

Ionophore-Based Sensors



Ionophore-Based Sensors

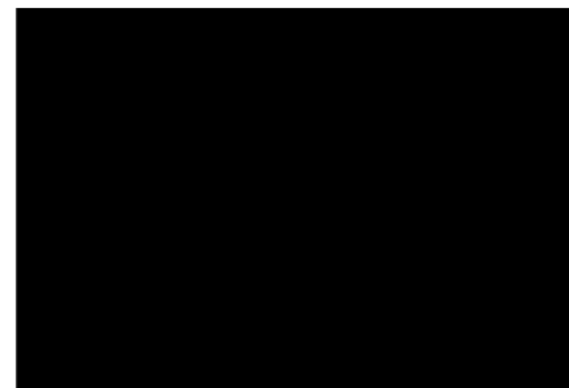


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PhD in Chemistry, University of Medicine and Pharmacy "Carol Davila" Bucharest, Romania (2012)
Postdoctoral Fellow, University of Medicine and Pharmacy "Carol Davila" Bucharest, Romania (2012-2014)
Senior Researcher, University of Medicine and Pharmacy "Carol Davila" Bucharest, Romania (2014-Present)
Research Interests: Ionophore-Based Sensors, Analytical Chemistry, Environmental Chemistry



Dr. Aleksandar Radu

- 1997; BSc Physical Chemistry – Belgrade University, Serbia
- 2005; PhD Chemistry – Auburn University, USA
- Postdoc – Dublin City University, Ireland
- 09/2010 – Senior Lecturer, School of Pharmacy and Biomedical Sciences, University of Portsmouth, United Kingdom
- 12/2011 Lecturer in Chemistry, Keele University
 - Room LJ106; phone: 33392
 - Email: a.radu@chem.keele.ac.uk





ciences, University of

Introduction

Module Aims

- To give appreciation of the field
- To give understanding of basic theoretical principles and mechanisms of response of ISSs

Reading Material

- Babbitt E., Hollmann F., Pitzalis E., Turner David Ian, Solid State Electrode and Bulk Electrolyte Cells in Electrochemical Sensors, *Journal of Materials*, 2001, 31, 3895
- Hollmann F., Chen L., Ian Solid State Electrodes With Inorganic Electrolyte and Solid Electrolyte Membranes, *Encyclopedia of Electrochemical Technology*, 2006, 1, 1011, John Wiley & Sons
- Ruck A., Pape S., Babbitt E., Hollmann F., Guidelines for Improving the Linear Detection Limit of Electrochemical Sensors, *Electrochimica Acta*, 2007, 52 (2), 344

Importance

- Used in many fields (clinical analysis, physiology, process control, environmental analysis)
- > billion measurements world-wide performed in clinical laboratories alone
- market value > 3 billion USD

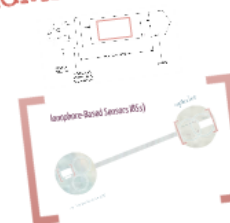
Applications

- Biochemical Laboratories: Ca^{2+} , K^+ , Cl^- in body fluids (blood, plasma, urine, sweat) - largest market segment
- Pollution Monitoring: CH_4 , F_2 , SO_2 , NO_2 etc. in effluents and natural waters
- Agriculture: NO_3^- , Cl^- , NH_4^+ , K^+ , Ca^{2+} , J^- , OH^- in soils (plant nutrient), fertilizers and herbicides
- Food Processing: NO_3^- , NO_2^- in meat preservatives
- Self-control of waste, fish, dairy products, fruit juices, brewing industries
- F^- in drinking water and other drinks
- Ca^{2+} in dairy products and beer
- K^+ in fruit juices and wine making
- Corrosion effect of NO_3^- in cement beds
- Development of Biosensors: Ca^{2+} , Ba^{2+} , F^- for studying effects on water quality
- Paper Manufacture: SiO_2 and Cl^- in pulping and nonrecycled papers
- Explosives: F^- , Cl^- , NO_3^- in explosive materials and combustion products
- Electroplating: F^- and Cl^- in etching baths, SiO_2 in etching baths
- F^- in dental and dental studies
- Education and Research: Wide range of applications

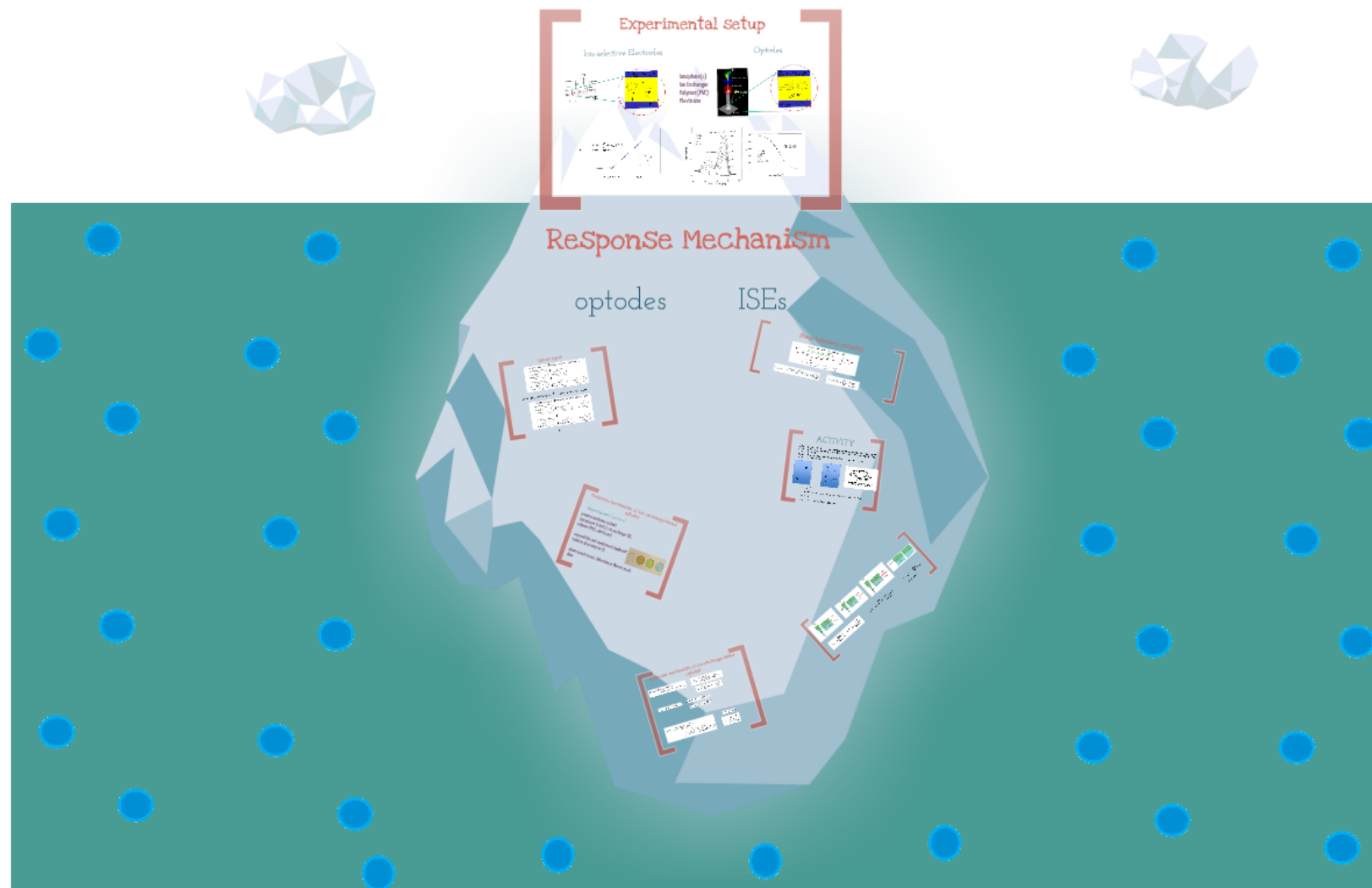
Advantages

- Measure activity and NOT concentration
- Cheap, simple to use, wide concentration range
- Cheap applications range
- Modern ISSs are very sensitive (part-per-billion), robust and durable - can be used in laboratories, clinical and domestic - can be used in laboratories, clinical and domestic
- Under the most favorable conditions ISSs can be used rapidly and easily (simply dipping)
- Excellent for on-line monitoring and as early warning systems
- They are particularly useful in applications where only an order of magnitude concentration is required
- ISSs are one of the few techniques which can measure both positive and negative ions
- They are unaffected by sample colour or turbidity

Chemical Sensors

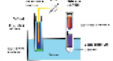


Mechanism of response



ISE measurement

Types of ISEs and corresponding LODs



Liquid contact "Classical"
~micromolar

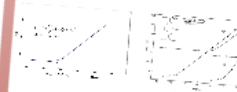


Liquid contact "Modern"
~nanomolar, picomolar



Solid contact
~nanomolar, picomolar

Detection limit



Experimental protocol

Classical Modern Solid

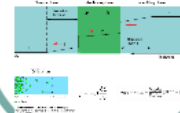
- Mix membrane components
- Cast and mount the membrane
- Condition the electrode

Prepare the membrane to
~100 pH solution of primary
ion / low ionic strength

Cast the membrane
to form a uniform
film on the substrate
by using a casting
solution

Condition the membrane
in a solution of the
primary ion for 24 hours
at room temperature

Ion fluxes



Selectivity

ISE selectivity is defined as the ability of the electrode to respond to a specific ion in the presence of other ions. It is determined by the selectivity coefficients of the electrode.

Experimental protocol (Sel. conf.)

Classical Modern (liquid- and solid-contact)

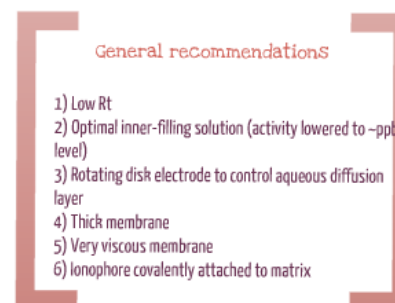
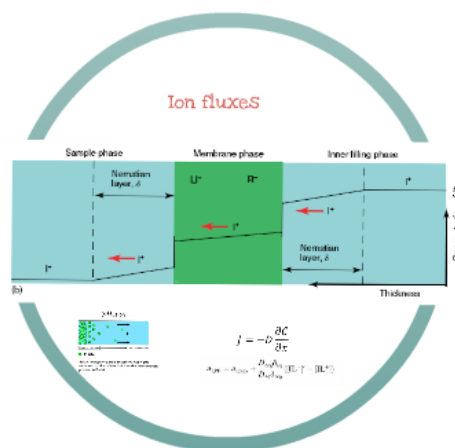
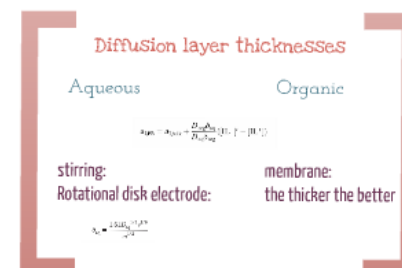
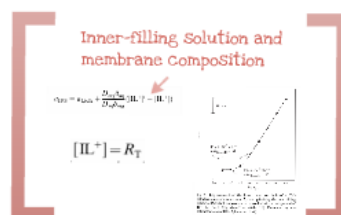
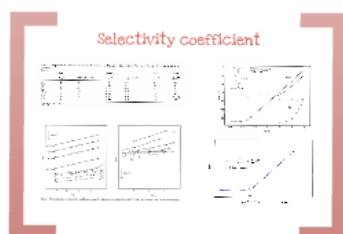
- Mix membrane components
- Cast and mount the membrane
- Condition the electrode

Prepare the membrane to
~100 pH solution of primary
ion / low ionic strength

Cast the membrane to
form a uniform film on the
substrate by using a casting
solution

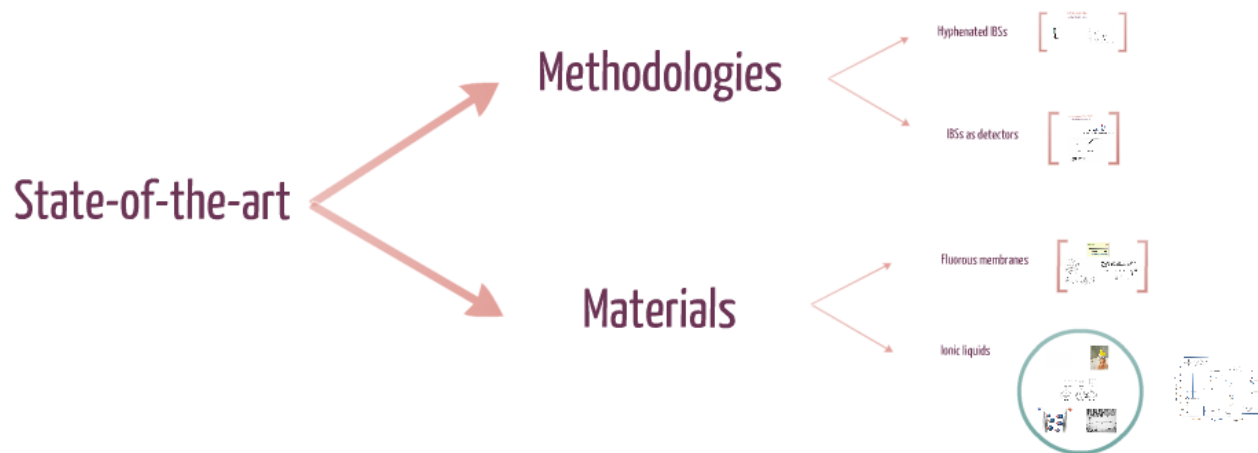
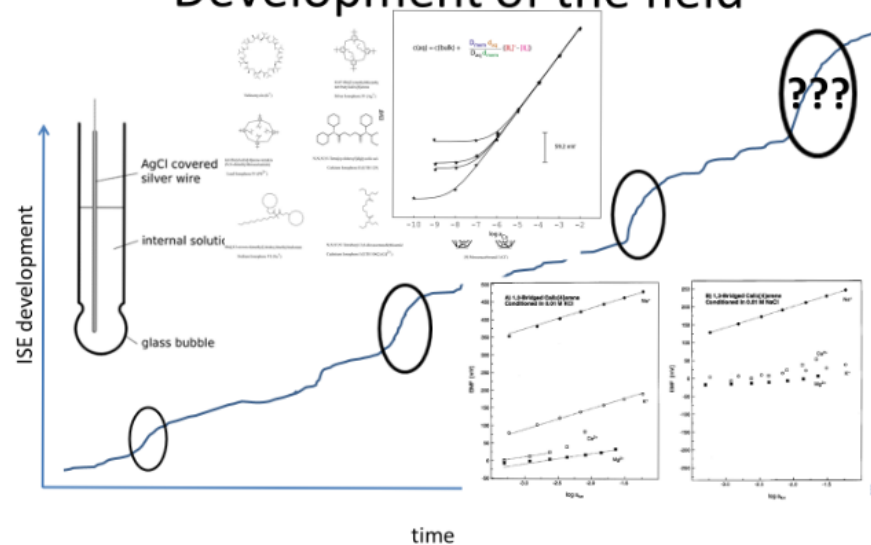
Condition the membrane
in a solution of the primary
ion for 24 hours at room
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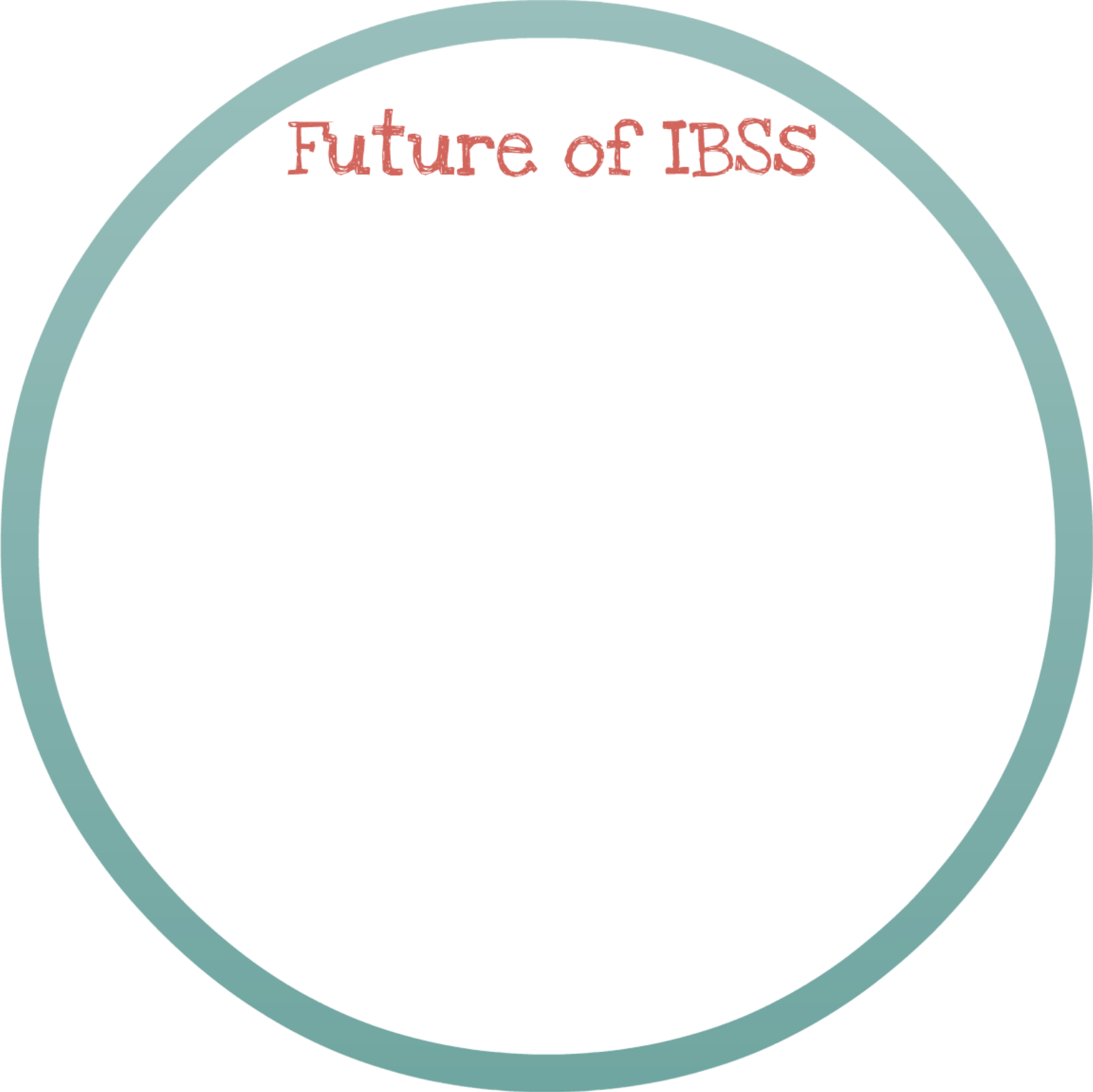
Guidelines for optimisation of critical parameters and obtaining ISES with optimal LOD



State-of-the-art

Development of the field





Future of IBSS

Module Aims

- To give appreciation of the field
- To give understanding of basic theoretical principles and mechanisms of response of IBSs

Reading Material

- Bakker E., Buhlmann P., Pretsch E, Carrier-Based Ion-Selective Electrodes and Bulk Optodes 1. General Characteristics; Chemical Reviews; 1997, 97, 3083
- Buhlmann P., Chen L.; Ion-Selective Electrodes With Ionophore-Doped Sensing Membranes; Supramolecular Chemistry: From molecules to nanomaterials; Ed Gale P., Steed J.; 2012; John Wiley & Sons
- Radu A., Peper S., Bakker E., Diamond D; Guidelines for Improving the Lower Detection Limit of Ion-Selective Electrodes: A Systematic Approach; Electroanalysis; 2007; 19 (2-3); 144

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Importance

- Used in many fields (clinical analysis, physiology, process control, environmental analysis)
- >billion measurements world-wide performed in clinical laboratories alone
- market value >3 billion USD

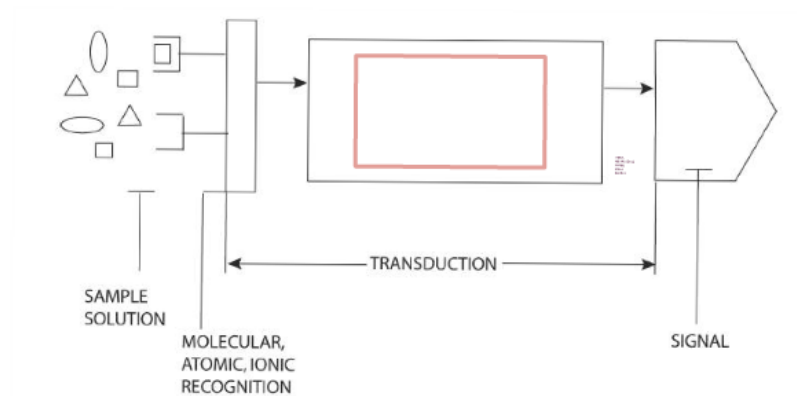
Applications

- Biomedical Laboratories: Ca^{2+} , K^{+} , Cl^{-} in body fluids (blood, plasma, serum, sweat) - largest market impact
- Pollution Monitoring: CN^{-} , F^{-} , S^{2-} , Cl^{-} , NO_3^{-} etc., in effluents, and natural waters.
- Agriculture: NO_3^{-} , Cl^{-} , NH_4^{+} , K^{+} , Ca^{2+} , I^{-} , CN^{-} in soils, plant material, fertilisers and feedstuffs.
- Food Processing: NO_3^{-} , NO_2^{-} in meat preservatives.
- Salt content of meat, fish, dairy products, fruit juices, brewing solutions.
- F^{-} in drinking water and other drinks.
- Ca^{2+} in dairy products and beer.
- K^{+} in fruit juices and wine making.
- Corrosive effect of NO_3^{-} in canned foods.
- Detergent Manufacture: Ca^{2+} , Ba^{2+} , F^{-} for studying effects on water quality.
- Paper Manufacture: S^{2-} and Cl^{-} in pulping and recovery-cycle liquors.
- Explosives: F^{-} , Cl^{-} , NO_3^{-} in explosive materials and combustion products.
- Electroplating: F^{-} and Cl^{-} in etching baths; S^{2-} in anodising baths.
- F^{-} in skeletal and dental studies.
- Education and Research: Wide range of applications.

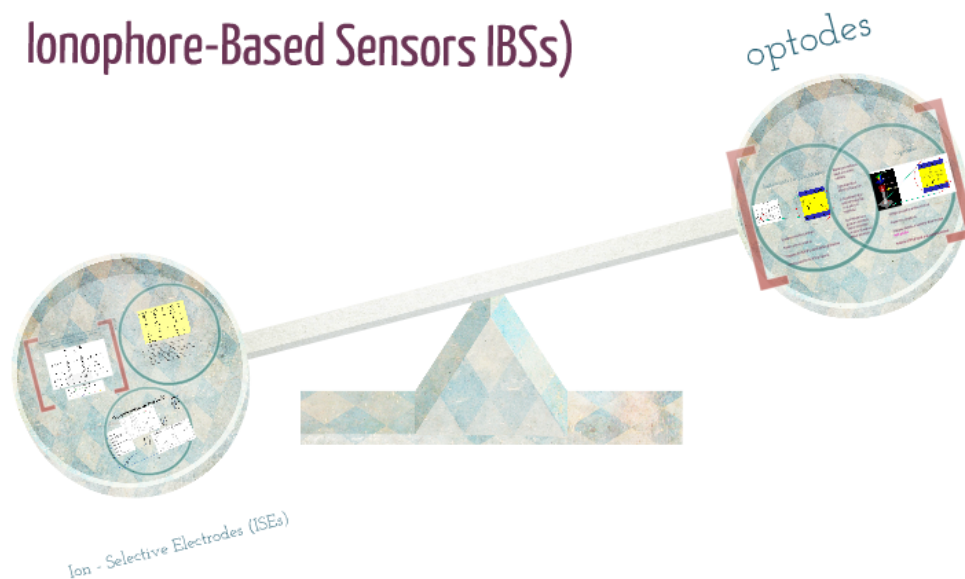
Advantages

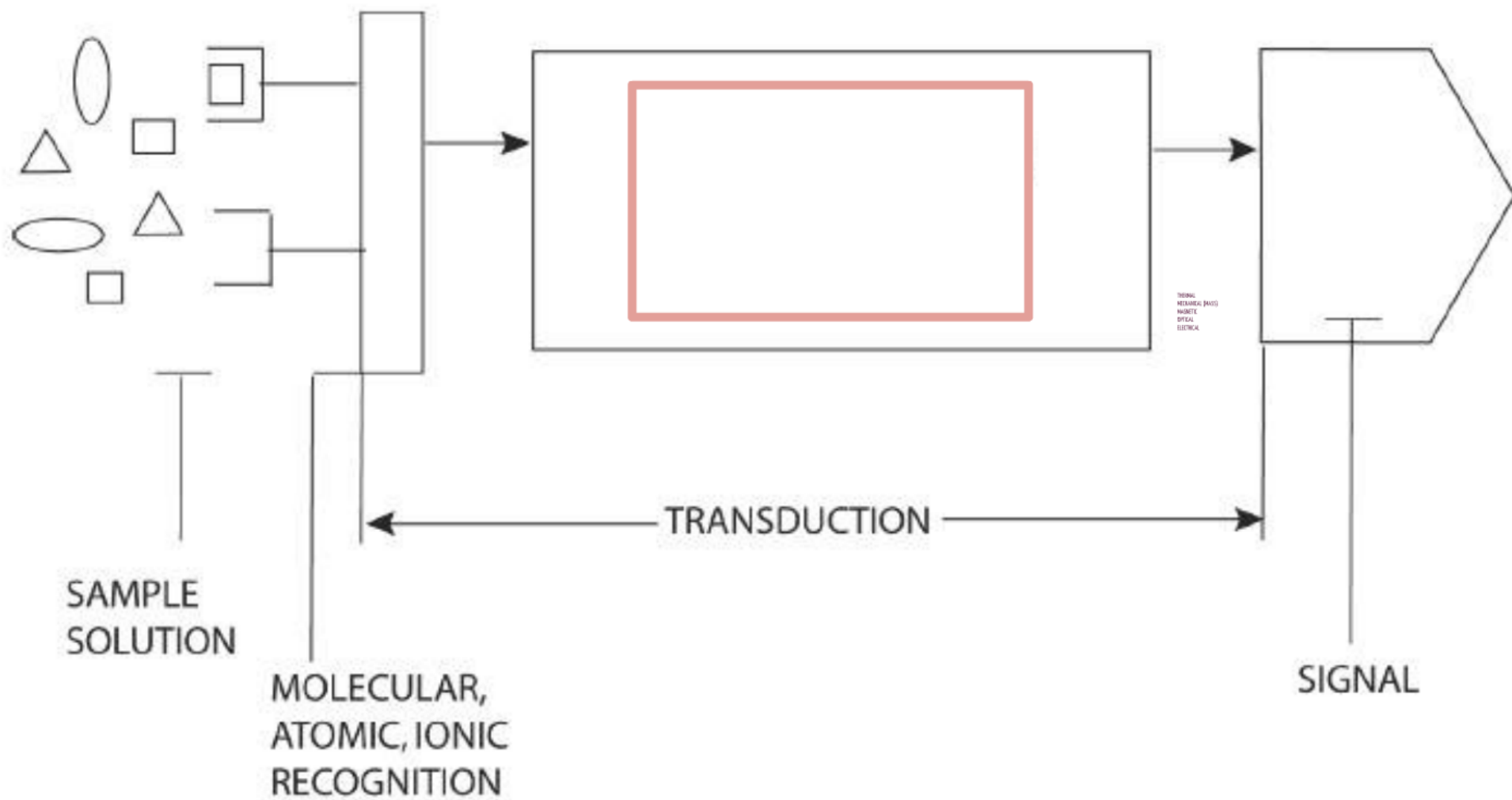
- Measure activity and NOT concentration
- Cheap, simple to use, wide concentration range, wide application range
- Modern IBSs are very sensitive (part-per-billion), robust and durable - can be used in laboratories AND in field
- Under the most favorable conditions IBSs can be used rapidly and easily (simply dipping)
- Excellent for routine monitoring and as early warning systems
- They are particularly useful in applications where only an order of magnitude concentration is required
- ISEs are one of the few techniques which can measure both positive and negative ions
- They are unaffected by sample colour or turbidity

Chemical Sensors



Ionophore-Based Sensors (IBSs)





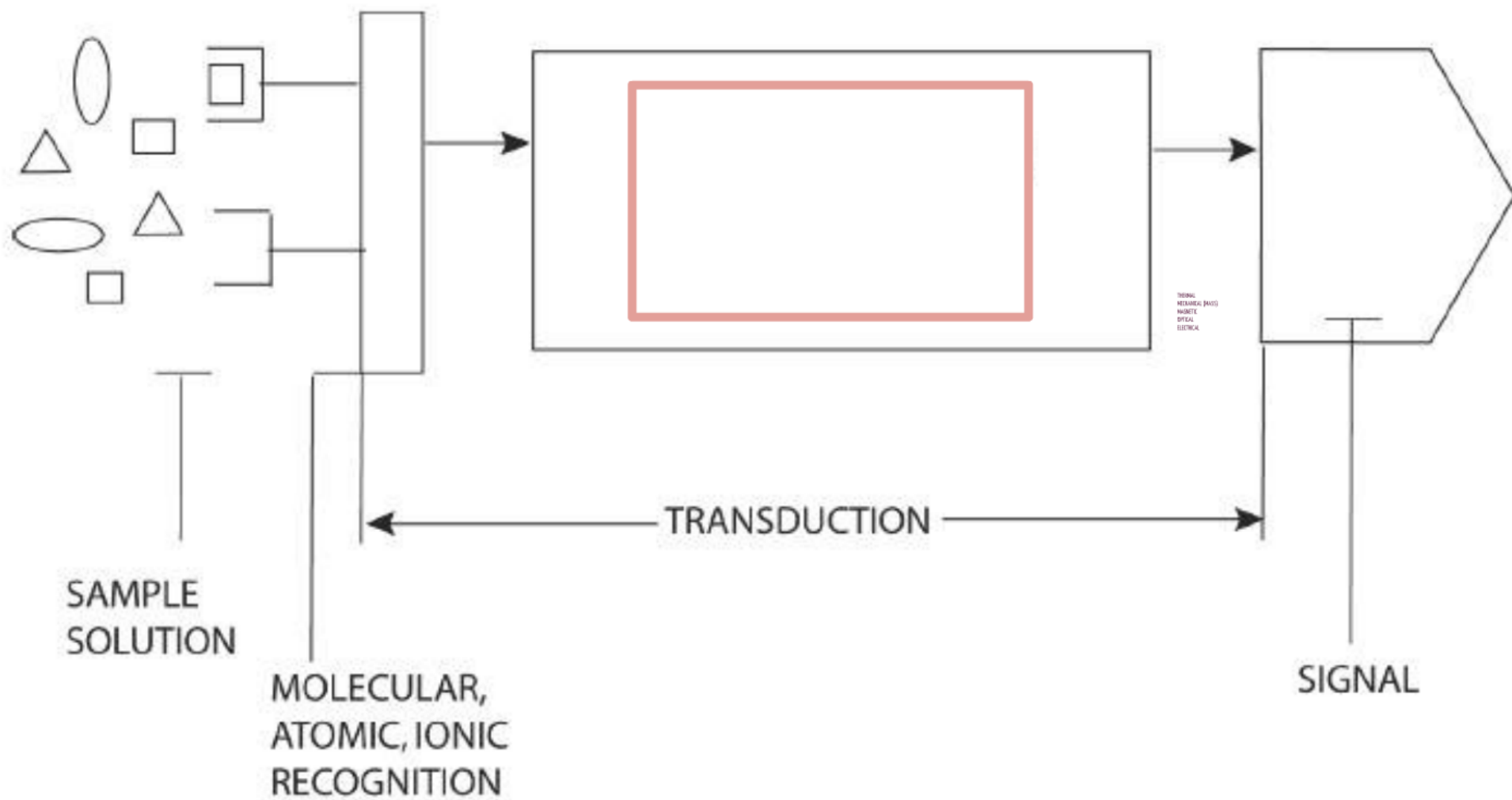
THERMAL

MECHANICAL (MASS)

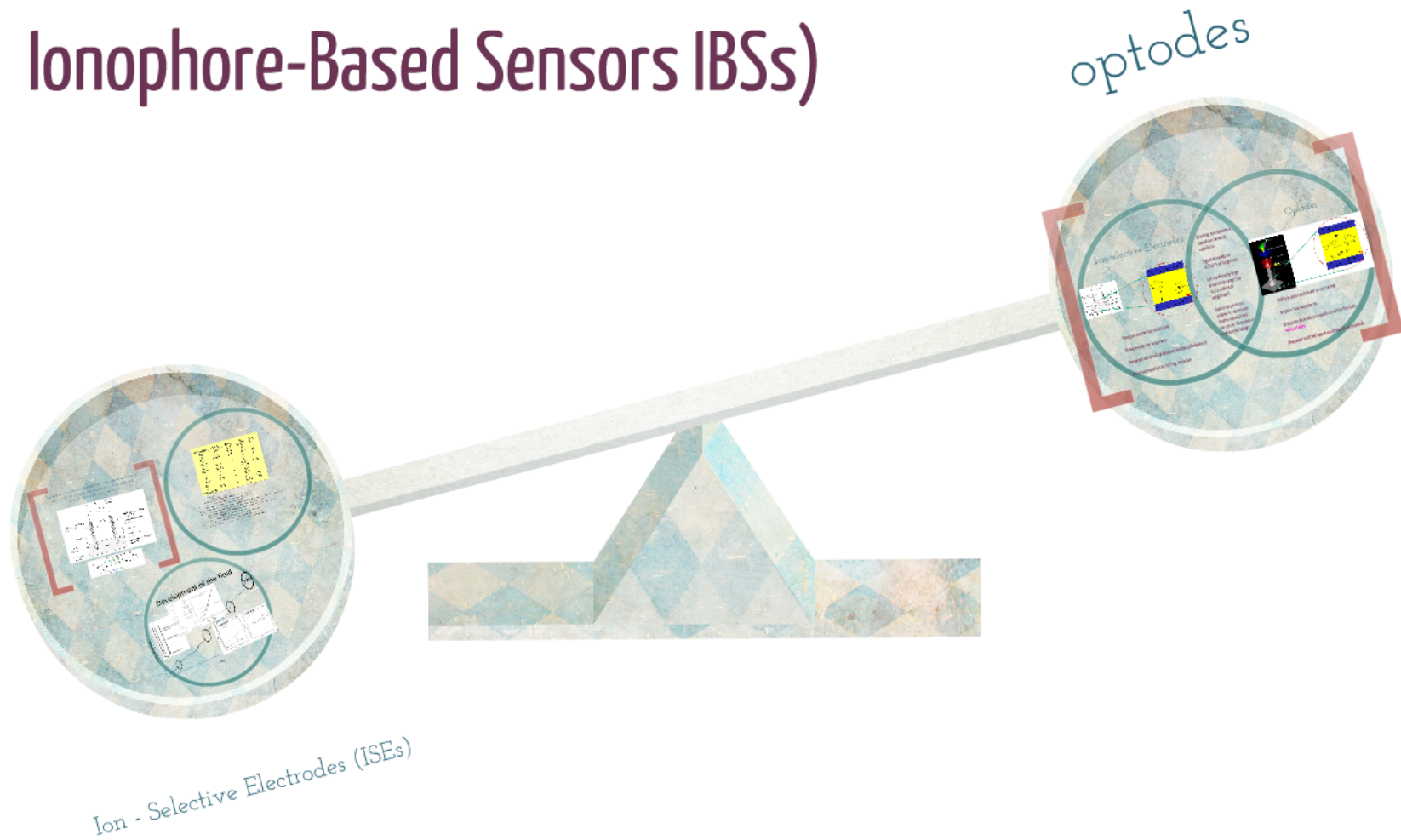
MAGNETIC

OPTICAL

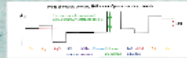
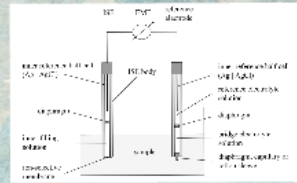
ELECTRICAL



Ionophore-Based Sensors IBSs)



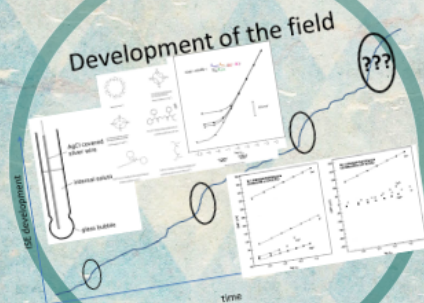
The diagram illustrates a three-electrode electrochemical cell and its corresponding cyclic voltammogram. The cell components include a 1M electrolyte solution, a reference electrode, a counter electrode, and a working electrode. The working electrode is connected to a potentiostat, which is also connected to the reference and counter electrodes. The potentiostat is labeled with '10V' and '10mA' and 'potentiostat'. The working electrode is labeled 'working electrode' and '10V' and '10mA'. The reference electrode is labeled 'reference electrode' and '10V' and '10mA'. The counter electrode is labeled 'counter electrode' and '10V' and '10mA'. The cyclic voltammogram shows the potential (V) on the x-axis and current (A) on the y-axis. The potential range is from -1.0V to 1.0V. The current range is from -1.0A to 1.0A. The voltammogram shows two redox couples: Fe(II)/Fe(III) and Fe(III)/Fe(IV). The Fe(II)/Fe(III) couple is reversible, with a peak potential of approximately 0.7V. The Fe(III)/Fe(IV) couple is irreversible, with a peak potential of approximately 0.9V. The voltammogram is labeled 'cyclic voltammogram' and 'Fe(II)/Fe(III) and Fe(III)/Fe(IV) redox couples'.



method/ion	ICP-MS	AAS	ISE	EPA
Ag ⁺	0.005	1.5	0.03 ¹	50
Ca ²⁺	0.5	1.5	0.1 ²	
Cd ²⁺	0.005	0.8	0.01 ¹	10
ClO ₄ ⁻			3 ³	1 ⁴
Cu ⁺	0.01	5	1 ⁵	
Cu ²⁺	0.005		0.01 ¹	1300 ⁶
F ⁻	1		0.25 ⁷	
K ⁺	0.5	3	0.2 ²	
Na ⁺	0.05	1	0.2 ⁸	
NH ₄ ⁺			0.2 ²	100 ⁹
Pb ²⁺	0.001	15	0.001 ¹	50
Vitamin B1				
			3.3 ¹⁰	

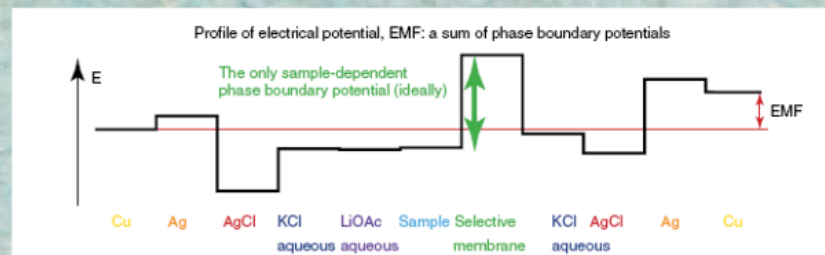
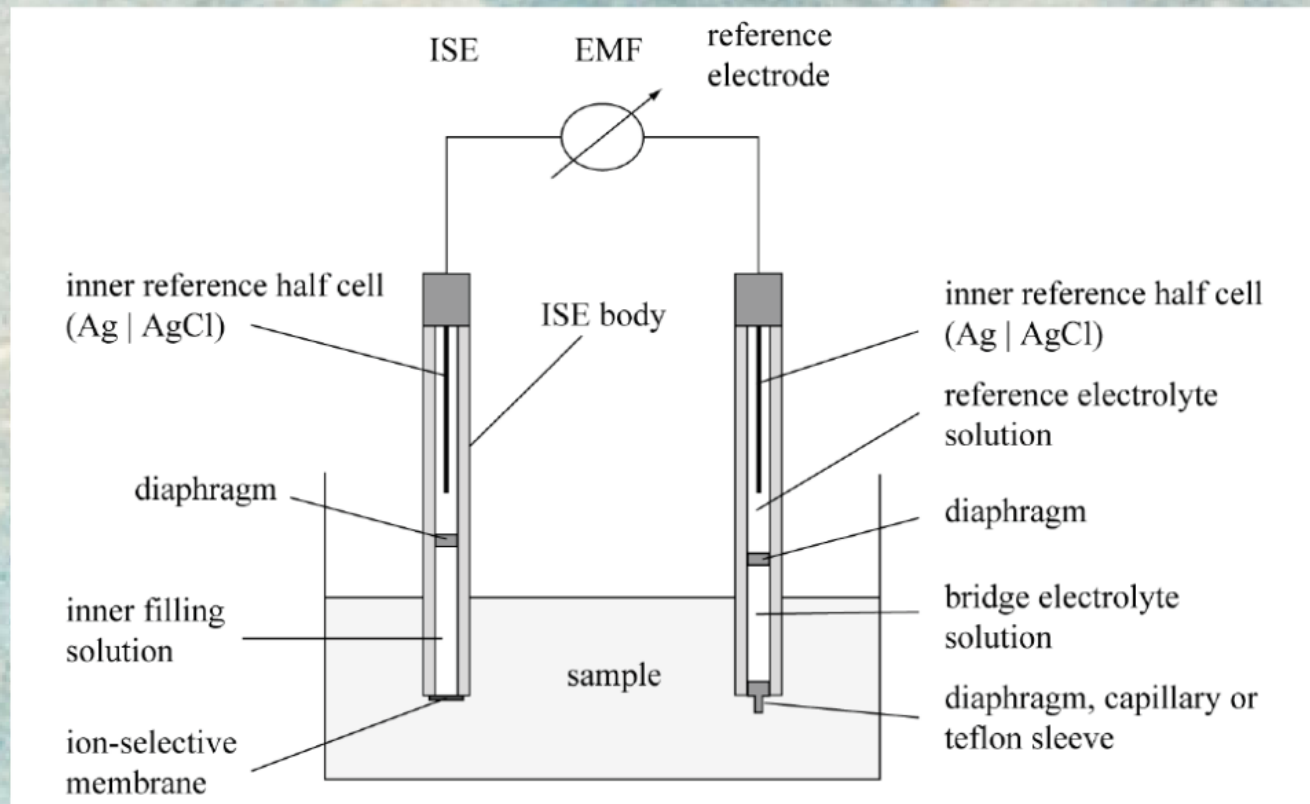
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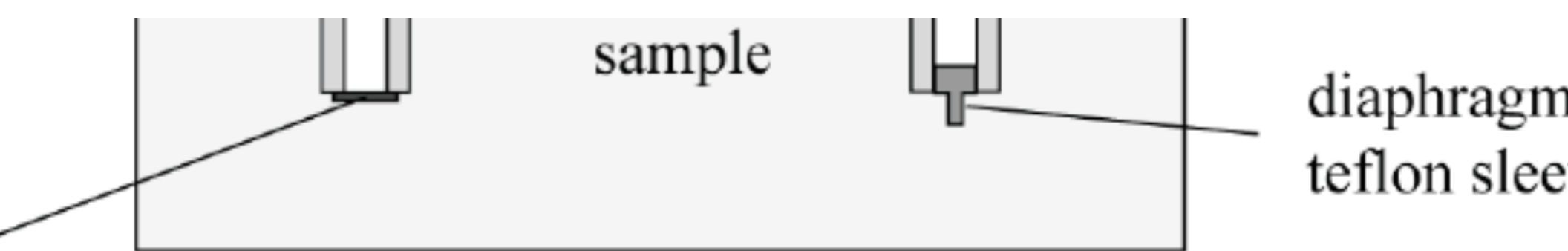
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118. *Journal*



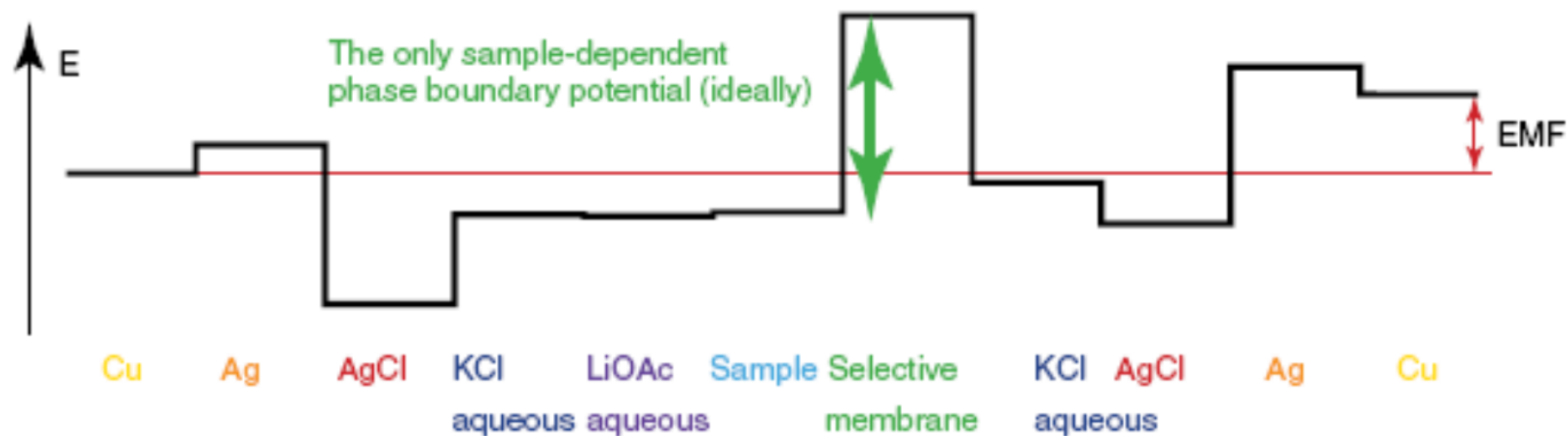
Ion - Selective Electrodes (ISEs)

Chemical sensor that determines the concentration of ion of interest by measuring potential between an indicator electrode and a reference electrode

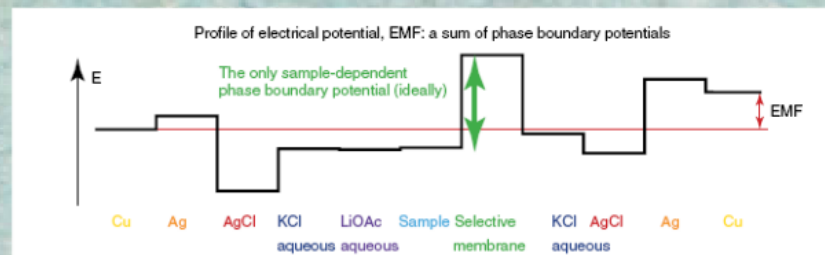
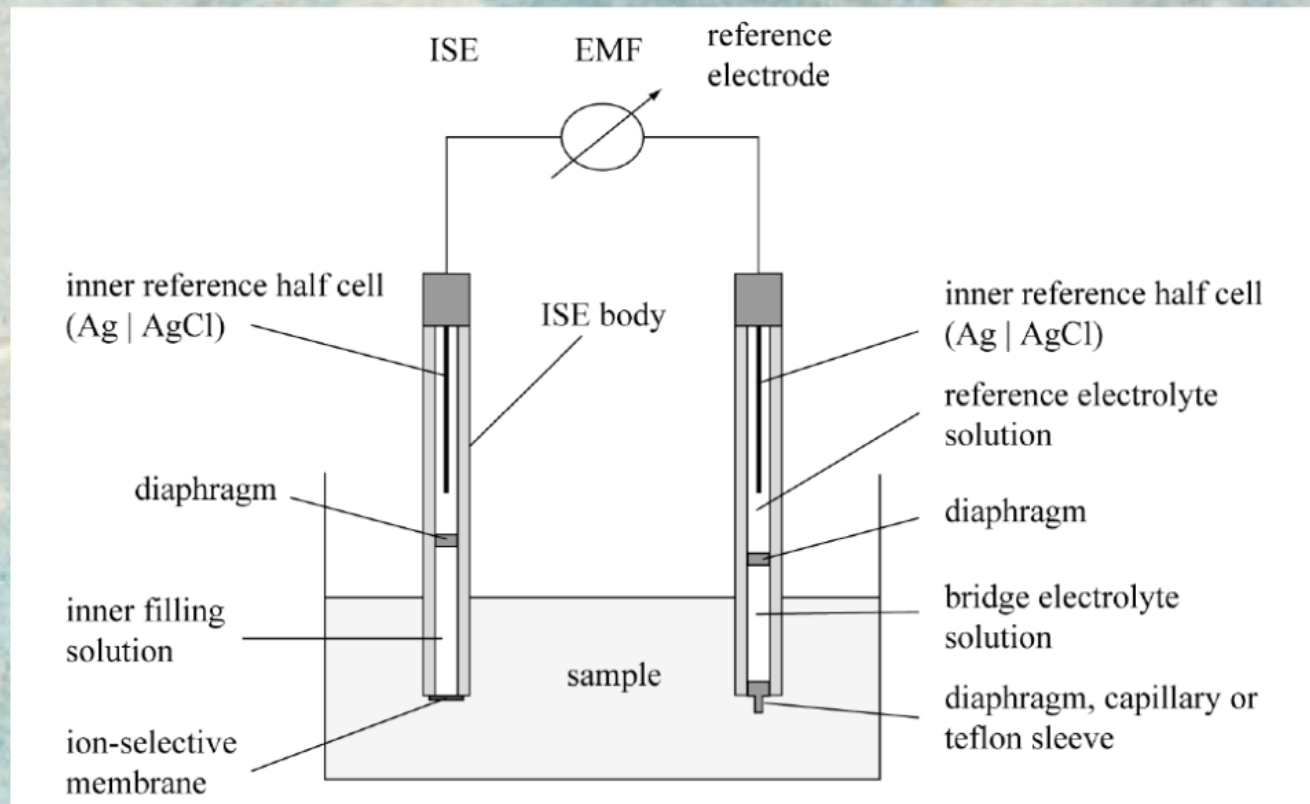




Profile of electrical potential, EMF: a sum of phase boundary potentials



Chemical sensor that determines the concentration of ion of interest by measuring potential between an indicator electrode and a reference electrode



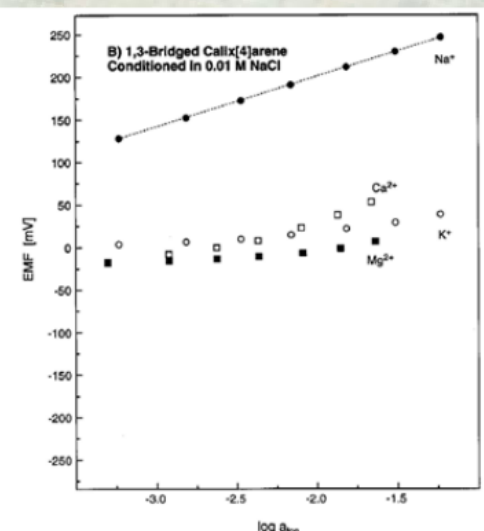
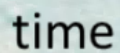
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Cd ²⁺	0.005	0.8	0.01 ³	10
ClO ₄ ⁻			3 ⁴	1 [*]
Cs ⁺	0.01	5	1 ⁵	
Cu ²⁺	0.005		0.01 ⁶	1300
I ⁻	1		0.25 ⁴	
K ⁺	0.5	3	0.2 ⁷	
Na ⁺	0.05	1	0.7 ⁸	
NH ₄ ⁺			0.2 ⁷	100 ^{**}
Pb ²⁺	0.001	15	0.001 ⁹	50
Vitamin B1			3.3 ¹⁰	

^{*} suggested

^{**} (depending on pH and T)

1. Wygladacz, K.; Radu, A.; Xu, C.; Qin, Y.; Bakker, E.; *Anal. Chem.* **2005**, *77* (15), 4706-4712
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5. Radu A., Peper S., Gonczy C., Diamond D., Runde W., *Electroanalysis*, **2006**, *13-14*, 1379-1388
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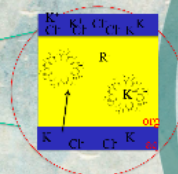
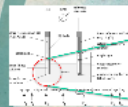
ISE development



???

optodes

Ion-selective Electrodes



- Need permselective membrane
- Require only one ionophore
- Response dictated by localized surface phenomena
- Universal equation for fitting response

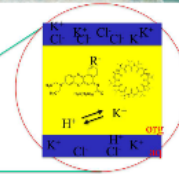
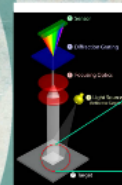
Working mechanism is based on chemical equilibria

Signal depends on ACTIVITY of target ion

Extraordinarily large sensitivity range (up to 12 orders of magnitude)

Essential parts are polymeric membrane (water-immiscible) ion carrier (ionophore) and ion-exchanger

Optodes



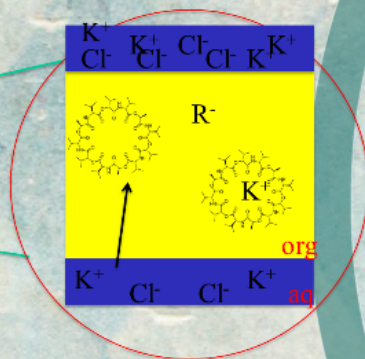
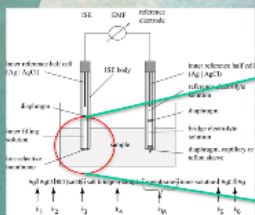
Multiple ions can/should be extracted

Require two ionophores

Response depends on equilibria within the bulk - **bulk optodes**

Response is fitted based on all **equilibria** involved

Ion-selective Electrodes



Need permselective membrane

Require only one ionophore

Response dictated by localized surface phenomena

Universal equation for fitting response

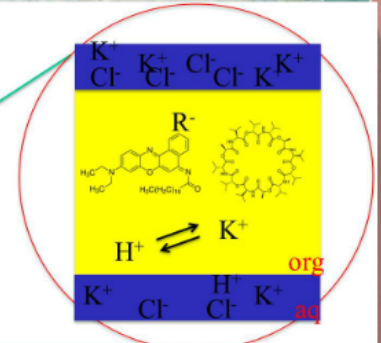
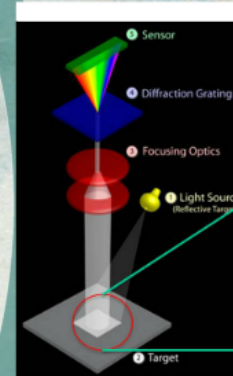
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Optodes



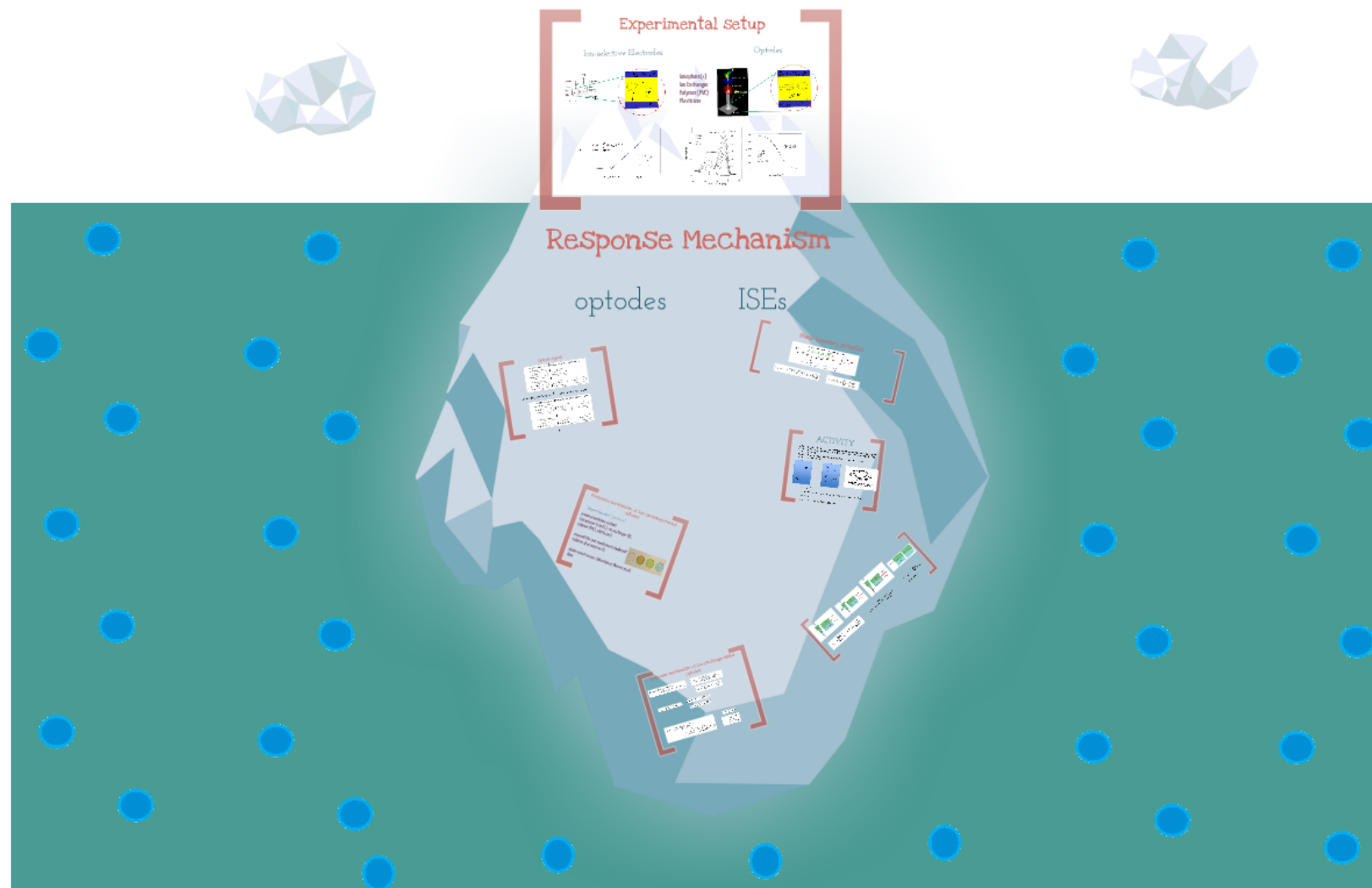
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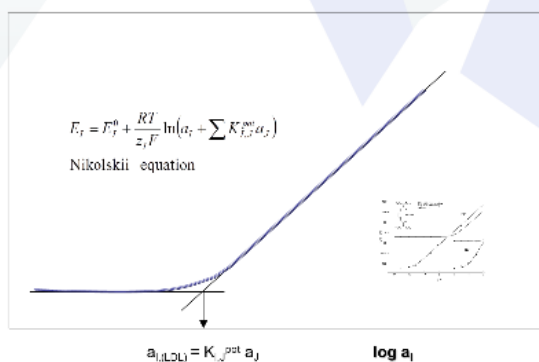
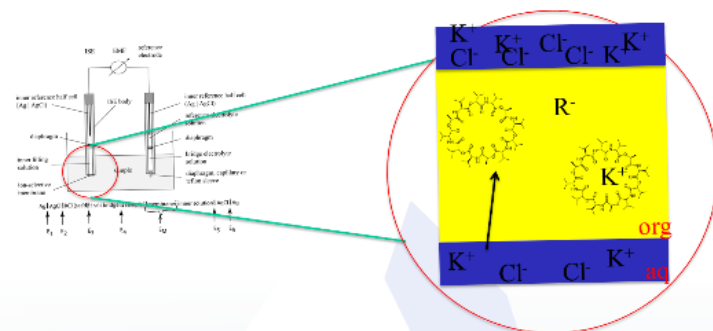
Response is fitted based on all equilibria involved

Mechanism of response



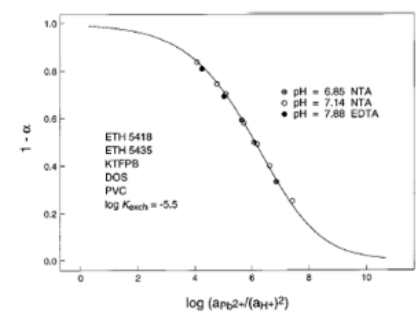
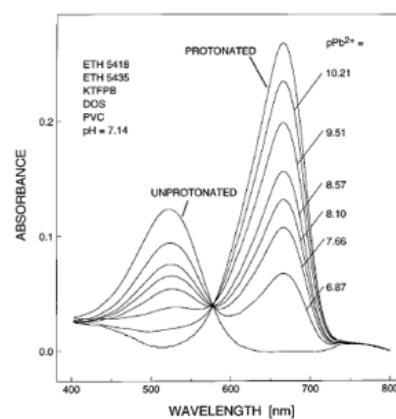
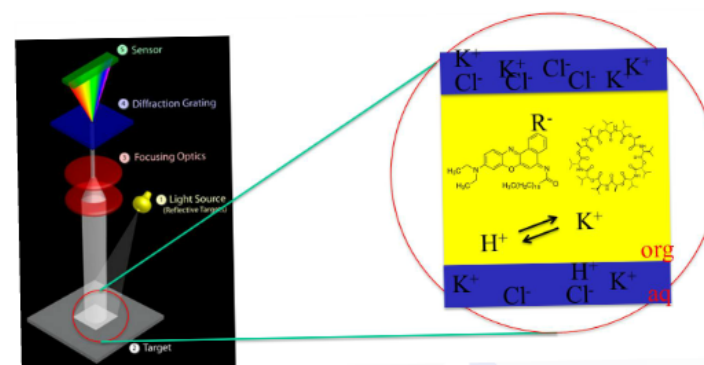
Experimental Setup

Ion-selective Electrodes



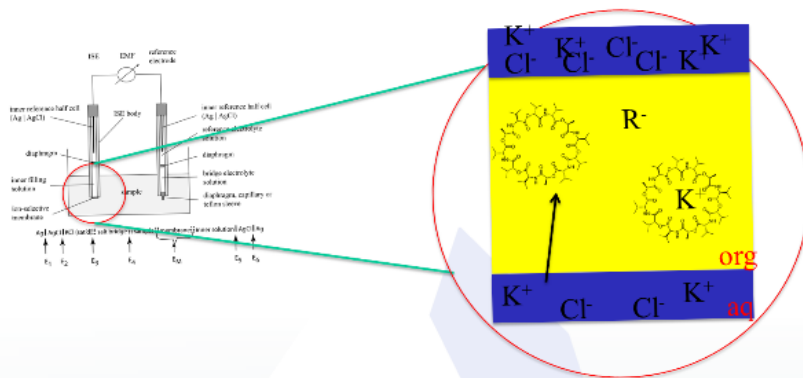
Ionophore(s)
Ion Exchanger
Polymer (PVC)
Plasticizer

Optodes



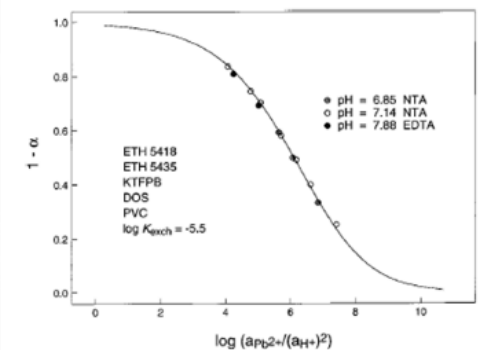
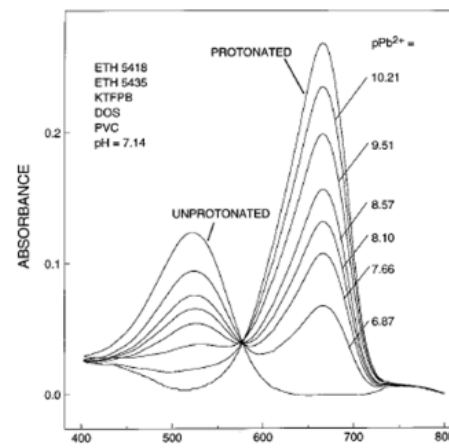
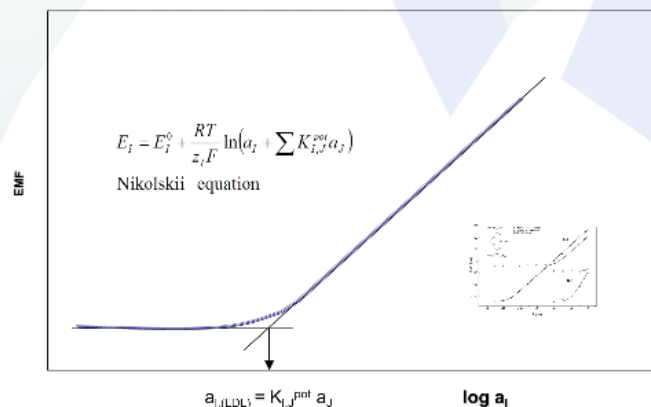
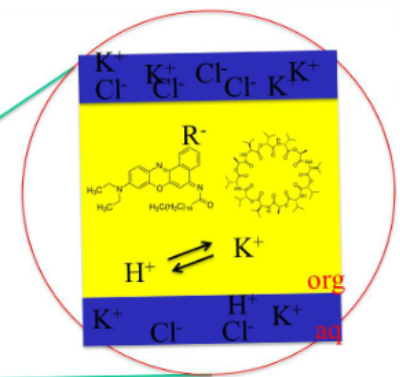
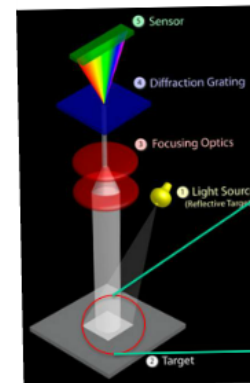
Experimental setup

Ion-selective Electrodes



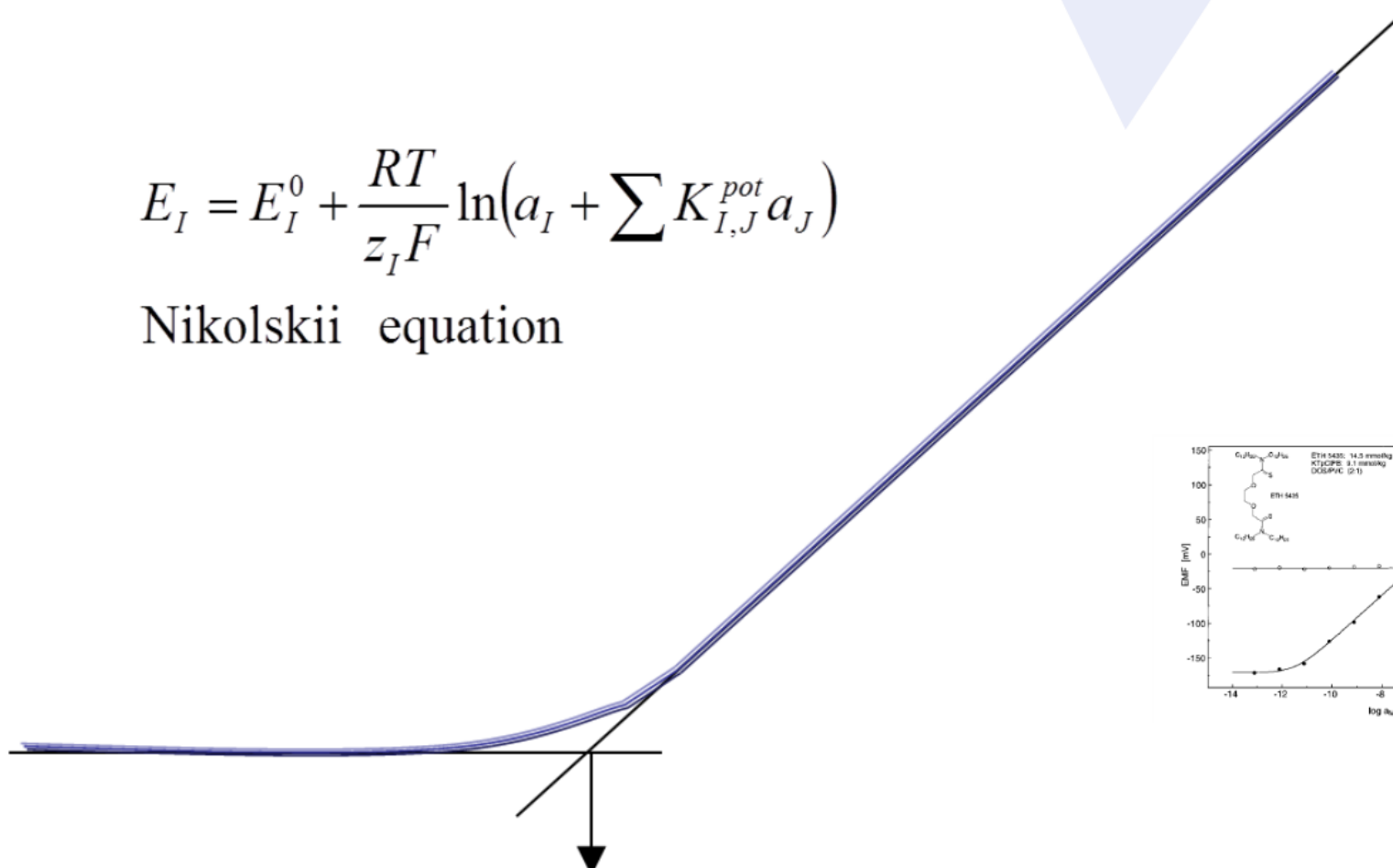
Optodes

Ionophore(s)
Ion Exchanger
Polymer (PVC)
Plasticizer



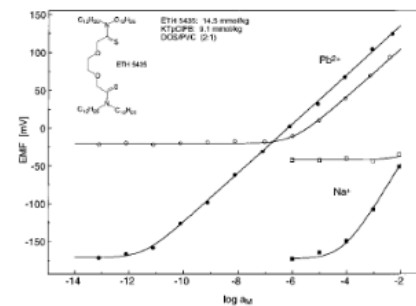
$$E_I = E_I^0 + \frac{RT}{z_I F} \ln(a_I + \sum K_{I,J}^{pot} a_J)$$

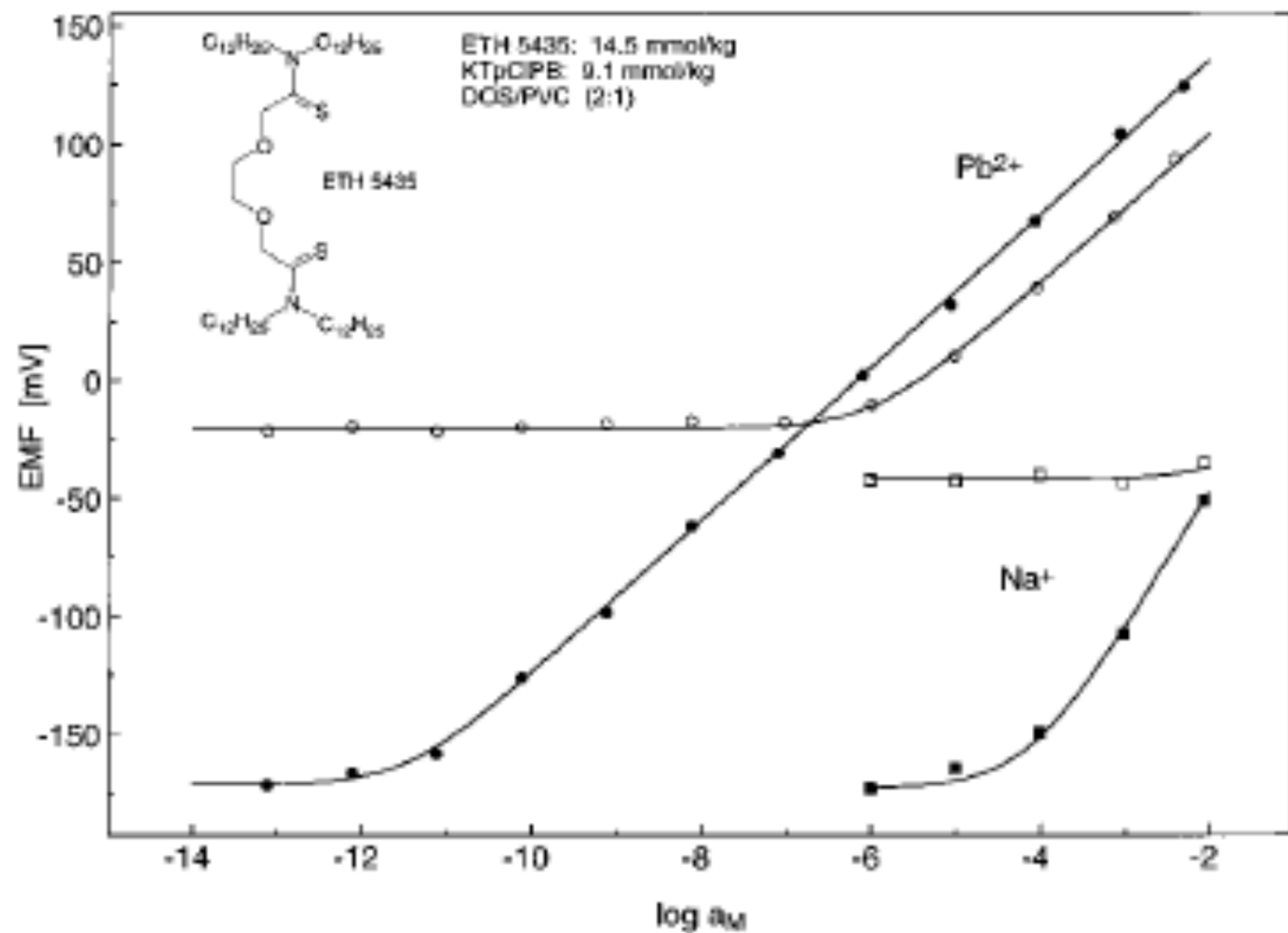
Nikolskii equation



$$a_{I,(LDL)} = K_{I,J}^{pot} a_J$$

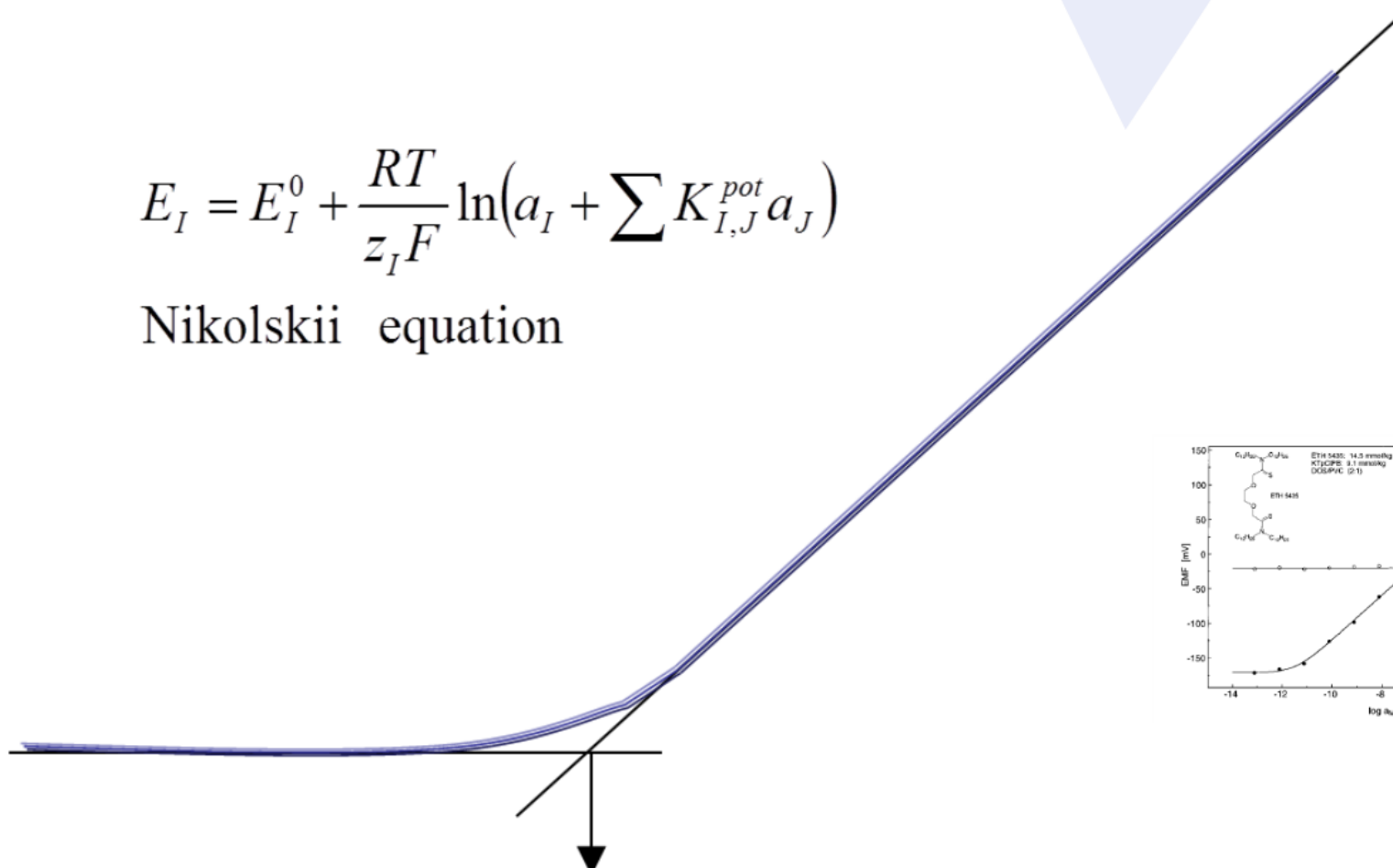
$\log a_I$





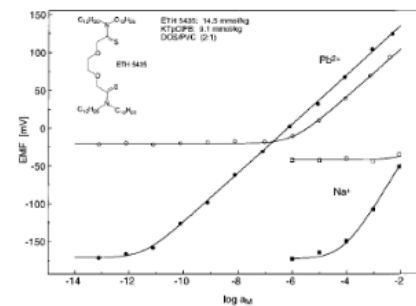
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Nikolskii equation



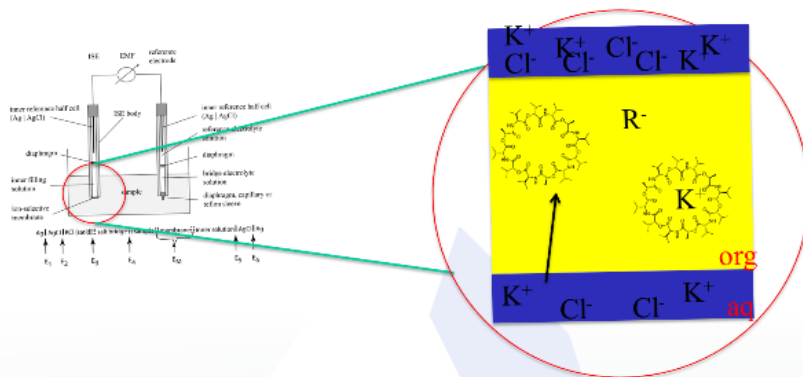
$$a_{I,(LDL)} = K_{I,J}^{pot} a_J$$

$\log a_I$



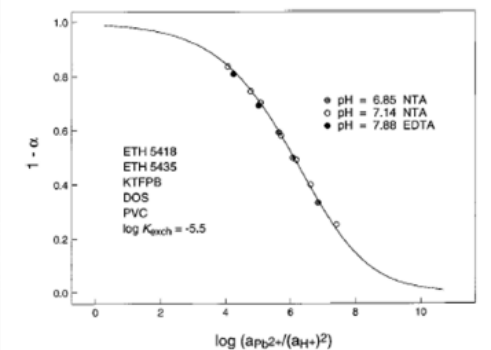
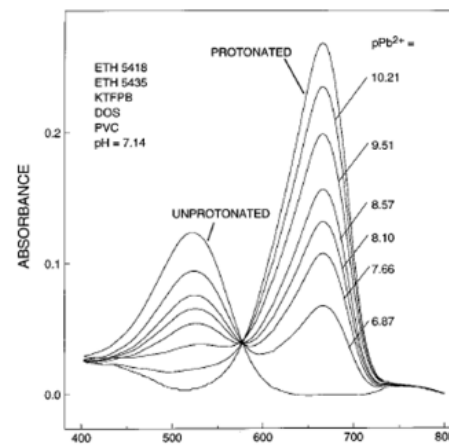
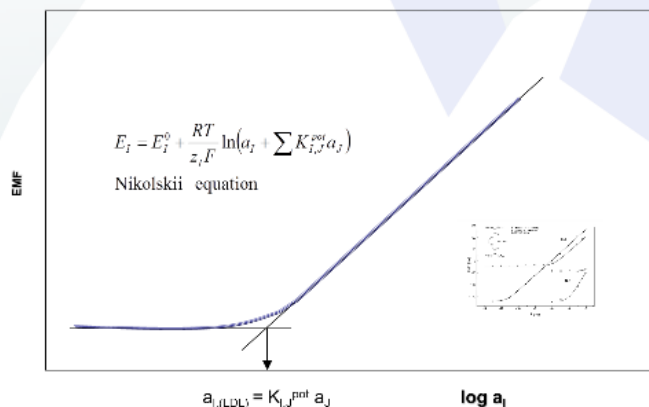
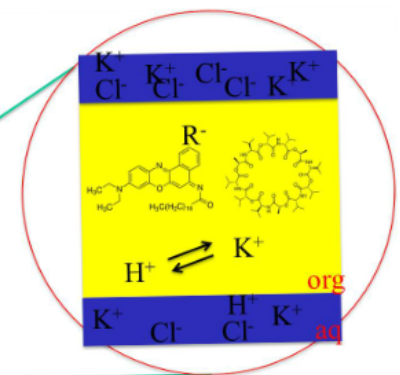
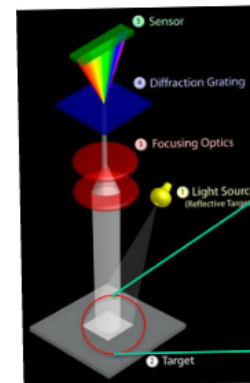
Experimental setup

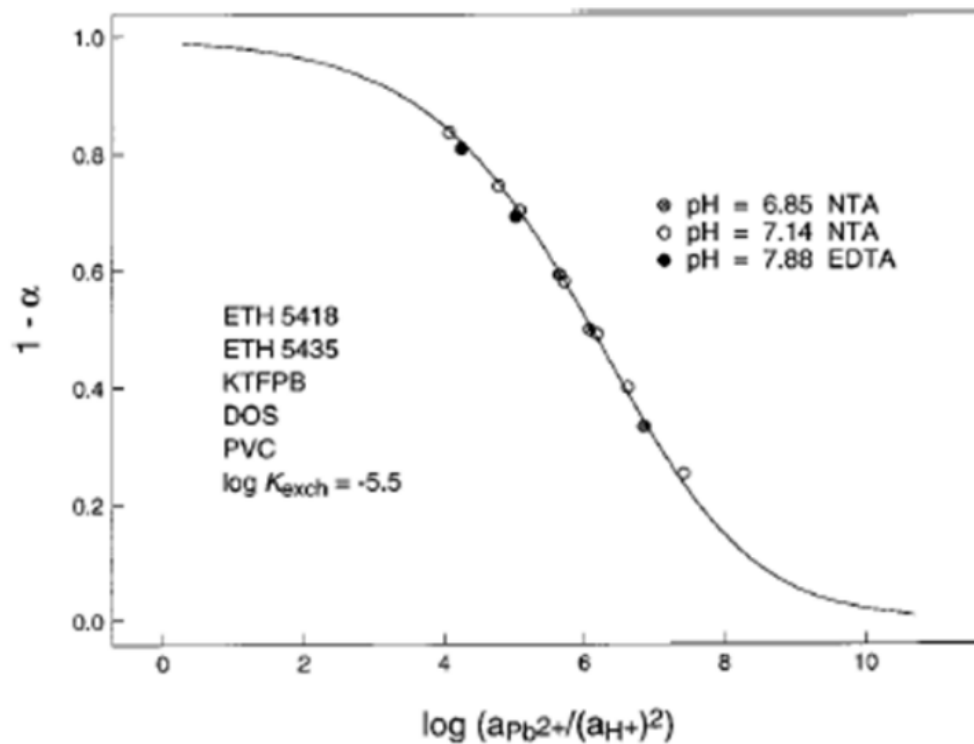
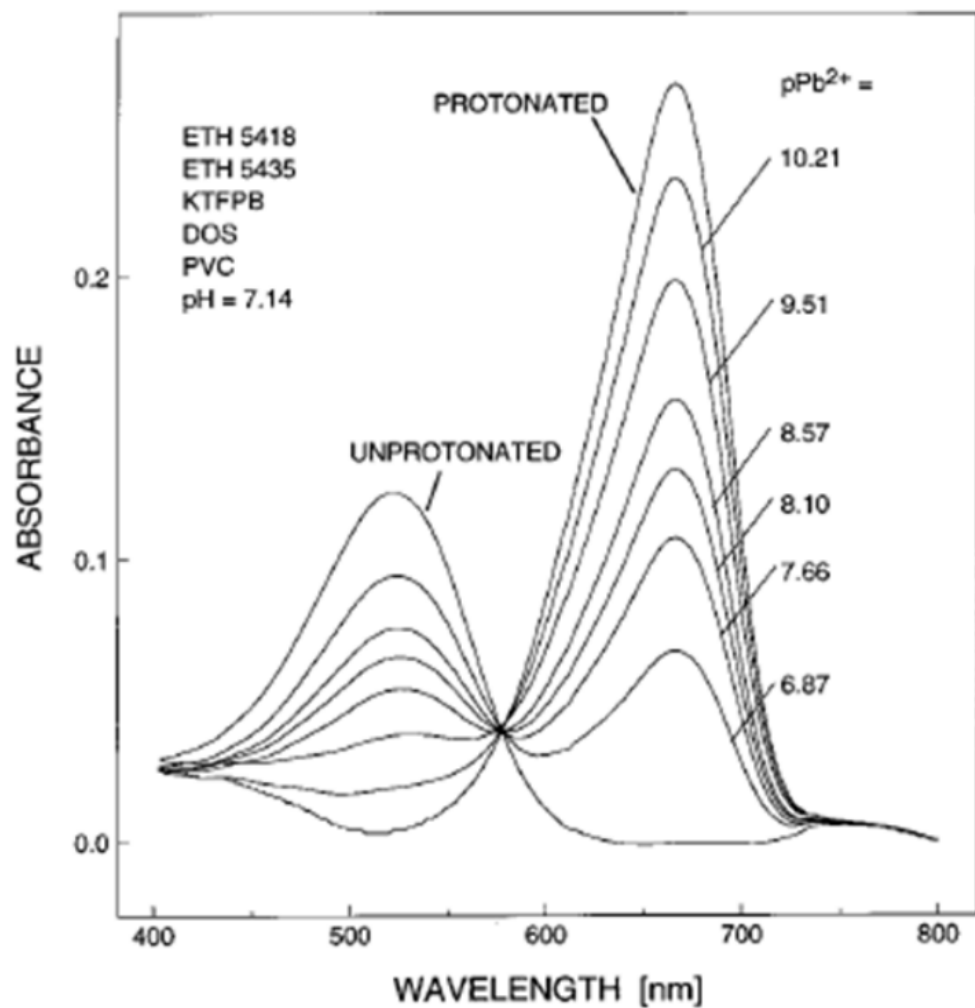
Ion-selective Electrodes

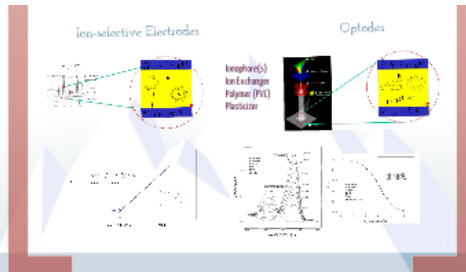


Optodes

Ionophore(s)
Ion Exchanger
Polymer (PVC)
Plasticizer



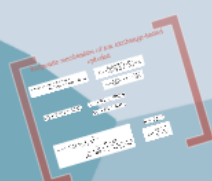
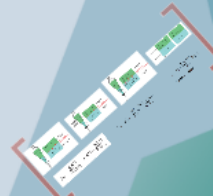
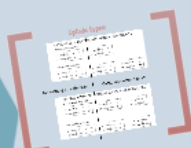


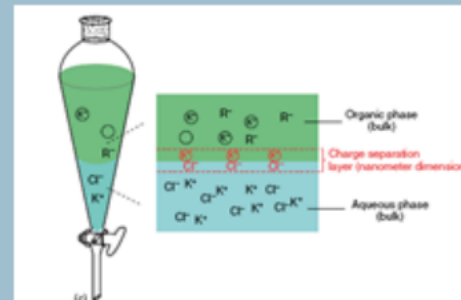
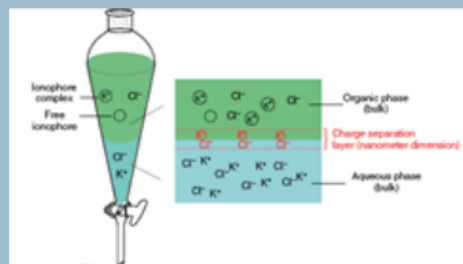
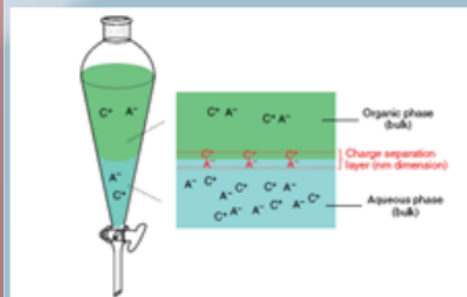


Response Mechanism

optodes

ISEs



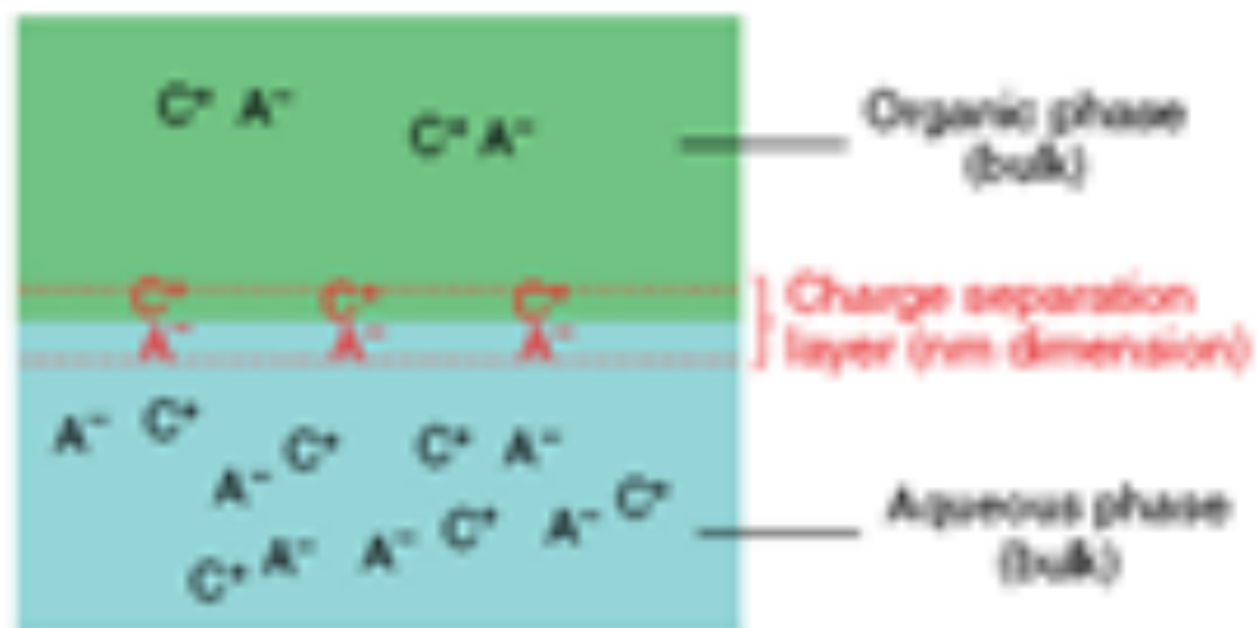


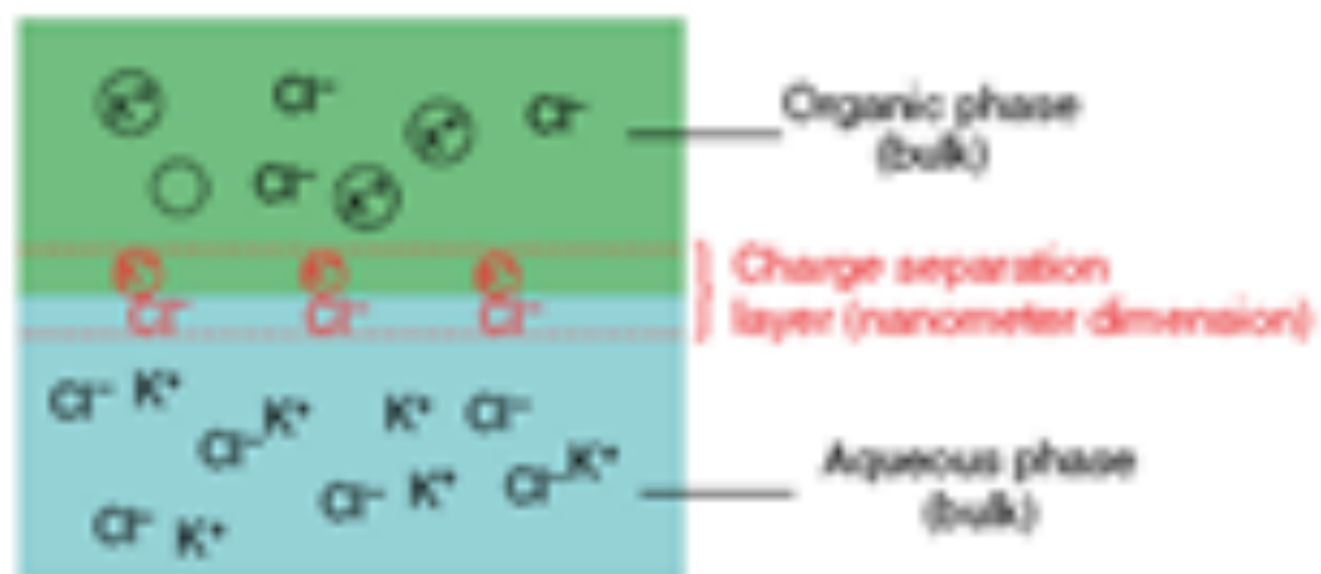
$$\beta_{1:1} = \frac{[LK^+]}{[L][K^+]} \Rightarrow [K^+] = \frac{[LK^+]}{[L]\beta_{1:1}}$$

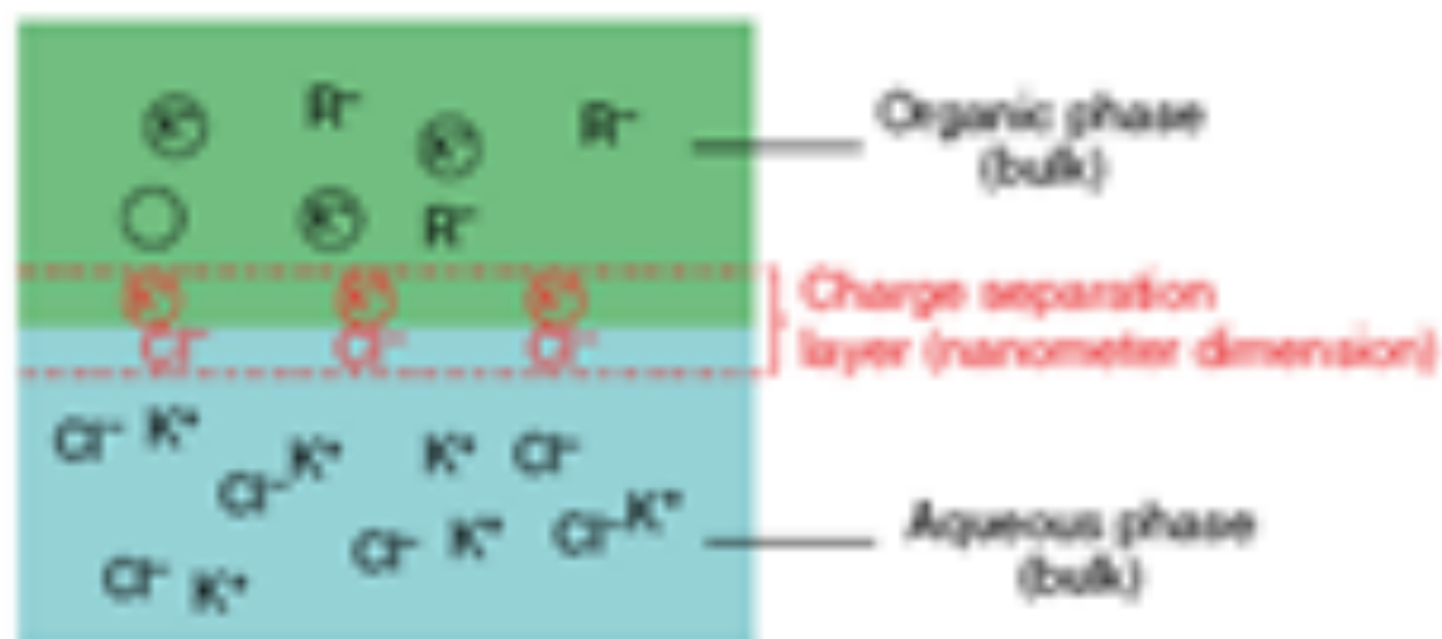
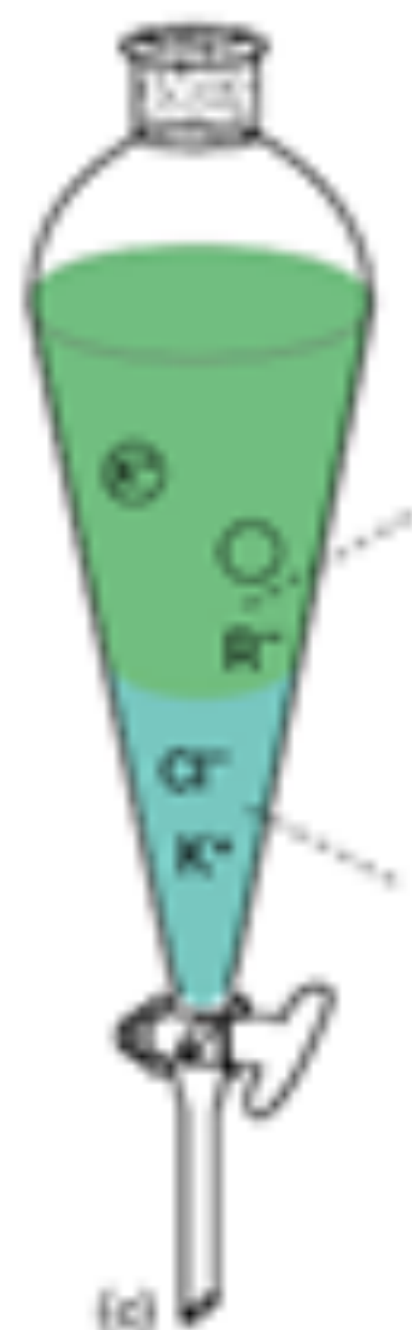
$$E_{PB} = E_{PB,I}^0 + \frac{RT}{z_I F} \ln \frac{k_I \beta_{IL} [L] a_{I,aq}}{[IL^+]_{org}}$$

$$E_I = E_I^0 + \frac{2.303RT}{z_I F} \log a_I$$

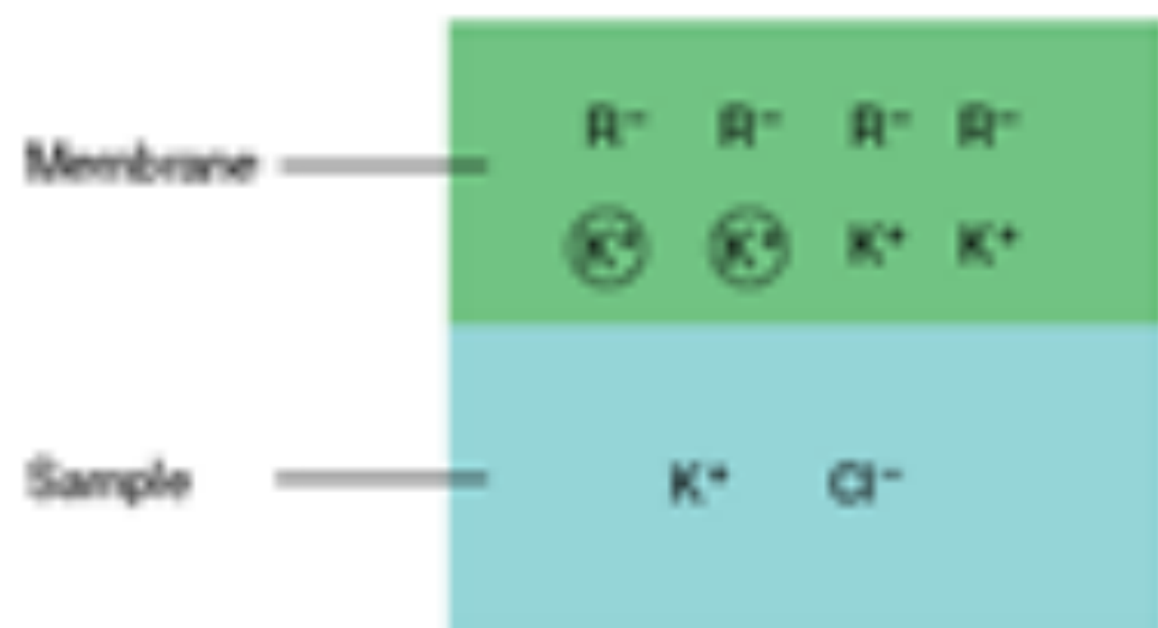
Nernst equation







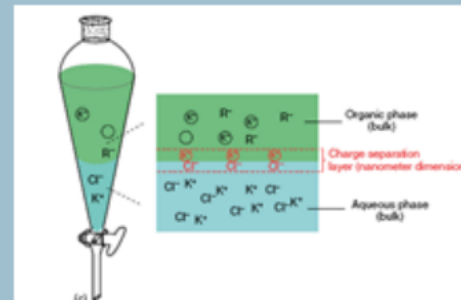
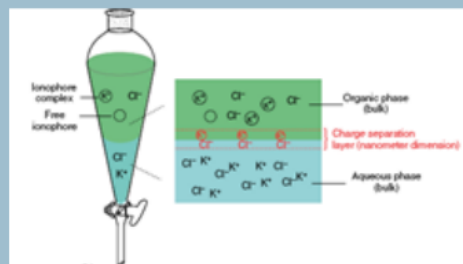
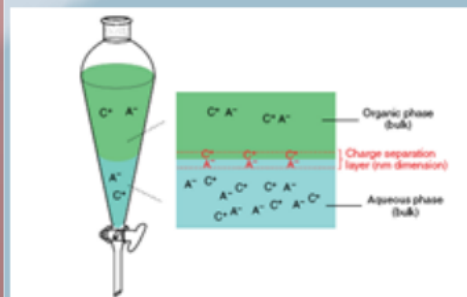
(c)



(a)



(b)



$$\beta_{1:1} = \frac{[LK^+]}{[L][K^+]} \Rightarrow [K^+] = \frac{[LK^+]}{[L]\beta_{1:1}}$$

$$E_{PB} = E_{PB,I}^0 + \frac{RT}{z_I F} \ln \frac{k_I \beta_{IL} [L] a_{I,aq}}{[IL^+]_{org}}$$

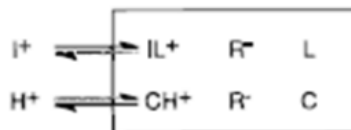
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Nernst equation

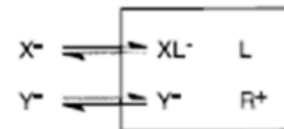
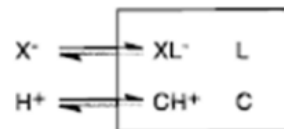
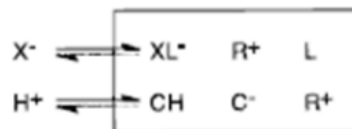
Optode types

OPTODES WITH ELECTRICALLY NEUTRAL IONOPHORE L

FOR CATIONIC ANALYTES



FOR ANIONIC ANALYTES

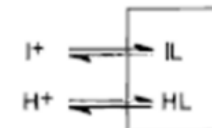
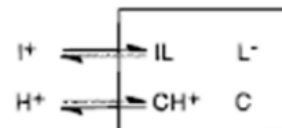


Ion exchange mechanism

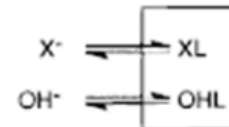
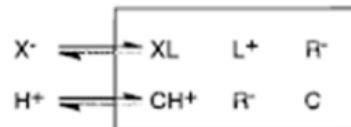
Coextraction mechanism

OPTODES WITH ELECTRICALLY CHARGED IONOPHORE L^- OR L^+

FOR CATIONIC ANALYTES



FOR ANIONIC ANALYTES



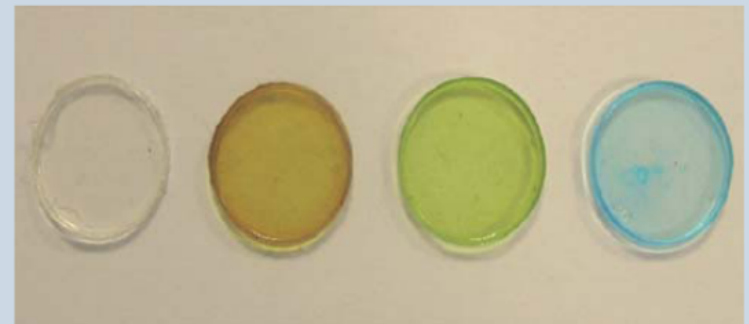
ReSponse mechanism of ion exchange-based optodes

Experimental protocol

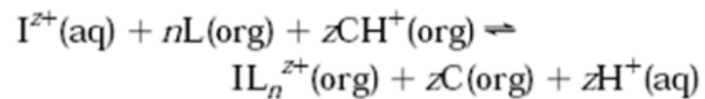
prepare membrane cocktail
(ionophores (L and C), ion exchanger (R),
polymer (PVC), plasticizer)

exposed the cast membrane to buffered!
solution of primary ion (I)

obtain spectroscopic (absorbance, fluorescence)
data



Response mechanism of ion exchange-based optodes



$$K_{\text{exch}}^{IL_n} = \left(\frac{a_H[C]}{[CH^+]} \right)^z \frac{[IL_n^{z+}]}{a_I[L]^n} = \left(\frac{K_a}{k_H} \right)^z k_V \beta_{IL_n}$$

$$\beta_{1:1} = \frac{[LK^+]}{[L][K^+]} \Rightarrow [K^+] = \frac{[LK^+]}{[L]\beta_{1:1}}$$

$$(R_T^- = [CH^+] + z[IL_n^{z+}])$$

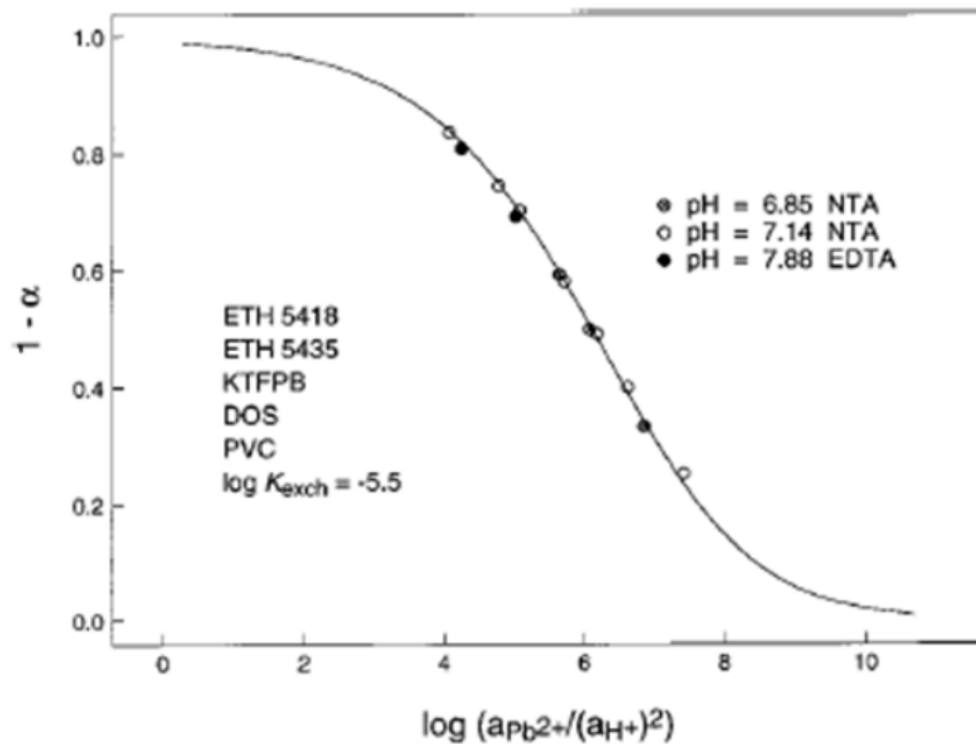
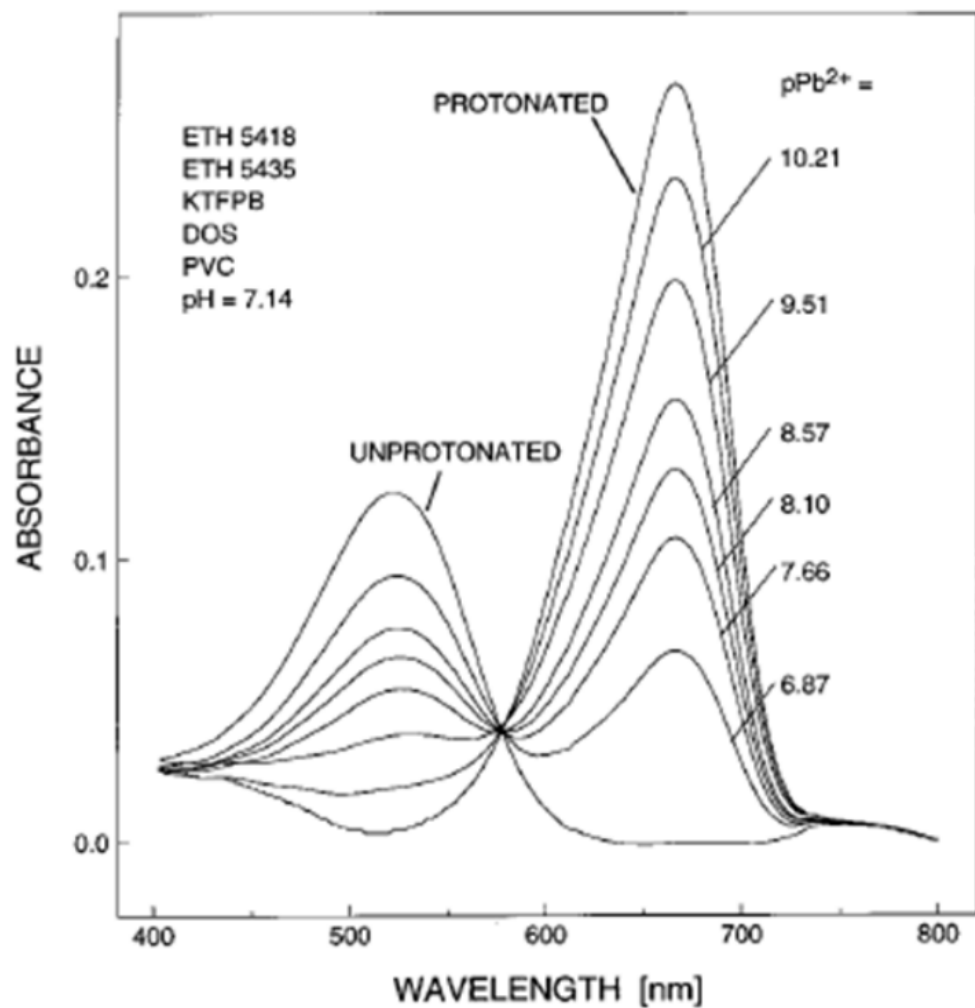
$$(L_T = [L] + n[IL_n^{z+}])$$

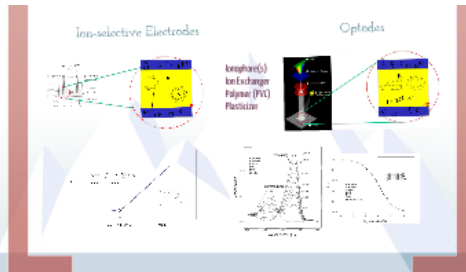
$$(C_T = [C] + [CH^+])$$

$$a_I = (zK_{\text{exch}}^{IL_n})^{-1} \left(\frac{\alpha}{1-\alpha} a_H \right)^z \times \frac{R_T^- - (1-\alpha)C_T}{\{L_T - (R_T^- - (1-\alpha)C_T)(n/z)\}^n}$$

$$(\alpha = [C]/C_T)$$

$$\alpha = \frac{A_P - A}{A_P - A_D}$$





Response Mechanism

optodes

ISEs

optode type

Optode type: Ion-selective electrode (ISE) with a membrane (PII) and a reference electrode (RE).

Response mechanism: The optode type is based on the ion-selective electrode (ISE) with a membrane (PII) and a reference electrode (RE).

Flow diagram of optode

Flow diagram of optode: The optode type is based on the ion-selective electrode (ISE) with a membrane (PII) and a reference electrode (RE).

ACTIVITY

ACTIVITY: The optode type is based on the ion-selective electrode (ISE) with a membrane (PII) and a reference electrode (RE).

Response mechanism of ion-selective electrode (ISE)

Response mechanism of ion-selective electrode (ISE): The optode type is based on the ion-selective electrode (ISE) with a membrane (PII) and a reference electrode (RE).

Response mechanism of ion-selective electrode (ISE)

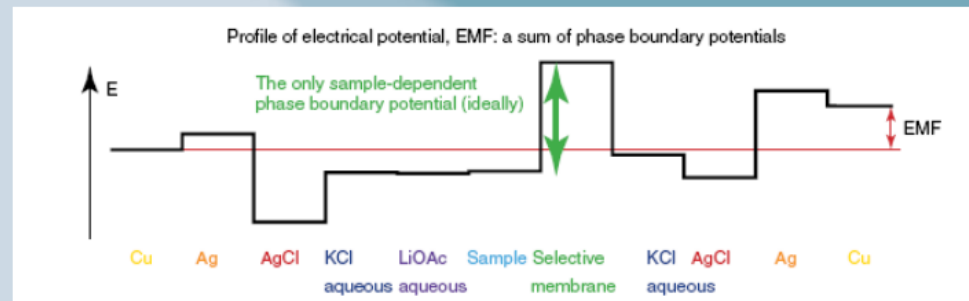
Response mechanism of ion-selective electrode (ISE): The optode type is based on the ion-selective electrode (ISE) with a membrane (PII) and a reference electrode (RE).

Response mechanism of ion-selective electrode (ISE)

Response mechanism of ion-selective electrode (ISE): The optode type is based on the ion-selective electrode (ISE) with a membrane (PII) and a reference electrode (RE).

LS

Phase boundary potential

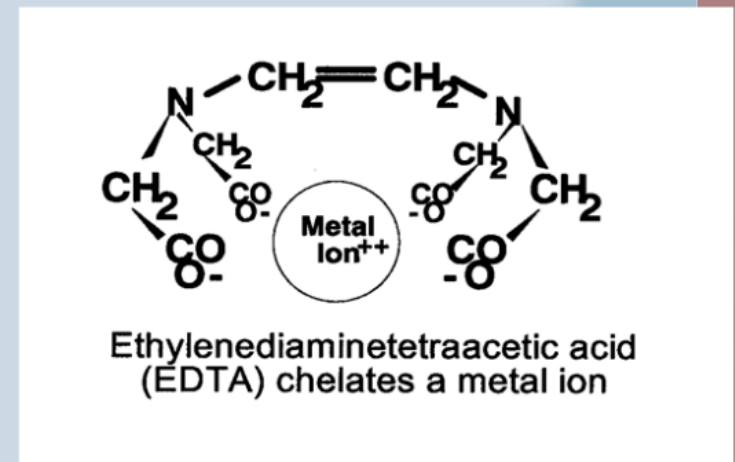
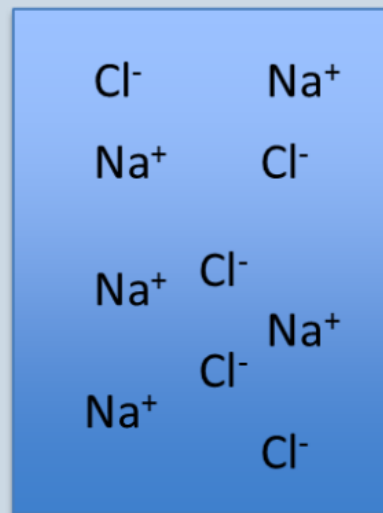
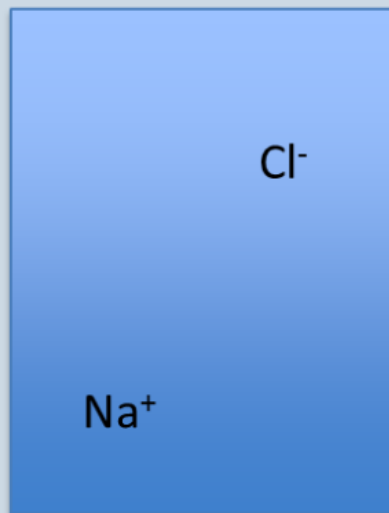


$$E_{PB} = \Delta\phi = -\frac{\mu^0(\text{org}) - \mu^0(\text{aq})}{zF} + \frac{RT}{zF} \ln \frac{a_1(\text{aq})}{a_1(\text{org})}$$

$$E_{PB} = E_{PB,i}^{\circ} + \frac{RT}{z_i F} \ln \frac{a_{i,\text{water}}}{a_{i,\text{organic}}}$$

ACTIVITY

- “effective concentration” – (chemical potential depends on the activity of a real solution in the same way that it would depend on concentration for an ideal solution)
- Activity of ion is affected by its surrounding (charge; presence of complexing agents etc)

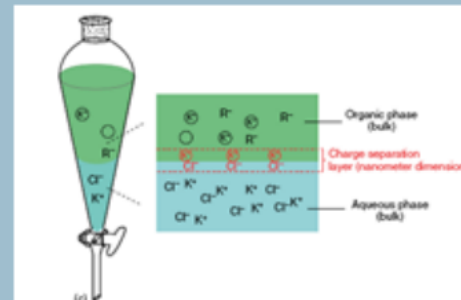
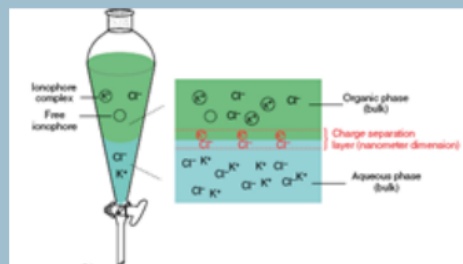
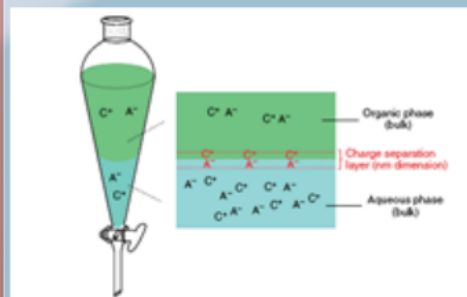


$$a = \gamma \times C$$

$a \rightarrow$ activity; $\gamma \rightarrow$ activity coefficient; $C \rightarrow$ concentration

$$0 < \gamma < 1$$

$\gamma = 1$ only in very diluted solutions



$$\beta_{1:1} = \frac{[LK^+]}{[L][K^+]} \Rightarrow [K^+] = \frac{[LK^+]}{[L]\beta_{1:1}}$$

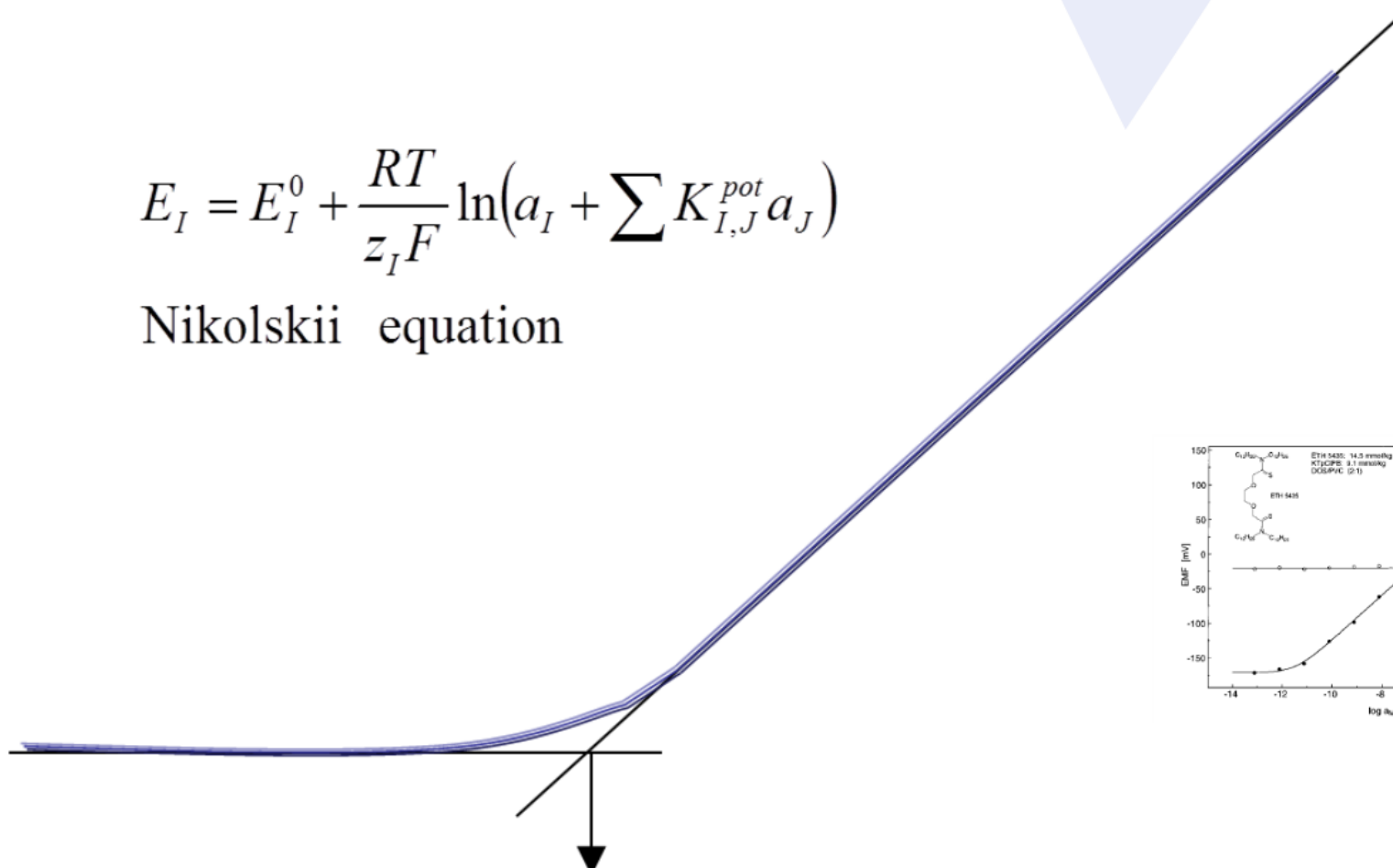
$$E_{PB} = E_{PB,I}^0 + \frac{RT}{z_I F} \ln \frac{k_I \beta_{IL} [L] a_{I,aq}}{[IL^+]_{org}}$$

$$E_I = E_I^0 + \frac{2.303RT}{z_I F} \log a_I$$

Nernst equation

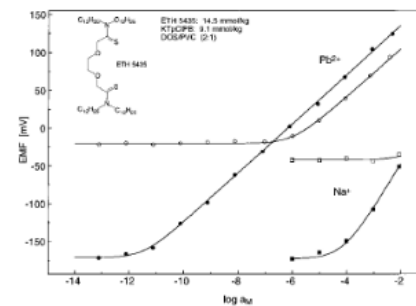
$$E_I = E_I^0 + \frac{RT}{z_I F} \ln(a_I + \sum K_{I,J}^{pot} a_J)$$

Nikolskii equation

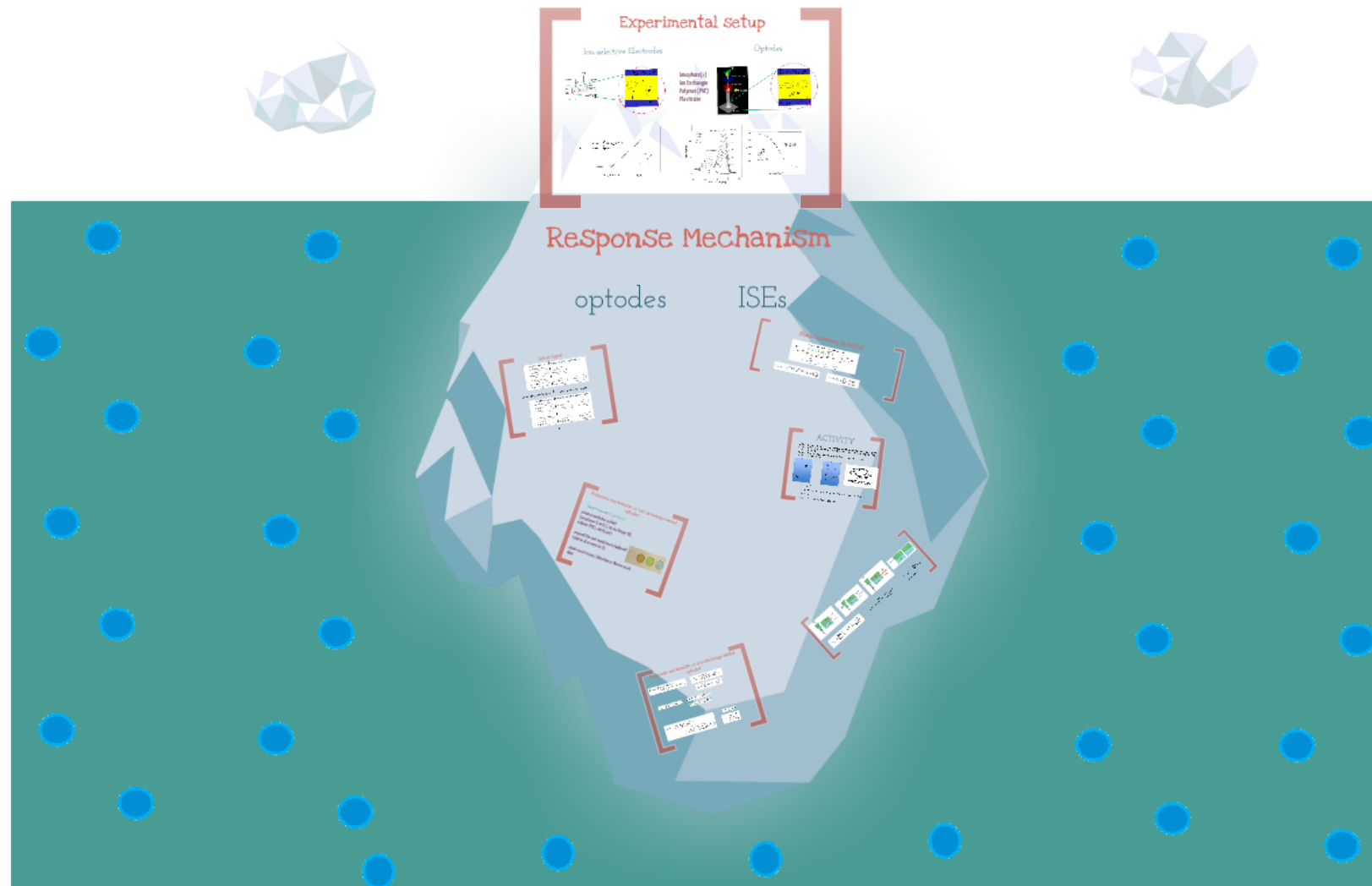


$$a_{I,(LDL)} = K_{I,J}^{pot} a_J$$

$\log a_I$

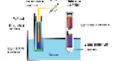


Mechanism of response



ISE measurement

Types of ISEs and corresponding LODs



Liquid contact "Classical"
~micromolar

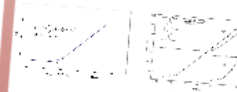


Liquid contact "Modern"
~nanomolar, picomolar



Solid contact
~nanomolar, picomolar

Detection limit



Experimental protocol

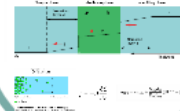
Classical Modern Solid

- Mix membrane components
- Cast and mount the membrane
- Condition the electrode

Prepare the membrane to ~100 pH solution of primary ion / low ionic strength

Cast the membrane on a glass or plastic substrate. Immerse the membrane in a solution of the primary ion for 24 hours. Rinse the membrane with distilled water.

Ion fluxes



Selectivity

Classical ISEs: Selectivity is determined by the membrane composition. Modern ISEs: Selectivity is determined by the membrane composition and the electrode design.

Experimental protocol (Sel. conf.)

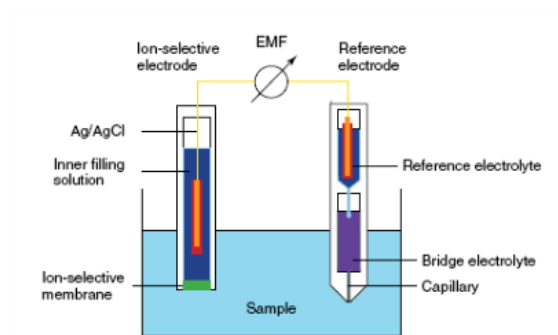
Classical Modern (liquid- and solid-contact)

- Mix membrane components
- Cast and mount the membrane
- Condition the electrode

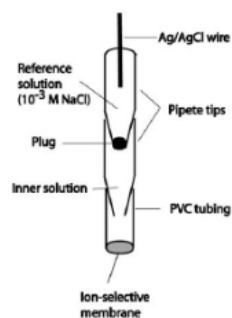
Prepare the membrane to ~100 pH solution of primary ion / low ionic strength

Expose the membrane to ~100 pH solution of interfering ion / low ionic strength. Measure the selectivity coefficient. Rinse the membrane with distilled water.

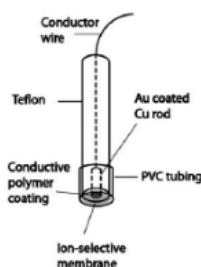
Types of ISEs and corresponding LODs



Liquid contact "Classical"
~micromolar



Liquid contact "Modern"
~nanomolar; picomolar



Solid contact
~nanomolar; picomolar

Experimental protocol

Classical

Modern

Solid

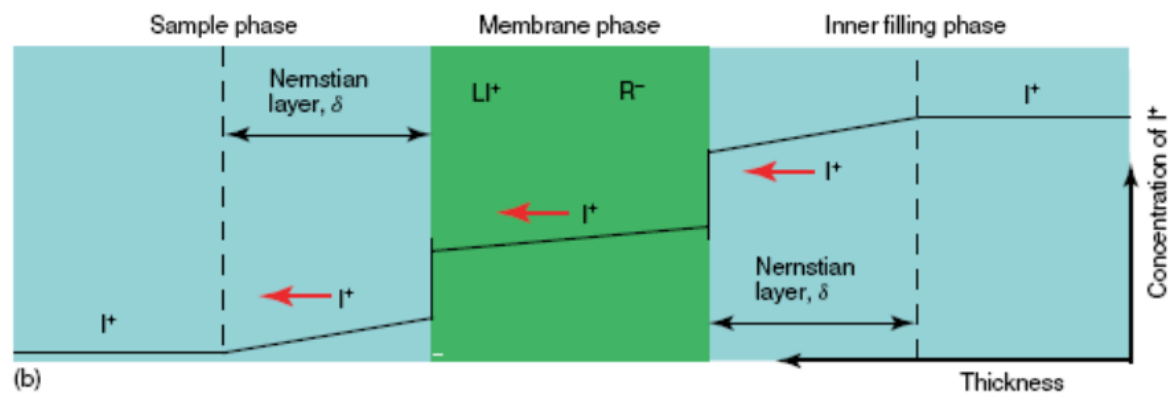
- Mix membrane components
- Cast and mount the membrane
- Condition the electrode

Expose the membrane to
~10⁻³M solution of primary
ion from both sides

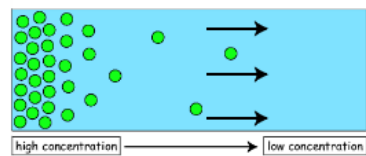
- Expose the membrane to ~10⁻³M solution of primary ion from both sides
- Expose the membrane to ~10⁻⁹M (may vary according to analyte) of primary ion from both sides

- Expose the membrane to ~10⁻³M solution of primary ion
- Expose the membrane to ~10⁻⁹M (may vary according to analyte) of primary ion

Ion fluxes



Diffusion

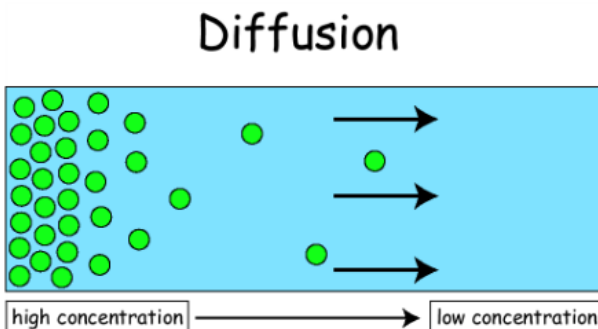
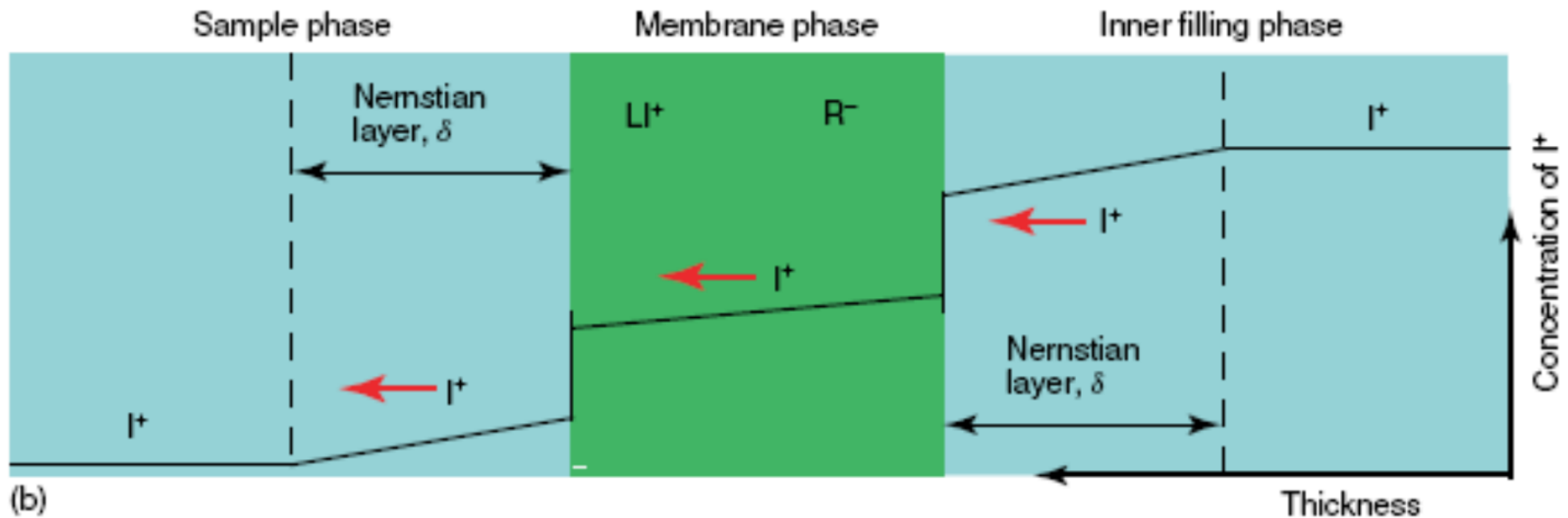


Solute transport is from the left to the right; movement of the solutes is due to the concentration gradient (dC/dx).

$$J = -D \frac{\partial C}{\partial x}$$

$$a_{I,PB} = a_{I,bulk} + \frac{D_{org}\delta_{aq}}{D_{aq}\delta_{org}} ([IL^+]' - [IL^+])$$

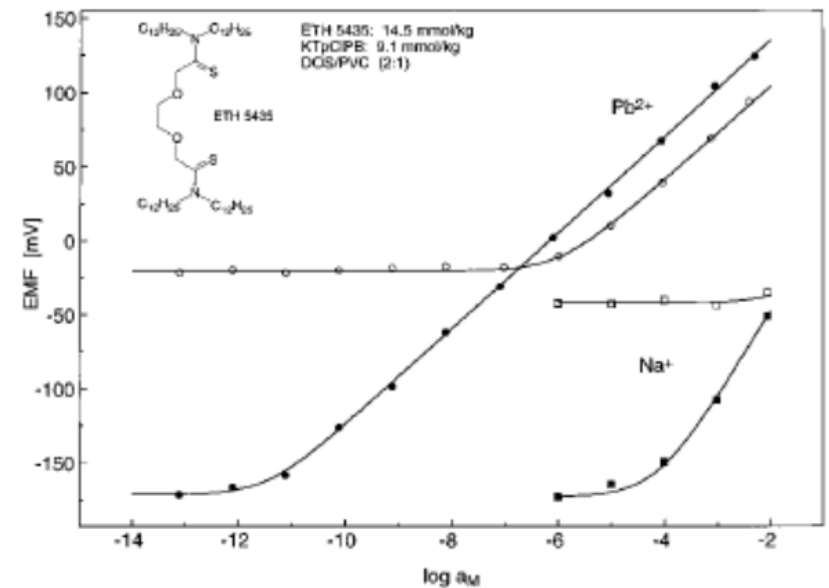
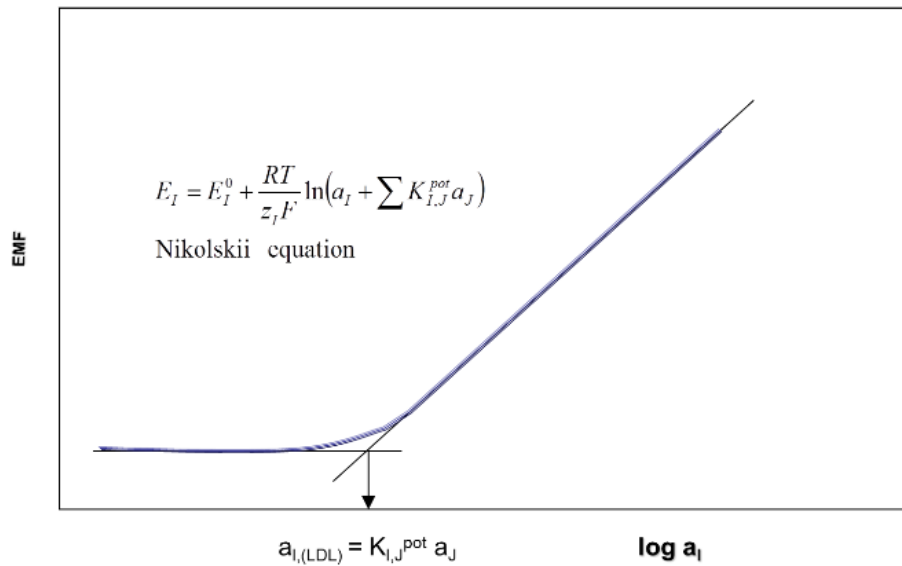
Ion fluxes



$$J = -D \frac{\partial C}{\partial x}$$

$$a_{I,PB} = a_{I,bulk} + \frac{D_{org}\delta_{aq}}{D_{aq}\delta_{org}} ([IL^+] - [IL^+])$$

Detection limit



Selectivity

ISEs are not ideally ion-specific – they are sensitive to other ions to some extent.

Selectivity coefficient defines the ability of ISE to distinguish between different ions.

If $K_{IJ}=0.001$ ($\log K_{IJ}=-3$), ISE is 1000 times more sensitive to I than to J.

Selectivity coefficient is independent of experimental conditions

True only in modern ISEs!

Experimental protocol (sel coef)

Classical

Expose the membrane to
~10⁻³M solution of **primary**
ion from both sides

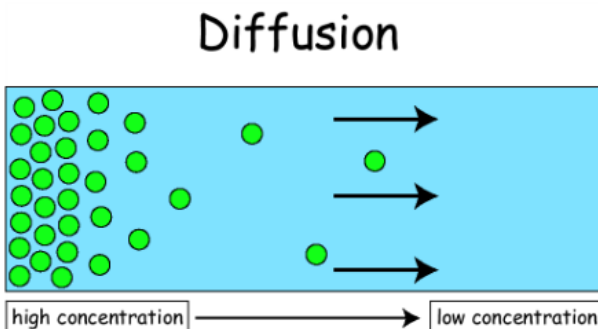
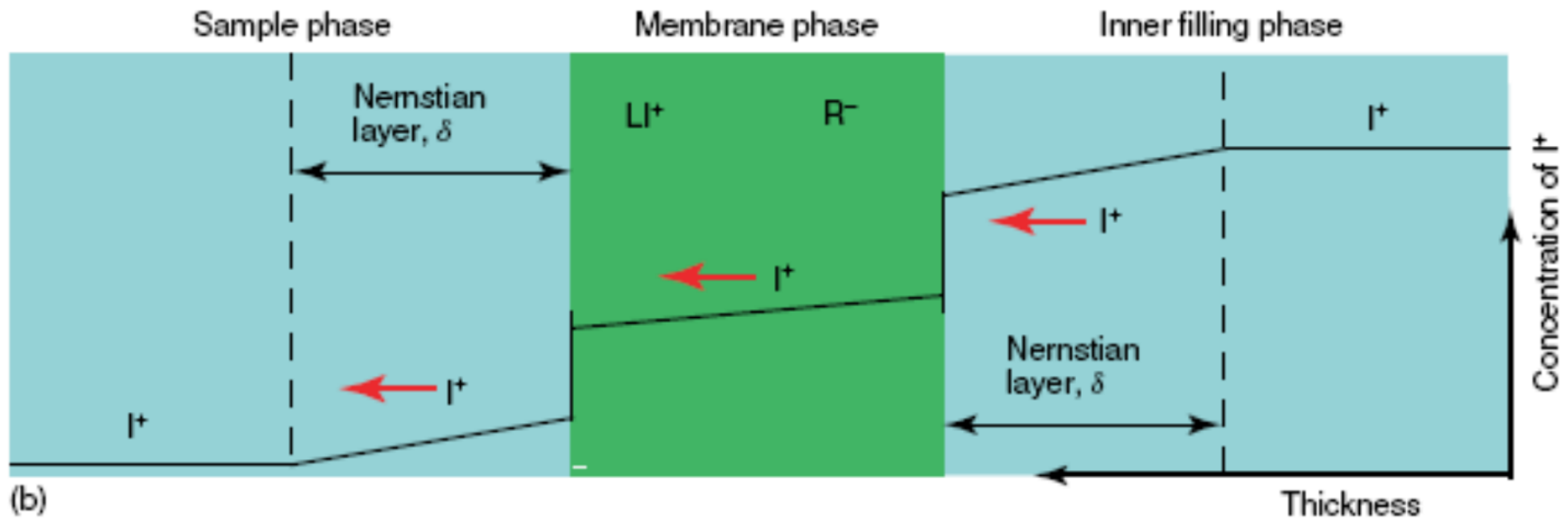
- Mix membrane components
- Cast and mount the membrane
- Condition the electrode

Modern (liquid- and solid-contact)

Expose the membrane to
~10⁻³M solution of
interfering ion from both
sides

Measure all interfering
ions prior to
measurement of primary
ion!

Ion fluxes

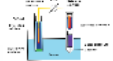


$$J = -D \frac{\partial C}{\partial x}$$

$$a_{I,PB} = a_{I,bulk} + \frac{D_{org}\delta_{aq}}{D_{aq}\delta_{org}} ([IL^+]' - [IL^+])$$

ISE measurement

Types of ISEs and corresponding LODs



Liquid contact "Classical"
~micromolar

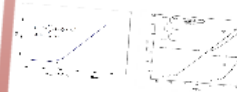


Liquid contact "Modern"
~nanomolar, picomolar



Solid contact
~nanomolar, picomolar

Detection limit



Experimental protocol

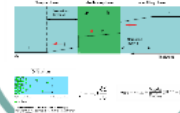
Classical Modern Solid

- Mix membrane components
- Cast and mount the membrane
- Condition the electrode

Prepare the membrane to
~100 pH solution of primary
ion / low ionic strength

Cast the membrane
to form a uniform
film on the electrode
surface. The thickness
of the film should be
controlled by the
casting process.

Ion fluxes



Selectivity

ISE selectivity is defined as the ability of the electrode to respond to a specific ion in the presence of other ions. It is a measure of the electrode's ability to discriminate between the primary ion and other ions that may interfere with the measurement.

Experimental protocol (Sel. conf.)

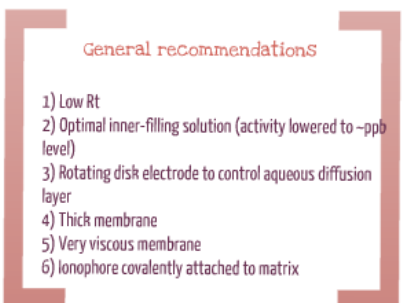
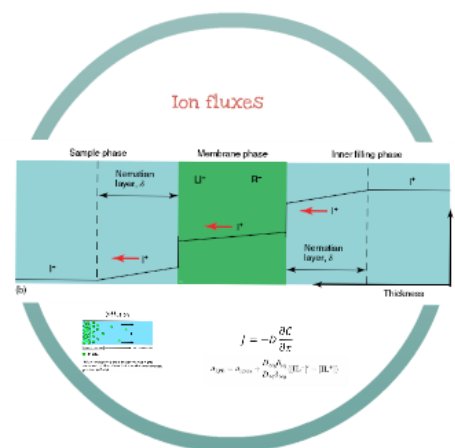
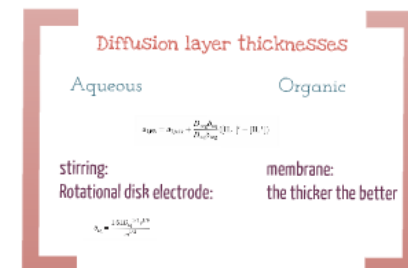
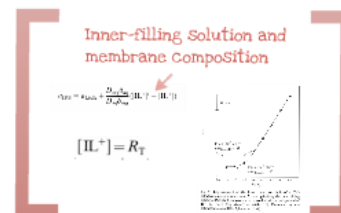
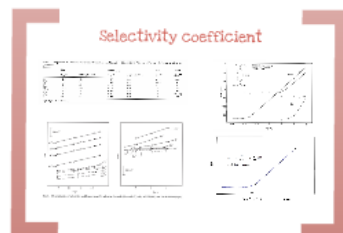
Classical Modern (liquid- and solid-contact)

- Mix membrane components
- Cast and mount the membrane
- Condition the electrode

Prepare the membrane to
~100 pH solution of primary
ion / low ionic strength

Expose the membrane to
~100 pH solution of
interfering ion / low ionic
strength. Measure all interfering
ions. In
improvement of primary
ion

Guidelines for optimisation of critical parameters and obtaining ISES with optimal LOD



Selectivity coefficient

Table 1. Comparison of potentiometric selectivity coefficients obtained by SSM, MSSM, FIM and MPM for a Cs⁺-selective electrode (electrode A).

	SSM		MSSM [11]		FIM	MPM
	$K_{Cs^+}^{pot}$	Slope (mV/dec)	$K_{Cs^+}^{pot}$	Slope (mV/dec)	$K_{Cs^+}^{pot}$	$K_{Cs^+}^{MPM}$
Li ⁺	-3.7	0.3	-6.8	64.5	-3.9	-4.4
Na ⁺	-4.1	14.7	-4.7	62.1	-4.0	-3.7
K ⁺	-2.5	40.9	-2.9	60.7	-2.5	-2.7
Rb ⁺	-1.2	51.0	-1.2	65.8	-1.2	-1.3
Mg ²⁺	-4.5	1.2	-8.7	21.0	-4.3	-4.1
Ca ²⁺	-4.5	1.7	-8.5	30.5	-4.4	N/A[a]
Sr ²⁺	-4.5	18.5	-6.8	36.3	-4.4	-3.5

[a] Not possible to determine

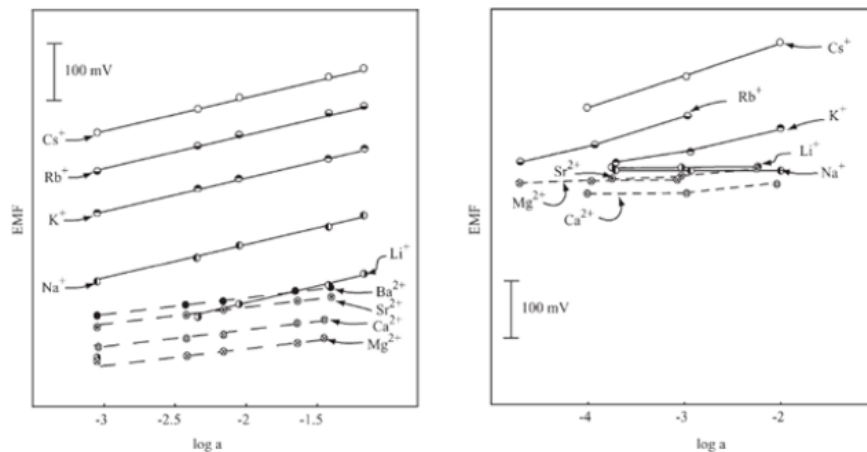
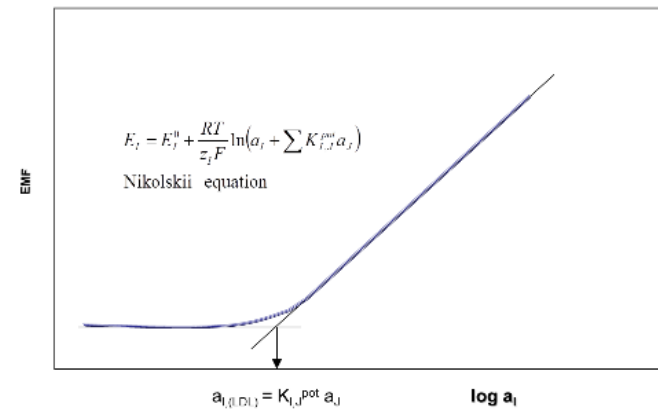
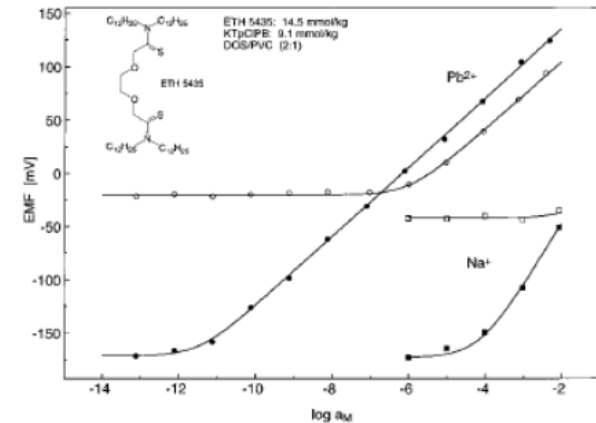
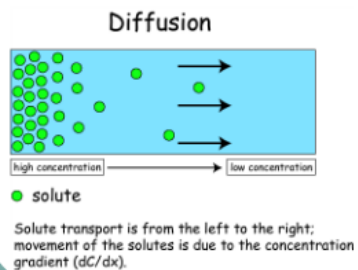
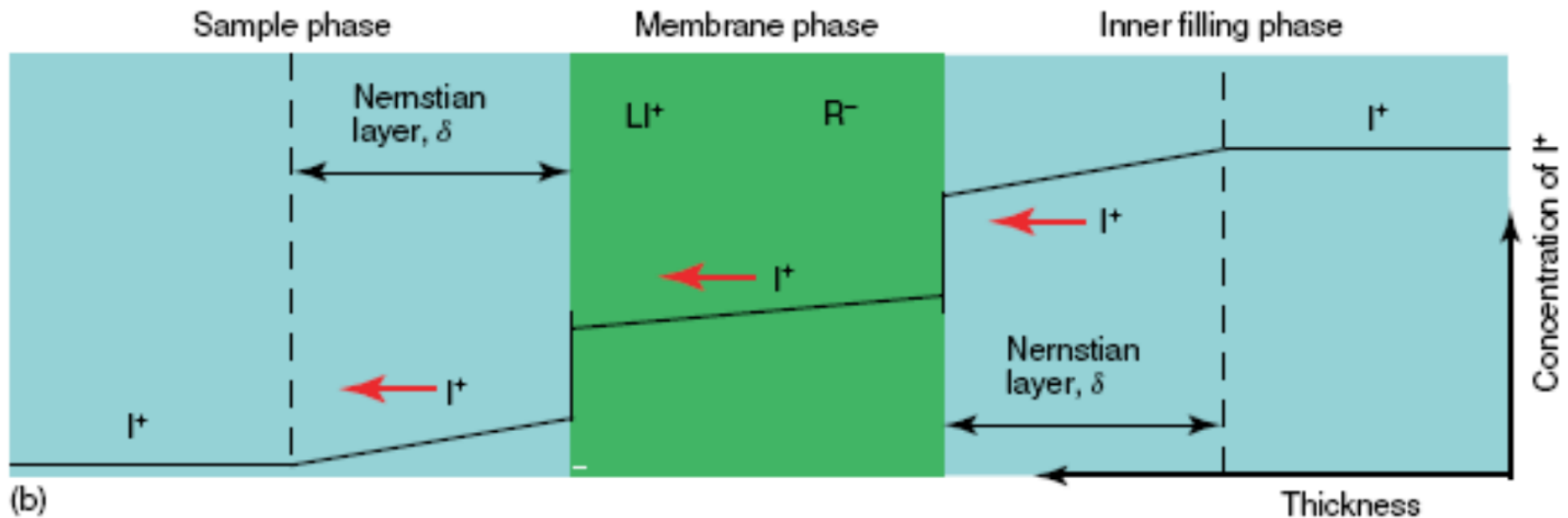


Fig. 1. Determination of selectivity coefficients for a Cs⁺-selective electrode (electrode A) using MSSM (left) and classical SSM (right).



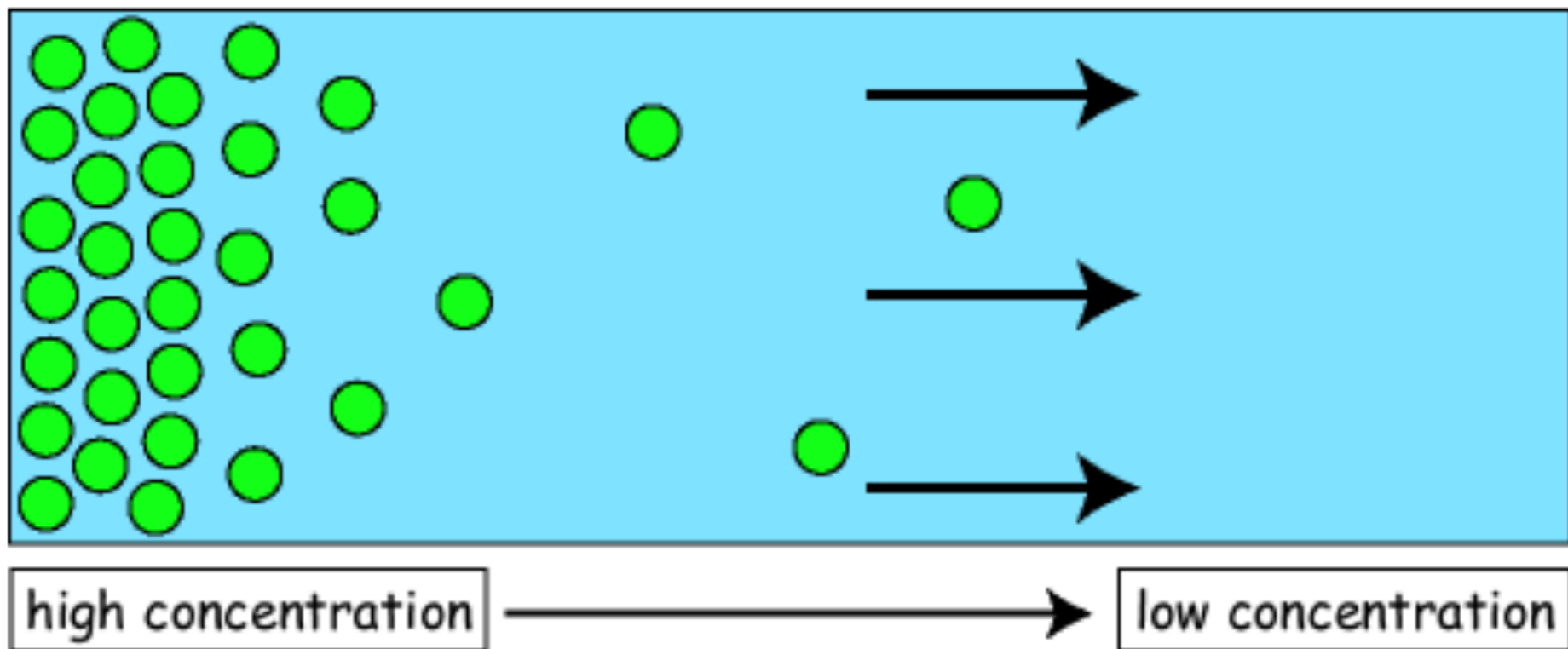
Ion fluxes



$$J = -D \frac{\partial C}{\partial x}$$

$$a_{I,PB} = a_{I,bulk} + \frac{D_{org} \delta_{aq}}{D_{aq} \delta_{org}} ([IL^+] - [IL^+]')$$

Diffusion



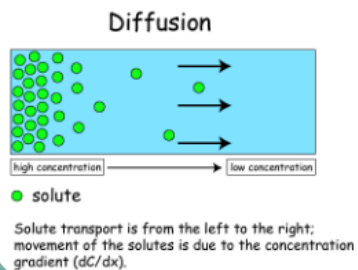
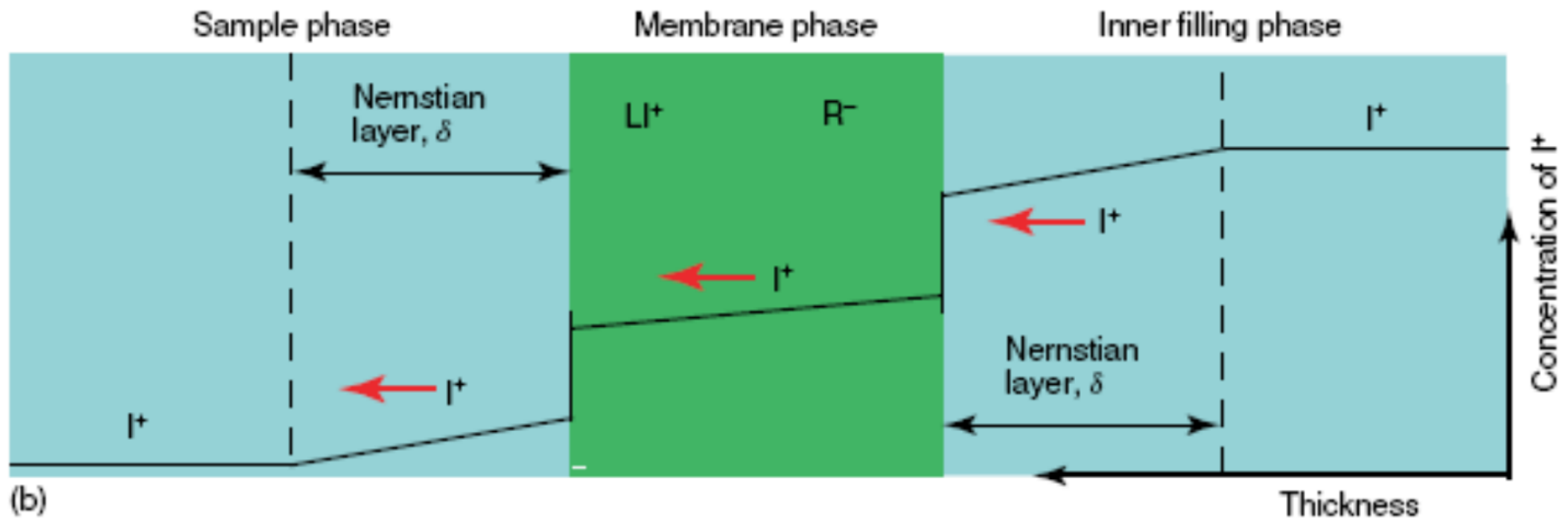
● solute

Solute transport is from the left to the right; movement of the solutes is due to the concentration gradient (dC/dx).

$$J = -D \frac{\partial \mathcal{C}}{\partial x}$$

$$a_{\text{I,PB}} = a_{\text{I,bulk}} + \frac{D_{\text{org}} \delta_{\text{aq}}}{D_{\text{aq}} \delta_{\text{org}}} ([\text{IL}^+] - [\text{IL}^+]')$$

Ion fluxes



$$J = -D \frac{\partial C}{\partial x}$$

$$a_{I,PB} = a_{I,bulk} + \frac{D_{org} \delta_{aq}}{D_{aq} \delta_{org}} ([IL^+] - [IL^+]')$$

Inner-filling Solution and membrane Composition

$$a_{I,PB} = a_{I,bulk} + \frac{D_{org}\delta_{aq}}{D_{aq}\delta_{org}} ([IL^+] - [IL^+]')$$

$$[IL^+] = R_T$$

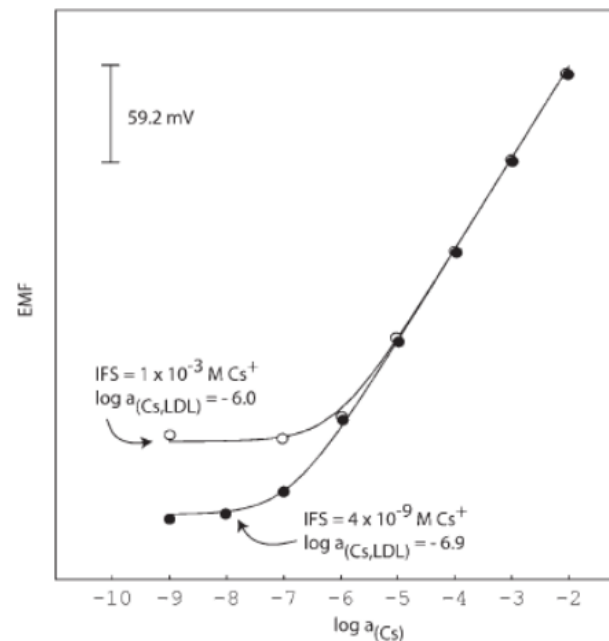


Fig.2. Improvement of the lower detection limit of a Cs^+ -selective electrode (electrode A) via optimizing the inner filling solution. Potential responses were recorded with a background of 10^{-5} M NaCl ($\log K_{CsNa}^{pot} = -4.68$) [11]. Parameter q was estimated as $q \approx 0.002$ (please see text).

Diffusion layer thicknesses

Aqueous

Organic

$$a_{\text{I,PB}} = a_{\text{I,bulk}} + \frac{D_{\text{org}}\delta_{\text{aq}}}{D_{\text{aq}}\delta_{\text{org}}} ([\text{IL}^+]' - [\text{IL}^+])$$

stirring:

Rotational disk electrode:

$$\delta_{\text{aq}} = \frac{1.61 D_{\text{aq}}^{1/3} \nu^{1/6}}{\omega^{1/2}}$$

membrane:

the thicker the better

Diffusion coefficient

organic phase

aqueous phase

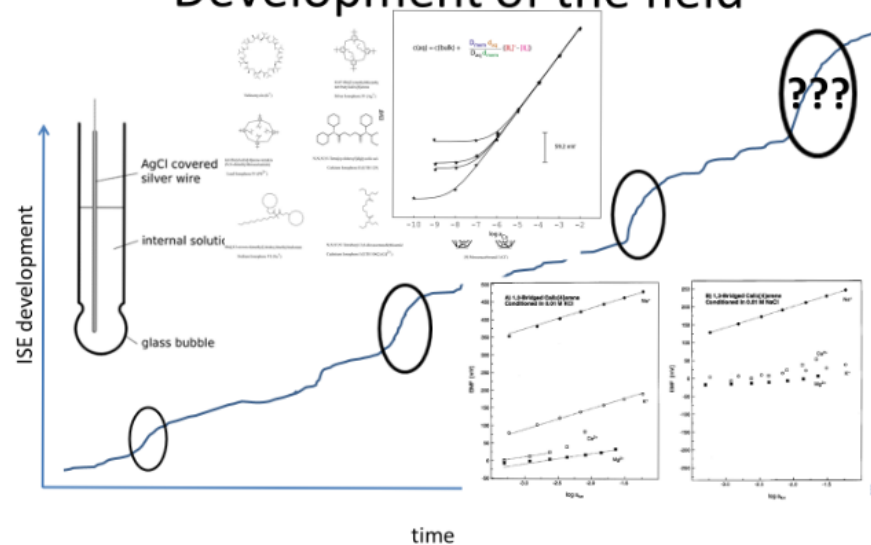
- increasing the viscosity of matrix
- covalently attaching ionophore

General recommendations

- 1) Low R_t
- 2) Optimal inner-filling solution (activity lowered to ~ppb level)
- 3) Rotating disk electrode to control aqueous diffusion layer
- 4) Thick membrane
- 5) Very viscous membrane
- 6) Ionophore covalently attached to matrix

State-of-the-art

Development of the field



State-of-the-art

Methodologies

Materials

Hyphenated IBSs



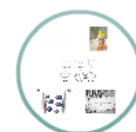
IBSs as detectors



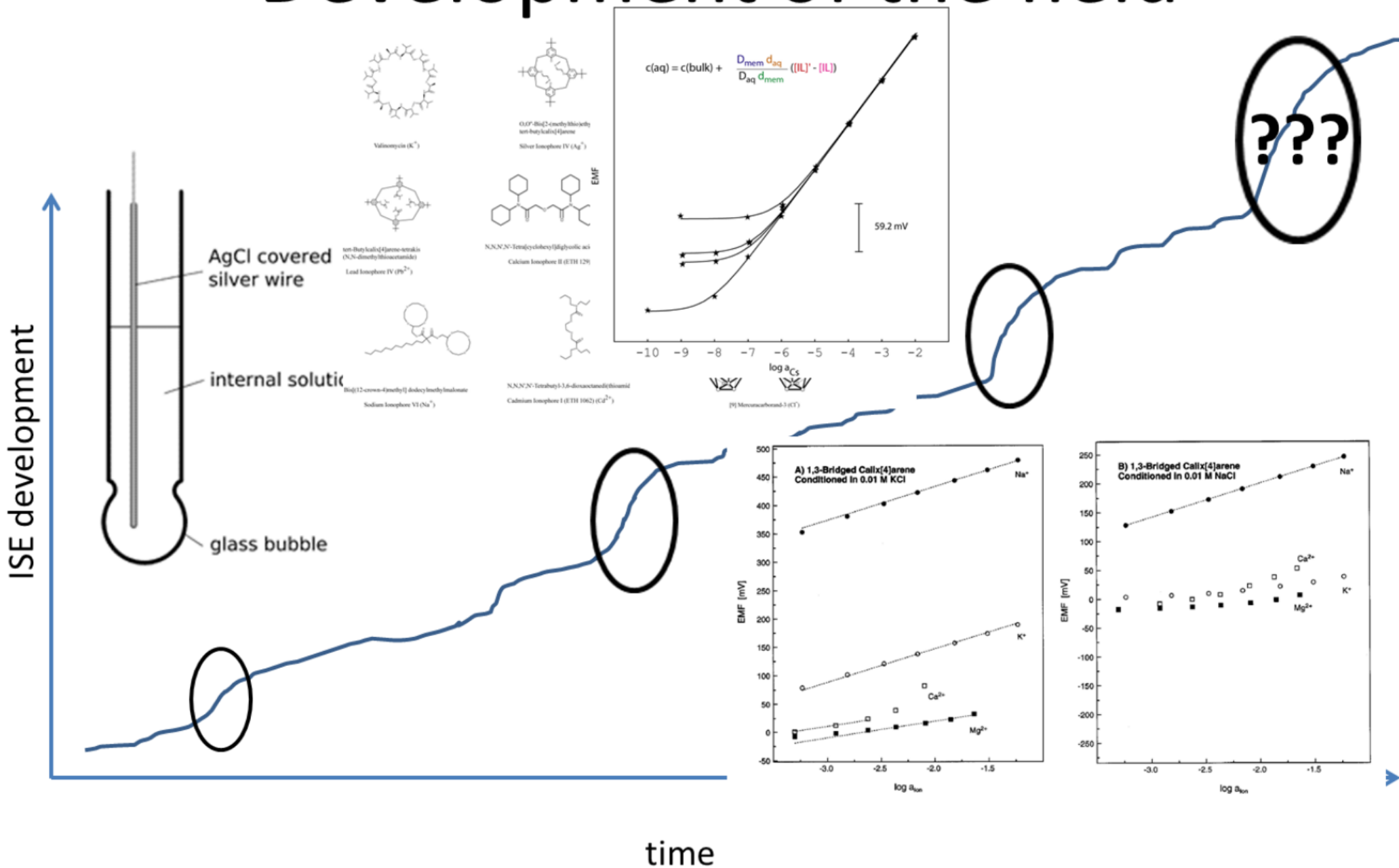
Fluorous membranes



Ionic liquids



Development of the field

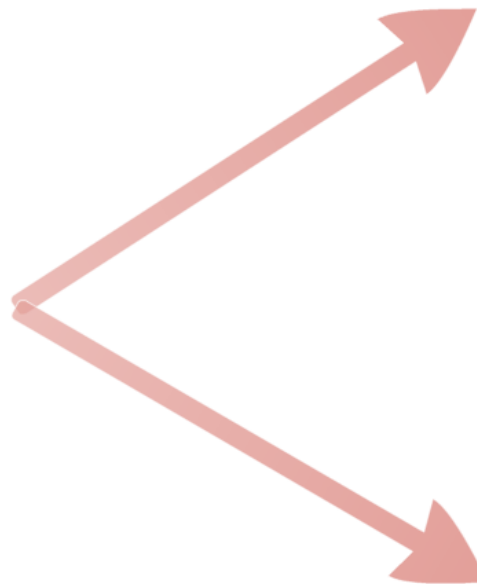


time

Methodologies

State-of-the-art

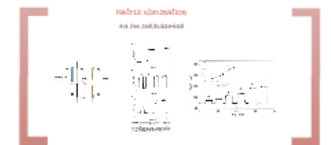
Materials



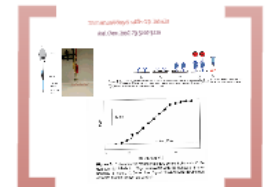
time

Methodologies

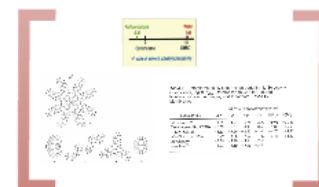
Hyphenated IBSs



IBSs as detectors

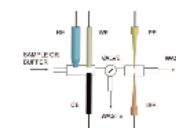


Fluorous membranes



Materials

Hyphenated IBSs



Matrix elimination

Anal. Chem. 2008, 80, 6114–6118

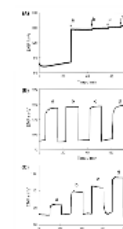
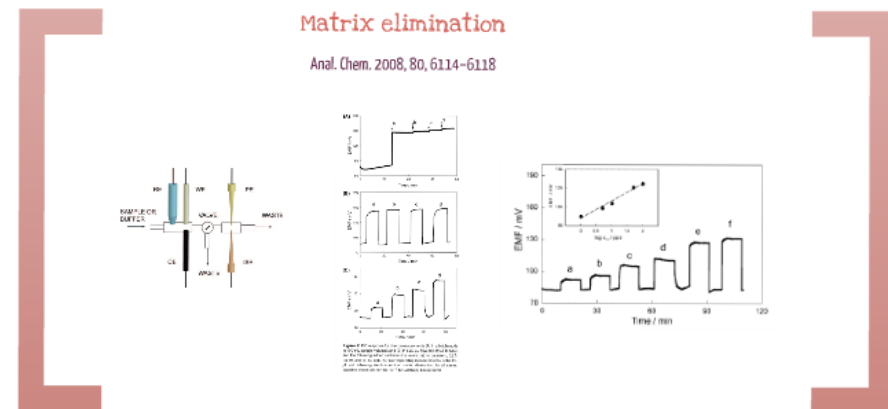
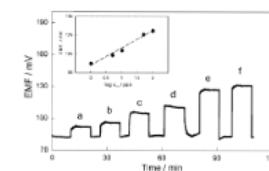


Figure 1. ESI mass spectrum of a sample. The x-axis is m/z (400–600) and the y-axis is relative intensity (0–100). The peaks are labeled a, b, c, d, e, and f.



Matrix elimination

Anal. Chem. 2008, 80, 6114–6118

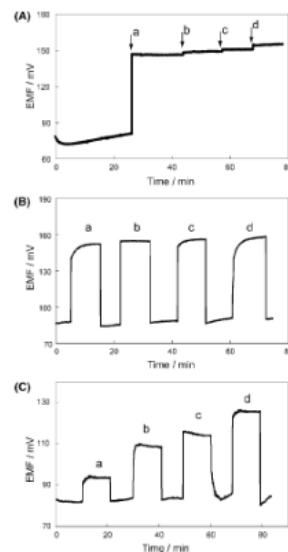
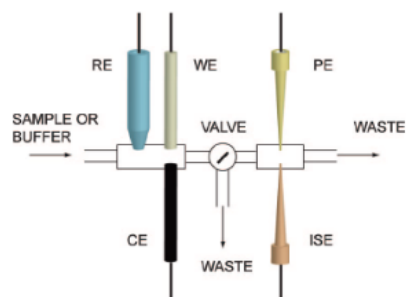
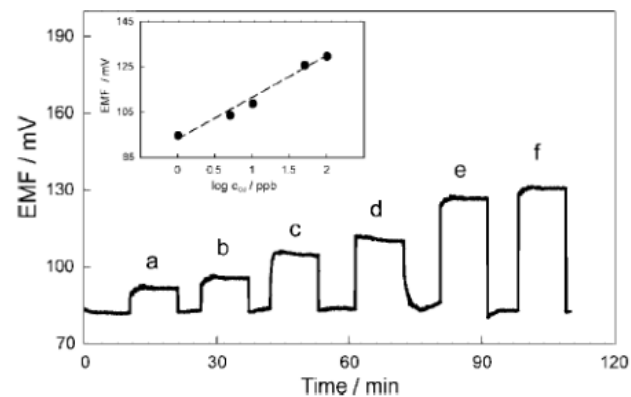


Figure 2. ISE response for direct measurements (A) in a batch mode in 100-mL sample volumes and (B) in a 20- μ L flow cell of 0.5 M NaCl and the following added cadmium ion levels: (a) no cadmium, (b) 5, (c) 10, and (d) 50 ppb. (C) Corresponding measurements in the 20- μ L cell following electrochemical matrix elimination. In all cases, baseline traces are for the 10^{-4} M $\text{Cu}(\text{NO}_3)_2$ background.



IBSs as detectors

Immunoassays with QD labels

Anal. Chem. 2007, 79, 5107-5110

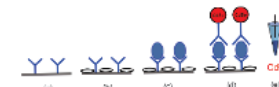
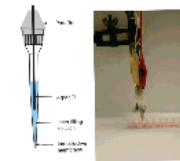


Figure 4. Intracellular proteolysis and in this study. (a) Histone H1 is stabilized in a monomeric state, (b) the substrate is complexed with DGA, (c) only the major IgG antigen is hydrolyzed, (d) the secondary antibody anti-CD56 recognizes the complex, and (e) the IgG is detected with HRP, and the released CD^{56} is detected with the CD^{56} -APC.

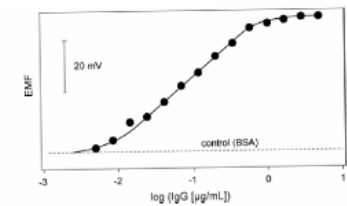


Figure 5. Potentiometric monitoring of IgG concentrations via CdSe quantum dot labels in 150- μ L microvials with the sandwich immunoassay (cf. Figure 4). Dotted line: Signal obtained with BSA instead of target protein (shown as control).

Immunoassays with QD labels

Anal. Chem. 2007, 79, 5107-5110

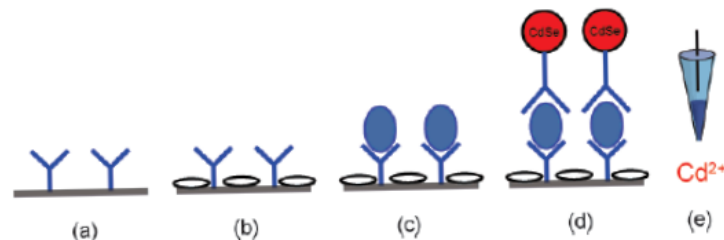
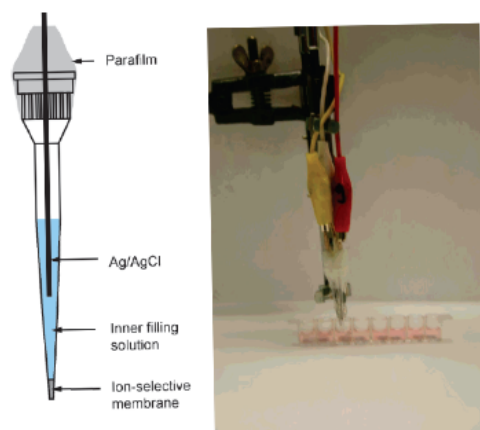


Figure 4. Immunoassay protocol used in this study. (a) Antibody is immobilized on a microwell plate, (b) the plate is blocked with BSA, (c) anti-mouse IgG antigen is incubated, (d) the secondary antibody with CdSe nanoparticle labels is bound, and (e) the label is dissolved with H₂O₂ and the released Cd²⁺ is detected with the Cd²⁺-ISE.

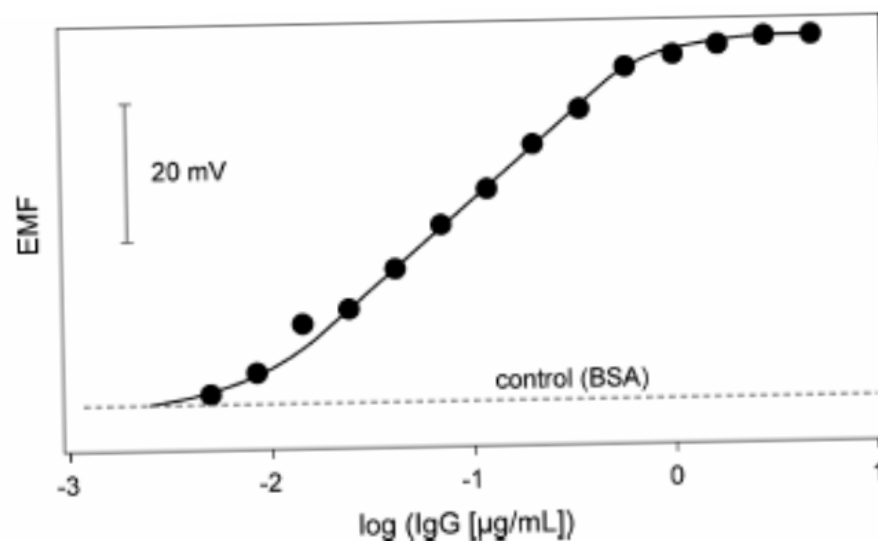
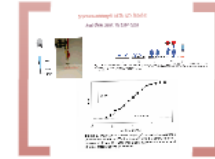


Figure 5. Potentiometric monitoring of IgG concentrations via CdSe quantum dot labels in 150-µL microvials with the sandwich immunoassay (cf. Figure 4). Dotted line: Signal obtained with BSA instead of target protein (shown as control).

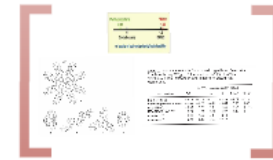
ethnologies

Materials

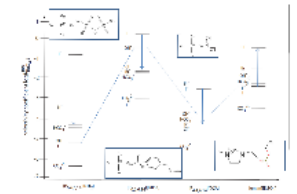
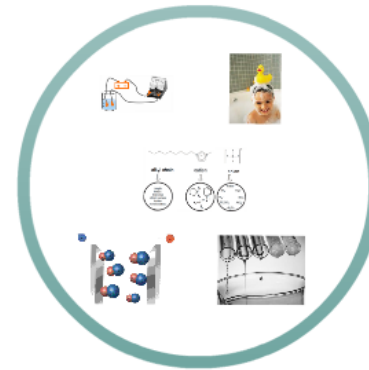
IBSs as detectors



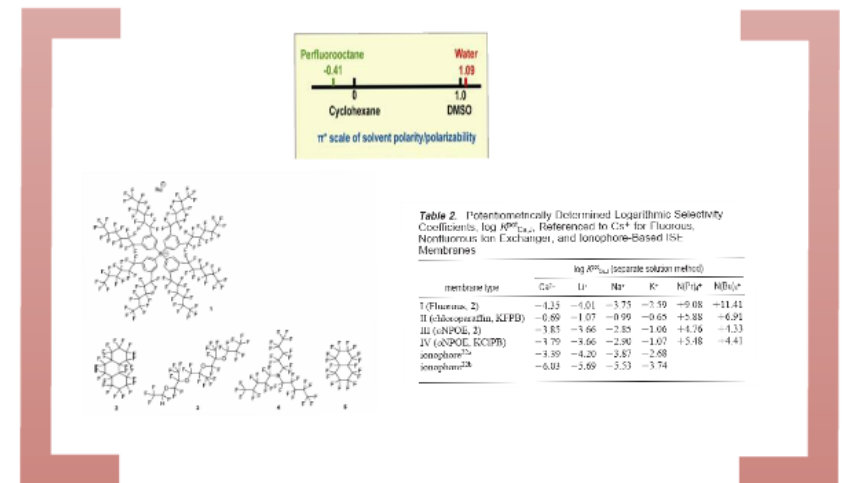
Fluorous membranes



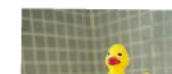
Ionic liquids



Fluorous membranes



Ionic liquids



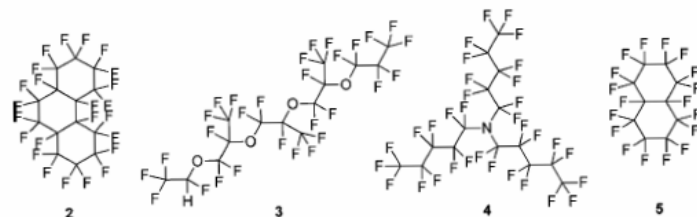
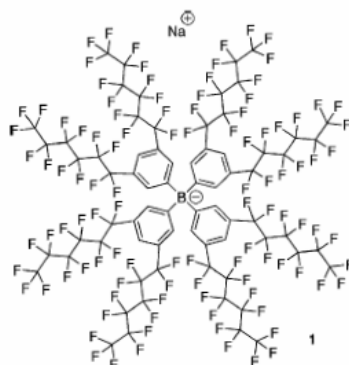
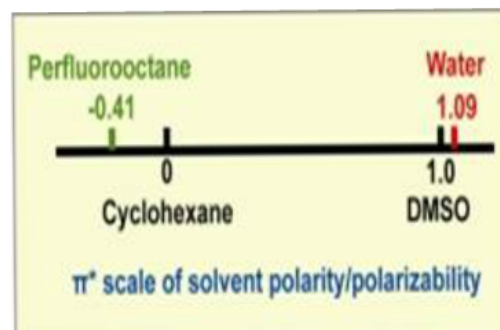


Table 2. Potentiometrically Determined Logarithmic Selectivity Coefficients, $\log K^{\text{pot}}_{\text{Cs},\text{J}}$, Referenced to Cs^+ for Fluorous, Nonfluorous Ion Exchanger, and Ionophore-Based ISE Membranes

membrane type	$\log K^{\text{pot}}_{\text{Cs},\text{J}}$ (separate solution method)					
	Ca^{2+}	Li^+	Na^+	K^+	$\text{N}(\text{Pr})_4^+$	$\text{N}(\text{Bu})_4^+$
I (Fluorous, 2)	−4.35	−4.01	−3.75	−2.59	+9.08	+11.41
II (chloroparaffin, KFPB)	−0.69	−1.07	−0.99	−0.65	+5.88	+6.91
III (<i>o</i> NPOE, 2)	−3.85	−3.66	−2.85	−1.06	+4.76	+4.33
IV (<i>o</i> NPOE, KCIPB)	−3.79	−3.66	−2.90	−1.07	+5.48	+4.41
ionophore ^{22a}	−3.39	−4.20	−3.87	−2.68		
ionophore ^{22b}	−6.03	−5.69	−5.53	−3.74		

Fluorous membranes

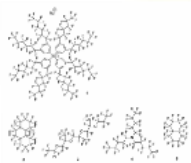
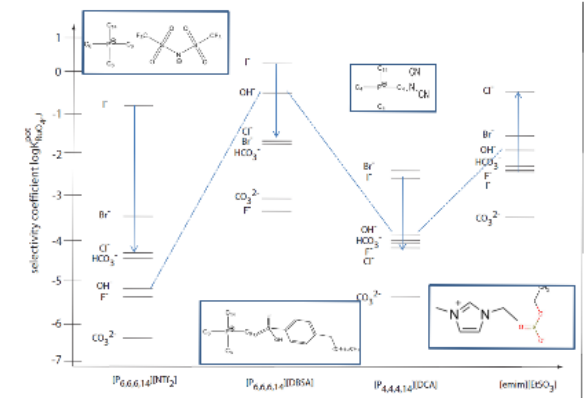
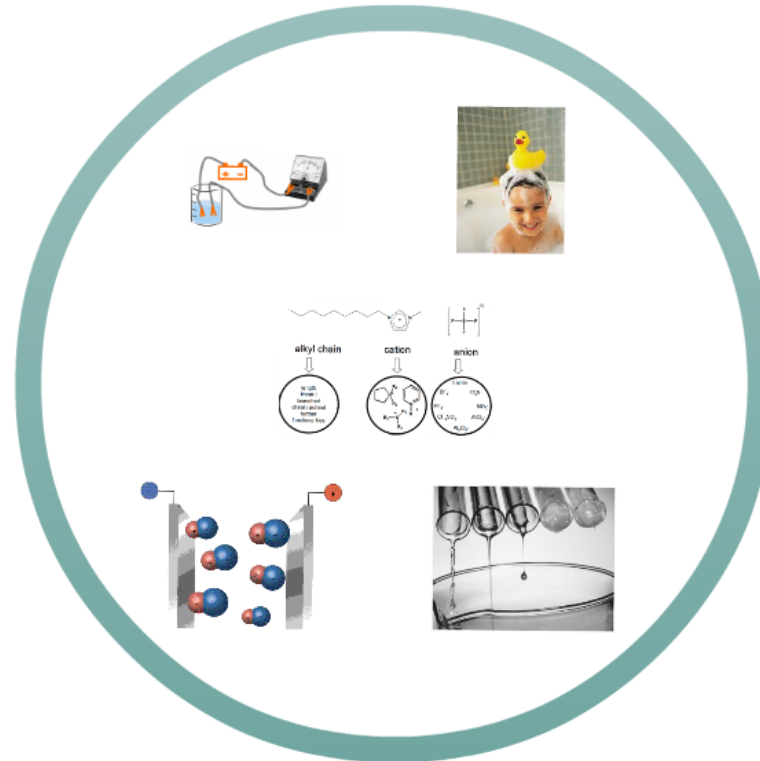
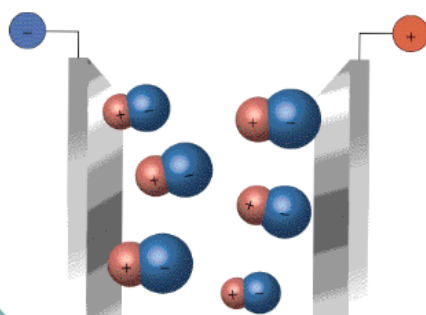
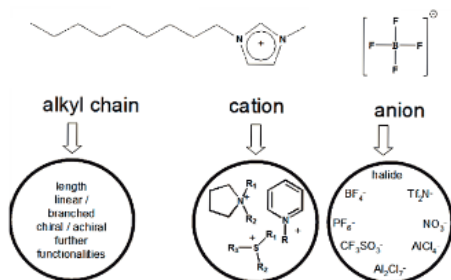


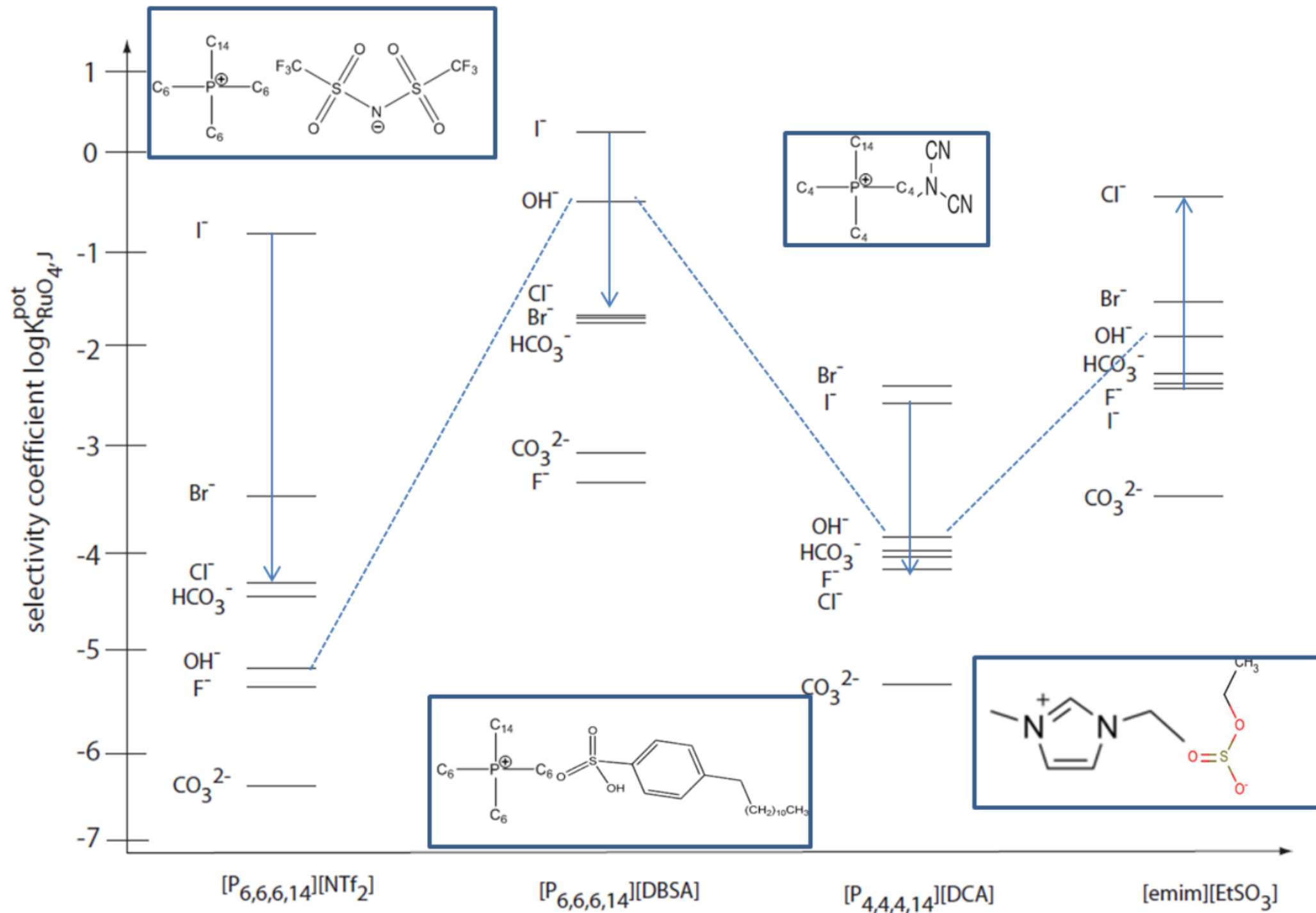
Table 2. Permeability and Diffusion Coefficients of Gases through Fluorous Membranes. The values are given for the pure polymer and for the membranes containing 10% of the fluorous phase.

Polymer	log P ₂₅ (cm ³ cm ² s ⁻¹ atm ⁻¹)				log D ₂₅ (cm ² s ⁻¹)			
	CO ₂	O ₂	N ₂	H ₂	CO ₂	O ₂	N ₂	H ₂
1. (F ₁₀) ₂	4.22	4.18	3.75	3.74	-6.8	-6.8	-7.1	-7.1
2. (F ₁₀) ₂ (20%)	3.85	3.75	3.45	3.45	-6.8	-6.8	-7.1	-7.1
3. (F ₁₀) ₂ (20%)	3.85	3.75	3.45	3.45	-6.8	-6.8	-7.1	-7.1
4. (F ₁₀) ₂ (20%)	3.85	3.75	3.45	3.45	-6.8	-6.8	-7.1	-7.1
5. (F ₁₀) ₂ (20%)	3.85	3.75	3.45	3.45	-6.8	-6.8	-7.1	-7.1
6. (F ₁₀) ₂ (20%)	3.85	3.75	3.45	3.45	-6.8	-6.8	-7.1	-7.1
7. (F ₁₀) ₂ (20%)	3.85	3.75	3.45	3.45	-6.8	-6.8	-7.1	-7.1
8. (F ₁₀) ₂ (20%)	3.85	3.75	3.45	3.45	-6.8	-6.8	-7.1	-7.1
9. (F ₁₀) ₂ (20%)	3.85	3.75	3.45	3.45	-6.8	-6.8	-7.1	-7.1
10. (F ₁₀) ₂ (20%)	3.85	3.75	3.45	3.45	-6.8	-6.8	-7.1	-7.1

Ionic liquids

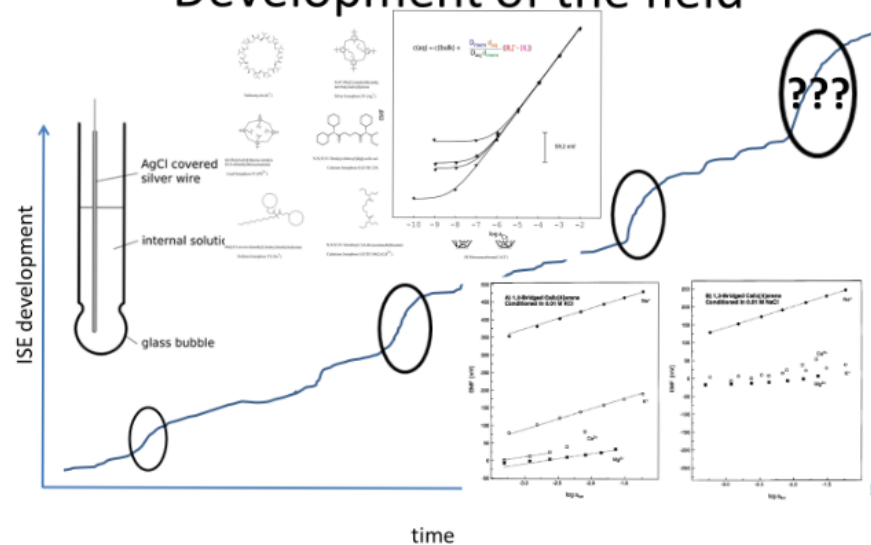






State-of-the-art

Development of the field



State-of-the-art

Methodologies

Materials

Hyphenated IBSs



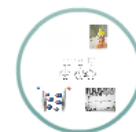
IBSs as detectors

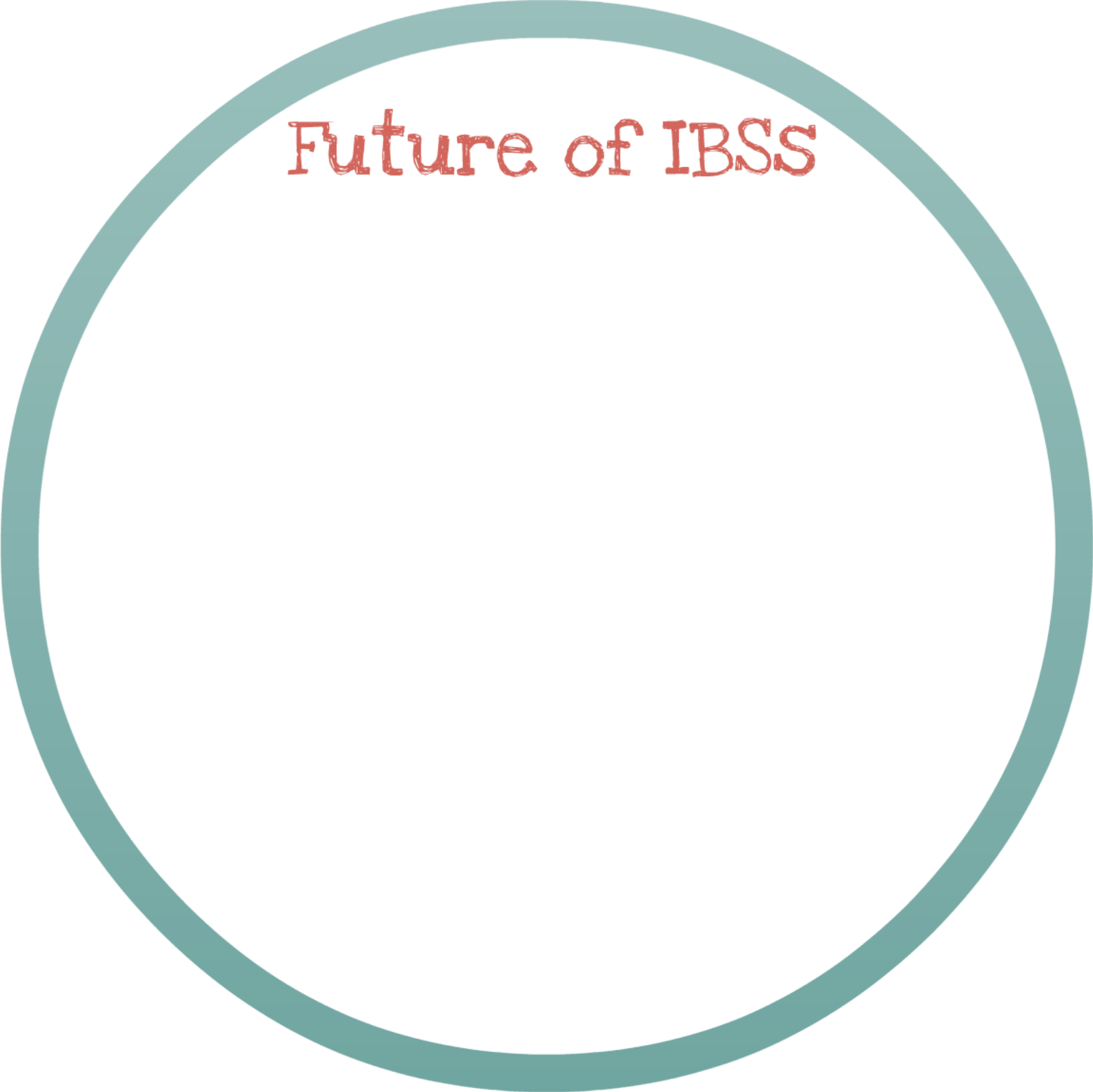


Fluorous membranes



Ionic liquids





Future of IBSS