

Lecture 15

Electrochemical Biosensors: pH, PO_2 , and PCO_2

References

Webster, Ch. 10 (Sec. 10.1-10.2).

CHEMICAL BIOSENSORS

→ Chap. 10

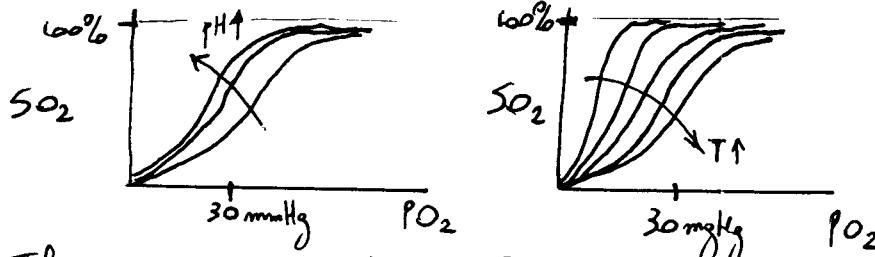
Blood levels of gases, electrolytes and metabolites
in medical analysis

- e.g.:
- blood gases : O_2 , CO_2
 - electrolytes: Na^+ , K^+ , Ca^{2+} , Cl^- , and of course H^+ and OH^- !
 - metabolites: glucose, lactate, creatinine, urea
- Blood-gas and acid-base physiology (Sec. 10.1):

- $P O_2$: partial pressure of O_2 : proportional to O_2 concentration in the blood. Units of pressure (mmHg or kPa)
- $S O_2$: saturation of O_2 in HEMOGLOBIN (Hb) :

$$S O_2 (\%) = \frac{[Hb\ O_2]}{[Hb]} \times 100\% : \text{fraction of oxygenated hemoglobin}$$

$P O_2$ and $S O_2$ are not the same !



(Fig. 10.1)

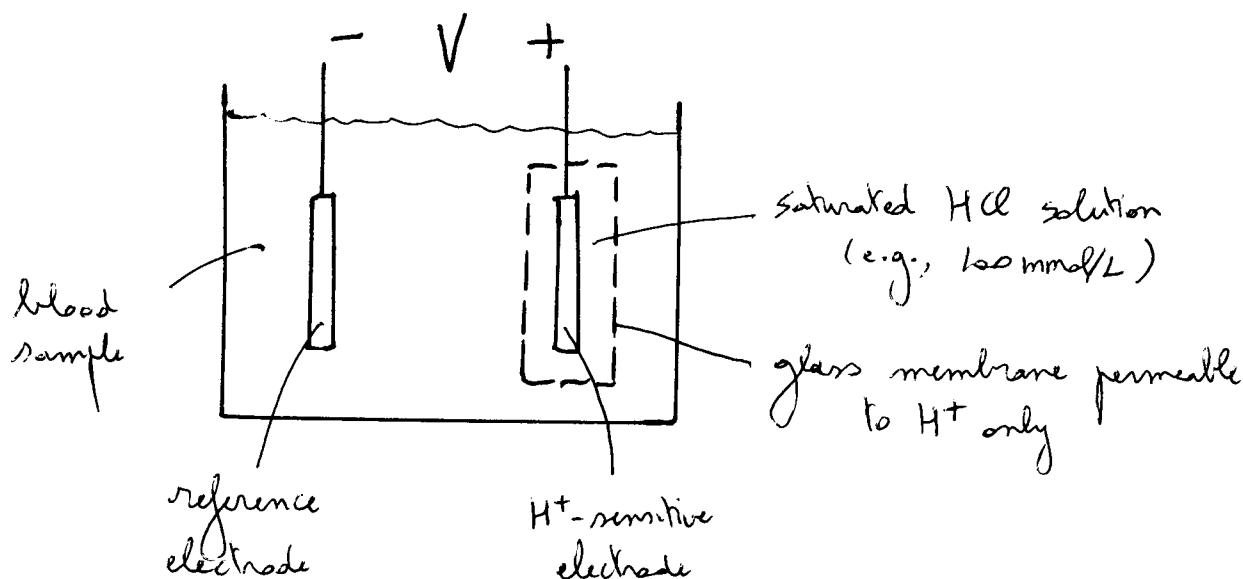
The relationship between $P O_2$ and $S O_2$ depends on pH and T.

- $P CO_2$: partial pressure of CO_2 in the blood (mmHg or kPa)
- $S CO_2$: saturation of CO_2 in Hb : fraction of carboxygenated hemoglobin
- pH : $pH = -\log_{10} [H^+]$:
 - > 7 for BASIC solution
 - $= 7$ for pure water
 - < 7 for ACID solution

- Electrochemical sensors: measure pH, $P\text{O}_2$, PCO_2 , ... as voltages and currents resulting from the underlying redox reactions.

- pH electrode:
- $$\text{H}_2\text{O} \rightleftharpoons \text{H}^+ + \text{OH}^-$$

$$[\text{H}^+] \cdot [\text{OH}^-] = (10^{-7} \frac{\text{mol}}{\text{L}})^2 \text{ at room temperature}$$



$$V = \underbrace{E_{\text{H}^+\text{el.}} - E_{\text{ref.el.}}}_{= 0 \text{ for two Ag/AgCl electrodes}} + E_{\text{Nernst}}$$

but non-zero if a calomel reference electrode is used!

$$= \frac{RT}{F} \ln(10) \cdot \log_{10} \frac{[\text{H}^+]_{\text{sample}}}{[\text{H}^+]_{\text{HCl}}} = 62 \text{ mV} \cdot (\text{pH}_{\text{HCl}} - \text{pH}_{\text{sample}})$$

at room temperature

= 1 for $0.1 \frac{\text{mol}}{\text{L}}$ HCl
in the glass bulb

- P_{CO_2} , partial pressure of CO_2 :

Typical range : 40 ± 3 mmHg awake
 44 ± 3 mmHg asleep

→ measured through linear relationship between $\log P_{CO_2}$ and pH in a saturated solution of sodium bicarbonate ($Na HCO_3$, or baking soda) :



At equilibrium : ($[H_2O]$ is approximately constant)

$$\frac{[H^+] [HCO_3^-]}{[CO_2]} = k \quad \begin{matrix} \text{approximately constant,} \\ \text{function of temperature} \end{matrix}$$

$$[CO_2] = \alpha \cdot P_{CO_2} \quad \alpha \approx 0.03 \quad \frac{\text{mmol/l}}{\text{mm Hg}}$$

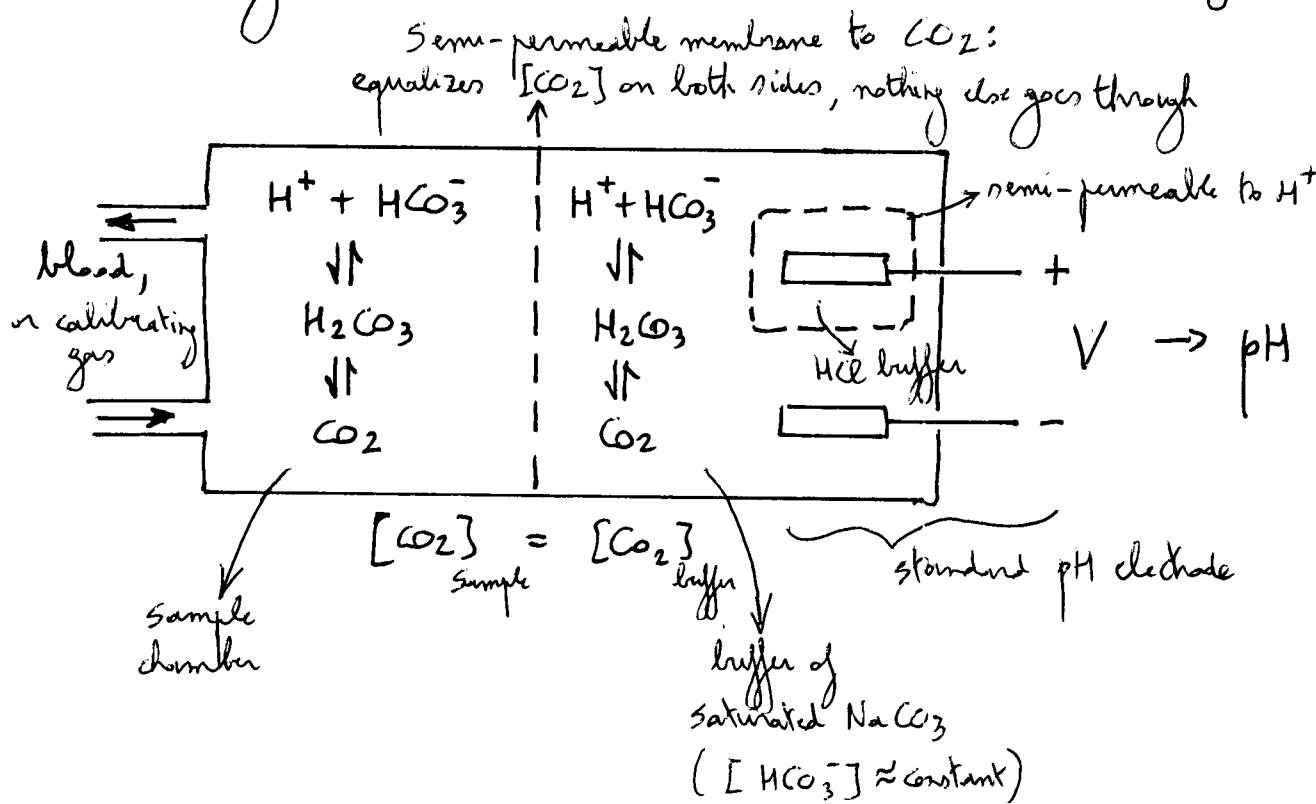
$$\Rightarrow \log_{10} P_{CO_2} \approx -pH + \log_{10} [HCO_3^-] - \log_{10} k - \log_{10} \alpha$$

↓ ↓ ↓

Indirect measure ... from ... in a buffered
of P_{CO_2} ... measure of pH ... saturated solution
of $Na HCO_3$ for
which $[HCO_3^-] \approx$ constant

Severinghaus PCO_2 electrode:

(Fig. 10.3)



$$\Rightarrow \log_{10} \text{PCO}_2 = -\text{pH} + \text{constant}$$

measured by
pH electrode

calibrated by
using a sample with
known PCO_2

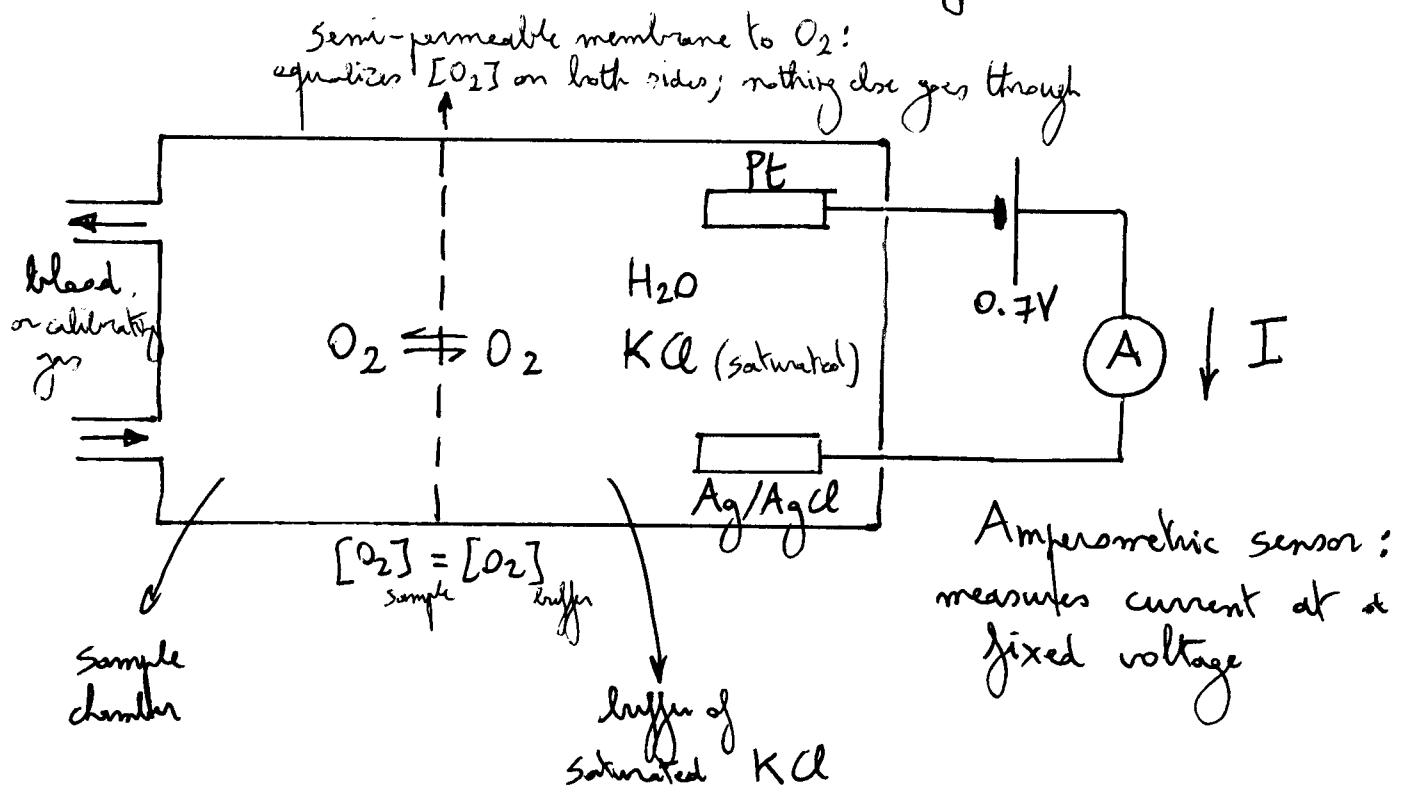
$$\text{or } \log_{10} \text{PCO}_2 = \frac{V}{62 \text{ mV}} + \text{constant}'$$

↓
different constant including
effect of $[\text{HCl}]$ in pH
buffer; calibrated in
one single step

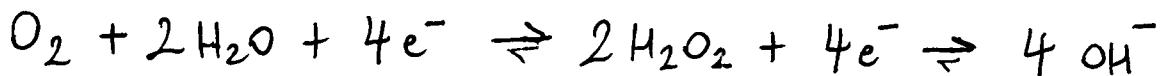
- P_{O_2} , partial pressure of O_2 :

Clark P_{O_2} electrode

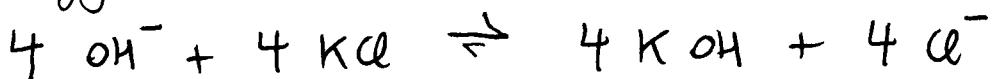
(Figs. 10.4 and 10.5)



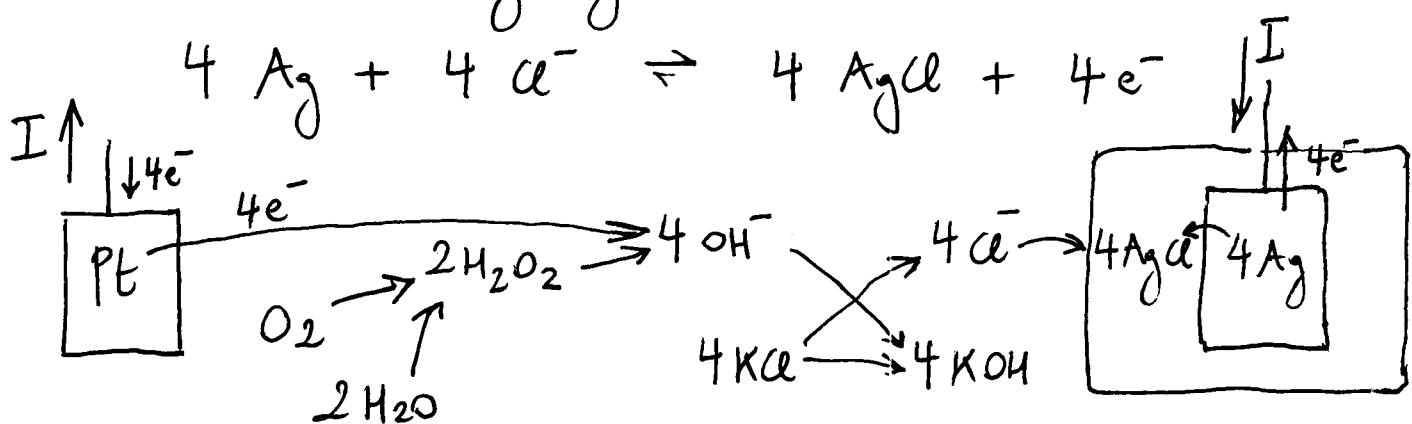
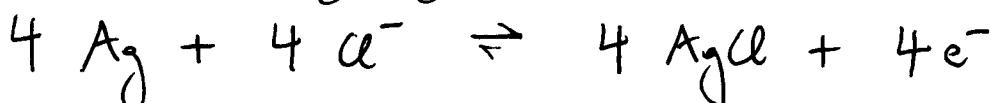
Reduction at the Pt CATHODE:



KCl buffer solution:

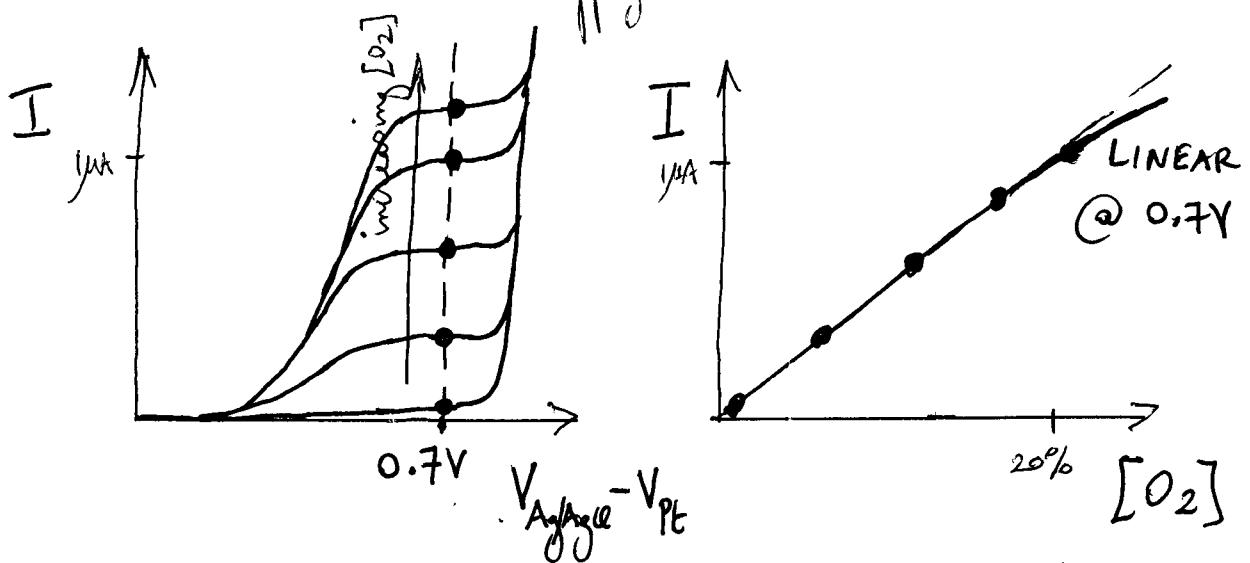


Oxidation at the Ag/AgCl ANODE:



To measure P_{O_2} , we want $[O_2]$ to be the reaction rate limiting factor:

- Saturated KCl solution as buffer
- Non-polarizable Ag/AgCl electrode
- Polarized Pt electrode requires a polarization potential of $\approx 0.7V$ in order to supply electrons to the solution:



(Fig. 10.5)

\Rightarrow For a polarizing voltage $\approx 0.7V$, the current I is approximately linear in $[O_2]$ (or P_{O_2}):

$$I \approx 4 \cdot F \cdot [O_2] \cdot \phi \quad [A = \frac{C}{s}]$$

4 electrons flow for every O_2 consumed.

FARADAY'S CONSTANT $\left[\frac{C}{mol}\right]$

Change of 1 mol of electrons (protons)

$$F = q \cdot N_A$$

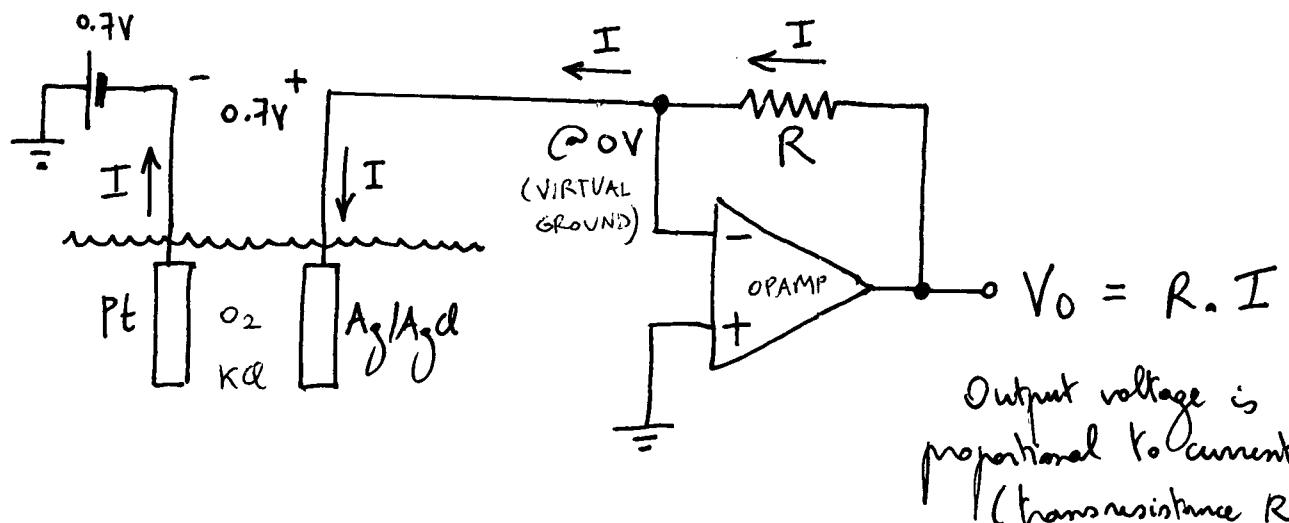
$$96,485 \frac{C}{mol} = 1.6 \cdot 10^{-19} C \cdot 6 \cdot 10^{23} \frac{1}{mol}$$

proton charge Avogadro

oxygen concentration $\left[\frac{mol}{l}\right]$

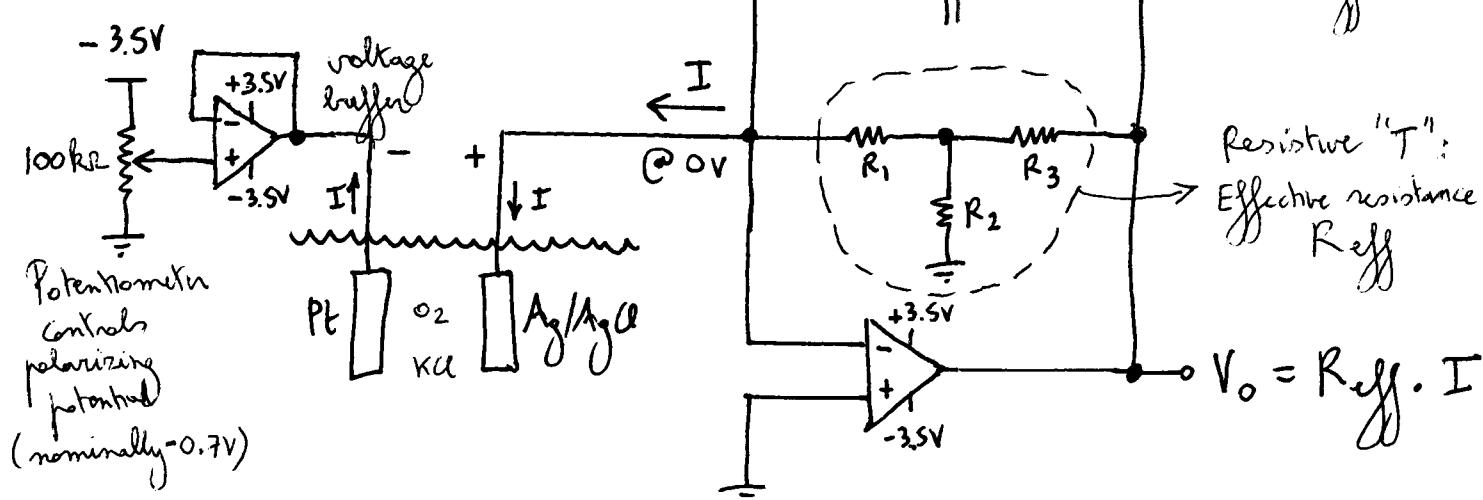
sample flow rate $\left[\frac{l}{s}\right]$

A POTENTIOSTAT measures the current I while applying a polarizing voltage ($0.7V$) between the electrodes:



R is large (several $M\Omega$) for high sensitivity (several mV per nA)

Practical potentiostat circuit:



Resistive "T" realizes very large effective resistance using lower resistances:

$$\text{THEVENIN } R_1 \parallel R_3 \text{ and } V_o \rightarrow \text{THEVENIN } R_1 \parallel R_2 \parallel R_3 \frac{R_2}{R_2 + R_3} V_o \Rightarrow \frac{R_2}{R_2 + R_3} V_o = \left(R_1 + \frac{R_2 R_3}{R_2 + R_3} \right) \cdot I$$

$$\text{or } R_2 \cdot V_o = (R_1 R_2 + R_1 R_3 + R_2 R_3) \cdot I$$

e.g.: $R_1 = R_3 = 1M\Omega$, $R_2 = 10k\Omega$
 $\Rightarrow R_{eff} = 100M\Omega$

$$\Rightarrow R_{eff} = \frac{R_1 R_2 + R_1 R_3 + R_2 R_3}{R_2} \approx \frac{R_1 R_3}{R_2} \text{ for } R_1, R_3 \gg R_2$$