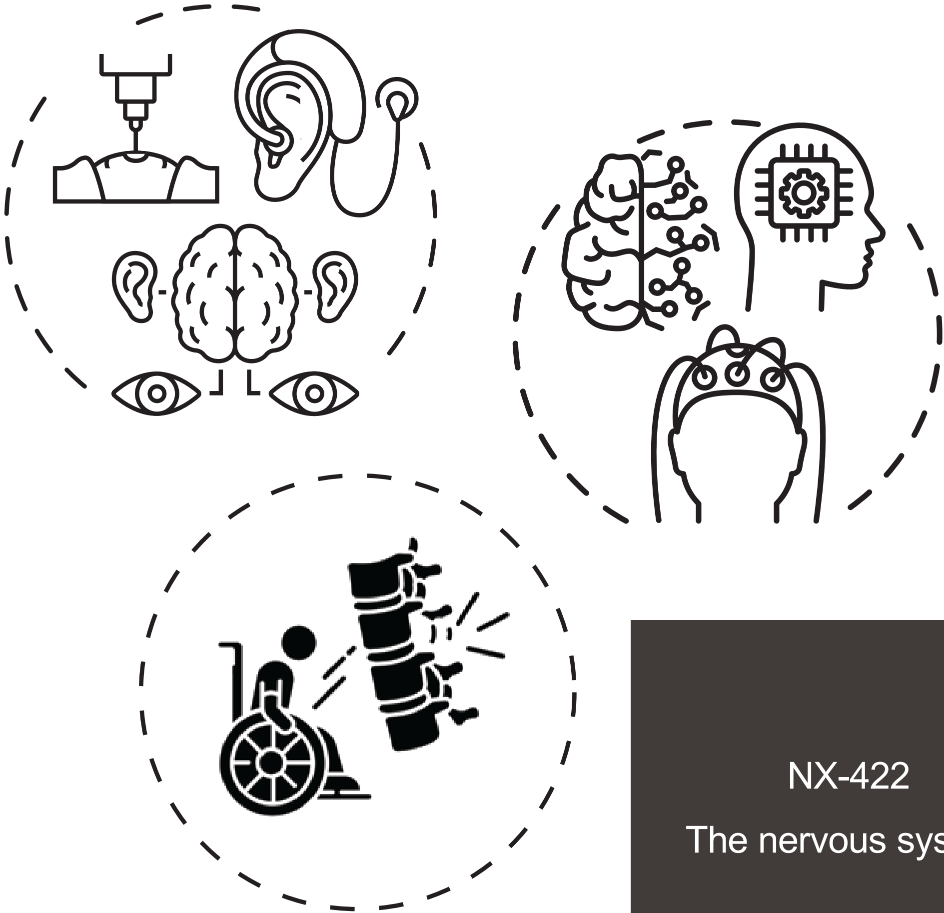


Neural Interfaces

NX-422

The nervous system

Stéphanie P. Lacour

Neuro-X Institute

Outline

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

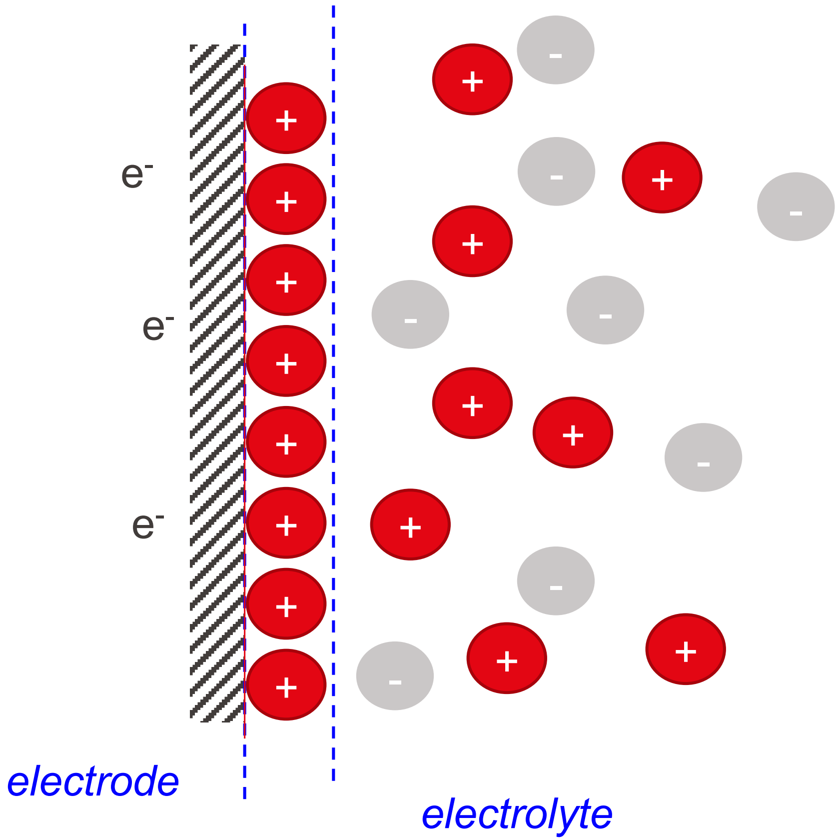
The interface

- 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** at the electrode-electrolyte interface

  - Electrode: metal, metal oxide
  - Electrolyte: conducting medium

The interface



1. **Electrostatic interactions at the interface**

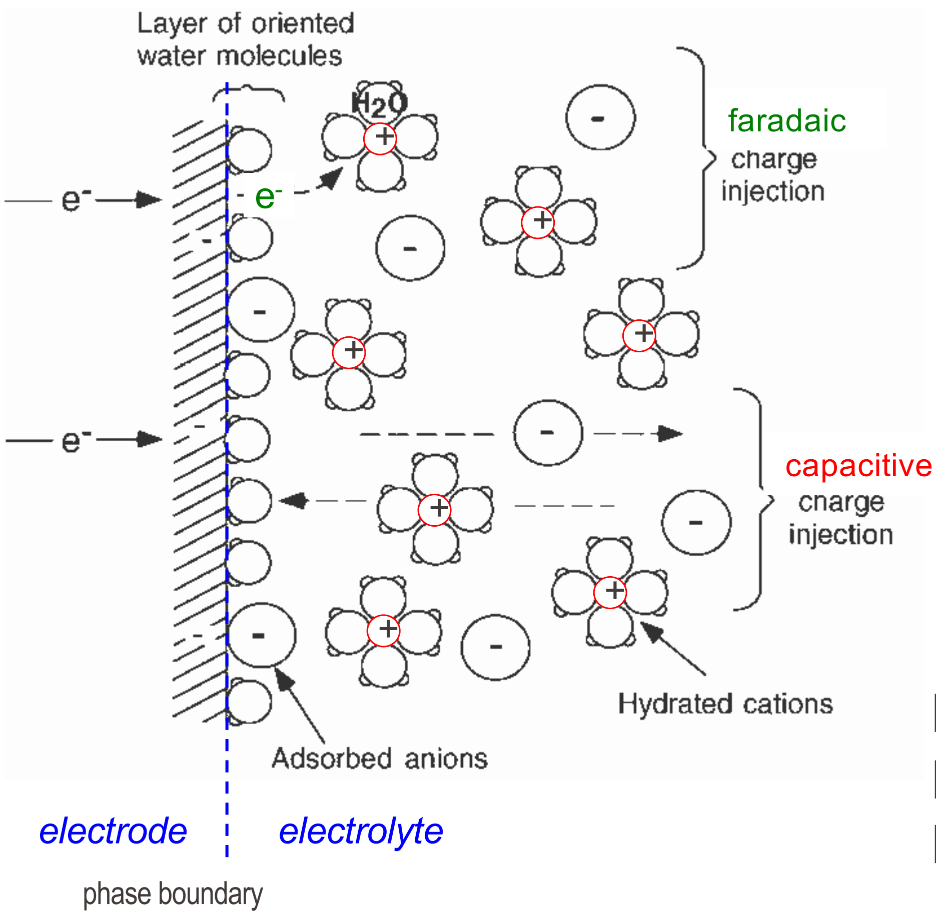
- Hydrated ions are attracted to the interface (charge balance)
- "double layer of charges"

➢ equivalent capacitor

Extracellular fluid (ECF):
Main cations: Na^+, Ca^{2+}, K^+
Main anions: Cl^-, HCO_3^-

Journal of Neuroscience Methods 141 (2005) 171–198

The interface



Possible mechanisms at the interface:
- Capacitive
- Faradaic (redox)
- Pseudocapacitive

Extracellular fluid (ECF):
Main cations: Na^+, Ca^{2+}, K^+
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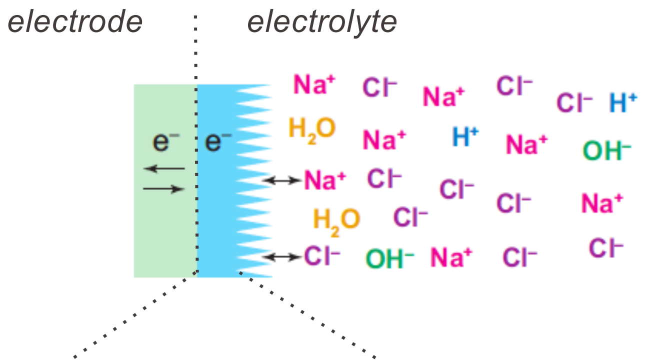
Journal of Neuroscience Methods 141 (2005) 171–198

Electrode-electrolyte interface

capacitive



Helmholtz double layer
or water layer
« plate capacitance »
~ 20µF/cm²

Titanium nitride

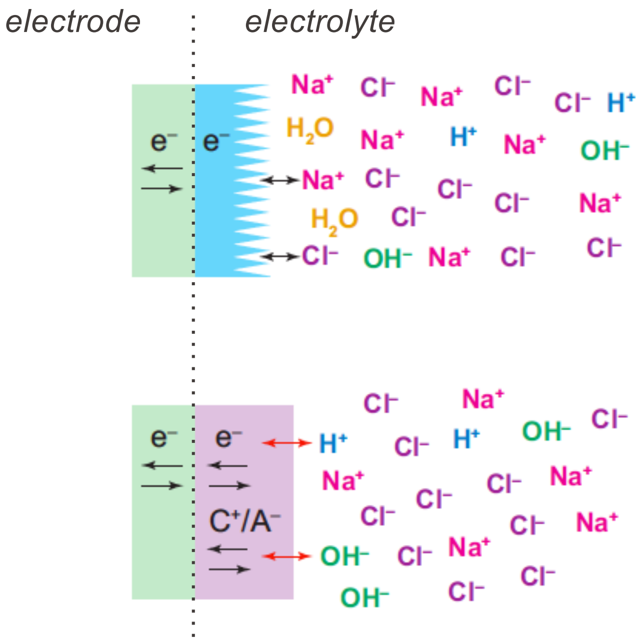
Double-layer charging
with a porous coating

SF Cogan, Annu. Rev. Biomed. 2008 10:275

Electrode-electrolyte interface

capacitive

faradaic



Titanium nitride

Double-layer charging with a porous coating

Iridium oxide

$Ir^{3+} \longleftrightarrow Ir^{4+} + e^-$

$Ir(OH)_n \longleftrightarrow IrO_n(OH)_{n-x} + xH^+ + xe^-$

reversible reactions
oxide formation; H-atom plating

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

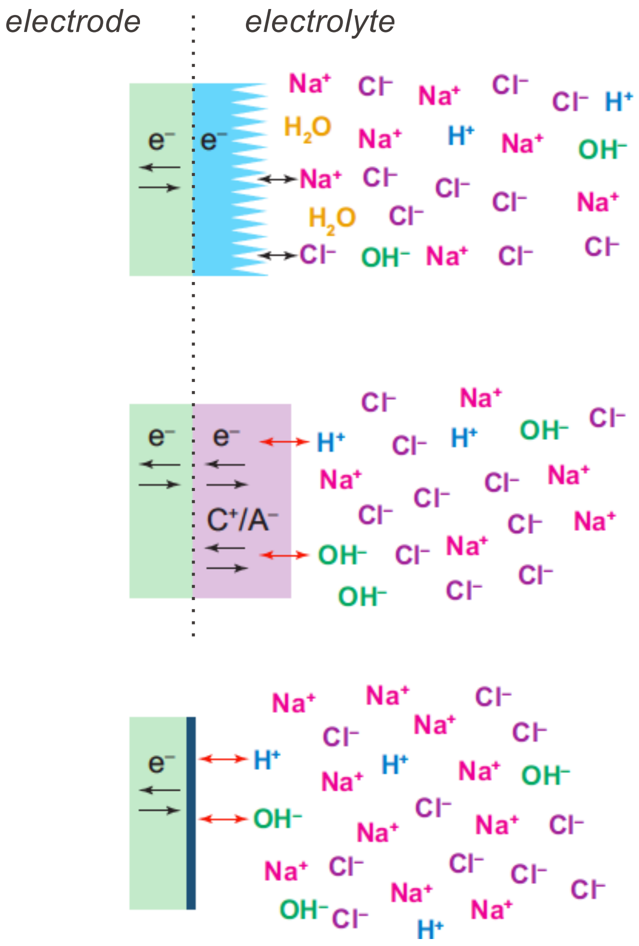
SF Cogan, Annu. Rev. Biomed. 2008 10:275

Electrode-electrolyte interface

capacitive

faradaic

pseudo-
capacitive



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

Platinum surface reactions

$Pt + H_2O \longleftrightarrow PtO + 2H^+ + 2e^-$

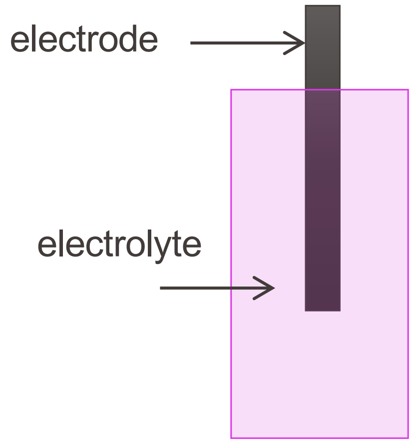
$Pt + H_2O + e^- \longleftrightarrow Pt\text{–}H + OH^-$

SF Cogan, Annu. Rev. Biomed. 2008 10:275

Half-cell potentials

Metals used in physiological systems

Metal / reaction	**Potential E_{hc} (V)**
$Al \rightarrow Al^{3+} + 3e^-$	1.67
$2H^+ + 2e^- \rightarrow H_2$	0 (reference)
$Ag \rightarrow Ag^+ + e^-$	-0.799
$Pt \rightarrow Pt^{2+} + 2e^-$	-1.2
$Au \rightarrow Au^{3+} + 3e^-$	-1.42
$Au \rightarrow Au^+ + e^-$	-1.68



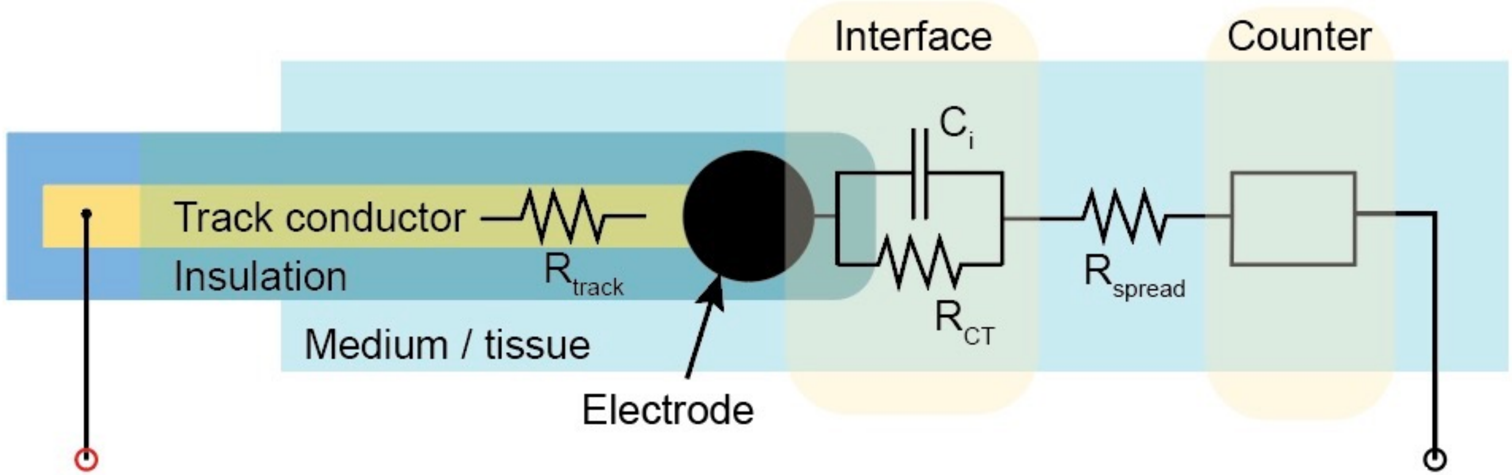
Half-cell

$Ag + Cl^- \leftrightharpoons AgCl + e^-$ 0.223V

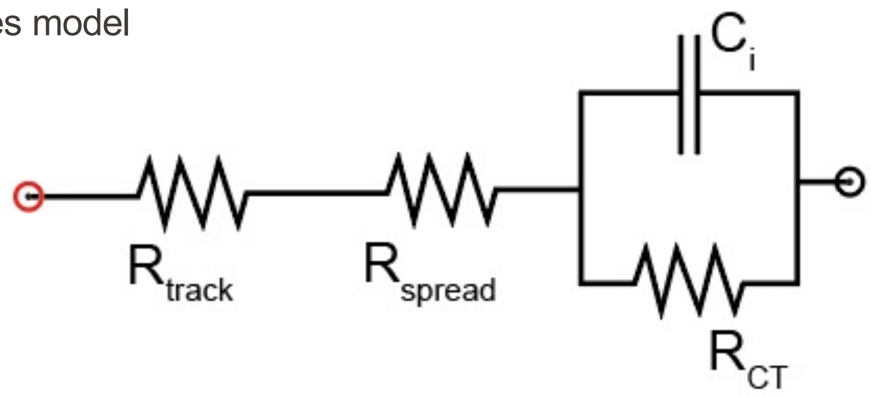
With reference to hydrogen

Equivalent electrical model of an electrode

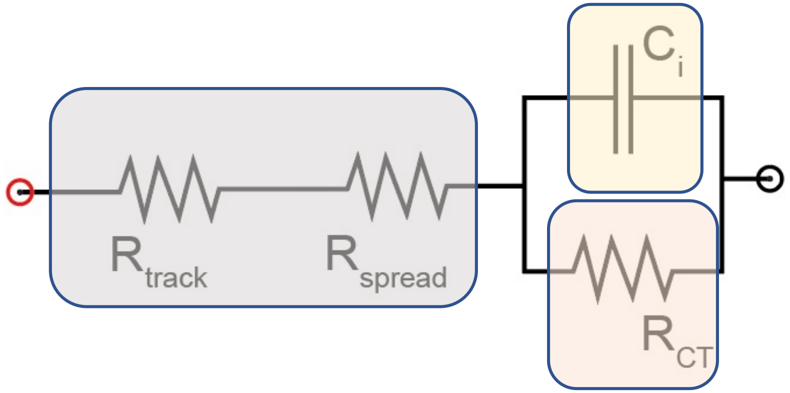
G. Schiavone et al, Neuron 2020



Randles model



Equivalent electrical model of an electrode



Series resistance

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

Capacitive charge injection

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

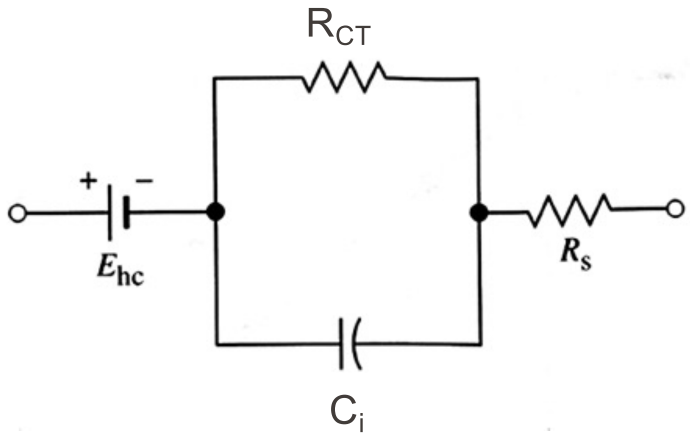
ESA: electrochemical surface area
→ depends on process, coating roughness, electrode size

Faradaic charge injection

R_{CT}

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

Electrode model

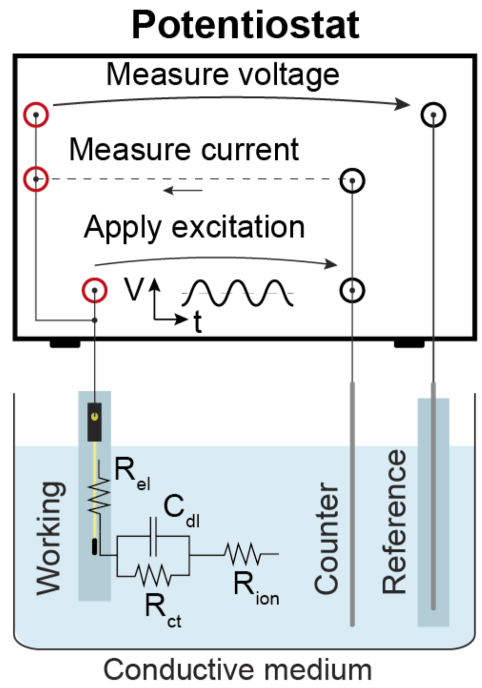


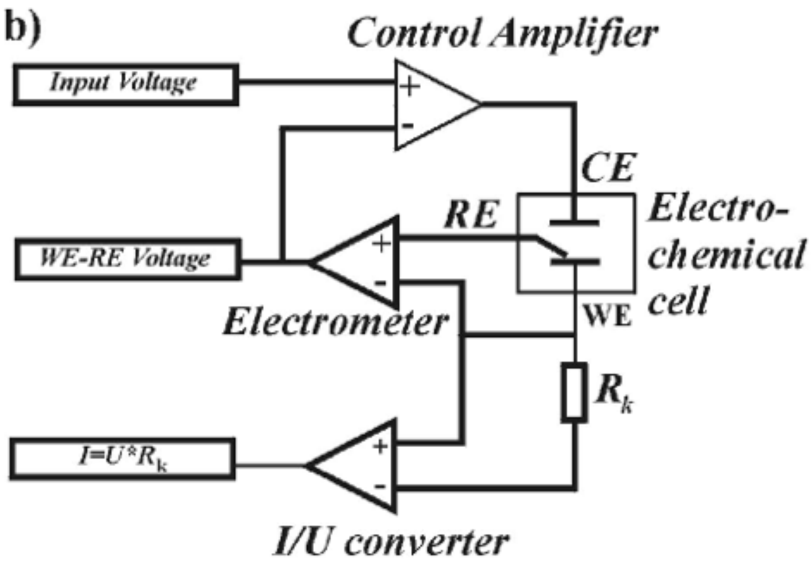
- No perfect / ideal electrode exists
  - **Non linear** (potential-dependent mechanisms)
  - Frequency-dependent charge inj. mechanisms
  - **Reactive behavior** → capacitance at the electrode/electrolyte interface, distributed capacitances along the circuit
  - **Metal electrode** → resistive losses,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

Electrochemical impedance

- a measure of the reluctance of a component to current flow when subject to an AC stimulus

3-electrode set-up





http://www.porous-35.com/electrochemistry-semiconductors-10.html

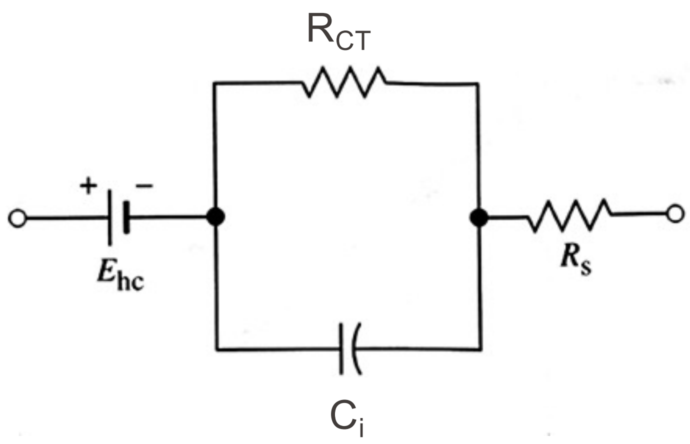
reminder

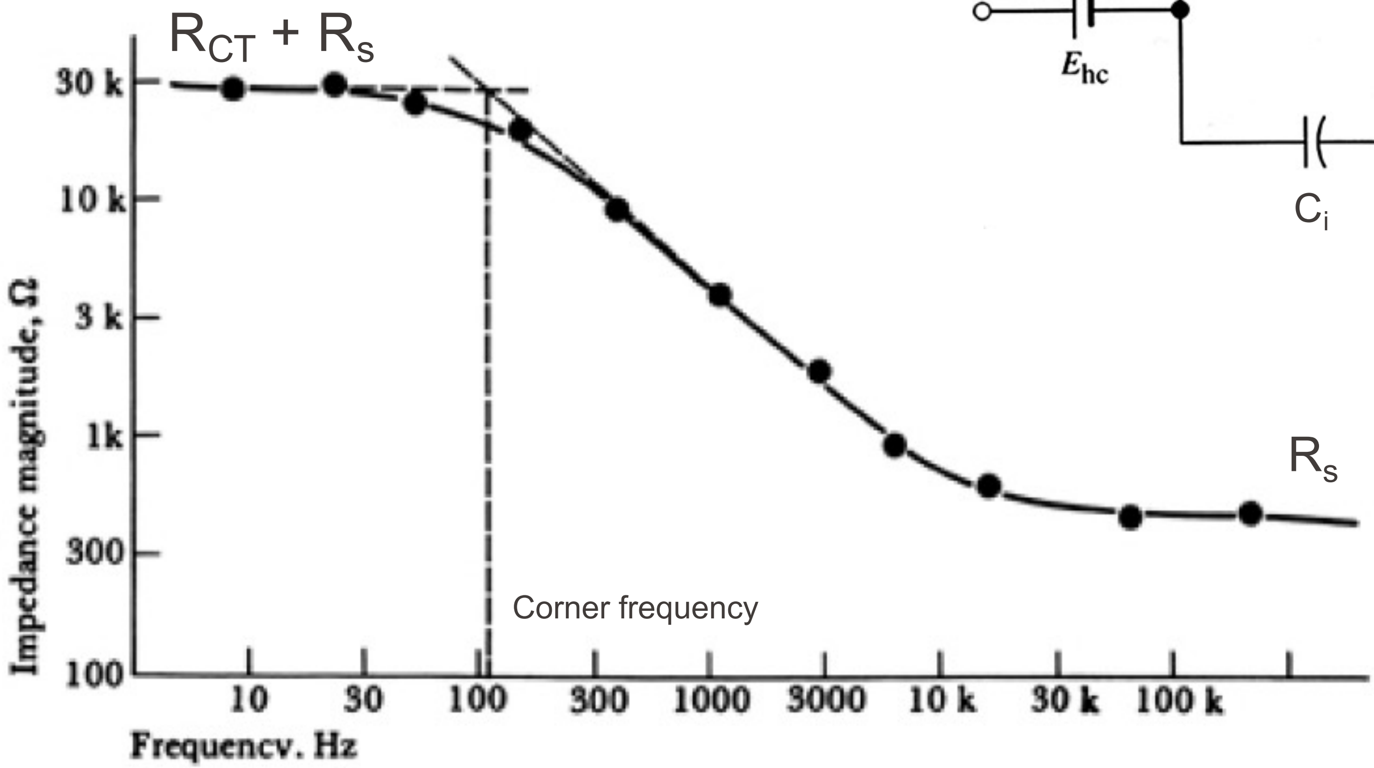
- AC domain → complex number notation
  - Any given sinusoidal stimulus can be expressed as
    - $A(t) = A_{max}\, e^{i\omega t}$ with Re(A) in phase with Im(A) at quadrature

- Resistor R: V = RI, $|Z| = \frac{V}{I} = R$ at any frequency

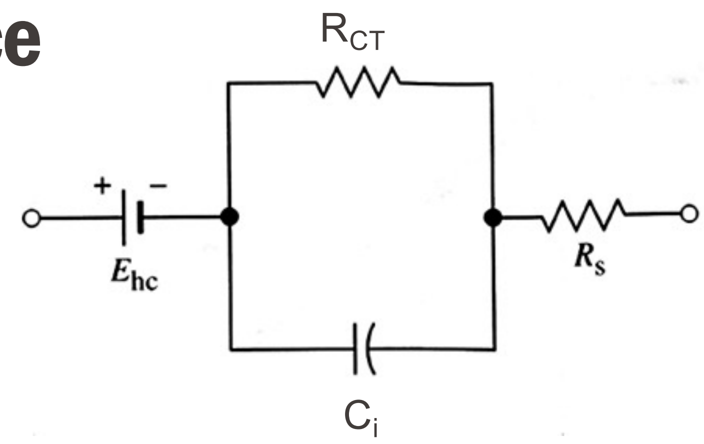
- Capacitor C: Q =CV, $|Z| = \frac{V}{I} = \frac{1}{\omega C}, Z_{phase}$ = -90° at any frequency

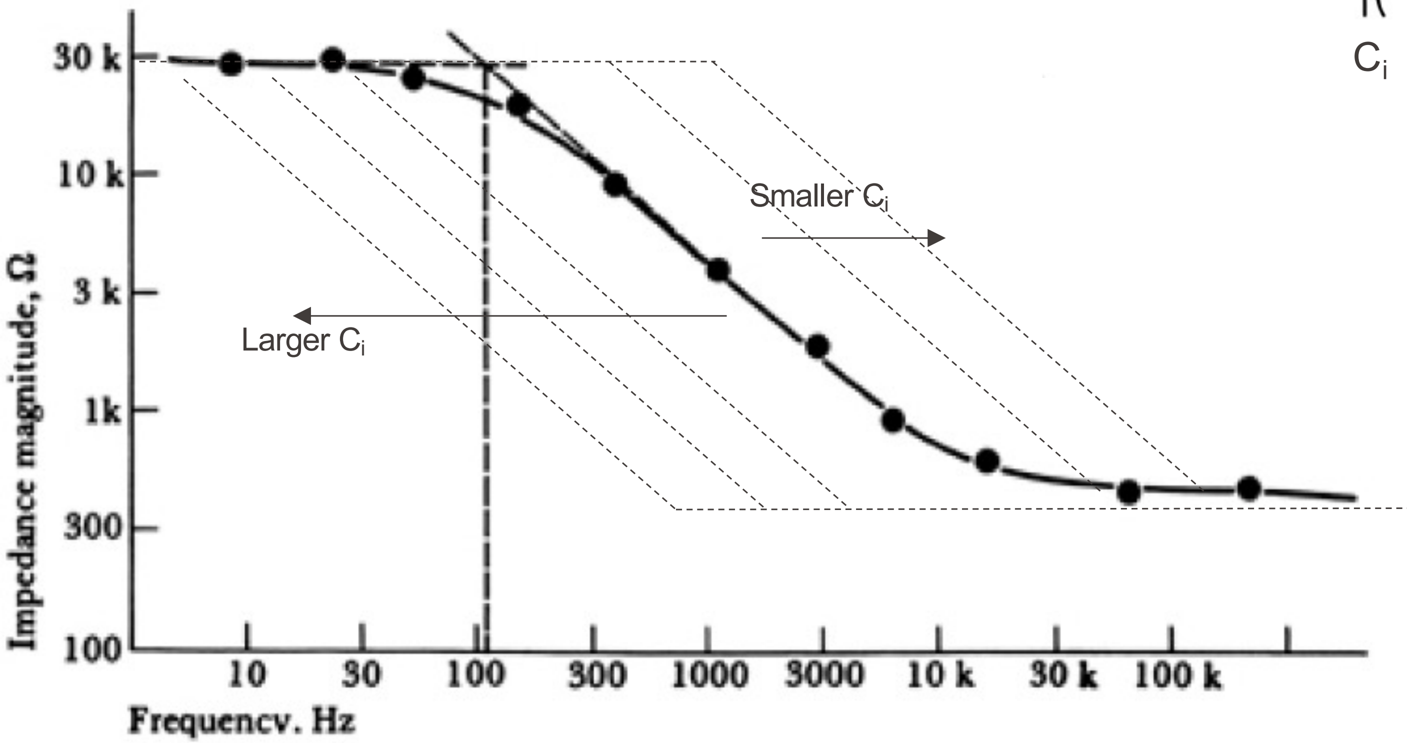
Impedance spectrum





How does the interface capacitance affect the impedance?





Polarization

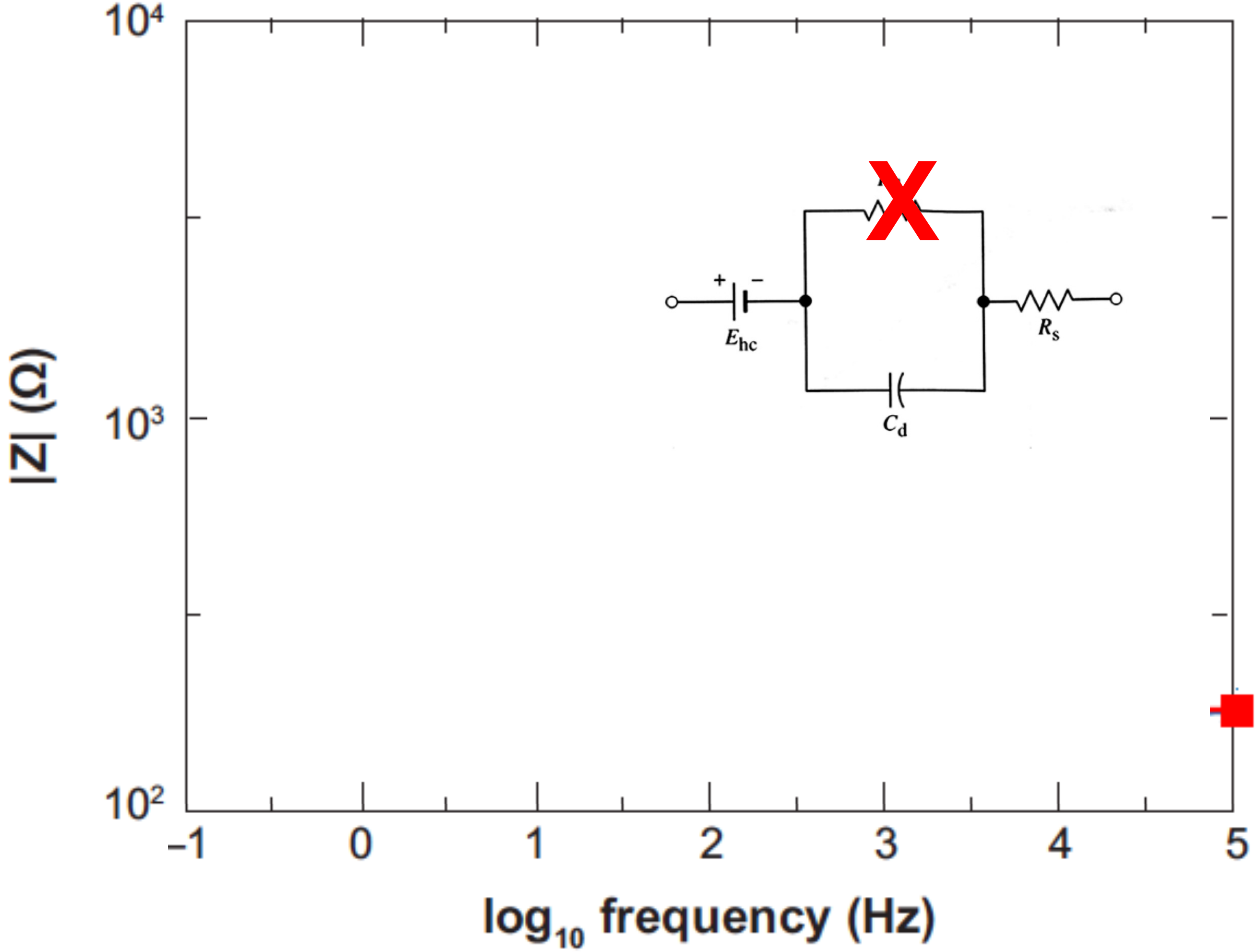
- If there is a current flowing from the electrode to the electrolyte, the potential is altered, $E = E_{hc} + i_F R_F$

$$\text{Overpotential: } \eta = |E - E_{hc}|$$

- **Perfectly polarizable electrodes** 
  - No actual charge crosses the interface when a current is applied
  - The current across the interface is a displacement current
  - e.g. TiN

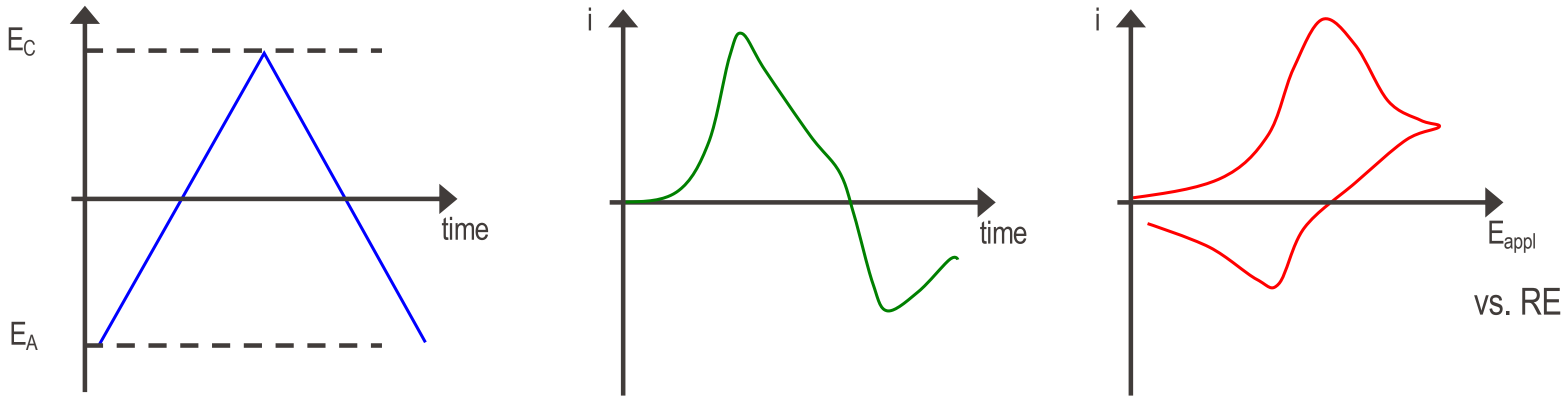
- **Perfectly non polarizable electrodes** 
  - Current passes freely across the interface, requiring energy to make the transition
  - e.g. Ag/AgCl

Electrode impedance in the case of inert coatings



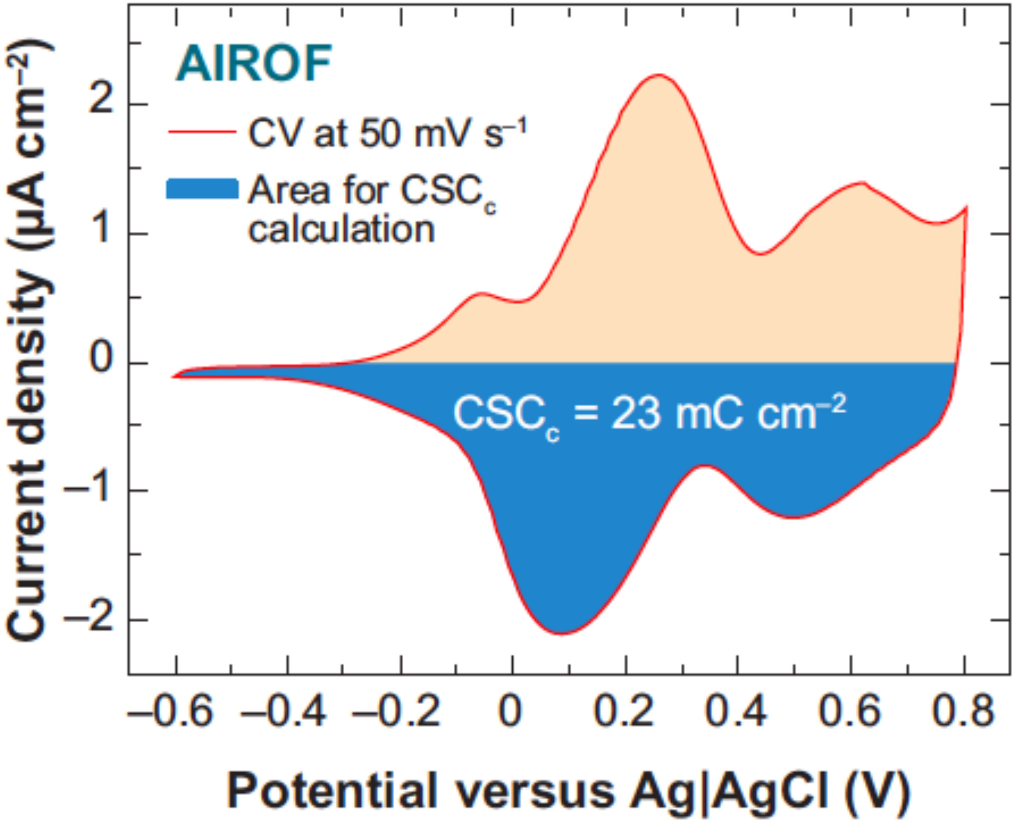
Cyclic voltammetry

- « spectroscopy of the electrochemist »
- 3-electrode setup:
  - Sweep the potential of WE applied against CE and measured against RE
  - Measure the current at WE



E_A and E_C within the water window

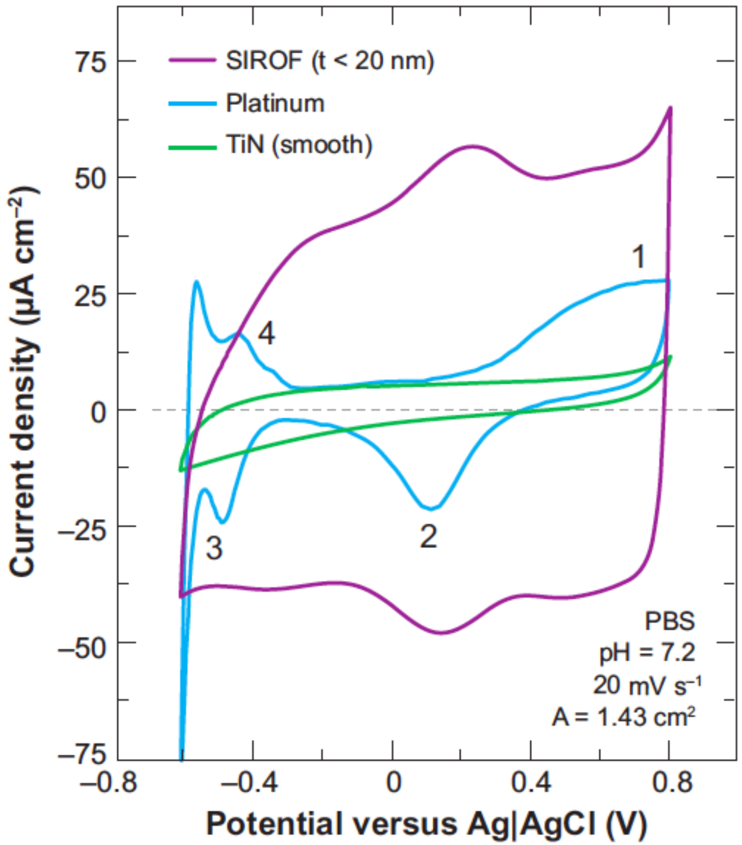
Cathodic storage capacity CSC



SF Cogan, Annu. Rev. Biomed. 2008 10:275

Slow voltage sweep
10-1000mV/sec

Comparison of materials



Electrode material	CSC ($\mu C/cm^2$)
Gold	20
Stainless steel	50
Platinum	75
Titanium nitride	250
Iridium oxide	Up to 3,000

1,2 Pt oxidation and reduction
3,4 H plating and stripping from Pt

SF Cogan, Annu. Rev. Biomed. 2008 10:275

Noise characteristics

- **Extracellular signals** have an amplitude in the 10µV to 1mV
  - Very low-level input signals

- System noise = electrode noise + preamp noise

- Thermal noise (electrode)

$$U_N = \sqrt{4\ k\ T\ R\ \Delta f}\ (in\ volts)$$

Important for recording electrodes

- Electrochemical/biological noise or 1/f noise

- Low impedance prevents shunting through parasitics

Take-home messages

- **Electrode impedance spectroscopy**
  - Frequency response 1Hz – 100kHz
  - High frequency: Resistive component (wire/interconnect)
  - Low frequency : interface nature