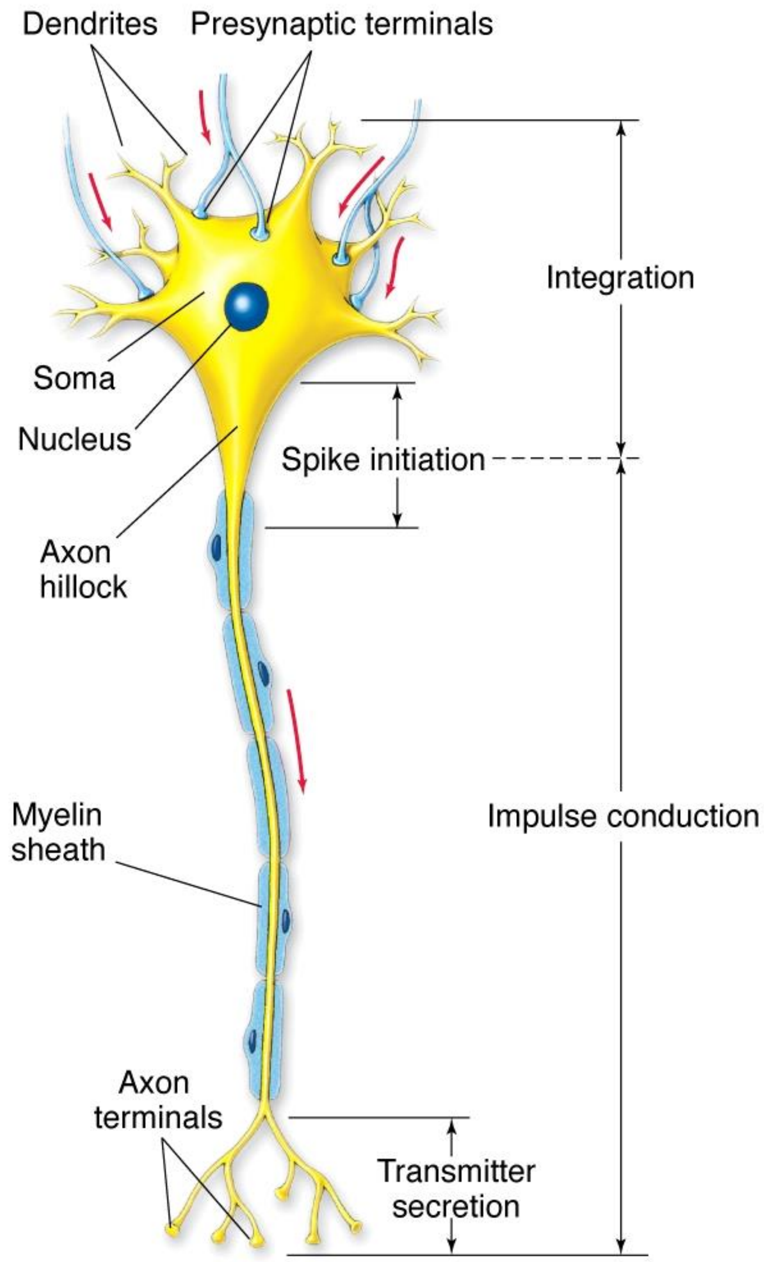
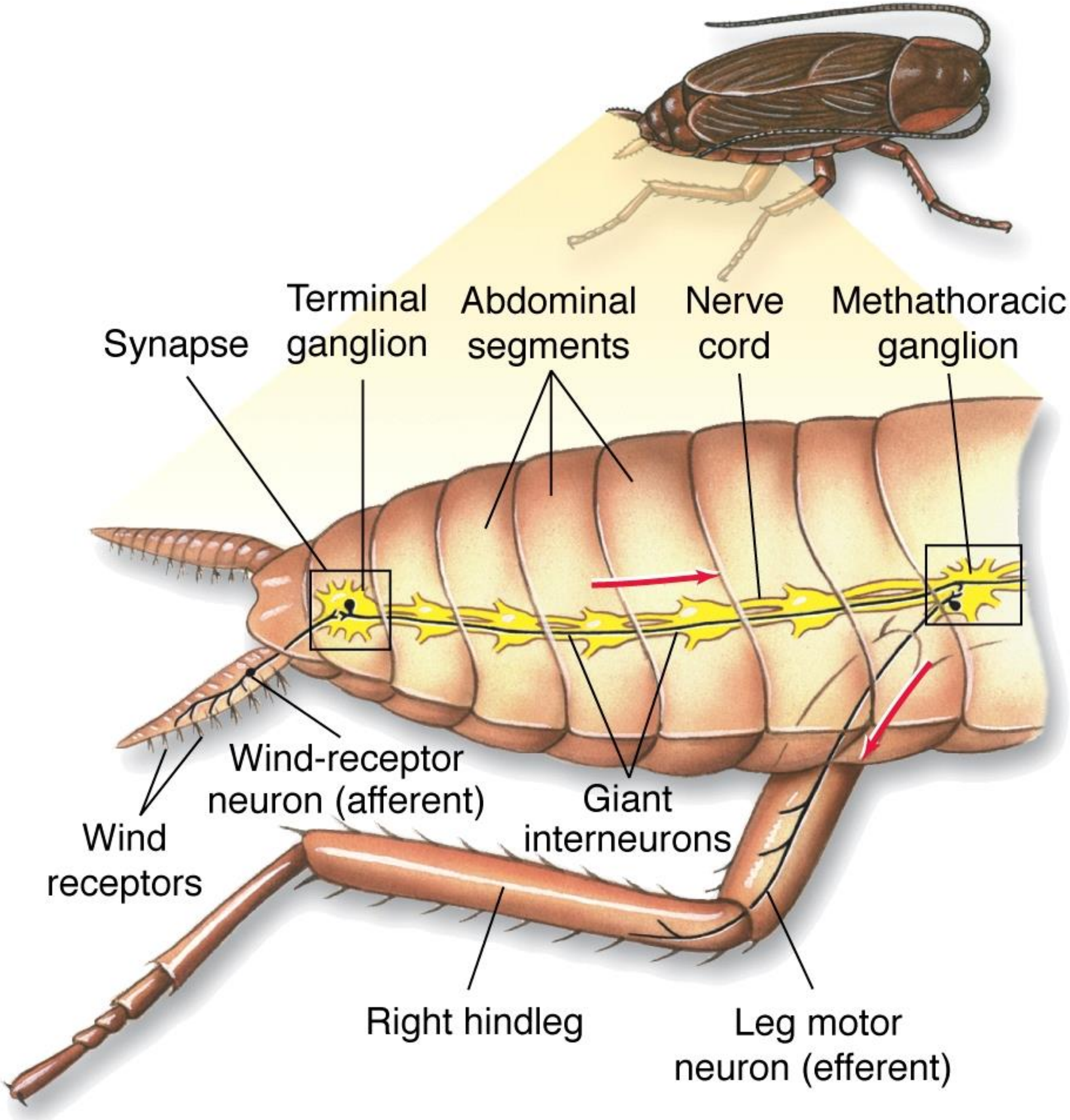
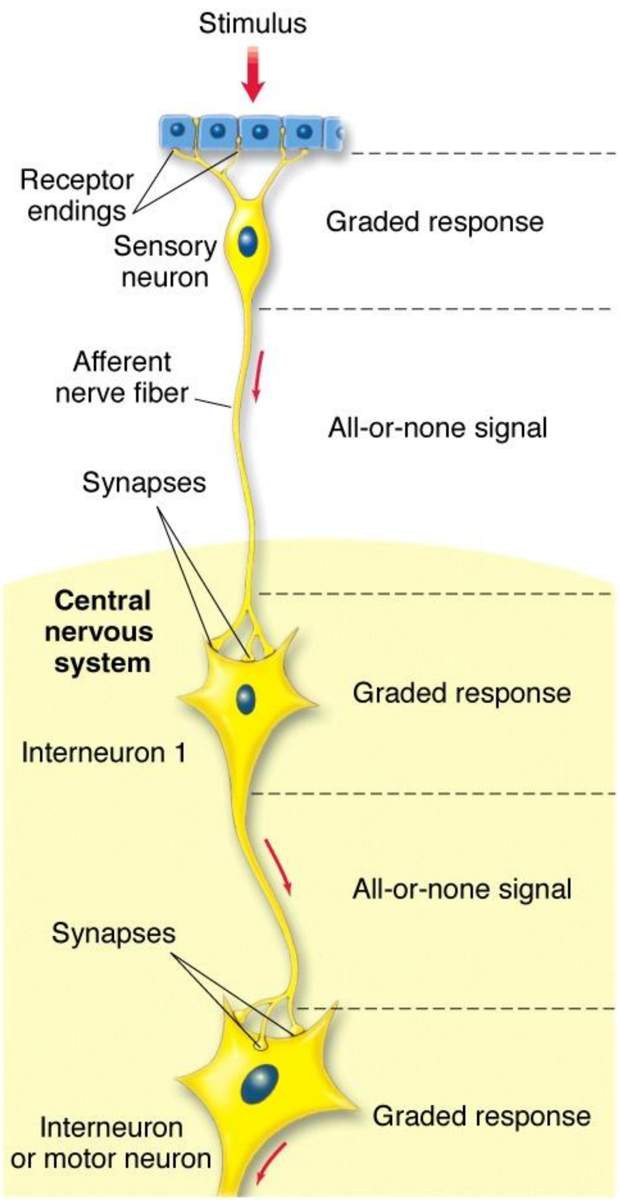
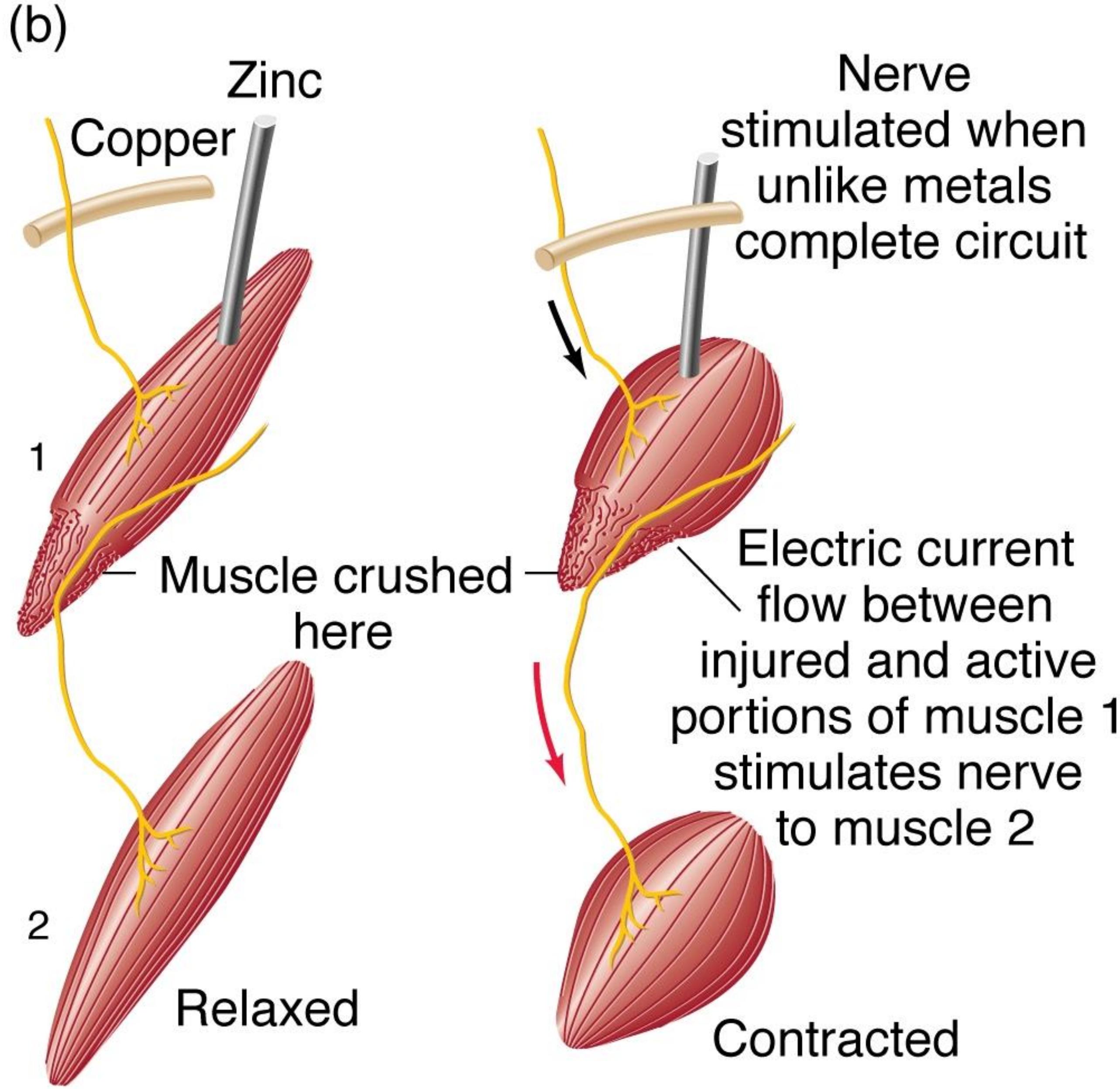
Neuronal function



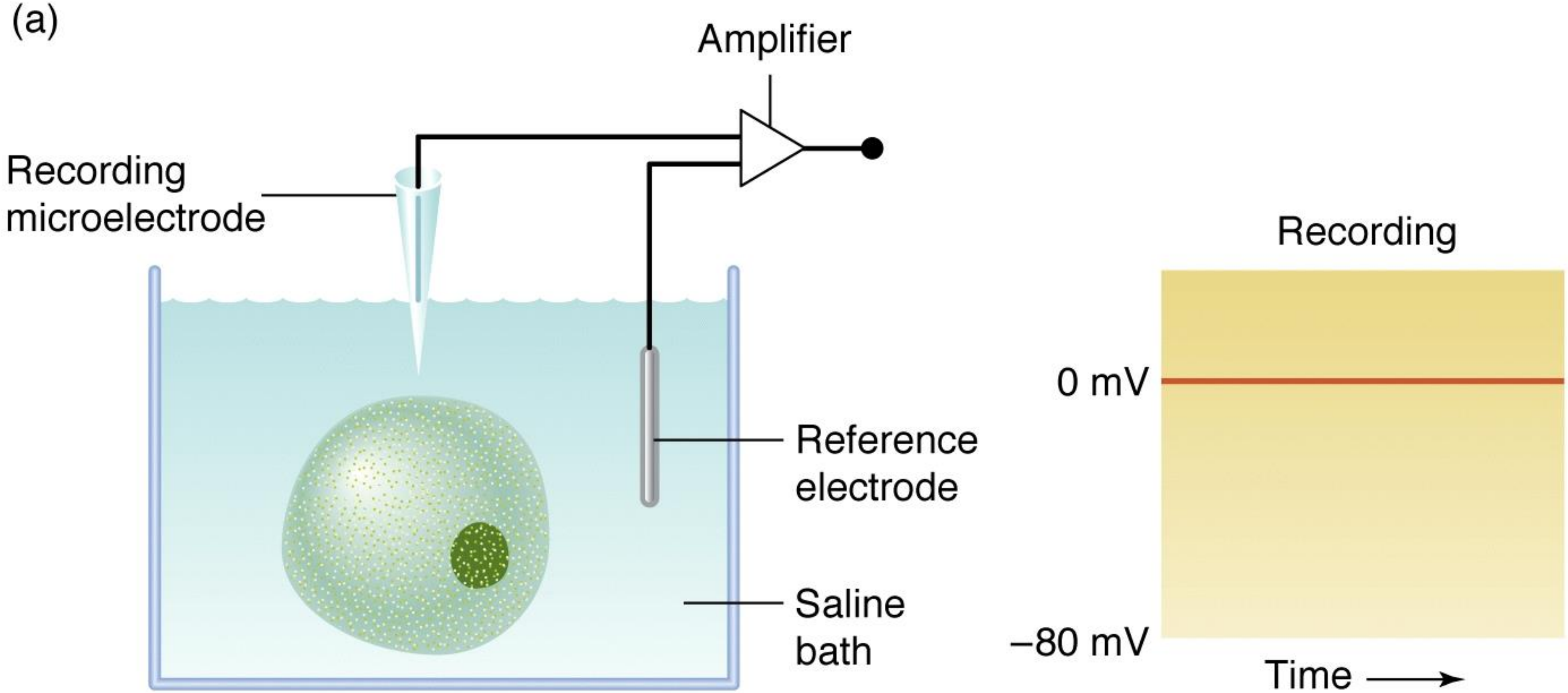
Dendrites
Presynaptic terminals
Integration
Soma
Nucleus
Spike initiation
Axon hillock
Myelin sheath
Impulse conduction
Axon terminals
Transmitter secretion

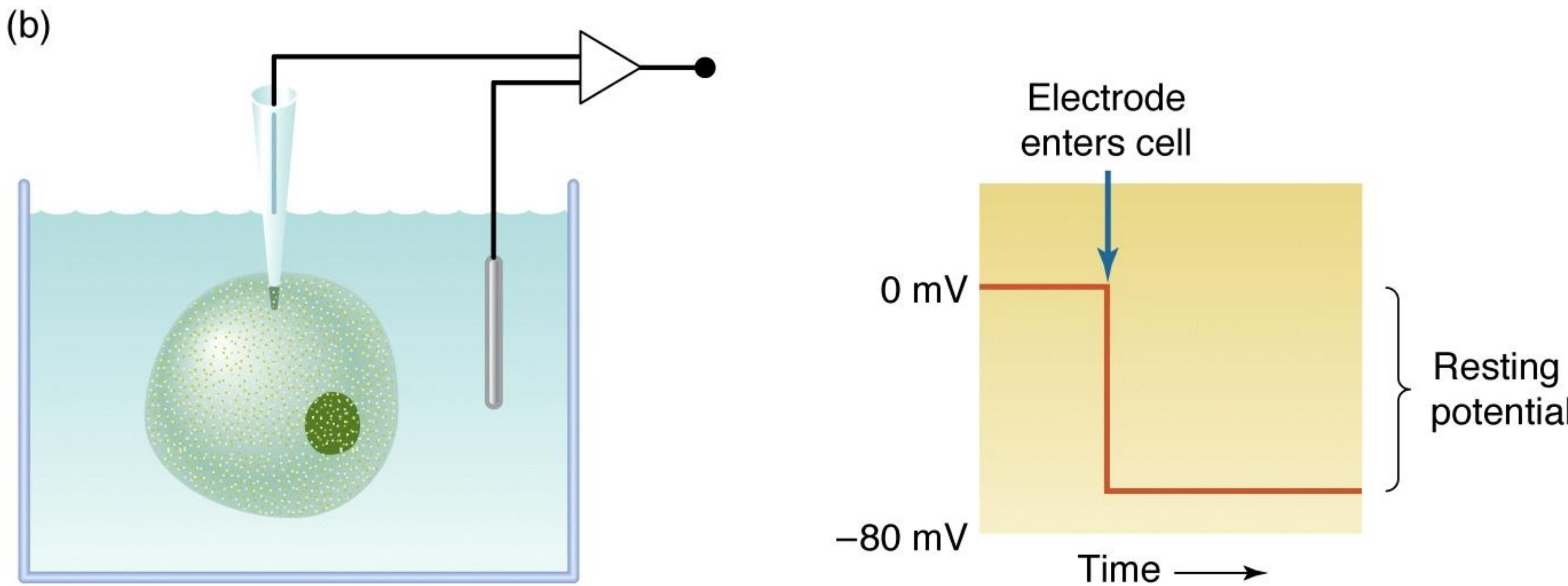

Synapse
Terminal ganglion
Abdominal segments
Nerve cord
Methathoracic ganglion
Wind-receptor neuron (afferent)
Wind receptors
Giant interneurons
Right hindleg
Leg motor neuron (efferent)


Stimulus
Receptor endings
Sensory neuron
Graded response
Afferent nerve fiber
All-or-none signal
Synapses
Central nervous system
Graded response
Interneuron 1
All-or-none signal
Synapses
Graded response
Interneuron or motor neuron


(b)
Zinc
Copper
Nerve stimulated when unlike metals complete circuit
1
Muscle crushed here
Electric current flow between injured and active portions of muscle 1 stimulates nerve to muscle 2
2
Relaxed
Contracted

(a)


Amplifier
Recording microelectrode
Reference electrode
Saline bath
Recording
0 mV
−80 mV
Time


(b)
Electrode
enters cell
0 mV
–80 mV
Resting
potential
Time

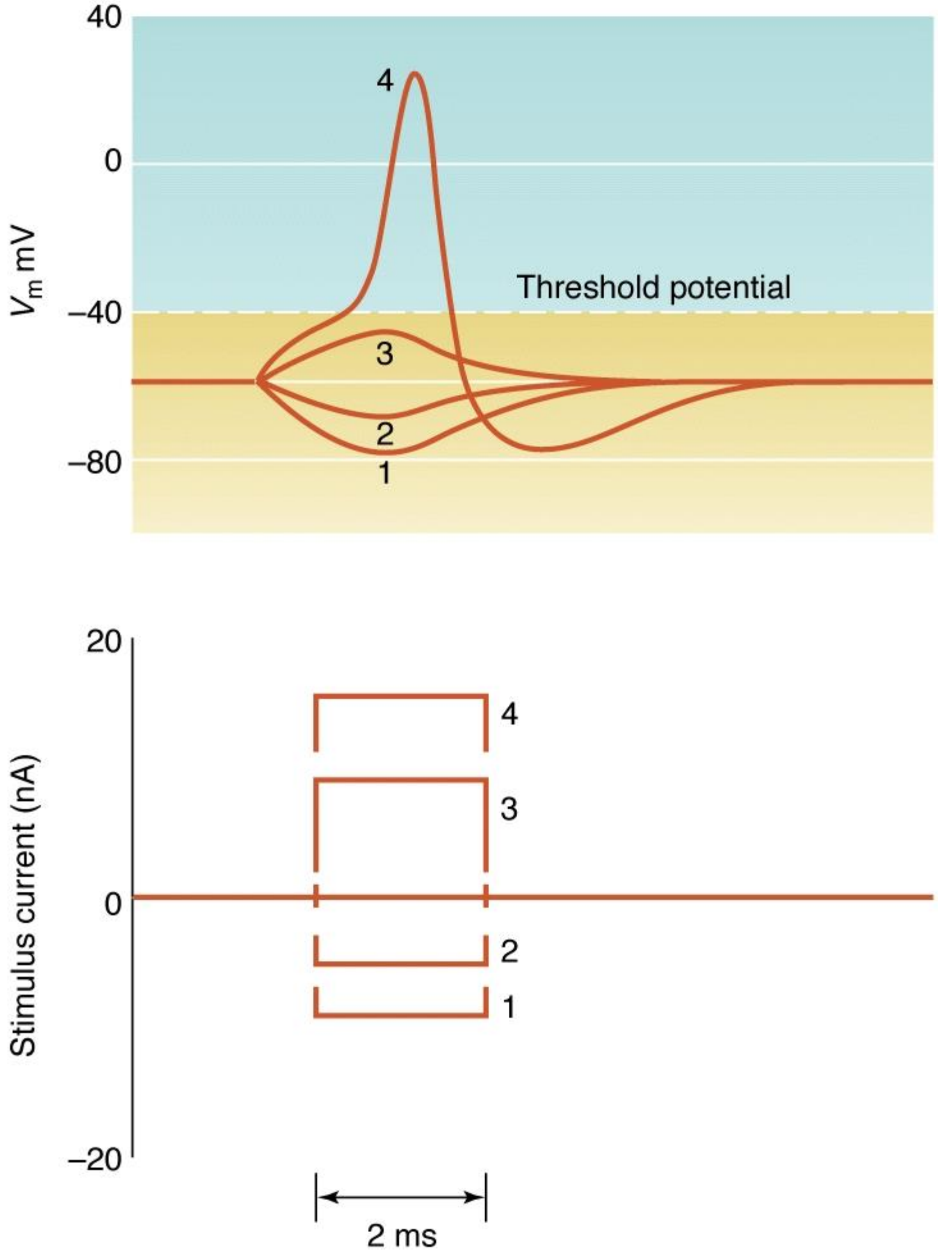
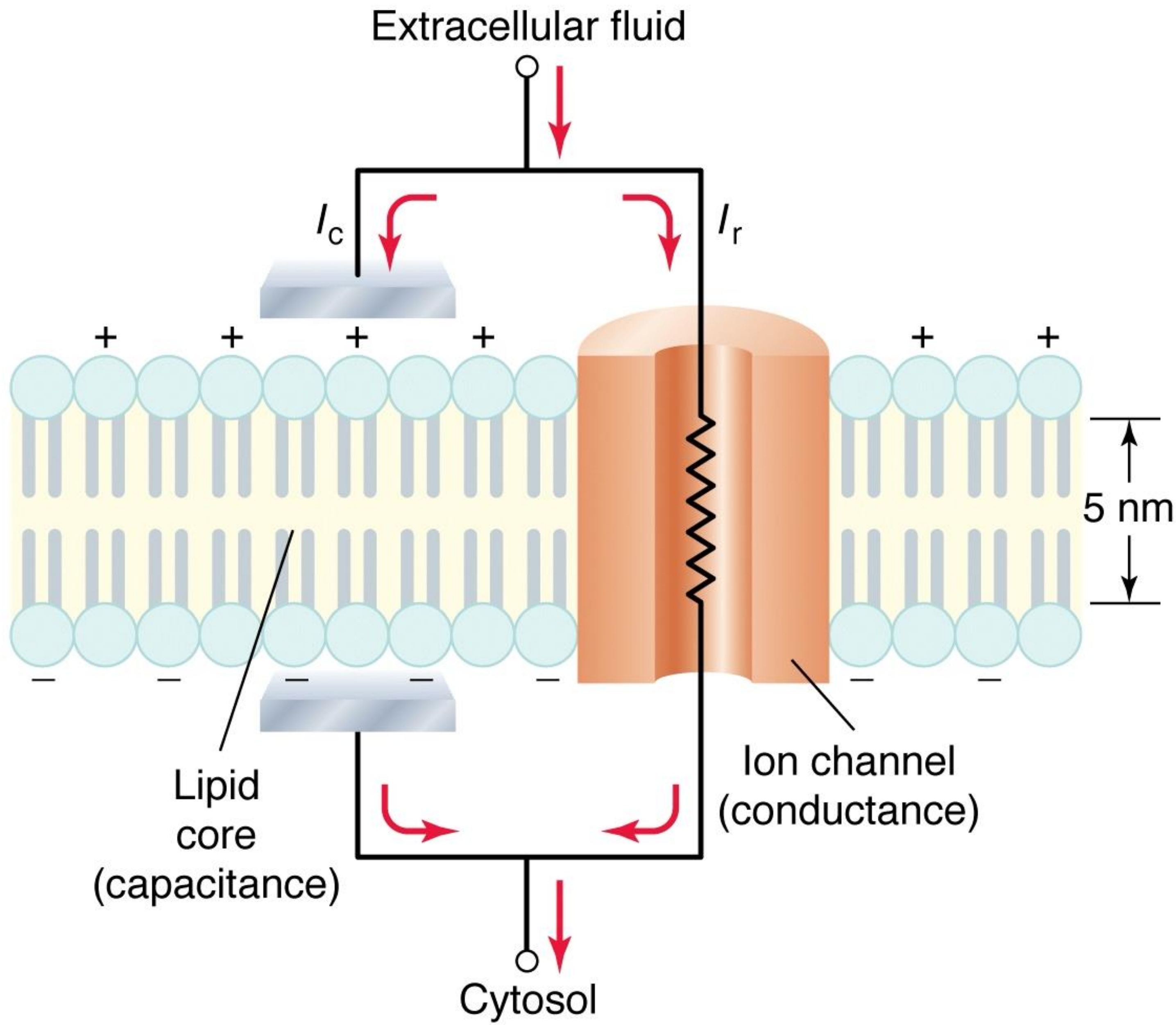
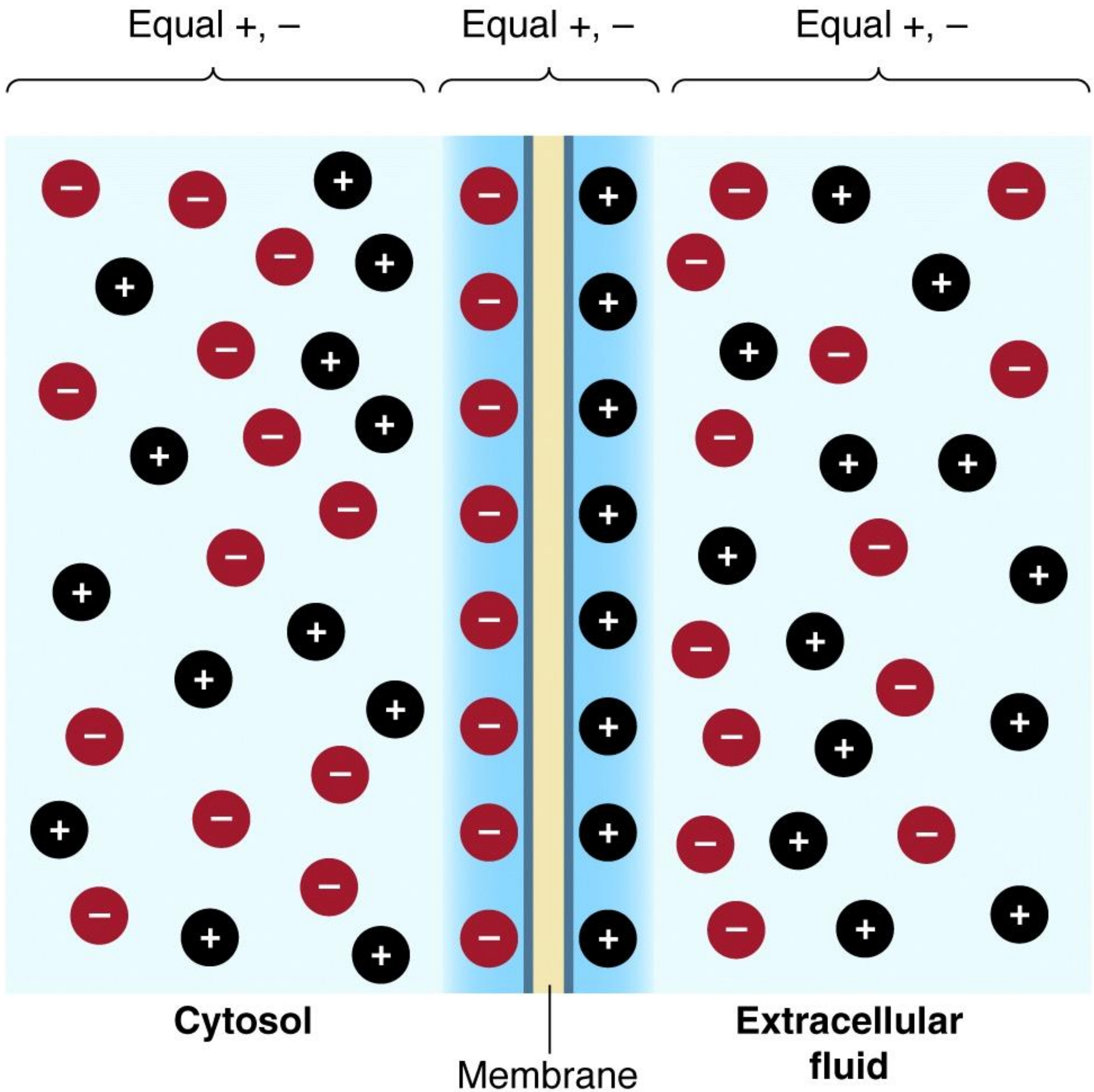

40
0
V_m mV
−40
−80
Threshold potential
4
3
2
1
20
0
−20
Stimulus current (nA)
4
3
2
1
2 ms

Table 5-1 **Examples of ion channels found in axons**

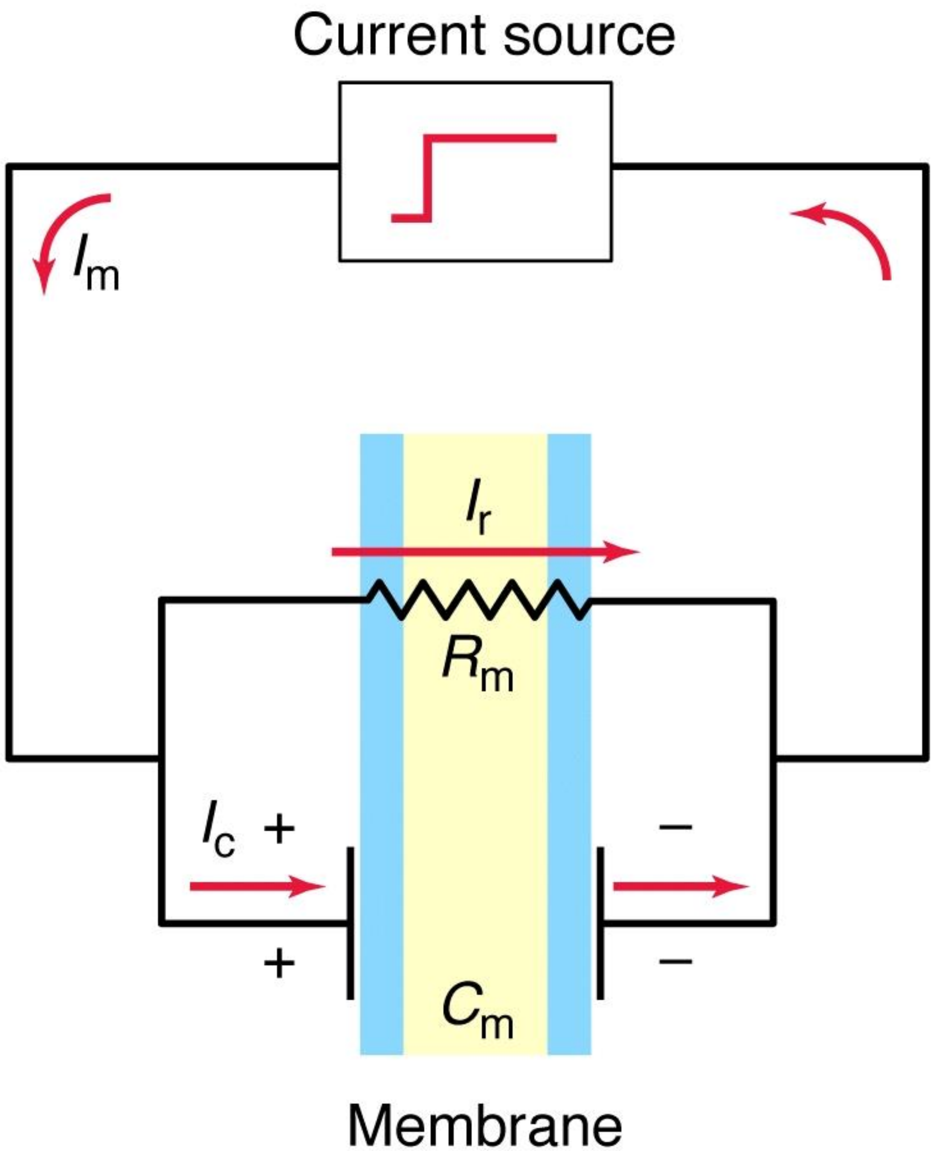
Channel	Current through channel	Characteristics	Selected blockers	Function
Leak channel (open in resting axon)	$I_{K\ (leak)}$	Produces relatively high P_K of resting cell	Partially blocked by tetraethylammonium (TEA)	Largely responsible for V_{rest}
Voltage-gated Na^+ channel	I_{Na}	Rapidly activated by depolarization; becomes inactivated even if V_m remains depolarized	Tetrodotoxin (TTX)	Produces rising phase of AP
Voltage-gated Ca^{2+} channel	I_{Ca}	Activated by depolarization but more slowly than Na^+ channel; inactivated as function of cytoplasmic [Ca^{2+}] or V_m	Verapamil, D600, Co^{2+}, Cd^{2+}, Mn^{2+}, Ni^{2+}, La^{3+}	Produces slow depolarization; allows Ca^{2+} to enter cell, where it can act as second messenger
Voltage-gated K^+ channel ("delayed rectifier")	$I_{K(V)}$	Activated by depolarization but more slowly than Na^+ channel; inactivated slowly and not completely if V_m remains depolarized	Intra- and extracellular TEA, amino pyridines	Carries current that rapidly repolarizes the membrane to terminate an AP
Ca^{2+}-dependent K^+ channel	$I_{K(Ca)}$	Activated by depolarization plus elevated cytoplasmic [Ca^{2+}]; remains open as long as cytoplasmic [Ca^{2+}] is higher than normal	Extracellular TEA	Carries current that repolarizes the cell following APs based on either Na^+ or Ca^{2+} and that balances I_{Ca}, thus limiting depolarization by I_{Ca}



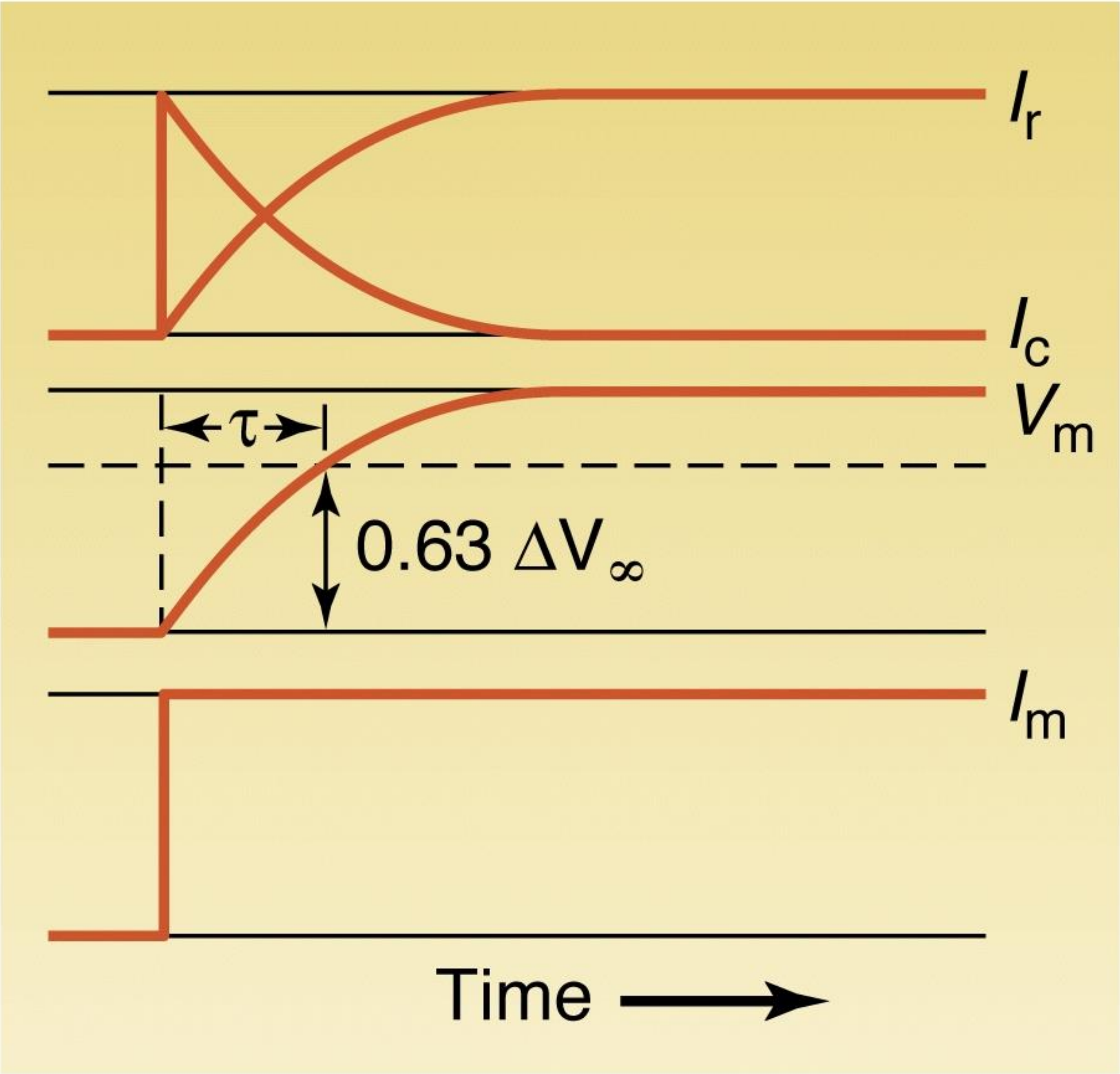
Extracellular fluid
I_c
I_r
+
−
5 nm
Lipid core (capacitance)
Ion channel (conductance)
Cytosol


Equal +, –
Equal +, –
Equal +, –
Cytosol
Membrane
Extracellular fluid

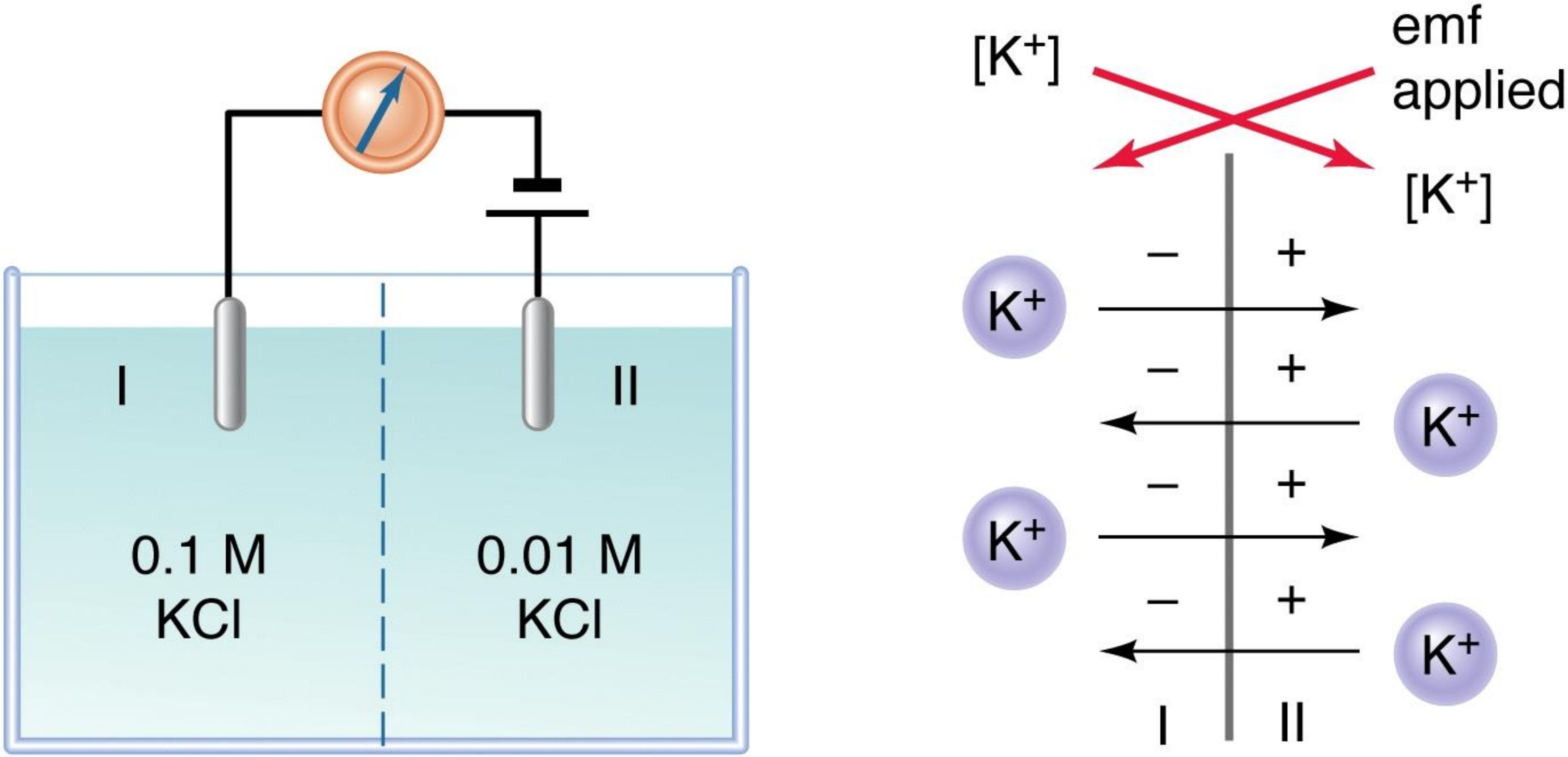
(a)



(b)



(c)



The Nernst equation is generally considered for ions across a membrane generating an electromotive force as commonly shown as:

$$V = \frac{RT}{zF} \cdot ln \frac{[X]_{out}}{[X]_{in}}$$

X = ion of interest
V = equilibrium voltage for the X ion across the membrane
R = gas constant [8.314 J/(mol•K)]
T = absolute temperature [Kelvin]
Z = valence of the ion
F = Faraday's constant [9.649 × 104 C/mol]

For the K^+ ion at 20°C and transformation of ln to $\log_{10}$ along with filling in the constants, one arrives at:

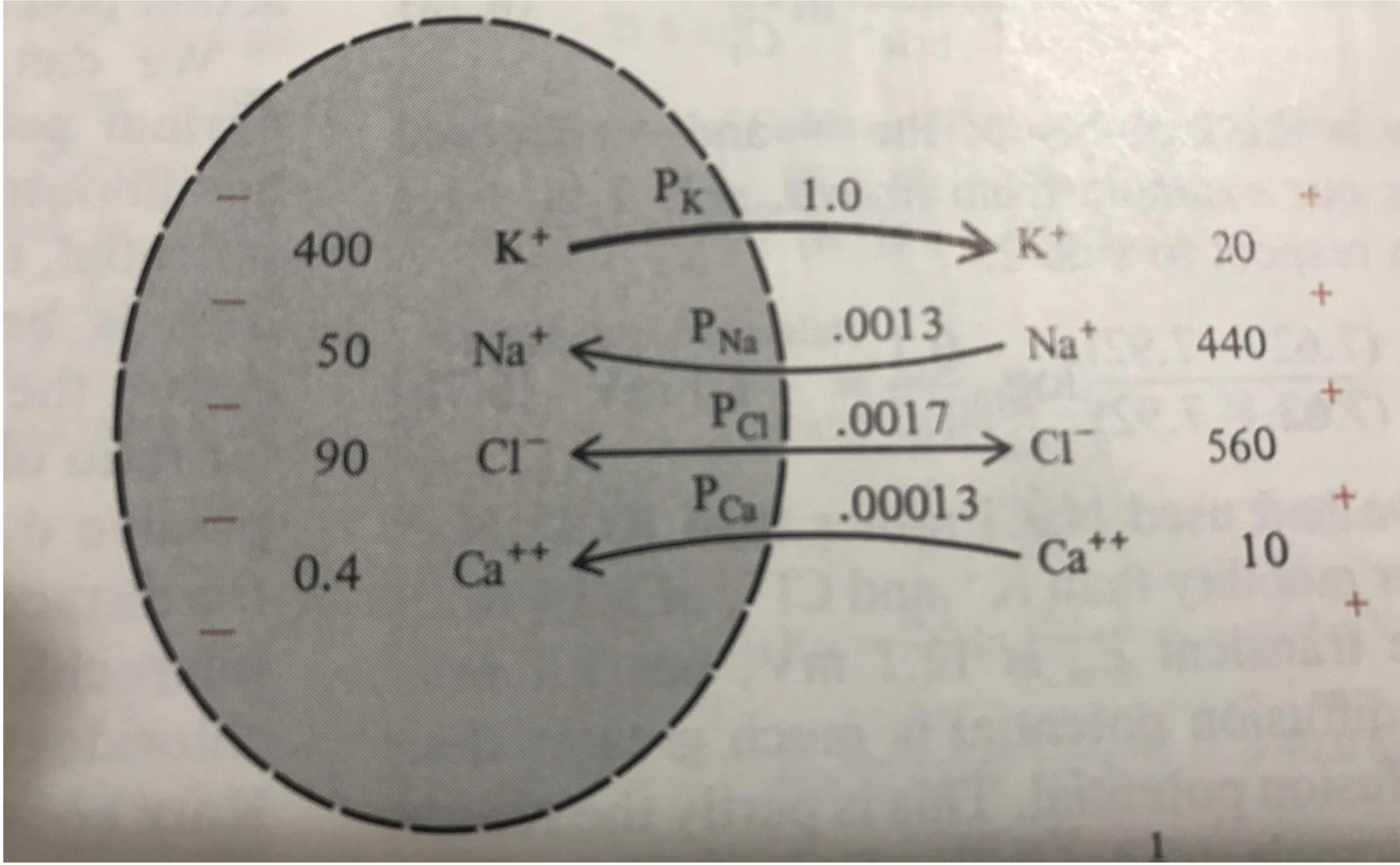
$$Potential = 58 \, log \frac{[K]_{out}}{[K]_{in}}$$

Here is a generalized G-H-K equation for Na^+, K^+, and Cl^- ions:

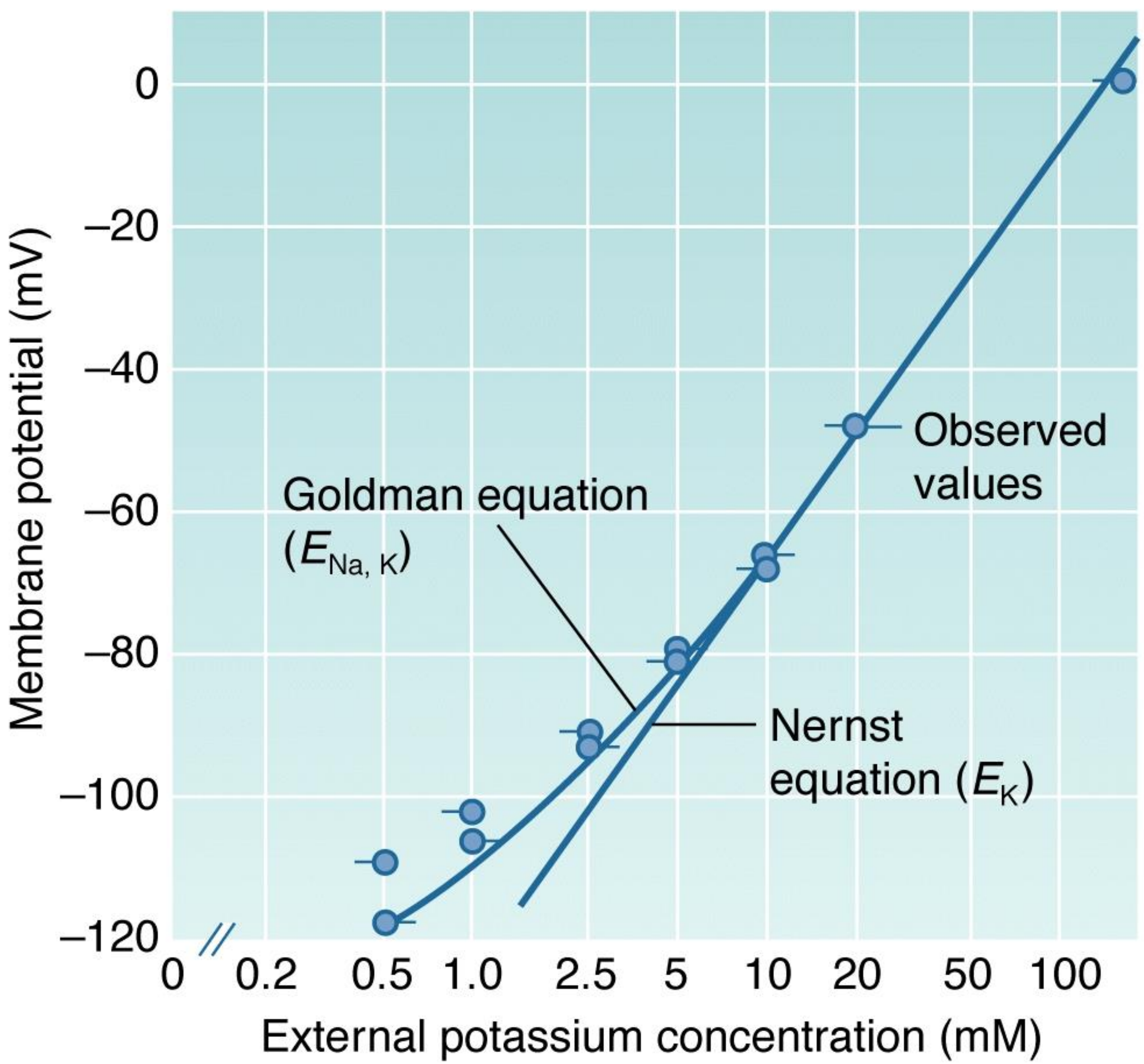
Goldman-Hodgkin-Katz (G-H-K) equation,

$$Em_{K,Na,Cl} = \frac{RT}{F} ln \frac{P_{Na^+}[Na^+]_{out} + P_{K^+}[K^+]_{out} + PCl[Cl]in}{P_{Na^+}[Na^+]_{in} + P_{K^+}[K^+]_{in} + PCl[Cl]out}$$

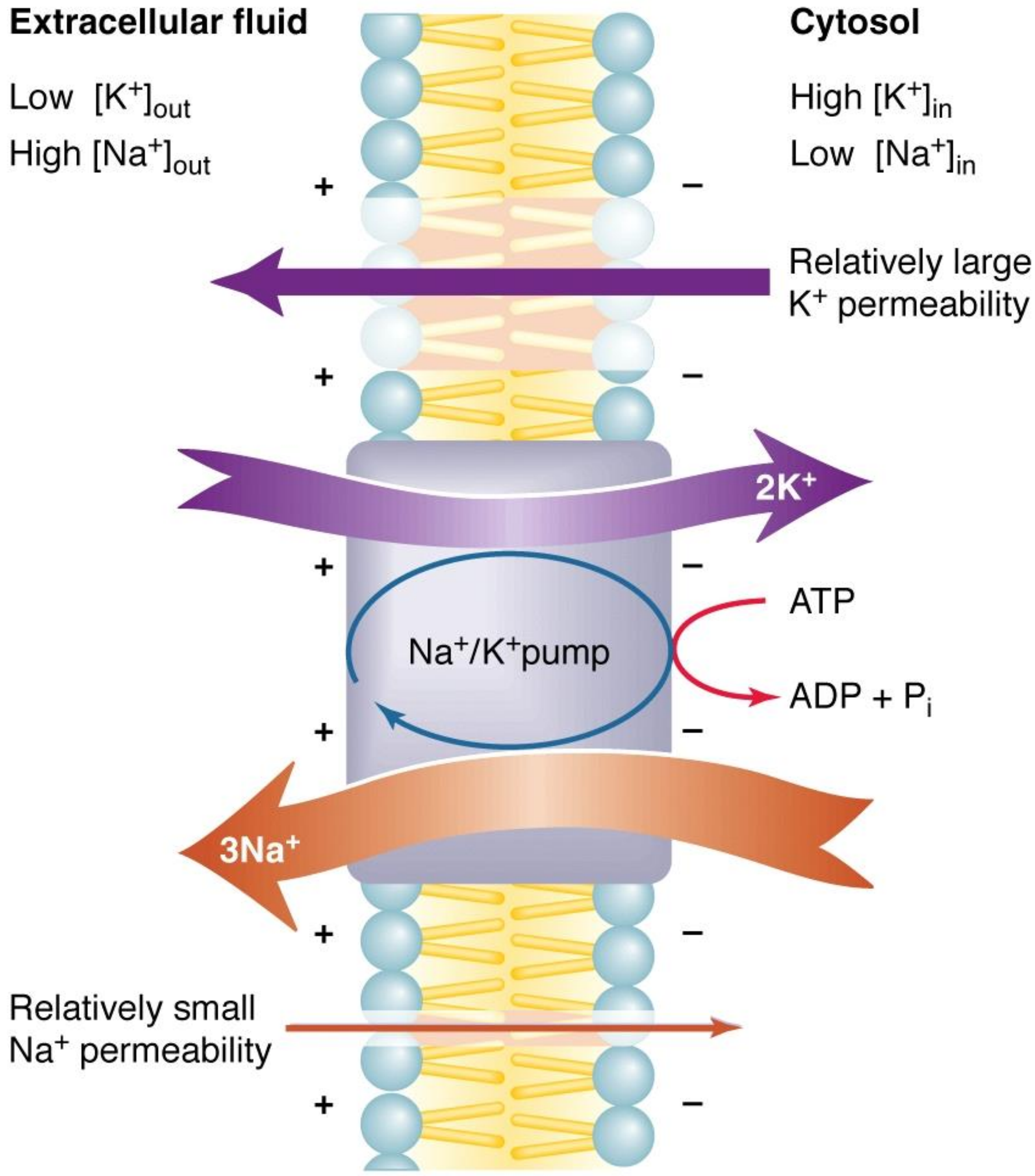
Squid neuron



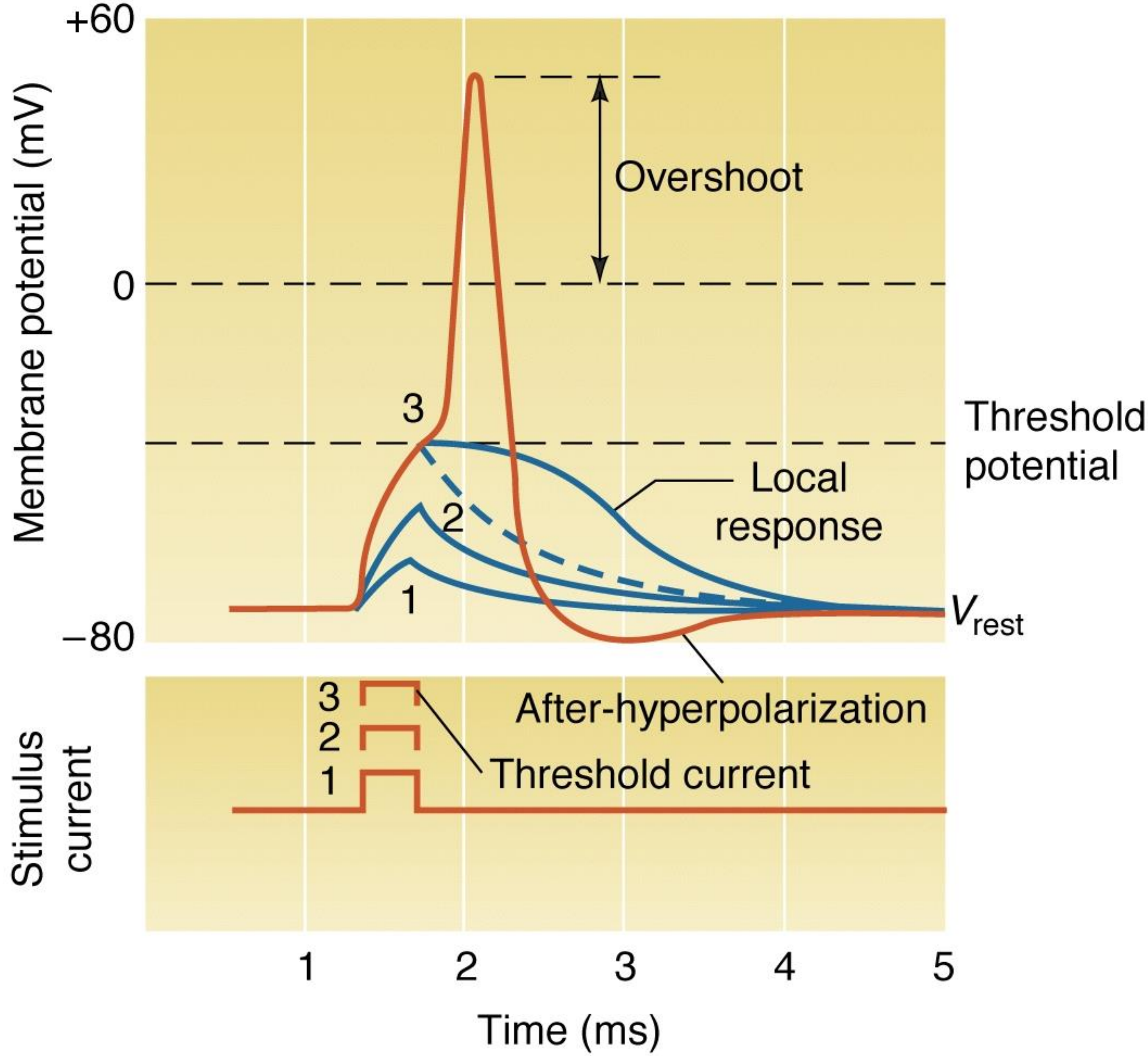
(b)



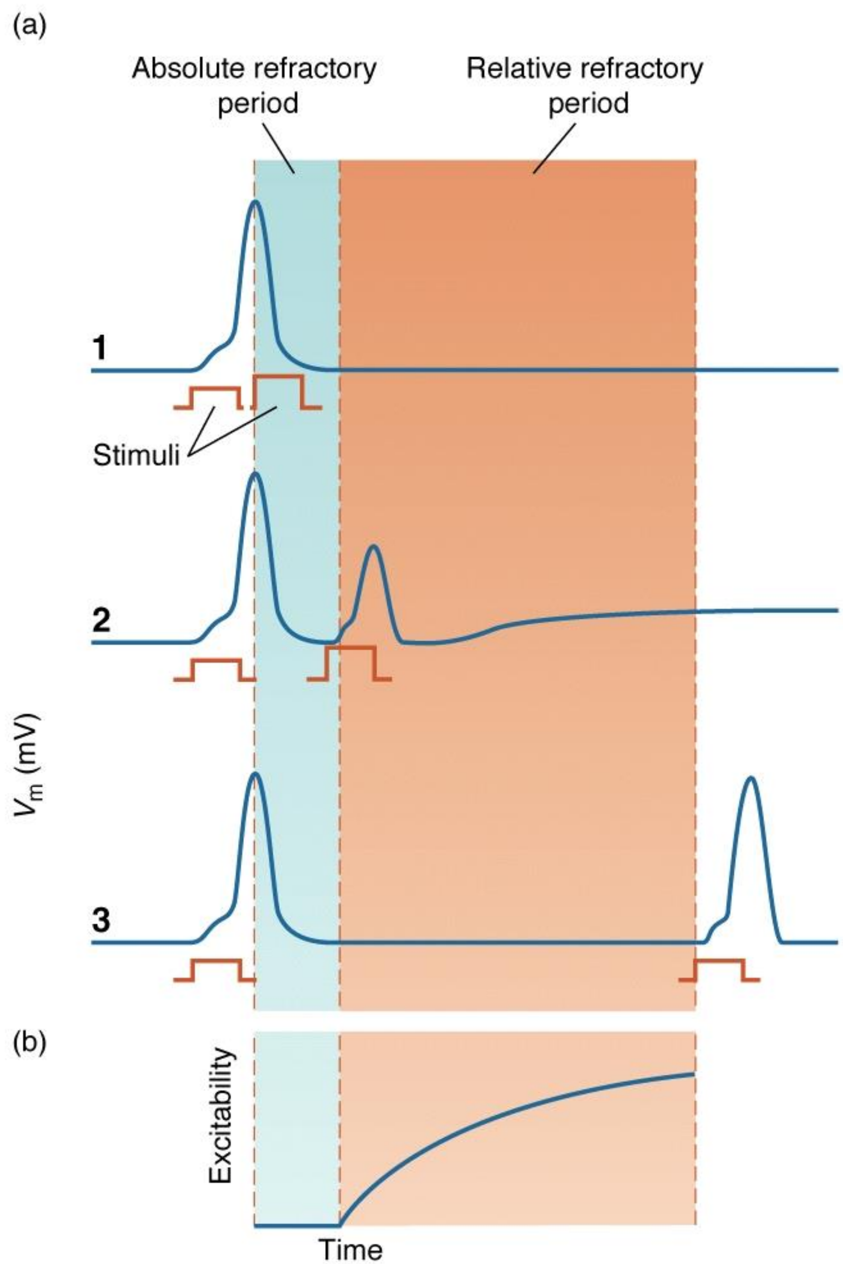
Membrane potential (mV)
0
–20
–40
–60
–80
–100
–120
0
0.2
0.5
1.0
2.5
5
10
20
50
100
External potassium concentration (mM)
Observed values
Goldman equation ($E_{Na, K}$)
Nernst equation (E_K)



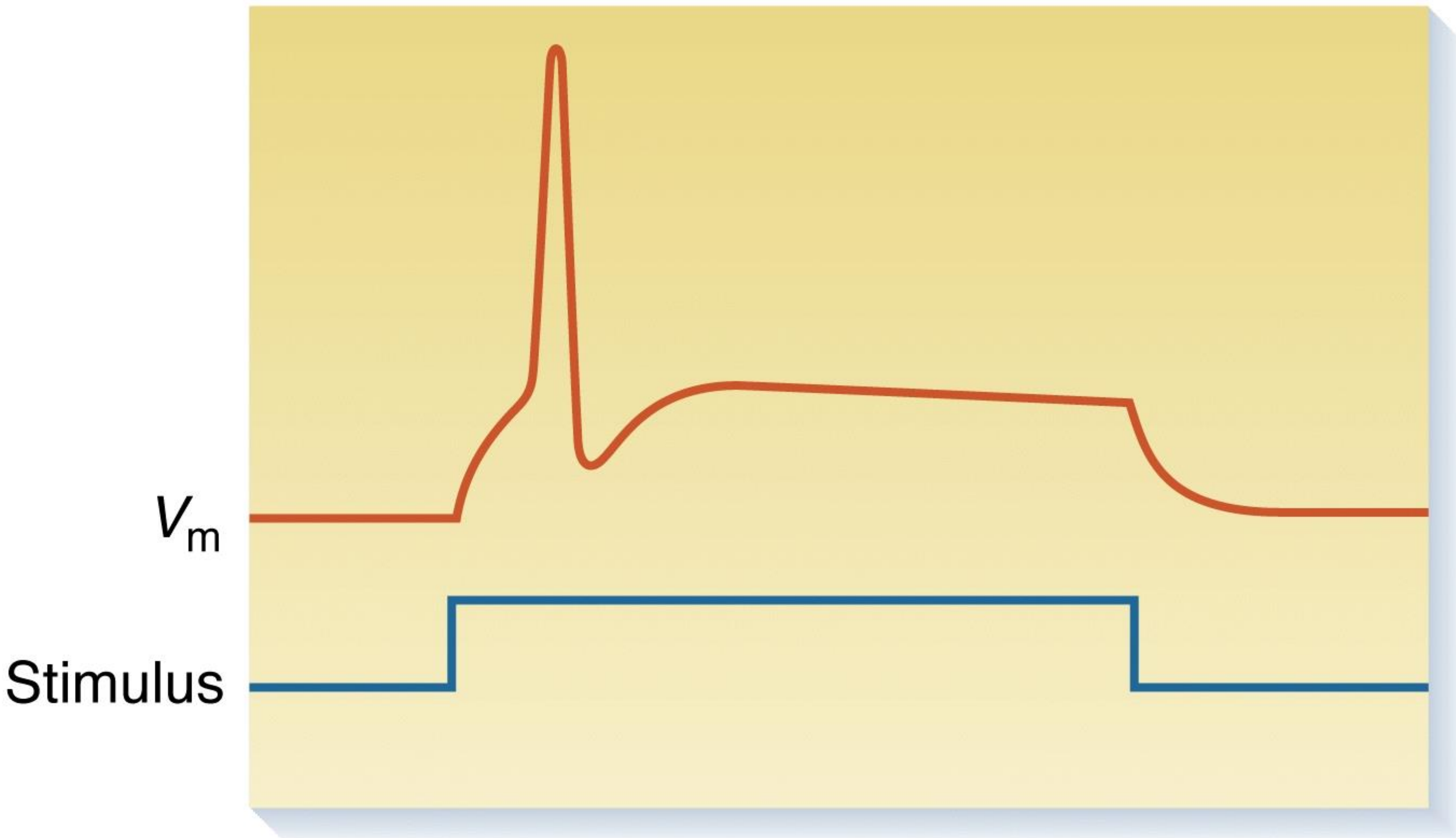
Extracellular fluid
Low [K+]out
High [Na+]out
Cytosol
High [K+]in
Low [Na+]in
Relatively large K+ permeability
2K+
ATP
Na+/K+pump
ADP + Pi
3Na+
Relatively small Na+ permeability



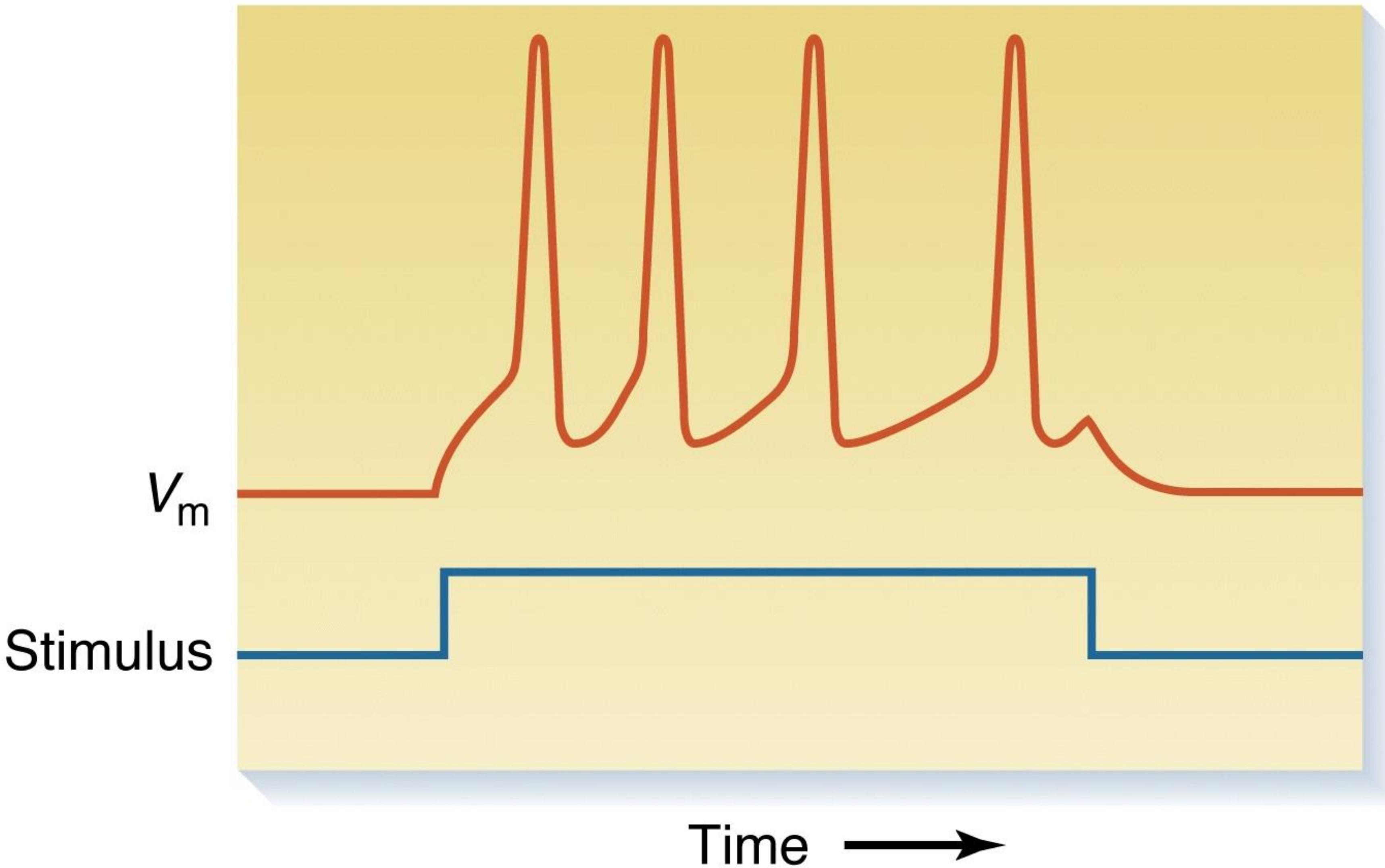
+60
0
−80
Membrane potential (mV)
Overshoot
Threshold potential
Local response
3
2
1
V_{rest}
After-hyperpolarization
Stimulus current
3
2
1
Threshold current
1
2
3
4
5
Time (ms)

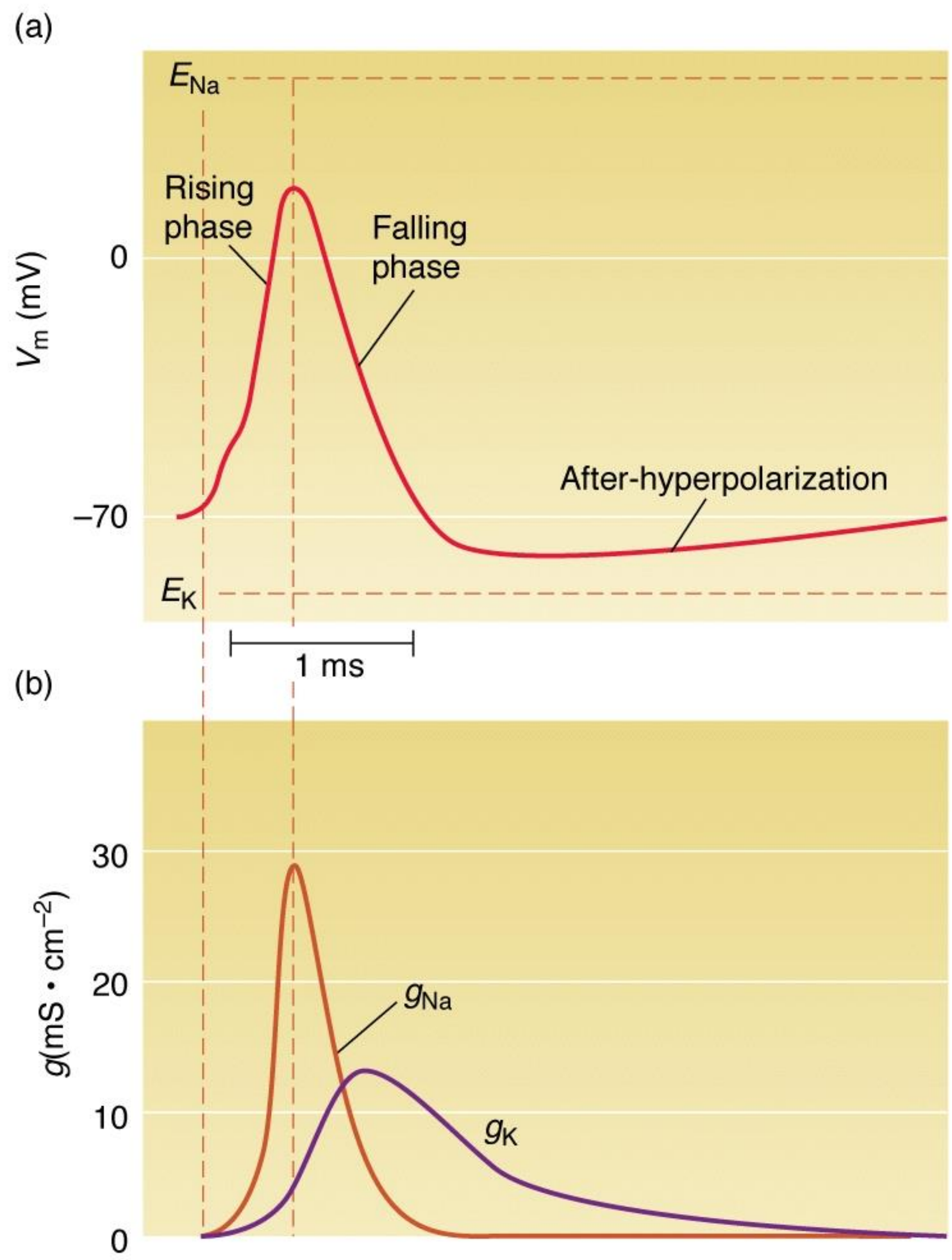

(a)
Absolute refractory period
Relative refractory period
1
Stimuli
2
V_m (mV)
3
(b)
Excitability
Time

(a) Phasic response



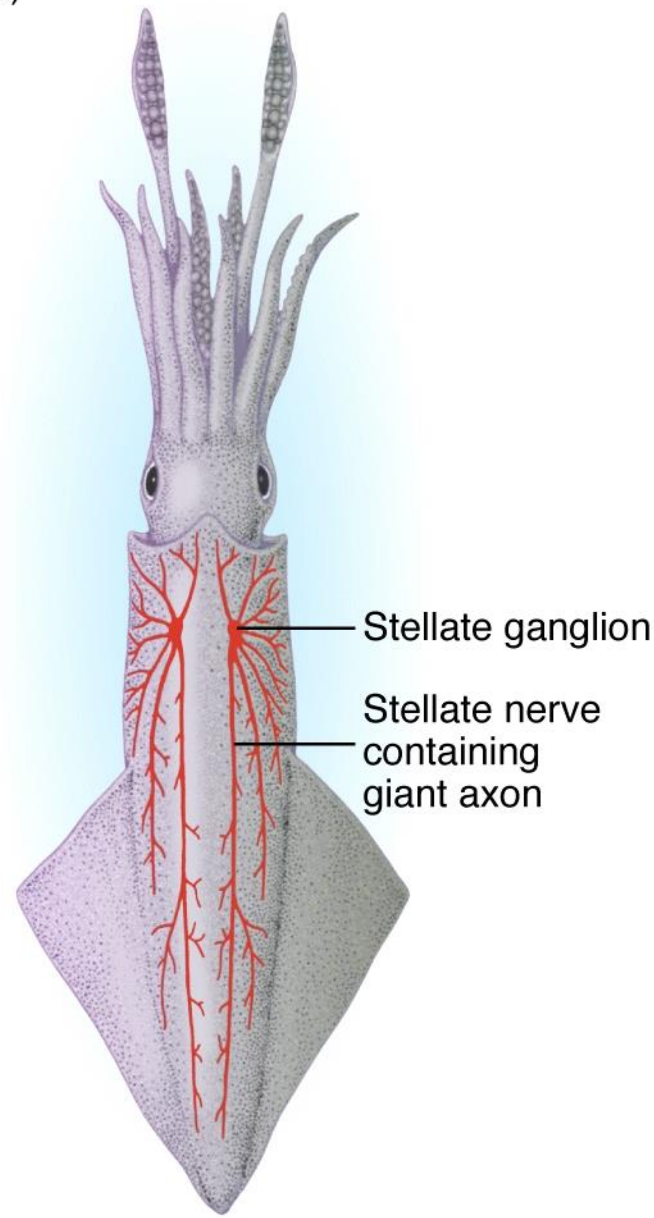
(b) Tonic response

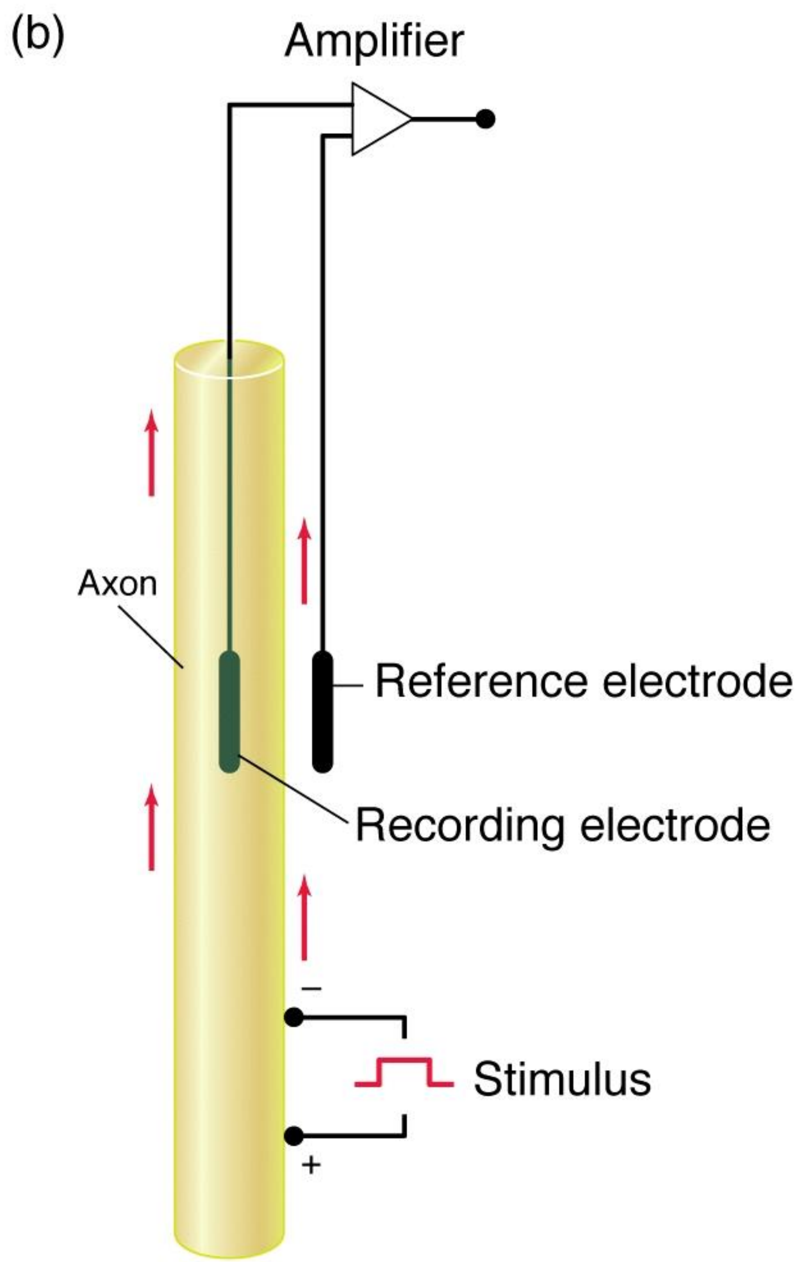


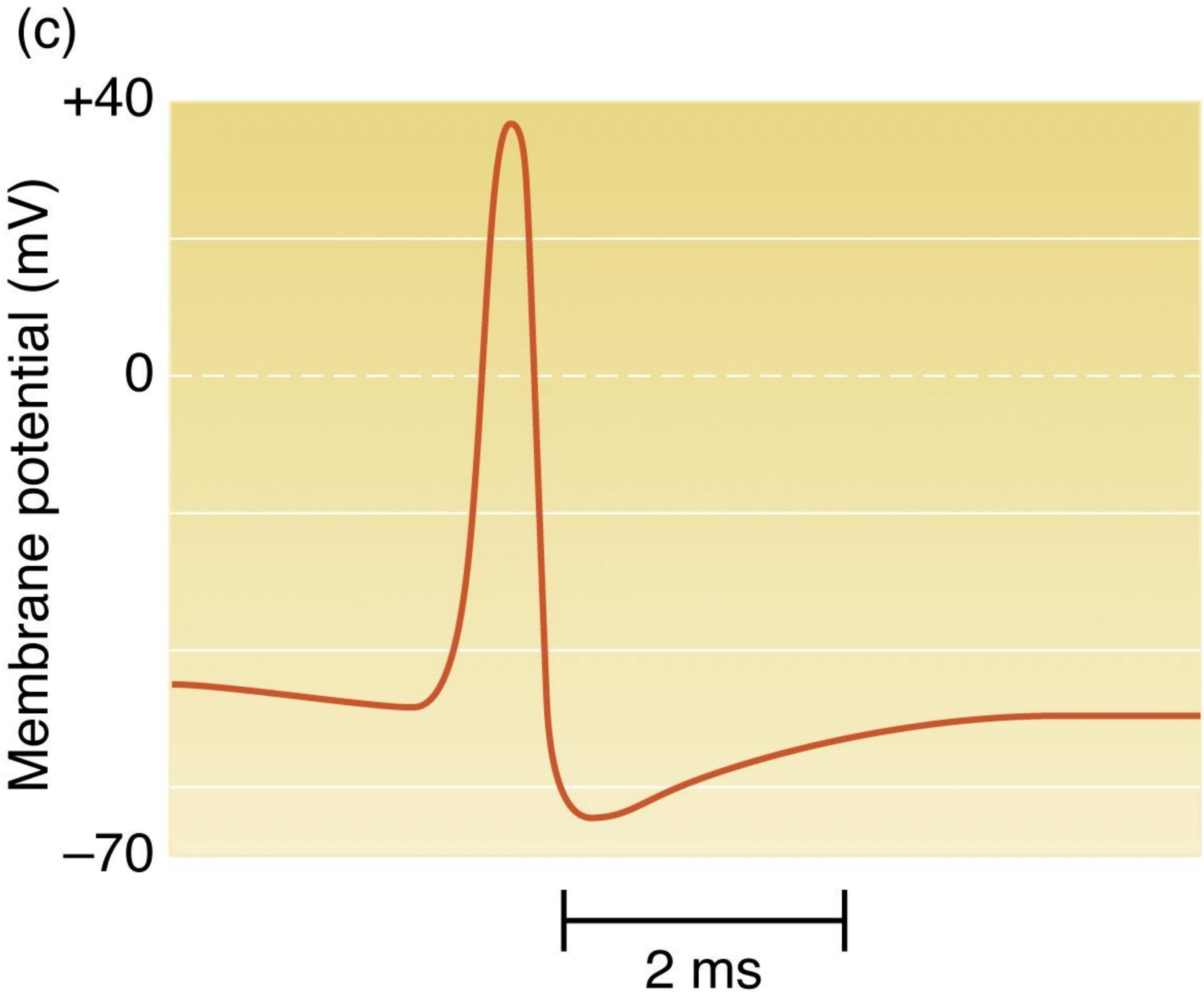


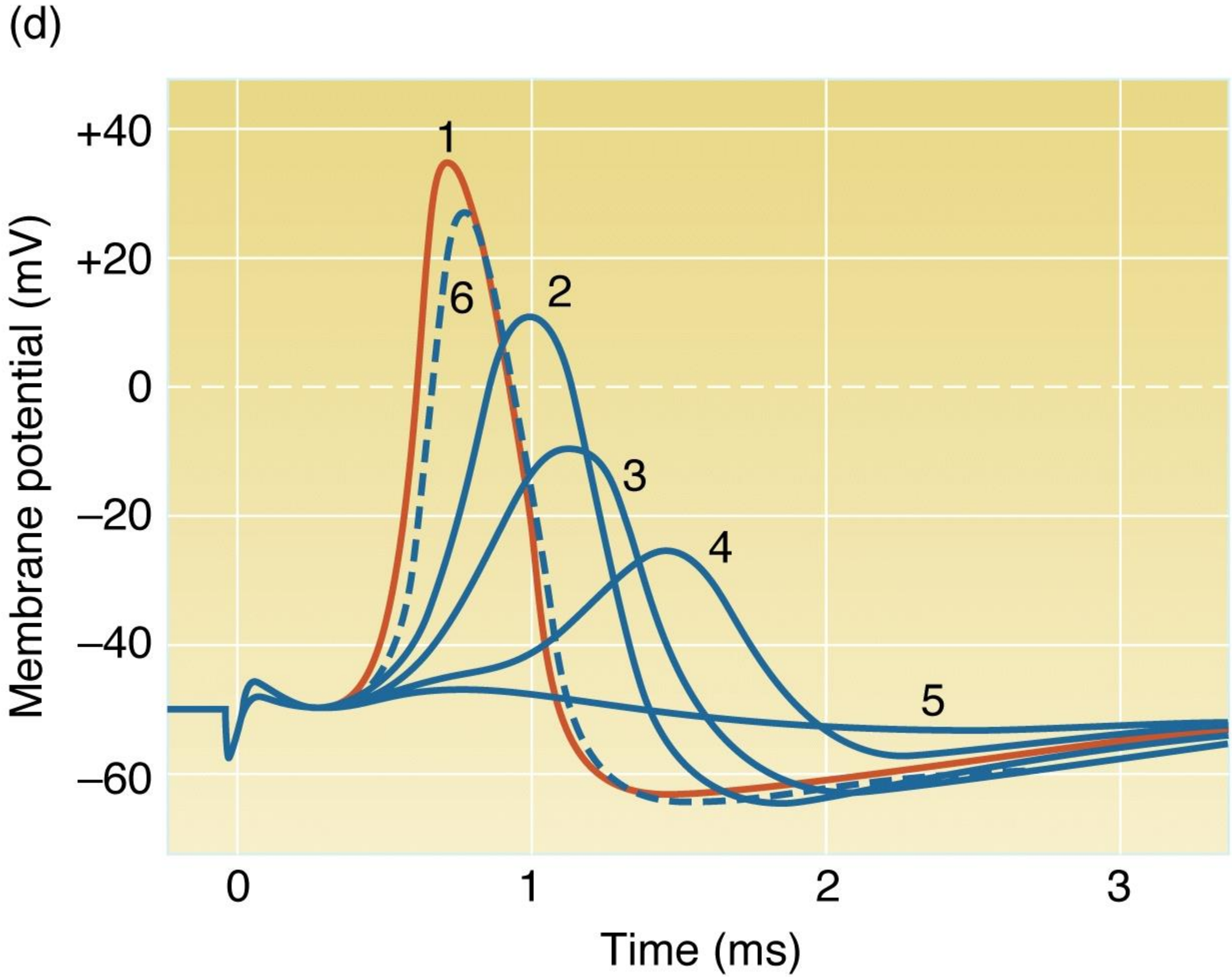
(a)
E_{Na}
Rising phase
Falling phase
0
V_m (mV)
After-hyperpolarization
–70
E_K
1 ms
(b)
30
20
10
0
g(mS • cm^{-2})
g_{Na}
g_K

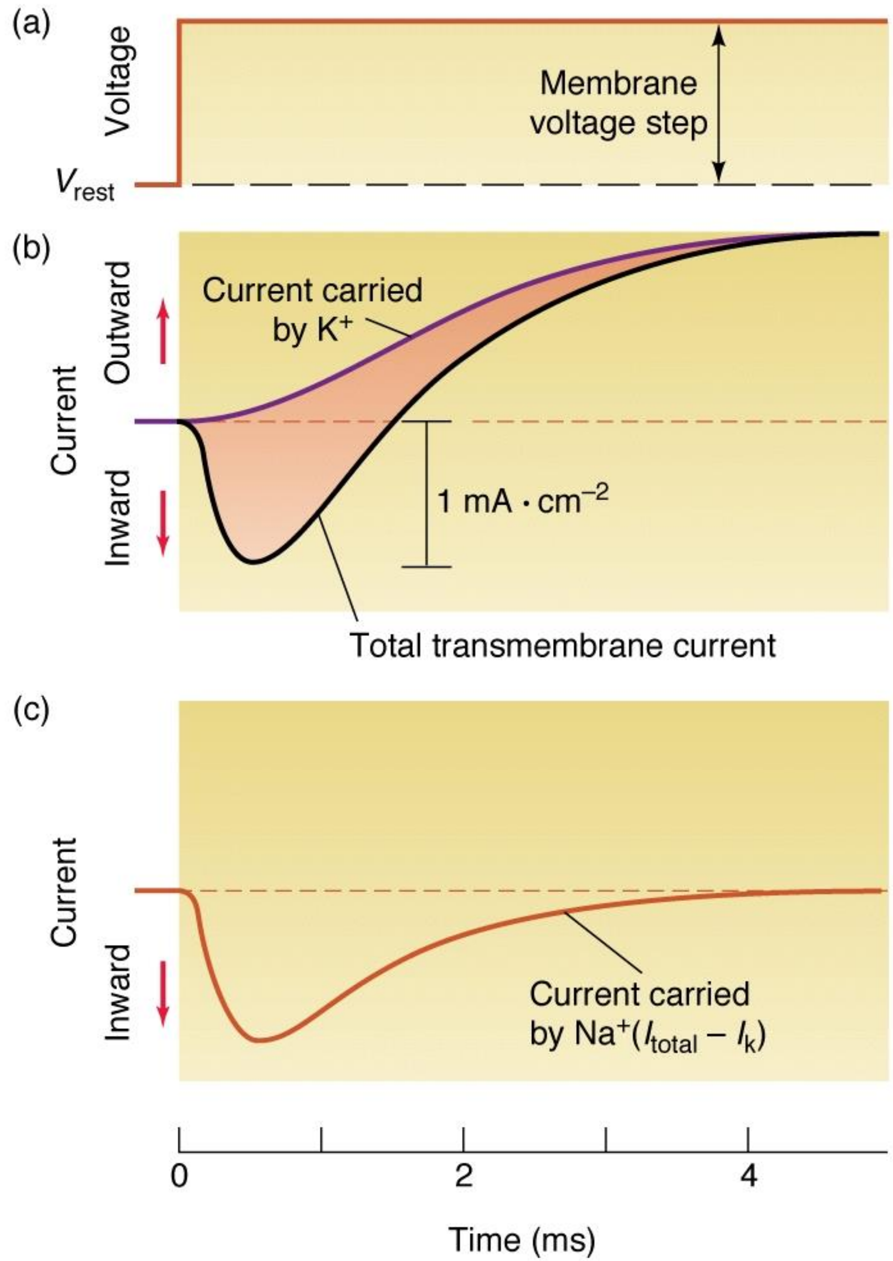
(a)



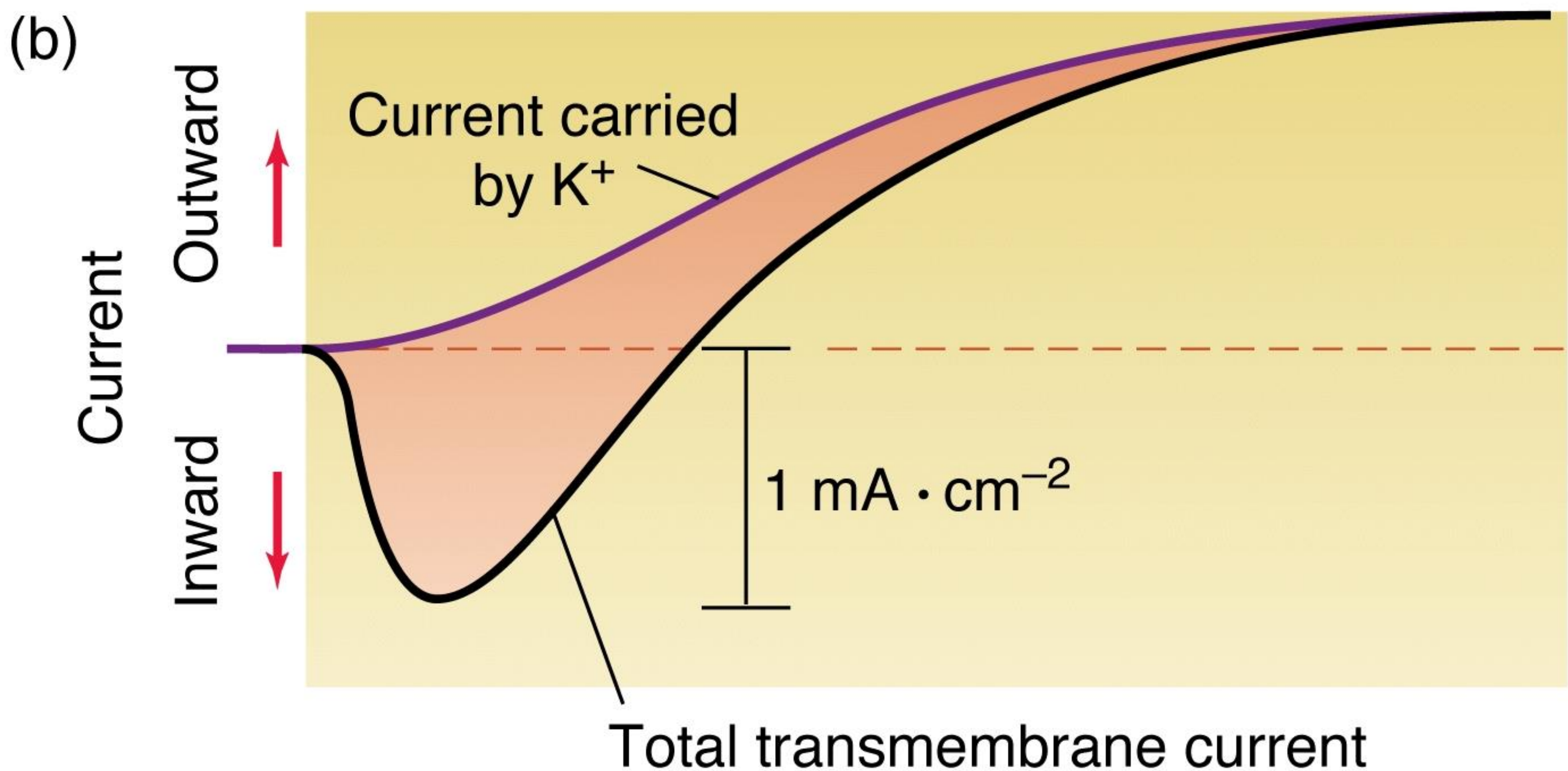

(b)
Amplifier
Axon
Reference electrode
Recording electrode
–
Stimulus
+


(c)
+40
0
–70
Membrane potential (mV)
2 ms

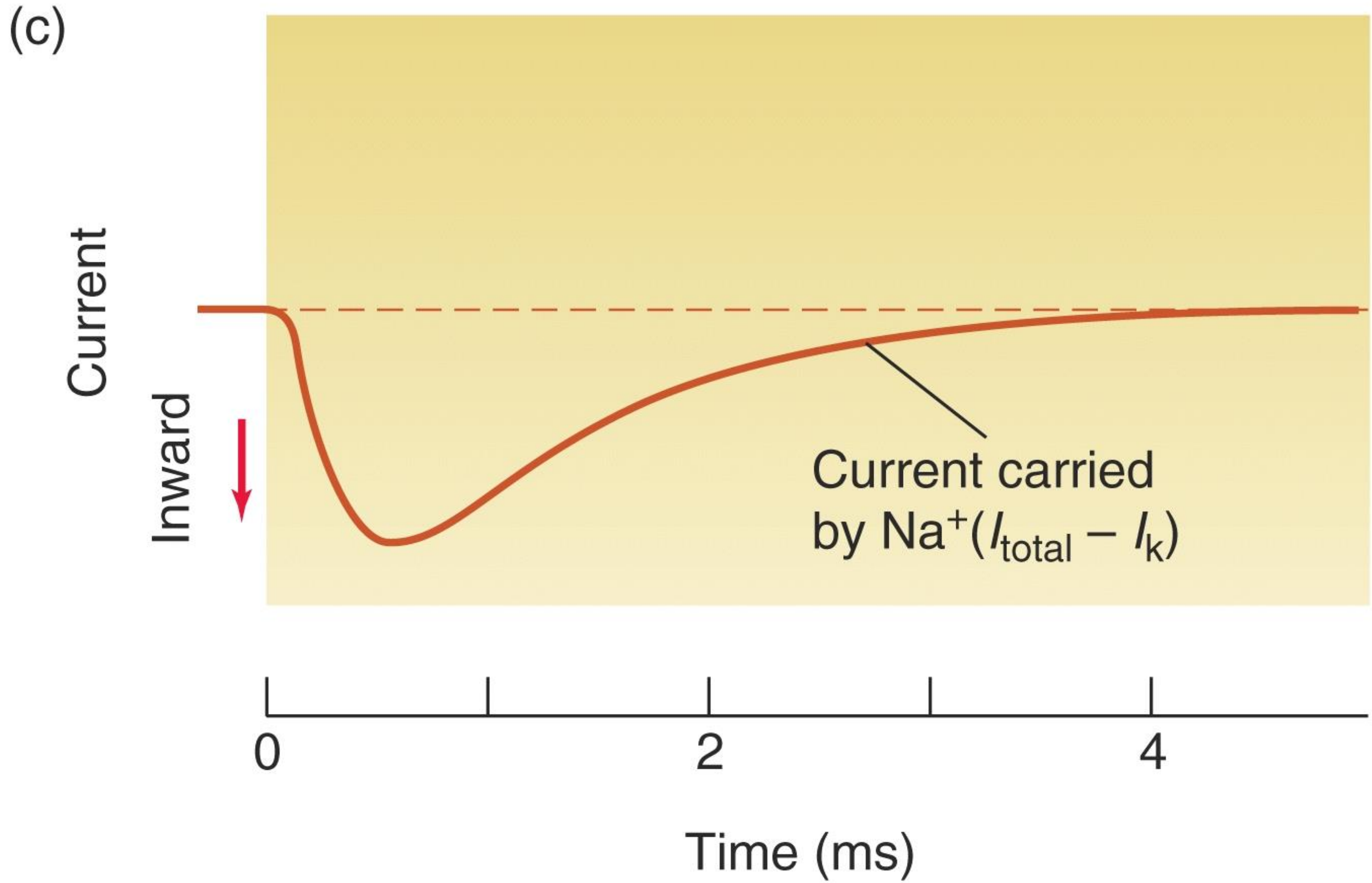

(d)
+40
+20
0
–20
–40
–60
Membrane potential (mV)
1
2
3
4
5
6
0
1
2
3
Time (ms)


(a)
Voltage
Membrane
voltage step
V_{rest}
(b)
Current
Outward
Inward
Current carried
by K^+
1 mA · cm^{-2}
Total transmembrane current
(c)
Current
Inward
Current carried
by $Na^+(I_{total} - I_k)$
0
2
4
Time (ms)


(a)
Voltage
Membrane
voltage step
V_{rest}

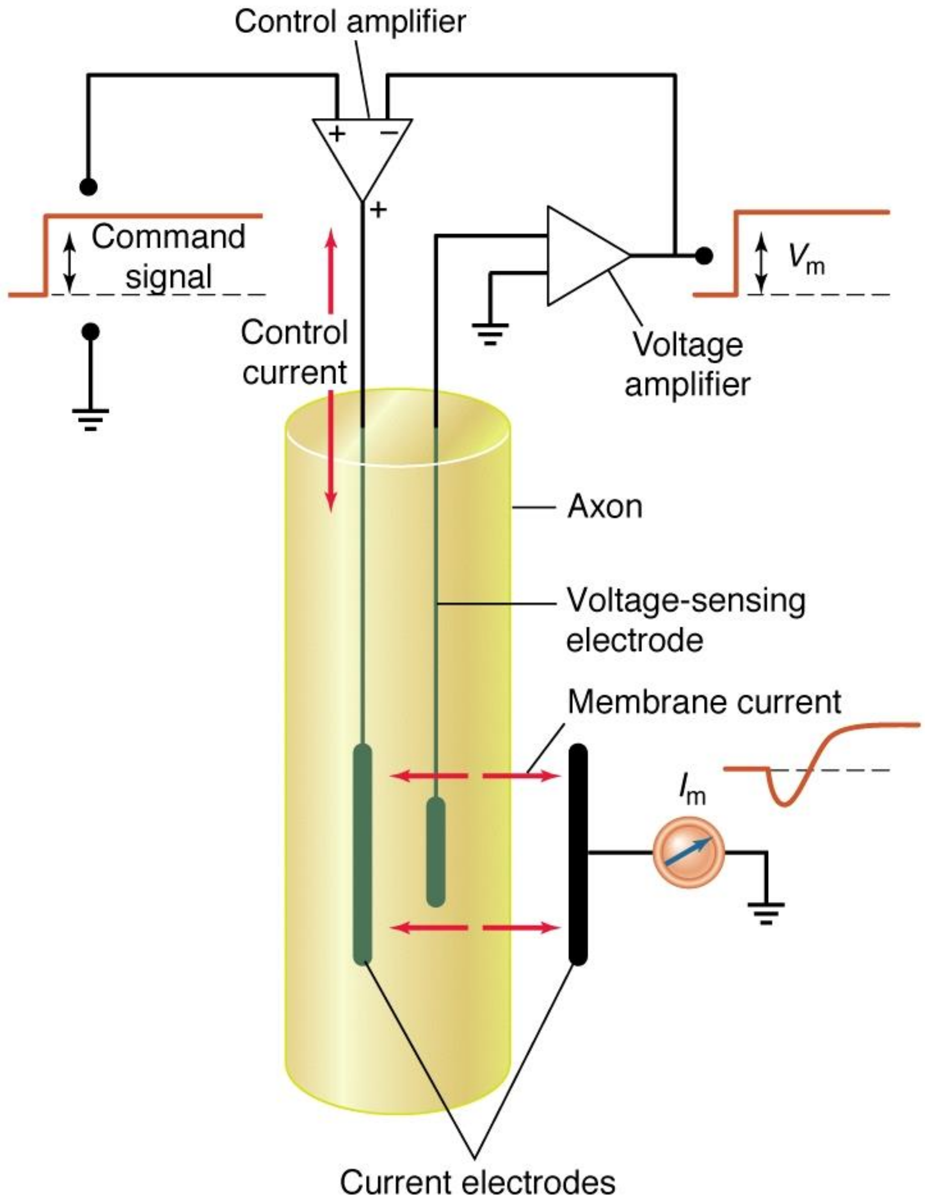


(b)
Current
Outward
Inward
Current carried
by K+
1 mA · cm−2
Total transmembrane current

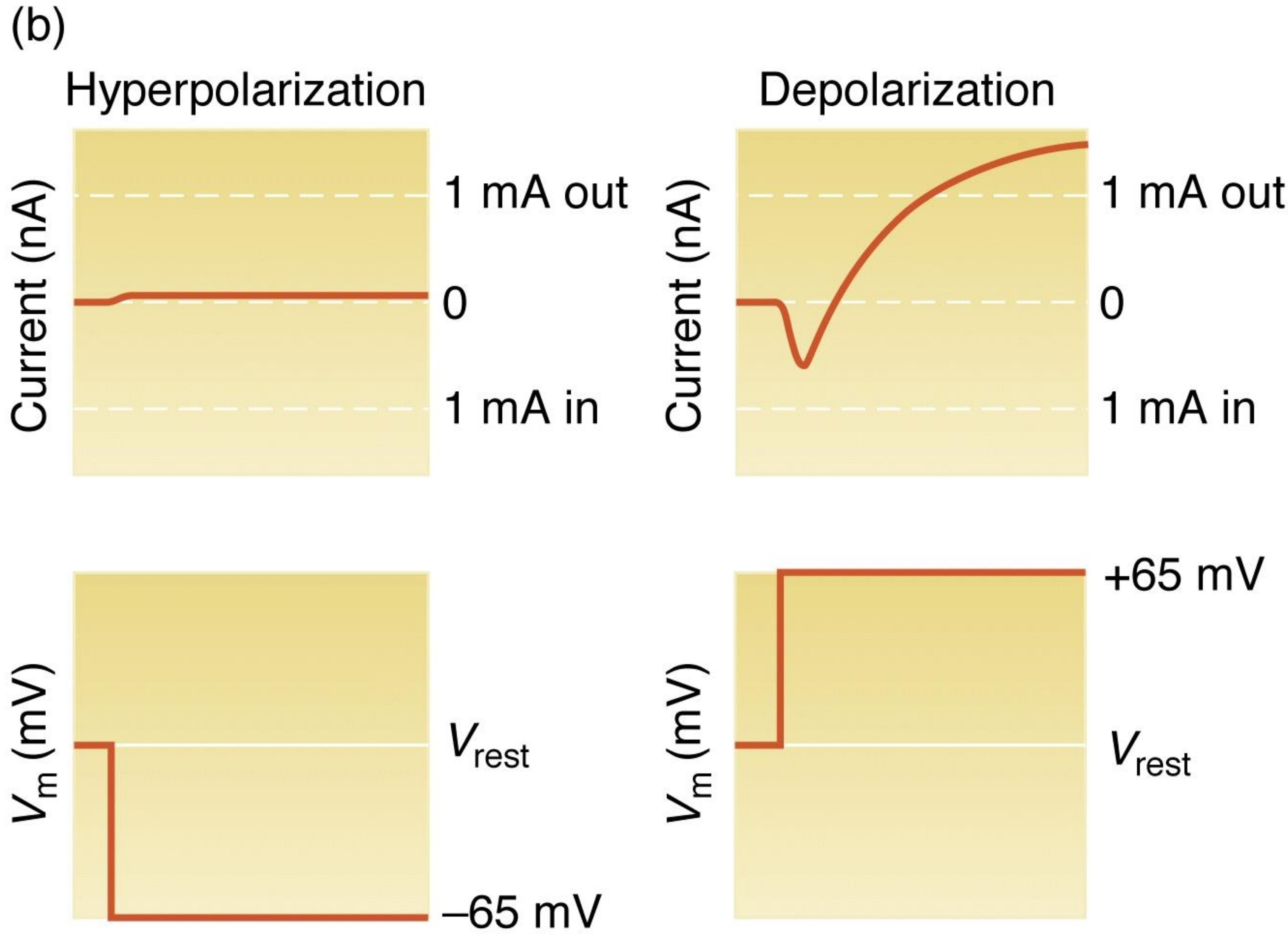


(c)
Current
Inward
Current carried
by $Na^+(I_{total} - I_k)$
0
2
4
Time (ms)

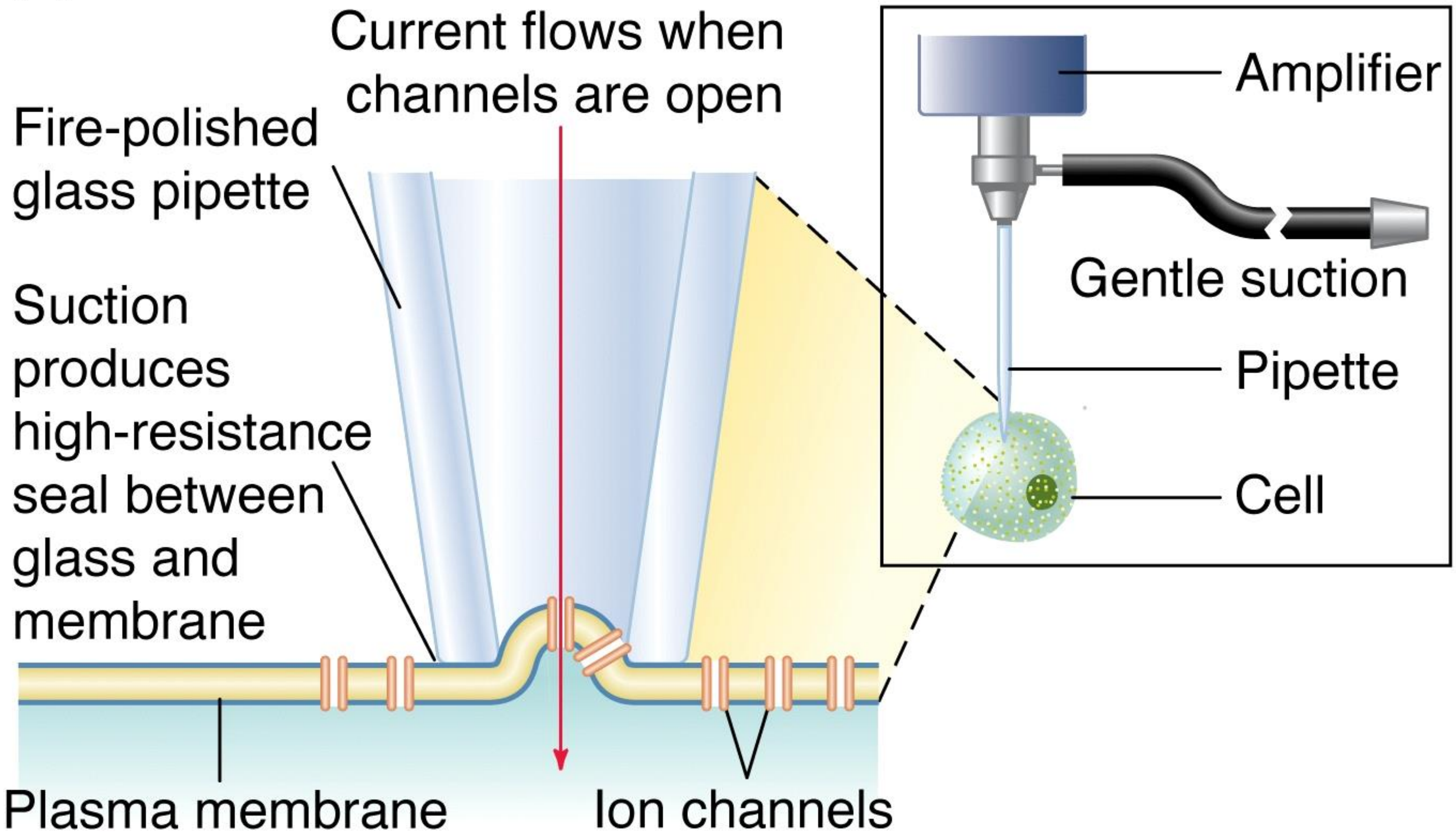
(a)



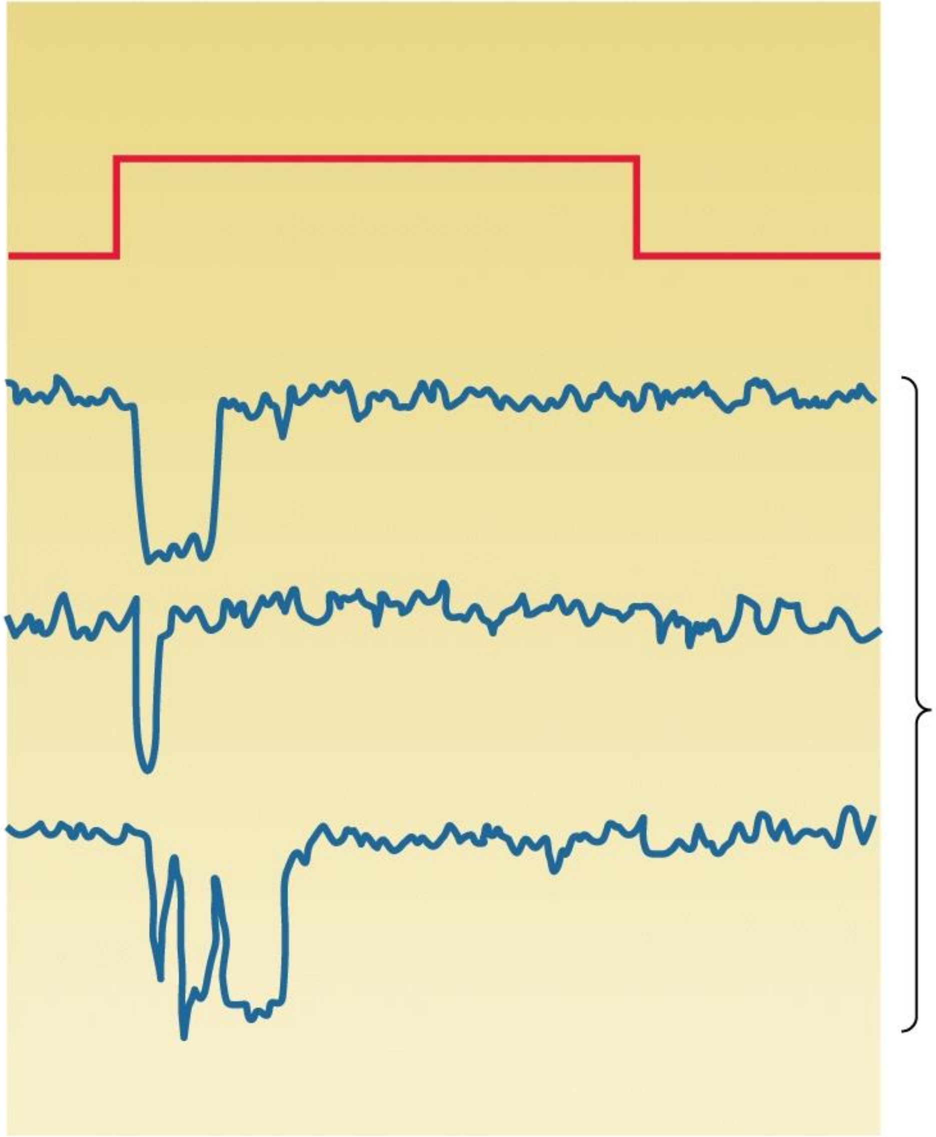
Control amplifier
+
−
+
Command
signal
Control
current
Vm
Voltage
amplifier
Axon
Voltage-sensing
electrode
Membrane current
Im
Current electrodes


(b)
Hyperpolarization
Depolarization
Current (nA)
1 mA out
0
1 mA in
Current (nA)
1 mA out
0
1 mA in
Vm (mV)
Vrest
–65 mV
Vm (mV)
+65 mV
Vrest

(a)

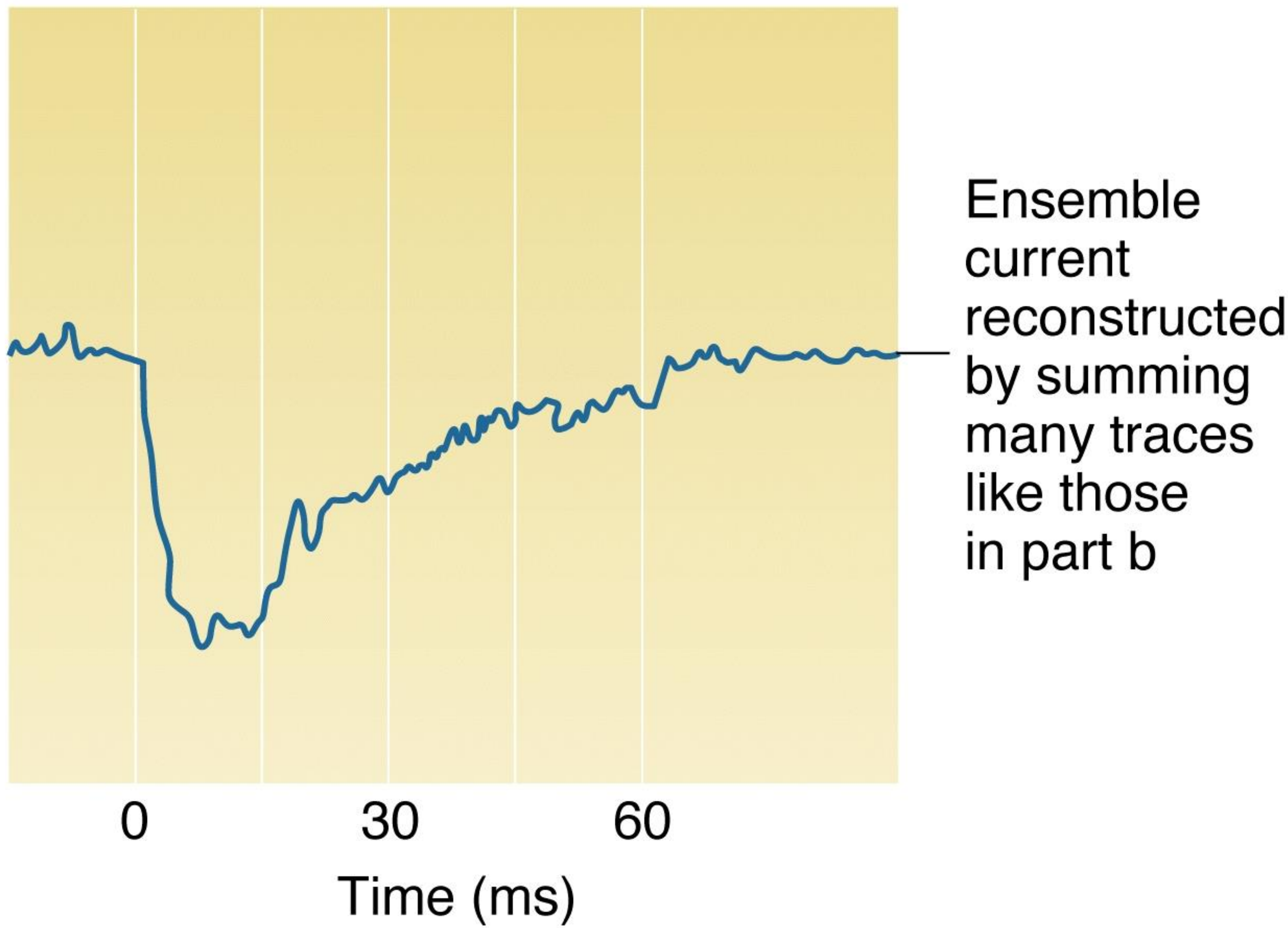

Current flows when channels are open
Fire-polished glass pipette
Suction produces high-resistance seal between glass and membrane
Plasma membrane
Ion channels
Amplifier
Gentle suction
Pipette
Cell

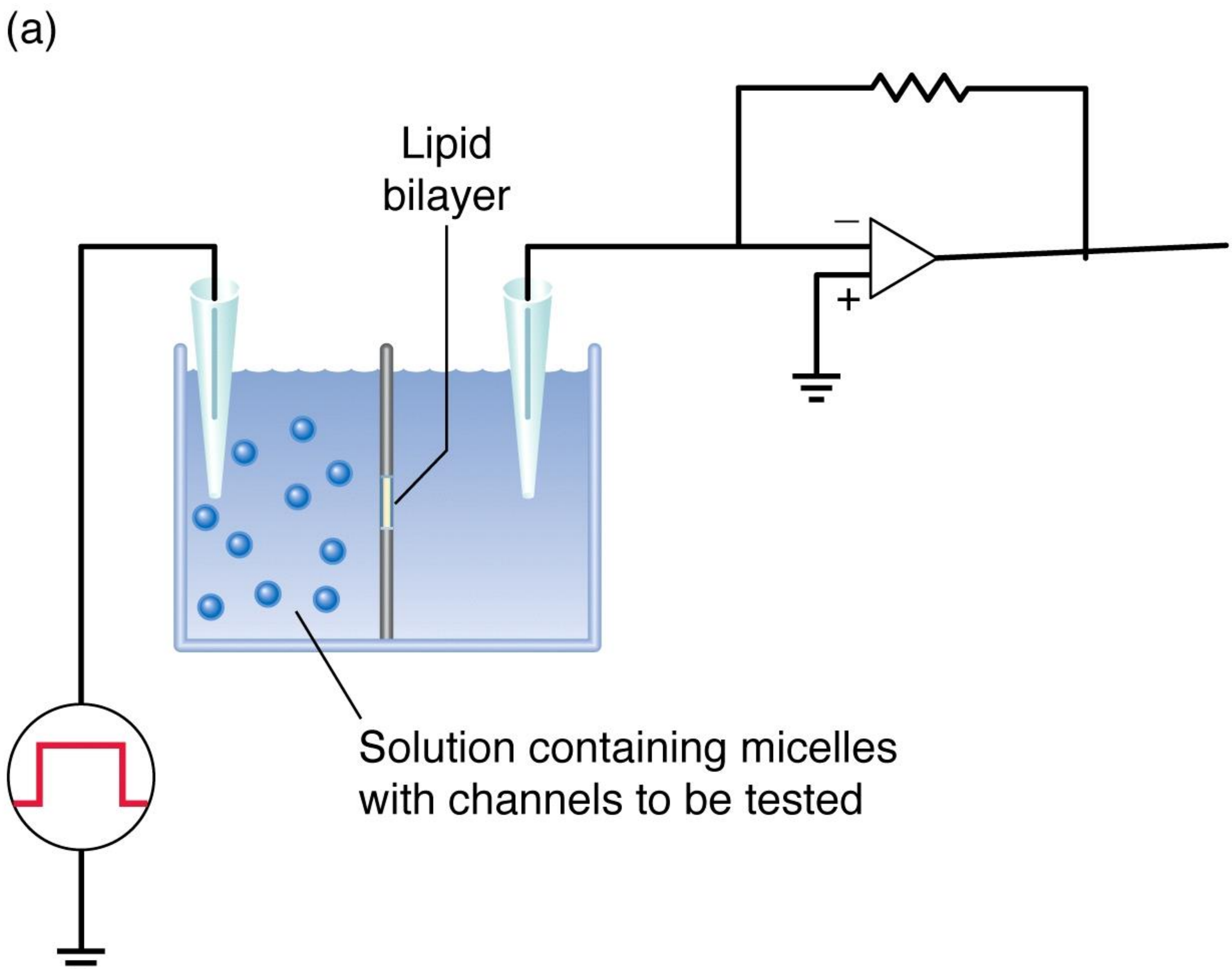
(b)



Individual traces showing unitary Na^+ currents during channel openings

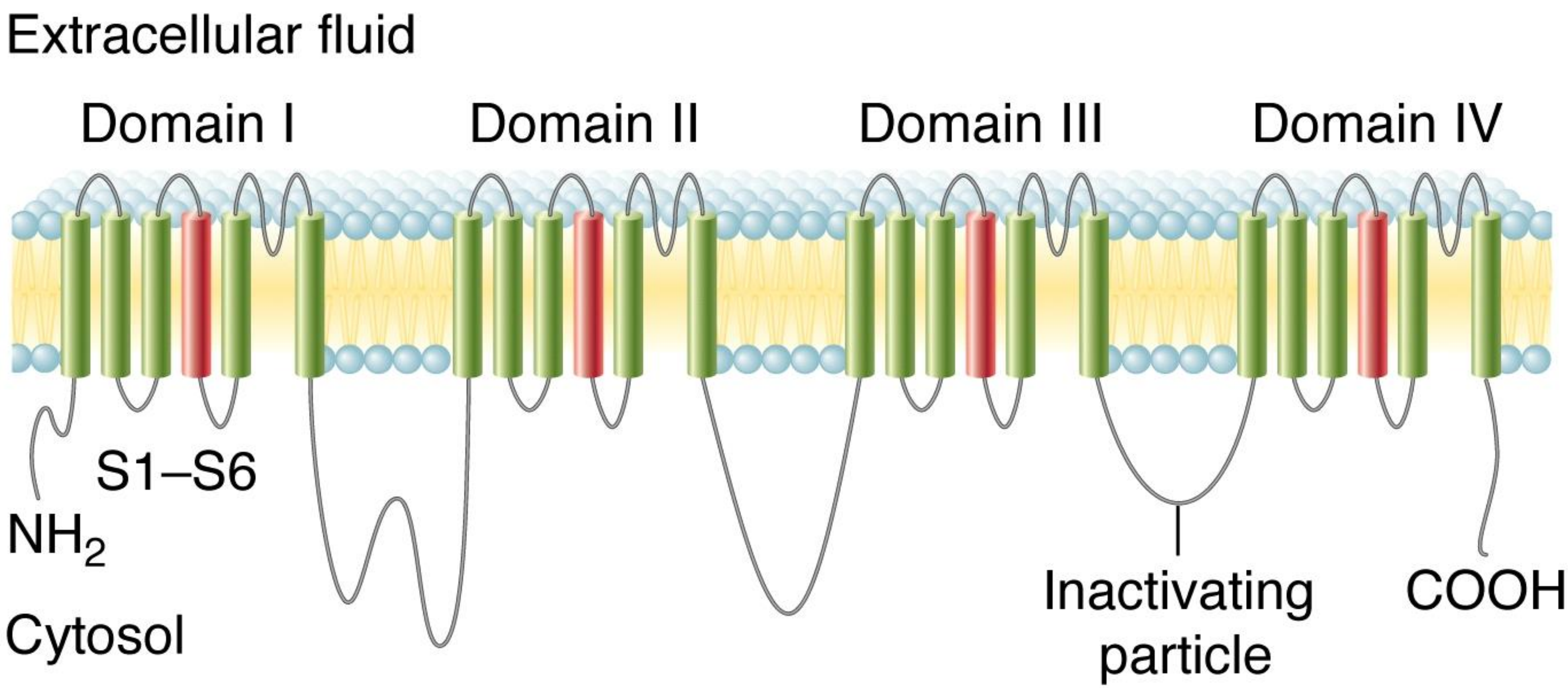
(c)


Ensemble current reconstructed by summing many traces like those in part b
0
30
60
Time (ms)


(a)
Lipid
bilayer
–
+
Solution containing micelles
with channels to be tested

(b)

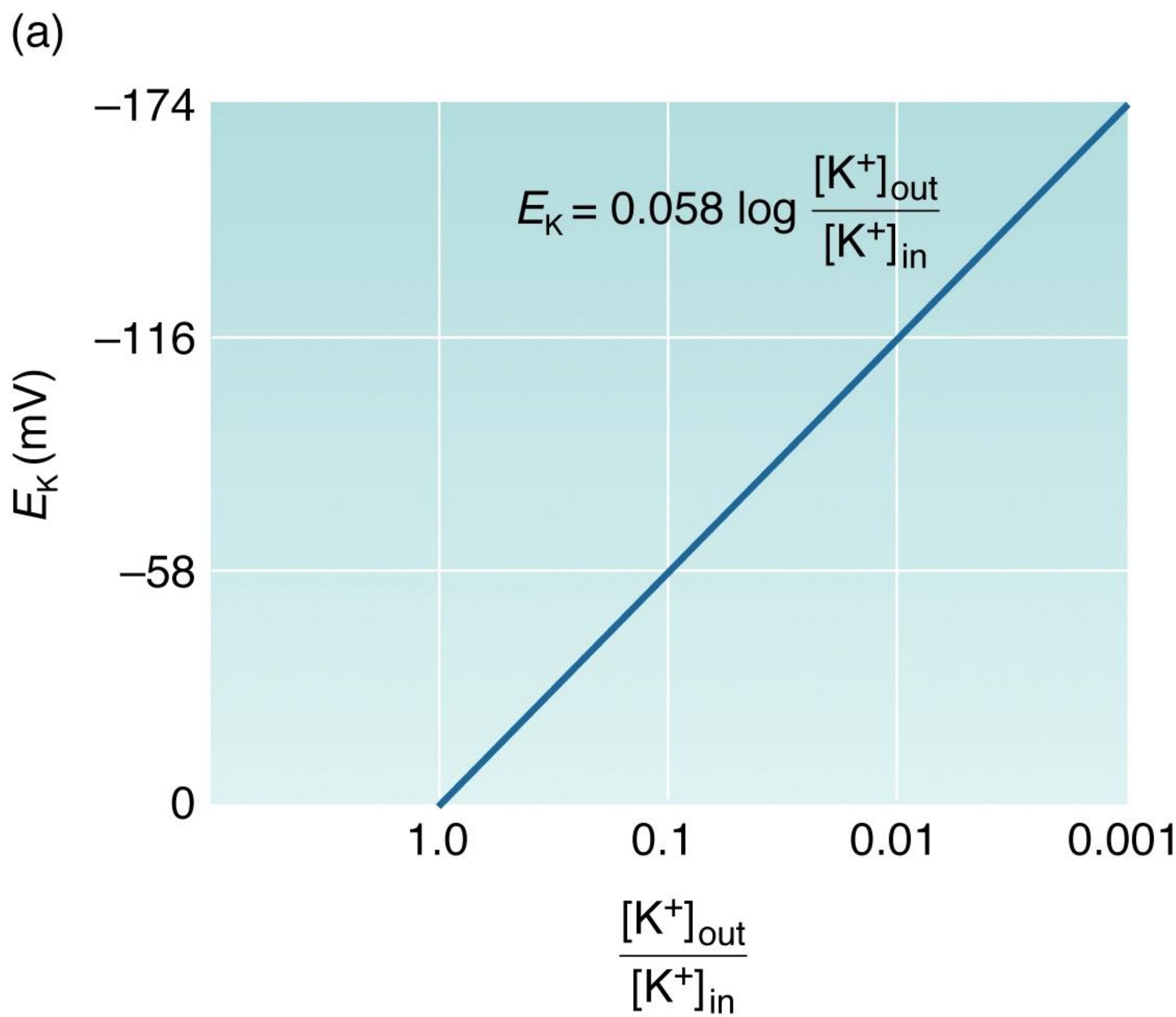
(a)

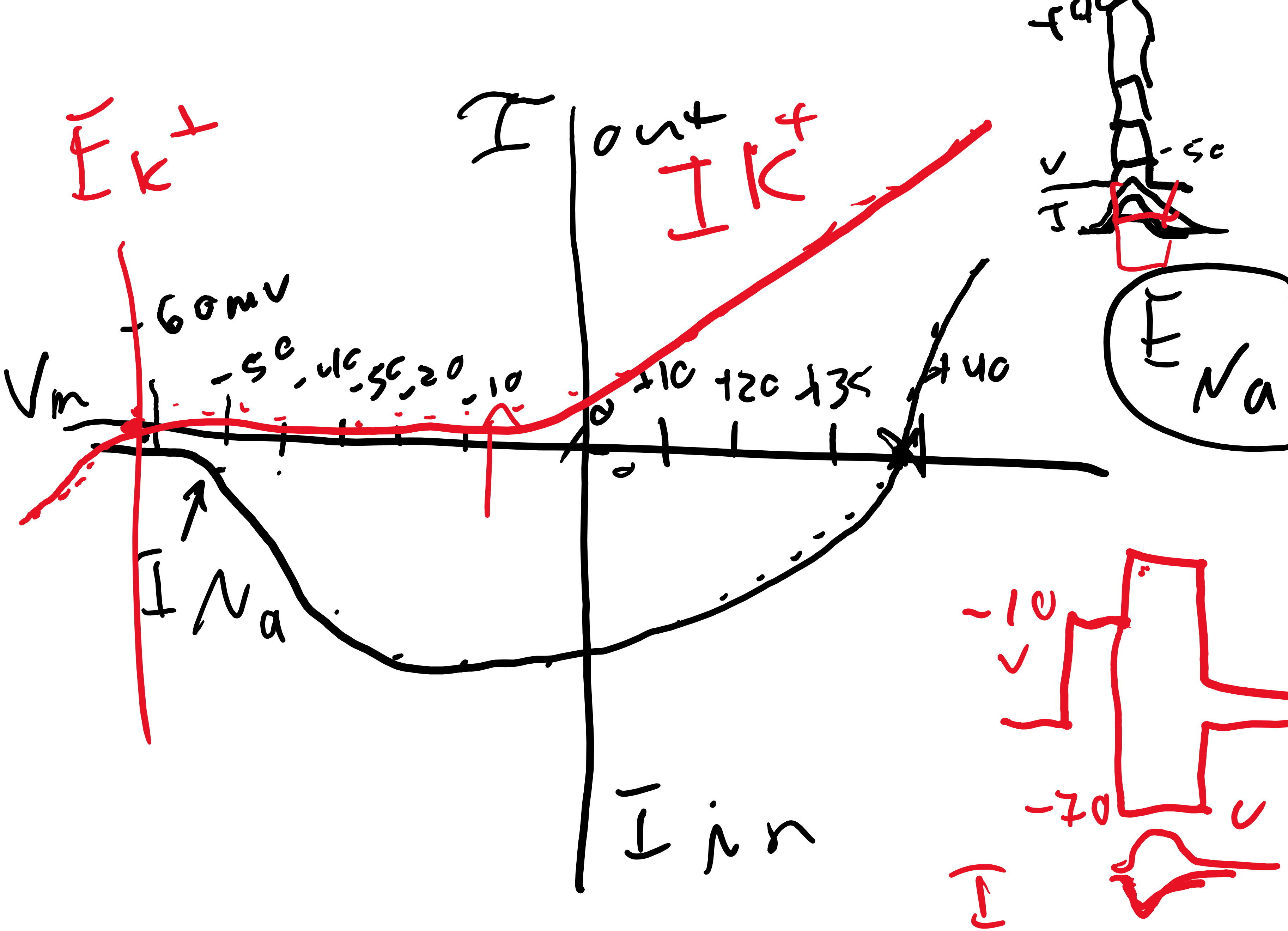

Extracellular fluid
Domain I
Domain II
Domain III
Domain IV
S1–S6
NH2
Cytosol
Inactivating particle
COOH

Nernst equation: 1864 – 1941. **Walther Nernst**

$$E = \frac{RT}{zF} \ln \frac{[\text{ion outside cell}]}{[\text{ion inside cell}]} = 2.3026 \frac{RT}{zF} \log_{10} \frac{[\text{ion outside cell}]}{[\text{ion inside cell}]}.$$

At room temperature (25 °C), $\frac{RT}{F}$ may be treated like a constant and replaced by 25.693 mV for cells.


(a)
–174
–116
–58
0
E_K (mV)
$E_K = 0.058 \log \frac{[K^+]_{out}}{[K^+]_{in}}$
1.0
0.1
0.01
0.001
$\frac{[K^+]_{out}}{[K^+]_{in}}$


I out
I K+
E K+
-60mV
Vm
-50
-40
-35
-20
-10
0
+10
+20
+35
+40
I Na
I in
E Na
-10
V
-70
I

https://www.physiologyweb.com/calculators/ghk_equation_calculator.html