# *Biothermal physics*

***tenth lecture***

# ***Bioelectricity***

## ***Part III***

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***Third Stage***

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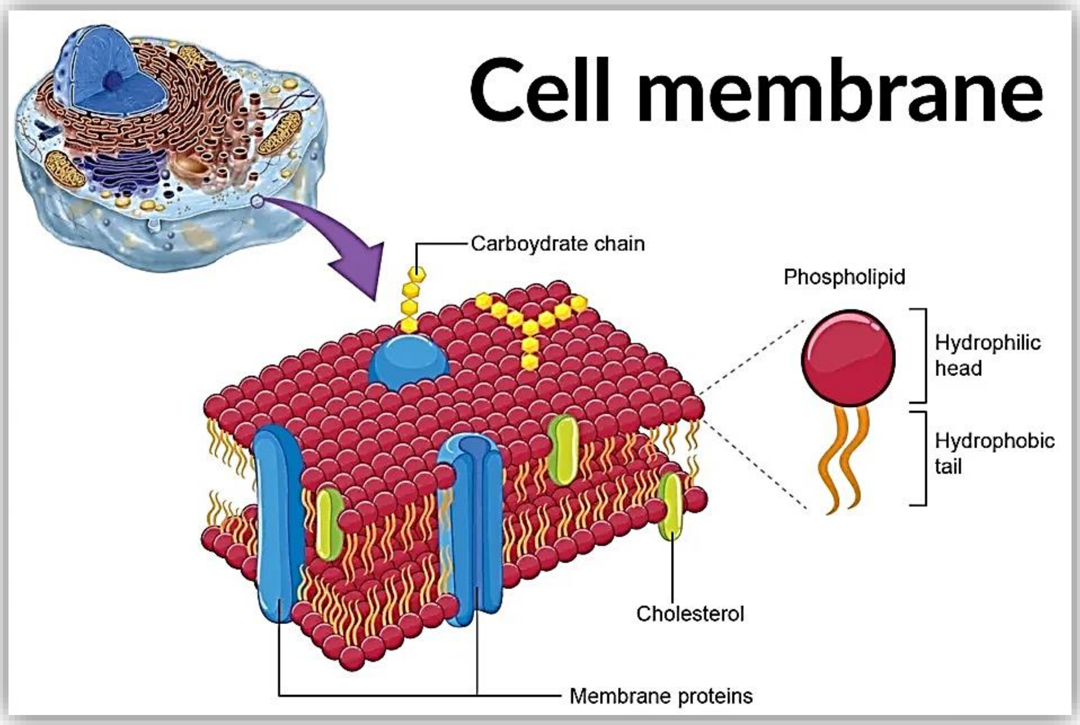
## Introduction

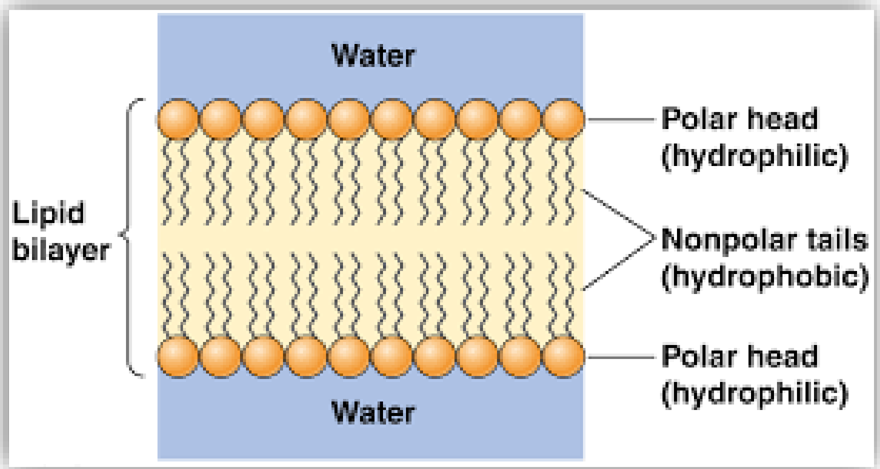
- The fundamental unit of all biological life is the **cell**, ***a mass of biomolecules in watery solution surrounded by a cell membrane.***
- One of the characteristic features of a living cell is that it ***controls the exchange of electrically charged ions across the cell membrane and therefore the electrical potential of its interior relative to the exterior.***
- The most important cells that have this electrical property are ***neurons***.

## Cells and cell membranes

- All cells are surrounded by a ***cell membrane.***
- We will neglect all the complexities of the metabolic and structural apparatus found in the interior of the cell and simply consider it as a little bag, formed by the cell membrane, and filled with saline (i.e., water with ions dissolved in it).
- We will assume that the exterior of the cell is a bath of saline.
- ***The cell membrane*** is a ***phospholipid bilayer***, ***i.e. a layer which is only two phospholipid molecules thick***. Each of these molecules has ***two ends*** (one is ***a phosphate group***, the other a ***hydrocarbon chain***, i.e. a lipid) and these two ends have very different properties.
- ***The phosphate end is hydrophilic*** (it likes to be in a watery environment and to be surrounded by water molecules)
- In contrast, ***the lipid end is hydrophobic*** (it hates to be close to water).
- Love and hate for molecules means that they will achieve a lower energy if they attain the loved state and are able to avoid the hated states.
- Each molecule attempts to get into the lowest-energy state possible.
- ***How can a phospholipid molecule be immersed in water at one of its ends and, at the same time, avoid to be in water at its other end?***




- If enough phospholipid molecules get together, they can bundle up their oily (hydrocarbon) ends together, forming a double-layered sheet with the hydrocarbon ends in the center, and, at the same time, bath their phosphate ends in water on the outside of the sheet.
- The result is a certain volume of water (or saline) enclosed by a double layer of phospholipid molecules.



## Conductance

- ***In artificial membranes the pure phospholipid bilayers are quite good insulators*** (there are no free ions in the membrane so there are no carriers to transport charges).
- Their specific conductance per unit area is only about $g_{pure}=10^{-13}\Omega^{-1}m^{-2}$.
- The conductance of biological membranes is much higher, typically by several orders of magnitude even at rest (i.e., without synaptic influences).
- The reason is that there are all kinds of ion channels and other pores penetrating the membrane and allowing additional currents to flow. It is these currents that make cells behave in complex and interesting ways.

## Capacitance

- The inside and the outside of the cell are both solutions of various salts in water. As opposed to the cell membrane.
- Salt water constitutes quite a good conductor because there are free ions that can transport electrical charges.
- So we have two conductors (the inside and the outside of the cell), separated by an insulator (the membrane).
- This makes it possible to have different amounts of electrical charges inside and outside the cell.
- If we can separate a charge Q by applying an electrical potential V across the membrane, the membrane has by definition as a capacitance, C=Q/V.
- In fact, because the membrane is so thin (only two molecules thick, with a total thickness of about $6\times10^{-9}$m), we don't need much voltage to separate the charges and therefore ***the membrane capacitance*** is quite high; per unit area, it is

$$c = C/S = 10^{-2}\ Fm^{-2}$$

where F is the unit of capacitance ("Farad").

- ✓ The specific capacitance of biological membranes is very close to what is obtained simply from the dielectric constant of lipids and the thickness of the bilayer.
- ✓ unlike the conductance, the capacitance is very little influenced by all the complexities of biology.

## Electrical potentials across the membrane

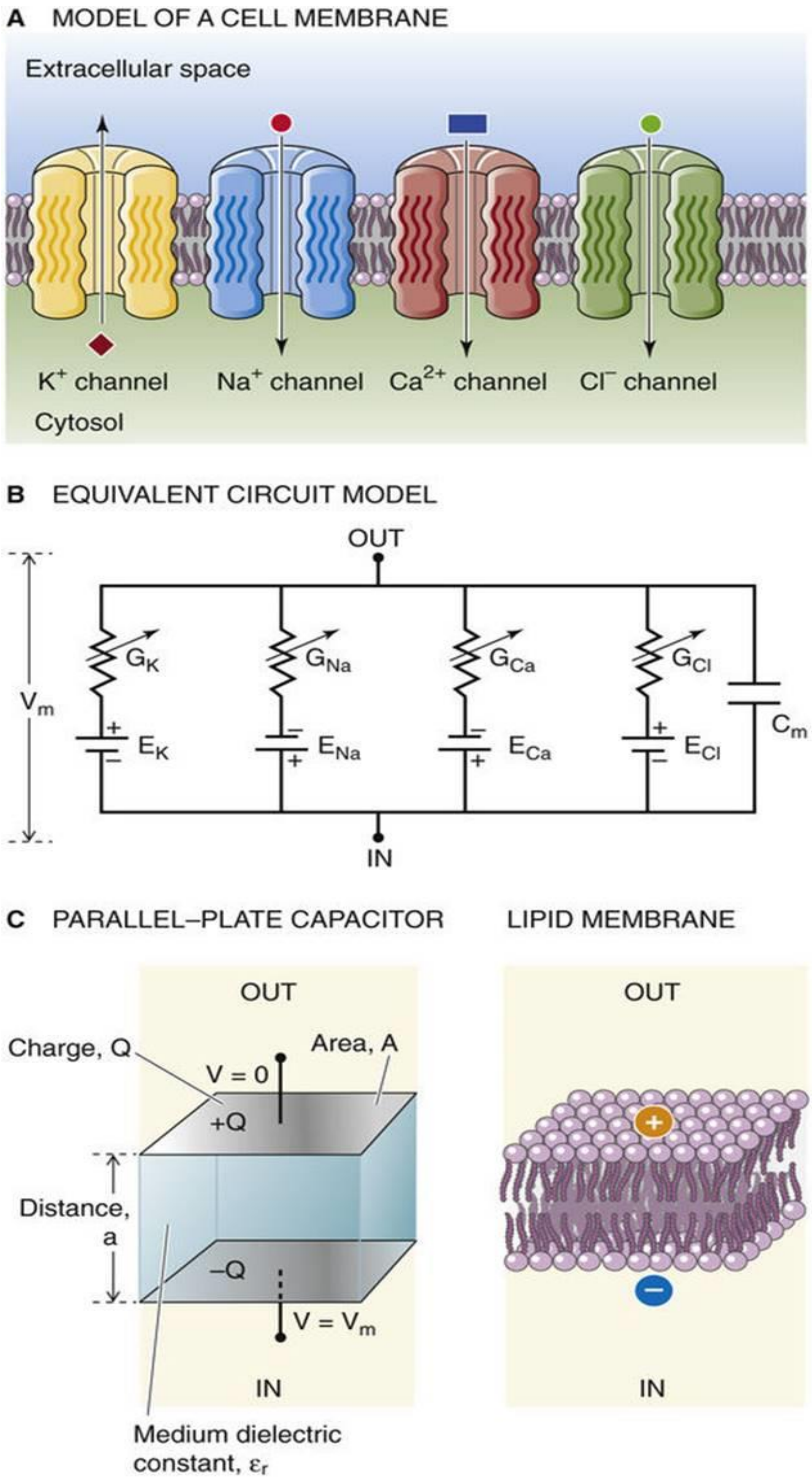
- Our interest is mainly on the ***function of neurons*** which ***is a class of cells that uses electrical signals for information processing***. How can a cell generate such signals?
- The first thing we need is some way of ***generating different voltages*** at different parts of the system, in particular, ***inside and outside of each cell***.
- Like all cells, ***neurons generate this difference by separating different ion species.***
- More specifically, in the ***cell membrane*** of each neuron are ***ion pumps***, ***which are protein molecules that span the membrane and use metabolic energy to transport some ions inside the cell and others outside.***
- A typical one is the ***$Na^+$ $K^+$ pump*** which moves ***two potassium ions*** into the cell and, at the same time, ***three sodium ions*** out of the cell.
- After this pump has been running for some time, ***the concentration of potassium inside the cell becomes larger than that outside, and the concentration of sodium becomes larger outside than inside***.
- Running the pump requires energy, which is provided to the pump in the usual energy currency of the cell, the ATP→ADP process.
- The voltage difference between the inside and the outside of the cell is obtained by the Nernst Equation

**Nernst Equation:**

$$E = \frac{RT}{zF} \ln\left(\frac{X_{out}}{X_{in}}\right)$$

- $E$ → Membrane Potential (voltage)
- $R$ → gas constant ( $8.314\ J\ mol^{-1}\ k^{-1}$ )
- $F$ → Faraday's constant ( $9.649 \times 10^{4}\ C\ .\ mol^{-1}$ )
- $X_{out}$ → concentration of ion outside the cell
- $X_{in}$ → concentration of ion inside the cell
- $z$ → number of electrons
- $T$ → temperature in Kelvin

- This voltage is commonly called the "***reversal potential***" of this ion because the current generated by these ions reverses its sign when this voltage is applied to the membrane.


A MODEL OF A CELL MEMBRANE
Extracellular space
K+ channel
Na+ channel
Ca2+ channel
Cl− channel
Cytosol
B EQUIVALENT CIRCUIT MODEL
OUT
GK
GNa
GCa
GCl
Vm
EK
ENa
ECa
ECl
Cm
IN
C PARALLEL–PLATE CAPACITOR
LIPID MEMBRANE
OUT
Charge, Q
Area, A
V = 0
+Q
Distance,
a
−Q
V = Vm
IN
Medium dielectric
constant, εr
OUT
IN