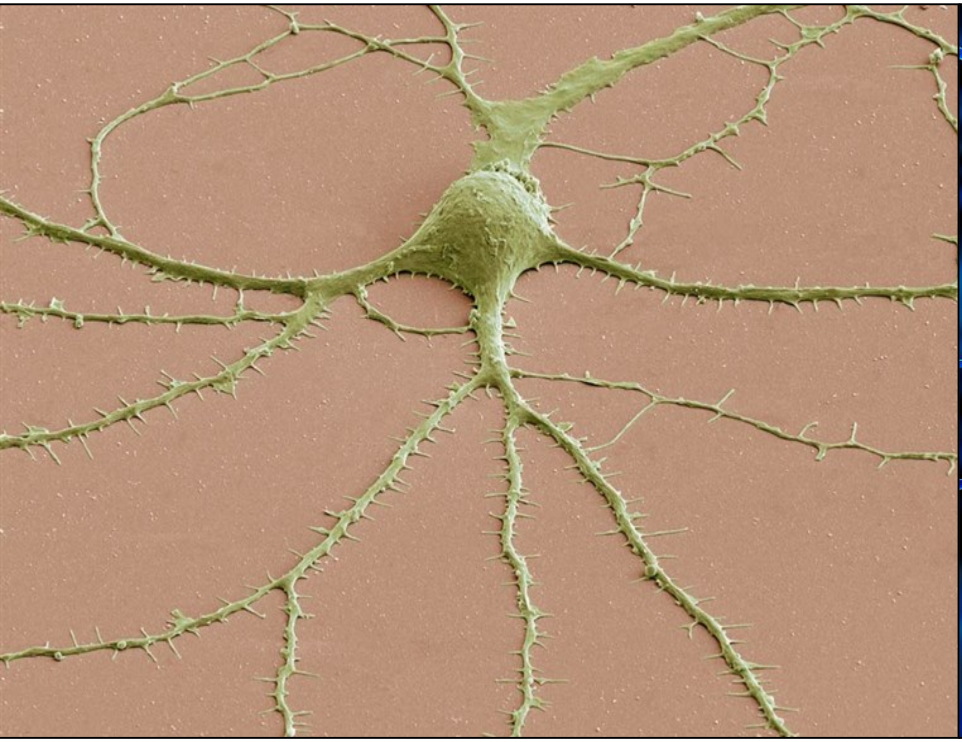
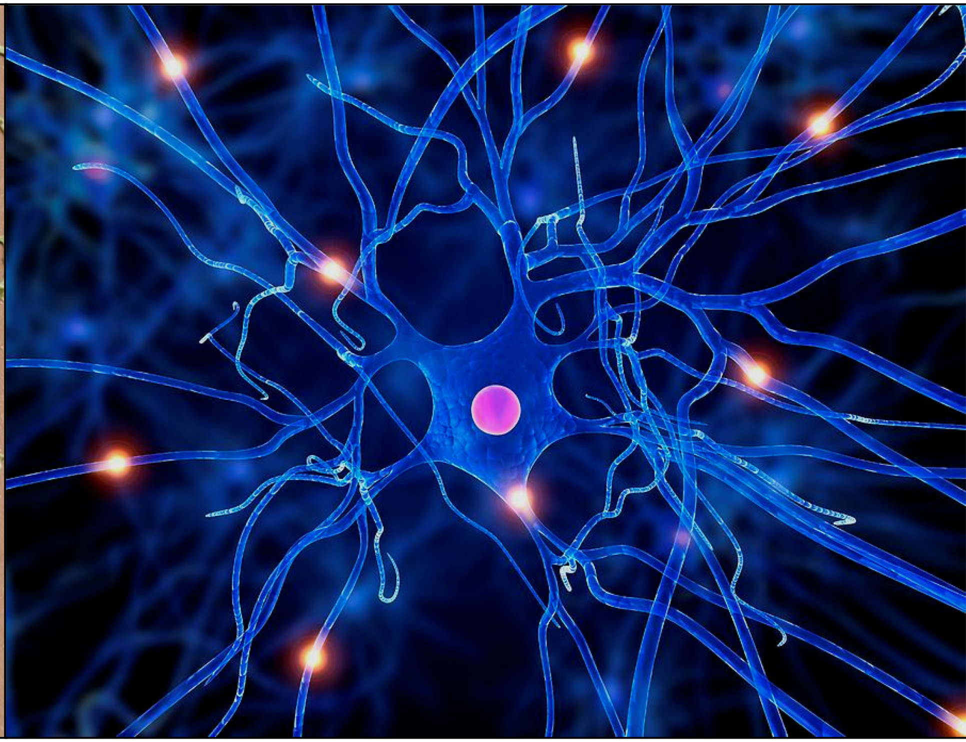
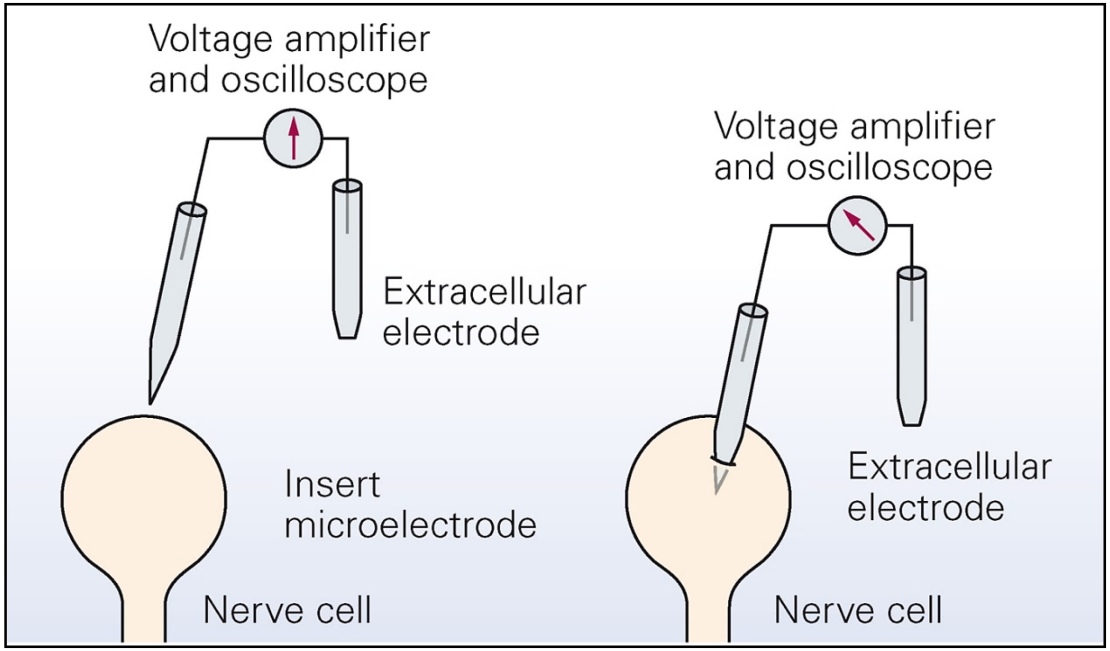
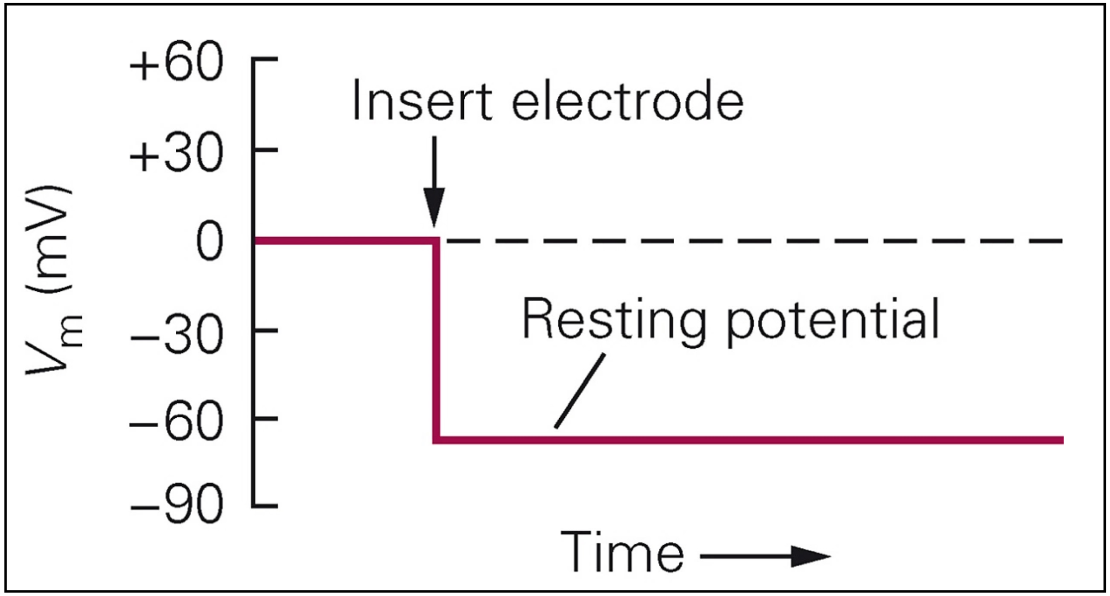
Chapter 9: Membrane Potential & Passive Electrical Properties of Neurons



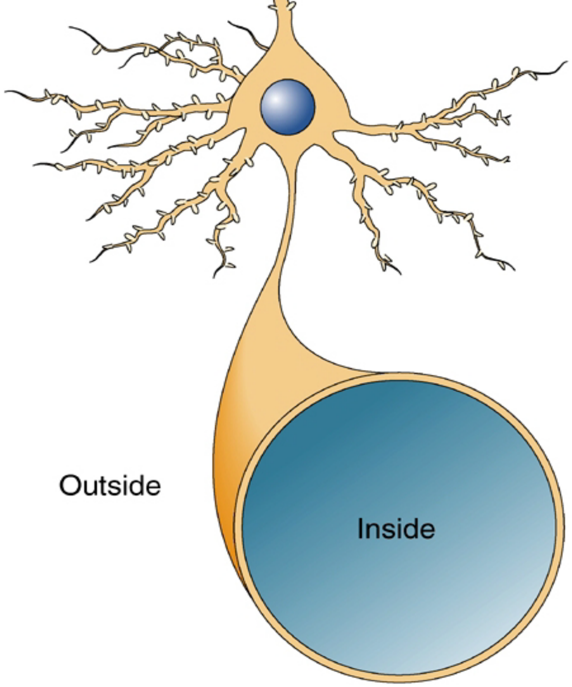


Resting Membrane Potential





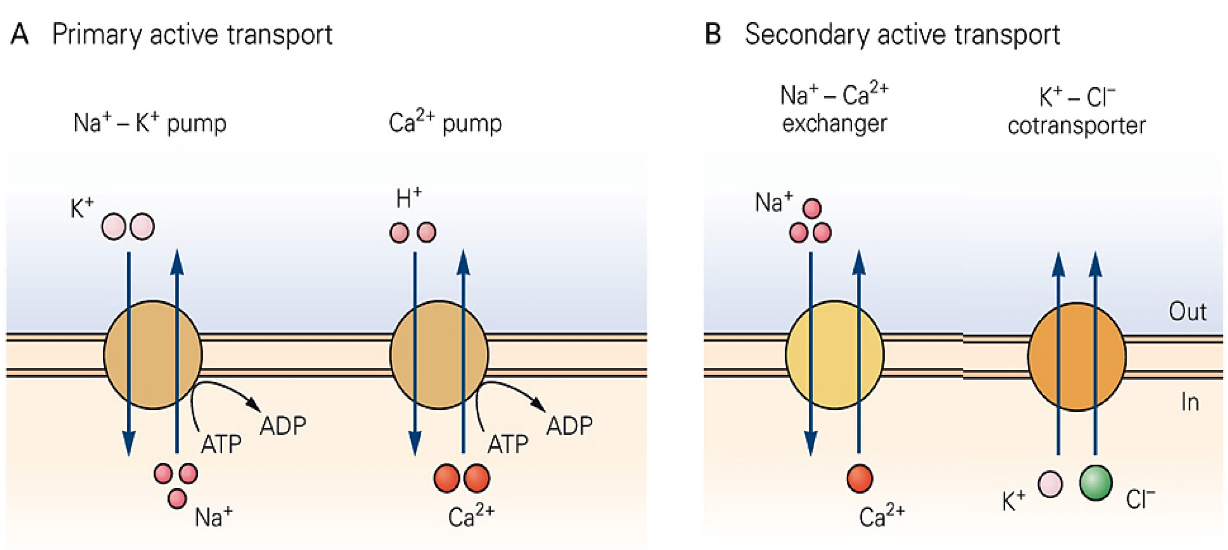
Ion Concentration Gradients



Ion	Concentration outside (in mM)	Concentration inside (in mM)
K^+	5	100
Na^+	150	15
Ca^{2+}	2	0.0002
Cl^-	150	13

Ion Pumps

- Establish and maintain ion concentration gradients
- Use energy to move ions against their concentration gradient
- Flow of ions is 100-100,000 times slower than through ion channels
- Are constantly active



Membrane Permeable to K^+

Drawing on the board…

Membrane Permeable to Na^+

Drawing on the board…

Equilibrium Potentials

Nernst Equation:

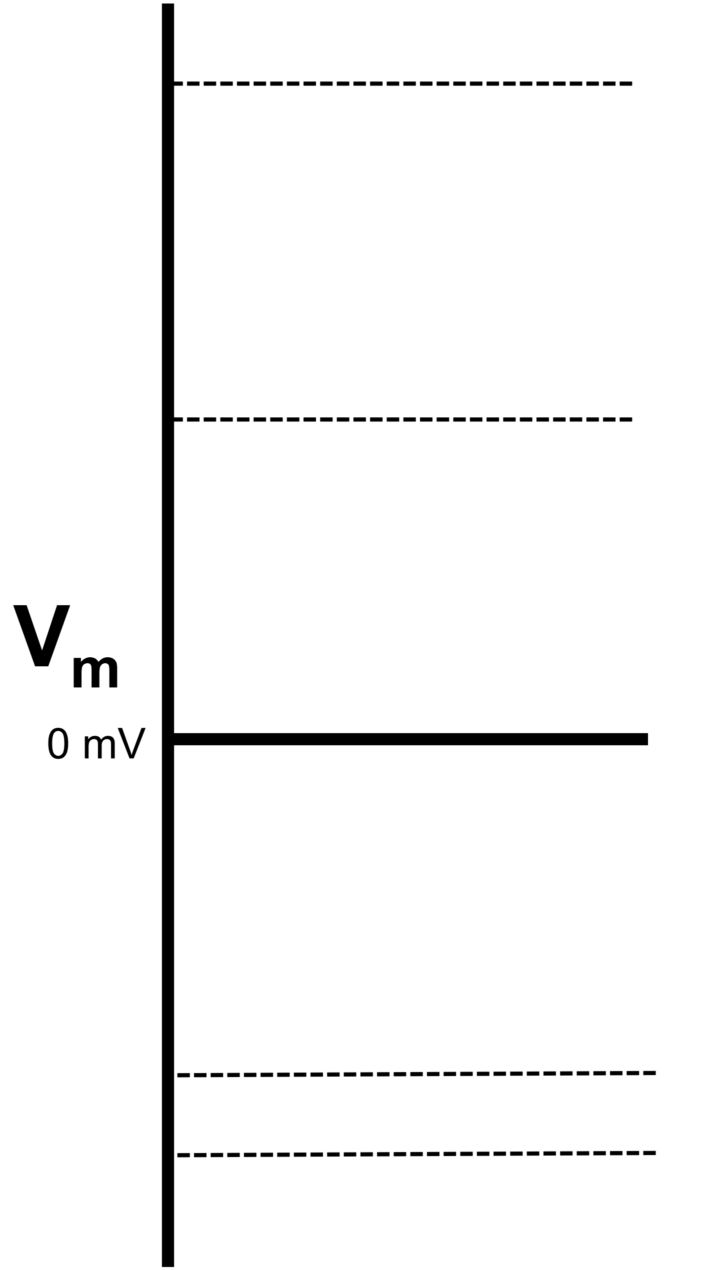
$$E_{ion} = \frac{61.5\text{mV}}{z} \log \frac{[\text{ion}]_{out}}{[\text{ion}]_{in}}$$

E_K =

E_{Na} =

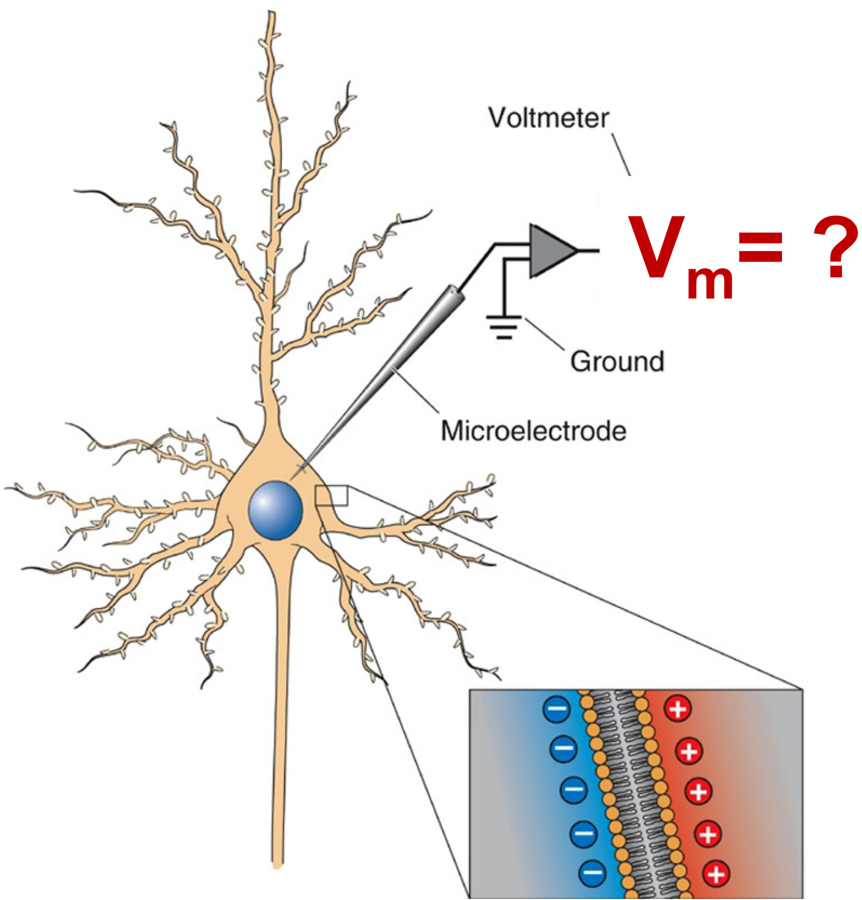
E_{Ca} =

E_{Cl} =



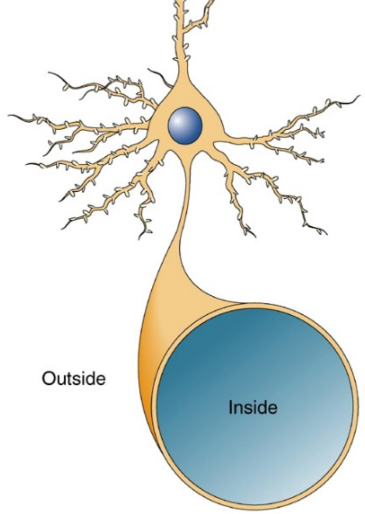
Predicting V_m using the Goldman Equation

$$V_m = 61.5\text{ mV} \log \left(\frac{P_K[K^+]_{out} + P_{Na}[Na^+]_{out} + P_{Cl}[Cl^-]_{in}}{P_K[K^+]_{in} + P_{Na}[Na^+]_{in} + P_{Cl}[Cl^-]_{out}} \right)$$



What is the predicted V_M if the relative membrane permeabilities are as follows:

P_K	:	P_{Na}	:	P_{Cl}
40	:	1	:	10



Ion	Concentration outside (in mM)	Concentration inside (in mM)
K^+	5	100
Na^+	150	15
Ca^{2+}	2	0.0002
Cl^-	150	13

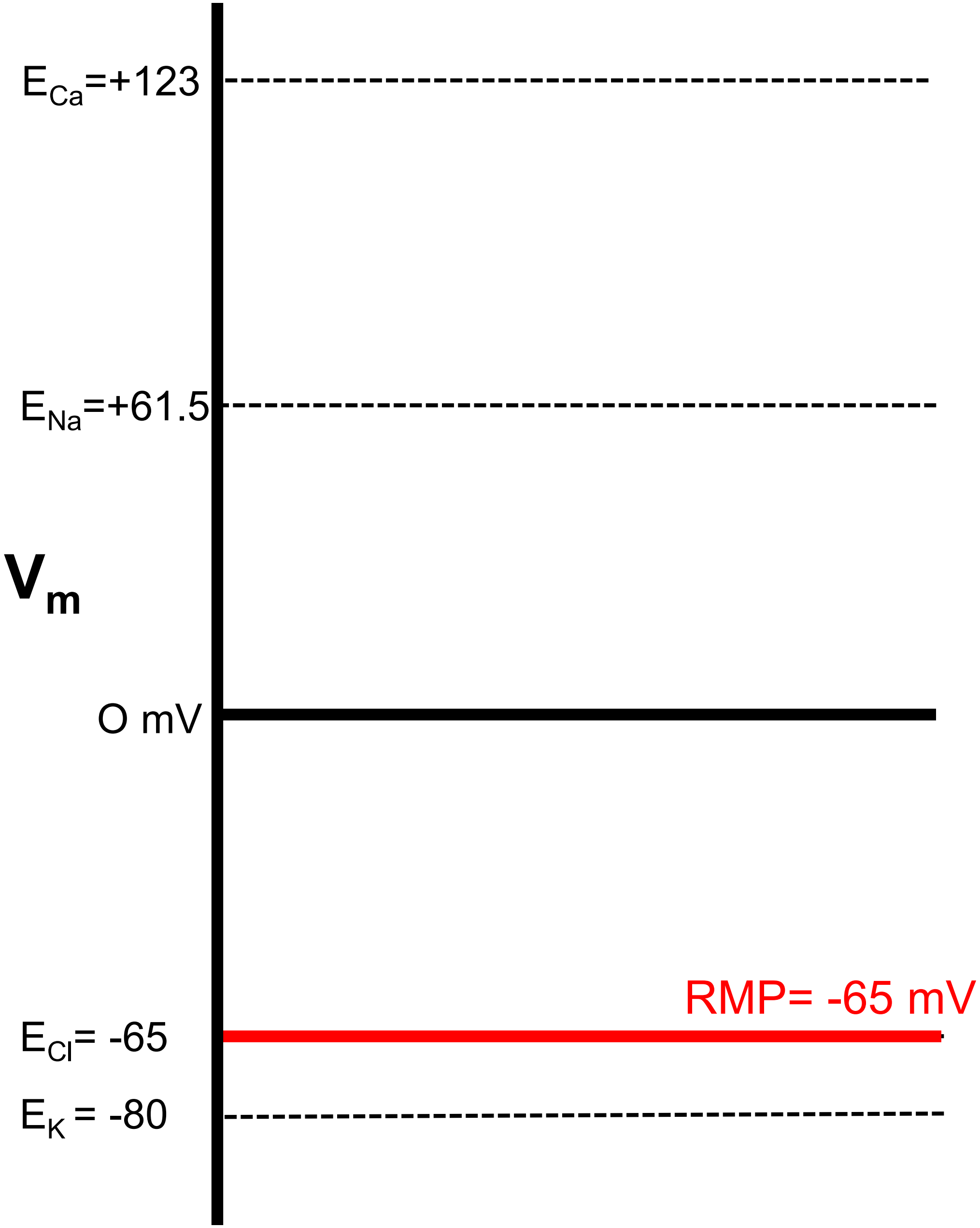
$$P_K : P_{Na} : P_{Cl}$$
$$40 : 1 : 10$$

Goldman Equation

$$V_m = 61.5 \text{ mV } \log \frac{P_K[K^+]_{out} + P_{Na}[Na^+]_{out} + P_{Cl}[Cl^-]_{in}}{P_K[K^+]_{in} + P_{Na}[Na^+]_{in} + P_{Cl}[Cl^-]_{out}}$$

$$V_m = 61.5 \text{ mV } \log \frac{\qquad}{\qquad}$$

$$V_m = 61.5 \text{ mV } \log \frac{\qquad}{\qquad} \quad =$$

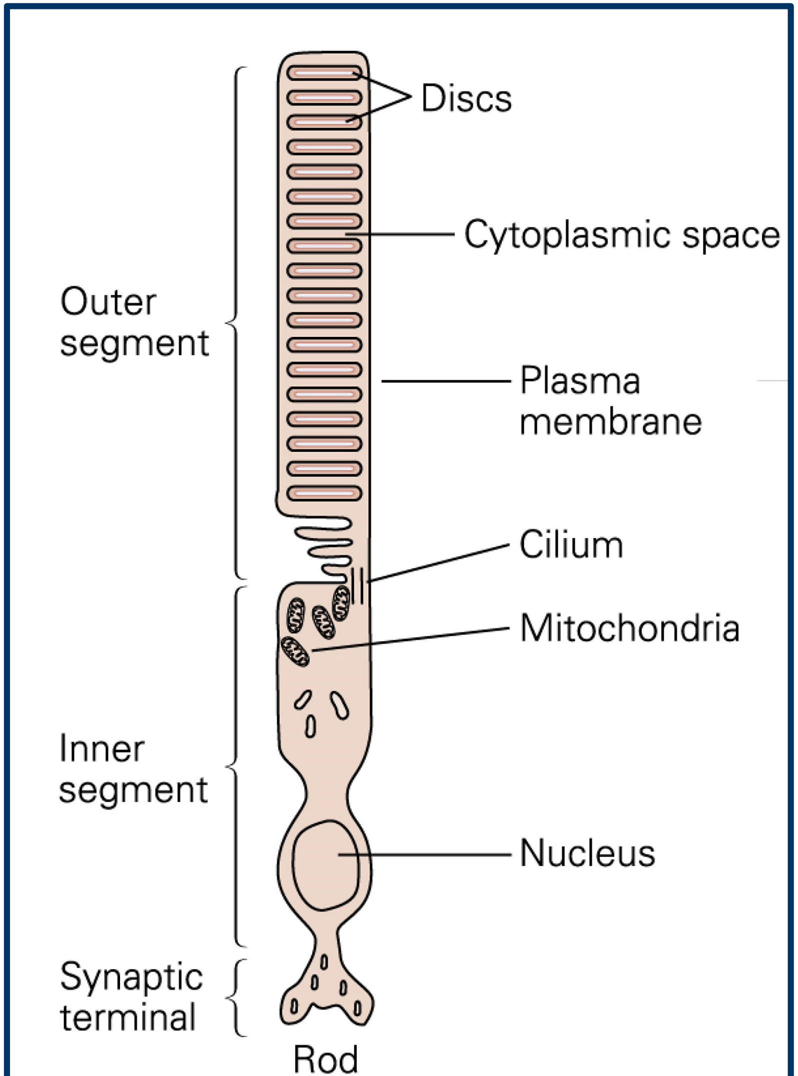


What would happen to V_m if…

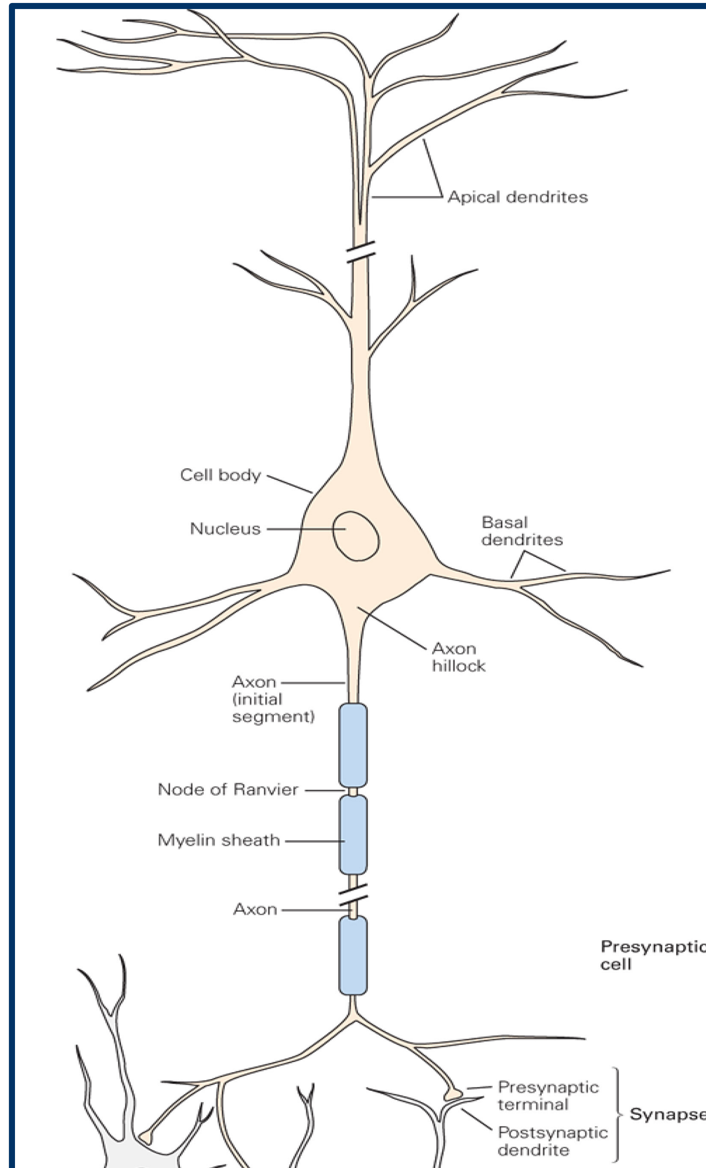
- P_{Na+} increased?
- P_{Na+} decreased?
- P_{K+} increased?
- P_{K+} decreased?
- P_{Cl-} increased?
- P_{Cl-} decreased?

Why might RMP differ?

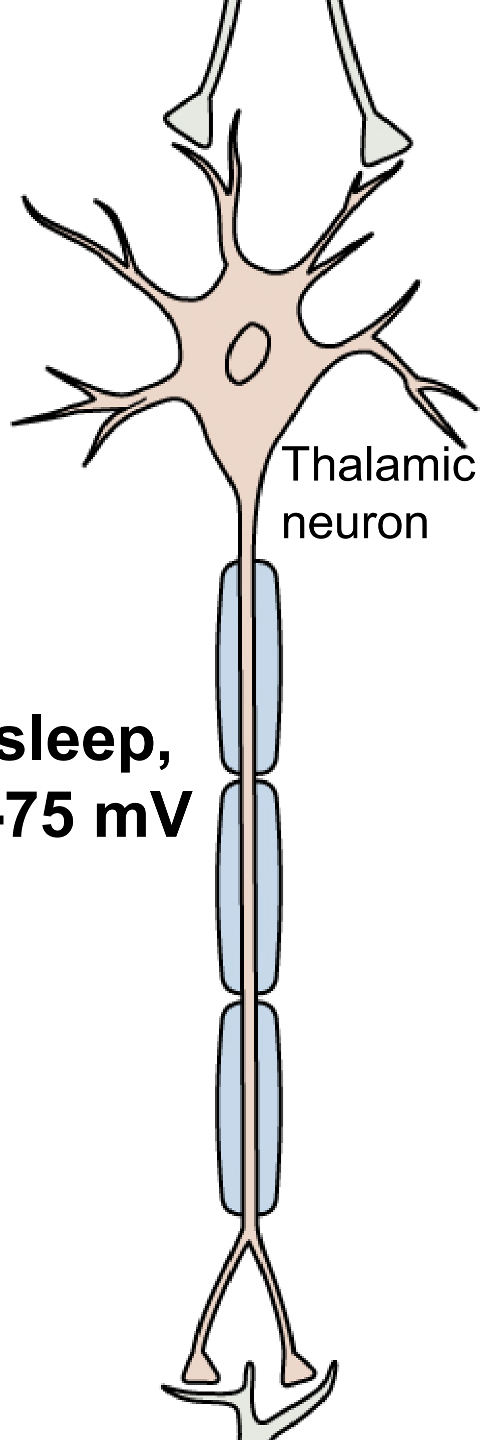
RMP = - 40 mV



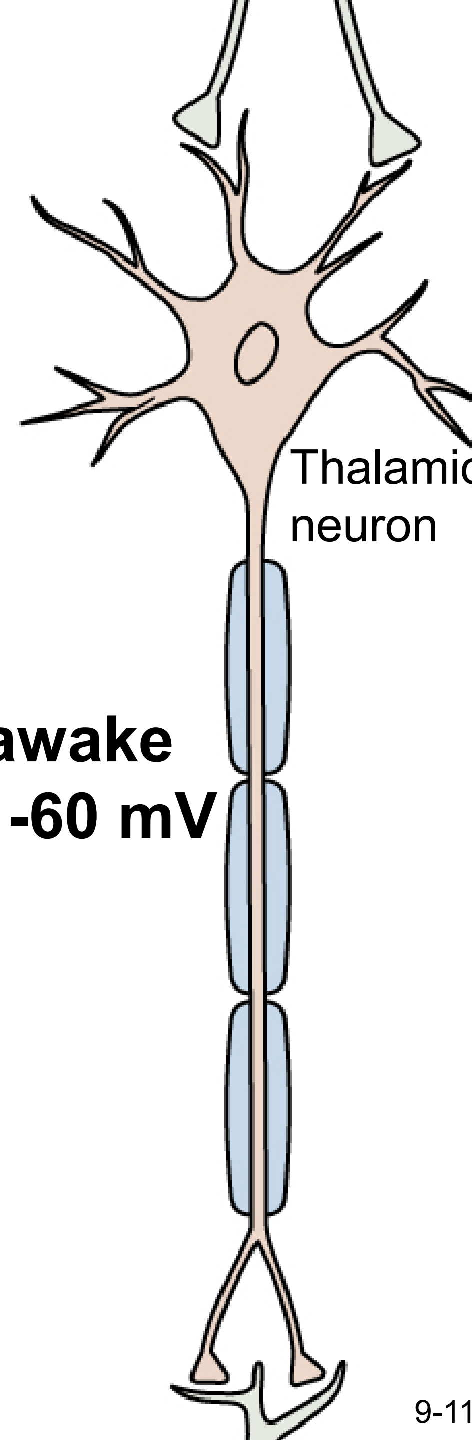
RMP = -75 mV



How could RMP change?



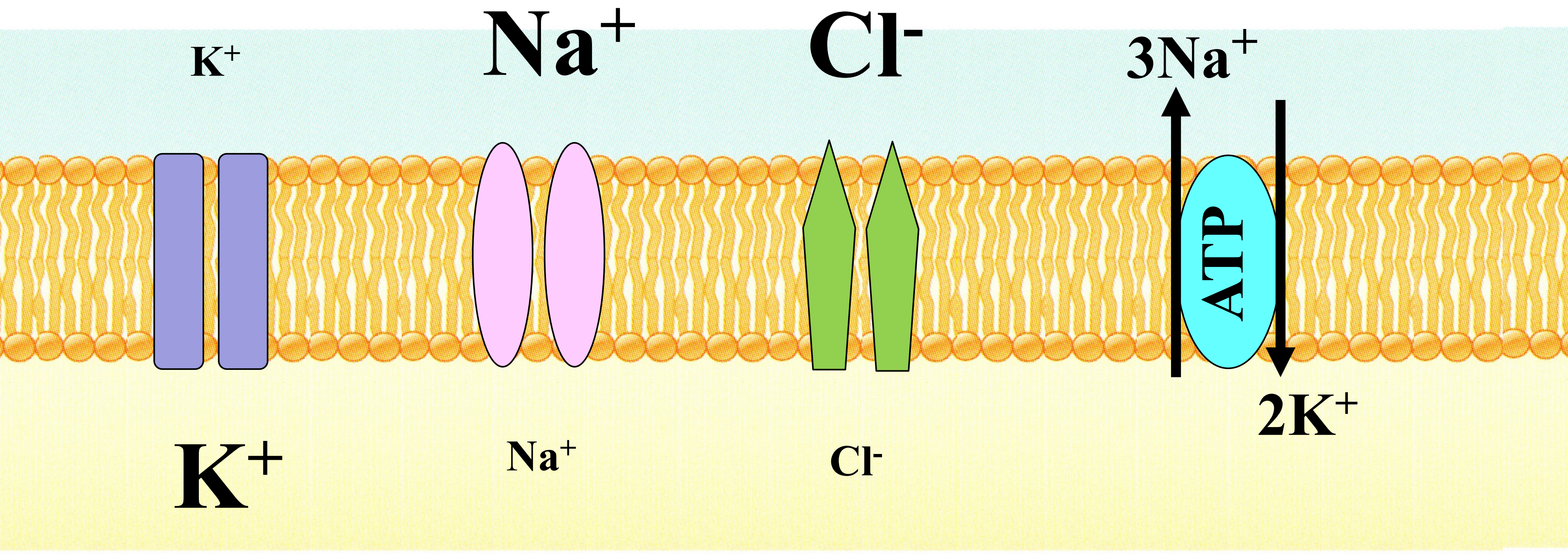
While asleep,
RMP = -75 mV



While awake
RMP = -60 mV

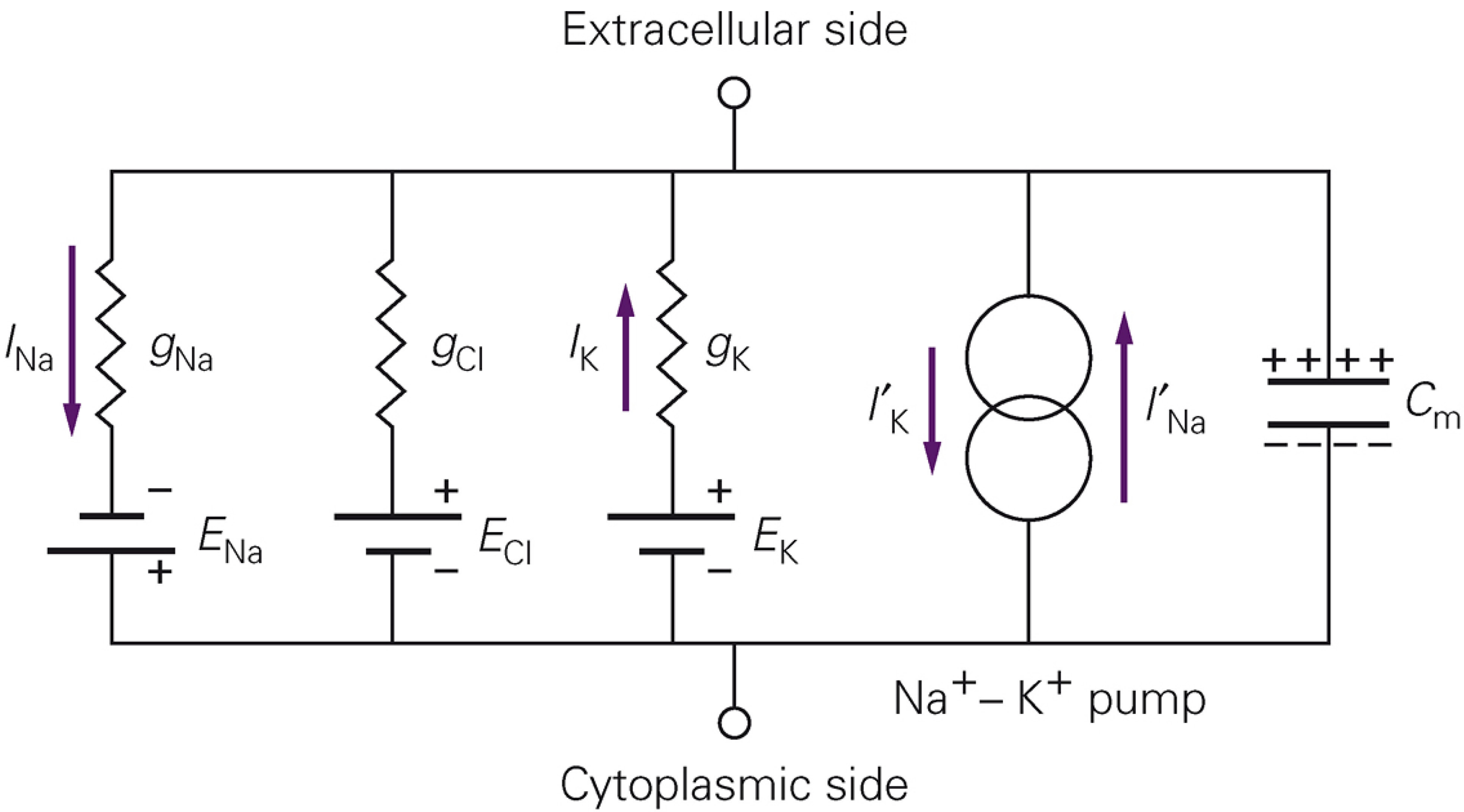
Voltage Clamp the Cell at RMP

What is happening at the membrane?

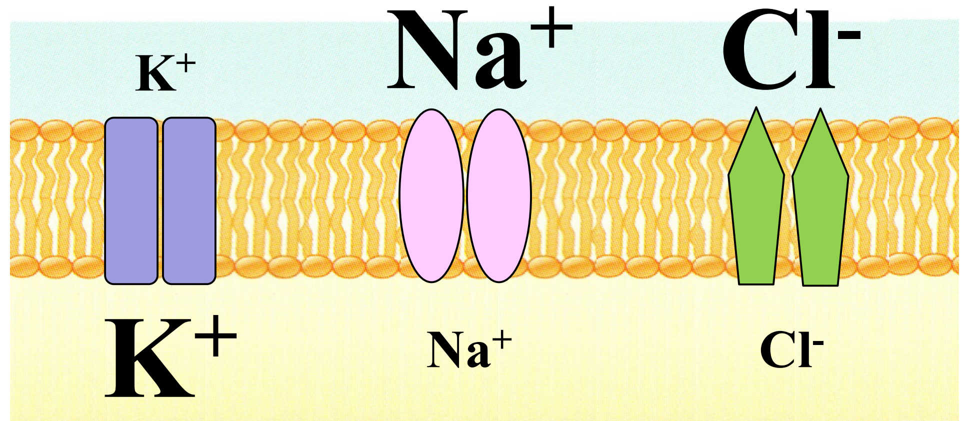


RMP = -65 mV

Drawing a Neuron's Membrane as an Equivalent Circuit

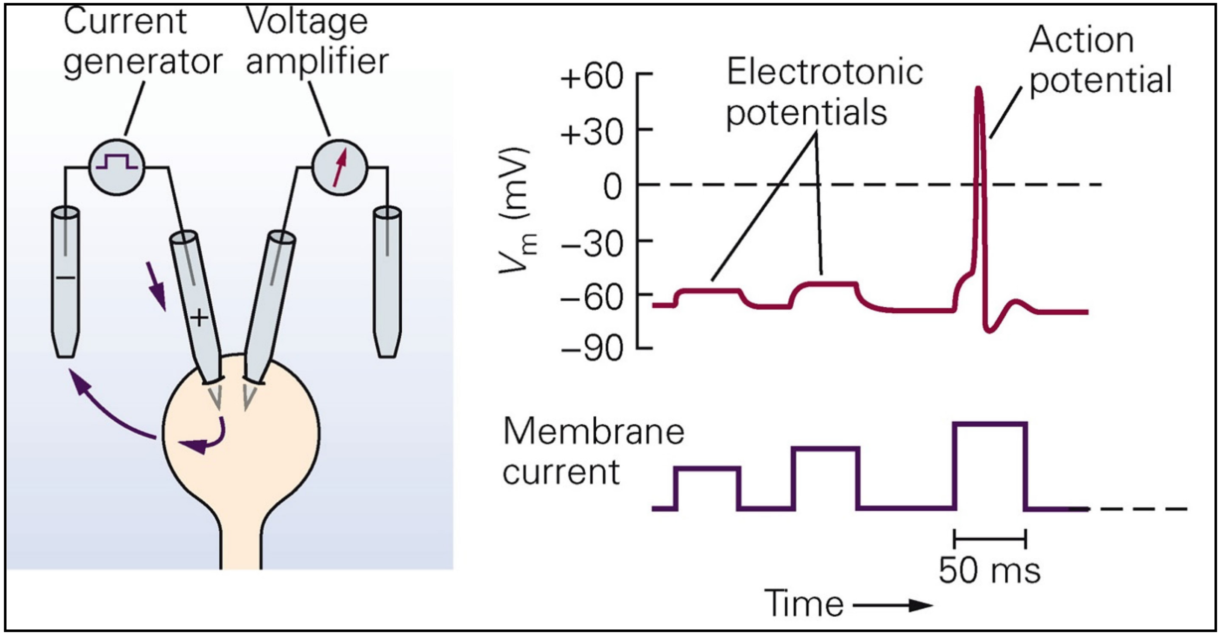


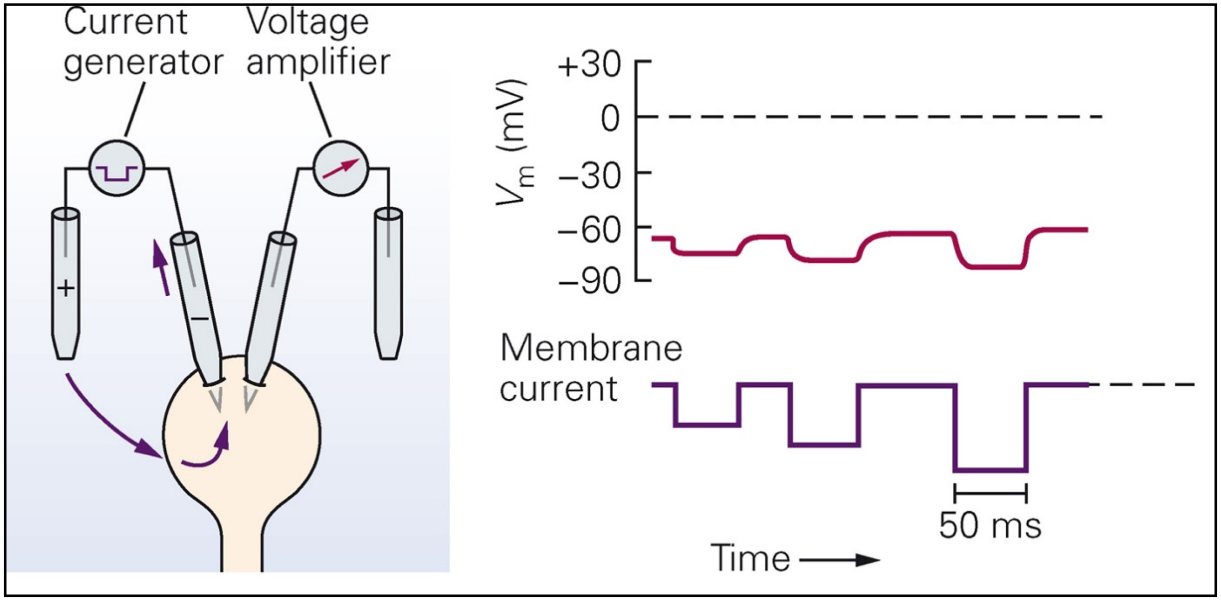
Voltage Clamp Experiment



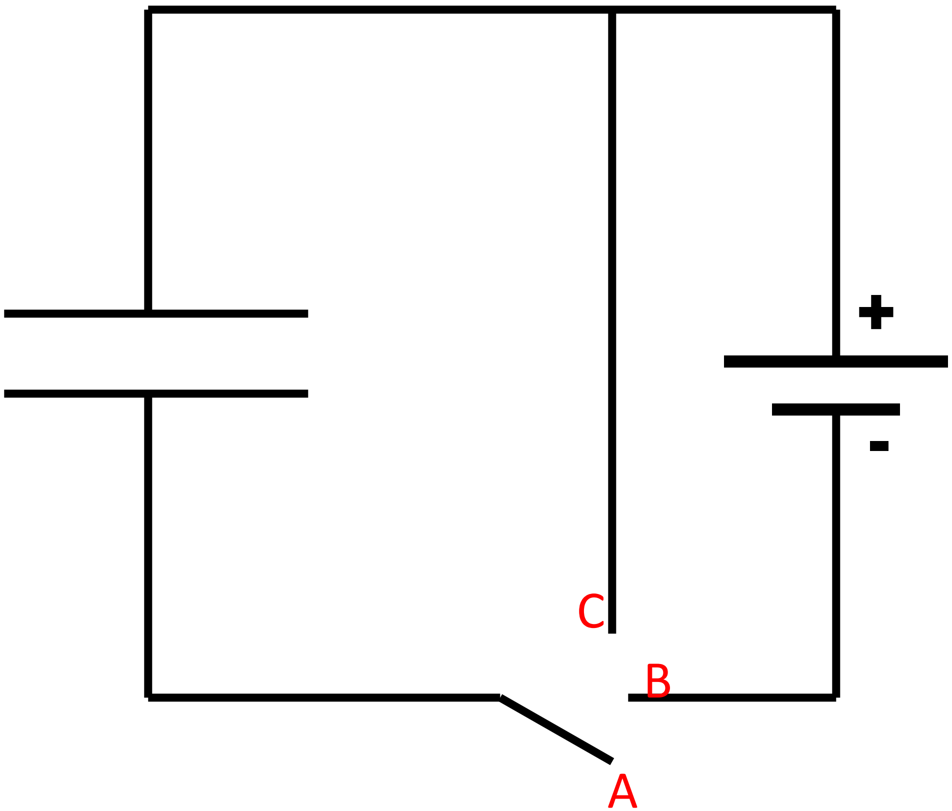
V_m	Net K^+ flux	Net Na^+ flux	Net Cl^- flux
+80 mV			
+65 mV			
+20 mV			
0 mV			
-20 mV			
-65 mV			
-80 mV			
-90 mV			

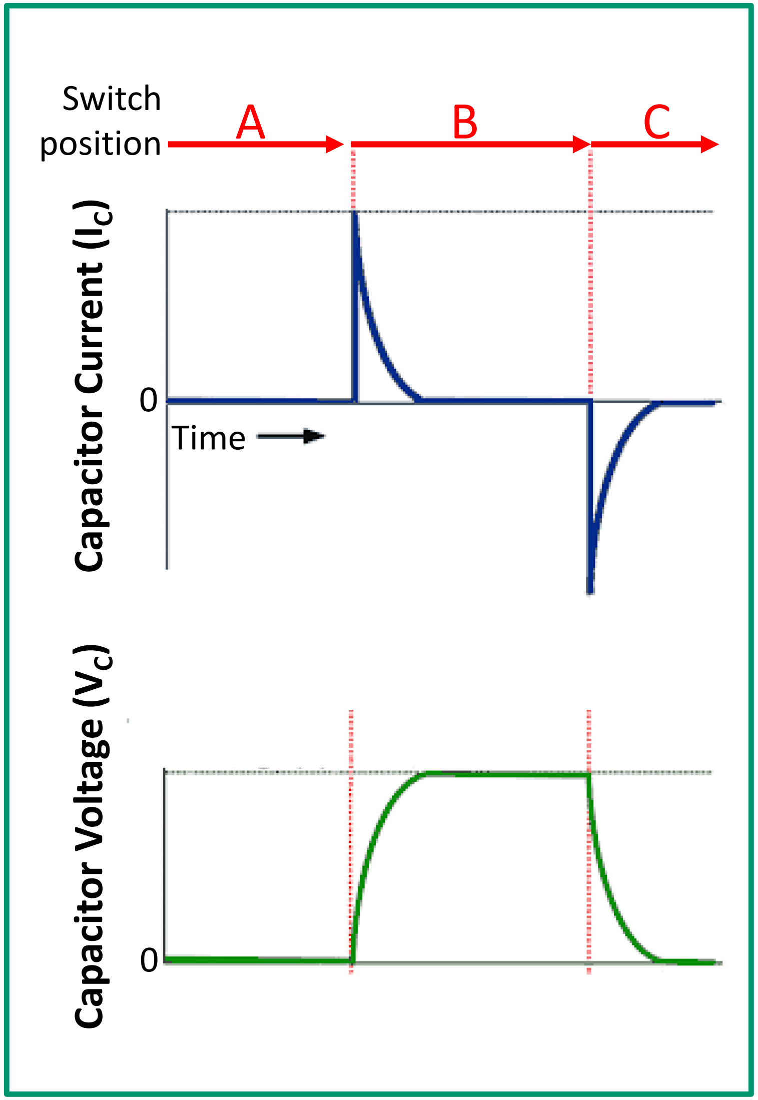
Passive Electrical Properties





Capacitor in a Circuit

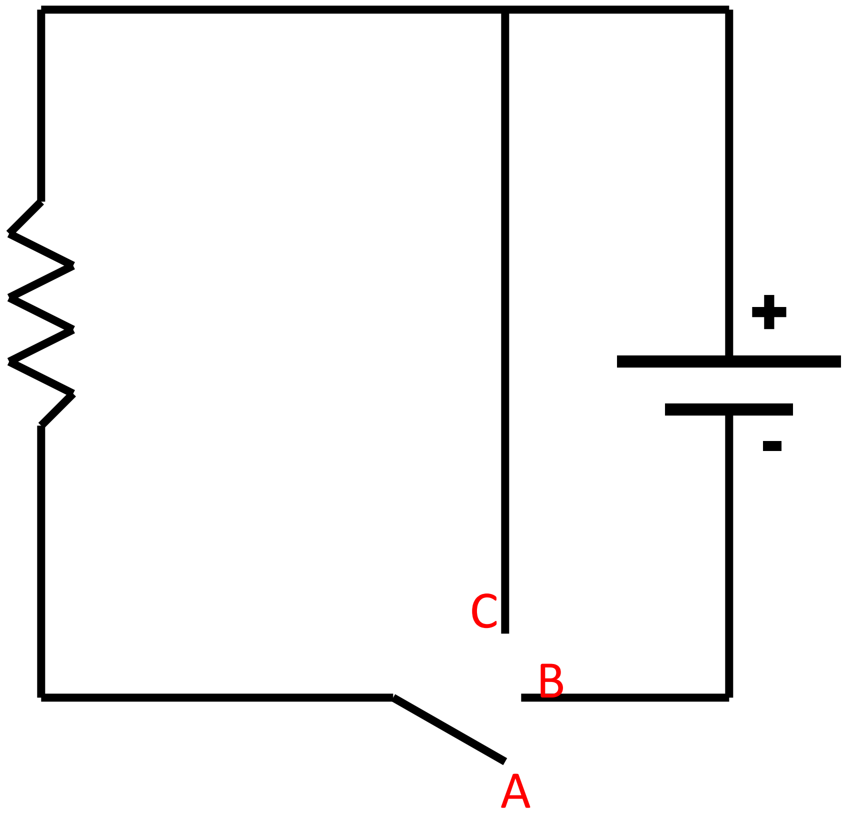


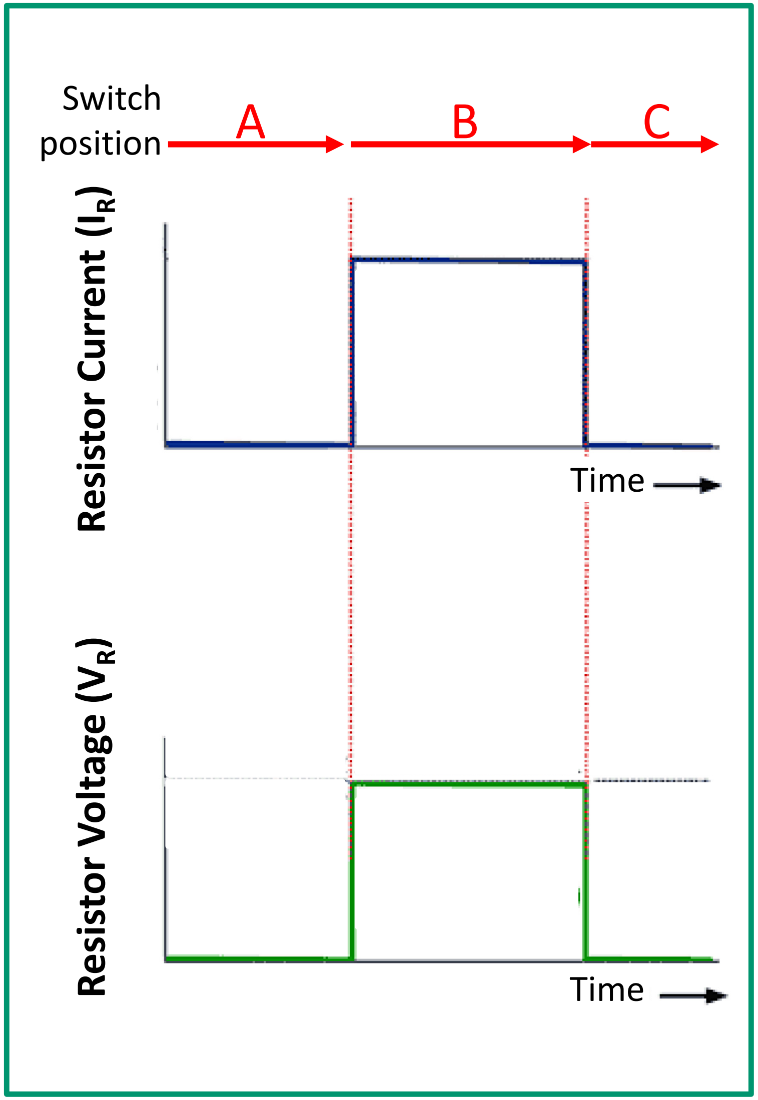


How could the capacitance be increased or decreased?

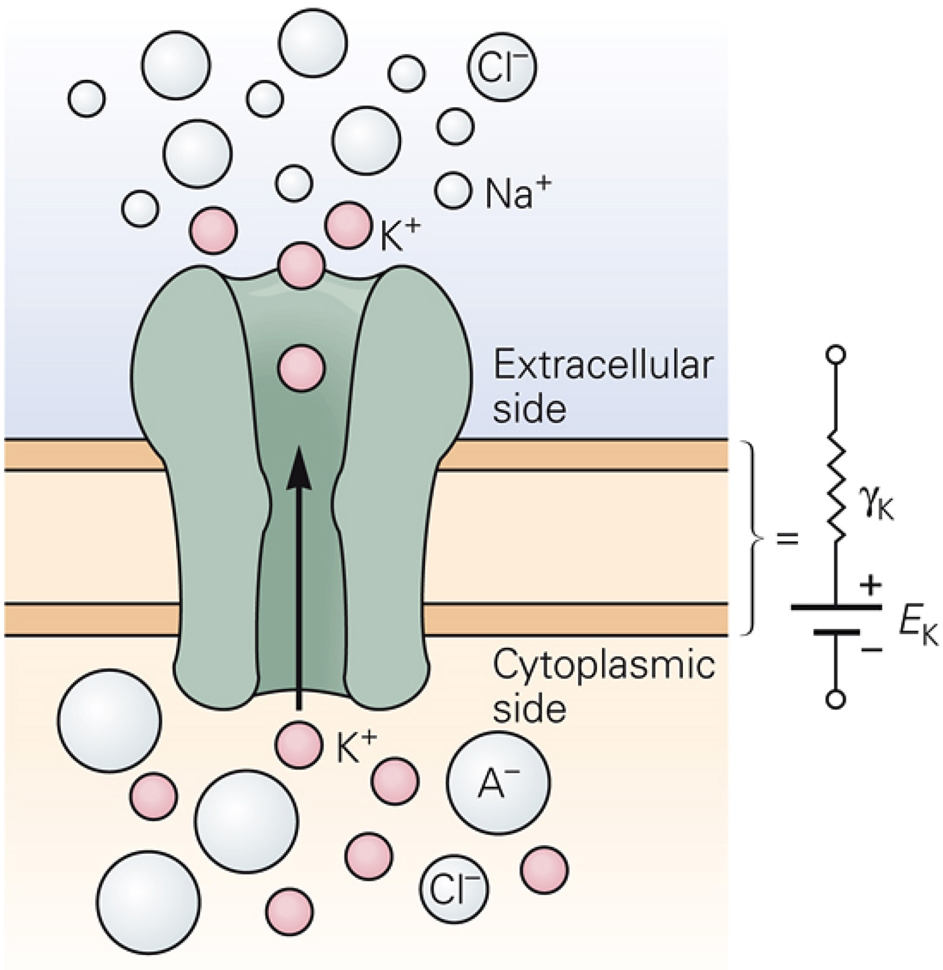
How would changing the capacitance affect current and voltage tracings?

Resistor in a Circuit





Ion Channels Behave Like Resistors



Ohms Law:

$$V=IR$$

$$I=V/R$$

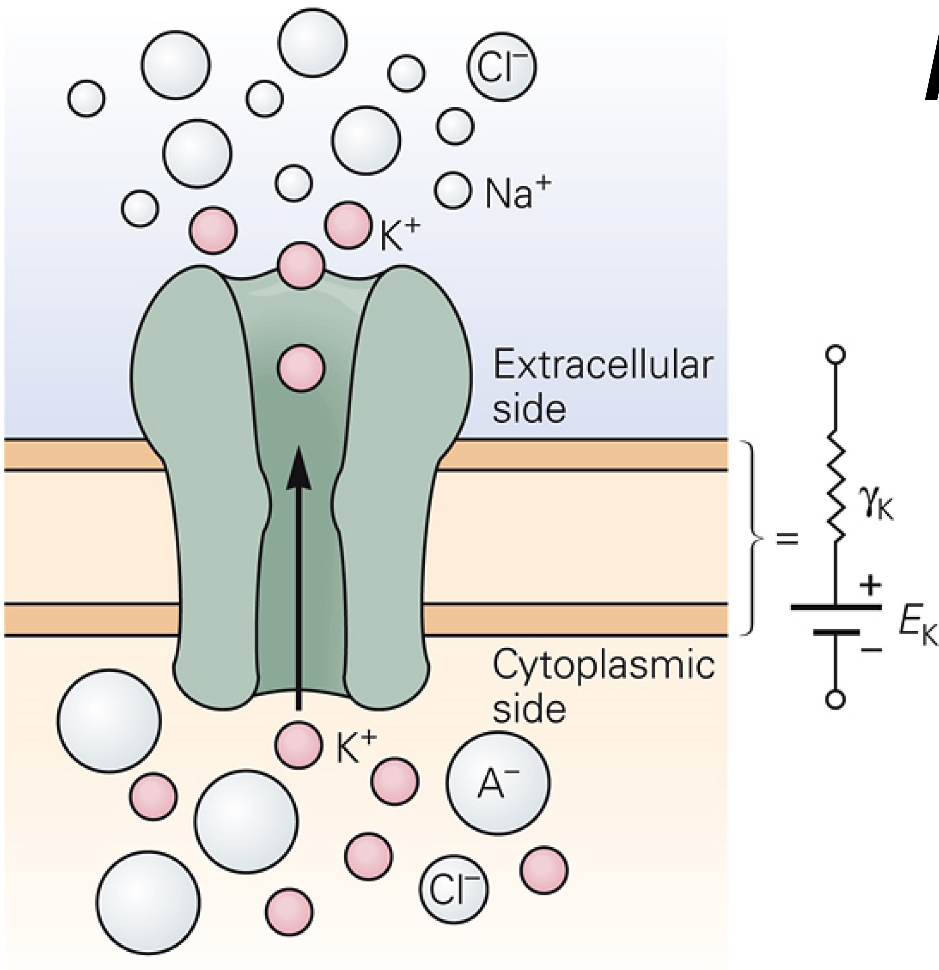
Conductance (γ or g) is the inverse of resistance

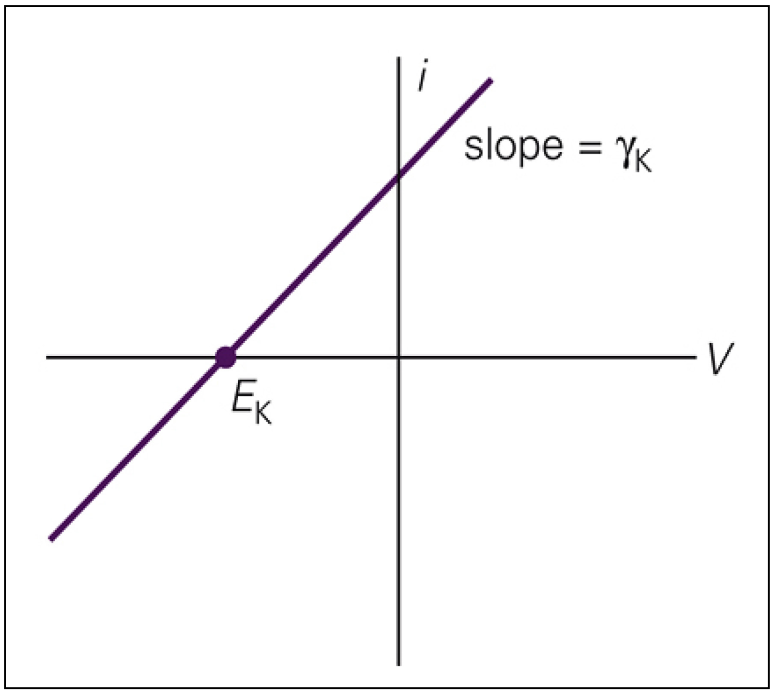
$$\gamma=1/R$$

$$I=\gamma V$$

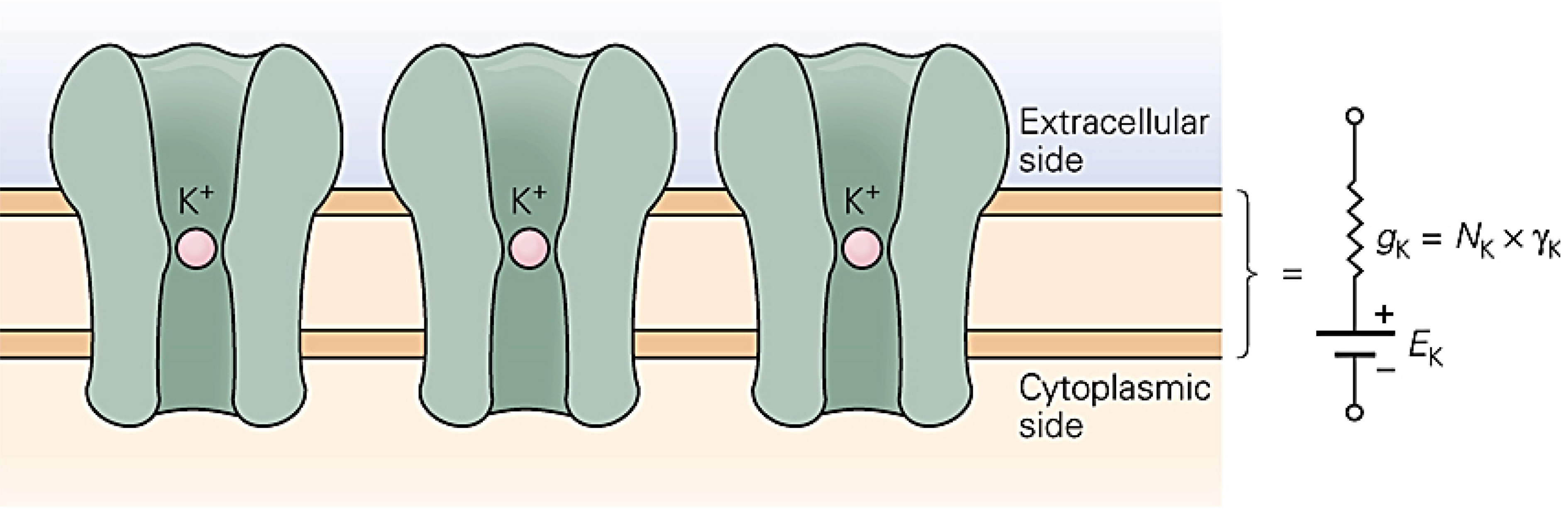
Ion Channels Behave Like Resistors

$$I_K = \gamma_K \, (V_m - E_K)$$

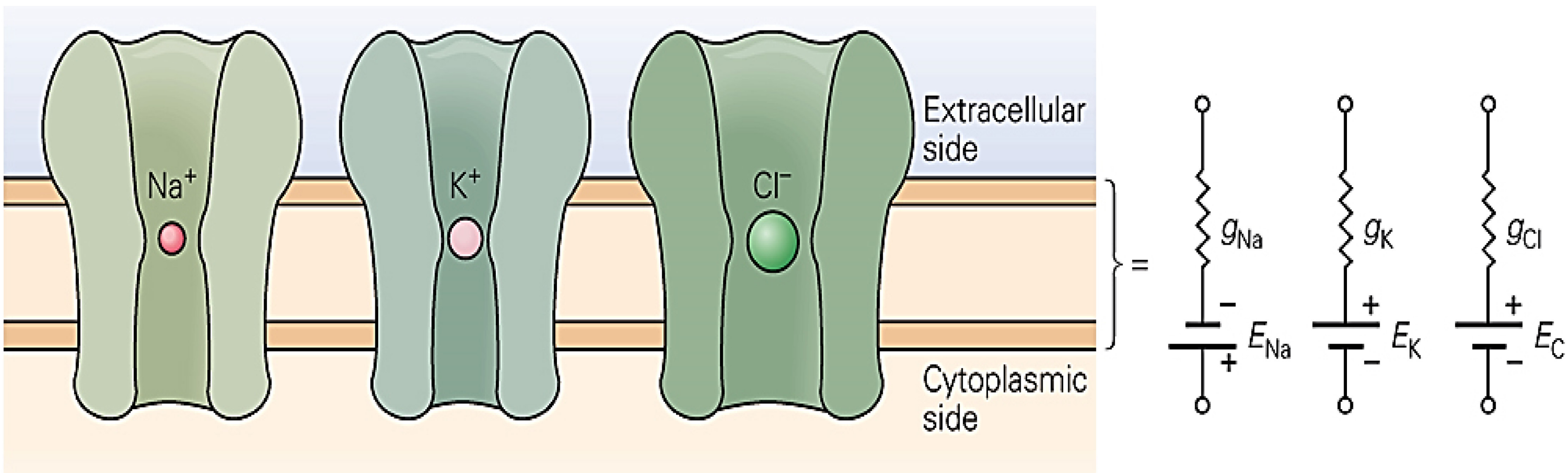




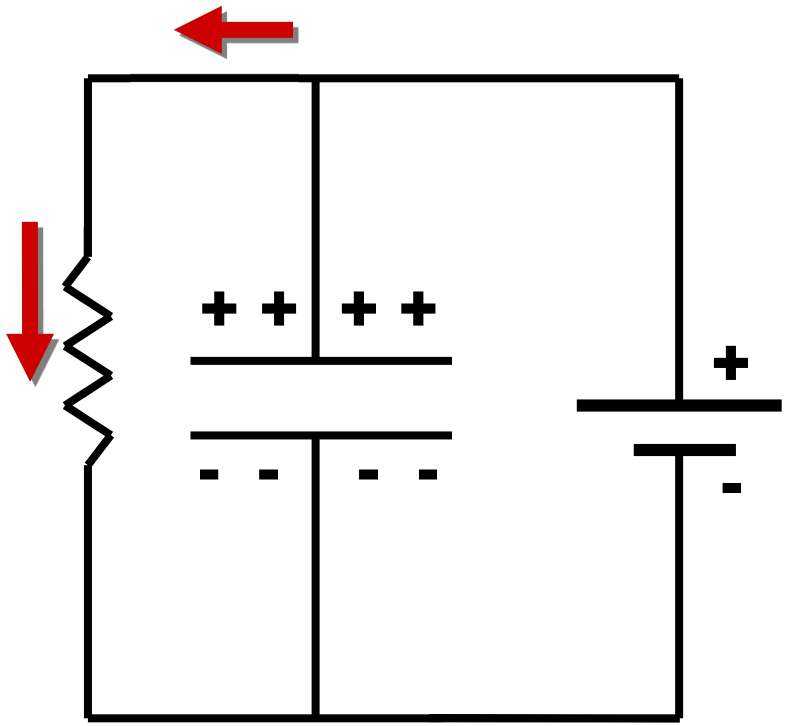
Combining Like Channels in an Equivalent Circuit



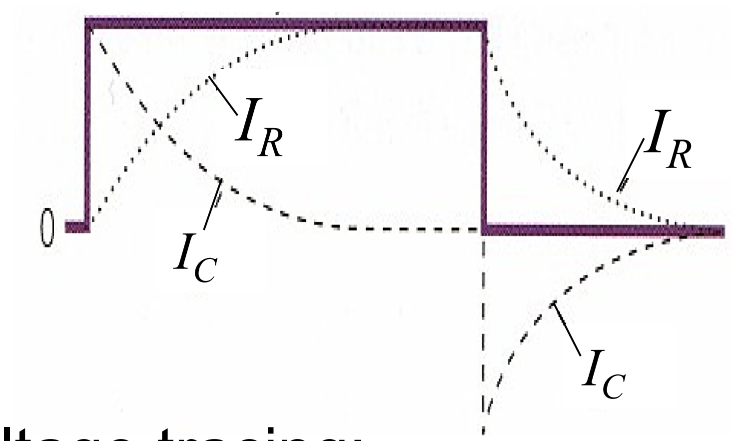
Na+, K+, and Cl- Channels in an Equivalent Circuit



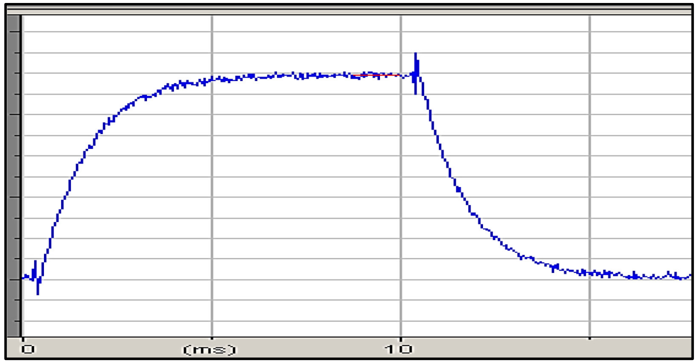
Resistor and Capacitor in Parallel



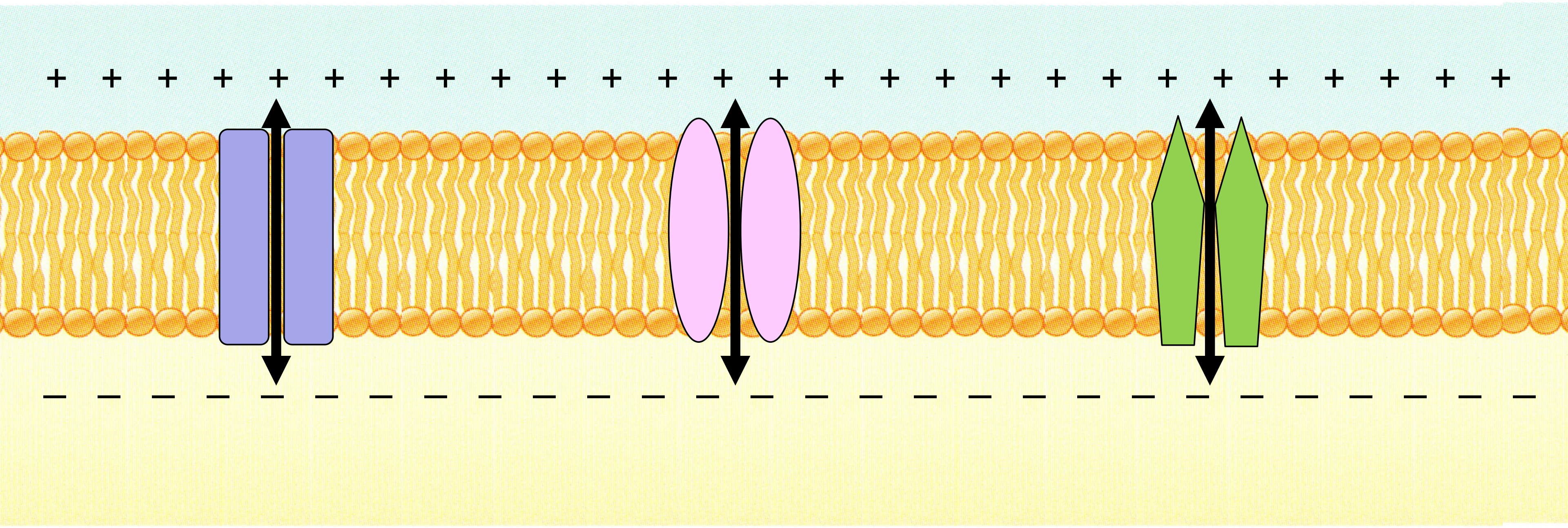
Current tracing:



Voltage tracing:



Cell membranes act like a resistor and capacitor in parallel

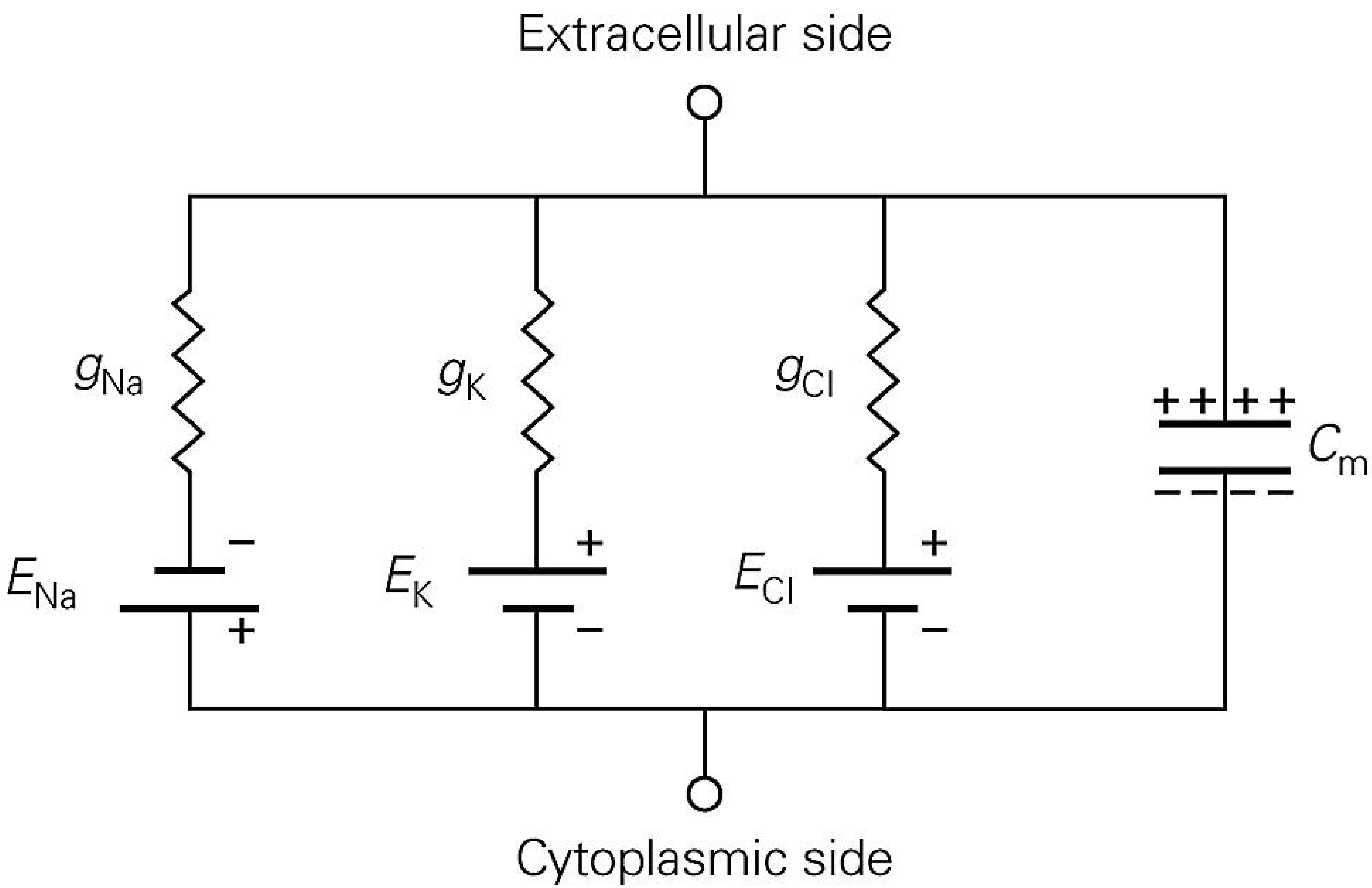


What is the resistor?

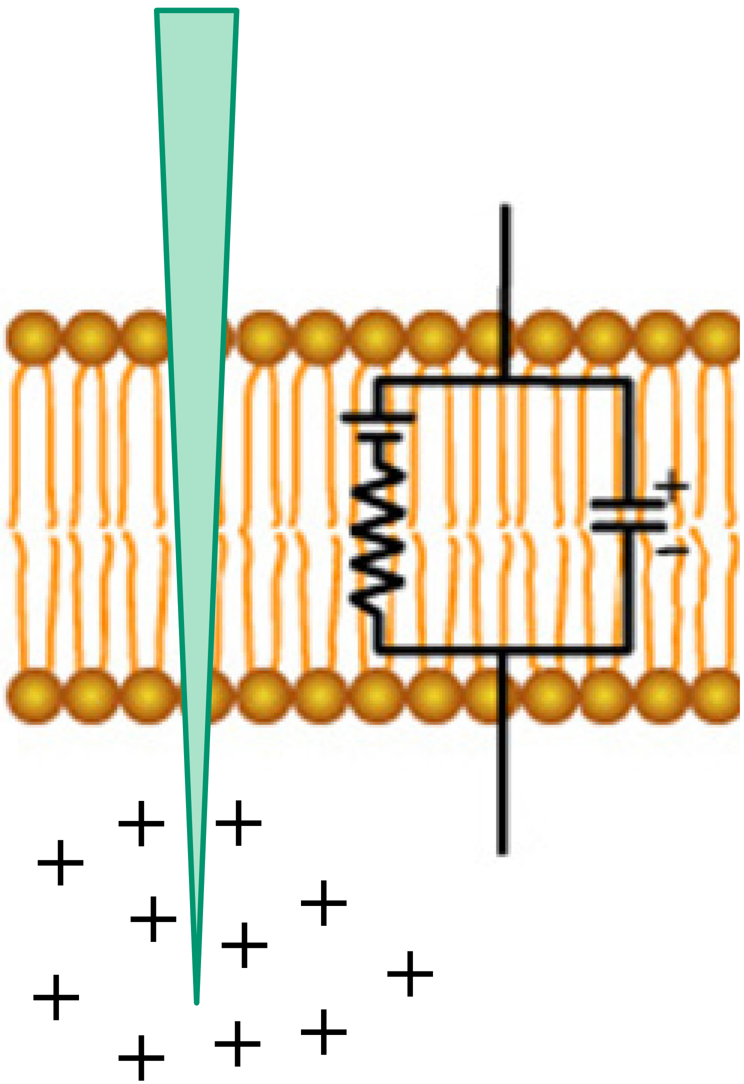
What are the plates of the capacitor?

What is the dielectric of the capacitor?

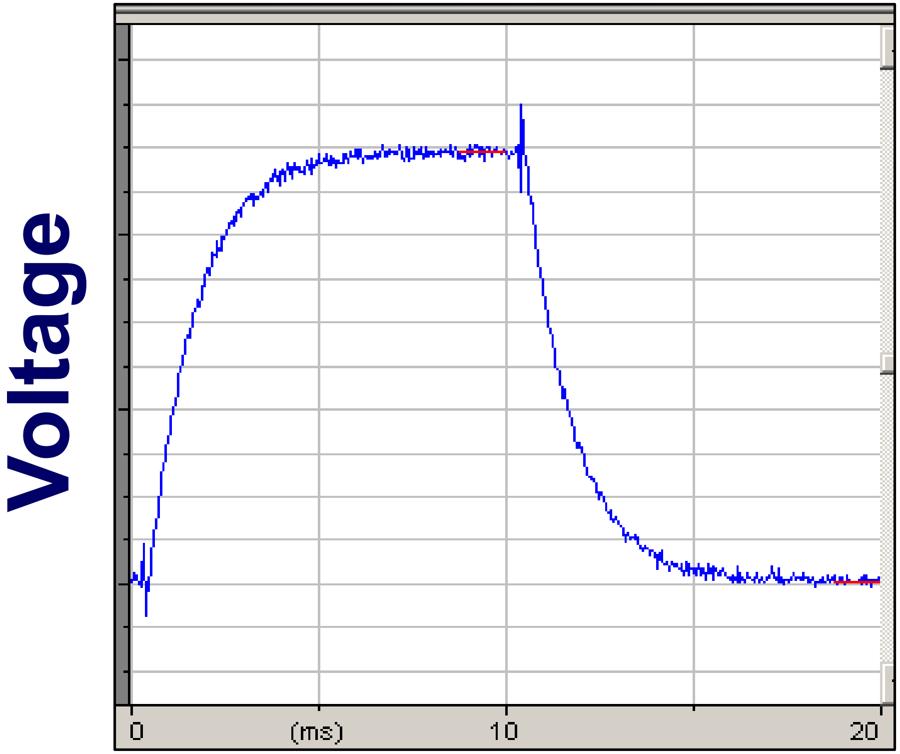
A Neuron's Membrane as an Equivalent Circuit



Cell membranes act like a resistor and capacitor in parallel



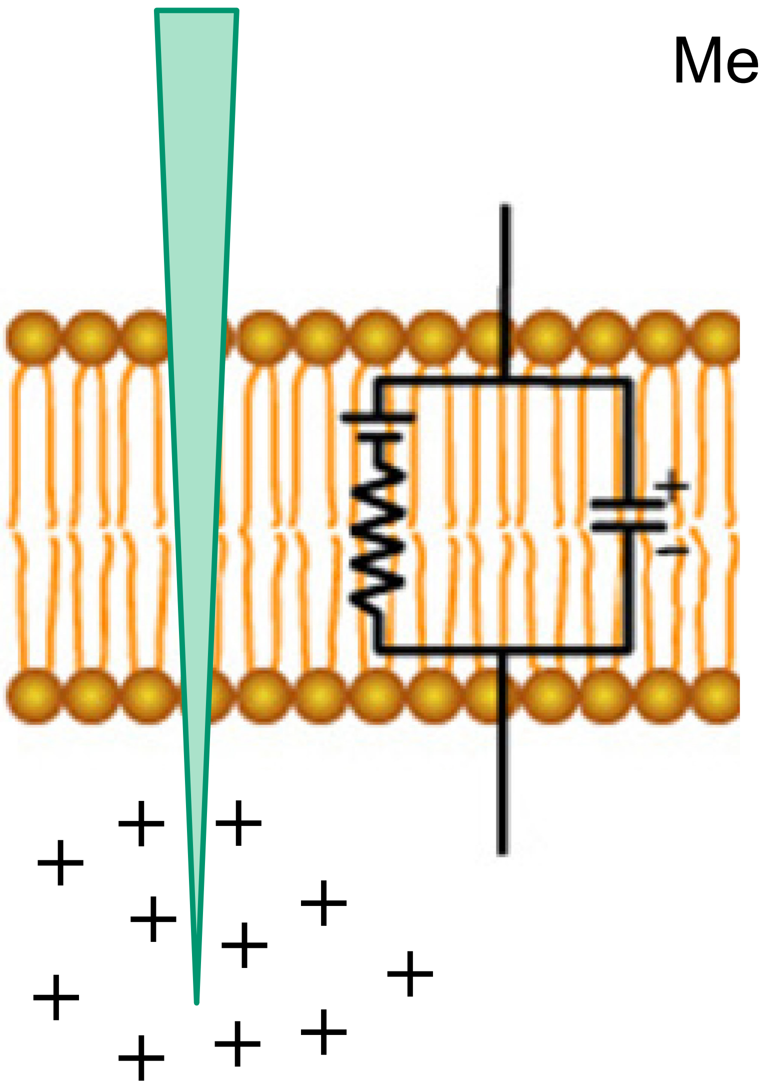
Inject current into a cell & measure voltage

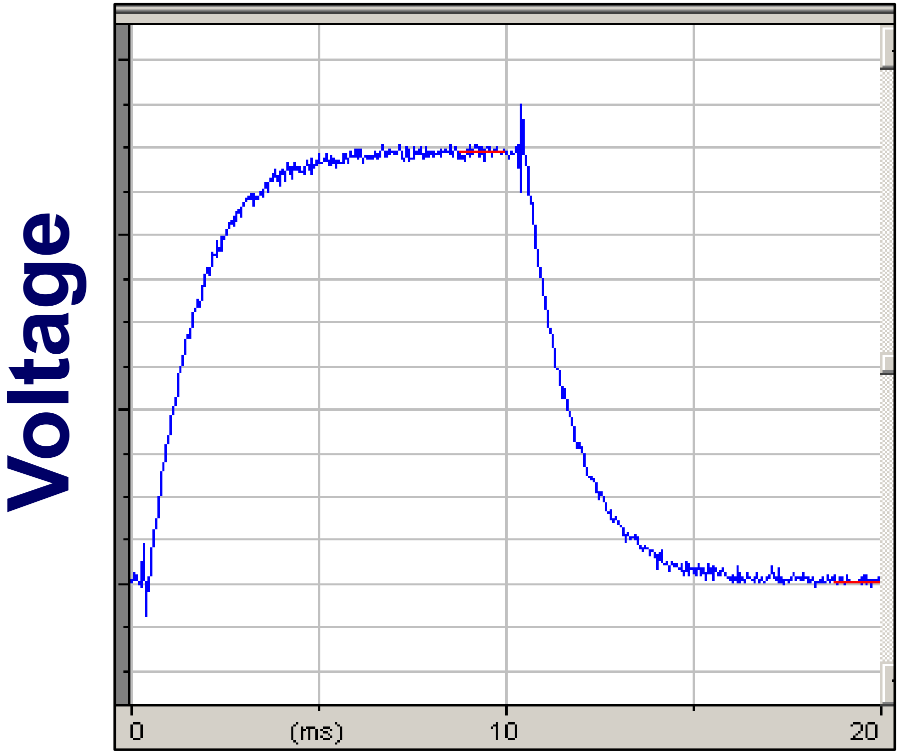


How would the tracing change if...

Membrane *capacitance* increased?

Membrane *capacitance* decreased?



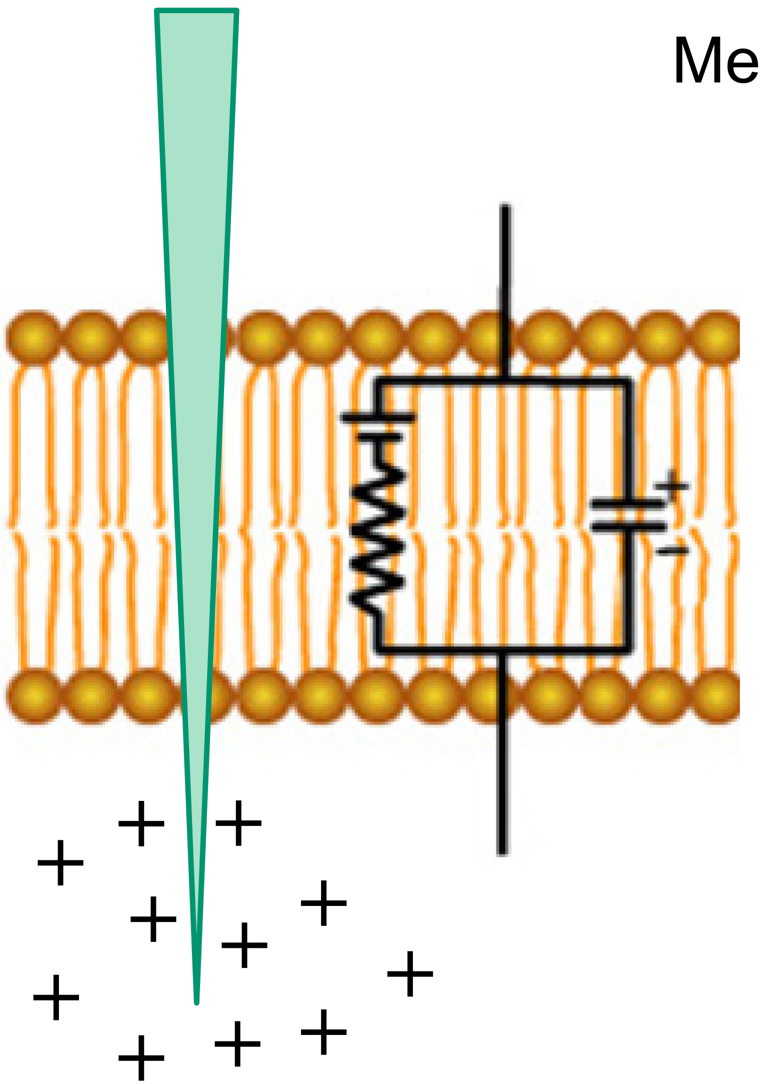


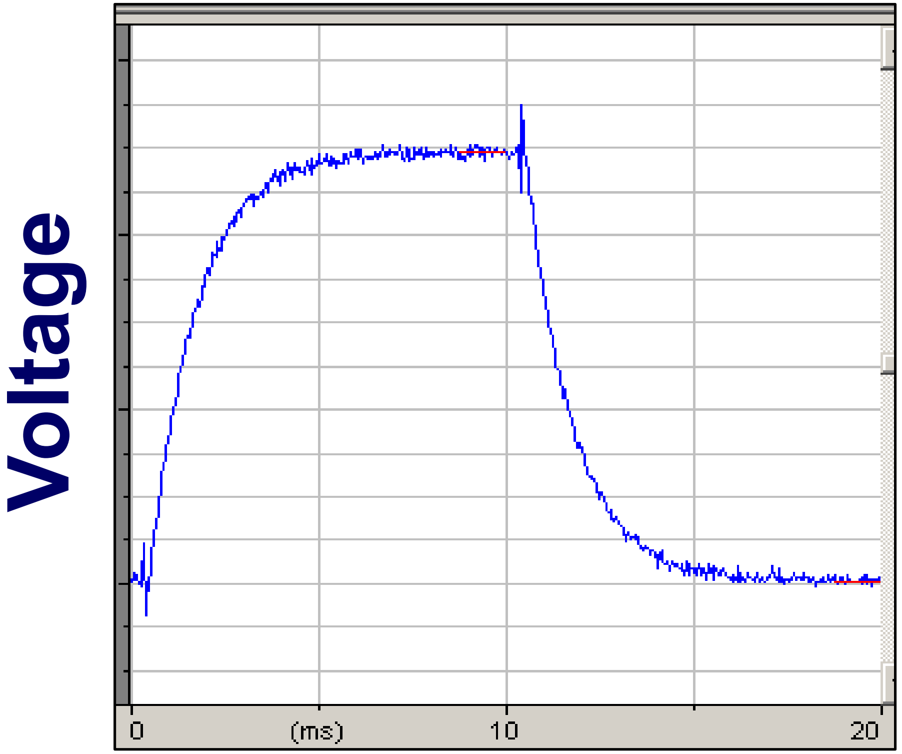
How would the tracing change if...

V=IR

Membrane *resistance* increased?

Membrane *resistance* decreased?

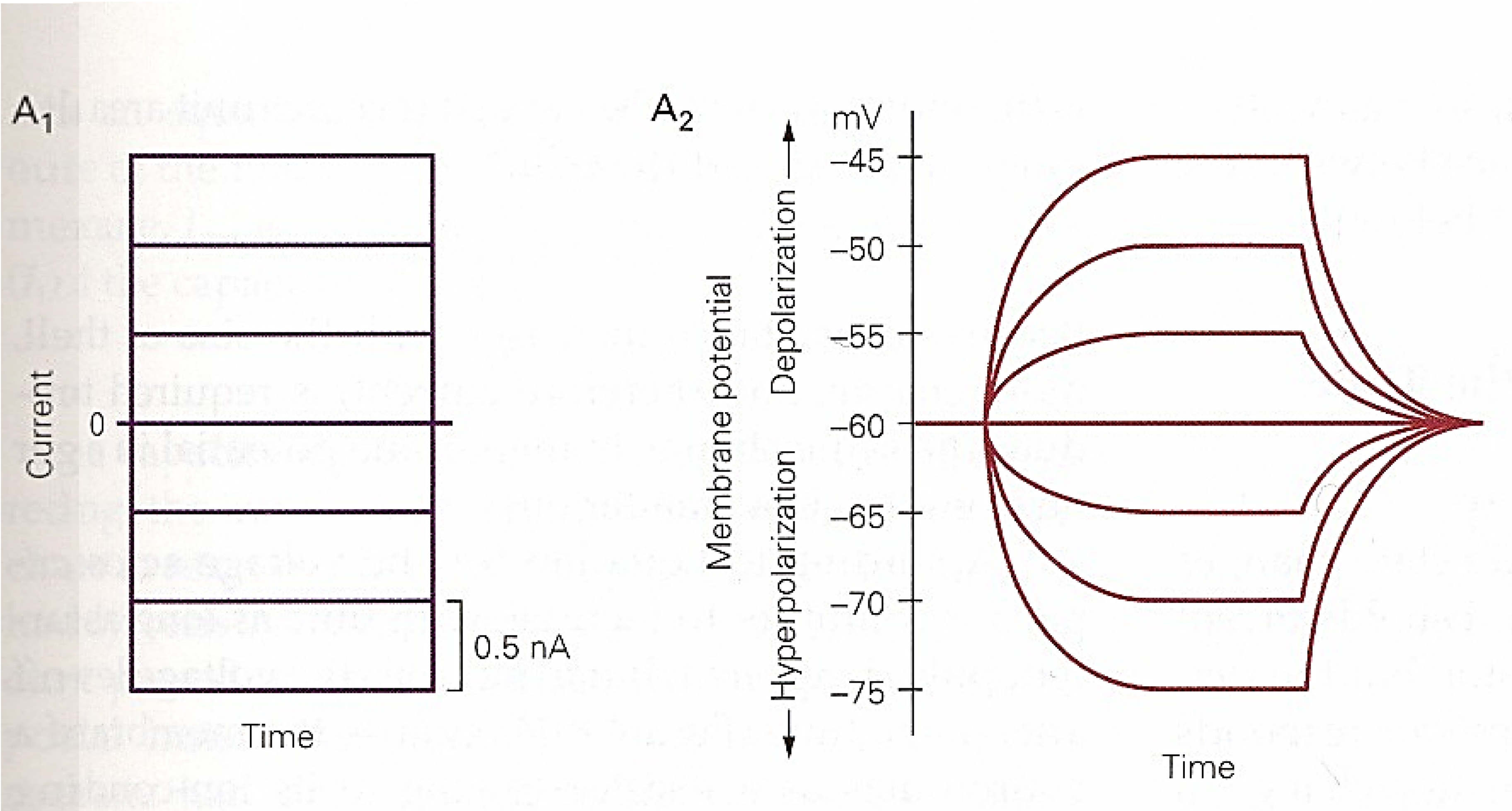




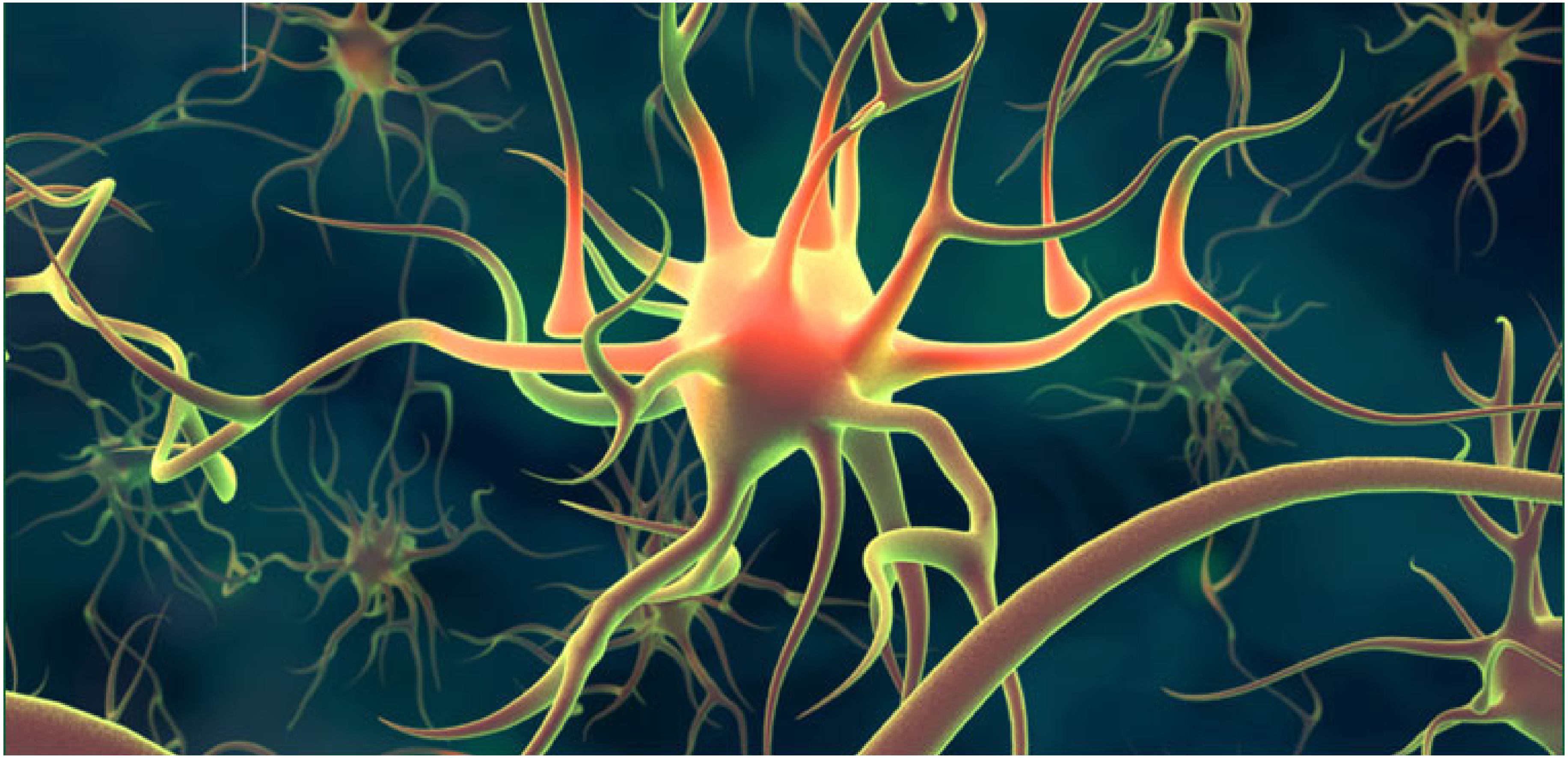
How would the tracing change if...

The amount of injected current changed?

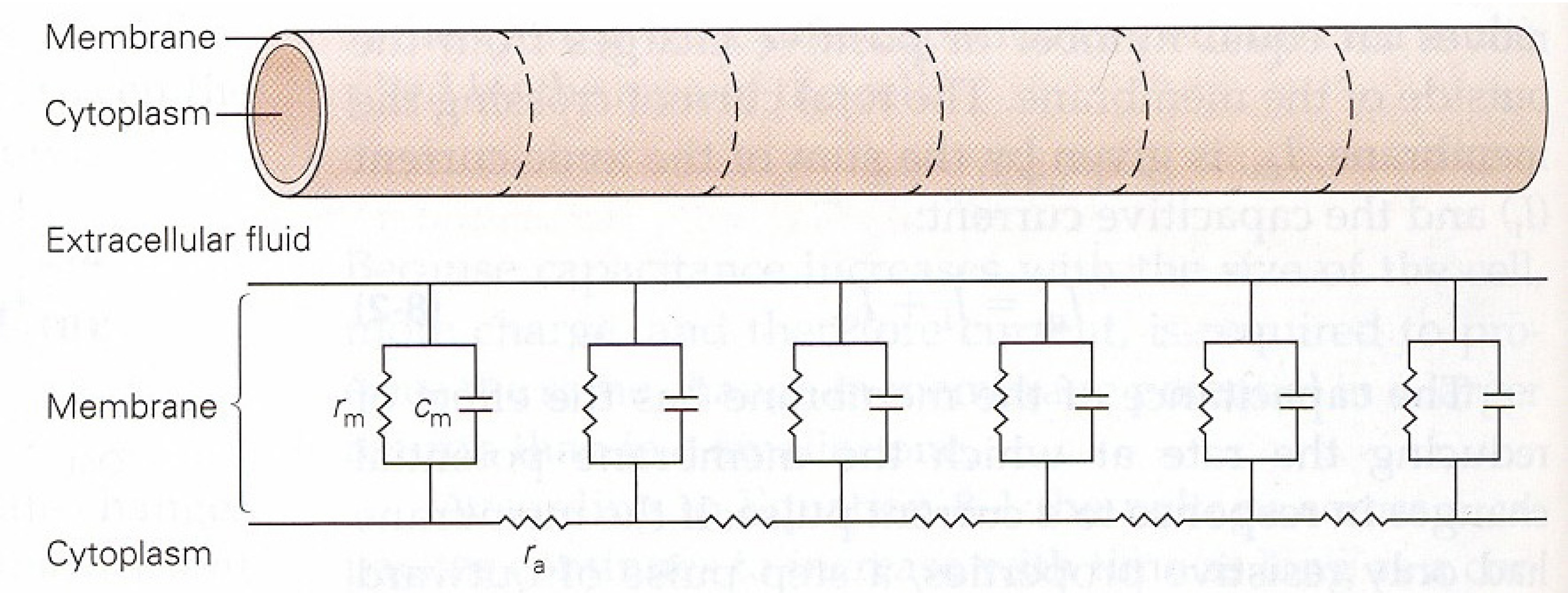
V=IR



Cable Properties of Neurites



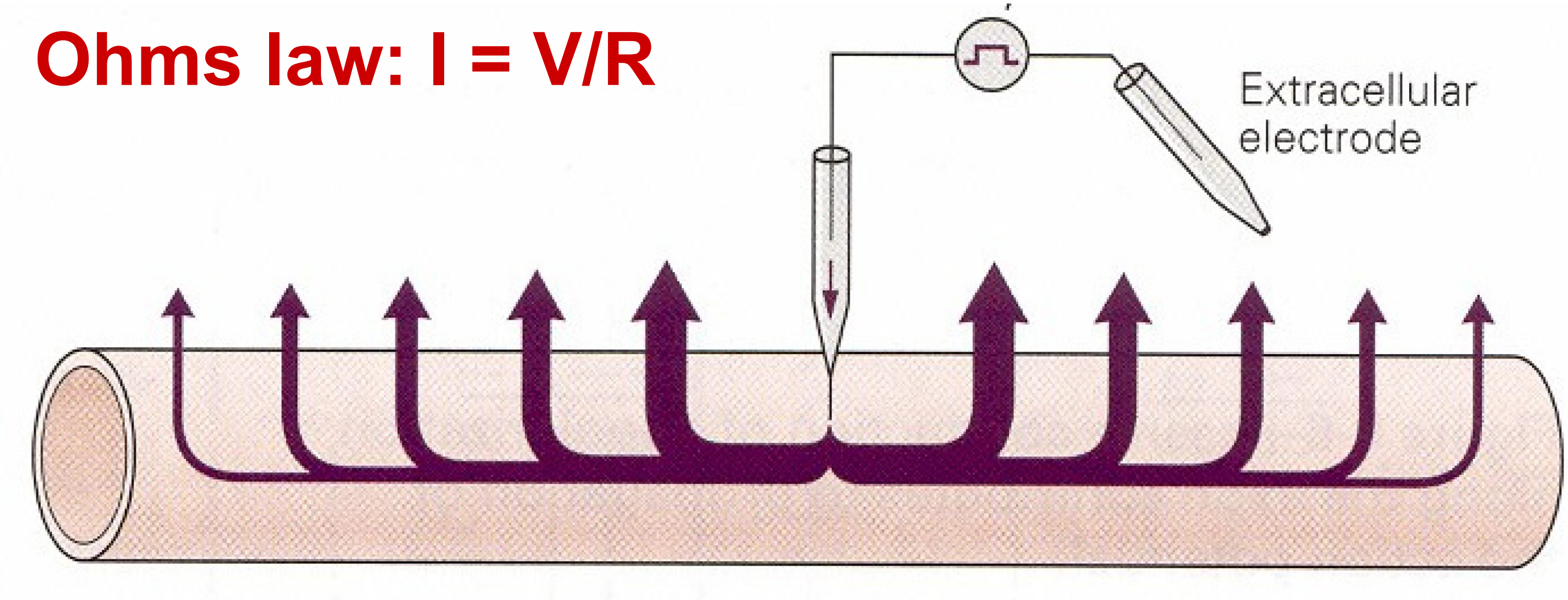
Cable Properties of Neurites



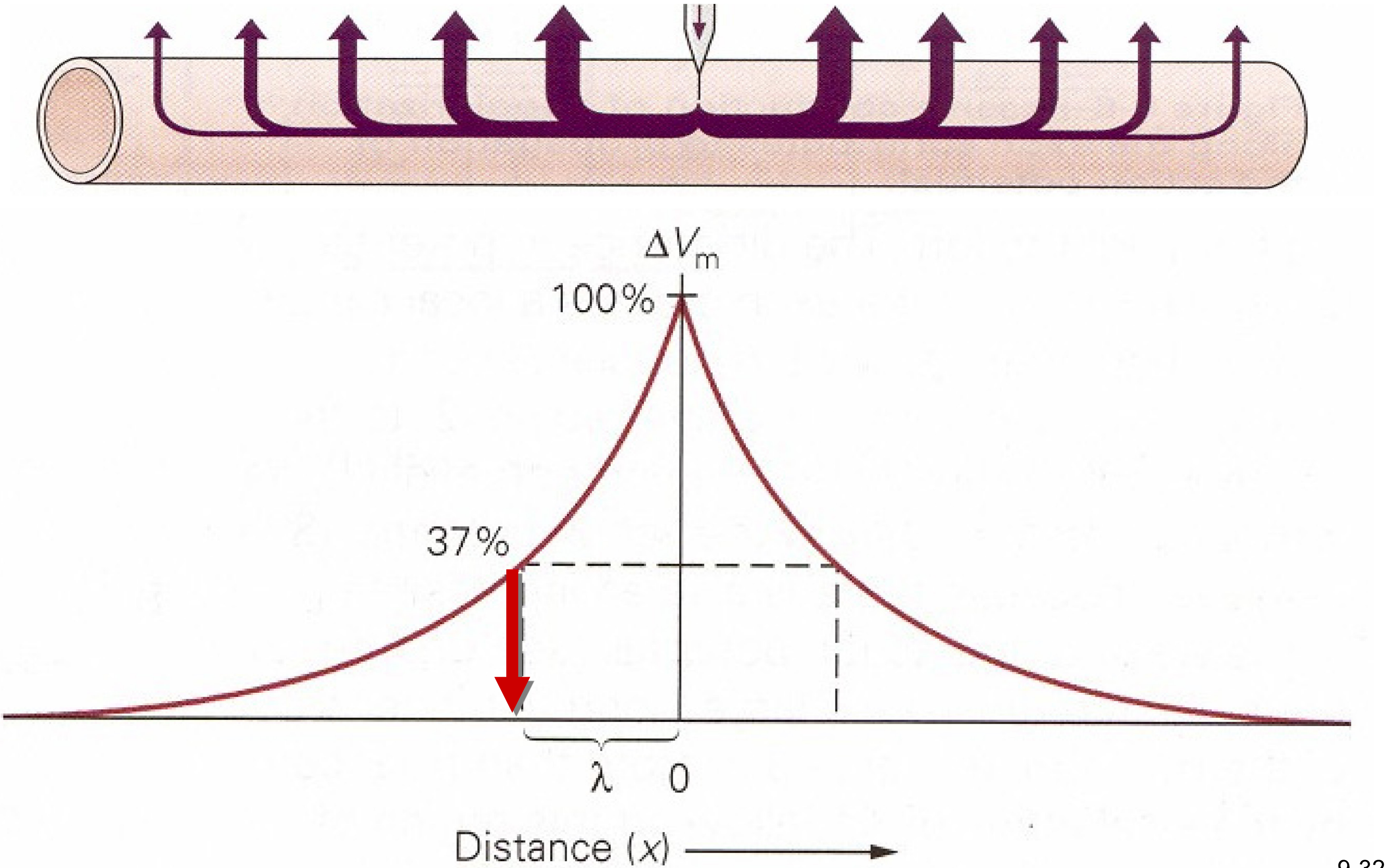
- As current moves down a neurite, we need to consider the capacitance (C_m) and membrane resistance (R_m) of each membrane patch
- We also need to consider the axial resistance (R_a) of the neurite cytoplasm

Current moving down a neurite will decay due to axial resistance

Ohms law: I = V/R

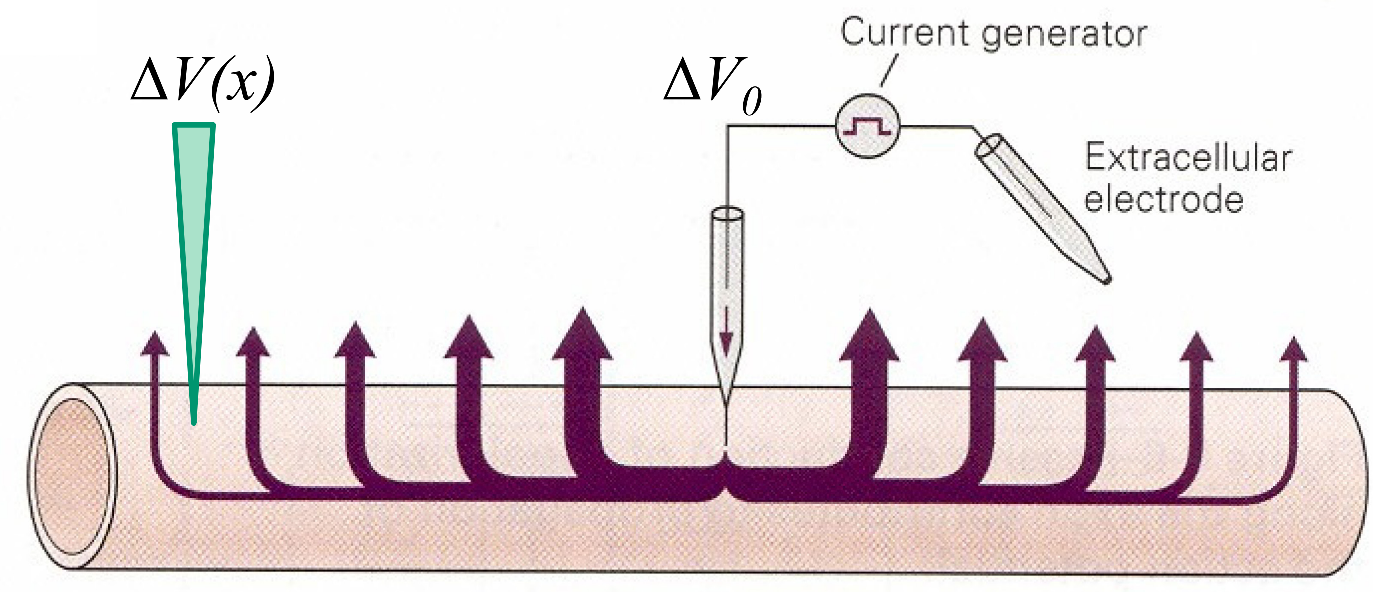


The Membrane Length Constant λ

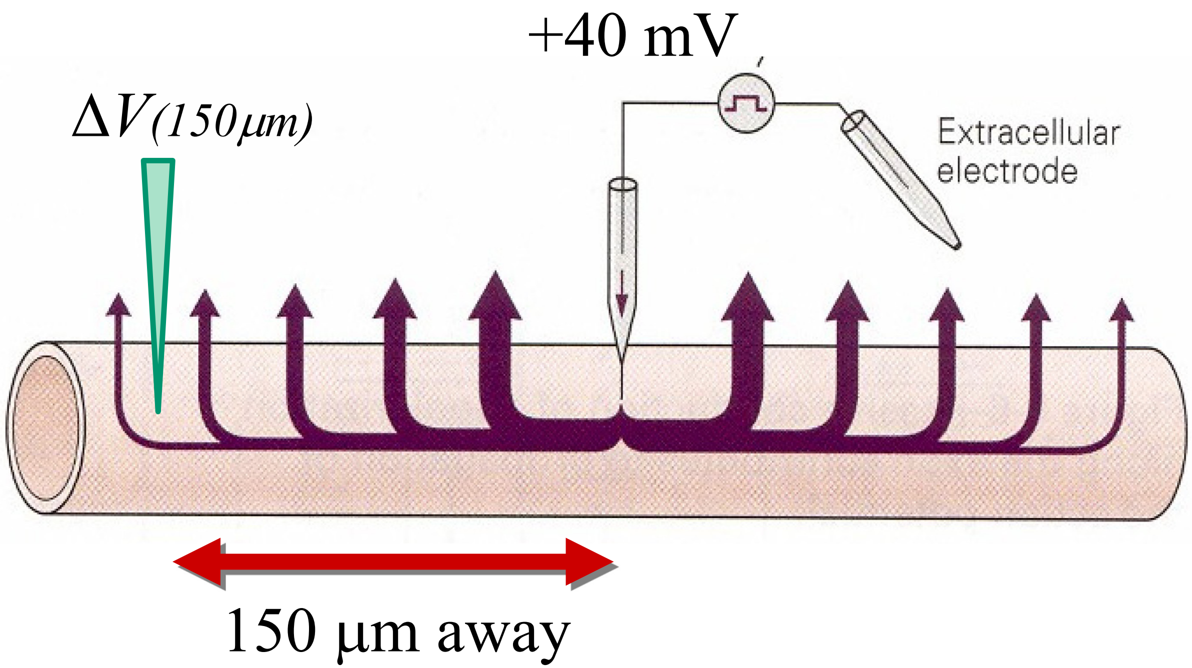


Calculating Current Decay

$$\Delta V(x) = \Delta V_o e^{\frac{-x}{\lambda}}$$



How much depolarization would be felt 150 μm down a dendrite from a 40 mV depolarization (e.g. from -60 to -20 mV) if the membrane length constant is 50 μm?

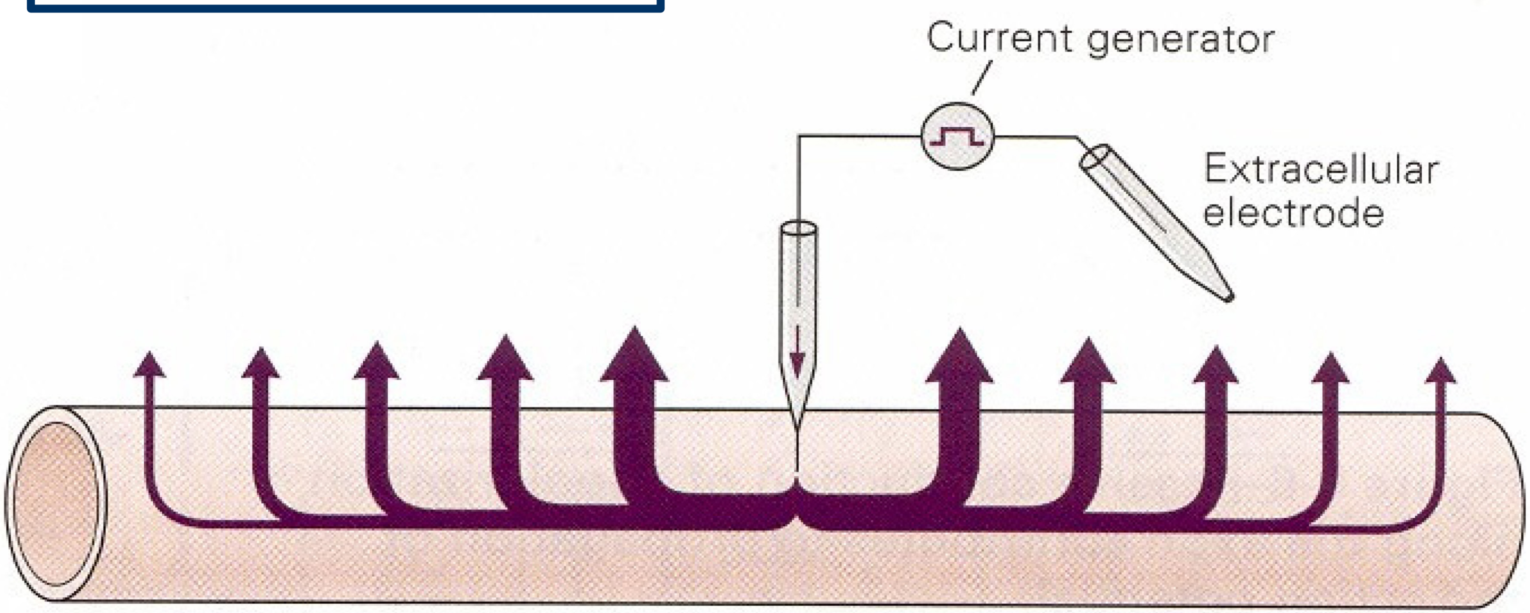


$$\Delta V(x) = \Delta V_o e^{\frac{-x}{\lambda}}$$

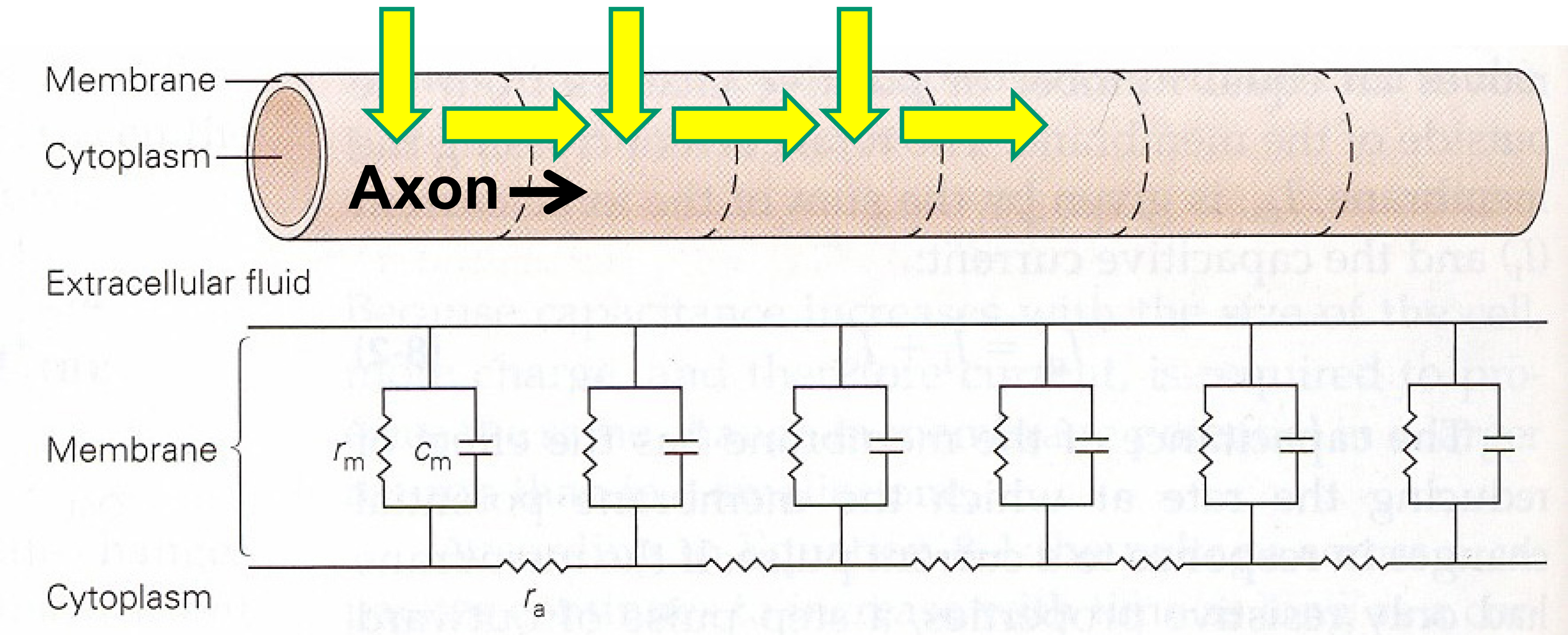
The Membrane Length Constant λ

$$\lambda = \sqrt{\frac{R_m}{R_a}}$$

What neuronal properties influence R_m and R_a?



Action Potentials

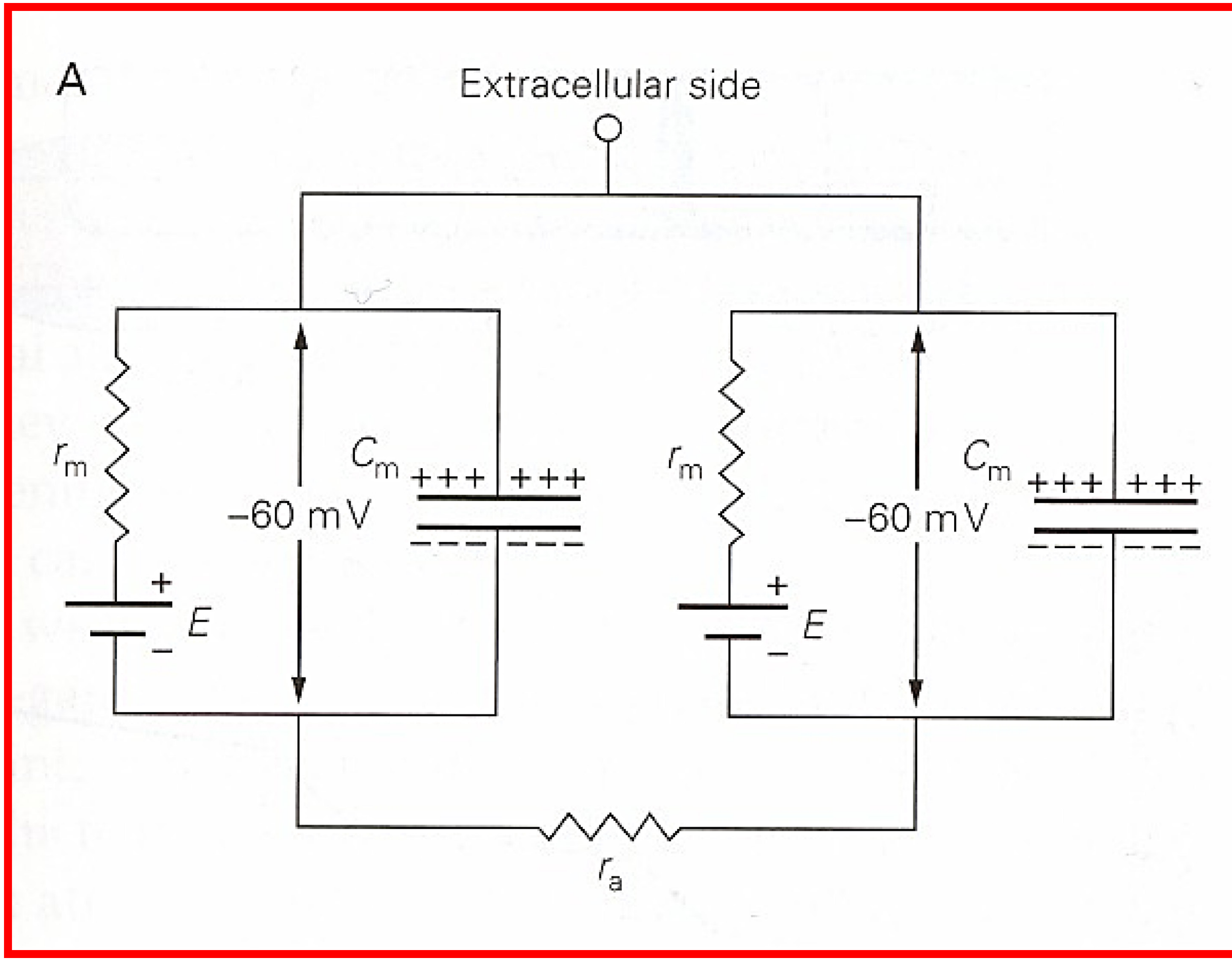


•Depolarization occurs due to Na^+ influx

•*Local current flow* moves down the axon, depolarizing neighboring voltage-gated Na^+ channels

Action Potentials

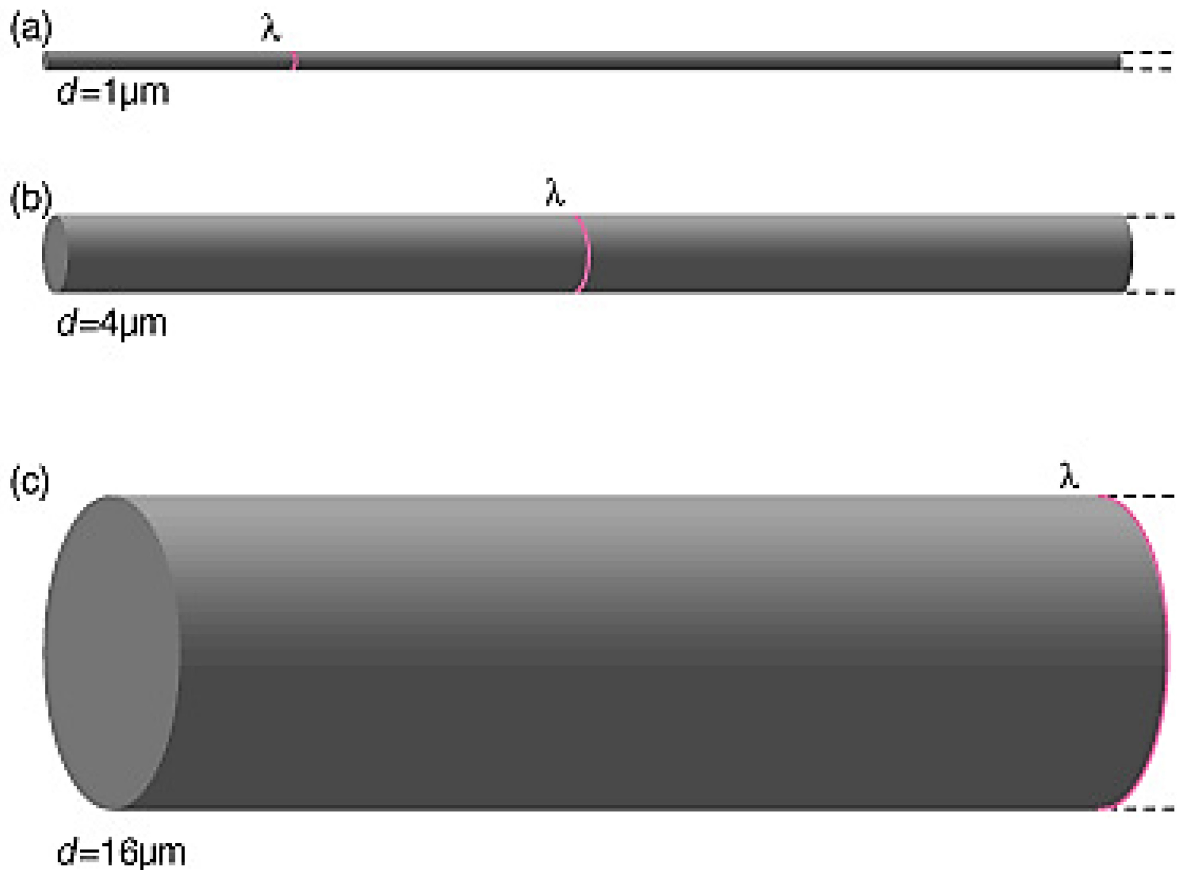
Local current flow can be modeled in a circuit



C_m, R_a and R_m of the axon influence the rate of spread of the depolarization

Action Potentials

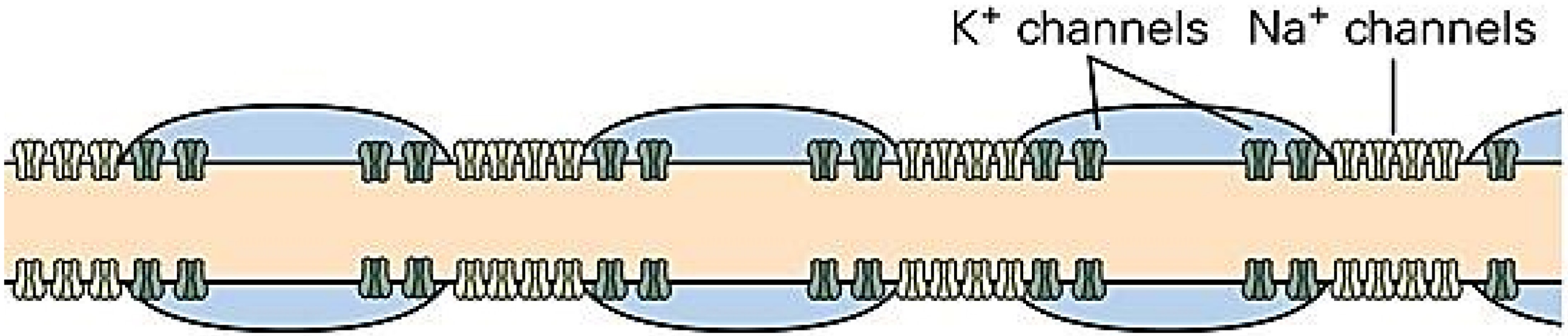
One evolutionary strategy to increase action potential speed has been to decrease R_a by increasing axon diameter.



Action Potentials

A second evolutionary strategy has been to myelinate axons. What does myelination do?

- Myelin __________ membrane capacitance (C_m)
- Myelin __________ membrane resistance (R_m)

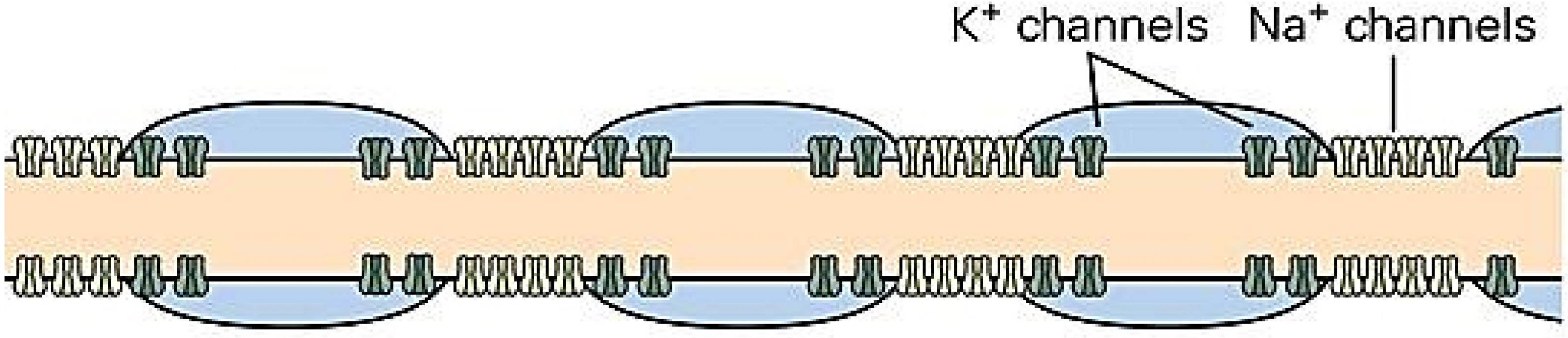


Action Potentials

Action potential propagation speeds up along internodes (areas covered by myelin). Why?

The action potential slows down at nodes of Ranvier. Why?

This creates “saltatory conduction”



Why not completely myelinate an axon? Why are nodes of Ranvier necessary?