Universidad
Carlos III de Madrid
www.uc3m.es

# Electronic Instrumentation

## Chapter 2

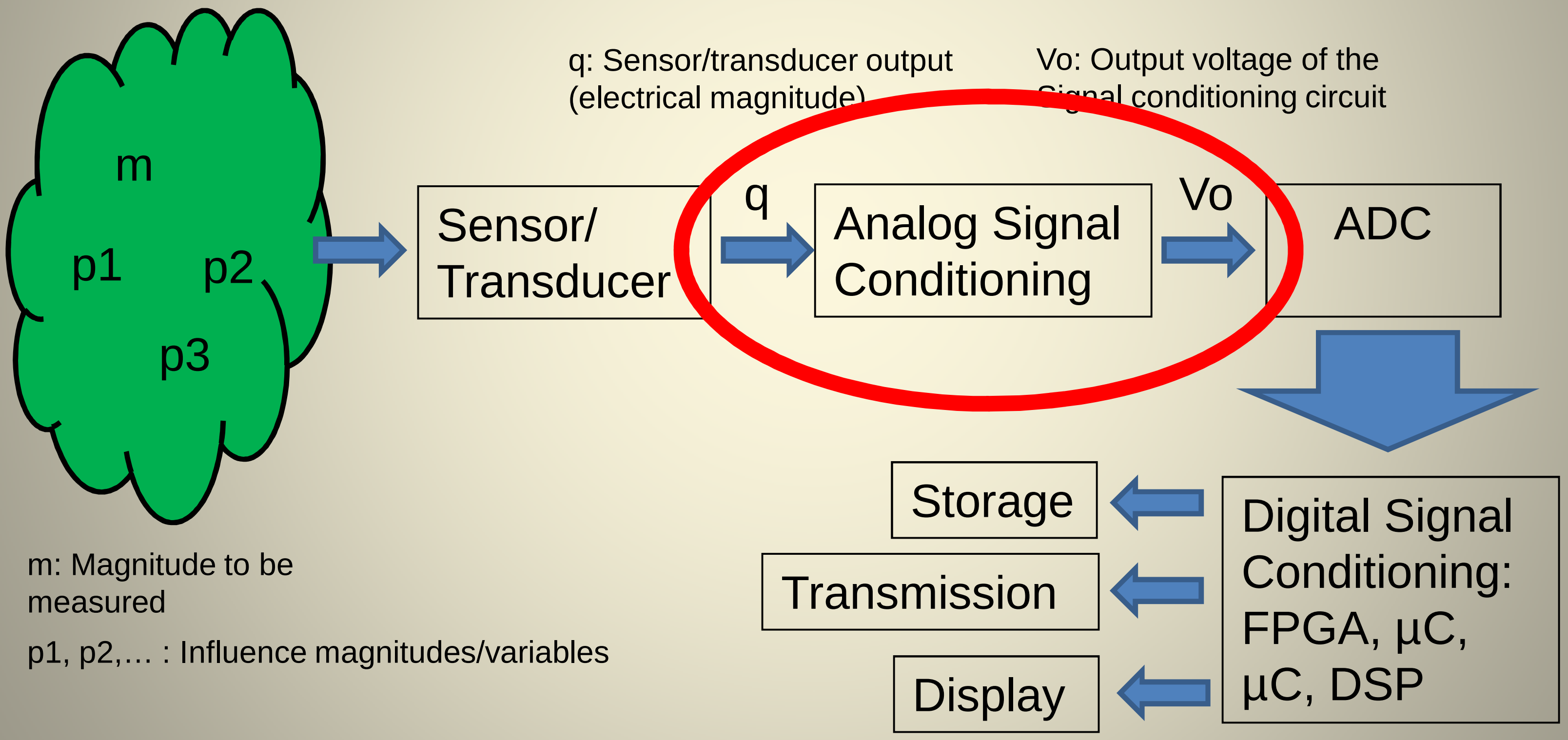
## Analog Signal Conditioning

Jose A. García Souto / Pablo Acedo

# Chapter 2. Signal Conditioning

- Introduction
- Passive Sensors Conditioning
- DC Null Measurements
- AC Null Measurements
- Instrumentation Amplifiers
- Linear and Nonlinear Analog Signal Processing and Special Function Modules
- Other specific Instrumentation Components and circuits

# Basic Architecture for an Electronic Instrumentation Measurement System



q: Sensor/transducer output (electrical magnitude)

Vo: Output voltage of the Signal conditioning circuit

m: Magnitude to be measured

p1, p2,… : Influence magnitudes/variables

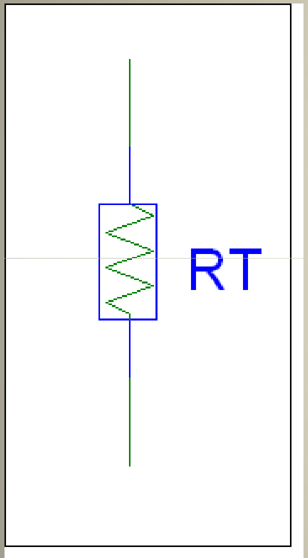
# Introduction to Analog Signal Conditioning

- Convert the changes of an impedance Z into an electric output that is easily processed (voltage).
- Minimize the non-linear error of the primarily output and the overall output.
- Compensate magnitudes of influence (sources of errors).
- Enhance the sensitivity (amplification).
- Adjust the signal levels (range, zero, etc.).
- Other practical issues: isolation, etc.
- Linear filtering (analog filters and integrators).
- In some cases, nonlinear processing: RMS, Log, phase-sensitive demodulators.

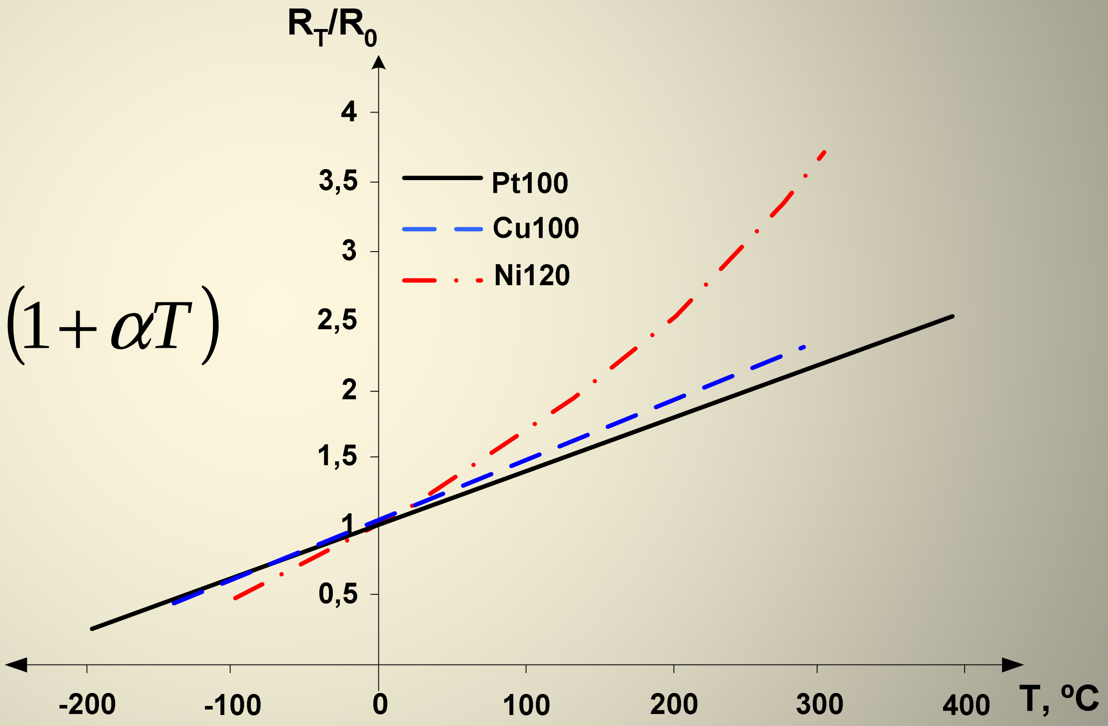
# Need of passive sensors conditioning

- Conversion of the changes of an impedance Z into an electric output that is easily processed (voltage Vm)
- NOTE: Sensitivity depends on the voltage reference Vcc
- Sensitivity is greater with more Vcc, but the limits to the voltage reference Vcc are:
  - Maximum power dissipation limits the sensitivity (Vcc max)
  - Self-heating of the sensor due to power dissipation introduce a source of error
- Impedance not only reduce the sensitivity, but also introduce non-linearity error due to sensitivity changes.
- Amplification completes the analog conditioning (adjustment of Gain and Zero, and high input impedance)

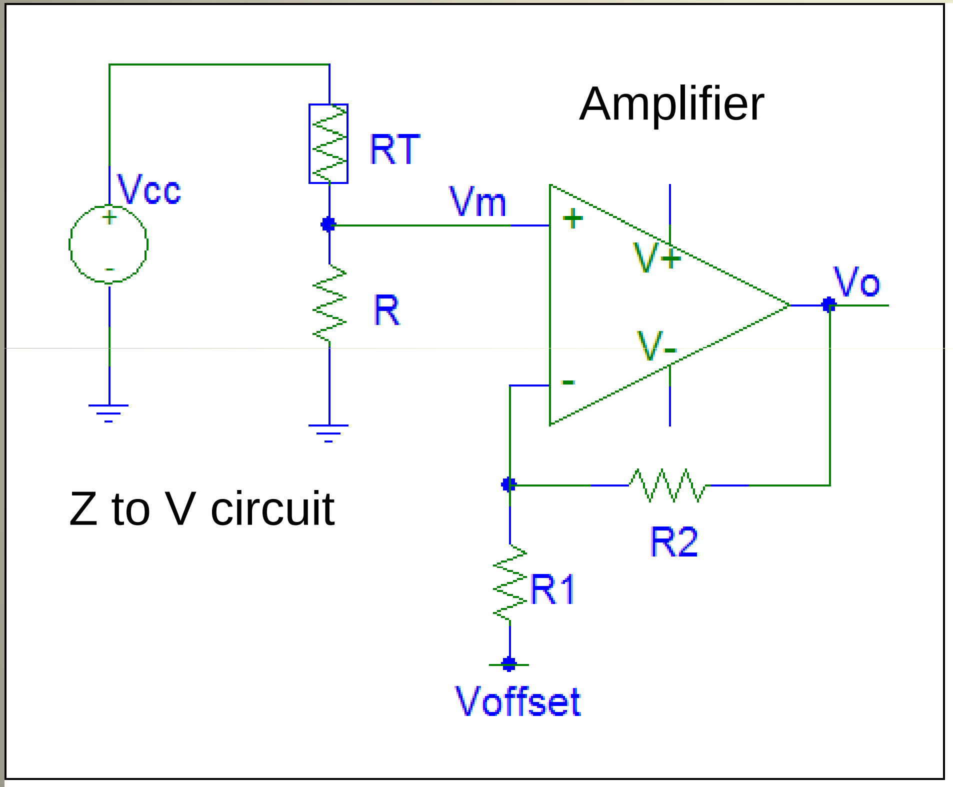
# Passive sensor: Example



$$R_T = R_0\left(1+\alpha T\right)$$



# Basic passive sensors conditioning circuits

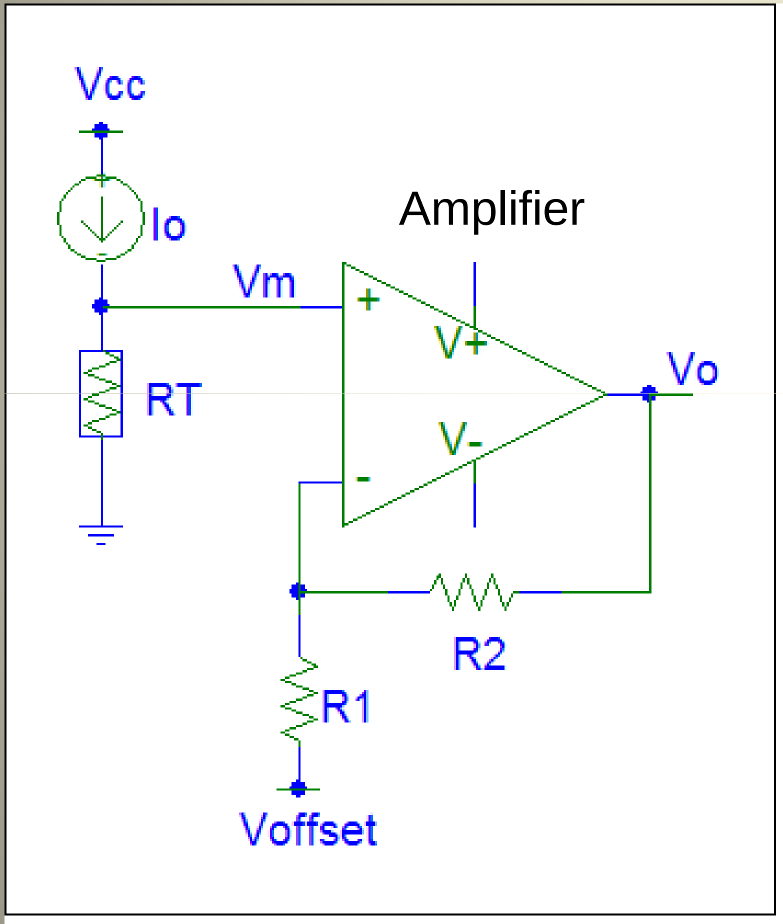


Amplifier with very high input impedance Zi, very low output impedance Zo

$$Vm = Vcc \frac{R}{R + \boxed{R_T}}$$

$$Vo = Vm \frac{R1 + R2}{R1} - V_{offset} \frac{R2}{R1}$$

# Basic passive sensors conditioning circuits

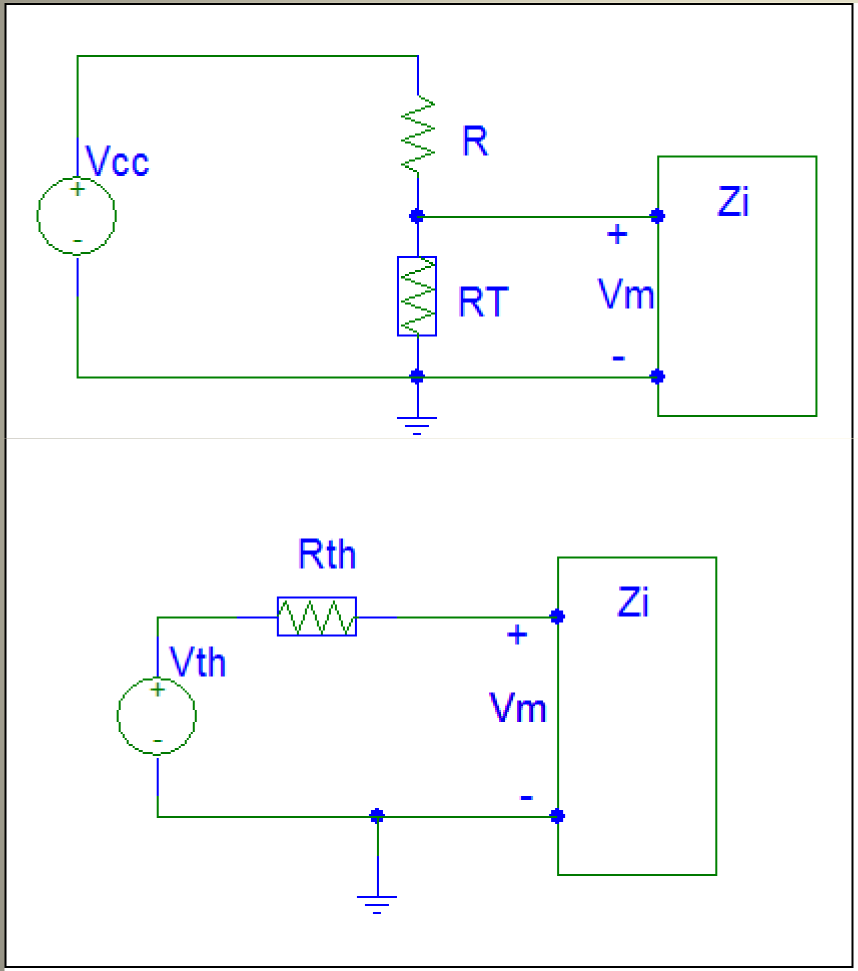


$$Vm = Io \cdot \boxed{R_T}$$

Good linearity over a wide range

$$Vo = Vm\frac{R1 + R2}{R1} - V_{offset}\frac{R2}{R1}$$

# Potentiometric circuit (a case study)



$$Vm = f\left(m, p_1, p_2, \ldots\right)$$

Equations:

$$Vm = Vcc\frac{R_T}{R + R_T}$$

$$R_T(m) = R_0 + \Delta R_m = R_0 + S_m \cdot m$$

$$R_T(m,i) = R_0 + S_m \cdot m + S_i \cdot i$$

Questions:

- Load effect Rth
- Linearity
- Maximum sensitivity (R=R0)
- Magnitudes of influence
- Vm not null if m=0 !!!

# Potentiometric circuit (a case study)

Sensitivity

$$S = \frac{\partial Vm}{\partial m} = S_m \cdot Vcc \frac{R}{\left(R + R_T\right)^2}$$

Maximum sensitivity

$$S_{\max} \Leftrightarrow \frac{\partial S}{\partial R} = 0 \Rightarrow R = R_0$$

Effect of magnitudes of influence

$$\frac{\partial Vm}{\partial i} = S_i \cdot Vcc \frac{R}{\left(R + R_T\right)^2}$$

Compensation of magnitudes of influence

$$\frac{\partial Vm}{\partial i} = 0$$

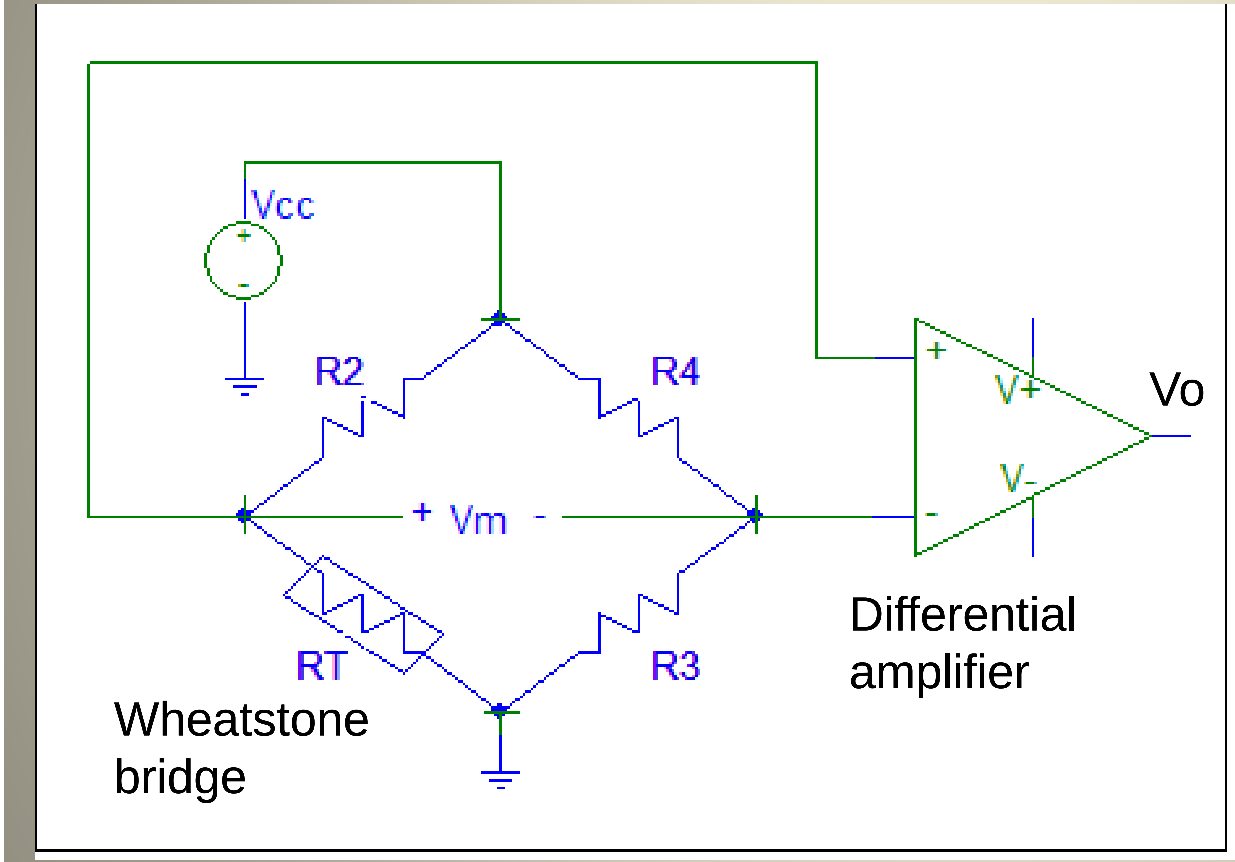
$$Vm = Vcc \frac{R_T}{R + R_T}$$

$$R_T(m) = R_0 + S_m \cdot m$$

$$R_T(m,i) = R_0 + S_m \cdot m + S_i \cdot i$$

$$R(i) = R_0 + S_i \cdot i$$

# DC Null Measurements



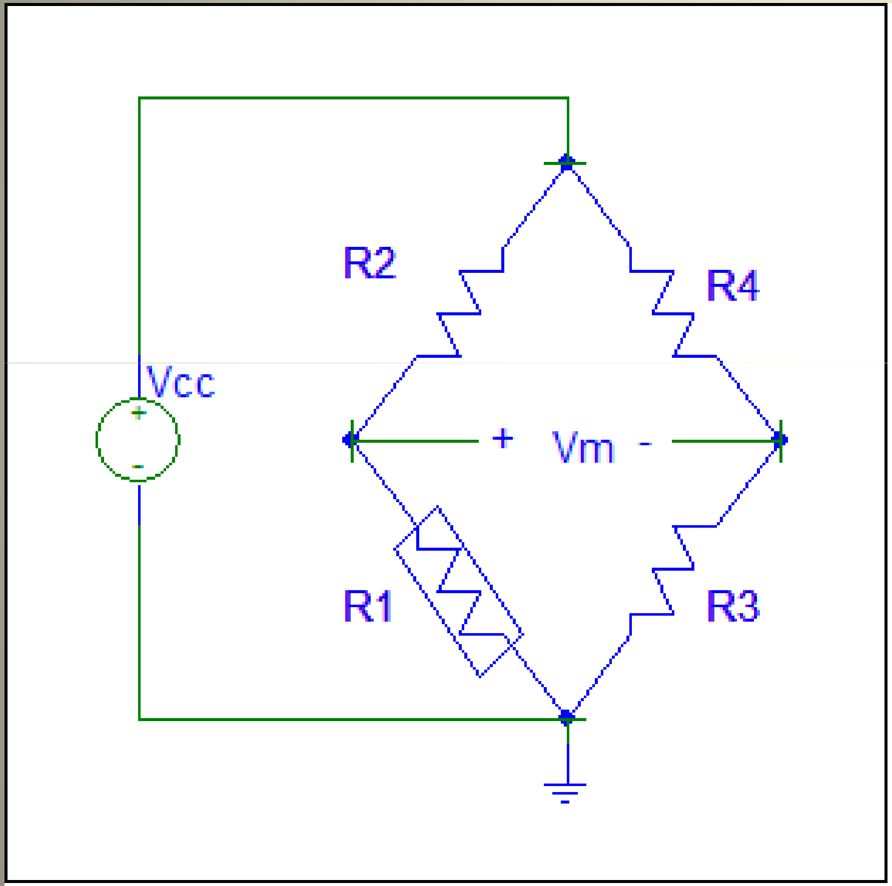
Output Vo is null if m = 0

Better detection of low magnitudes around zero

Differential amplification and high Common Mode Rejection Ratio (CMRR)

Loading of differential amplifier input impedance

# Wheatstone bridge



Equations:

$$Vm = Vcc\left[\frac{R_1}{R_1 + R_2} - \frac{R_3}{R_3 + R_4}\right]$$

Equilibrium (Vm =0):

$$R_1 \cdot R_4 = R_2 \cdot R_3$$

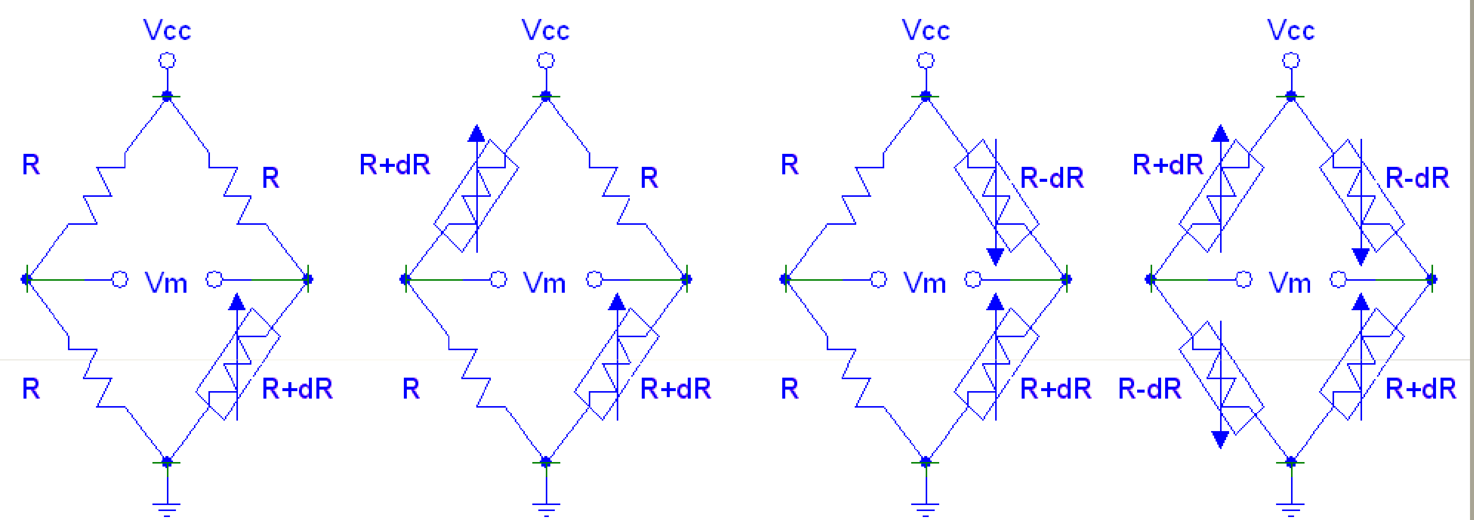
Maximum sensitivity:

$$R_1(m) = R_0 + \Delta R_m = R_0 + S_m \cdot m$$

$$R_2 = R_0 \quad and \quad R_3 = R_4$$

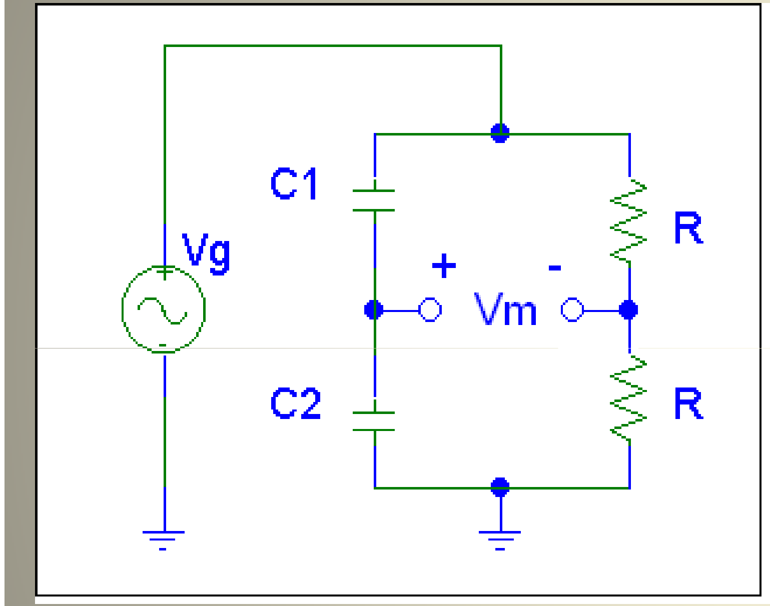
$$Vm = Vcc\left[\frac{R_0 + \Delta R_m}{2R_o + \Delta R_m} - \frac{1}{2}\right] = Vcc\left[\frac{\Delta R_m}{4R_o + 2\Delta R_m}\right]$$

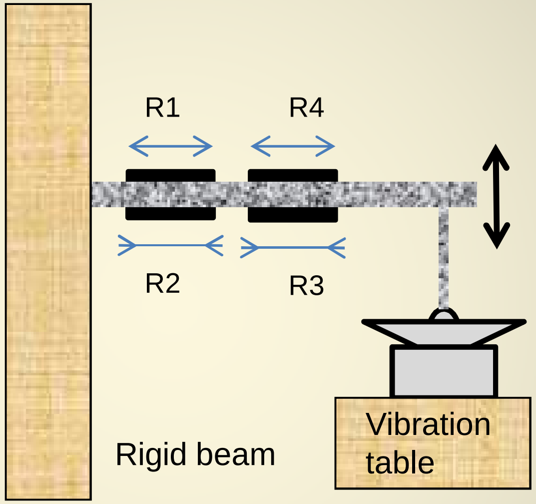
# Wheatstone bridge sensitivity, linearity, push-pull and errors due to magnitudes of influence

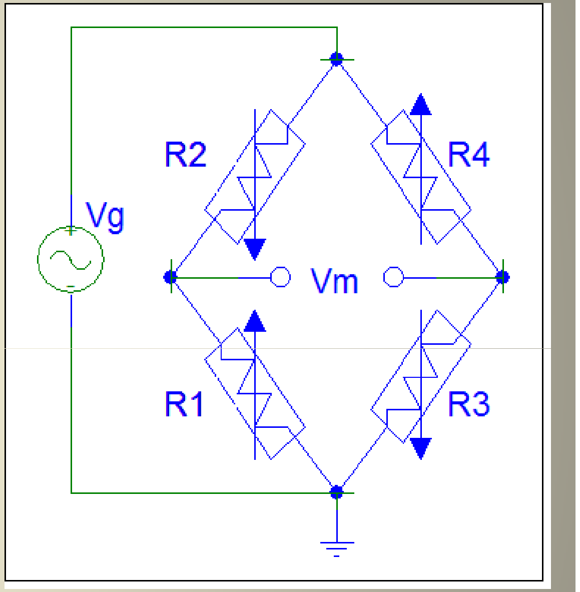


| | | | | |
|---|---|---|---|---|
| **Vm** | $\frac{Vcc}{4}\left[\frac{\Delta R}{R_o+\frac{\Delta R}{2}}\right]$ | $\frac{Vcc}{2}\left[\frac{\Delta R}{R_o+\frac{\Delta R}{2}}\right]$ | $\frac{Vcc}{2}\left[\frac{\Delta R}{R_o}\right]$ | $Vcc\left[\frac{\Delta R}{R_o}\right]$ |
| Linearity Error | 0.5%/% | 0.5%/% | 0 | 0 |
| | A) Single-Element varying | B) Two-Element varying (1) | C) Two-Element varying (2) Push-pull | D) All-Element varying |

# Need of AC Null Measurements



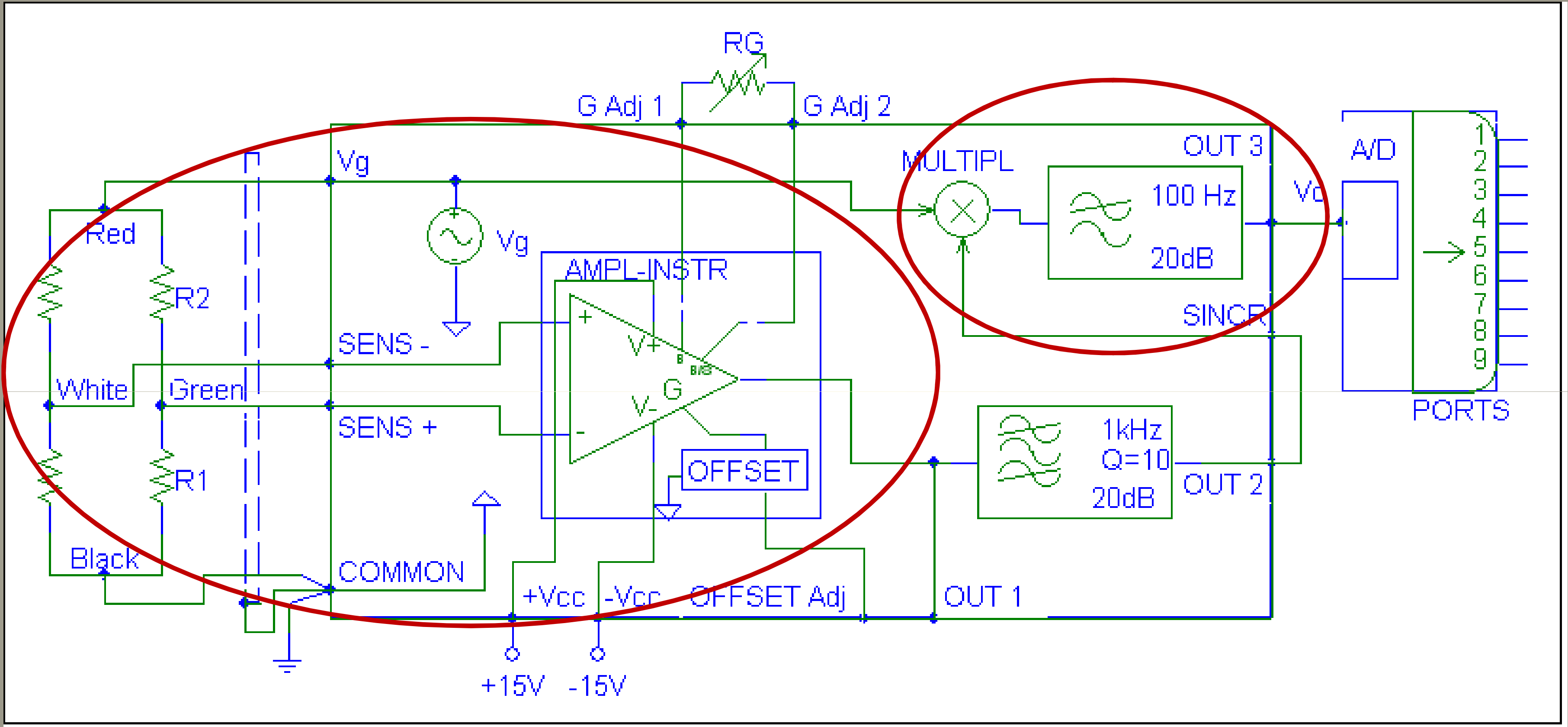




Analog conditioning of
Capacitive and inductive sensors
(complex impedances)

Vg is the carrier of the
modulated electronic system
(reference oscillator)

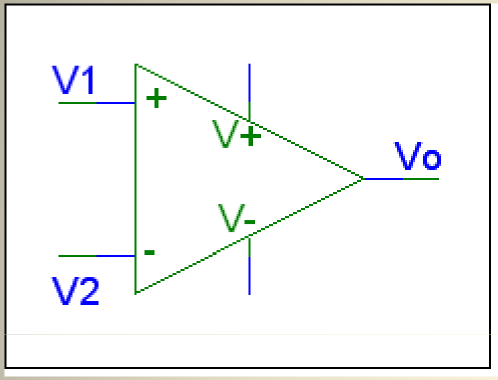
# Demodulation in AC Null Measurements



Vg Carrier
Wheatstone bridge configuration
Instrumentation amplifier (differential)

Band-pass filters
Multiplier and Low-pass filter
or Synchronous demodulator

# Differential amplifiers



Differential input

$$Vm = V1 - V2$$

Common mode input

$$Vc = \frac{V1 + V2}{2}$$

General

$$Vo = A \cdot V1 + B \cdot V2$$

Differential mode gain and Common mode gain

$$Vo = A_{DM} \cdot Vm + A_{CM} \cdot Vc$$

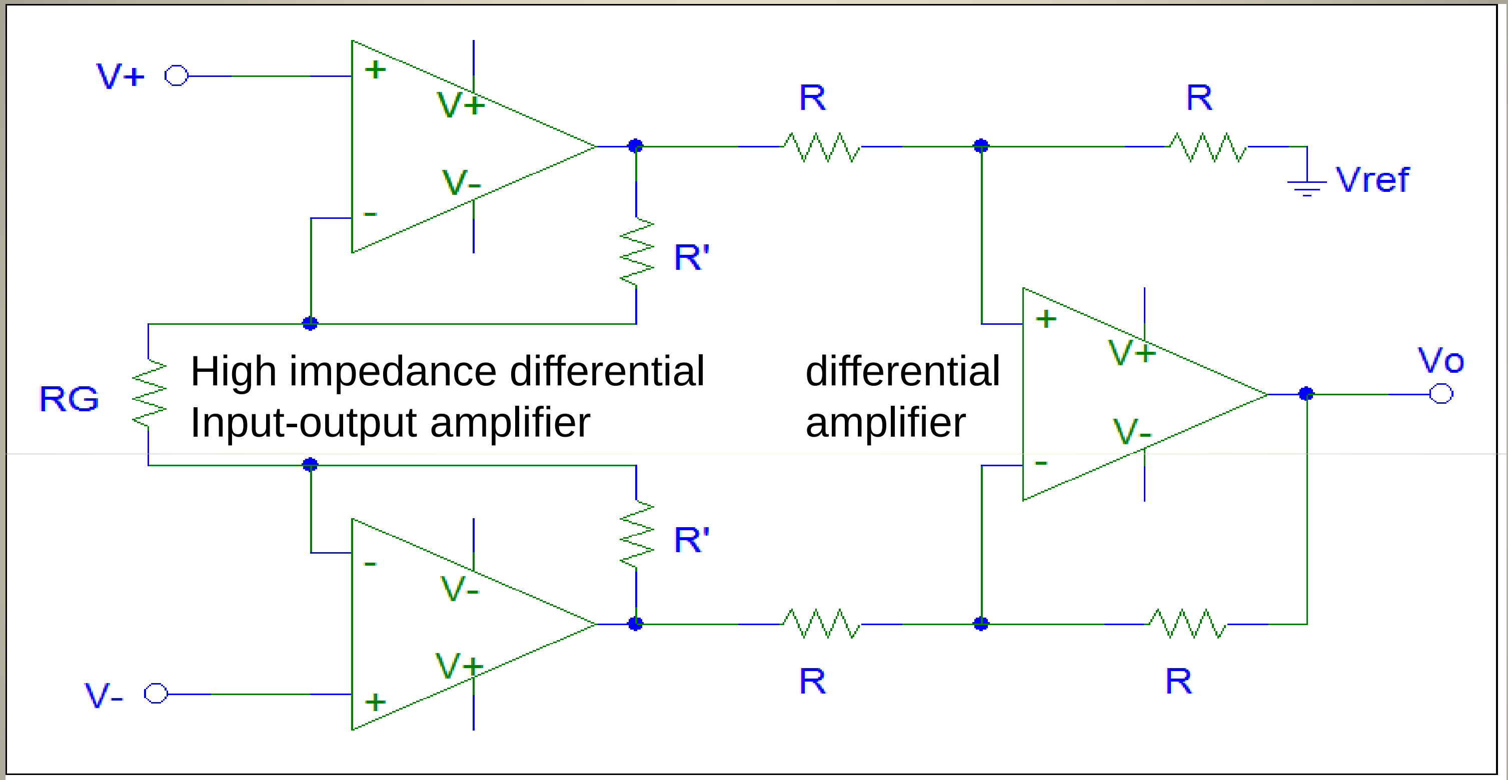
Common Mode Rejection Ratio

$$Vo = A_{DM}\left(Vm + \frac{Vc}{CMRR}\right)$$

# Need of instrumentation amplifiers

- High differential gain
- High CMRR (common mode rejection ratio)
- High input impedance minimize loading effects maximizing the overall sensitivity and avoiding non-linearity error due to sensitivity changes
- Easy adjustment of the gain with a simple passive component
- Integrated circuit for a trim adjustment of the parameters

# Structure of instrumentation amplifiers



High impedance differential Input-output amplifier

differential amplifier

$$v_o = \frac{R}{R} \cdot \left(1 + \frac{2R'}{R_G}\right)(v_+ - v_-)$$

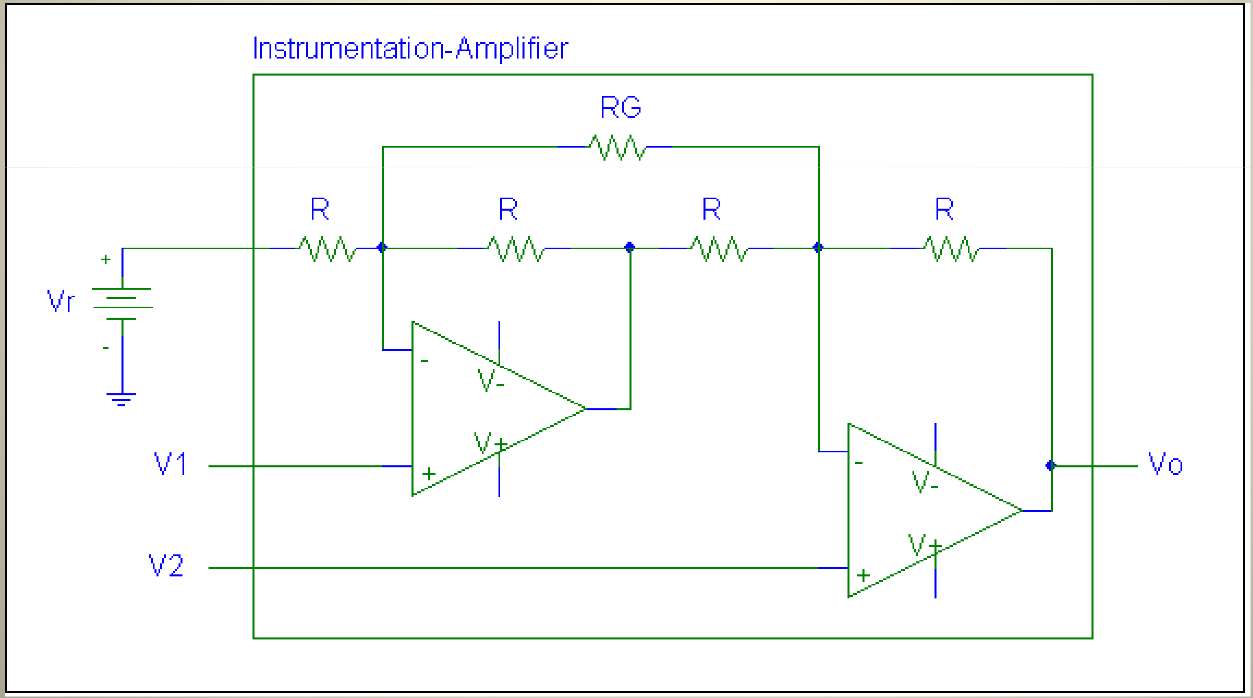
RG selects Gain

Trimmed R values

# Integrated instrumentation amplifiers

* AD620　　* Others

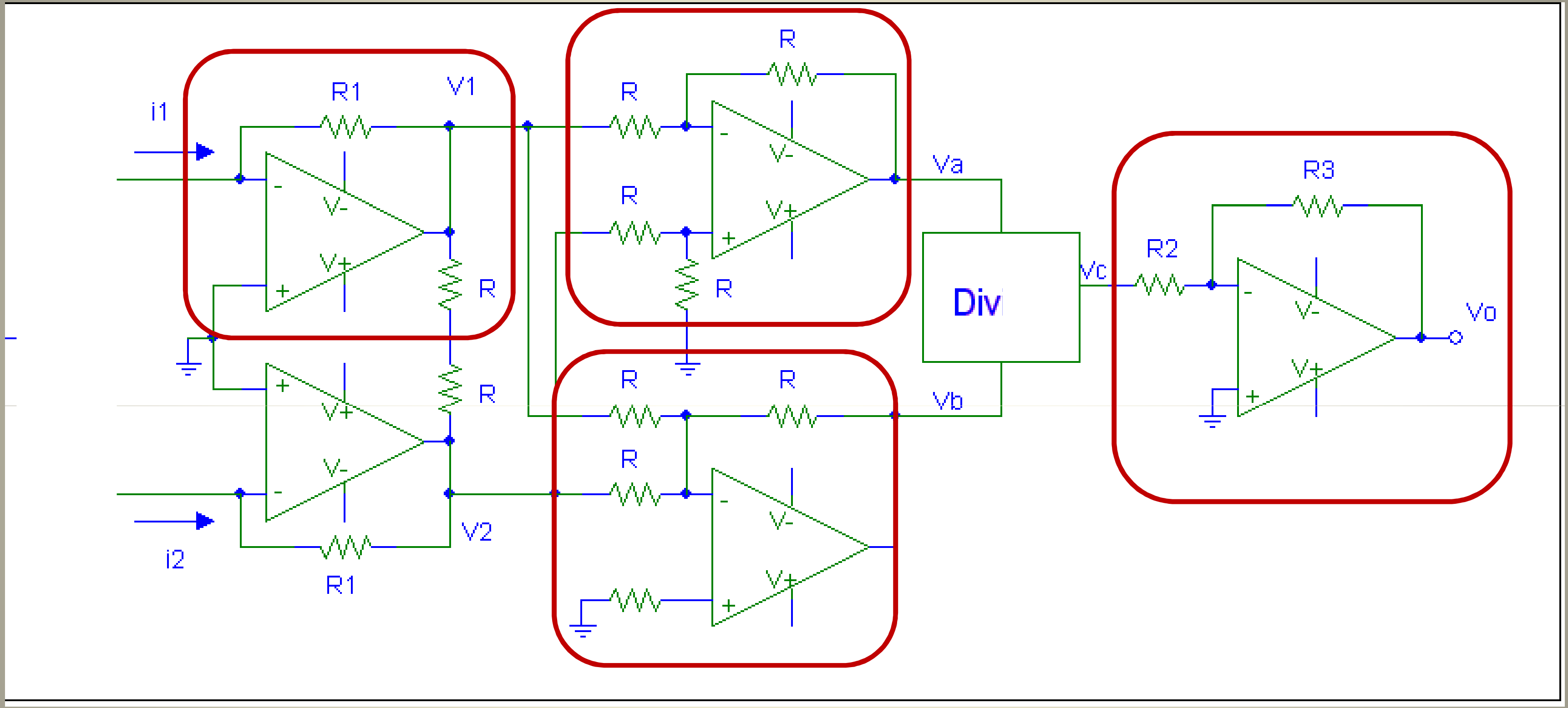
Two OA intrumentation amplifier



# Basic linear analog signal processing

- Operational Amplifiers are used in a circuit as a negative feedback amplifier
- Types of Operational Amplifiers
- Survey of applications
  - Inverting, non-inverting, adding and differential amplifiers
  - Current to voltage and voltage to current conversions
  - Integrators and differentiators
  - Analog active filters

# Example of signal conditioning with OA

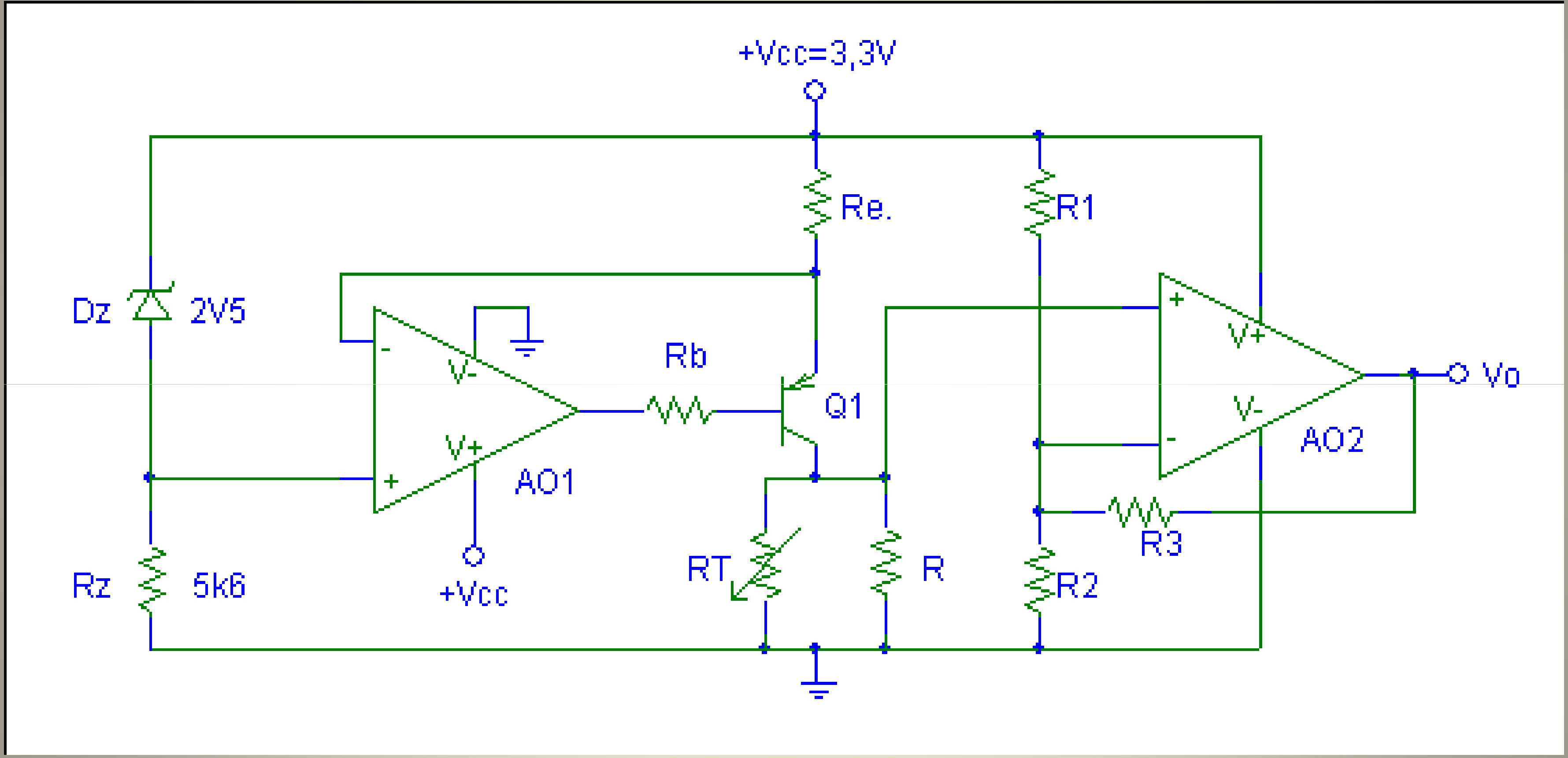


Current to voltage amplifiers

Differential amplifier and Adding amplifiers

Inverting amplifier (recommended)

# Example of signal conditioning with OA



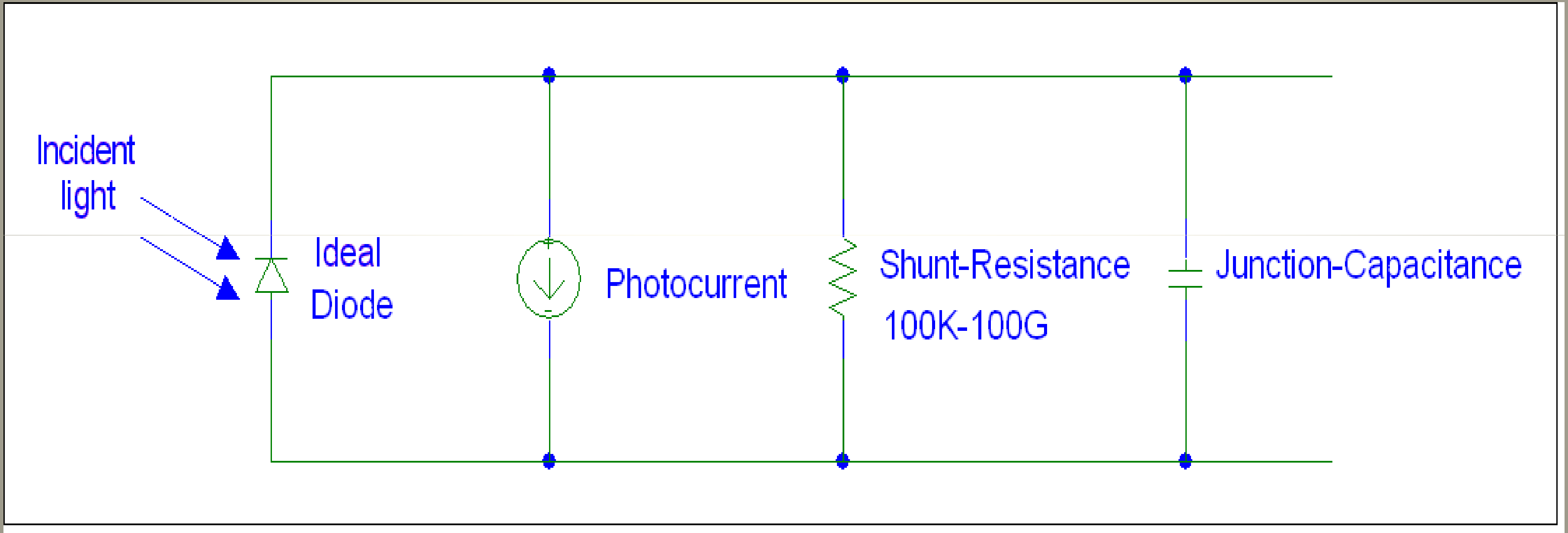
Voltage to current amplifier
or current source

Amplifier with gain and zero
adjustment

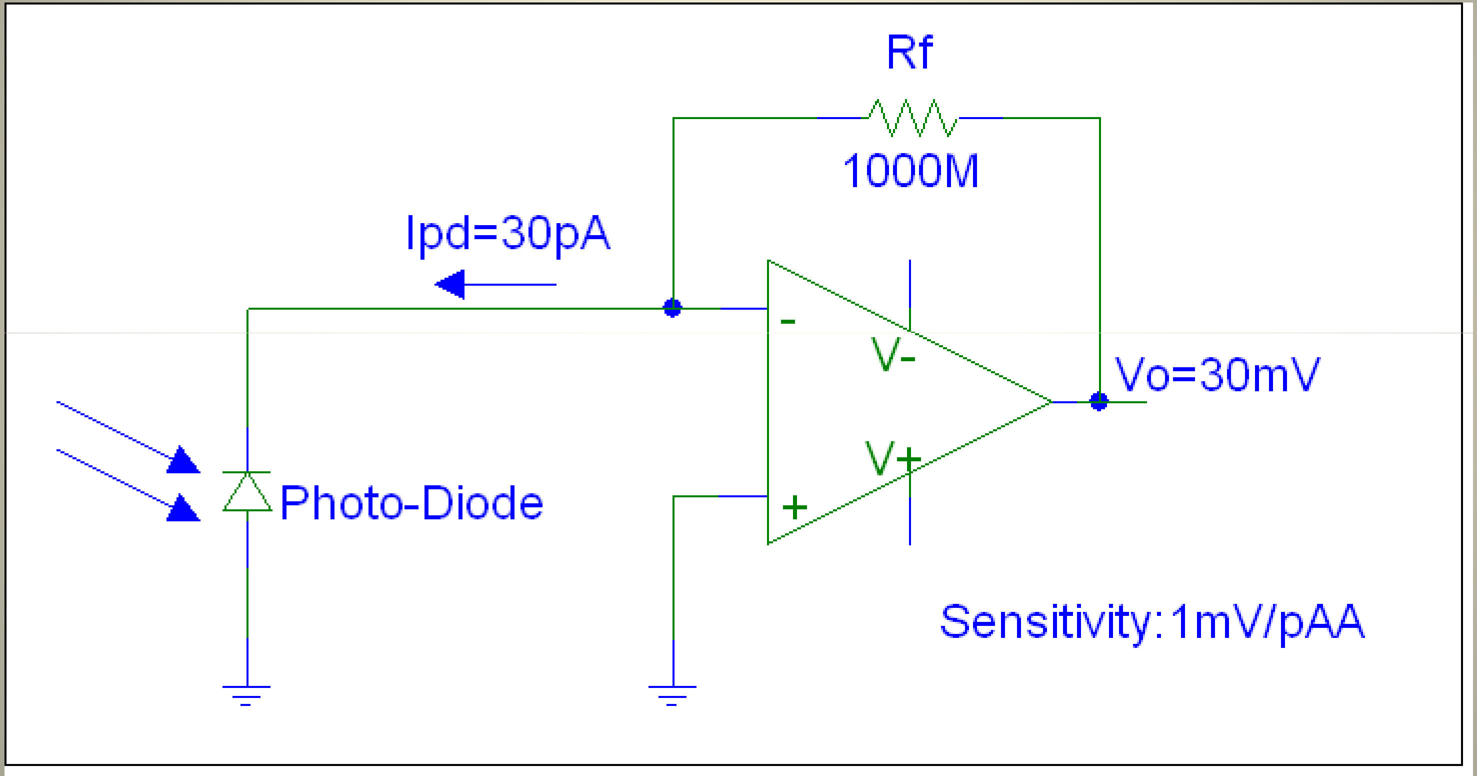
# Analog signal conditioning of optoelectronic sensors

- Primarily light is detected by photodiodes, APDs, photoconductors.
- Current output with high impedance or variable high impedance is mainly obtained.
- Current to voltage circuits are basically used.
- Light may be externally injected into optoelectronic measurement systems by means of Lamps, LEDs and LASERs biased by a current source or voltage to current conversion circuit.

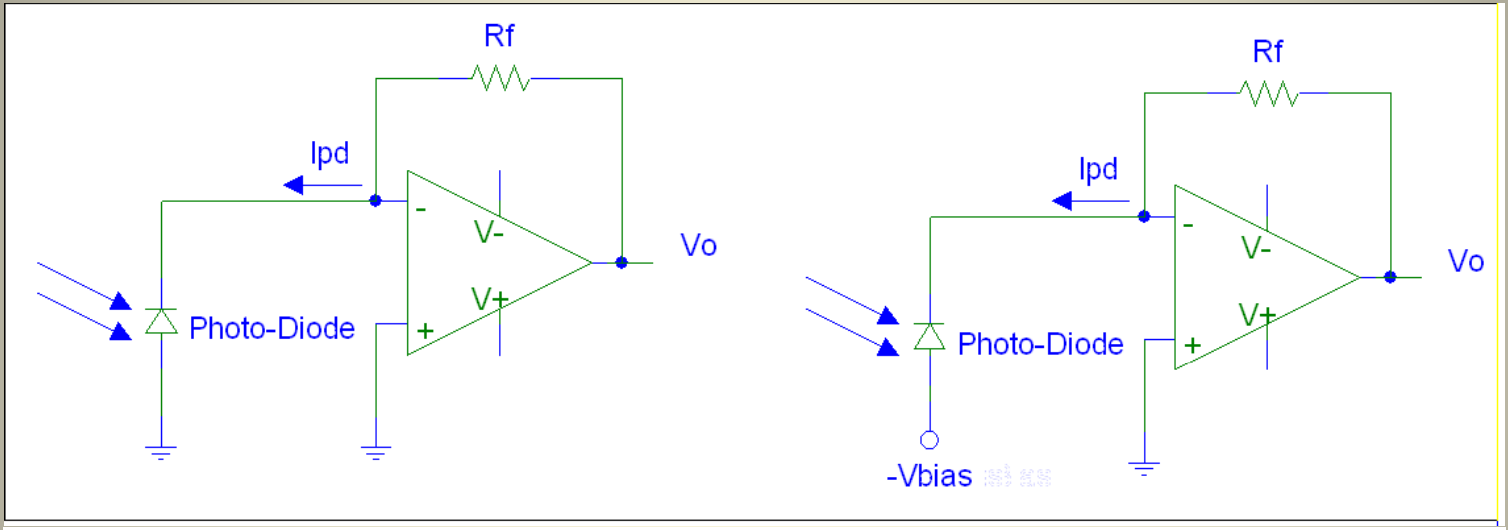
# Equivalent of photodiodes and APDs



# Current to voltage circuit



# Biasing light detectors

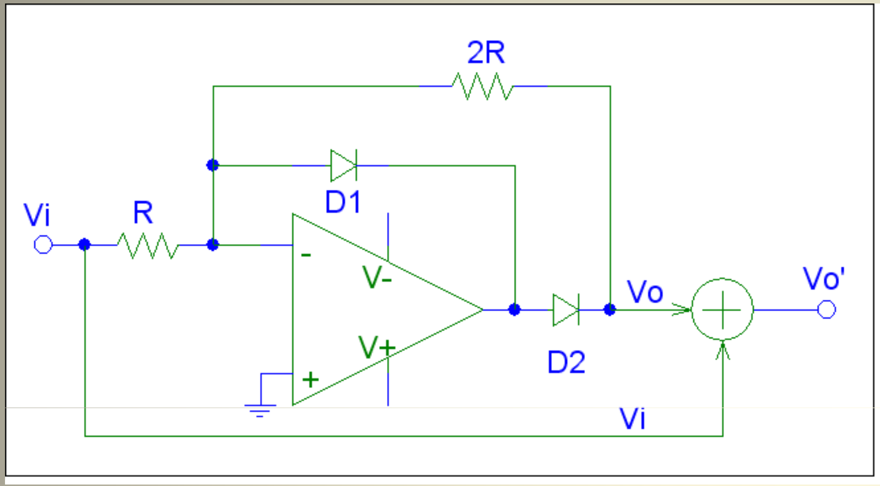


| PHOTOVOLTAIC | PHOTOCONDUCTIVE |
|---|---|
| Zero Bias | Reverse Bias |
| No “Dark” Current | Has “Dark” Current |
| Low Noise (Johnson) | Higher Noise (Johnson + Shot) |
| Precision Applications | High Speed Applications |

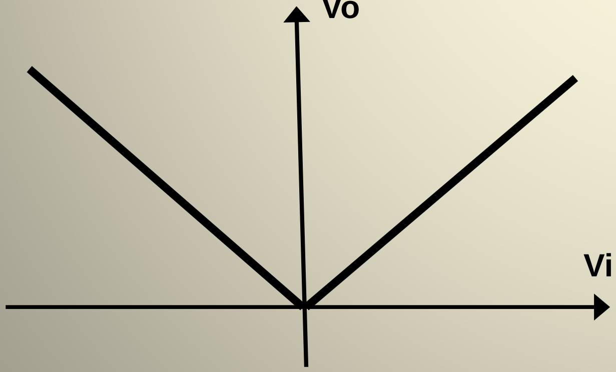
# Non-linear analog signal processing

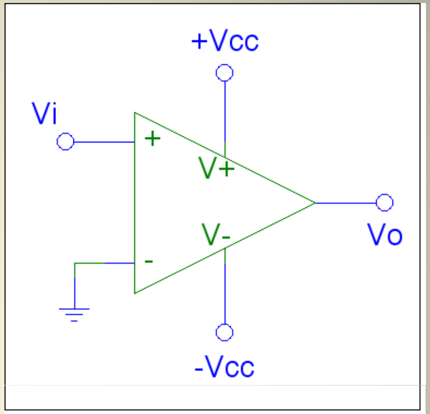
- Operational Amplifiers are used in saturated mode
- Special Amplifiers and Comparators
- Survey of applications
  - Precision rectifiers, Peak detectors, envelope and RMS detectors
  - Schmitz –trigger comparators
  - Logarithmic amplifier

# Examples of Non-linear signal processing

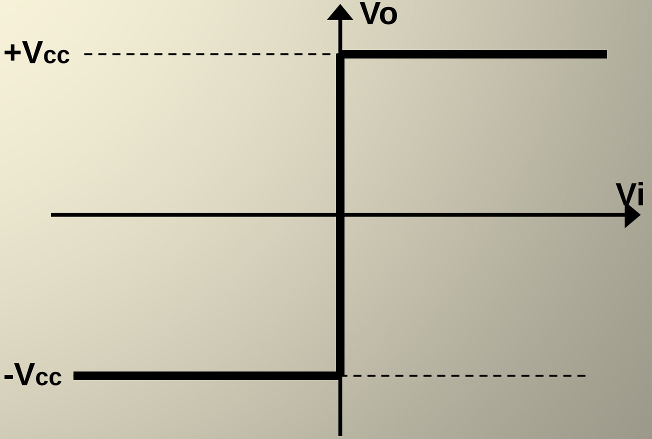


Full-wave precision amplifier

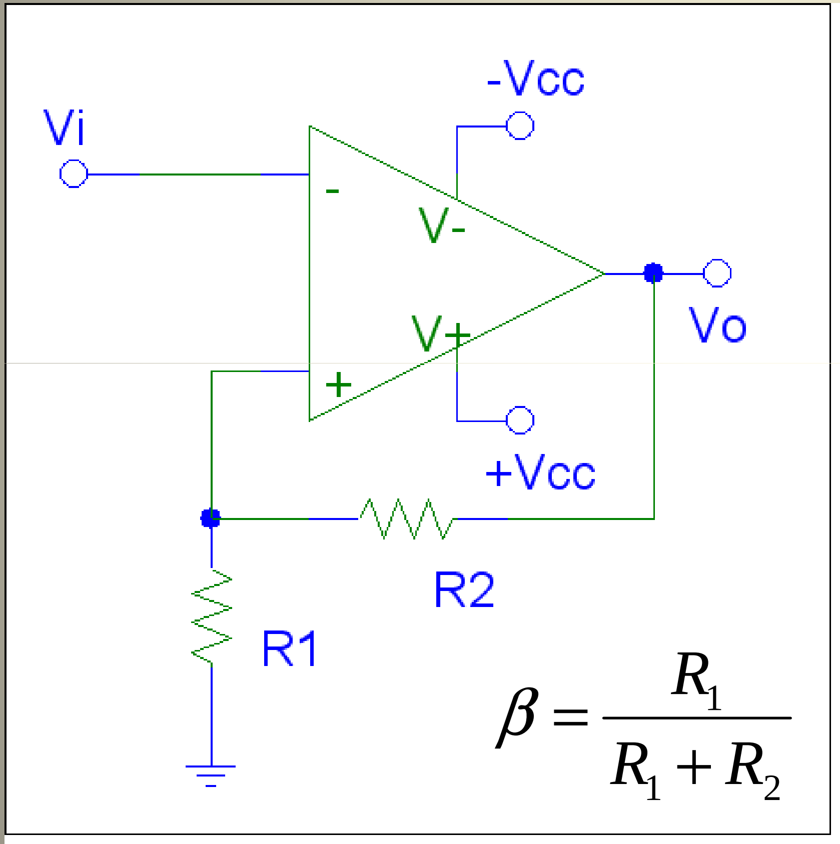




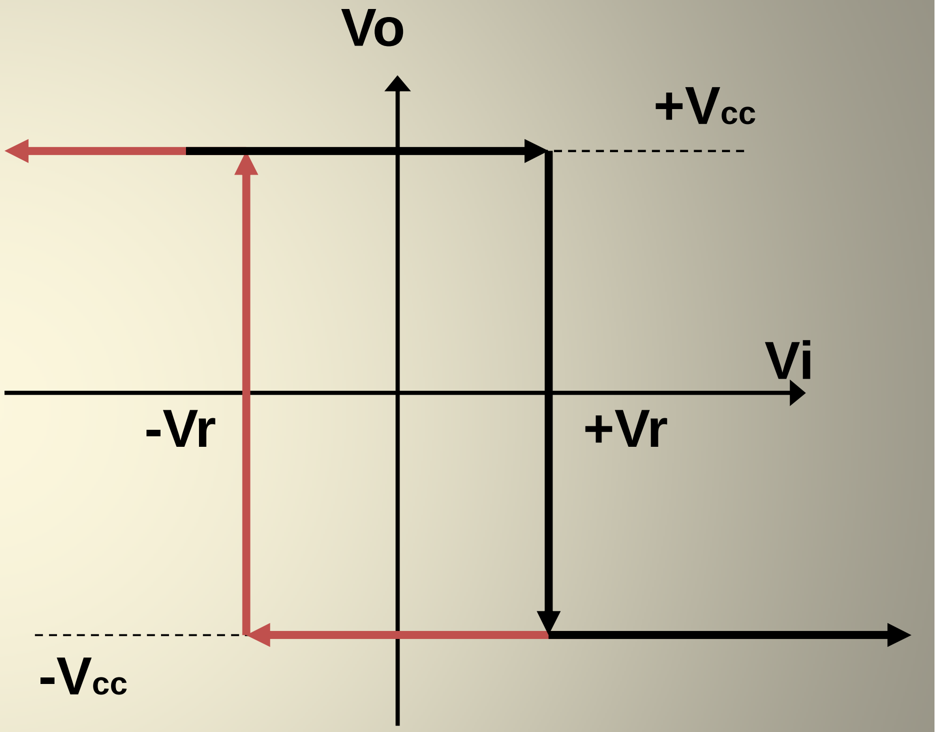
Comparator with zero



# Smith-trigger comparator

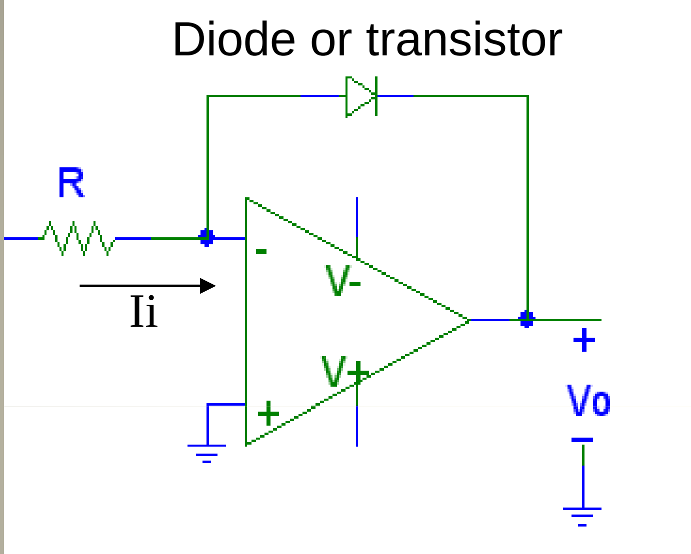


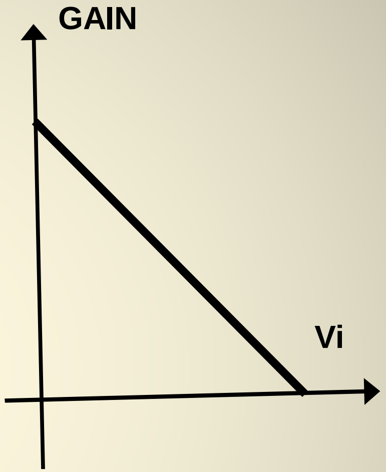
$$\beta = \frac{R_1}{R_1 + R_2}$$



*Vr=β·Vcc   noise margin*

# Logarithmic amplifiers





$$Vo = -\frac{KT}{q} Ln[Ii / Io]$$

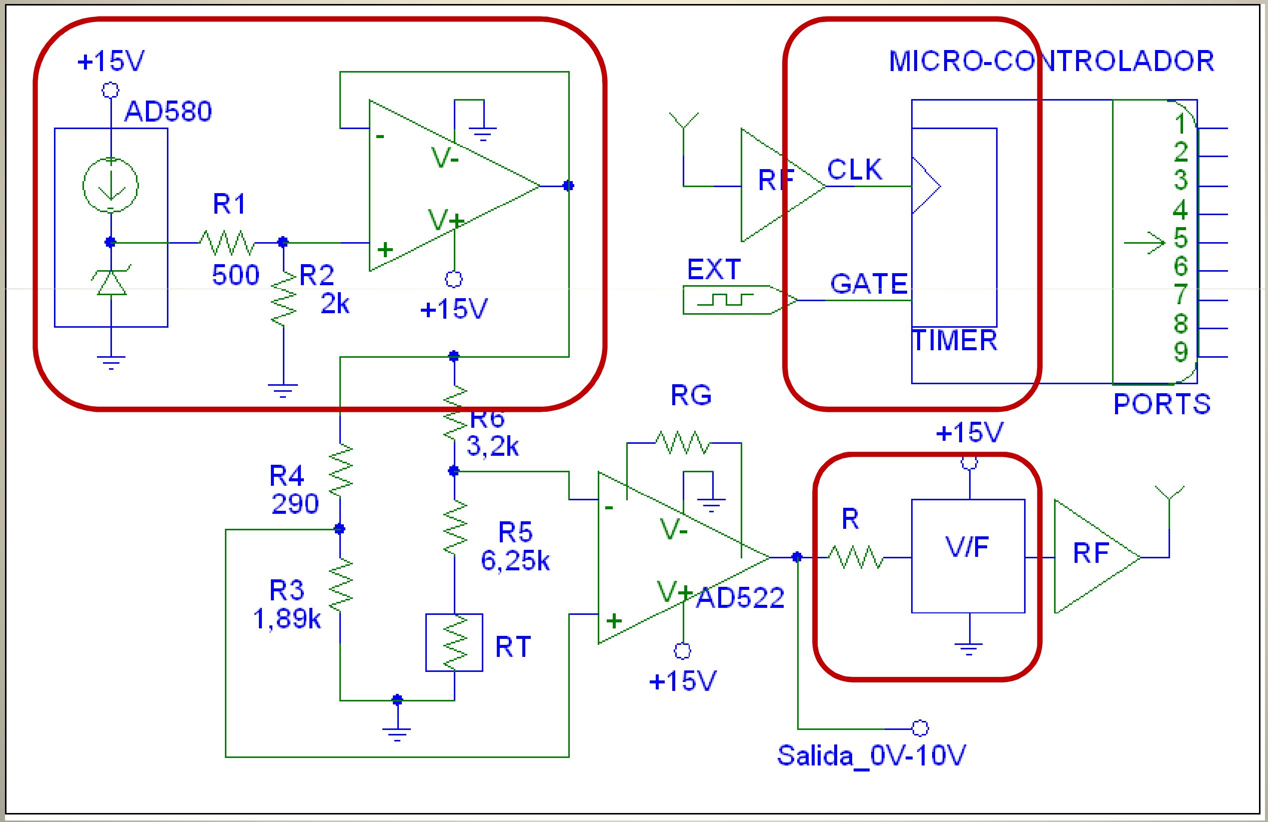
Linearization of exponential sensitivity
Gain change extends the input range

* Log101

# Special Function Modules

- Multipliers and modulators / demodulators
- Voltage to Frequency converters and frequency detectors

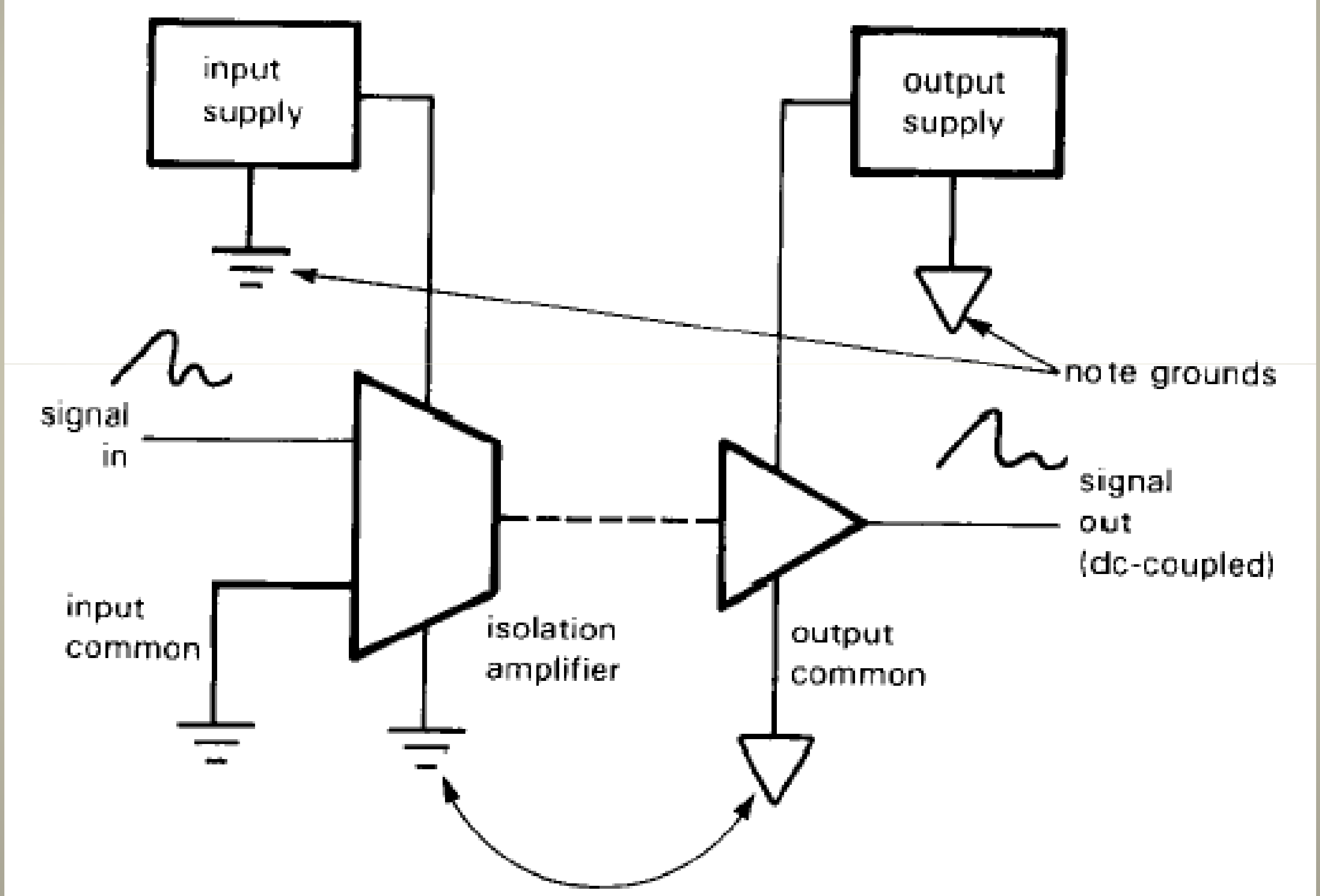
# Example of analog signal conditioning and special function modules



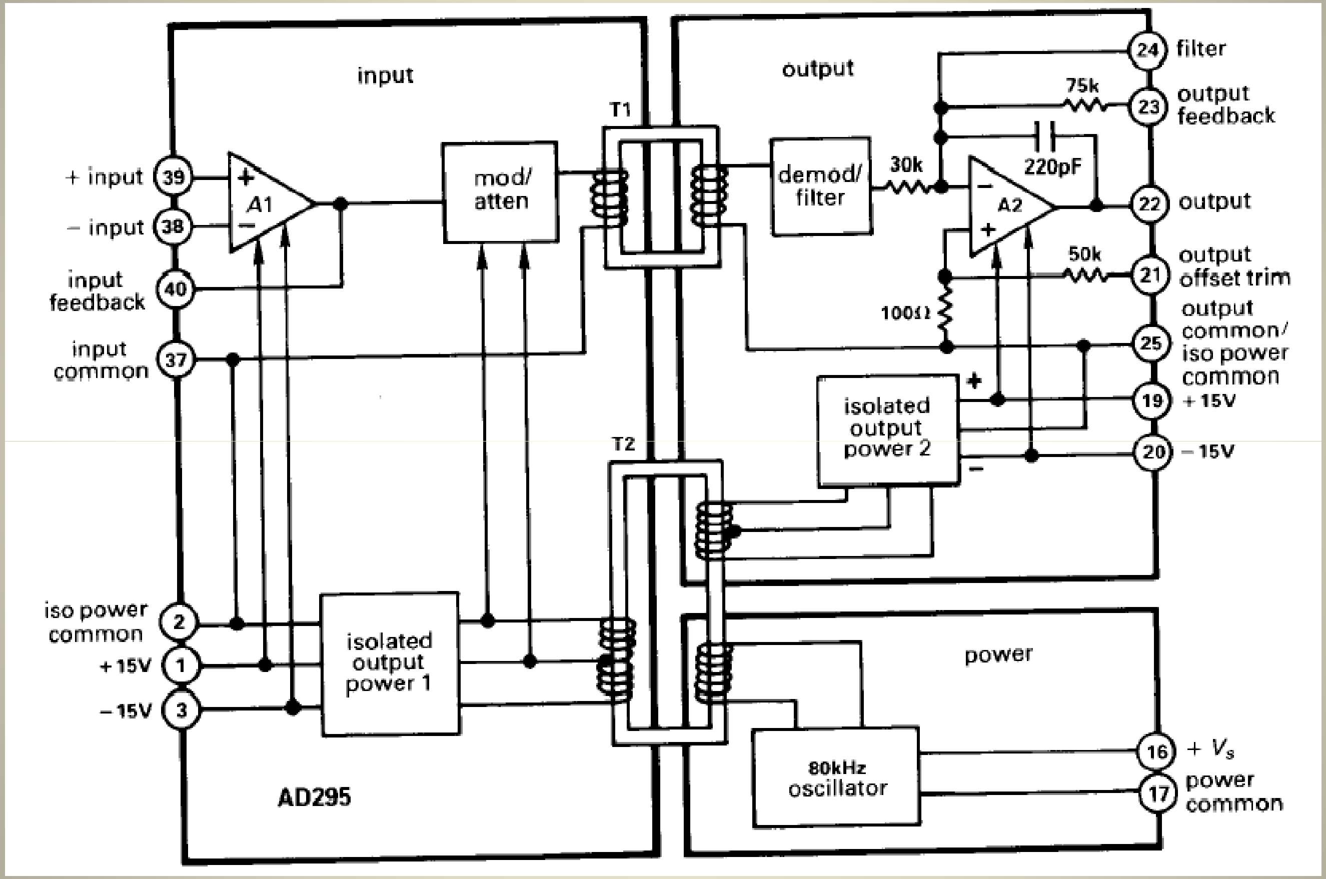
# Other specific instrumentation components and circuits

- Isolation amplifiers
- Auto-zero Amplifiers
- Charge Amplifiers
- Switched-capacitor amplifiers and filters

# Isolation amplifiers basic principles

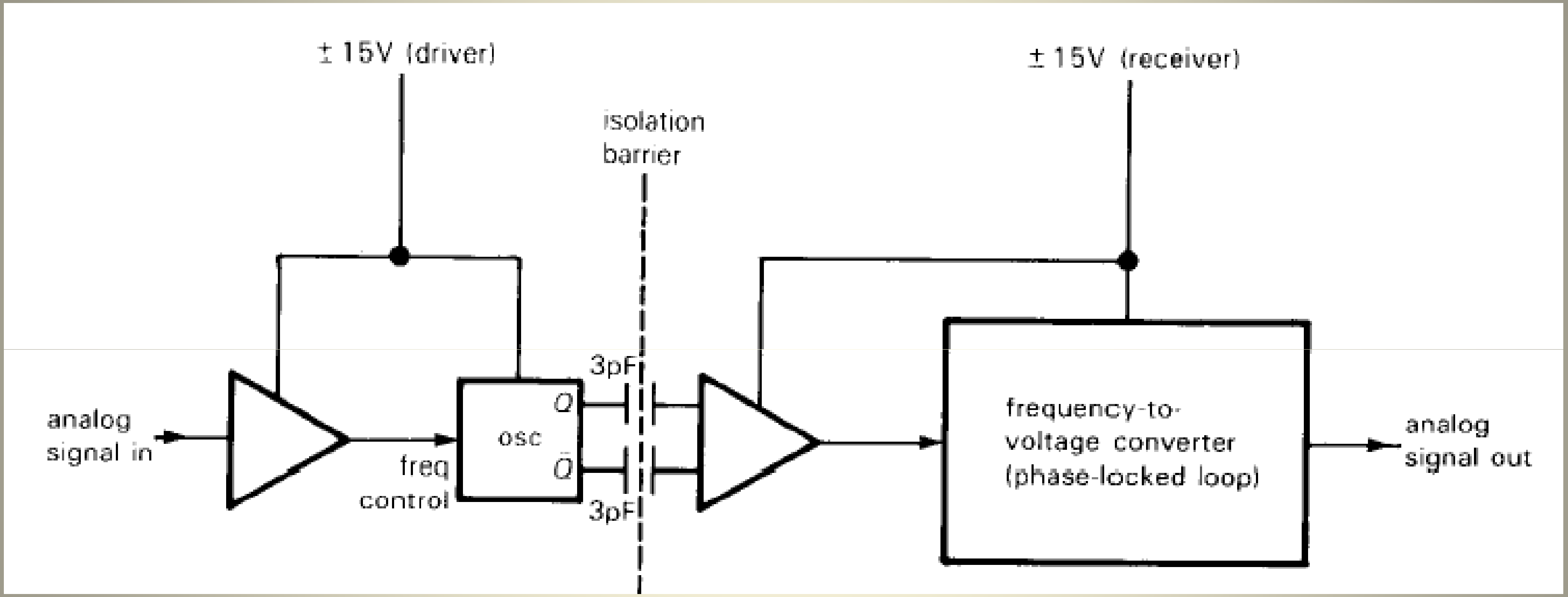


# Transformer (inductive) isolation barrier



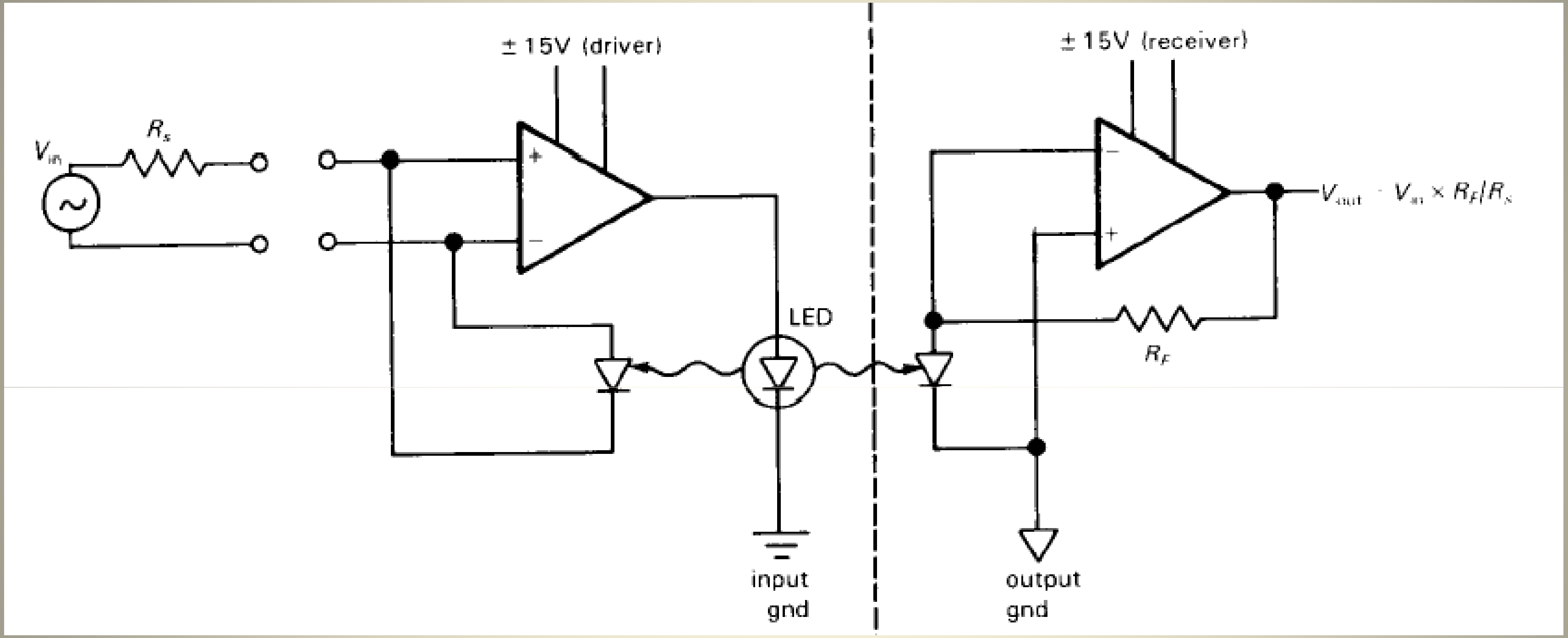
[* AD210]

# Capacitive isolation barrier



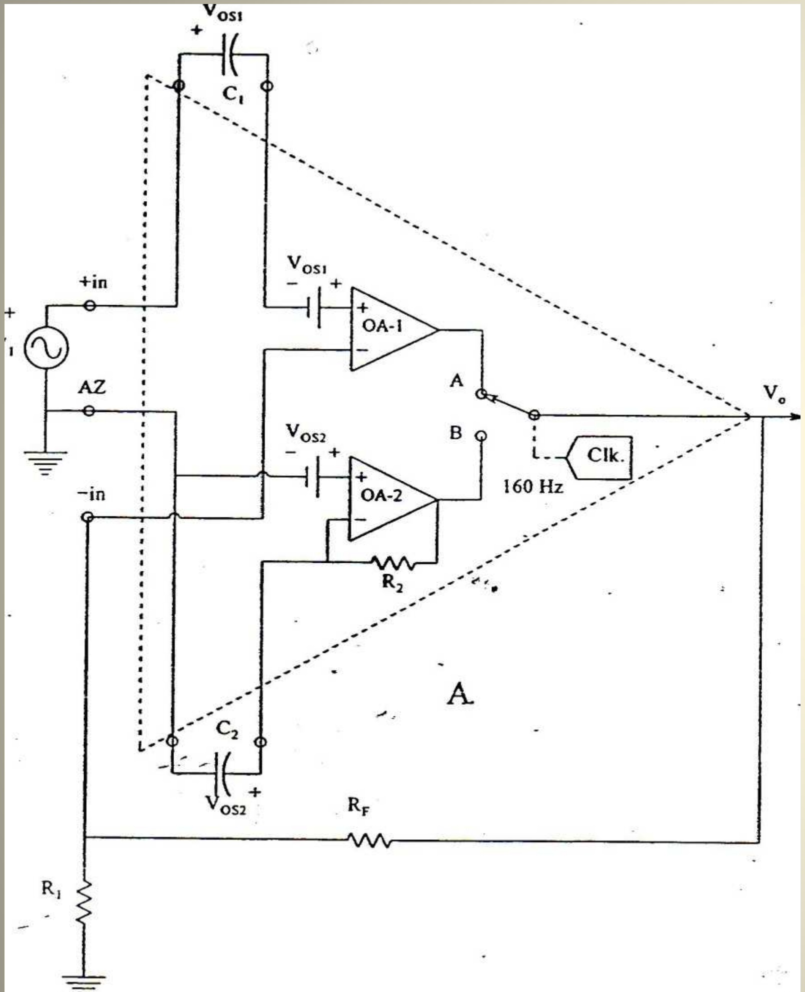
* Iso102

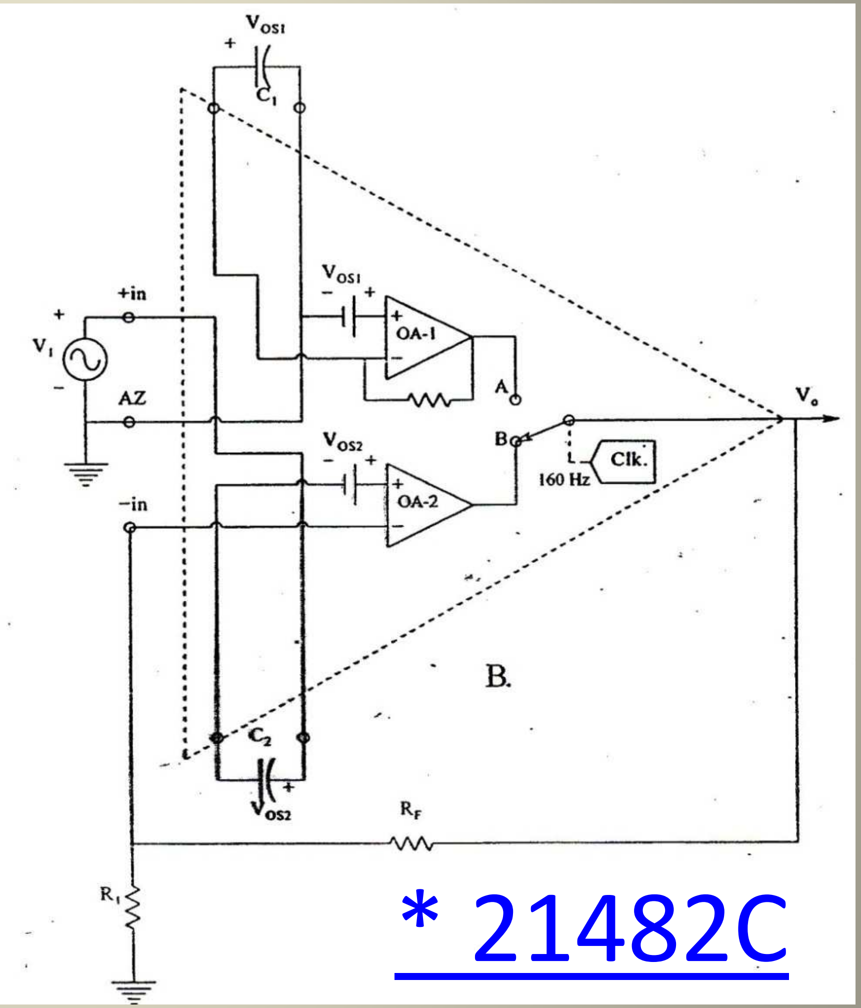
# Optic isolation barrier



* Iso100

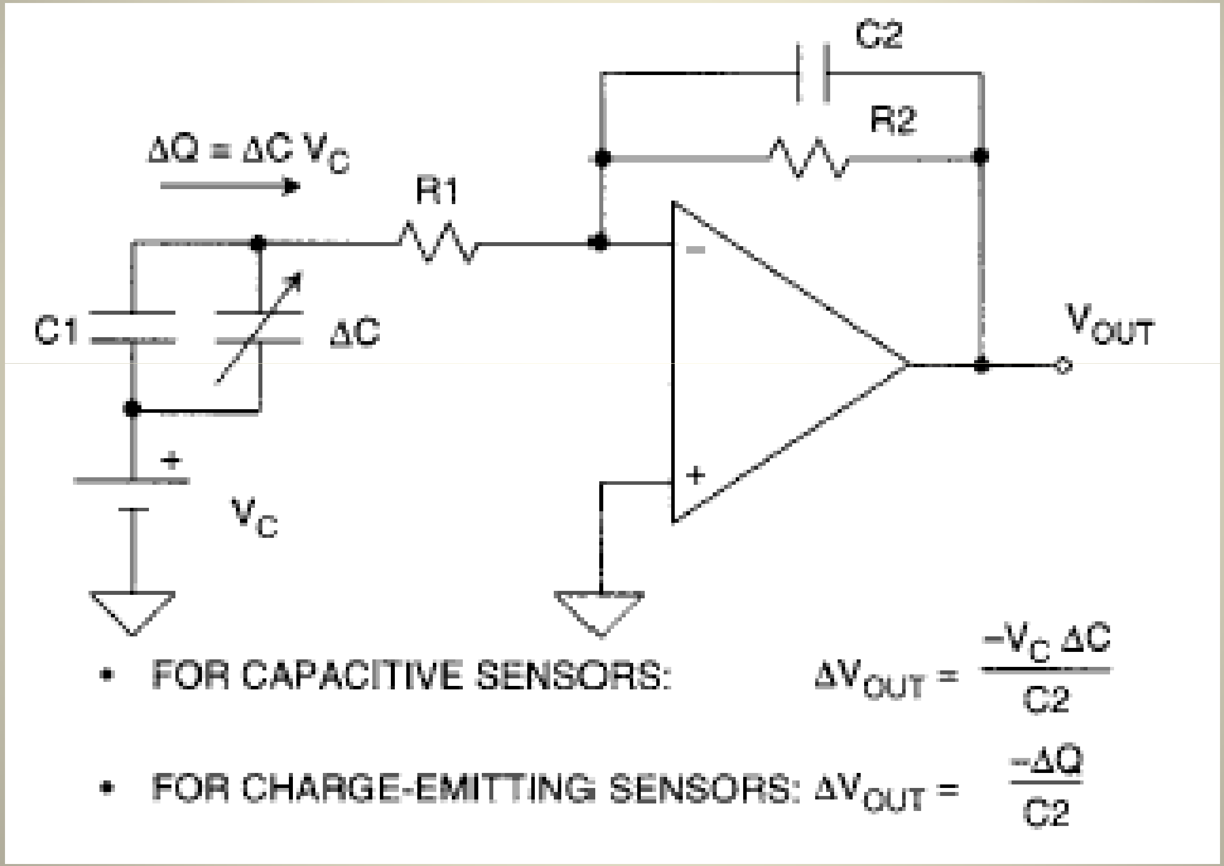
# Auto-zero Amplifiers





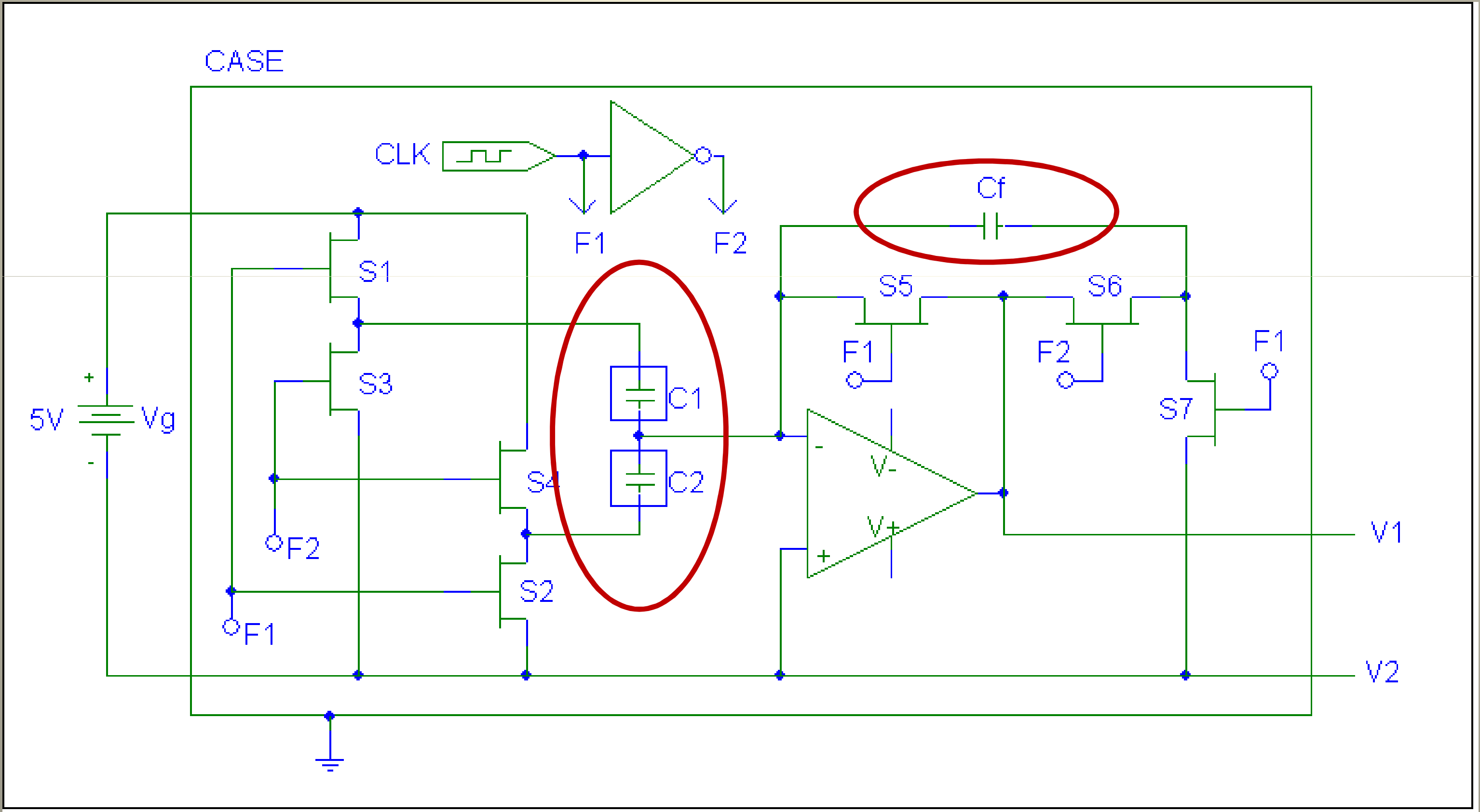
* 21482C

# Charge amplifiers basics



- FOR CAPACITIVE SENSORS: $\Delta V_{OUT} = \dfrac{-V_C\, \Delta C}{C2}$
- FOR CHARGE-EMITTING SENSORS: $\Delta V_{OUT} = \dfrac{-\Delta Q}{C2}$

# Switched-capacitor amplifier basics



# Summary

- We have described the basis for passive sensors signal conditioning, stressing the importance of the influence variables and null conditioning schemes.
- Instrumentation amplifiers have also been presented as main components in instrumentation systems where diffeential signals are present.
- Several schemes for analog signal condition, linear and nonlinear, based on operational amplifiers have also been presented.
- Finally, other specific instrumentation components and circuits have also been presented.