Dendritic Integration

Foundations of Cellular Neuroscience

FAES

Spring 2018

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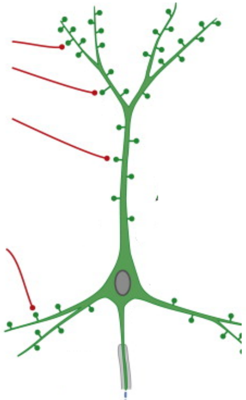
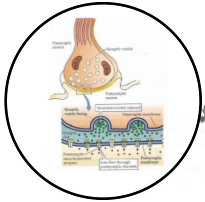
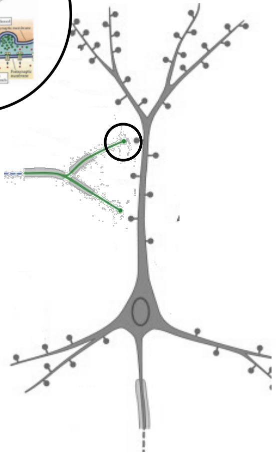
Dendritic integration

Action Potential

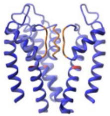


Synaptic transmission





Voltage gated channels



Today:
Passive signal spread along dendrites

Next week:
Influence of voltage gated channels

Dendritic function

Dendrites:

- Receive synaptic contacts
- Conduct information
- Filter information
- Perform computations

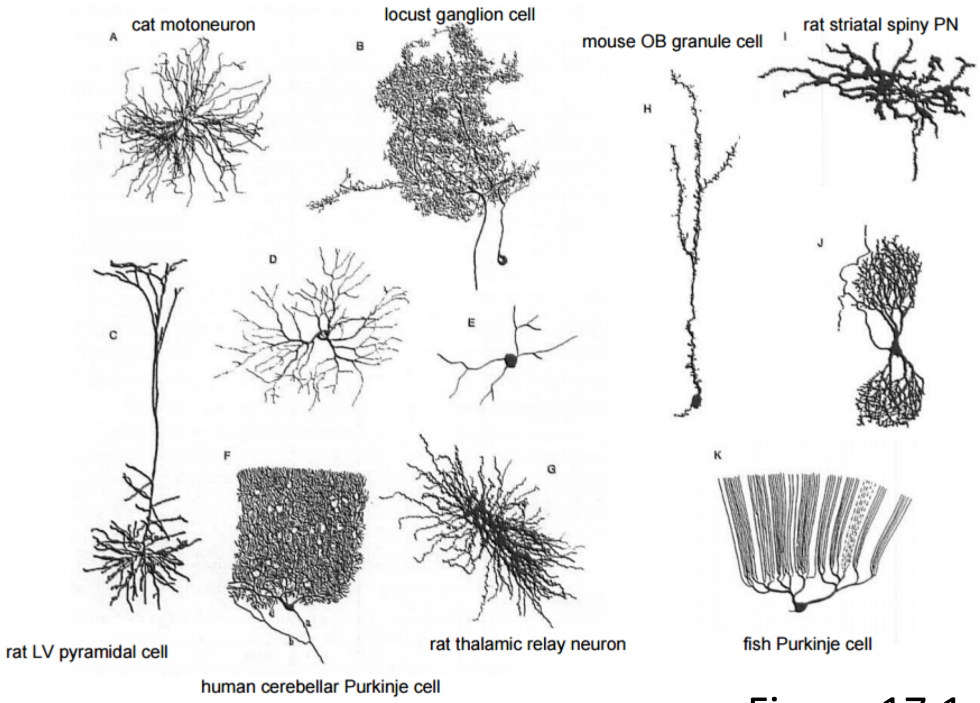
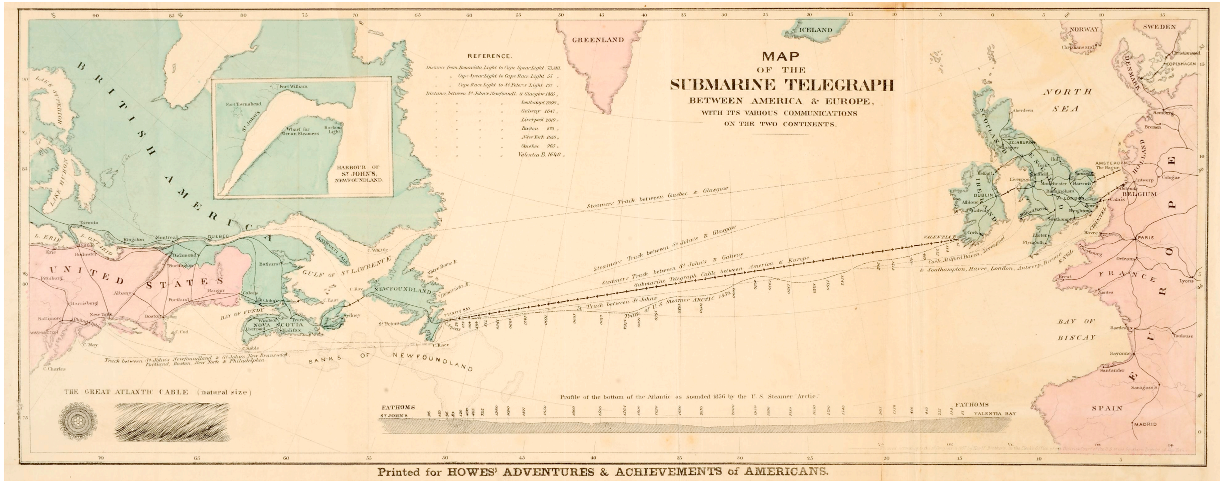
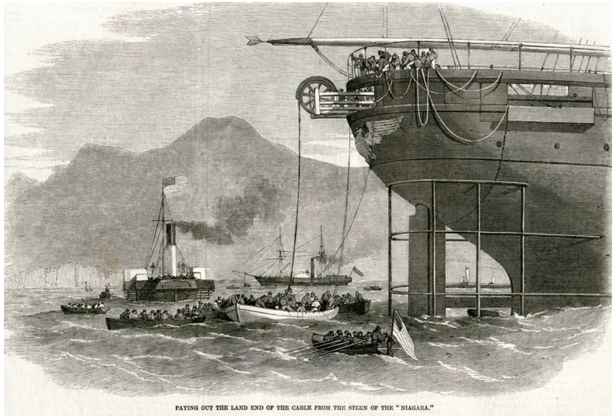


Figure 17.1

Cable theory

The original cable theory, 1858



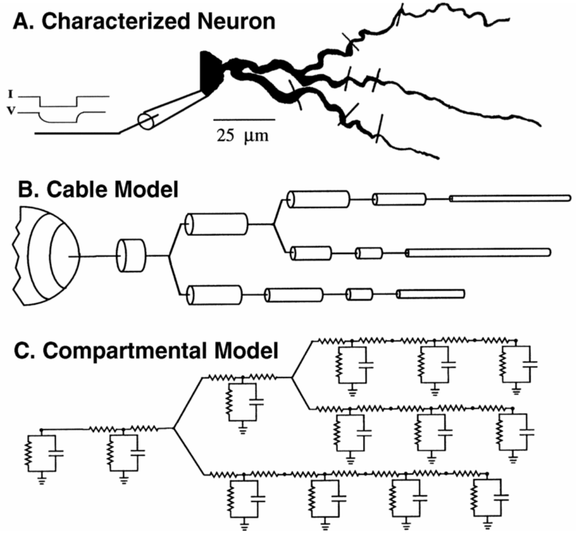


Cable theory

Assumptions:

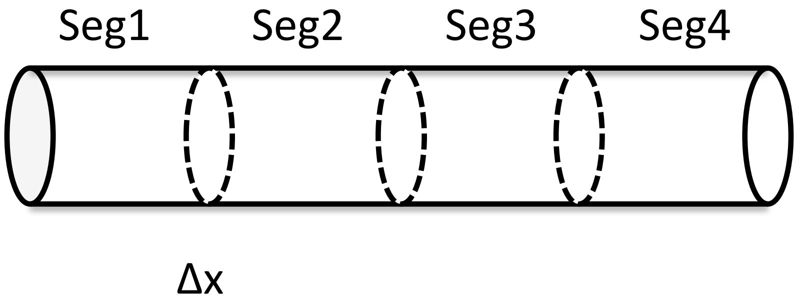
1. Consider the neuron as body of cytoplasm with a membrane around it (garden hose)
2. Neural segments are cylinders

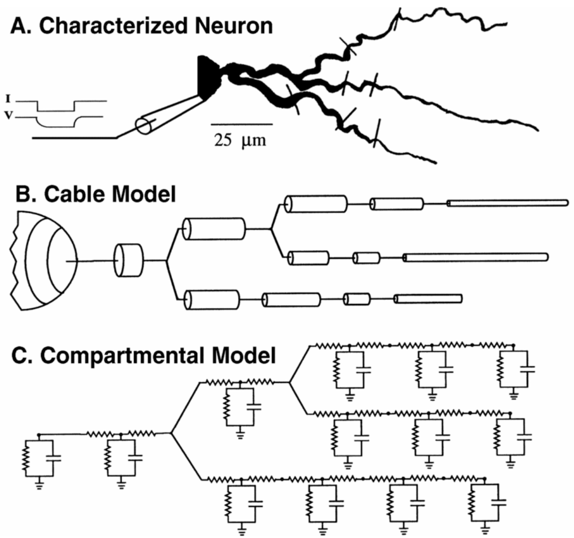
Wilfrid Rall, 1962



Cable theory

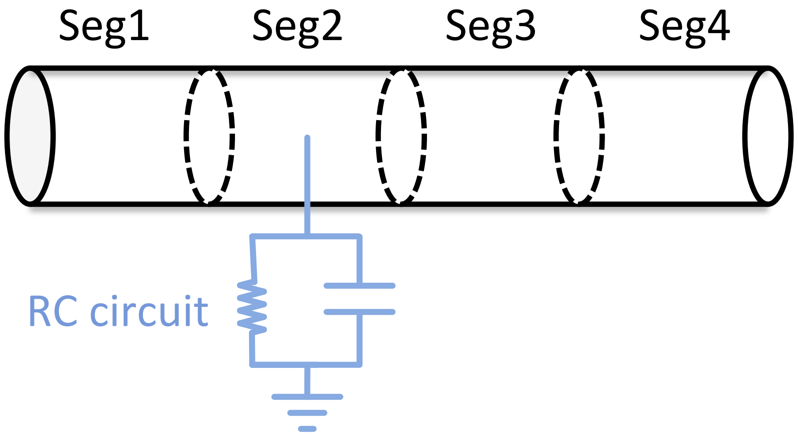
Complex morphologies can be broken into simple segments

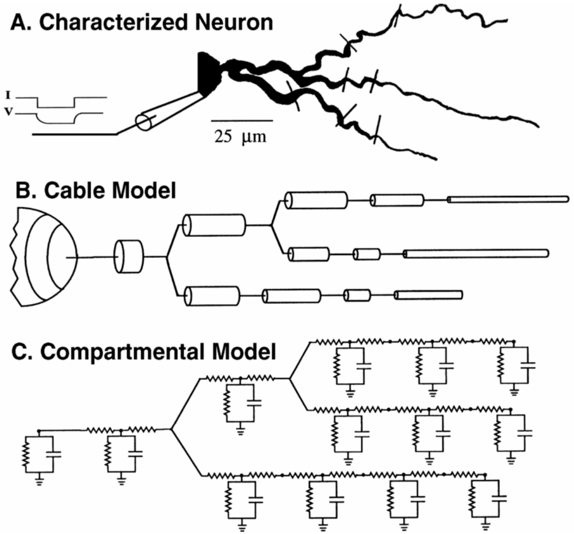




Cable theory

Complex morphologies can be broken into simple segments





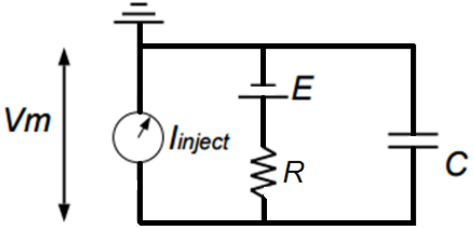
RC Circuit

What we need to know (about electric circuits)

Ohm law:

$I = V/R = V \cdot G$

V: Voltage
I: Current
R: Resistance
G: Conductance



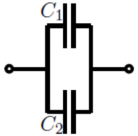
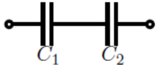
Resistors:

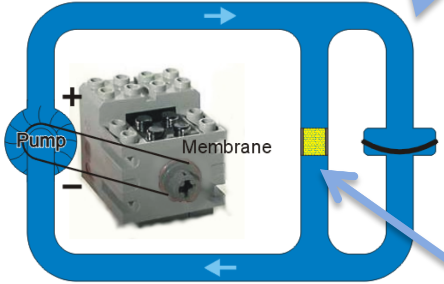
Series

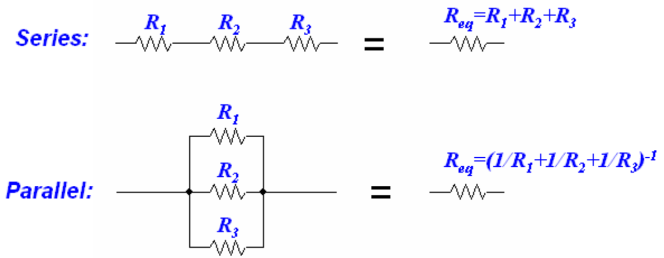
Parallel

Capacitors:

Parallel

PARALLEL		$C_p = C_1 + C_2$
SERIES		$\frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2}$



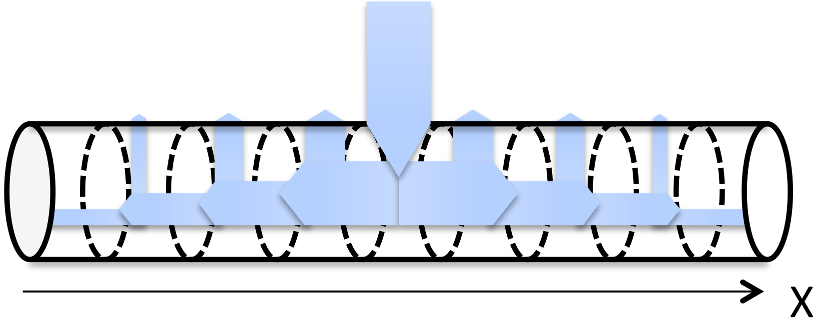


$G_{eq} = G_1 + G_2 + G_3$

Cable theory

<u>Current spread in cables</u>

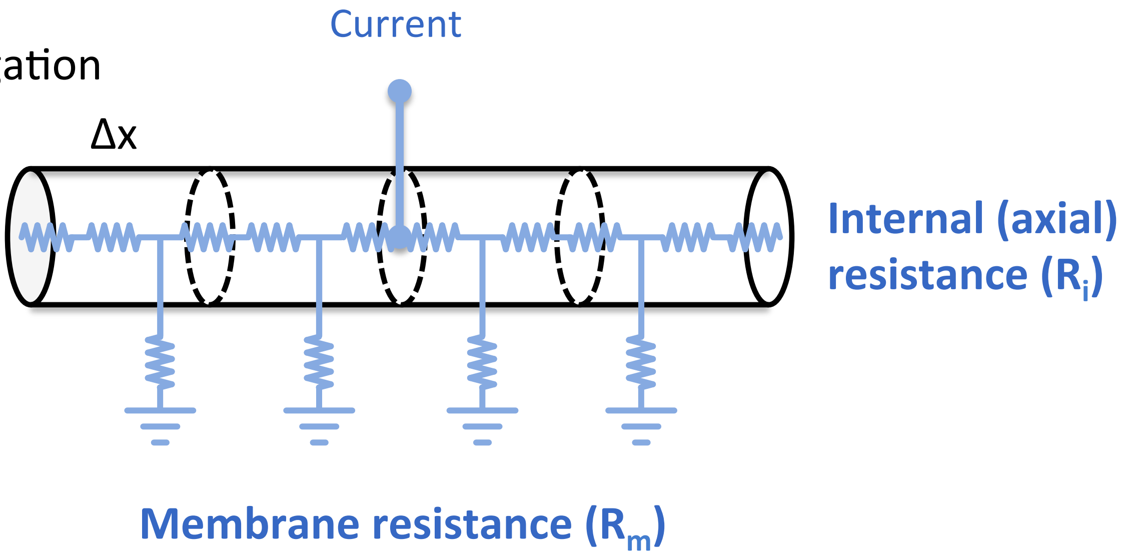
1. Cables are leaky



Cable theory

Current spread in cables

1. Cables are leaky
2. Steady state propagation

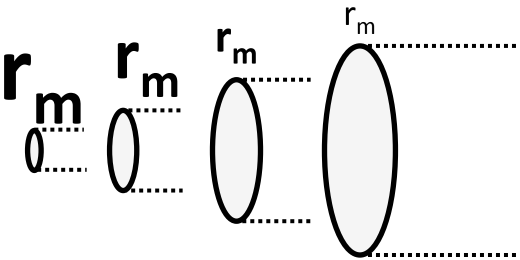


membrane capacitance is ignored in the steady state

Membrane resistance

R_m
Specific membrane resistance
Typical values: 10,000-50,000 Ωcm^2

$\mathbf{r_m}=R_m/\pi d$
Membrane resistance of the cable, per unit length (Ωcm)



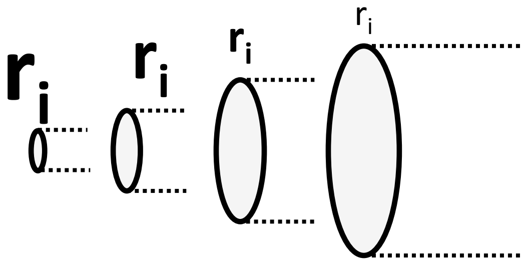
Circumference

d: diameter

Internal (axial) resistance

R_i
Specific internal resistance
Typical values: 100-200 Ωcm

r_i $=4R_i/\pi d^2$
Internal resistance of the cable, per unit length (Ω/cm)



Cable theory

Quiz:

How are R_i and R_m affected by the following changes in geometry?
How about r_i and r_m?

The cable:

A) Longer:

B) Wider:

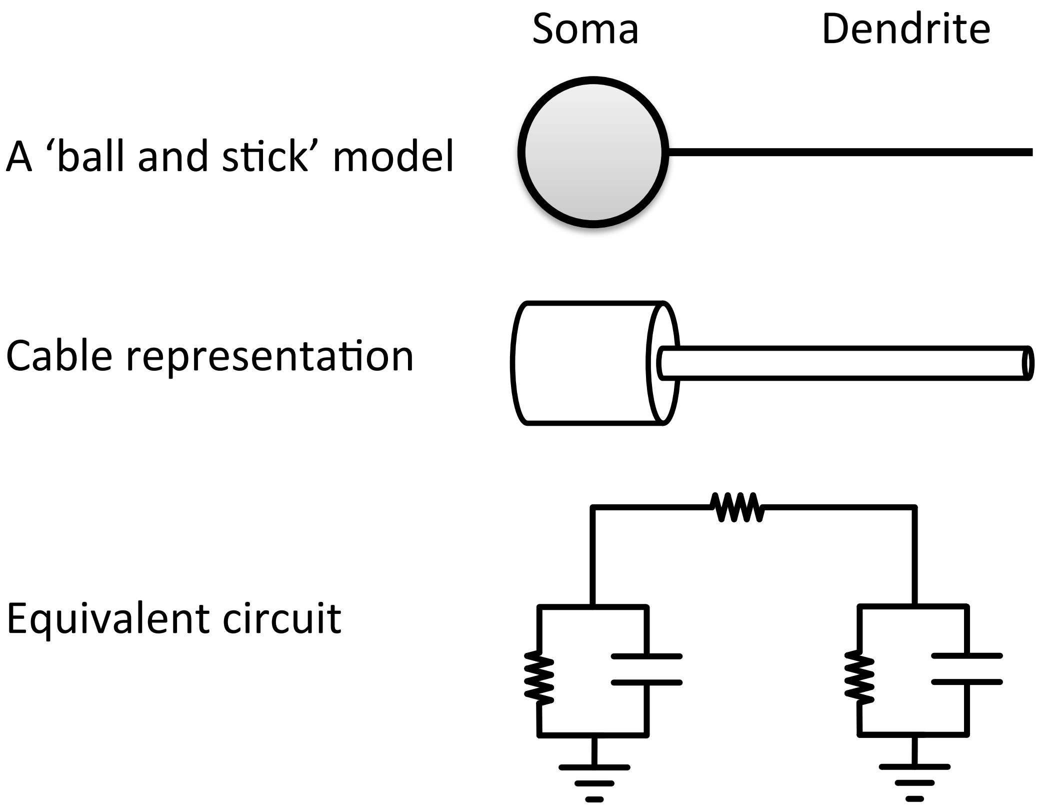
Answer:

R_i and R_m do not change

A) $\mathbf{r_i}$ same, $\mathbf{r_m}$ same

B) $\mathbf{r_i}$ smaller, $\mathbf{r_m}$ smaller

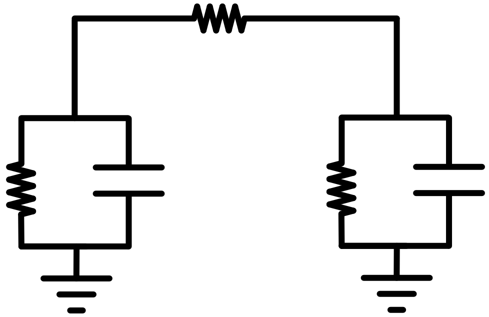
Dendritic signal attenuation



Dendritic signal attenuation

Soma Dendrite

Equivalent circuit



Dendritic signal attenuation

Soma Dendrite

Current

Steady state

$I=100\ pA$

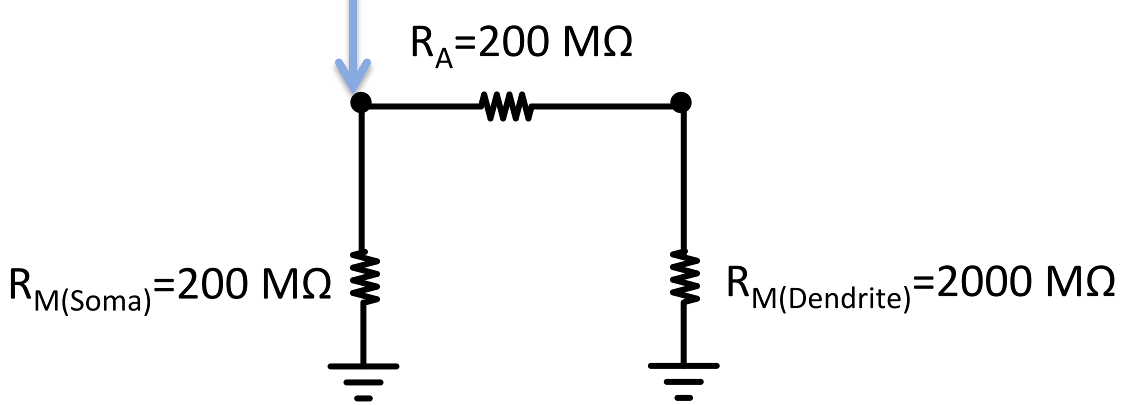
$V=I\cdot R=100\cdot 10^{-12}\cdot 183\cdot 10^{6}$

$V=18.3\ mV$

$$R_{Input\ Resistance(Soma)}=(1/(R_{M(Soma)})+1/(R_{M(Dendrite)}+R_A))^{-1}$$

$$R_{IR(Soma)}=(1/200+1/(2000+200))^{-1}$$

$$R_{IR(Soma)}\sim 183\ M\Omega$$



Dendritic signal attenuation

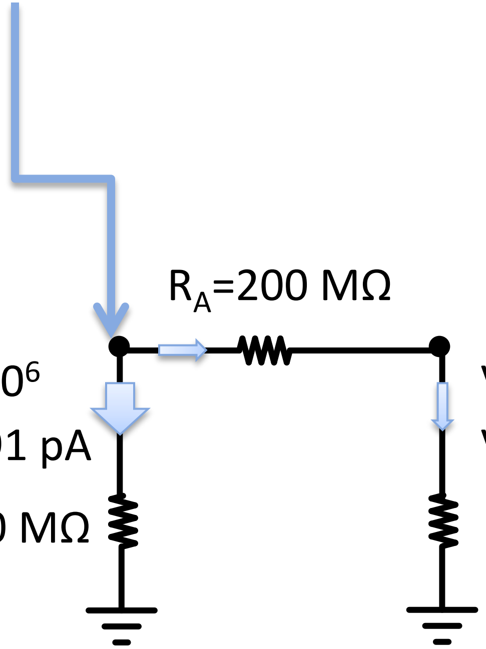
Soma Dendrite

Current

$I=100$ pA

$V=I \cdot R=100 \cdot 10^{-12} \cdot 183 \cdot 10^{6}$

$V=18.3$ mV



$R_A=200\ M\Omega$

$I_{Soma}=V/R=18.3 \cdot 10^{-3}/200 \cdot 10^{6}$

$I_{Soma}=91$ pA

$R_{M(Soma)}=200\ M\Omega$

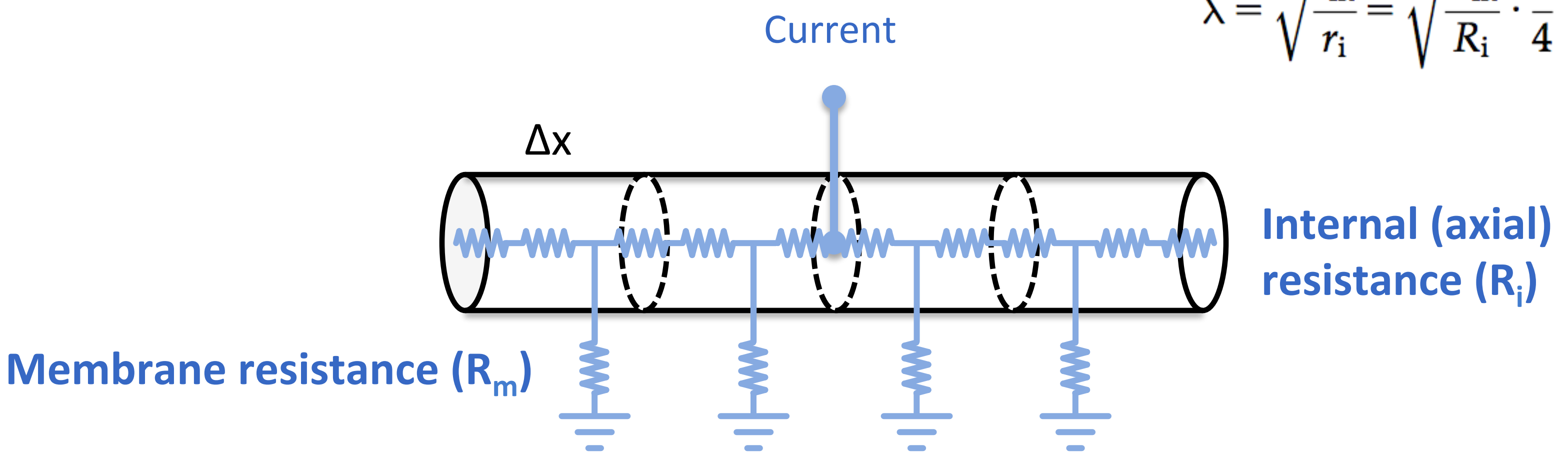
$Vm_{(Dendrite)}=I \cdot R=9 \cdot 10^{-12} \cdot 2000 \cdot 10^{6}$

$Vm_{(Dendrite)}=18mV$

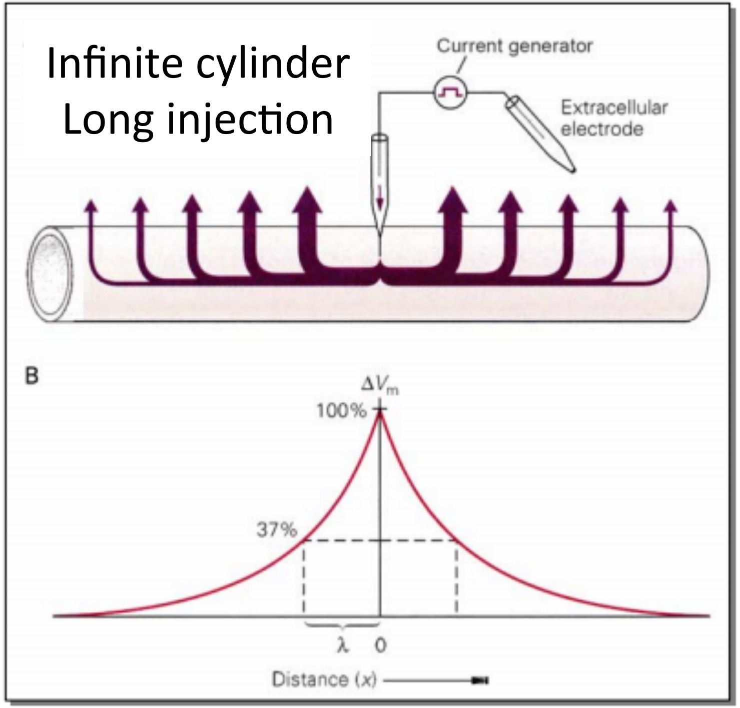
$R_{M(Dendrite)}=2000\ M\Omega$

Space Constant

$$\lambda = \sqrt{\frac{r_m}{r_i}} = \sqrt{\frac{R_m}{R_i} \cdot \frac{d}{4}}$$



Space Constant

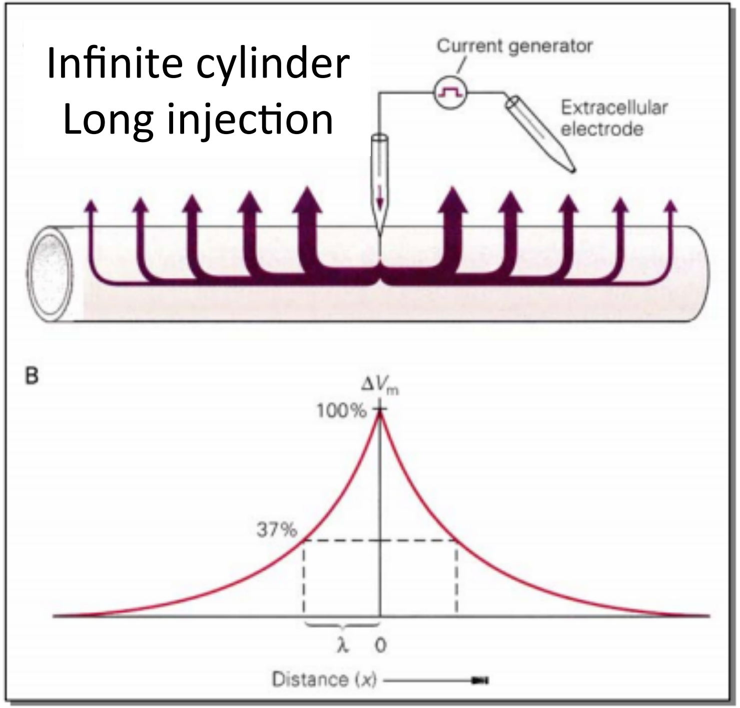


Voltage spread along the x axis

$$V_x = V_0 e^{-x/\lambda}$$

$$V_\lambda / V_0 = e^{-1} = 0.37$$

Space Constant



$$\lambda = \sqrt{\frac{r_m}{r_i}} = \sqrt{\frac{R_m}{R_i} \cdot \frac{d}{4}}$$

R_m=40,000 Ωcm^2
R_i=100 Ωcm
d=1μm=10^{-4}cm

$$\lambda = \sqrt{\frac{R_m}{R_i} \cdot \frac{d}{4}} = \sqrt{\frac{40,000}{100} \cdot \frac{10^{-4}}{4}} = 0.1cm = 1000\,\mu\text{m}$$

Space Constant

Quiz:

How is the space constant affected by the following changes?

$$\lambda = \sqrt{\frac{r_m}{r_i}} = \sqrt{\frac{R_m}{R_i} \cdot \frac{d}{4}}$$

The cable:

A) 2x longer:

B) 3x wider:

C) 3x R_m

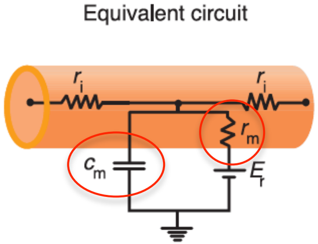
Answer:

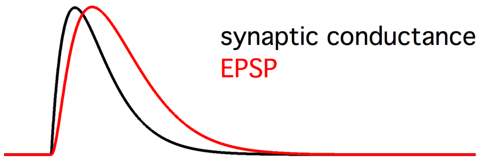
A) No change

B) Increase by $\sqrt{3}$

C) Increase by $\sqrt{3}$

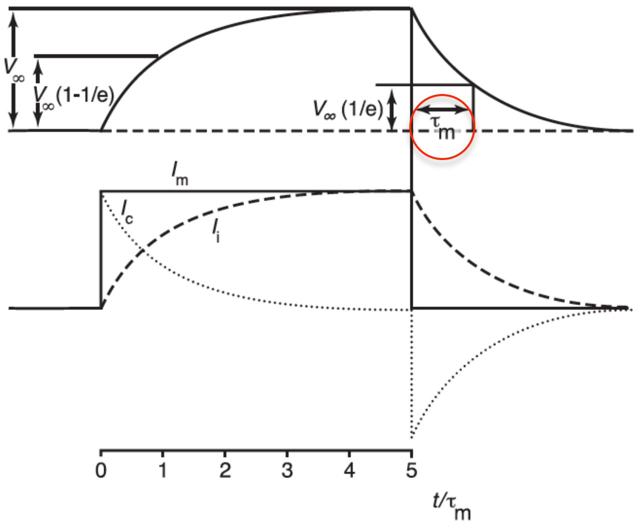
Time Constant





membrane time constant

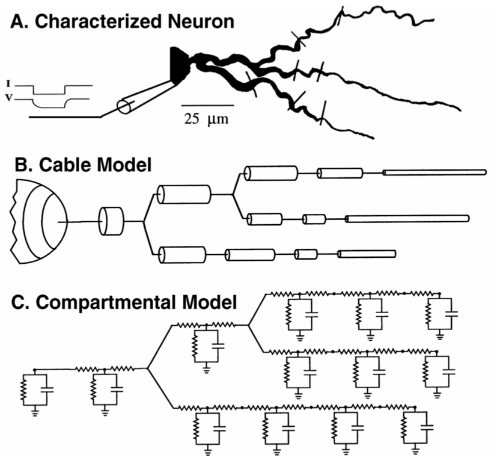
$$\tau_m = r_m \times c_m$$



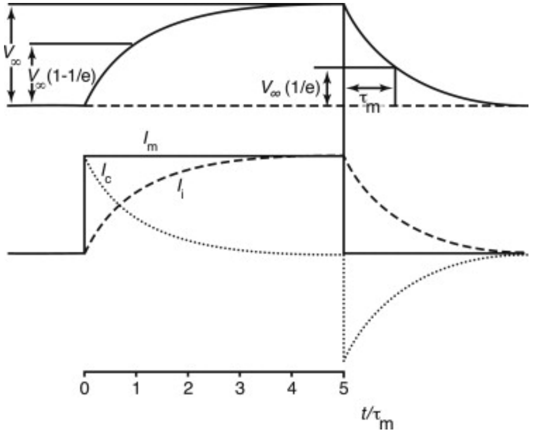
Jack, et al. (1975) Electric Current Flow in Excitable Cells

Summary

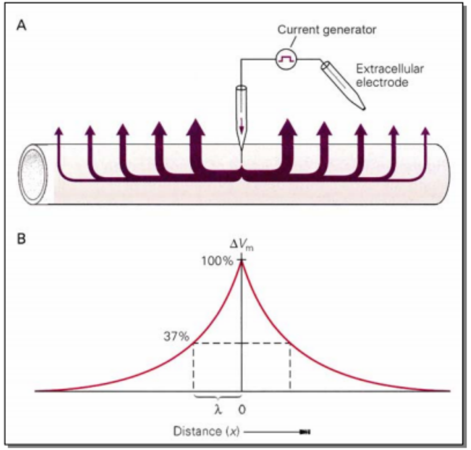
Input Resistance



Time constant $\tau=RC$



Space constant $\lambda=\sqrt{R_m / R_i \cdot d/4}$



Passive dendritic computations

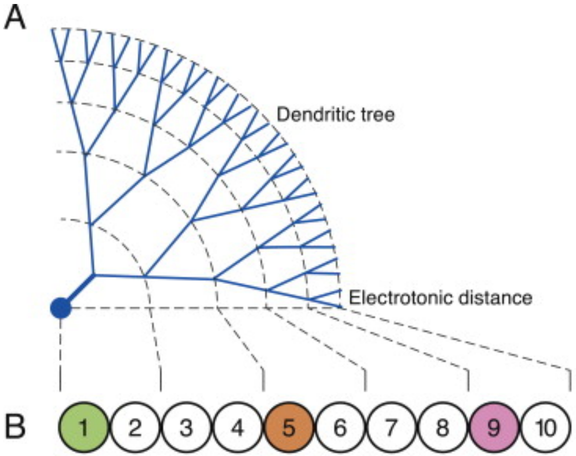
<u>**Synaptic input will depend on:**</u>

- **Distance from soma**
- Distance from other inputs
    - Excitatory
    - Inhibitory
- Dendritic spines

Dendritic signal attenuation

Excitatory Post-Synaptic Potential (EPSP)

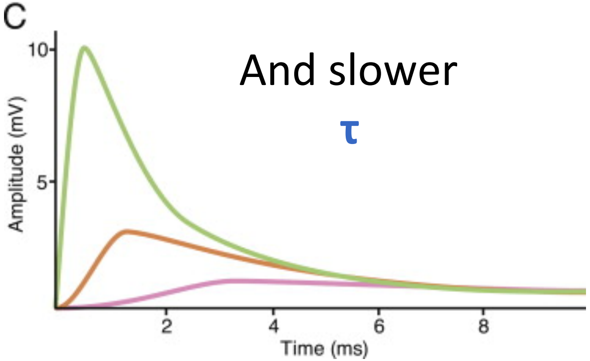
Wilfrid Rall



Rall 1967

Signals are smaller

λ

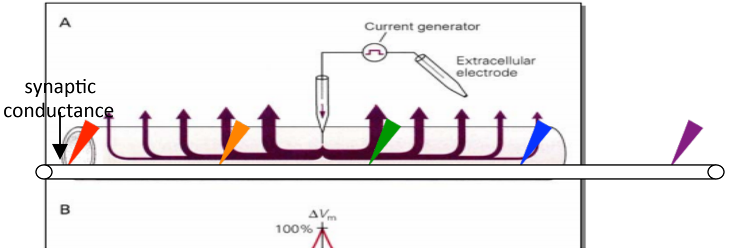


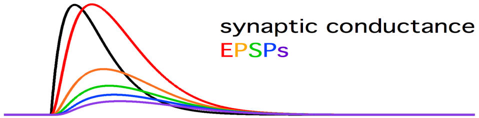
And slower

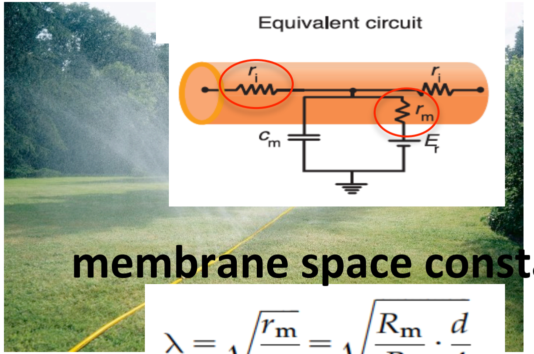
τ

Where is the site of the current injection?

The dendritic cable attenuates signals







membrane space constant

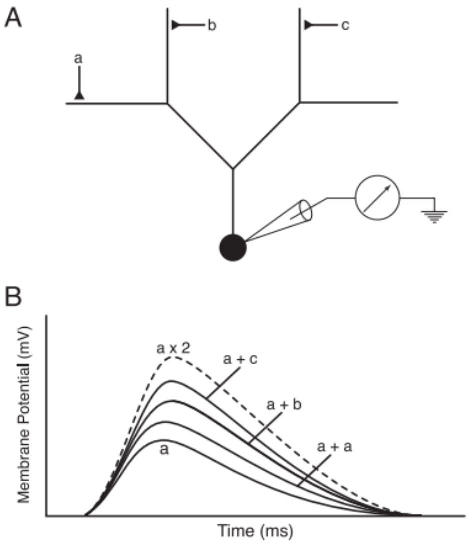
$$\lambda = \sqrt{\frac{r_m}{r_i}} = \sqrt{\frac{R_m}{R_i} \cdot \frac{d}{4}}$$

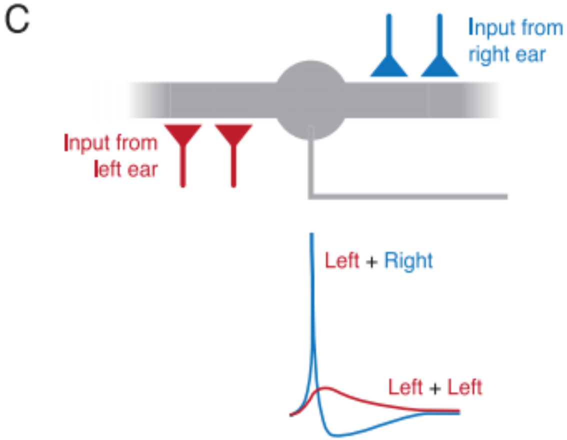
Passive dendritic computations

Synaptic input will depend on:

- Distance from soma
- **Distance from other inputs**
  - **Excitatory**
  - **Inhibitory**
- Dendritic spines

Passive dendritic computations



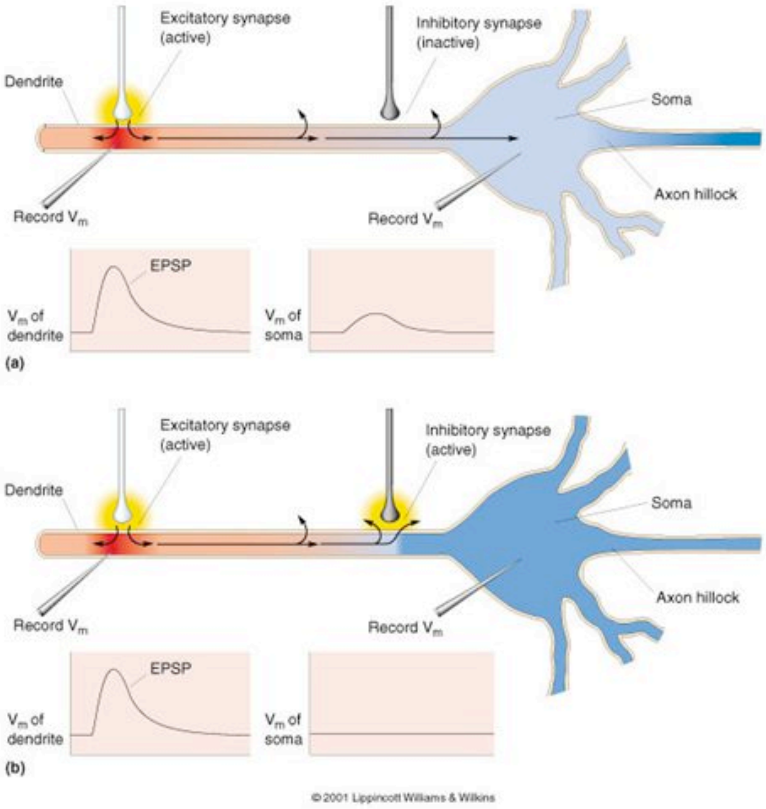


binaural neurons

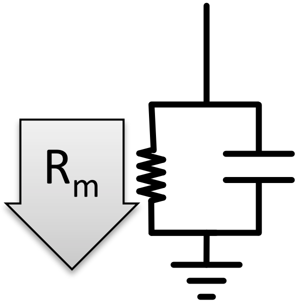
Shepherd and Koch 1990

Agmon-Snir et al 1998

Passive dendritic computations



Shunting inhibition



How would shunting inhibition affect
Time constant?
Space constant?

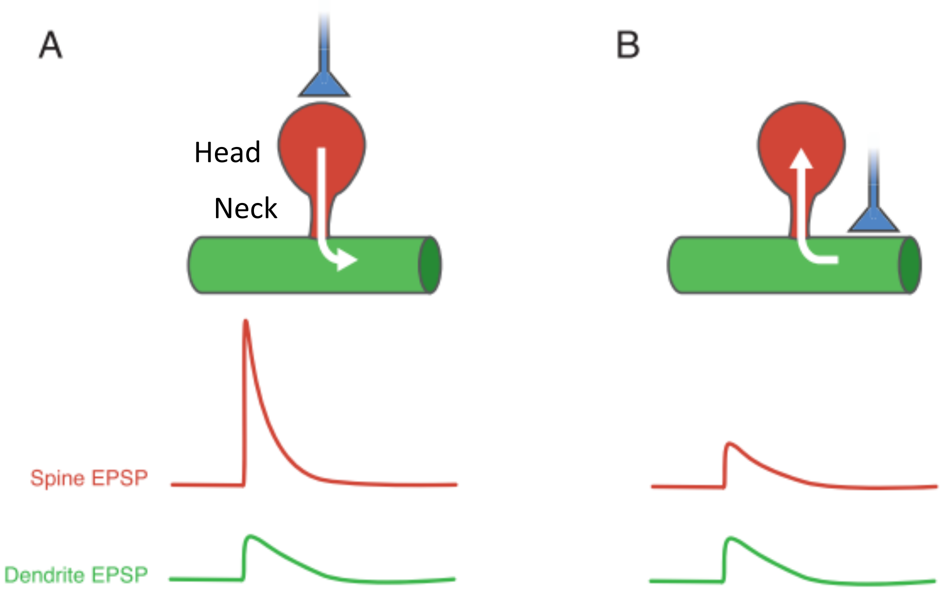
$$\lambda = \sqrt{\frac{r_m}{r_i}} = \sqrt{\frac{R_m}{R_i} \cdot \frac{d}{4}}$$

Passive dendritic computations

<u>Synaptic input will depend on:</u>

- Distance from soma
- Distance from other inputs
  - Excitatory
  - Inhibitory
- **Dendritic spines**

Dendritic spines



Spruston 2008

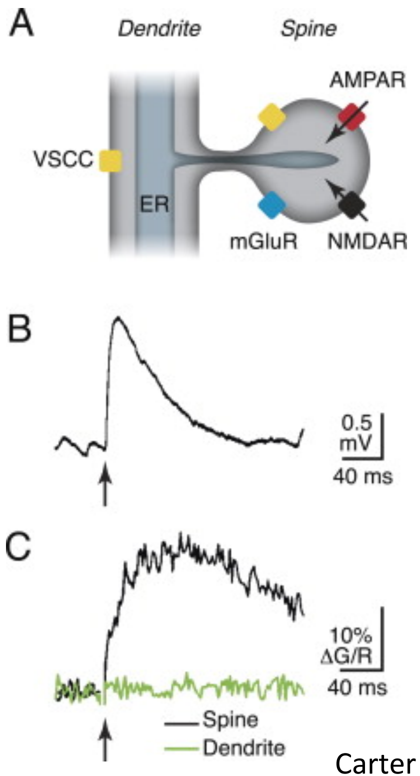
In many neurons spines are the target of the majority of synaptic inputs

Spines have a small membrane

r_m High
c_m Low

R_{IN} High

Spines are calcium traps



Spines are important for plasticity!

Carter and Sabatini 2008