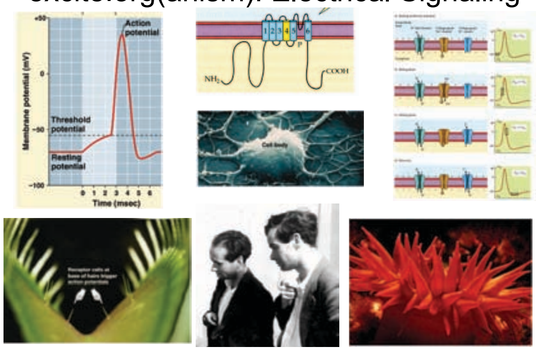
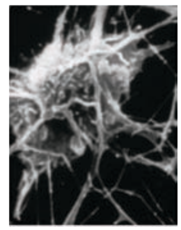
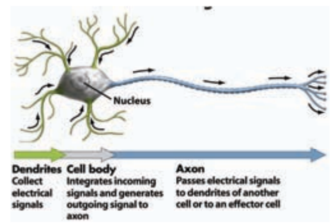
excite.org(anism): Electrical Signaling



Today's lecture – we'll use clickers
Review today – 11:30-1:00 in 2242 HJ Patterson

The Neuron - F. Fig. 45.3





- Electrical signals
  - Dendrites: graded post-synaptic potentials
  - Axons: all-or-none action potentials
- Chemical signals
  - Synapses: neurotransmitters

Key concept: different structures, different proteins, different functions

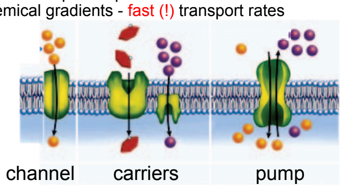
Electrical signaling occurs via membrane proteins

Membrane proteins controlling ion flow across membranes

pumps - use ATP to move ions against their electrochemical gradients - (e.g., Na^+/K^+ pump or H^+ pump) - slow rates of ion transport

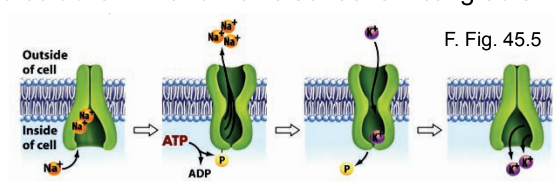
carriers (transporters) - undergo conformational changes that carry solutes/ions down electrochemical gradients - intermediate transport rates

channels - form aqueous pores for solutes/ions to diffuse down electrochemical gradients - fast (!) transport rates



Different roles in electrical signaling for different proteins

Animal cell membranes - Na^+/K^+ pump uses ATP to establish K^+ and Na^+ electrochemical gradients



F. Fig. 45.5

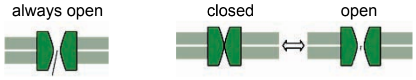
Na^+/K^+ pump maintains Na^+ and K^+ electrochemical gradients

- transports Na^+ out of cell for nutrient assimilation and osmoregulation
- transports K^+ into cell --> first step toward generating **membrane potential,** i.e., the composite of the electrical components of all electrochemical gradients = the electrical charge difference across the membrane (voltage)
- adds several mV by itself to membrane potential

Channel proteins - electrical signaling

channels - form aqueous pores with **selectivity filters** for particular solutes/ions to diffuse down their EG gradients

always open | closed | open

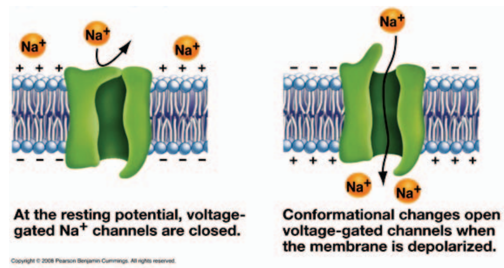


leak channels | gated channels

Alberts et al. Figs. 11.03 and 11.20

Channel proteins - electrical signaling

For example, voltage-gated Na^+ channel

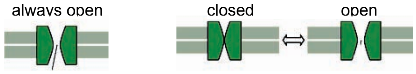


F. FIG. 45.9

Channel proteins - electrical signaling

channels - form aqueous pores with **selectivity filters** for particular solutes/ions to diffuse down their EG gradients

always open | closed | open



leak channels | gated channels

Telegraphing the story …

Membrane potential (entire neuron) - Na^+/K^+ pump, K^+ and Na^+ leak channels

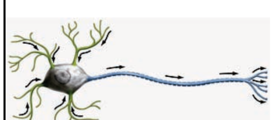
Action potential (axon) - voltage-gated Na^+ and K^+ channels

Post-synaptic potentials (dendrites) - neurotransmitter-gated Na^+, K^+, and Cl^- channels (also called ligand-gated)

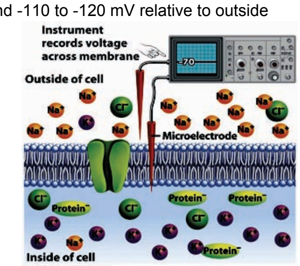
Alberts et al. Figs. 11.03 and 11.20

Membrane potential

- Sum of electrical components of all electrochemical gradients is known as the resting (or steady-state) membrane potential.
- Membrane potential is measured using very thin electrodes coupled to the equivalent of a very sensitive voltmeter.
- Inside of an animal cell is often around -60 to -70 mV relative to outside
- Inside of a plant cell is often around -110 to -120 mV relative to outside

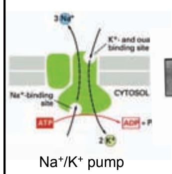


F Fig 45.3 and 45.4

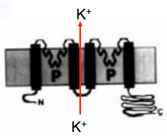


How is the membrane potential established?

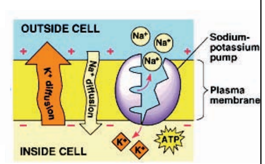
1. Cation pumping - Na^+/K^+ pump in animal cell membranes, or H^+ pump in cell membranes of other organisms
2. Passive diffusion of ions (especially K^+) in "ungated" or "leak" channels down their net electrochemical gradients



Na^+/K^+ pump



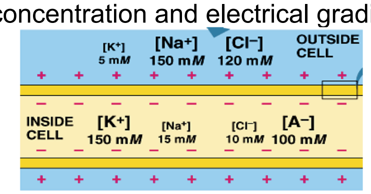
K^+ leak channel



C & R Fig. 48.7

Na^+/K^+ pump → EC gradients
Leak channels → resting membrane potential

Determine the direction of K^+ movement due to its concentration and electrical gradients



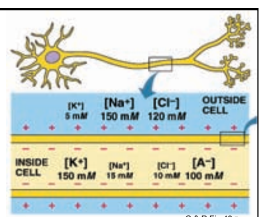
1. Conc. gradient moves K^+ into cell, elect. gradient moves it into cell
2. Conc. gradient moves K^+ into cell, elect. gradient moves it out of cell
3. Conc. gradient moves K^+ out of cell, elect. gradient moves it into the cell
4. Conc. gradient moves K^+ out of cell, elect. gradient moves it out of cell

The rules for K^+ diffusion

General principles apply to all animal cells

Specific example - mammalian neuron

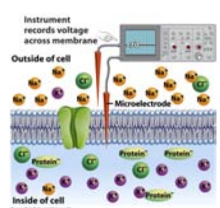
see F. Table 45.1 for ion concentrations on opposite sides of the membrane

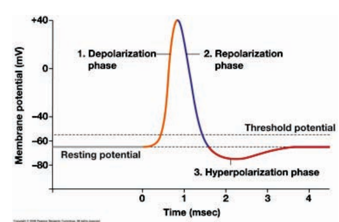


C & R Fig 48.7 -

- For K+, charge acts in opposite direction from concentration
- K+ diffusion from the cytoplasm to the outside of the cell results in the inside becoming more and more negative relative to the outside
- Net K+ will move out of the cell until it reaches equilibrium where diffusion (concentration gradient) is counterbalanced by electrical attraction (membrane potential)
- This equilibrium state approaches resting potential of -70 mV

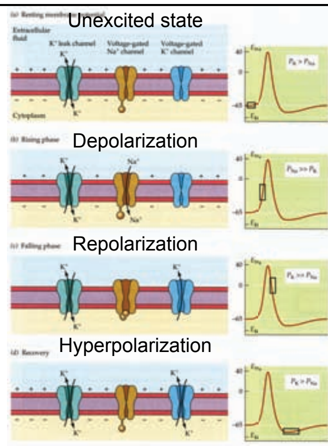
Action potential – initiated as a localized change in membrane potential - F. Fig 45.6





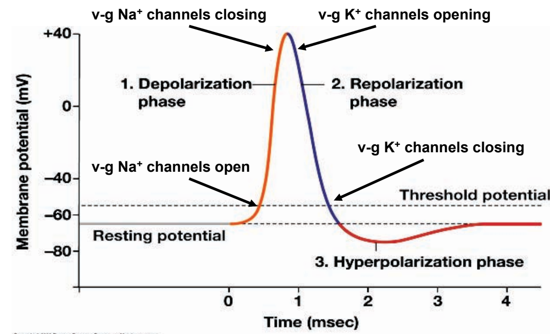
Threshold potential - minimum depolarization needed to trigger action potential
Action potentials - characteristic shape, all-or-none property, and rapid propagation (up to 150 m/s)

Action potential - sequential activation of voltage-gated Na^+ and K^+channels

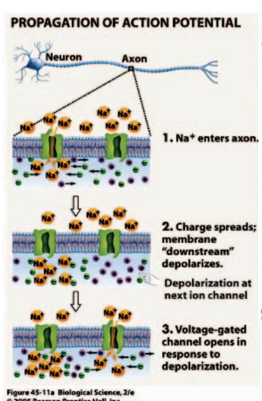


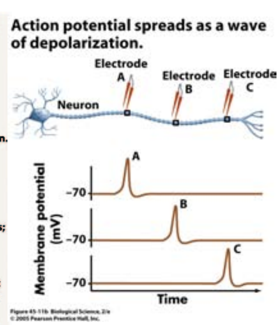
Hill et al. 2004 Animal Physiology Fig.11.18

Action potential - sequential ion flows via voltage-gated channels



Action potential – its movement down the axon

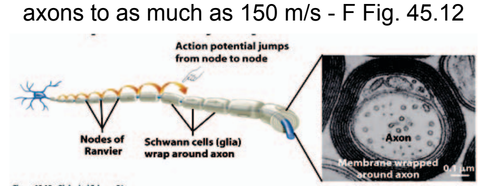




F Fig. 45.11

Speeding up the action…

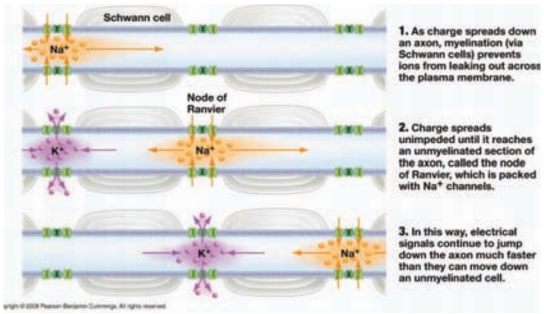
myelin increases speed of conduction down vertebrate axons to as much as 150 m/s - F Fig. 45.12



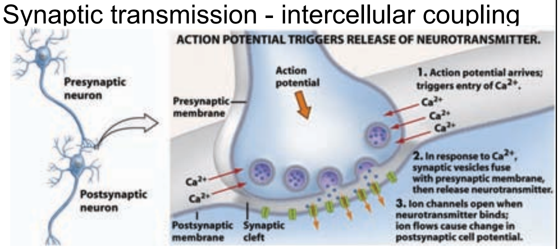
- Myelin is composed of multiple membrane layers of a Schwann cell wrapped around axon
- Prevents leakage of ions across membrane - acts like plastic insulation on wire -> more rapid longitudinal current down the axon
- Action potential appears to "jump" from one unmyelinated node of Ranvier to the next node

Speeding up the action…

myelin increases speed of conduction down vertebrate axons to as much as 150 m/s - F Fig. 45.12



Synaptic transmission - intercellular coupling



Action potential activates voltage-gated Ca^{2+} channels

Ca^{2+} mediates the fusion of synaptic vesicles (with e.g., acetylcholine, gamma aminobutyric acid, dopamine, or serotonin) with presynaptic membrane

Neurotransmitter will either directly open ion channels or act via signal transduction to alter membrane potential of postsynaptic cell

Rapid degradation of neurotransmitter F Fig. 45.15

Cocaine Blues - "I've got cocaine running all around my brain"

Cocaine – targets dopamine-producing neurons in the vegetal tagmental area (VTA) = "pleasure/reward center"

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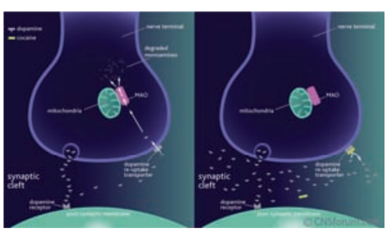
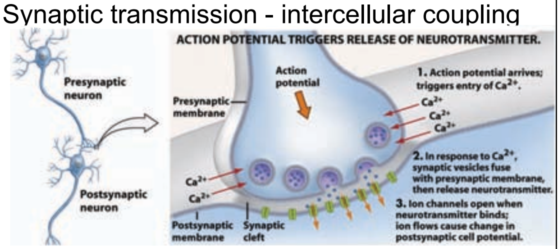


Dopamine is resorbed via dopamine re-uptake transporters, and is then degraded by monoamine oxidase on the outer membrane of mitochondria

Cocaine blocks the DR-UT, resulting in prolonged stimulation = the "high"

Synaptic transmission - intercellular coupling



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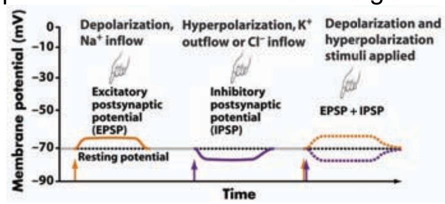
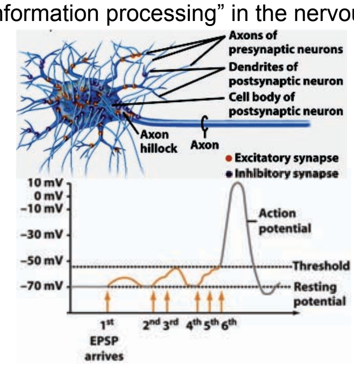
Rapid degradation of neurotransmitter F Fig. 45.15

Neurotransmitter binding results in postsynaptic potentials in the dendrites - F Fig. 45.16



- Postsynaptic changes in membrane potential occur as a result of ion flow
- Excitatory synapse - neurotransmitter triggers, e.g., Na^+ influx
- Inhibitory synapse - neurotransmitter triggers, e.g., Cl^- influx and/or K^+ efflux
- Postsynaptic potential spreads as a graded change down the dendrites to cell body
- Potential change decreases with time and distance
- How are graded potentials similar to and different from action potentials?

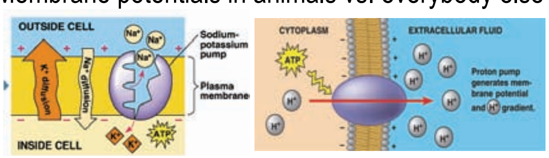
All postsynaptic signals are summed at axon hillock - this is "information processing" in the nervous system



F Fig. 45.17

Sufficient depolarization to reach threshold triggers new action potential

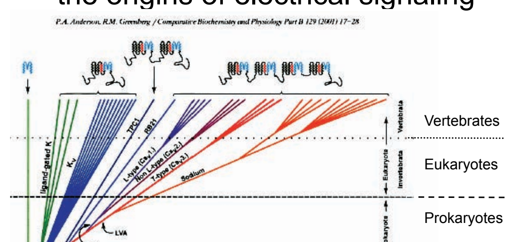
Membrane potentials in animals vs. everybody else



1. Electrogenic ion pumping (unbalanced ion exchange) - Na^+/K^+ pump in animal cell membranes, or H^+ pump in cell membranes of other organisms = electrogenic potential
2. Passive diffusion of ions (especially K^+) in "leak" channels down their electrochemical gradients = diffusion potential

Typical animal cell membrane - 2 >> 1
Typical plant/fungal cell membrane - 1 $\geq$ 2

Gated ion channels are ancient proteins - the origins of electrical signaling



- Ancestral protein - K^+ channel for osmoregulation
- Green - ligand-gated K^+ channels
- Blue - voltage-gated K^+ channels
- Purple/red - voltage-gated Ca^{2+} channels
- Red - voltage-gated Na^+ channels

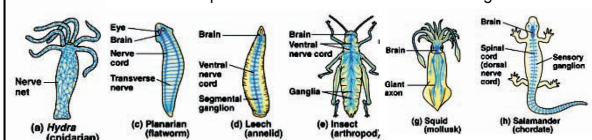
Action potentials - common property of excitable membranes having voltage-gated channels

Carnivorous plants (e.g., venus fly traps) F Fig. 39.12

	Animal	Plant
Velocity (m/s)	0.5 to 150	0.01 to 0.2
Depolarization	Na^+ influx	Cl^- efflux
Repolarization	K^+ efflux	K^+ efflux
Cell-to-cell coupling	Chemical	Electrical

Evolution of nervous systems

General principles: All organisms respond to environmental stimuli
Voltage-gated channels evolved in early life
Action potentials have arisen in several lineages



So what makes eumetazoans so special?

- cnidarians - origin of specialized cell (neuron) devoted to electrical signaling
- bilaterians - evolution of more complex neural networks associated with the effects of bilateral symmetry, namely, head formation (= cephalization)
- bilaterians - common neurotransmitters often with different functions
- cephalopods (e.g., squids) and vertebrates - evolution of complex brains for integrating sophisticated sensory organs and rapid motor responses

Neuron signaling – Fill out this table

Structure	Size	Mechanism	Molecules
Neuron	Up to ≥1 m or more		
Axon	Up to ≥1 m or more		
Synapse	20 to 40 nm		
Dendrites	1-2 mm		

Study Questions = Learning objectives

- Describe the basic features of different types of transport proteins (pumps, carriers, and channels) that convey ions across membrane.
- Describe the role of the Na+/K+ pump and the K+ leak channel in establishing the membrane potential across animal cell membranes.
- Characterize the following processes: resting potential, action potential, neurotransmitter diffusion, and post-synaptic potential, in terms of the structures exhibiting these processes and the molecules/ proteins involved in these processes.
- Characterize the membrane potential changes that occur during an action potential, and describe the activities of the different channels responsible for those potential changes.

Study Questions = Learning Objectives (cont.)

- Describe the events that occur during synaptic transmission of intercellular signals.
- Characterize the membrane potential changes that occur with excitatory and inhibitory post-synaptic potentials, and describe the activities of the different channels responsible for those potential changes.
- Describe the integration of post-synaptic potentials that occurs at the hillock, and then describe possible consequences of that integration.
- What the limits of the molecular mechanism for cocaine action for explaining addiction?