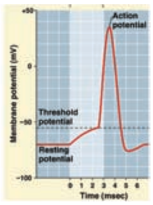
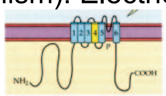
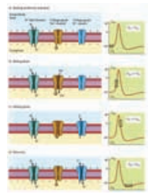
excite.org(anism): Electrical Signaling





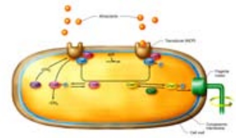


Today's lecture – we'll use clickers
Friday's lecture – both sections in BPS 1250 at 9 AM!

Universality of sensory-response systems

Three step process: sensation-integration-response

Bacterial chemotaxis

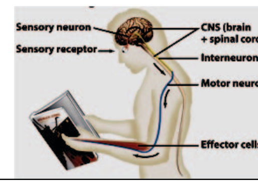


Madigan et al. Fig. 8.24

Rick Stewart (CBMG)

Human nervous system

F Fig. 45.1



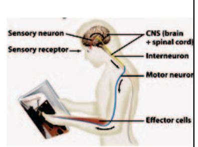
Universality of sensory-response systems

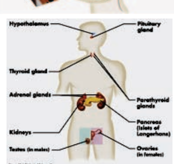
Three general classes of communication signals

Chemicals via diffusion - rapid communication over short distances within cells or between cells (e.g., neurotransmitters)

Electricity via ion flows - very rapid communication over longer distances along individual cells or between cells (e.g., action potentials)

Chemicals via bulk flow - slower communication over longer distances in body fluids of large organisms (e.g., endocrine hormones)





F. Fig. 47.3

The hierarchy of electrical signaling in animals

Molecular level - transmembrane ion flows

Cellular level - lateral electrical signaling

Tissue level - cell-to-cell signaling

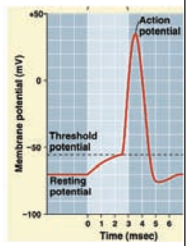
Organ level - signal processing

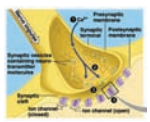
System level - perception, integration, and response

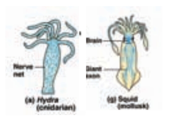
Higher-order phenomena - consciousness, learning, memory, etc.

Lecture outline

- **Neuron** - fundamental cell of nervous systems
- **Membrane proteins -** molecular players in electrical signaling
- **Axons** - action potentials
- **Synapse** - narrow gap between adjacent neurons
- **Neurotransmitters** - chemical communication across the synapse
- **Dendrites** - graded potentials
- **Evolution** of electrical signaling







Evolutionary challenge facing ancient eumetazoans - How to coordinate muscle cell activity associated with feeding

Challenges:

How to evolve a communication system for coordinating feeding behavior in often mobile multicellular organism

How to evolve this system by using available proteins, cell structures and their functions

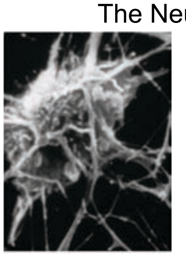
Solution:

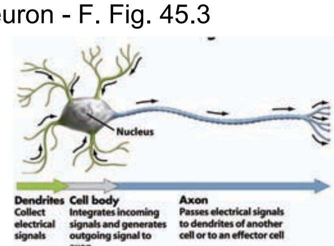
Evolve a specialized cell (= neuron) with an extended axon (up to $\geq$ 1 m in some vertebrates) for very rapid, long distance communication

Axon is specialized for conducting the ***action potential*** -
are electrical signals propagated along the cell membrane
are based on fundamental physical and chemical processes

Utilize voltage-gated channels that have ancient evolutionary origin

The Neuron - F. Fig. 45.3



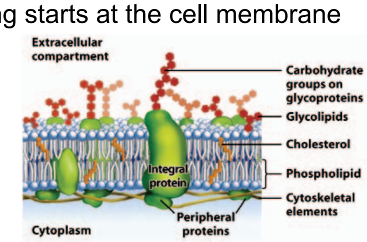


- Electrical signals
  - –Dendrites: graded post-synaptic potentials
  - –Axons: all-or-none action potentials
- Chemical signals
  - – Synapses: neurotransmitters

Key concept: different structures, different proteins, different functions

Signaling starts at the cell membrane

Cell membrane
(F. Fig. 8.1)



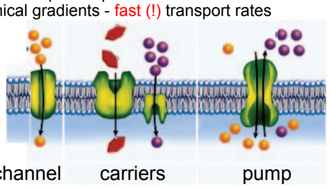
Lipid bilayer - differential permeability
charge separation

Transmembrane proteins - energy transduction (electrochemical gradients)
transport - facilitated diffusion and active transport
conformational changes - ligand binding

Electrical signaling occurs via membrane proteins

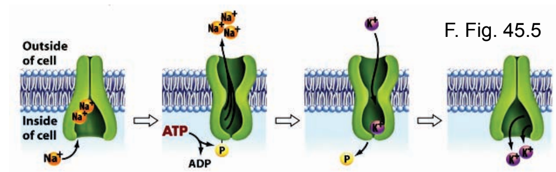
Membrane proteins controlling ion flow across membranes

- ***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



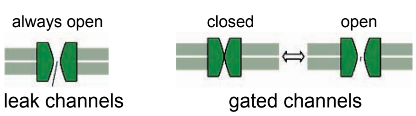
F. Fig. 45.5

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

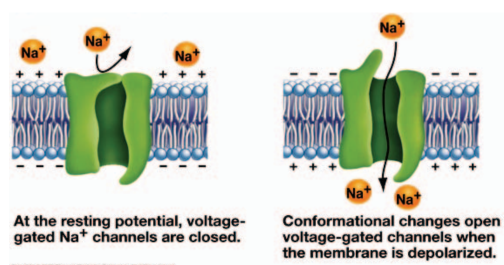
channels - form aqueous pores with **selectivity filters** for particular solutes/ions to diffuse down their EG gradients



Alberts et al. Figs. 11.03 and 11.20

Channel proteins - electrical signaling

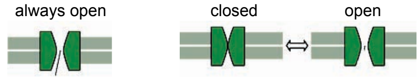
For example, voltage-gated Na^+ channel



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



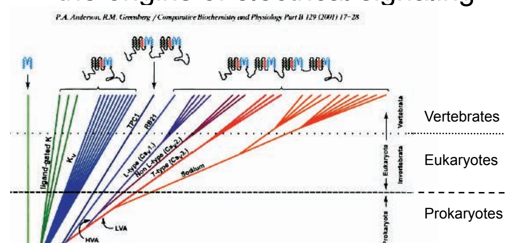
Membrane potential (entire neuron) - Na^+/K^+ pump, K^+ and Na^+ leak channels

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

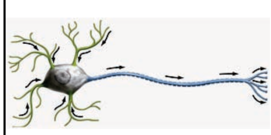
Gated ion channels are ancient proteins - the origins of electrical signaling



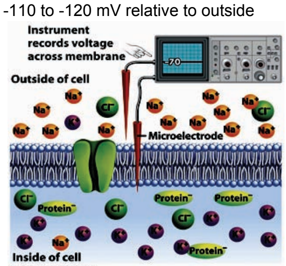
- Ancestral protein - K^+ channel for osmoregulation
- Green - ligand-gated K^+ channels
- Blue - voltage-gated K^+ channels
- Purple/red - voltage-gated Ca^{2+} channels
- Red - voltage-gated Na^+ channels

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

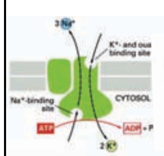


F Fig 45.3 and 45.4

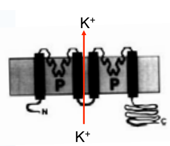


How is the membrane potential established?

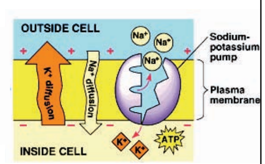
1. Cation pumping - Na^+/K^+ pump in animal cell membranes, or H^+ pump in cell membranes of other organisms
2. Passive diffusion of ions (especially K^+) in "ungated" or "leak" channels down their net electrochemical gradients



Na^+/K^+ pump



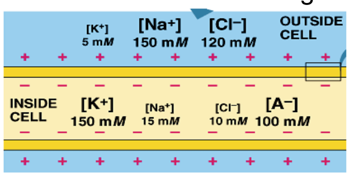
K^+ leak channel



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



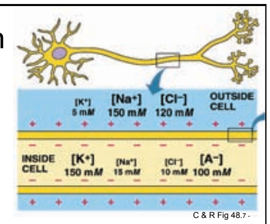
1. Conc. gradient moves K^+ into cell, elect. gradient moves it into cell
2. Conc. gradient moves K^+ into cell, elect. gradient moves it out of cell
3. Conc. gradient moves K^+ out of cell, elect. gradient moves it into the cell
4. Conc. gradient moves K^+ out of cell, elect. gradient moves it out of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

The rules for K^+ diffusion

General principles apply to all animal cells

Specific example - mammalian neuron

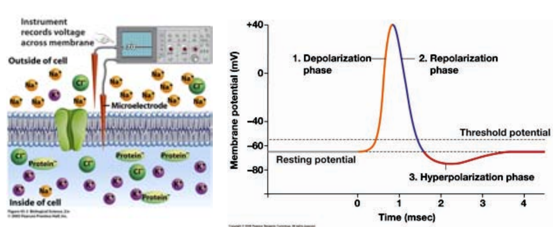
see F. Table 45.1 for ion concentrations on opposite sides of the membrane



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 equals the resting potential of -70 mV

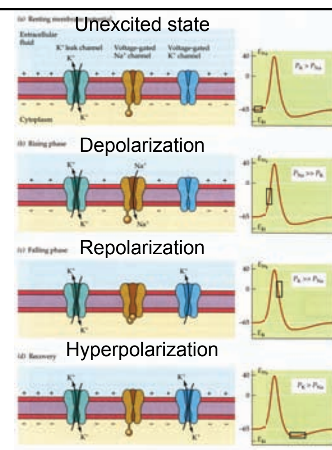
Action potential – initiated as a localized change in membrane potential - F. Fig 45.6



Threshold potential - minimum depolarization needed to trigger action potential

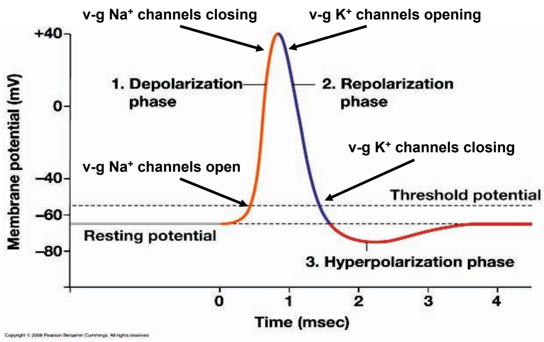
Action potentials - characteristic shape, all-or-none property, and rapid propagation (up to 150 m/s)

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

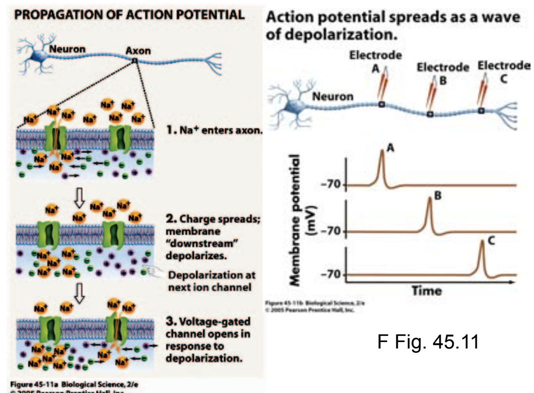


Hill et al. 2004 Animal Physiology Fig.11.18

Action potential - sequential ion flows via voltage-gated channels



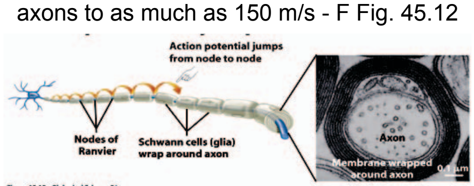
Action potential – its movement down the axon



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