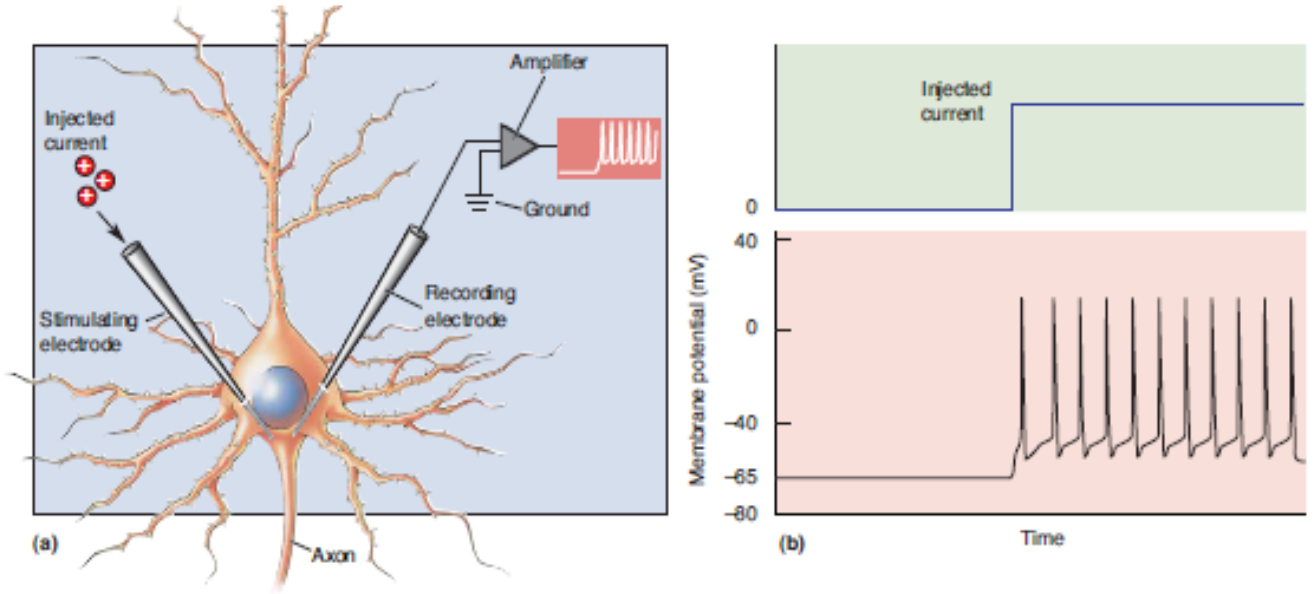


FIGURE A,Box4.3 , Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

Recording passive and active electrical signals in a nerve cell

1

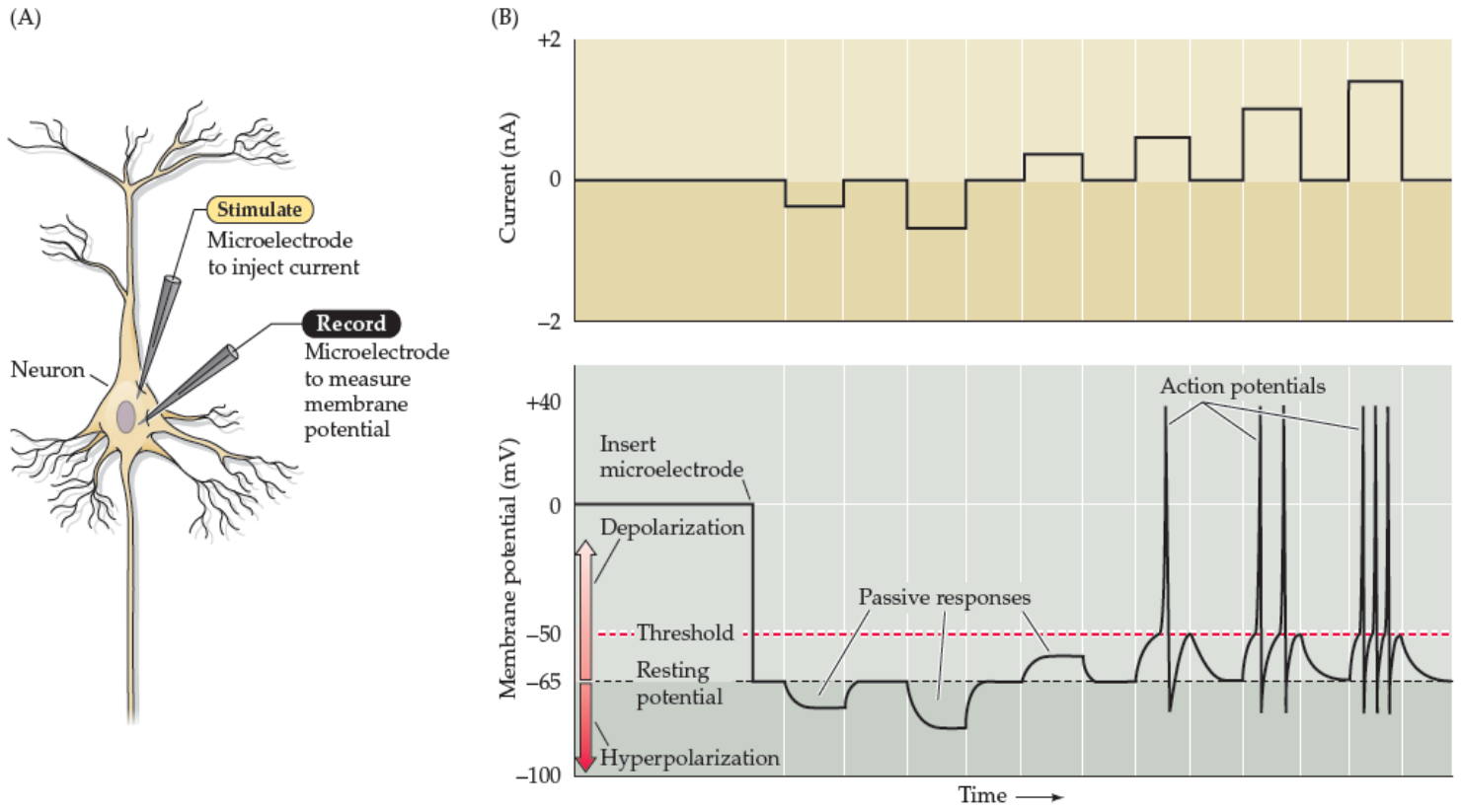
If injected current does not depolarize the membrane to threshold, no action potentials will be generated.

2

if injected current depolarizes the membrane beyond threshold, action potentials will be generated.

3

The action potential firing rate increases as the depolarizing current increases



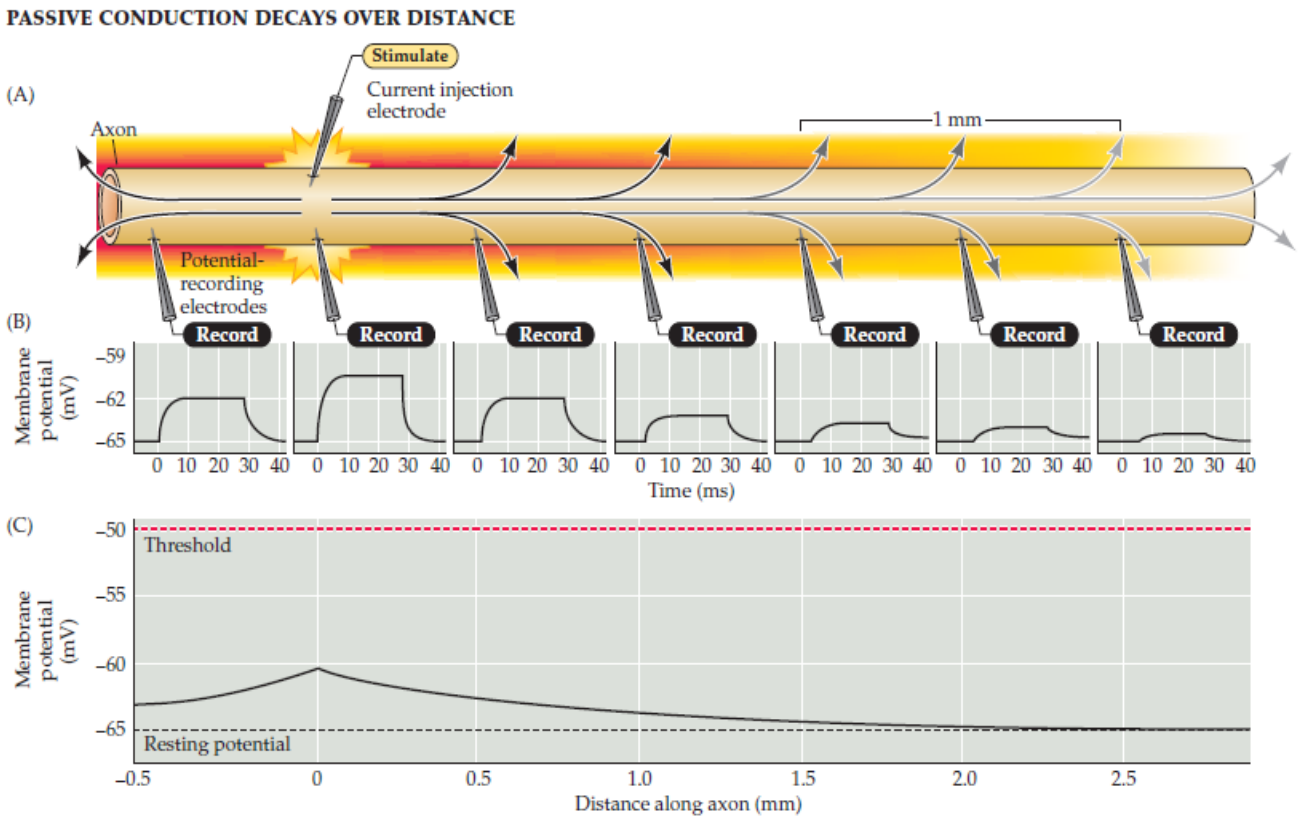
(A) Two microelectrodes are inserted into a neuron; one for stimulate and another for recording.

(B) Inserting the voltage-measuring microelectrode into the neuron (bottom) reveals a negative potential, the resting membrane potential. Injecting current through the other microelectrode (top) alters the neuronal membrane potential. Hyperpolarizing current pulses produce only passive changes in the membrane potential. While small depolarizing currents also elicit only passive responses, depolarization that cause the membrane potential to meet or exceed threshold additionally evoke action potentials.

Electrical Conduction (Passive conduction)

If this current pulse is **below the threshold** for generating an action potential, then the magnitude of the resulting potential change will **decay** with **increasing distance** from the site of current injection .Typically, the potential falls to a small fraction of its initial value at a distance of no more than a **few millimeters** away from the site of injection.

Passive conduction decays over distance



(A) Experimental arrangement for examining passive flow of electrical current in an axon. A current-passing electrode produces a current that yields a subthreshold change in membrane potential, which spreads passively along the axon.
(B) Potential responses recorded by microelectrodes at the positions indicated. With increasing distance from the site of current injection, the amplitude of the potential change is attenuated as current leaks out of the axon.
(C) Relationship between the amplitude of potential responses and distance.

FIGURE 2.3, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

saltatory conduction

- Myelinated nerve fibres are covered by an insulating sheath of ***myelin***, interrupted every few milli meters by spaces known as the ***nodes of Ranvier***, where the fibre is exposed to the extracellular fluid.
- the primary function of **oligodendroglial** and **Schwann** cells is providing layers of membrane that insulate axons.
- For example, oligodendroglia are found only in the **central nervous system** (brain and spinal cord),Schwann cells are found only in the **peripheral nervous system** (parts outside the skull and vertebral column).
- One oligodendroglial cell contributes myelin to several axons, whereas each Schwann cell myelinates only a single axon

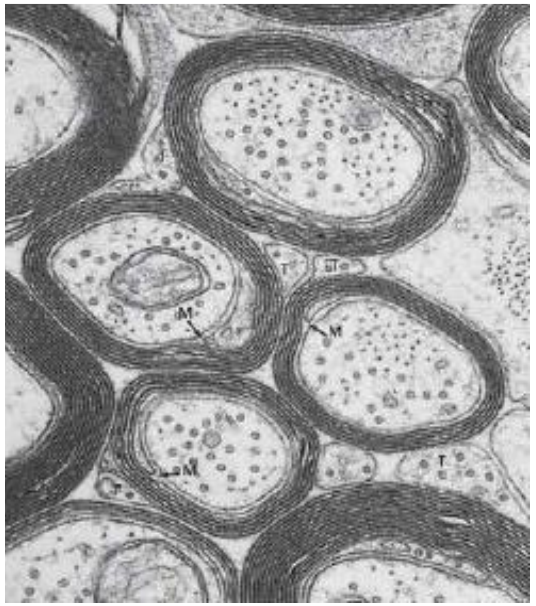
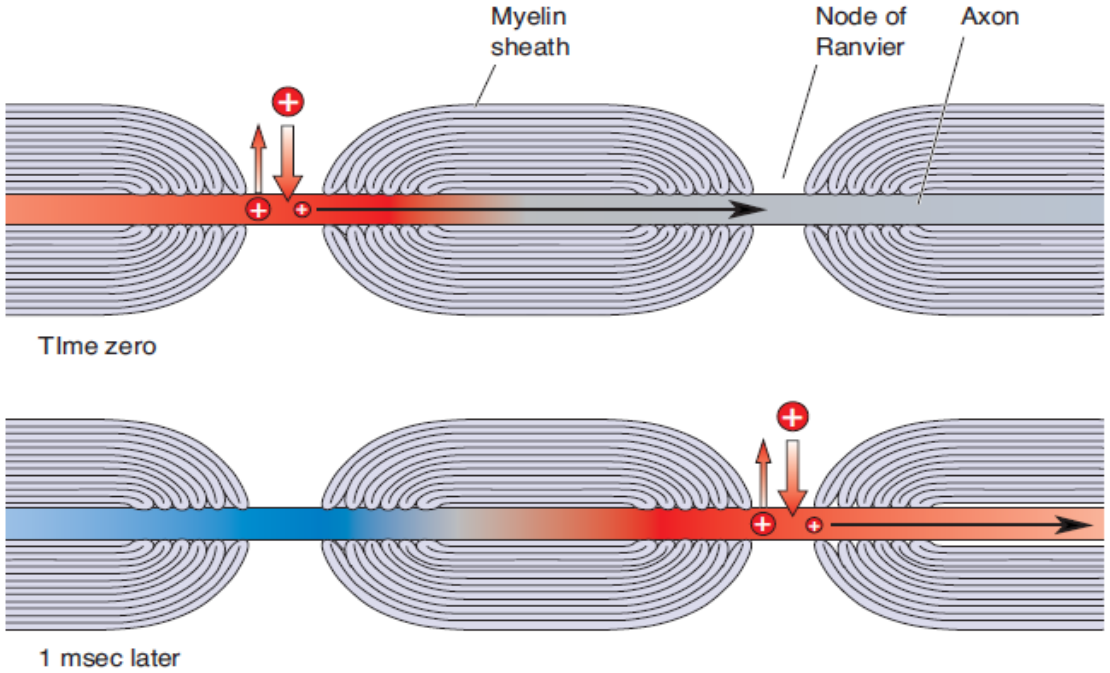


FIGURE 2.27, Figure2.27, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

saltatory conduction …

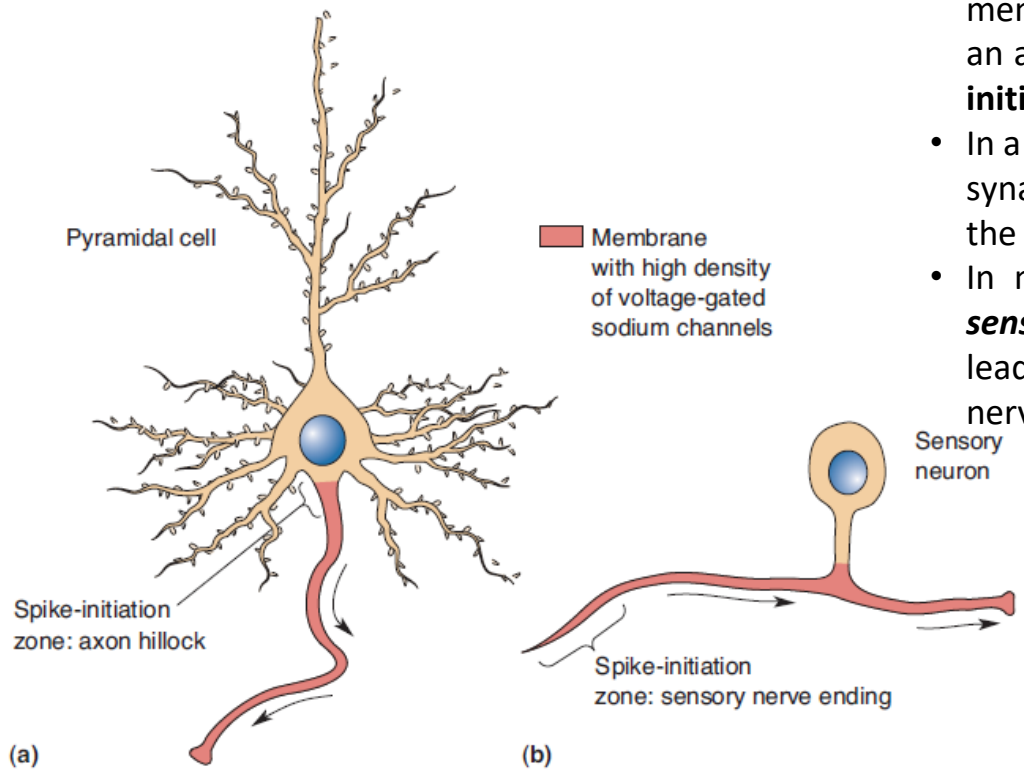


▲ FIGURE 4.15
Saltatory conduction. Myelin allows current to spread farther and faster between nodes, thus speeding action potential conduction. Compare this figure with Figure 4.12.

- **Sites of excitation** and changes of membrane permeability exist only at the nodes. current flows by jumping from one node to the next in a process known as ***saltatory conduction.***
- Voltage-gated sodium channels are concentrated in the axonal membrane at the nodes of Ranvier

FIGURE 4.15, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

spike-initiation zone



▲ FIGURE 4.16

- As a rule, the membranes of **dendrites and neuronal cell bodies** do not generate sodium-dependent action potentials because they have very **few voltage-gated sodium** channels. Only membrane that contains these specialized protein molecules is capable of generating action potentials, and this type of excitable membrane is usually found only in axons. Therefore, the part of the neuron where an axon originates from the soma, the **axon hillock**, is often also called the **spike-initiation zone** .
- In a typical neuron in CNS, the depolarization of the dendrites and soma caused by synaptic input from other neurons leads to the generation of action potentials if the membrane of the *axon hillock* is depolarized beyond threshold.
- In most sensory neurons, however, the spike-initiation zone occurs near the ***sensory nerve endings***, where the depolarization caused by sensory stimulation leads to the generation of action potentials that propagate along the sensory nerves.

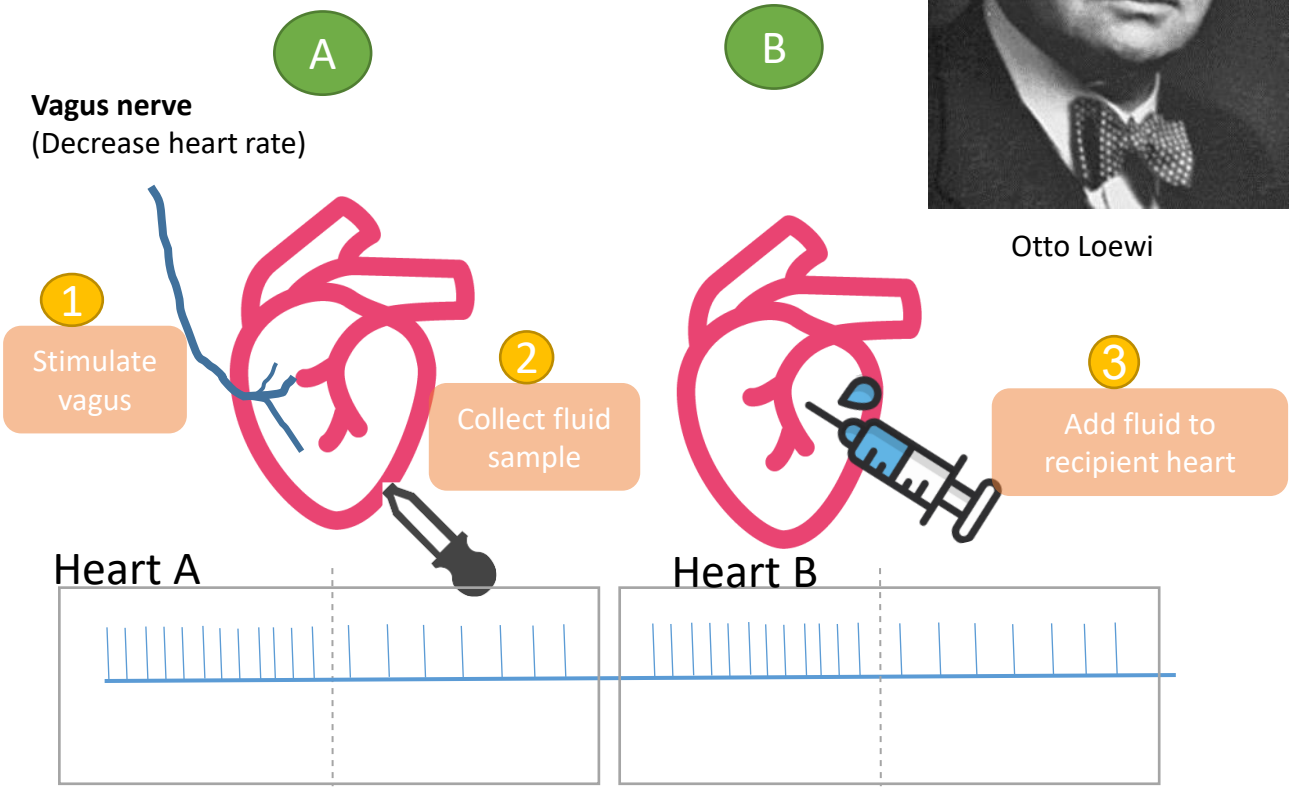
The spike-initiation zone. Membrane proteins specify the function of different parts of the neuron.
(A) Cortical pyramidal neuron.
(B) Primary sensory neuron.
Despite the diversity of neuronal structure, the axonal membrane can be identified at the molecular level by its **high density of voltage-gated sodium channels**. This molecular distinction enables axons to generate and conduct action potentials. The region of membrane where action potentials are normally generated is called the **spike-initiation zone**. The arrows indicate the normal direction of action potential propagation in these two types of neuron.

FIGURE 4.16, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

synaptic transmission ...

- The actions of **psychoactive drugs**, the causes of **mental disorders**, the neural bases of **learning and memory**—indeed, all the operations of the nervous system—cannot be understood without knowledge of synaptic transmission.
- Solid support for the concept of chemical synapses was provided in **1921 by Otto Loewi**.
- Loewi showed that electrical stimulation of axons innervating the frog's heart caused the release of a chemical that could mimic the effects of neuron stimulation on the heartbeat.
- Later, Bernard Katz and his colleagues at University College London conclusively demonstrated that fast transmission at the synapse between a **motor neuron** axon and **skeletal muscle** was **chemically mediated**.

Otto Loewi



Electrical Synapse

- The existence of such **electrical synapses** was finally proven in the late **1950s by Edwin Furshpan and David Potter**.

- Electrical synapses are relatively **simple** in structure and function, and they allow the **direct transfer** of ionic current from one cell to the next. Electrical synapses occur at specialized sites called **gap junctions** .

- Transmission at electrical synapses is **very fast**. Thus, an action potential in the presynaptic neuron can produce, with **very little delay**, an action potential in the postsynaptic neuron.

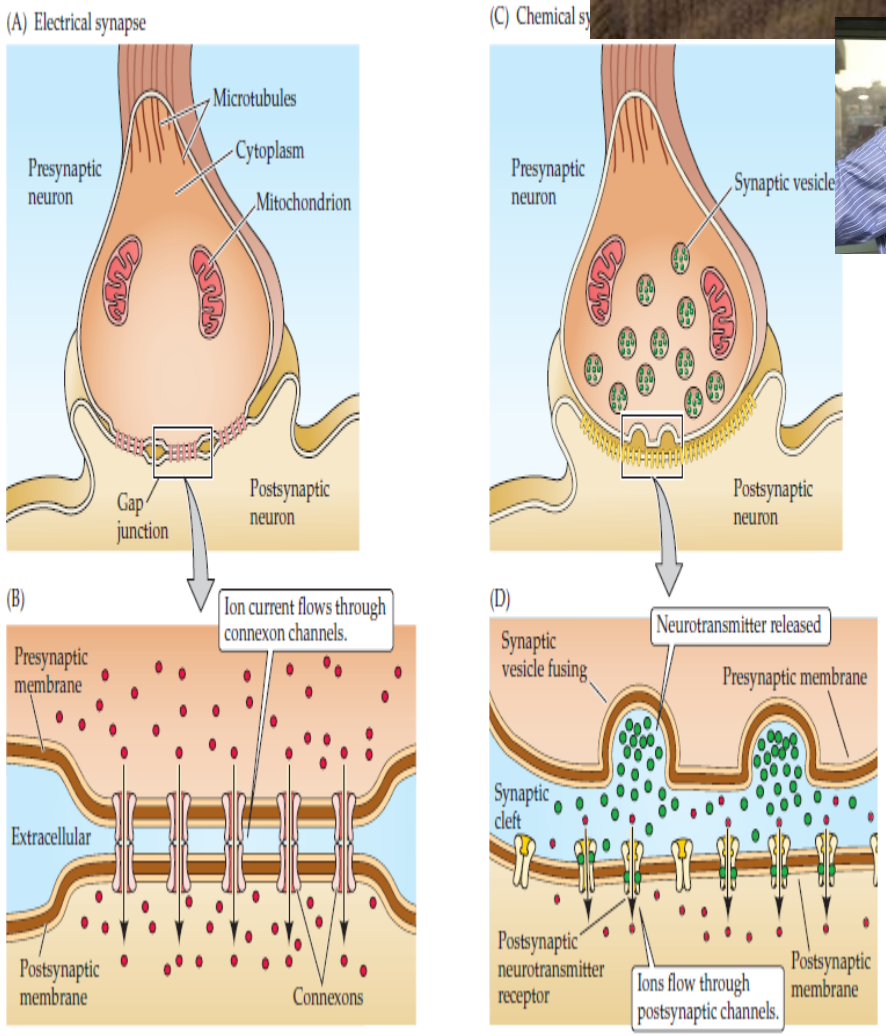


Fig5.1, Neuroscience, six edition ,Edited by Dale Purves

Electrical Synapse...

- At a gap junction, the membranes of two cells are separated by only **about 3 nm**, and this narrow gap is spanned by clusters of special proteins called **connexins** . Six connexin subunits combine to form a channel called a *connexon* , and two connexons (one from each cell) meet and combine to form a **gap junction channel .**
- The channel allows ions to pass directly from the cytoplasm of one cell. Most gap junctions allow ionic current to pass equally well in both directions; therefore, unlike the vast majority of chemical synapses, electrical synapses are **bidirectional.** Because electrical current (in the form of ions) can pass through these channels, cells connected by gap junctions are said to be **electrically coupled** .
- They are often found where normal function requires that the activity of neighboring neurons be **highly synchronized.**

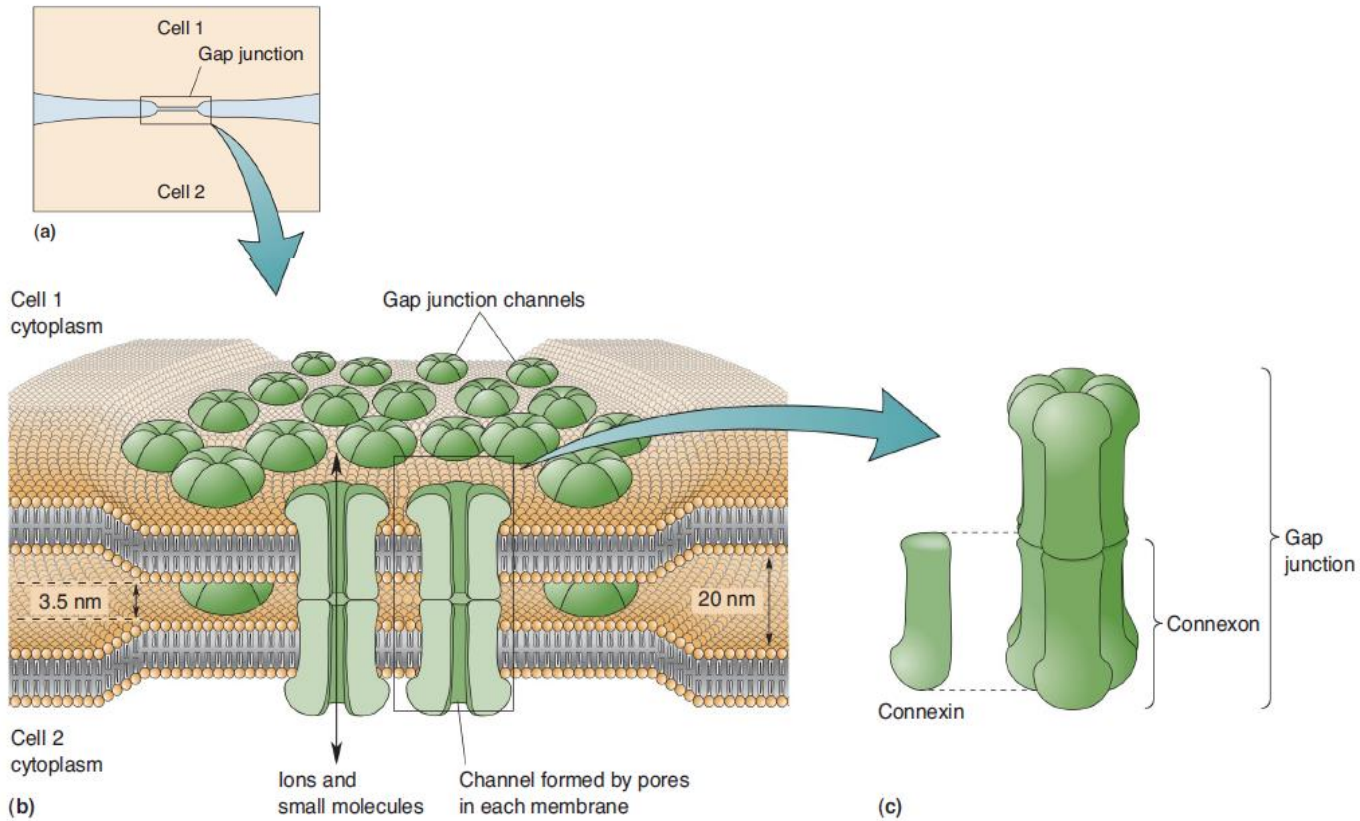
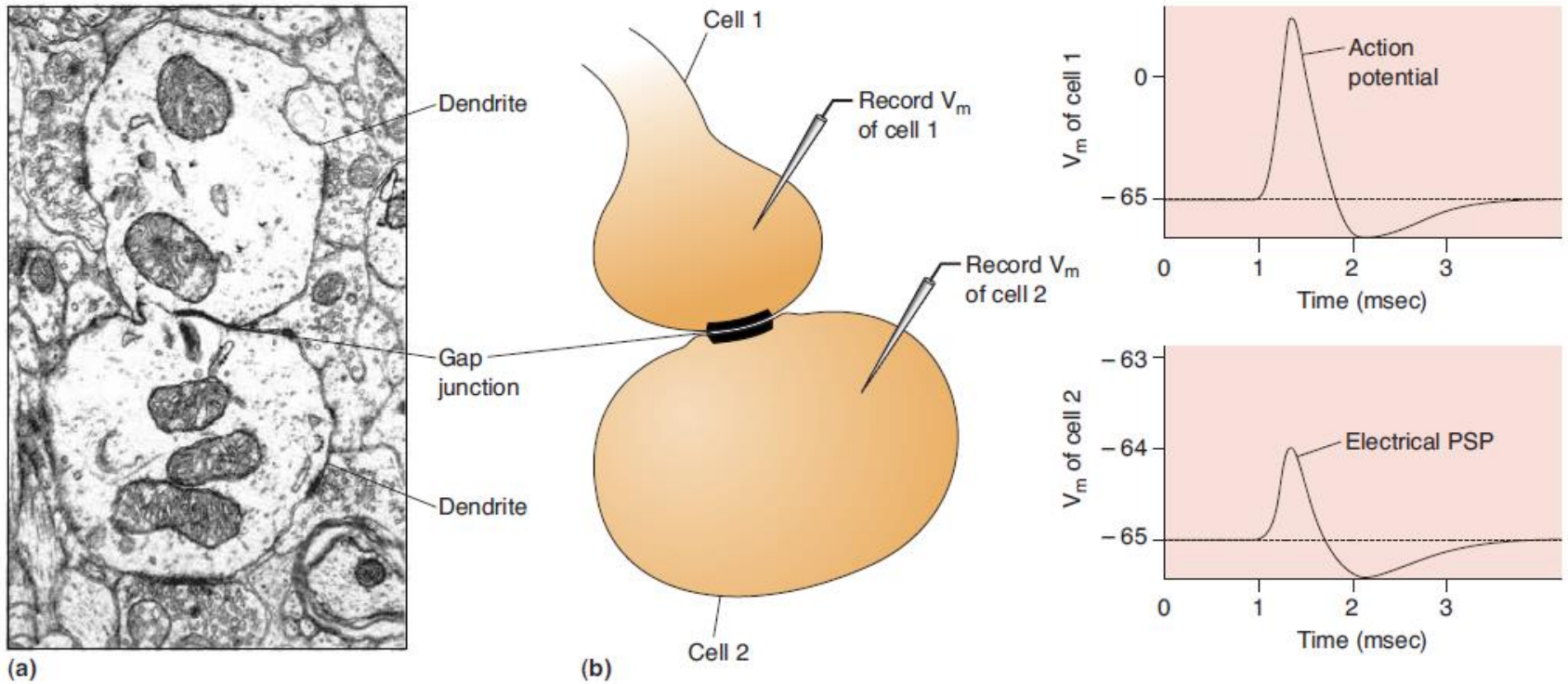


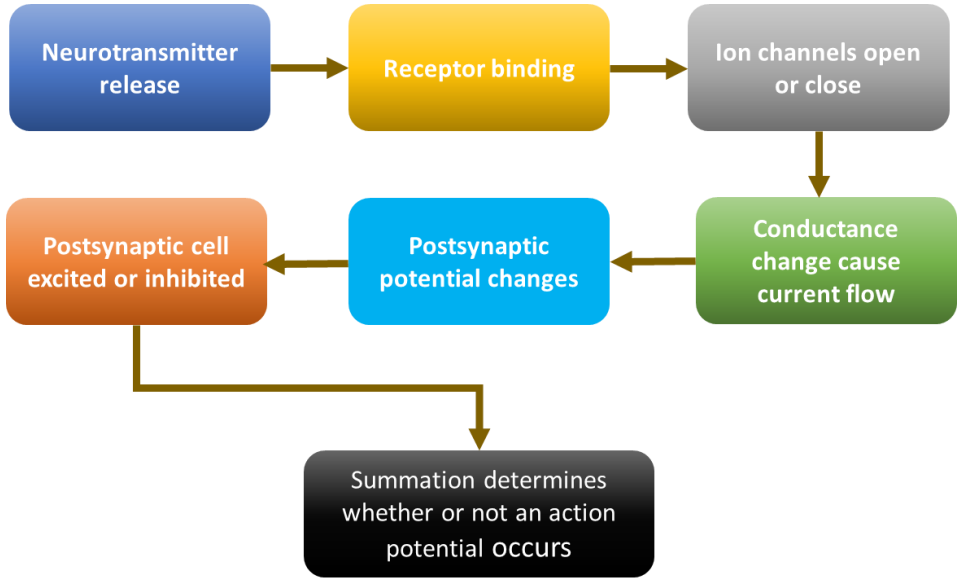
FIGURE 5.1, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear



Electrical synapses.
(a) A gap junction interconnecting the dendrites of two neurons constitutes an electrical synapse.
(b) An action potential generated in one neuron causes a small amount of ionic current to flow through gap junction channels into a second neuron, inducing an electrical PSP. (Source: Part a from Sloper and Powell, 1978.)

FIGURE 5.2, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

Chemical Synapses



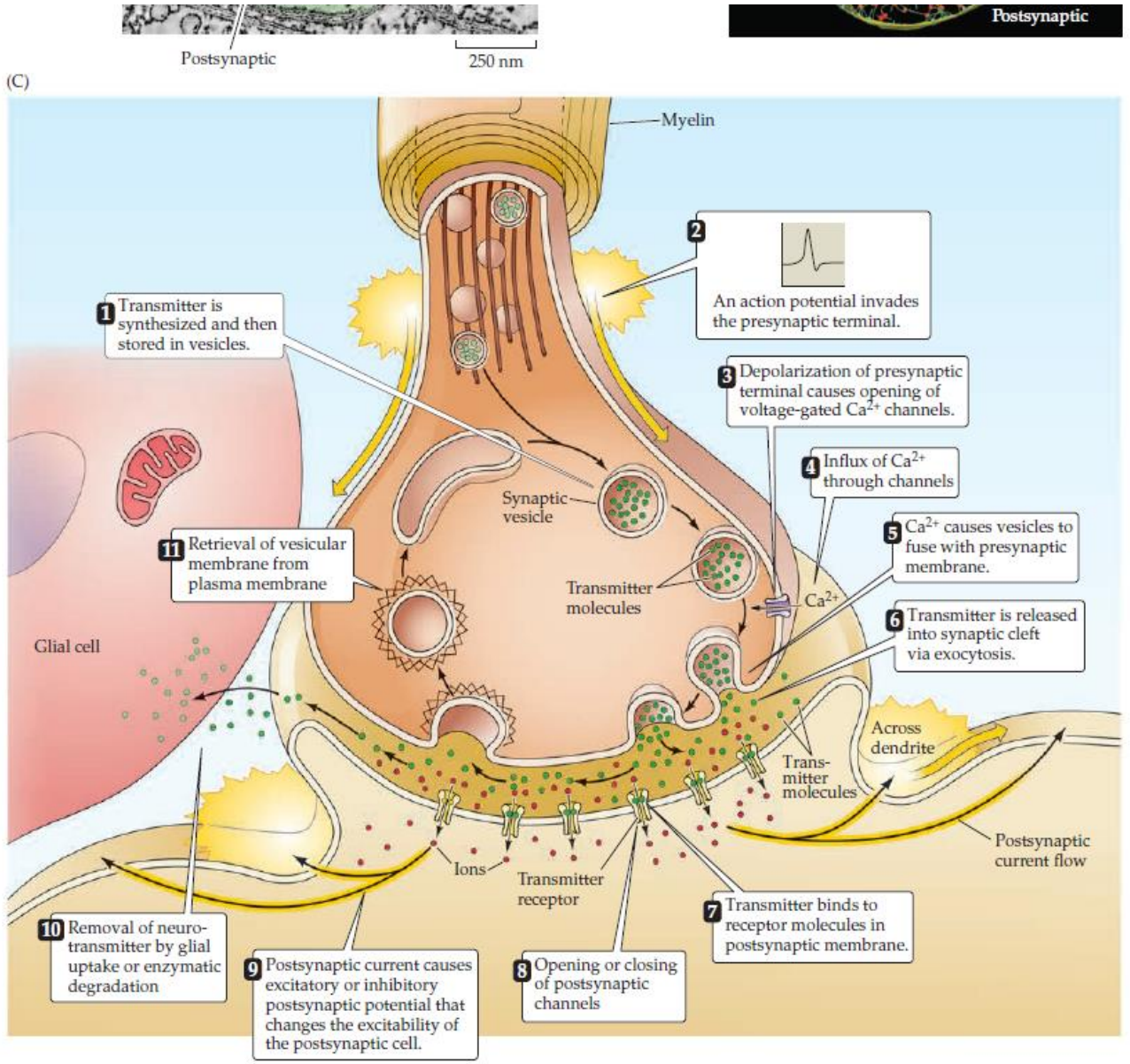


Fig5.4, Neuroscience, six edition ,Edited by Dale Purves

Excitatory Post Synaptic Potential

The generation of an EPSP

(a) An action potential arriving in the presynaptic terminal causes the release of neurotransmitter.

(b) The molecules bind to transmitter-gated ion channels in the postsynaptic membrane. If Na enters the postsynaptic cell through the open channels, the membrane will become depolarized.

(c) The resulting change in membrane potential (Vm), as recorded by a microelectrode in the cell, is the **EPSP**.

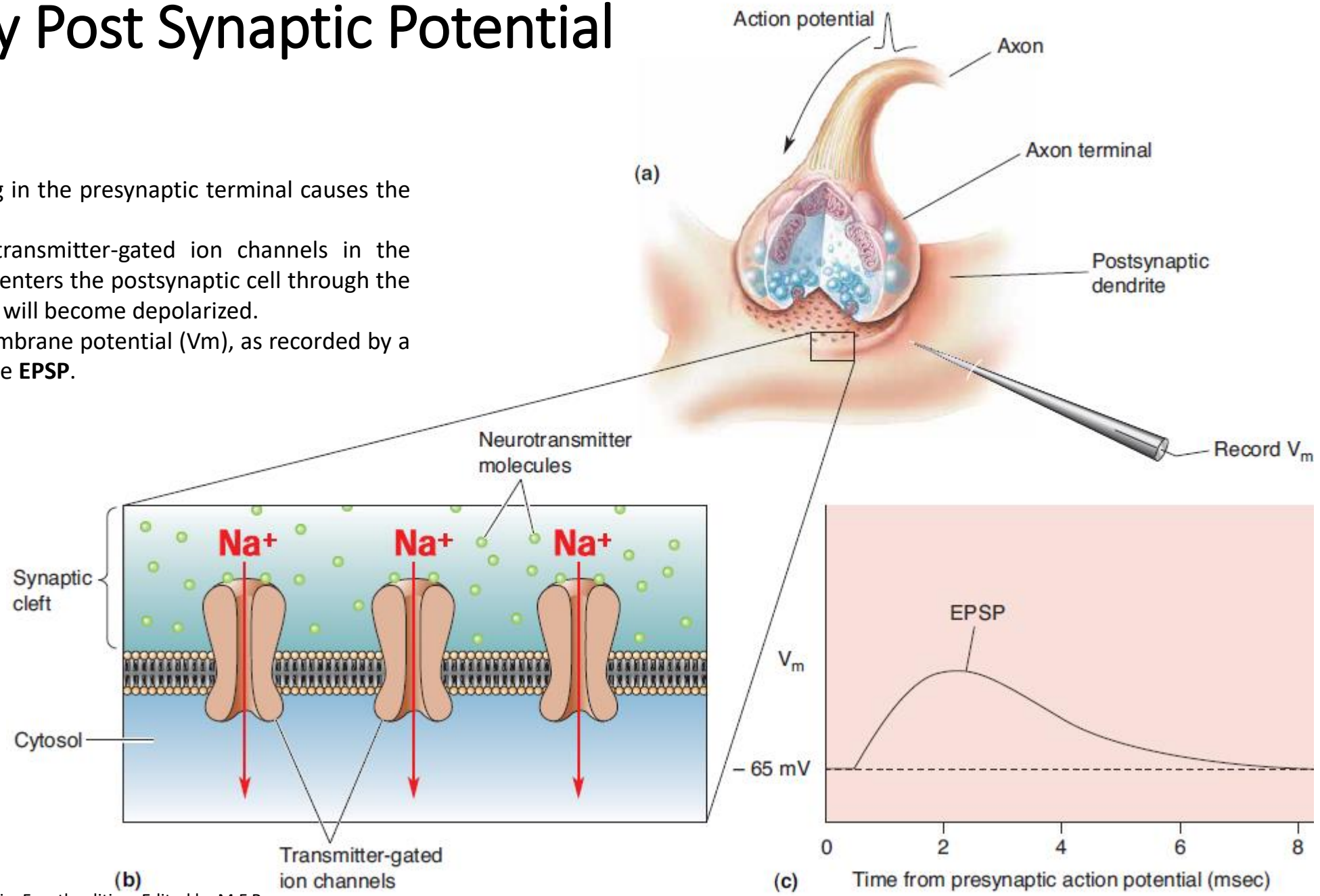


FIGURE 5.15, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

Inhibitory Post Synaptic Potential

The generation of an IPSP.
(a) An action potential arriving in the presynaptic terminal causes the release of neurotransmitter.
(b) The molecules bind to transmitter-gated ion channels in the postsynaptic membrane. If Cl enters the postsynaptic cell through the open channels, the membrane will become hyperpolarized.
(c) The resulting change in membrane potential (Vm), as recorded by a microelectrode in the cell, is the IPSP

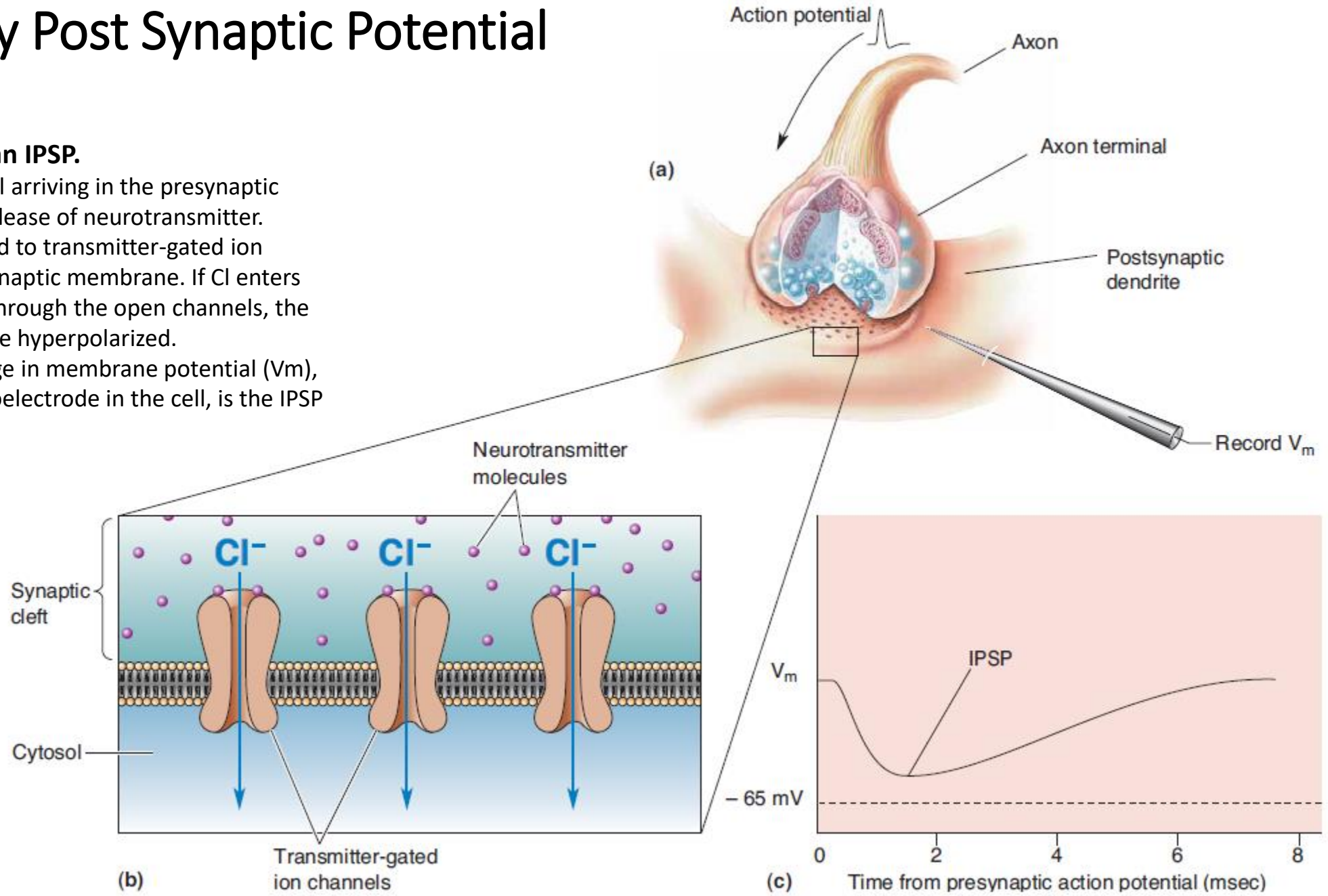
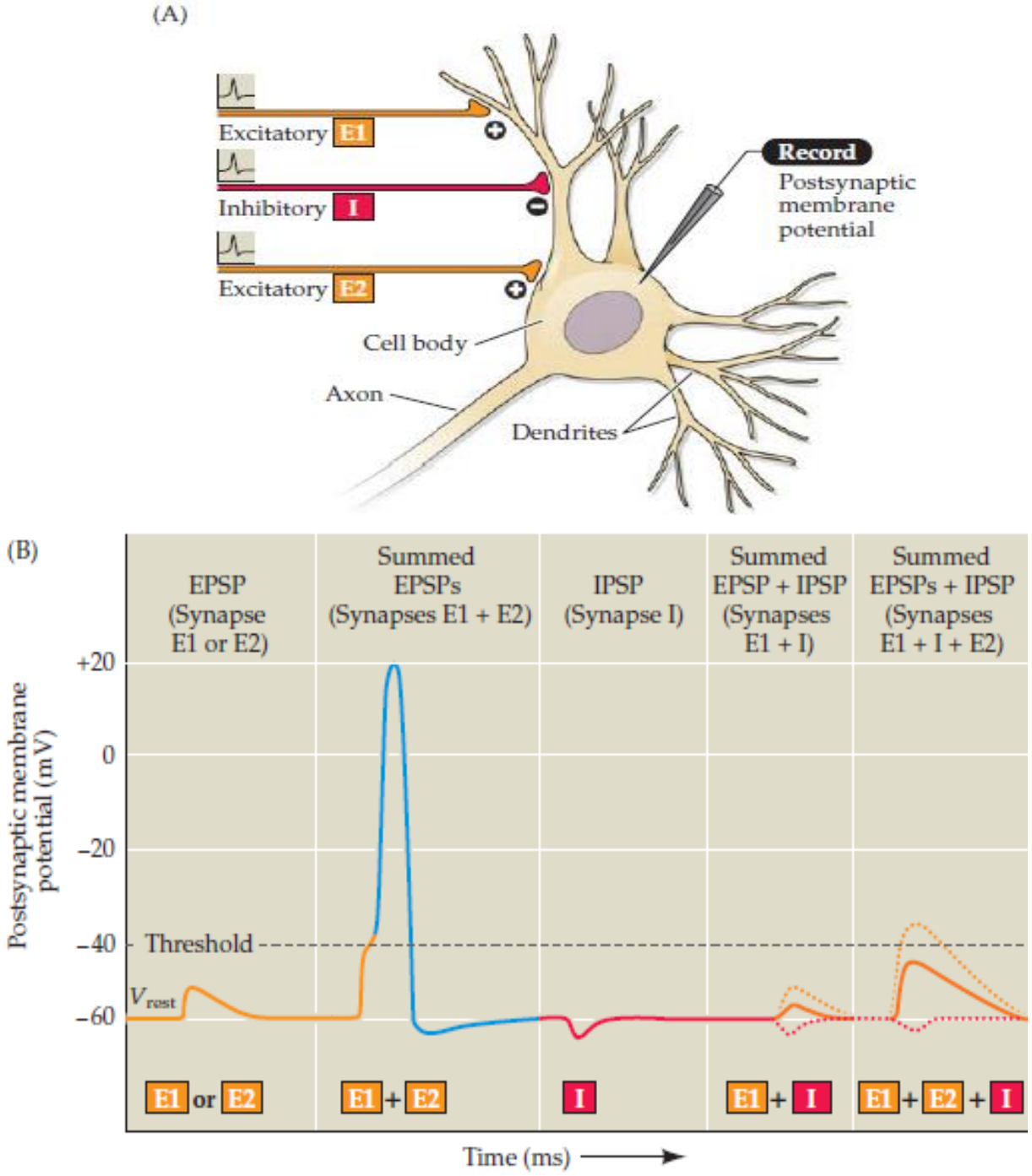
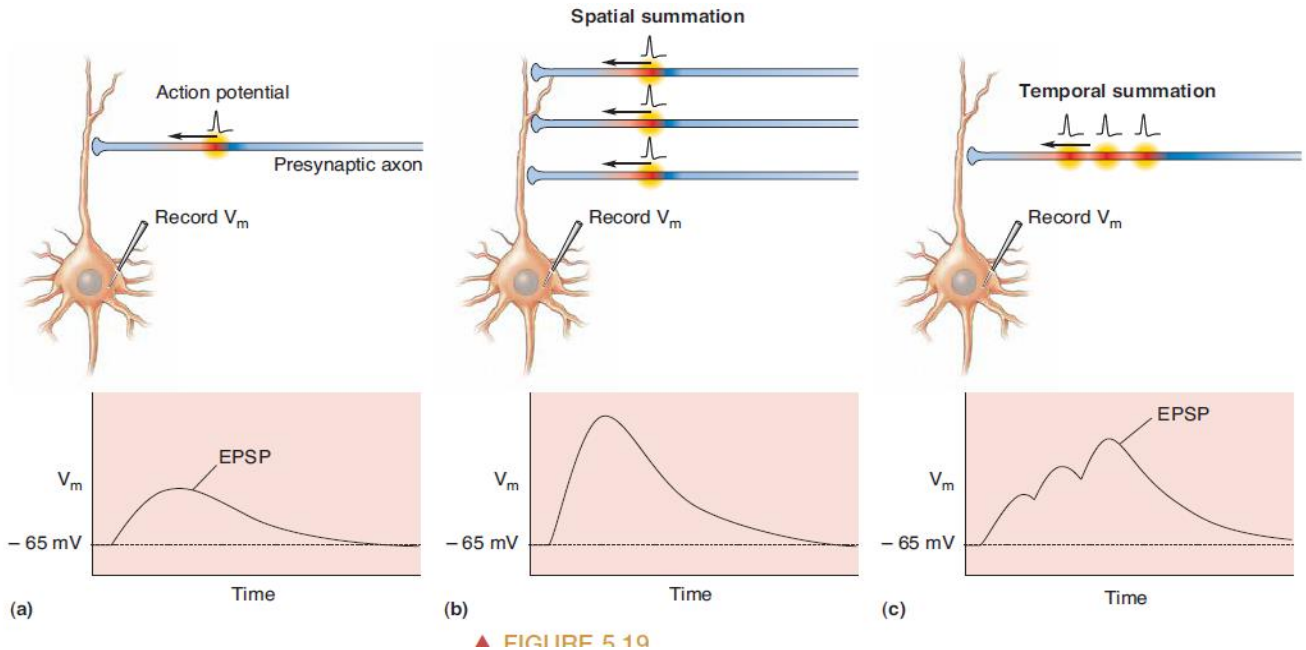


FIGURE 5.16, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

Summation of postsynaptic potentials

(A) A microelectrode records the postsynaptic potentials produced by the activity of two excitatory synapses (E1 and E2) and an inhibitory synapse (I).
(B) Electrical responses to synaptic activation. Stimulating either excitatory synapse (E1 or E2) produces a subthreshold EPSP, whereas stimulating both synapses at the same time (E1 + E2) produces a supra threshold EPSP that evokes a postsynaptic action potential (shown in blue). Activation of the inhibitory synapse alone (I) results in a hyperpolarizing IPSP. Summing this IPSP (dashed red line) with the EPSP (dashed yellow line) produced by one excitatory synapse (E1 + I) reduces the amplitude of the EPSP (solid orange line), while summing it with the supra threshold EPSP produced by activating synapses E1 and E2 keeps the postsynaptic neuron below threshold, so that no action potential is evoked.





EPSP summation.
(a) A presynaptic action potential triggers a small EPSP in a postsynaptic neuron.
(b) Spatial summation of EPSPs: When two or more presynaptic inputs are active at the same time, their individual EPSPs add together.
(c) Temporal summation of EPSPs: When the same presynaptic fiber fires action potentials in quick succession, the individual EPSPs add together

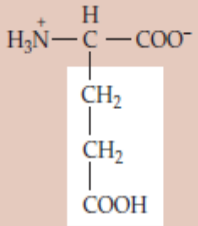
FIGURE 5.19, Neuroscience, exploring the brain, Fourth edition ,Edited by M.F Bear

SMALL-MOLECULE NEUROTRANSMITTERS

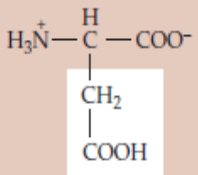
Acetylcholine $(CH_3)_3\overset{+}{N}-CH_2-CH_2-O-\overset{O}{\overset{\|}{C}}-CH_3$

AMINO ACIDS

Glutamate

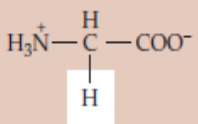


Aspartate



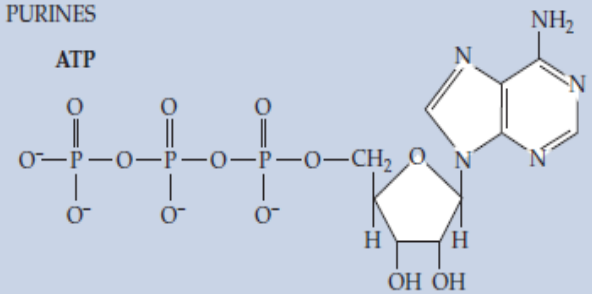
GABA $H_3\overset{+}{N}-CH_2-CH_2-CH_2-COO^-$

Glycine



PURINES

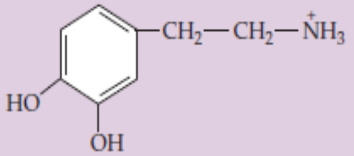
ATP



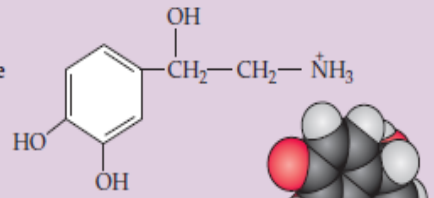
BIOGENIC AMINES

CATECHOLAMINES

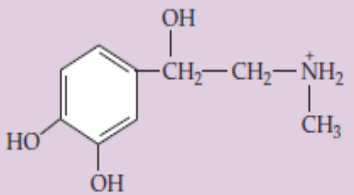
Dopamine



Norepinephrine

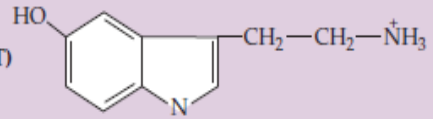


Epinephrine



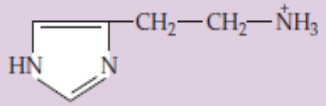
INDOLEAMINE

Serotonin (5-HT)

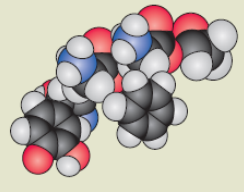


IMIDAZOLEAMINE

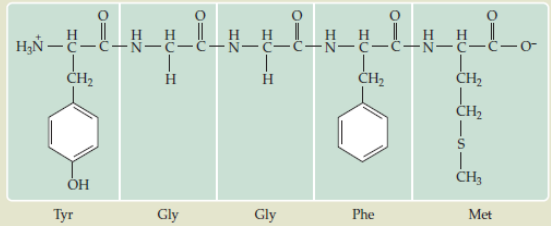
Histamine



PEPTIDE NEUROTRANSMITTERS (more than 100 peptides, usually 3–36 amino acids long)



Example: Methionine enkephalin (Tyr–Gly–Gly–Phe–Met)



Neurotransmitter	Postsynaptic effect[a]
ACh	Excitatory
Glutamate	Excitatory
GABA	Inhibitory
Glycine	Inhibitory
Catecholamines (epinephrine, norepinephrine, dopamine)	Excitatory
Serotonin (5-HT)	Excitatory
Histamine	Excitatory
ATP	Excitatory
Neuropeptides	Excitatory and inhibitory
Endocannabinoids	Inhibits inhibition
Nitric oxide	Excitatory and inhibitory