系统和计算神经科学导论

二、神经信号传导

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1. 膜电位和动作电位

2. 数学模型

1. 膜电位和动作电位

2. 数学模型

Cell membrane & Ion Channel

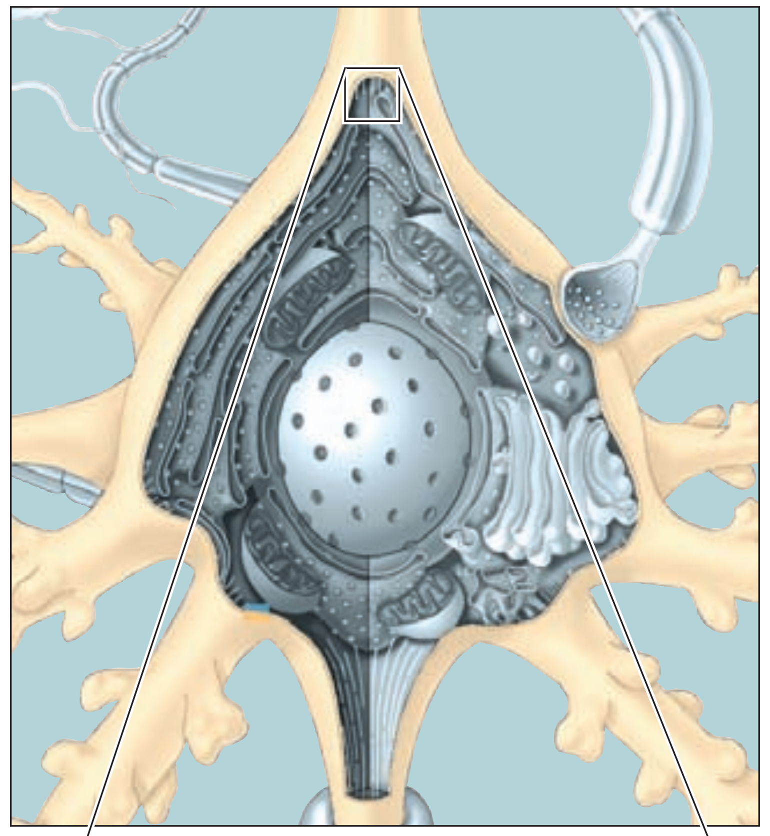
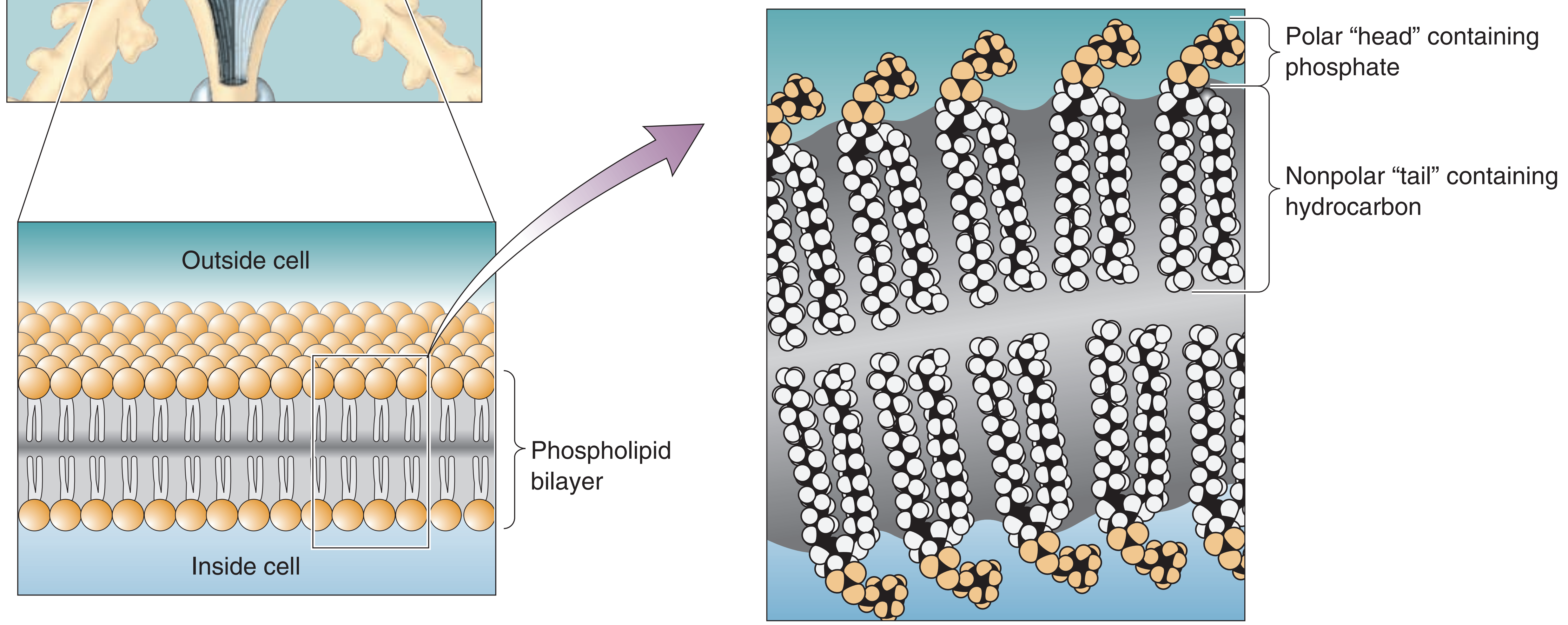


FIGURE 3.3
The phospholipid bilayer. The phospholipid bilayer is the core of the neuronal membrane and forms a barrier to water-soluble ions.



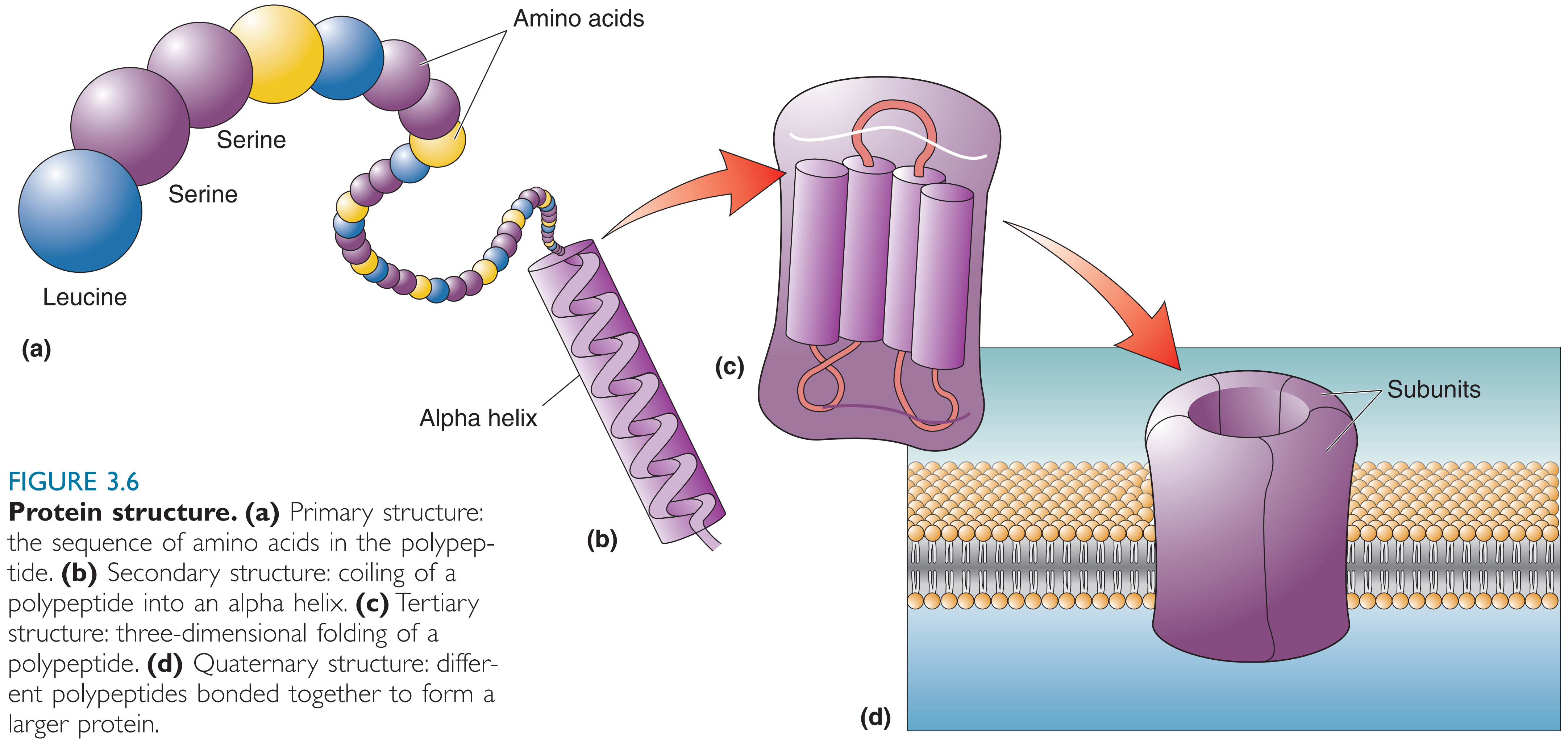
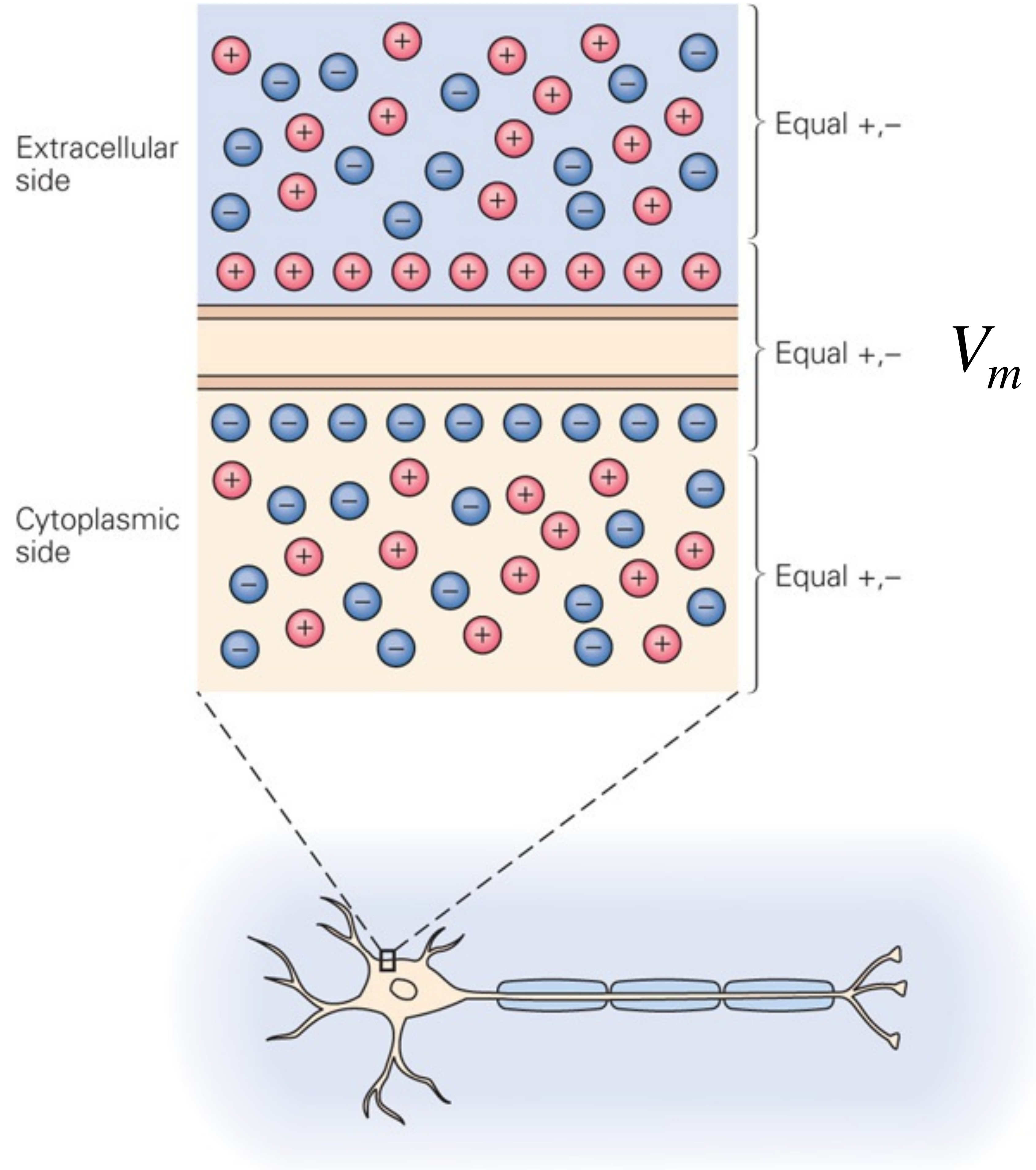


FIGURE 3.6
Protein structure. (a) Primary structure: the sequence of amino acids in the polypeptide. **(b)** Secondary structure: coiling of a polypeptide into an alpha helix. **(c)** Tertiary structure: three-dimensional folding of a polypeptide. **(d)** Quaternary structure: different polypeptides bonded together to form a larger protein.

Membrane Potential

胞外

胞质

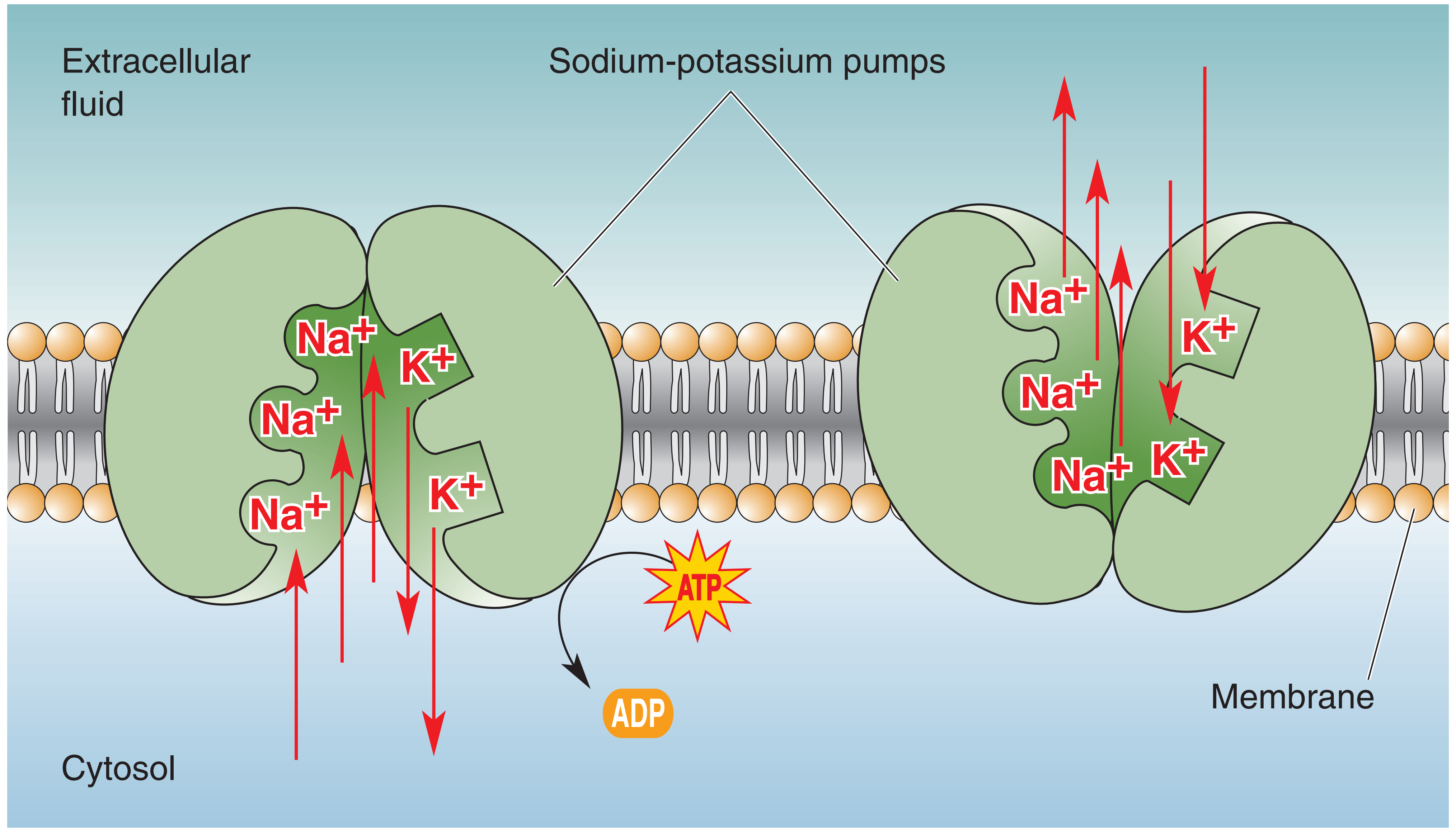


$$V_m = V_{in} - V_{out}$$

静息电位

-60~-70mV

Establishing the resting potential



气体常数　温度

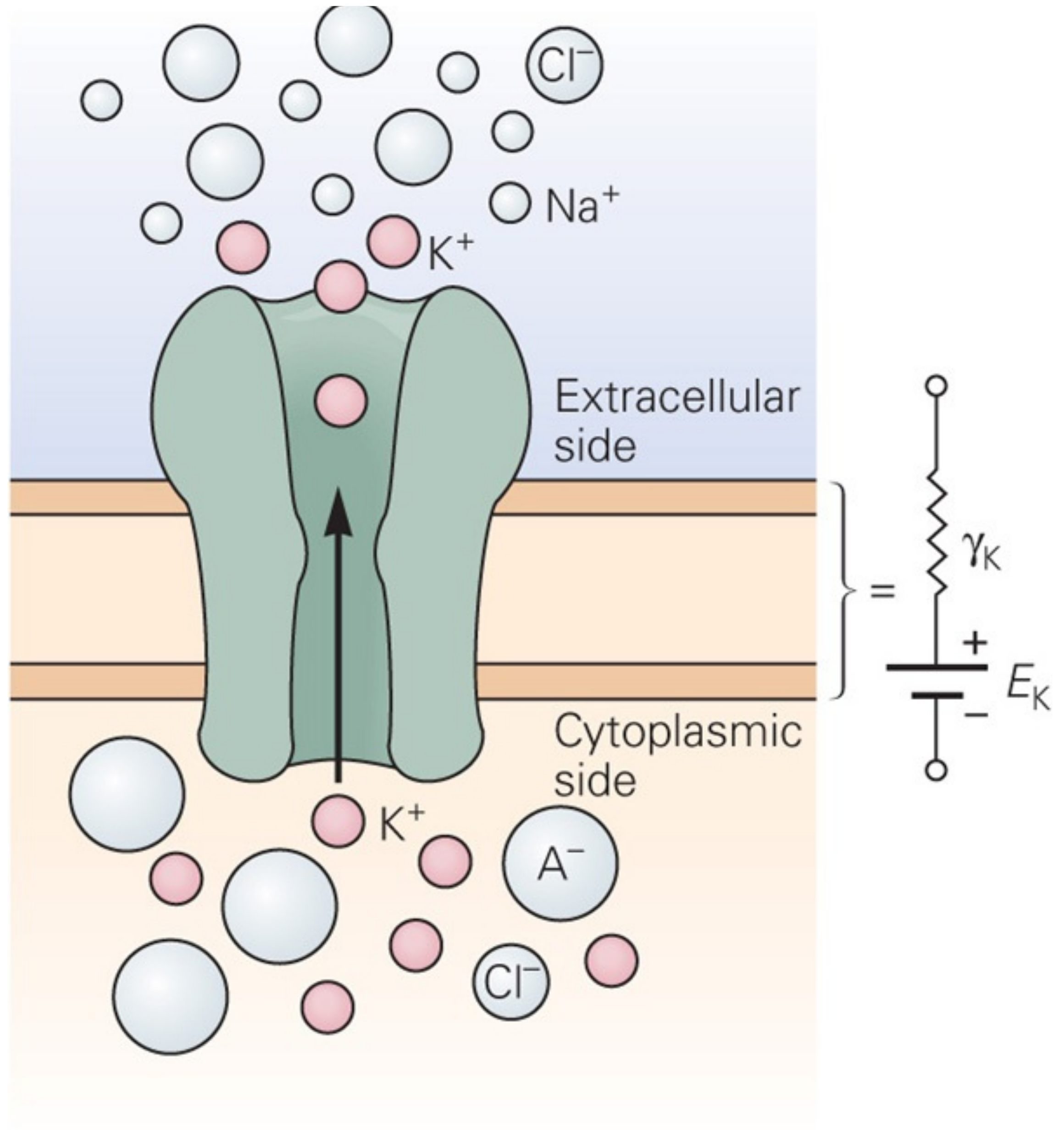
Nernst Eq. $$E_{ion} = \frac{RT}{zF} ln \frac{[ion]_{out}}{[ion]_{in}}$$

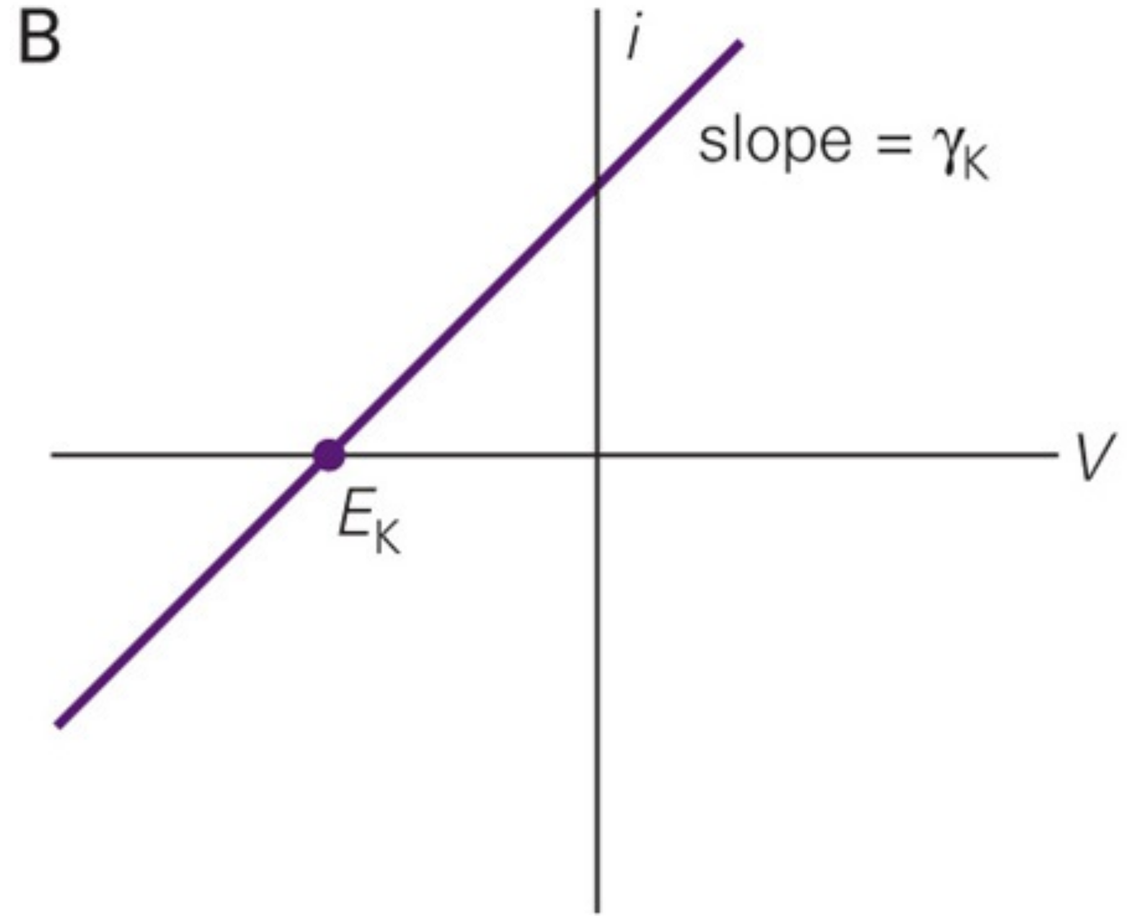
电荷数　法拉第常数

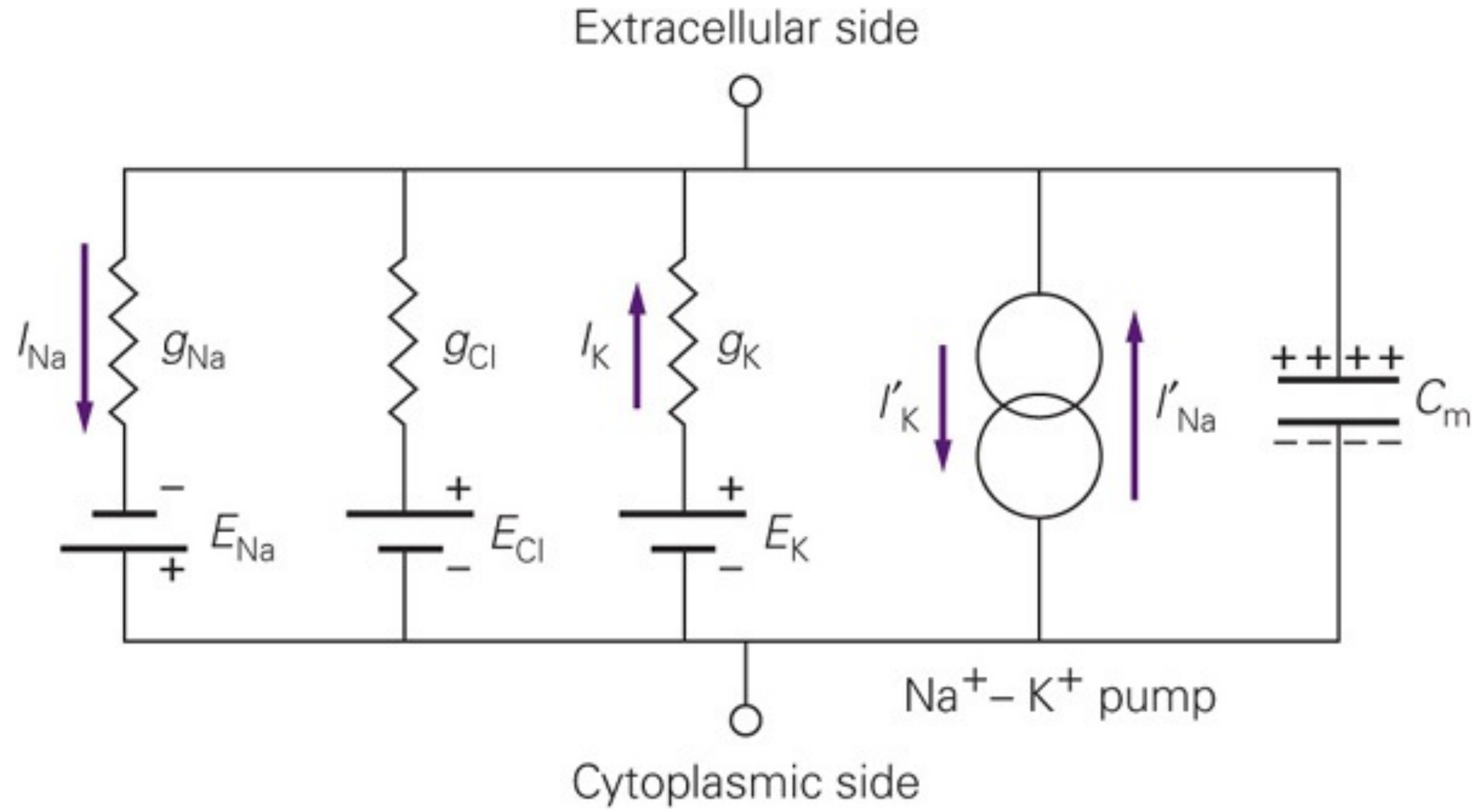
Ion	Concentration outside (in mM)	Concentration inside (in mM)	Ratio Out : In	E_{ion} (at 37°C)
K^+	5	100	1 : 20	−80 mV
Na^+	150	15	10 : 1	62 mV
Ca^{2+}	2	0.0002	10,000 : 1	123 mV
Cl^-	150	13	11.5 : 1	−65 mV

Goldman Eq. $$V_m = \frac{RT}{F} ln \frac{P[K^+]_o + P[Na^+]_o + P[Cl^-]_i}{P[K^+]_i + P[Na^+]_i + P[Cl^-]_o}$$

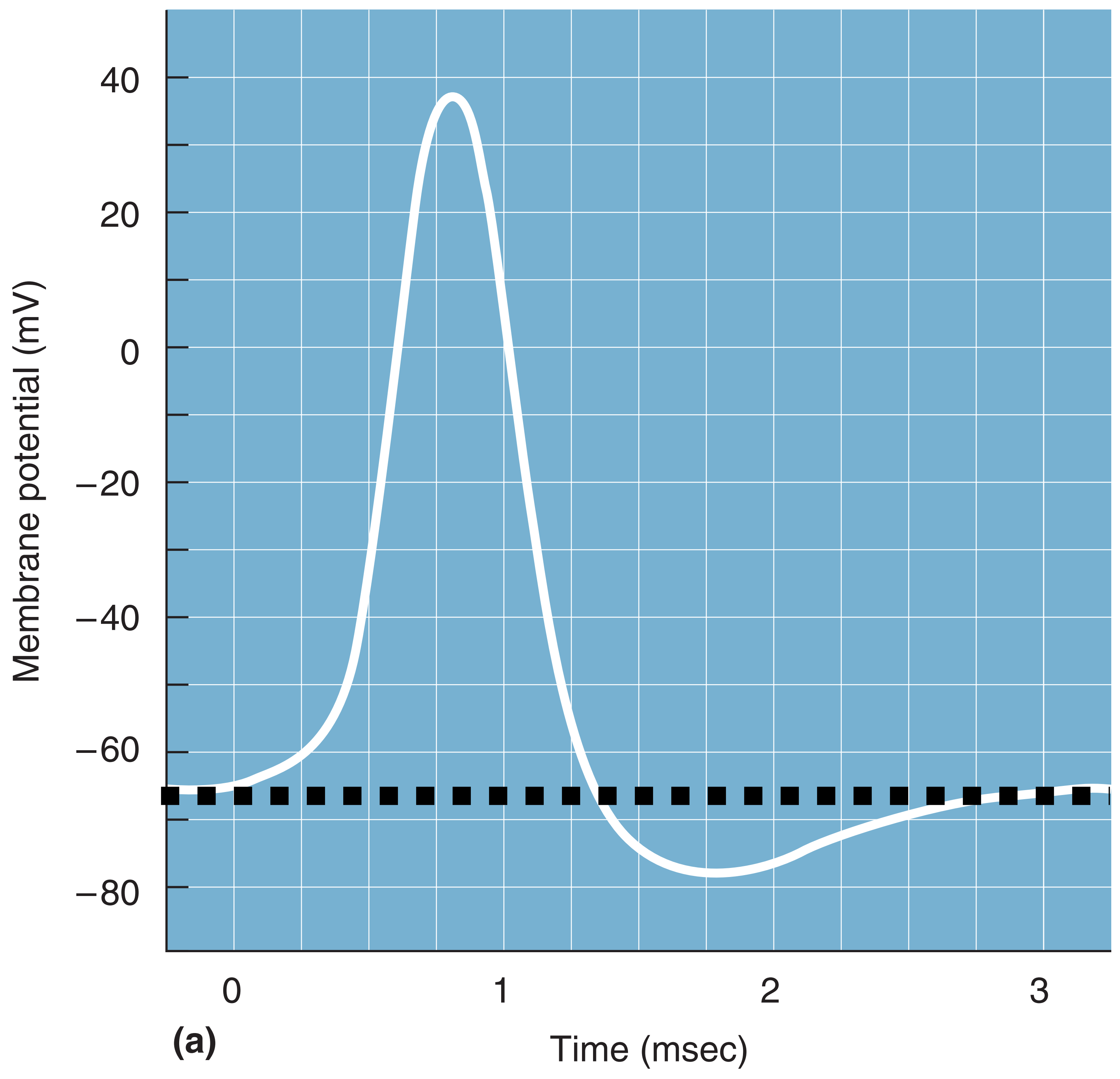
Equivalent Circuitry



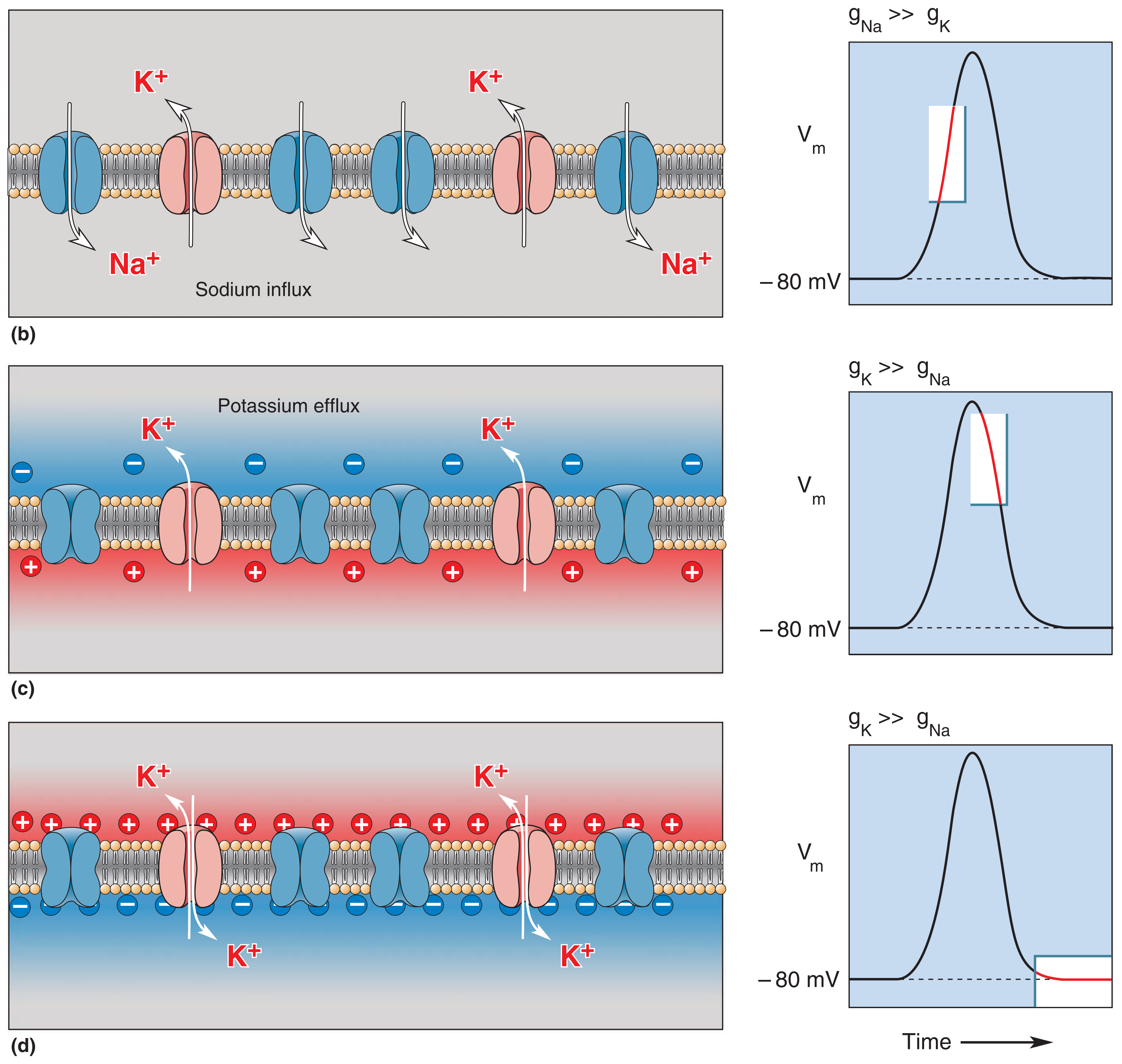




Generation of Action Potentials



静息电位



Na^+通道打开

Na^+内流

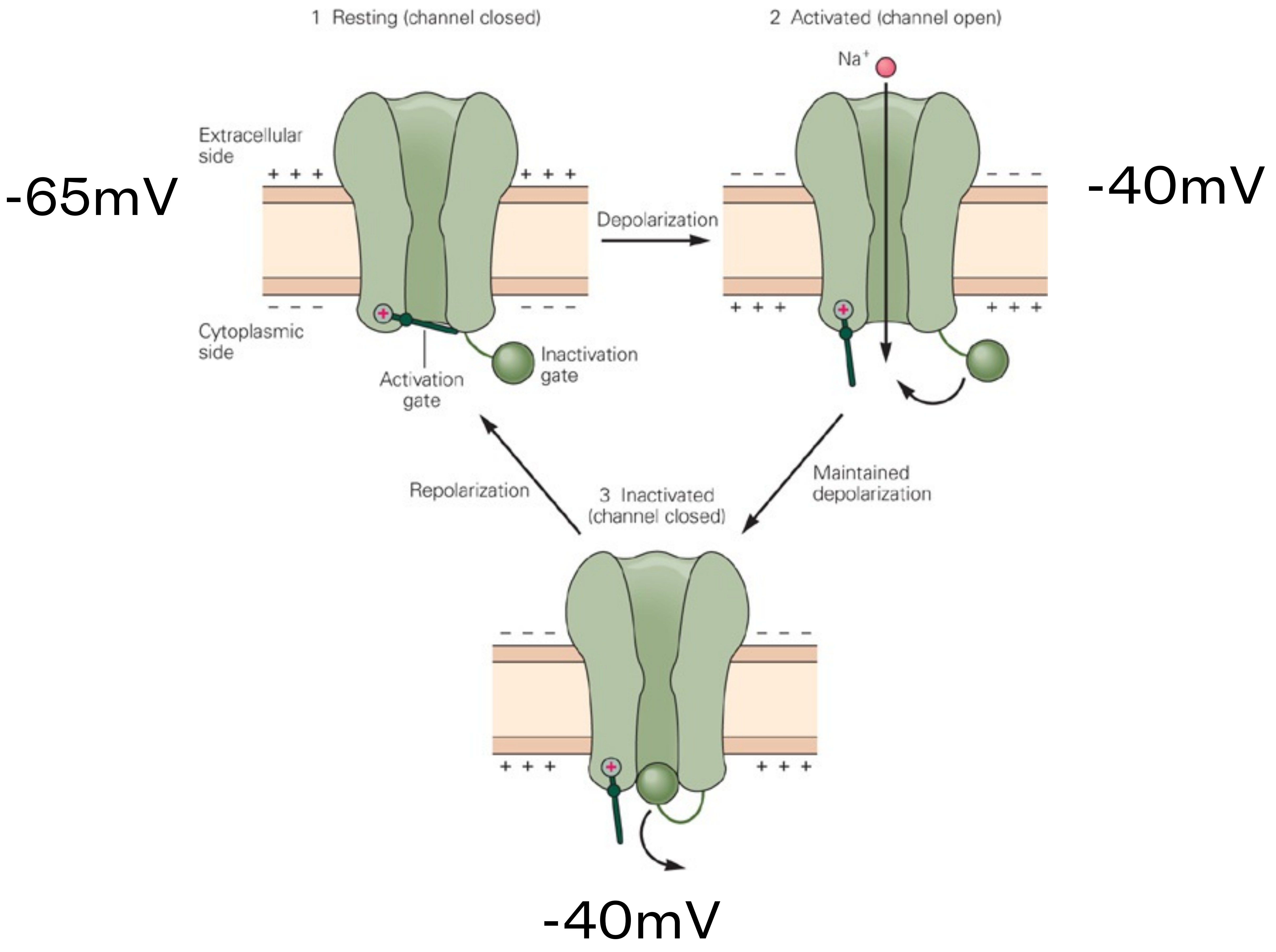
K^+通道打开

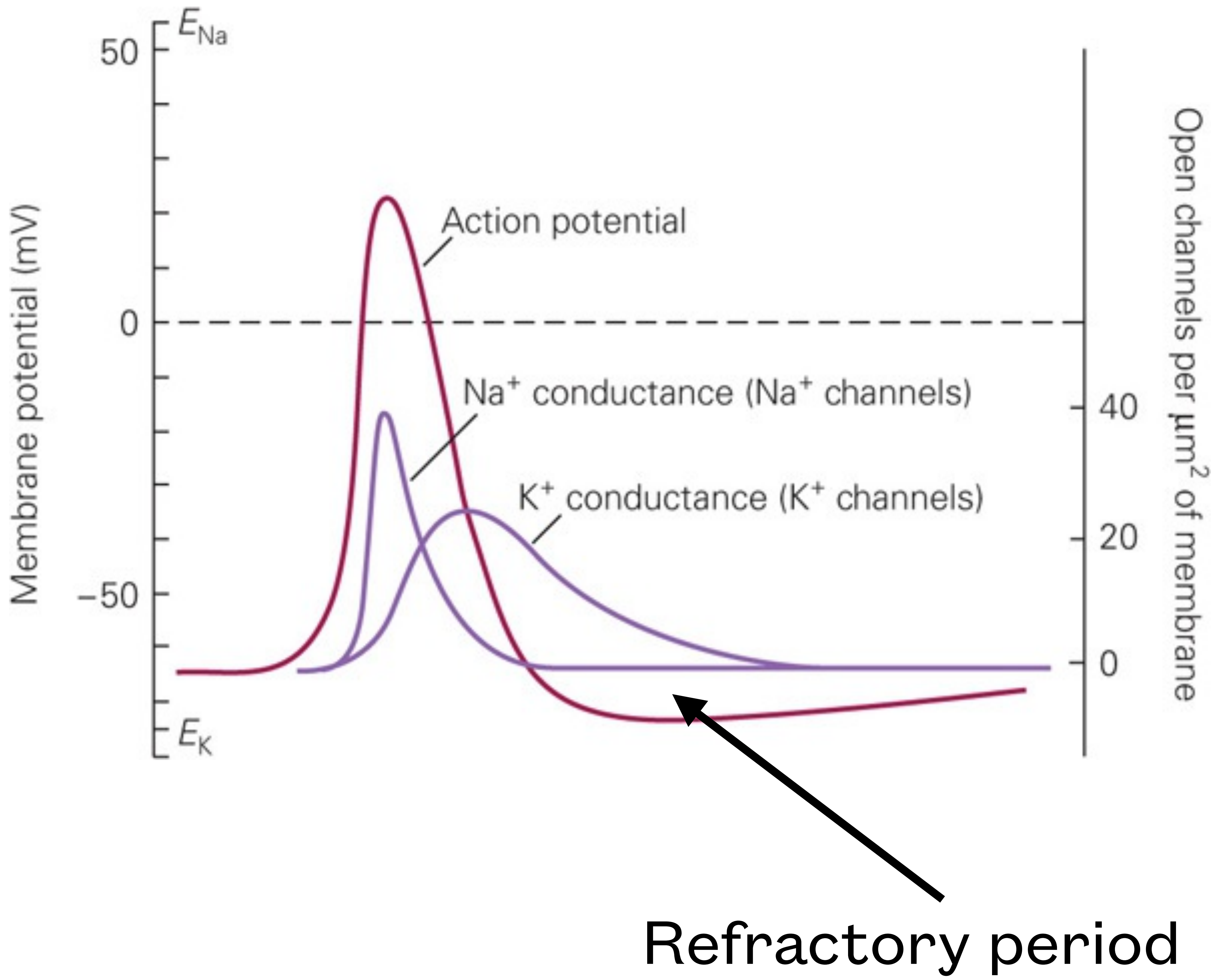
K^+外流

所有通道关闭

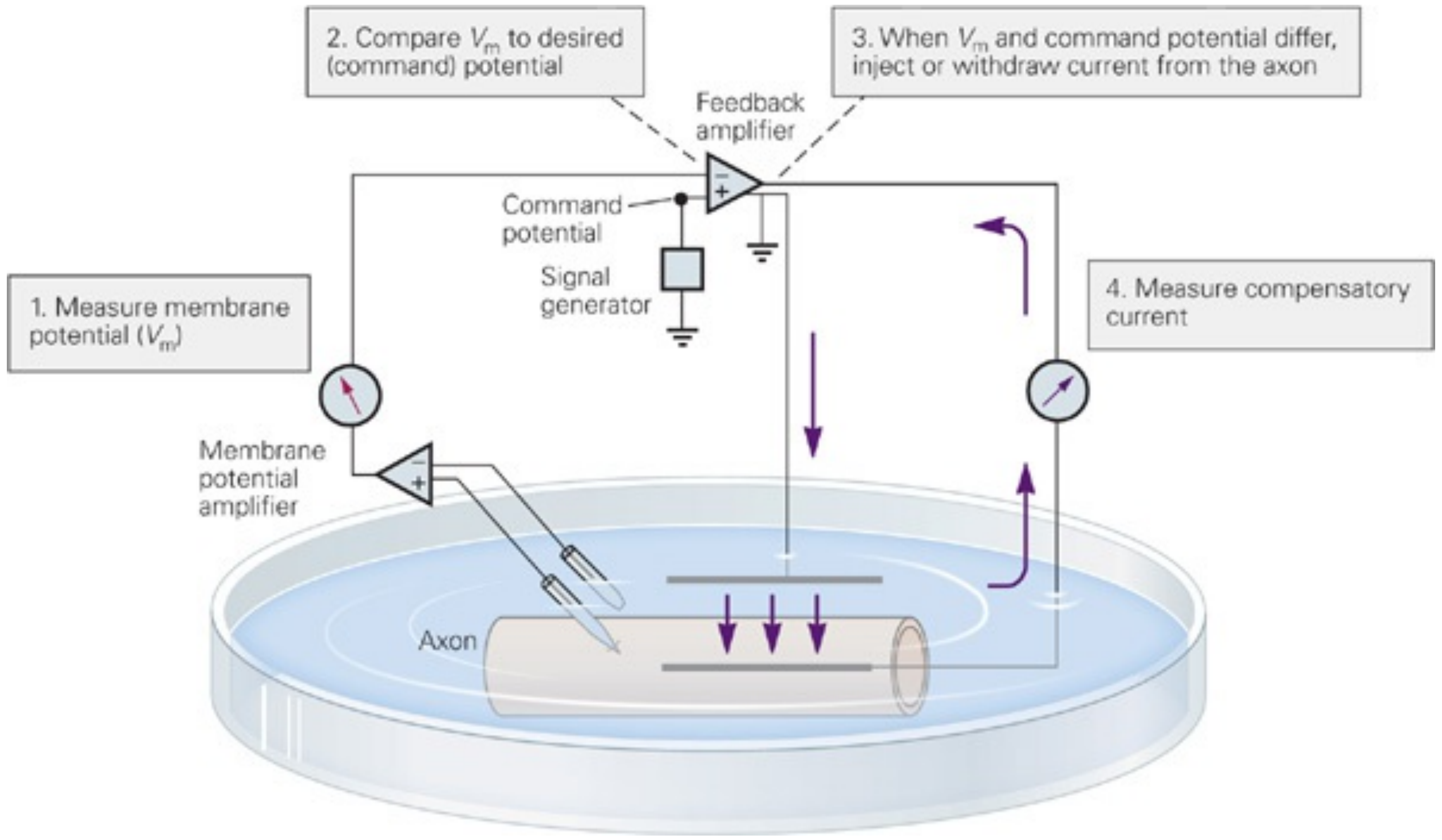
恢复静息电位

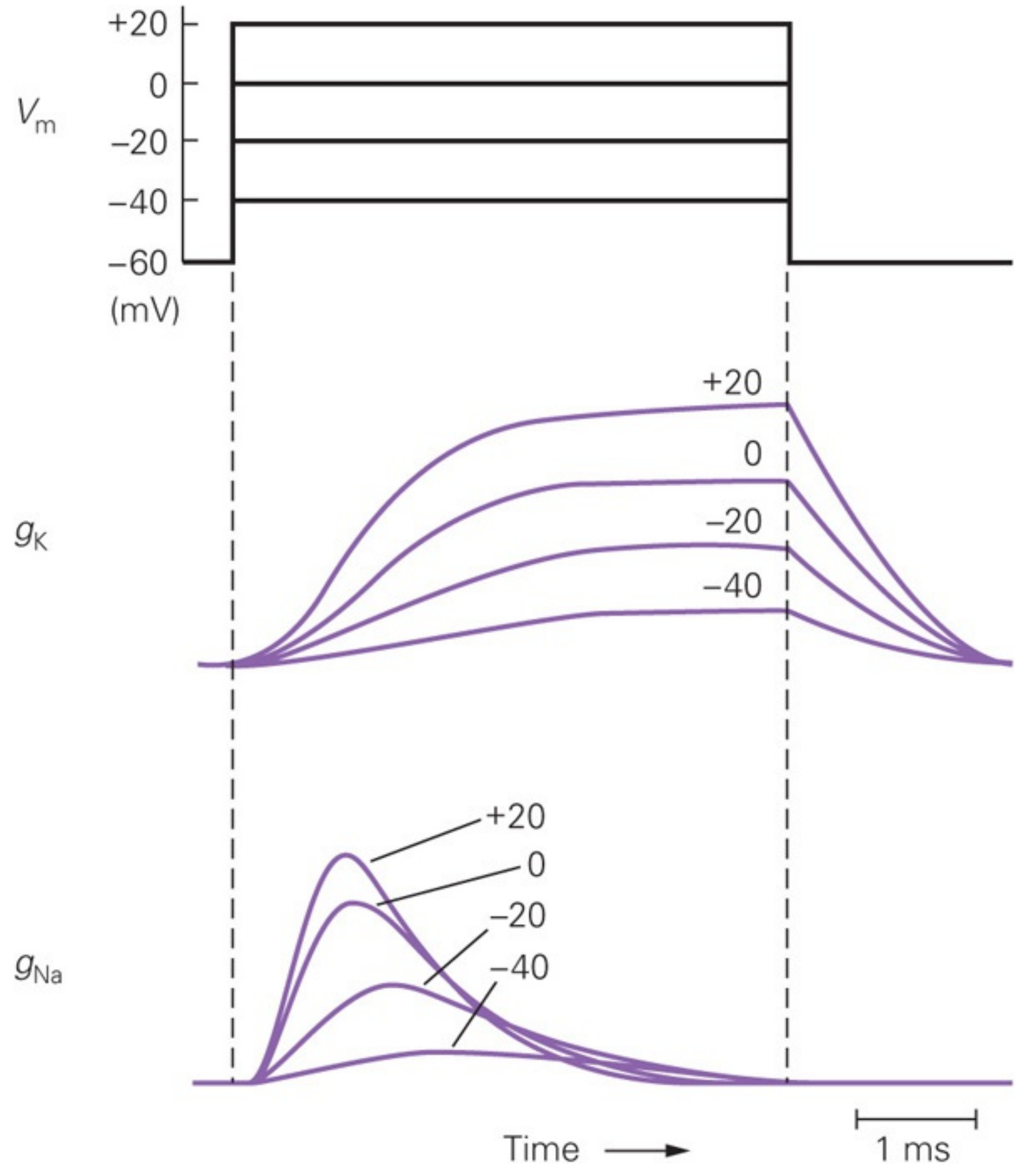
Voltage-gate Na⁺ Channel





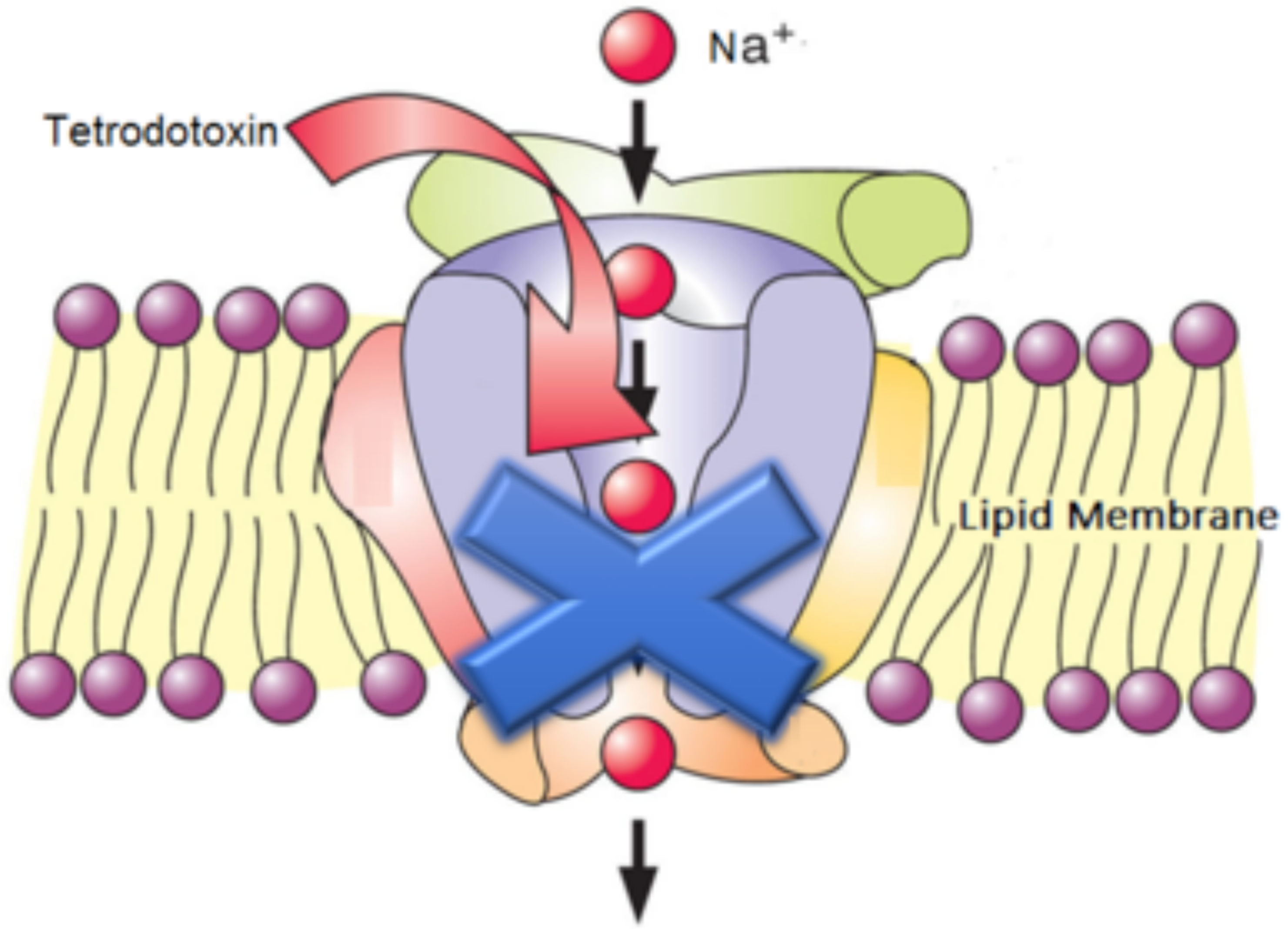
Voltage Clamp



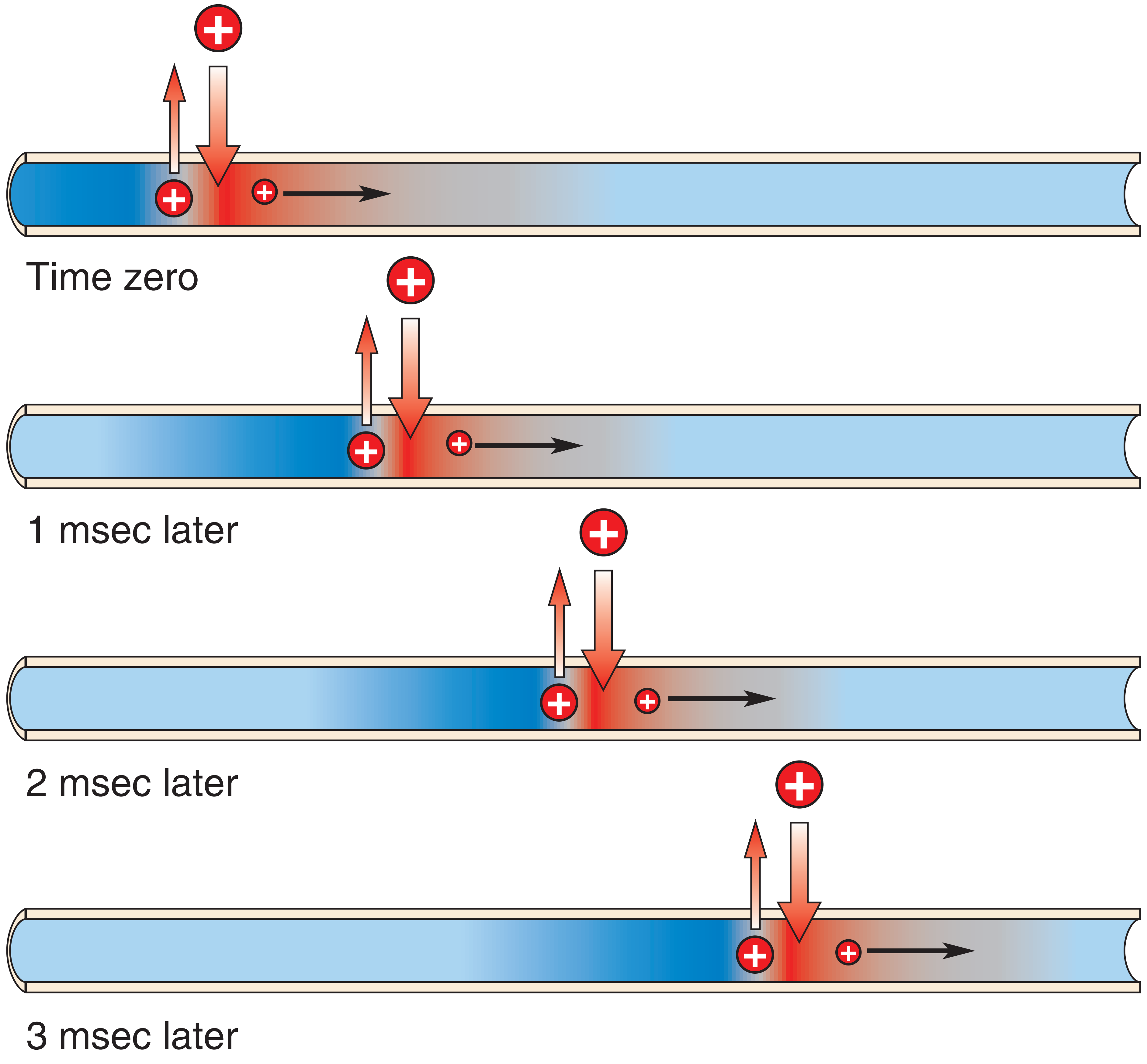


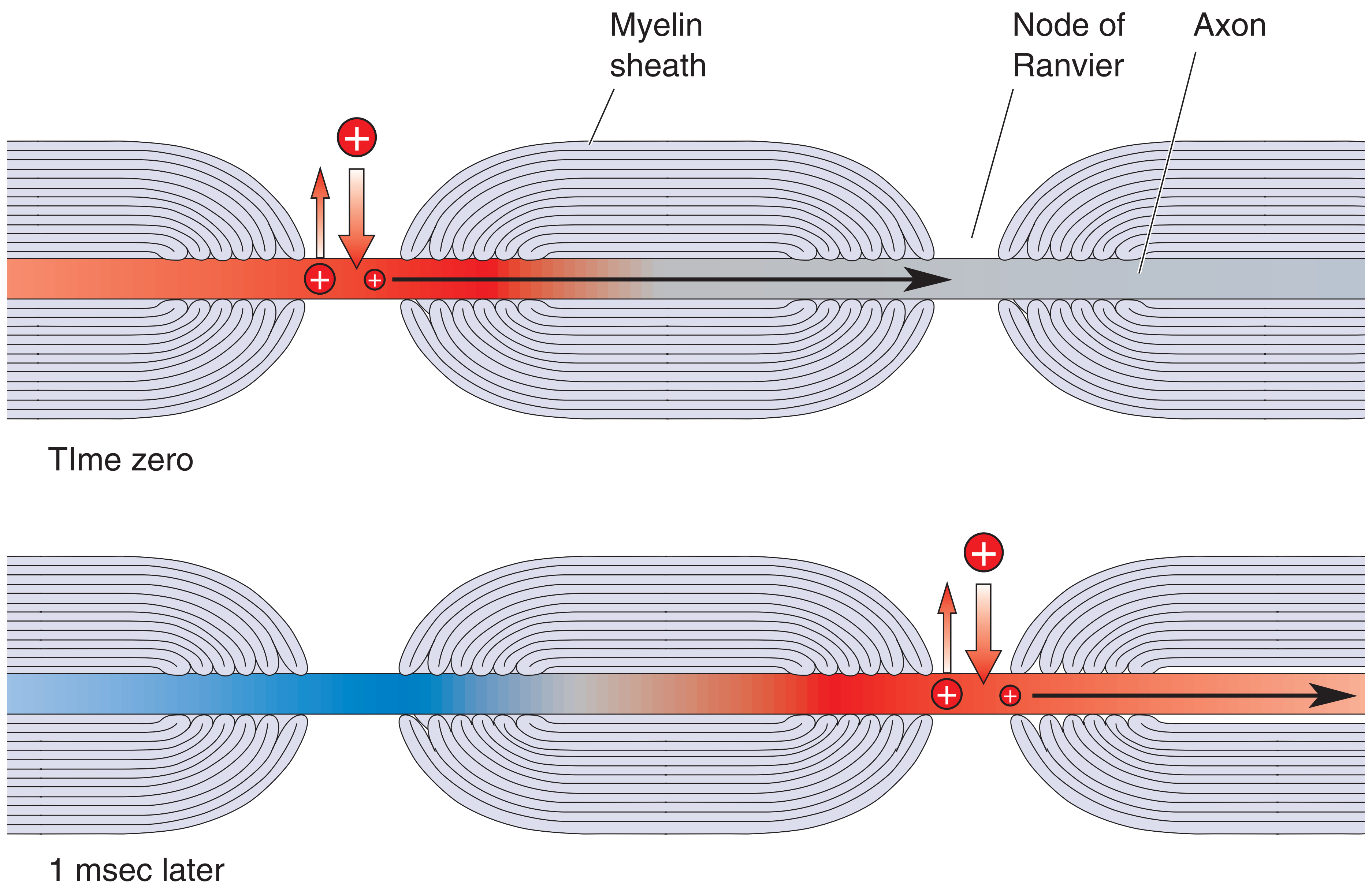
TTX

河豚

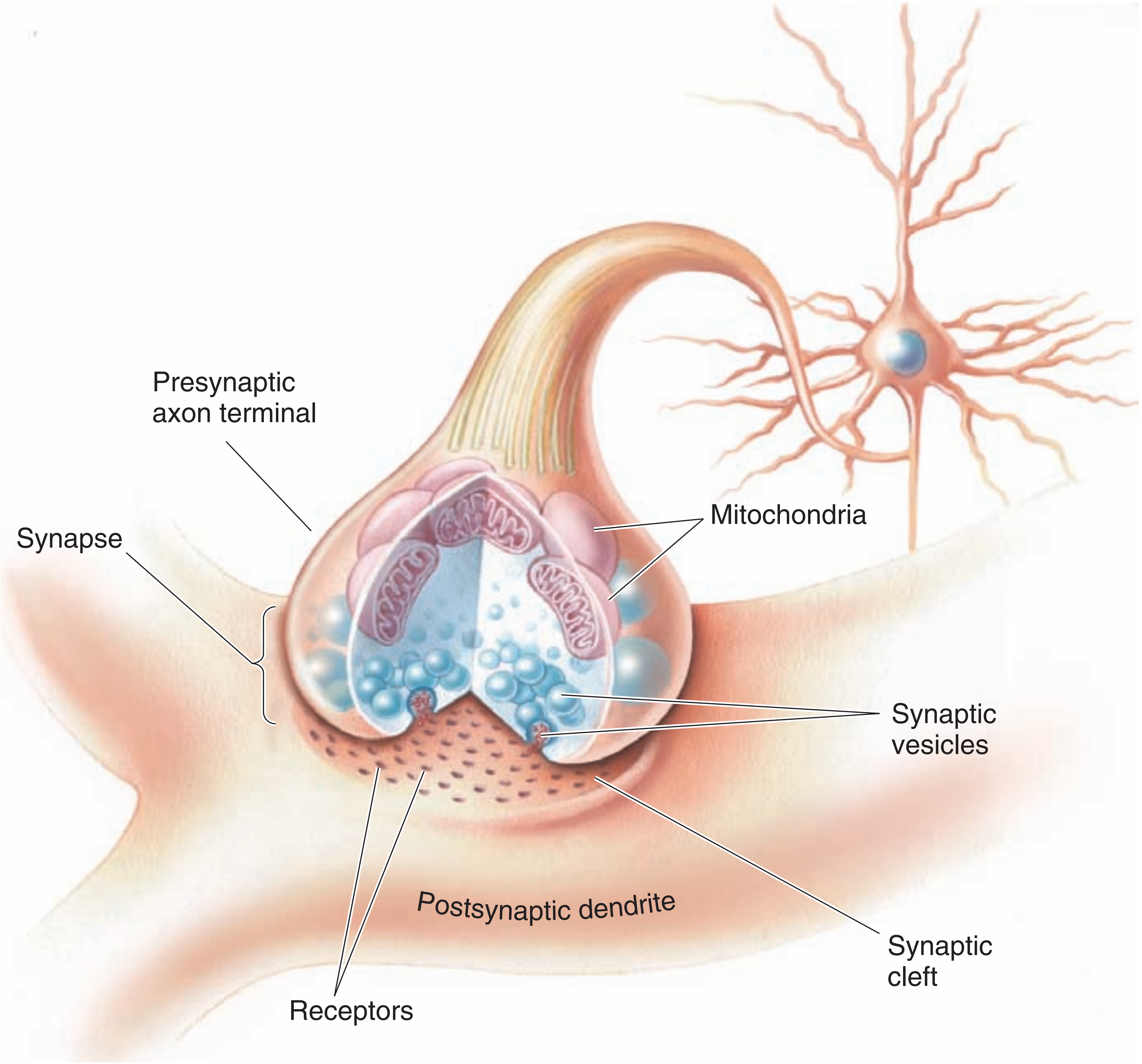


Propogation of Action Potentials

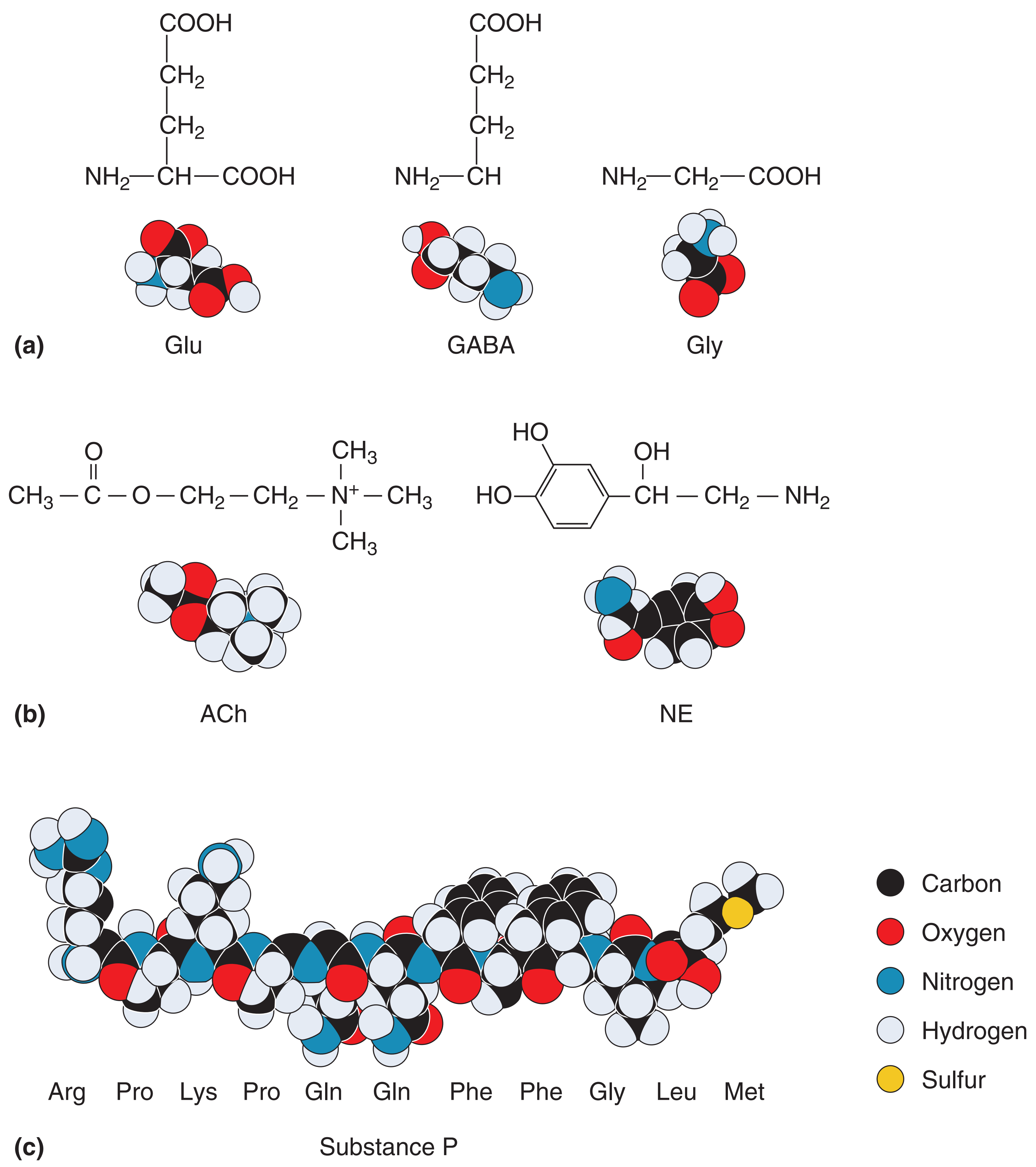




Synapse



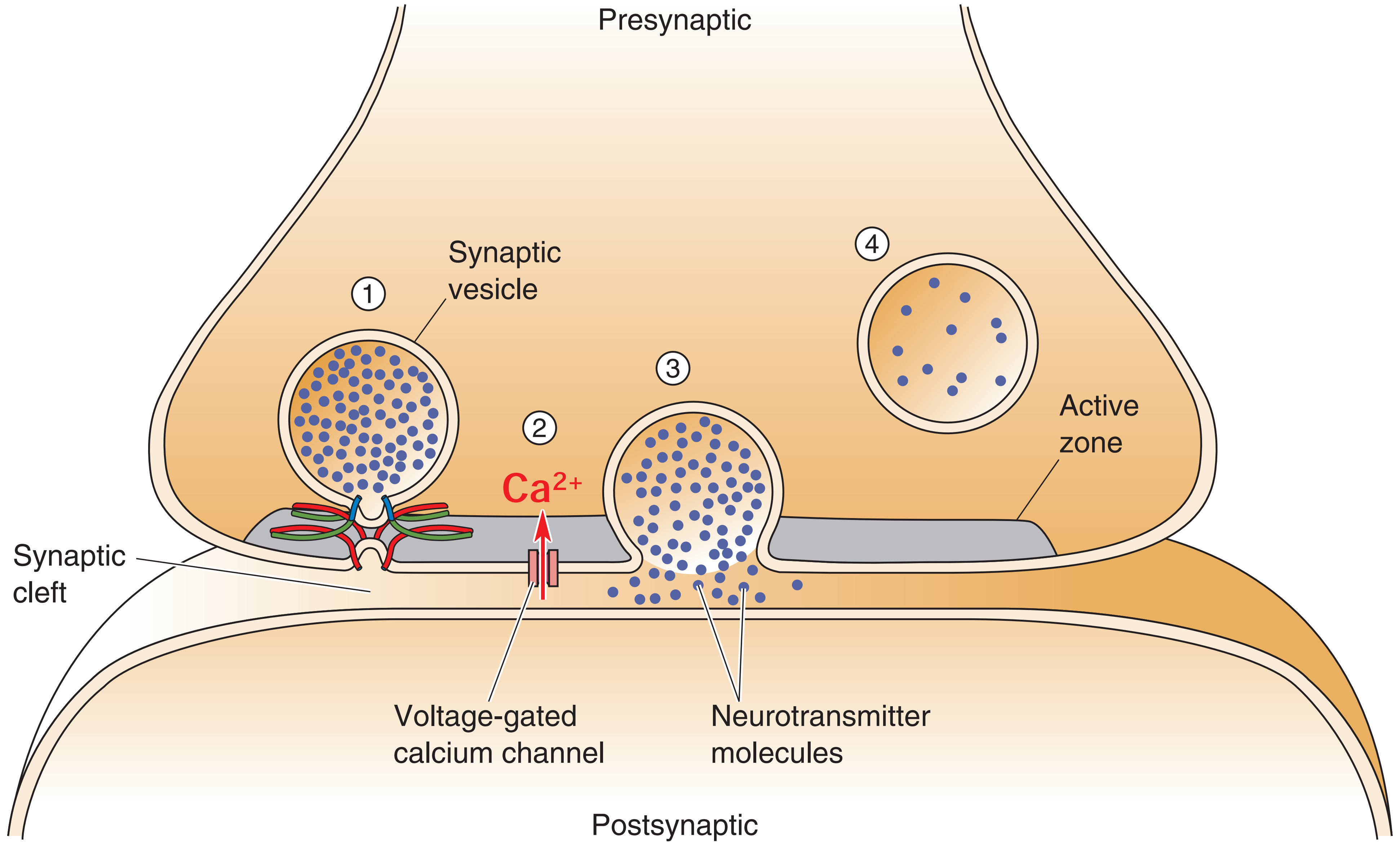
Presynaptic axon terminal
Synapse
Mitochondria
Synaptic vesicles
Postsynaptic dendrite
Synaptic cleft
Receptors



COOH
CH2
CH2
NH2—CH—COOH
COOH
CH2
CH2
NH2—CH
NH2—CH2—COOH
(a)
Glu
GABA
Gly
O
CH3—C—O—CH2—CH2—N+—CH3
CH3
CH3
HO
OH
HO—
CH—CH2—NH2
(b)
ACh
NE
Arg Pro Lys Pro Gln Gln Phe Phe Gly Leu Met
(c)
Substance P
Carbon
Oxygen
Nitrogen
Hydrogen
Sulfur

Pre-synaptic reactions

Axon



Dendrite / Soma

1. Action potential arrives
2. Voltage-gated Ca^{+} channel opens
3. Synaptic vesicle fuses with membrane
4. Neurotransmitter molecules are released

Post-synaptic reactions (excitatory)

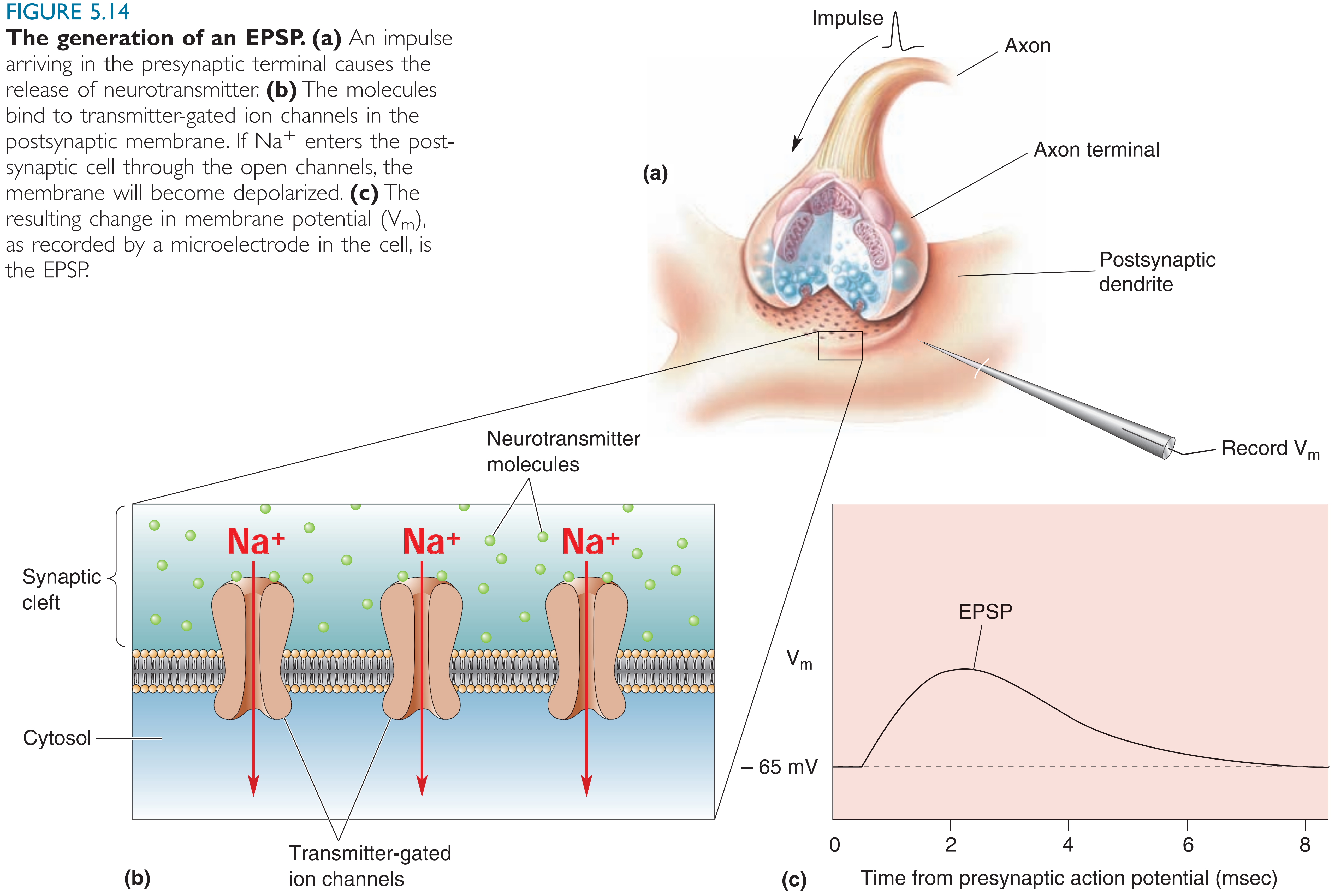
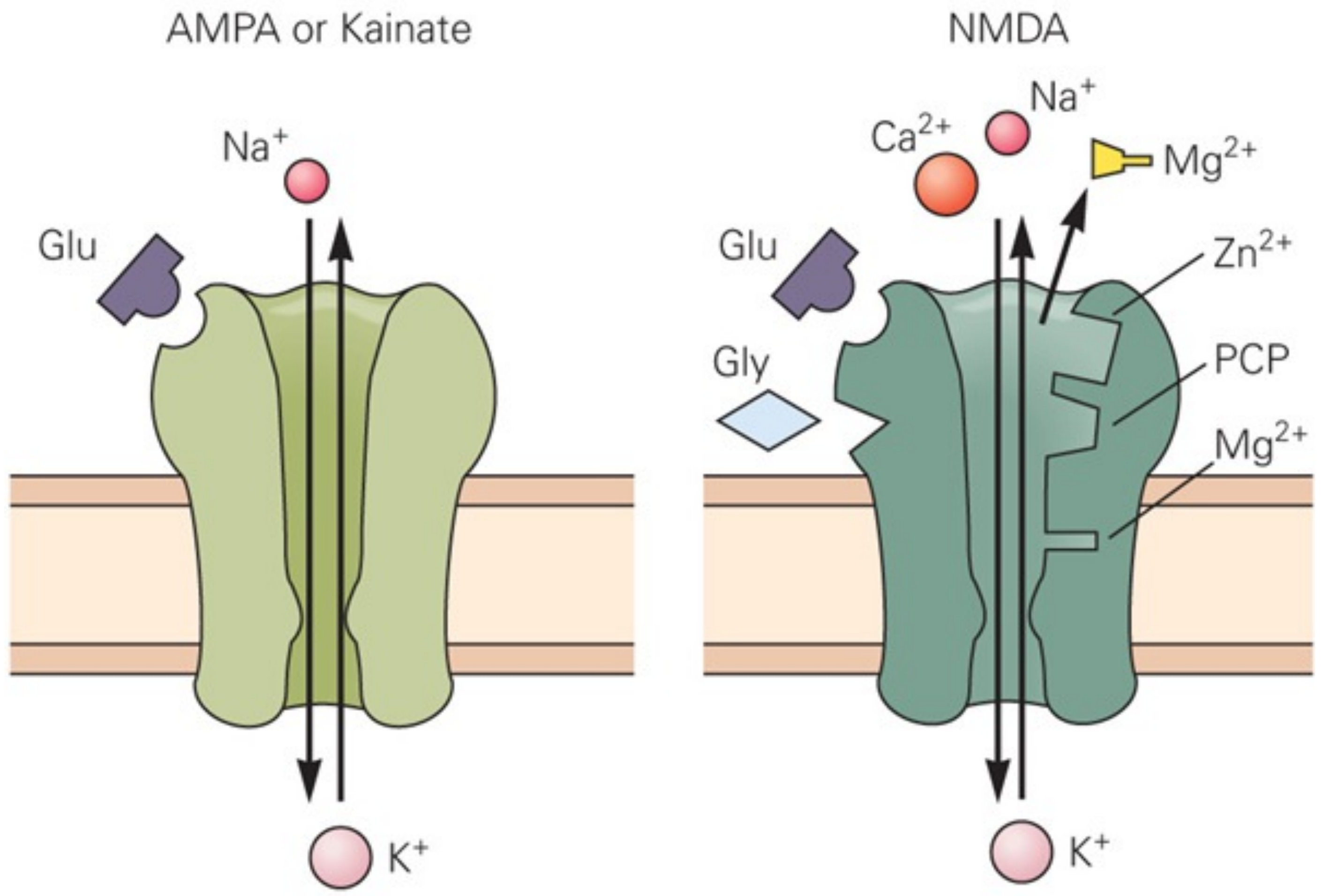


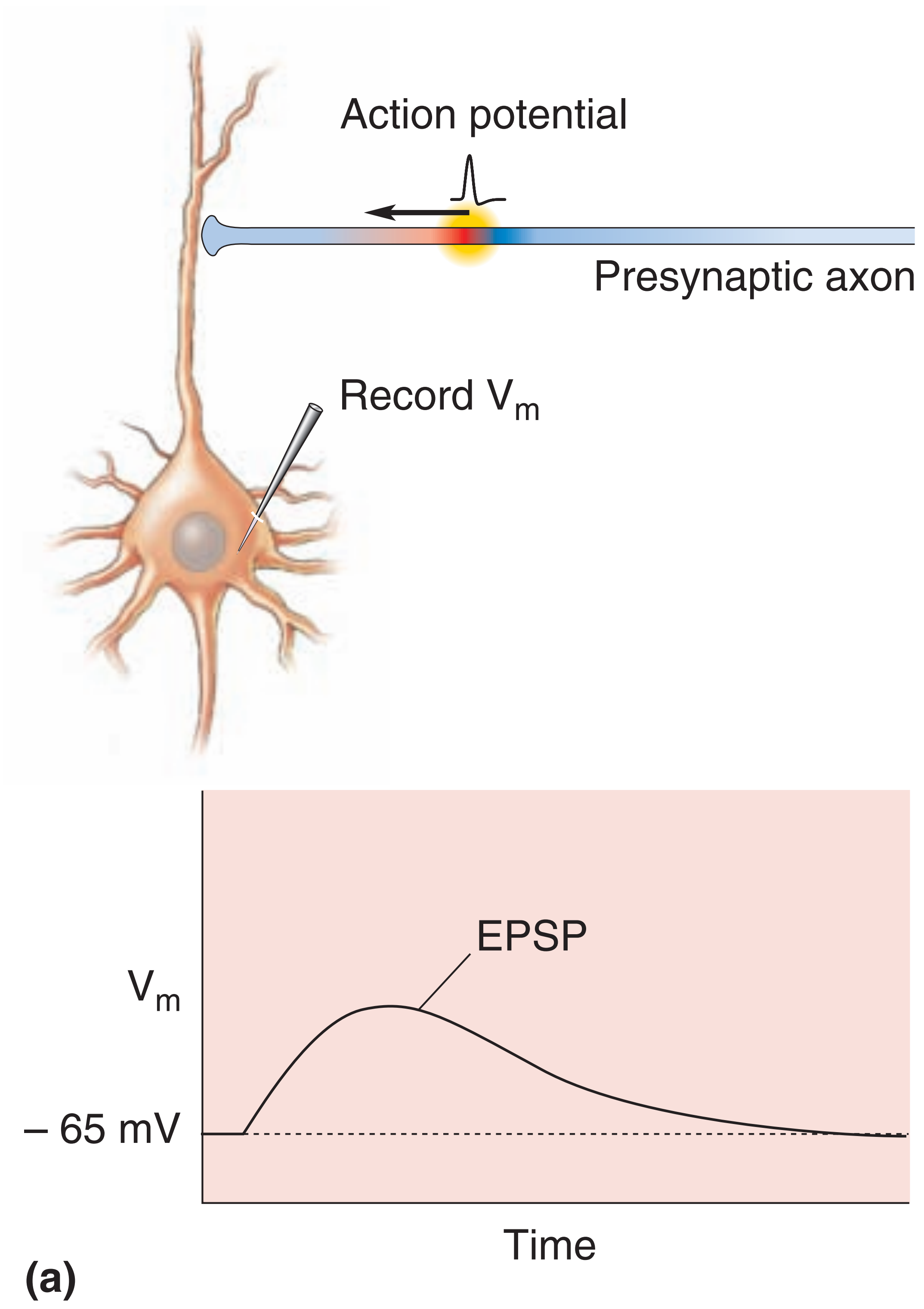
FIGURE 5.14
The generation of an EPSP. (a) An impulse arriving in the presynaptic terminal causes the release of neurotransmitter. **(b)** The molecules bind to transmitter-gated ion channels in the postsynaptic membrane. If Na^+ enters the postsynaptic cell through the open channels, the membrane will become depolarized. **(c)** The resulting change in membrane potential (V_m), as recorded by a microelectrode in the cell, is the EPSP.



Glutamate

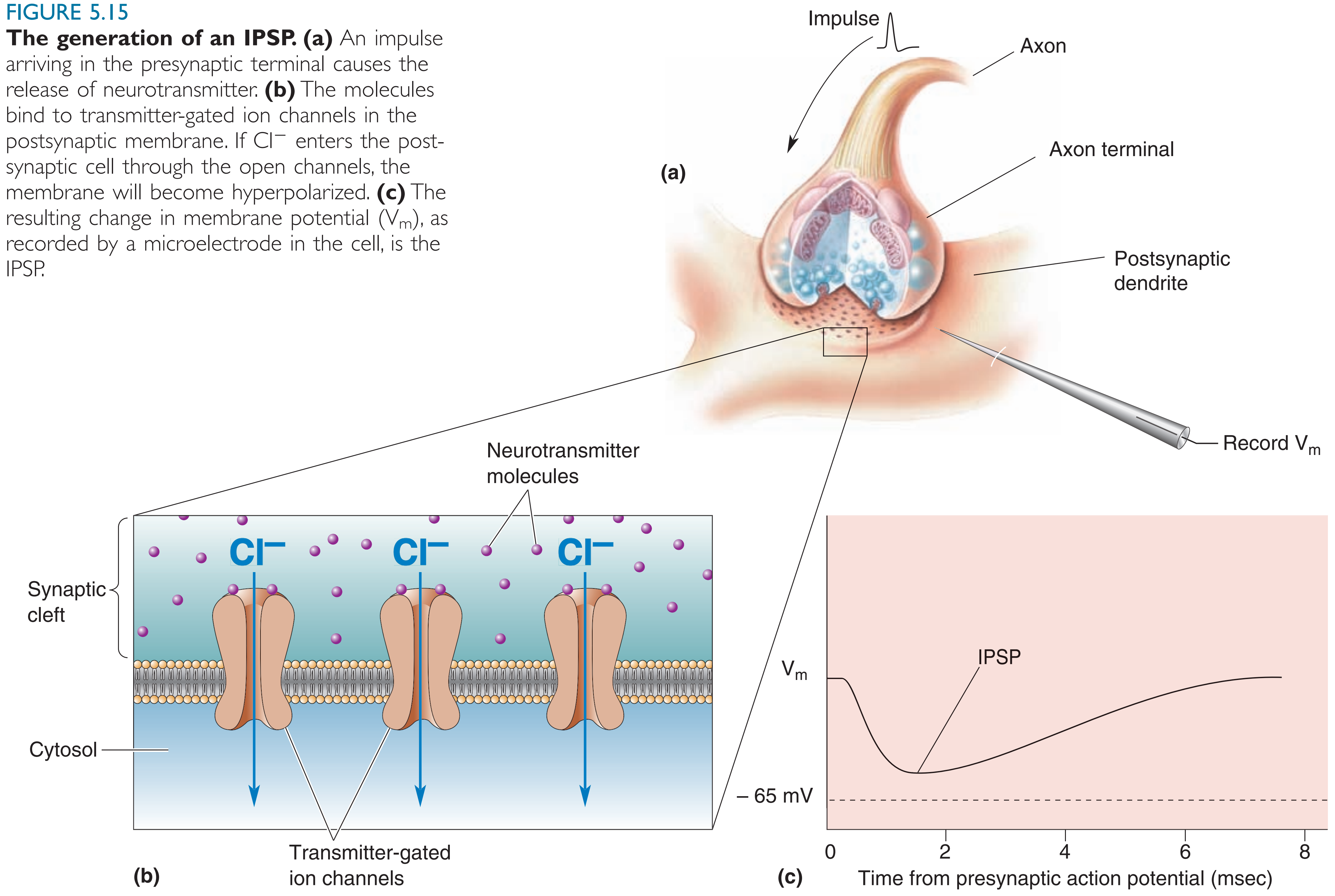
谷氨酸

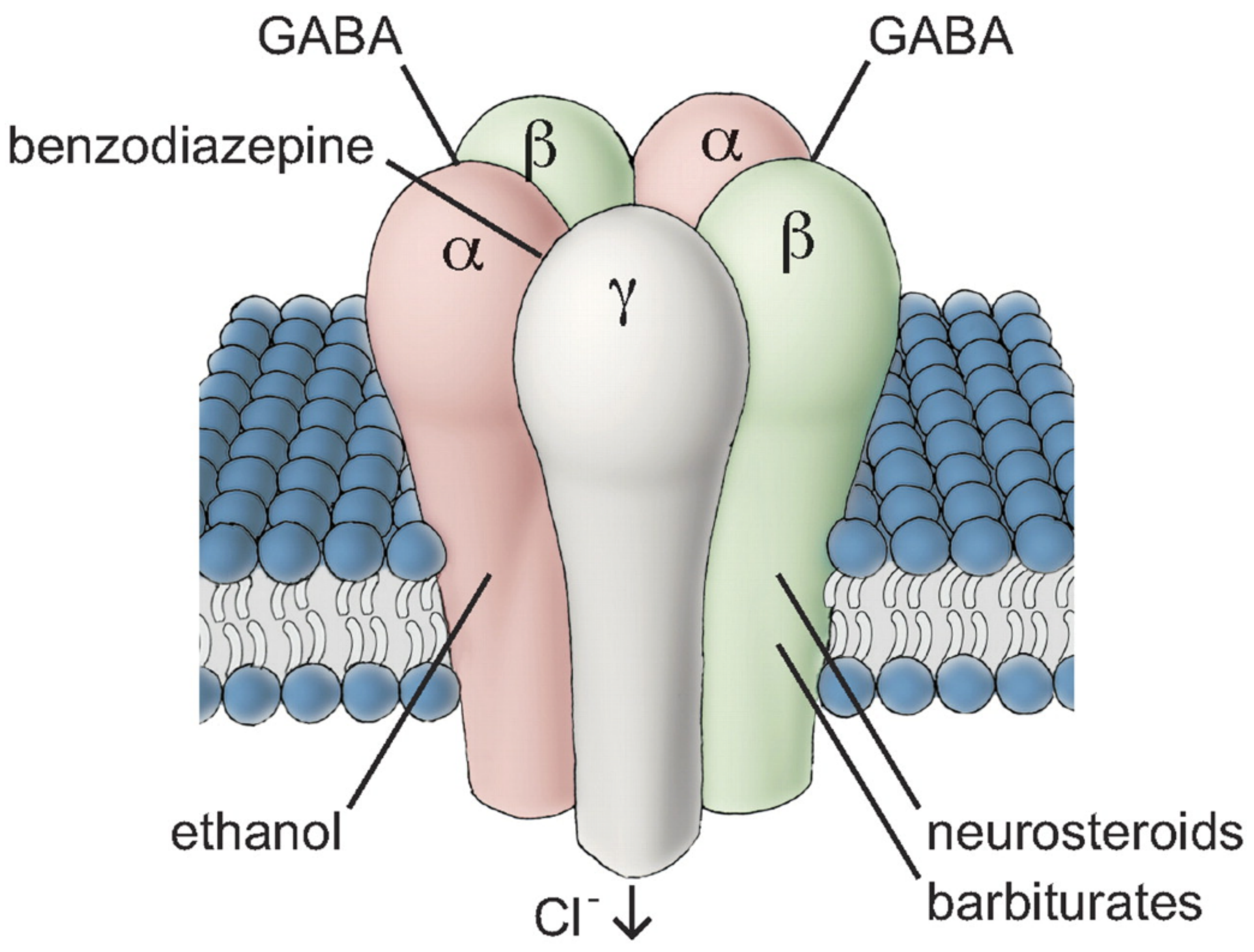
Post-synaptic reactions (excitatory)



Post-synaptic reactions (inhibitory)

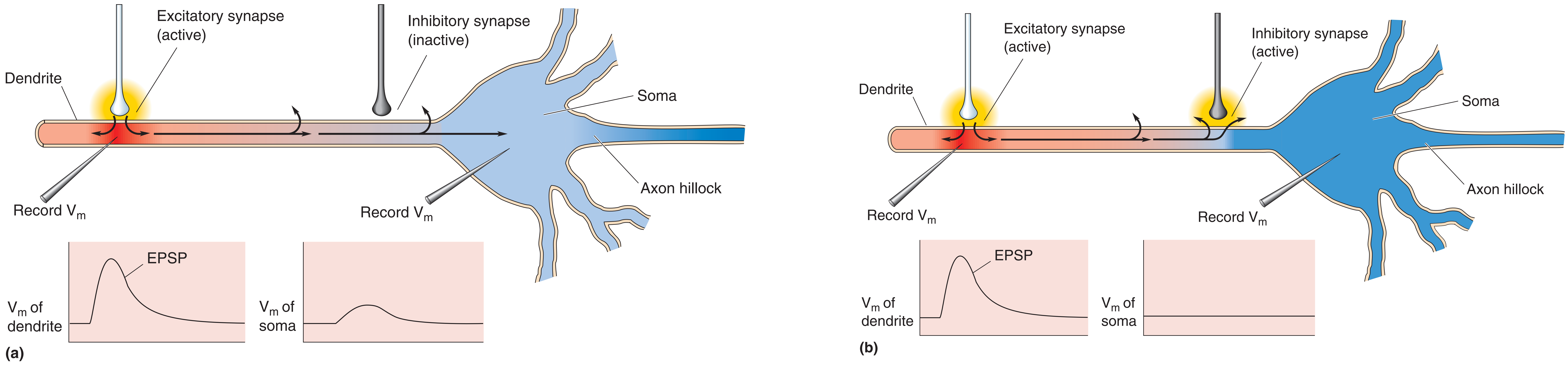
FIGURE 5.15
The generation of an IPSP. (a) An impulse arriving in the presynaptic terminal causes the release of neurotransmitter. **(b)** The molecules bind to transmitter-gated ion channels in the postsynaptic membrane. If Cl^- enters the postsynaptic cell through the open channels, the membrane will become hyperpolarized. **(c)** The resulting change in membrane potential (V_m), as recorded by a microelectrode in the cell, is the IPSP.





GABA
γ-氨基丁酸

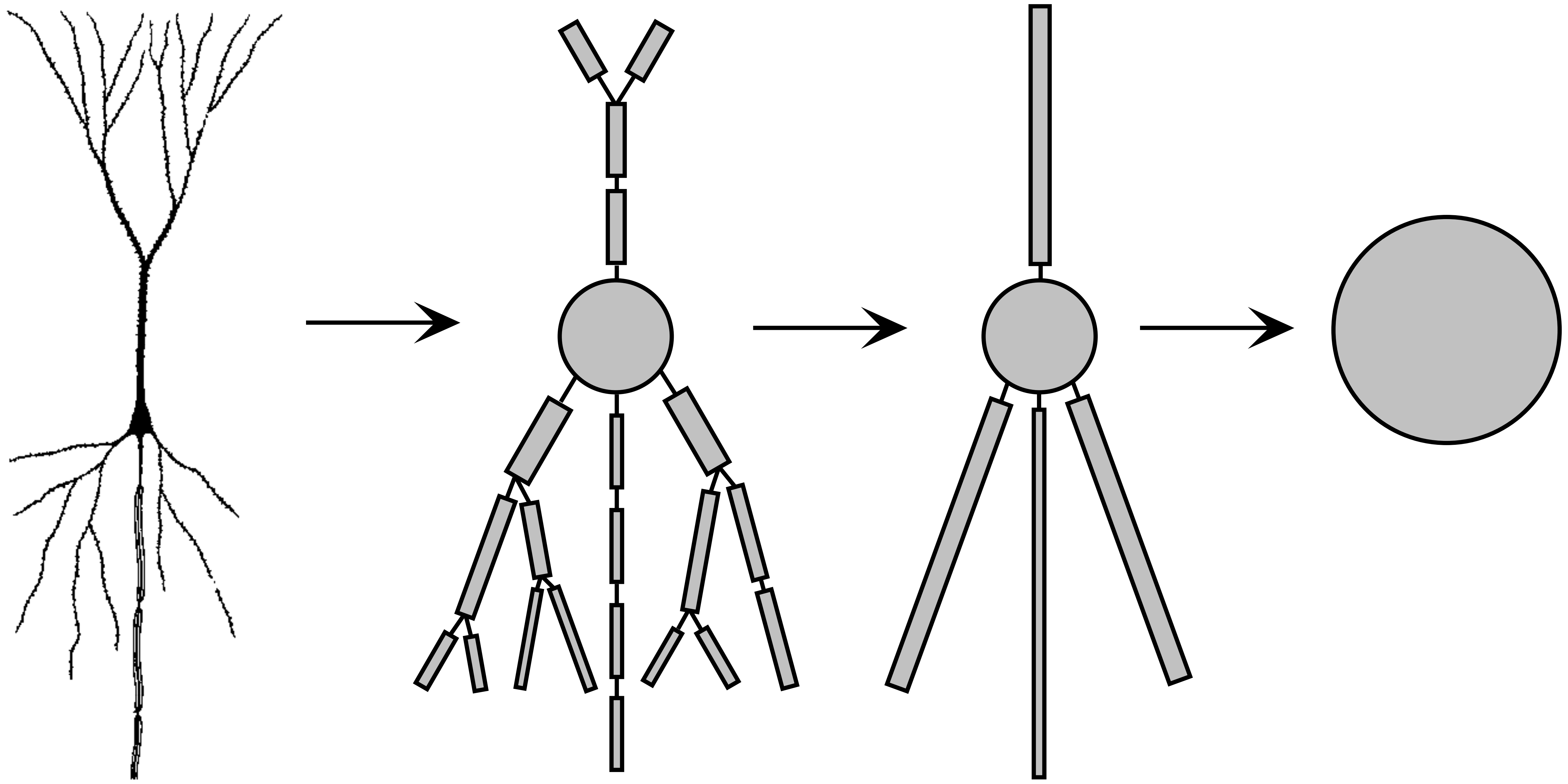
Shunting Inhibition



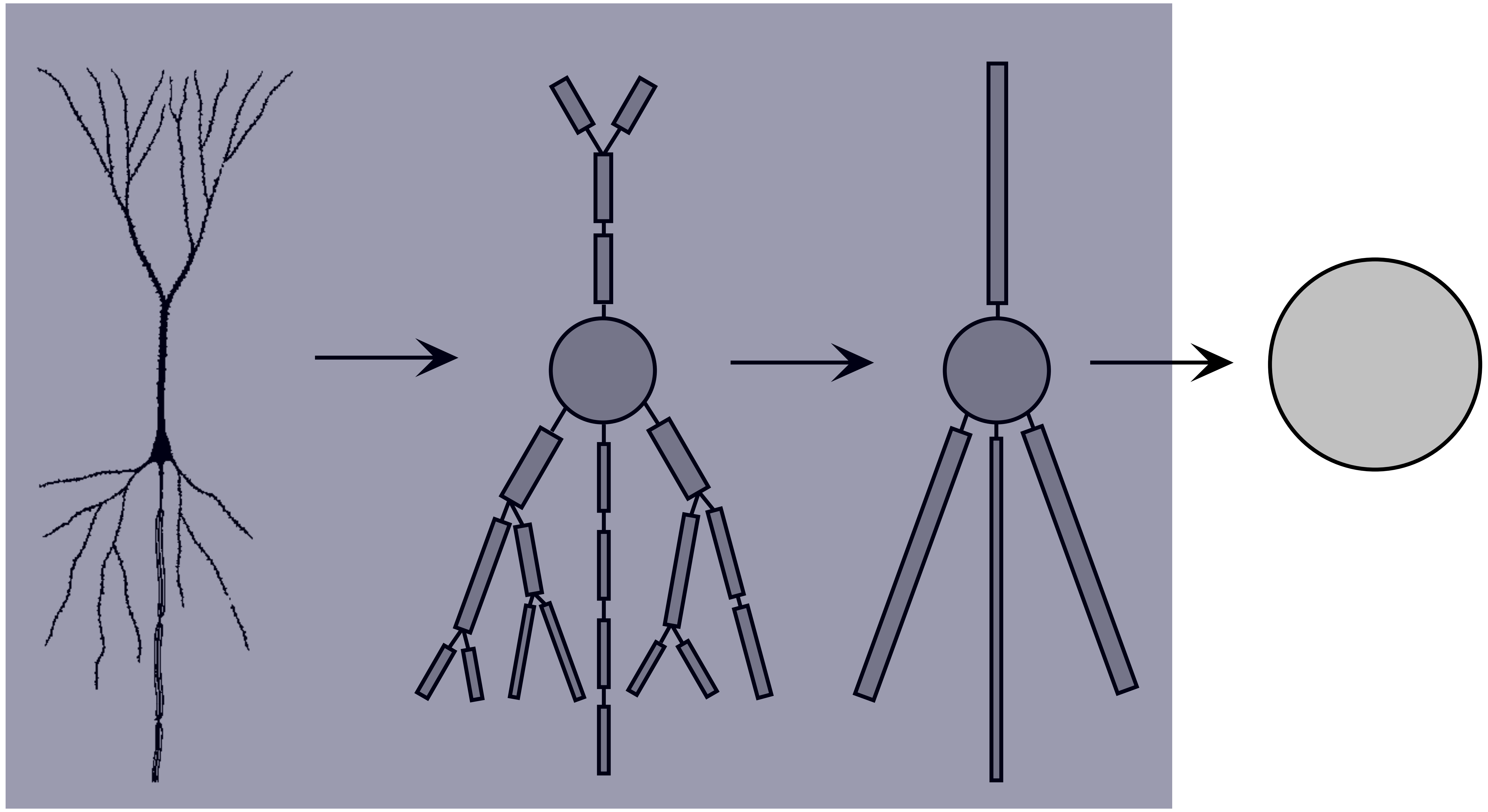
1. 膜电位和动作电位

2. 数学模型

Approximating a neuron



Integrate-and-Fire Model

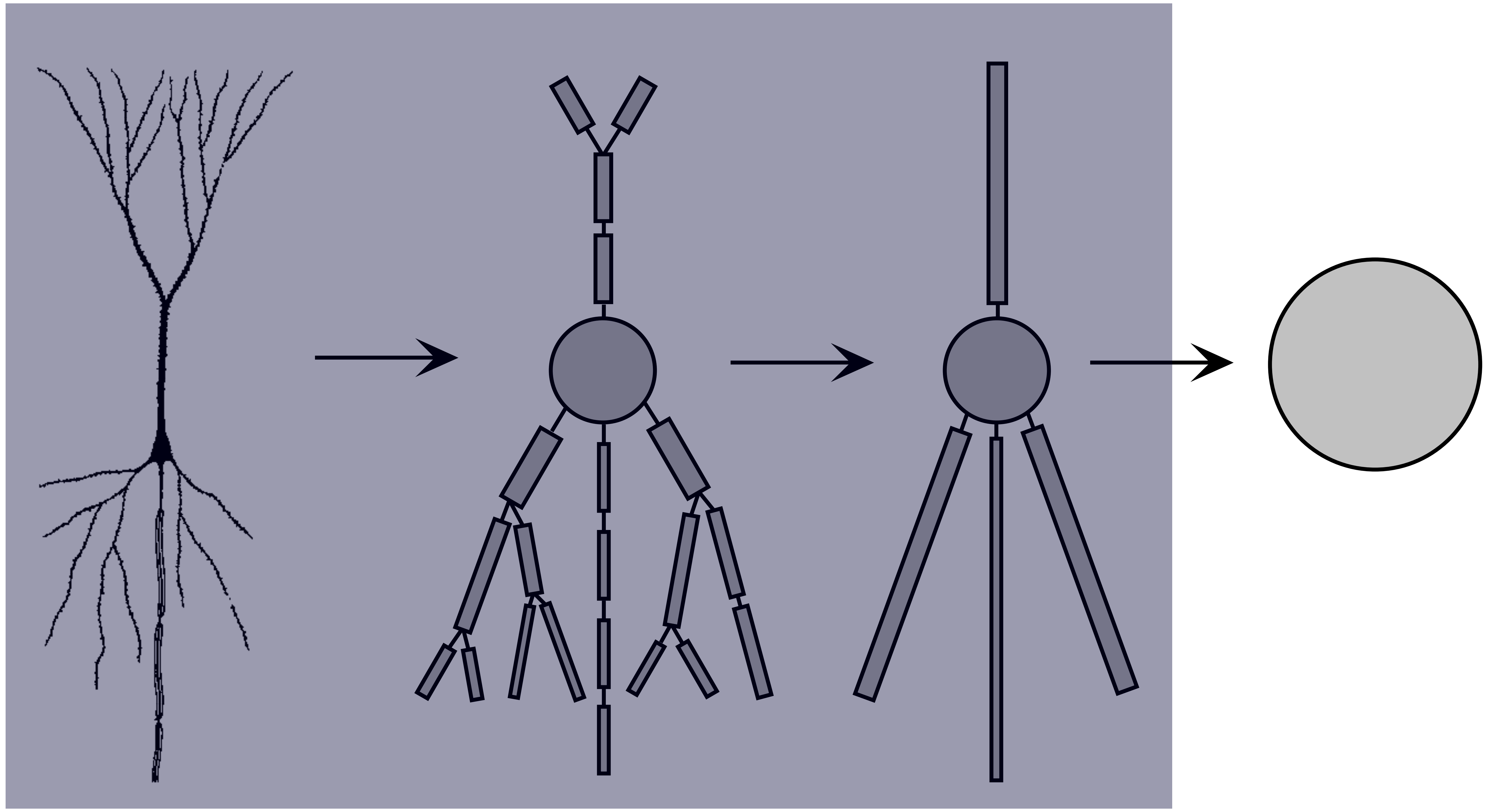


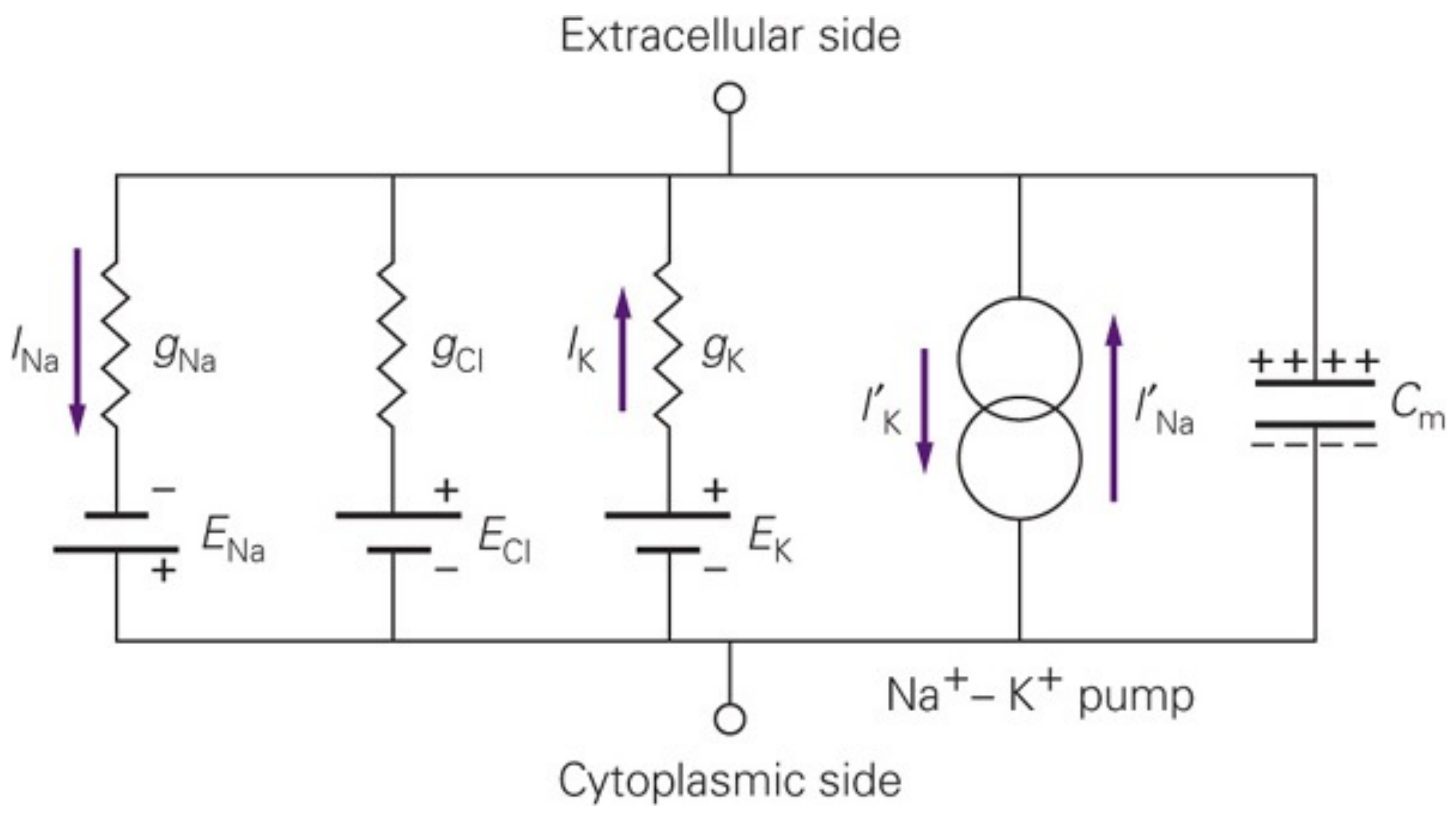
$$C_m \frac{dV}{dt} = -g_L(V - E_L) + I_e \qquad V < V_{th}$$

$$V = V_{reset} \qquad V \geq V_{th} \quad \text{Spike!}$$

$$\frac{dV}{dt} = 0 \qquad \text{Refractory period}$$

Single Compartment Model





Hodgkin-Huxley Model

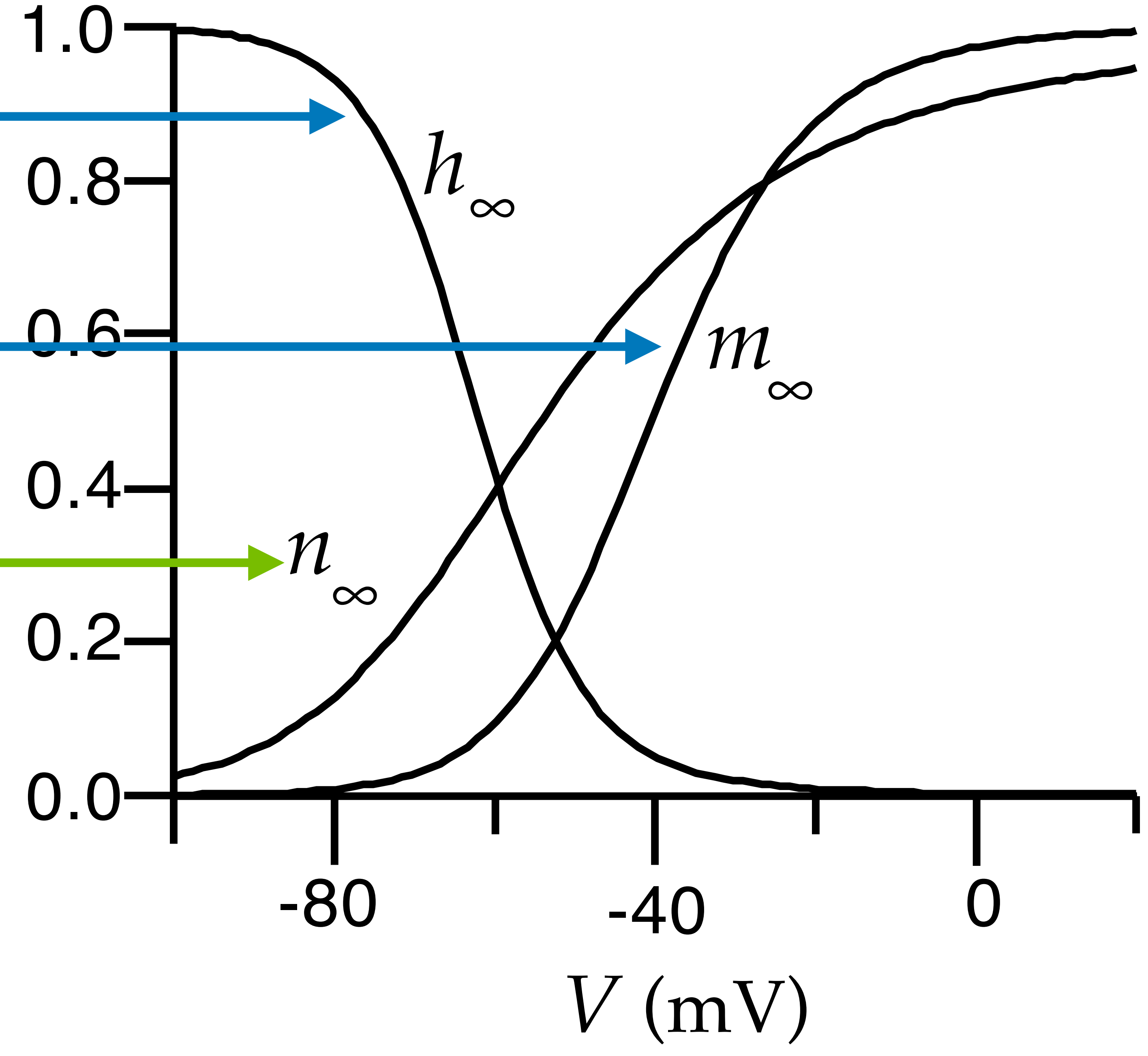
$$C\frac{dV}{dt} = -g_L(V - E_L) - g_K n^4(V - E_k) - g_{Na} m^3 h(V - E_{Na}) - I_E$$

Inactivation

Activation

Activation

Gating Variables

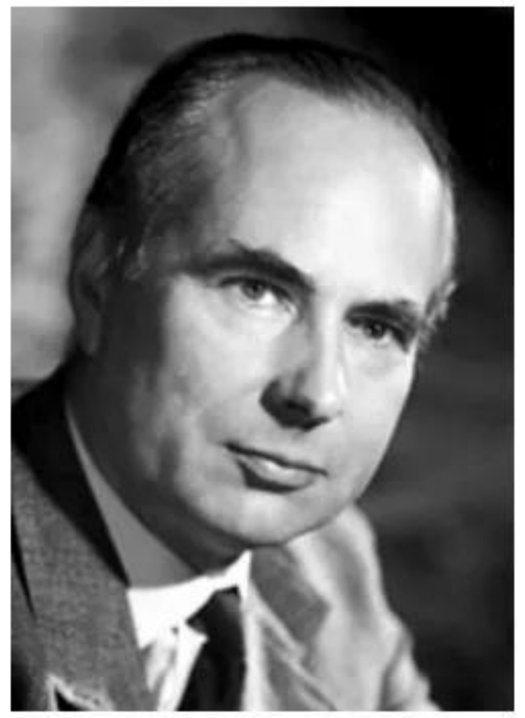


Opening Rate

Closing Rate

$$\frac{dn}{dt} = \underset{\text{Opening Rate}}{\alpha_n(V)}(1 - n) - \underset{\text{Closing Rate}}{\beta_n(V)}n$$

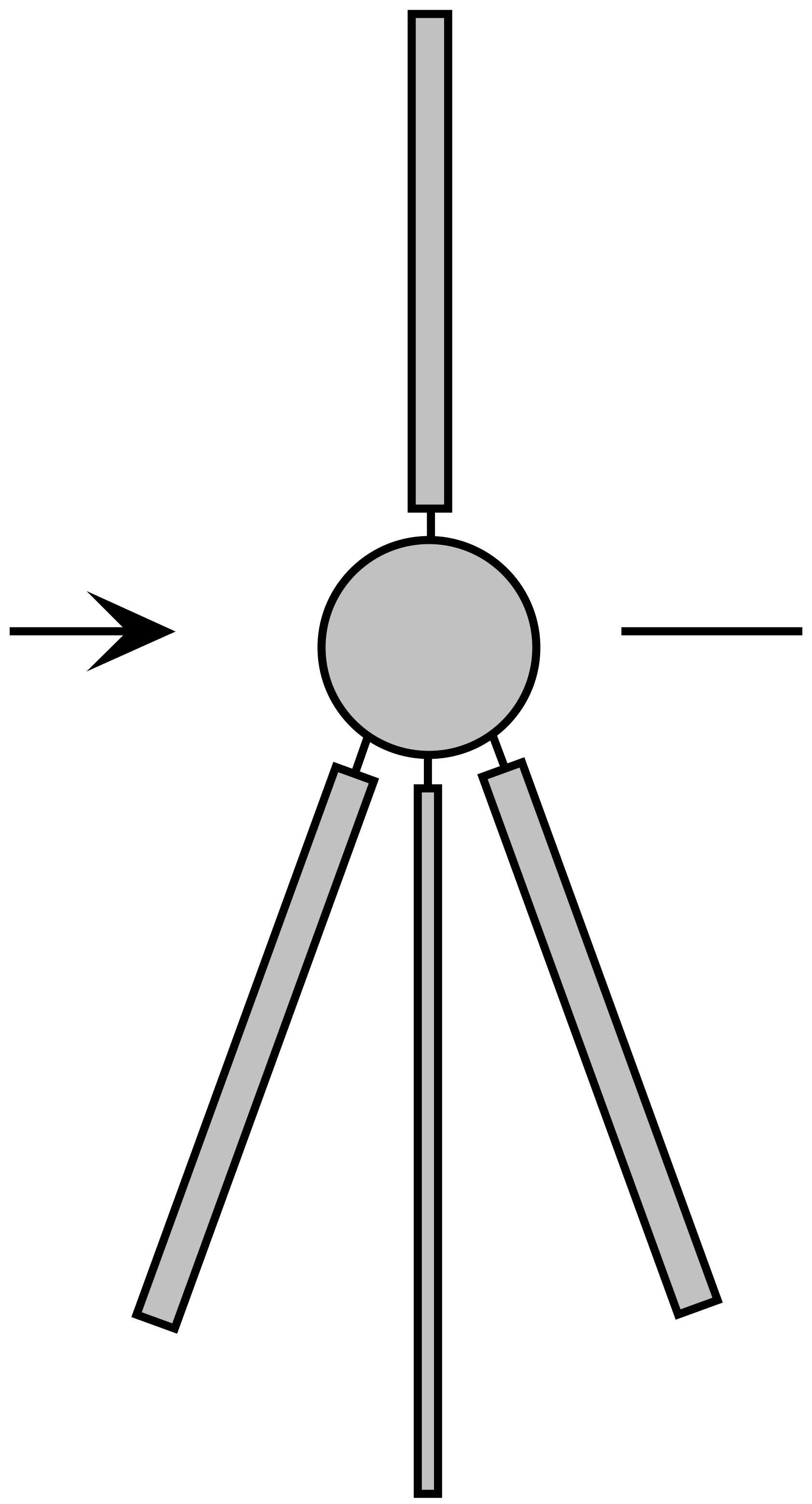
Alan Lloyd Hodgkin



Andrew Fielding Huxley

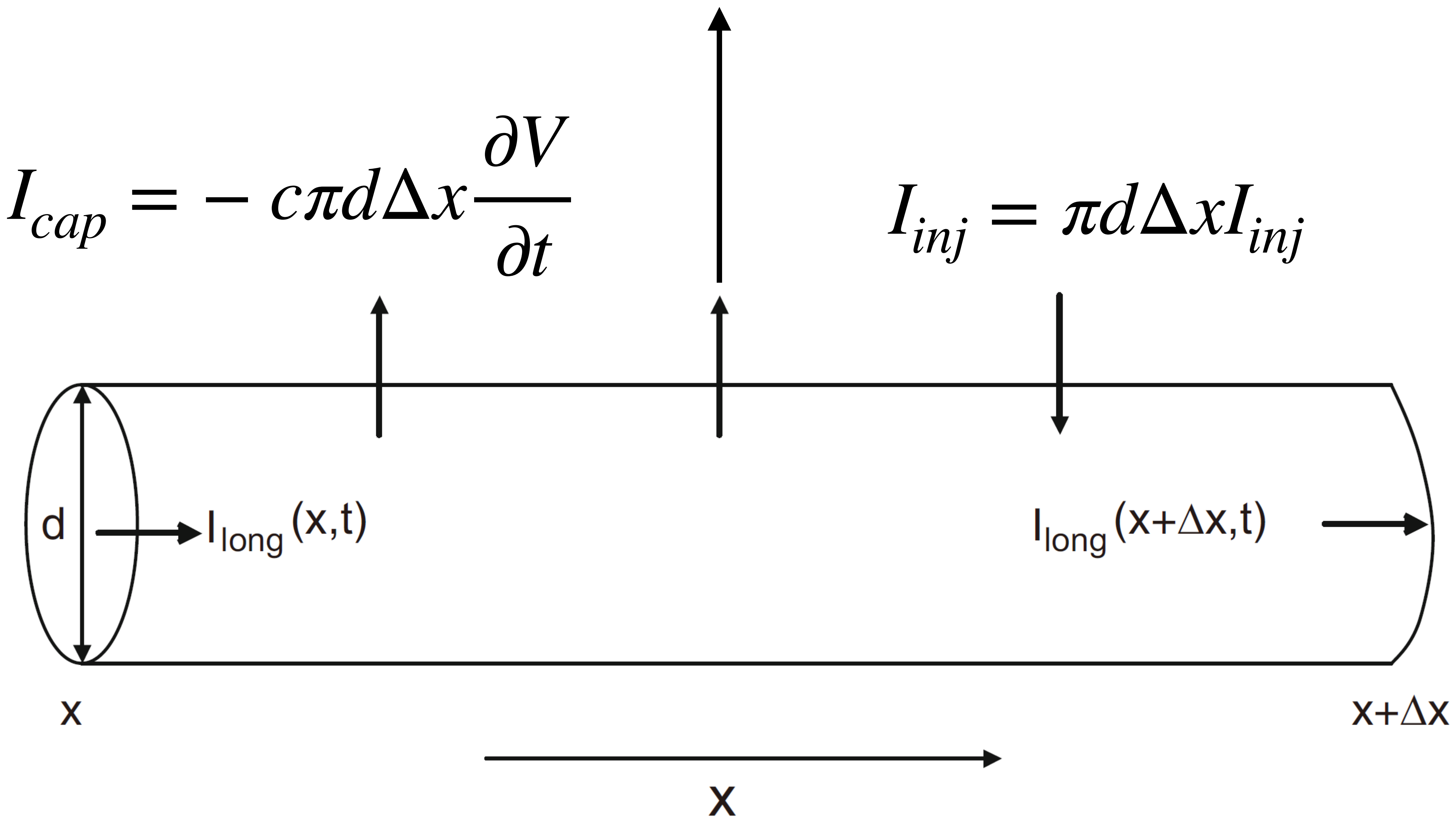
1963 Nobel Prize Winners

Cable Theory



$$I_{leak} = -\, g_L \pi d \Delta x (E_L - V)$$

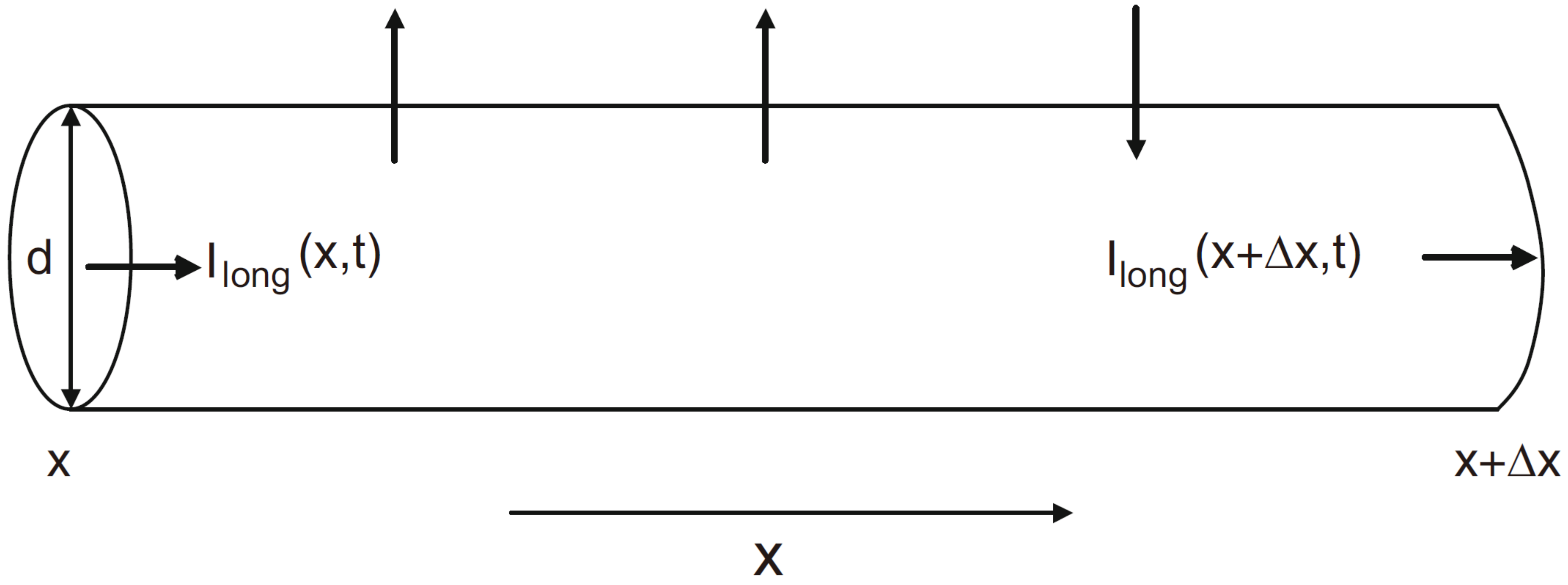
$$I_{cap} = -\, c \pi d \Delta x \frac{\partial V}{\partial t} \qquad I_{inj} = \pi d \Delta x I_{inj}$$



$$I_{long}(x) = -\, \frac{\pi d^2}{4 r_a} \frac{\partial V}{\partial x}$$

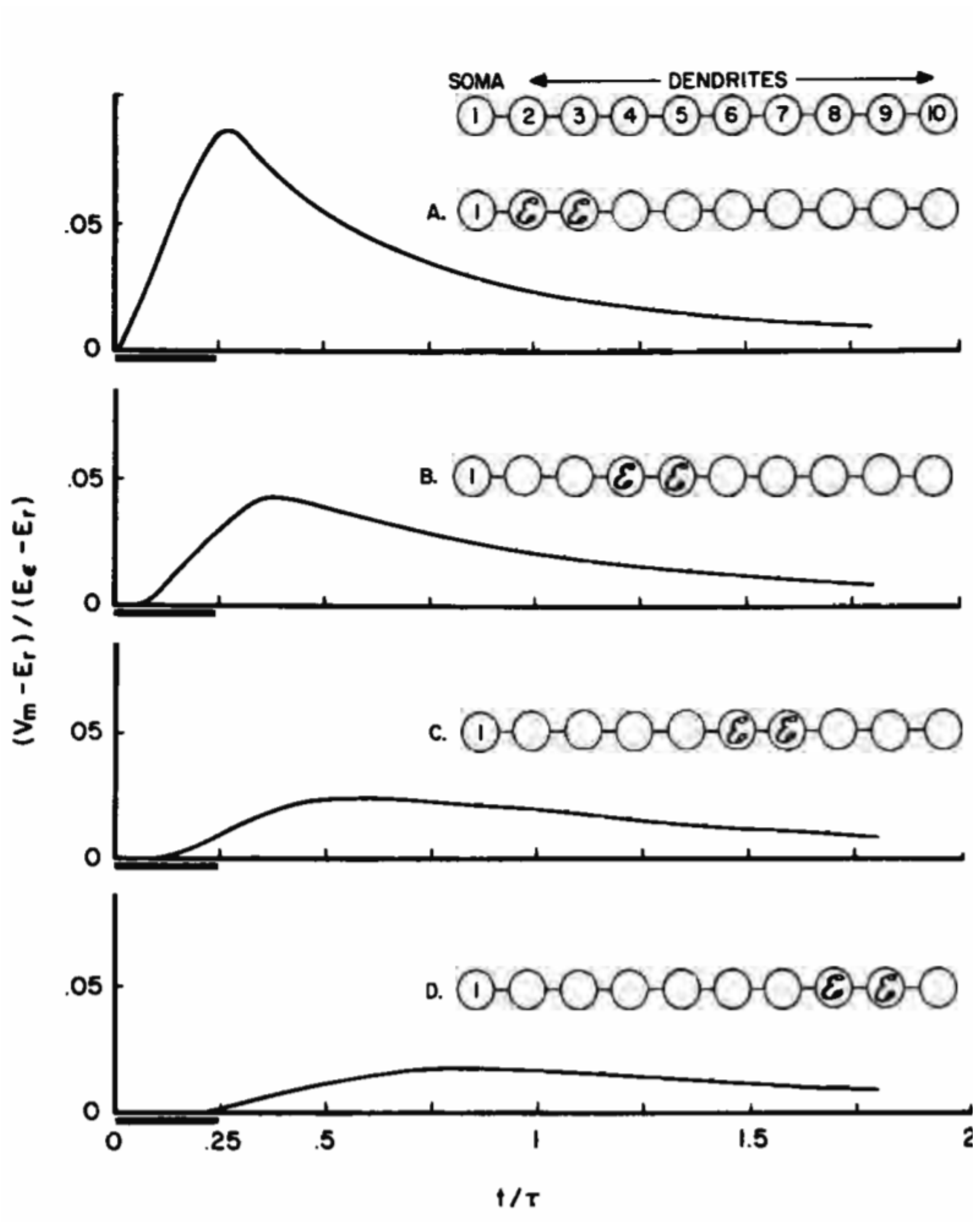
resistance

Cable Theory



$$\left.\frac{\pi d^2}{4r_a}\frac{\partial V}{\partial x}\right|_{x+\Delta x} - \left.\frac{\pi d^2}{4r_a}\frac{\partial V}{\partial x}\right|_{x} = -c\pi d\Delta x\frac{\partial V}{\partial t} - g_L\pi d\Delta x(E_L - V) + \pi d\Delta x I_{inj}$$

$$c\frac{\partial V}{\partial t} = -g_L(V - E_L) + I_{inj} + \frac{d}{4r_a}\frac{\partial^2 V}{\partial x^2}$$



Rall, 1964

$$c\frac{\partial V}{\partial t} = -\, g_L(V - E_L) + \boxed{I_{inj}} + \frac{d}{4r_a}\frac{\partial^2 V}{\partial x^2}$$

Synaptic input

Summary

- Membrane Potential
  - Ion pumps
- Action Potentials
  - Voltage-gated Ion channels
- Modeling
  - Single-compartment models: I&F, H&H
  - Cable theory

Homework

- Play with the simulation code that I sent out and learn how different patterns of input may affect the voltage response.

Project Idea

- Combine a single-compartment model and the cable equation, and create a neuron that can carry out some interesting computations.