# Bioelectrical Phenomena of the Cell:

## 1: Resting Membrane Potential

# Recap of Basic Concepts
# Forces that determine ions movement

- Electrostatic forces
  - Opposite charges attract
  - Identical charges repel
- Concentration forces
  - Diffusion – movement of ions through semipermeable membrane
  - Osmosis – movement of water from region of high concentration to low

# Selective Permeability of Membranes

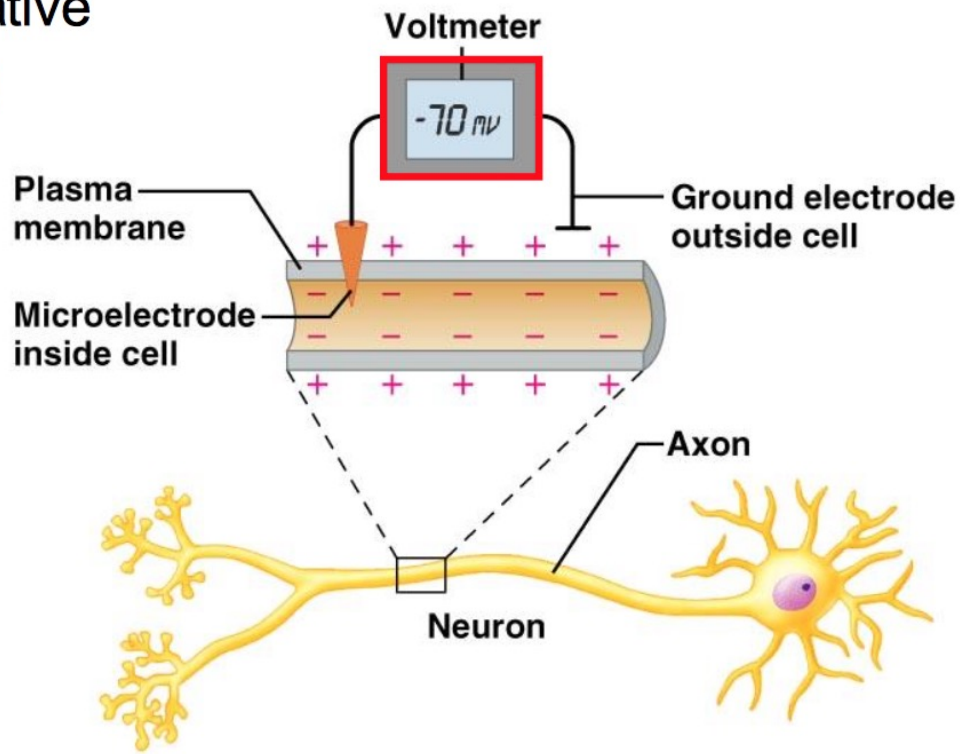
- Some ions permitted to cross more easily than others
- Neuronal membranes contain ion channels
  - Protein tubes that span the membrane
  - Some stay open all the time (nongated)
  - Some open on the occasion of an action potential, causing a change in the permeability of the membrane (gated)

# Resting Membrane Potential

- A constant potential difference across the resting cell membrane

The basic signaling properties of neurons are influenced by changes in the resting potential

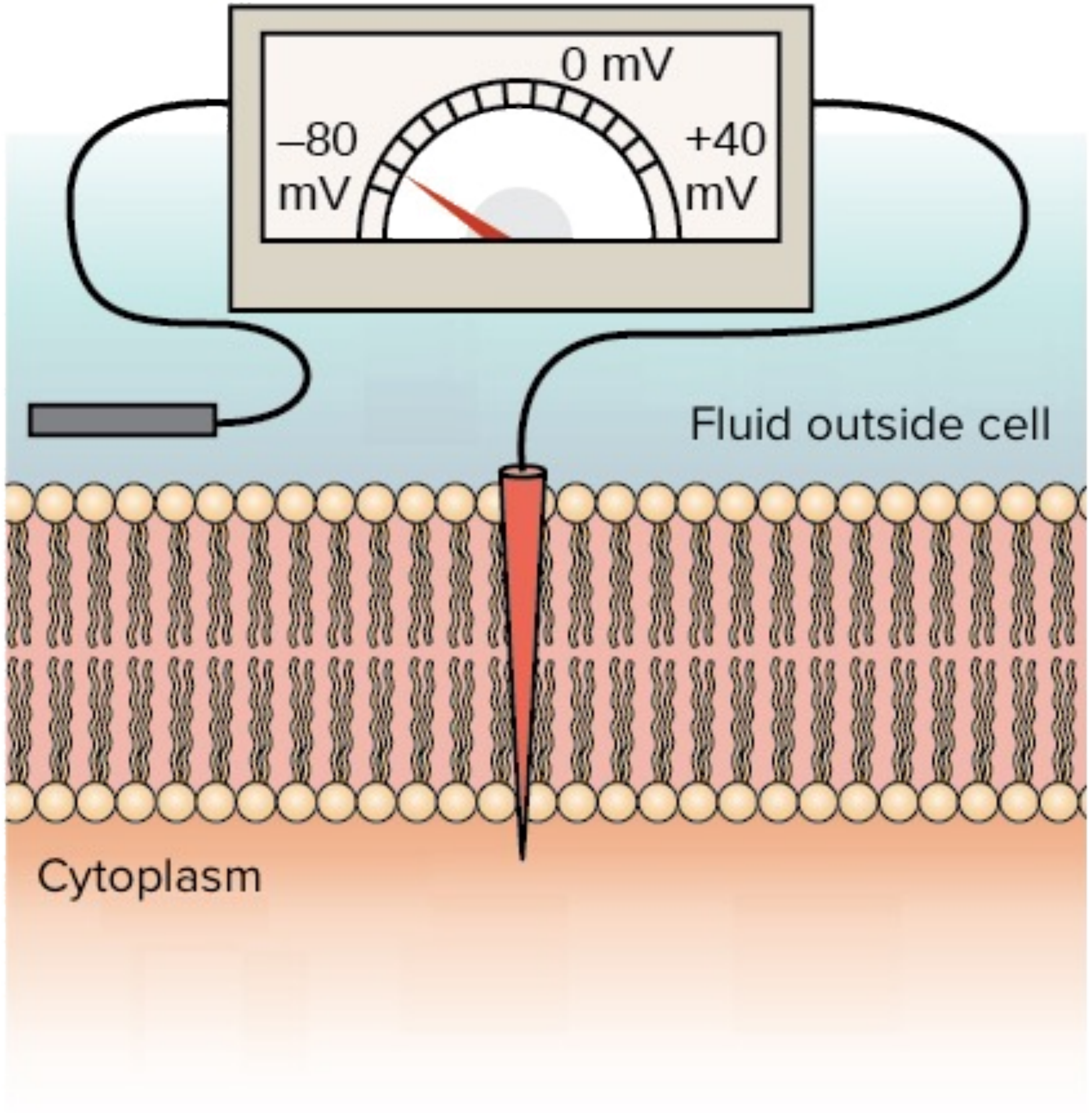
- *Usually* the cytoplasm is negative
  - (-20 to -110 mV; relative to the ECF = 0 mV)
- Depends upon ions present:
  - Permeability
  - Electrochemical gradients



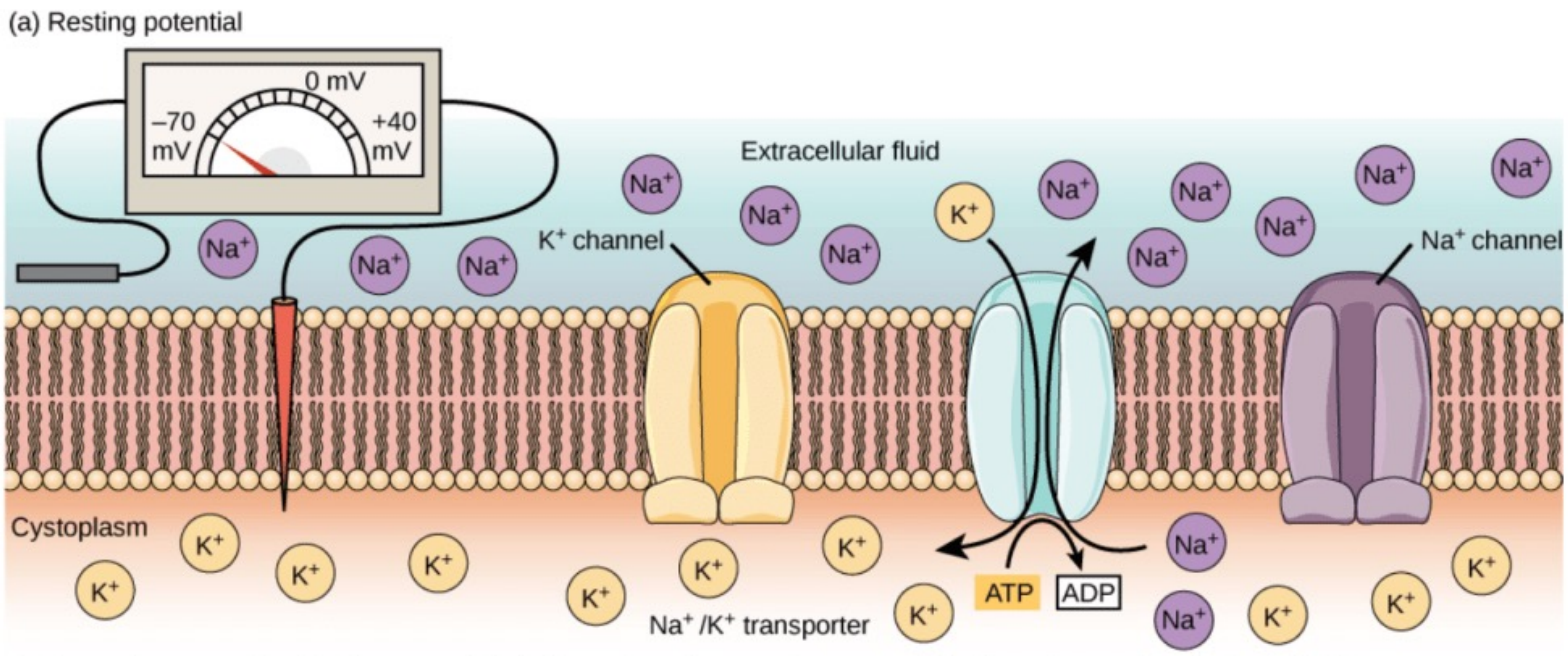
# Resting Membrane Potential

Imagine taking two electrodes and placing one on the outside and the other on the inside of the plasma membrane of a living cell.

If you did this, you would measure an electrical potential difference, or voltage, between the electrodes. This electrical potential difference is called the **membrane potential**.



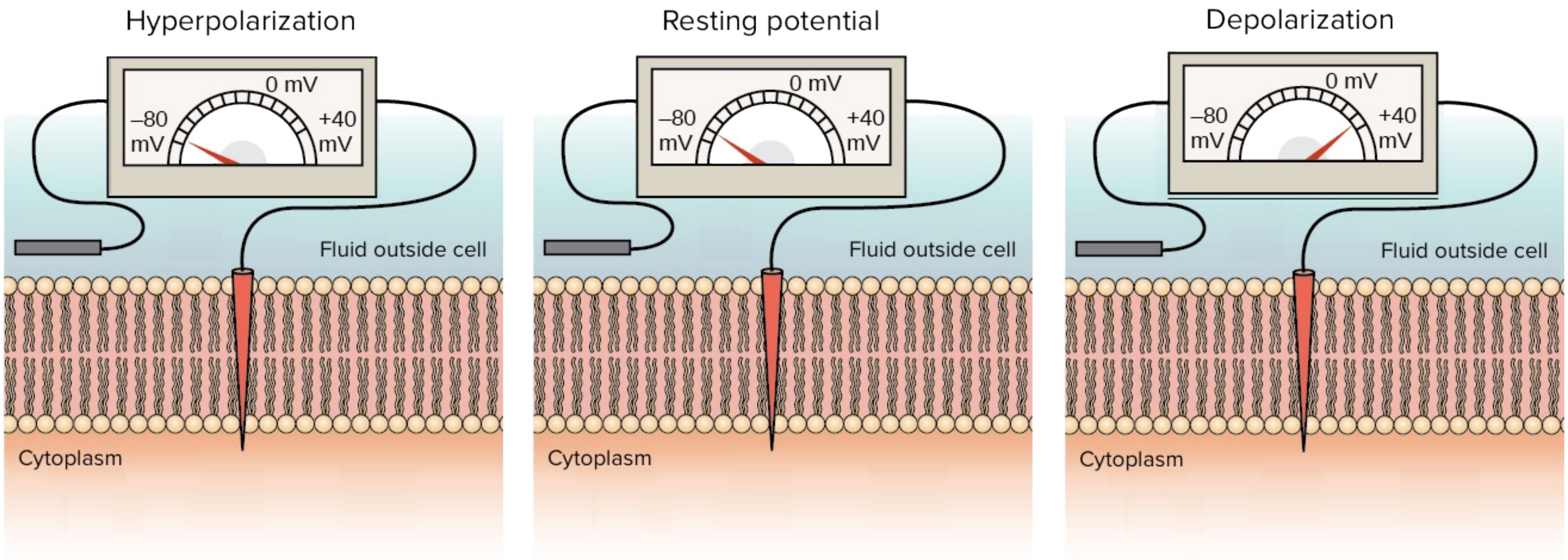
# Resting Membrane Potential




At the resting potential, all voltage-gated $Na^+$ channels and most voltage-gated $K^+$ channels are closed. The $Na^+/K^+$ transporter pumps $K^+$ ions into the cell and $Na^+$ ions out.

- Every neuron has a separation of electrical charge across its cell membrane.
- The membrane potential results from a separation of positive and negative charges across the cell membrane.

# Membrane Potentials




Because there is a potential difference across the cell membrane, the membrane is said to be **polarized**.

•If the membrane potential becomes more positive than it is at the resting potential, the membrane is said to be **depolarized**.

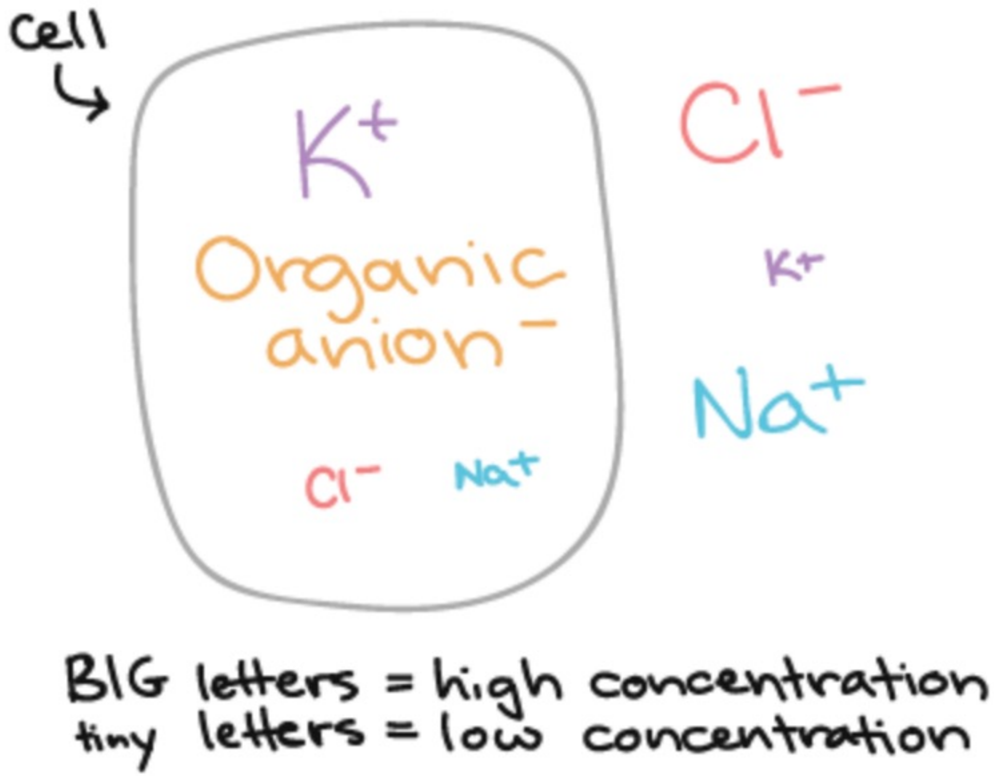
•If the membrane potential becomes more negative than it is at the resting potential, the membrane is said to be **hyperpolarized**.

# Resting Membrane Potential

- A potential difference across the cell membrane at the rest stage or when the cell is not stimulated.
- Property:
  - It is constant or stable
  - It is negative inside relative to the outside
  - Resting potentials are different in different cells.

# Where does the resting membrane potential come from?

The resting membrane potential is determined by the uneven distribution of **ions** (charged particles) between the inside and the outside of the cell, and by the different permeability of the membrane to different types of ions.



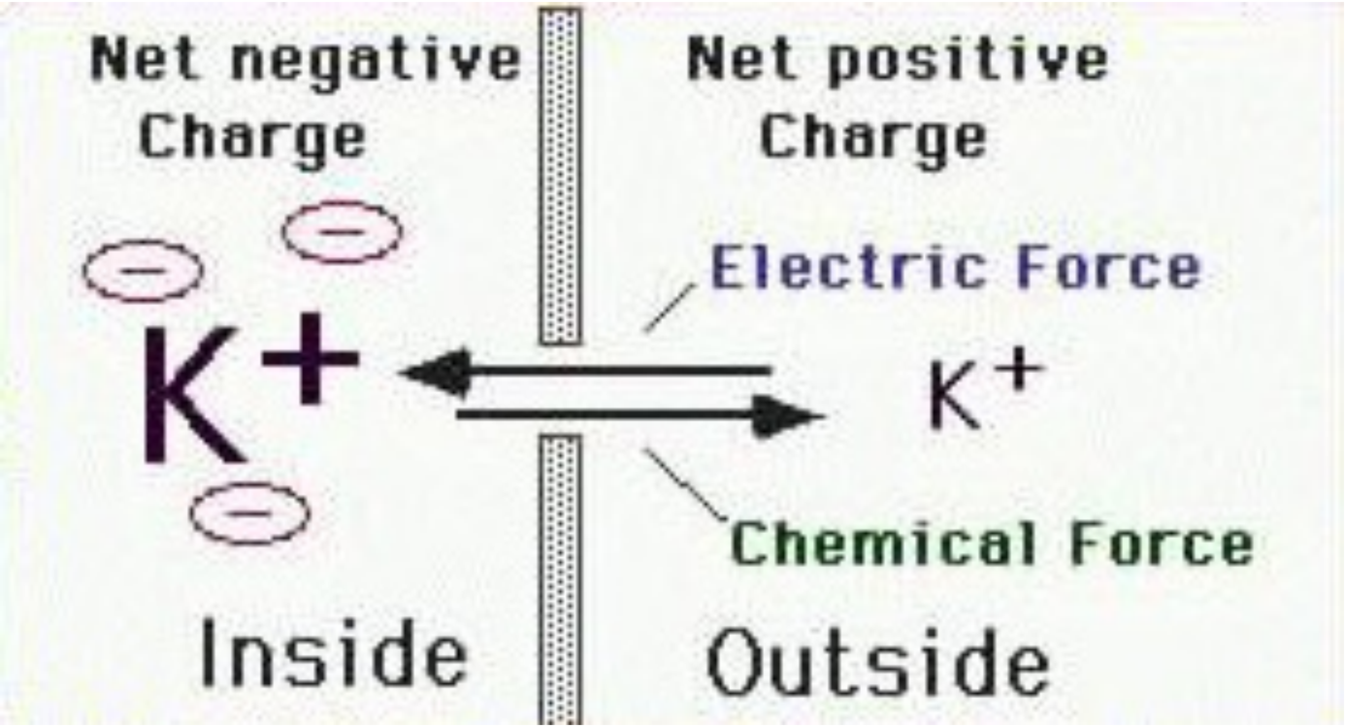
# We always have to take in mind that….

| Ion | Intracellular concentration (mM) | Extracellular concentration (mM) |
|---|---|---|
| K+ | 140 | 4 |
| Na+ | 15 | 145 |
| Cl- | 4 | 110 |
| Ca2+ | 0.0001 | 5 |

# We have an additional information here…

| Ion | Intracellular concentration (mM) | Extracellular concentration (mM) | Membrane permeability at rest |
|---|---|---|---|
| K+ | 140 | 4 | 1 |
| Na+ | 15 | 145 | 0.05 |
| Cl- | 4 | 110 | 0.1 |
| Ca2+ | 0.0001 | 5 | 0 |

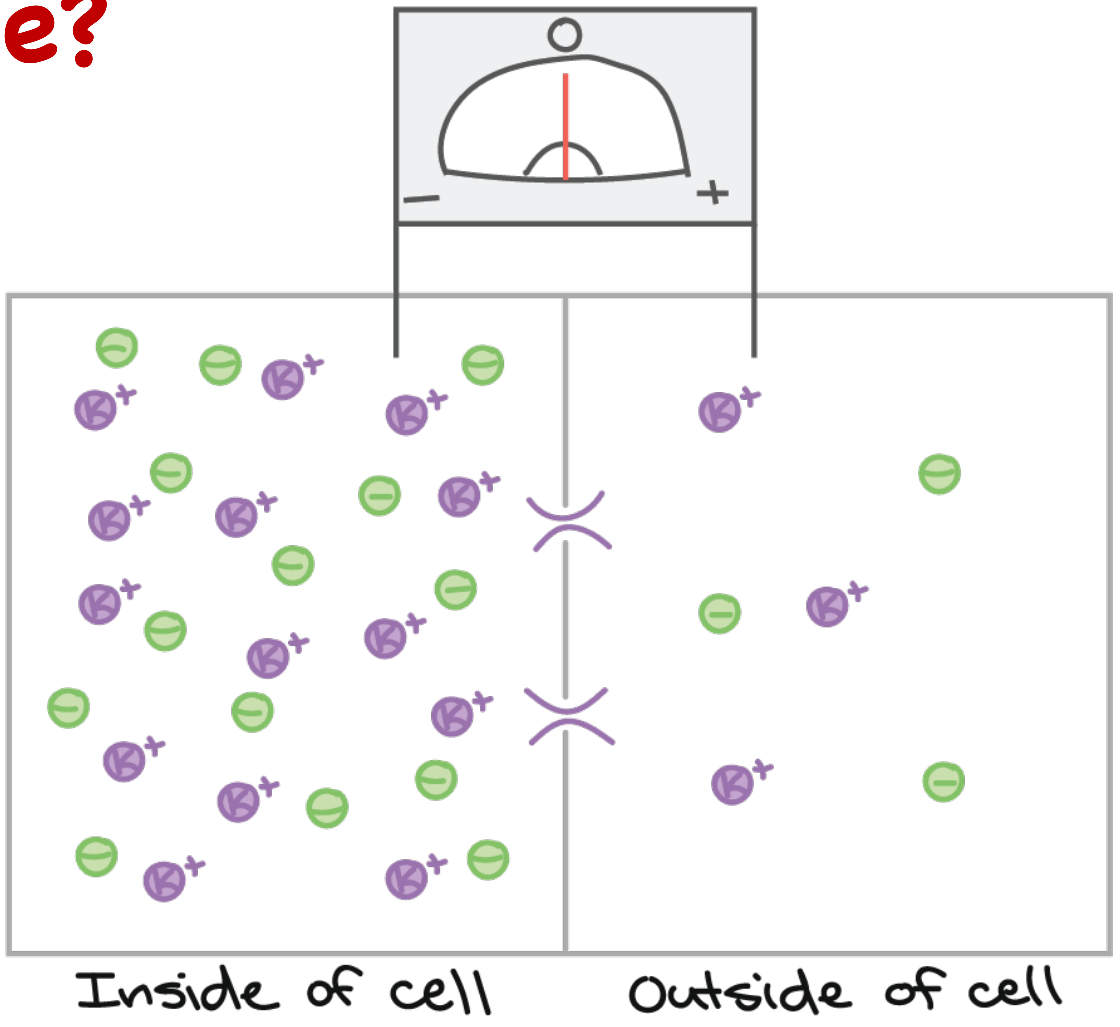
# Resting Membrane Potential




- Potassium ions, concentrated inside the cell tend to move outward down their concentration gradient through non-gated potassium channels
- But the relative excess of negative charge inside the membrane tend to push potassium ions out of the cell

# What happens if only K+ can cross the membrane?

1



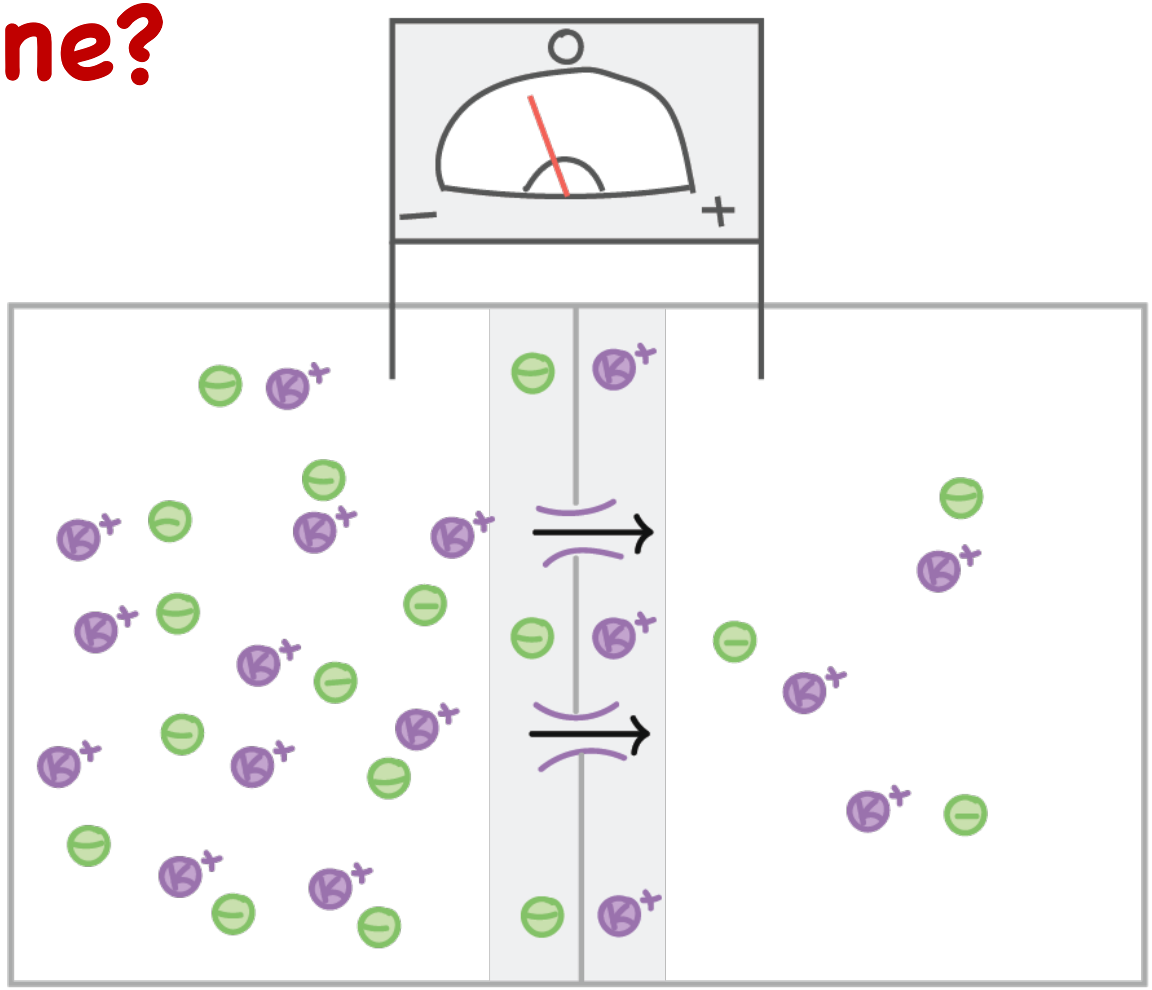

STARTING STATE:

There are potassium ($K^+$) ions and other ions (including anions) inside and outside the cell.

$K^+$ is more concentrated on the inside and less concentrated outside of the cell.

# What happens if only K+ can cross the membrane?

2



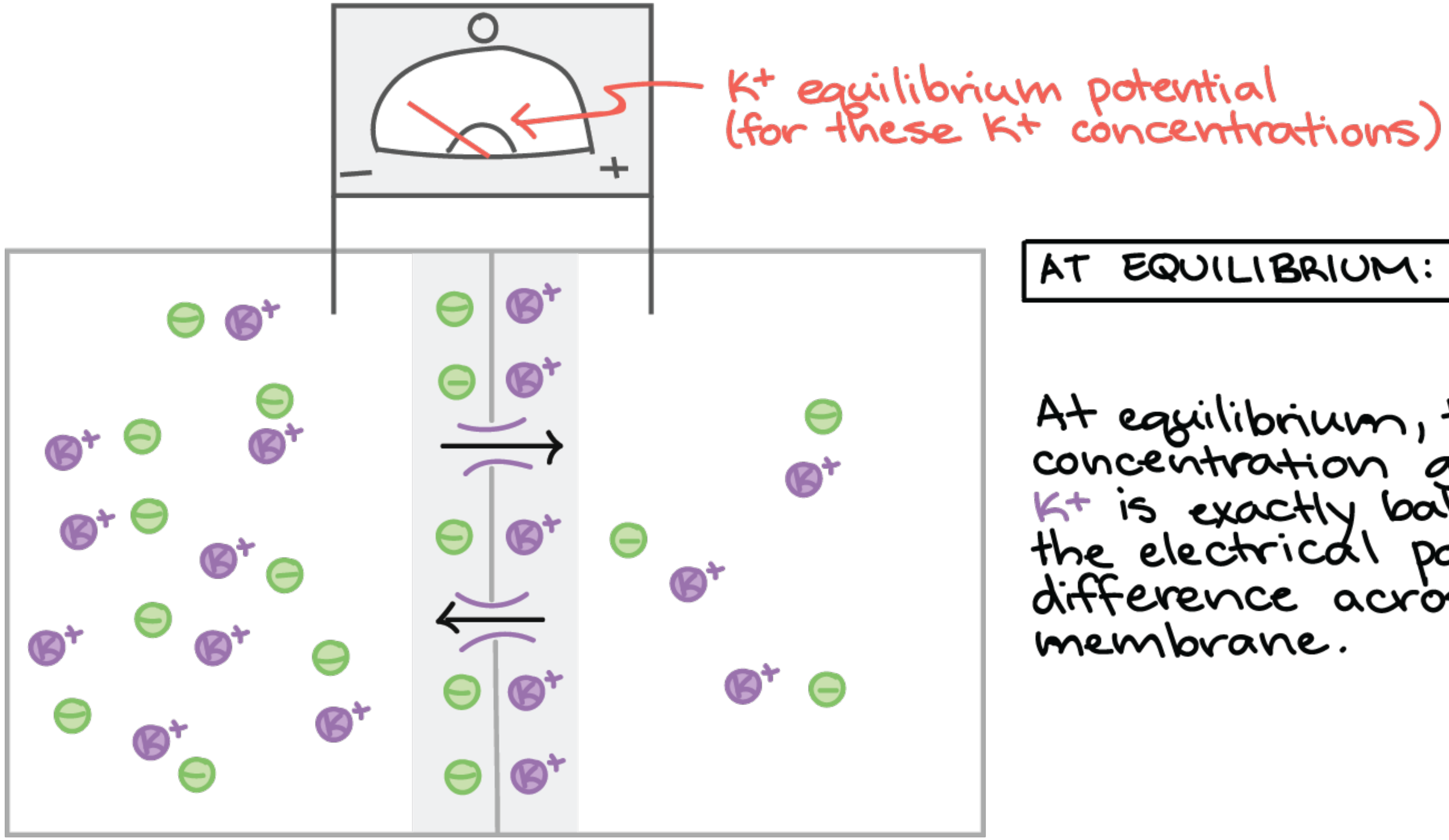

If $K^+$ can cross via channels, it will begin to move down its concentration gradient and out of the cell.

The movement of $K^+$ ions down their concentration gradient creates a charge imbalance across the membrane.

The charge imbalance opposes the flow of $K^+$ down the concentration gradient.

# What happens if only K+ can cross the membrane?

3




AT EQUILIBRIUM:

At equilibrium, the concentration gradient of K+ is exactly balanced by the electrical potential difference across the membrane.

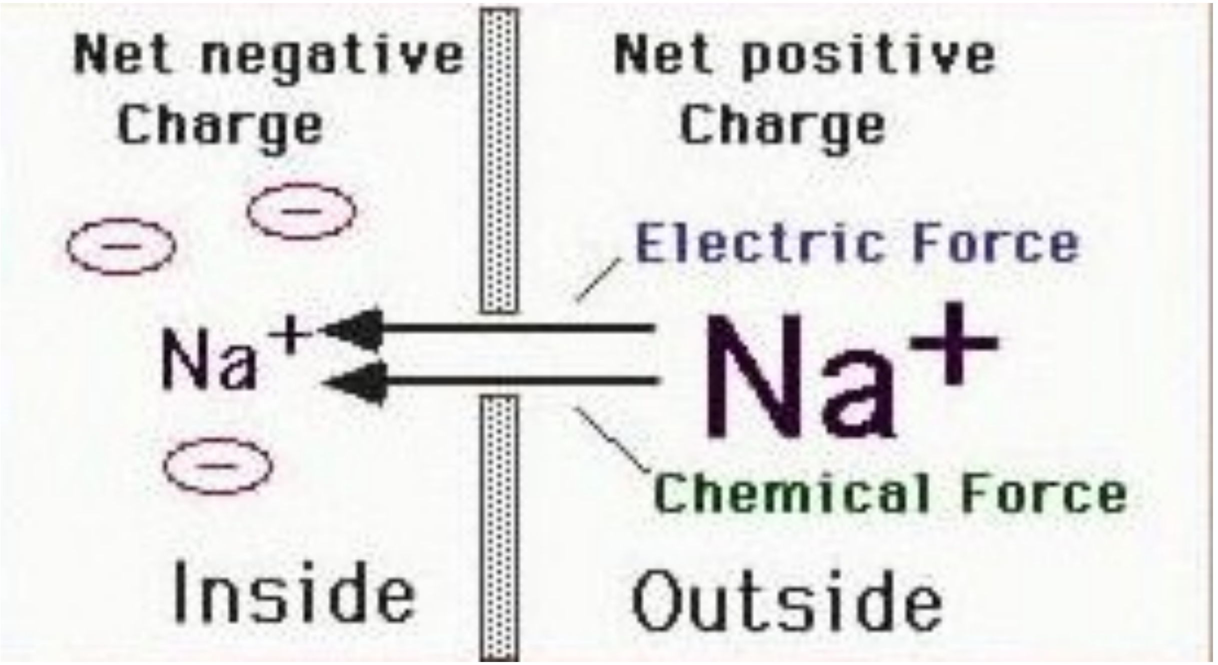
Does membrane potential equal $K^+$ equilibrium potential?

In glial cells the resting membrane potential is equal to the K equilibrium potential.
In neurons, however, the resting membrane potential is close but not identical to K equilibrium potential.

In physiological conditions neuron resting membrane potentials are slightly less negative than K equilibrium potential.

What does that mean? In a neuron, other types of ions besides K must contribute significantly to the resting membrane potential.

# Resting Membrane Potential

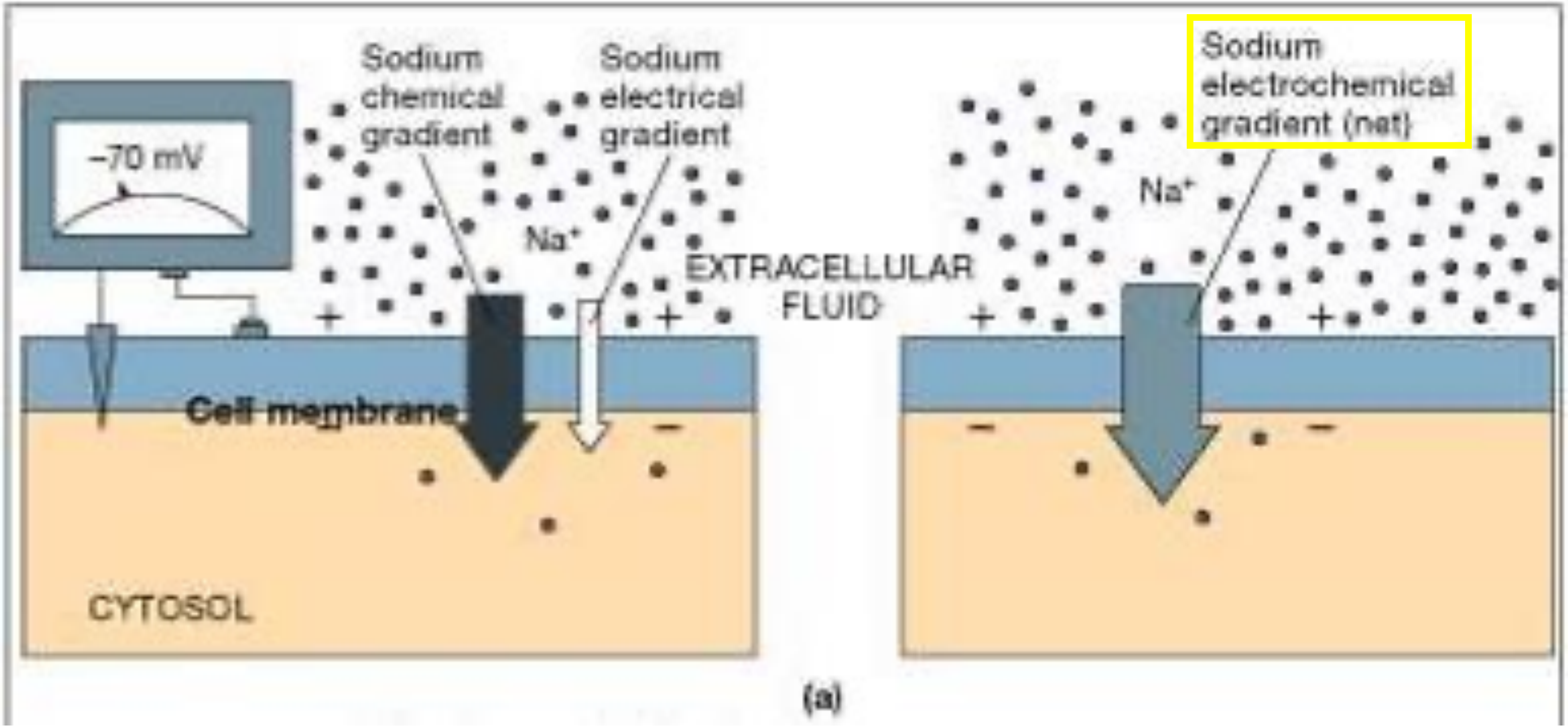



$Na^+$ is more concentrated outside than inside and therefore tends to flow into the cell down its concentration gradient

$Na^+$ is driven into the cell by the electrical potential difference across the membrane.

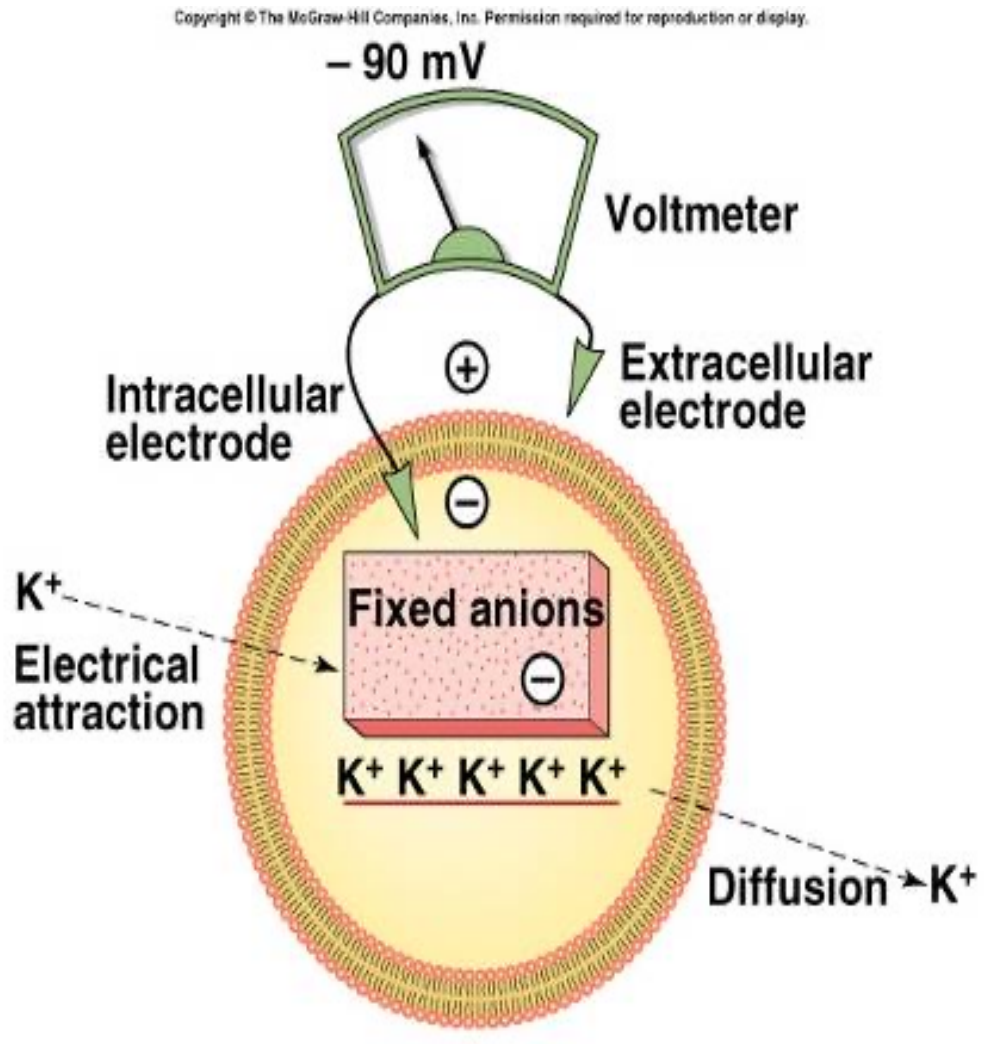
- *But what about sodium?*
- Electrostatic and Chemical forces act together on $Na^+$ ions to drive them into the cell
- The $Na^+$ channel close during the resting state

# $Na^+$ electrochemical gradient



# Equilibrium Potentials

- Theoretical voltage produced across the membrane
  - if only one kind of ion could diffuse through the membrane.
  - If membrane only permeable to $K^+$, $K^+$ diffuses until $[K^+]$ is at equilibrium.
- Force of electrical attraction and diffusion are = opposite.



# Calculating equilibrium potential
# Nernst Equation

- Allows theoretical membrane potential to be calculated for particular ion.
  - Membrane potential that would exactly balance the diffusion gradient and prevent the net movement of a particular ion.
  - Value depends on the ratio of [ion] on the 2 sides of the membrane.

# Calculating equilibrium potential
# Nernst Equation

Nernst Equation (at body temp RT/F simplifies to 61.5):

E= membrane potential in mV

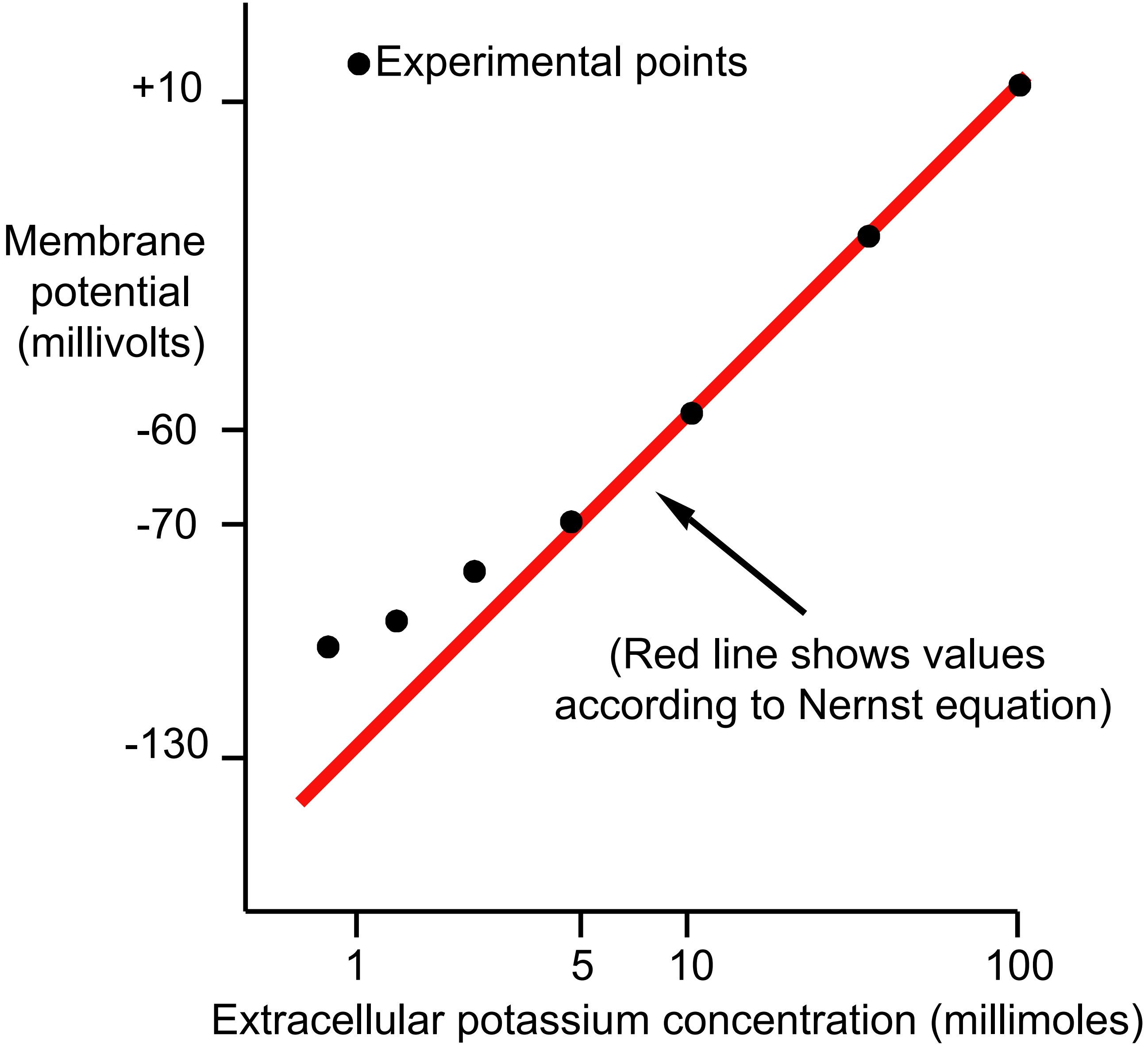
R= Ideal Gas Constant 8.314 J/(K*mol)

T= temp in K

z= charge of ion in question ex: for Ca2+ z= +2

F= Faraday's Constant 96,485 C/mol e-

$$E = \frac{RT}{zF} \ln \frac{[\text{ion}_{\text{outside}}]}{[\text{ion}_{\text{inside}}]} = \frac{61.5}{z} \log \frac{[\text{ion}_{\text{outside}}]}{[\text{ion}_{\text{inside}}]}$$



Experimental points
+10
Membrane
potential
(millivolts)
-60
-70
-130
(Red line shows values
according to Nernst equation)
1
5
10
100
Extracellular potassium concentration (millimoles)


$[K^+]_o$ = 4 mmol.l$^{-1}$

# Resting Membrane Potential

- Resting membrane potential is less than $E_k$ because some $Na^+$ can also enter the cell.
- The slow rate of $Na^+$ influx is accompanied by slow rate of $K^+$ outflux.
- Depends upon 2 factors:
  - Ratio of the concentrations of each ion on the 2 sides of the plasma membrane.
  - Specific permeability of membrane to each different ion.
- Resting membrane potential of most cells ranges from - 65  to – 85 mV.

# The Goldman-Hodgkin-Katz voltage equation,

Goldman–Hodgkin–Katz Voltage Equation (derived from Nernst):
Vm= membrane potential in mV
P= permeability for relevant ion

$$V_m = 61.5 \log \left[ \frac{P_{Na^+} \times [Na^+]_{outside} + P_{K^+} \times [K^+]_{outside} + P_{Cl^-} \times [Cl^-]_{inside}}{P_{Na^+} \times [Na^+]_{inside} + P_{K^+} \times [K^+]_{inside} + P_{Cl^-} \times [Cl^-]_{outside}} \right]$$

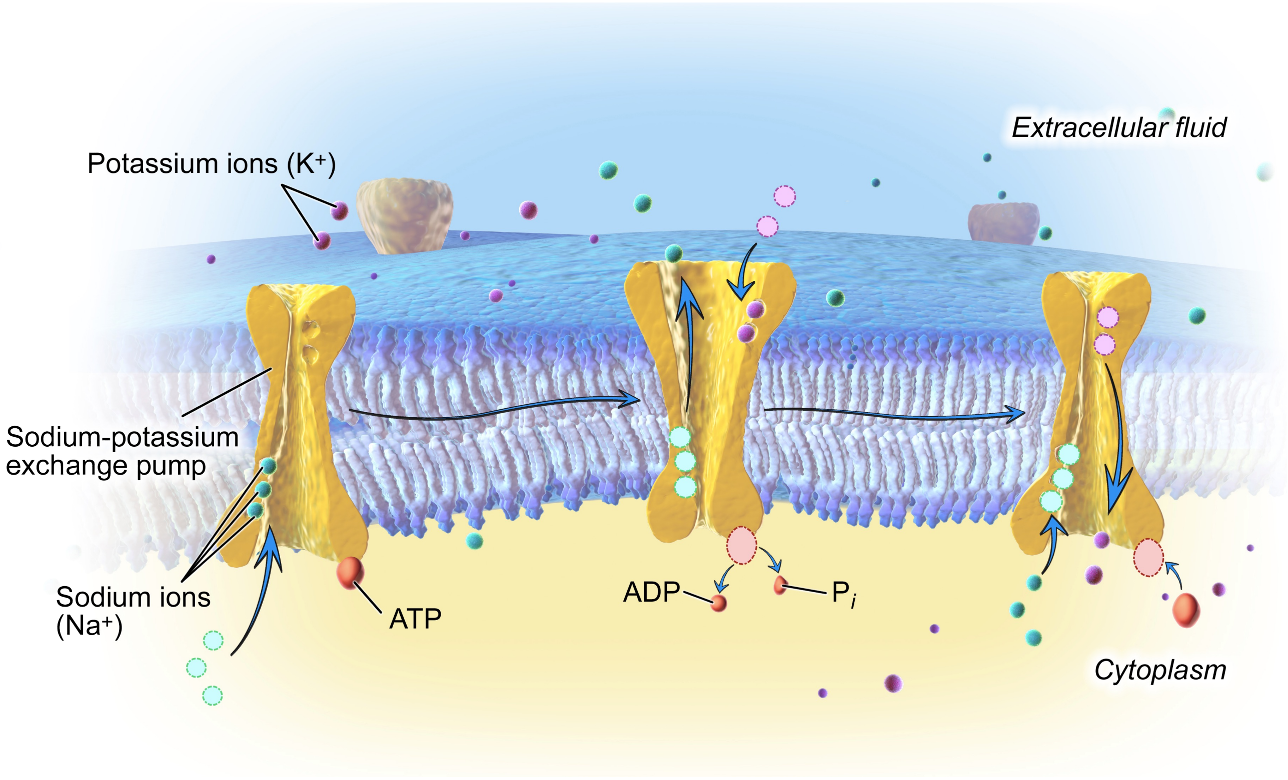
# The Goldman-Hodgkin-Katz voltage equation,

The membrane potential is a weighted mean of the equilibrium potentials of the different permeant ions.

If only one permeant ionic species is present, the membrane potential will be determined by that ion's equilibrium potential. It doesn't matter how permeable it is (how readily it can cross the membrane), because there is nothing to counter it.

If multiple permeant ionic species are present (and not at equilibrium), the resting potential will be between the equilibrium potentials for the different permeant ions. The greater the permeability to a given ionic species, the more it will dominate the final membrane potential.

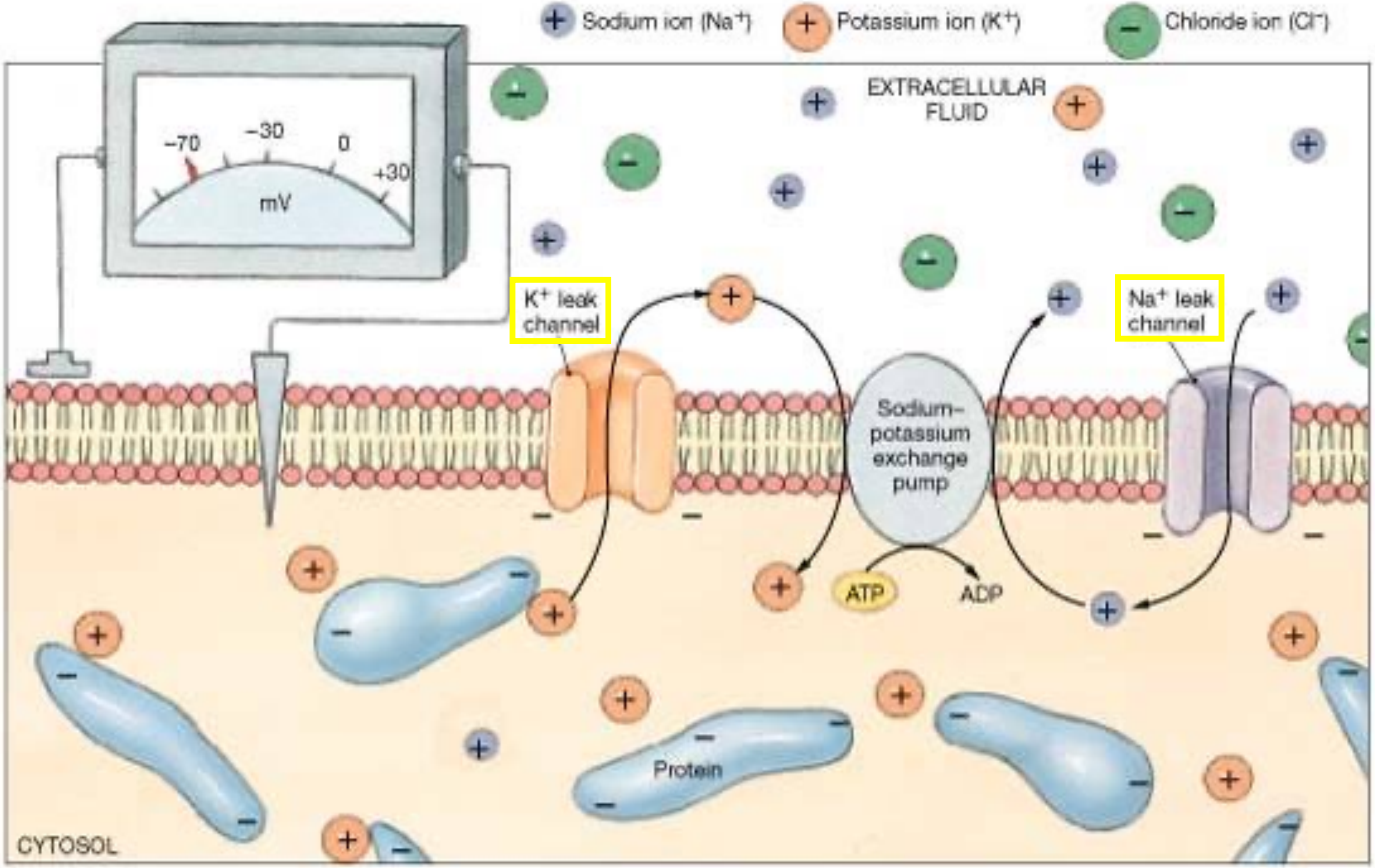
# The Sodium-Potassium Pump




extrudes $Na^+$ from the cell while taking in $K^+$

- Dissipation of ionic gradients is ultimately prevented by $Na^+$-$K^+$ pumps

# Resting Membrane Potential

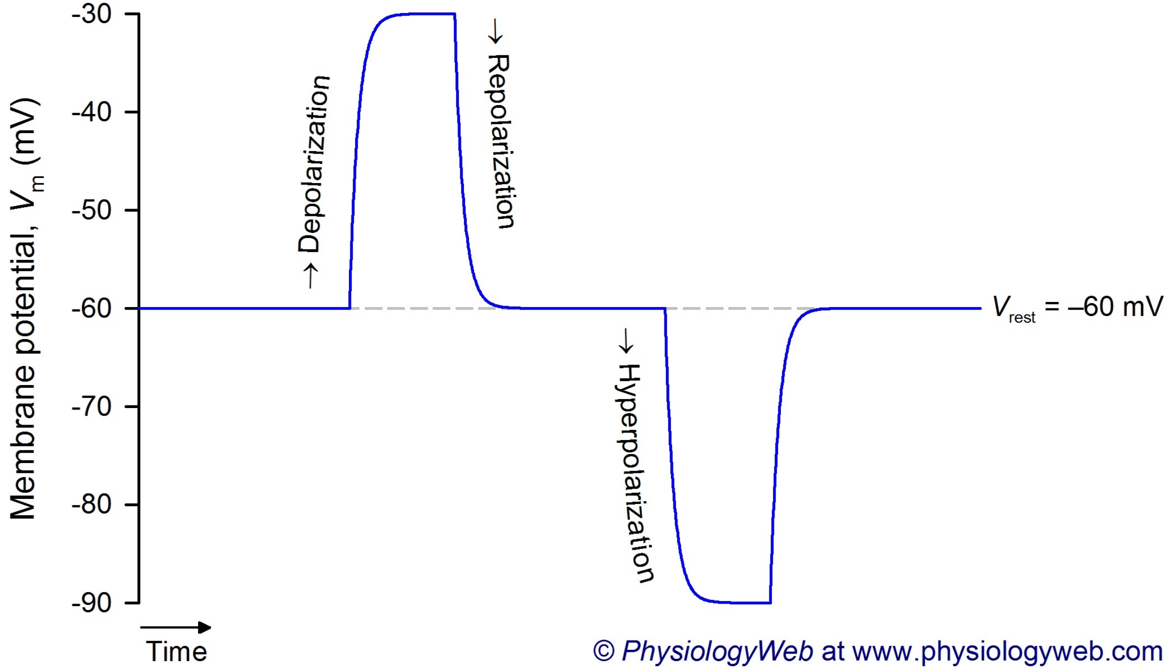


# The formation of resting potential depends on:

- Concentration difference of $K^+$ across the membrane
- Permeability of $Na^+$ and $K^+$ during the resting state
- $Na^+$-$K^+$ pump

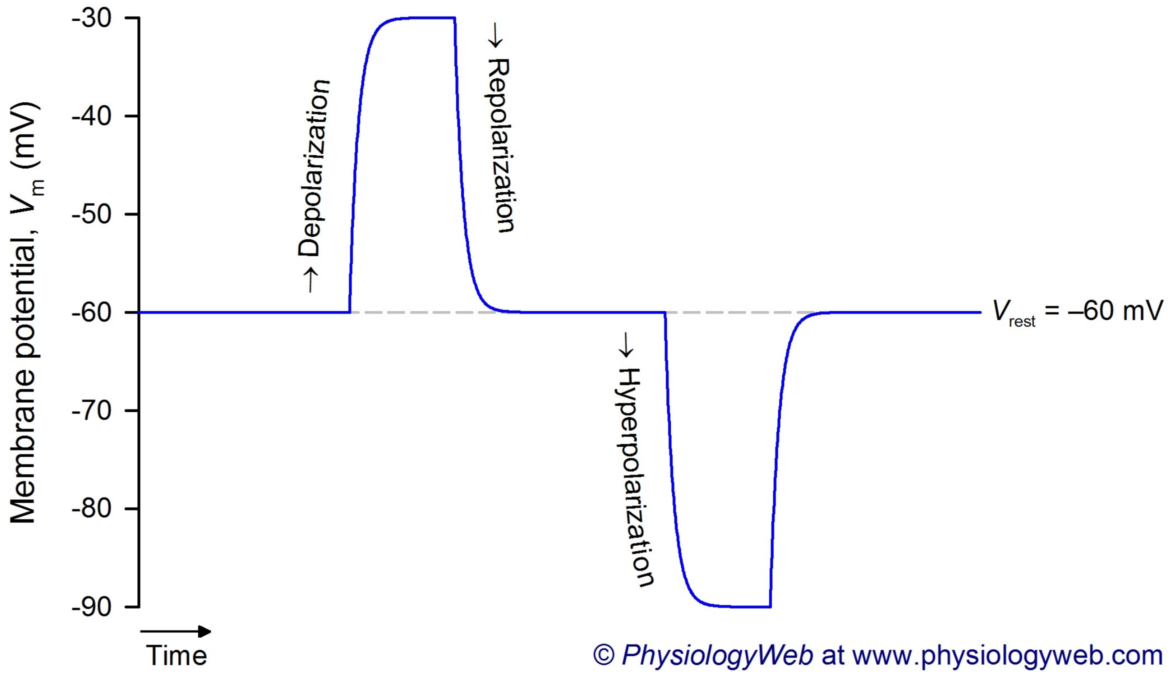
- Bioelectrical Phenomena of the Cell:
- 2: Action Potential

# Basic Electrophysiological Terms



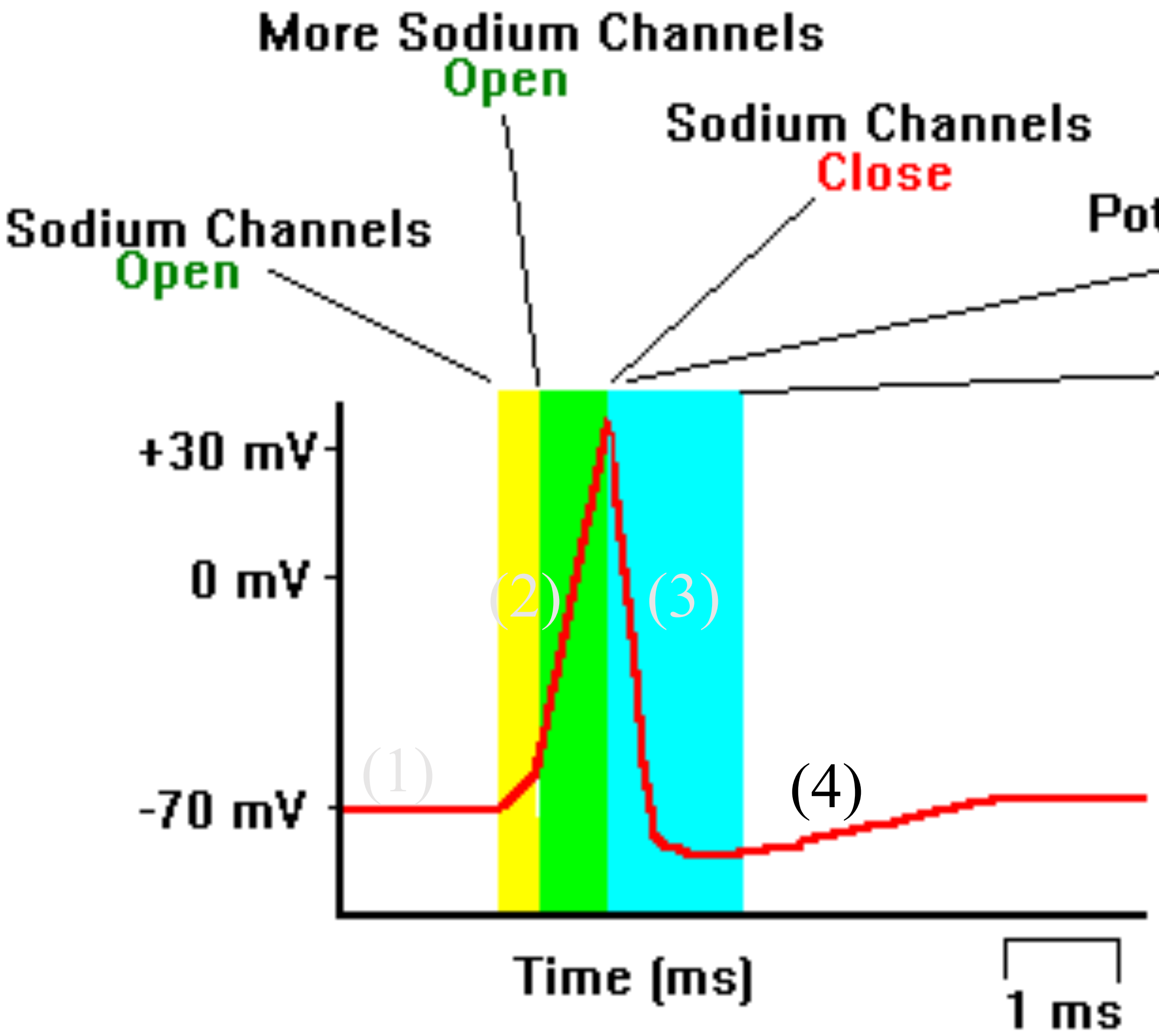

- **Polarization**: a state in which membrane is polarized at rest, negative inside and positive outside.
- **Depolarization**: the membrane potential becomes less negative than the resting potential (close to zero).
- **Hyperpolarization**: the membrane potential is more negative than the resting level.

# Basic Electrophysiological Terms




- **Reverspolarization**: a reversal of membrane potential polarity.
  - The inside of a cell becomes positive relative to the outside.
- **Repolarization**: restoration of normal polarization state of membrane.
  - from depolarized level

# Action Potential




Successive Stages:

(1) Resting Stage

(2) Depolarization stage

(3) Repolarization stage

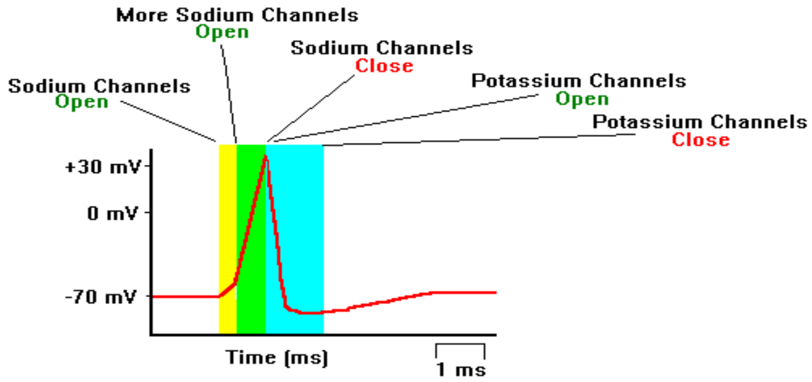
(4) After-potential stage

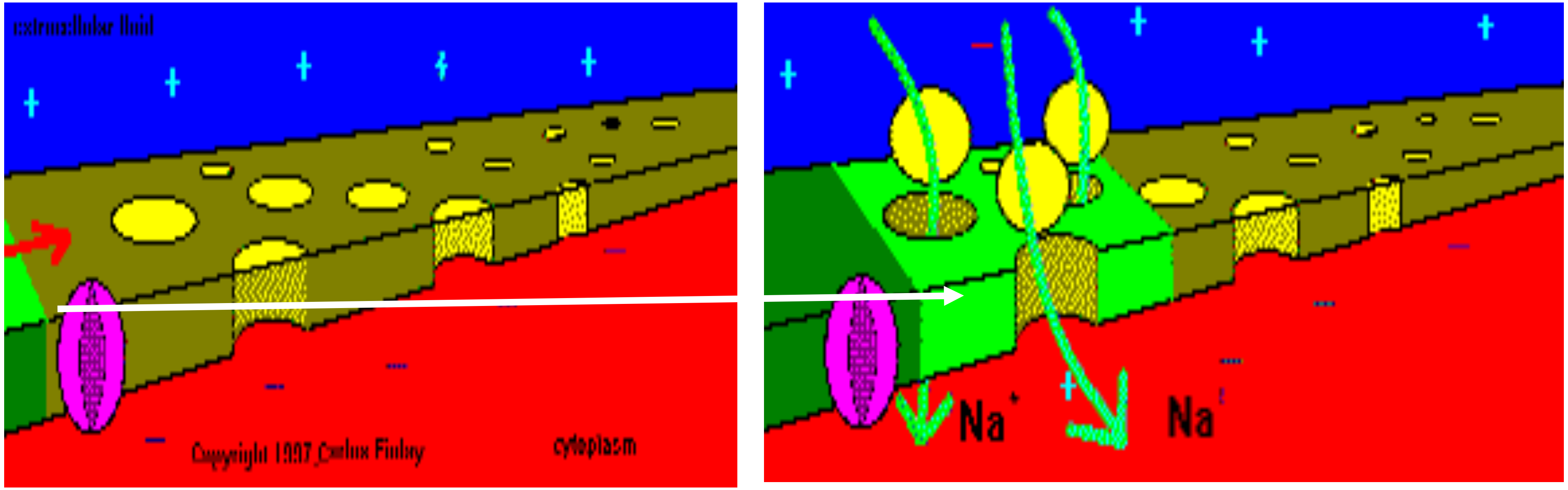
# Concept

- Action potential is a **rapid, reversible**, and **conductive** change of the membrane potential after the cell is stimulated.

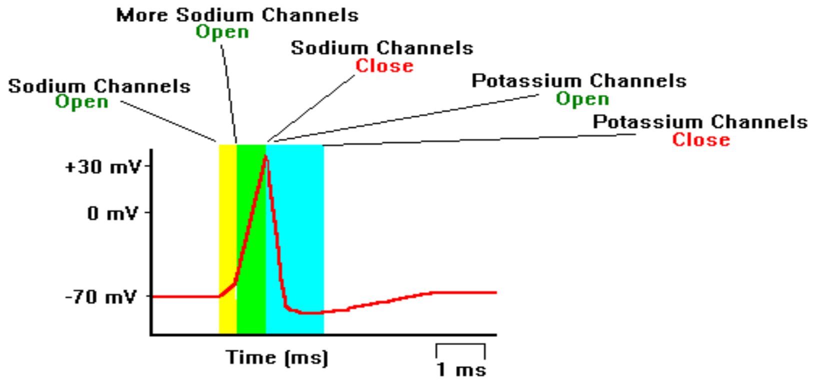
- Nerve signals are transmitted by action potentials.

# Action Potential Sequence

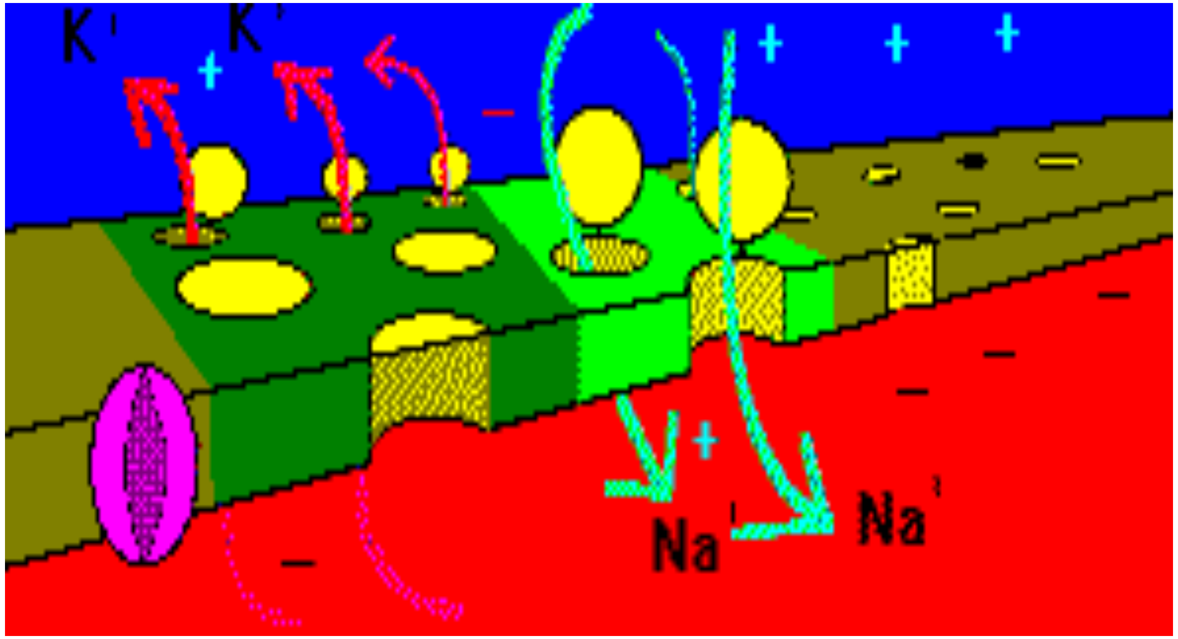



- **Voltage-gated $Na^{+}$ Channels open and $Na^{+}$ rushes into the cell**

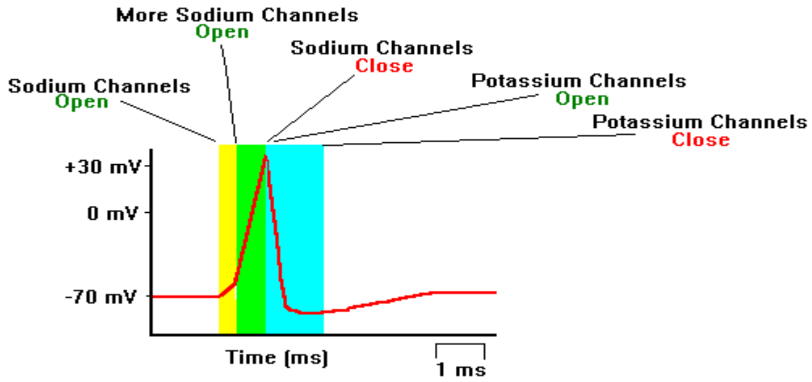


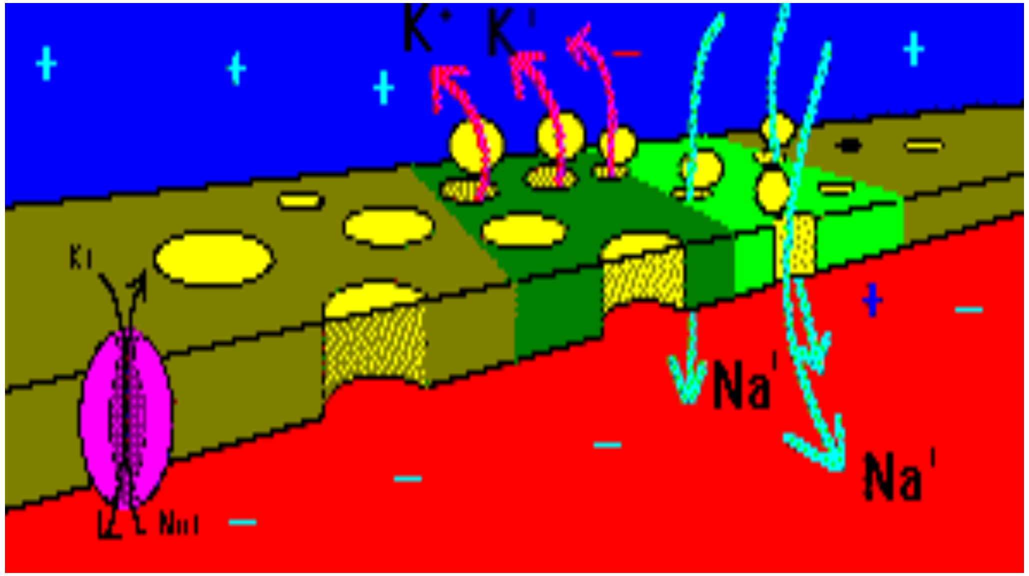

# Action Potential Sequence




- At about +40 mV, Sodium channels close, but now, voltage-gated potassium channels open, causing an outflow of potassium, down its electrochemical gradient

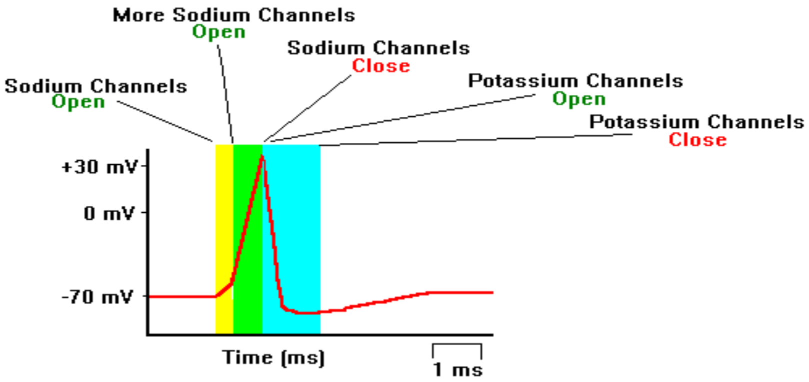
# Action Potential Sequence

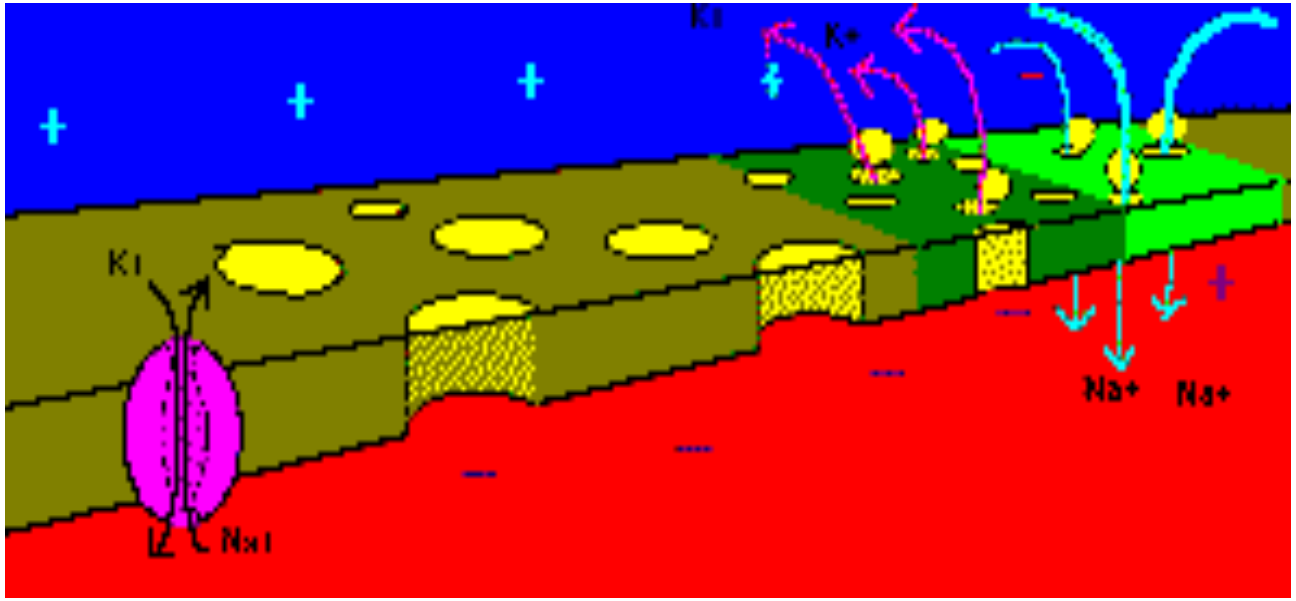


equilibrium potential of the cell is restored

# Action Potential Sequence




- **The Sodium – Potassium Pump is left to clean up the mess…**

# Ion Permeability during the AP

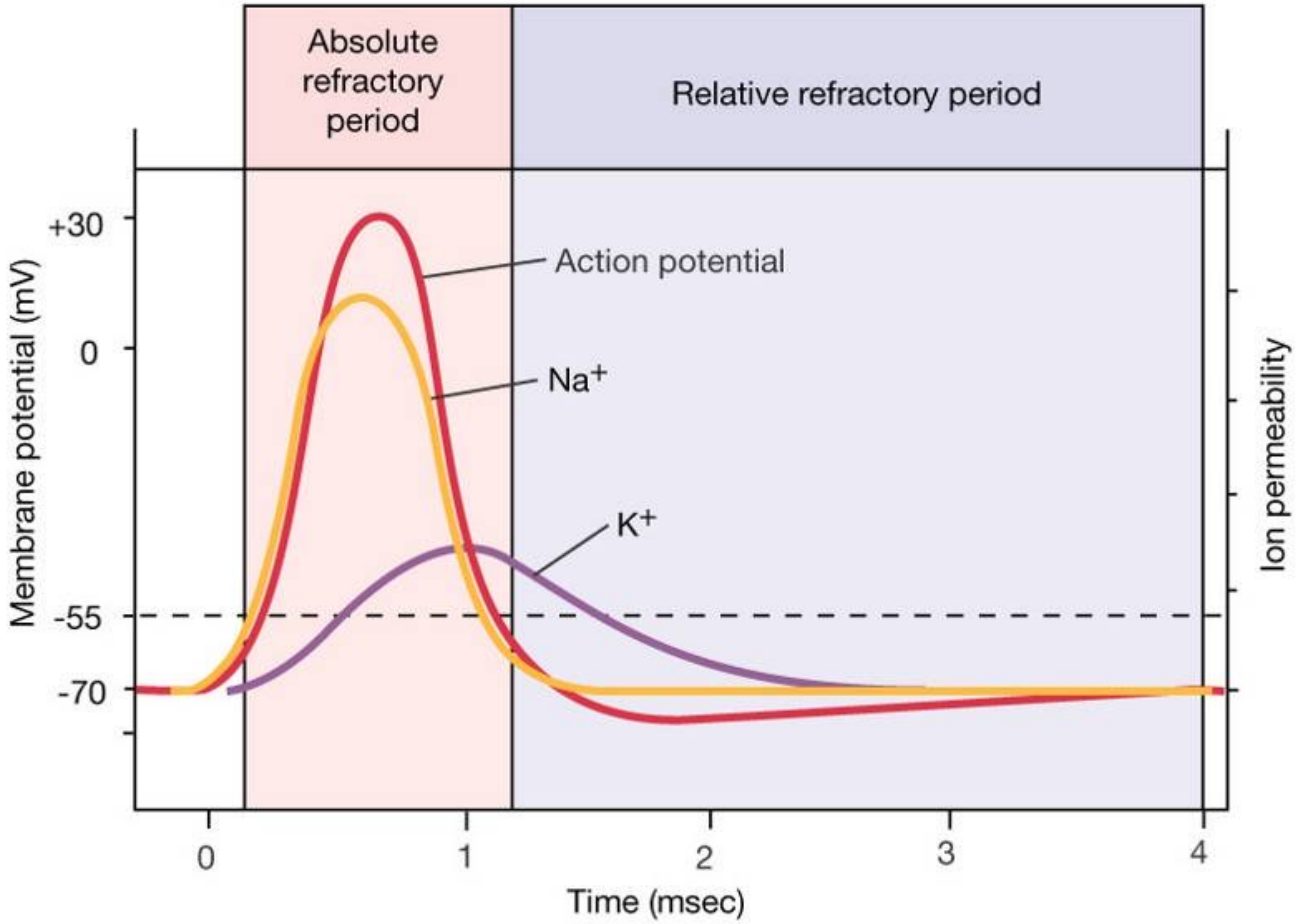



Figure 8-12: Refractory periods

# Basic Electrophysiological Terms

- **Excitability**: The ability of the cell to generate the action potential

- **Excitable cells**: Cells that generate action potential during excitation.
  - in excitable cells (muscle, nerve, secretary cells), the action potential is the **marker** of excitation.

# Basic Electrophysiological Terms

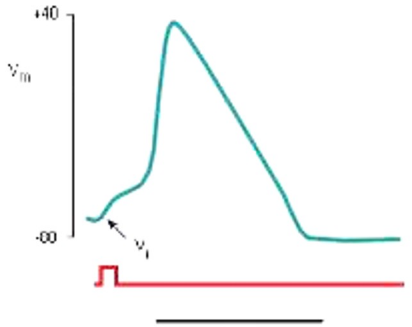
- **Stimulus**: a sudden change of the (internal or external) environmental condition of the cell.
  - includes physical and chemical stimulus.
  - The electrical stimulus is often used for the physiological research.

- **Threshold** (intensity): the lowest or minimal intensity of stimulus to elicit an action potential
  - (Three factors of the stimulation: intensity, duration, rate of intensity change)

# Basic Electrophysiological Terms

- **Types of stimulus:**
  - **Threshold stimulus**: The stimulus with the intensity equal to threshold
  - **Subthreshold stimulus**: The stimulus with the intensity weaker than the threshold
  - **Suprathreshold stimulus**: The stimulus with the intensity greater than the threshold.

# Action Potential Summary



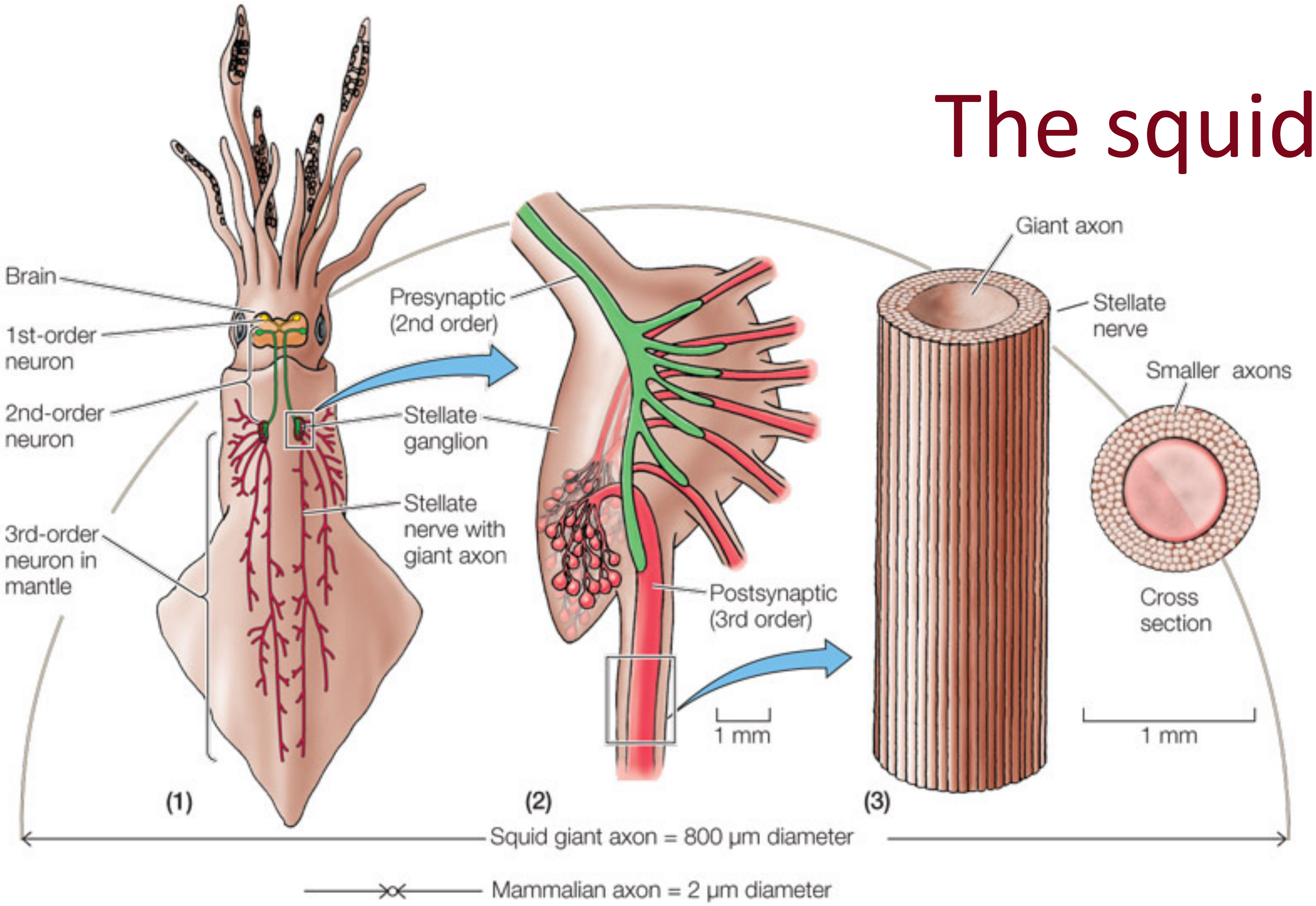

- Reduction in membrane potential (depolarization) to "threshold" level leads to opening of $Na^+$ channels, allowing $Na^+$ to enter the cell
- Interior becomes positive
- The $Na^+$ channels then close automatically followed by a period of inactivation.
- $K^+$ channels open, $K^+$ leaves the cell and the interior again becomes negative.
- AP Process lasts about 1ms

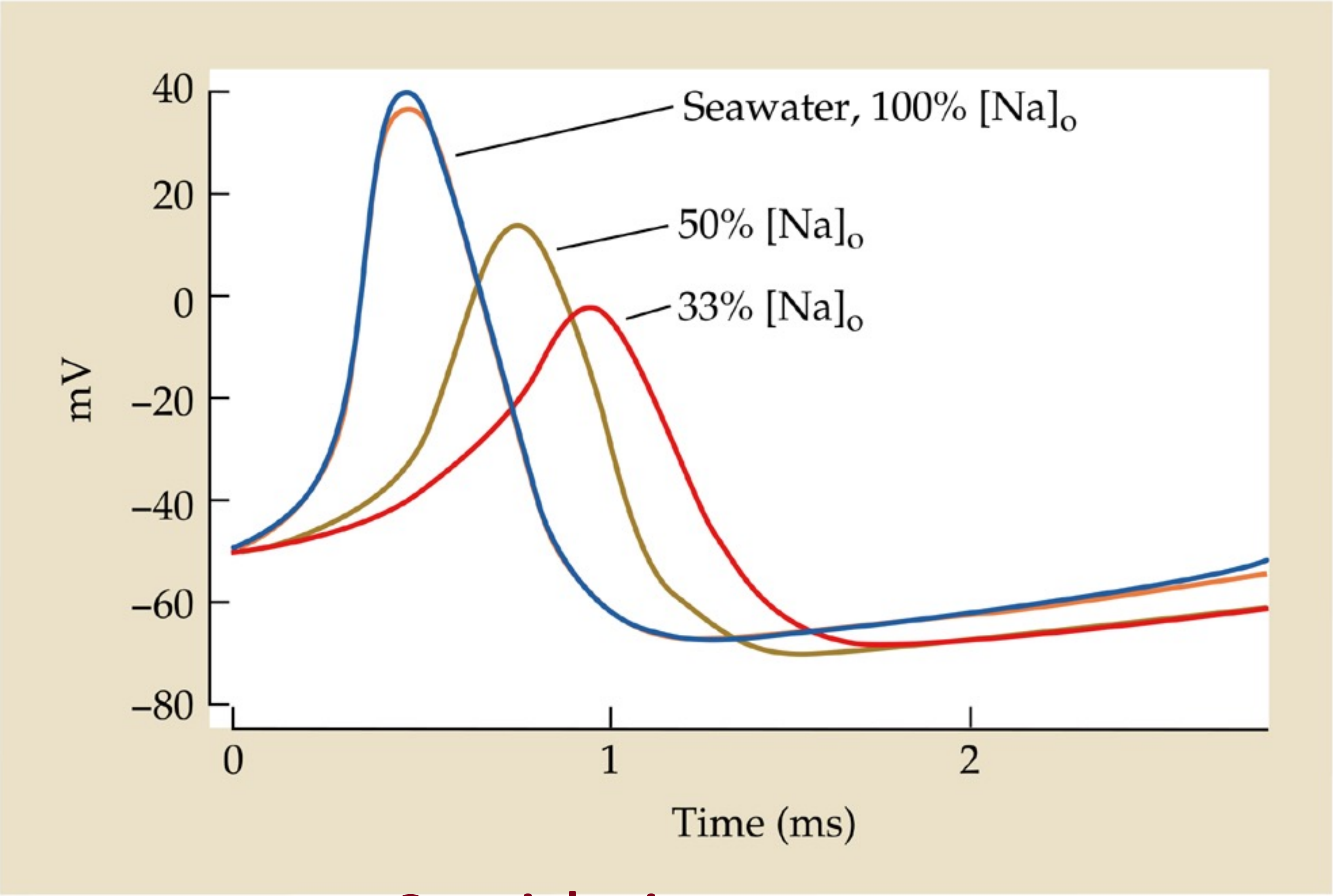
# Properties of the Action Potential

- "All or none" phenomenon
  - constant **amplitude**, **time course** and **propagation velocity**.
- Propagation
- Transmitted in both direction in a nerve fiber?

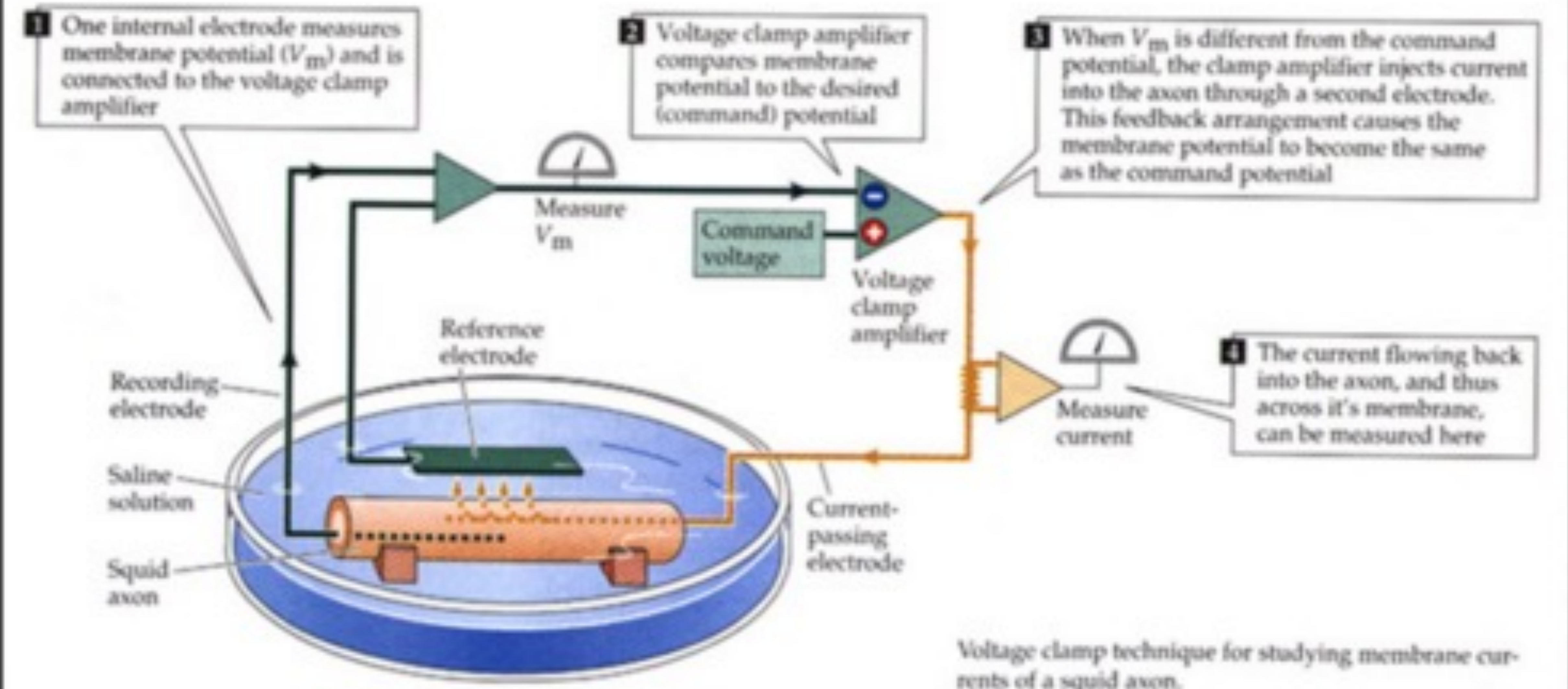
# Initiation of Action Potential

## The squid giant axon



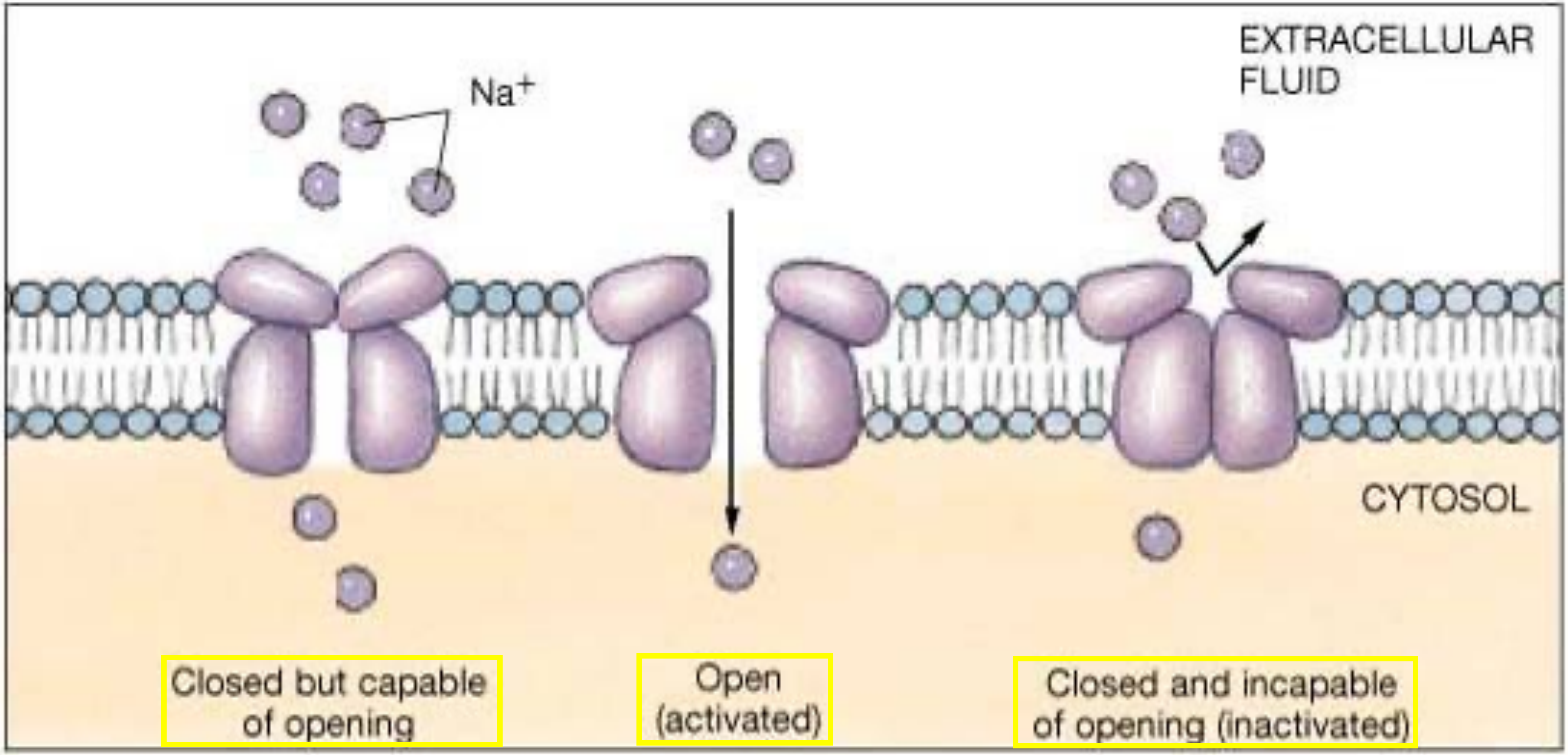



# Squid giant axon



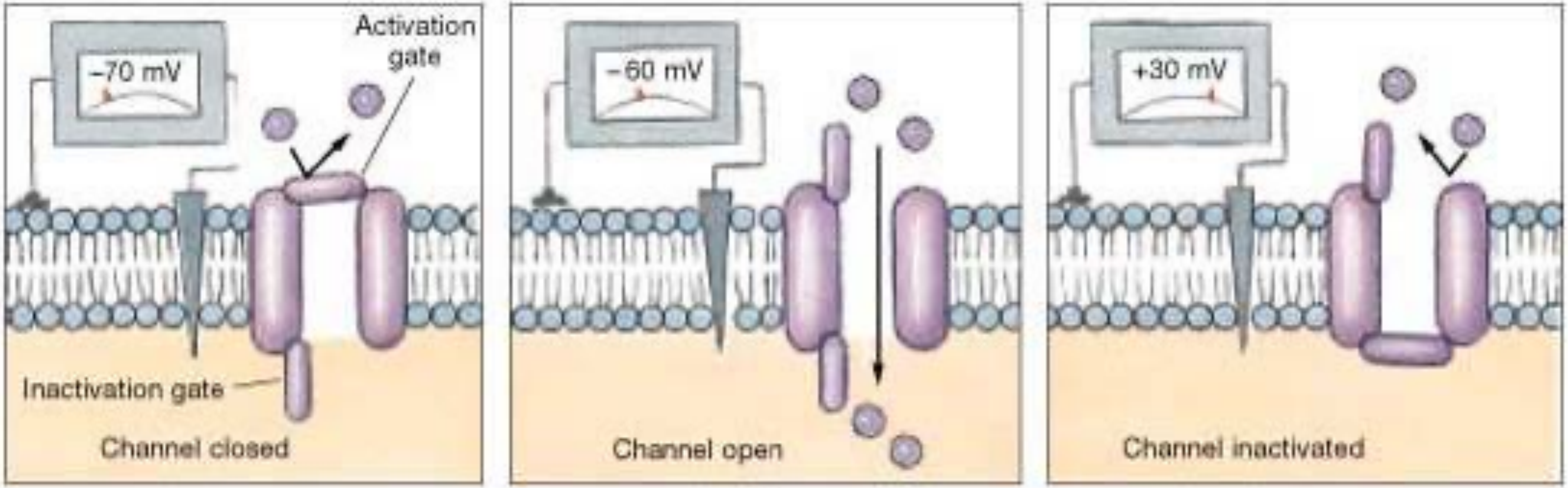

Voltage clamp technique for studying membrane currents of a squid axon.

# Voltage Gated $Na^+$ Channels



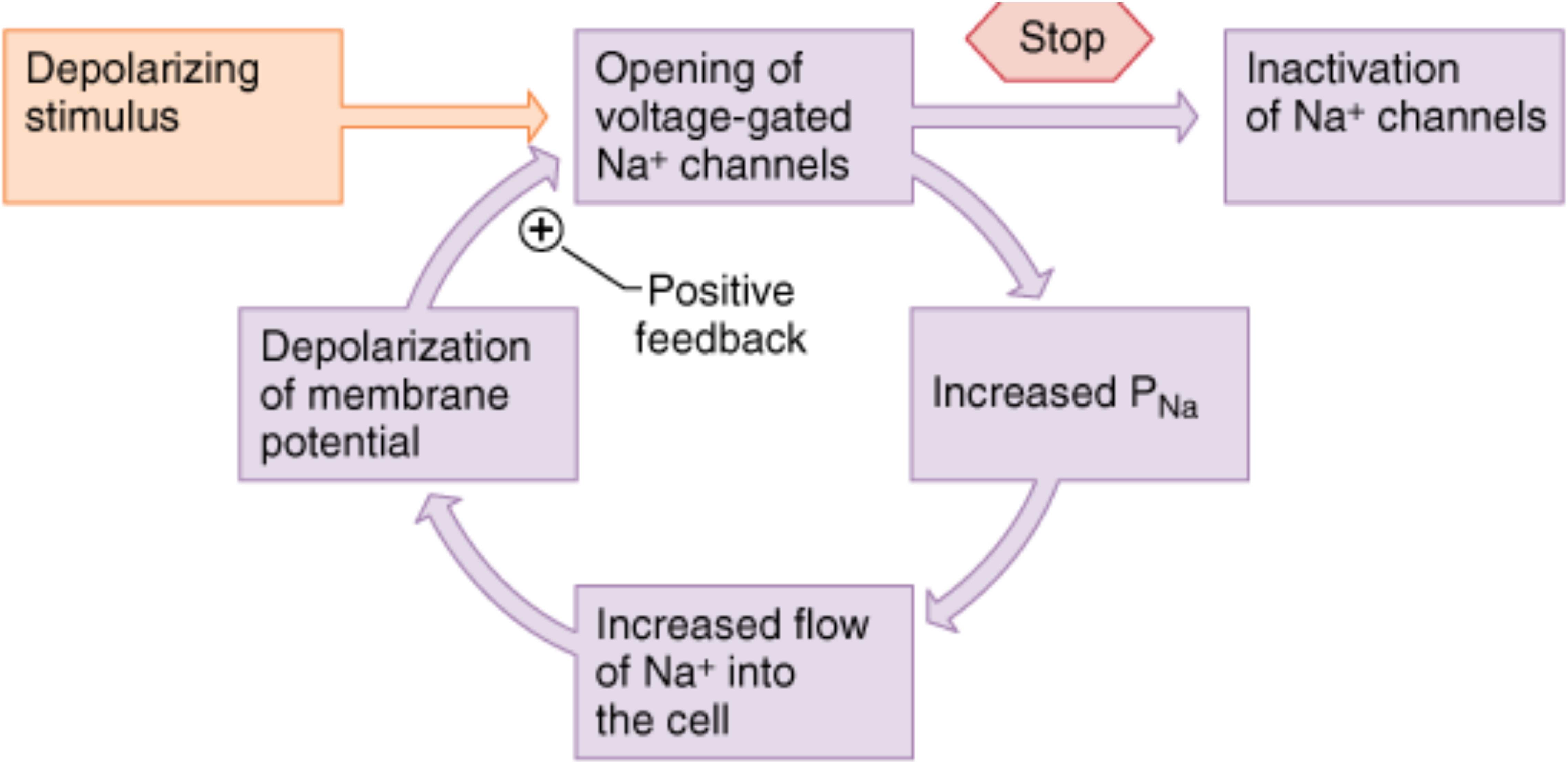
(a)

# Voltage gates

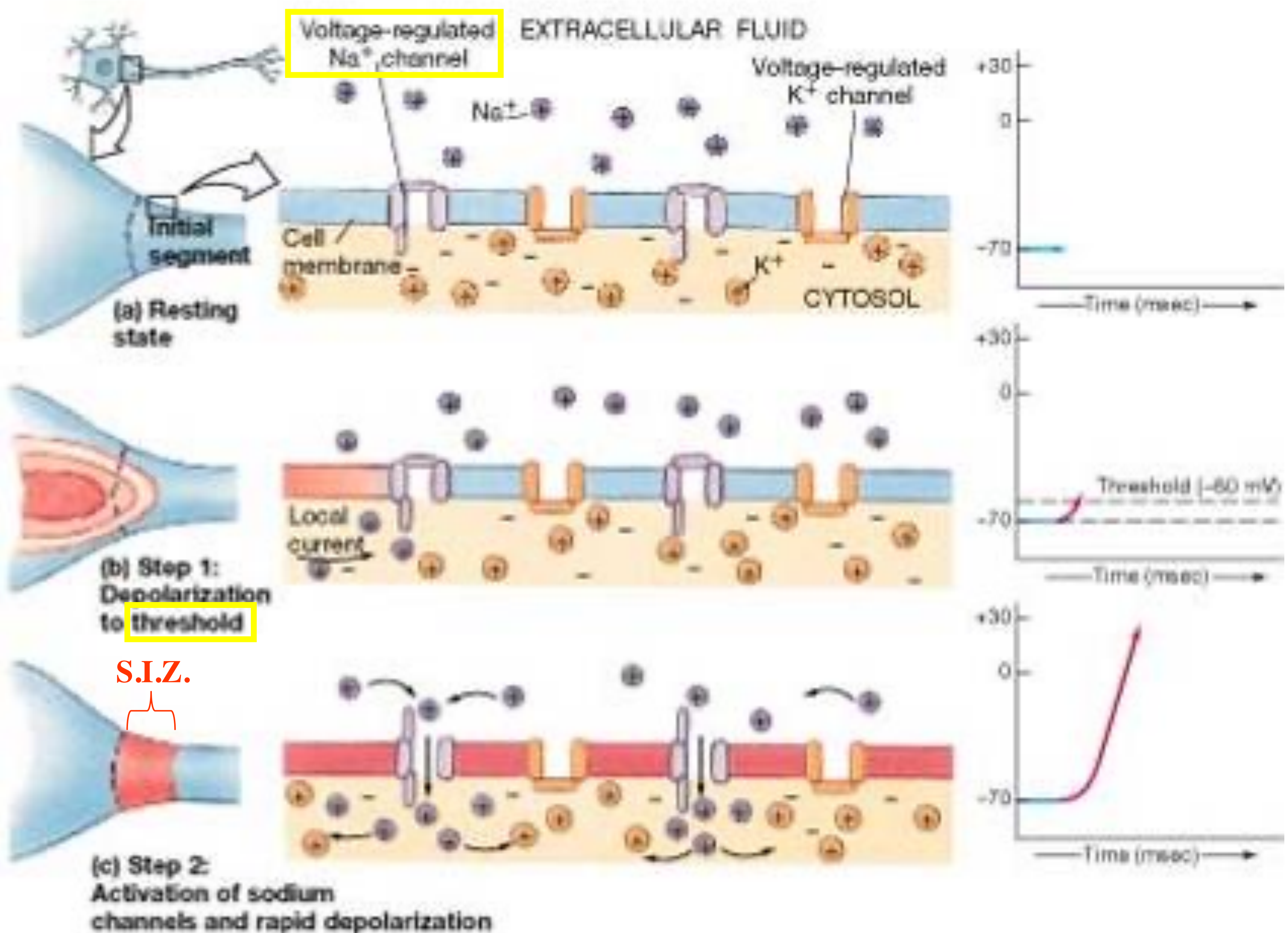



(c)

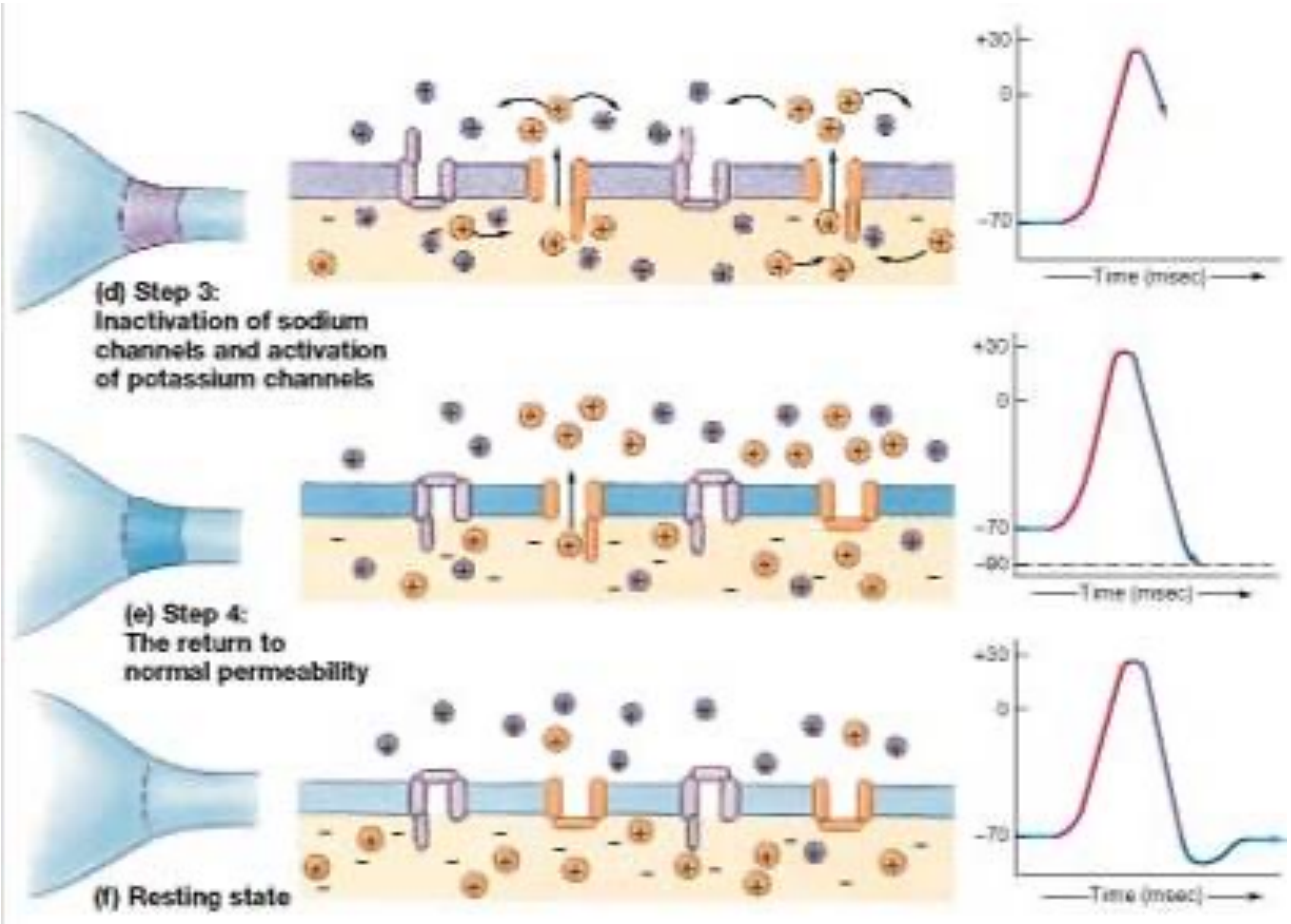
# Positive feedback loop



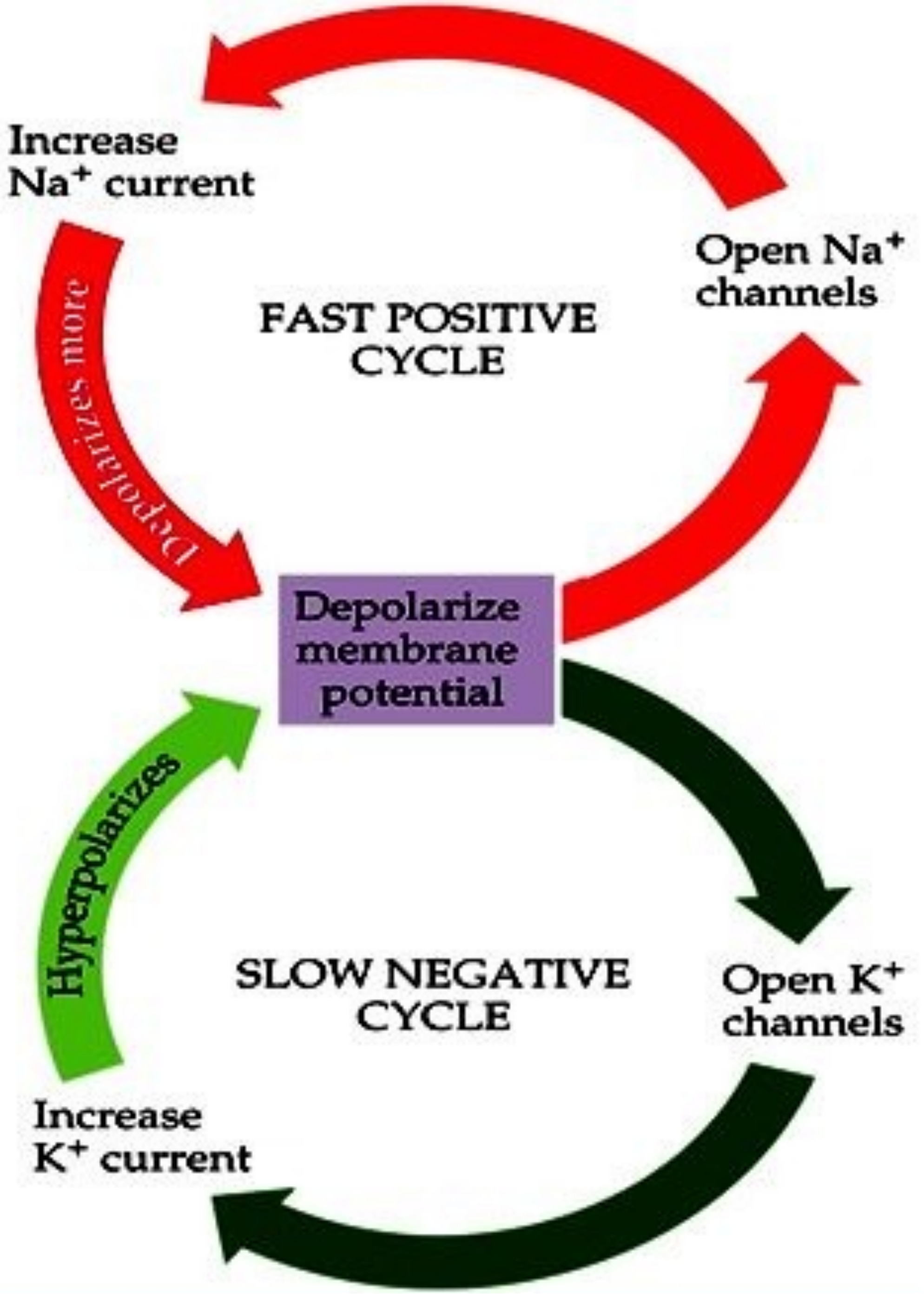
# Action potential initiation

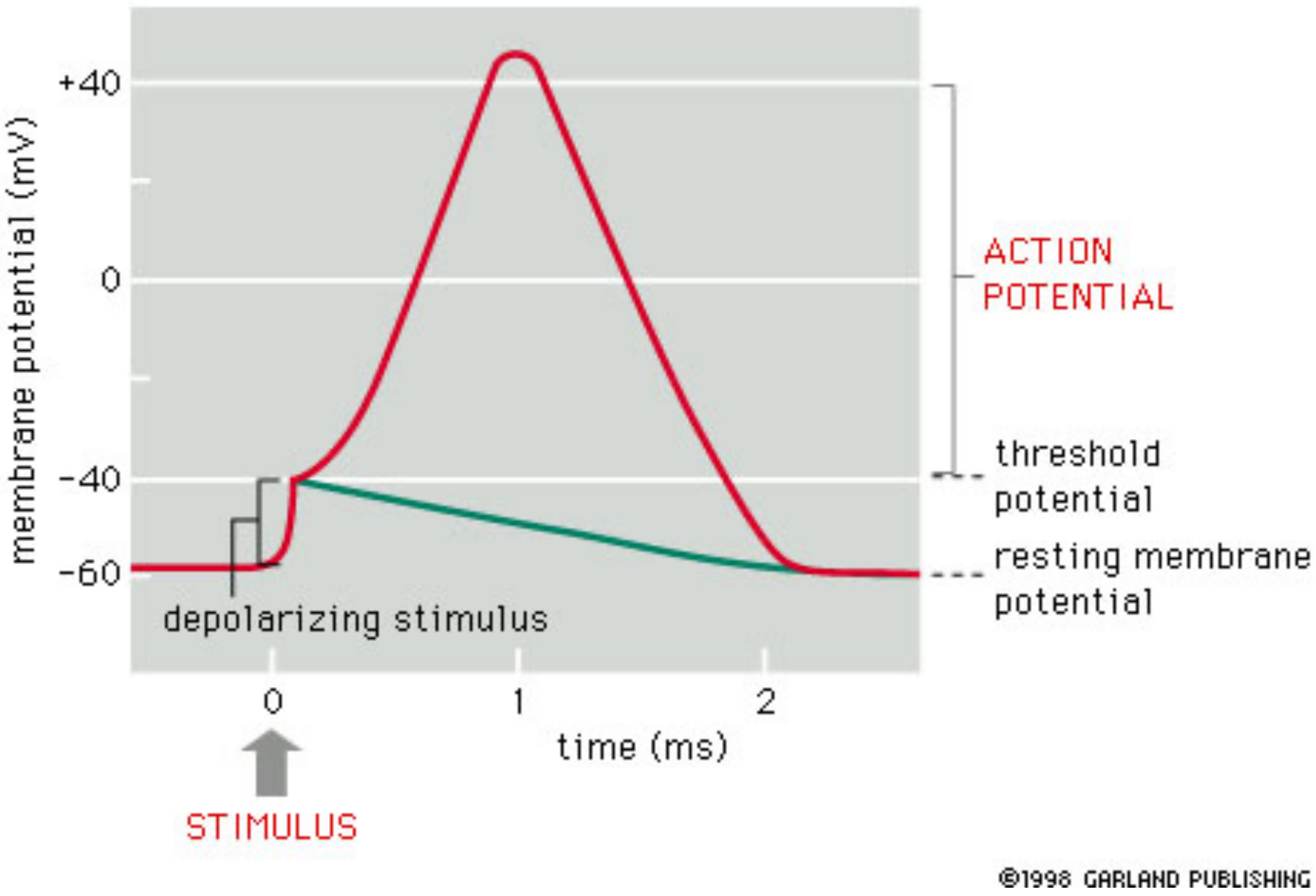


# Action potential termination



# Double feedback loop




+40
0
-40
-60
membrane potential (mV)
ACTION
POTENTIAL
threshold
potential
resting membrane
potential
depolarizing stimulus
0
1
2
time (ms)
STIMULUS
©1998 GARLAND PUBLISHING

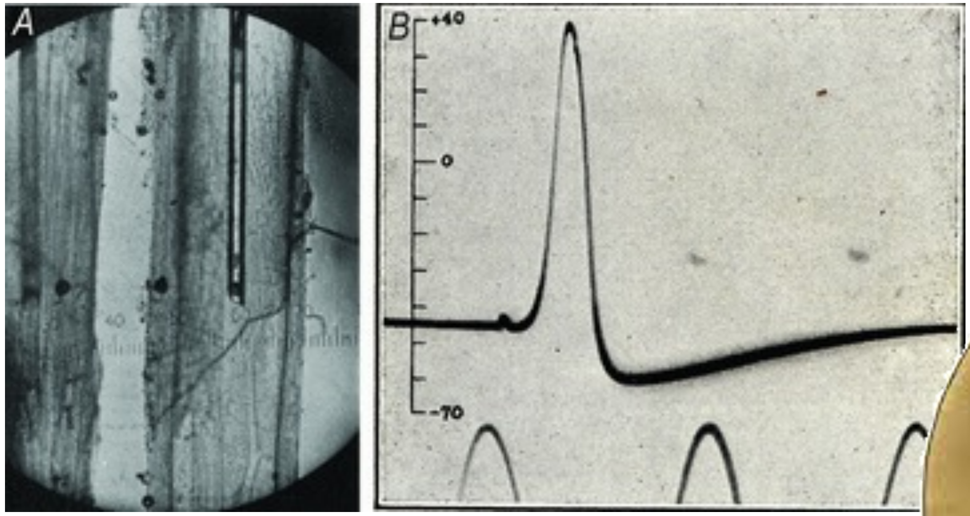
# Threshold Potential

- **Threshold potential**
  - a critical membrane potential level at which an action potential can occur.
  - plays a key role in the genesis of action potential.
- **threshold stimulus**
  - Stimulus is just strong enough to depolarize the membrane to the threshold potential level

# Electrophysiological Methods to Record Membrane Potential

- Two electrodes Voltage Clamp

# Hodgkin and Huxley

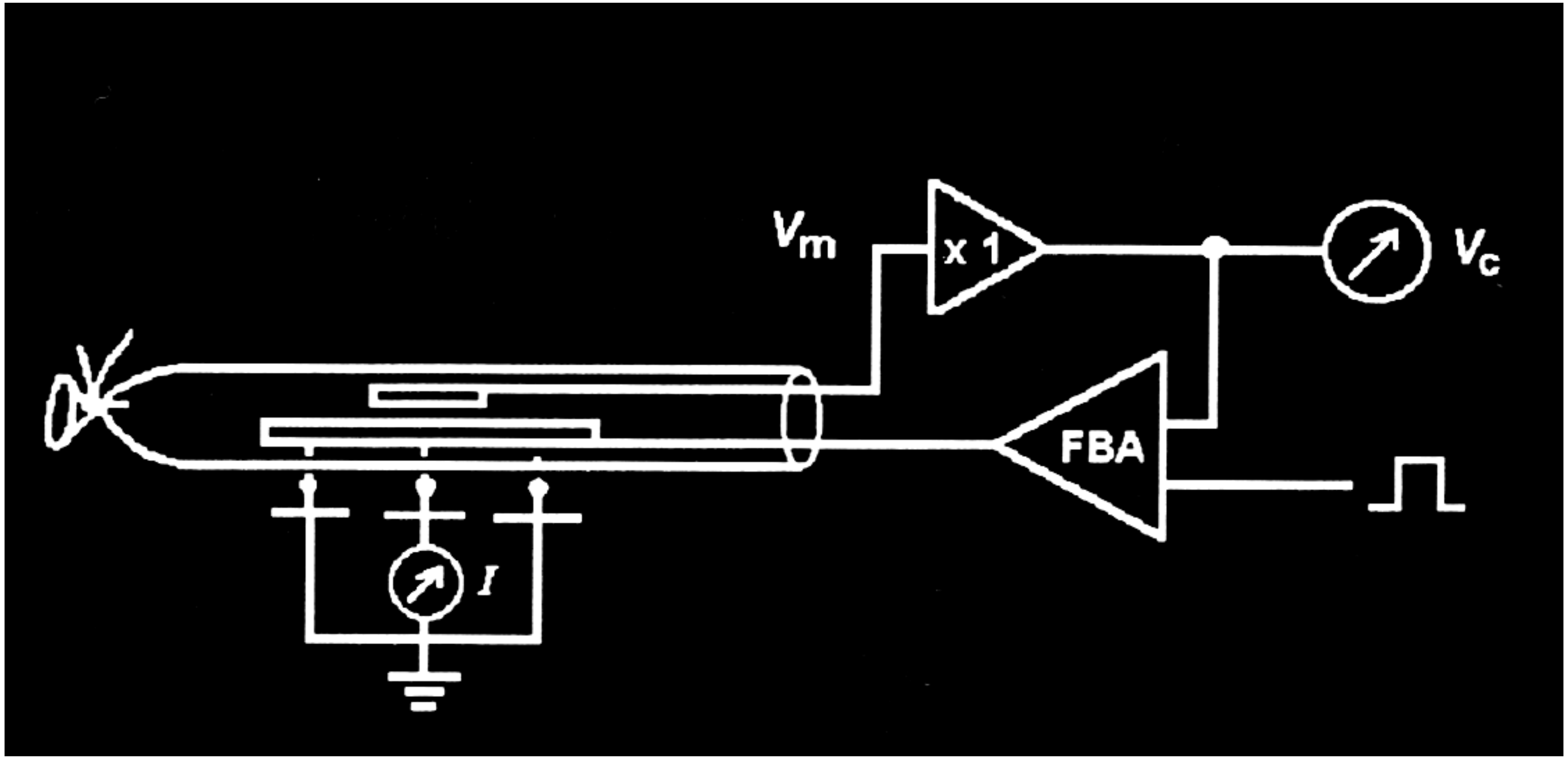




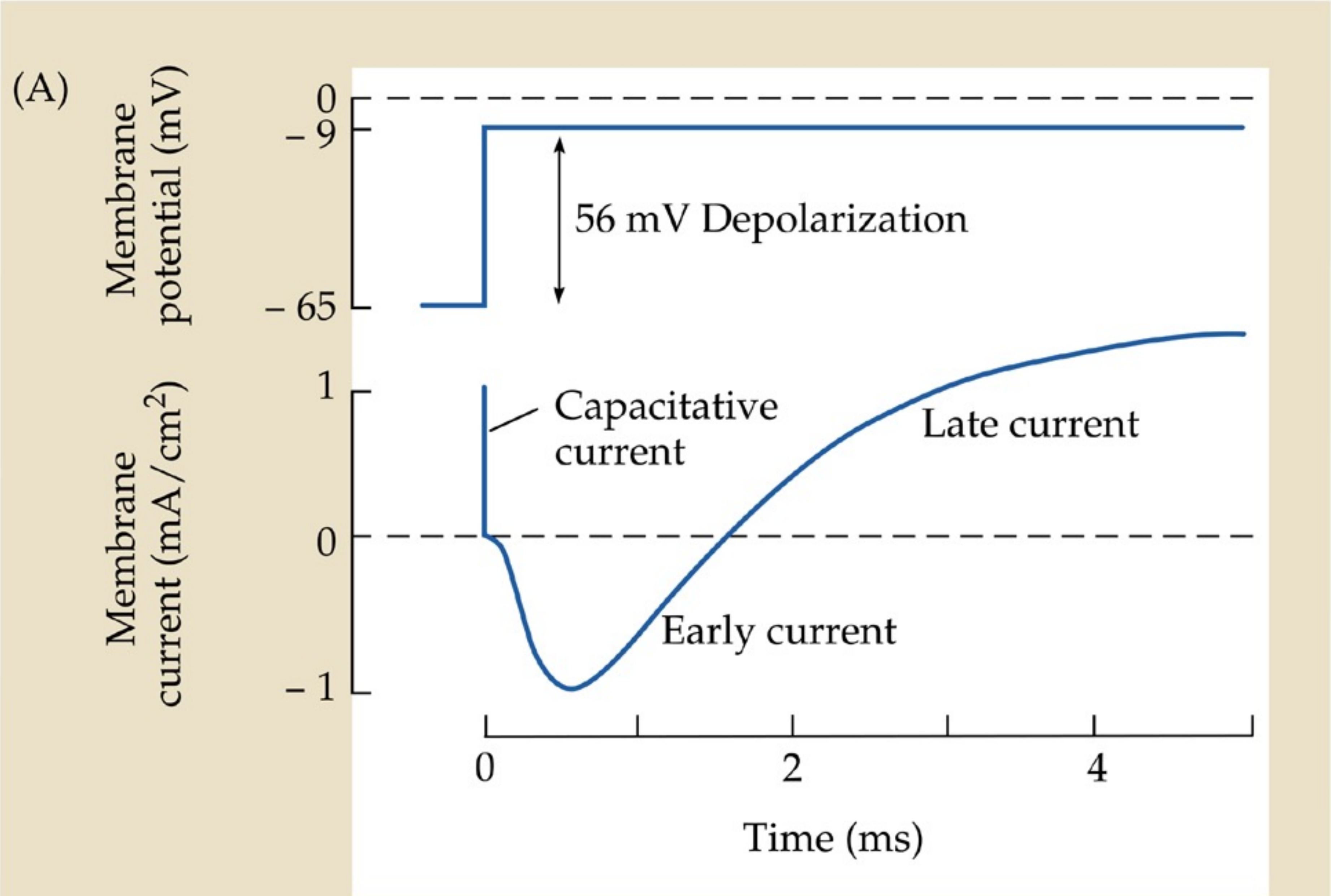
*"for their discoveries concerning the ionic mechanisms involved in excitation and inhibition in the peripheral and central portions of the nerve cell membrane"*

*1963*

# The voltage clamp

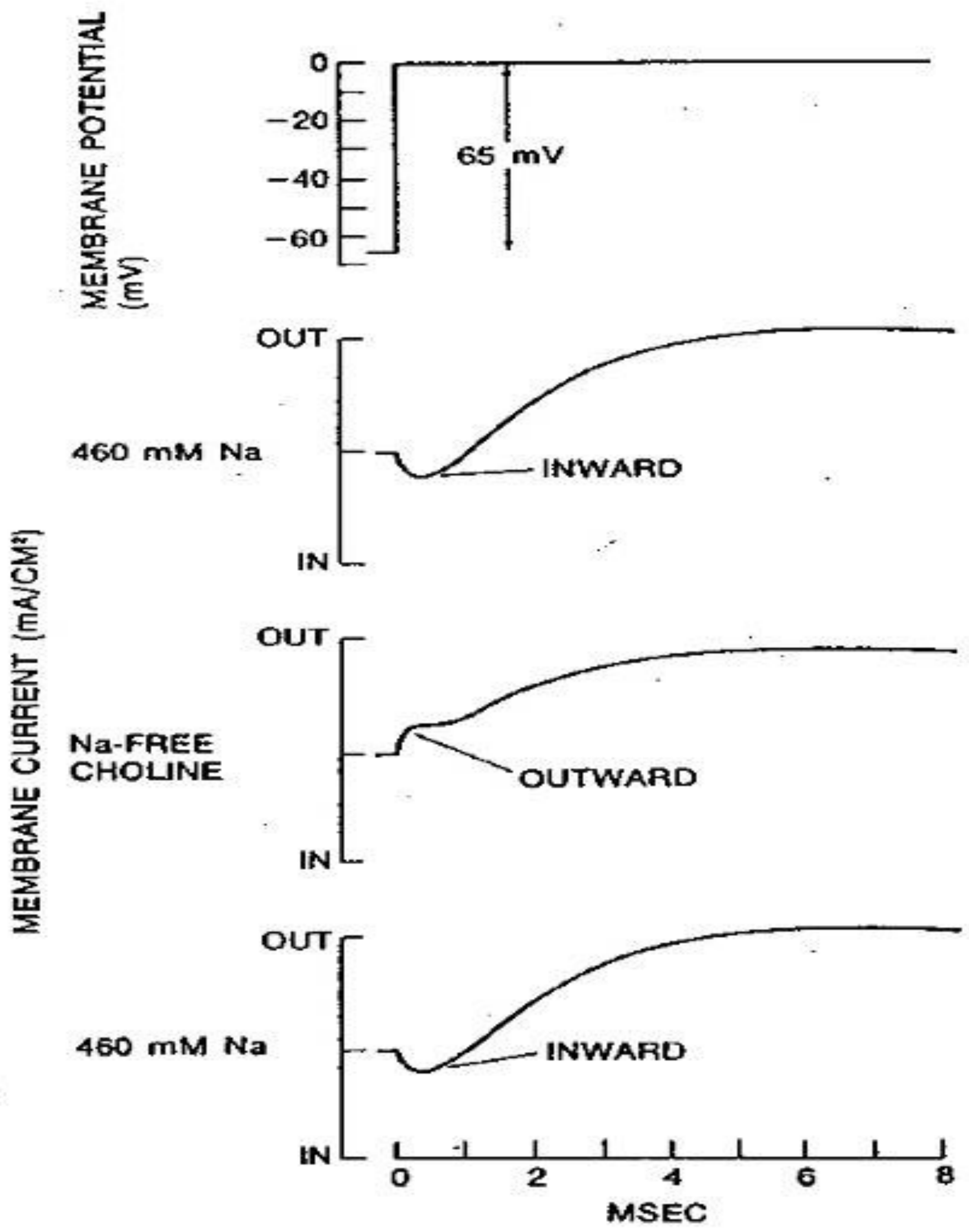



- a method for maintaining $V_m$ at any desired voltage level (FBA, Feedback Amplifier)



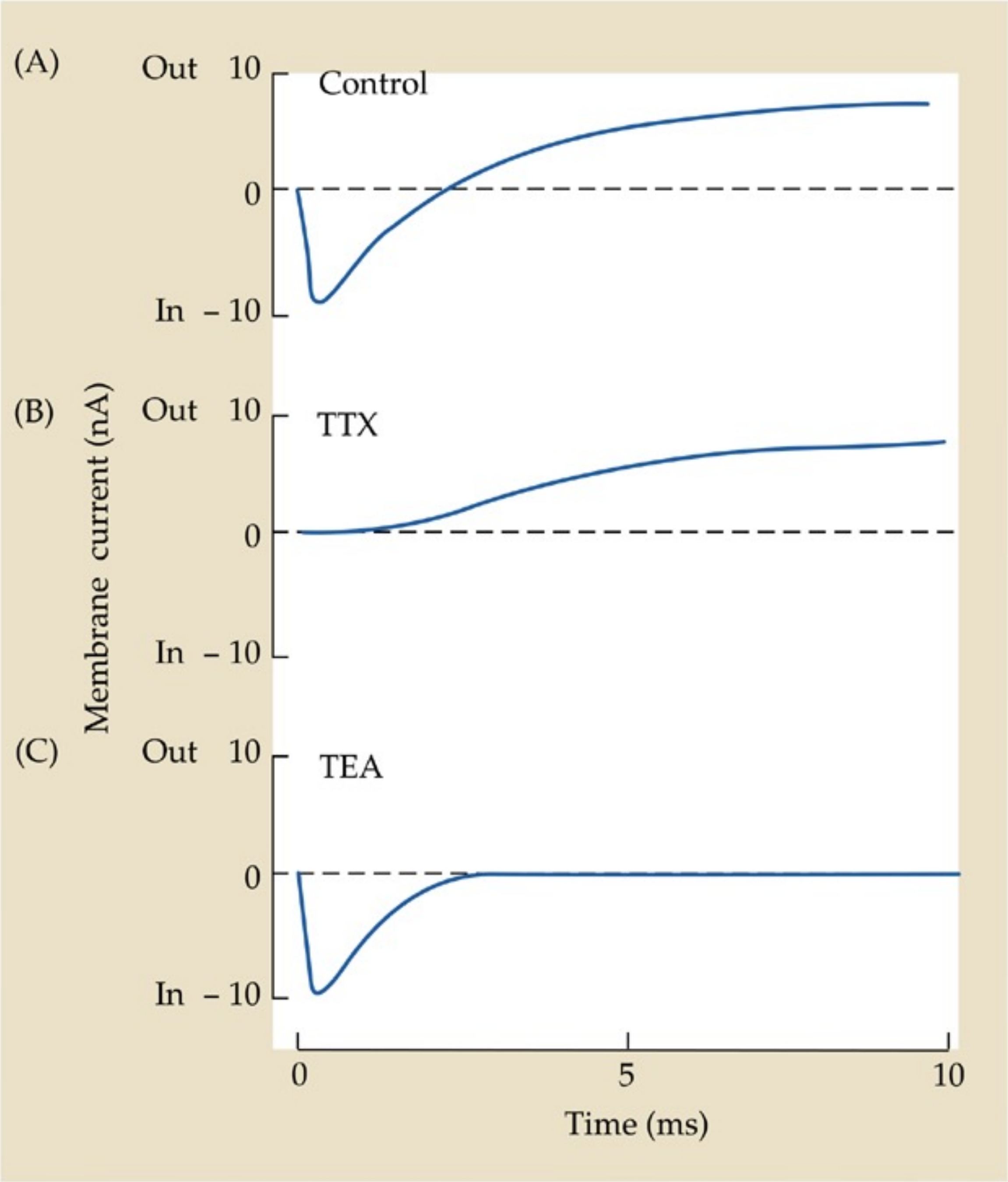

Triphasic response

# Evidence for a Sodium Current



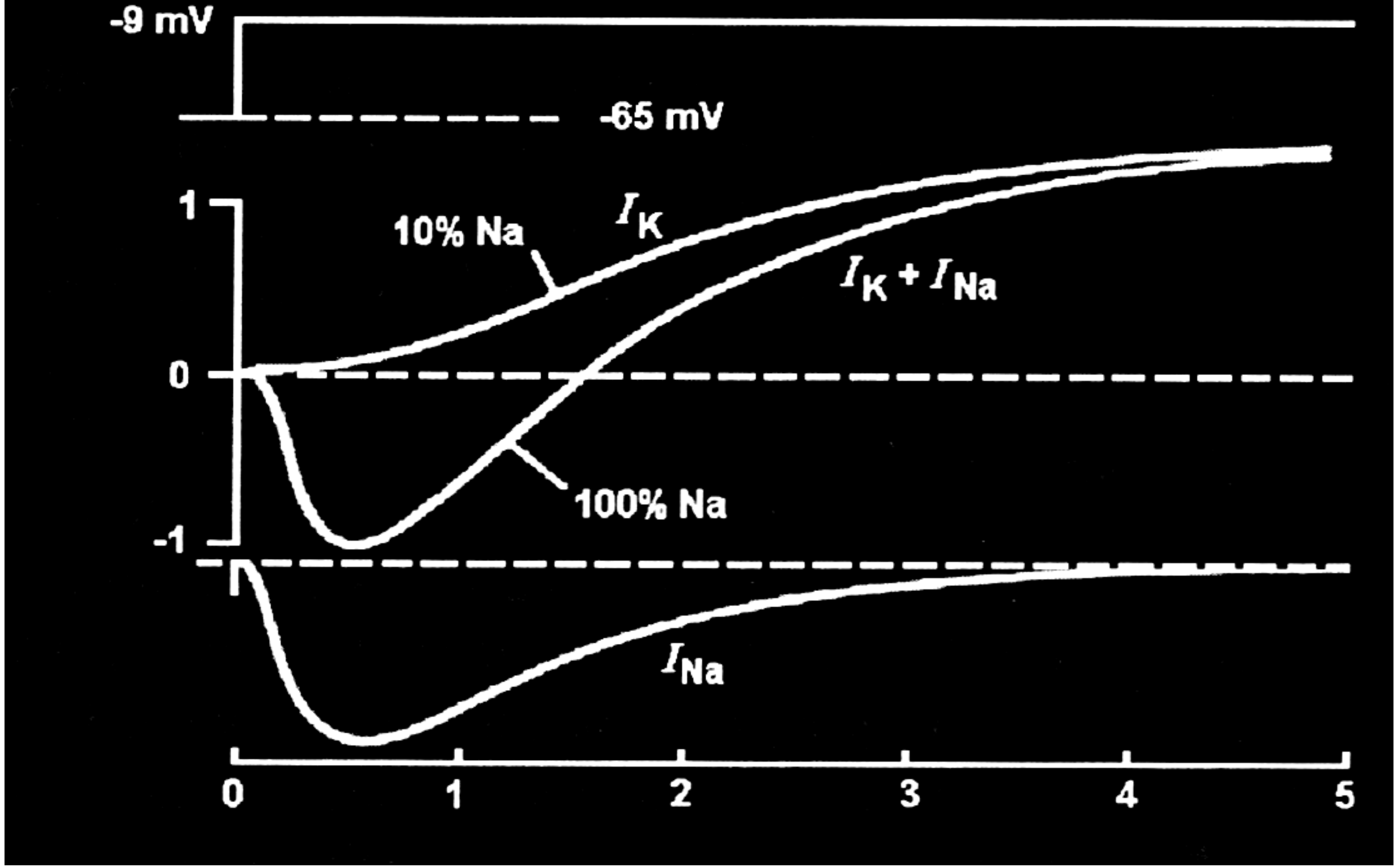

Remove extracellular sodium

# Modern proof of nature of currents

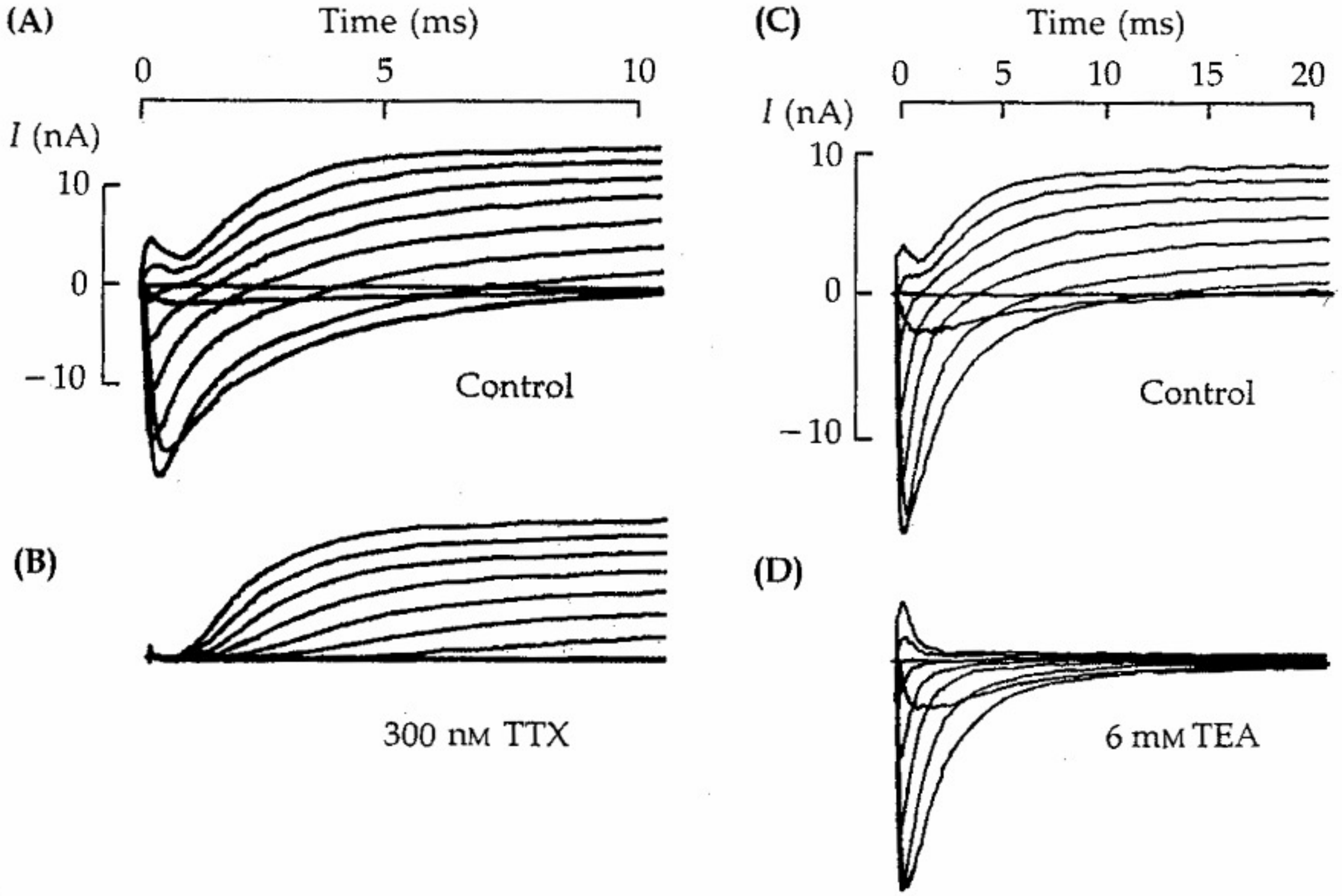





Use ion selective agents

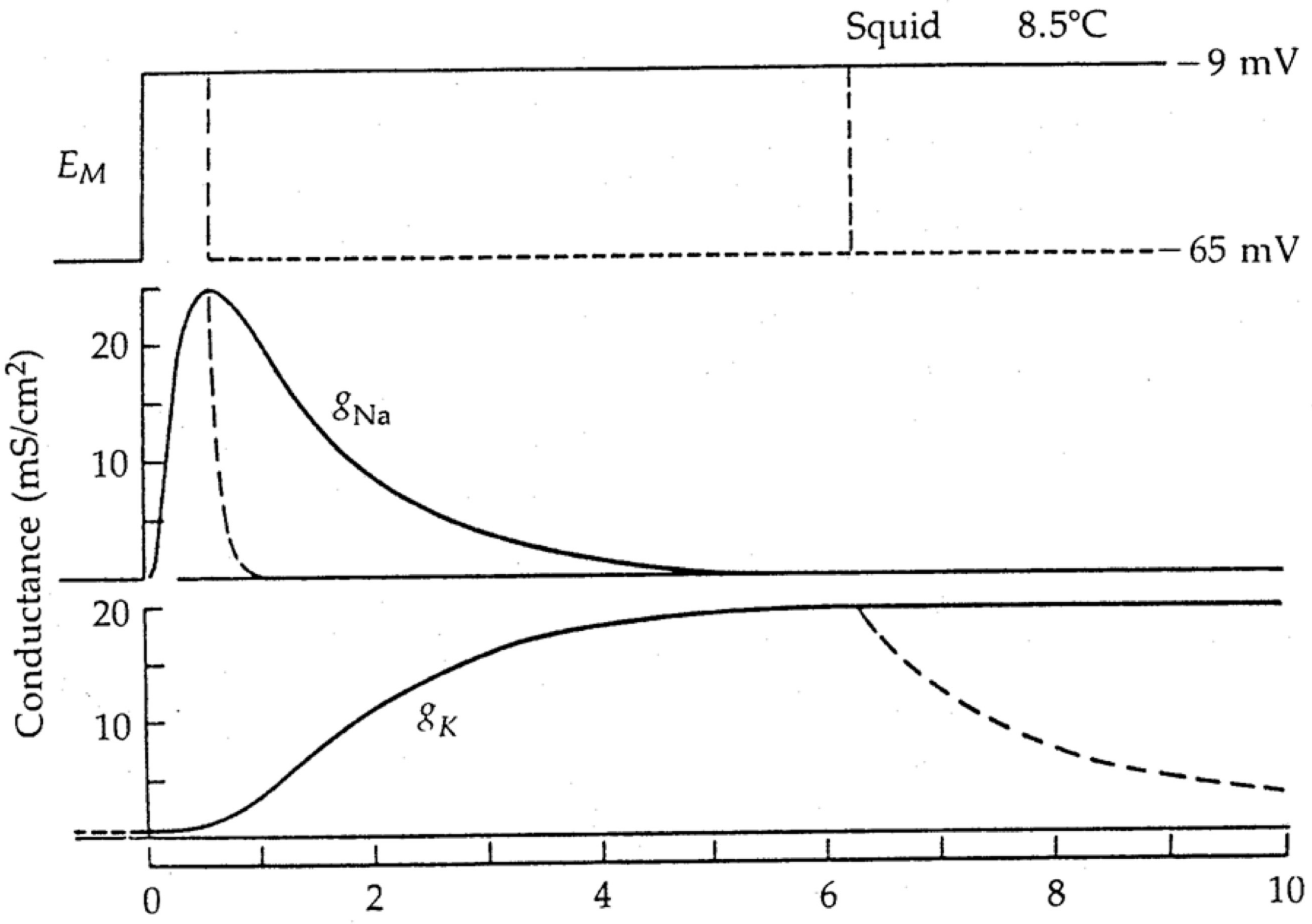



- Removing $Na^+$ from the bathing medium, $I_{Na}$ becomes negligible so $I_K$ can be measured directly.
- Subtracting this current from the total current yielded $I_{Na}$.

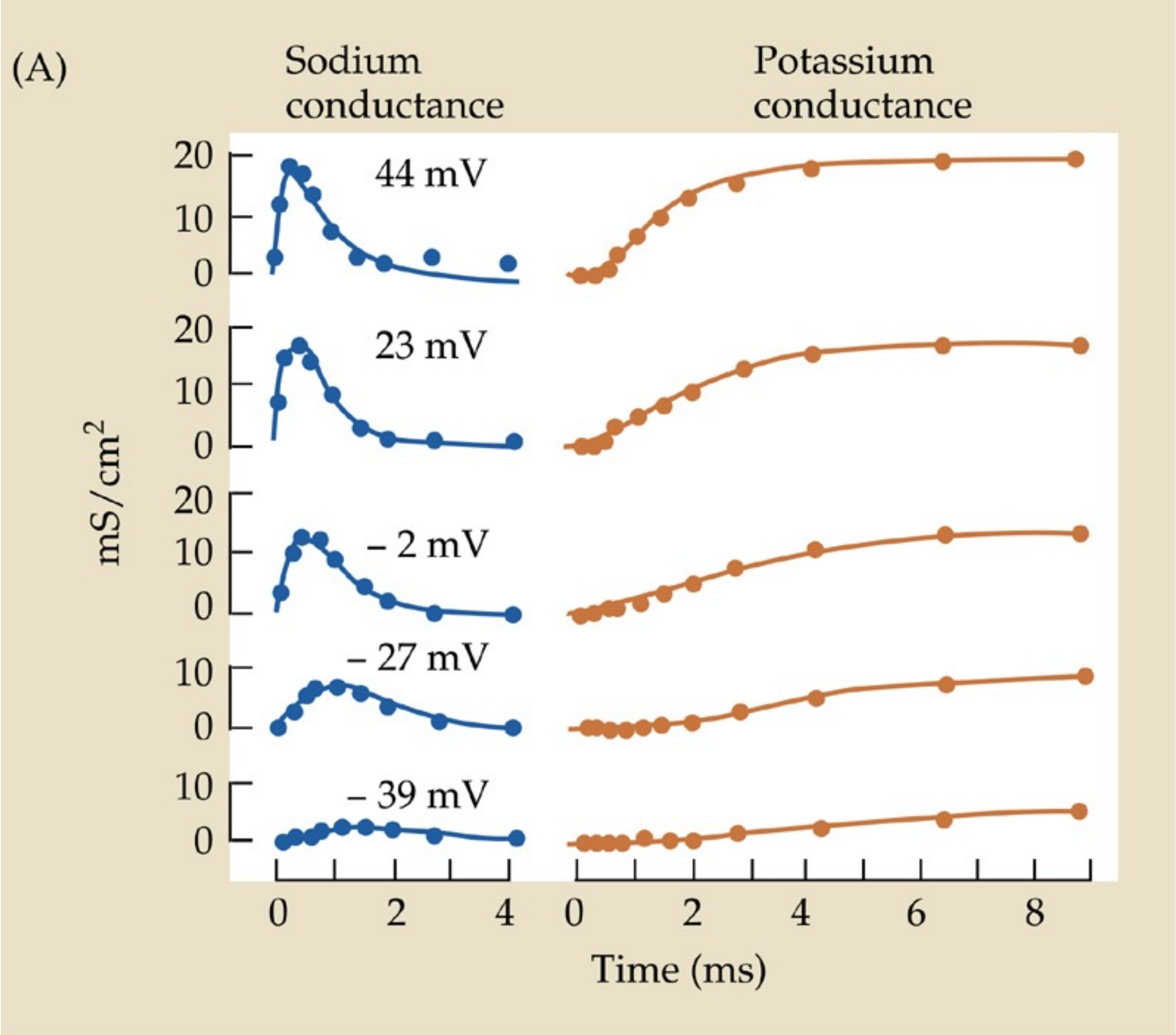


(A)
Time (ms)
0
5
10
I (nA)
10
0
−10
Control
(B)
300 nM TTX
(C)
Time (ms)
0
5
10
15
20
I (nA)
10
0
−10
Control
(D)
6 mM TEA

# Conductance of $Na^+$ and $K^+$ channels

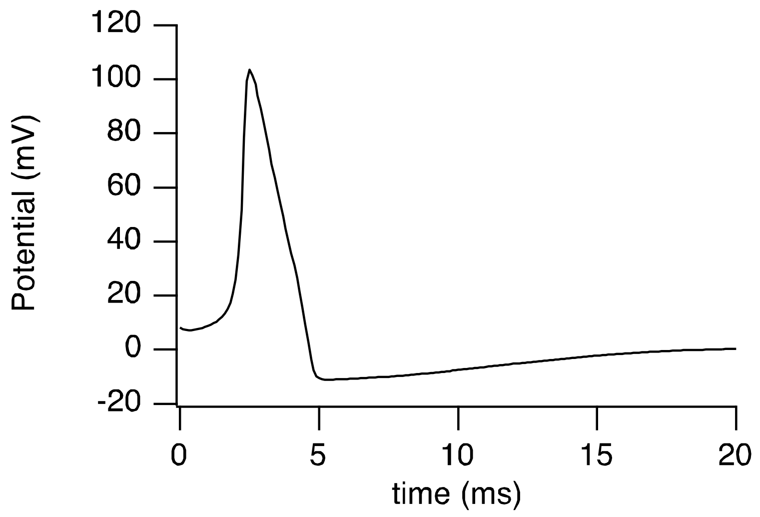


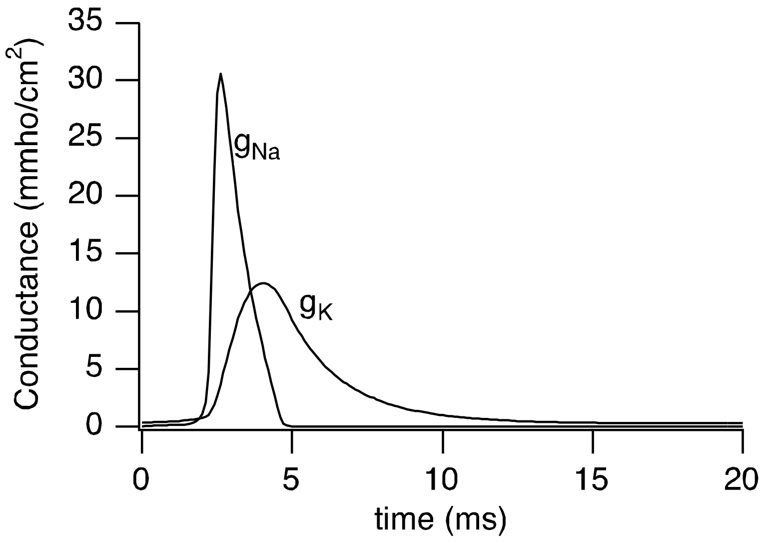
# Voltage-Dependence of Conductance



# Action potential

- $g_{Na}$ increases quickly, but then inactivation kicks in and it decreases again.
- $g_K$ increases more slowly, and only decreases once the voltage has decreased.
- The $Na^+$ current is **autocatalytic**. An increase in *V* increases $g_{Na}$ , which increases the $Na^+$ current, and increases *V*, etc.
- Hence, **the threshold for action potential initiation is where the inward $Na^+$ current exactly balances the outward $K^+$ current**.

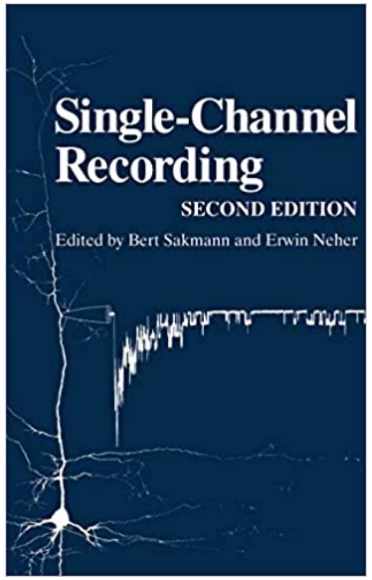


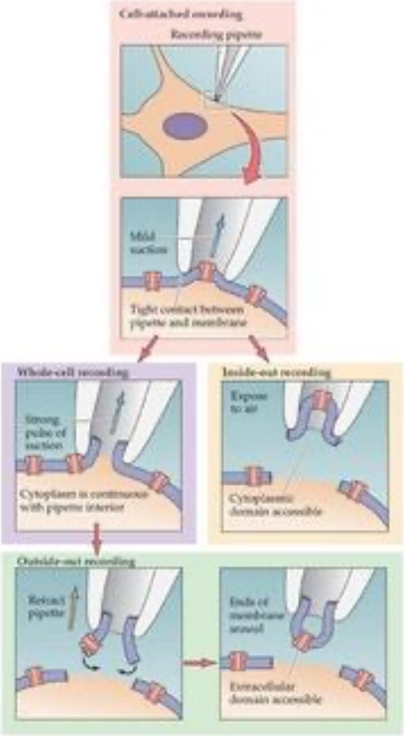



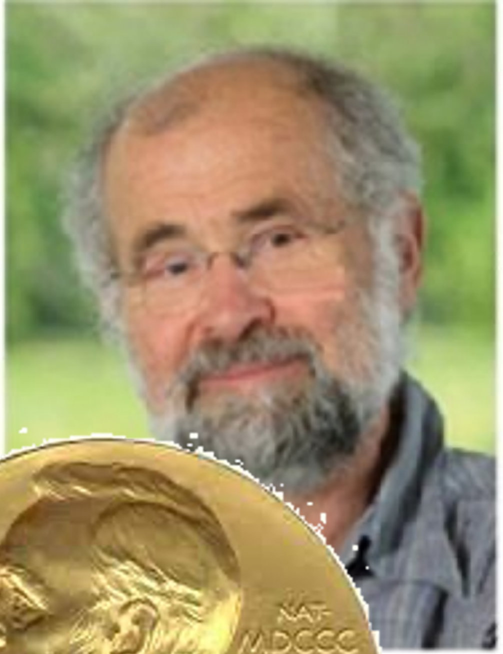
# Electrophysiological Methods to Record Membrane Potential

## Patch Clamp

# Erwin Neher and Bert Sakmann



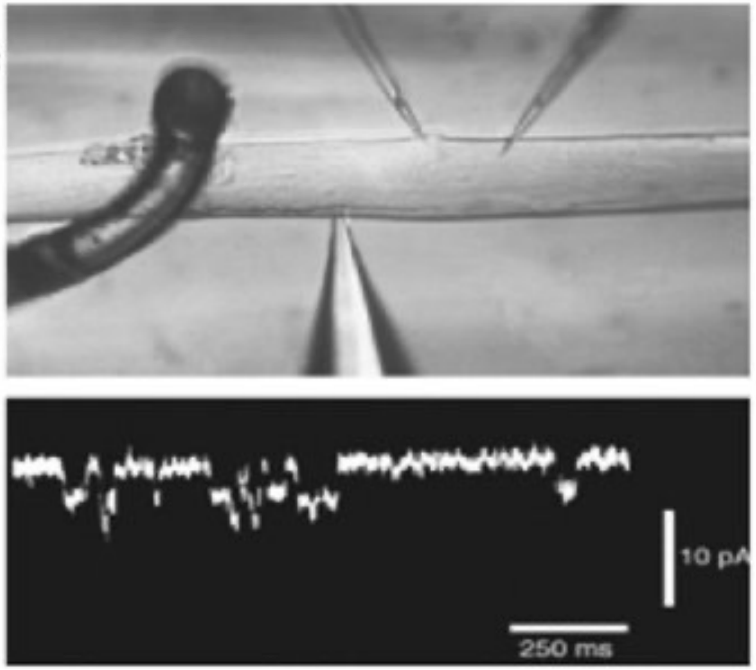




Bert Sakmann (1942)

B

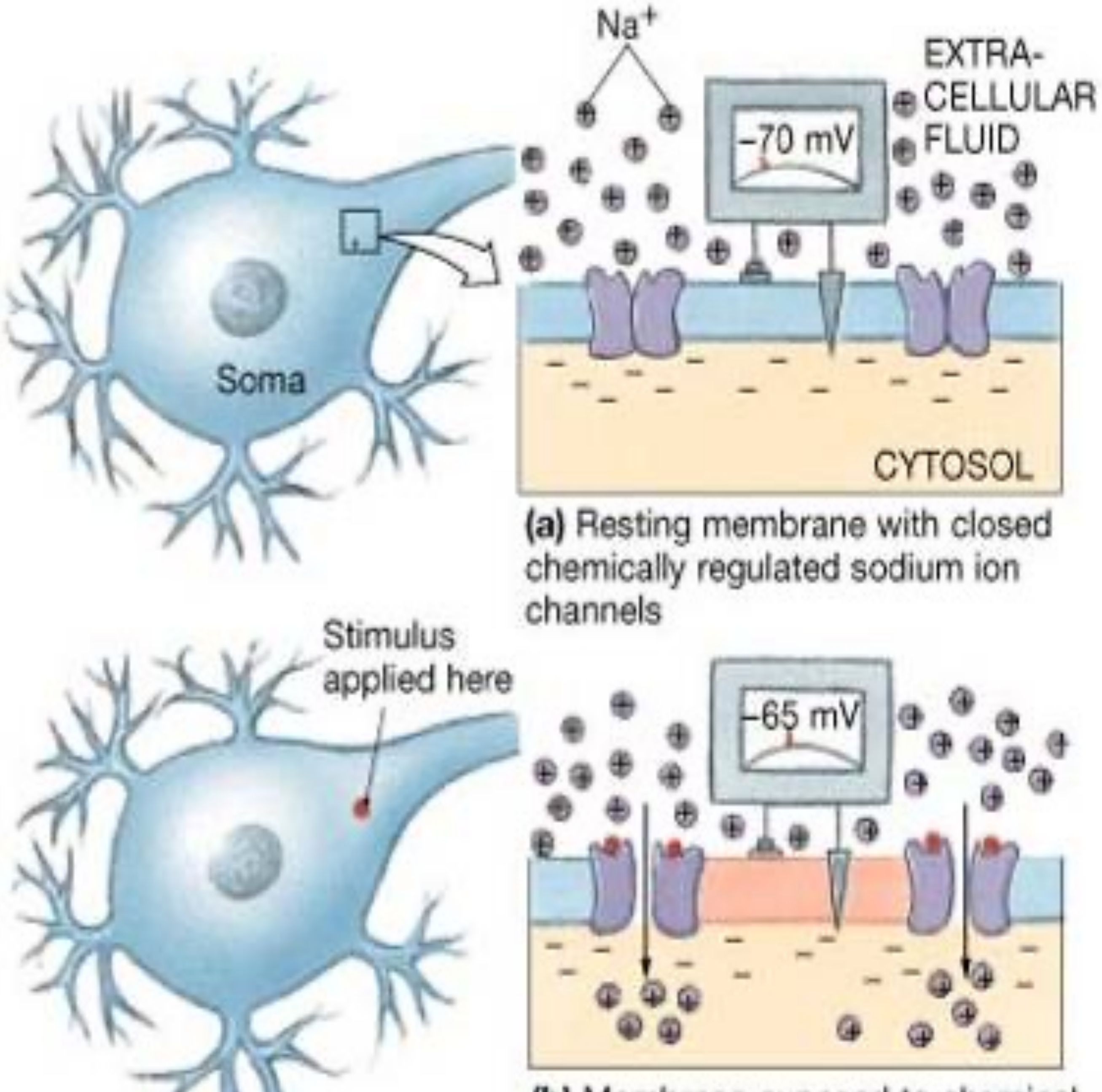
C




*"for their discoveries concerning the function of single ion channels in cells"*
*1991*

- Bioelectrical Phenomena of the Cell:
- 3: Local responses

# Graded (local) potential changes




(a) Resting membrane with closed chemically regulated sodium ion channels

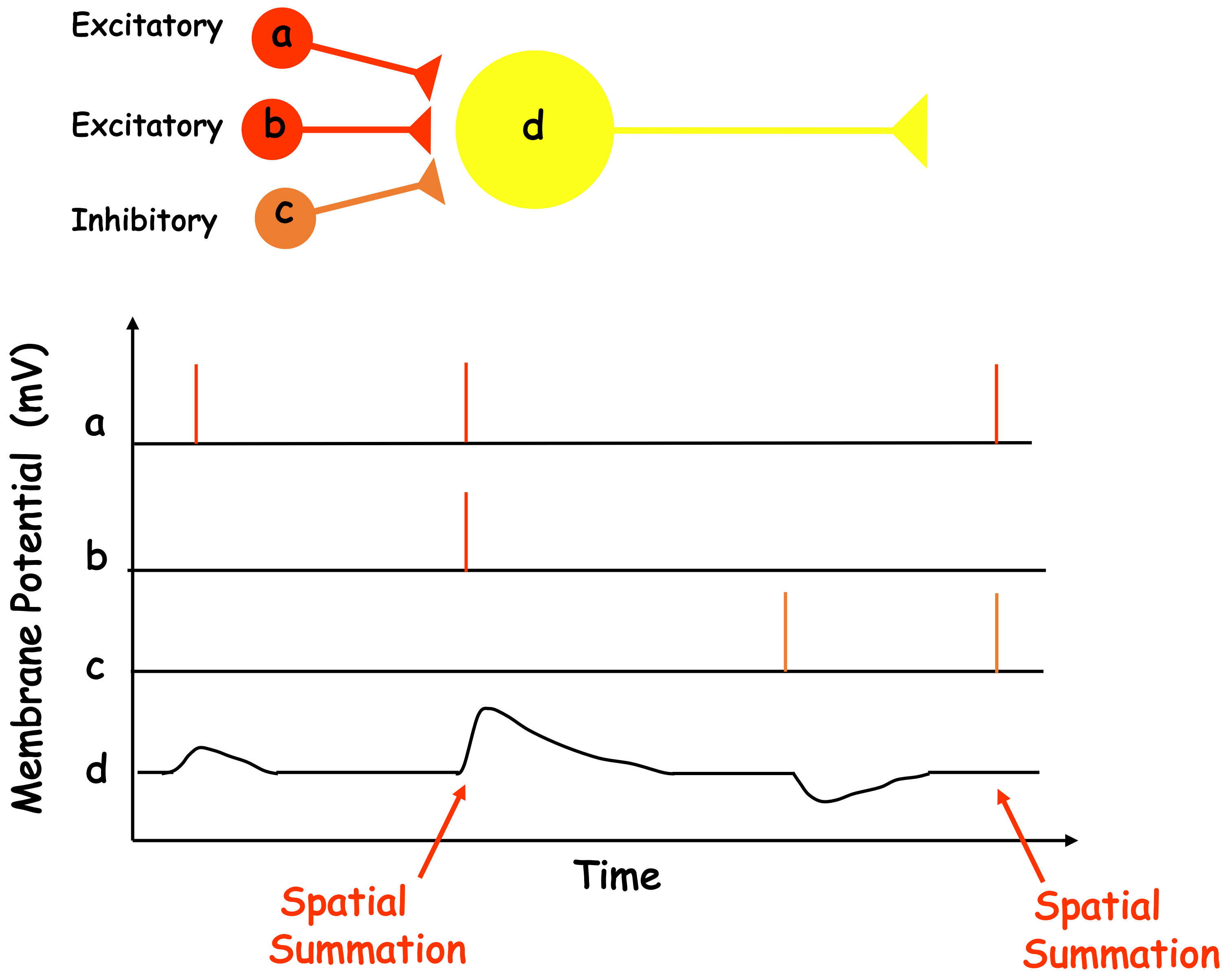
(b) Membrane exposed to chemical that triggers the opening of these sodium ion channels

2 x more chemical=
2 x more potential change

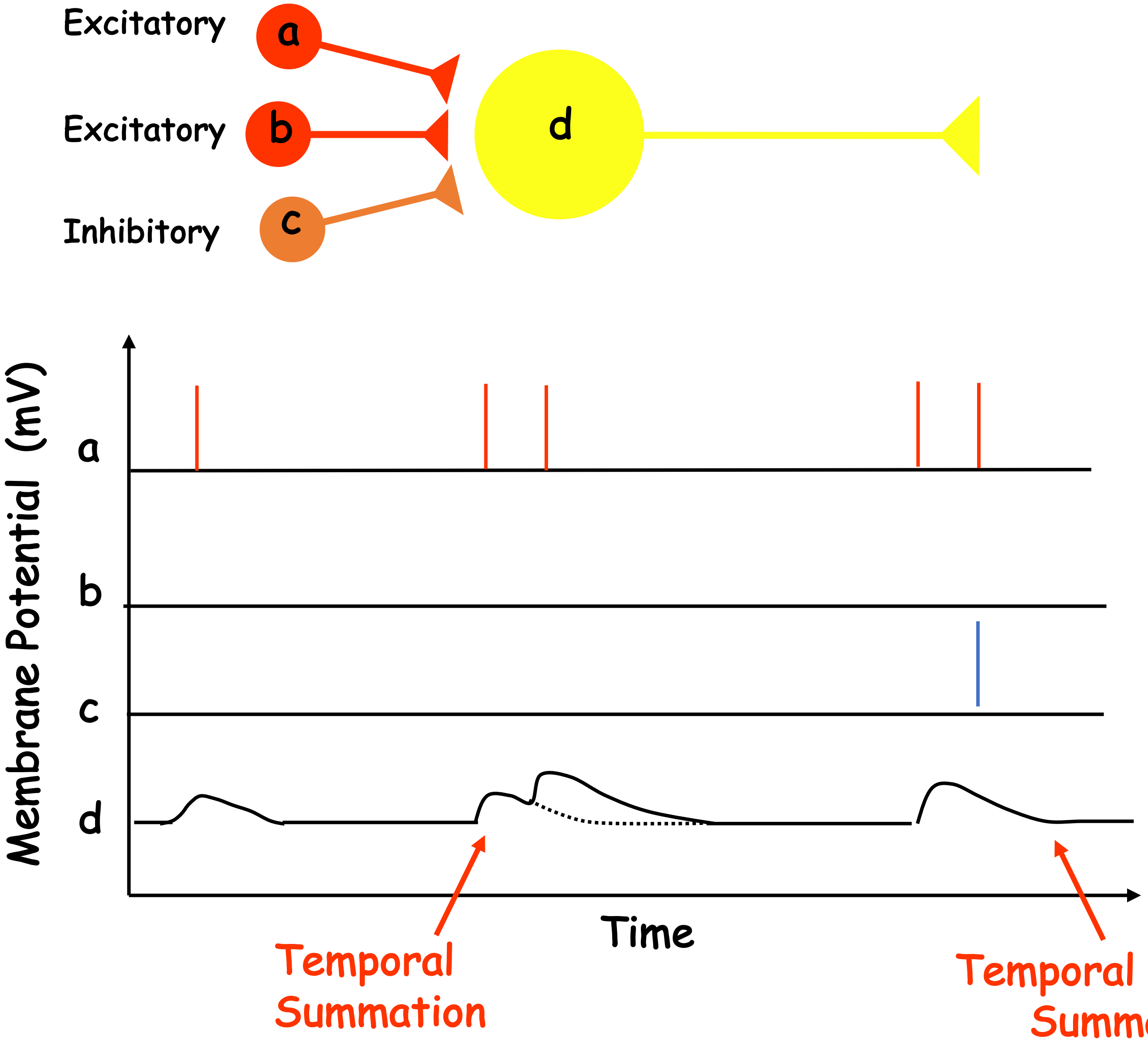
# Local Response

- Definition:
  - a small change in membrane potential caused by a subthreshold stimulus
- Properties:
  - graded potential
  - Propagation: electronic conduction
  - can be summed by two ways
    - Spatial summation
    - Temporal summation

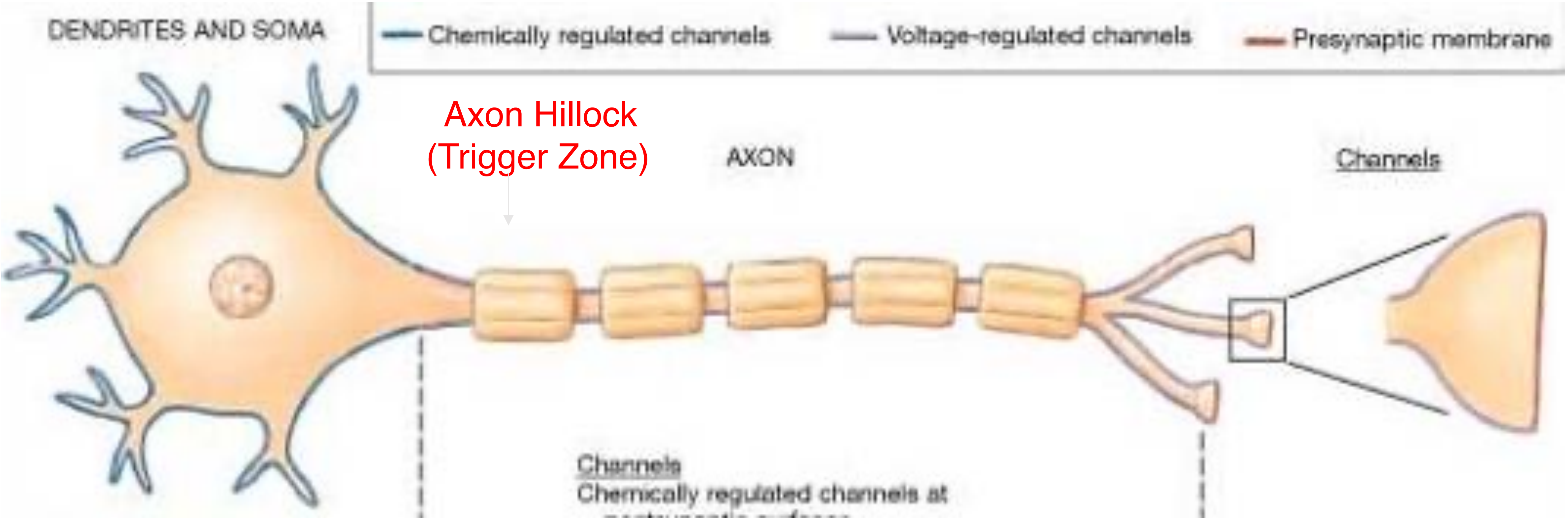
# Local Response: spatial summation



# Local Response: temporal summation



# Distribution of ion channels

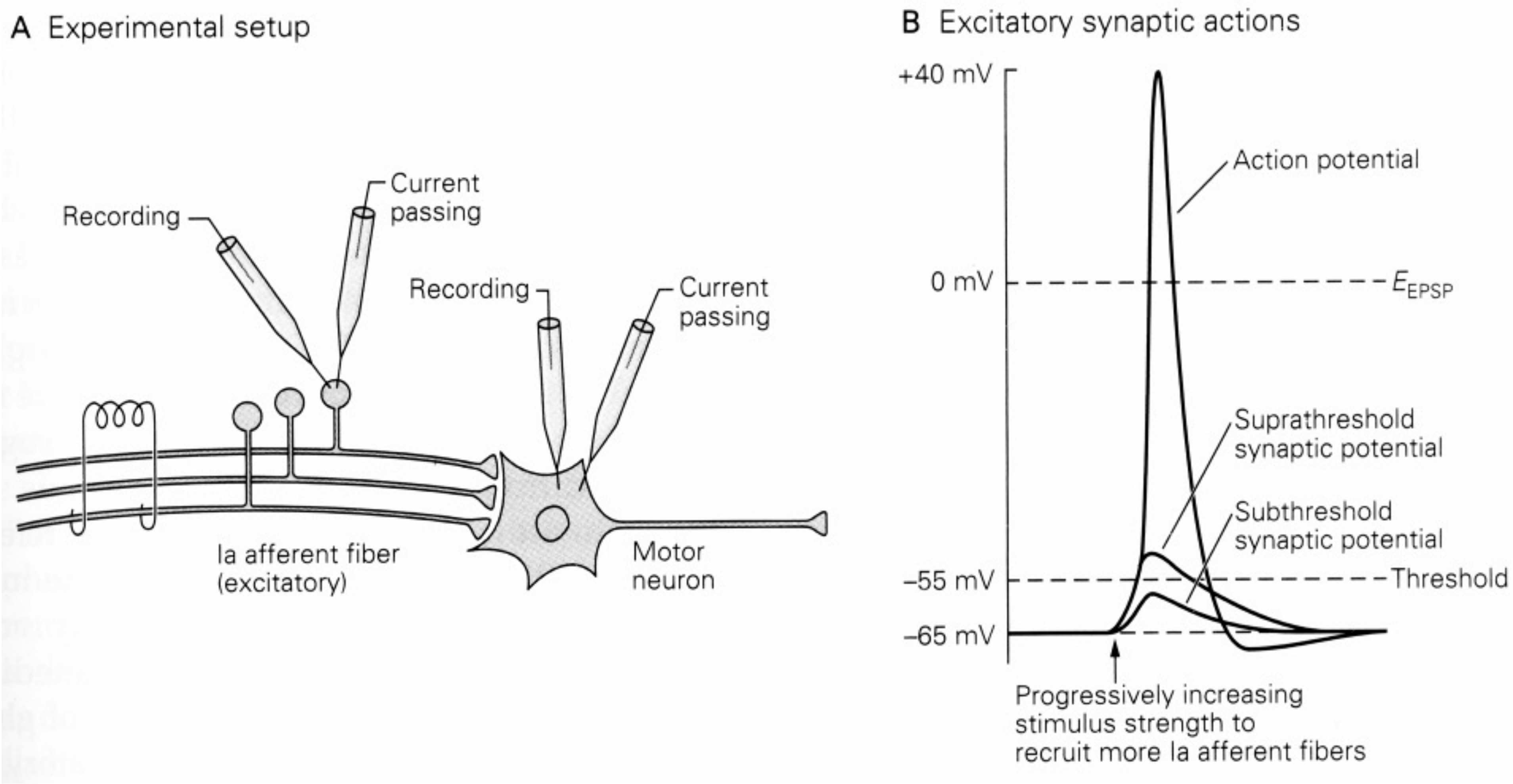



*Leak channels everywhere*

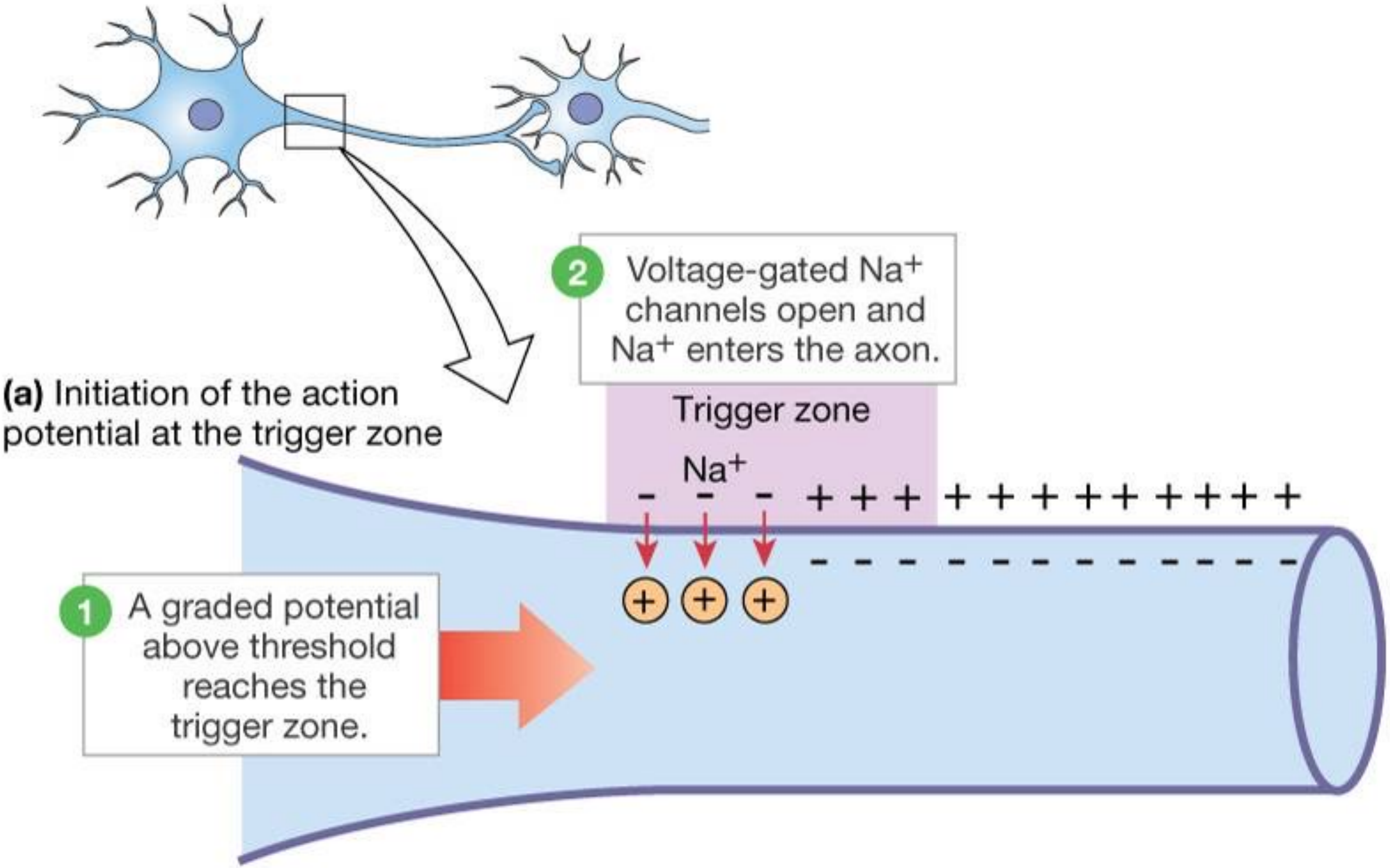
# Role of the Local Potential

- Facilitate the cell.
  - This means it increase excitability of the stimulated cell
- Cause the cell to excite once it is summed to reach the threshold potential

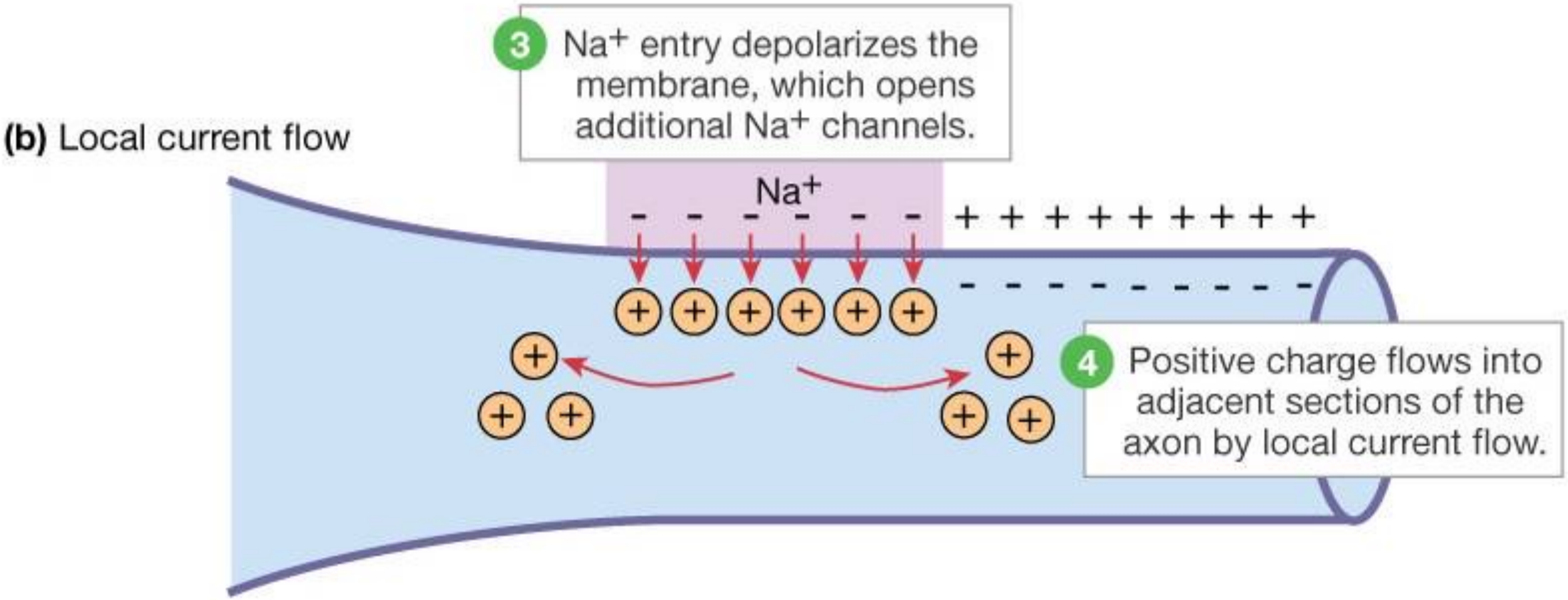
# Role of the Local Potential



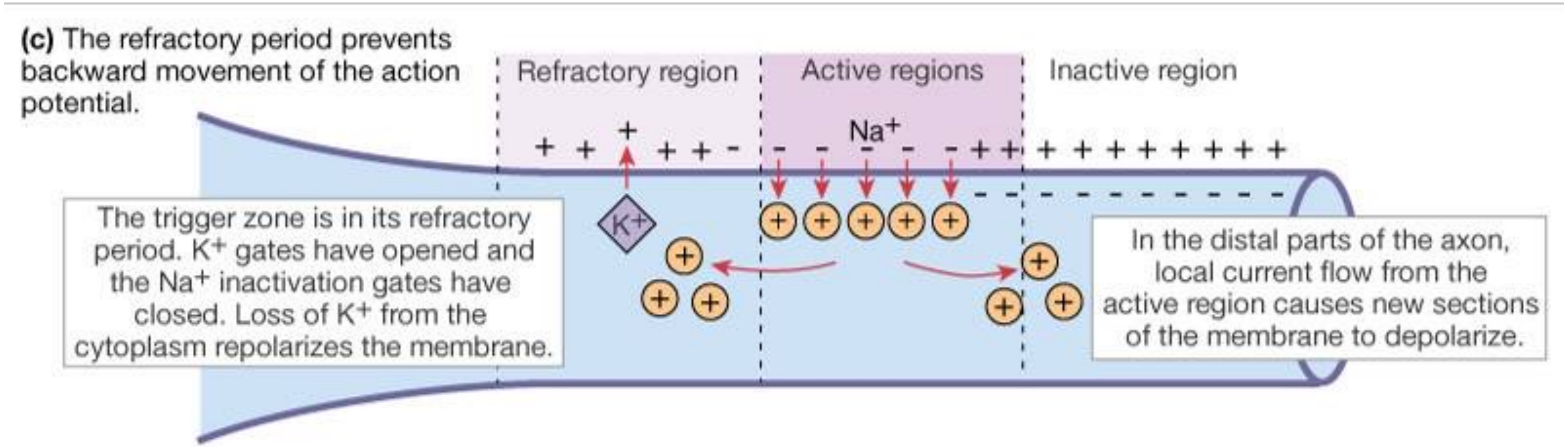
# Propagation of the Action Potential



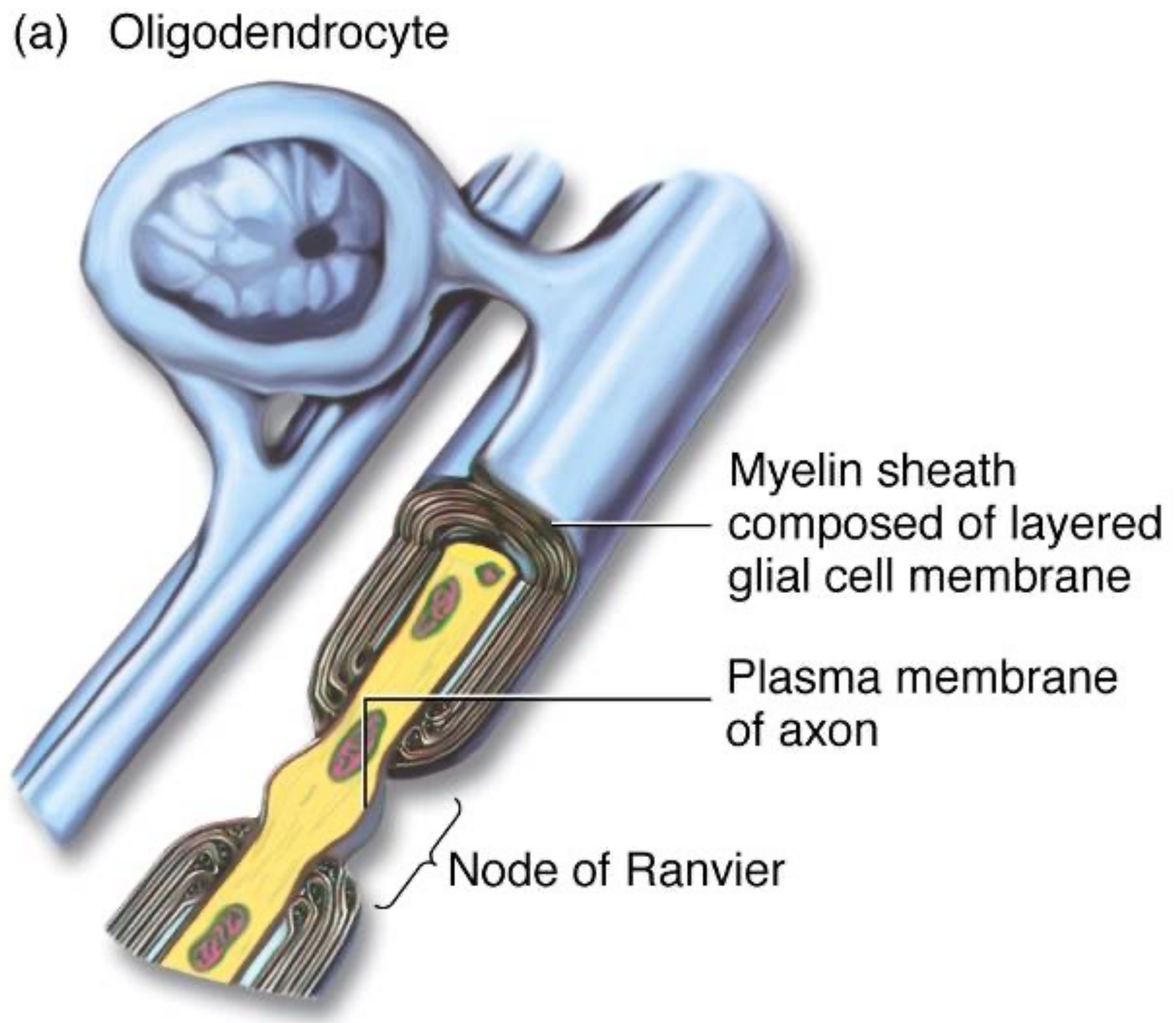
# Propagation of the Action Potential



# Propagation of the Action Potential

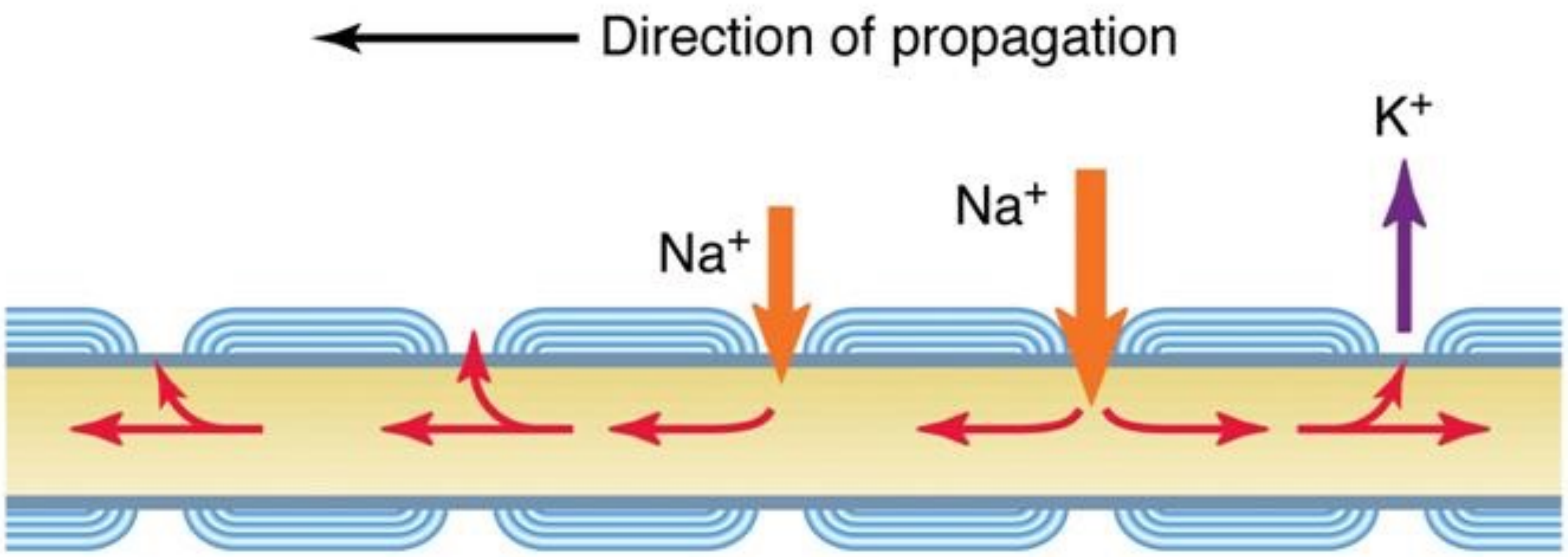


# Propagation of the Action Potential: Myelin




Myelinated neuron of the central nervous system

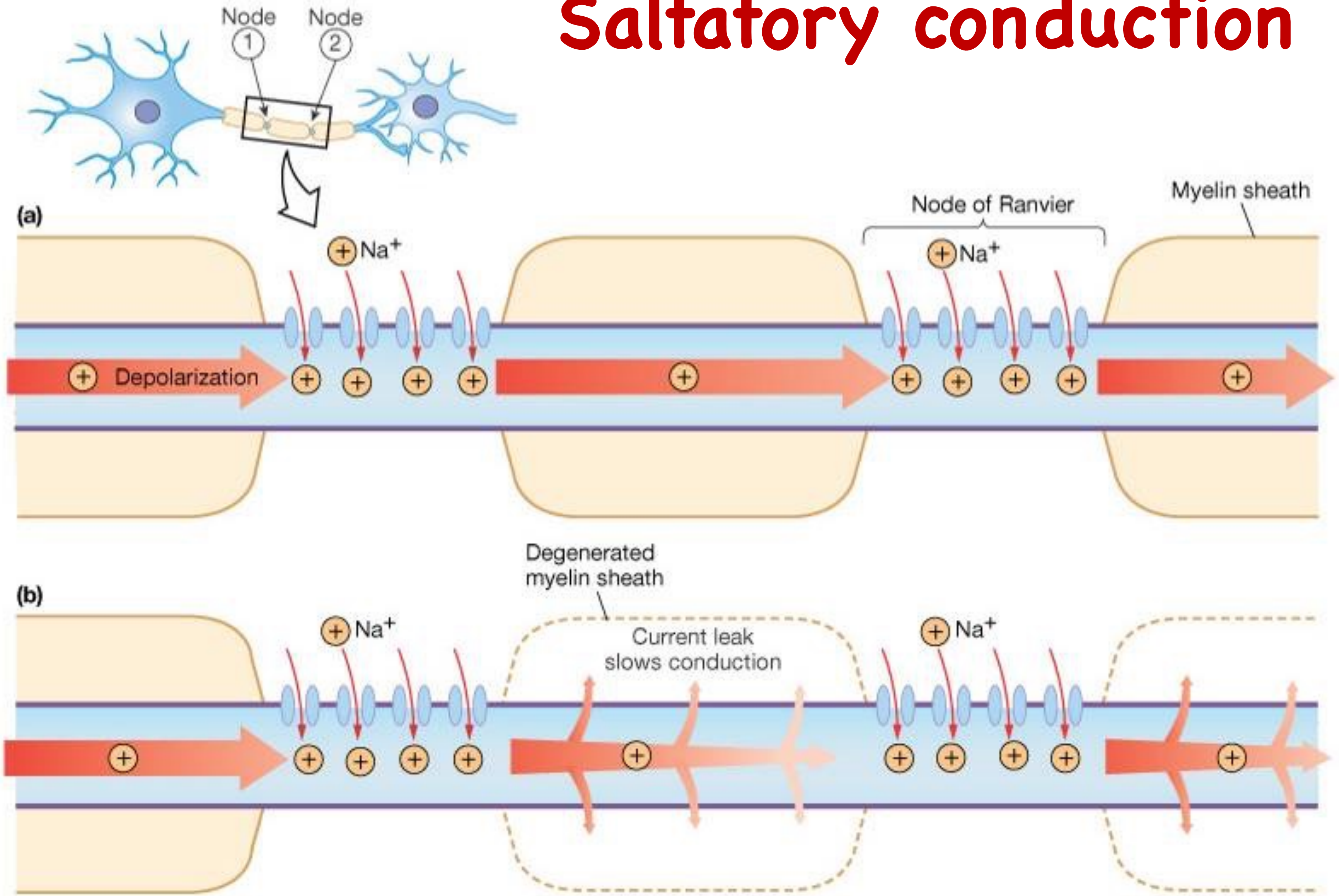
# Propagation of the Action Potential: Myelin



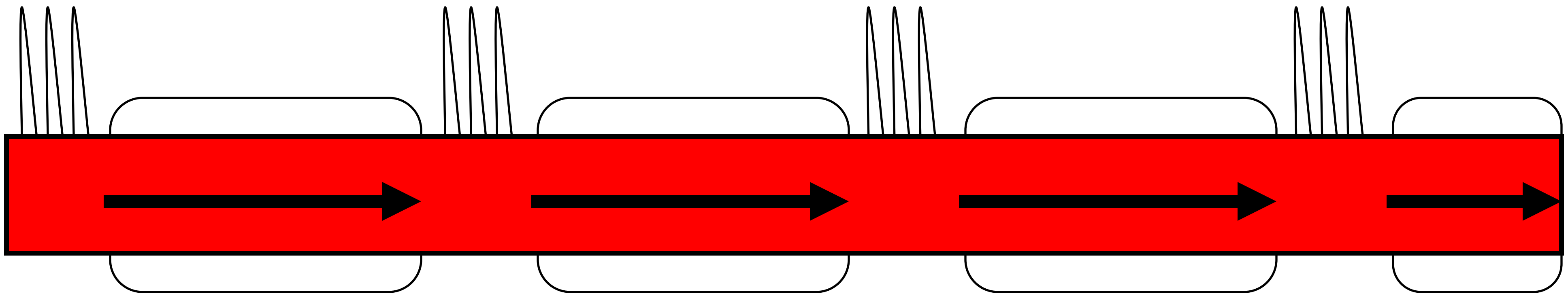

**Saltatory conduction:**

**The action potential jumps from node to node**

# Saltatory conduction



# Saltatory conduction



# Saltatory conduction

- The pattern of conduction in the myelinated nerve fiber from node to node
- It is of value for two reasons:
  - very fast
  - preserves energy.

# Propagation of the Action Potential

*Table 6-1* The diameter of frog axons and the presence or absence of myelination control the conduction velocity.

| Fiber type | Average axon diameter (μm) | Conduction velocity ($m \cdot s^{-1}$) |
|---|---|---|
| **Myelinated fibers** | | |
| Aα | 18.5 | 42 |
| Aβ | 14.0 | 25 |
| Aγ | 11.0 | 17 |
| B | Approximately 3.0 | 4.2 |
| **Unmyelinated fibers** | | |
| C | 2.5 | 0.4–0.5 |

Source: Erlanger and Gasser, 1937.

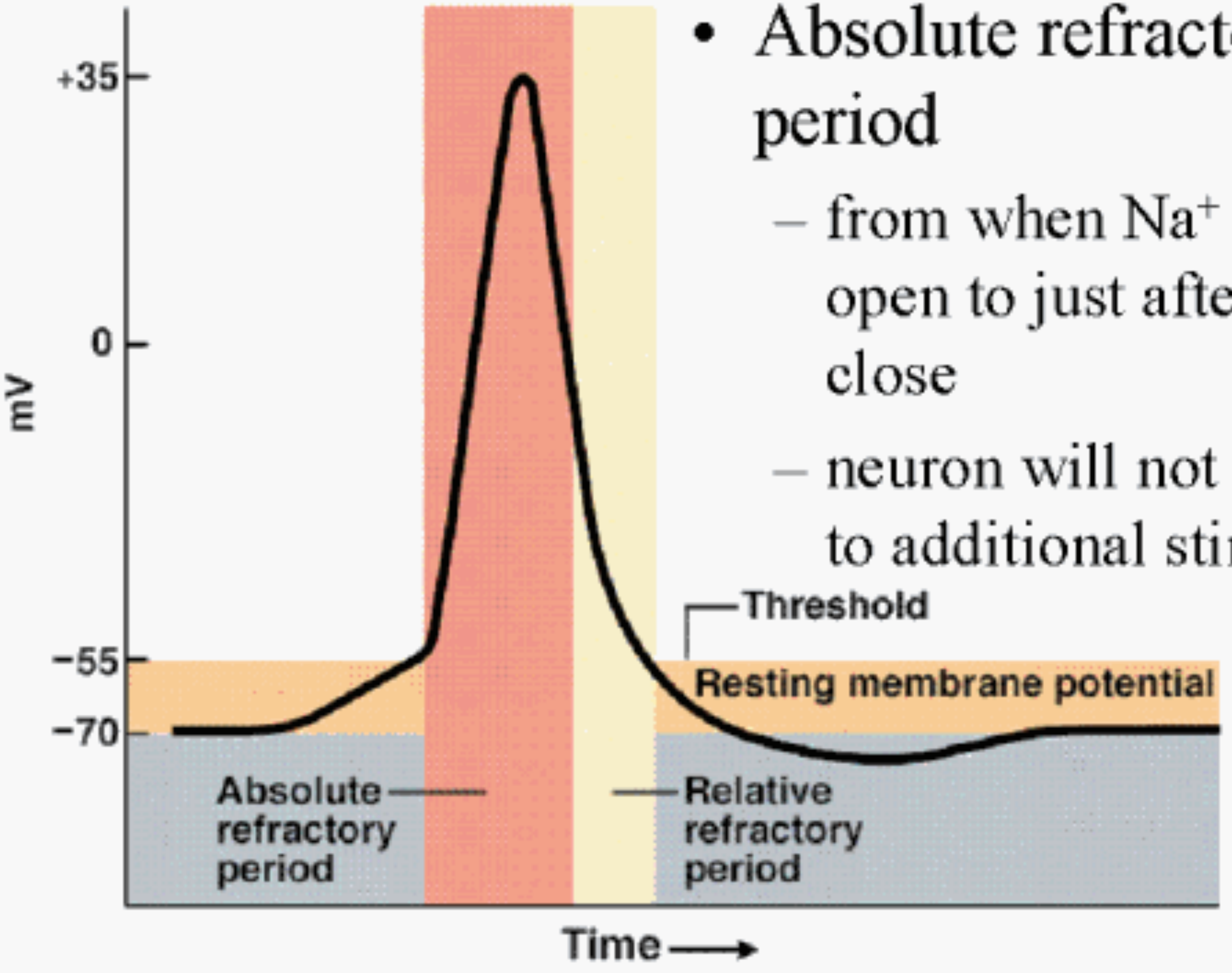
# Factors that affect the propagation

- Bioelectric properties of the membrane
- Velocity and amplitude of membrane depolarization

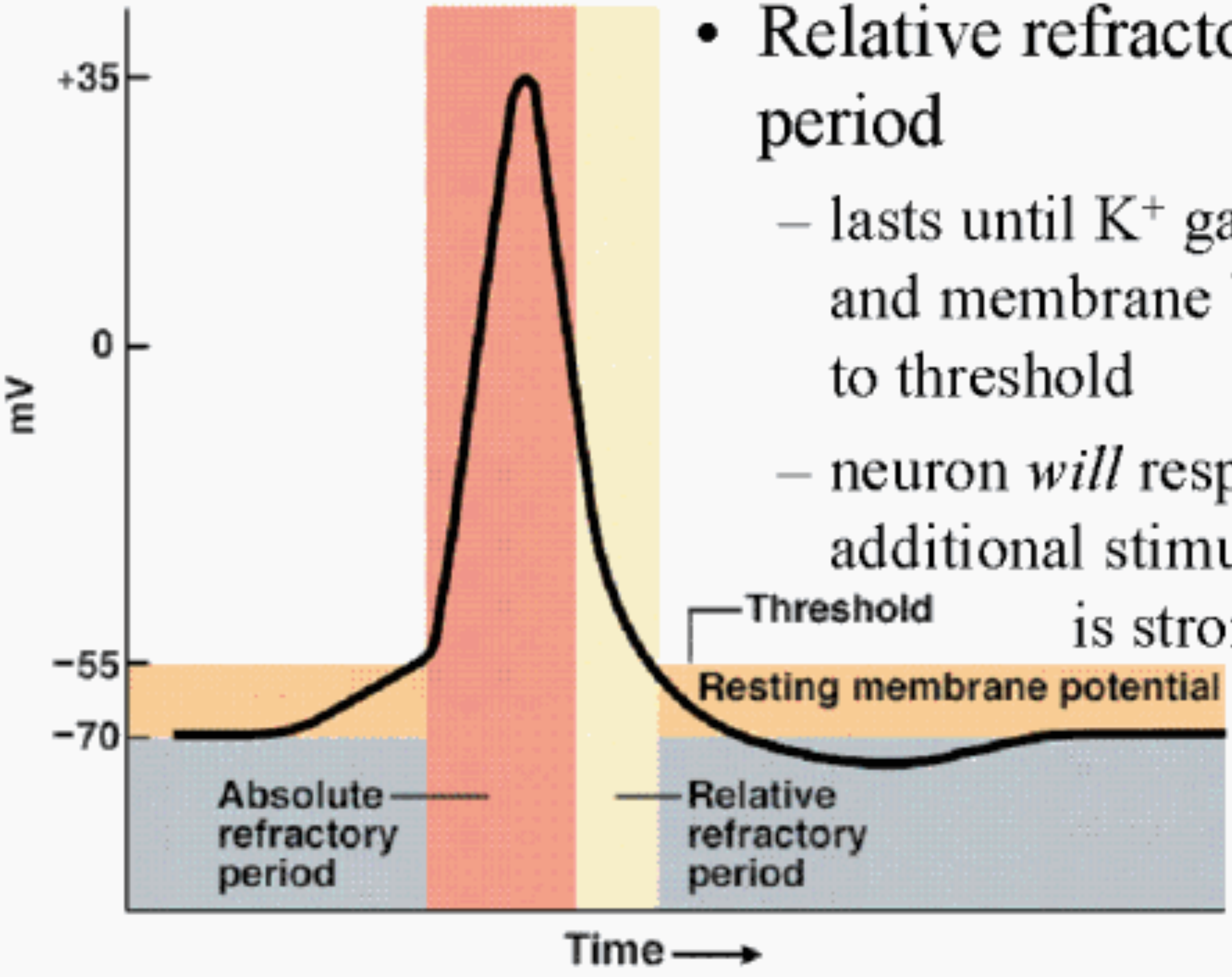
# Refractory periods:

# Refractory periods:

- Absolute refractory period
  - from when $Na^+$ gates are open to just after they close
  - neuron will not respond to additional stimulation



# Refractory periods:




- Relative refractory period
  - lasts until $K^+$ gates close and membrane V. returns to threshold
  - neuron *will* respond to additional stimulation if it is strong enough

# Debriefing:

# Excitation and Excitability

# Excitation and Excitability

- Review: Excitation and Excitable Cell
- Review: Threshold Stimulation and Excitability
- Change of Excitability after the Excitation