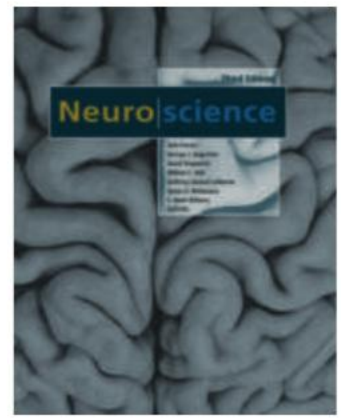
Passive Membrane Properties

Communicating through a leaky garden hose....

Topics I	Topics II
Introduction	Synaptic Transmission
Electrochemical Gradients	Electrophysiology Techniques
Passive Membrane Properties	Basic Circuits (Spinal Cord)
Action Potential	Sensory Systems Overview
Voltage-Gated Ion Channels	Synaptic Plasticity
Ligand-Gated Ion Channels	Recapitulation

Study Material

- NEUROSCIENCE Third Edition
  - Dale Purves
- Chapter 3 pages 58-61
- (The textbook is not very detailed about these things)



THE COVER
Dorsal view of the human brain.
(Courtesy of S. Mark Williams.)

NEUROSCIENCE: Third Edition

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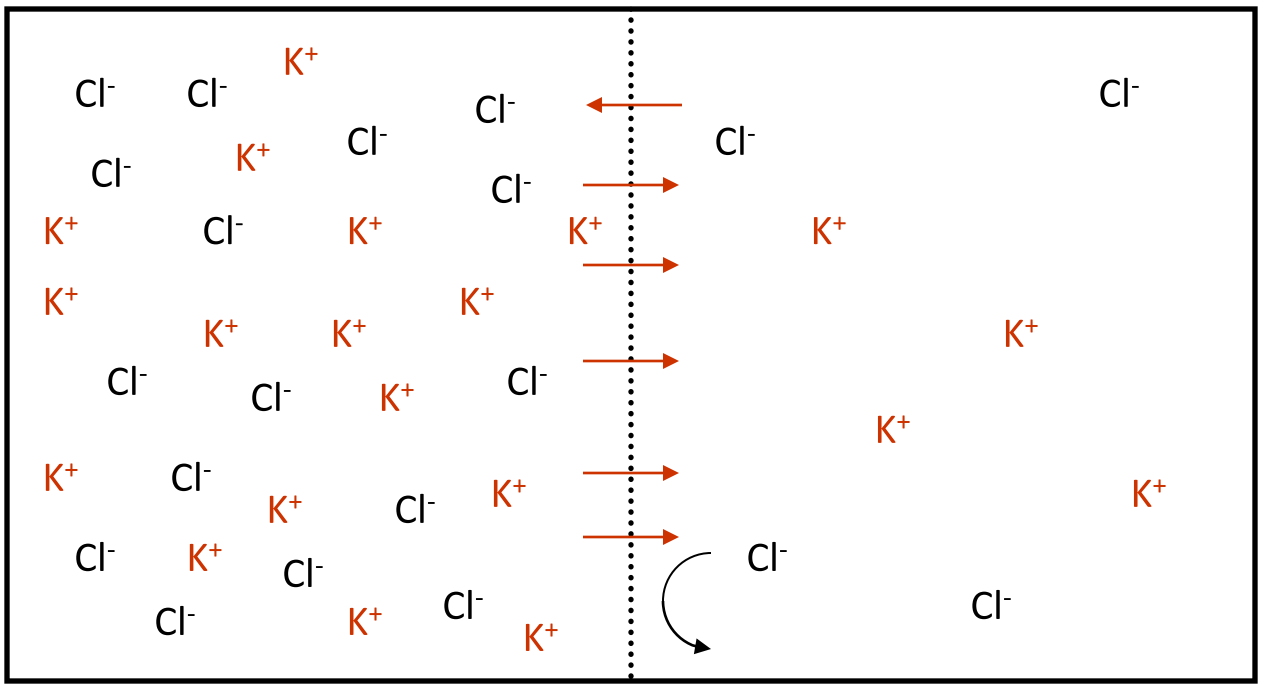
Aims

- Understand the cell membrane as a capacitor and a resistor.
- Understand that the capacitor acts as an ‚elastic‘ element that stores charge.
- Know how to calculate the membrane time constant.
- Understand that the time constant limits the speed with which the membrane voltage can be changed.
- Understand how membrane resistance and capacitance affect the propagation of signals in neuronal processes.

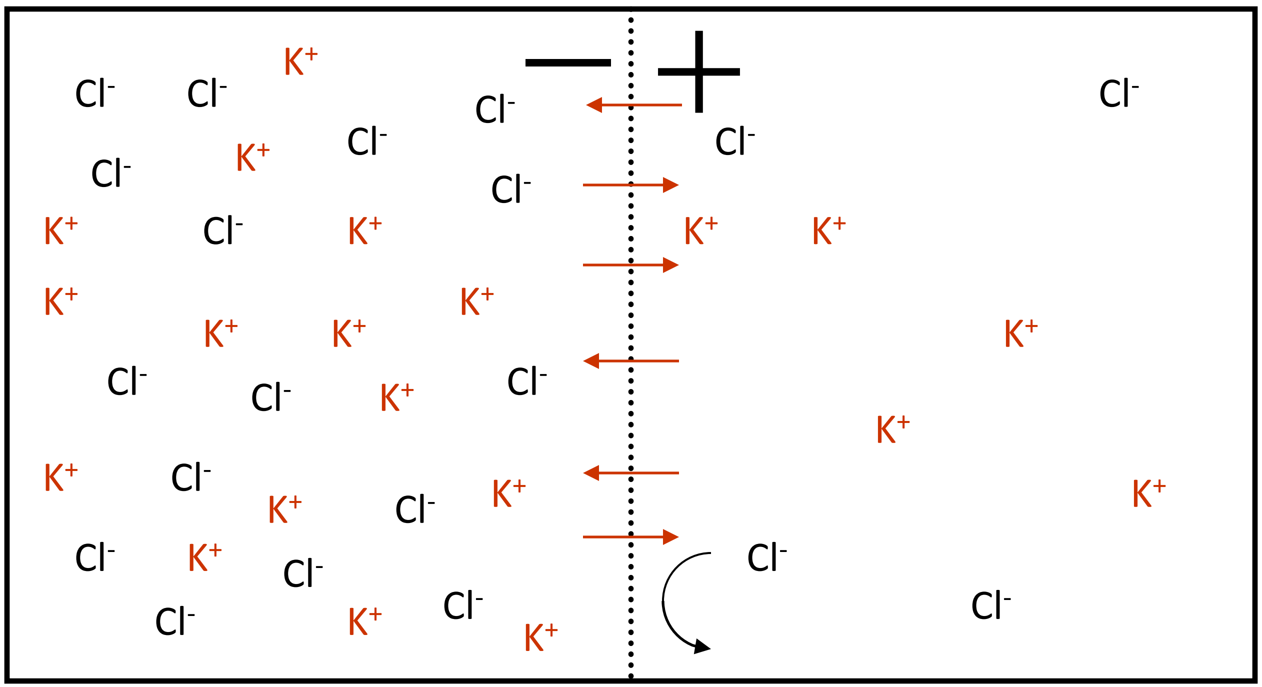
Recapitulation L2

- Ion concentrations are very different inside and outside of neurons. The inside is rich in K and poor in Na. The outside is rich in Na and poor in K.
- Coupled with selective permeability these gradients produce electrical potentials.
- At rest the dominant permeability is for K ions, the resulting potential is around -60 mV (inside relative to outside the neuron).

Recapitulation



Recapitulation



Recapitulation

Electrical Field

$$nzF(E_i - E_o)$$

Chemical Energy

$$nRT \ln \frac{[K^+]_o}{[K^+]_i}$$

n	Amount (Mol)
z	Valence (+1 for K)
F	Faraday‘s constant (charge of one Mole of Ions)
E	Potential
R	Gas constant
T	Temperature (absolute K)
[ ]	Concentration in the respective compartment

Recapitulation

$$zF(E_i - E_o) = RT \ln \frac{[K^+]_o}{[K^+]_i}$$

$$E_i = \frac{RT}{zF} \ln \frac{[K^+]_o}{[K^+]_i}$$

Nernst Equation
Describes equilibrium
No **net** flux

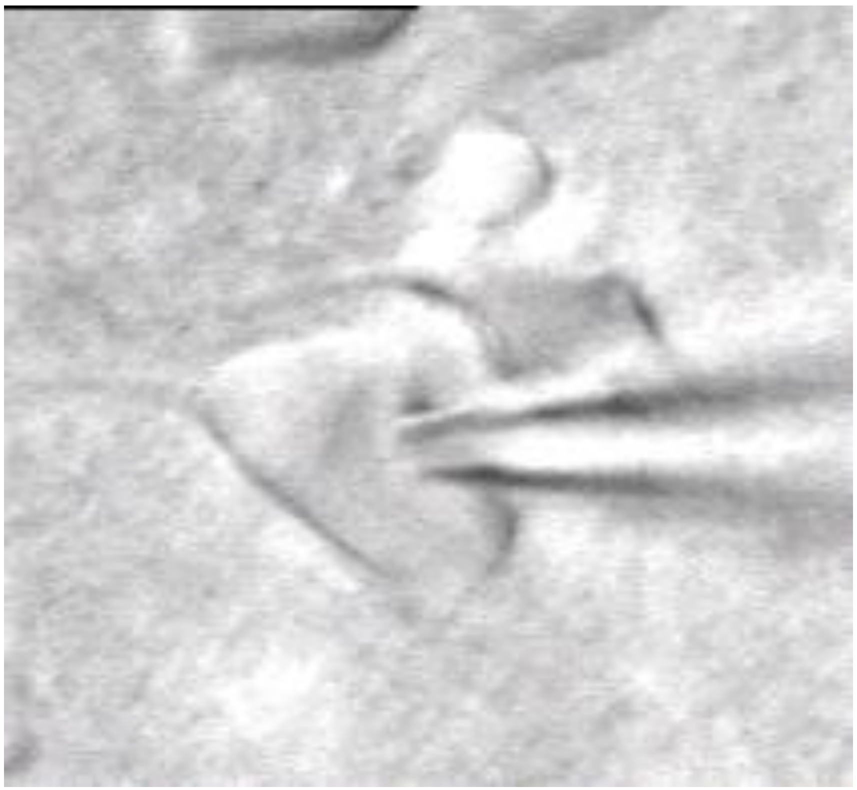
Recapitulation

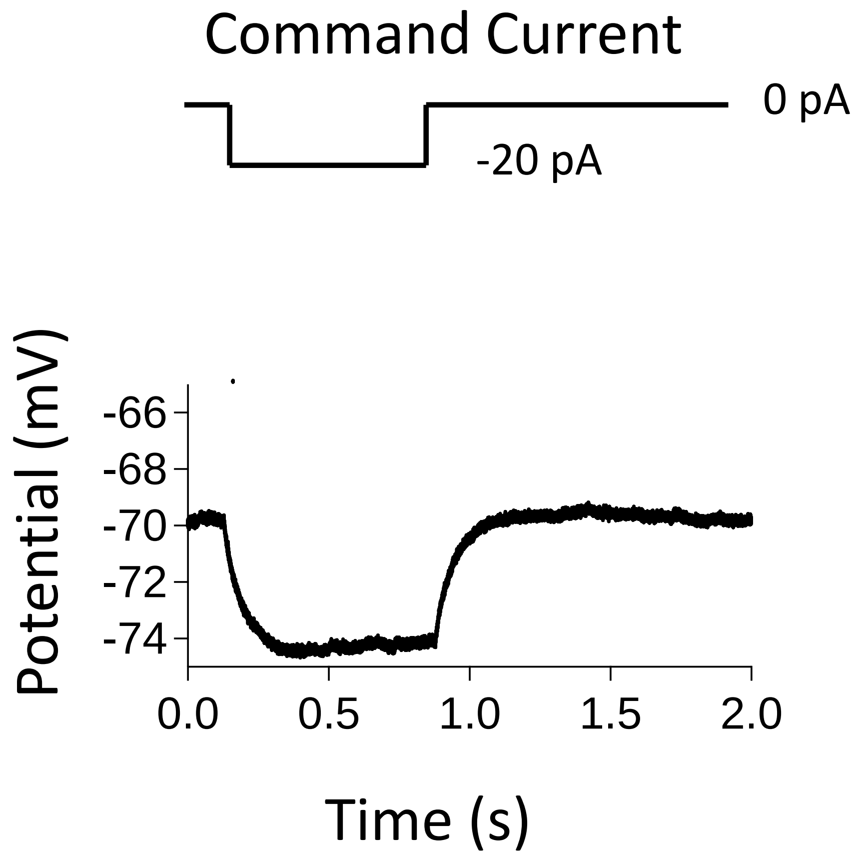
$$E_i = \frac{RT}{zF} \ln \frac{[K^+]_o}{[K^+]_i}$$

$$E_i = 61(mV) \log \frac{[K^+]_o}{[K^+]_i}$$

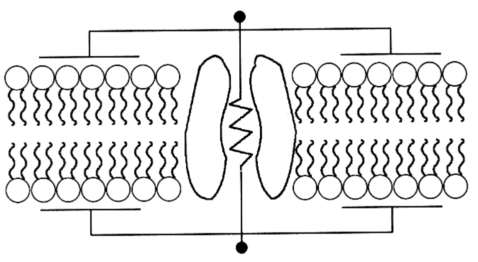
	Intracellular	Extracellular	E
Potassium Ions	155 mM	4 mM	-98 mV
Sodium Ions	12 mM	145 mM	+67mV

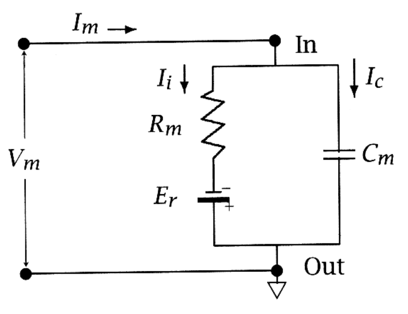
Passive Membrane Properties

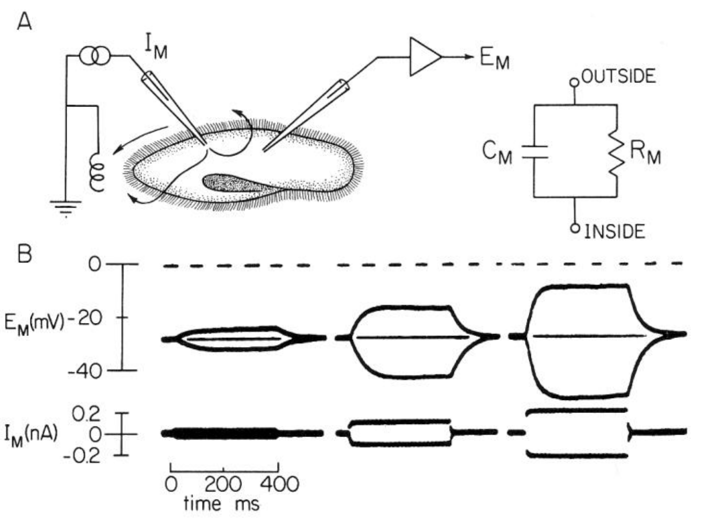




The Electrical Circuit







Cell membranes are acting as capacitors and resistors.

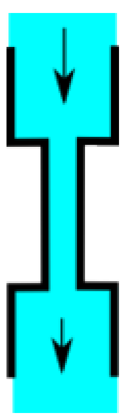
Hydraulic Analogy

Electrical Property

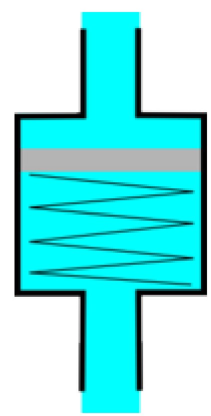
- Voltage
- Charge
- Current
- Resistor
- Capacitor

Hydraulic Property

- Pressure
- Water Volume
- Flow of Water
- Control Valve
- Elastic Container



Resistor

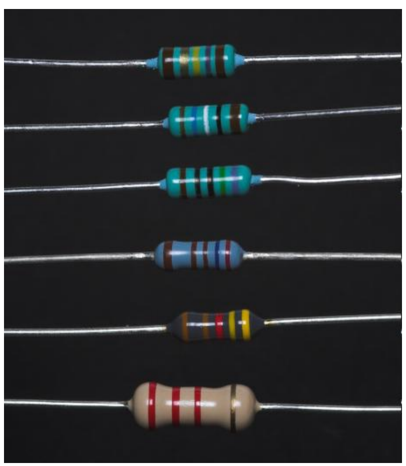


Capacitor

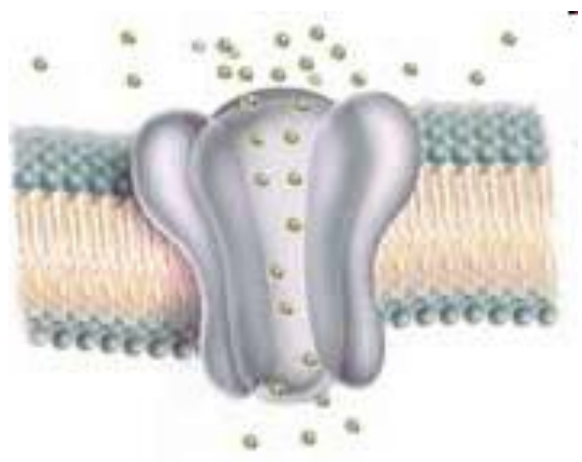
Ohmic Resistor

Linear relationship between current through resistor (I) and voltage across resistor (U)

$$R = \frac{U}{I}$$



Electronics



Biology

$$U = R \cdot I$$

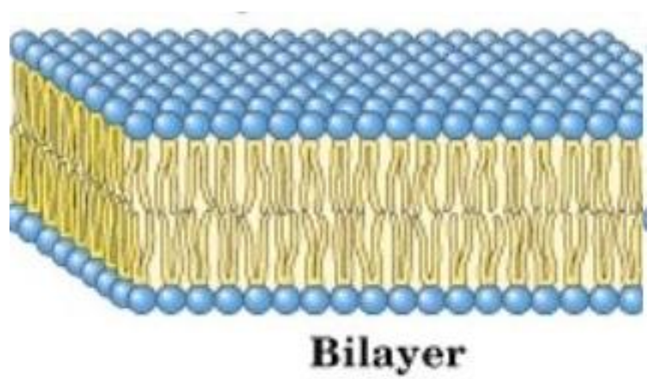
Capacitor

Can store electrical charge (Q) in proportion to an applied voltage (U), the linear relationship between the two describes the capacitance (C).

$$C = \frac{Q}{U}$$

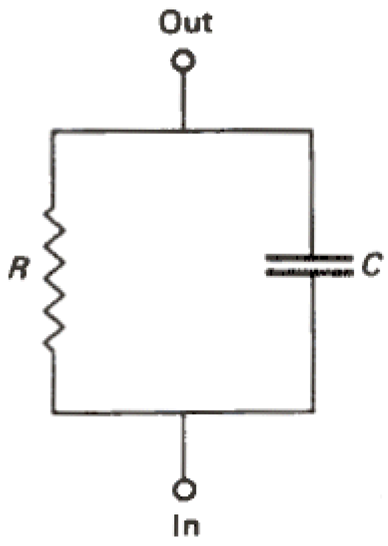
$$U = \frac{1}{C} \cdot Q$$

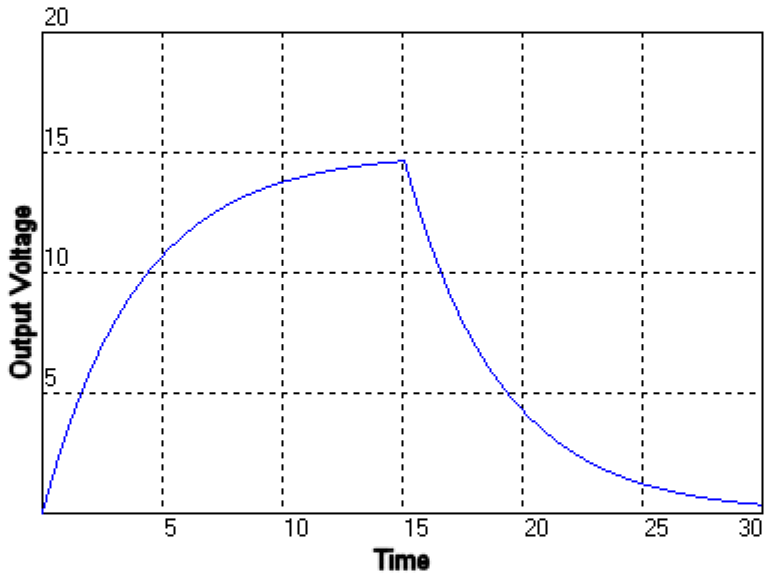
Electronics



Biology

Bringing the two together





Since they can store charge, capacitors act as ‘buffer’, slowing voltage changes down. Any change in the voltage across a capacitor needs to move charges. The larger the resistance through which the charges have to flow the slower this is happening.

Differential Equation

Connecting a capacitor and a resistor in the manner shown in the previous slide means that the capacitor discharges through the resistor. The voltage across the two is always equal.

The loss of charge is proportional to the remaining charge and to 1/RC.

This is a first order differential equation – compare to radioactive decay. The solution to this equation in the case ot the RC circuit is shown below – an exponential decay from an initial maximum Q_0 with a time constant RC.

$$U = RI$$

$$U = \frac{1}{C}Q$$

$$RI = \frac{1}{C}Q$$

$$I = -\frac{dQ}{dt}$$

$$-R\frac{dQ(t)}{dt} = \frac{1}{C}Q(t)$$

$$\frac{dQ(t)}{dt} = -\frac{1}{RC}Q(t)$$

$$Q(t) = Q_0 e^{-\frac{t}{RC}}$$

What this Means for Neurons

- Changing the membrane voltage of neurons requires the charging or discharging of the membrane capacitance.
- The larger the capacitance and the higher the resistance the slower this process is happening.
- In order to speed things up the capacitance has to be reduced or the membrane resistance has to come down.

$$100\,pF$$

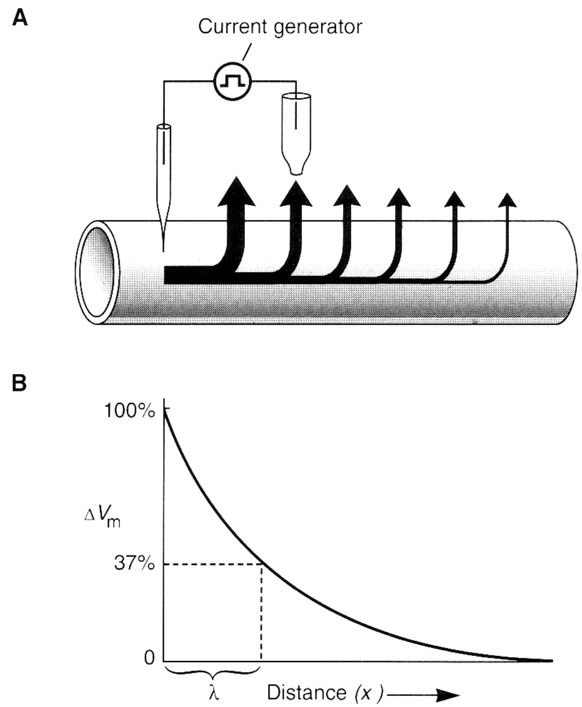
$$500M\Omega$$

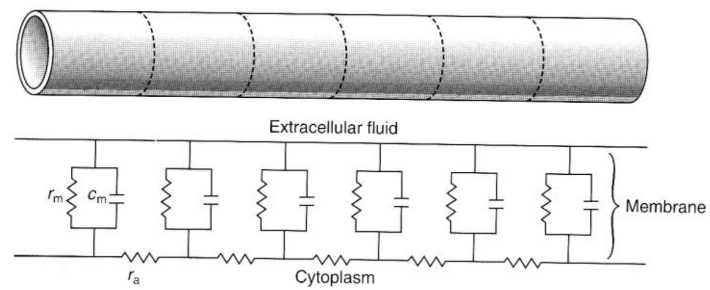
$$100 \cdot 10^{-12} C/V \cdot 500 \cdot 10^{6} Vs/C$$

$$50000 \cdot 10^{-6} s$$

$$50ms$$

Leaky Cables



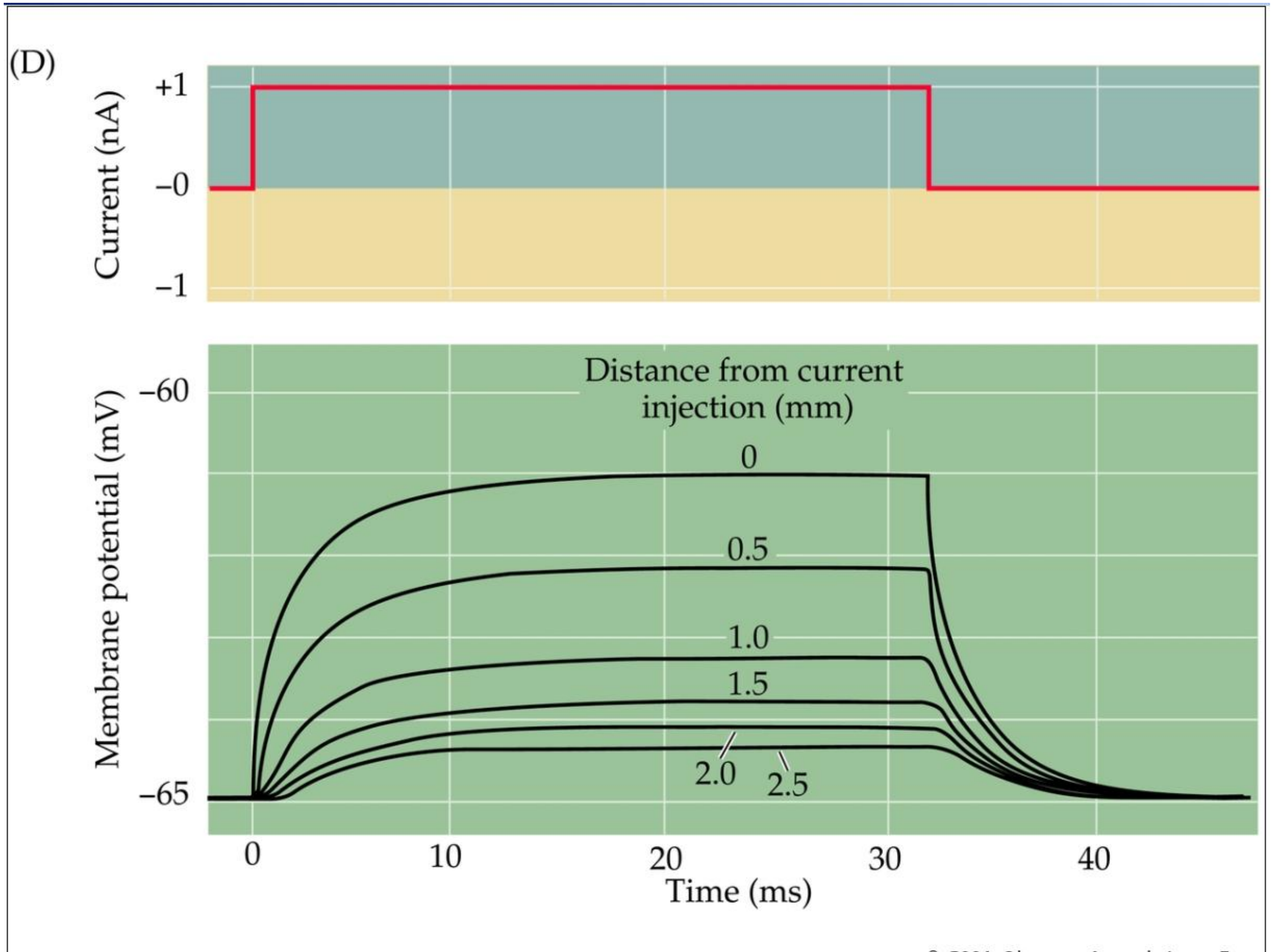


λ is typically between 0.1 bis 1 mm

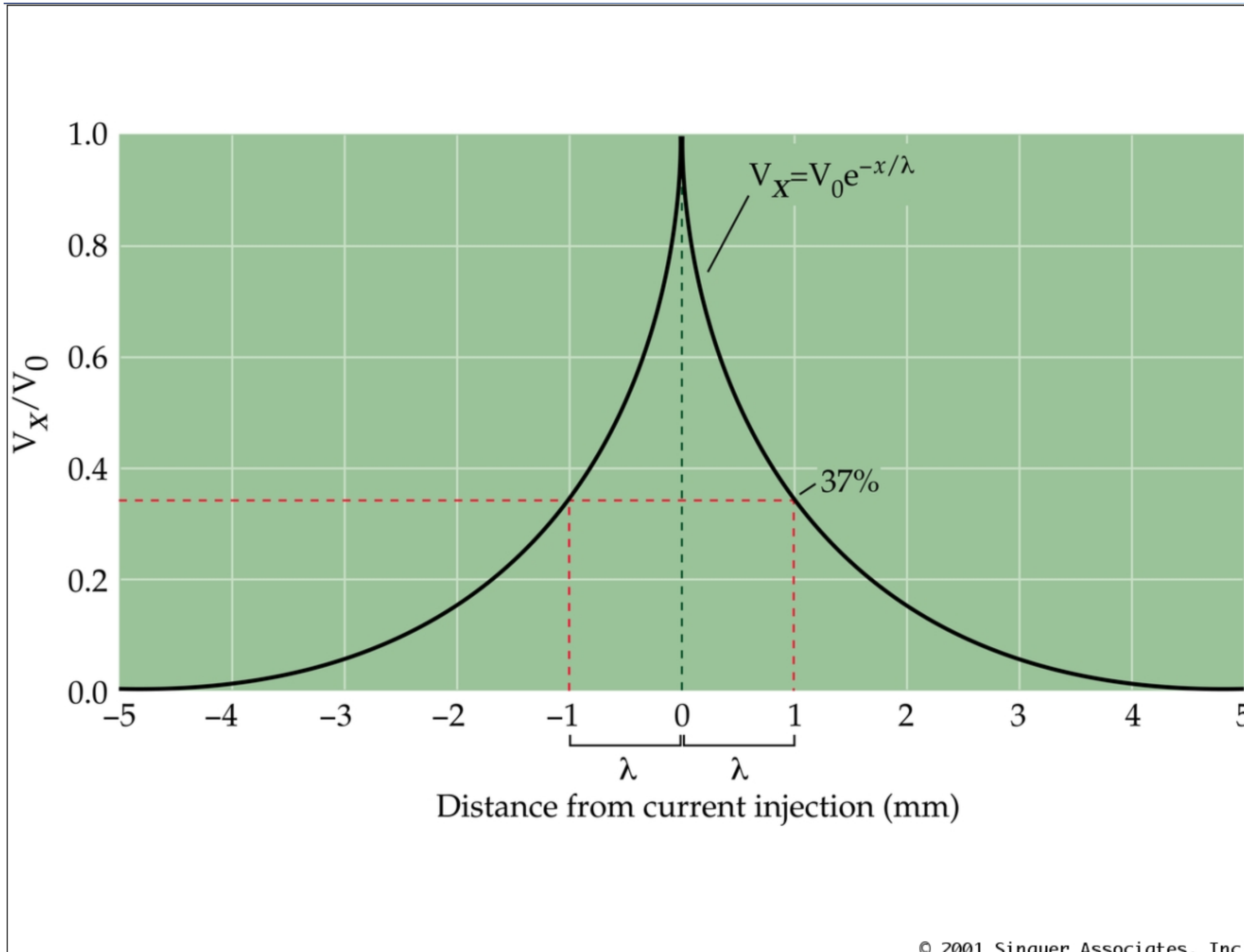
The length constant increases the smaller the longitudinal resistance gets. This is mostly a function of the diameter of the fiber. The thicker the fiber the larger the length constant.

$$\lambda = \sqrt{\frac{r_{membrane}}{r_{longitudinal}}}$$

Loss of Signal



Length Constant



Adding Capacitive Effects

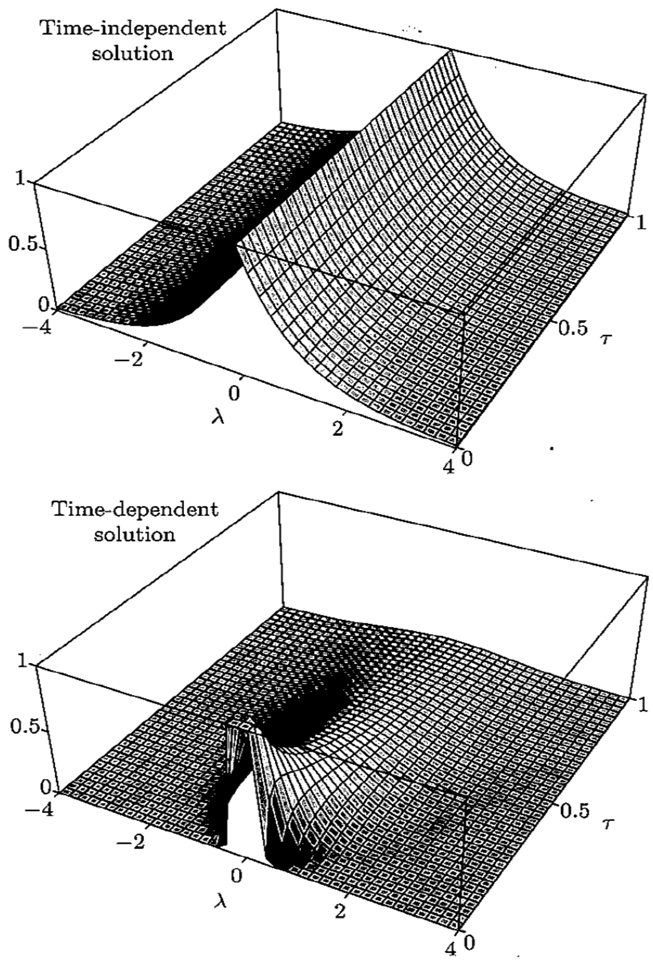


Figure 3.25 Comparison of waveforms of the time-independent (upper panel) and time-dependent (lower panel) solutions of the cable equation in response to point current sources. The membrane potential responses are shown normalized. The upper panel shows the function $e^{-|\lambda|}$, and the lower panel shows the quantity $(1/\sqrt{4\pi\tau})e^{-\lambda^2/4\tau}e^{-\tau}$, both plotted versus λ and τ.

It is like sending a stream of water down a leaky and elastic garden hose.

It is like sending a pulse of water down a leaky and elastic garden hose.

page 124 - Cellular Biophysics V2 - T.F. Weiss, MIT Press 1996

Summary

- Passive neuronal membranes behave like circuits composed of resistors and capacitors.
- The membrane potential can not change faster than the time constant.
- In the passive mode, neuronal processes conduct signals with a loss, depending on the membrane resistance and the longitudinal resistance.