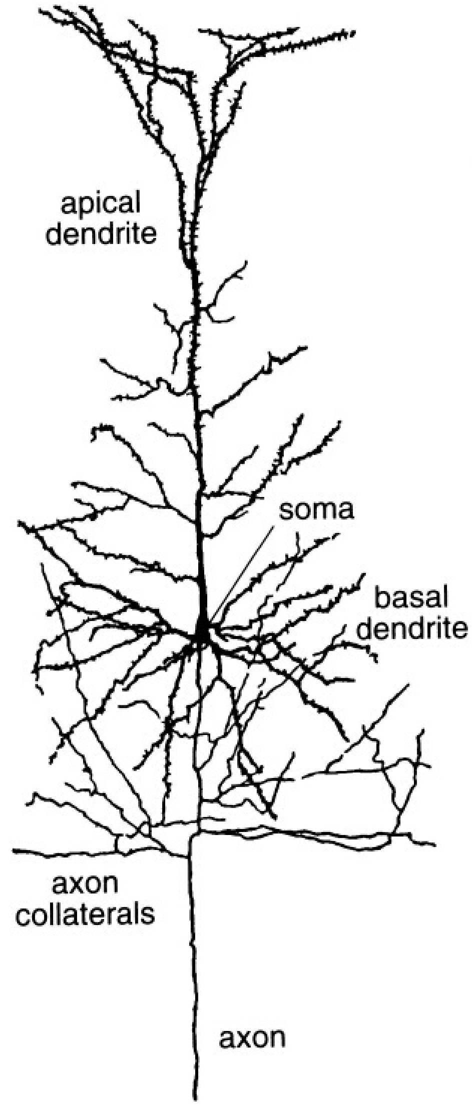
Neuroelectronics

The Neuron



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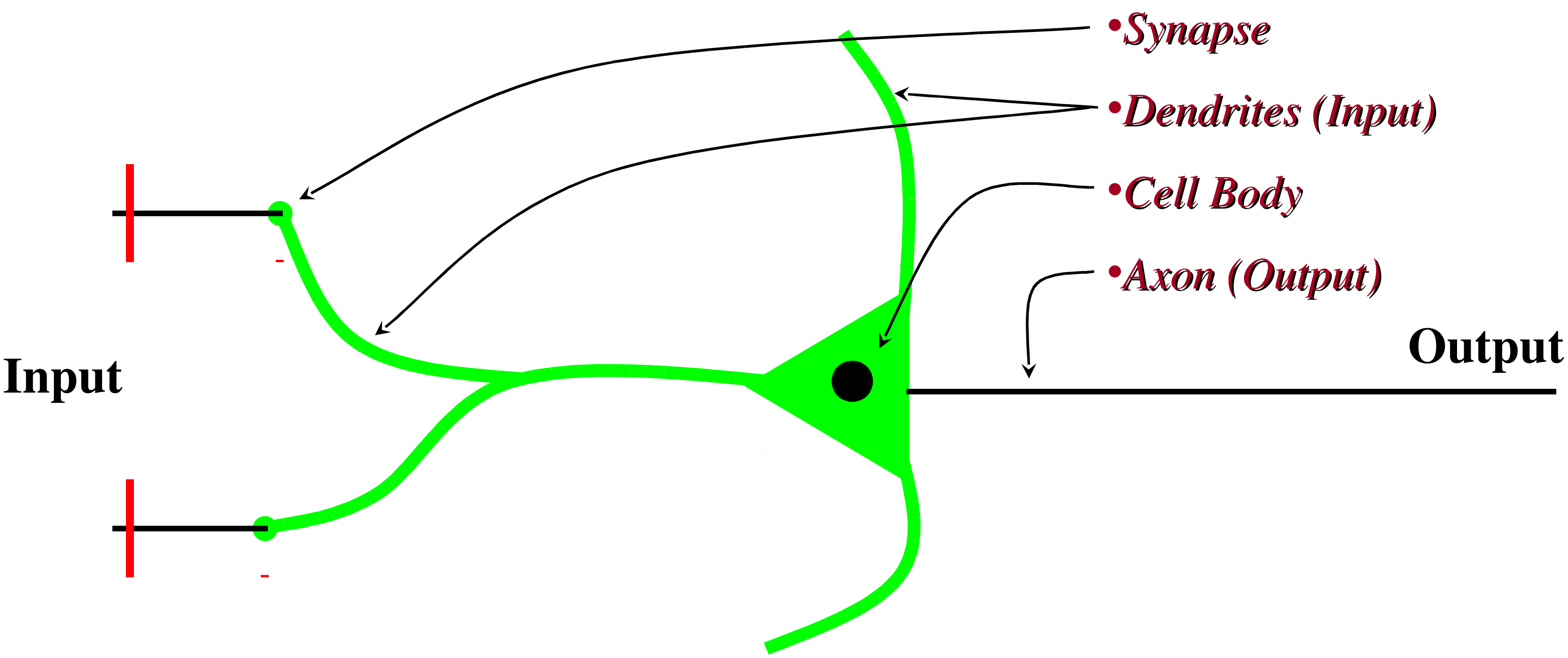
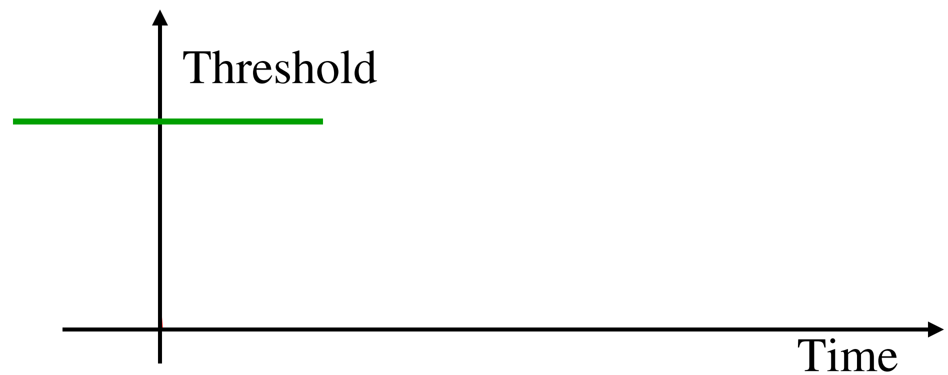
Neuron: The Device



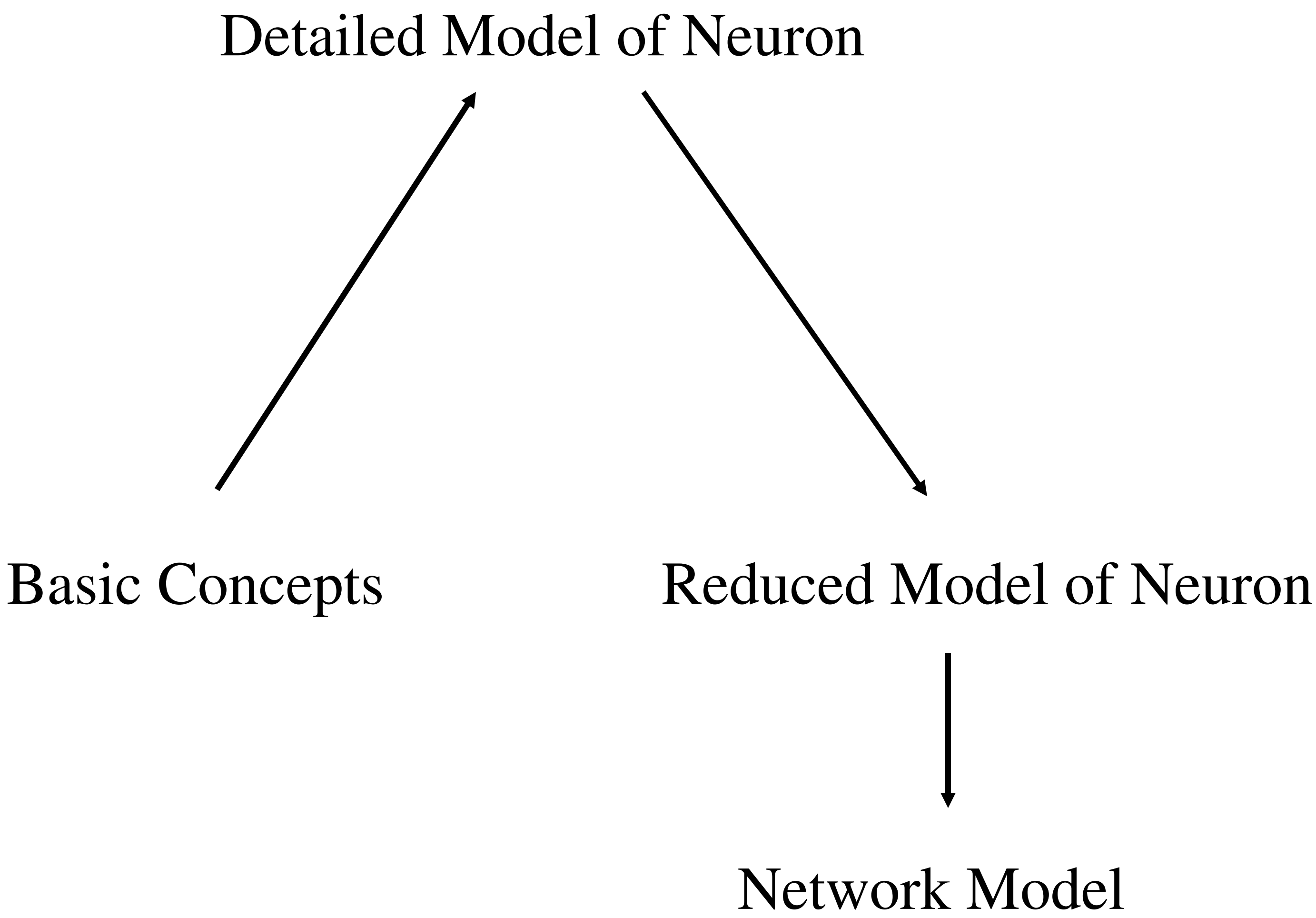
Equilibrium: Membrane Potential

Dendrites: Passive Conductance

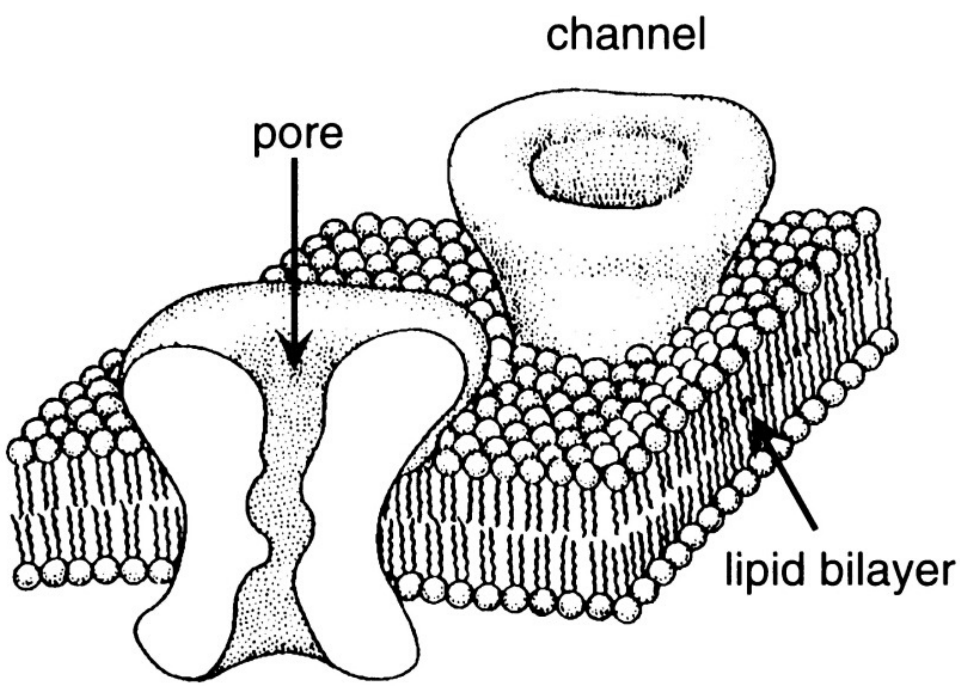
Axon: Spikes (Hodgkin Huxley Eqns)



Approach


Detailed Model of Neuron
Basic Concepts
Reduced Model of Neuron
Network Model

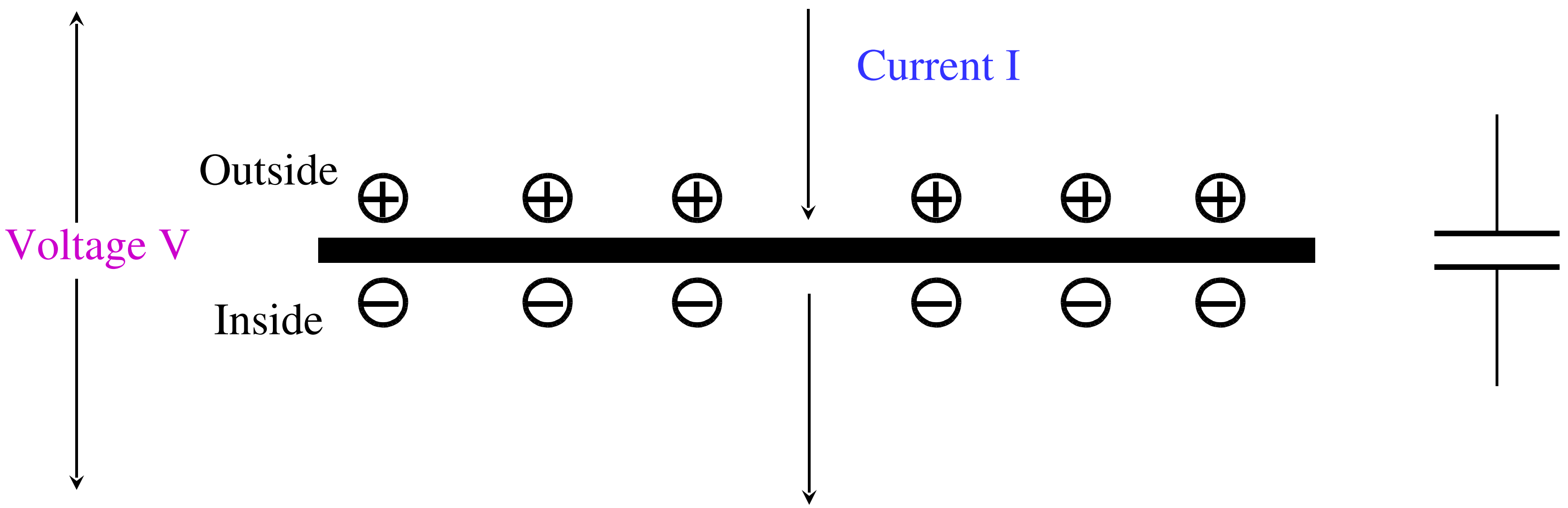
The Membrane



Membrane: 3 to 4 nm thick, essentially impermeable

Ionic Channels: Selectively permeable (10,000 times smaller resistance)

The Membrane: Capacitance

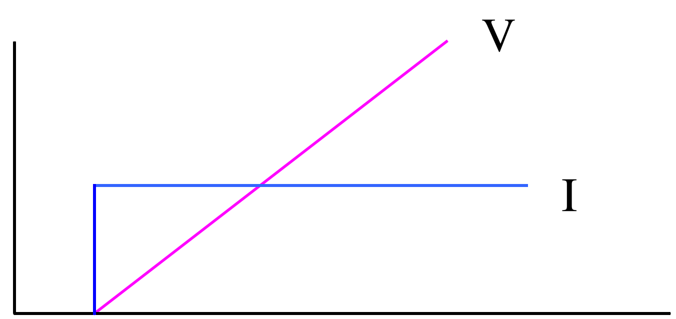


$C = Q/V$ 1 Farad = 1 Coulomb/ 1 Volt

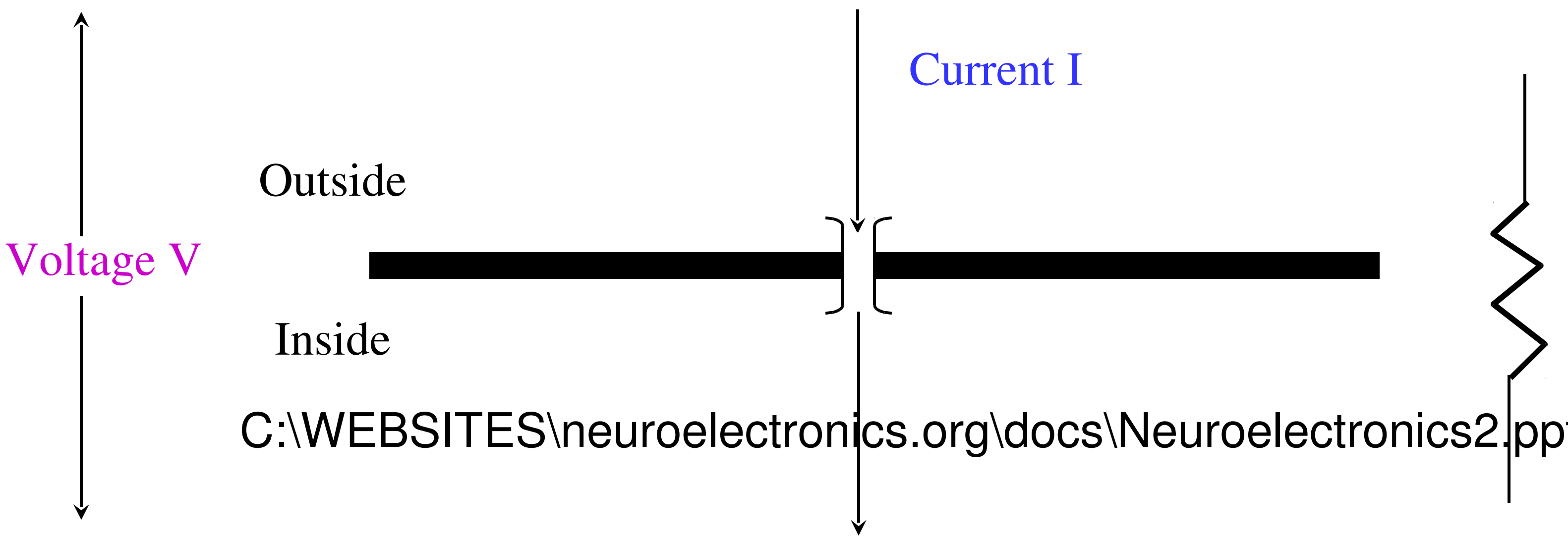
$(Q = CV)$;

$dQ/dt = I$

$I = C\, dV/dt$



The Membrane: Resistance



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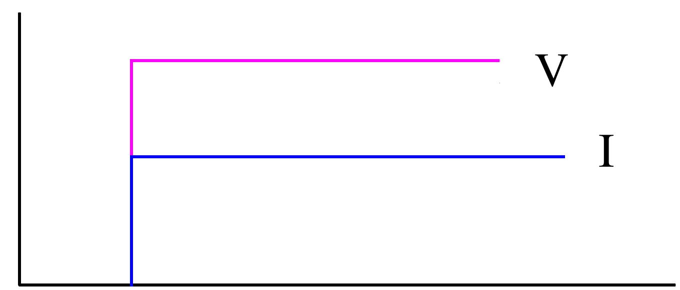
R = V/I   1 Ohm = 1 Volt/ 1 Ampere

I = V/R



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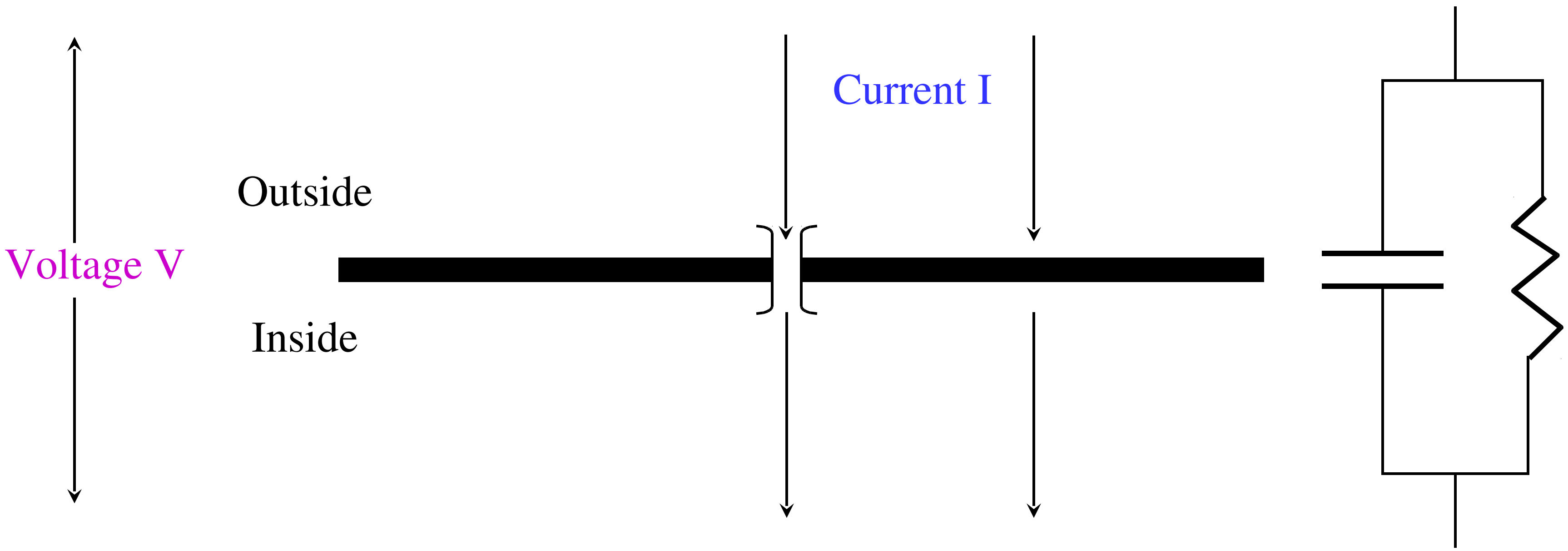
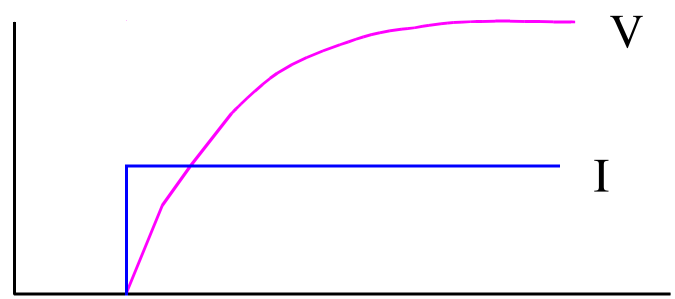
The Membrane: Capacitance and Resistance



$$I = C\, dV/dt + V/R$$

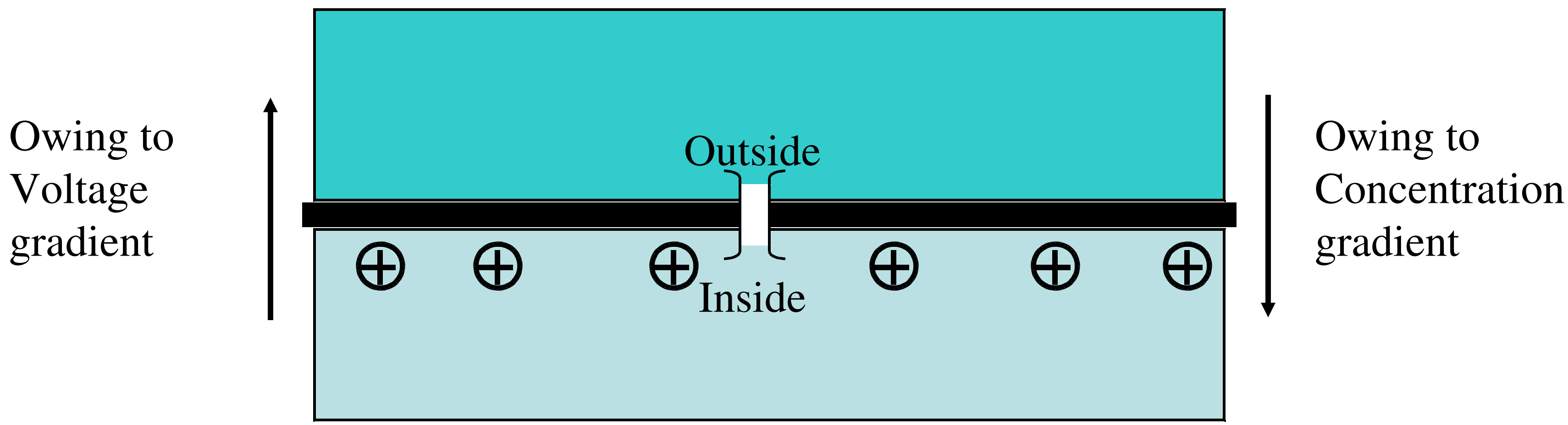
$$(C*R)\, dV/dt = -V + IR$$



The Membrane: Membrane Potential

Case 1: Single type of Ion (Na^+)

Charge Balanced out by impermeable ion



Reversal Potential : When opposing currents balance each other out.

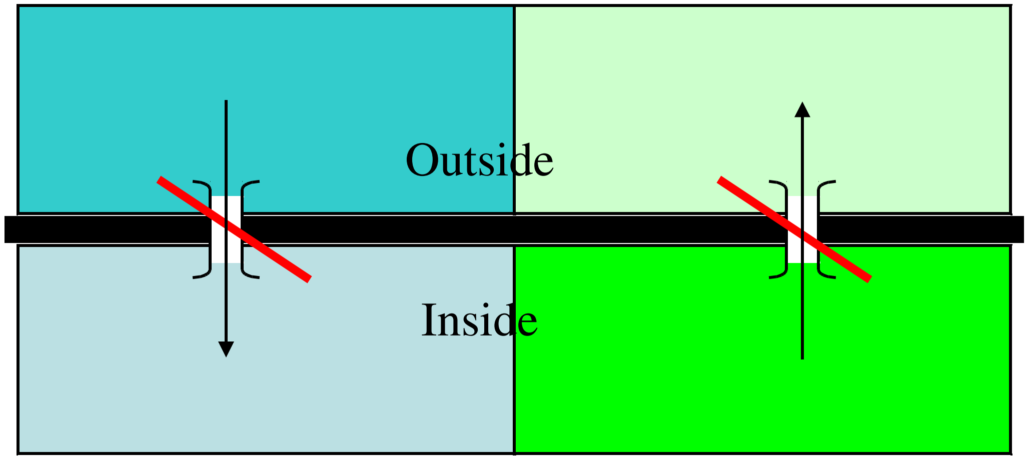
Nernst Equation: E= (RT/z) ln([outside]/[inside])

Reversal Potential for Na^+ is around *+50 mV* (based on typical concentration gradients)

Note: Reversal potential **does not** depend upon *resistance.*

The Membrane: Membrane Potential

Case 1: Two types of Ions (Na^+ and K^+)



Equilibrium Potential : When opposing currents balance each other out (*-70 mV)*.

Goldman Equation:

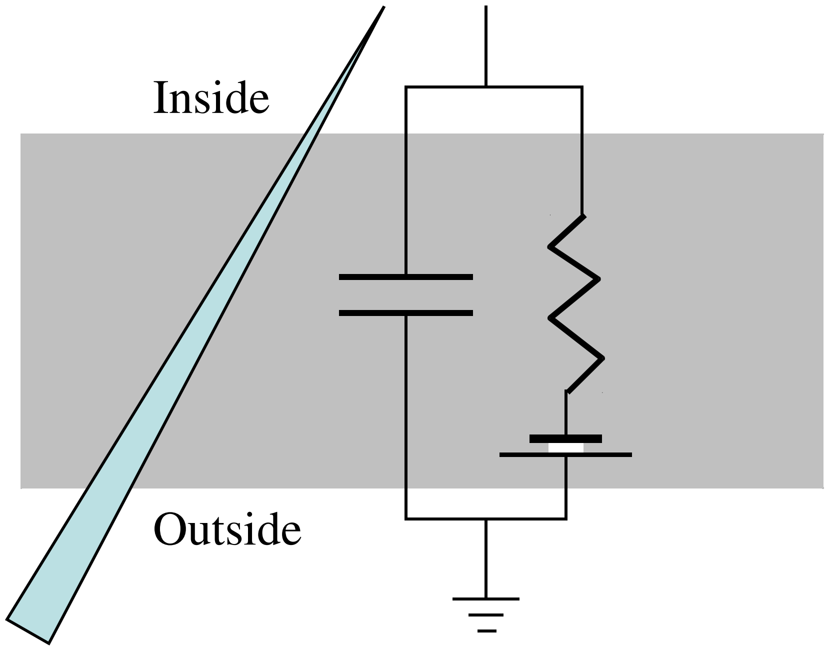
$$V= (-60\ mV)*\ \log_{10}((P_K[K]_{in}+P_{Na}[Na]_{in}+P_{Cl}[Cl]_{out})/(P_K[K]_{out}+P_{Na}[Na]_{out}+P_{Cl}[Cl]_{in}))$$

Note: Equilibrium potential **does** depend upon relative *resistances.*

Reversal potentials ---- Na^+ *: +50 mV* K^+ *: -80 mV*

Why ingesting Pottasium Cloride is deadly; ingesting Sodium Cloride is not.

Passive membrane: Equivalent Circuit



Voltage independent channels

Single Compartment

Electrotonically compact neuron.

$$I_{INJ} = I$$

$$I = C\, dV/dt + (V - E_L)/R$$

Use new variable: $V = V - E_L$

$$(C*R)\, dV/dt = -V + IR$$

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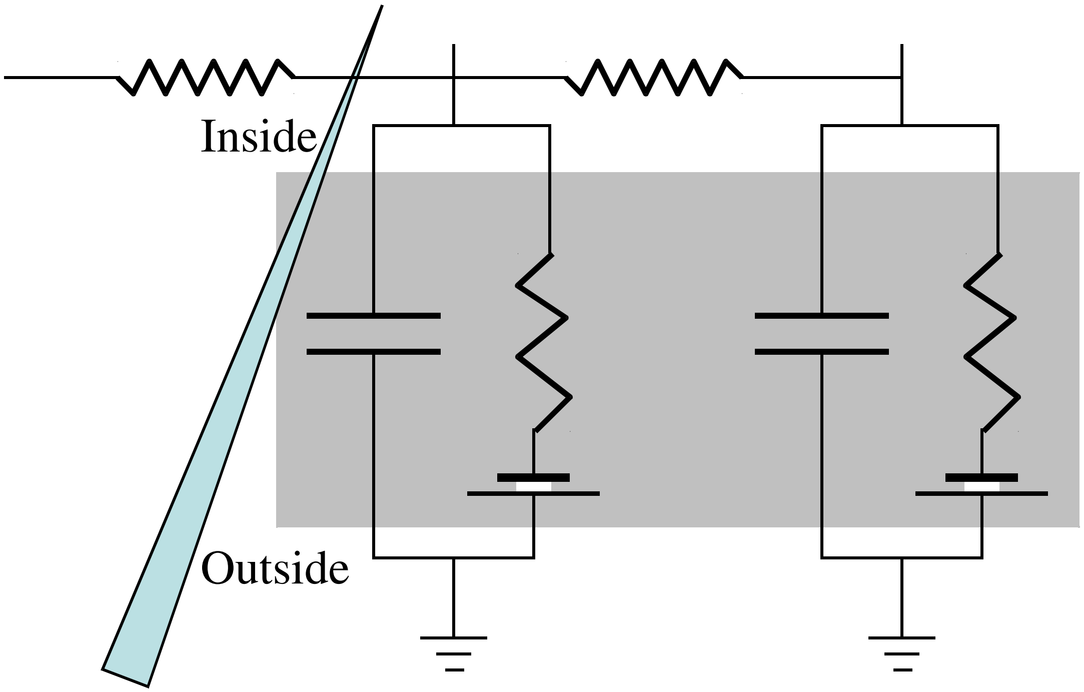
Passive membrane: Cable Equation



Voltage independent channels

Multiple Compartments

Electrotonically non-compact neuron.

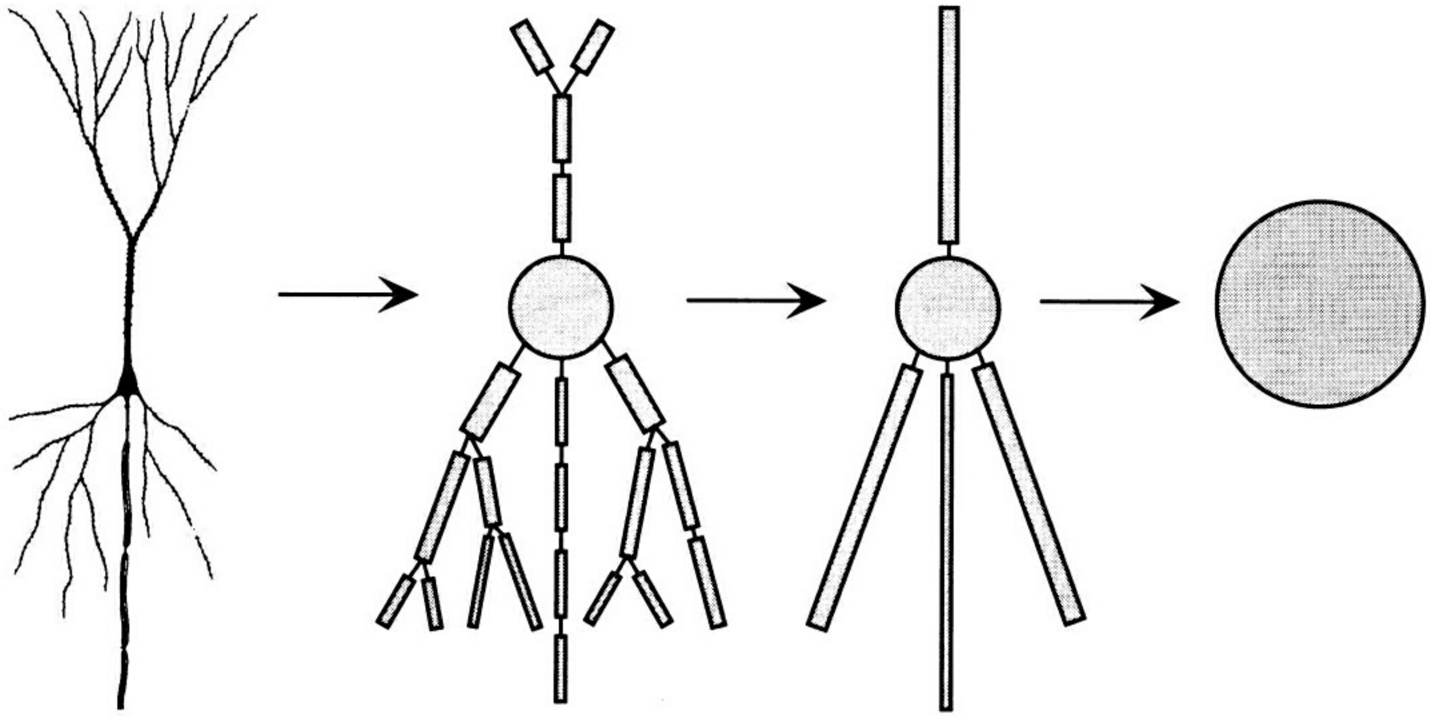
$$C\ \partial V/\partial t = -V/R + I$$

$$\partial V/\partial x = ir \qquad \text{hence } \partial^2 V/\partial x^2 = r\partial i/\partial x$$

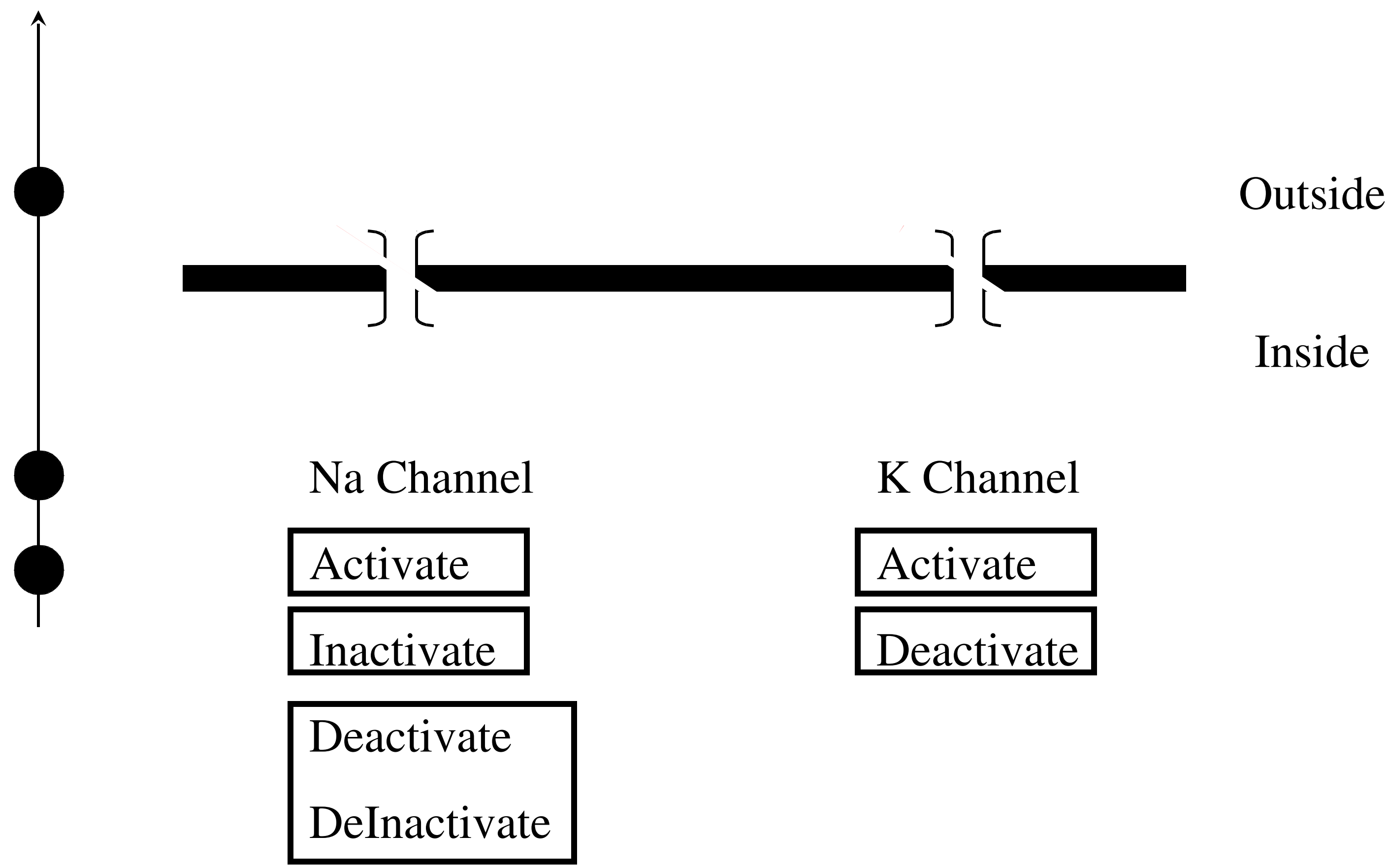
$$I_{INJ} = I - \partial i/\partial x \qquad \text{hence } I = I_{INJ} + \partial i/\partial x$$

$$C\partial V/\partial t = (1/r)\ \partial^2 V/\partial x^2 - (1/R)V + I_{INJ}$$

Passive membrane: Compartmental Model



Active membrane: Voltage Dependent Conductance



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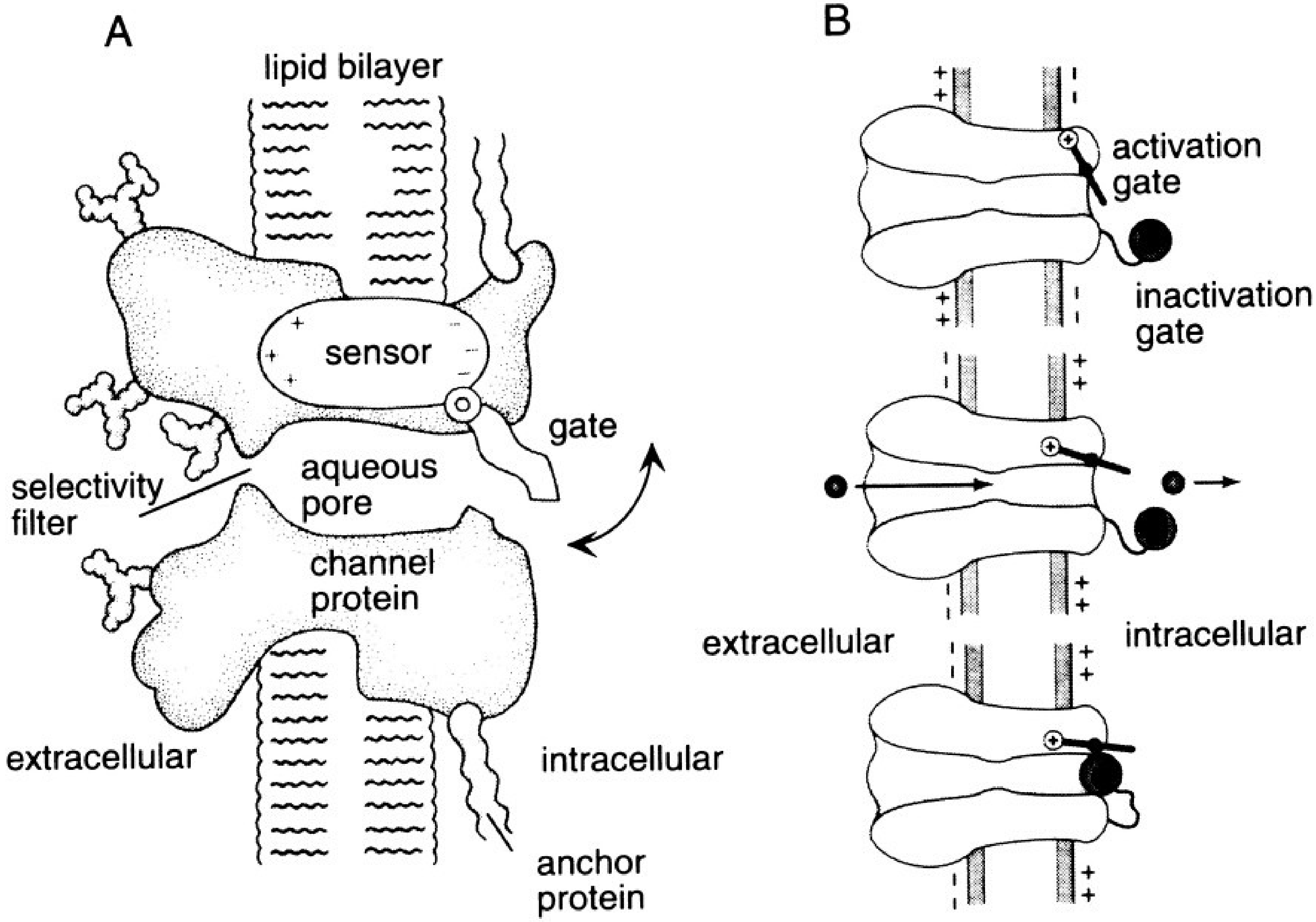
Active membrane: Sodium Channel



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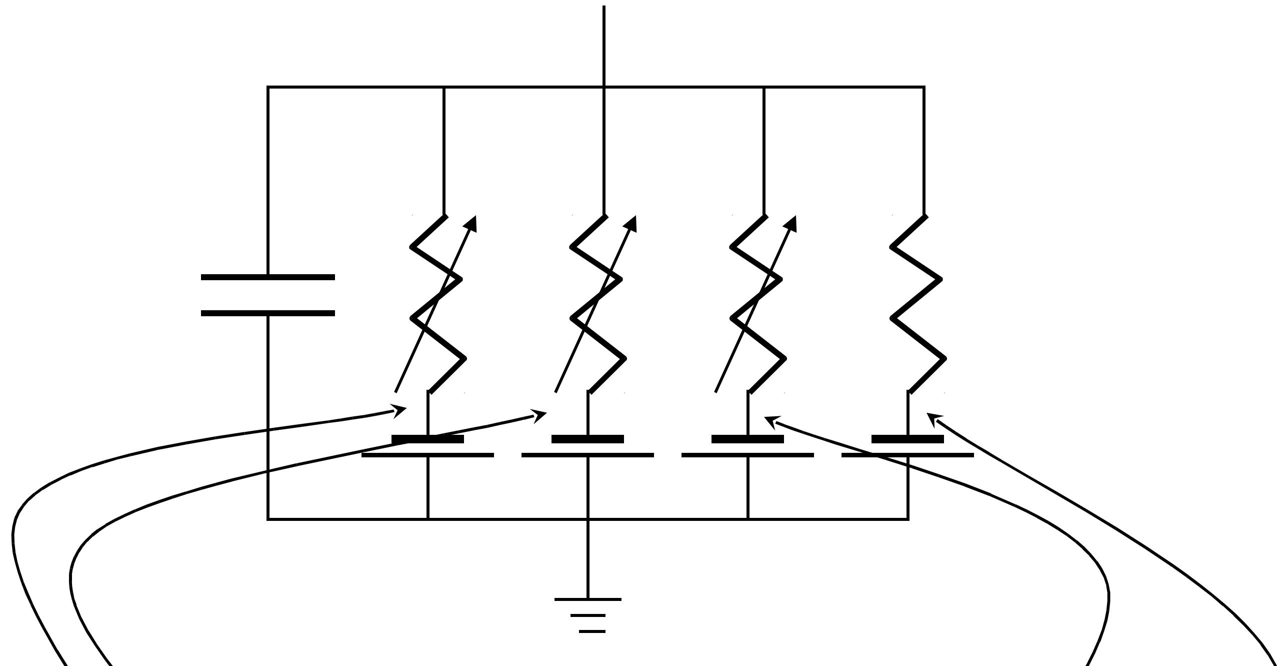
Active membrane: Voltage Dependent Conductance



Na^+ Channels: G_{Na} ($1/R_{Na}$) and E_{Na}

K^+ Channels: G_K ($1/R_K$) and E_K

Ca^{2+} Channels: G_{Ca} ($1/R_{Ca}$) and E_{Ca}

Leak Channels: G_L ($1/R_L$) and E_L

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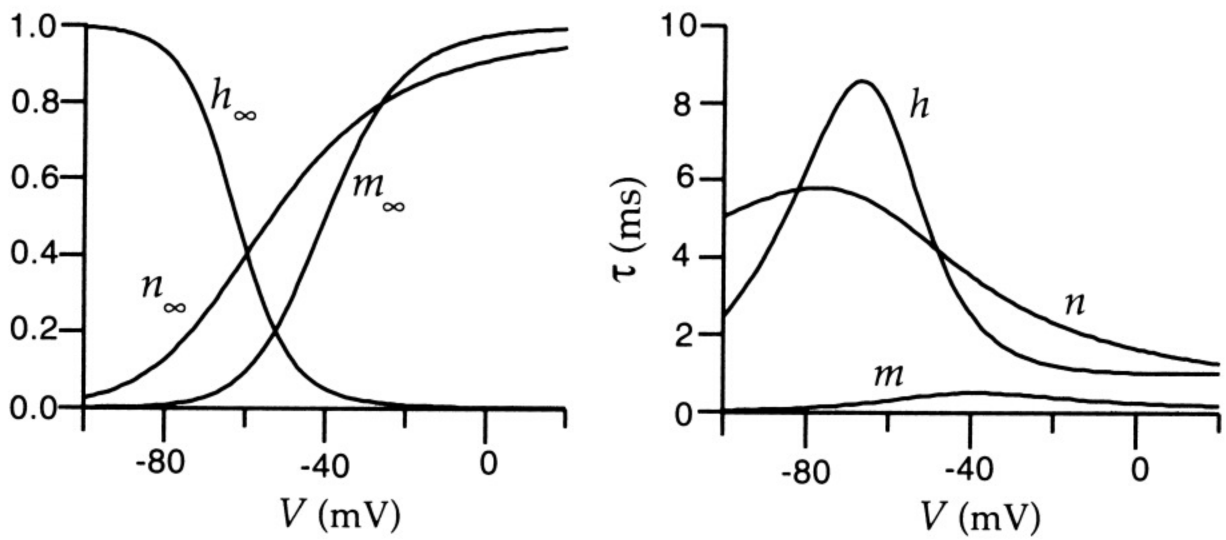
Active membrane: Hodgkin Huxley Equations

$$I = C\,dV/dt + G_L(V - E_L)$$

⬇

$$I = C\,dV/dt + G_L(V - E_L) + G_K n^4 (V - E_K) + G_{Na} m^3 h (V - E_{Na})$$



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Active membrane: Hodgkin Huxley Equations

$dn/dt=a_n(V)(1-n)-b_n(V)n$ $a_n(V)$ = opening rate $b_n(V)$ = closing rate

$dm/dt=a_m(V)(1-m)-b_m(V)m$ $a_m(V)$ = opening rate $b_m(V)$ = closing rate

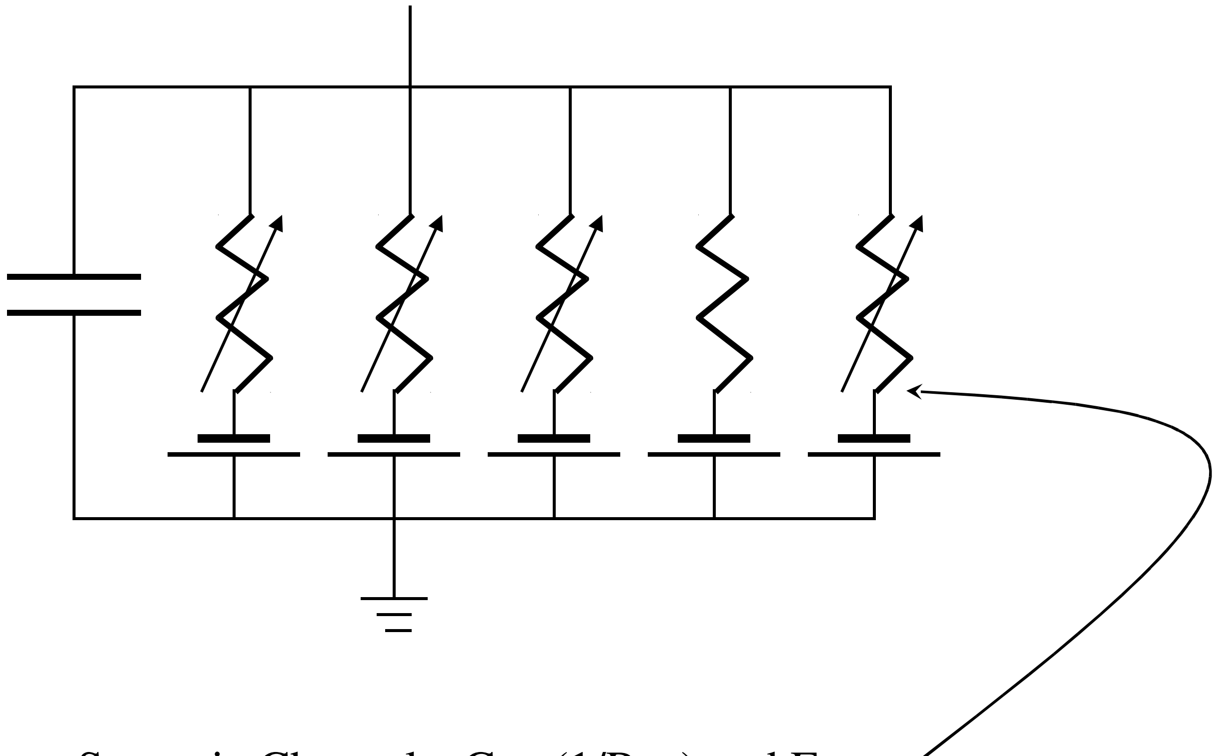
$dh/dt=a_h(V)(1-h)-b_h(V)h$ $a_h(V)$ = opening rate $b_h(V)$ = closing rate

$a_n=(0.01(V+55))/(1-\exp(-0.1(V+55)))$ $b_n=0.125\exp(-0.0125(V+65))$

$a_m=(0.1(V+40))/(1-\exp(-0.1(V+40)))$ $b_m=4.00\exp(-0.0556(V+65))$

$a_h=0.07\exp(-0.05(V+65))$ $b_h=1.0/(1+\exp(-0.1(V+35)))$

Active membrane: Synaptic Conductance



Synaptic Channels: G_{Syn} ($1/R_{Syn}$) and E_{Syn}

Reduced Model: Leaky Integrate and Fire

$CdV/dt = -G_L(V-E_L) + I$

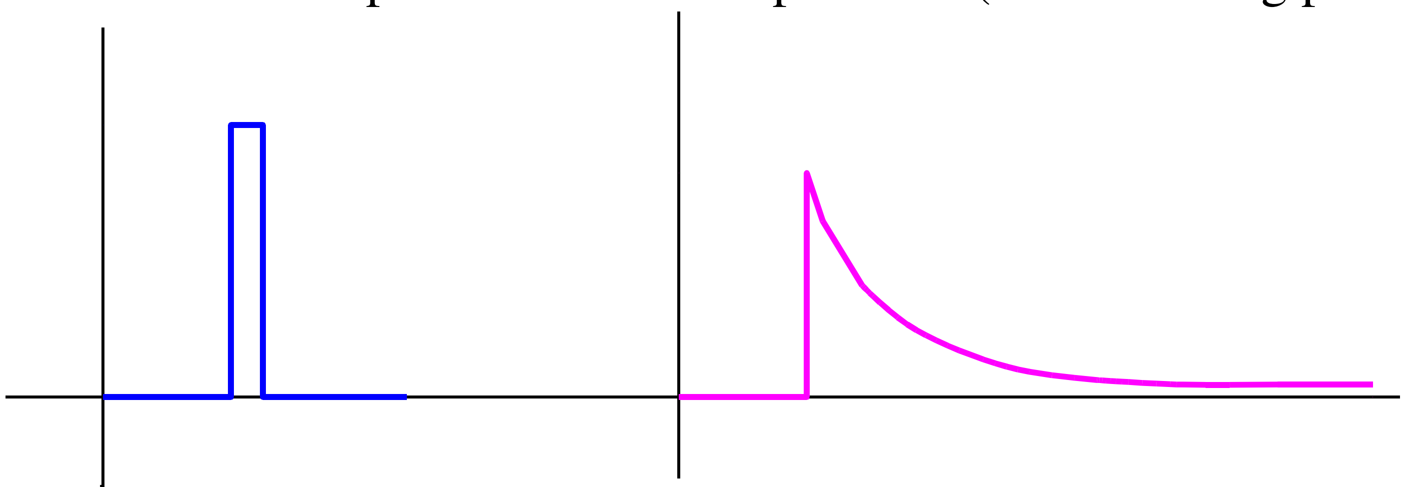
•Assume that synaptic response is an injected current rather than a change in conductance.

•Assume injected current is a δ function; Results in PSP

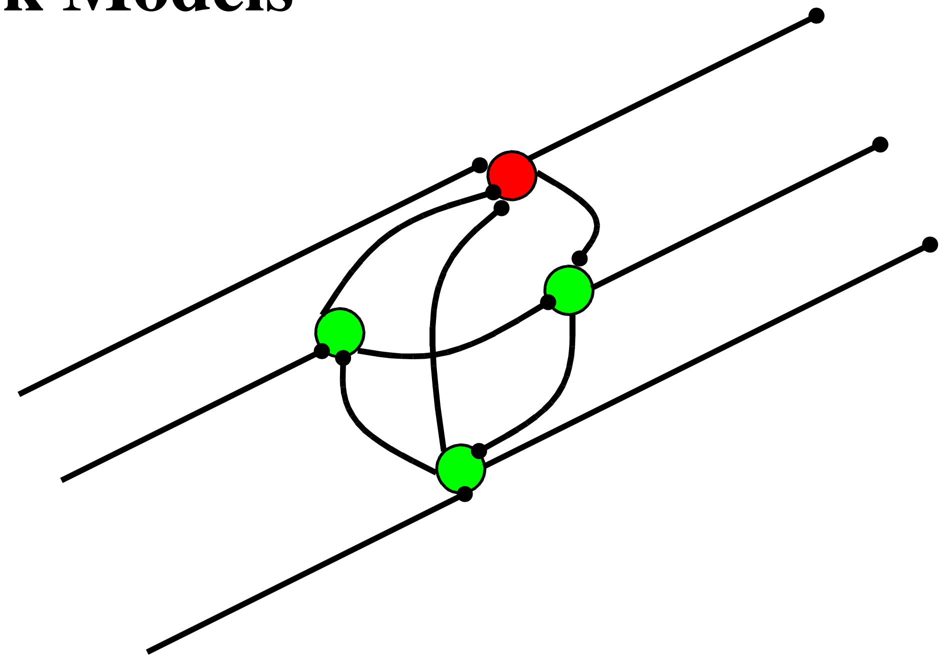
•Linear System: Total effect at soma = sum of individual PSP's

•Neuron Spikes when total potential at soma crosses a threshold.

•Reset membrane potential to a reset potential (can be resting potential)



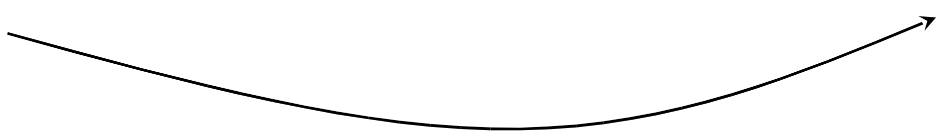
Network Models



Biggest Difficulty:

Spikes ⟶ Membrane Potential ⟶ Spikes

Membrane Potential ⟶ Spikes ⟶ Membrane Potential



Firing Rate Model

Exact spike sequence converted into instantaneous rate r(t)

Justification: Each neuron has large number of inputs which are generally not very correlated.

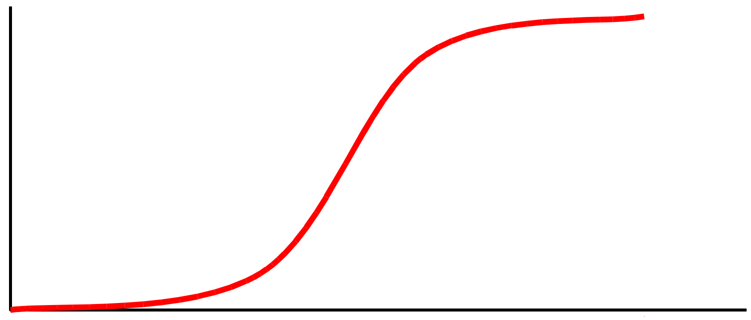
2 Steps:

Firing Rate of Presynaptic Neuron → Synaptic Input to Postsynaptic Neurons

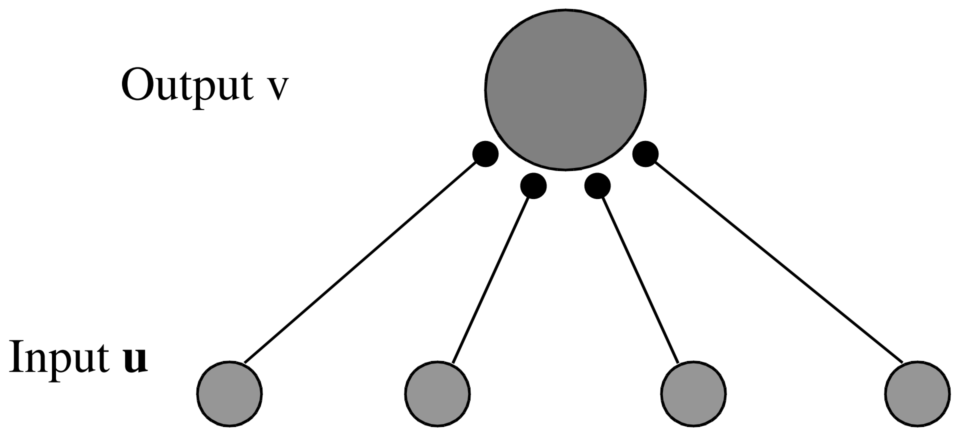
Total Input to Postsynaptic Neuron → Firing rate of Postsynaptic Neuron

Total Synaptic Input modeled as total current injected into the soma

f-I curve: Output Spike Frequency vs. Injected Current curve



Firing Rate Model

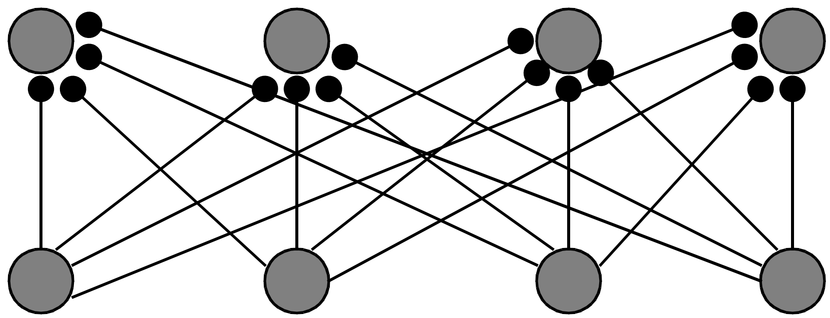


Firing rate does not follow changes in total synaptic current instantaneously, hence

$\tau \, dv/dt = -v + F(I(t))$

$I(t)=\mathbf{w}.\mathbf{u}(t)$

Firing Rate Network Model



$\mathbf{v}(t)$

$\mathbf{u}(t)$

$$\tau \, d\mathbf{v}/dt = -\mathbf{v} + F(\mathbf{w}.\mathbf{u}(t))$$