Master in Electrical and Electronics Engineering

EE-517: Bio-Nano-Chip Design

# Lecture #10
# CMOS Building Blocks

# Lecture Outline

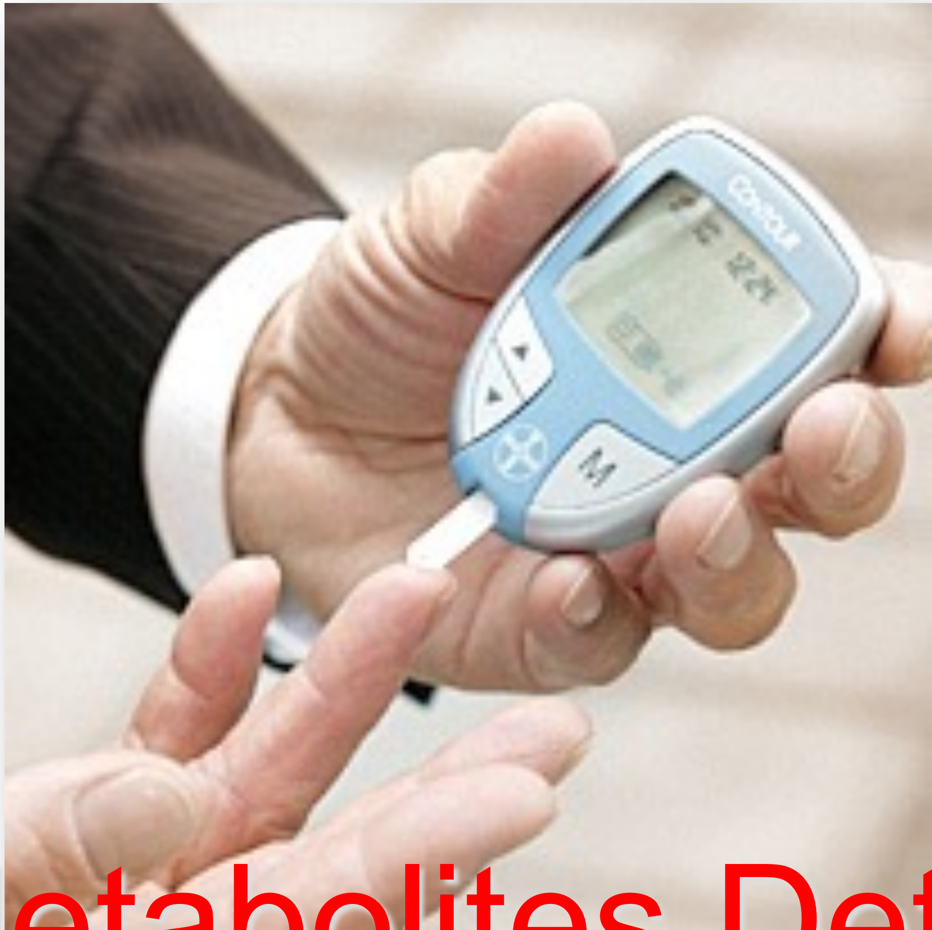
**(Book Bio/CMOS:** Appendix B & Chapter' paragraph 8.9.3, 9.1.1, 9.2)

- 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

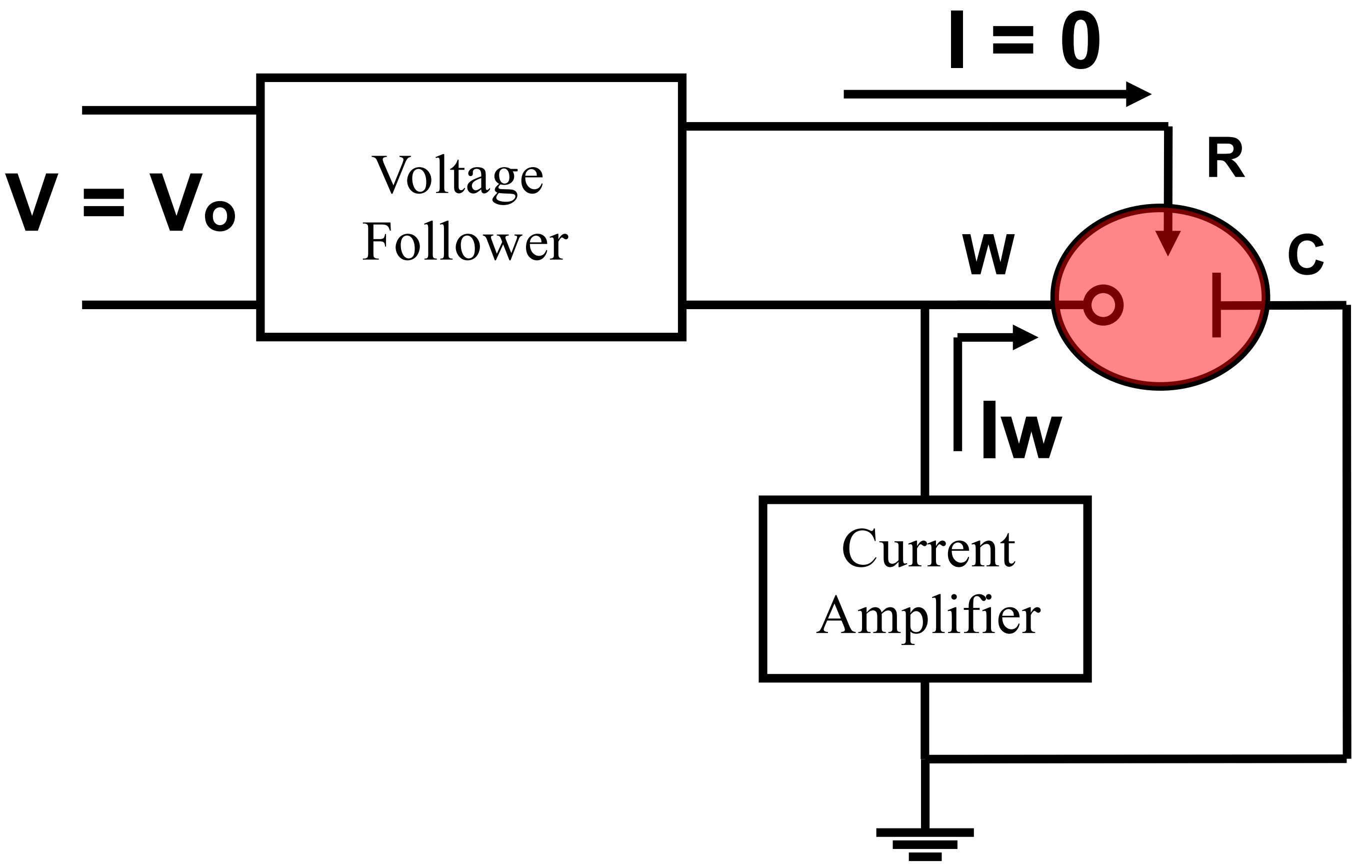
# CMOS architectures for Portable



# in Metabolites Detection

# CMOS architectures for iPhone

# Required Blocks



Q1

# Why the electrochemical cell needs three electrodes?

A. Because we need redundancy to improve the measure

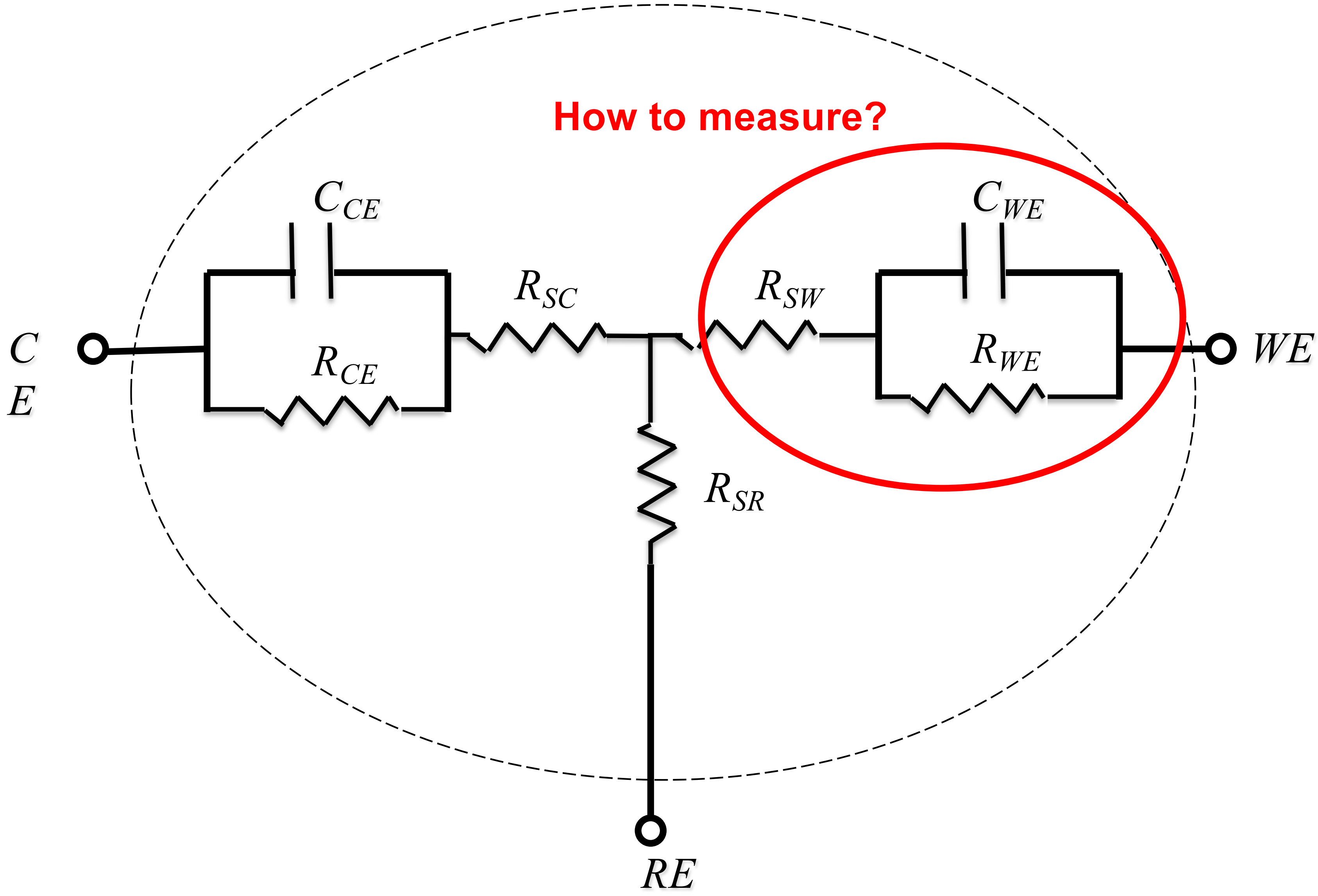
B. Because we need to measure a current, a voltage, and a flux

C. Because we need to measure a current, while applying a precise voltage

D. Because we need to measure a voltage, while supplying a precise current

E. Because the cell is a node with three entering currents

# Equivalent circuit: passive model

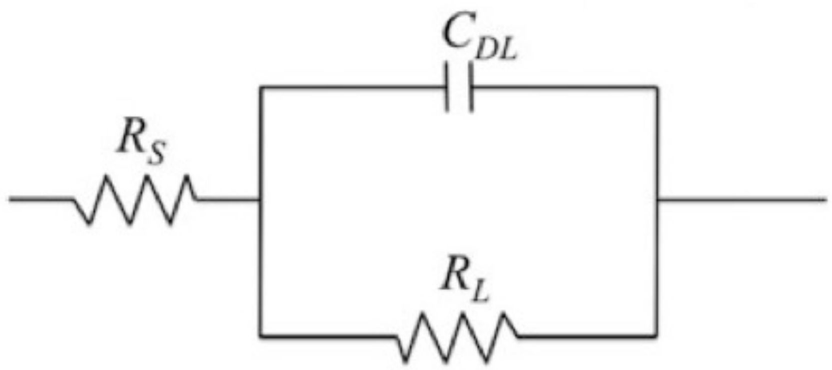


Q2

# How to measure the equivalent circuit of an electrochemical cell?

A. Impossible to measure, that's just a theoretical model
B. Possible but very difficult to measure since it contains too many parameters
C. Possible but not very useful since that's just a theoretical model
D. That's enough to perform a measure of impedance

# Equivalent Impedance




$$Z_{//} = Z = C_{DL} // R_L$$

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

The Layering effects result in the impedance in parallel

# Equivalent Impedance

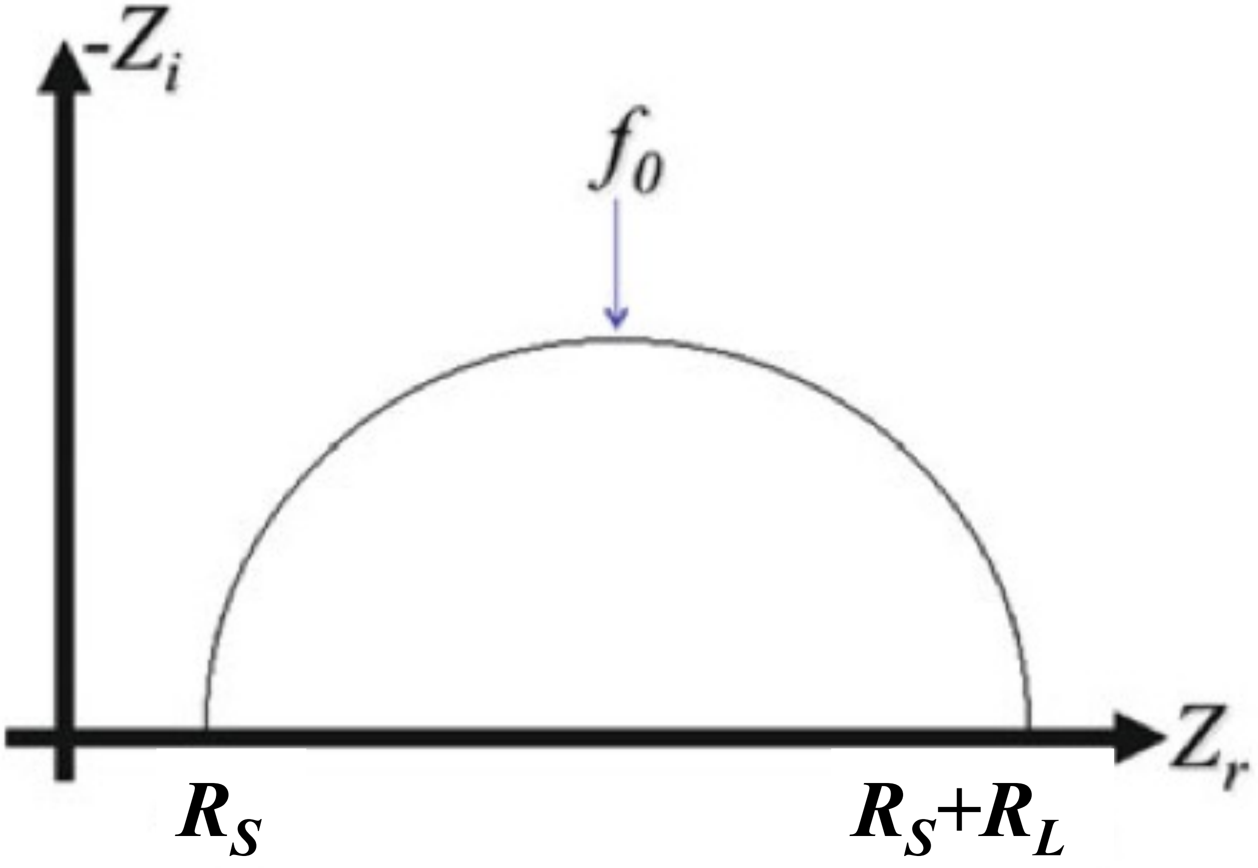
$$Z = \frac{R_L}{j\omega C_{DL} R_L + 1} \cdot \frac{1 - j\omega C_{DL} R_L}{1 - j\omega C_{DL} R_L}$$

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

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

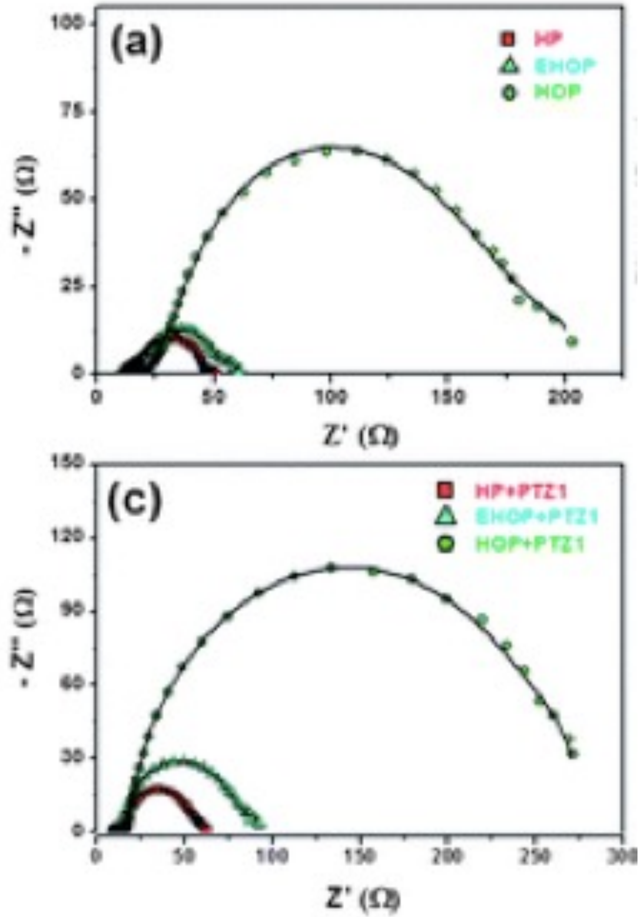
This impedance presents both resistive and reactive components

# 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

Q3

# In real cases, are layering phenomena correctly described by capacitors?

A. Yes, of course!
B. Impossible to correctly model the layering
C. Possible but very difficult to correctly model the layering
D. Possible but not very useful since that's just a theoretical model
E. Not really

# Capacitance vs Frequency

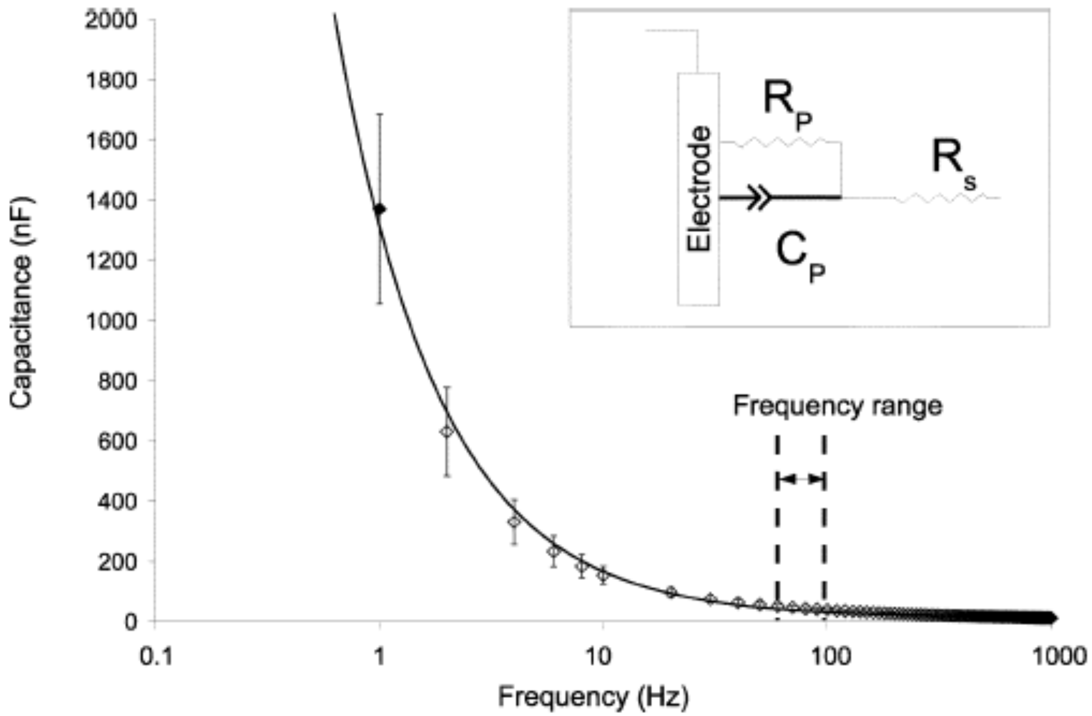
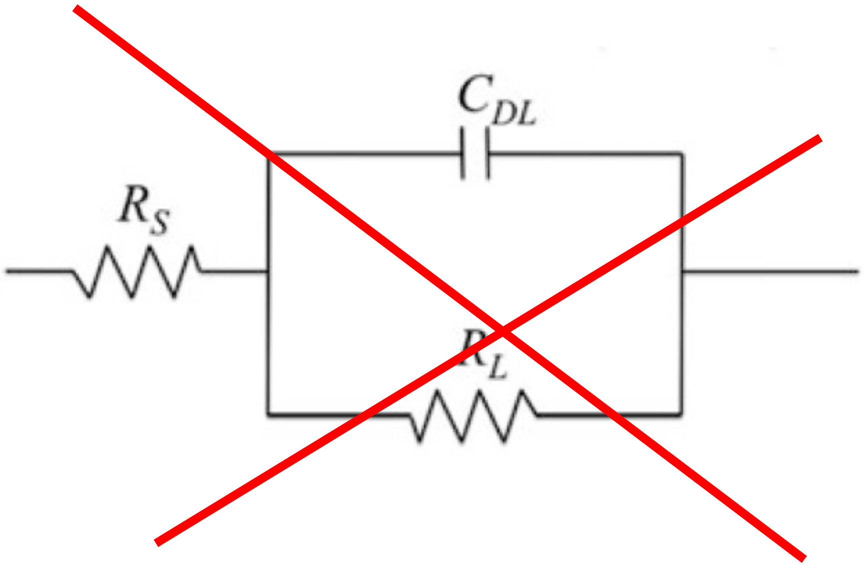
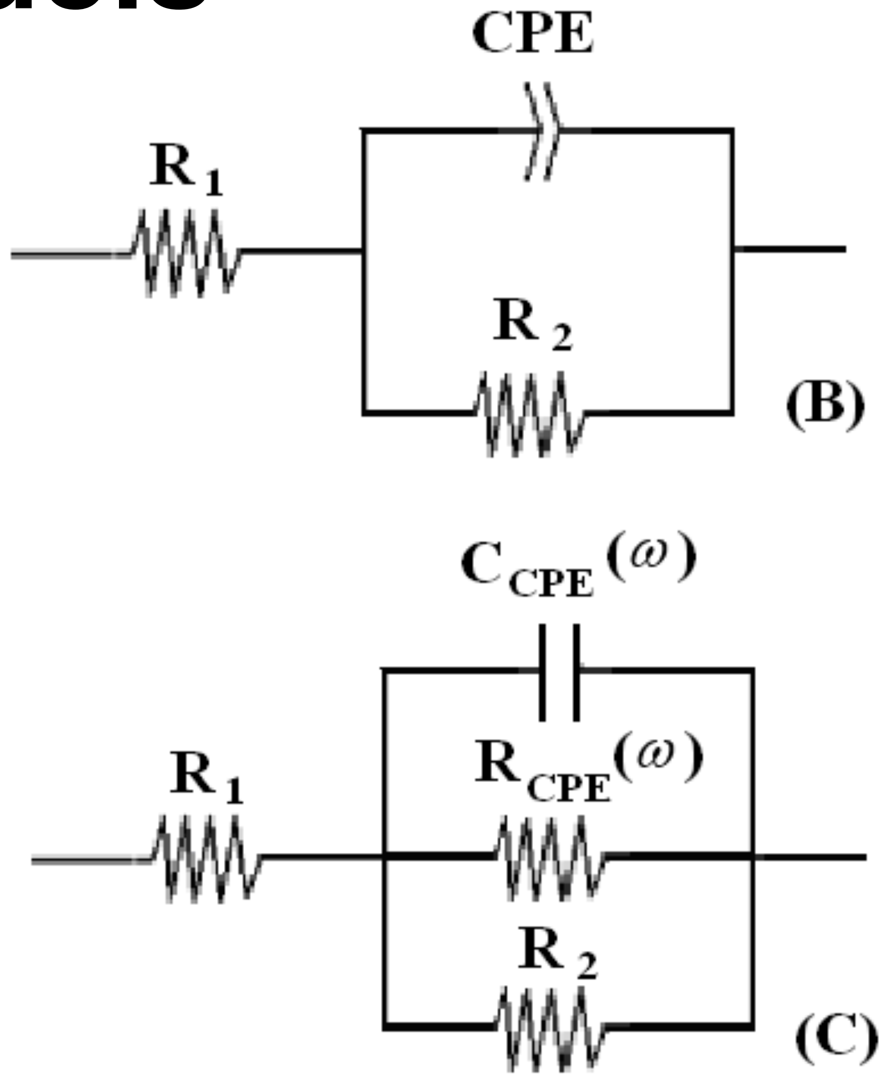



Fig. 9. Measured capacitance versus charge/discharge frequency on clean gold electrodes. The continuous line shows the fitting.

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

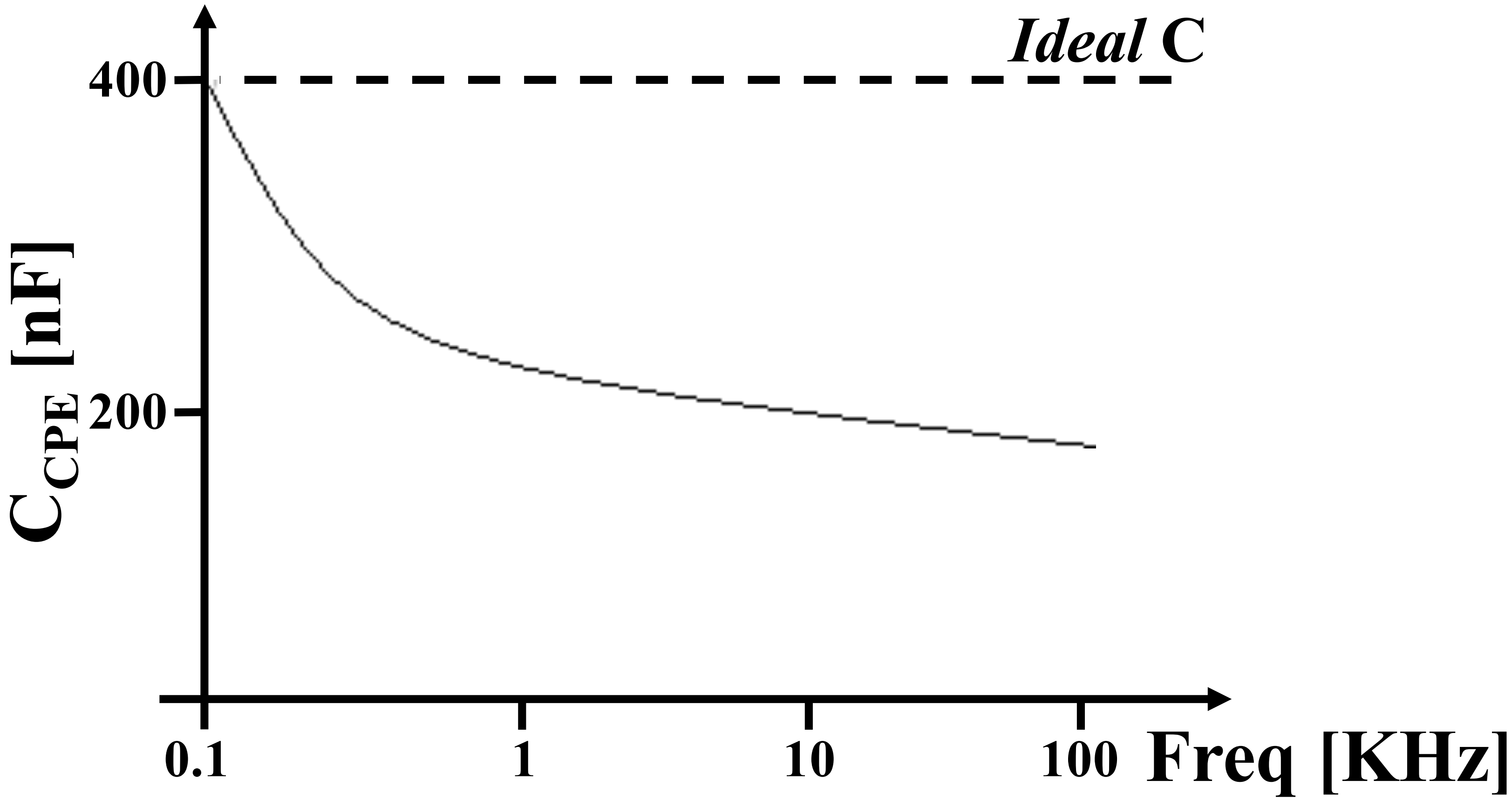
# CPE element

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

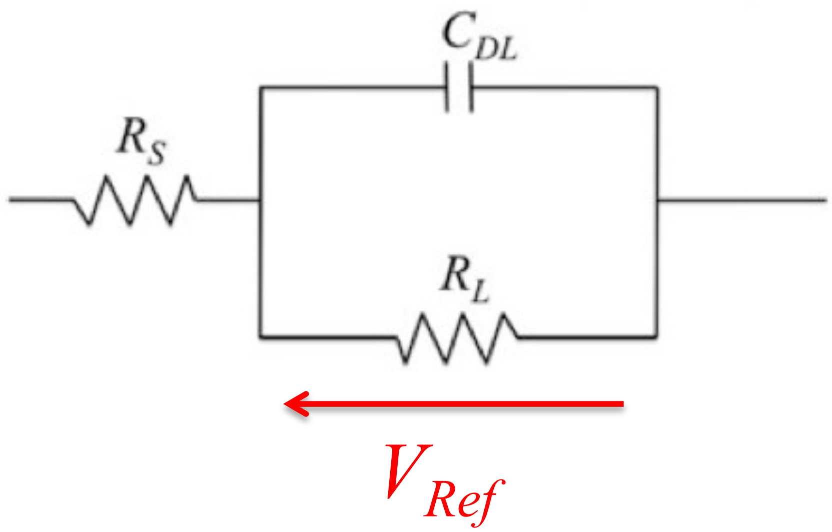
$$|X_{CPE}| \cong \frac{1}{\omega^{\alpha}C_p}\alpha = \frac{1}{\omega^{\alpha-1}\omega\, C_p}\alpha = \frac{1}{\omega\left(\frac{C_p}{\alpha\,\omega^{1-\alpha}}\right)}$$

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

# 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

Q4

# Why $C_{DL}//R_L$ do not correctly model Faradaic currents ?

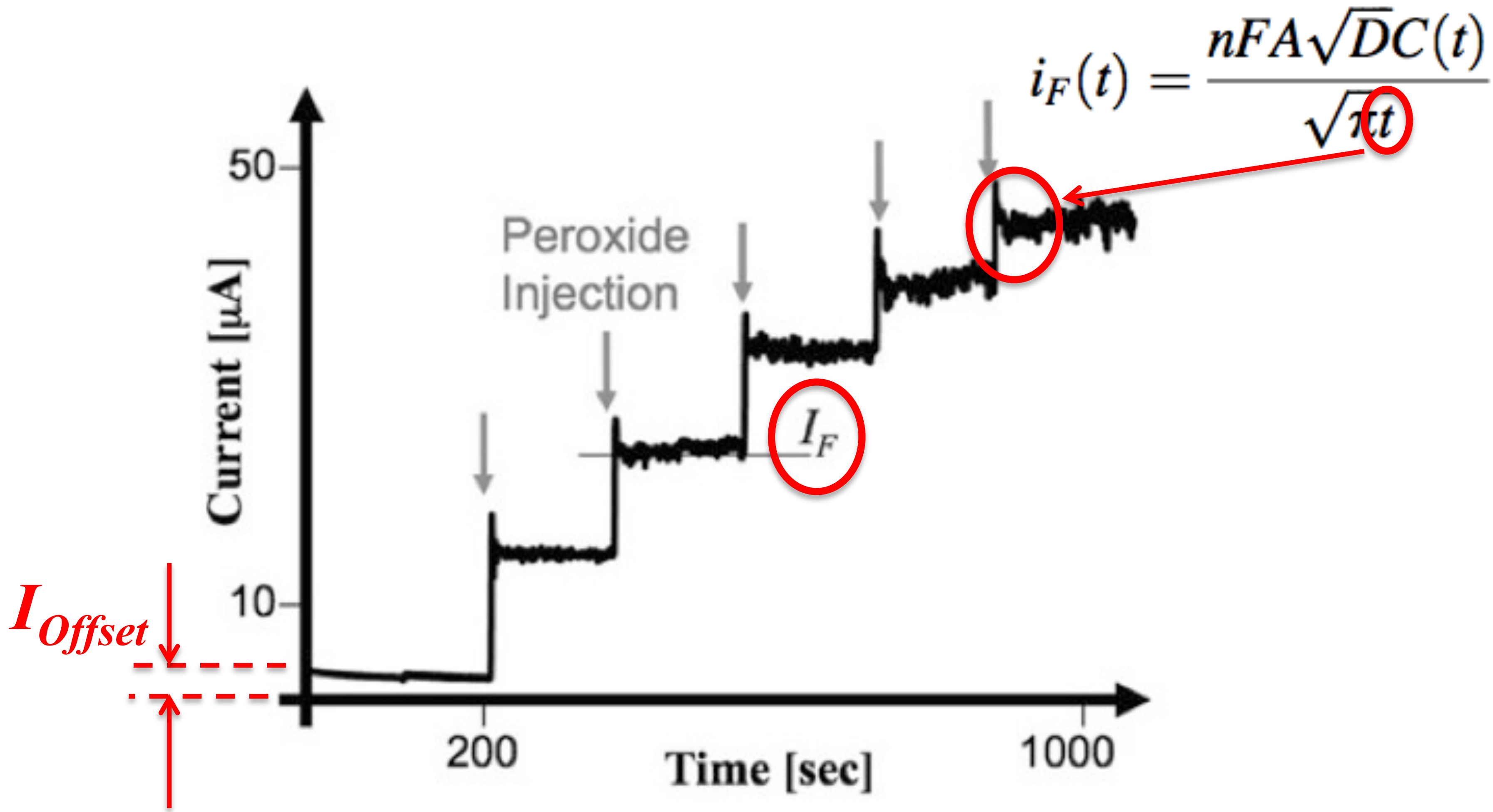
A. Since Faradaic currents do not follow Ohm law

B. Since Faradaic currents also depend on species' concentration

C. Since it is not possible to correctly model the Faradaic currents

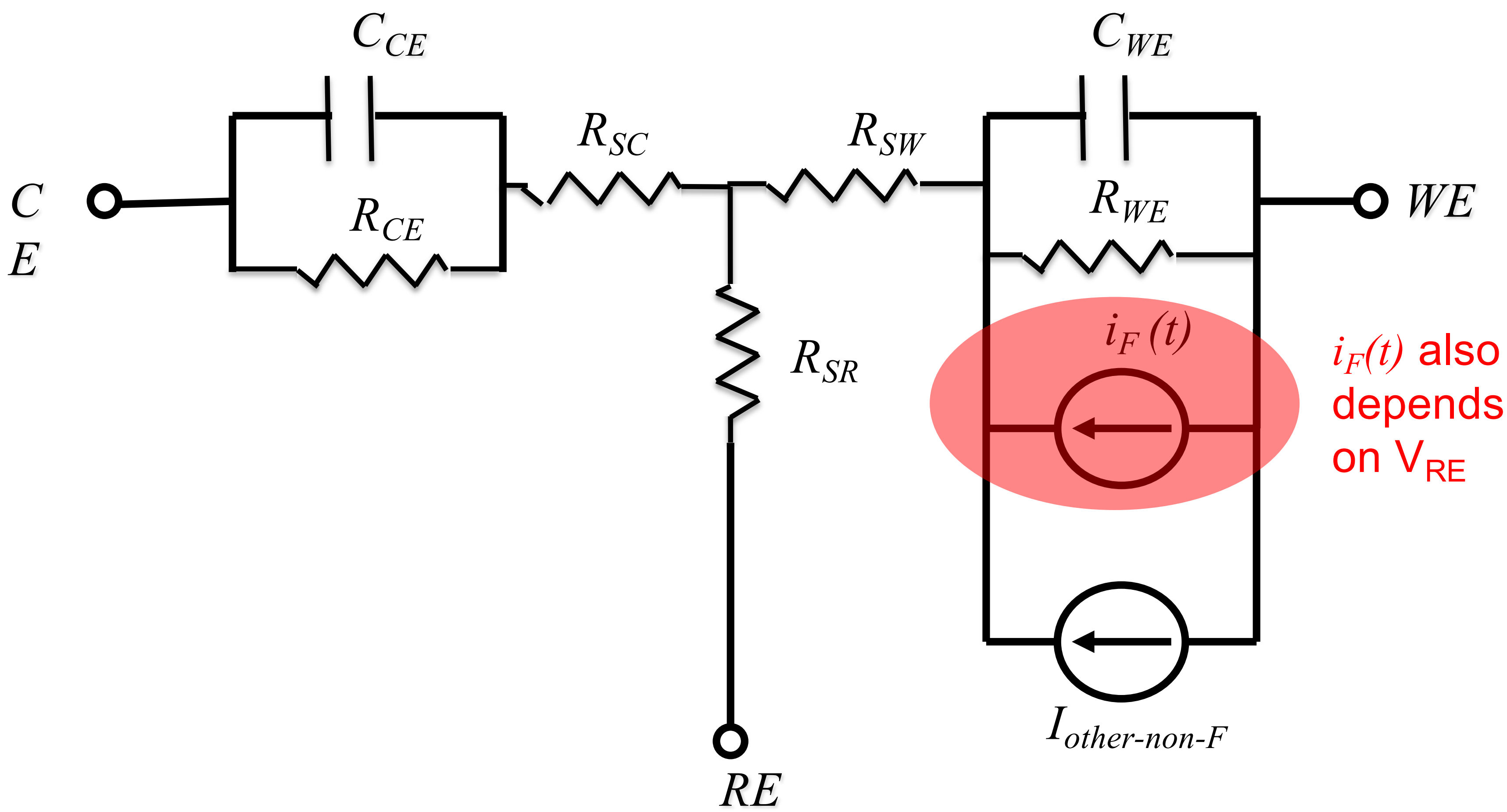
D. Since it is very difficult to correctly model the Faradaic currents

# Faradaic Current



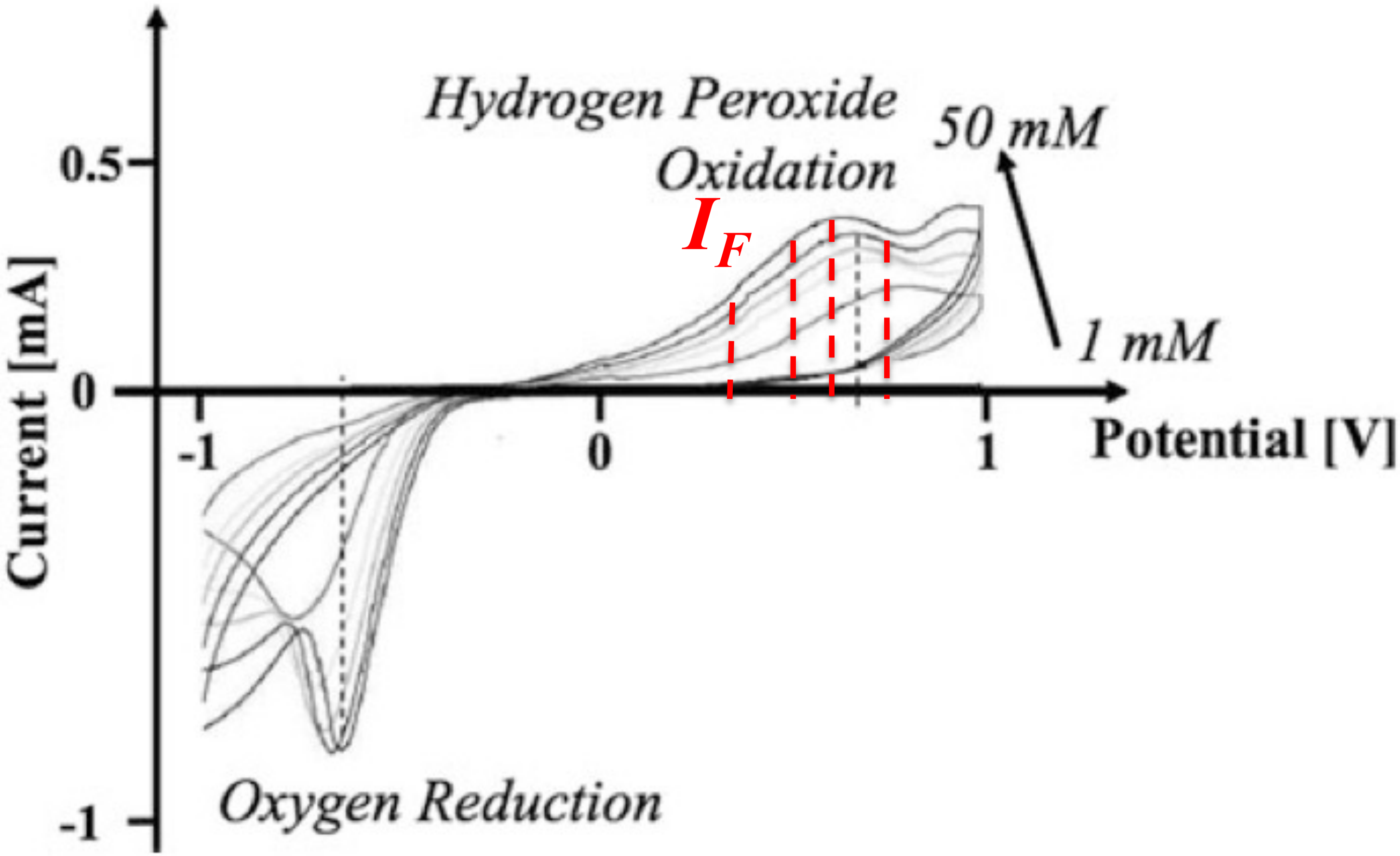

Typical curve in chronoamperometry

# Equivalent circuit: active model



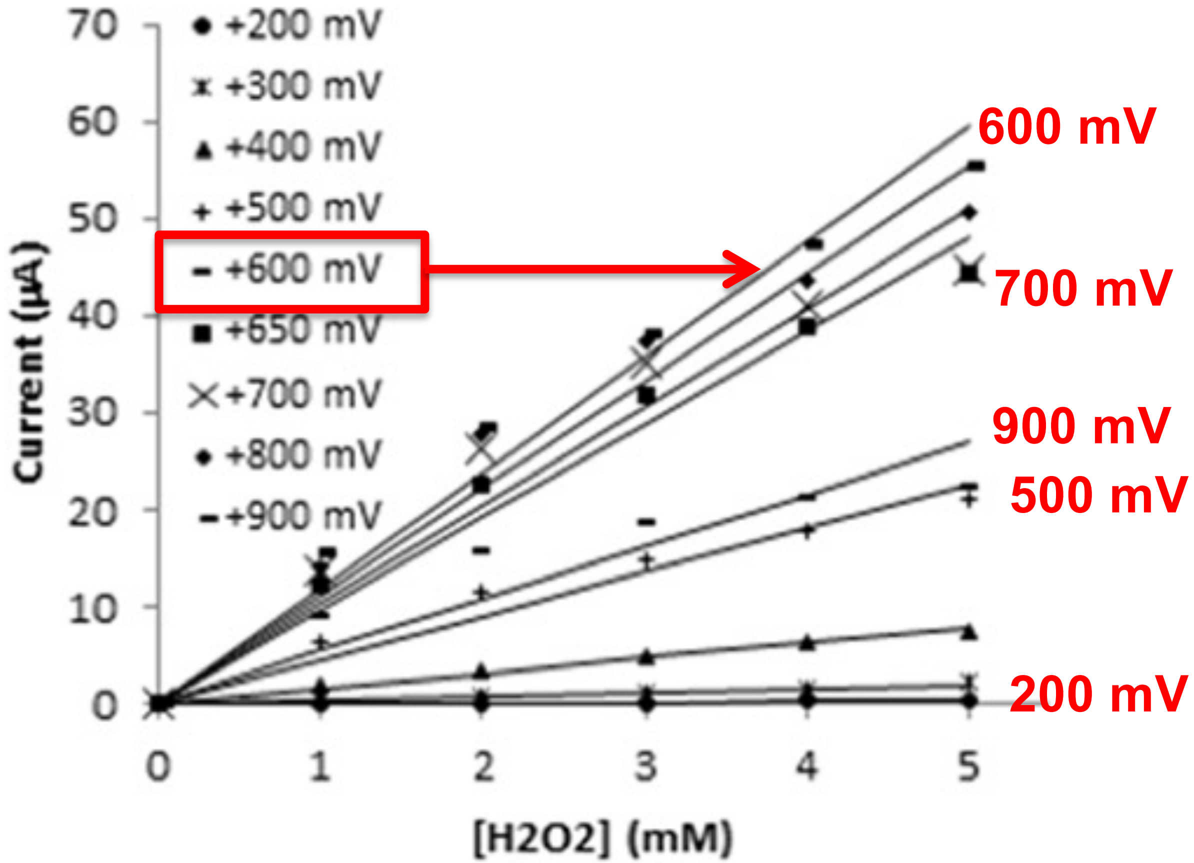

$i_F(t)$ also depends on $V_{RE}$

# 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

Q5

# How to correctly apply the right Reference Potential (to RE)?

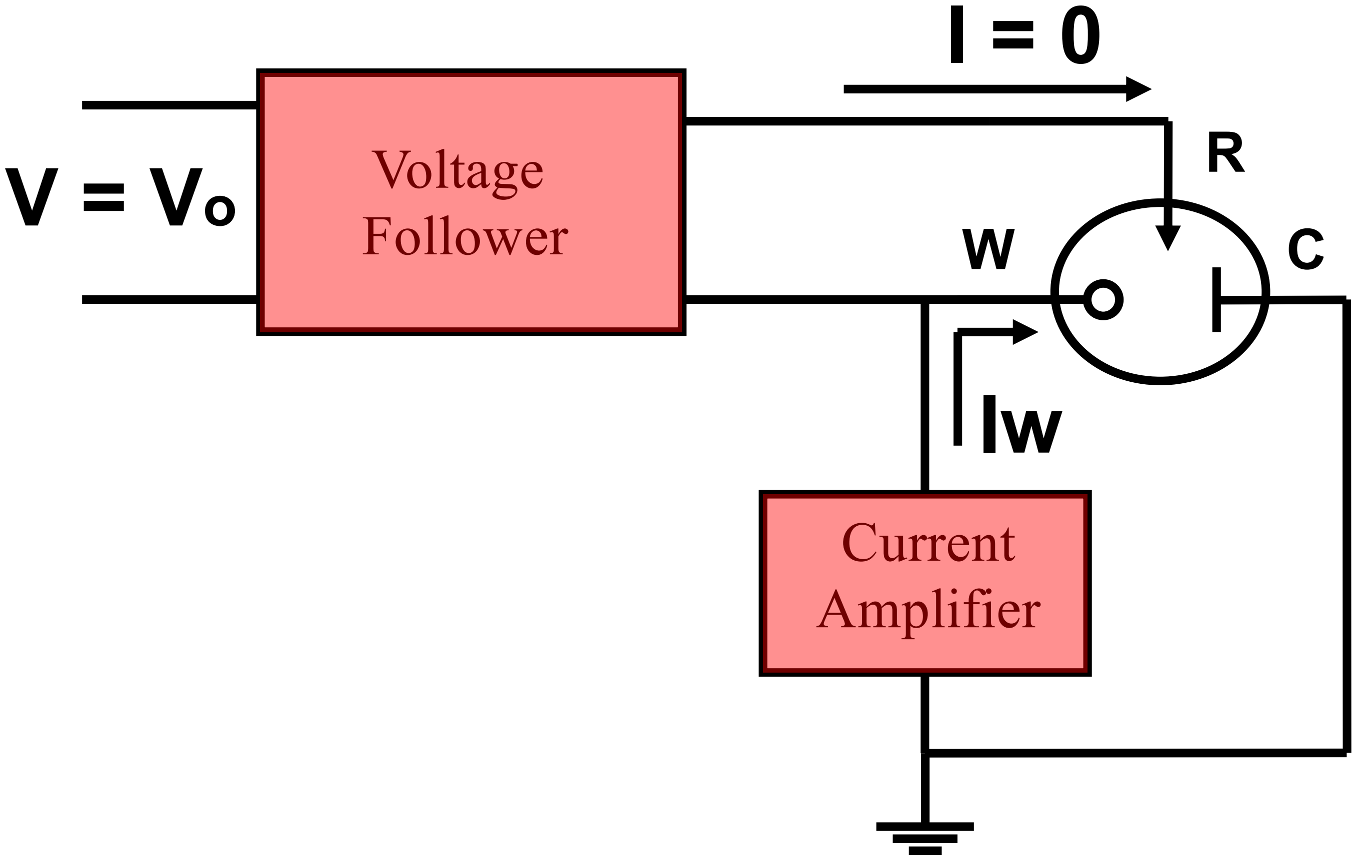
A. In closed loop
B. In open loop
C. With a power supplier
D. Without current supply
E. Without changes in frequency

Q6

# How to apply the Reference Potential without current supply?

A. Designing a proper voltage supplier
B. Designing a proper current supplier
C. Designing a proper frequency supplier
D. Designing a proper electrochemical cell

# 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)

Q7

# What is an Operational Amplifier?

A. A normal Differential Amplifier

B. A special Differential Amplifier

C. A differential Amplifier Operating at special frequency

D. An Amplifier Operating differently

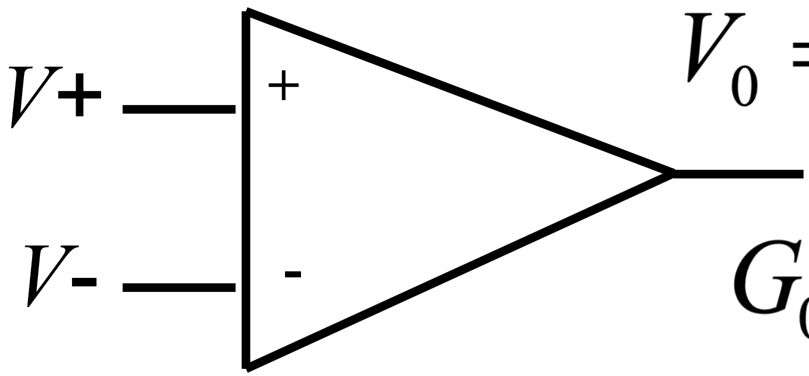
Q8

# Why an Operational Amplifier is a Special Differential Amplifier?

A. Since it has an enormous gain
B. Since it has enormous input impedance
C. Since it has negligible output impedance
D. Since it has several special features

# What' s an Op. Amp.?

**DIFFERENTIAL AMPLIFIER**



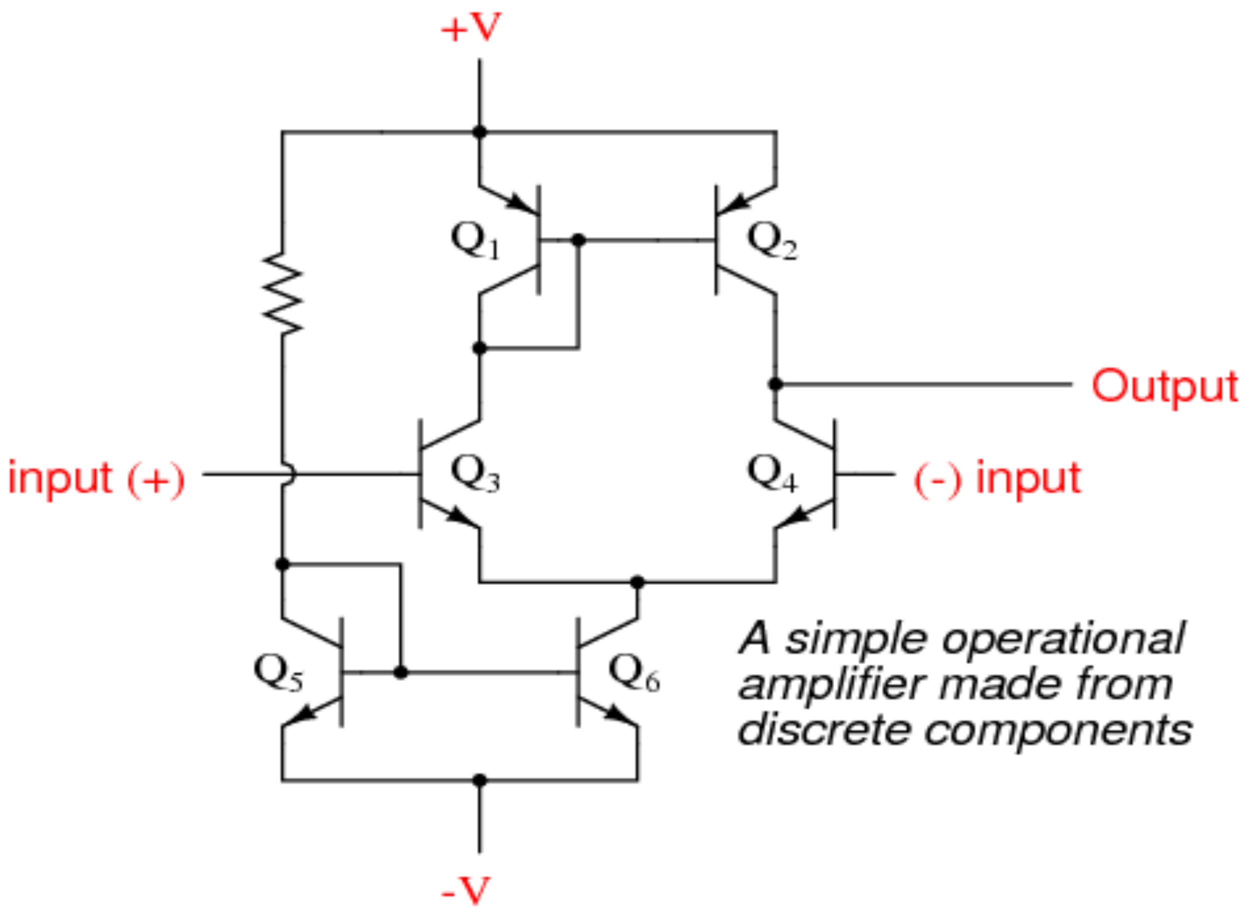

$$V_0 = G_0(V_+ - V_-)$$

$$G_0 \to \infty$$

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

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

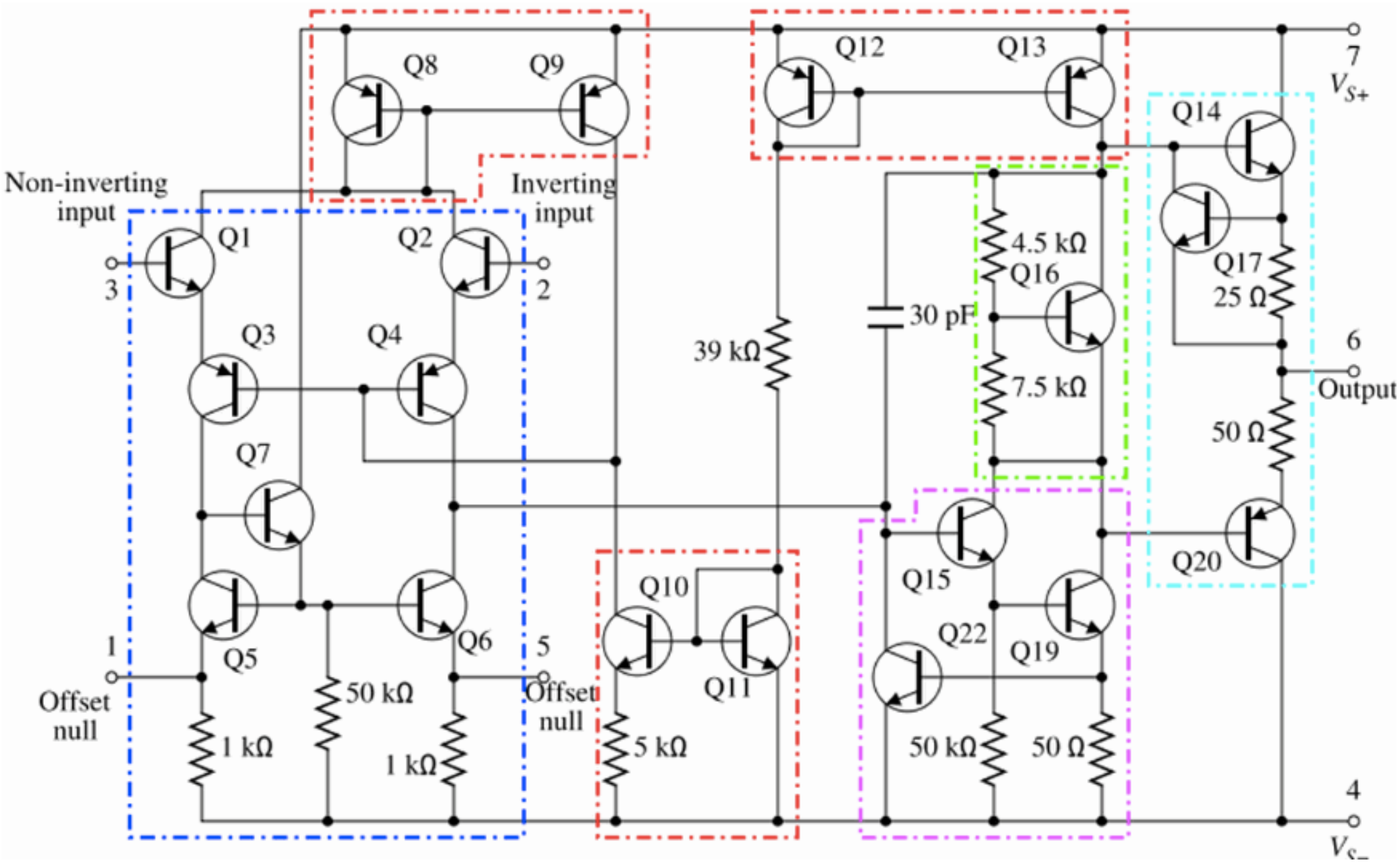
# What's an Op. Amp.?




*A simple operational amplifier made from discrete components*

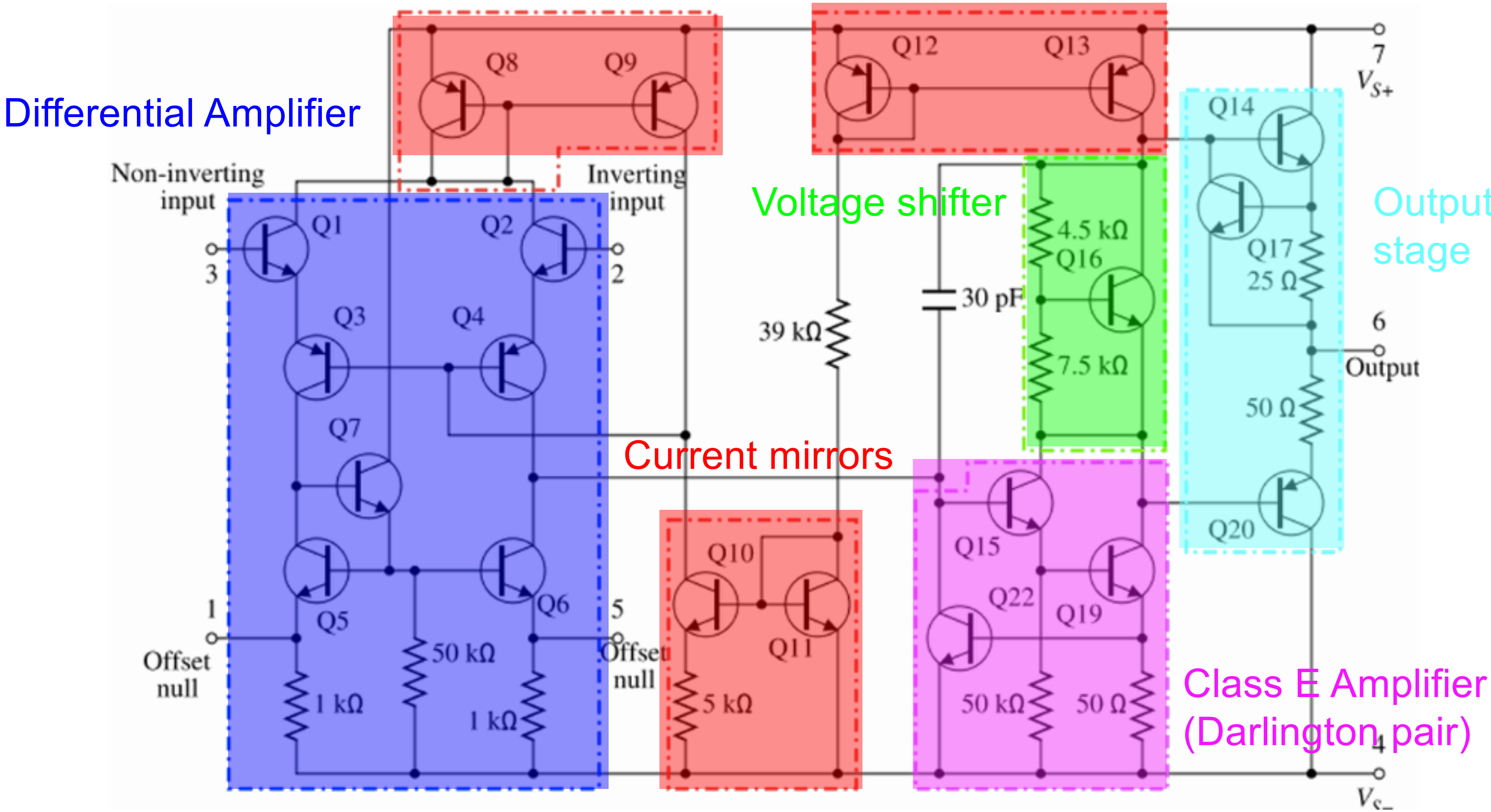
A simple scheme of a differential amplifier at transistosr level

# What's an Op. Amp.?



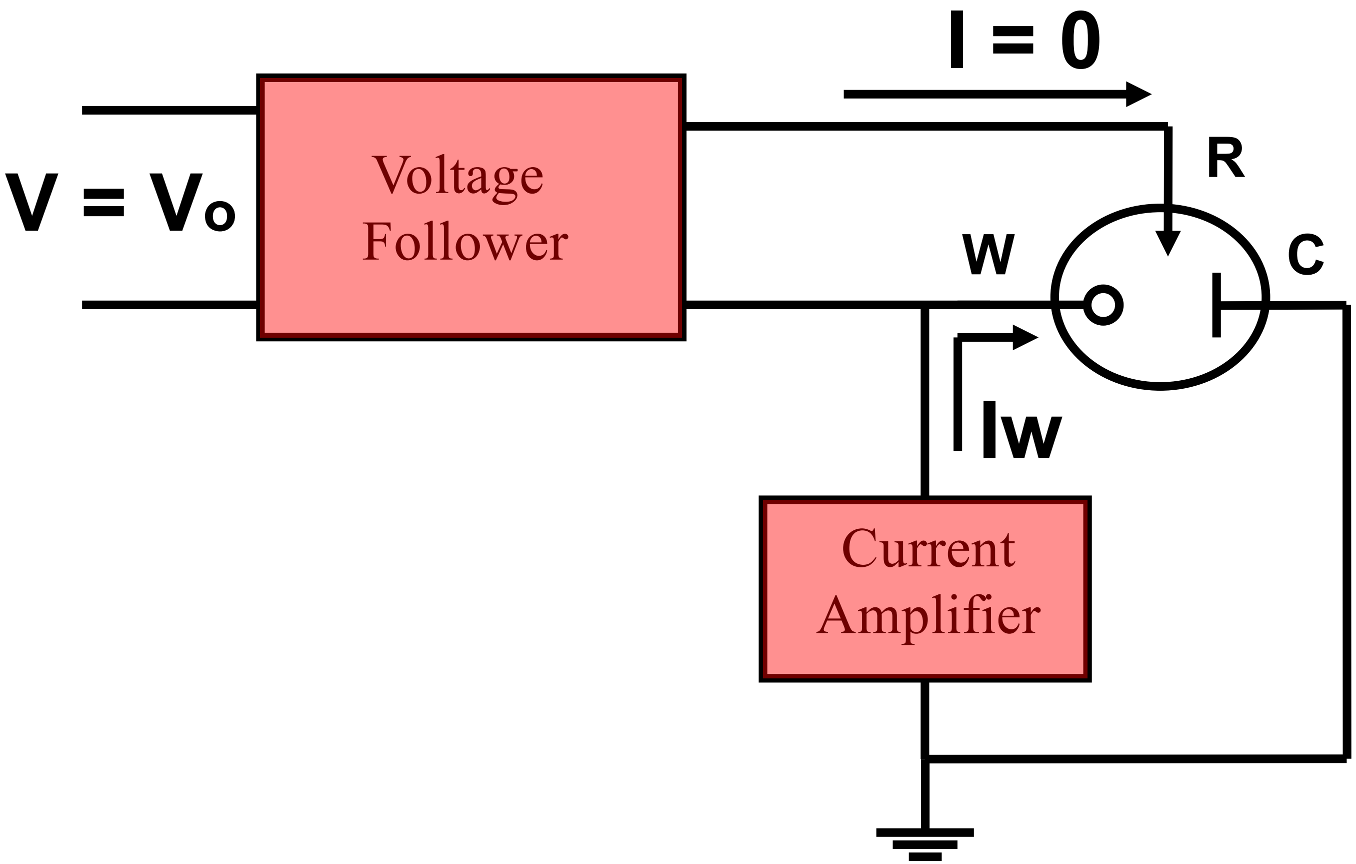

A more complex architecture of an Operational Amplifier (the common 741)

# What's an Op. Amp.?

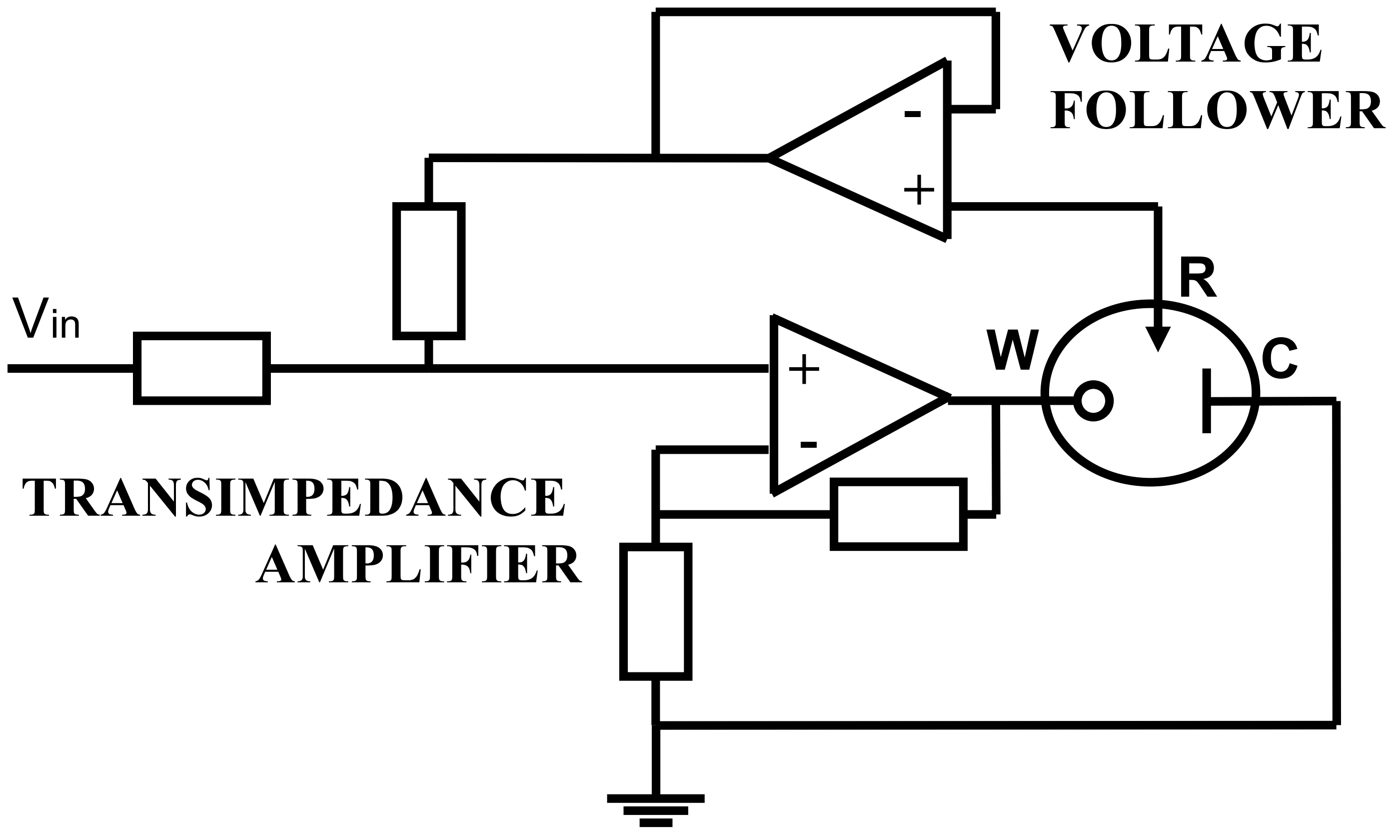



A more complex architecture of an Operational Amplifier (the common 741)

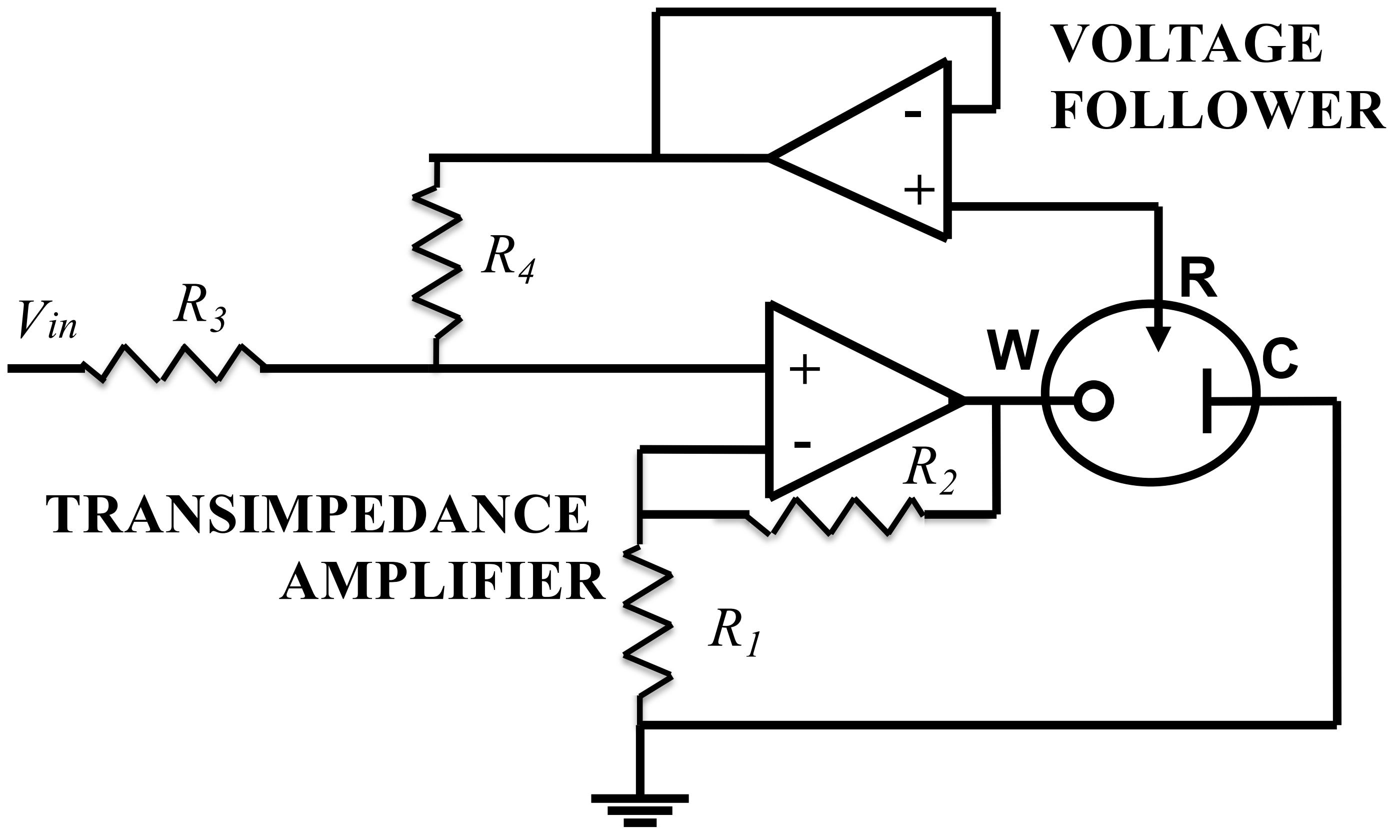
# CMOS for Redox



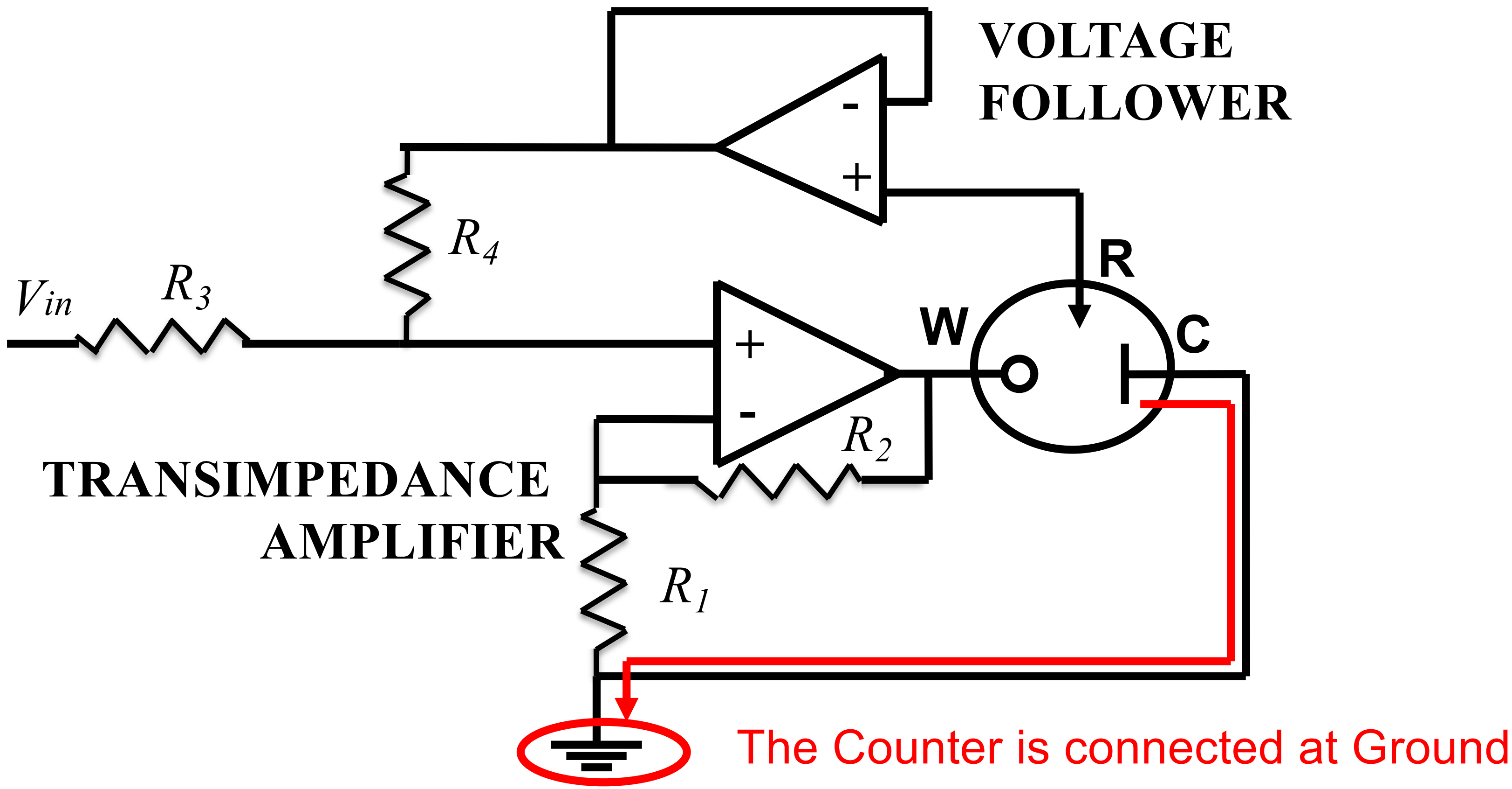
# The basic CMOS for Redox



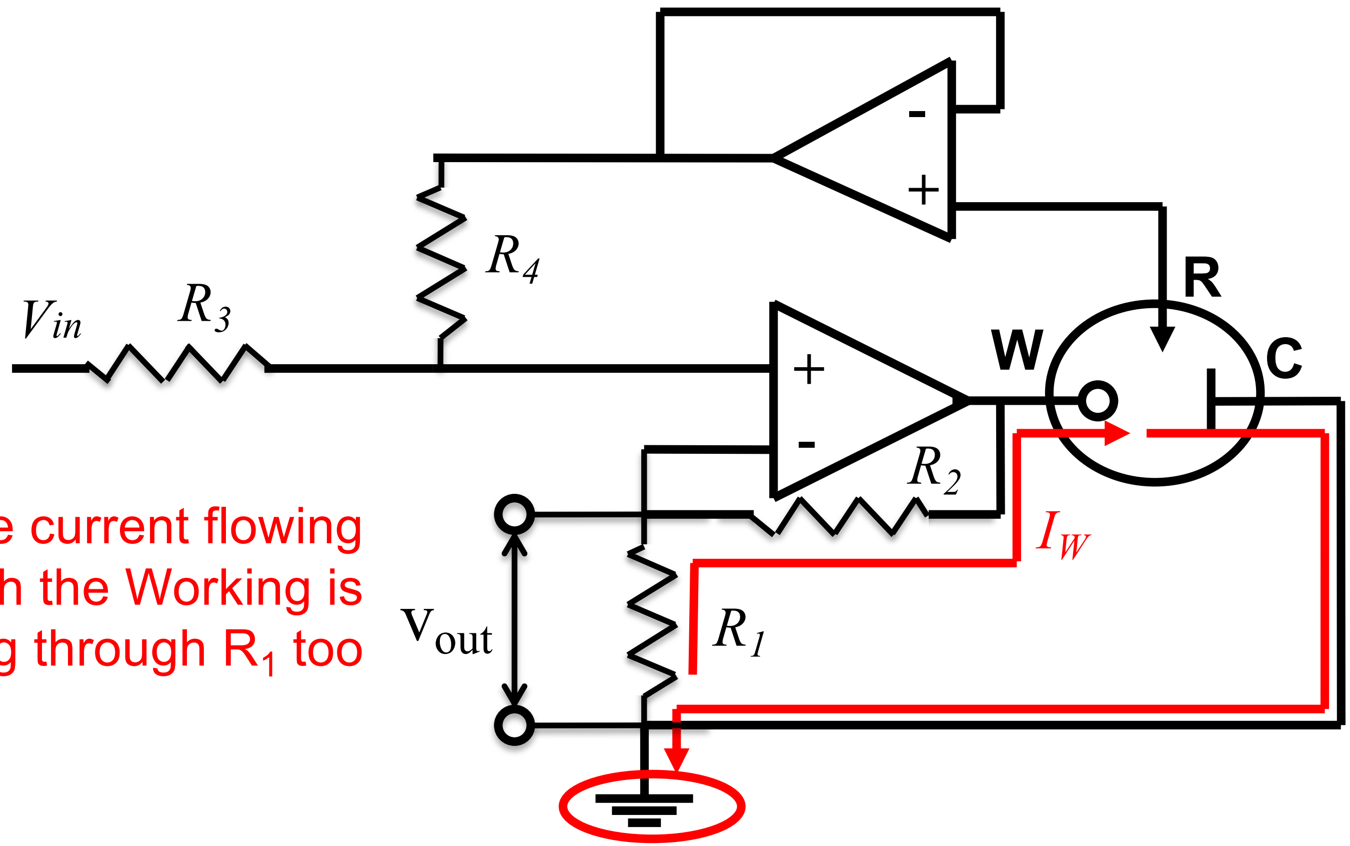
# The basic CMOS for Redox



# Grounded Counter

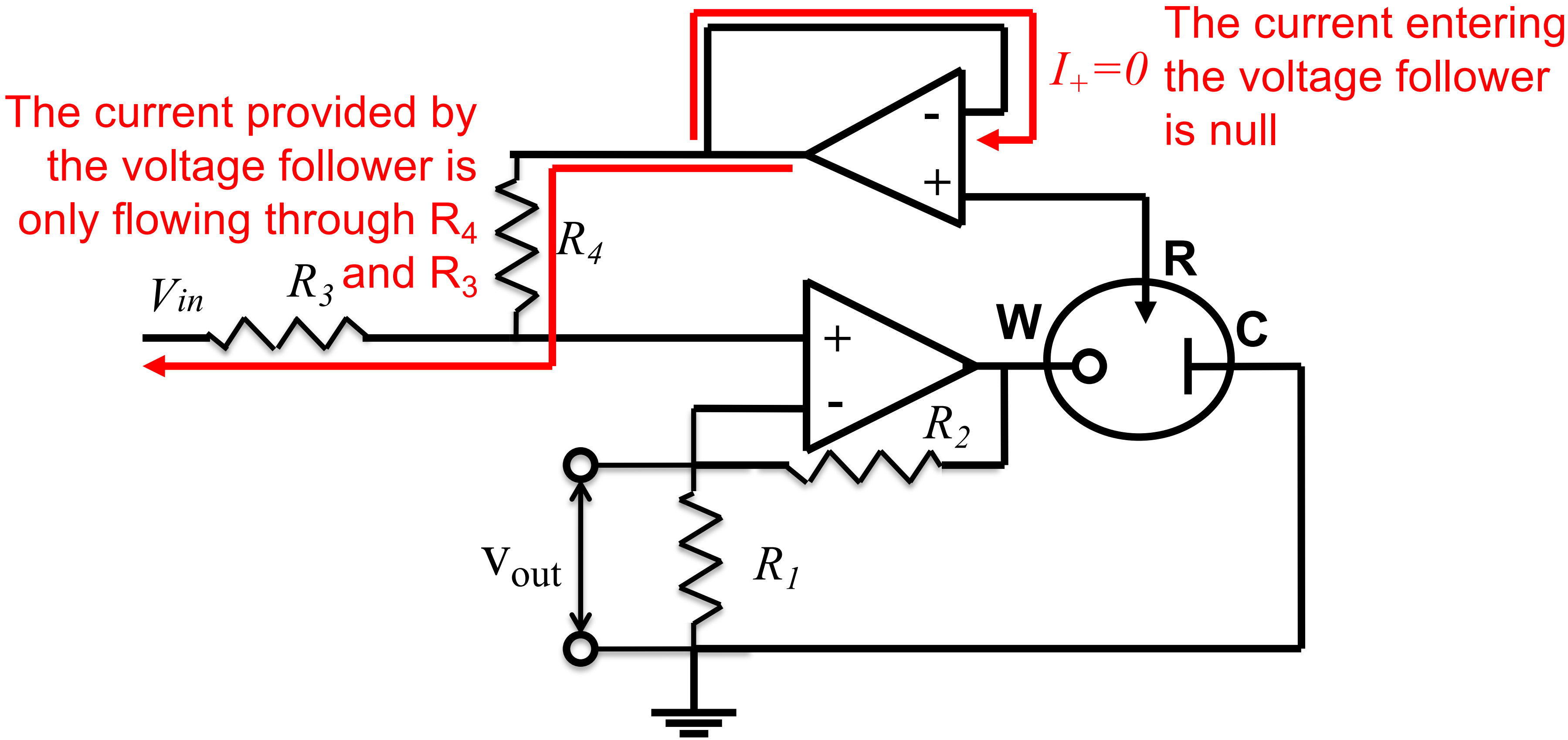


# Grounded Counter

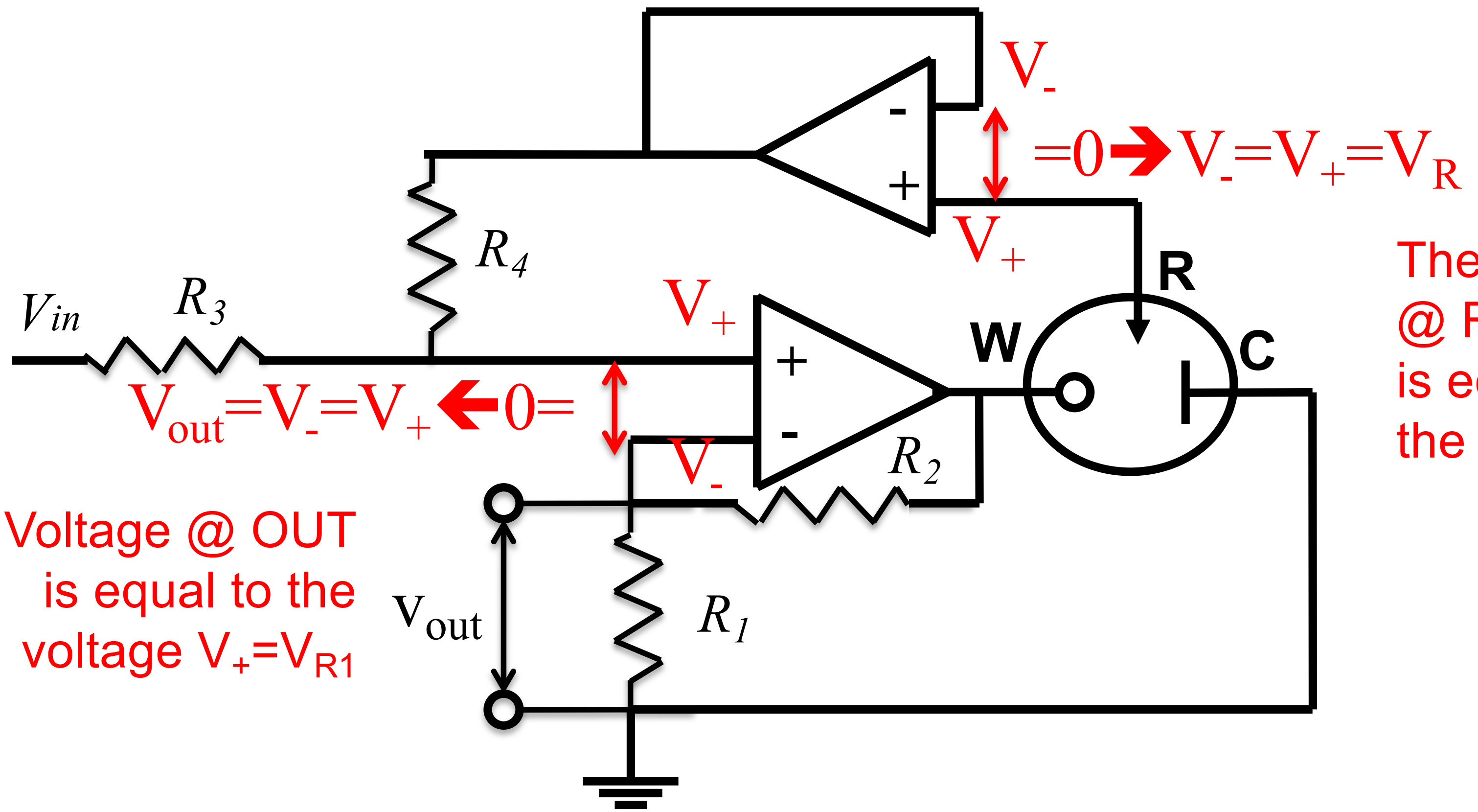



The current flowing through the Working is flowing through $R_1$ too

# Grounded Counter



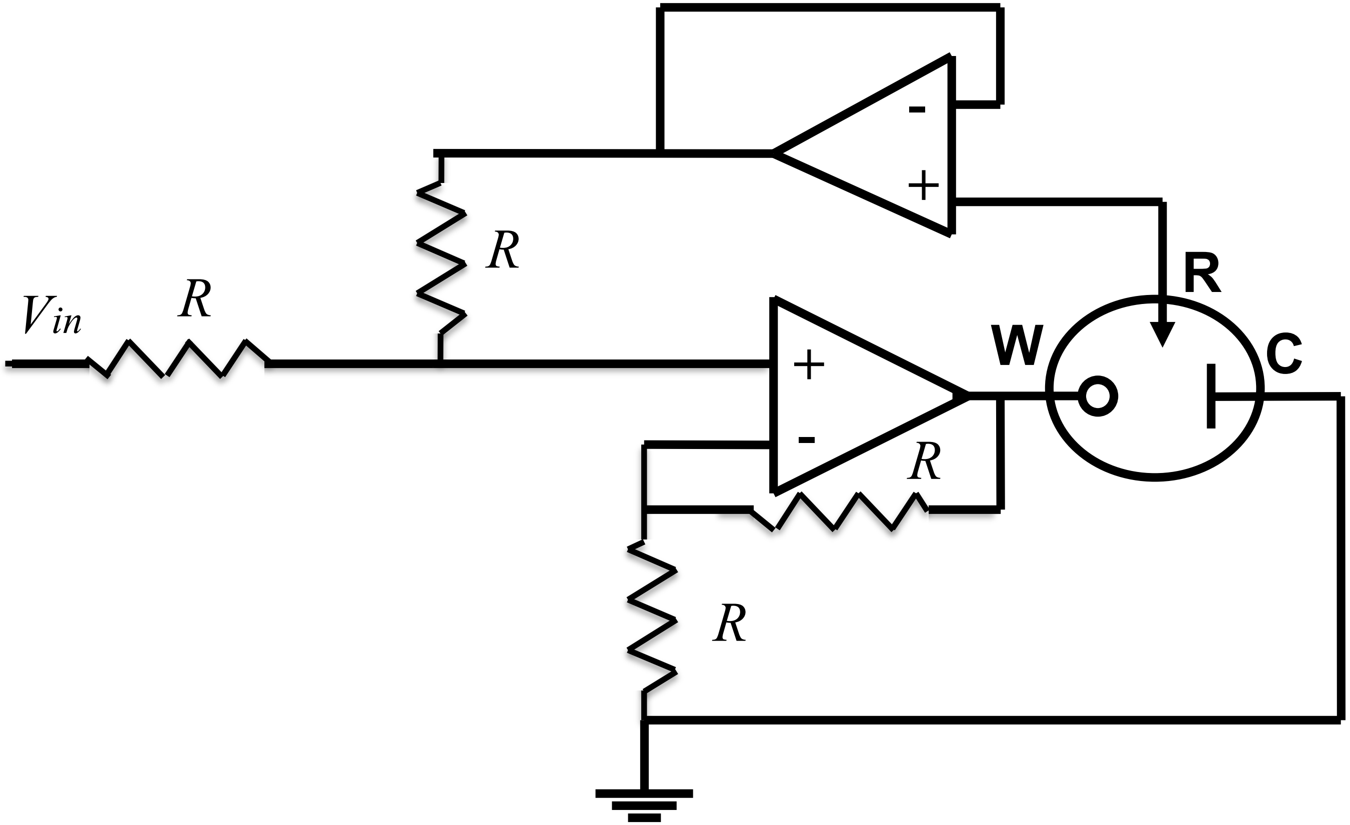
# Grounded Counter




The Voltage @ Reference is equal to the voltage $V_-$

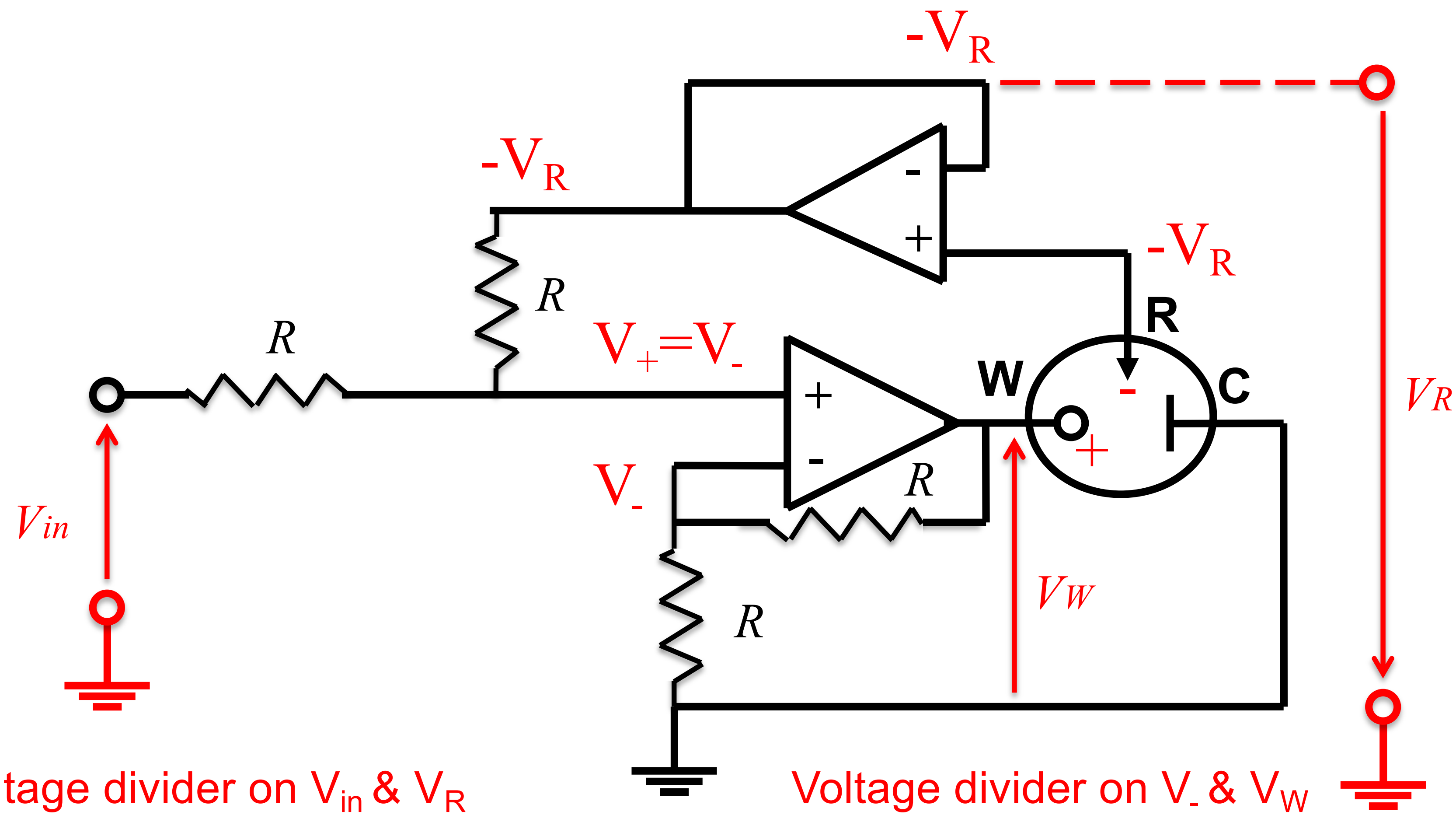
The Voltage @ OUT is equal to the voltage $V_+=V_{R1}$

# Grounded Counter




$R_1=R_2=R_3=R_4=R$

# Grounded Counter



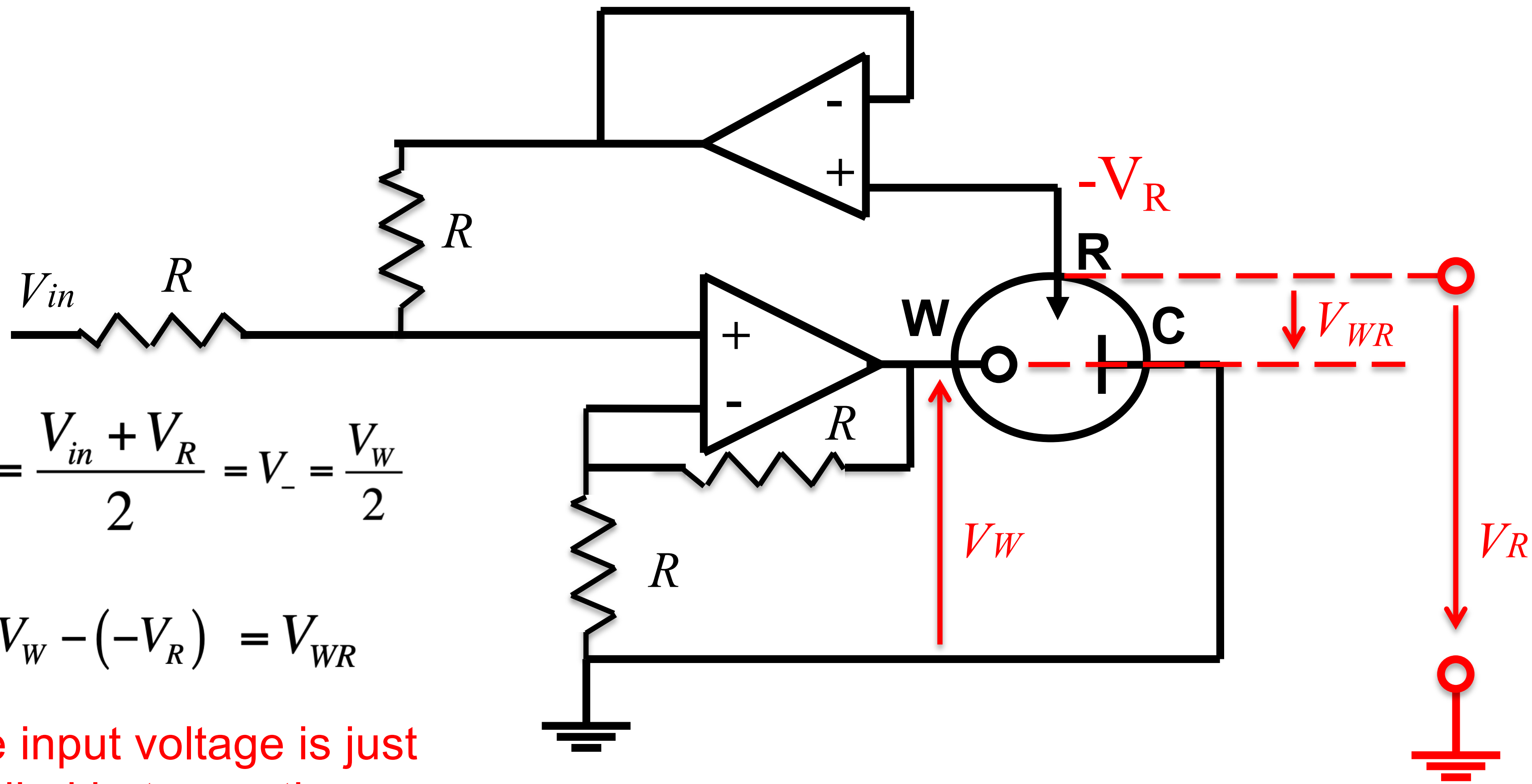

Voltage divider on $V_{in}$ & $V_R$

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

Voltage divider on $V_-$ & $V_W$

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

# Grounded Counter

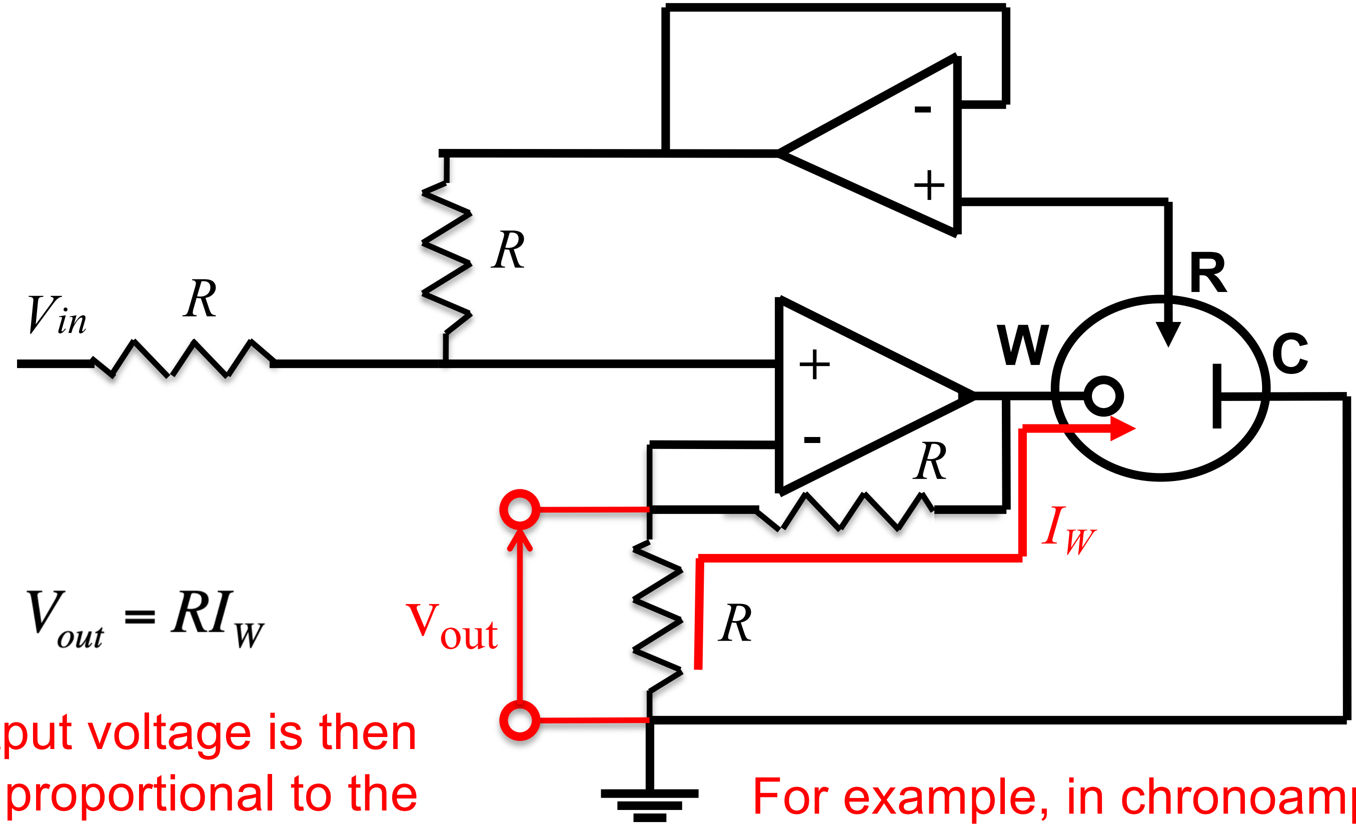



$$V_- = \frac{V_{in} + V_R}{2} = V_- = \frac{V_W}{2}$$

$$V_{in} = V_W - (-V_R) = V_{WR}$$

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 current 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

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

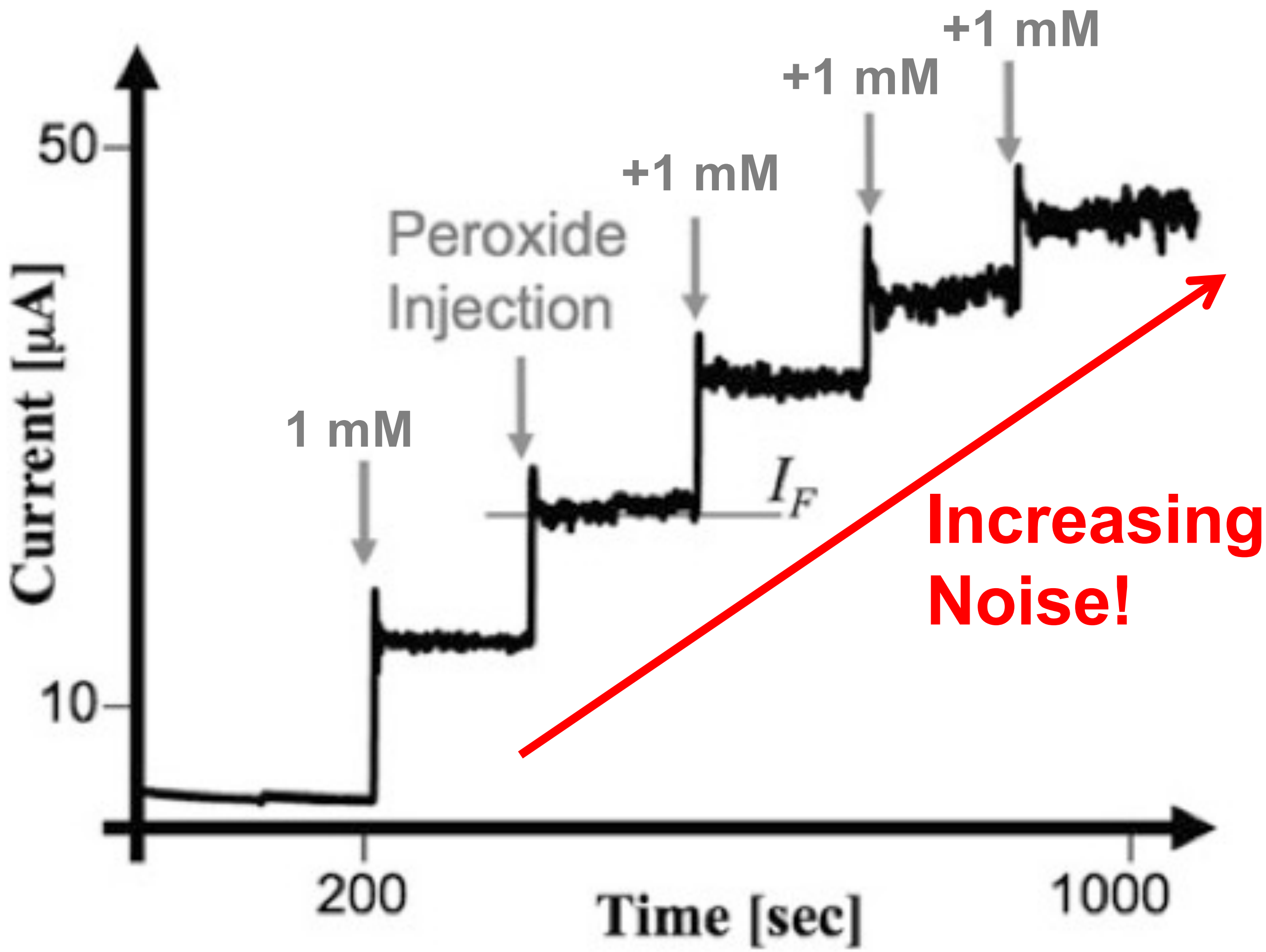
Flicker noise, which has a spectral density that decreases with the frequency. It is the dominant noise source at low frequencies

Q9

# Does the electronic noise is the only one in the system?

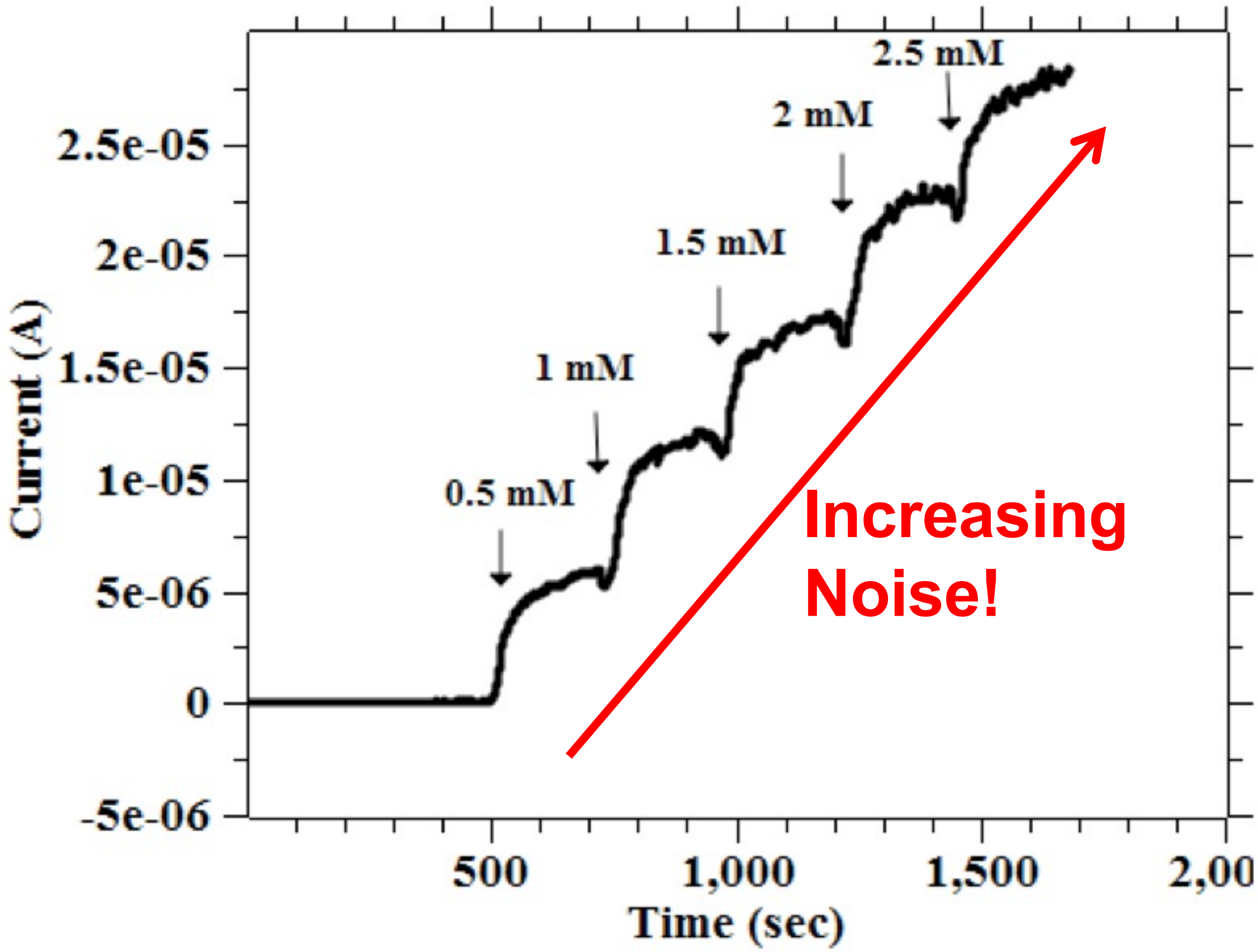
A. Yes, of course!
B. Almost, since it is the dominant one
C. No, since it is not the dominant one
D. Not Really

# 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

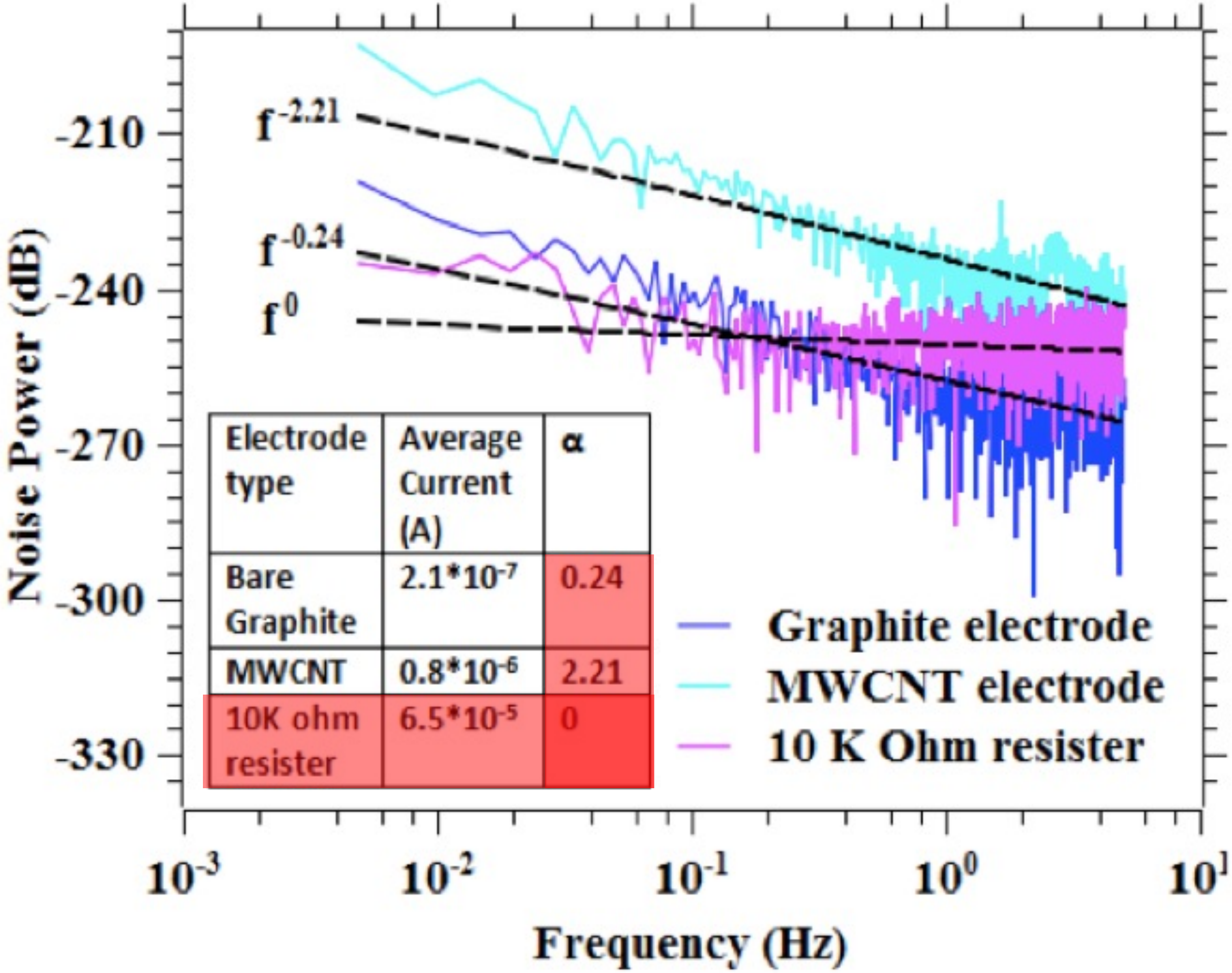
The inverse SNR of the measurement at 1Hz

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

Generalized frequency dependence

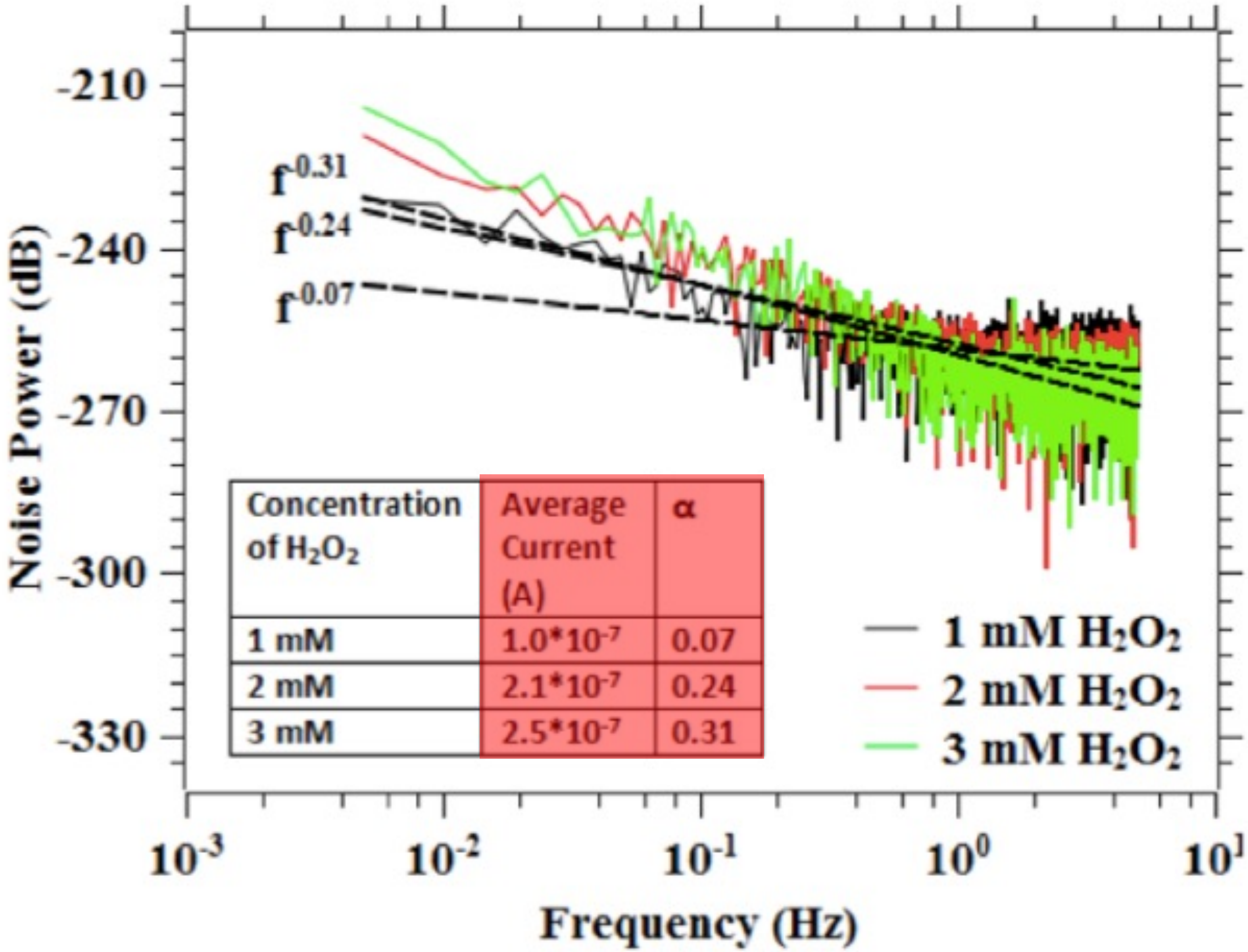
Generalized flicker formula to extract the values of noise coefficients by fittings on the electrochemical interface

# Power Spectra Density



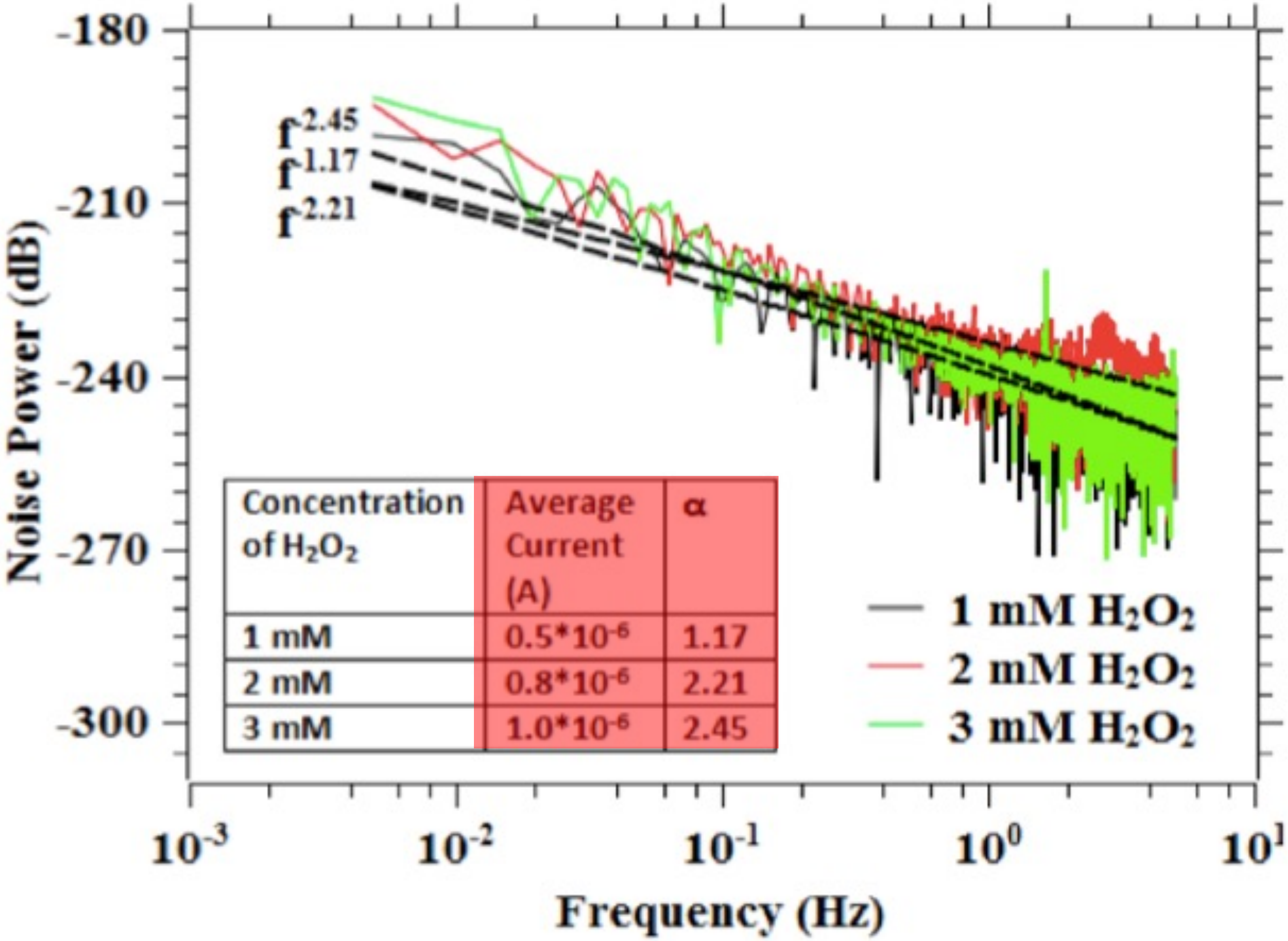

Noise PSD in chronoamperometry measurements with bare and MWCNT electrodes and a 10 kΩ resistor

# Noise PSD on Bare




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

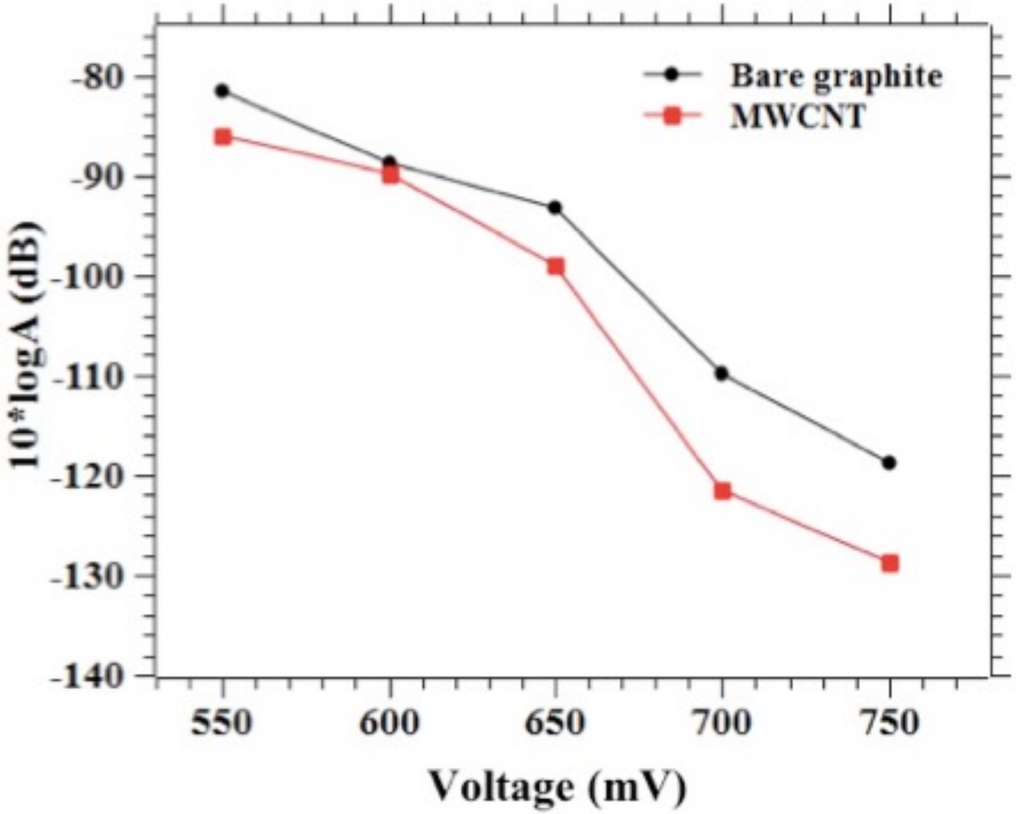
# Noise PSD on MWCNT

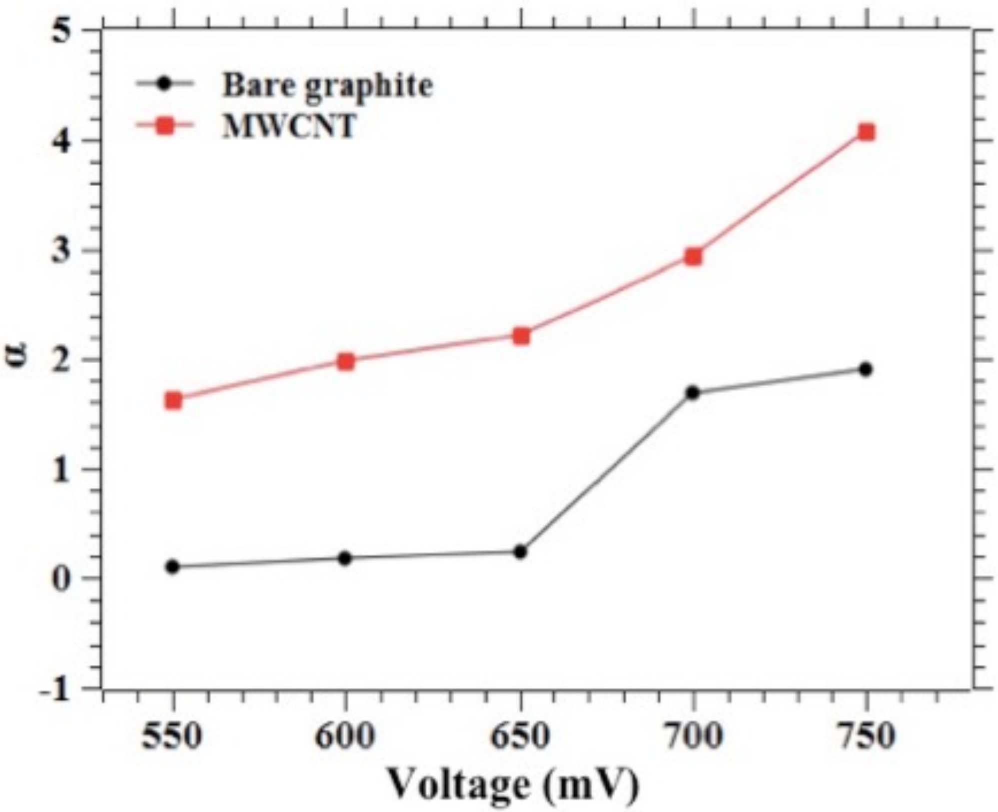



| Concentration of $H_2O_2$ | Average Current (A) | α |
|---|---|---|
| 1 mM | $0.5*10^{-6}$ | 1.17 |
| 2 mM | $0.8*10^{-6}$ | 2.21 |
| 3 mM | $1.0*10^{-6}$ | 2.45 |

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

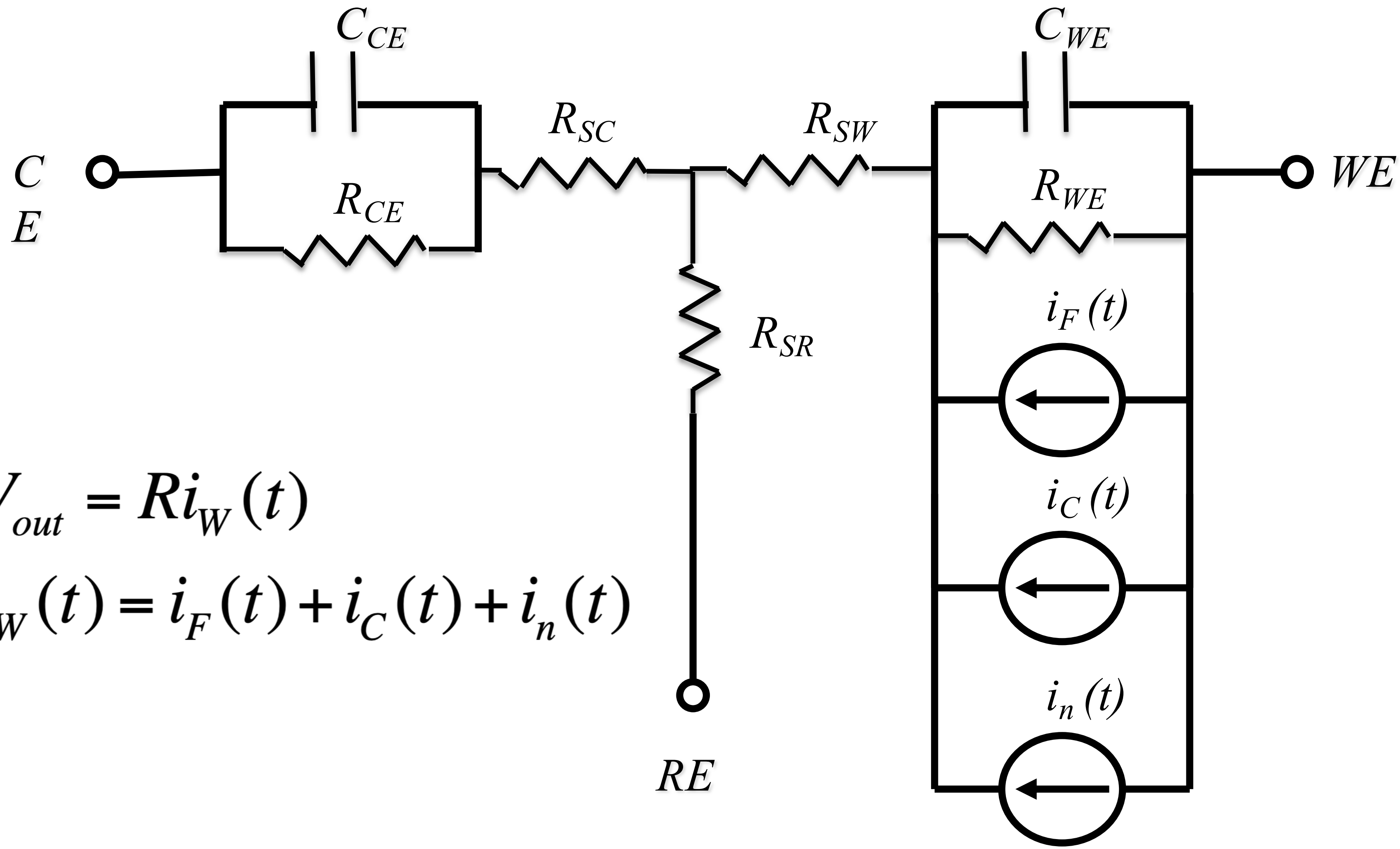
# Dependence by the Voltage




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




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

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