2006

Elements of Neuronal Biophysics

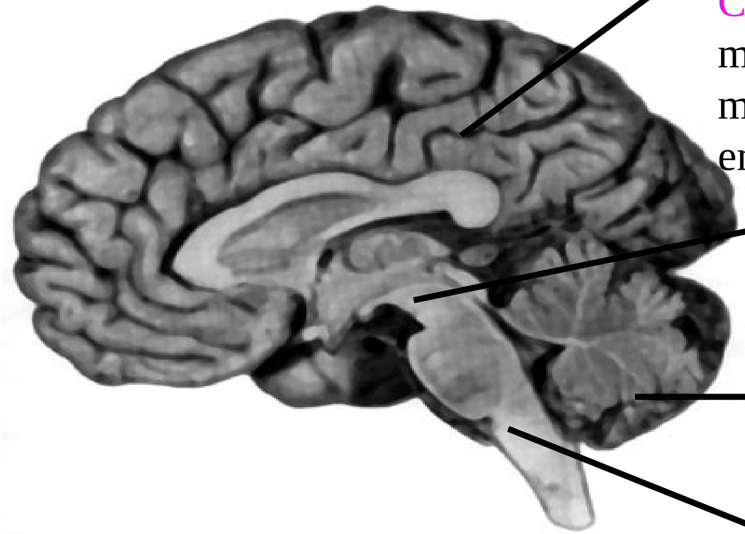
The human brain

Seat of consciousness and cognition

Perhaps the most complex information processing machine in nature

Historically, considered as a monolithic information processing machine

Beginner's Brain Map



Forebrain (Cerebral Cortex): Language, maths, sensation, movement, cognition, emotion

Midbrain: Information Routing; involuntary controls

Cerebellum: Motor Control

Hindbrain: Control of breathing, heartbeat, blood circulation

Spinal cord: Reflexes, information highways between body & brain

Brain : a computational machine?

Information processing: brains vs computers

- brains better at perception / cognition
- slower at numerical calculations

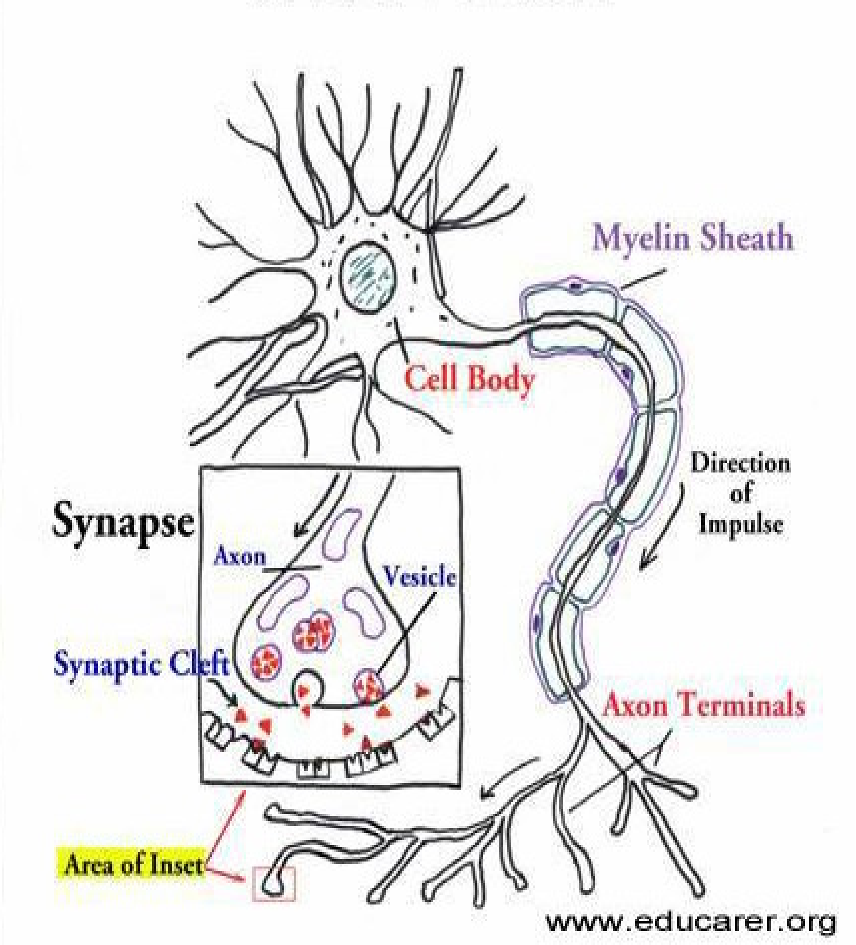
- Evolutionarily, brain has developed algorithms most suitable for survival
- Algorithms unknown: the search is on
- Brain astonishing in the amount of information it processes
  - Typical computers: 10^9 operations/sec
  - Housefly brain: 10^{11} operations/sec

Brain facts & figures

- Basic building block of nervous system: nerve cell (neuron)
- $\sim 10^{12}$ neurons in brain
- $\sim 10^{15}$ connections between them
- Connections made at "synapses"
- The speed: events on millisecond scale in neurons, nanosecond scale in silicon chips

Neuron - “classical”

- Dendrites
  - Receiving stations of neurons
  - Don't generate action potentials
- Cell body
  - Site at which information received is integrated
- Axon
  - Generate and relay action potential
  - Terminal
    - Relays information to next neuron in the pathway



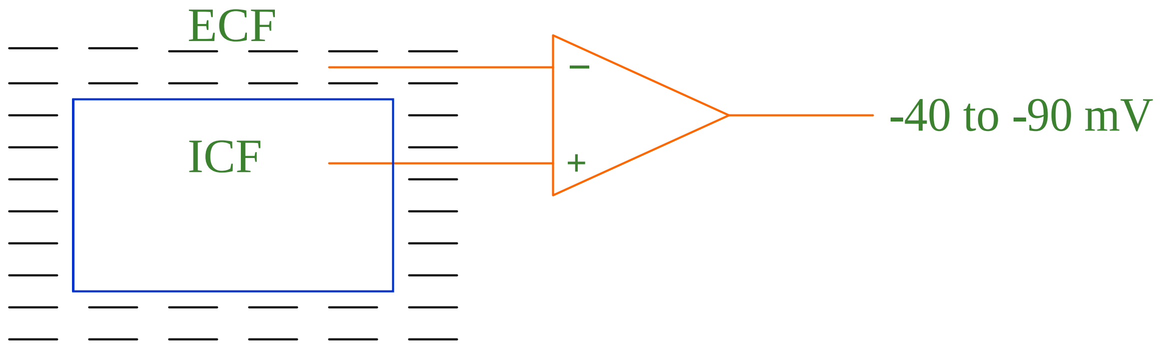
http://www.educarer.com/images/brain-nerve-axon.jpg

Membrane Biophysics: Overview

Part 1: Resting membrane potential

Resting Membrane Potential

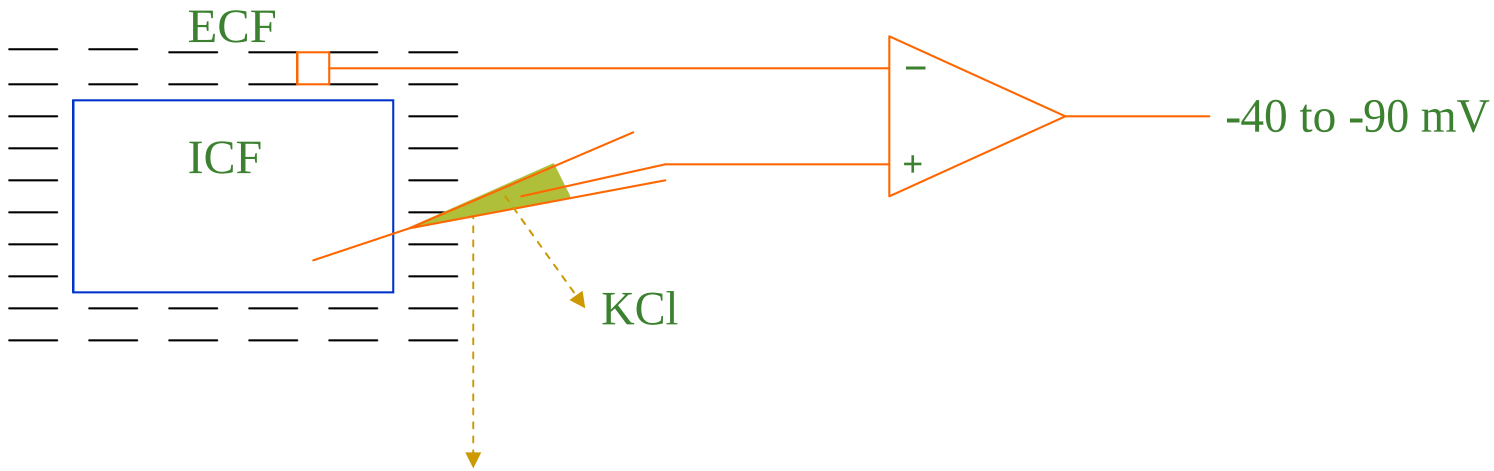
- Measurement of potential between ICF and ECF



  - $V_m = V_i - V_o$
  - ICF and ECF at isopotential separately.
  - ECF and ICF are different from each other.

Resting Membrane Potential - recording

- Electrode wires can not be inserted in the cells without damaging them (cell membrane thickness: 7nm)



- Solution: Glass microelectrodes (Tip diameter: 10 nm)
  - Glass → Non conductor
  - Therefore, while pulling a capillary after heating, it is filled with KCl and tip of electrode is open and KCl is interfaced with a wire.

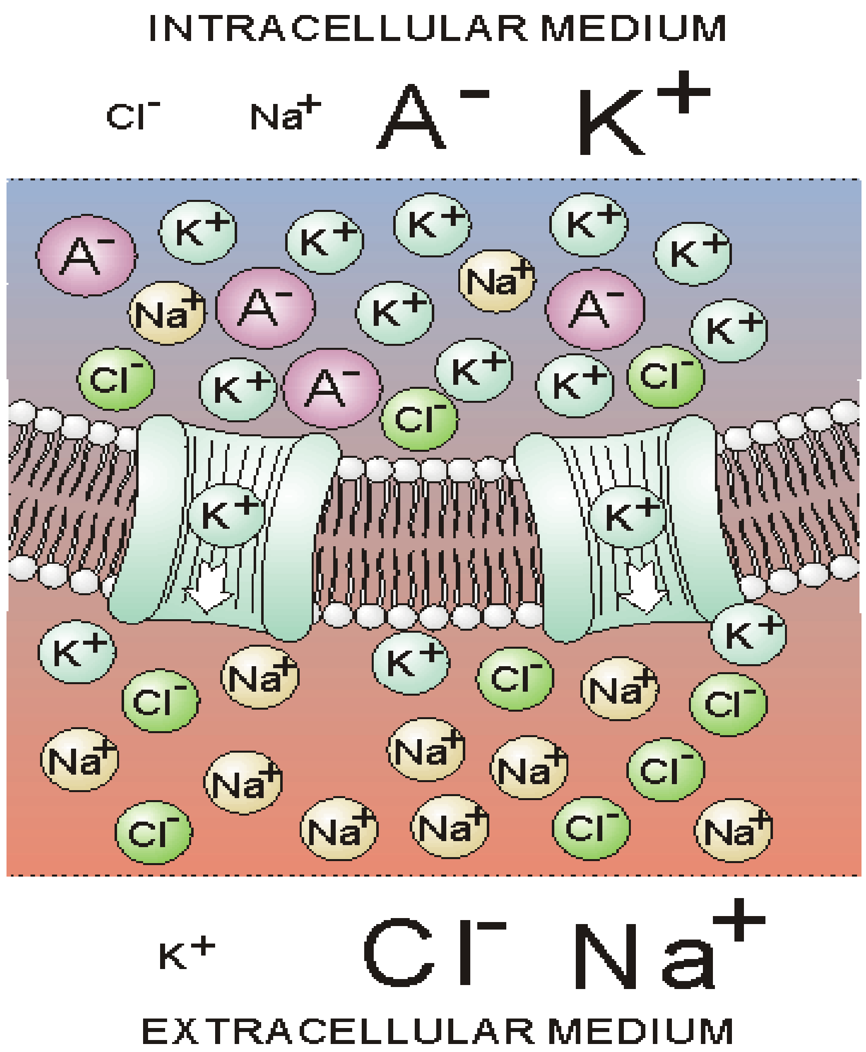
R.m.p. - towards a theory

- Ionic concentration gradients across biological cell membrane

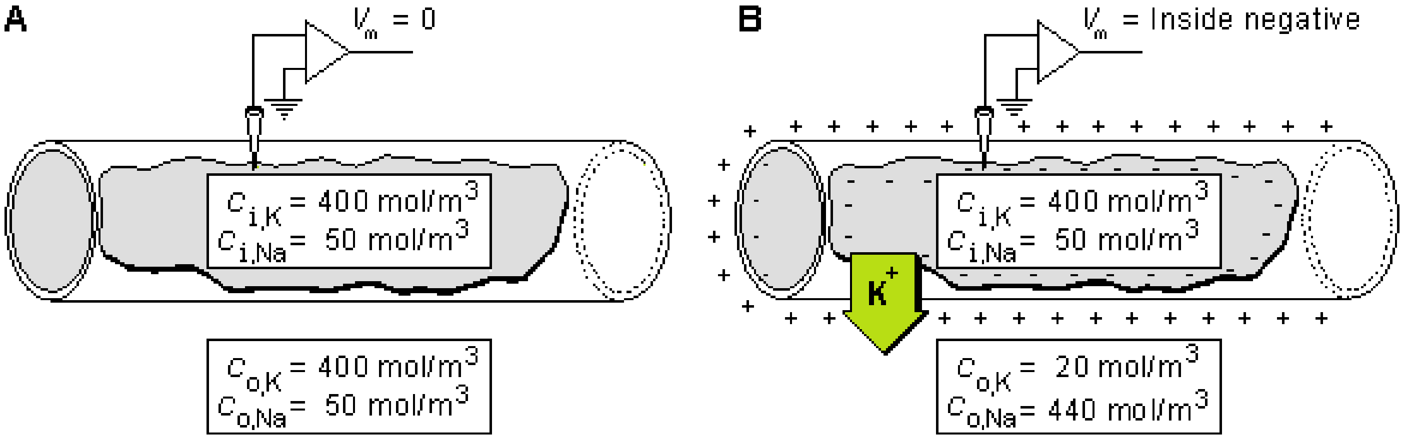
Mammalian muscle (rmp = -75 mV)		
	ECF	ICF
Cations		
Na^+	145 mM	12 mM
K^+	4 mM	155 mM
Anions		
Cl^-	120 mM	4 mM

Frog muscle (rmp = -80 mV)		
	ECF	ICF
Cations		
Na^+	109 mM	4 mM
K^+	2.2 mM	124 mM
Anions		
Cl^-	77 mM	1.5 mM

Trans-membrane Ionic Distributions



Resting potential as a K^+ equilibrium (Nernst) potential



Resting Membrane Potential: Nernst Eqn

Nernst Equations

$$V_m = \frac{RT}{F}\left\{\frac{[K^+]_o}{[K^+]_i}\right\} = E_K$$

$$V_m = \frac{RT}{F}\left\{\frac{[Na^+]_o}{[Na^+]_i}\right\} = E_{Na}$$

$$V_m = \frac{RT}{F}\left\{\frac{[Cl^-]_i}{[Cl^-]_o}\right\} = E_{Cl}$$

Consider values for typical concentration ratios

E_K = -90 mV

E_{Na} = +60 mV

r.m.p. = {-60 to –80} mV

Goldman-Hodgkin-Katz (GHK) eqn

Resting Membrane Potential approximated by the GHK eq.

$$V_m = \frac{RT}{F} \ln \left\{ \frac{P_K [K^+]_o + P_{Na} [Na^+]_o}{P_K [K^+]_i + P_{Na} [Na^+]_i} \right\}$$

If $P_K >> P_{Na}$

$$V_m = \frac{RT}{F} \left\{ \frac{[K^+]_o}{[K^+]_i} \right\} = E_K$$

If $P_{Na} >> P_K$

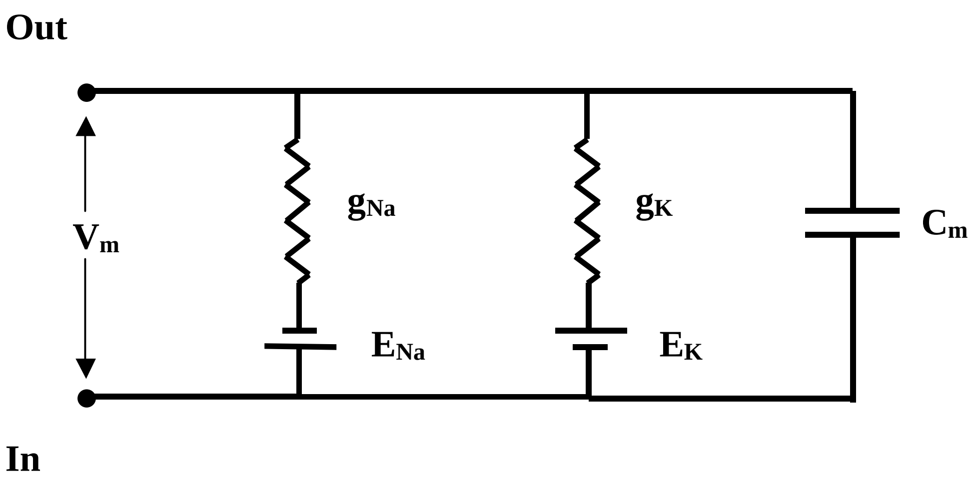
$$V_m = \frac{RT}{F} \left\{ \frac{[Na^+]_o}{[Na^+]_i} \right\} = E_{Na}$$

Taking values of R,T &F and dividing throughout by P_K:

$$V_m = 58 \log \left\{ \frac{[K^+]_o + \alpha [Na^+]_o}{[K^+]_i + \alpha [Na^+]_i} \right\} \text{mV}, \quad \alpha = \frac{\mathrm{P_{Na}}}{\mathrm{P_K}}$$

Consider α = V. large, v. small, and intermediate

Equivalent Circuit Model: Resting Membrane



$$I_{Na} = (V_m - E_{Na})g_{Na}$$

$$I_K = (V_m - E_K)g_K$$

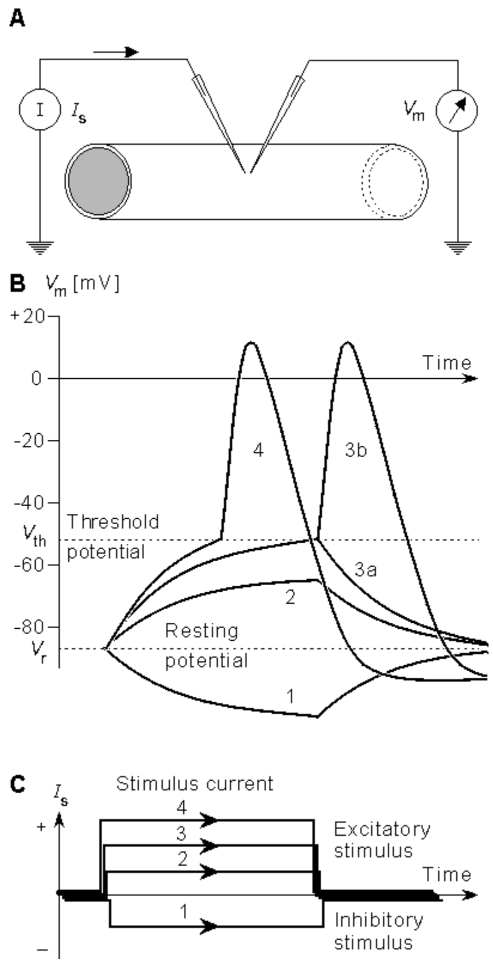
$$\text{At steady state, } I_{Na} = I_K$$

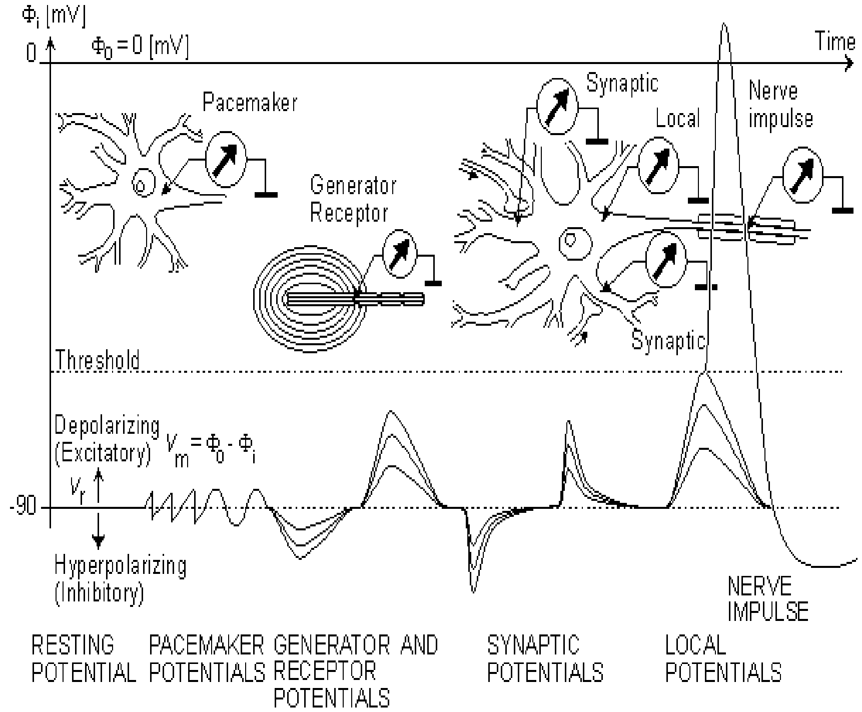
$$\text{Therefore, } \mathrm{V_m} = \frac{E_{Na}g_{Na} + E_K g_K}{g_{Na} + g_K}$$

Membrane Biophysics: Overview

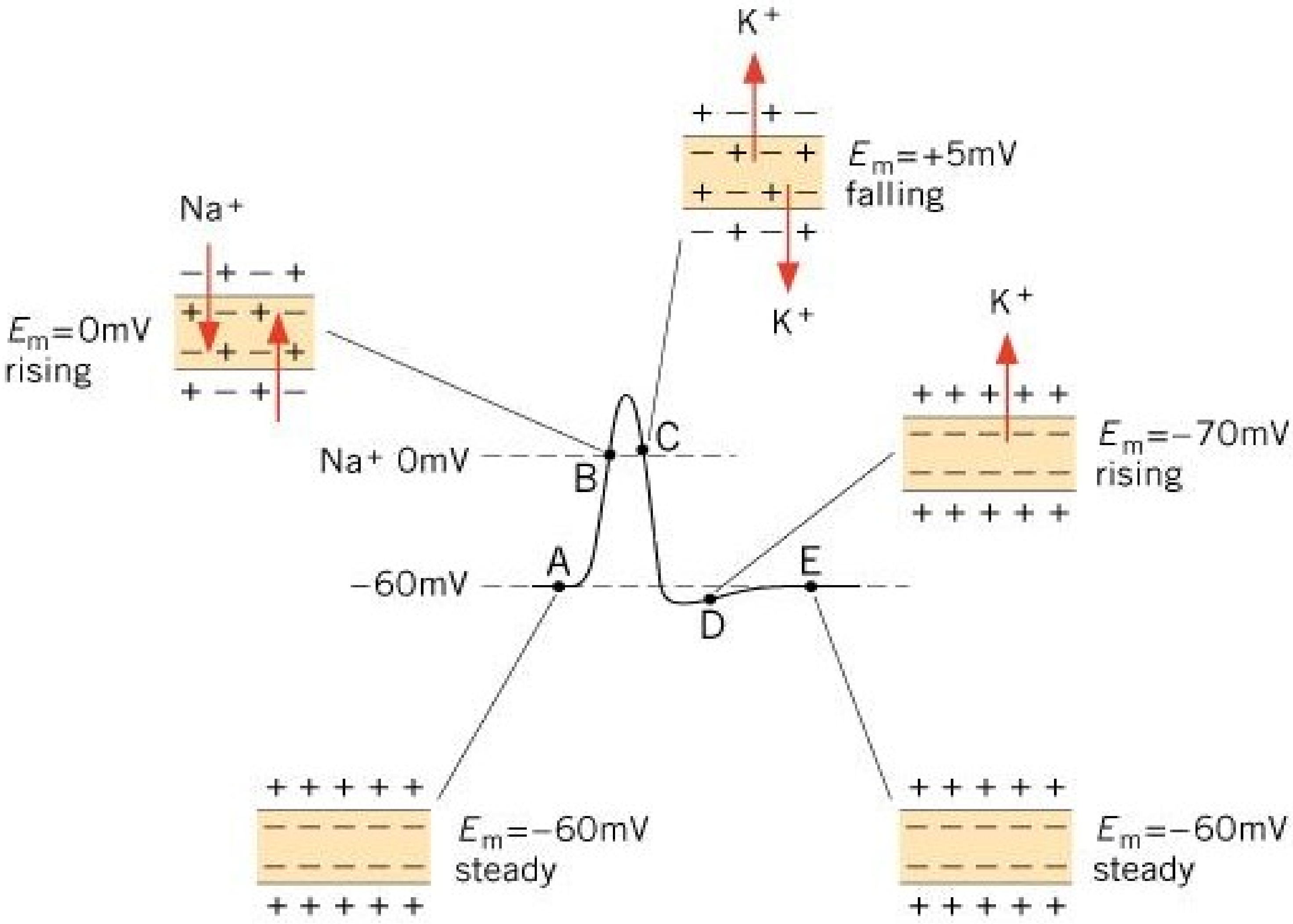
Part 2: Action potential

ACTION POTENTIAL





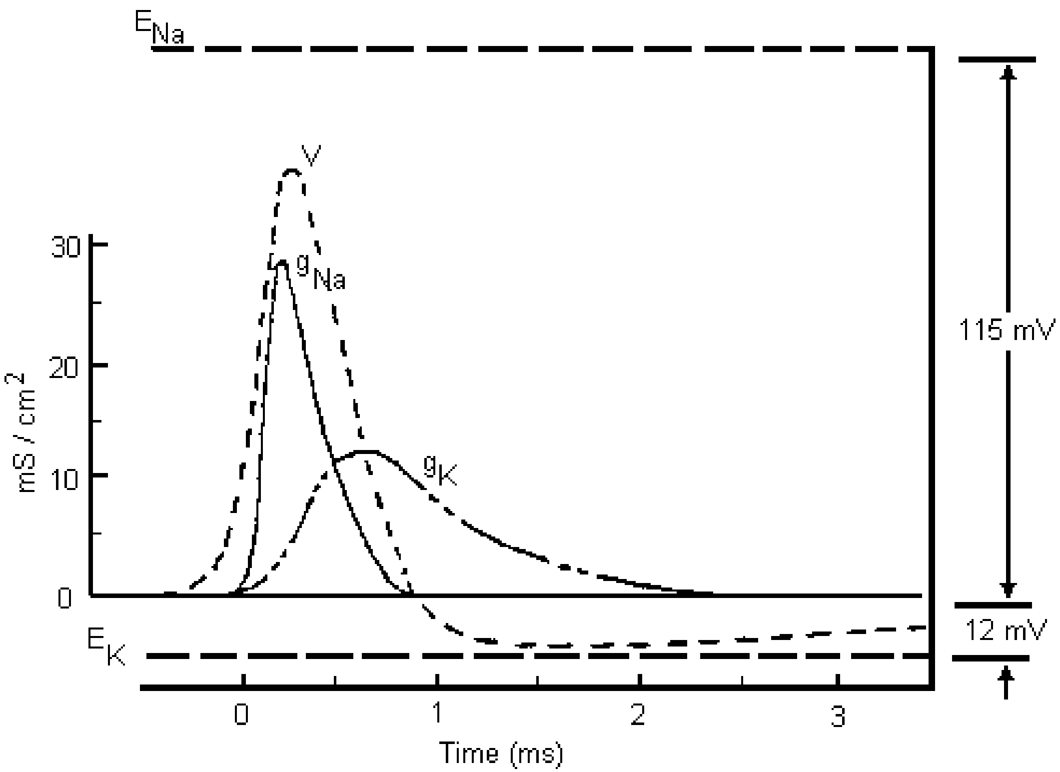
ACTION POTENTIAL: Ionic mechanisms



Action Potential: Na^+ and K^+ Conductance

$$g_K(V_m, t) = \overline{g_K}\{n(V_m, t)\}^4$$

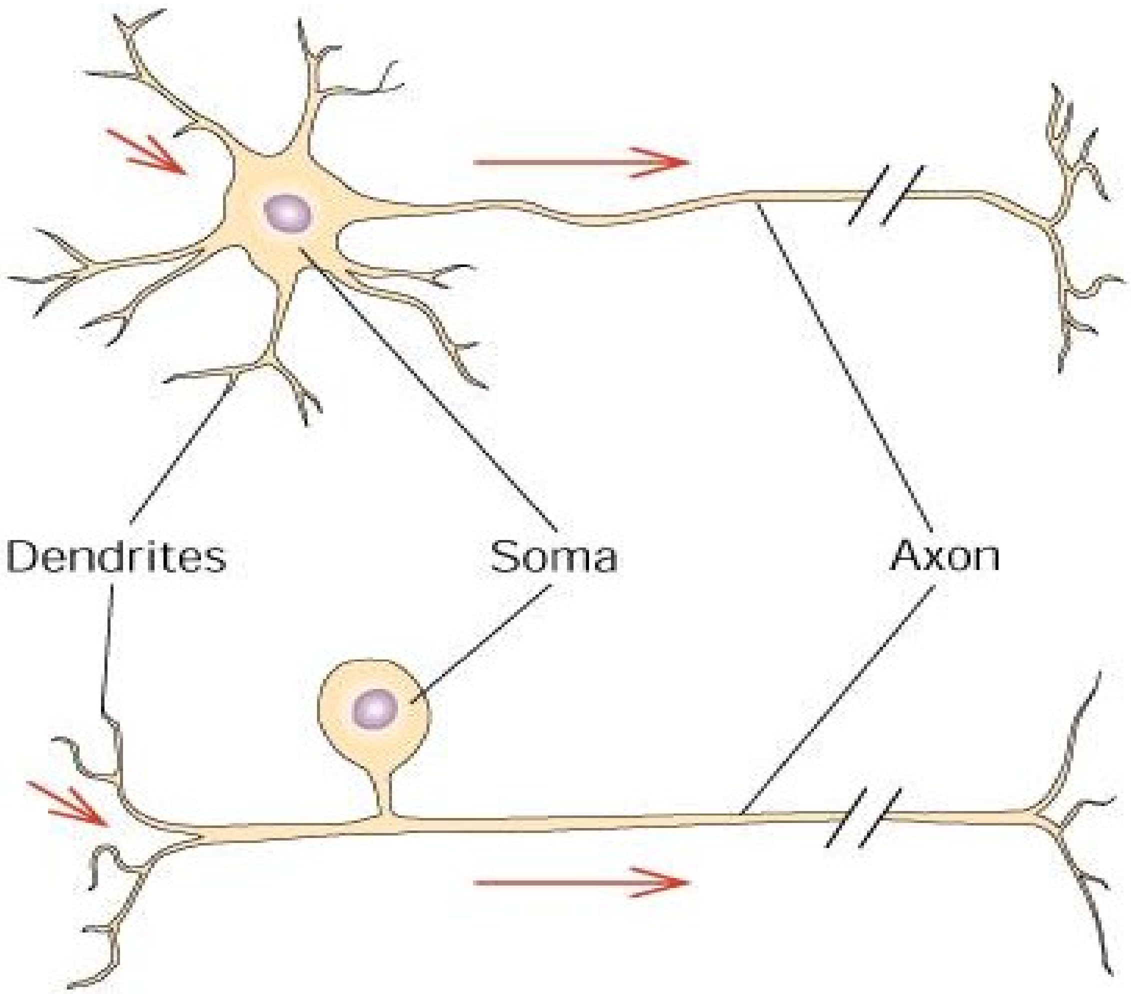
$$g_{Na}(V_m, t) = \overline{g_{Na}}\{m(V_m, t)\}^3 h(V_m, t)$$



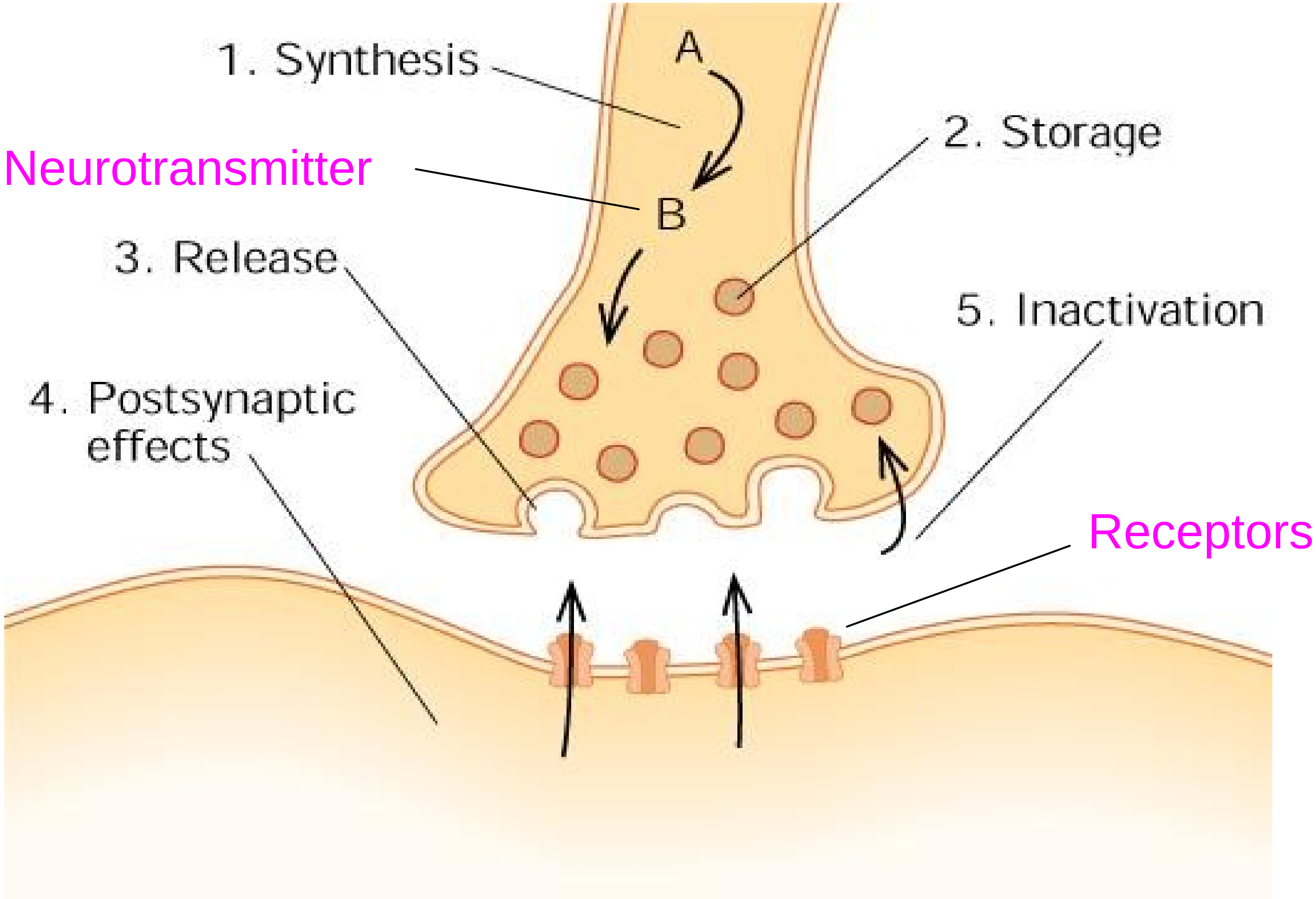
Membrane Biophysics: Overview

Part 3: Synaptic transmission & potentials

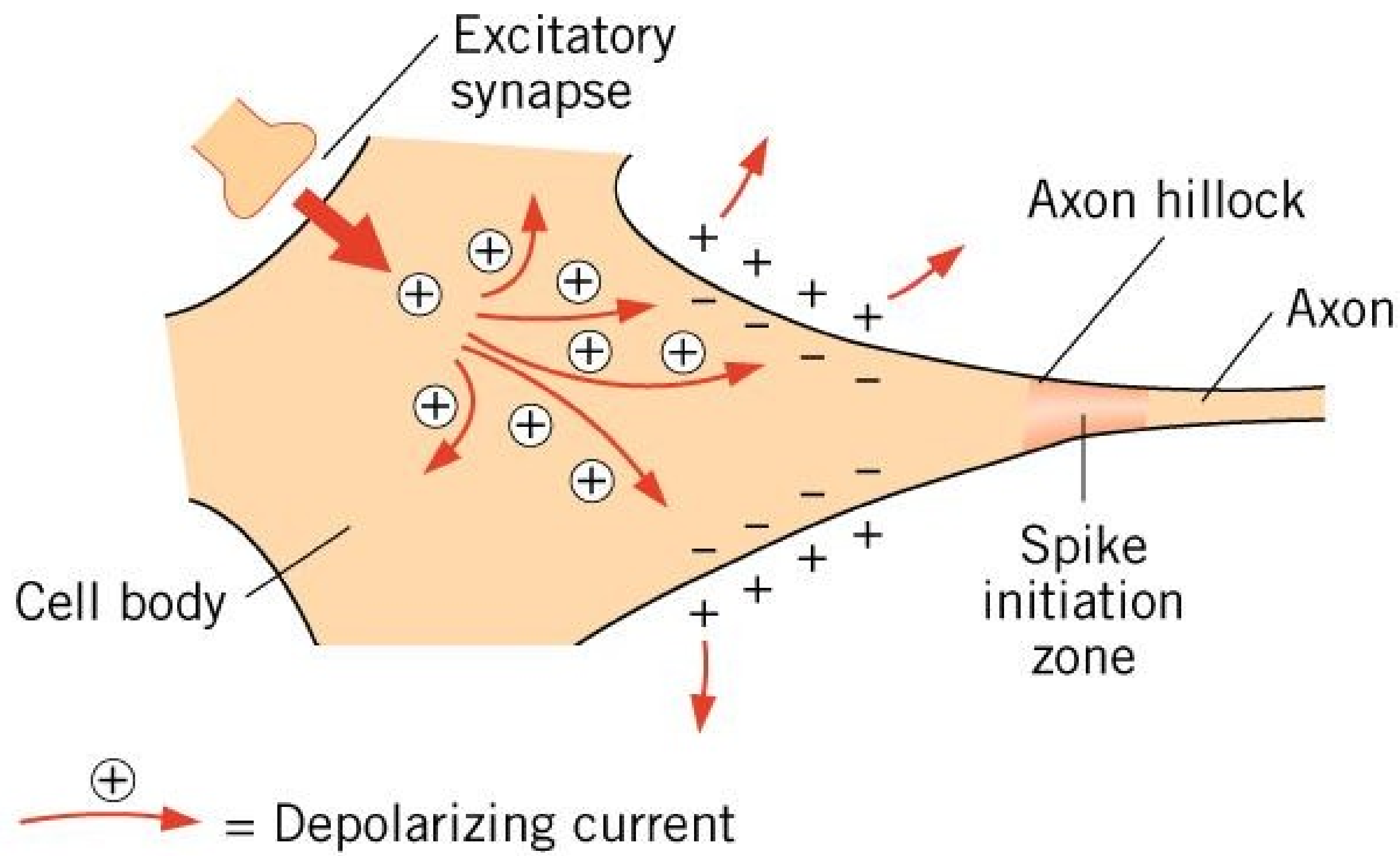
“Canonical” neurons: Neuroscience



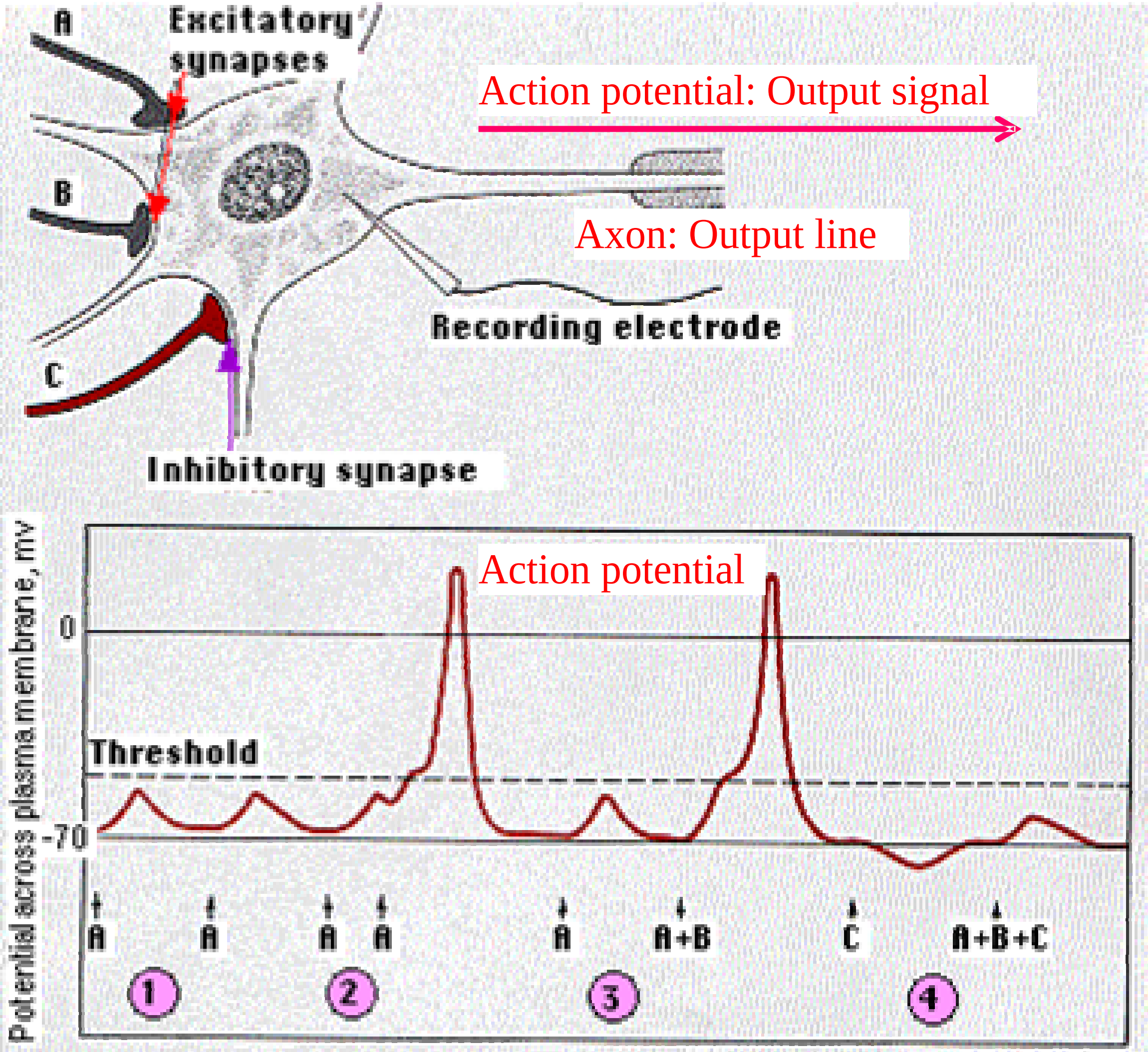
Chemical Transmission



Postsynaptic Electrical Effects



Synaptic Integration: The Canonical Picture



The Perceptron Model

A perceptron is a computing element with input lines having associated weights and the cell having a threshold value. The perceptron model is motivated by the biological neuron.