

In the segments of electrolytes, the separating membrane introduces an asymmetry, and on the two sides of the membrane, a charge layer is formed. As we derived in Eq.(5), that asymmetry produces an electric field on the surface

$$E_z(c, \Delta z) = \frac{\sigma_A(c, \Delta z)}{\epsilon_o} = 10.89 * 10^3 * c * \Delta z \left[\frac{V}{m \text{ nm} * mM} \right] \quad (1)$$

We can express the concentration with the electric field and the solution's

$$E = c * N_A * e_{el} * \Delta z$$

On the other hand, we know that in a balanced state, the Nernst-Planck equation (see Eq.(2)) describes the interdependence of the electric force field and the thermodynamic force field on each other

$$E(z) = \frac{d}{dx} V(z) = -\frac{RT}{q * F} \frac{1}{C_k(z)} \frac{d}{dz} C_k(z) \quad (2)$$

$$\sigma_V(c) = c * 6.023 * 10^{20} * 1.602 * 10^{-19} = 96.4 * c \left[\frac{C}{mM * m^3} \right] \quad (3)$$

By assuming an arbitrary 'physical layers thickness' Δz we can calculate the *surface charge density* $\sigma_A(\Delta z)$ we need for our calculations below as

$$\sigma_A(c, \Delta z) = 96.4 * c * \Delta z \left[\frac{C}{mM * m^2} \right] \quad (4)$$

$$E_z(c, \Delta z) = \frac{\sigma_A(c, \Delta z)}{\epsilon_o} = 10.89 * 10^3 * c * \Delta z \left[\frac{V}{m \text{ nm} * mM} \right] \quad (5)$$

0.0.1 Dielectric segments

0.1 XXX****

As we know from theory of electricity, outside the two charged sheets, there is no electric field due to the charged sheets. However, the charged sheet itself means simultaneously a 'concentration sheet', i.e., a steep concentration gradient, that according to Eq.(??) generates an electric field outside that elemental condenser. The Nernst-Planck force compensates for the difference between the electric field between the two neighboring condensers. The contribution of the dipoles, according to the Nernst-Planck equation is

$$E_{dipoles}(z) = \frac{d}{dx} V_m(z) = -\frac{RT}{q * F} \frac{1}{C_k(z)} \frac{d}{dz} C_k(z) \quad (6)$$

We consider the electrolyte consisting of parallel plate condensers of thickness dz where the electric field between the plates is reduced due to the change of concentration gradient, that is

$$E_{electrolyte}(z) = \frac{C_k(z) * dz}{2 * \epsilon_o} - \frac{RT}{q * F} \frac{1}{C_k(z)} \frac{d}{dz} C_k(z) \quad (7)$$

The electri showing that for freely moving ions in steady state the electric force must be counterbalanced by the corresponding thermodynamic force.

$$E_{condenser} = \frac{\sigma_A}{2 * \epsilon_o} = F * C_k(z) * dz \quad (8)$$

We can imagine the electrolyte comprising parallel plate condensers with electrode distance dz

In electrolytes, molecules with balanced electrically charged ions are present, that ions dynamically change their relations to each other, depending on their local macroscopic or microscopic conditions. Electrolytes, as a solution are neutral.

When thermodynamic or electrical invasion happens, the ion's distribution changes. (Above we assumed an infinitely large volume. Limiting the volume's size means an asymmetry for the ions in the volume and brings to light unexpected phenomena.) We must also discuss another fallacy that the structured biological objects behave as the metals do under the effect of electrical forces. To derive an abstraction similar to the ones as sciences derive their laws, we assumed that the ions are tiny charged heavy balls, and they attempt to have a uniformly distributed concentration and potential in the considered space segment. We discuss the cases when an external electrical or chemical invasion happens in one segment, the case when a physical surface (with different thickness) mechanically separates the ions in two neighboring segments, when the solutions on the two sides have different features, when the two separated segments are not symmetrical due to 'Maxwell-demon'-like transmit gates (semipermeable membrane); and when a physical effect concerts the operation of the demons.

The cellular electrodiffusion phenomena are very complex, and it is not a simple task to choose which physical/chemical effects can be omitted so that their omission does not prevent us from explaining physiological phenomena. We discuss mainly the commonly used fundamental omission that the speed of ionic movement cannot play a role in describing neuronal operation.

0.2 XXX****

The contribution of the dipoles, according to the Nernst-Planck equation is

$$E_{dipoles}(z) = \frac{d}{dx} V_m(z) = -\frac{RT}{q * F} \frac{1}{C_k(z)} \frac{d}{dz} C_k(z) \quad (9)$$

We consider the electrolyte consisting of parallel plate condensers of thickness dz where the electric field between the plates is reduced due to the change of concentration gradient, that is

$$E_{electrolyte}(z) = \frac{C_k(z) * dz}{2 * \epsilon_o} - \frac{RT}{q * F} \frac{1}{C_k(z)} \frac{d}{dz} C_k(z) \quad (10)$$

$$E_{condenser} = \frac{\sigma A}{2 * \epsilon_o} = F * C_k(z) * dz \quad (11)$$

Electrolytes, as a solution are neutral.

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The cellular electrodiffusion phenomena are very complex, and it is not a simple task to choose which physical/chemical effects can be omitted so that their omission does not prevent us from explaining physiological phenomena. We discuss mainly the commonly used fundamental omission that the speed of ionic movement cannot play a role in describing neuronal operation.

0.3 One segment

We prepare a tiny electrolyte volume filled with a solution containing ions (such as Na^+ , K^+ and Ca^+ ; furthermore, of course Cl^- or similar). The overwhelming majority of those ions is chemically bound, but a minority might exist separately from each other; especially under external macroscopic changes applied to the volume. Electrodiffusion experience shows that, when applying such changes, reaching a steady state is a temporal *process*, and even the spatial and temporal development of the concentration gradients can be measured as individual processes (the voltage gradient is too fast to measure it). It is also evident from experiments that diffusion is a fast *process* and that the propagation of the electrostatic field is unimaginably fast ; see our discussion around Eq. (??), but it must be process, too. In other words, we have two enormously different interaction speeds. Eq. (??) provides only position derivatives. However, Eq.(??) and Eq.(??) provide the time derivatives for describing the time course of the processes.

In the calculations below, we use the notion of 'surface charge density' (given in $C * m^{-2}$). We know the permittivity of free space, $\epsilon_o = 8.854 * 10^{-12} C *$

$V^{-1} * m^{-1}$, furthermore, 1 mM concentration means that $6 * 10^{20}$ atoms are present in 1 m^3 . This way, if the concentration c is given in mM , we can derive that the *volume charge density* from the concentration

$$\sigma_V = c * 6.023 * 10^{20} * 1.602 * 10^{-19} = 96.4 * c \left[\frac{C}{m^3 * mM} \right] \quad (12)$$

and, for a layer with thickness dx the *surface charge density* $\sigma_A(dx)$ is

$$\sigma_A(dx) = \sigma_V * dx \quad (13)$$

We presume that the charges are confined into a physically well-defined layer.

In a segmented electrolyte we experience electric fields that have different sources. For the closed system, the electric charges are balanced, but locally they may be unbalanced due to physical reasons. In steady state, the some other force must counterbalance the electric force. That force may be a mechanical one: the ions sitting on the surface of the membrane press the surface due to the attractive force on ions on the and the membrane mechanically provides the needed counterforce. We discuss the case when the electrolyte is separated by an isolator membrane

0.4 Two segments

The membrane is a perfect isolator, i.e., no charge carriers exist between its two surfaces. (There may be ion channels built into the membrane that deliver ions, as we discuss in section ??, but it is a different mechanism.) For the discussion below, we assume that a two-dimensional surface separates the volume and we discuss the gradient along a line, perpendicular to that plane surface. Having the membrane's shape in mind, we introduce the idea of 'thin physical layer', that is parallel with the membrane. We compose the segments from such layers (sheets) having different potentials. We consider the immediate environment of the neuron's membrane as parallel (x, y) plates and find the electric field's z component of those plates in the points as shown in Fig. ??.

Inside the cell, the charge distribution is homogeneous, so the electric field contributions cancel each other, even if an infinitely thin isolating (bilayer of lipid molecules) membrane separates the volume in two segments. In the segments, (a tiny fraction of) the components decompose into ionized state (dissociate), and the created ions interact with the membrane using a not entirely understood mechanism [?]. The ionic basis of a membrane potential shows and explains the cases introduced by the finite-width membrane. On the left side (the case of infinitely thin membrane), at an exact balance of charges on each side, the membrane potential is zero. We assume the membrane is transparent for the electrical interaction (the electrical field affects the ions in the other segment on the other side of the membrane) but not for their masses (mechanically separates the segments). We actually do not affect the electrical and thermal distributions in the now separated segments.

Separating a volume into two segments has no initial effects: the *bulk* concentration and potential remain the same on the two sides of the membrane. However, the finite thickness will result in a lack of balance (create a voltage and concentration gradient) near the surfaces of the membrane, even if the concentration on the two sides are the same. Changing the bulk concentration or potential in one of the segments creates a corresponding gradient across the separating membrane (and also evokes new bulk parameters in the resting state). In the layers proximal to the membrane, the ions will experience an extra force. The *concentration and potential, inseparably and having the same time course*, will change across the two sides of the membrane just because of the gap in physical features the membrane represents, as we discussed above. (Notice, however, that while increasing the concentration in one segment means having an unlimited possibility of increasing bulk potential, decreasing it may be limited by the reduced number of charge carriers.)

The electrical repulsion/attraction across the membrane will form two layers on the two surfaces: a positive ion-rich layer on the high-concentration side and a negative ion-rich layer on the low-concentration side. Here, refer to Fig.(??). We do not clone the figure, although the bulk parameters differ. The ions in the other segment do not counterbalance the repulsion force at the membrane, so the values of the local potential in the proximal layer near the membrane in the segment with the higher concentration will be above the one in the bulk of the segment and of course, the potential will also be higher. The opposite charges distribute in the two bulk layers and do not cause a significant concentration or potential change. However, the values of the local concentration and potential remain the same in the bulk of the respective layer.

The result is a condenser-plate effect: two layers are formed on the isolator's two sides where the charges' repulsion does not counterbalance the repulsion in the bulk of the corresponding segment. Fig. ?? displays how the function shapes of the potential and its gradient change in the function of the distance from the membrane. Here, we assume that no ion channels are in the excellently isolating wall (ion channels would mean a current drain and, therefore, a voltage drop). The attraction between the ions in the two skin layers prevents the ions in the layers on the two sides from diffusing into/from the bulk without a current drain in the layer for an extended period. This steady state results from the interplay of the concentration and the potential described by Eq. (??). The gradients change gradually within the segWe can calculate the amount of chargeswe need for our calculation, see Eq. (13). ments and drop linearly across the membrane. Recall our remark above on the limitations of the thickness of the layers in proximity to the membrane, which also enforces limitations on the potential in the layer. No current can flow through the membrane; there is no leaking current.

We also need to notice the difference in the local gradients in the function of distance from the membrane's surface. If something changes, a dV_{assist} gradient appears between the layers and will rearrange concentration and voltage in the segment. Notice that this gradient is by orders of magnitudes smaller than the gradient $dV_{accelerate}$ which accelerates the ions in the proximity of the channel

entrance (see the red ball in front of the entrance of the ion channel). According to the Stokes formula (see Eq. (??)), the corresponding speeds also differ by orders of magnitudes, enabling us to distinguish *potential-assisted* and *potential-accelerated* speeds, and correspondingly, speak about '*slow*' and '*fast*' *currents* that the ions represent at a macroscopic level. For this study, we assume the diffusion, potential-assisted and potential-accelerated speeds, in m/s to be 10^{-4} , 10^{-1} (also inside neurons [?]), 10^{+3} , respectively (used only to estimate the order of magnitude of some respective operating times). When staging, we assume the greater of the mixing speeds as 'infinitely large' and omit the time that the process needs, while discussing how the slower process proceeds.