

Neural Interfaces

NX-422

Neural electrodes

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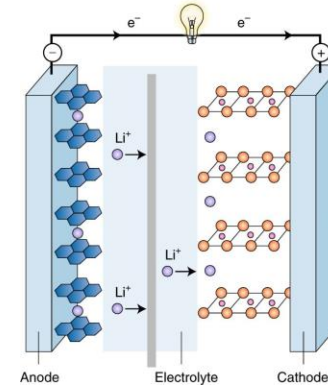
Outline for the next 2 classes

- The nervous system
- Neural signals
- **Neural electrodes**
- Electrochemistry of bioelectrodes

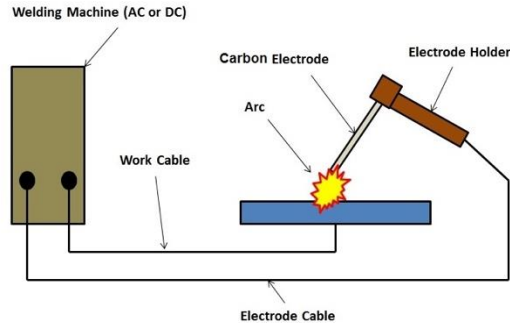
What is an electrode?

An **electrode** is a solid electric conductor that carries electric current into non-metallic solids, or liquids, or gases, or plasmas, or vacuums

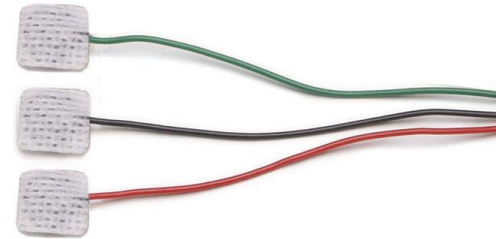
<https://www.chemicool.com/definition/electrodes.html>



John B. Goodenough Nature Electronics volume 1, page204(2018)



<https://www.theweldingmaster.com/carbon-arc-welding/>

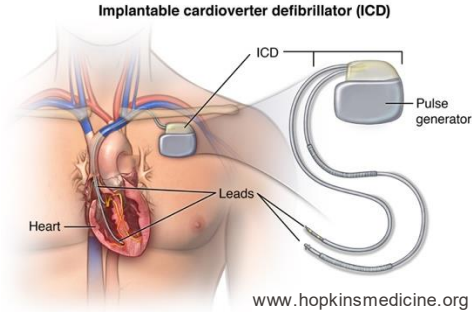


<https://electrodestore.com/products/1023-disposable-surface>

Defibrillation paddles



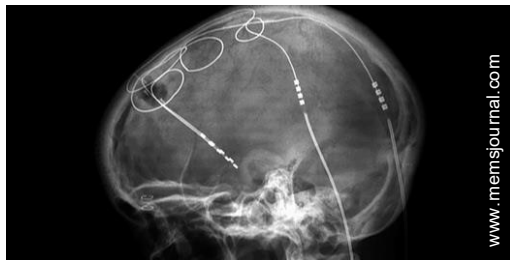
Pacemaker



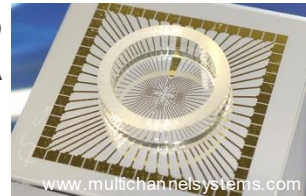
EEG electrodes



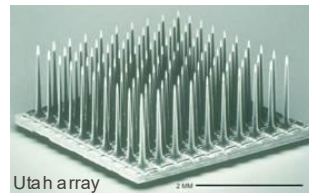
Deep brain stimulation



In vitro MEA



Cortical electrodes




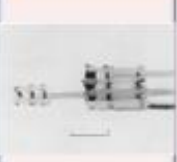
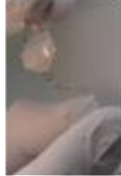


Vagal nerve cuff



Neural electrodes

Superficial and distal CNS electrodes

<p>EEG</p>  <p>J. Milan - EPFL</p>	<p>ECoG</p>  <p>Am. Museum of Nat. History Science Bulletin</p>	<p>Epidural (SC)</p>  <p>Medtronic, RestoreULTRA</p>	<p>Sacral root</p>  <p>Brindley - Finetech</p>	<p>Subdural (SC)</p>  <p>EPFL e-dura</p>
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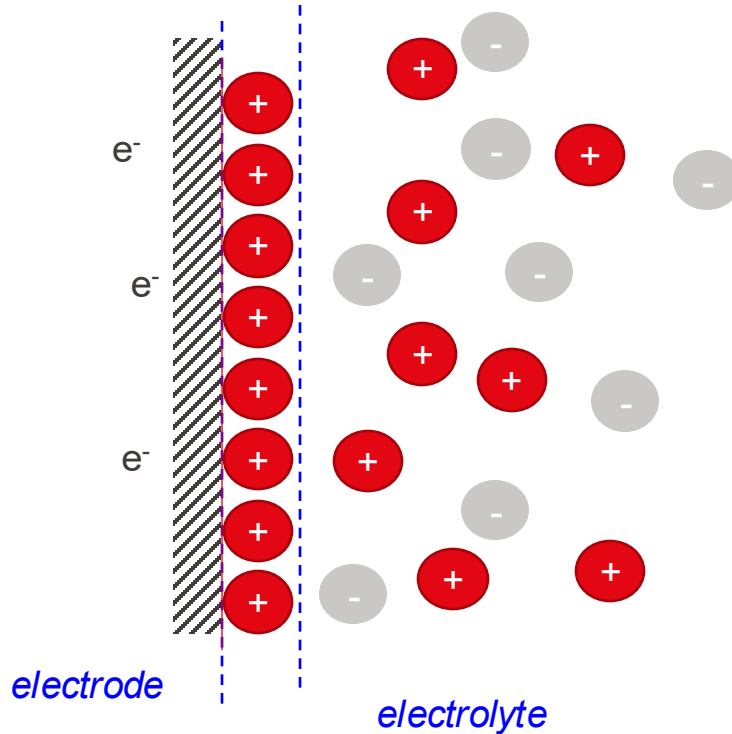
Invasive CNS electrodes

<p>Deep brain</p>  <p>Cleveland Clinic</p>	<p>Shallow brain</p>		<p>@ the clinic</p>
 <p>Utah MEA</p>	 <p>M. Nicolelis - Duke</p>	 <p>NeuroNexus</p>	

Organ / Peripheral nerve electrodes

<p>Cochlear</p>  <p>Cochlear™</p>	<p>Retina</p>  <p>Second Sight</p>	<p>Whole peripheral nerve</p>  <p>neurocuff™ NEUROSTREAM</p>	<p>Invasive peripheral nerve</p>  <p>K. Hofmann - IBMT</p>	 <p>EPFL CNP</p>
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- Support electric exchanges between the body and the electronic hardware
 - The current in the body is carried by **ions**,
 - whereas the current in wires is carried by **electrons**.
- **Charge transfer/transduction** at the electrode-electrolyte interface
 - Electrode: metal, metal oxide
 - Electrolyte: conducting medium



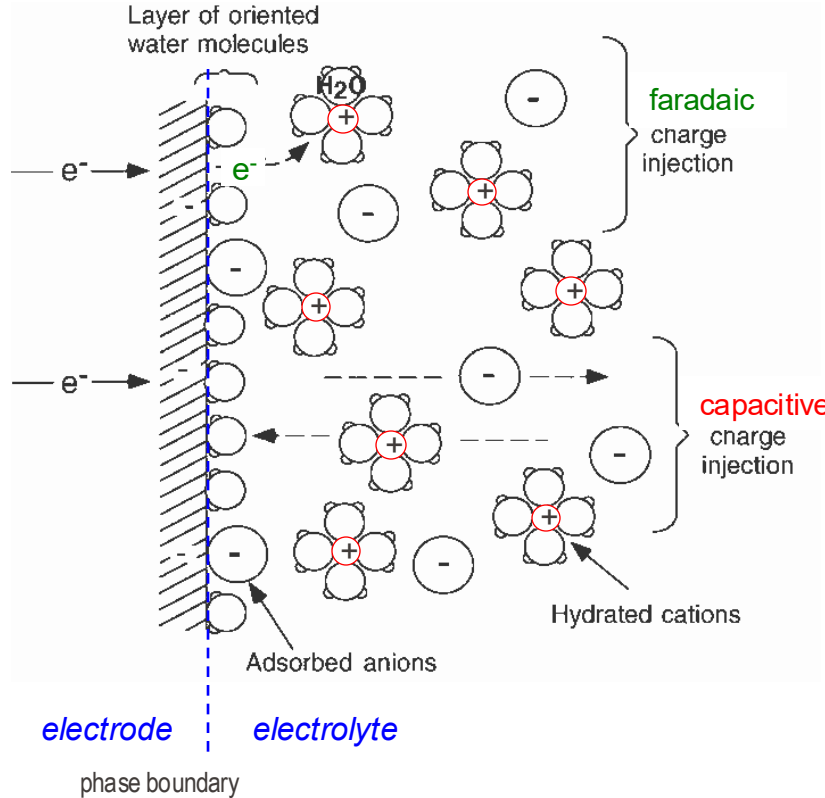
1. Electrostatic interactions at the interface

- Hydrated ions are attracted to the interface (charge balance)
- “double layer of charges”
- equivalent capacitor

Extracellular fluid (ECF):

Main cations: Na^+ , Ca^{2+} , K^+

Main anions: Cl^- , HCO_3^-



Possible mechanisms at the interface:

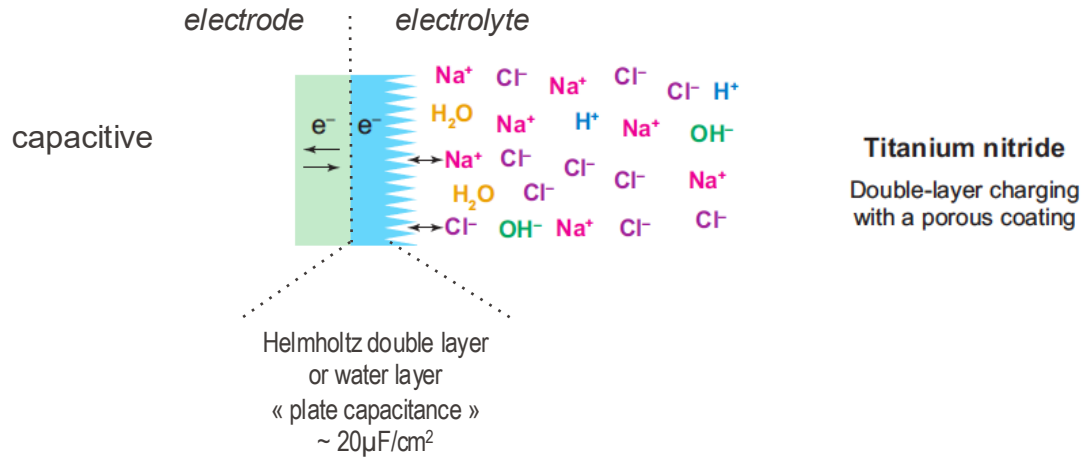
- Capacitive
- Faradaic (redox)
- Pseudocapacitive

Extracellular fluid (ECF):

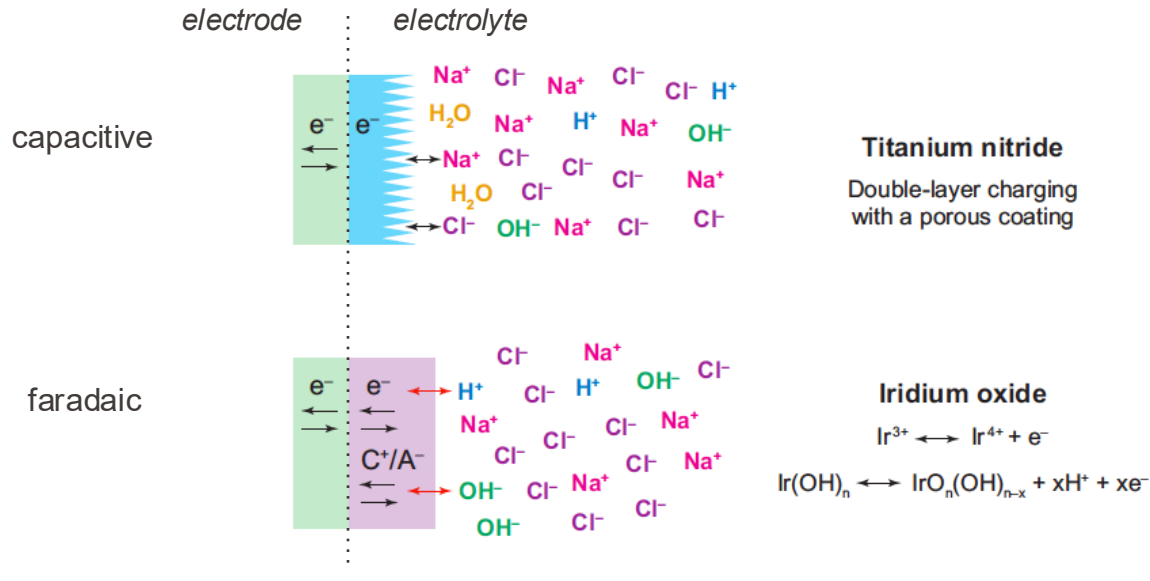
Main cations: Na^+ , Ca^{2+} , K^+

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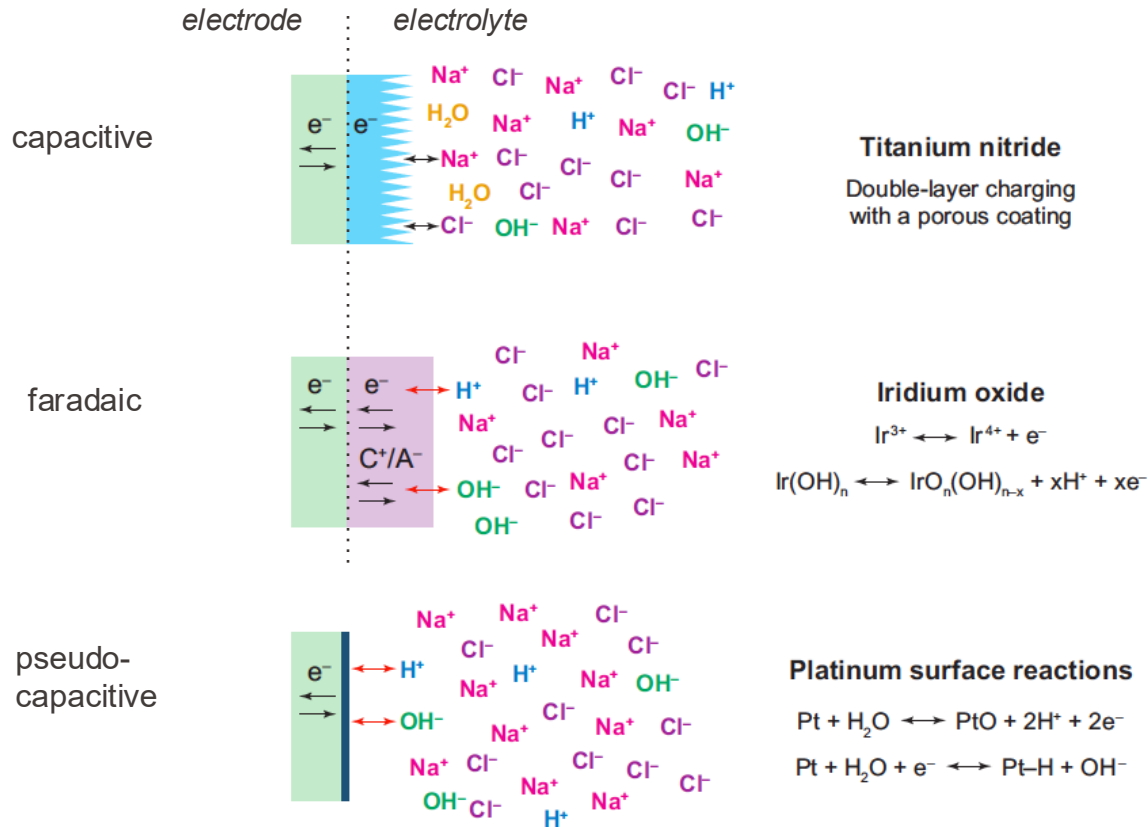
Electrode-electrolyte interface



Electrode-electrolyte interface



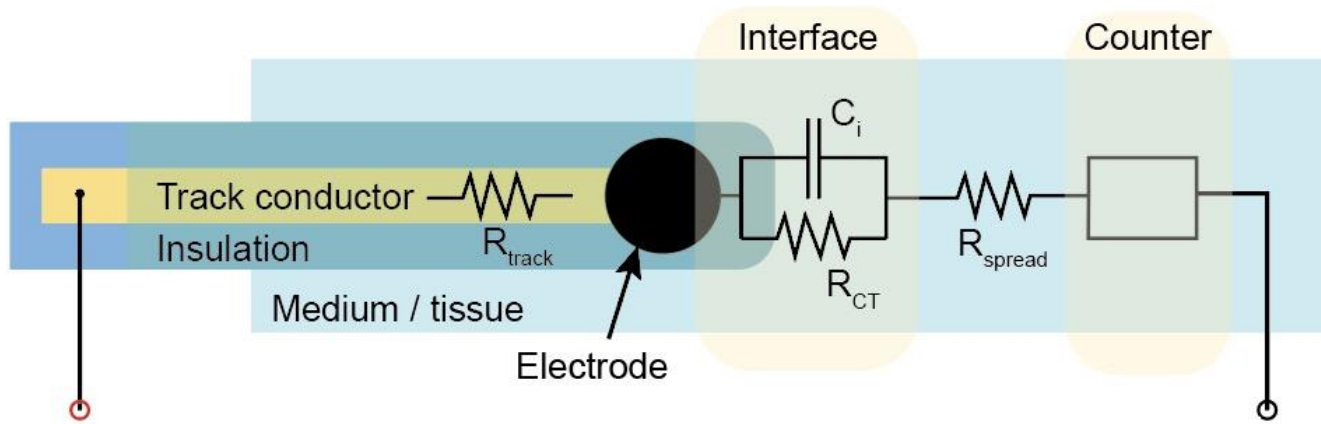
Electrode-electrolyte interface



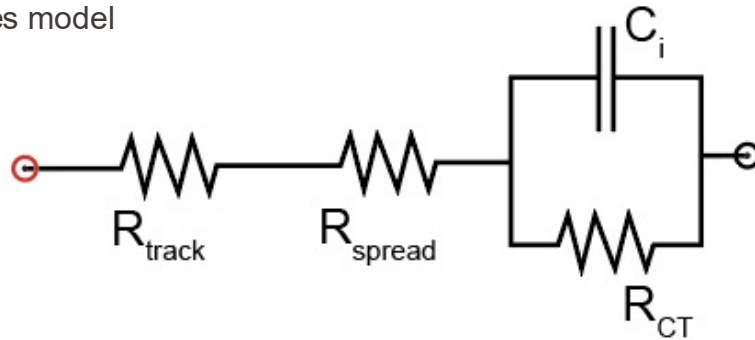
reversible reactions
oxide formation; H-atom plating

irreversible reactions
electrolysis of water, pH shift,
production of H_2 , O_2

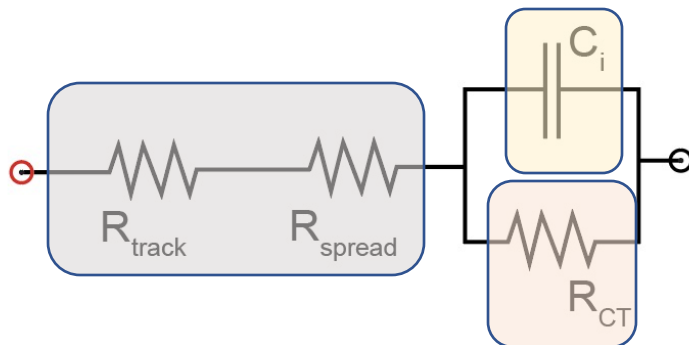
Equivalent electrical model of an electrode



Randles model



Equivalent electrical model of an electrode



R_s : sheet resistance

L, W : track length, width

ρ : medium resistivity (0.6 – 3 Ohm m)

r : electrode radius (10 μm – 1 cm)

t_{dl} : double layer thickness (\sim nm)

Series resistance

- $R_{\text{track}} = R_s L / W$
- $R_{\text{spread}} = \frac{\rho_{\text{medium}}}{4r} \rightarrow$ depends on medium and electrode size

Capacitive charge injection

$$|Z_i| \propto \frac{1}{2\pi f \cdot ESA}$$

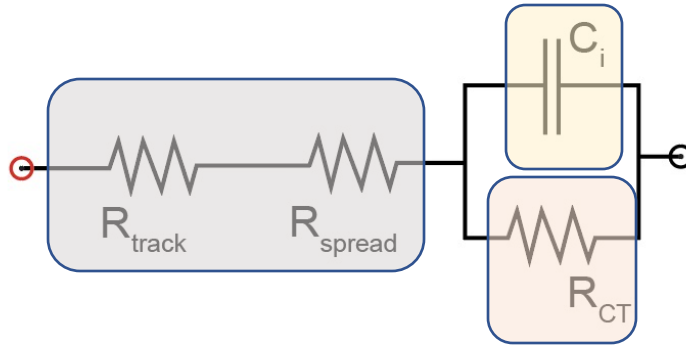
ESA: electrochemical surface area
 \rightarrow depends on process, coating roughness, electrode size

Faradaic charge injection

$$R_{CT}$$

\rightarrow depends on coating materials and electrode size
 \rightarrow the material affects the voltage onset of electrochemical reactions

Equivalent electrical model of an electrode



R_s : sheet resistance

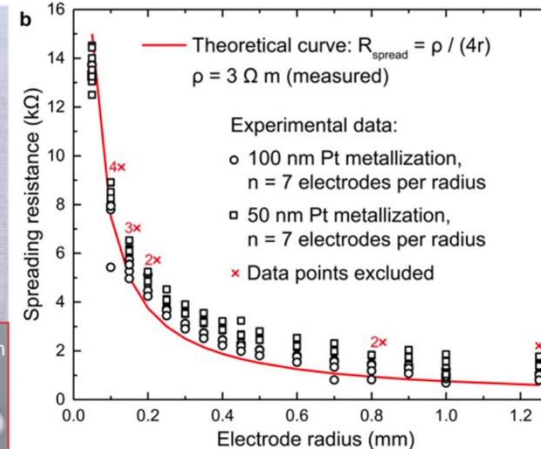
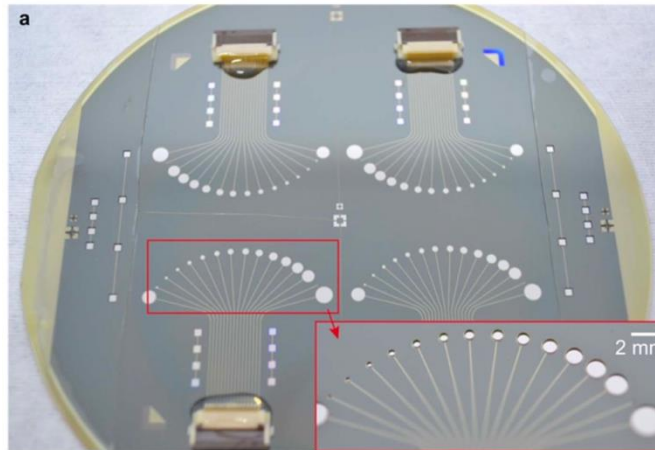
L, W : track length, width

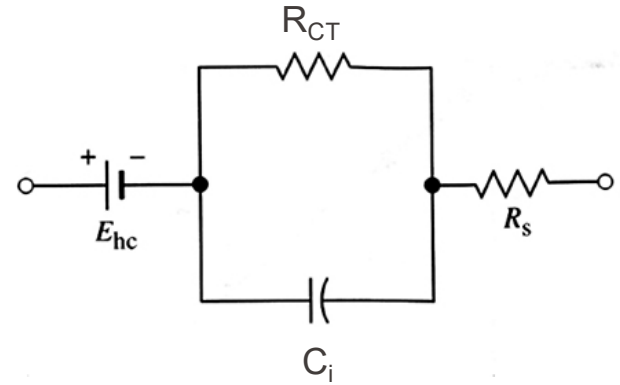
ρ : medium resistivity (0.6 – 3 Ohm m)

r : electrode radius (10 μm – 1 cm)

t_{dl} : double layer thickness (\sim nm)

Spreading resistance measurements: $R_{spread} = \frac{\rho_{medium}}{4r}$





- No perfect / ideal electrode exists
 - **Non linear** (potential-dependent mechanisms)
 - Frequency-dependent charge inj. mechanisms
 - **Reactive behavior** → capacitance at the electrode/electrolyte interface, distributed capacitances along the circuit
 - **Metal electrode** → resistive losses, corrosion, irreversible reactions

- **Electrode as a transducer between electronic and ionic media**
- **Mechanisms of charge transduction (for both sensing and actuating)**
- **Equivalent electrical circuit model of the electrode system**