Lecture #10
CMOS Building Blocks

Lecture Outline

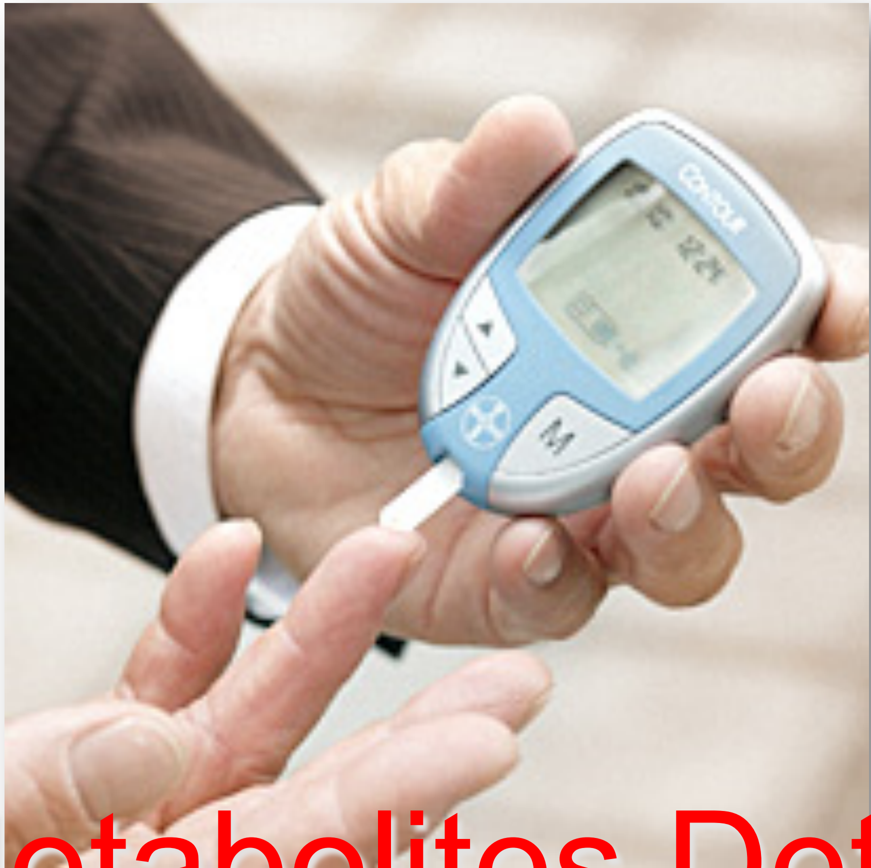
(Book Bio/CMOS: Appendix B & Chapter' paragraph 8.9.3, 9.1.1, 9.2)

- CMOS design to drive the electrochemical cell
- Electrical properties of the electrochemical cell
- Basic Configuration of the cell: Grounded Counter
- Noise of the electrochemical interface

CMOS architectures for Portable

in DNA Detection

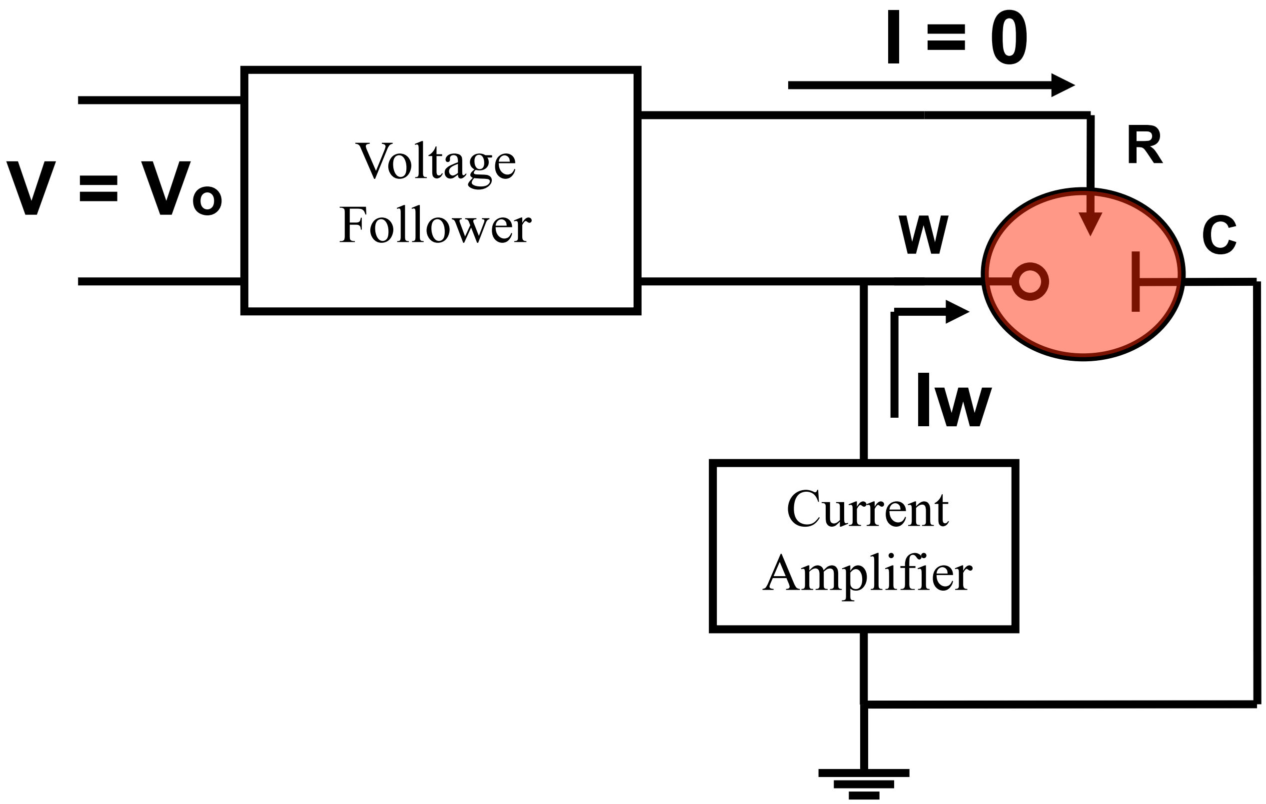
CMOS architectures for Portable



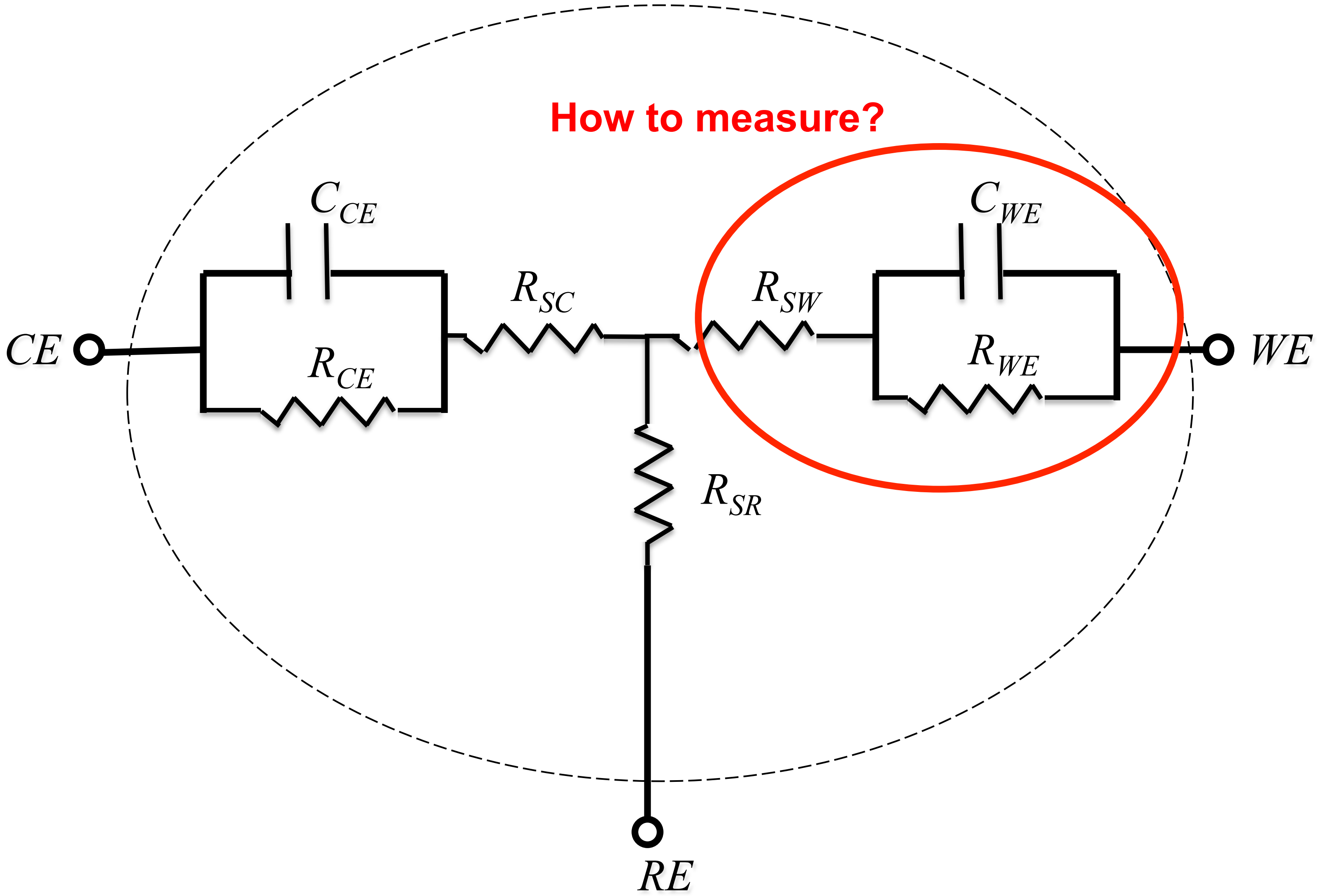
in Metabolites Detection

CMOS architectures for iPhone

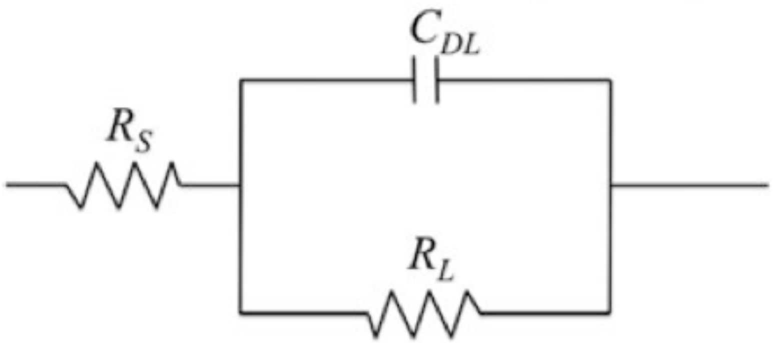
Required Blocks



Equivalent circuit: passive model



Equivalent Impedance



$$Z_{//} = Z = C_{DL} // R_L \qquad \begin{cases} Z = \dfrac{R_L}{j\omega C_{DL} R_L + 1} \xrightarrow{\omega \to 0} R_L \\ Z = \dfrac{R_L}{j\omega C_{DL} R_L + 1} \xrightarrow{\omega \to \infty} 0 \end{cases}$$

The Layering effects result in the impedance in parallel

Equivalent Impedance

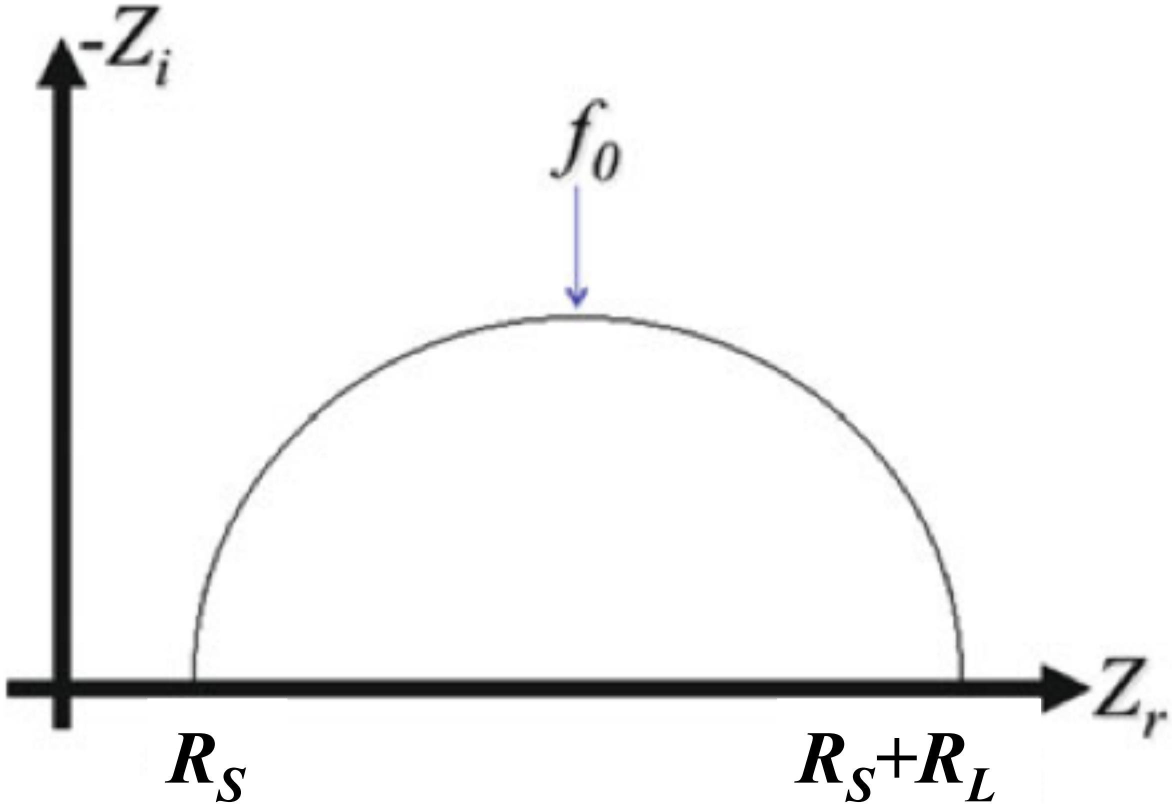
$$Z = \frac{R_L}{j\omega C_{DL} R_L + 1} \cdot \frac{1 - j\omega C_{DL} R_L}{1 - j\omega C_{DL} R_L}$$

$$Z = \frac{R_L - j\omega C_{DL} R_L^2}{1 + (\omega C_{DL} R_L)^2}$$

$$Z = \frac{R_L}{1 + (\omega C_{DL} R_L)^2} - j \frac{\omega C_{DL} R_L^2}{1 + (\omega C_{DL} R_L)^2} \quad \begin{cases} Z_{\mathrm{Re}} = \frac{R_L}{1+(\omega C_{DL} R_L)^2} \\ Z_{\mathrm{Im}} = -\frac{\omega C_{DL} R_L^2}{1+(\omega C_{DL} R_L)^2} \end{cases}$$

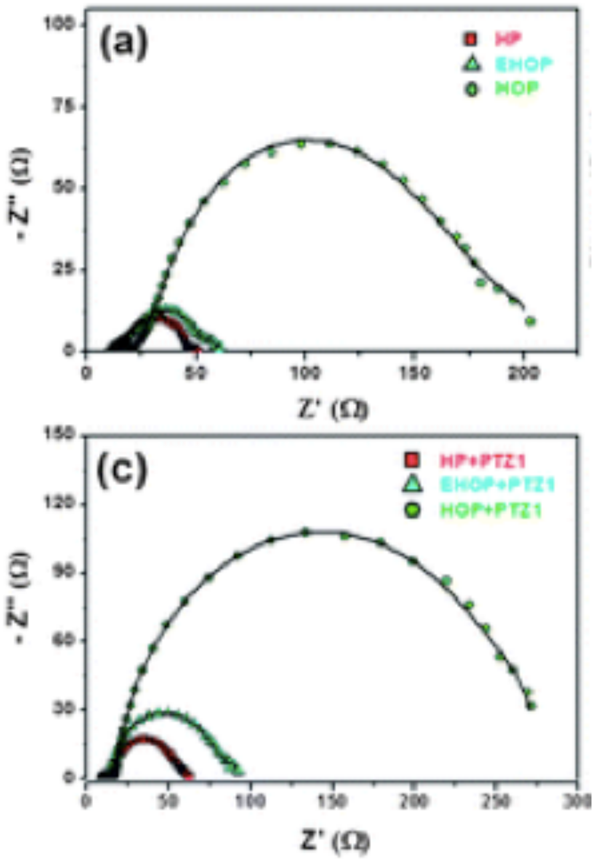
This impedance presents both resistive and reactive components

Nyquist Plot



The Nyquist plot is also a mean to fit data about a specific electrochemical cell

Nyquist Plot



The Nyquist plot is also a mean to fit data about a specific electrochemical cell

Capacitance vs Frequency

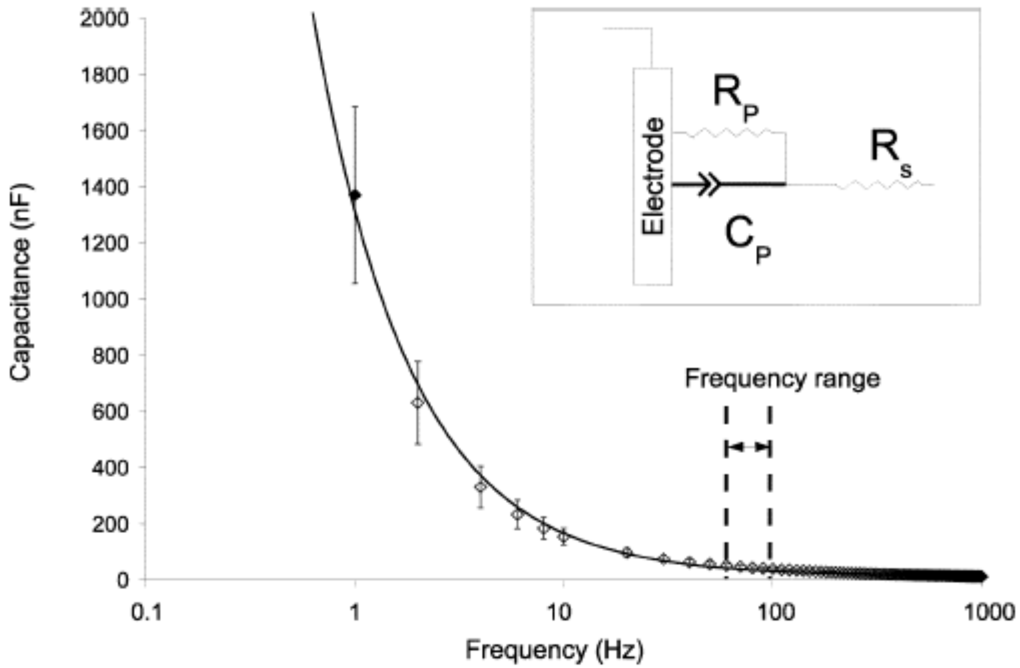
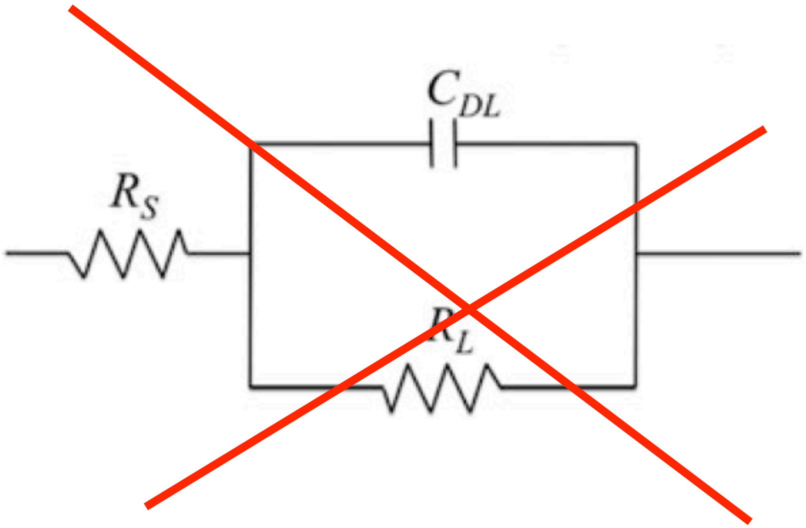
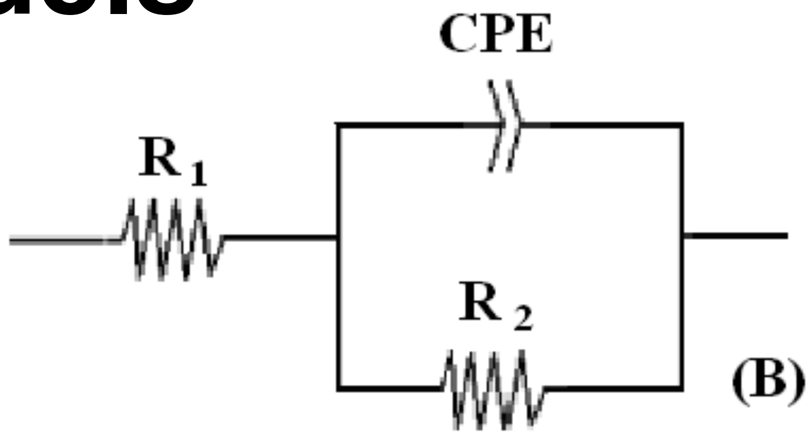


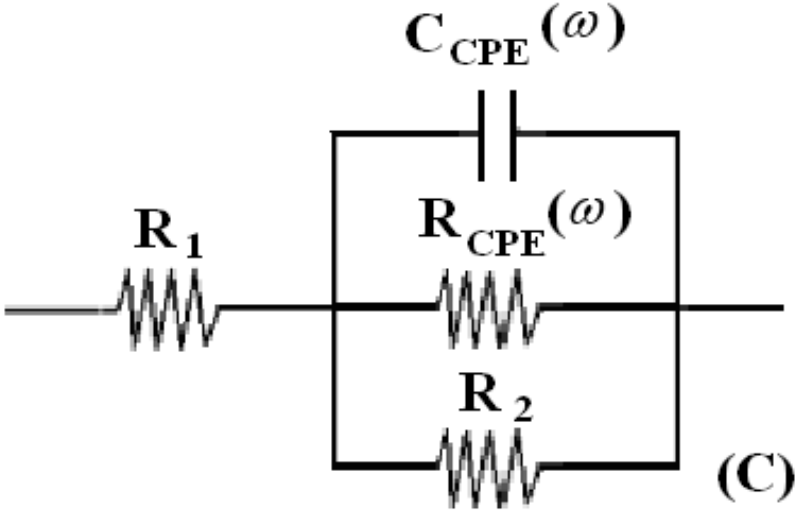
Fig. 9. Measured capacitance versus charge/discharge frequency on clean gold electrodes. The continuous line shows the fitting.

Some times, the Layering effect corresponds to non-ideal capacitances

Interface models







Equivalent circuits for non-ideal layering effects

CPE element

$$Z_{CPE} = \frac{1}{C_p(j\omega)^{\alpha}} = \frac{\cos\left(\frac{\pi}{2}\alpha\right)}{C_p\omega^{\alpha}} - j\frac{\sin\left(\frac{\pi}{2}\alpha\right)}{C_p\omega^{\alpha}}$$

$$Z_{CPE} \cong \frac{1}{\omega^{\alpha}C_p}\sqrt{1-\alpha^2} + \frac{1}{j\omega^{\alpha}C_p}\alpha.$$

The Constant Phase Element (CPE)
as Equivalent Component

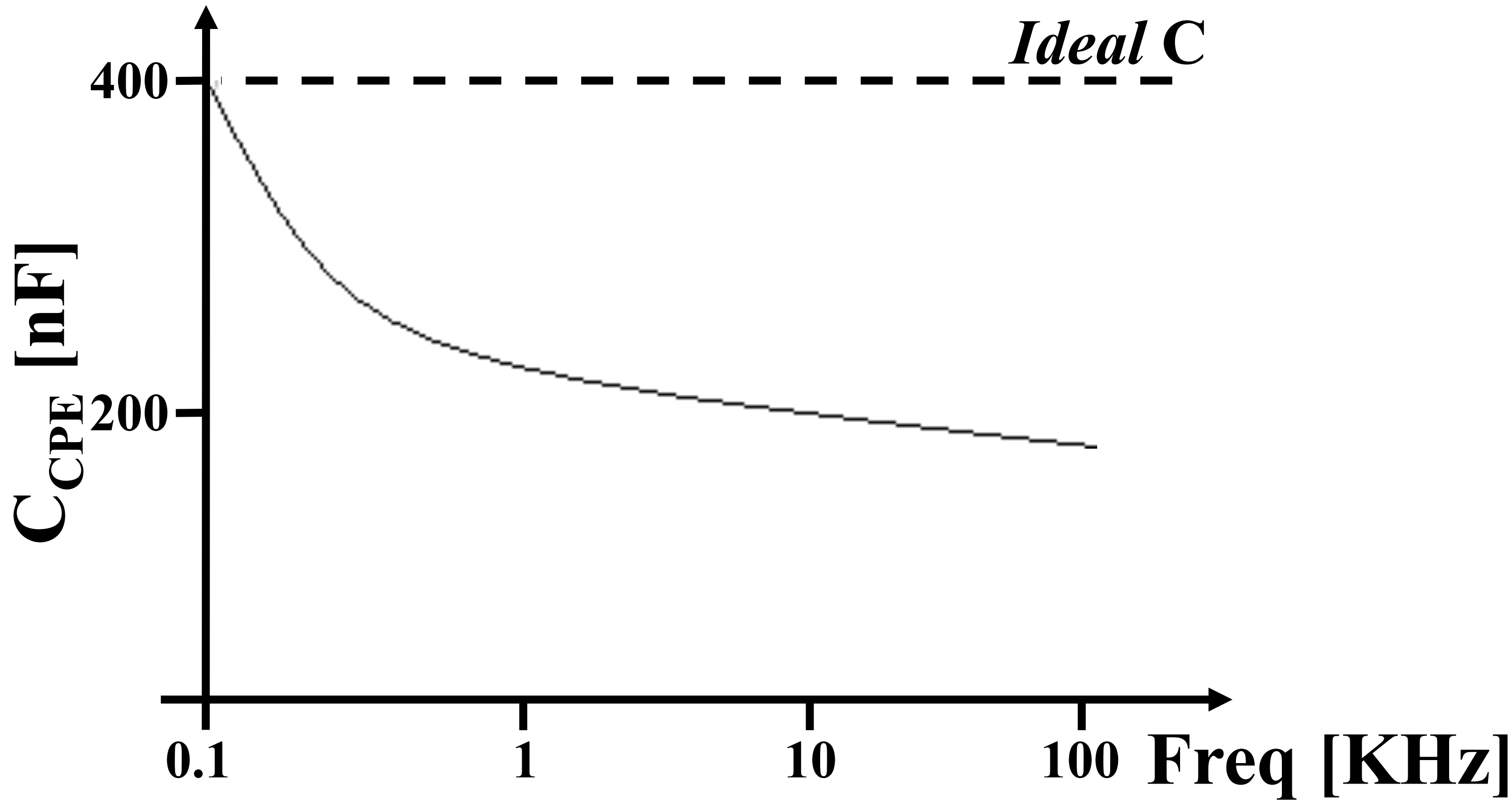
CPE element

$$Z_{CPE}\begin{cases} R_{CPE} \cong \frac{1}{\omega^{\alpha} C_p}\sqrt{1-\alpha^2} \\ X_{CPE} \cong \frac{-1}{\omega^{\alpha} C_p}\alpha \end{cases}$$

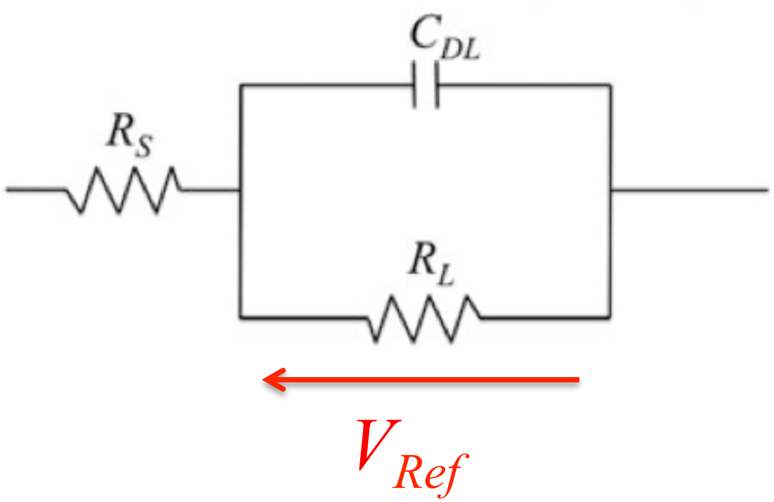
$$|X_{CPE}| \cong \frac{1}{\omega^{\alpha} C_p}\alpha = \frac{1}{\omega^{\alpha-1}\omega\, C_p}\alpha = \frac{1}{\omega\left(\frac{C_p}{\alpha\,\omega^{1-\alpha}}\right)}$$

$$C_{CPE} \cong \frac{C_p}{\alpha\,\omega^{1-\alpha}}$$

Equivalent Capacitance vs frequency



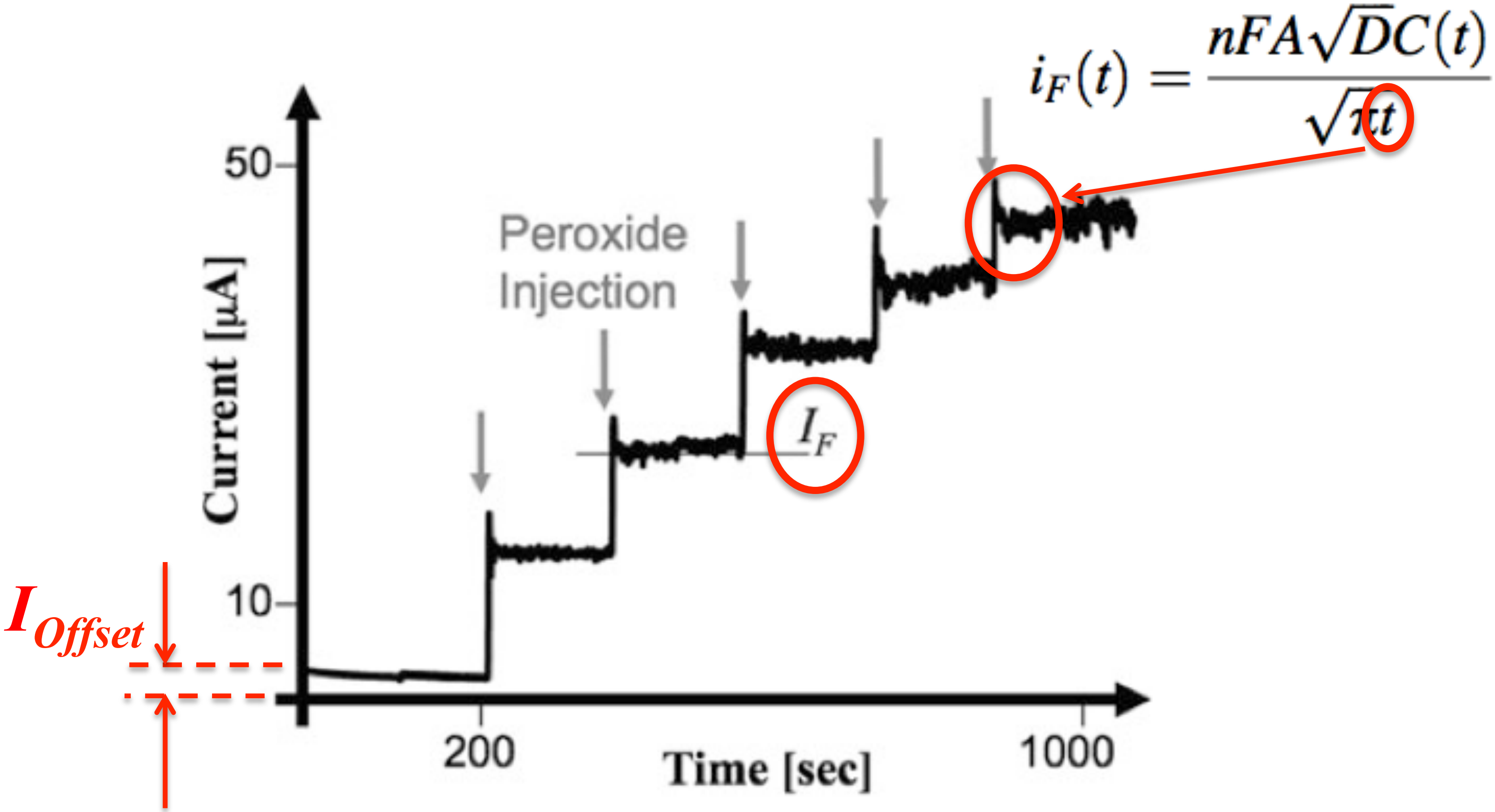
Non-Faradaic Current



$$I_{non-F} = \frac{V_{ref}}{Z} = \frac{1 + j\omega C_{DL} R_L}{R_L} V_{ref}$$

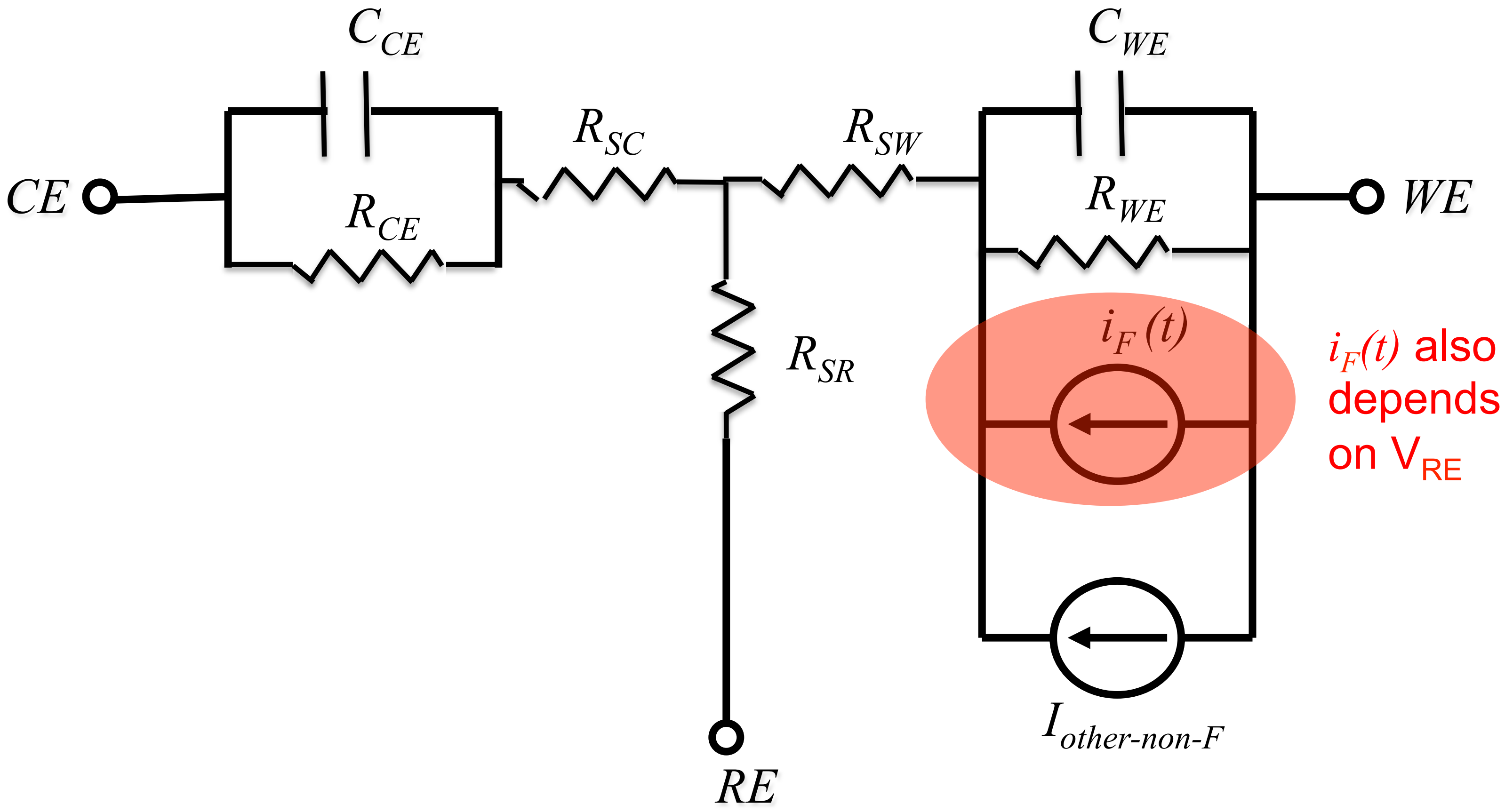
Non-Faradaic currents are also circulating in the cell

Faradaic Current

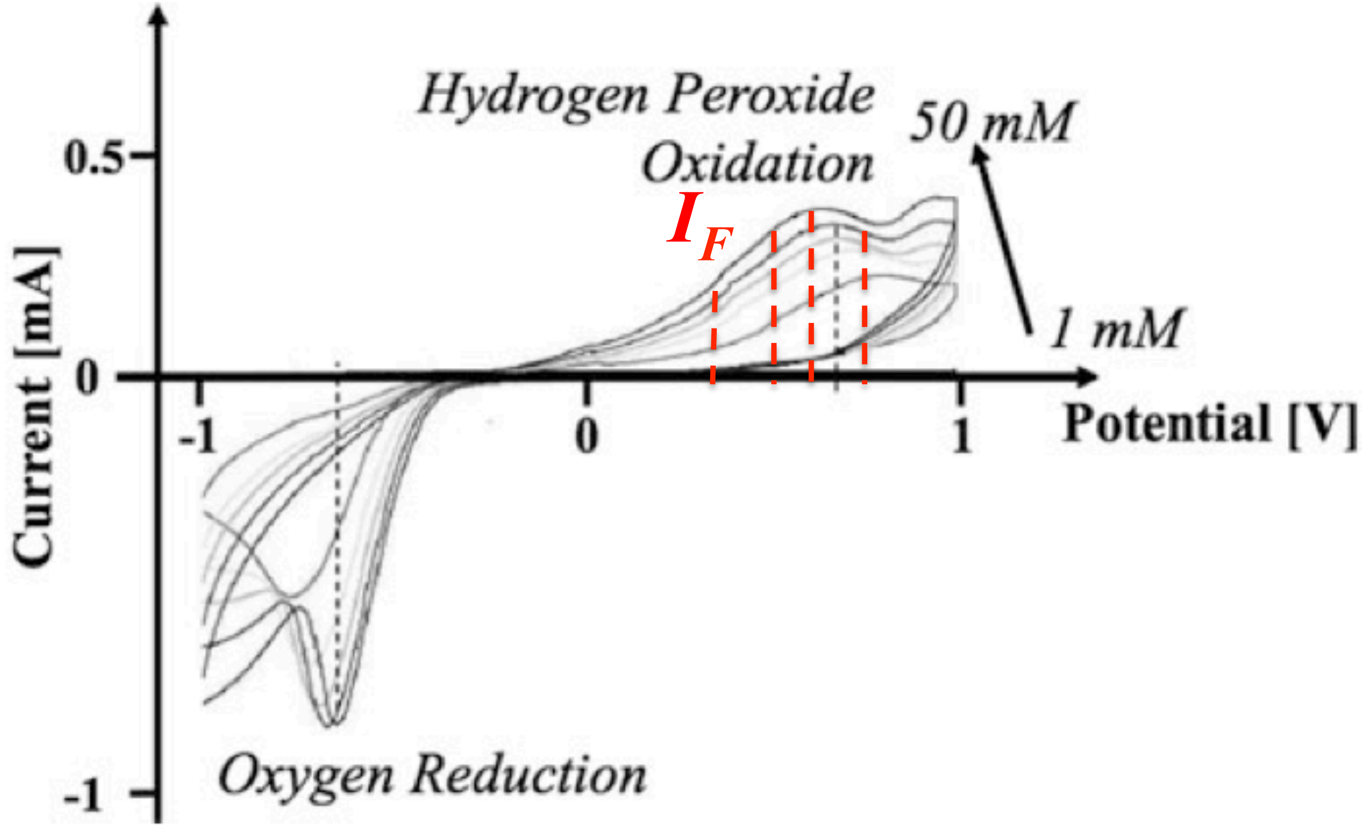


Typical curve in cronoamperometry

Equivalent circuit: active model

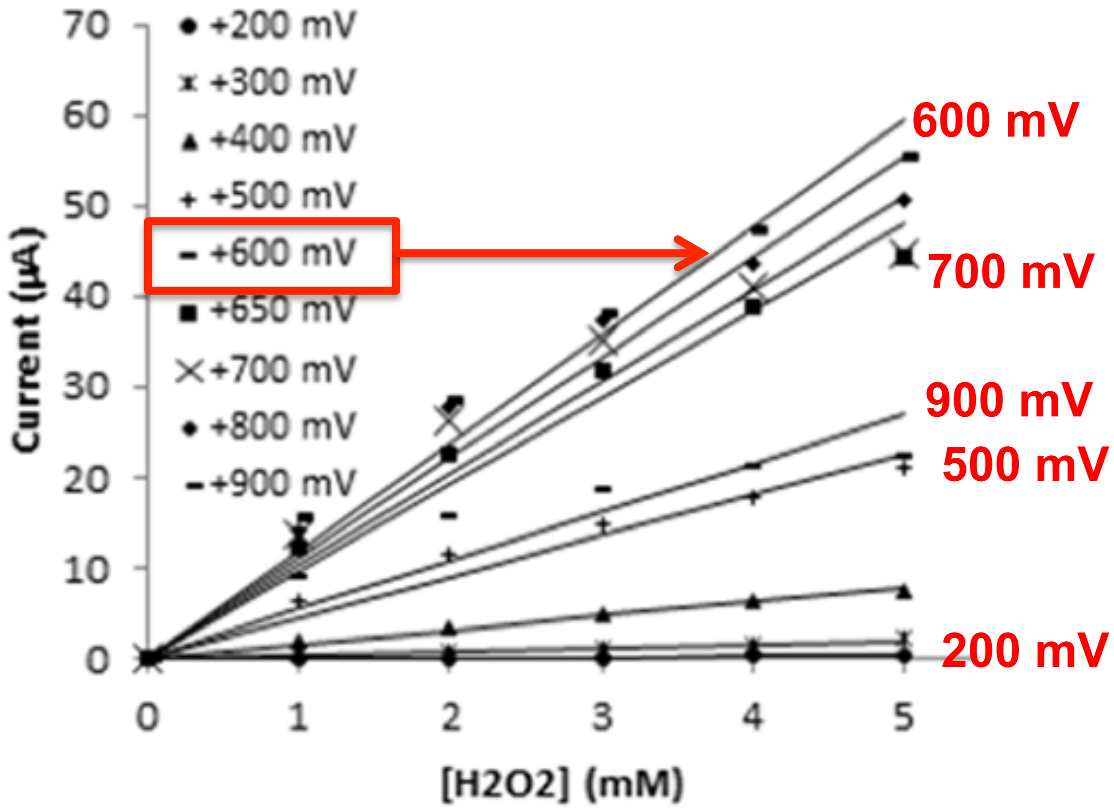


Redox with hydrogen peroxide



O+ reduction and H_2O_2 oxidation observed by potential sweeping

Faradaic Current Generator



The sensitivity depends on the Reference Potential

Faradaic Current Generator

$$I = SC + I_{Offset}$$

$$I_{Offset} = 0$$

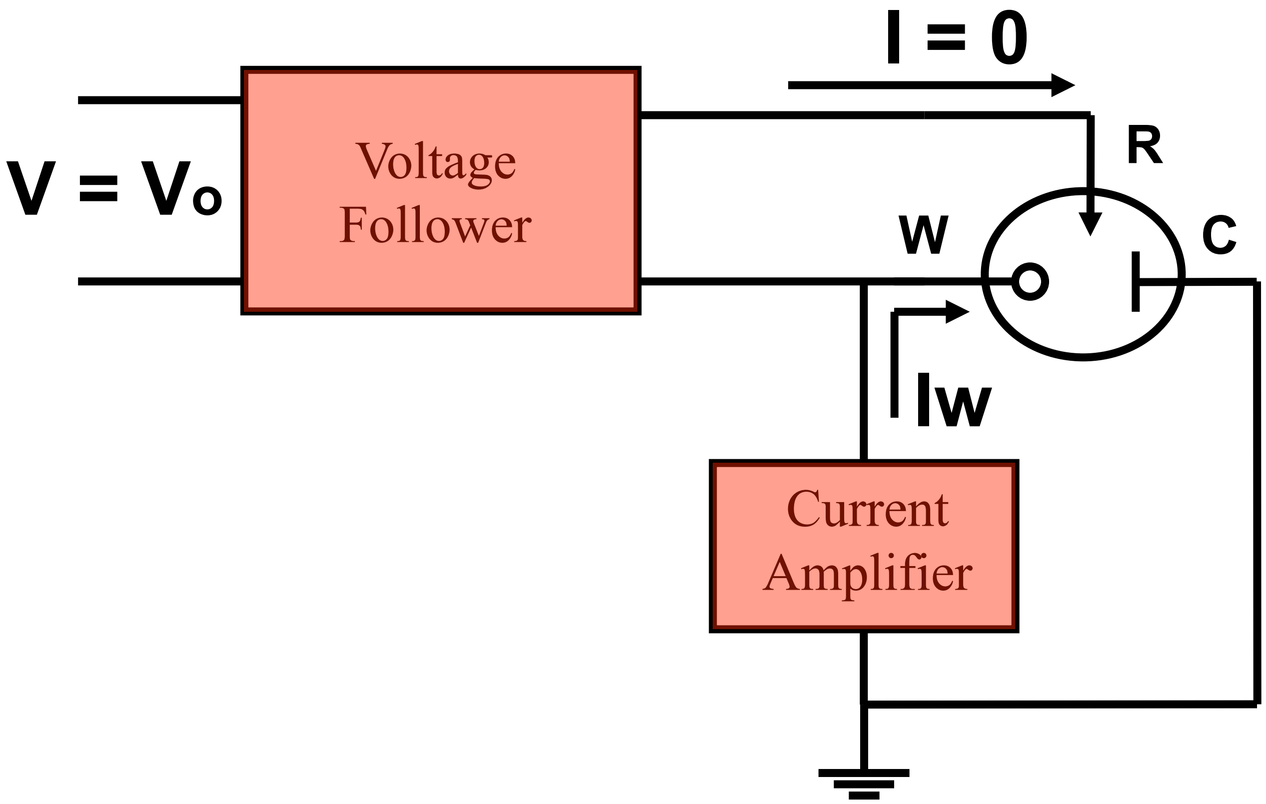
$$I = SC$$

$$I(t,V) = S(V)C(t)$$

$$S(V) = S_0 e^{-\frac{(V-V_0)^2}{\sigma}}$$

The sensitivity depends on the Reference Potential

Required Blocks



Required Building Blocks

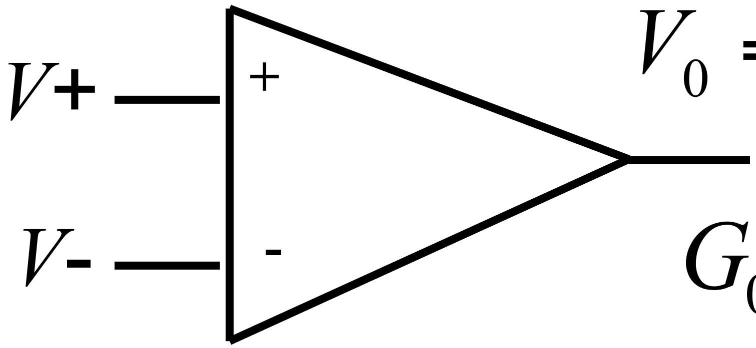
Voltage Follower	Analog Adder	Analog Shifter
Current Amplifier	Analog MUX	Analog Integrator

Basic Configurations of Operational Amplifiers

(Book Bio/CMOS: Appendix B)

What' s an Op. Amp.?

DIFFERENTIAL AMPLIFIER



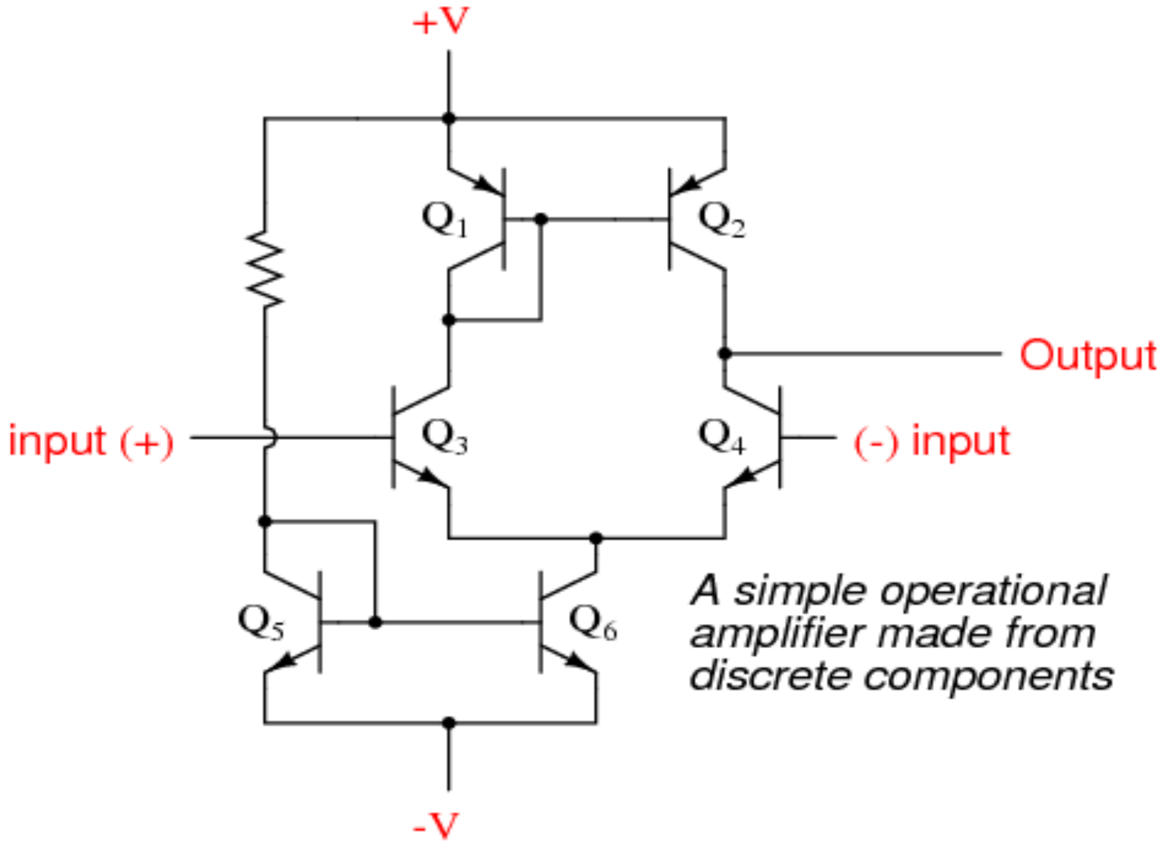
$$V_0 = G_0 (V_+ - V_-)$$

$$G_0 \rightarrow \infty$$

$$R_i \rightarrow \infty \quad \rightarrow I_i \cong 0$$

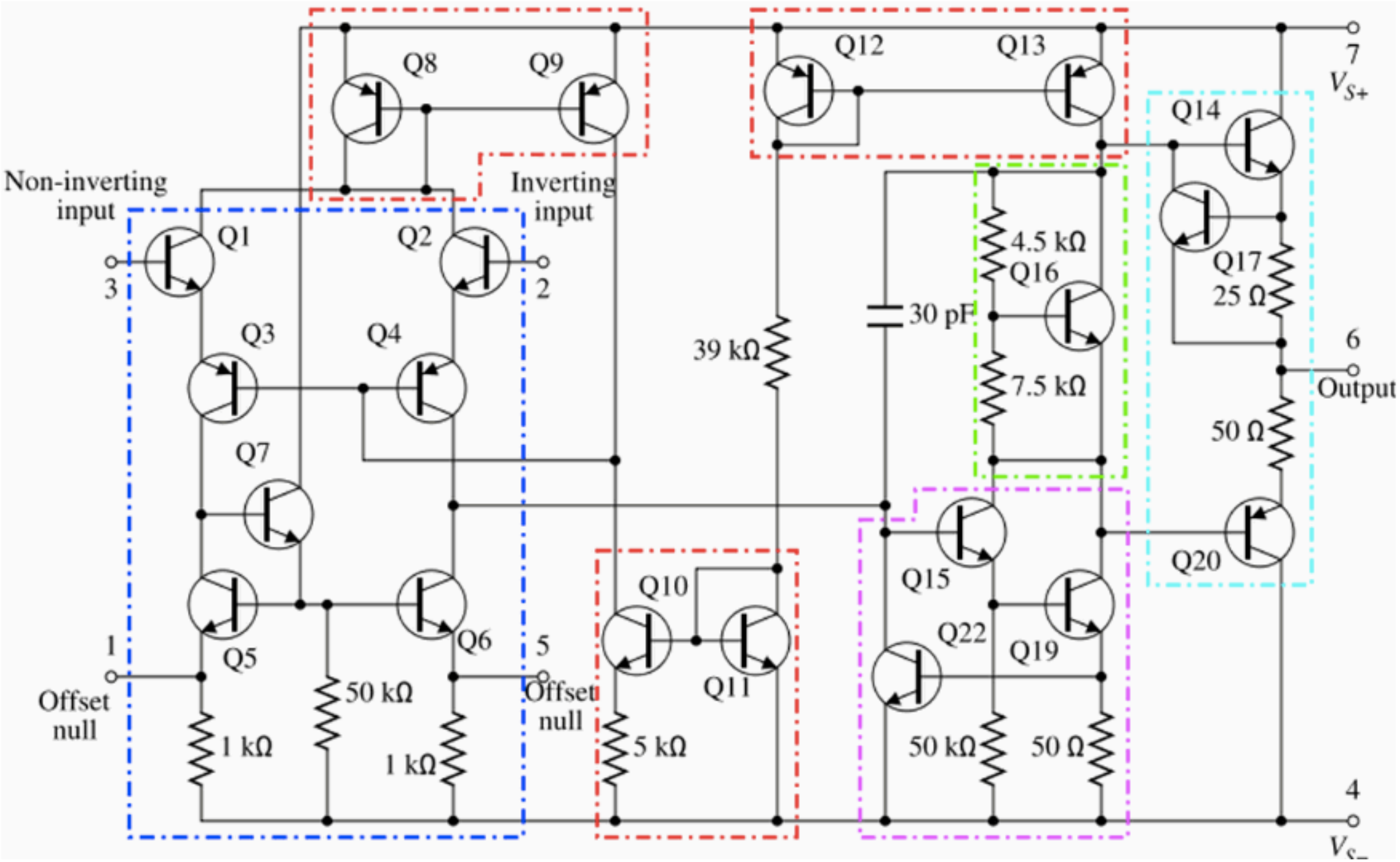
$$R_o \cong 0 \quad \rightarrow V_o \neq f(R_L)$$

What' s an Op. Amp.?



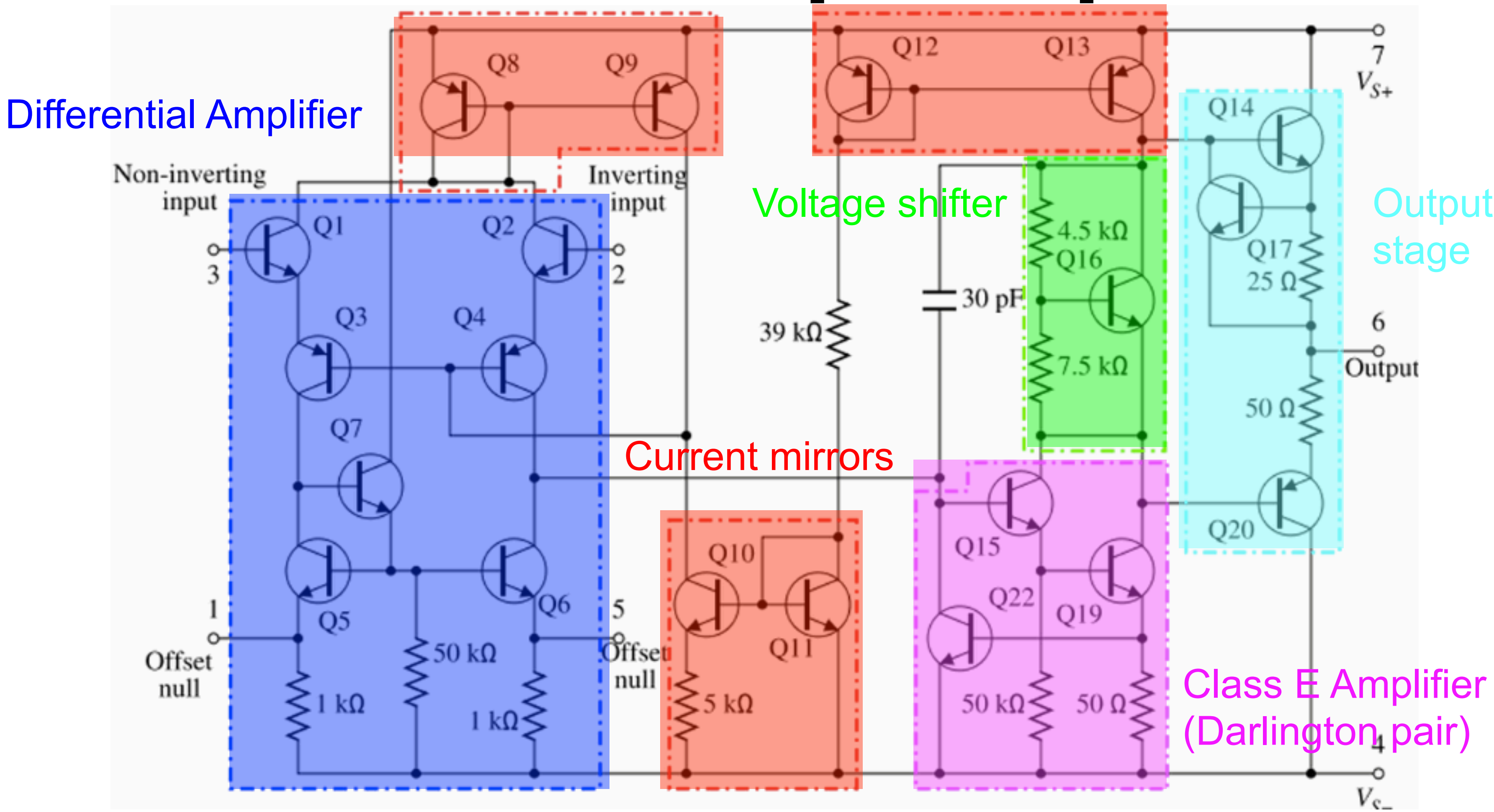
A simple scheme of a differential amplifier at transistosr level

What’s an Op. Amp.?



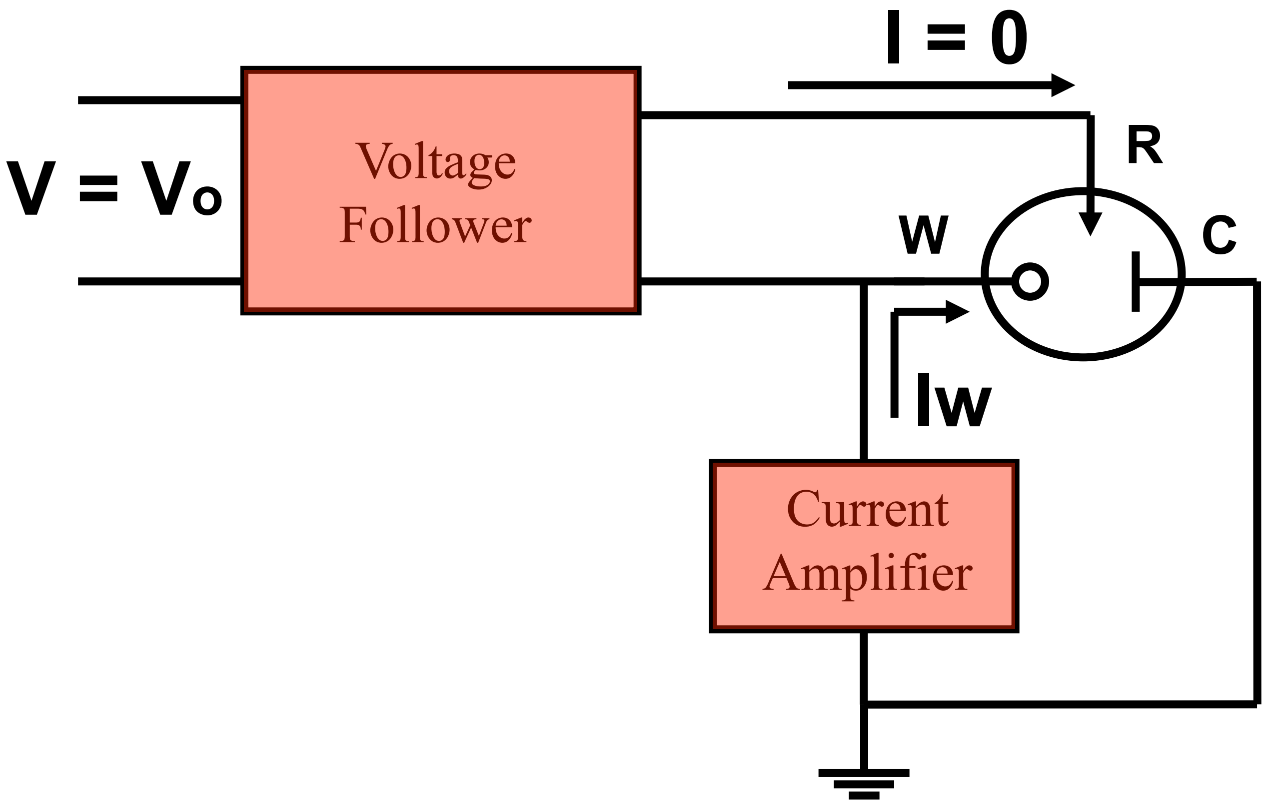
A more complex architecture of an Operational Amplifier (the common 741)

What's an Op. Amp.?

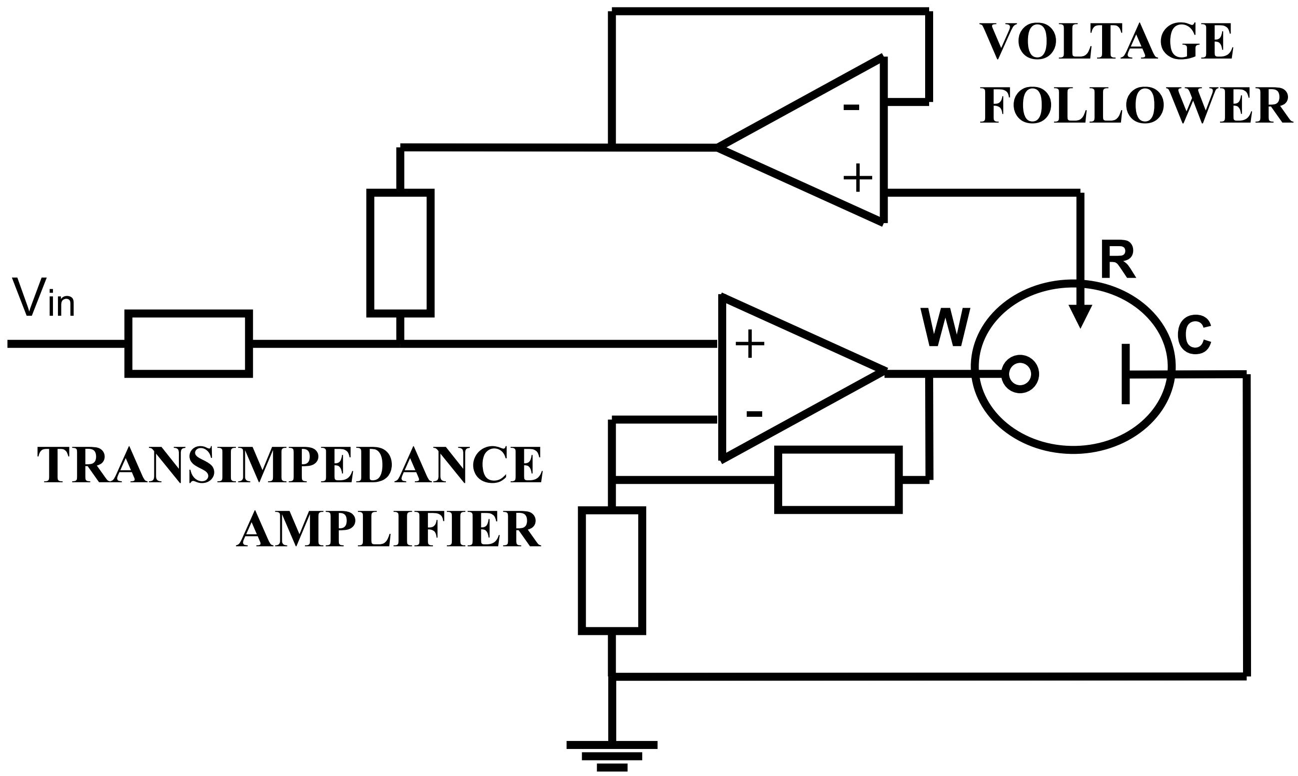


A more complex architecture of an Operational Amplifier (the common 741)

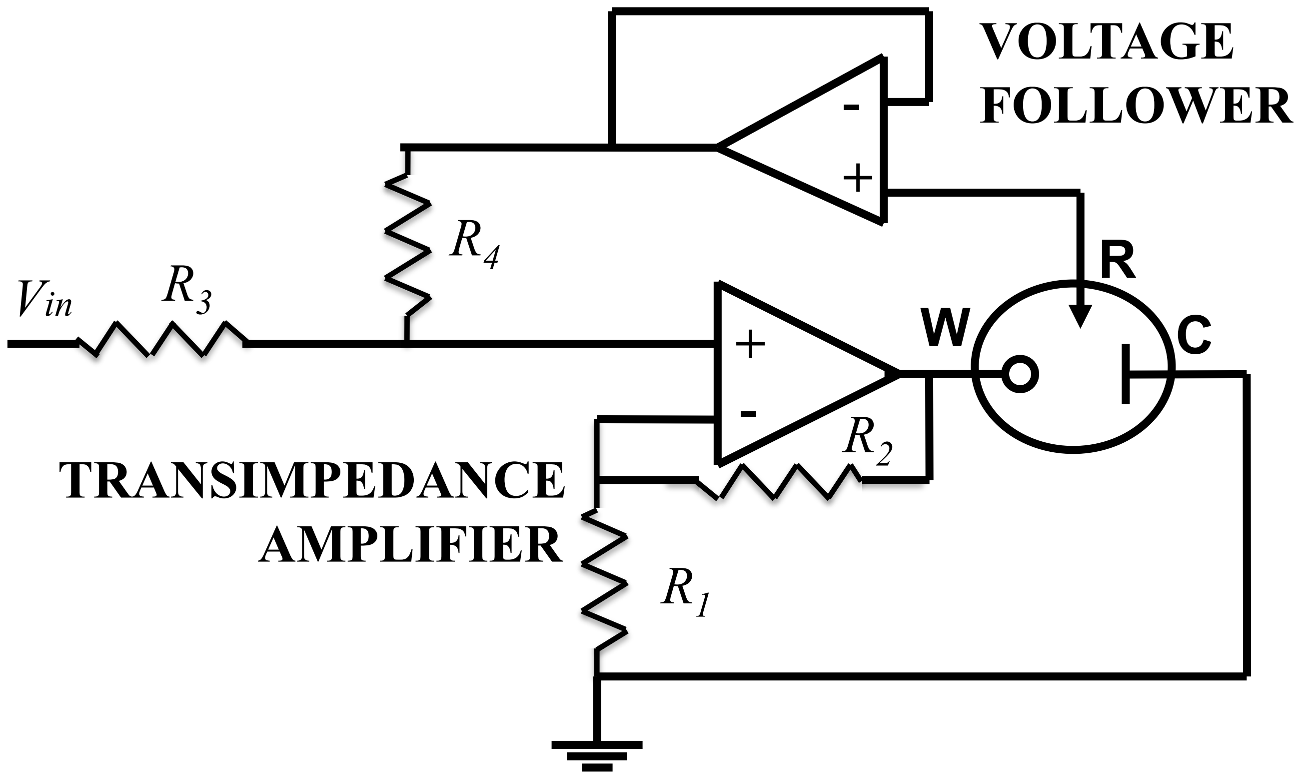
CMOS for Redox



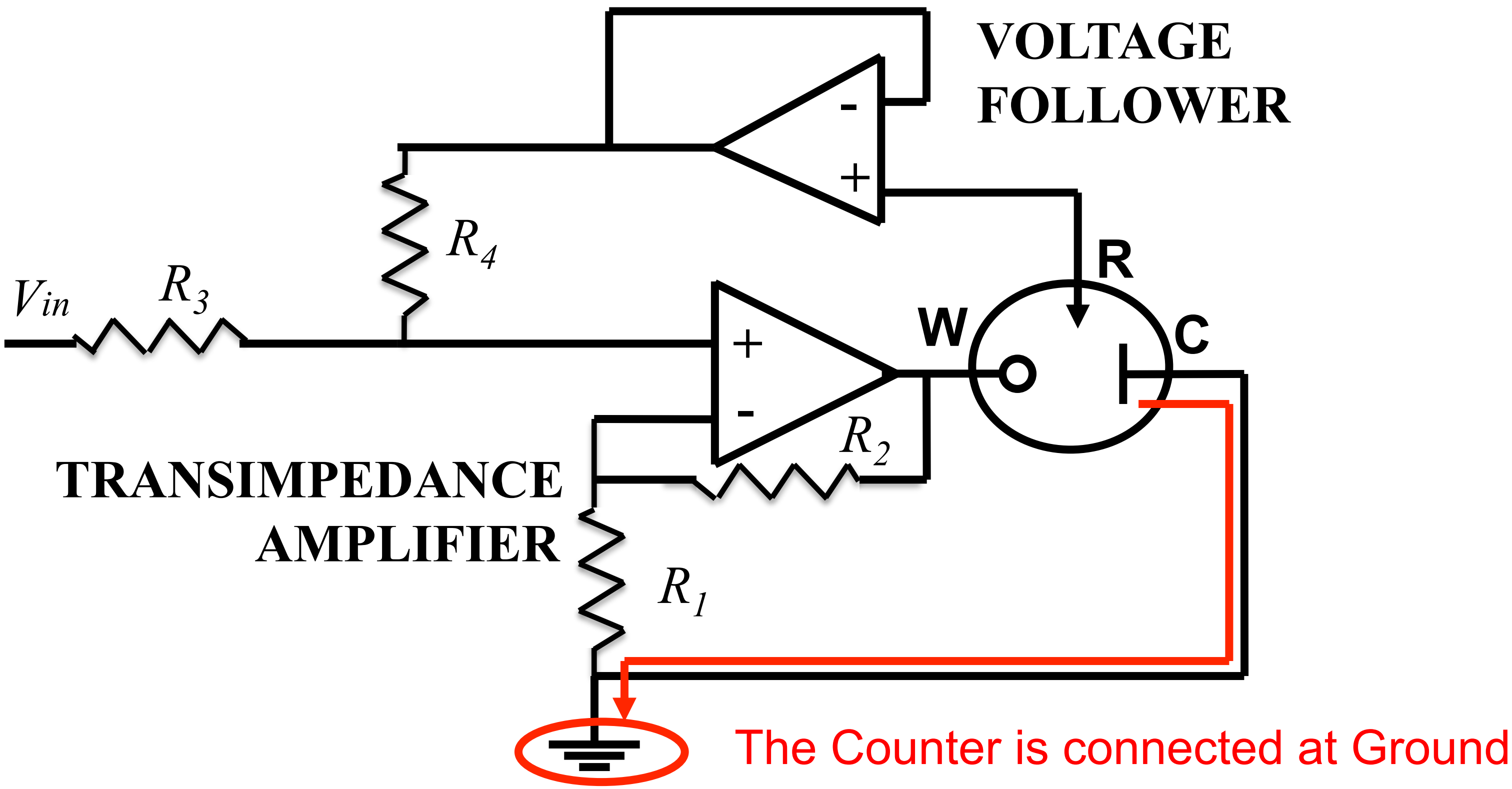
The basic CMOS for Redox



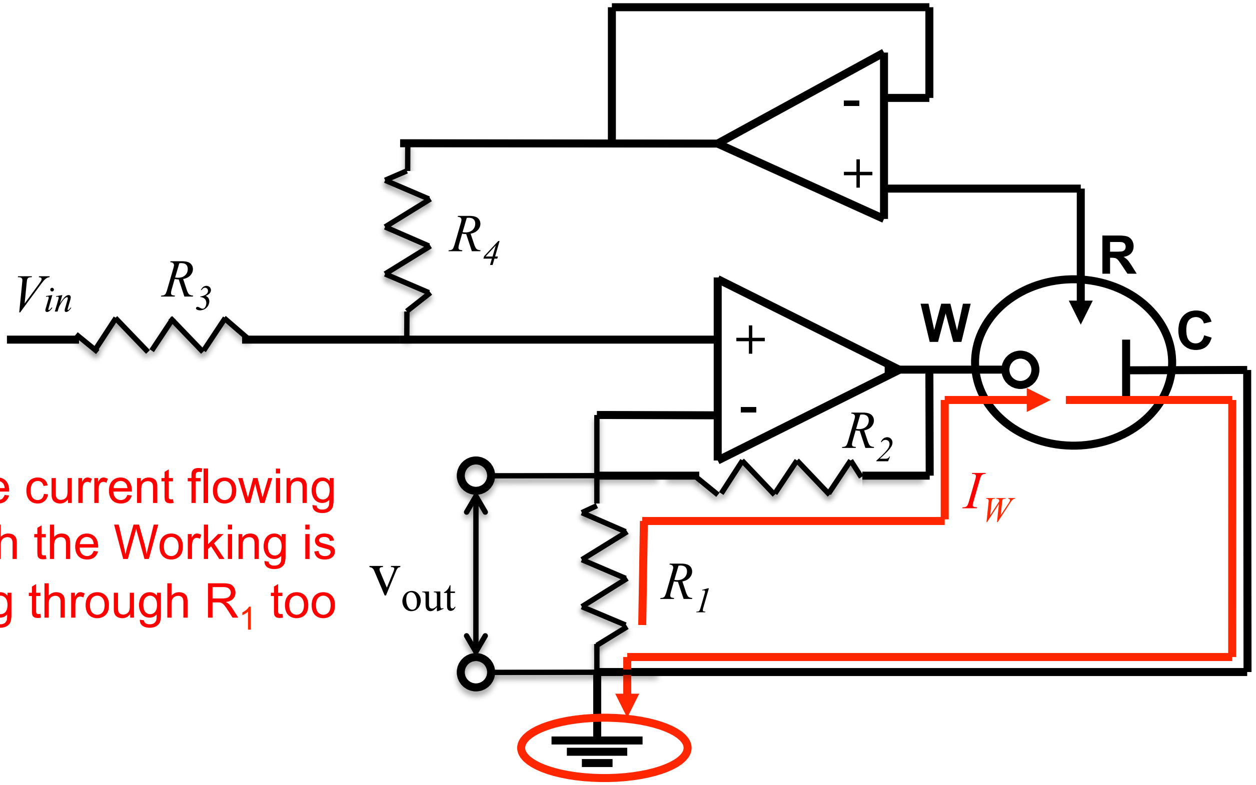
The basic CMOS for Redox



Grounded Counter

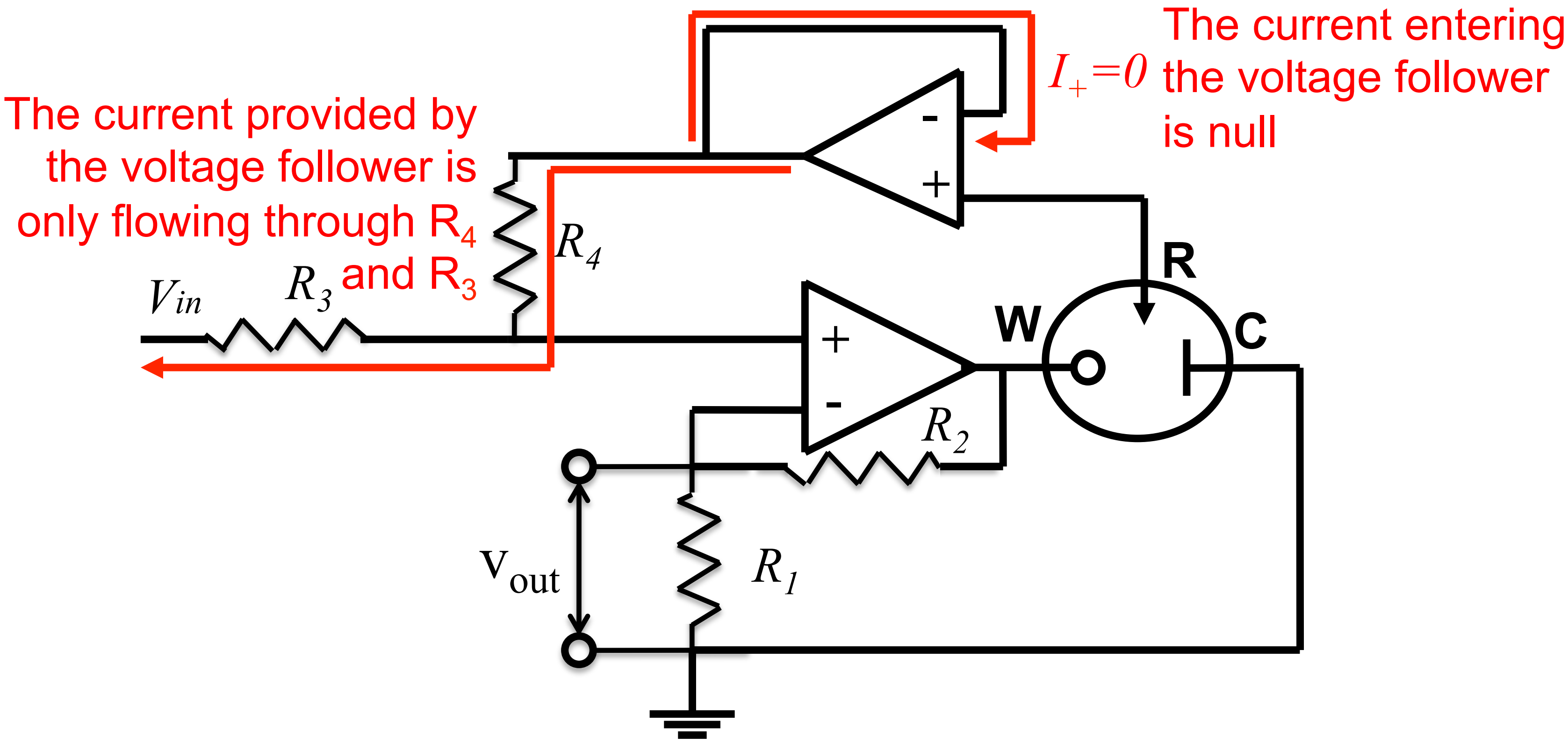


Grounded Counter

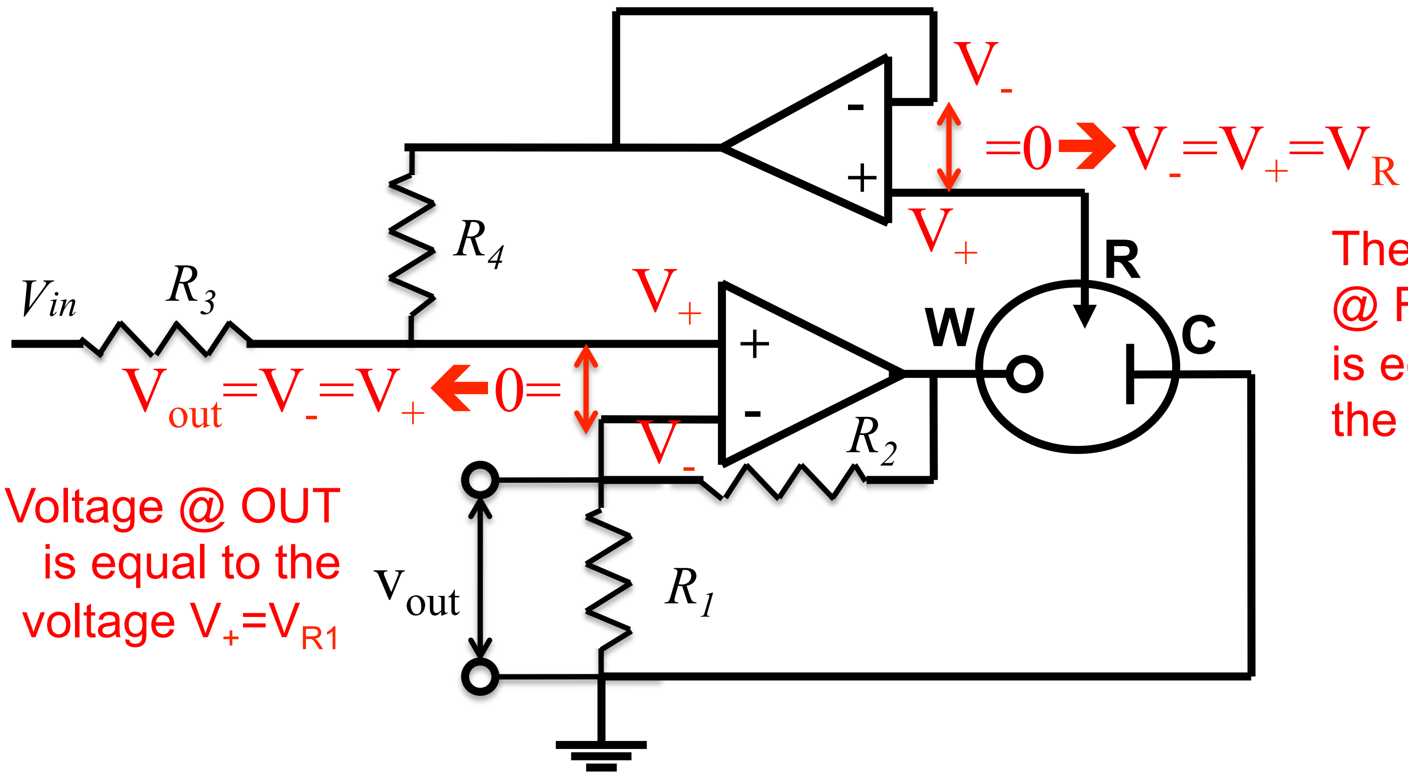


The current flowing through the Working is flowing through R_1 too

Grounded Counter



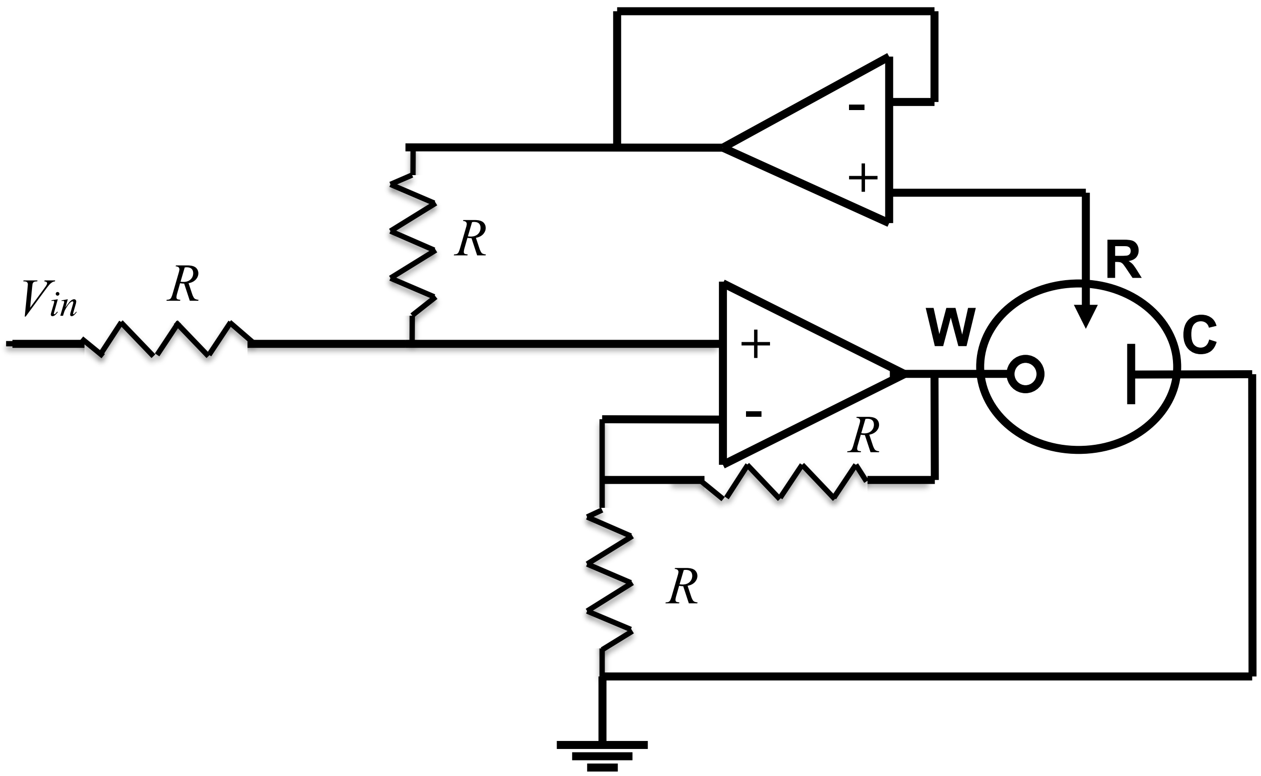
Grounded Counter



The Voltage @ Reference is equal to the voltage V_-

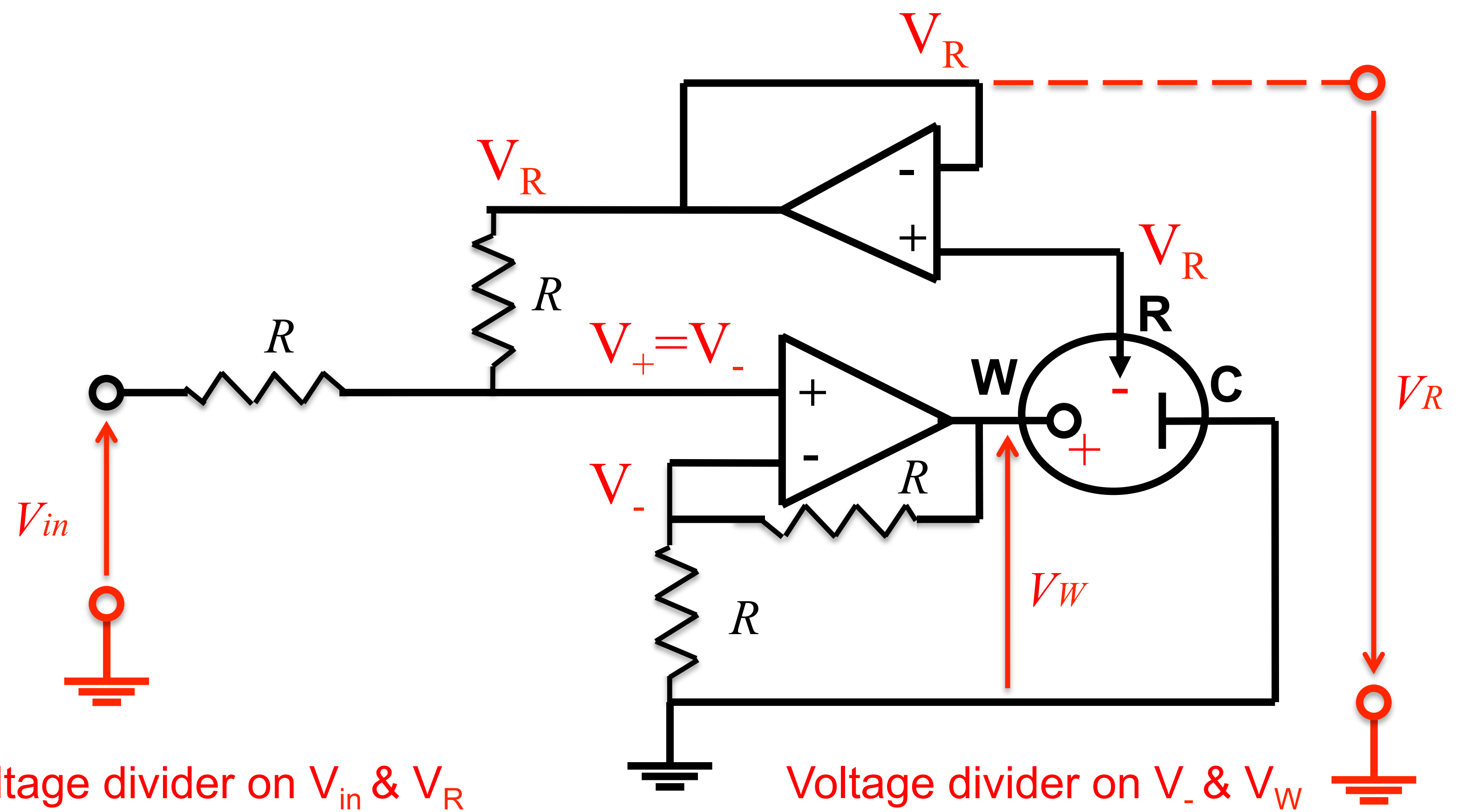
The Voltage @ OUT is equal to the voltage $V_+=V_{R1}$

Grounded Counter



$R_1=R_2=R_3=R_4=R$

Grounded Counter



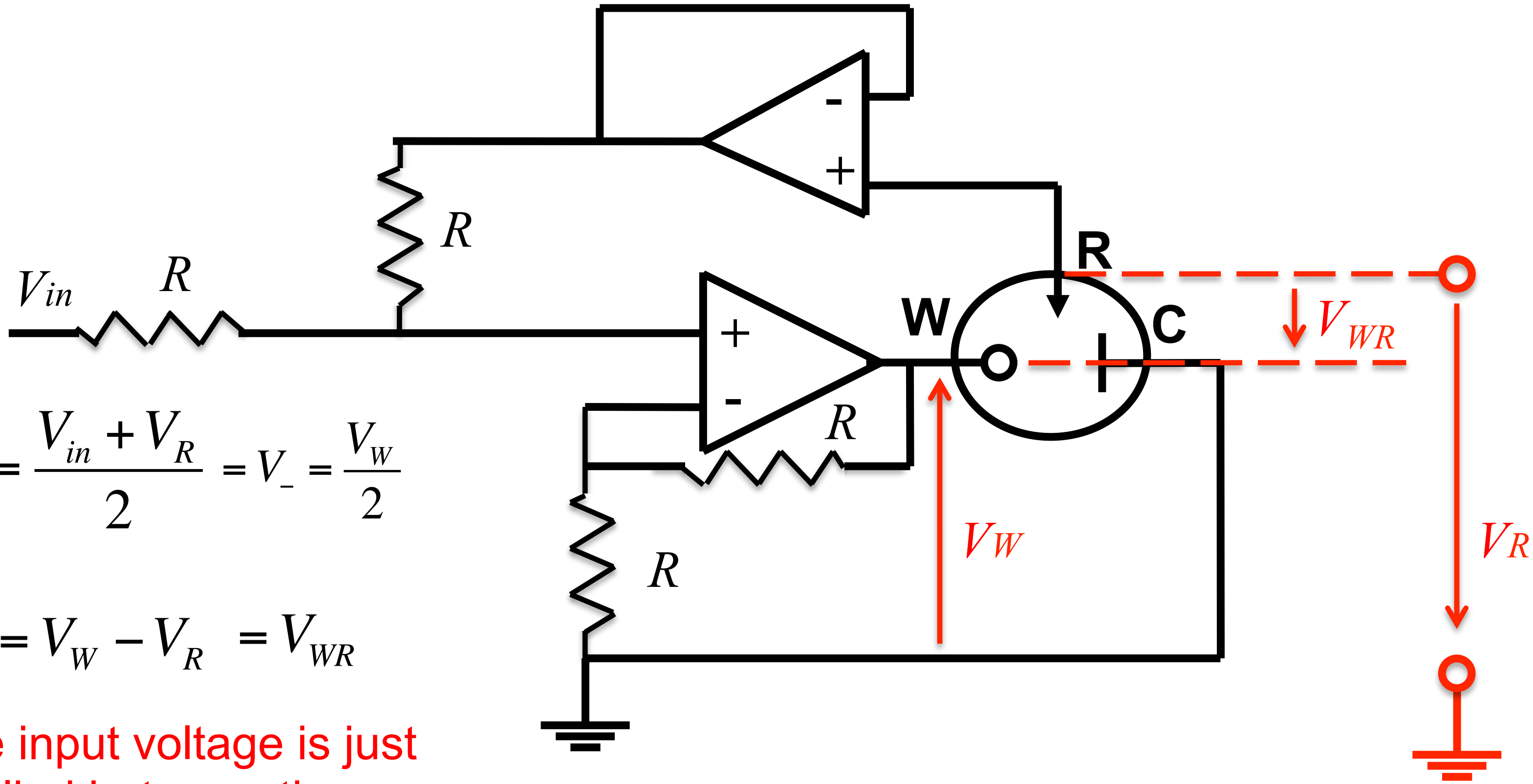
Voltage divider on V_{in} & V_R

$$V_- = (V_{in} + V_R)\frac{R}{R+R} = \frac{V_{in}+V_R}{2}$$

Voltage divider on V_- & V_W

$$V_- = V_W \frac{R}{R+R} = \frac{V_W}{2}$$

Grounded Counter

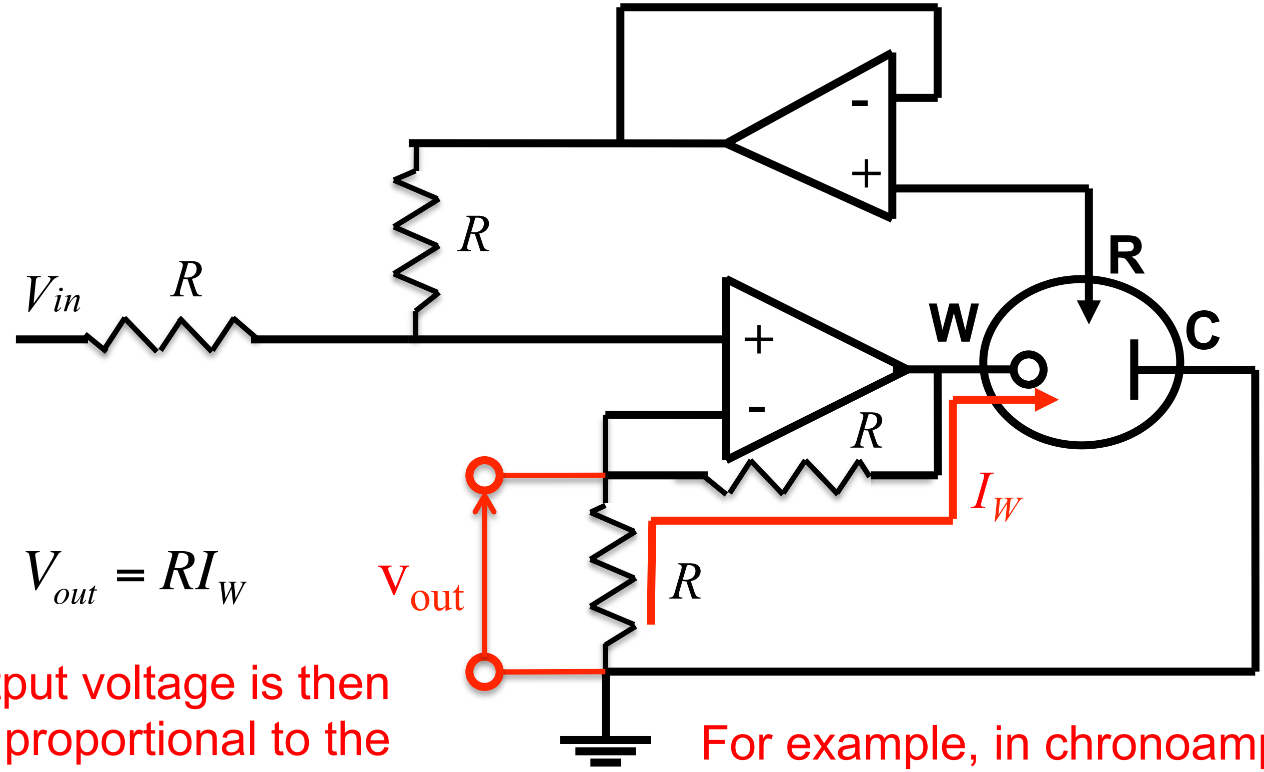


$$V_- = \frac{V_{in} + V_R}{2} = V_- = \frac{V_W}{2}$$

$$V_{in} = V_W - V_R \; = V_{WR}$$

The input voltage is just applied between the Reference and the Working

Grounded Counter



$$V_{out} = RI_W$$

The output voltage is then directly proportional to the Faradaic currents generated by the redox occurring at the working electrode

For example, in chronoamperometry

$$V_{out} = R\frac{nFA\sqrt{D}}{\sqrt{\pi t}}C_R$$

Concentration of Redox specie

Noise issues!

$$V_{out} = RI_F = R\frac{nFA\sqrt{D}}{\sqrt{\pi t}}C_R$$

This is only the Faradaic contribution

$$V_{out} = RI_W = I_F + I_C + I_n$$

Total noise in the output signal

$$I_n = I_{thermal} + I_{shot} + I_{flicker}$$

Usual sources of noise in electronics

White noise

$$I_{thermal} \rightarrow PSD = \frac{4kT}{R}$$

Johnson-Nyquist thermal noise current

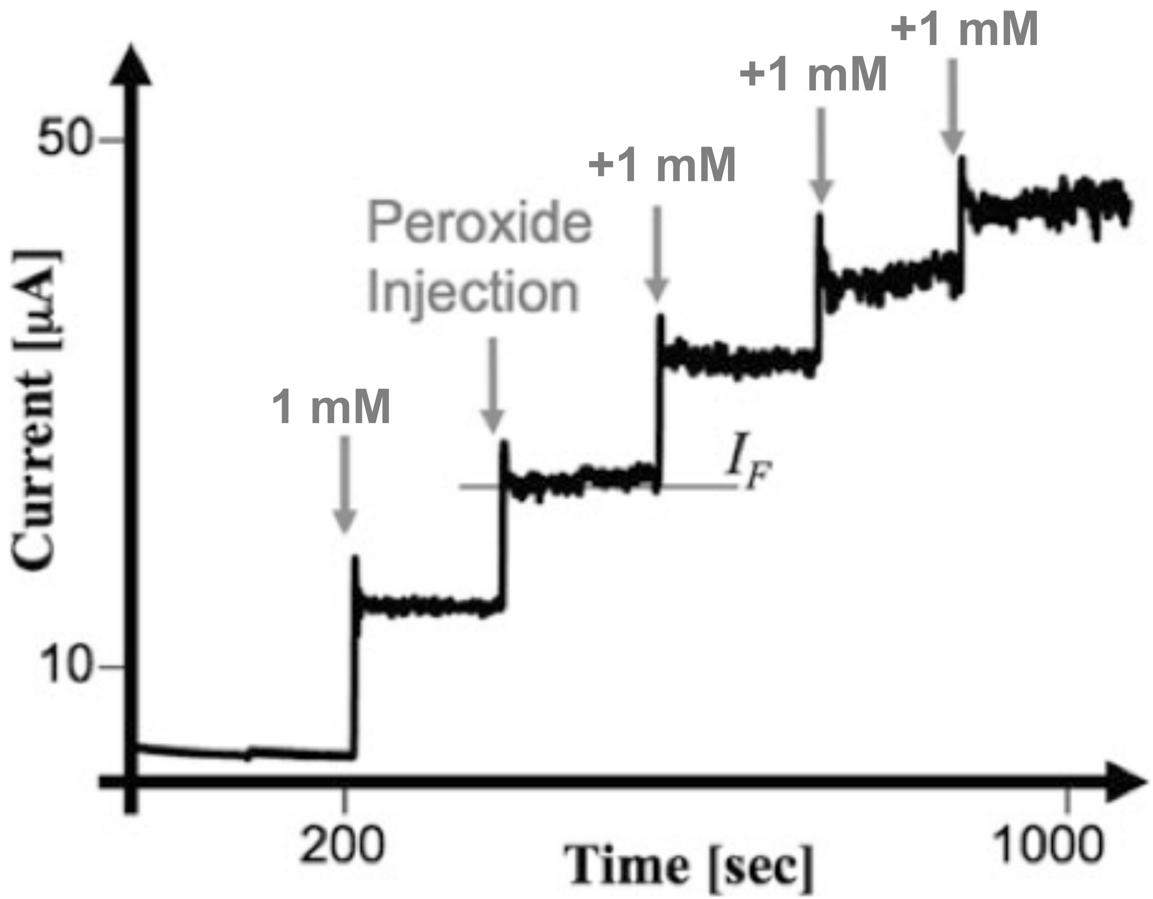
$$I_{shot} \neq \Phi(T, f)$$

originates from the discrete nature of electric charge. Shot noise is temperature and frequency independent

$$I_{flicker} = \frac{A}{f}$$

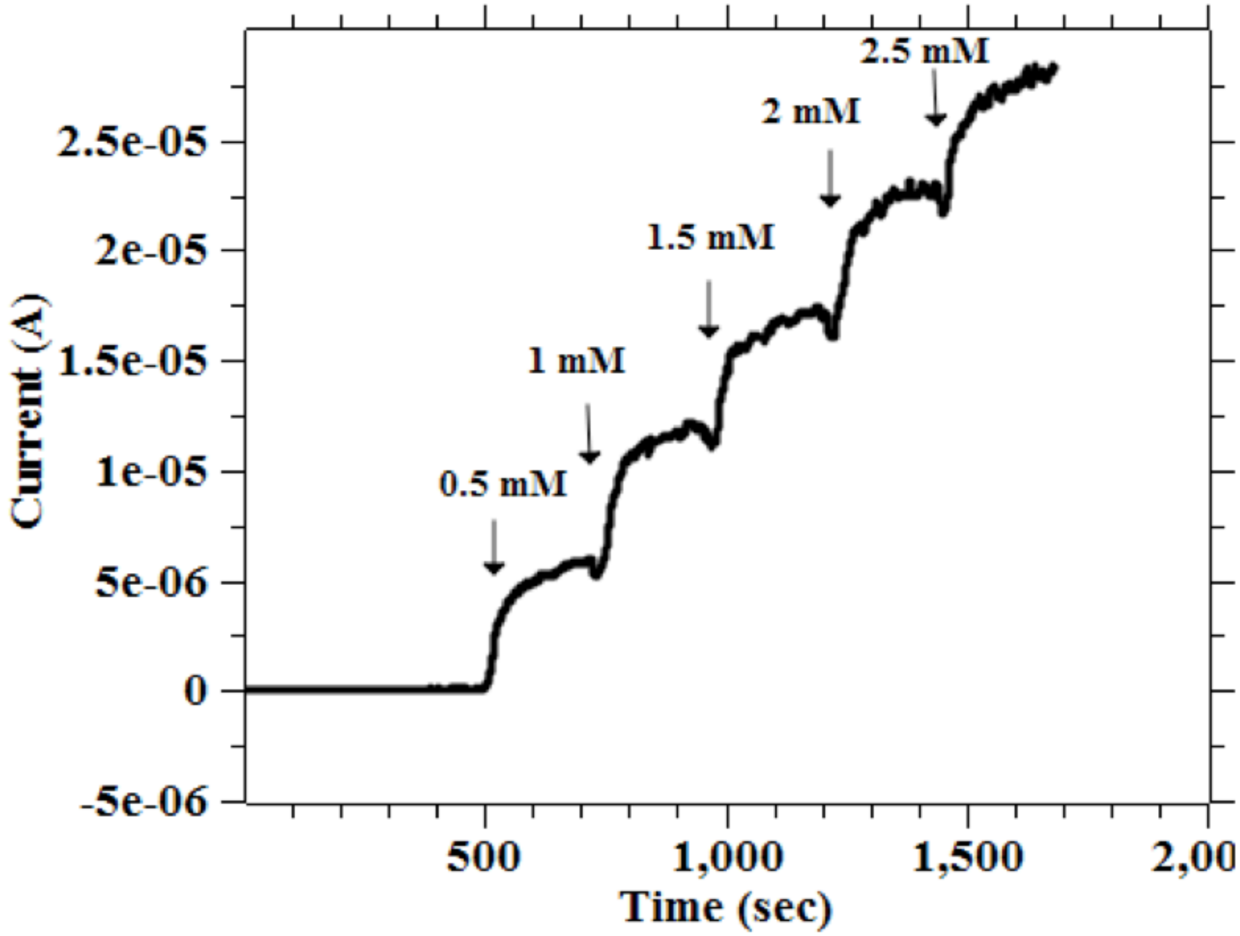
Flicker noise, which has a spectral density that decreases with the frequency. It is the dominant noise source at low frequencies

Noise @ the Bio-interface



Typical chronoamperometry (650 mV) on hydrogen peroxide

Noise @ the Bio-interface



Typical chronoamperometry (300 mV) on Ferrocyanide

Noise Power Spectra Density

Average current of the biosensor

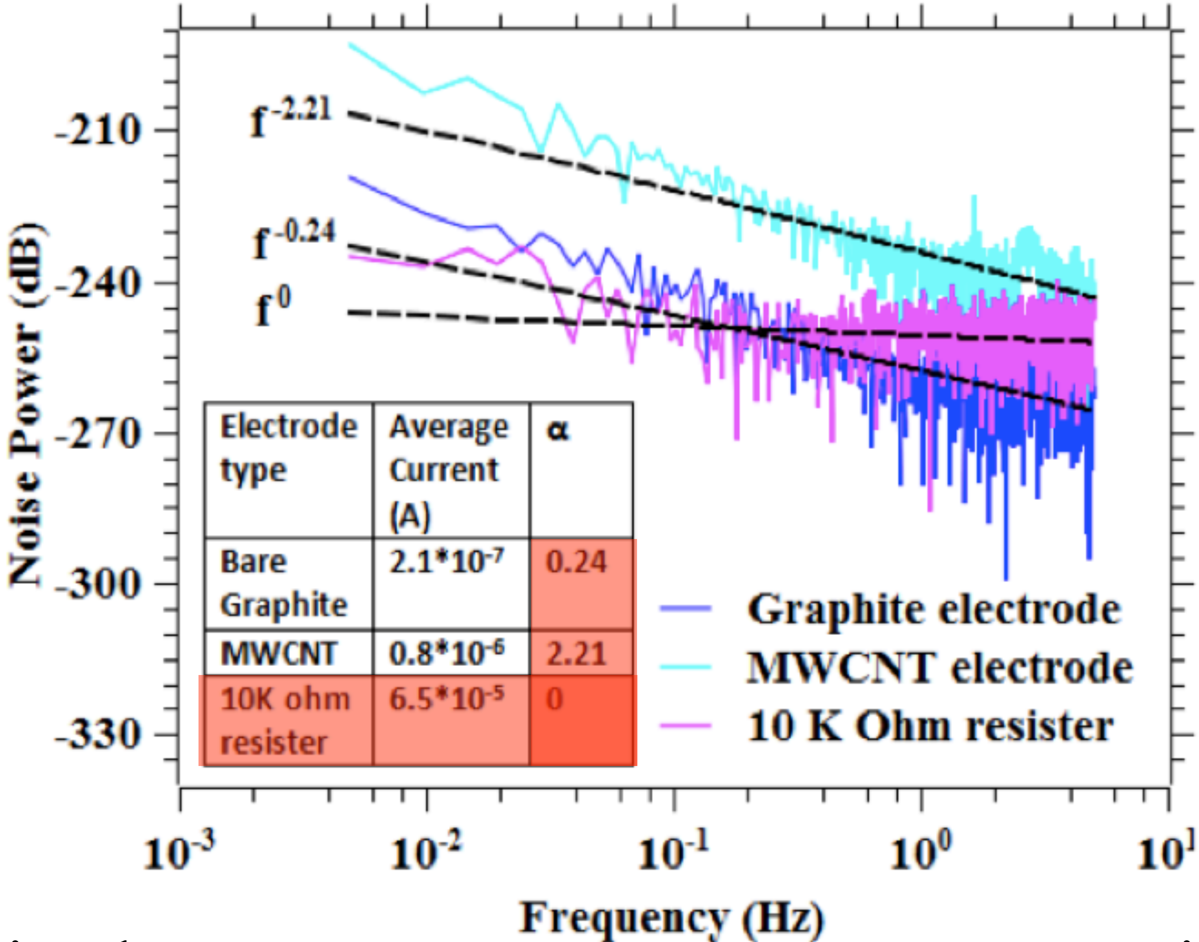
The inverse SNR of the measurement at 1Hz

$$PSD_{flicker} = \frac{AI_{avr}^2}{f^{\alpha}}$$

Generalized frequency dependence

Generalized flicker formula to extract the values of noise coefficients by fittings on the electrochemical interface

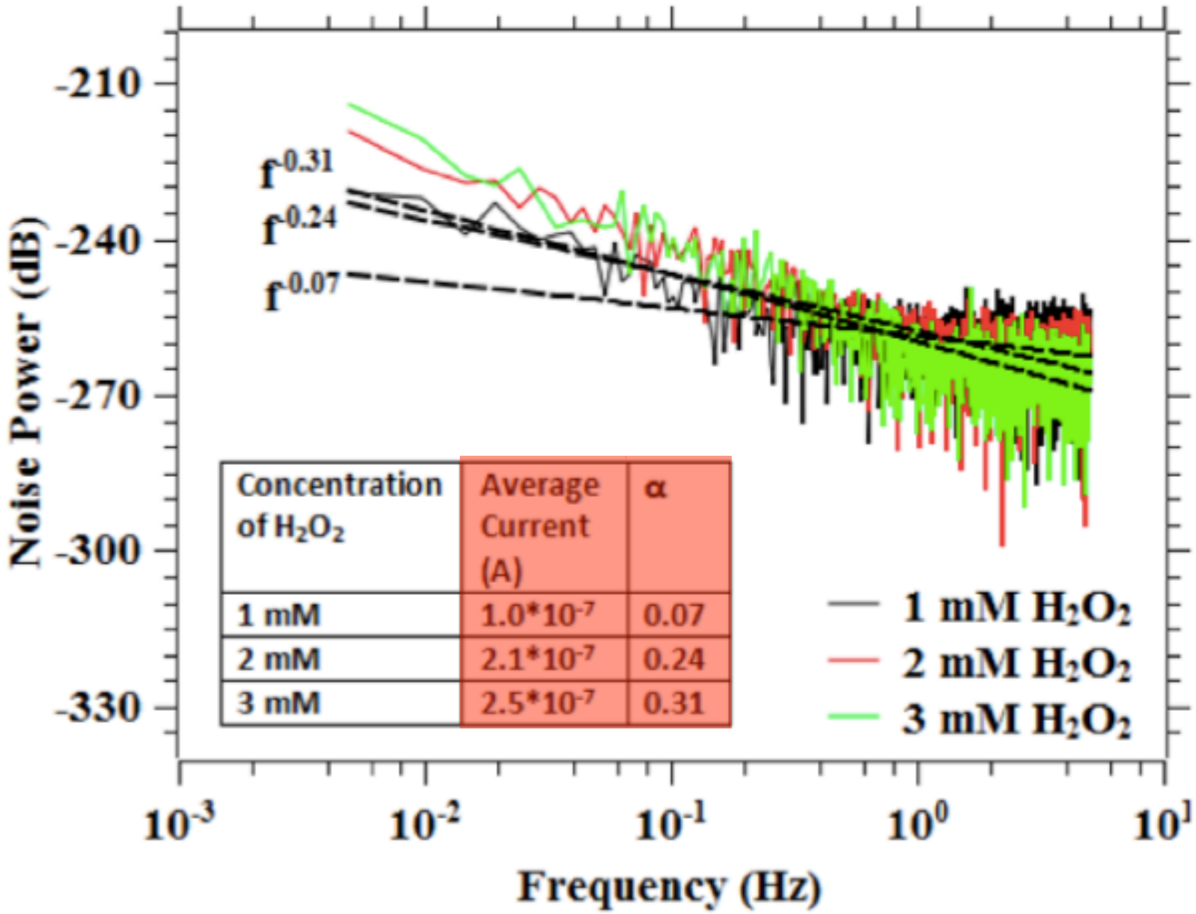
Power Spectra Density



Electrode type	Average Current (A)	α
Bare Graphite	$2.1*10^{-7}$	0.24
MWCNT	$0.8*10^{-6}$	2.21
10K ohm resister	$6.5*10^{-5}$	0

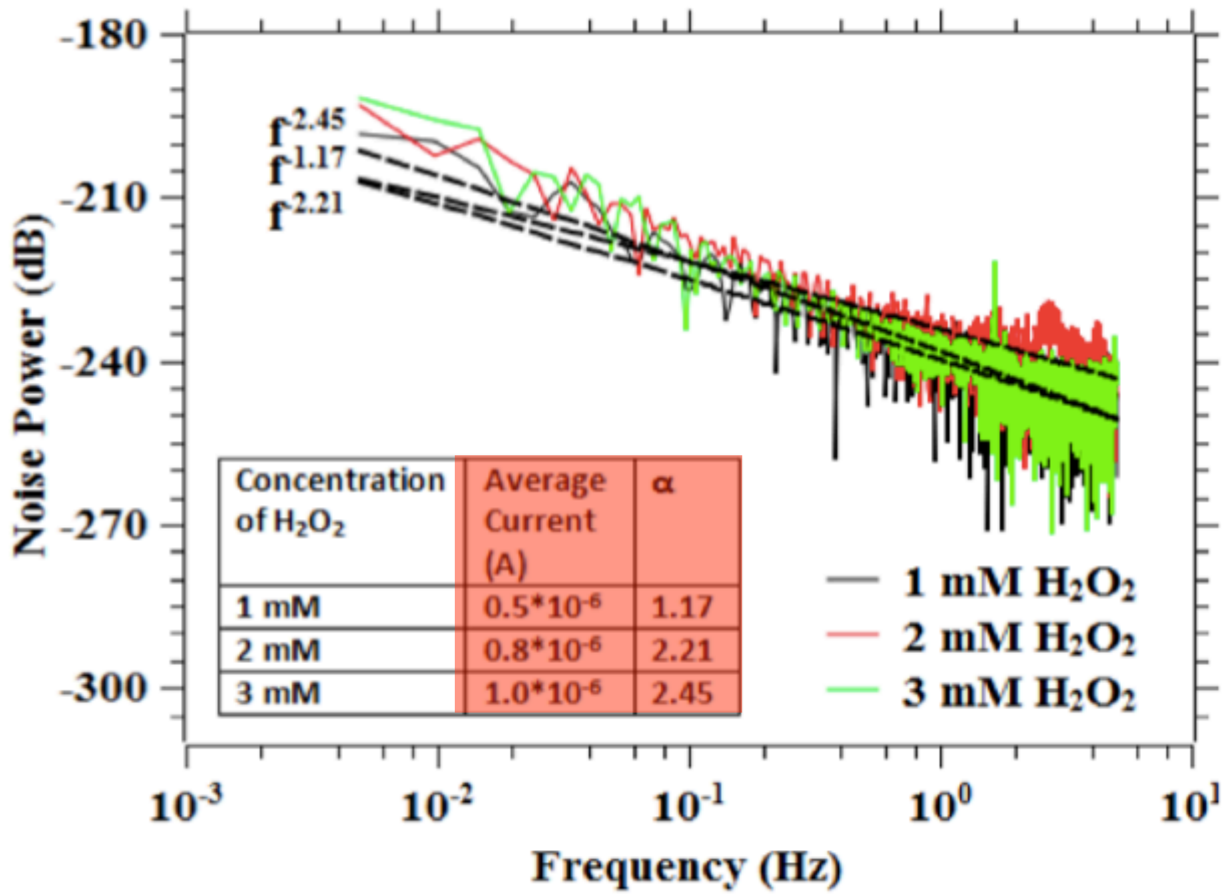
Noise PSD in chronoamperometry measurement with bare and MWCNT electrodes and a 10 kΩ resistor

Noise PSD on Bare



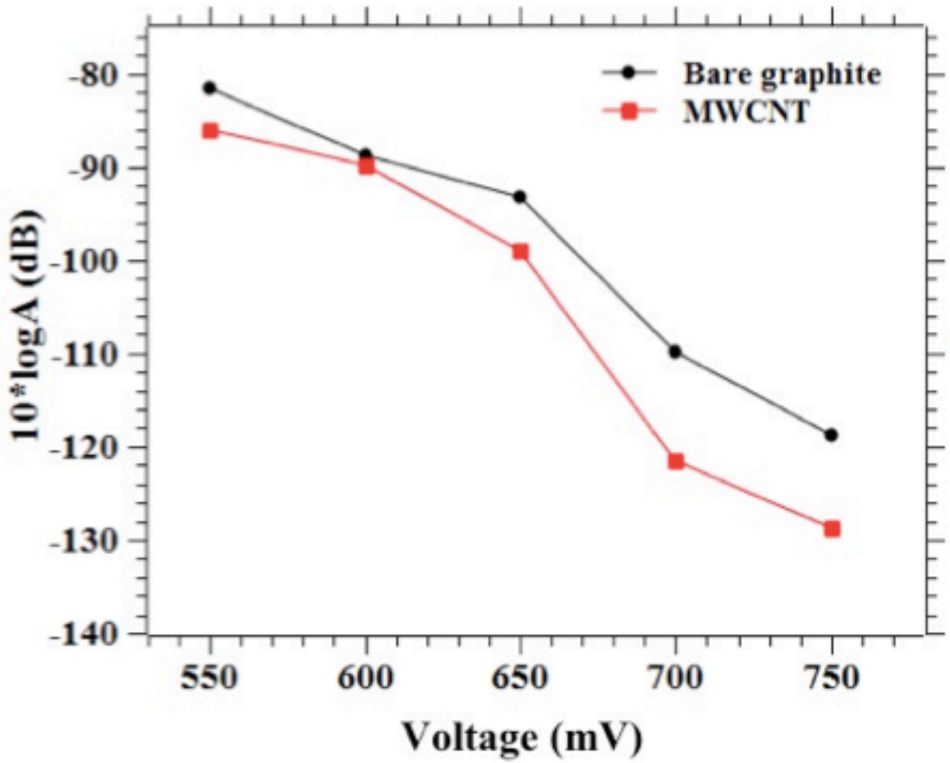
Noise PSD in chronoamperometry measurement (650 mV) of H_2O_2 with bare screen-printed electrode

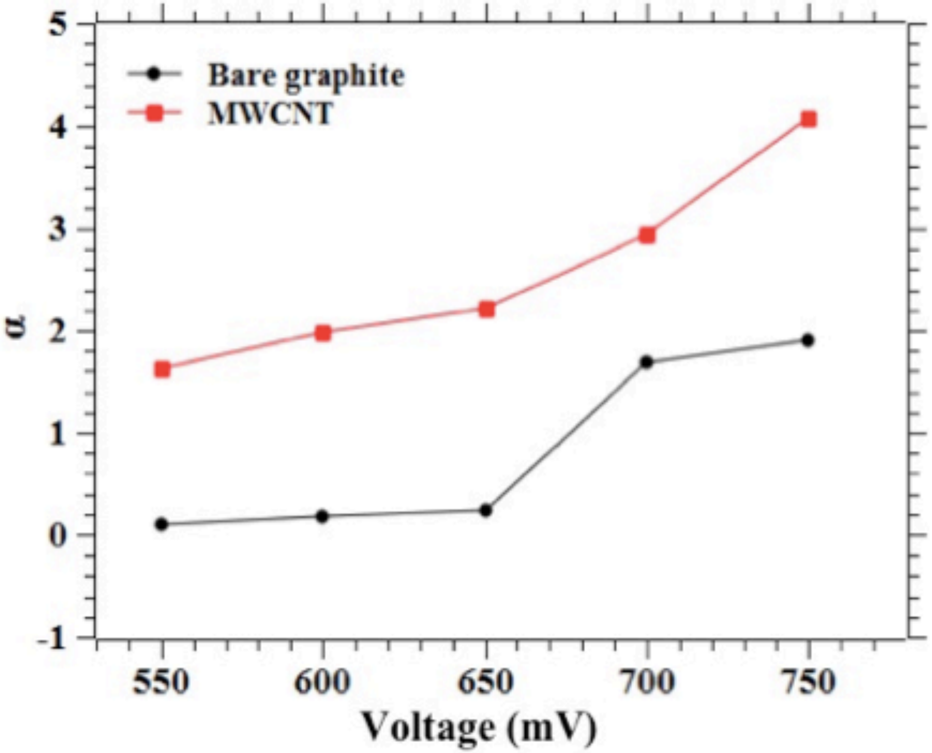
Noise PSD on MWCNT



Noise PSD in chronoamperometry measurement (650 mV) of H_2O_2 with MWCNT structured electrode

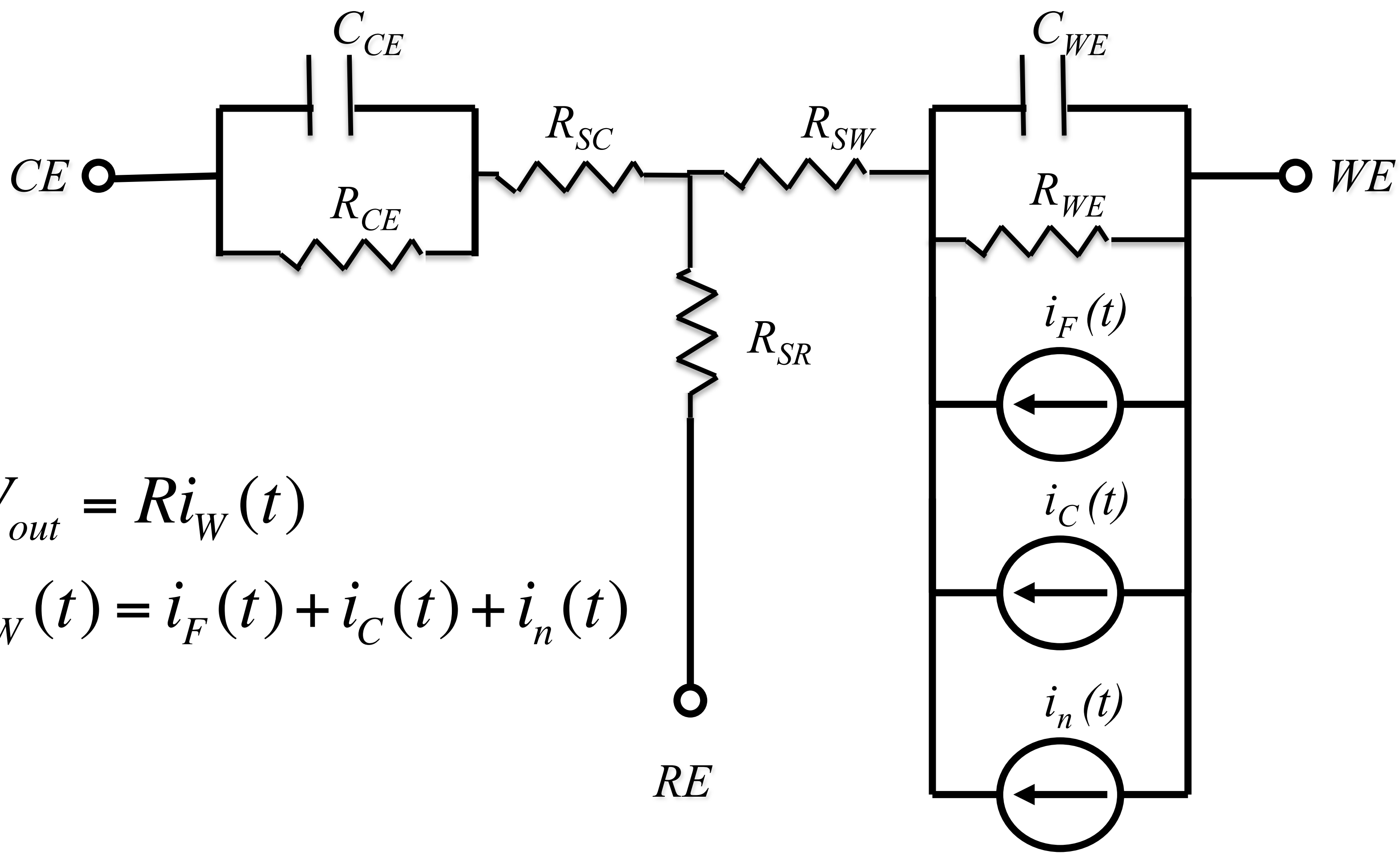
Dependence by the Voltage





Values of parameters A (left) and α (right) versus the applied voltage, estimated on 2mM of H_2O_2

Equivalent circuit with all the current sources



$$V_{out} = Ri_W(t)$$

$$i_W(t) = i_F(t) + i_C(t) + i_n(t)$$

Summary

- **Specific CMOS design is required to develop biochip for Amperometric Detection of metabolites**
- **Bio/CMOS circuits are easy to design with Analog building-blocks**
- **Analog building-blocks are easy to design with Operational Amplifiers**
- **In some conditions, CMOS simulations might be performed by using the equivalent circuit of the electrochemical cells**
- **In CMOS simulations, we usually also need to take into account the noise of the Bio/CMOS interface**