ELEC ENG 3BB3:

Cellular Bioelectricity

Notes for Lecture #2

Thursday, January 9, 2014

1. INTRODUCTION TO BIOELECTRICITY AND EXCITABLE CELLS

Historical perspective:

- Bioelectricity first discovered by Luigi Galvani in 1780s
- Originally termed “animal electricity”
- Galvani thought that a special electrical fluid was prepared by the brain, flowing through the nerve tubes into muscles

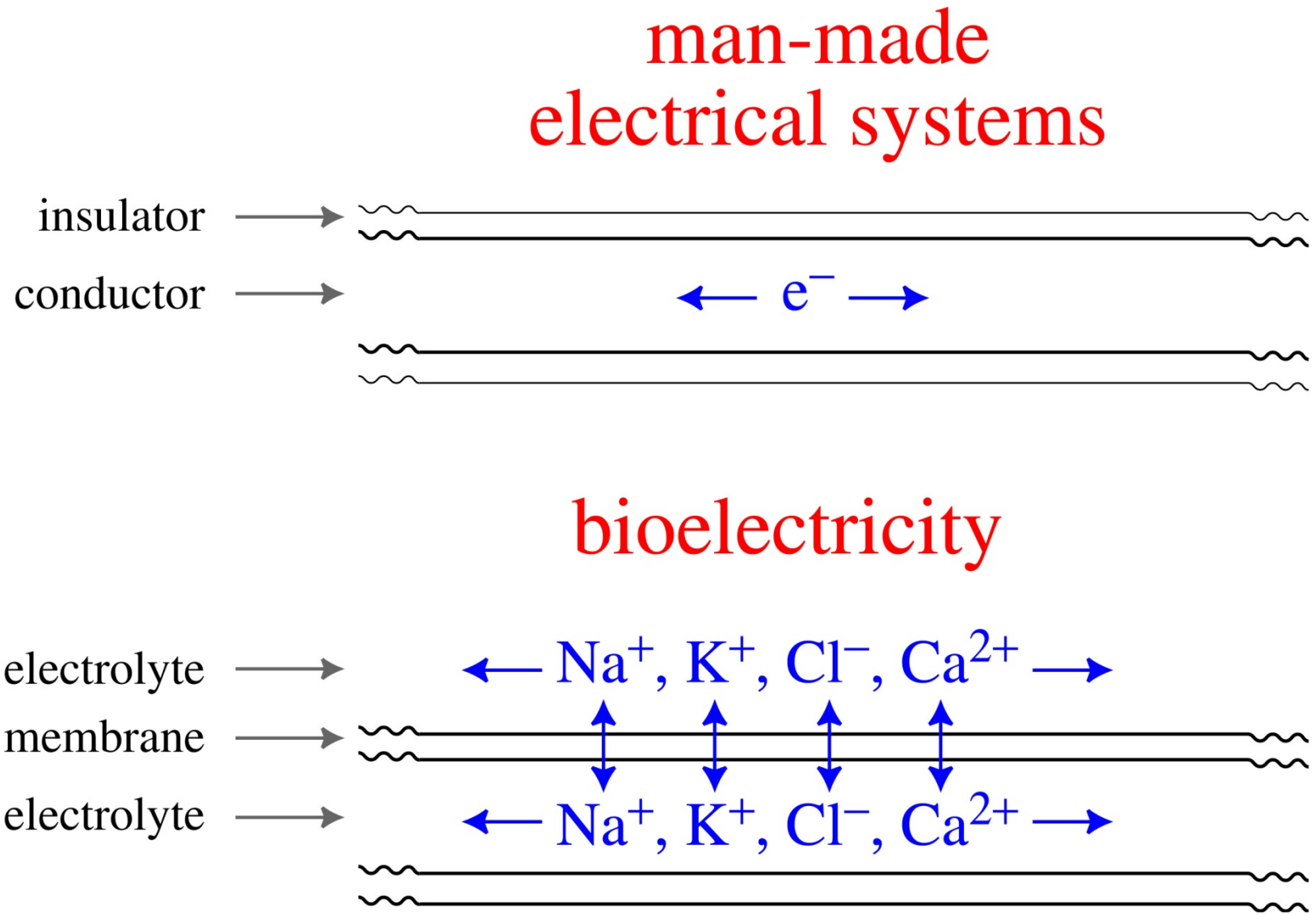
Modern perspective:

- Bioelectricity is now known to obey the same fundamental laws of electricity in the atmosphere, conducting wires, semiconductors, etc.
- However, there are some substantial differences between bioelectrical systems and man-made electrical systems.

Comparison of bioelectricity and man-made electrical systems:

Man-made electrical systems	Charge carriers are electrons within a conductor	Current flow within (insulated) conductors
Bioelectricity	Charge carriers are ions within an electrolyte	Current flow inside *and outside* of (partially-insulated) cell membranes

Comparison (cont.):



Ionic flow in terms of particle movement:

- From the perspective of *chemistry*, ionic movements are described in terms of *moles*, where one mole is:

  $N_A = 6.0225 \times 10^{23}$ molecules,

  Avogadro's number.

- *Ionic flows* are then described in units of moles per second and *fluxes* (here denoted by the lowercase letter j) in units of moles per second per unit area.

Ionic flow in terms of charge movement:

- From the perspective of *electricity*, ionic movements are described in terms of *columbs*, where an electron (and hence a *univalent ion*) has an electrical charge of 1.6×10^{-19} coulombs.
- *Ionic flows* are then described in units of coulombs per second (or amperes) and *fluxes* (here denoted by the uppercase letter J) in units of amperes per unit area, e.g., amperes per cm^2.

Converting between particle flow and electrical current:

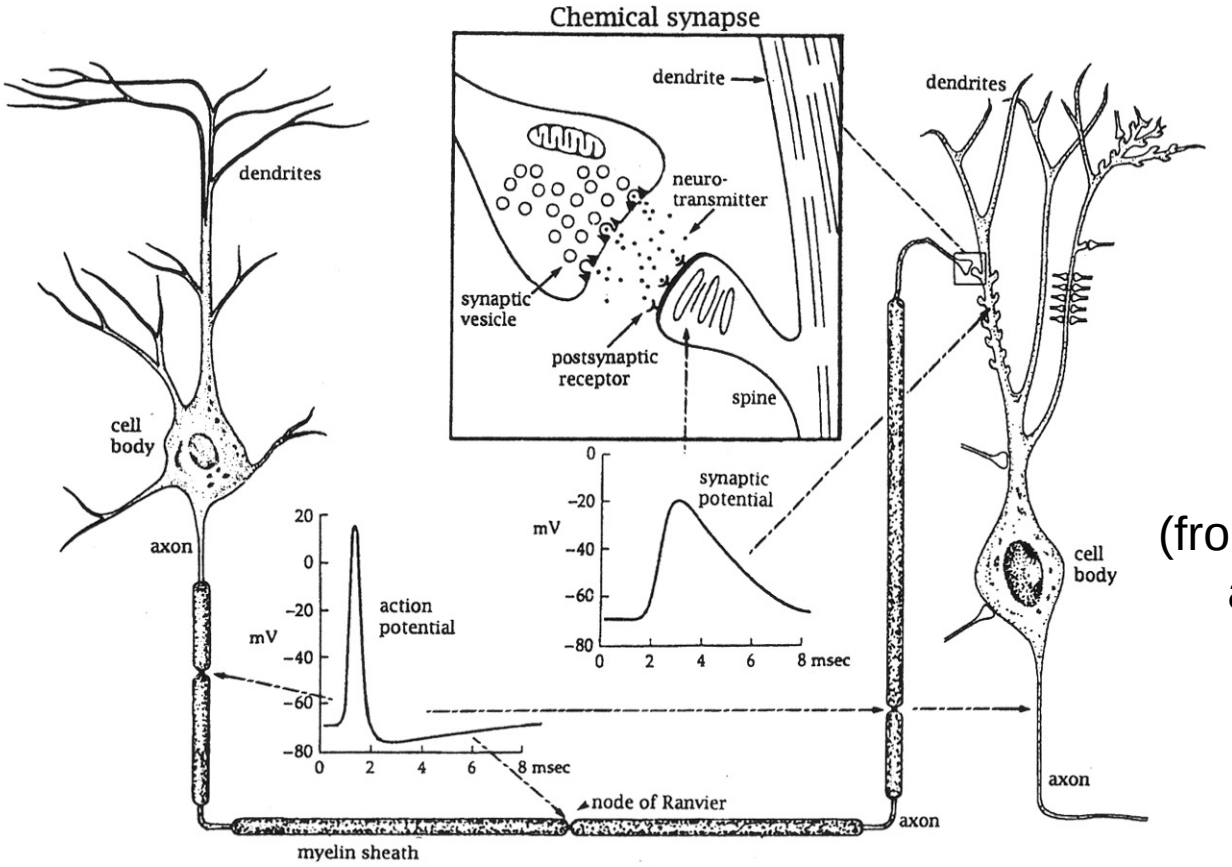
- Ionic movement can be described in terms of either particle flow or electrical current.
- The conversion factor is Faraday's constant:

$$F = \left(6.02 \times 10^{23}\right) \frac{\text{particles}}{\text{mole}} \times \left(1.6 \times 10^{-19}\right) \frac{\text{columbs}}{\text{particle}} = 96,487 \ \frac{\text{columbs}}{\text{mole}}$$

Excitable cells:

- Cells that can generate electrical potentials and currents are referred to as *excitable cells*.
- These potentials and currents can be observed in the cells' interior volume, across their membranes, and in their surrounding conducting volume.
- Excitable cells include *nerve cells* (*neurons*), *muscle fibers*, and *sensory receptor* (*transducer*) *cells*.

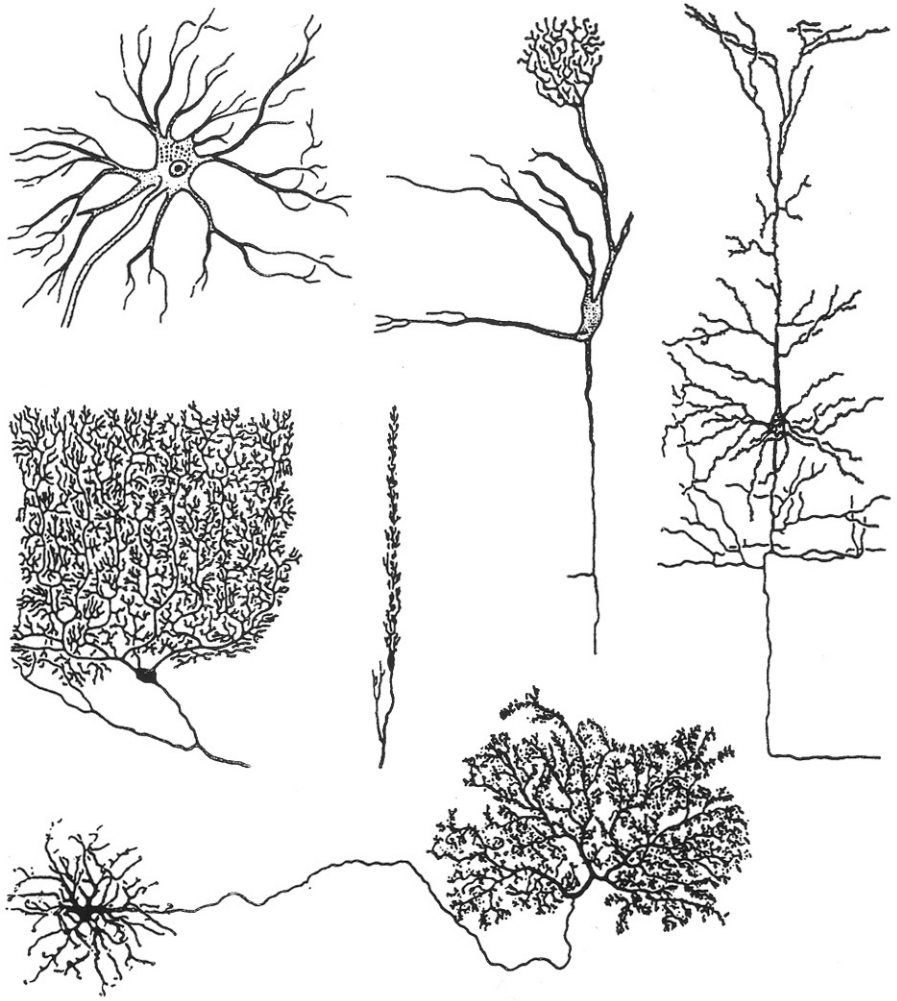
Nerve cells:



(from Johnston and Wu)

Figure 1.2 Neurons convey information by electrical and chemical signals. Electrical signals travel from the cell body of a neuron (left) to its axon terminal in the form of action potentials. Action potentials trigger the secretion of neurotransmitters from synaptic terminals (upper insert). Neurotransmitters bind to postsynaptic receptors and cause electric signals (synaptic potential) in the postsynaptic neuron (right). Synaptic potentials trigger action potentials, which propagate to the axon terminal and trigger secretion of neurotransmitters to the next neuron. (Adapted from Kandel et al. 1991 and from L.L. Iversen, copyright © 1979 by Scientific American, Inc. All rights reserved.)

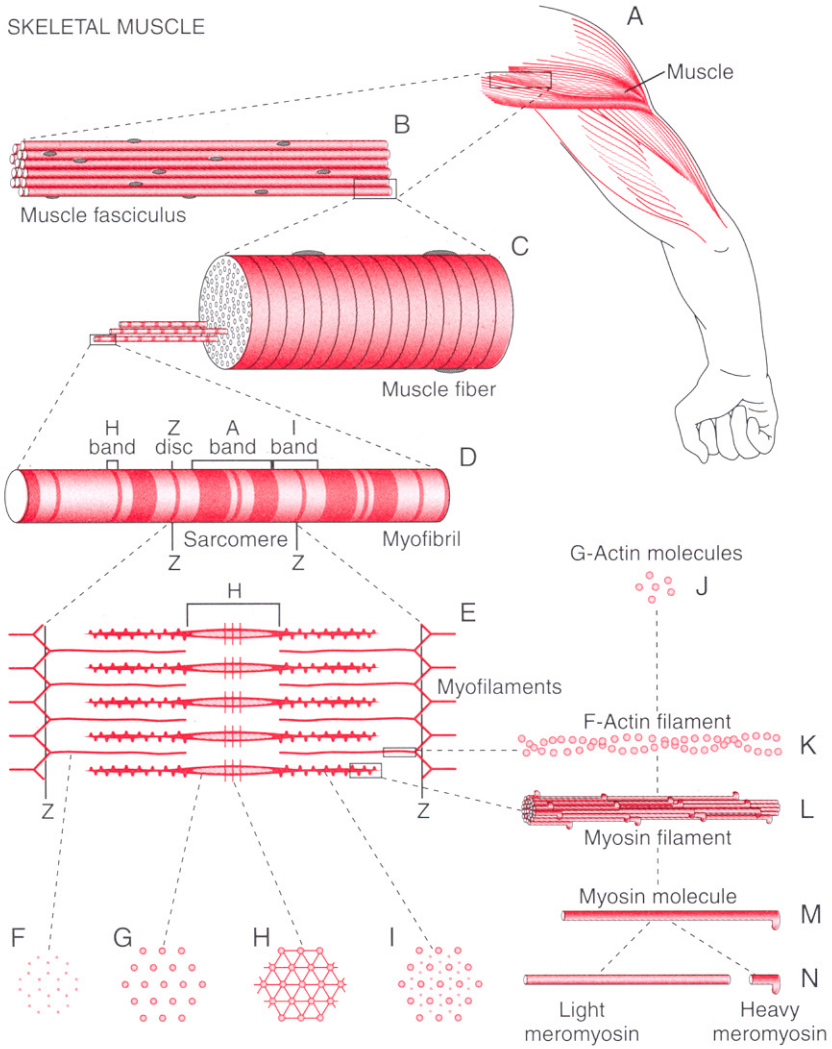
Examples of neuron morphologies:



(from Johnston and Wu)

Figure 1.1 Examples of neurons in the nervous system exhibiting various morphology. From the upper left in clockwise order: motor neuron from the spinal cord, mitral cell from olfactory bulb, pyramidal cell from cortex, horizontal cell from retina, and Purkinje cell (front and side views) from cerebellum. (From Nicholls et al. 1992 and Fisher and Boycott 1974.)

Skeletal muscle cells:

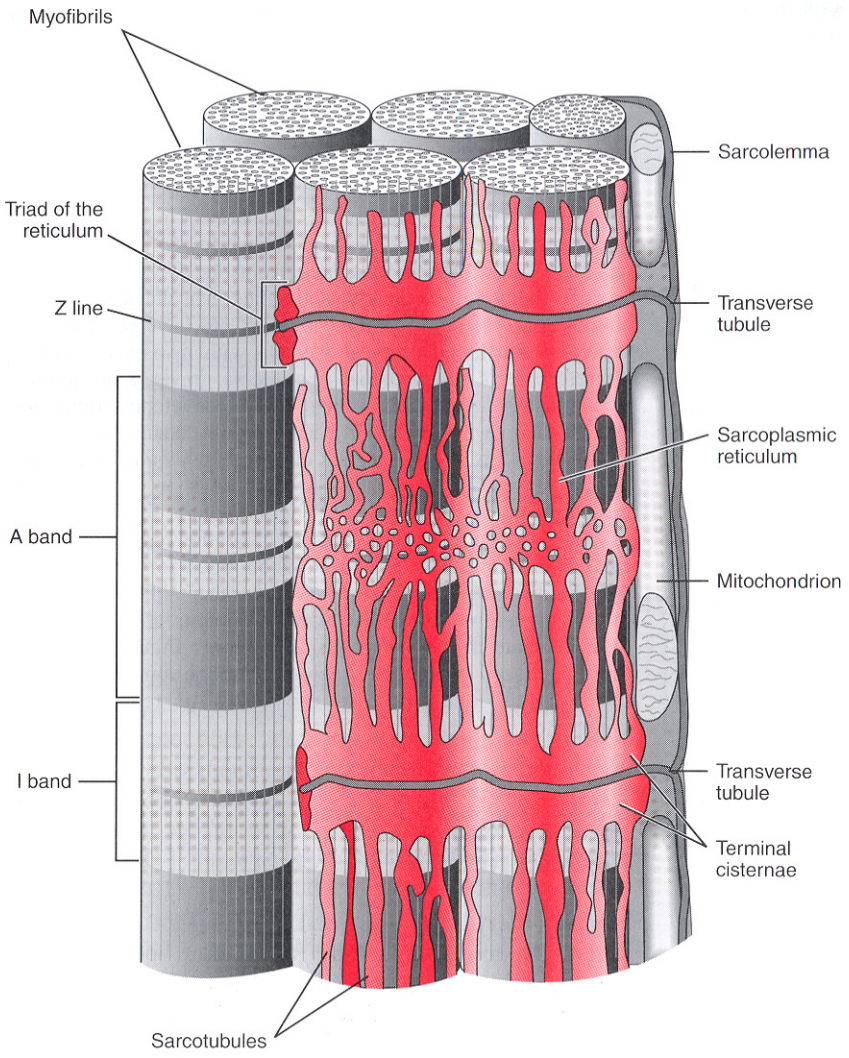


(from Guyten)

FIGURE 6–1

Organization of skeletal muscle, from the gross to the molecular level. *F, G, H,* and *I* are cross sections at the levels indicated. (Drawing by Sylvia Colard Keene. Modified from Fawcett DW: Bloom and Fawcett: A Textbook of Histology. Philadelphia: WB Saunders Co, 1986.)

Transverse tubule-sarcoplasmic reticulum system for excitation-contraction coupling:



(from Guyten)

FIGURE 7–5

Transverse (T) tubule-sarcoplasmic reticulum system. Note the *longitudinal tubules* that terminate in large *cisternae*. The cisternae in turn abut the T tubules. Note also that the T tubules communicate with the outside of the cell membrane. This illustration was drawn from frog muscle, which has one T tubule per sarcomere, located at the Z line. A similar arrangement is found in mammalian heart muscle, but mammalian skeletal muscle has two T tubules per sarcomere, located at the A-I junctions. (Redrawn from Bloom W, Fawcett DW: A Textbook of Histology. Philadelphia: WB Saunders Co, 1986. Modified after Peachey LD: J Cell Biol 25:209, 1965. Drawn by Sylvia Colard Keene.)

Cardiac muscle cells are interconnected via electrical "gap junctions":

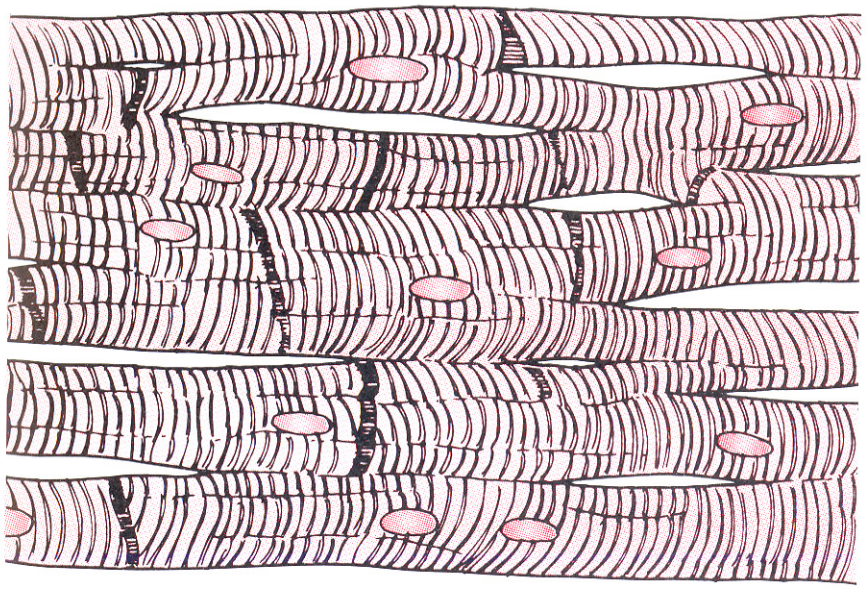


FIGURE 9 – 2

"Syncytial," interconnecting nature of cardiac muscle fibers.

(from Guyten)

Electrical "gap junctions" in cardiac cells:

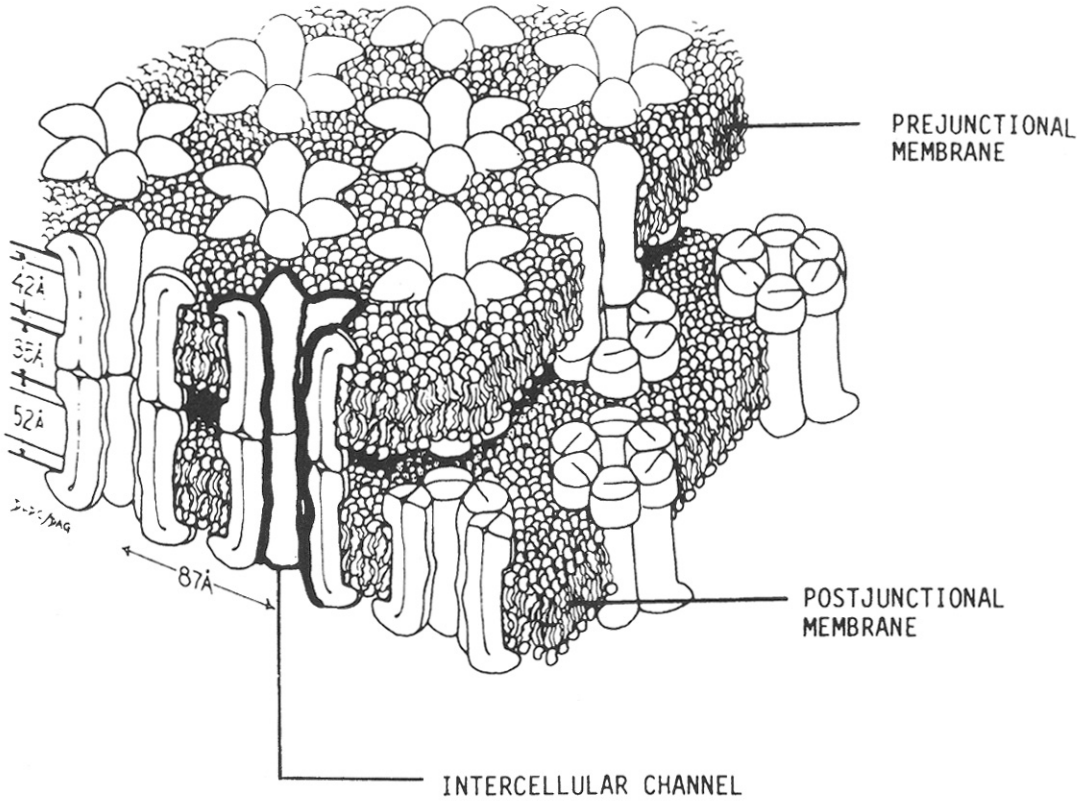


Figure 9.4. Details of the communicating-type intercellular cardiac junction (connexon array) is shown. Each unit (connexon) is a protein channel running transverse to the opposing membranes. Connexons from abutting cells align themselves to form structural continuity. The structural detail shown is based on morphometry obtained from X-ray diffraction, electron microscopy, and chemical studies. The gap spacing is given as 35 Å. [R. Plonsey, The use of a bidomain model for the study of excitable media, *Lectures on Mathematics in the Life Sciences* **21**:123–149 (1989). From L. Makowski, D. L. D. Caspar, W.C. Phillips, and D. A. Goodenough, Gap junctional structures II. Analysis of x-ray diffraction, *J. Cell Biol.* **74**:629–645 (1977). Reproduced from the Journal of Cell Biology, 1977, vol. 74, pp. 629–645 by copyright permission of the Rockefeller University Press.]

Sensory receptors:

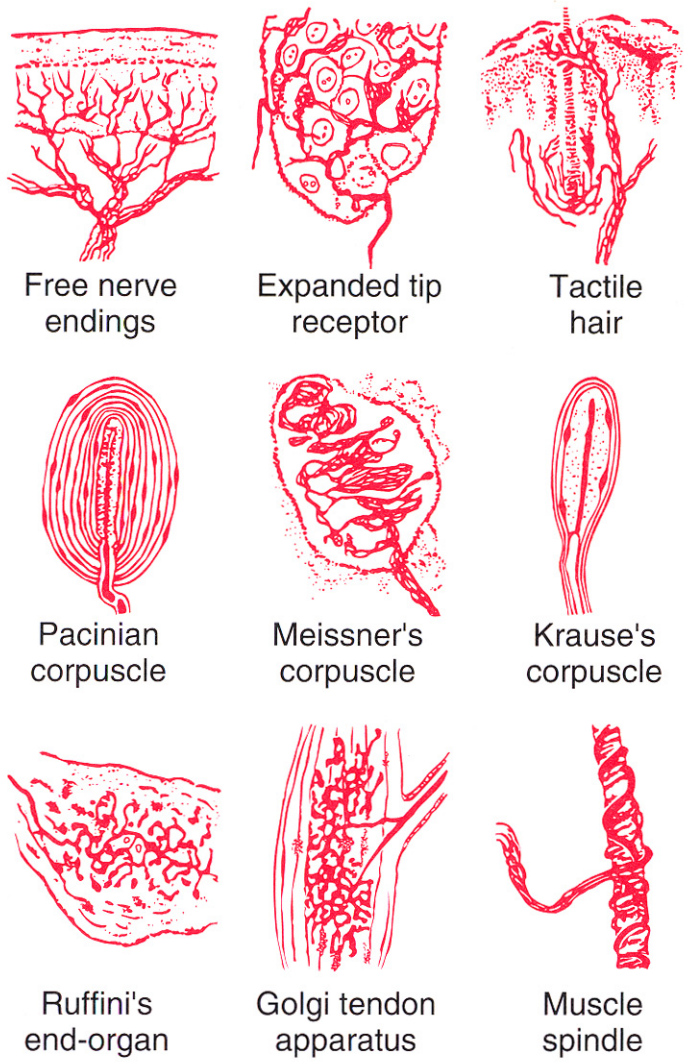


FIGURE 46–1

Several types of somatic sensory nerve endings.

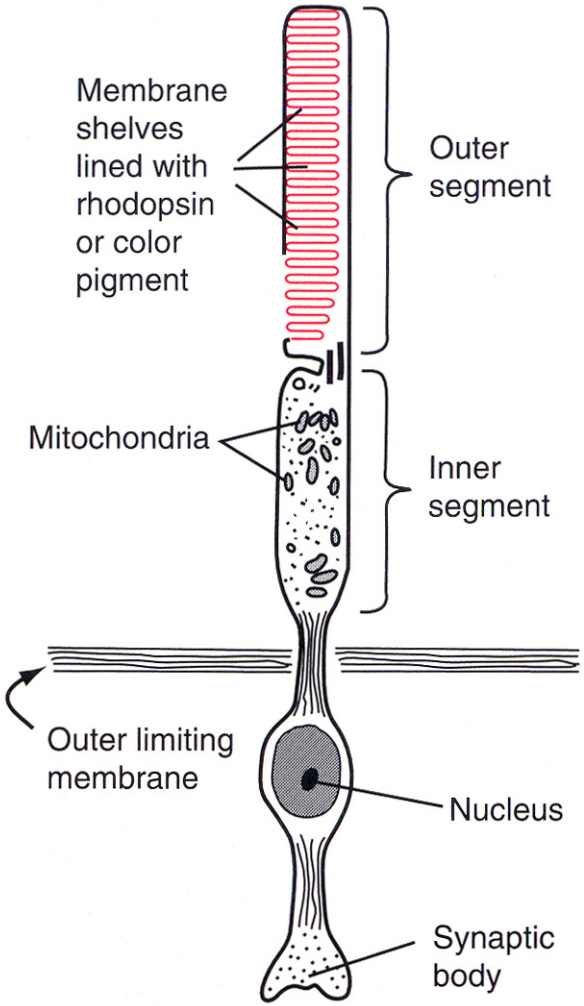


FIGURE 50–3

Schematic drawing of the functional parts of the rods and cones.

(from Guyten)

Sensory receptors (cont.):

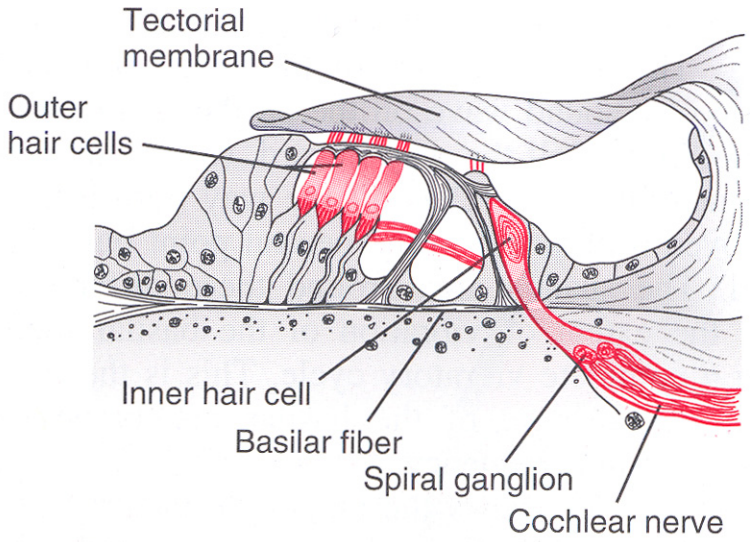


FIGURE 52–7

Organ of Corti, showing especially the hair cells and the tectorial membrane against the projecting hairs.

(from Guyten)

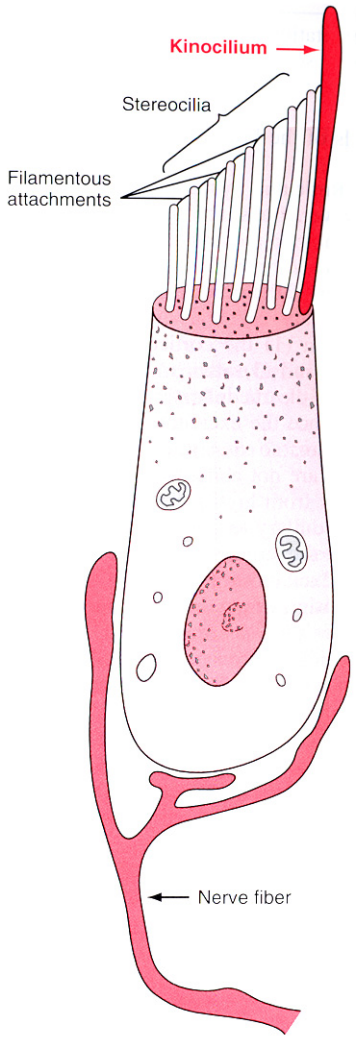


FIGURE 55–10

Hair cell of the equilibrium apparatus and its synapses with the vestibular nerve.

Sensory receptors (cont.):

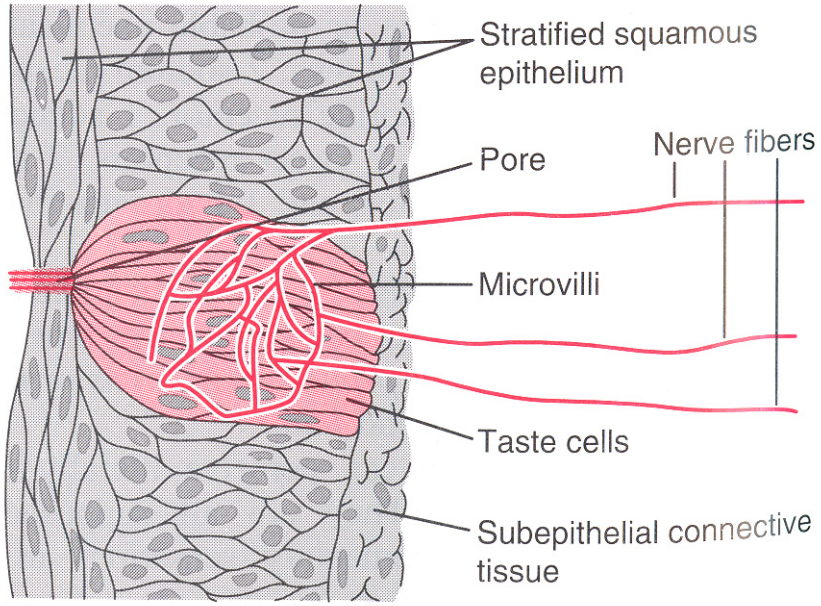


FIGURE 53–1

Taste bud.

(from Guyten)

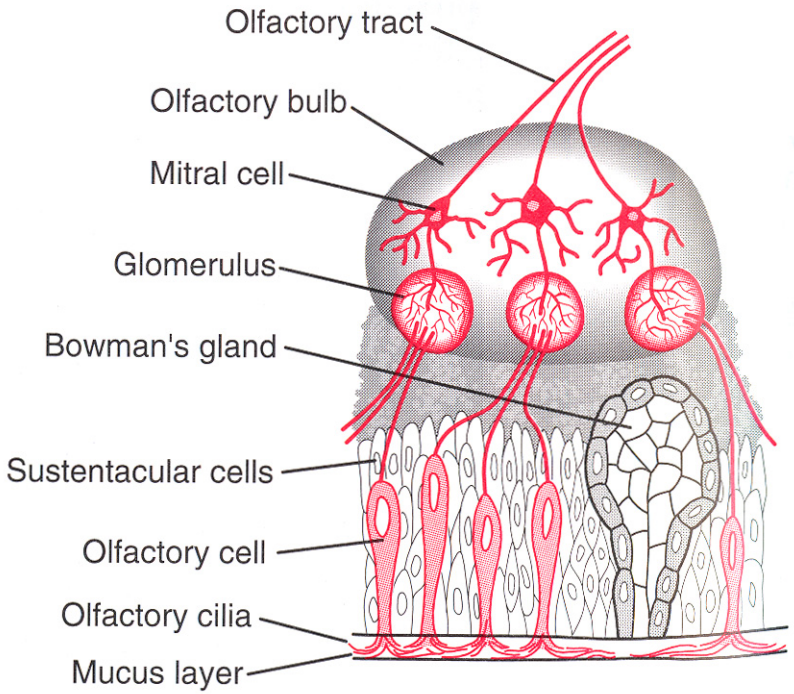


FIGURE 53–3

Organization of the olfactory membrane and olfactory bulb of the superlying brain.

Examples of action potential morphologies:

(from Koch)

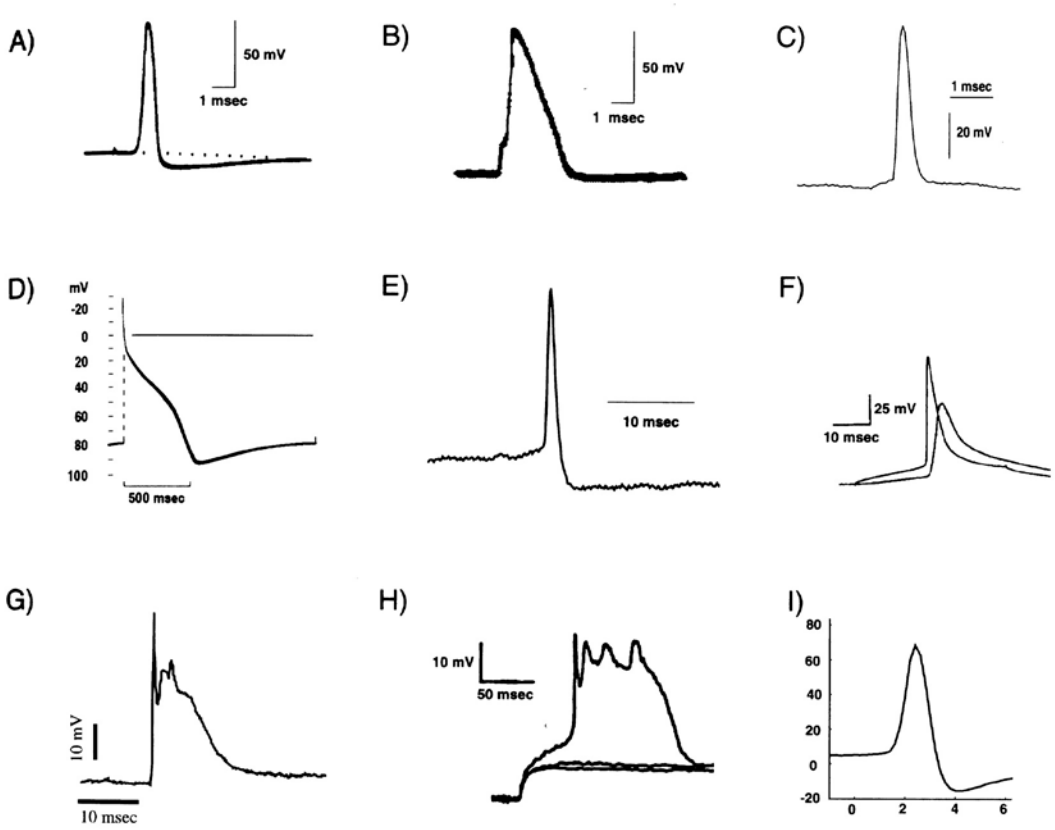


Fig. 6.1 ACTION POTENTIALS OF THE WORLD Action potentials in different invertebrate and vertebrate preparations. Common to all is a threshold below which no impulse is initiated, and a stereotypical shape that depends only on intrinsic membrane properties and not on the type or the duration of the input. **(A)** Giant squid axon at 16° C. Reprinted by permission from Baker, Hodgkin, and Shaw (1962). **(B)** Axonal spike from the node of Ranvier in a myelinated frog fiber at 22° C. Reprinted by permission from Dodge (1963). **(C)** Cat visual cortex at 37° C. Unpublished data from J. Allison, printed with permission. **(D)** Sheep heart Purkinje fiber at 10° C. Reprinted by permission from Weidmann (1956). **(E)** Patch-clamp recording from a rabbit retinal ganglion cell at 37° C. Unpublished data from F. Amthor, printed with permission. **(F)** Layer 5 pyramidal cell in the rat at room temperatures. Simultaneous recordings from the soma and the apical trunk. Reprinted by permission from Stuart and Sakmann (1994). **(G)** A complex spike—consisting of a large EPSP superimposed onto a slow dendritic calcium spike and several fast somatic sodium spikes—from a Purkinje cell body in the rat cerebellum at 36° C. Unpublished data from D. Jaeger, printed with permission. **(H)** Layer 5 pyramidal cell in the rat at room temperature. Three dendritic voltage traces in response to three current steps of different amplitudes reveal the all-or-none character of this slow event. Notice the fast superimposed spikes. Reprinted by permission from Kim and Connors (1993). **(I)** Cell body of a projection neuron in the antennal lobe in the locust at 23° C. Unpublished data from G. Laurent, printed with permission.