Using biological cells as source of electrical energy

NiPS Laboratory
Noise in Physical Systems

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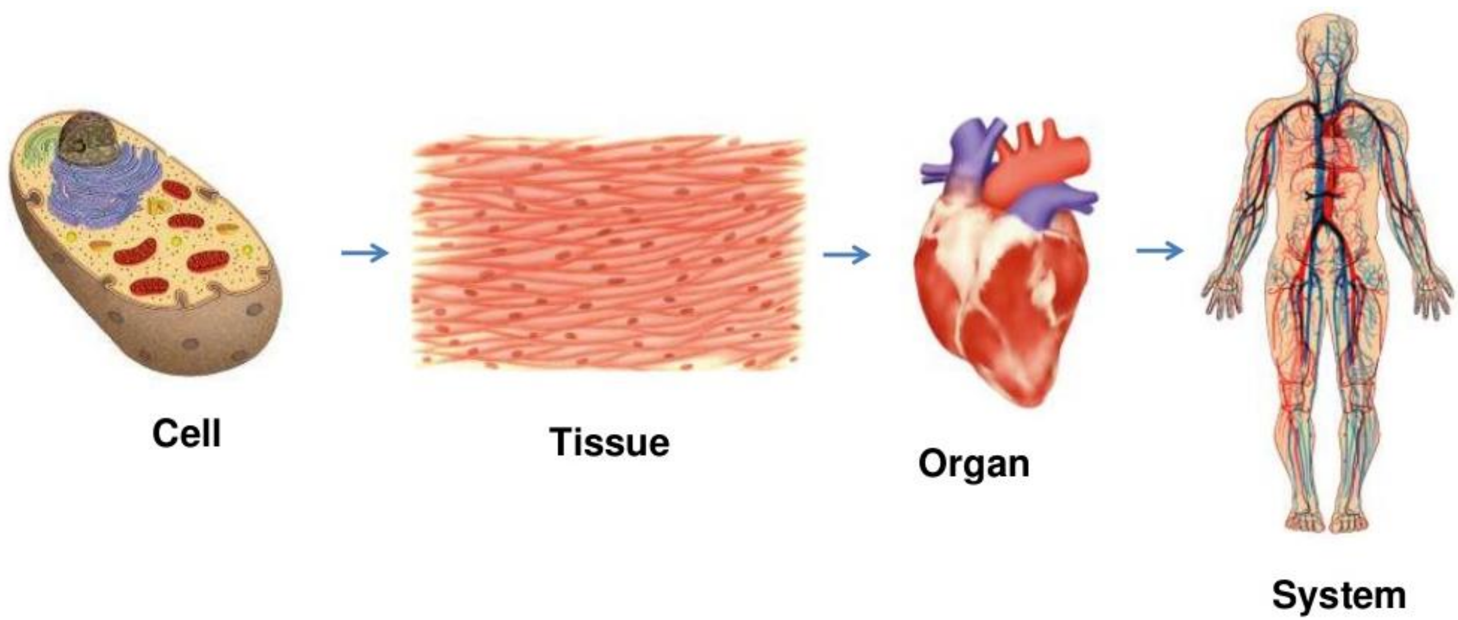
Cells are the "building blocks" of life

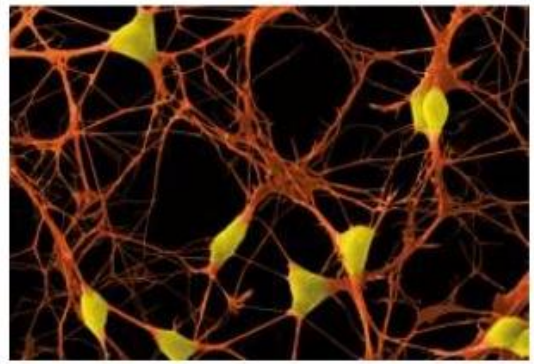
The **cell** is the basic structural, functional, and biological unit of all known organisms. A cell is the smallest unit of life. A living organism is formed by about 10^{12} cells.



Similar cells join together to form tissues. Different tissues join together to form organs. Organs work together to form systems.

There are different types of cells in a living organism

Red blood cells



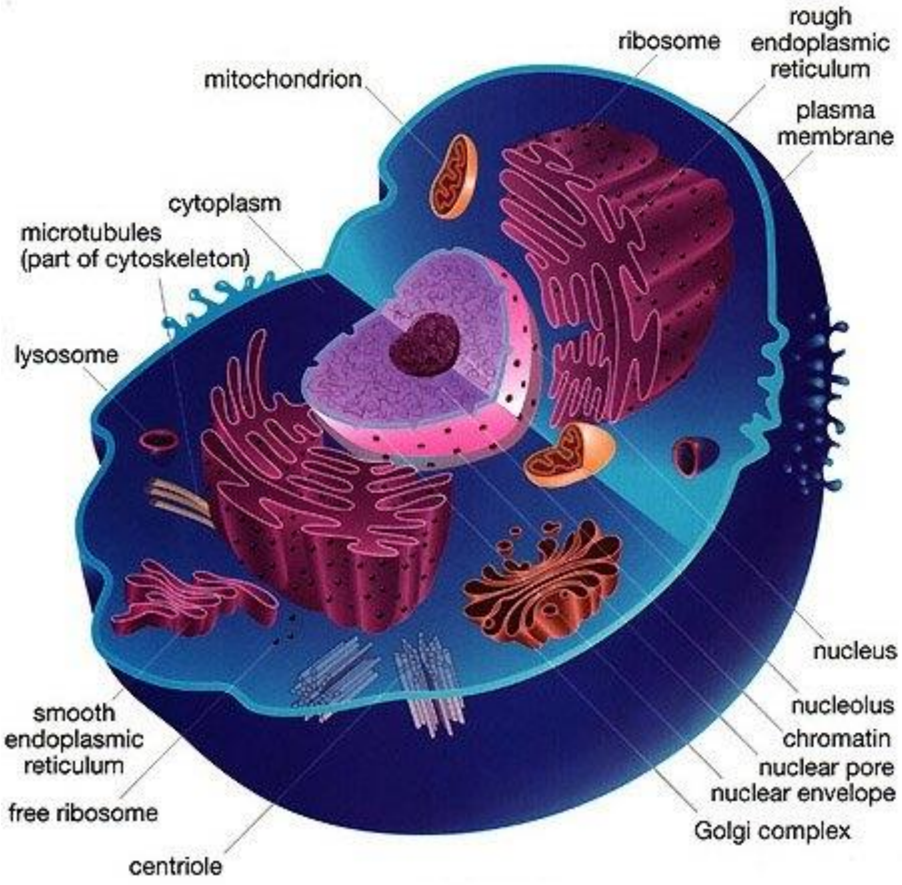
Nerve cells

Reproductive cells

Not all cells are the same. Different cells have different functions.

Cells are delimited by a plasma-membrane

The plasmamembrane delimits the cell and separates it from the extracellular ambient.



Functions of the plasmamembrane:

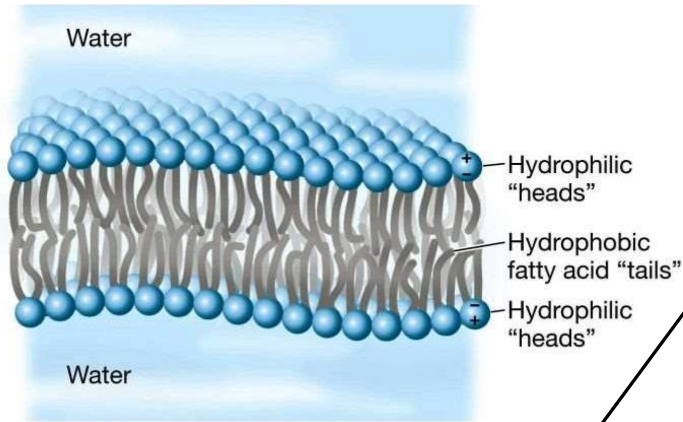
- exchange of water, ions, nutrients and waste substances With the extracellular space

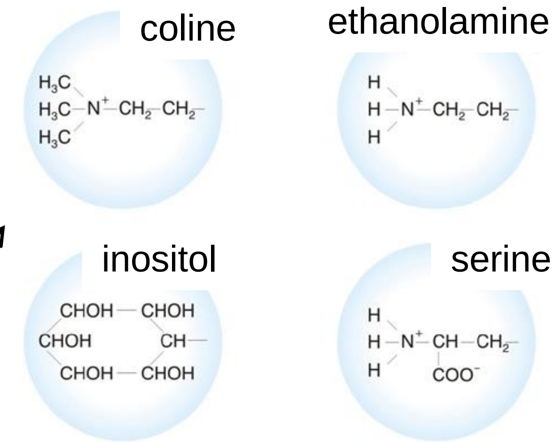
- Reception and interpretations of signals caming from other cells

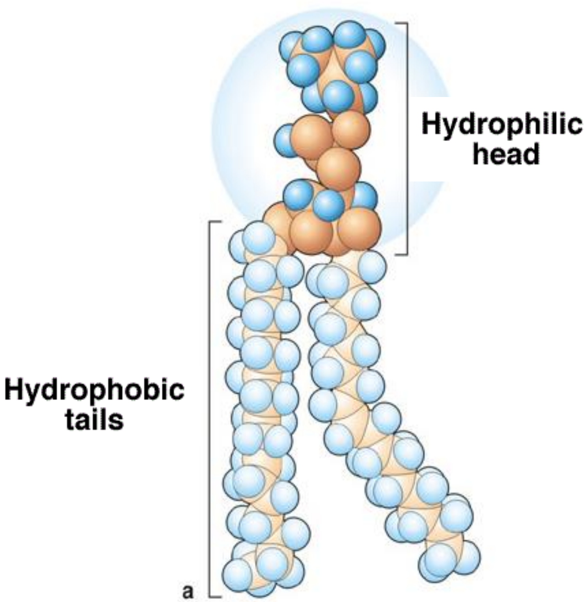
- Shape determination

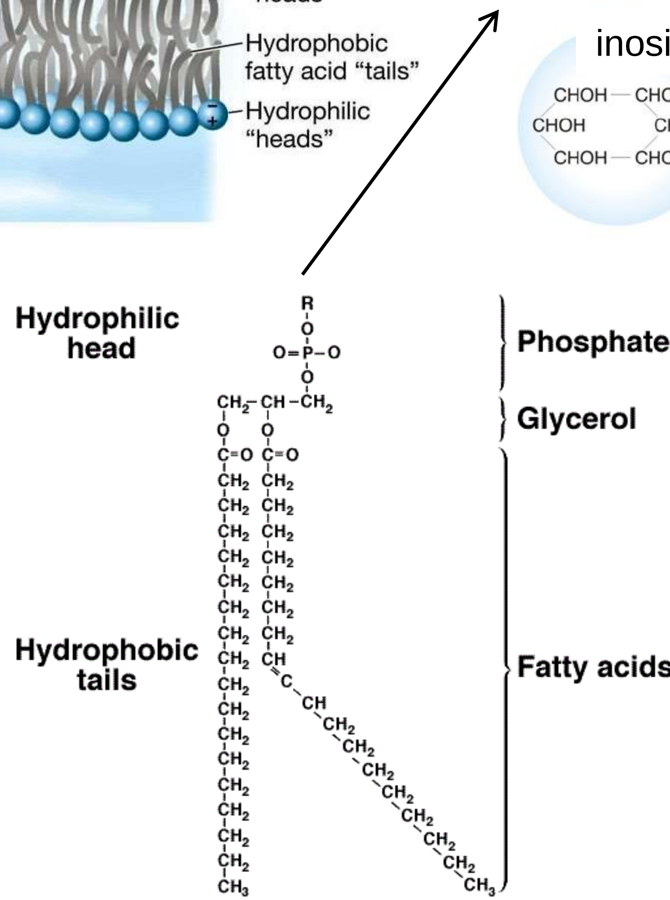
The main component of the plasma-membrane are phospholipids

Phospholipids in water solution spontaneously organized to form bilayers



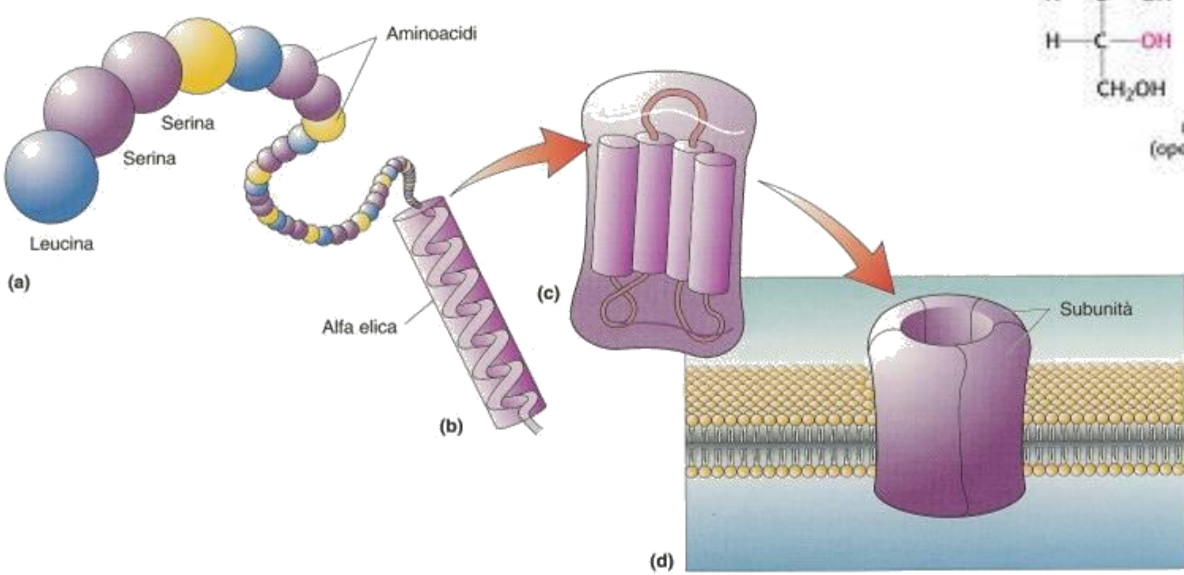




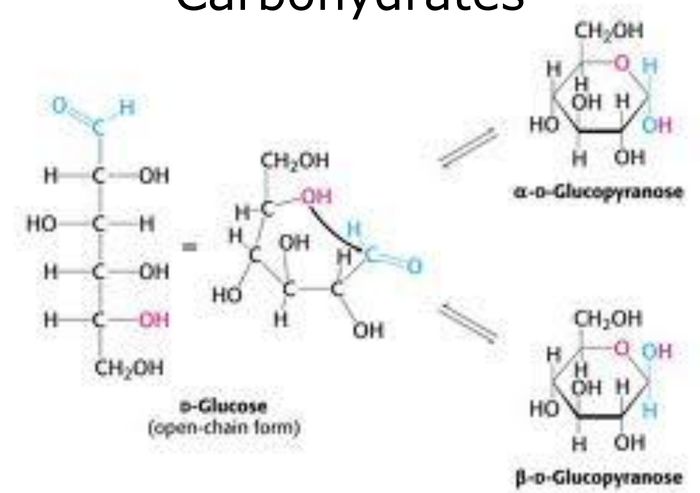


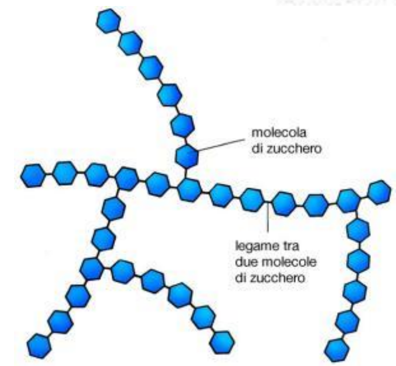
Other components of the plasma-membrane are proteins and carbohydrates

Proteins

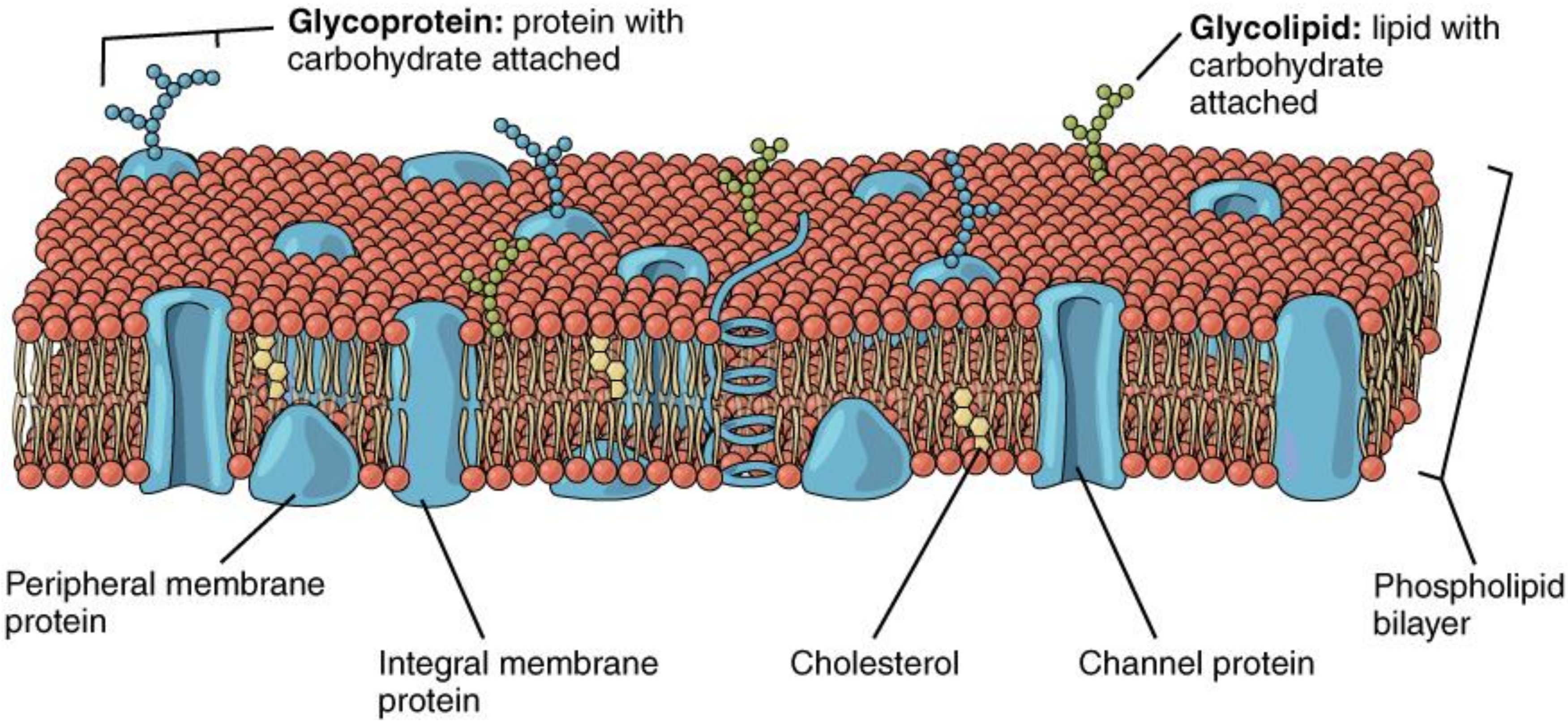


Carbohydrates

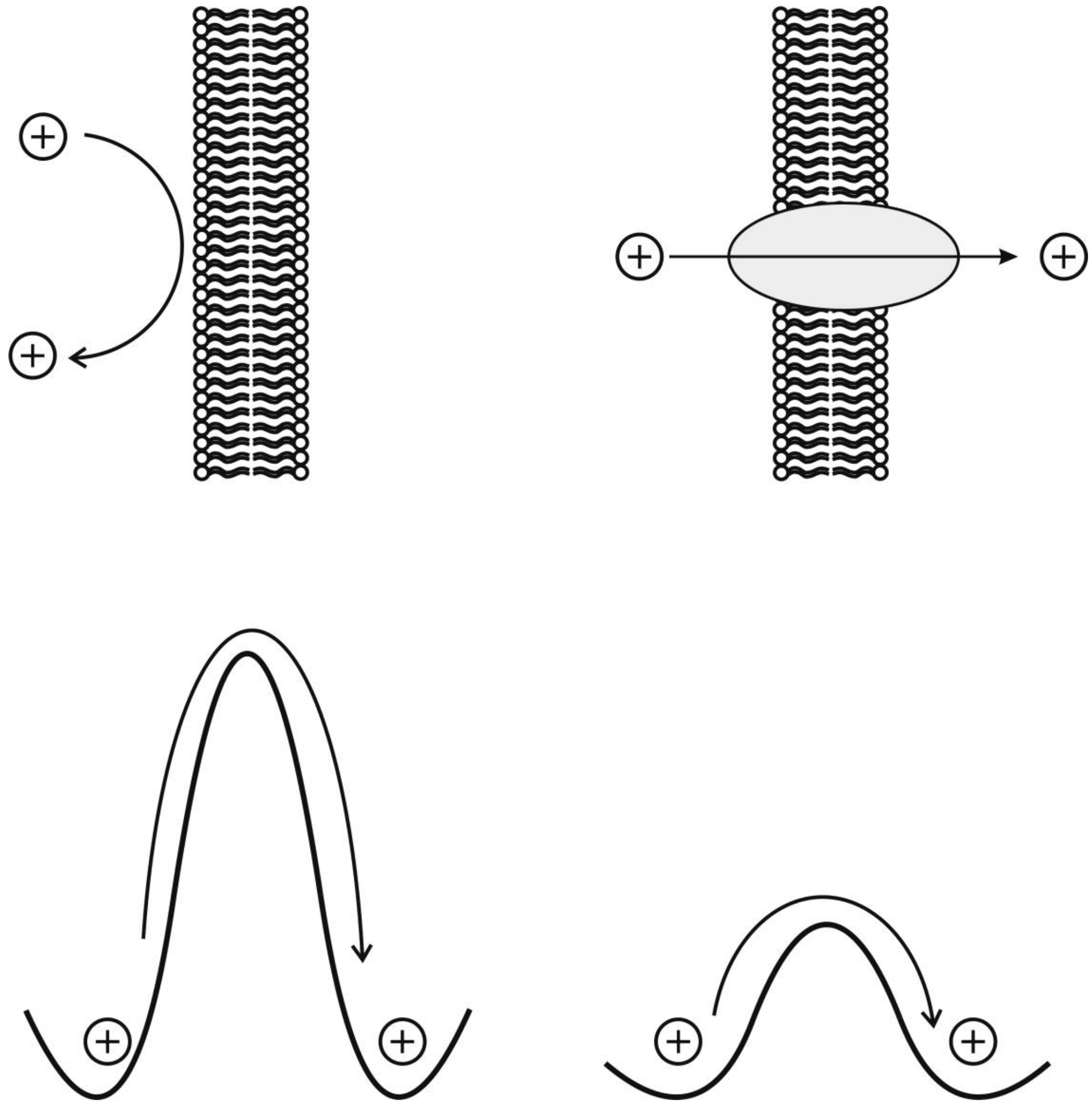




Structure of the plasma-membrane: the fluid mosaic model (Singer and Nicholson, 1972)



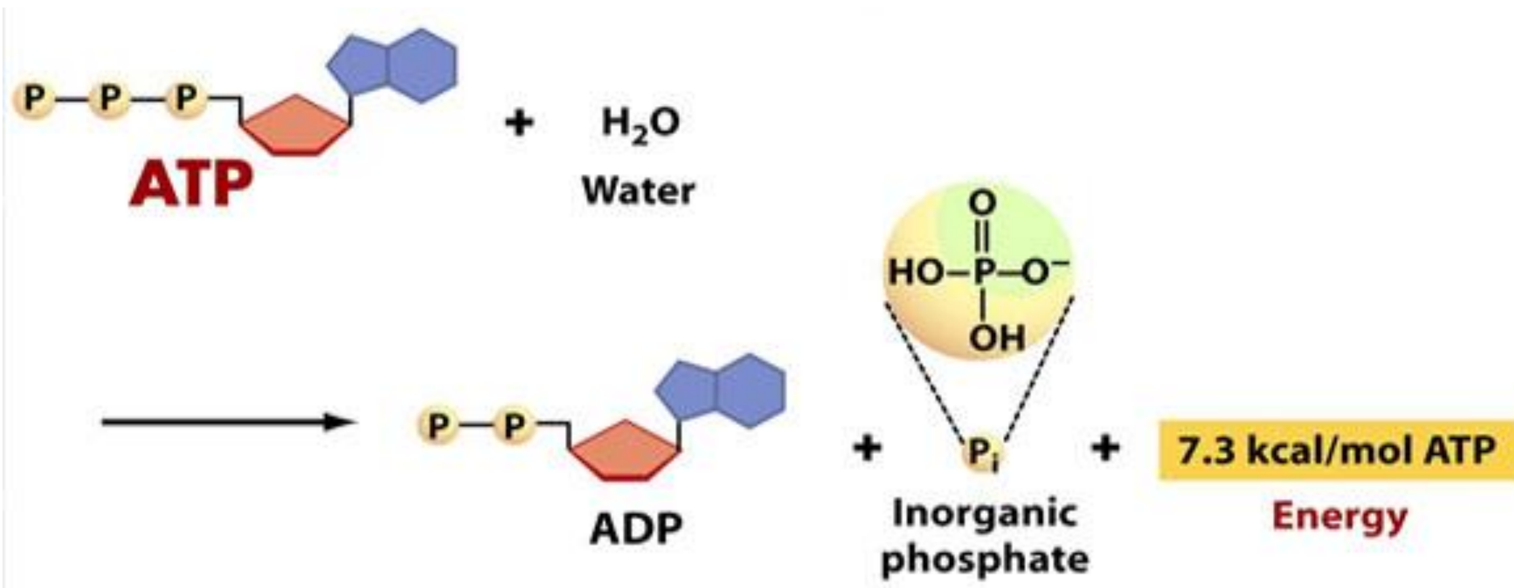
Ions permeate the plasma-membrane only with the help of transmembrane proteins



Passive and active ion transporters

Passive transport: ions move along their electrochemical gradient. No additional energy is required since this is a spontaneous process.

Active transport: ions move against their electrochemical gradient, using the energy derived by adenosine triphosphate



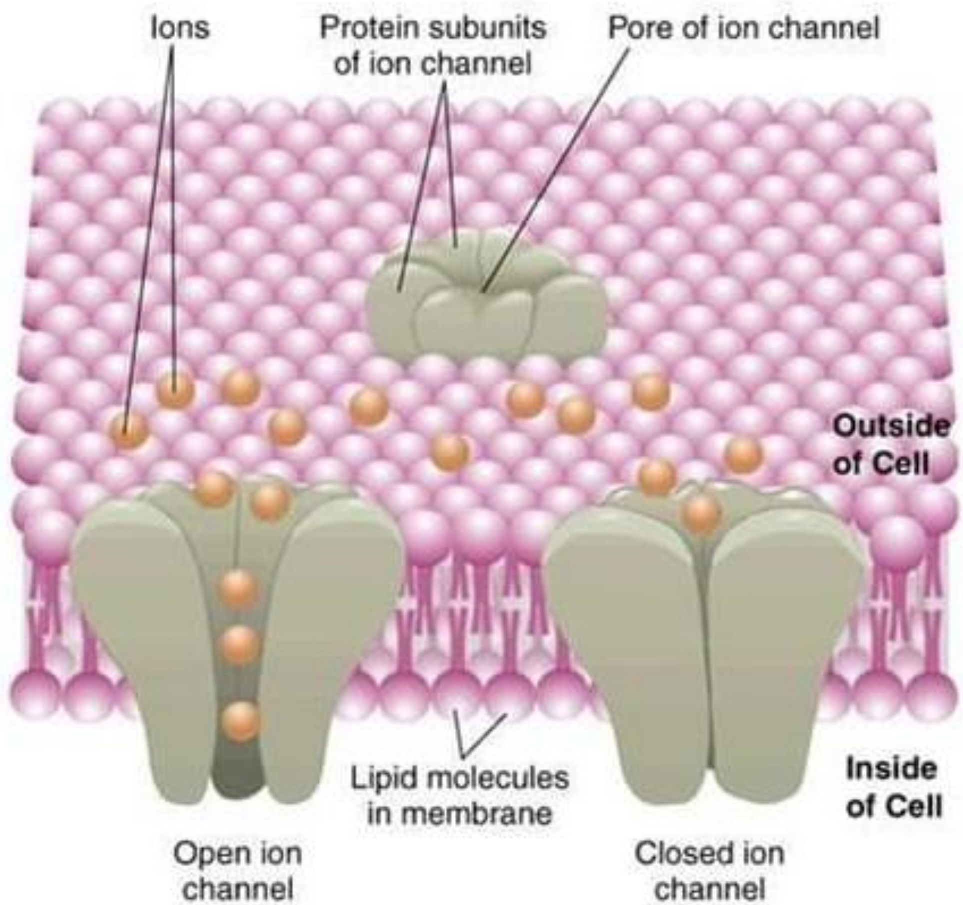
Passive transport of ions is mediated by ion channels

Ion channels are integral membrane proteins forming a hydrophilc pore where ions may easily permeate.

Main properties of ion channels

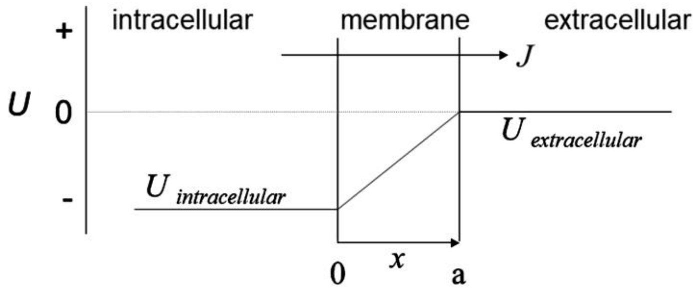
1. Selectivity for one or few ions

2. Gating: The pore opens and closes depending on the conditions

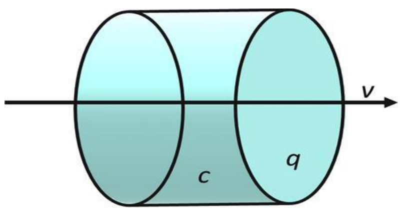


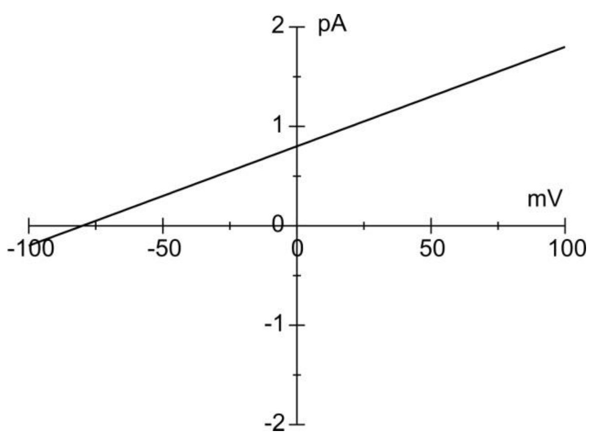
Permeation through ion channels

Goldman assumption: constant electric field inside the membrane (dU/dx = constant).



$$\frac{dU}{dx} = \frac{U_{ex} - U_{in}}{a} = \frac{-U_m}{a}$$





$$f = -D\frac{dC}{dx} - \frac{D\,z\,F}{RT}C\frac{dV}{dx}$$

Nernst-Planck equation

$$I = P\frac{z^2\,F^2}{RT}V\frac{C_{in} - C_{ex}\,e^{-\frac{zF}{RT}V}}{1 - e^{-\frac{zF}{RT}V}}$$

Goldman-Hodgkin-Katz equation

$$\frac{zFV}{RT} \ll 1$$ and constant C_{in}

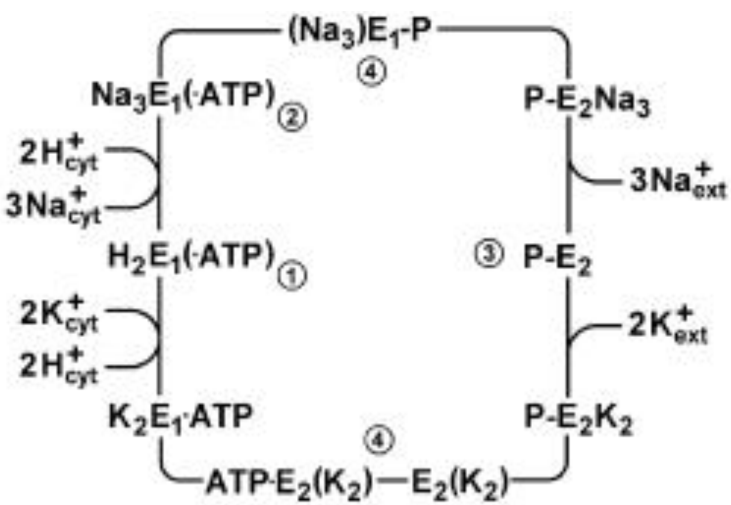
$$I = g\,(V - V_{in})$$

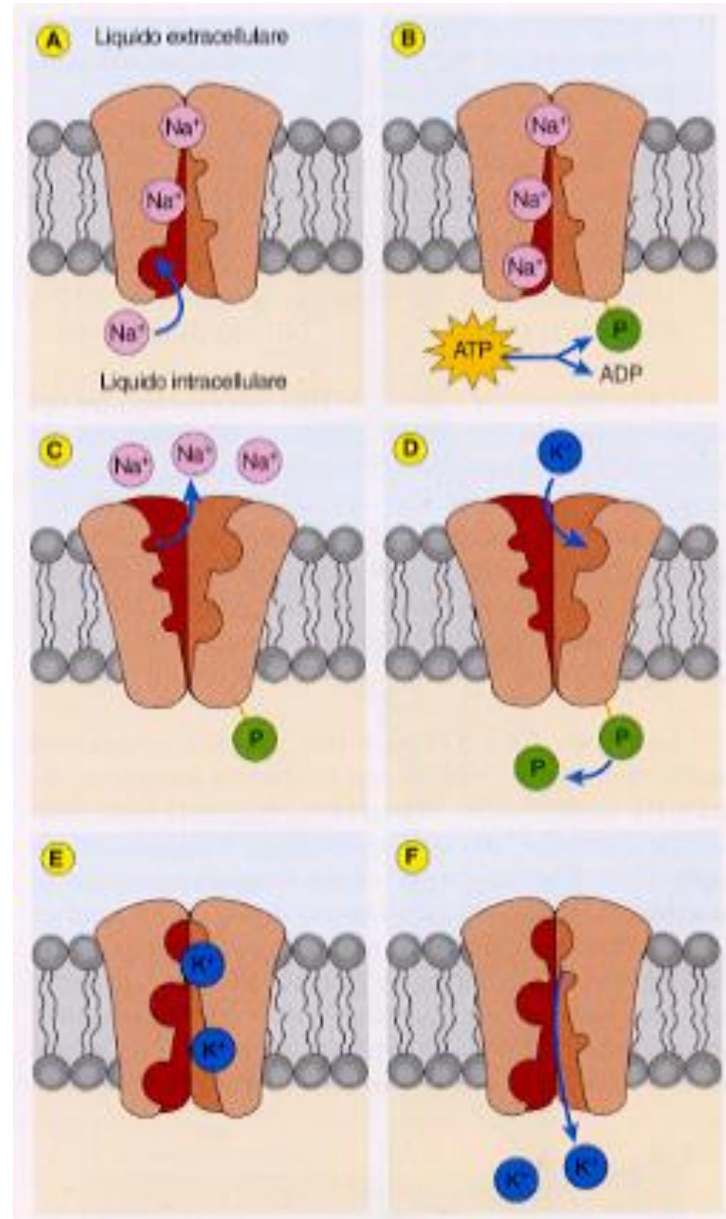
$$V_{in} = \frac{RT}{z\,F}\ln\frac{C_{ex}}{C_{in}}$$

Ion channels are ohmic devices

Active transport of ions: The Na/K ATPase

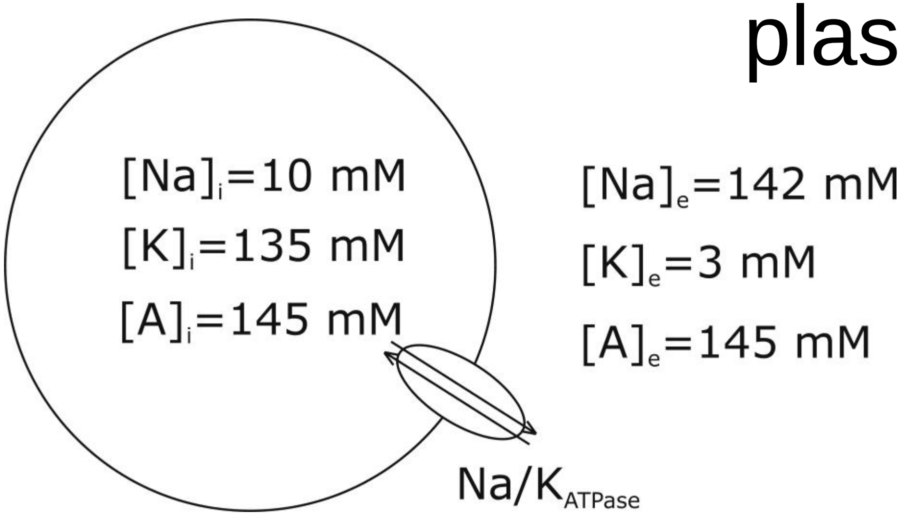
ATP hydrolisis is coupled to the transport of ions





$$turnover\ rate = \frac{\rho_{max}}{\left(1+e^{\frac{25-[Na]i}{3}}\right)\left(1+e^{(3.5-[K]e)}\right)}$$

The activity of the Na/K ATPase is responsible for A permanent ionic gradient across the plasma-membrane



Power absorbed by the Na/K ATPase

Turnover rate of the Na/K ATPasi: 25 - 80 ATP/s (Liang et al., 2007)

Number of Na/K ATPase in a typical cell: $8*10^4$ - $3*10^7$ (Liang et al., 2007)

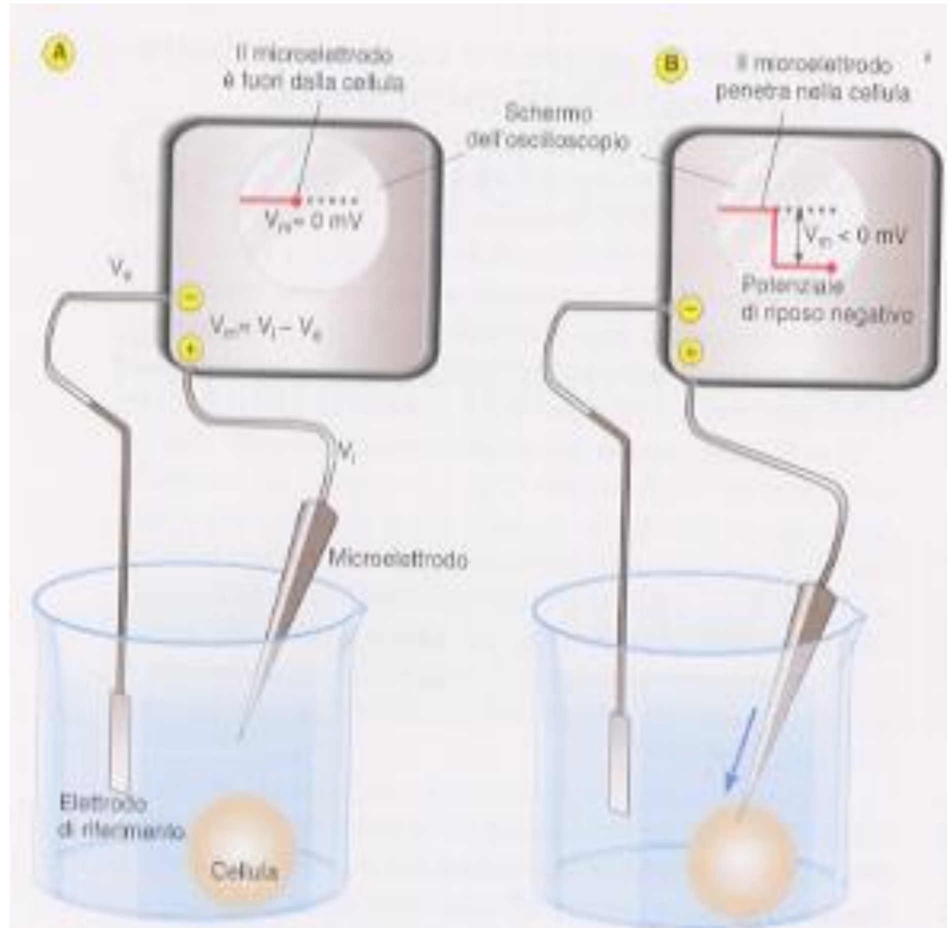
Overall turnover: $3*10^{-6}$ - $4*10^{-3}$ pmol ATP/s

Energy delivered by the hydrolisis of one ATP molecule: 7.3 kcal/mol

Power absorbed by Na/K ATPase in a typical cell: 0.1 pW – 100 pW

Biological cells possess an electric potential difference across the plasma-membrane

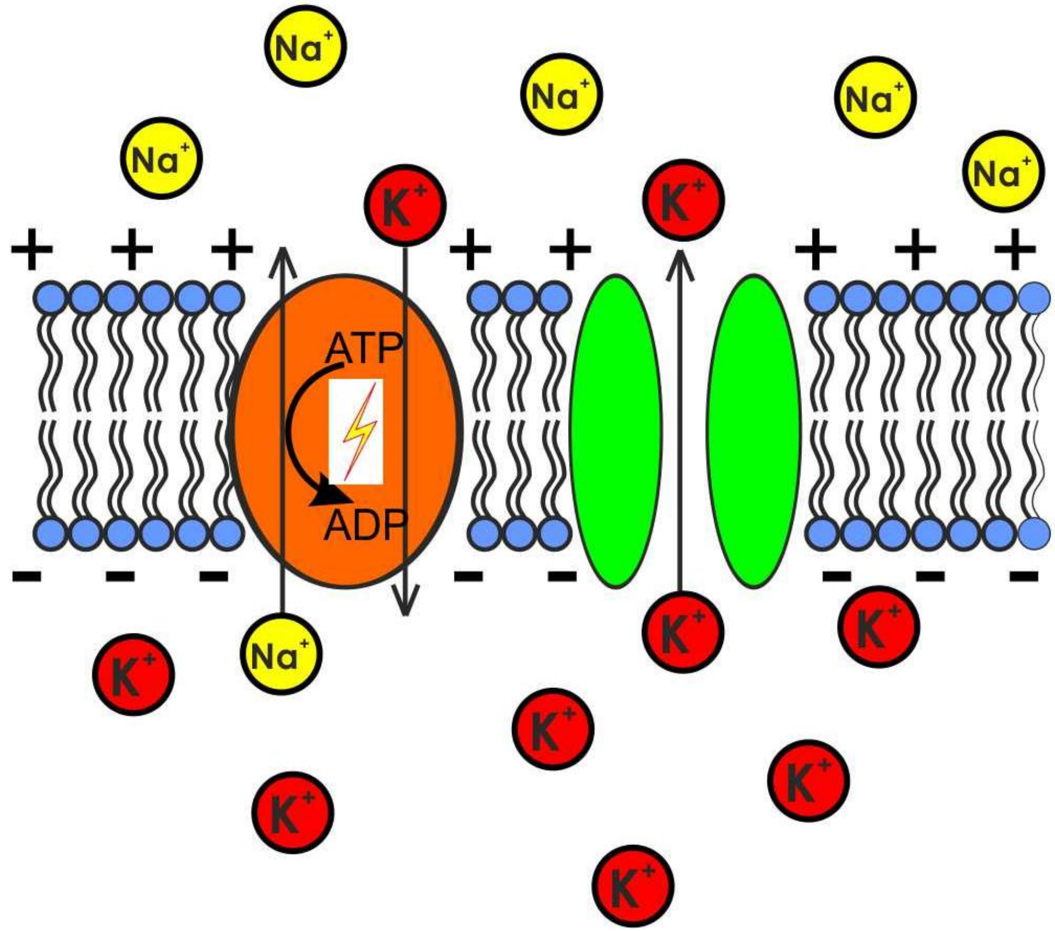
Cell type	Resting membrane potential
Neurons	-60/-75 mV
Skeletal muscle cells	-90 mV
Cardiac muscle cells	-85 mV
Epithelial cells	-20 mV
Glial cells	-80 mV
Red blood cells	-15 mV



Mechanism of generation of the electric potential difference across the plasma-membrane

1. Na/K ATPases accumulate K ions inside the cell

2. The accumulated K ions then leave the cell through K channels, creating a charge separation



Mechanism of generation of the electric potential difference across the plasma-membrane

Needed conditions:

1. It exists an ionic gradient between the inside and outside of the cell

2. The plasma-membrane is differentially permeable to the different ionic species

$$\Delta G_{el} = \Delta G_{ch}$$

$$\underbrace{z\,F\,V_m}_{\Delta G_{el}} = \underbrace{RT\,ln\frac{C_{ex}}{C_{in}}}_{\Delta G_{ch}}$$

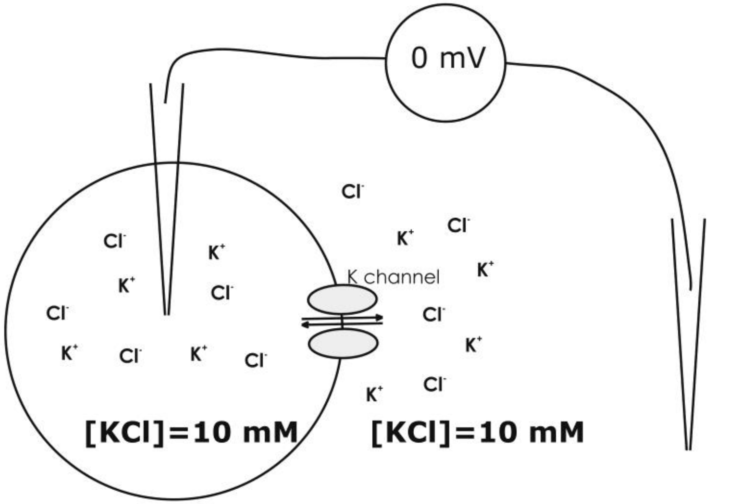
$$V_m = \frac{RT}{z\,F}\,ln\frac{C_{ex}}{C_{in}}$$

eq. di Nernst

$$I = P\,\frac{z^2\,F^2}{RT}V\,\frac{C_{in} - C_{ex}\,e^{-\frac{zF}{RT}V}}{1 - e^{-\frac{zF}{RT}V}}$$

$$I = 0\;\;at\;V = V_m$$

1



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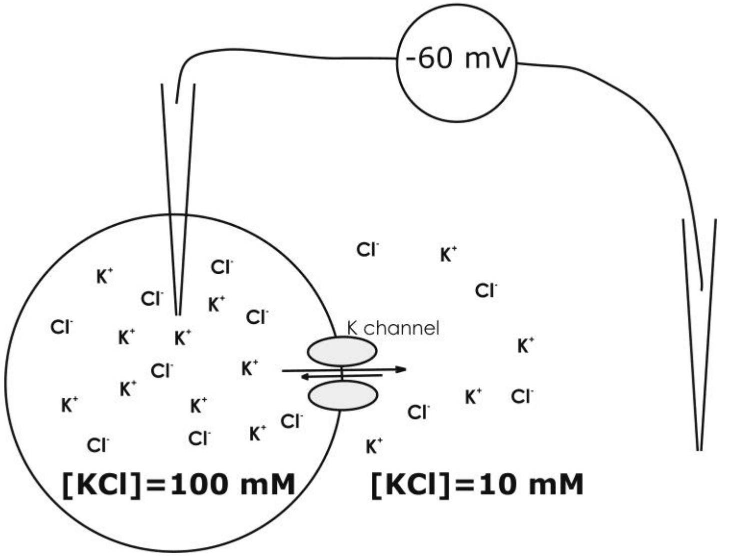
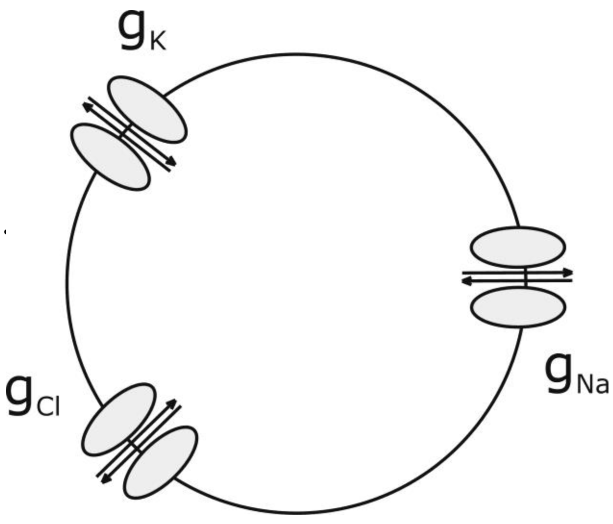


The membrane potential difference across the plasma-membrane depends on the ion concentrations and membrane permeabilities



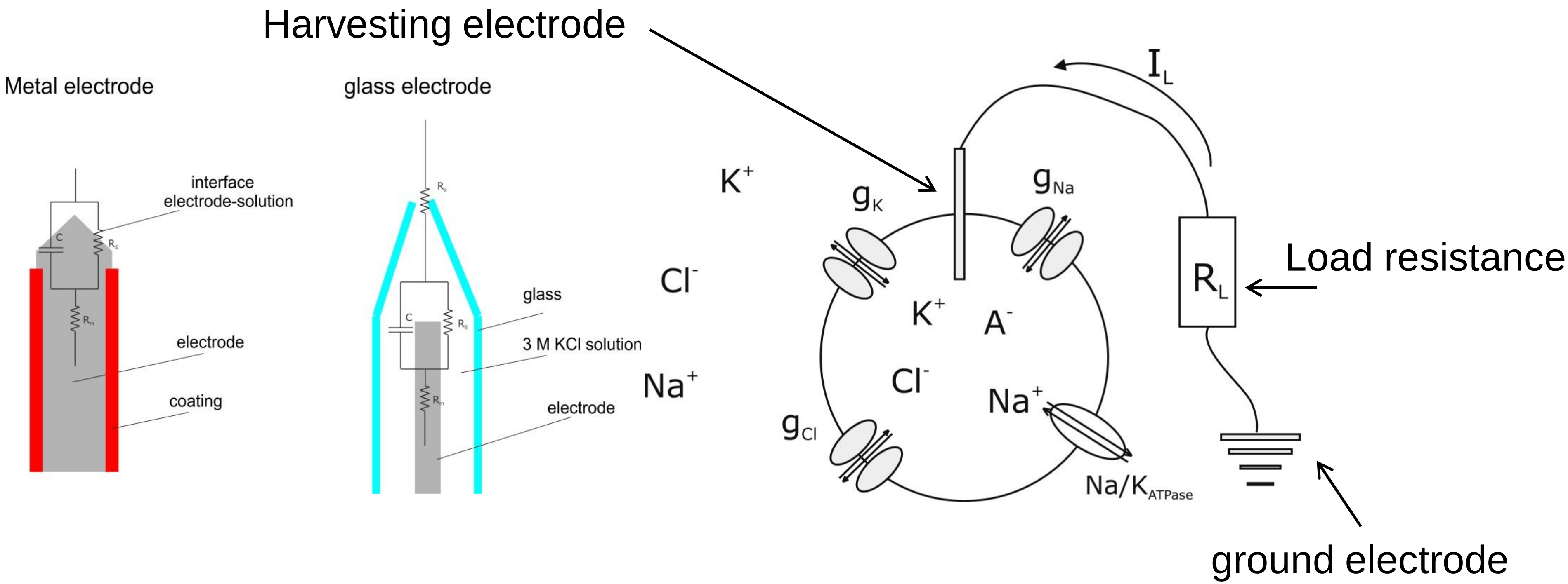
$$I = P_i \frac{z_i^2 F^2}{RT} V \frac{C_{i,in} - C_{i,ex} e^{-\frac{z_i F}{RT}V}}{1 - e^{-\frac{z_i F}{RT}V}} + P_j \frac{z_j^2 F^2}{RT} V \frac{C_{j,in} - C_{j,ex} e^{-\frac{z_j F}{RT}V}}{1 - e^{-\frac{z_j F}{RT}V}} + \ldots\ldots$$

$$I = 0 \;\; quando\, V = V_m$$

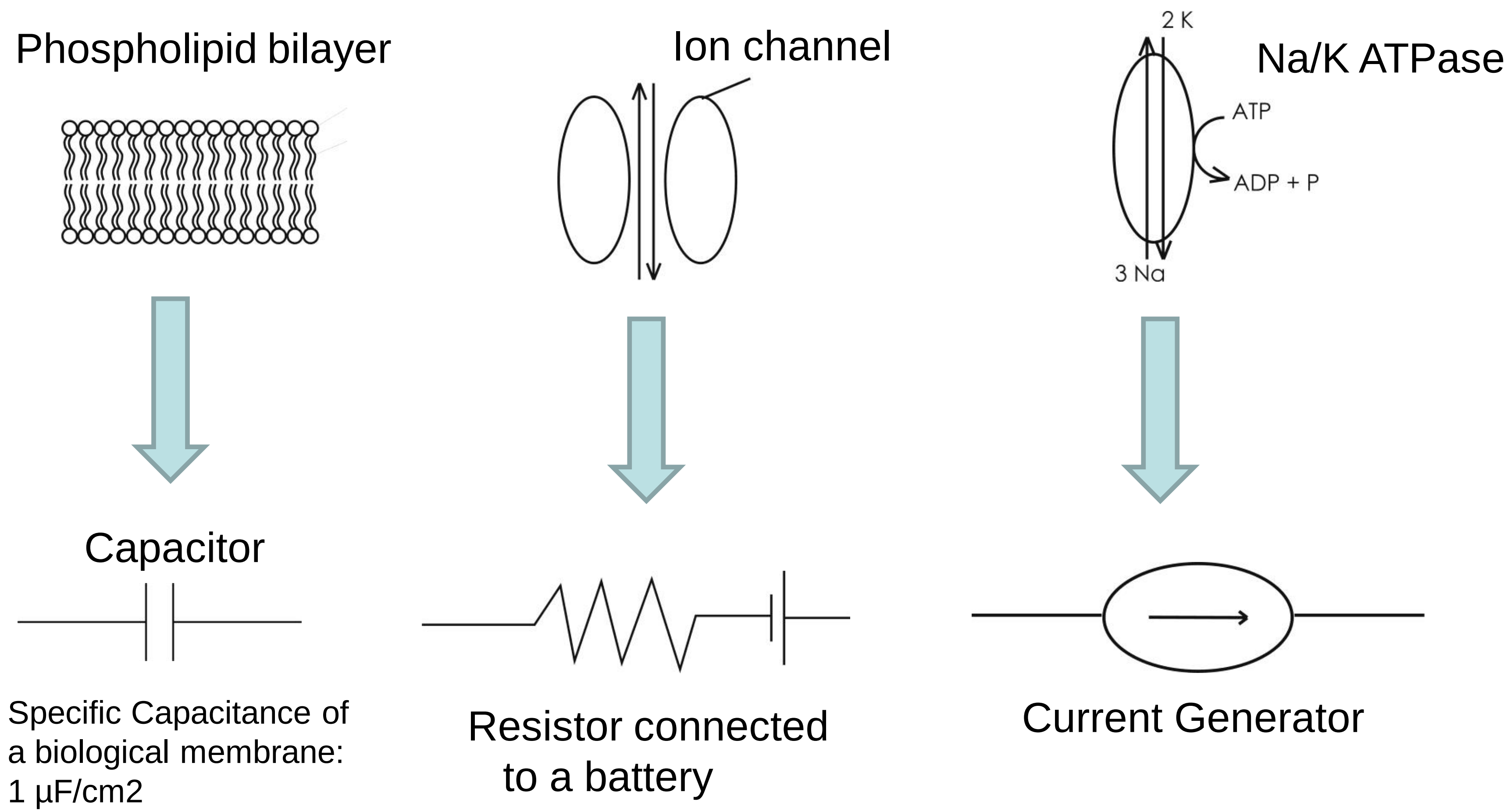
$$V_m = \frac{RT}{F} ln \frac{\sum P_c \, C_{c\,ex} + \sum P_A \, C_{A\,ex}}{\sum P_A \, C_{A\,ex} + \sum P_C \, C_{C\,ex}}$$

If the membrane is particularly permeable to an ion type, that ion will contribute very much to establish the resting membrane potential

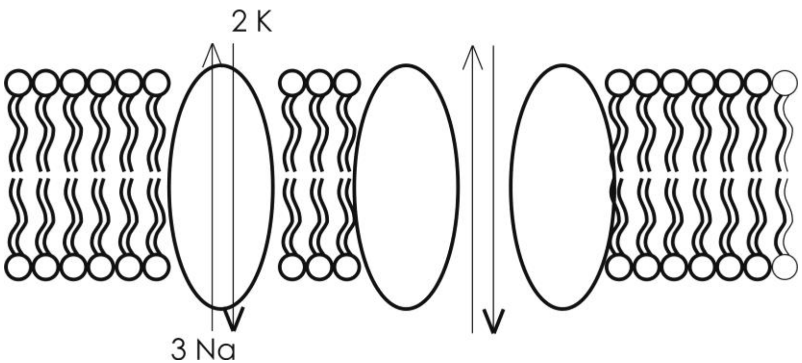
Can we extract the energy accumulated in the electric Potential difference of a cell? How much power may we extract from a a typical cell?

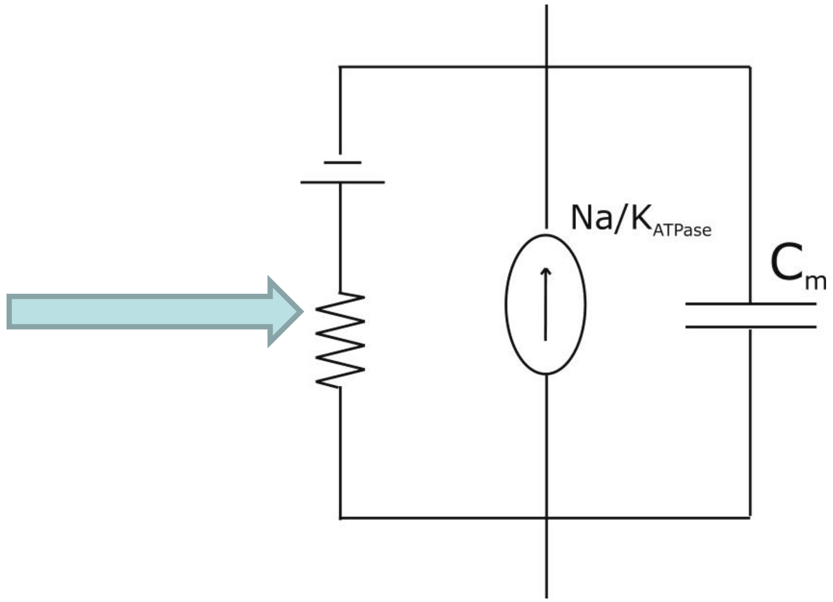


The plasma-membrane may be assimilated to an electrical circuit, and each plasma-membrane component behaves as a particular circuit elements



Equivalent electrical circuit for a plasma-membrane

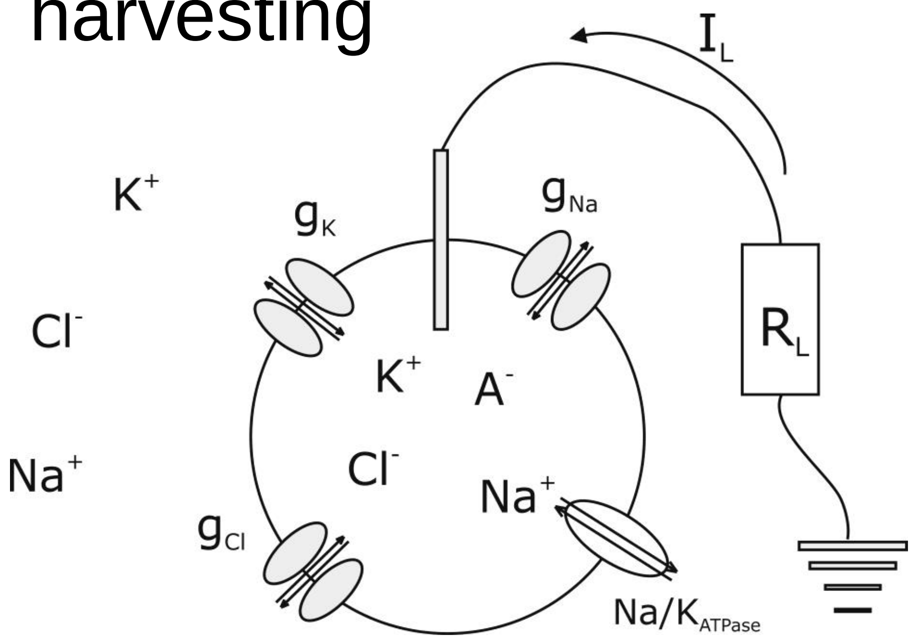


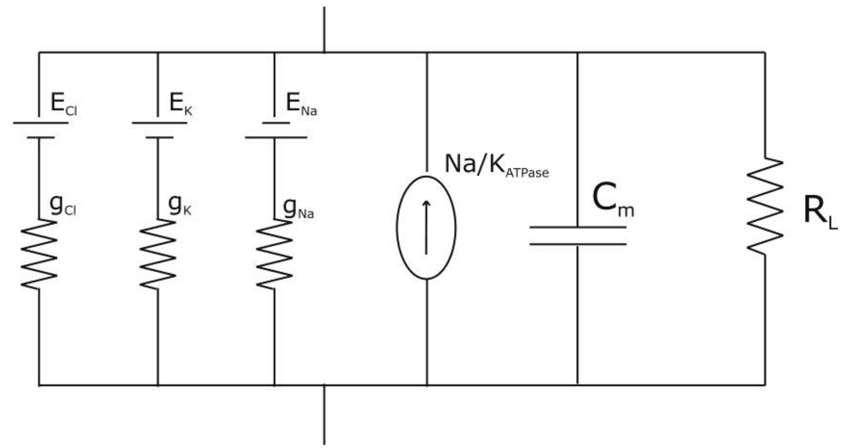


$$\frac{dV_m}{dt} = -\frac{I_m}{C_m}$$

$$I_m = I_p + \sum g\,(V_m - V_{inv})$$

Model of the electric behaviour of a cell during energy harvesting





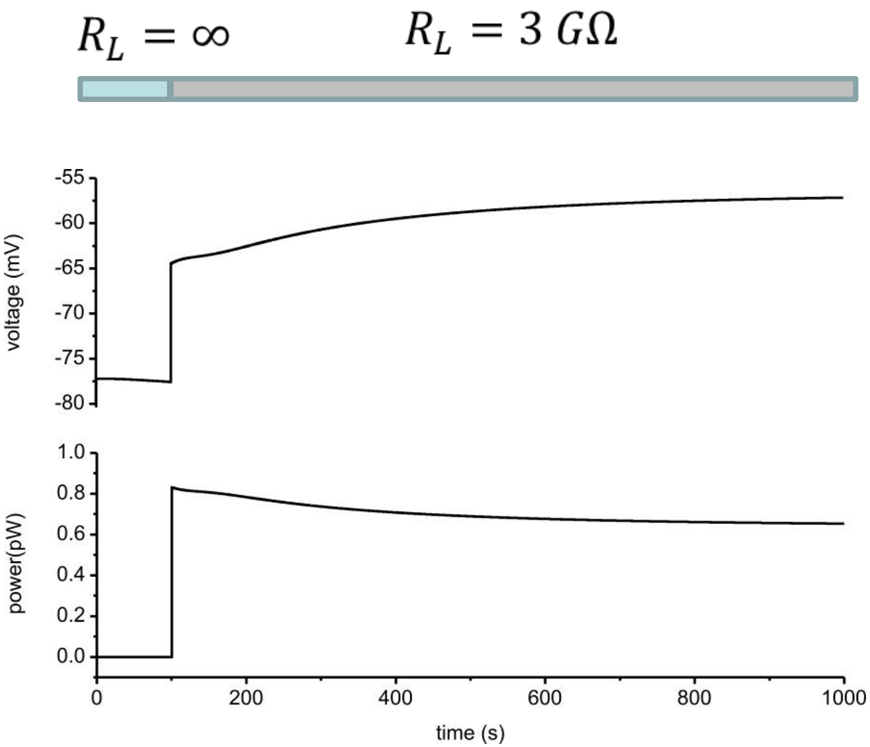
$$\frac{dV_m}{dt} = -\frac{I_m}{C_m}$$

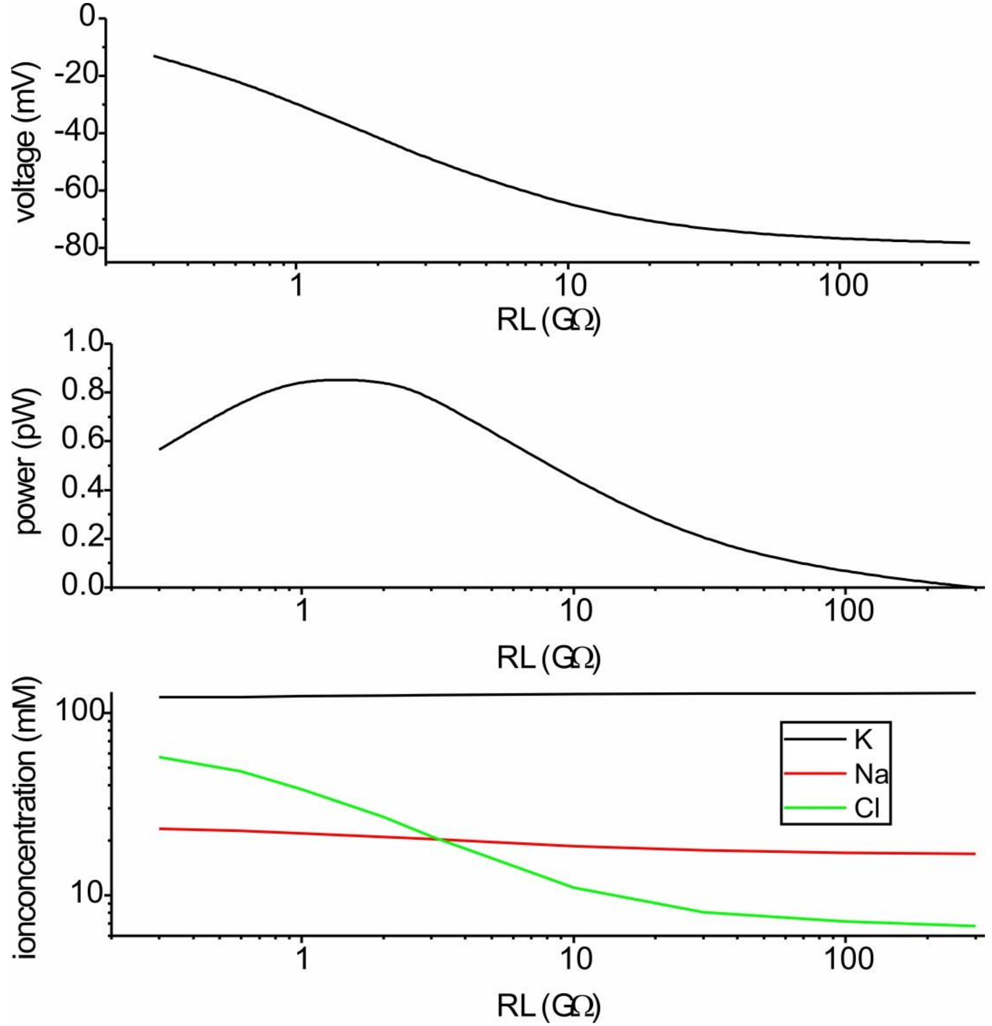
$$\frac{d[ion]_i}{dt} = -\frac{I_{ion}}{z\,F\,Vol}$$

$$P = I_L\,V_m$$

Parameter	Description	Value
r	Cell radius	7 µm
C_S	Specific membranecapacitance	0.01 pF/µm^2
g_{KS}	Specific K channel conductance	5*10^{-4} nS/µm^2
g_{Na}	Specific Na channel conductance	1*10^{-4} nS/µm^2
g_{Cl}	Cl channel conductance	1*10^{-3} nS/µm^2
R_L	Load resistance	variable
ρ	Maximal turnover of the Na/K ATPase	133 ATP/s
D_{ATPase}	Density of Na/K ATPase	3350/µm^2
K_O	Extracellular K concentration	3 mM
Na_O	Extracellular Na concentration	142 mM
Cl_O	Extracellular Cl concentration	145 mM
nAA_i	Intracellular impermeable anions	0.198 pmol

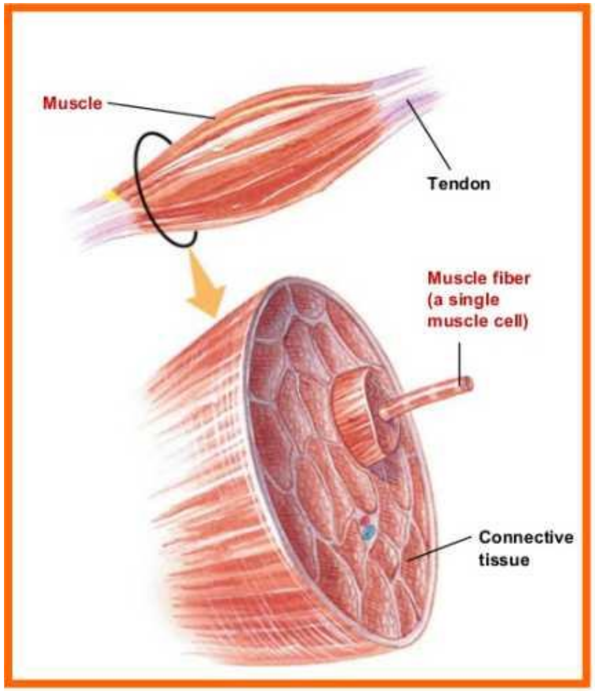
Estimation of the power harvested from a typical cell

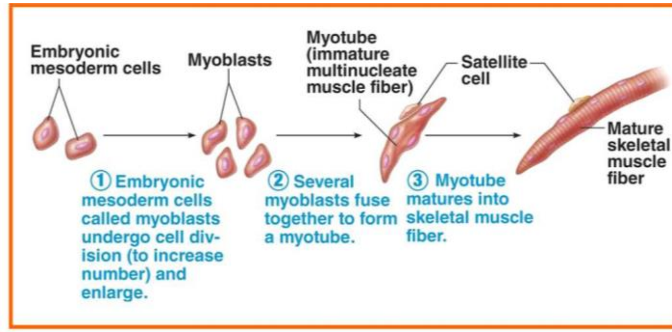




Efficiency: harvested power/power absorbed by the Na/K ATPase 1 pW/(50 pW)= 2 %

Skeletal muscle cells are very big and a much higher energy is obsorbed by Na/K ATPases





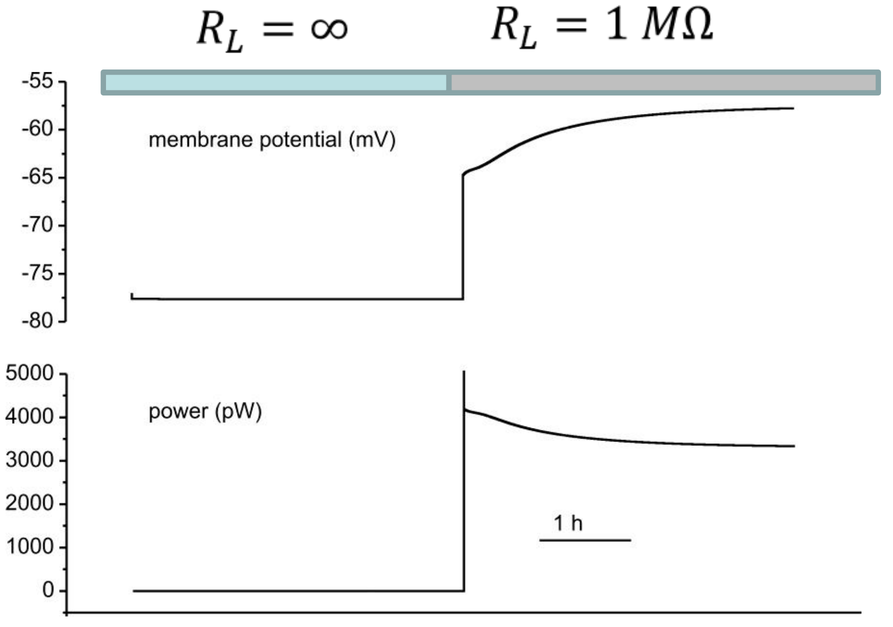
	Other cells	Skeletal muscle fiber
Number of nuclei	1	50/mm
Typical dimensions	diam=5-20 μm	Diam=500 μm, length= up to few cm
Volumes	$10^{-5} – 10^{-3}$ nL	Few μL
Number of Na/K ATPases	$10^{3} – 10^{7}$	$10^{10} – 10^{11}$
Adsorbed power	50 pW	70 nW

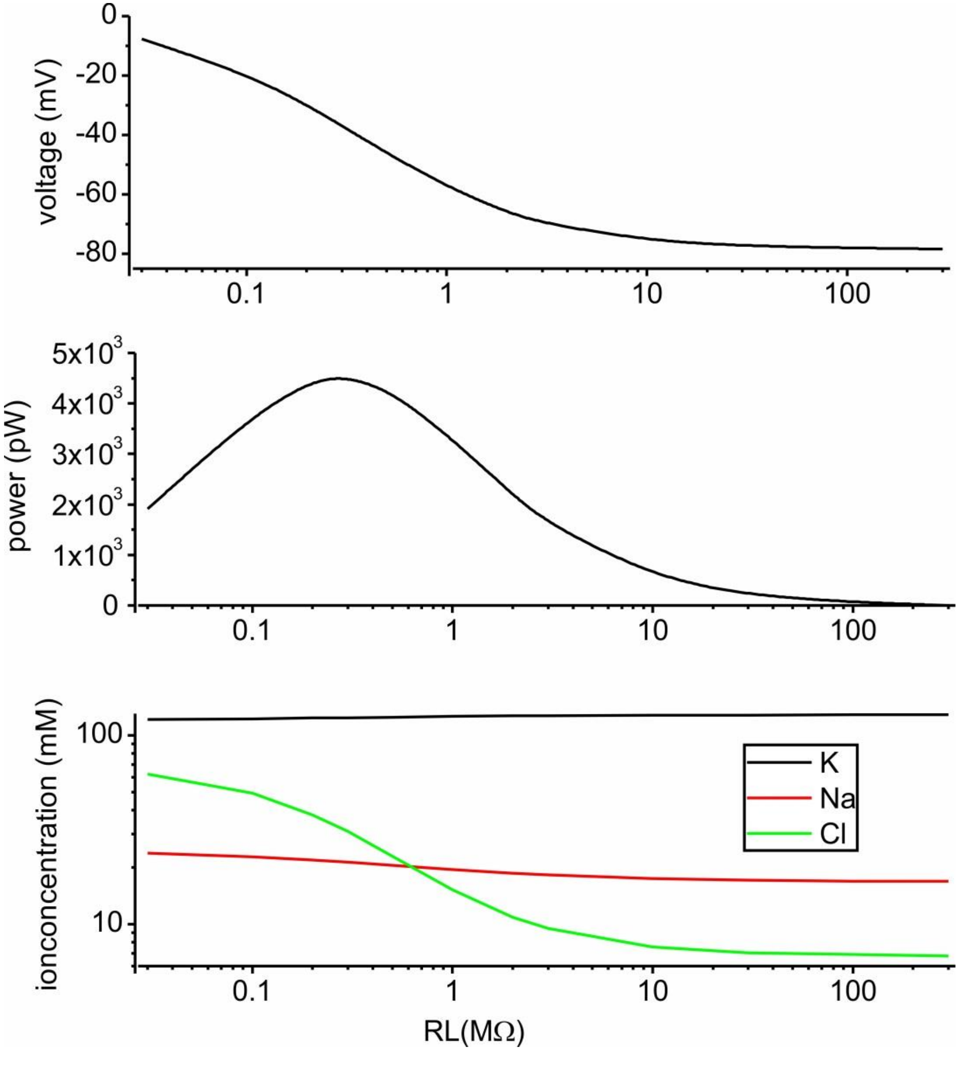
Power absorbed by the Na/K ATPase

Turnover rate of the Na/K ATPasi: 130 ATP/s (Plesner, 1981)
Number of Na/K ATPase in muscle cells: 3350 /μm^2 (Clausen, 2003)
Overall turnover: 2.27 pmol ATP/s
Energy delivered by the hydrolisis of one ATP molecule: 7.3 kcal/mol

Power absorbed by Na/K ATPase in a typical cell: 70 nW

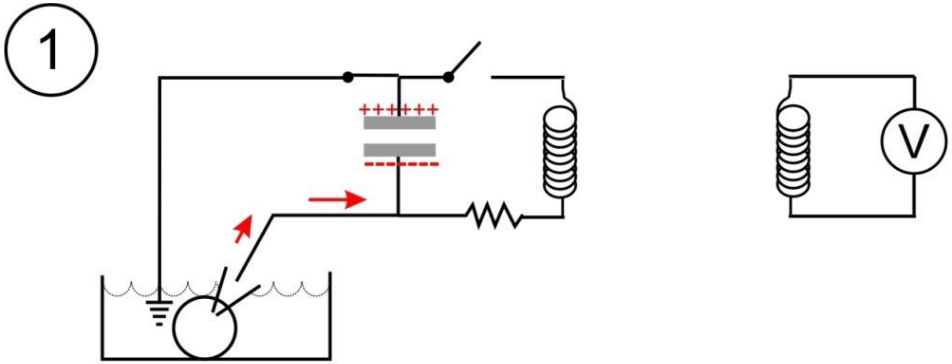
Estimation of the power harvested from a skeletal muscle cell

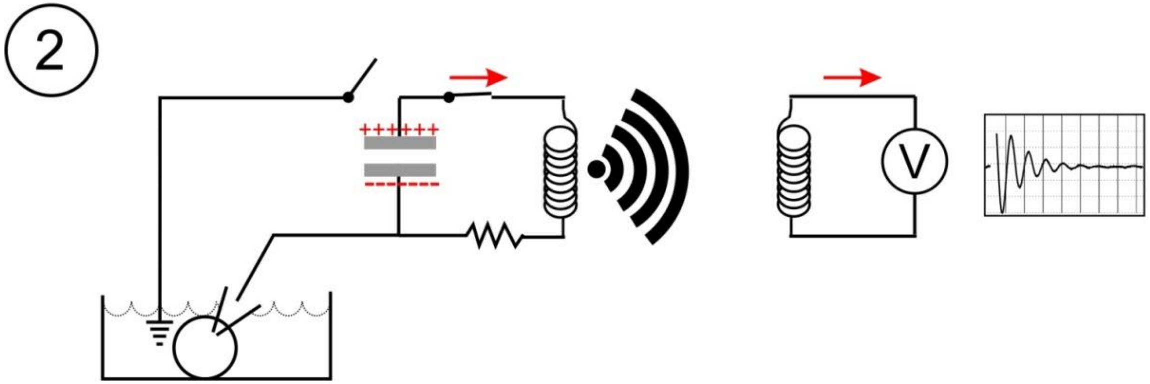




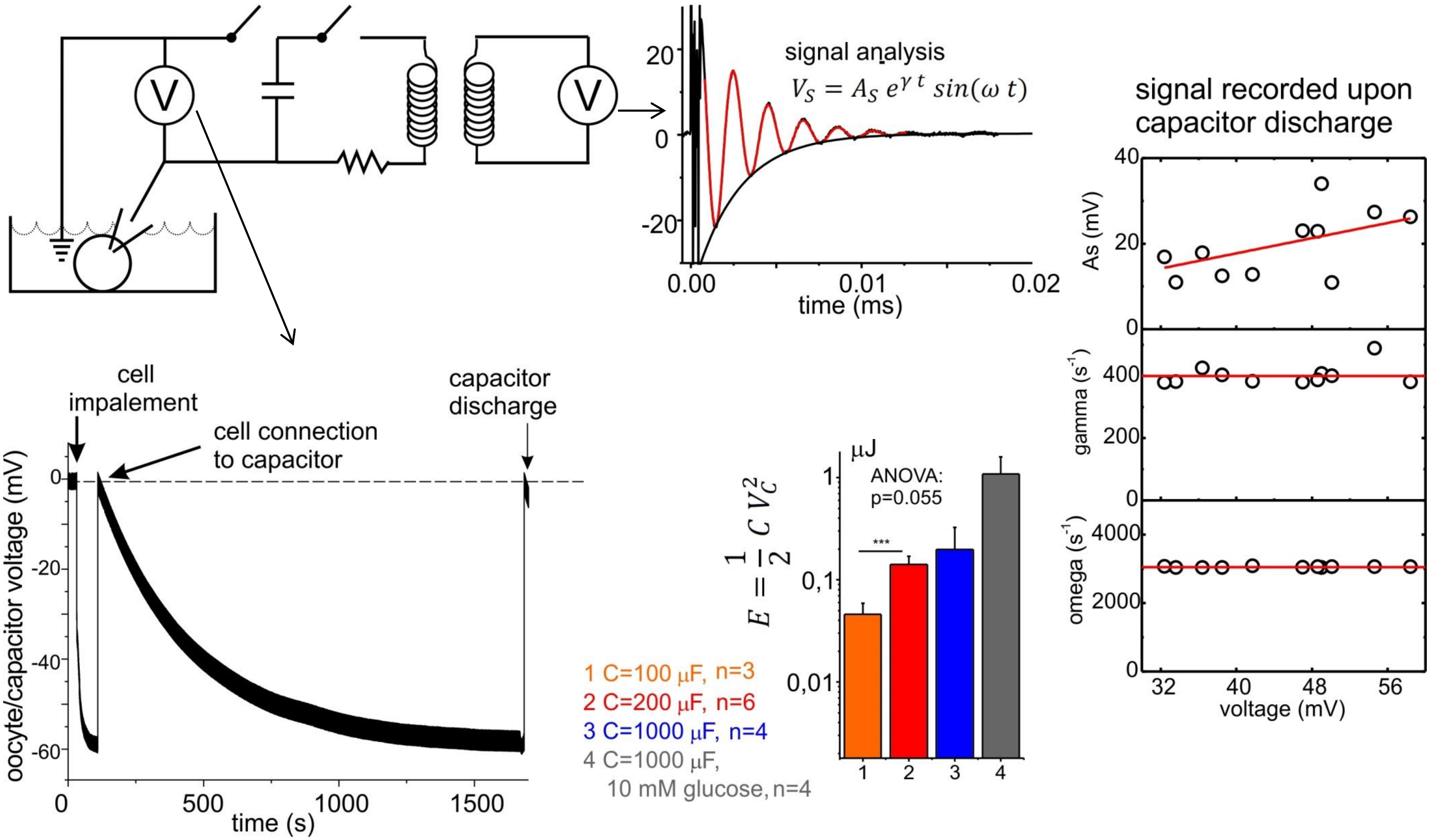
Efficiency: harvested power/power absorbed by the Na/K ATPase:
5 nW/(70 nW)= 7.1 %

Experimental proof of concept in Xenopus oocytes

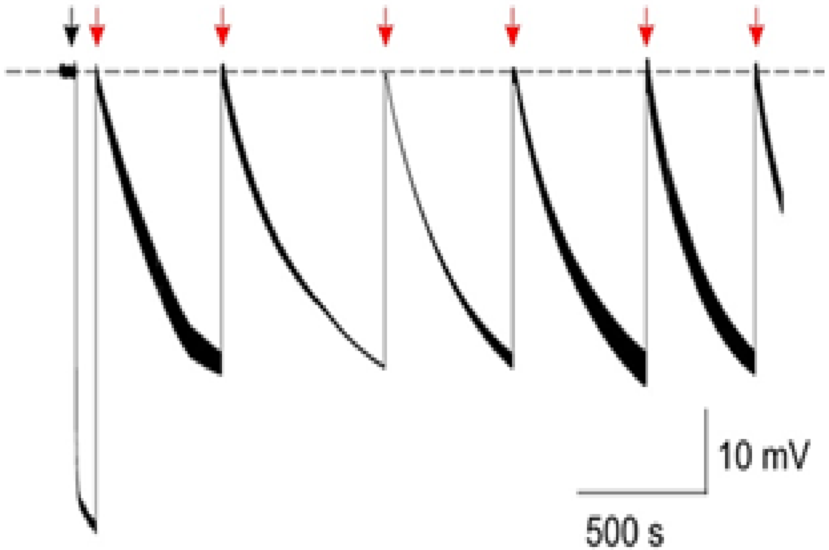


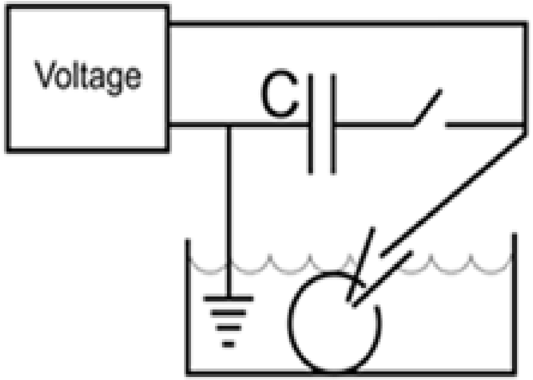


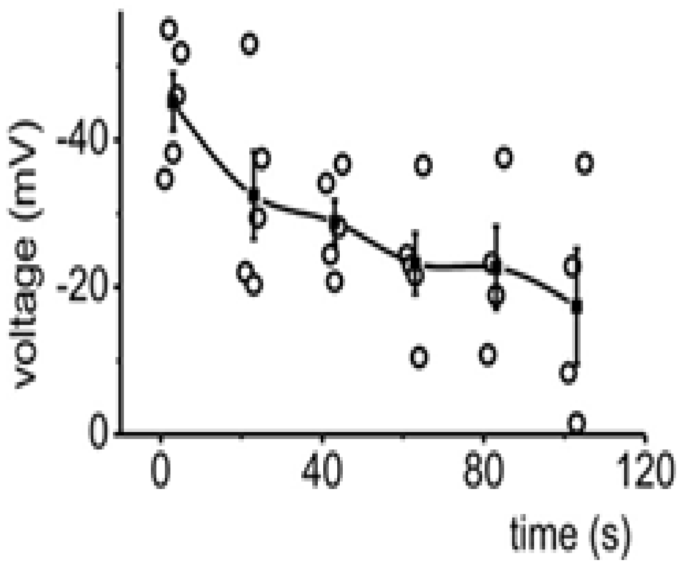
Energy may be harvested from a single oocyte and used later for wireless communication

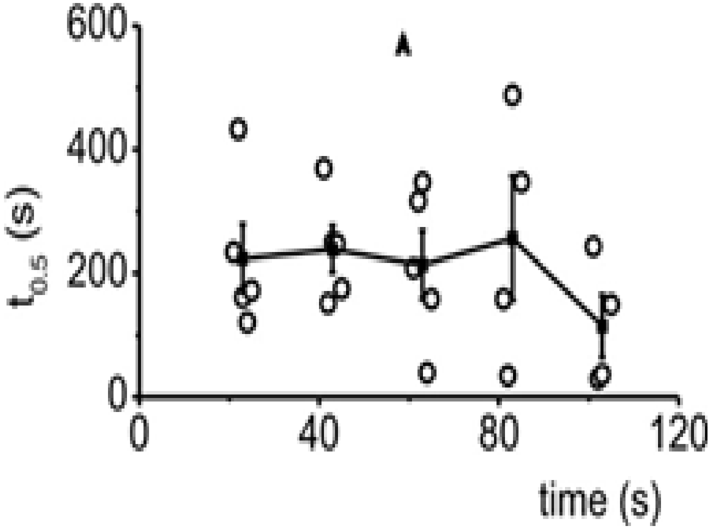


Energy may be harvested repeatedly from the same cell

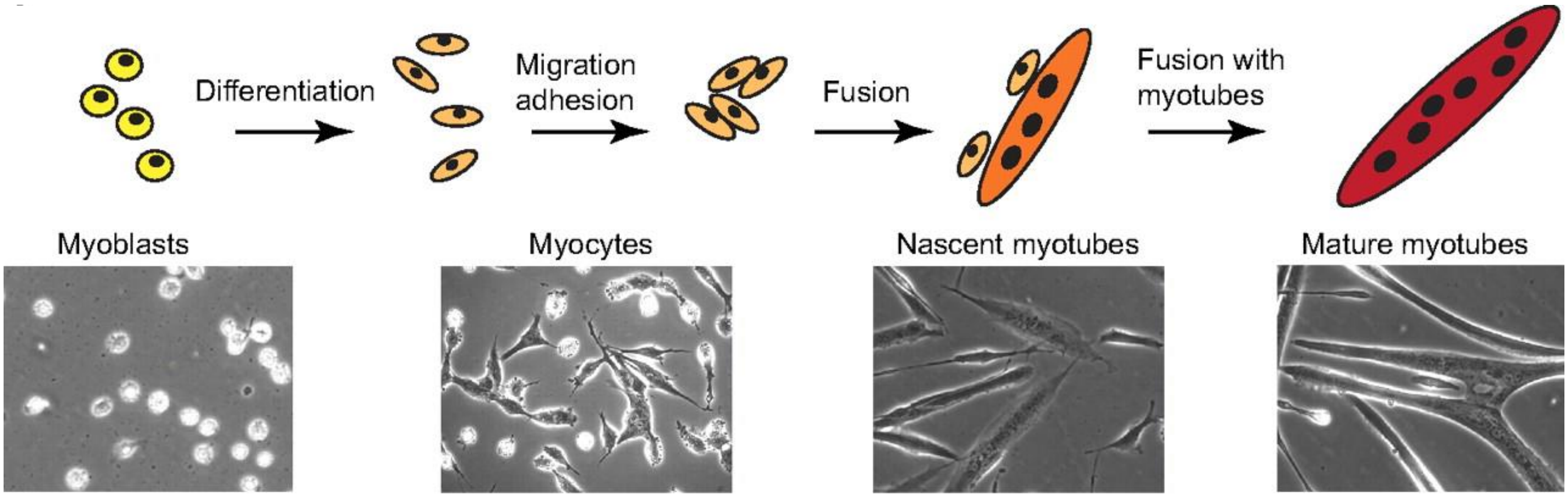




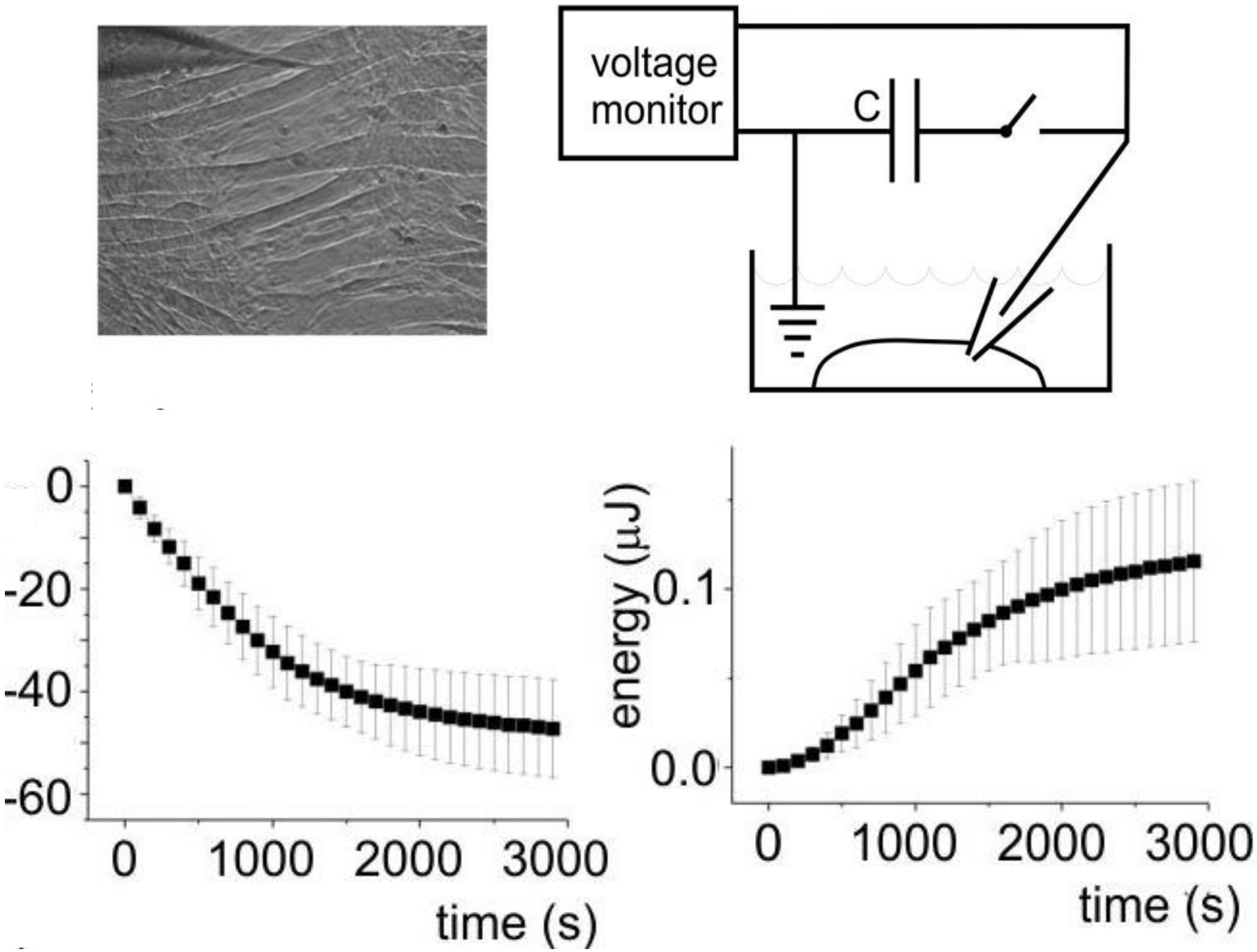




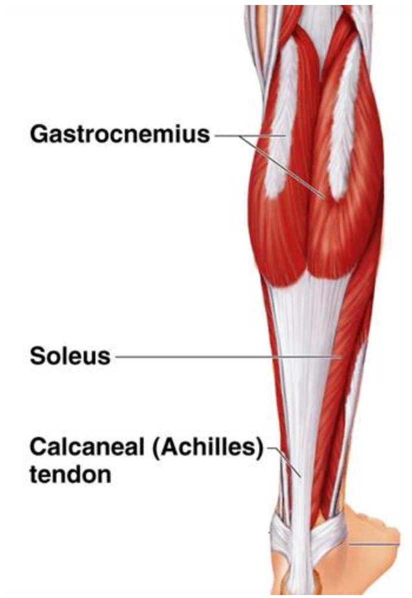
Experimental proof-of-concept on myotubes

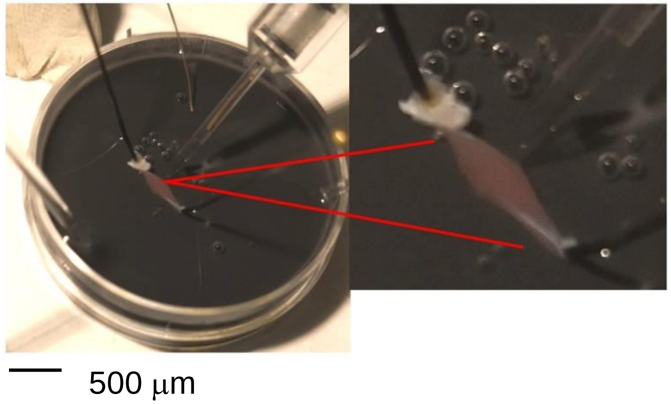


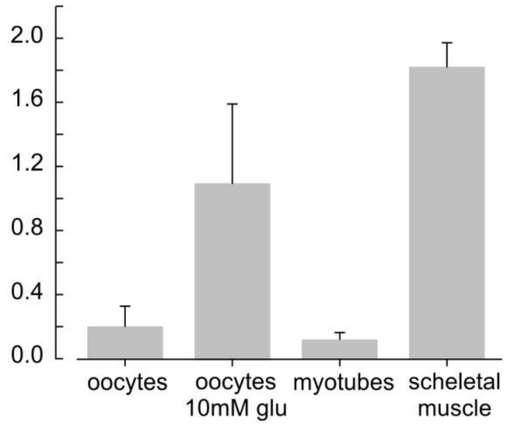
Energy may be harvested from a single myotube and stored in a capacitor

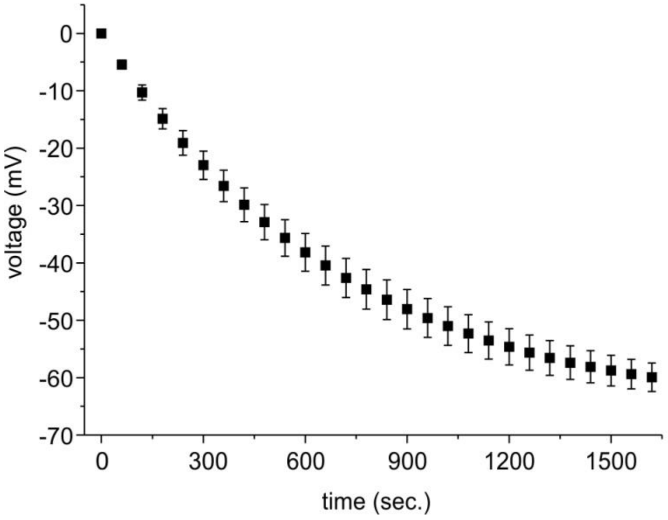


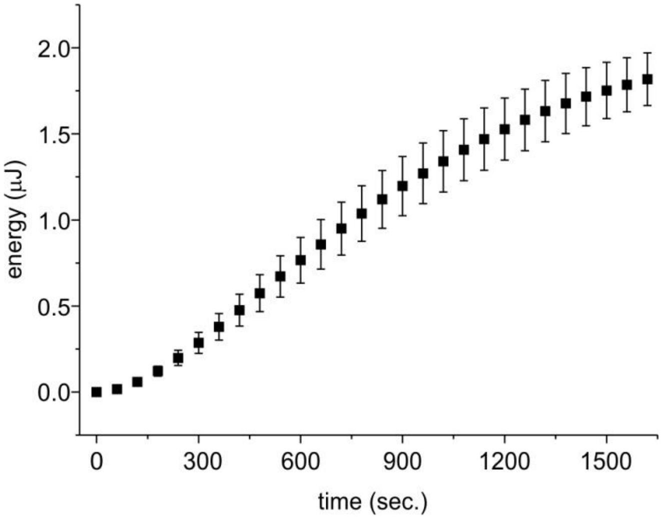
Skeletal muscle fibers recorded from mice provide a relatively high energy











Conclusions

- Biological cells have an electrical potential difference across their plasmamembrane
- Electrodes inserted inside cells may be used to harvest energy from the plasmamembrane potential difference
- Single high-dimension biological cells are able to provide powers small but likely sufficient to let next generation biosensors
- The harvested energy can be stored over time to reach values sufficiently high to operate a wireless system for a limited time

Perspectives