Interfacing Sensors and Actuators

Methods and Circuits for Interfacing Sensors and Actuators

Sensors

The output is an electrical signal: U, I, R, C, L, f…

They need additional measuring circuits for:

- Amplification
  - Instrumentation amplifiers
  - Bridge Amplifiers
  - Lock-in Amplifiers
- Filtering
- Impedance matching
- Peak values detecting
- Analog to Digital conversion- for interfacing with microprocessors or digital displays

Actuators

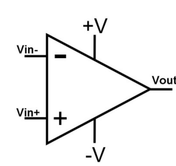
They need high values of currents and voltages:

- Power amplifiers for driving the actuators
- Digital to Analog conversion –for interfacing with microprocessors

Other circuits:

- Excitation circuits
- Power supplies
- Oscillators

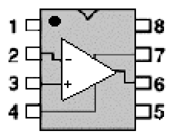
Operational amplifiers (Op-amp) solutions

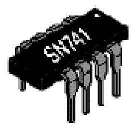


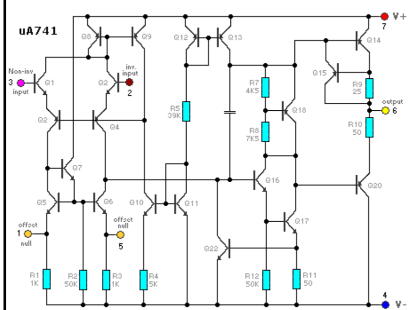
Amplification in instrumentation

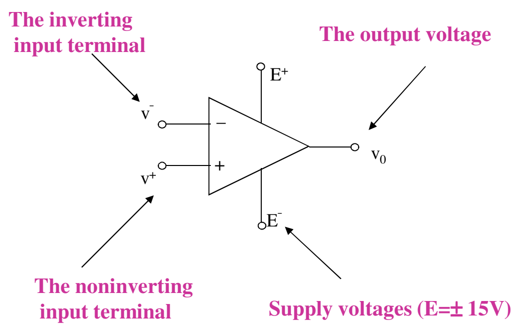
Operational Amplifiers (OA)- Review

Integrated circuit that amplifiers the signal across its input terminals.







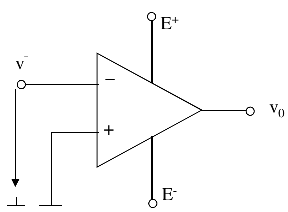


$$v_0 = a_D(v^+ - v^-)$$

a_D-differential gain (in open loop)

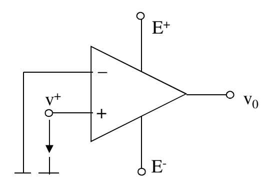
Op-amps

(-) The inverting input terminal means:



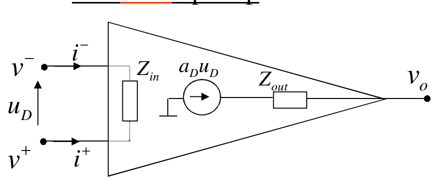
$v_o = -a_D\, v^-$

(+) The noninverting input terminal means:



$v_o = a_D\, v^+$

The ideal op-amp



$Z_{in} \to \infty \Rightarrow i^+ = i^- = 0$

$Z_{out} \to 0$

$a_D \to \infty$ $\quad u_D = v^+ - v^- = \frac{v_0}{a_D} \to 0 \Rightarrow$ $v^+ = v^-$

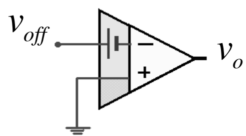
The real op-amp

$Z_{in} \approx 10^6\,\Omega$ $\quad a_D \approx 10^5 - 10^9$ $\quad Z_{out} \approx 100...1000\Omega$

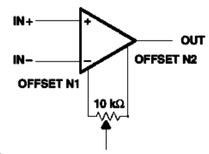
Offset voltage

Practically when $v^+=v^-=0$ the output voltage $v_0 \neq 0$

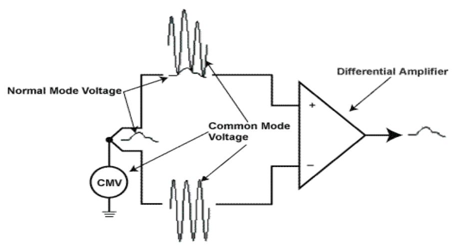
Why? Because of the transistors mismatching in the input stage

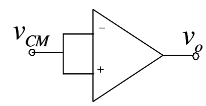


Determine $V_{off} \rightarrow$ when $v_o=0$



The common-mode voltage





Ideally if $\mathbf{v_{CM} \neq 0}$ then $\mathbf{v_0 = 0}$

Really if $\mathbf{v_{CM} \neq 0}$ then $\mathbf{v_0 = a_{CM} \cdot v_{CM} \neq 0}$

a_{CM} -the common-mode gain

The Common-Mode Rejection Ratio (CMRR)

CMRR describes the ability of a differential amplifier to reject the signals common to both inputs, and to amplify only the difference between the inputs.

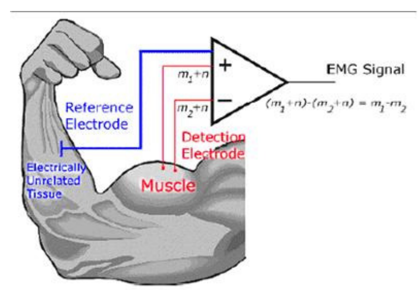
$$CMMR = \frac{a_D}{a_{CM}} = \frac{\frac{v_0}{u_D}}{\frac{v_0}{v_{CM}}} = \frac{v_{CM}}{u_D}$$

$$CMMR(dB) = 20\lg \frac{a_D}{a_{CM}}$$

Ideally $a_{CM} \rightarrow 0 \Rightarrow CMMR \rightarrow \infty$

Electromyography

https://www.youtube.com/watch?v=gHsZ0bwxMsg



Really $CMMR = 100 \div 120 dB$

Real op-amps (like the 741) have CMRR of ~90 dB, meaning the ratio of gains is 30000.

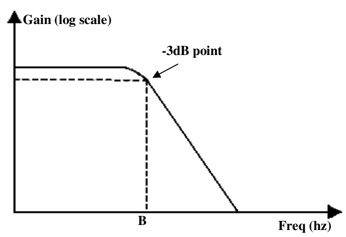
The frequency response of the op-amps

•*Really* a_D has a finite value and it's function of frequency.

•The ***frequency response*** of any circuit is the graph of the magnitude of the gain in decibels (dB) as a function of the frequency of the input signal.

•The frequency response of an op-amp is a **low pass filter characteristic**.

•The bandwidth (B) is the frequency at which the power of the output signal is reduced to ***half*** that of the maximum output power. This occurs when the gain drops by **3 dB**.



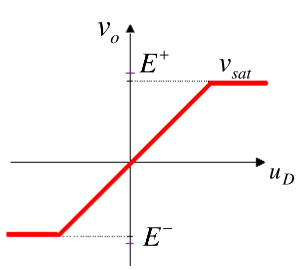
$$10\lg\left(\frac{1}{2}\right) = -3.0103dB$$ →power

$$20\lg\left(\frac{1}{\sqrt{2}}\right) = 20\lg(0.707) = -3.0103dB$$ →voltage

Ideal OA versus real OA

Parameter	Ideal Operational Amplifier	Typical Operational Amplifier
Differential voltage gain a_D	∞	10^5-10^9
Common mode voltage gain	0	10^{-5}
Gain bandwidth product f	∞	1-20 MHz
Input resistance R	∞	$10^6\Omega$ (bipolar) 10^9-$10^{12}\Omega$ (FET)
Output resistance	0	100-1000Ω

The transfer characteristic of an op-amp



Saturation means that the output voltage clips at some maximum value V_{sat}, typically a couple of volts lower than the positive supply voltage E^+_{supply}.

Application. Saturation

Given: The gain of an op-amp (in open loop) is 1 million (a_D = 10^6). The high supply voltage E^+_{supply} is 15 V. The op-amp saturates at 13 V.

To do: Calculate the input voltage difference v_D that will cause saturation.

Solution:

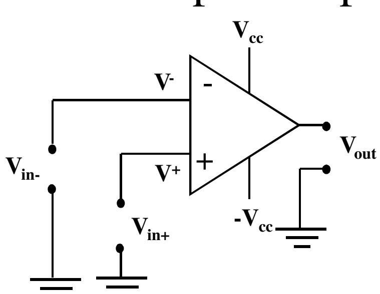
$$v_D = \frac{v_0}{a_D} = \frac{13V}{10^6} = 13\mu V$$

With only 13 μV of differential input, the op-amp **is already saturated**!

•Because of their very high open loop gain, OAs are almost exclusively used with some additional circuitry (mostly with resistors and capacitors), required to ensure a ***negative feedback loop***.

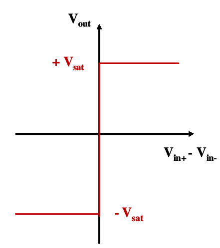
• The negative feedback stabilizes the output within the operational range and provides a much smaller but precisely controlled gain, the so-called ***closed loop gain*** .

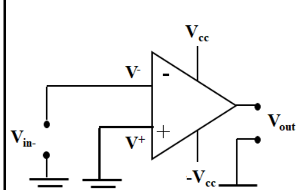
The Open-loop op-amp→ The Comparator



If $V^+ > V^-$ $V_{out} = V_{sat} \approx V_{cc}$

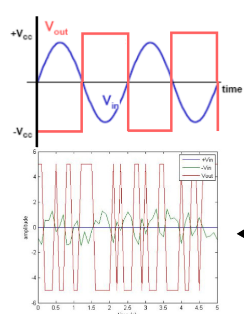
If $V^+ < V^-$ $V_{out} = -V_{sat} \approx -V_{cc}$





If $0 > V^-$ $V_{in} < 0$ $V_{out} = V_{sat}$

If $0 < V^-$ $V_{in} > 0$ $V_{out} = -V_{sat}$



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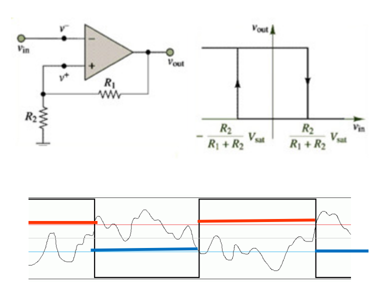
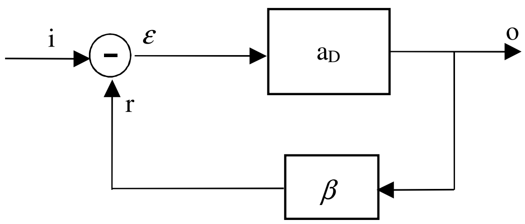
Schmitt trigger circuit (inverting)-hysteresis



The Closed-loop op-amp. The negative feedback



$$o = a_D \varepsilon$$

$$r = \beta \cdot o$$

$$\varepsilon = i - r = i - \beta \cdot o$$

$$A = \frac{o}{i} = \frac{a_D \varepsilon \cdot}{i} = \frac{a_D (i - \beta \cdot o)}{i}$$

$$A = a_D (1 - \beta \cdot A) \quad \Rightarrow$$

$$A = \frac{a_D}{1 + \beta \cdot a_D}$$

For a *high a_D* it results *$\beta a_D >> 1$* and finally:

$$A = \frac{a_D}{\beta \cdot a_D} = \frac{1}{\beta}$$

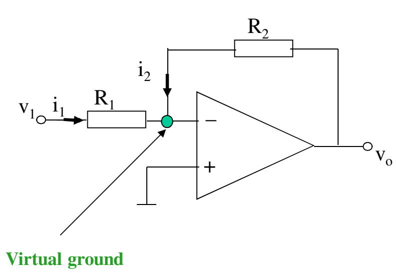
The gain is **independent** of a_D and the circuit is **very stable.**

Basic Operational Amplifier Circuits

There are a lot of circuits with OAs performing various mathematical operations.
The transfer characteristic can be derived applying **Kirchhoff's rules** and the following assumptions (Op-amp is considered **ideal**):

$$\mathbf{v^+ = v^-;\ i^+ = i^-}$$

The inverting amplifier



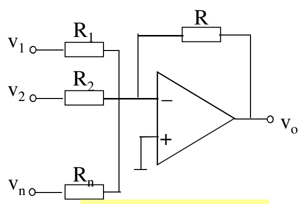
$$\left.\begin{aligned} & i_1 + i_2 = 0 \\ & i_1 = \frac{v_1 - v^-}{R_1} = \frac{v_1}{R_1} \\ & i_2 = \frac{v_0 - v^-}{R_2} = \frac{v_0}{R_2} \end{aligned}\right\} \Rightarrow \frac{v_1}{R_1} + \frac{v_0}{R_2} = 0 \Rightarrow \quad v_0 = -\frac{R_2}{R_1} v_1$$

The inverting voltage follower

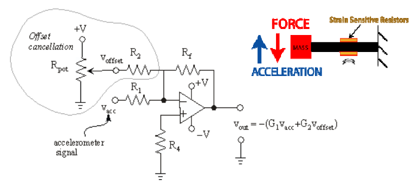
$$\textit{If}\ R_1 = R_2 \quad \Rightarrow \quad A = -1 \quad v_0 = -v_1$$

The summing amplifier

It's a logical extension of the inverting amplifier circuit , with two or more inputs.



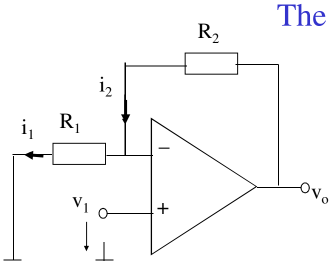
$$v_0 = \sum_{i=1}^{n}\left(-\frac{R}{R_i}v_i\right)$$



Application: adjusting d.c. offset in a *piezoresistive accelerometer* signal
https://www.youtube.com/watch?v=ykBn4IxStrU

Piezoresistive strain gauges - **semiconductor material** -changes in resistance when the material stretched or compressed. They have a much higher gauge factor than bonded foil strain gauges.

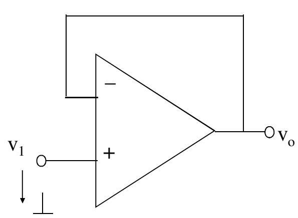
The noninverting amplifier



$$\left.\begin{aligned} & i_1 = i_2 \\ & i_1 = \frac{v_1 - 0}{R_1} = \frac{v_1}{R_1} \\ & i_2 = \frac{v_0 - v^-}{R_2} = \frac{v_0 - v_1}{R_2} \end{aligned}\right\} \Rightarrow \frac{v_1}{R_1} = \frac{v_0 - v_1}{R_2} \Rightarrow$$

$$v_0 = (1 + \frac{R_2}{R_1})v_1$$

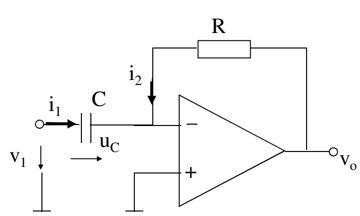
The follower



$$v_0 = v_1$$
$$A = 1$$

•This configuration is very important when the input signal needs **to be isolated** from the output.
•It has a very low output impedance that is very useful in some **impedance-matching applications**.

Differentiator circuit



$$i_1 + i_2 = 0$$

$$i_1 = C\frac{dv_1}{dt}; \quad i_2 = \frac{v_0}{R}$$

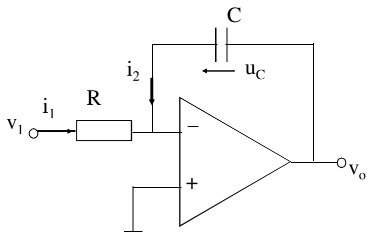
$$C\frac{dv_1}{dt} + \frac{v_0}{R} = 0$$

$$v_0 = -RC\frac{dv_1}{dt}$$

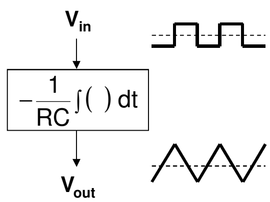
Applications include the rate-of-change indicators for process instrumentation.

- monitoring (or controlling) the rate of temperature change in a furnace, where too high or too low of a temperature rise rate could be detrimental. V_{out} could be used to drive a comparator, which would signal an alarm or activate a control if the rate of change exceeded a preset level.

The integrator

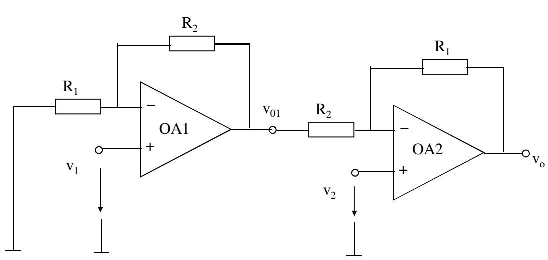


$$\left.\begin{aligned} & i_1 + i_2 = 0 \\ & i_1 = \frac{v_1 - 0}{R} = \frac{v_1}{R} \\ & i_2 = \frac{dq}{dt} = \frac{d(Cu_C)}{dt} = C\frac{du_C}{dt} \\ & u_C = v_0 - 0 = v_0 \Rightarrow \\ & i_2 = C\frac{dv_0}{dt} \\ & \frac{v_1}{R} + C\frac{dv_0}{dt} = 0 \end{aligned}\right\} \Rightarrow \boxed{v_0 = -\frac{1}{RC}\int v_1 dt}$$



Application: totalizer in the industrial instrumentation trade
-to integrate a signal representing water flow, producing a signal representing total quantity of water that has passed by the flowmeter.

Difference amplifier



$$v_{01} = (1 + \frac{R_2}{R_1})v_1$$

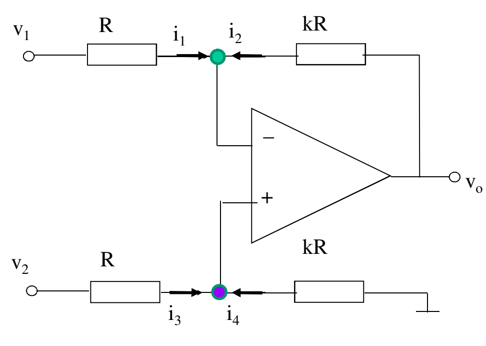
$$v'_0 = -\frac{R_1}{R_2}v_{01} = -\frac{R_1}{R_2}(1 + \frac{R_2}{R_1})v_1 = -(1 + \frac{R_1}{R_2})v_1$$

$$v''_0 = (1 + \frac{R_1}{R_2})v_2 \xrightarrow{\text{Using the overlapping principle}} \boxed{v_0 = v'_0 + v''_0 = (1 + \frac{R_1}{R_2})(v_2 - v_1)}$$

Instrumentation amplifiers

- The **instrumentation amplifier** amplifiers the difference between two input signals (-) and (+). It has the next essential characteristics:
  - High input impedance
  - Low output impedance
  - Low offset
  - High linearity
  - Stable gain
  - ability to reject common-mode inputs (CMRR)
- **Instrumentation amplifier**→interface sensors into the electronics package →noises, ground-voltages differences=common-mode voltages.
- **Instrumentation amplifier** → **VERY HIGH CMRR**

ONE-op-amp Instrumentation Amplifier



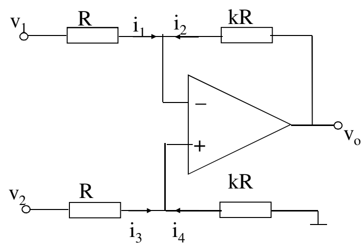
$$\begin{cases} \dfrac{v_1 - v^-}{R} + \dfrac{v_0 - v^-}{kR} = 0\,/(-1) \\ \dfrac{v_2 - v^+}{R} + \dfrac{0 - v^+}{kR} = 0 \end{cases}$$

$$\frac{v_2 - v_1 + v^- - v^+}{R} + \frac{v^- - v^+ - v_0}{kR} = 0$$

$$\begin{cases} i_1 + i_2 = 0 \\ i_3 + i_4 = 0 \end{cases}$$

$$v^+ = v^-$$

$$k(v_2 - v_1) - v_0 = 0 \Rightarrow$$
$$v_0 = k(v_2 - v_1) \quad \Rightarrow \quad A = k$$



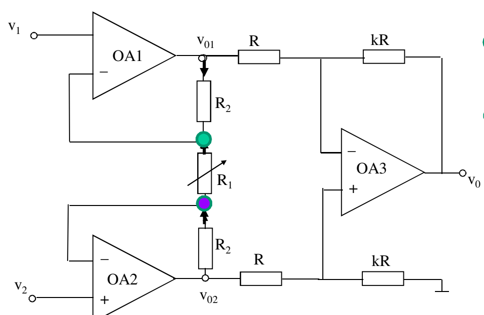
When external feedback resistors are used with OA →resistor-mismatch errors →low CMRR

Solution: one-op-amp instrumentation amplifier realized in **integrated** technology (IC).

It can be demonstrated that:

$$CMRR_{IA} = CMRR_{OA}$$

THREE-op-amp Instrumentation Amplifier



$$\frac{v_{01}-v_1}{R_2}+\frac{v_2-v_1}{R_1}=0/(-1)$$

$$\frac{v_{02}-v_2}{R_2}-\frac{v_2-v_1}{R_1}=0$$

$$\frac{v_{02}-v_{01}}{R_2}+\frac{v_1-v_2}{R_2}+2\frac{v_1-v_2}{R_1}=0$$

$$\frac{v_{02}-v_{01}}{R_2}=(\frac{1}{R_2}+\frac{2}{R_1})(v_2-v_1) \Rightarrow$$

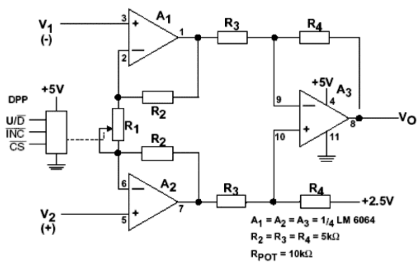
$$v_0=k(v_{02}-v_{01}) \Rightarrow \frac{v_0}{kR_2}=(\frac{1}{R_2}+\frac{2}{R_1})(v_2-v_1)$$

$$v_0=k(1+2\frac{R_2}{R_1})(v_2-v_1)$$

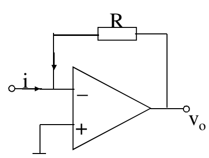
$$CMRR_{AI}=(1+2\frac{R_2}{R_1})CMRR_{AO3}$$

https://www.youtube.com/watch?v=c2rW4EPuXyw Bionic eye video

In multiplexed systems →Programmable gain IA →R_1 is a digitally programmed potentiometer

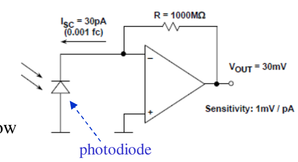


CURRENT measurement (relative to ground)
CURRENT TO VOLTAGE CONVERTOR

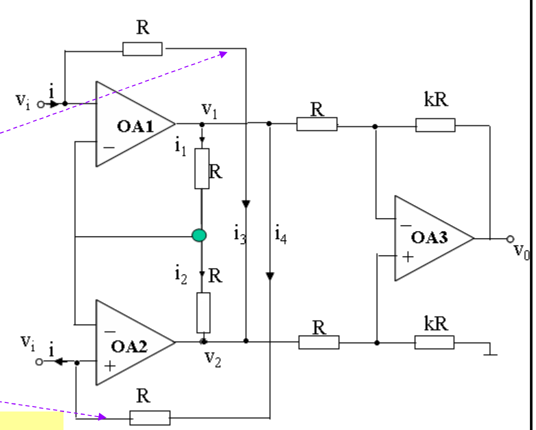


$$i + \frac{v_0 - 0}{R} = 0 \qquad v_0 = -Ri$$

This is a very useful device when sensing with very low impedance sensors (thermocouple or photodiode)



CURRENT measurement (floating)
CURRENT TO VOLTAGE CONVERTOR



$$i_1 = i_2$$

$$v^+ = v^- = v_i$$

$$i_3 = i = \frac{v_i - v_2}{R} \Rightarrow v_i - v_2 = iR \ (1)$$

$$i_4 = i = \frac{v_1 - v_i}{R} \Rightarrow v_1 - v_i = iR \ (2)$$

$$(1)+(2):$$

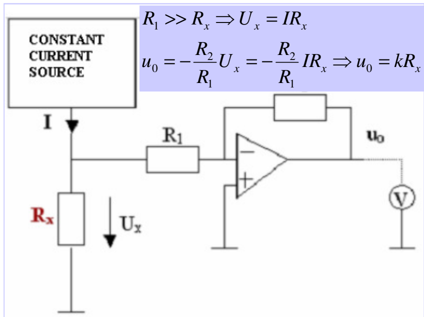
$$v_i - v_2 + v_1 - v_i = 2Ri \Rightarrow v_2 - v_1 = -2Ri$$

$$v_0 = k(v_2 - v_1) = -2kRi$$

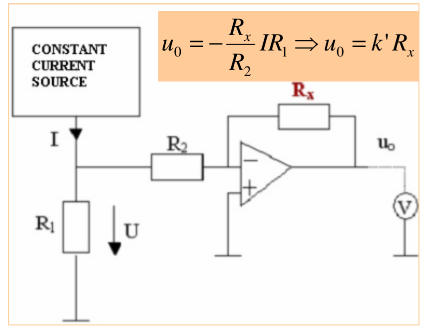
Resistance to voltage converter

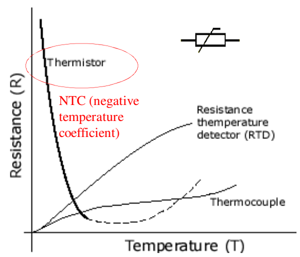
$R_1 >> R_x \Rightarrow U_x = IR_x$

$u_0 = -\frac{R_2}{R_1}U_x = -\frac{R_2}{R_1}IR_x \Rightarrow u_0 = kR_x$

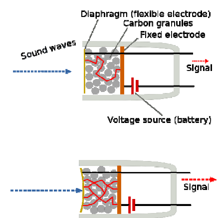


$u_0 = -\frac{R_x}{R_2}IR_1 \Rightarrow u_0 = k'R_x$

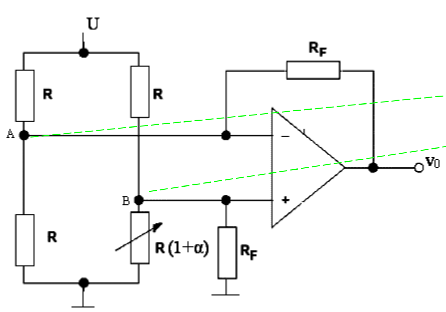




Example of sensors associated with resistance to voltage converters:
-**thermistors** which change resistance as a function of the temperature
-**carbon microphones** which alter their resistance in response to the changing in acoustical pressure



Single op-amp **bridge amplifier** for single-element varying bridge



R+dR=R(1+dR/R)=R(1+α)

$$v_A = \frac{U}{2}; \quad v_B = \frac{1+\alpha}{2+\alpha}U$$

$$(+) \quad \frac{v_B - U}{R} + \frac{v_B - 0}{R(1+\alpha)} + \frac{v_B - 0}{R_F} = 0$$

$$(-) \quad \frac{v_A - U}{R} + \frac{v_A - 0}{R} + \frac{v_A - v_0}{R_F} = 0$$

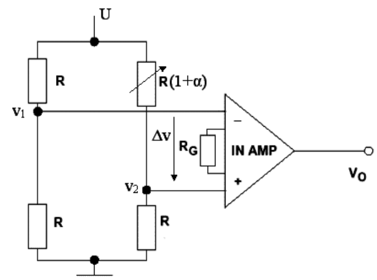
It results: $$v_0 = \frac{U}{2}\frac{R_F}{R(1+\frac{R}{2R_F})}\frac{\alpha}{1+\alpha}$$

-poor gain accuracy

-low CMRR

-The output is nonlinear

Instrumentation amplifier for single-element varying bridge



$$v_0 = A\Delta v$$

$$\Delta v = v_1 - v_2 = \frac{U}{2} - \frac{U}{\alpha+2}$$

$$v_0 = A \cdot U \frac{\alpha}{4(1+\frac{\alpha}{2})} \approx AU\frac{\alpha}{4} \quad \alpha << 1$$

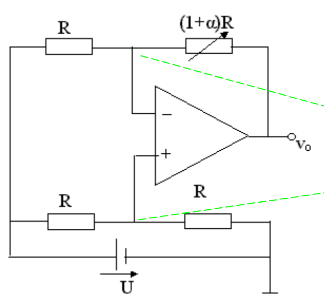
Linear response

-Better gain accuracy (by adjusting R_G)

-high CMRR (due to AI)

-The output is nonlinear (can be corrected by a software procedure)

Active bridge- linear bridge- hardware procedure



$$v^+ = \frac{U}{2} = v^-$$

$$\left.\begin{array}{l} \dfrac{U-v^-}{R} + \dfrac{v_0 - v^-}{R(1+\alpha)} = 0 \\ \dfrac{U-v^+}{R} + \dfrac{0-v^+}{R} = 0 / \cdot (-1) \\ \hline \dfrac{\cancel{v^+} - \cancel{v^-}}{R} + \dfrac{v_0 - v^-}{R(1+\alpha)} + \dfrac{v^+}{R} = 0 \end{array}\right\} \Rightarrow \quad v_0 = -\alpha\frac{U}{2}$$

-The response is linear for every value of α

-Because the output voltage is a small one, this will be amplified with a second amplifier circuit

Power amplifiers

$$P_o = P_i A_p \quad [\mathrm{W}]$$

output input · power gain

Linear DC Motors, Voice Coil Motors (VCM) or Voice Coil Actuators (VCA) consist of two separate parts: the magnetic housing and the coil. A current carrying conductor placed in a magnetic field will have a force applied upon it.
https://www.youtube.com/watch?v=PT42TQ9_LEw

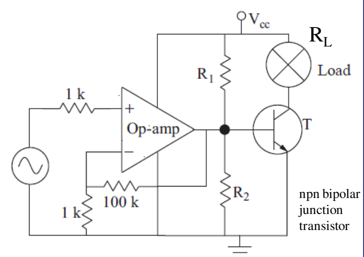
They are used in driving actuators:

- audio amplifiers: used to ***drive speakers*** and ***voice coil actuators***
- amplifiers for ***solenoid actuators*** and ***motors***.

Power amplifiers: ***linear amplifiers & pulse modulated amplifiers***

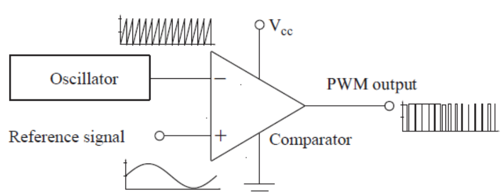
Class A power amplifier-LINEAR

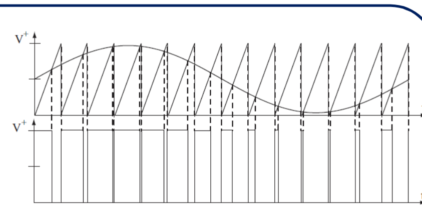
- The amplifier is set for a gain of 101 (noninverting amplifier).
- The output drives the transistor, whose output will swing, at most between 0 and Vcc, and supplies a current that is V_{cc}/R_L,
- The transistor may be viewed as a current amplifier since its collector current is the base current multiplied by the amplification of the transistor



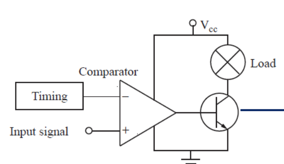
Pulse Width Modulated (PWM) Amplifiers

- **Control the power** supplied to a load by controlling how long the load is connected to the power (pulse width) rather than by controlling the amplitude.
- **Triangular wave frequency** must be much higher than the signal being represented.
  - Example: if this is used to dim a lightbulb using a 60Hz source, the PWM must be on the order of 10–20 times that (i.e., 600–1200 Hz) to properly represent the signal





The sinusoidal signal's amplitude is represented as pulse widths.



A load driven by a PWM circuit.

The transistor serves as a switch
The power is controlled by the average of the PWM signal.

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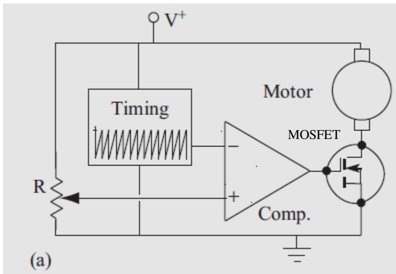
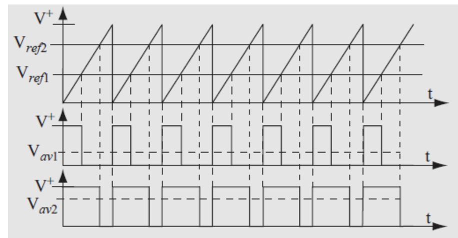
Speed control of a DC motor

The speed is proportional to the average voltage across the motor





- The speed control potentiometer
- The PWM generator

The generation of PWM signals for two positions of the potentiometer.

https://www.youtube.com/watch?v=K-TaJooK6sM

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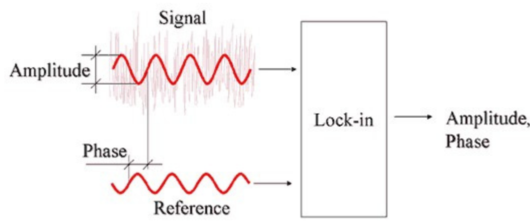
- Consider a case in which you need to extract a 5 mV sine wave from a white noise signal with 5 V amplitude. Are those measurements even possible?

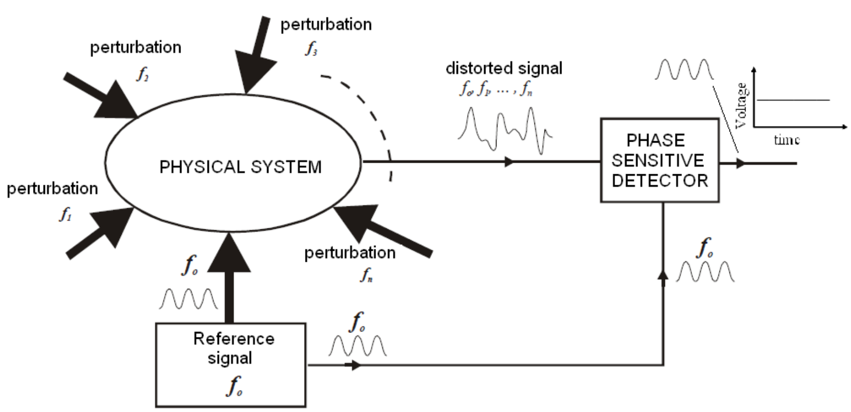
- The answer is **YES**!

Lock-in amplifiers
The phase-sensitive detectors

- Lock-in amplifiers are used to detect and measure very small AC signals (few nV).
- Accurate measurements may be made even when the small signal is obscured by noise sources many thousands of times larger.
- Lock-in amplifiers use a technique known as phase-sensitive detection: the useful signal depends on the phase difference between it and a reference signal ***with the same frequency*** or a frequency very close to that of useful signal.
- Noise signals, at frequencies other than the reference frequency, are rejected and do not affect the measurement.
- Measured signal is greater as the phase difference between the two signals is less, becoming maximum when the signals are in phase.



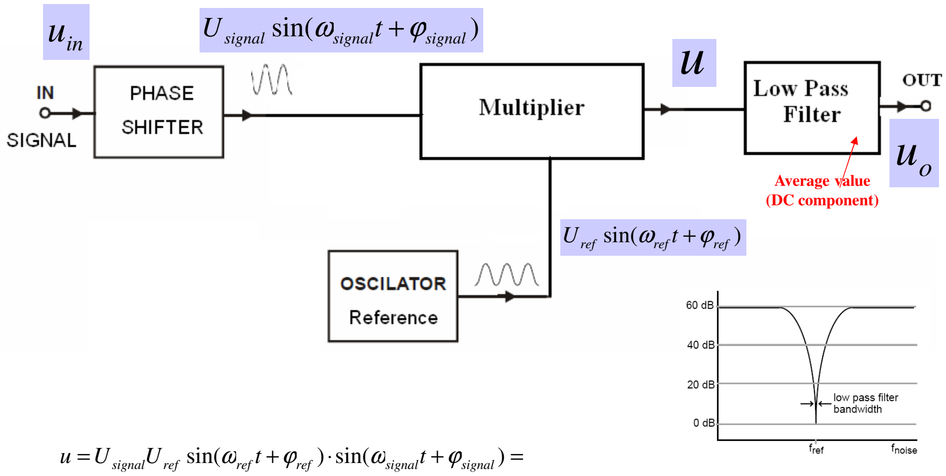
The principle of phase-sensitive detectors



•The output signal is **maximum** when the detector input signals are synchronized → synchronous detection.

• It acts like a filter-The centre frequency of the filter is locked (hence lock-in)

The principle of phase-sensitive detectors

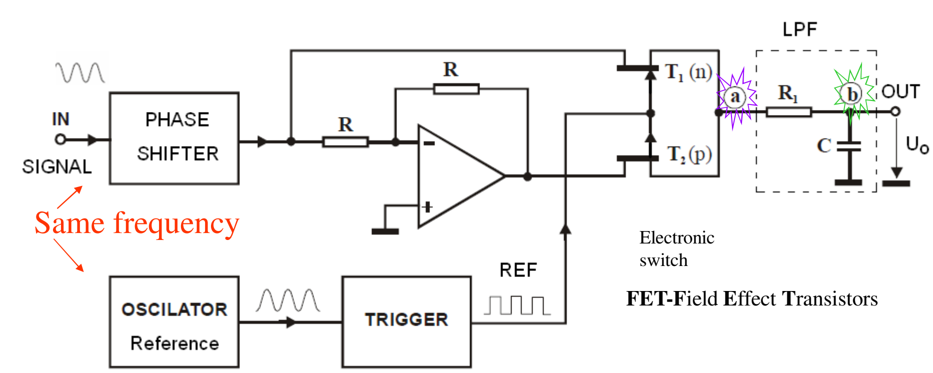


$$u = U_{signal}U_{ref}\sin(\omega_{ref}t+\varphi_{ref})\cdot\sin(\omega_{signal}t+\varphi_{signal}) =$$

$$=\frac{1}{2}U_{signal}U_{ref}\cos[(\omega_{ref}-\omega_{signal})t+\varphi_{ref}-\varphi_{signal}]-\frac{1}{2}U_{signal}U_{ref}\cos[(\omega_{ref}+\omega_{signal})t+\varphi_{signal}+\varphi_{ref}]$$

When $\omega_{ref} \neq \omega_{signal} \rightarrow u_0=0$ (LPF-average value) and when $\omega_{ref}=\omega_{signal} \rightarrow u_0 \neq 0$

The principle of phase-sensitive detectors



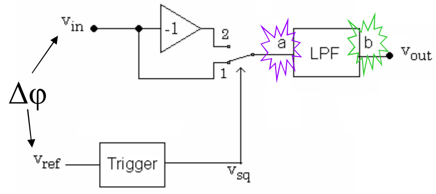
•The two FETs (T_1 AND T_2) play the role of electronic switches controlled by alternating rectangular signal (from triggered reference signal)

•When REF>0 →T1 drives →SIGNAL at (a)

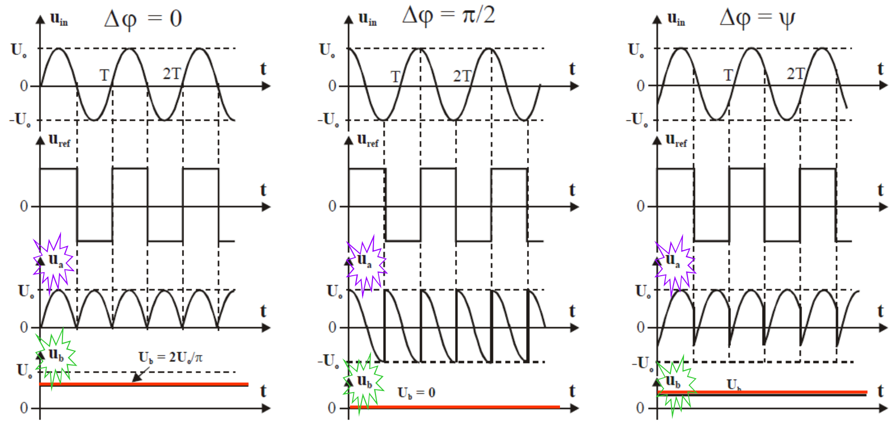
•When REF<0 →T2 drives → signal + inverting follower→ inverting SIGNAL at (a)

•LPF(Low Pass Filter)-Detects the DC component

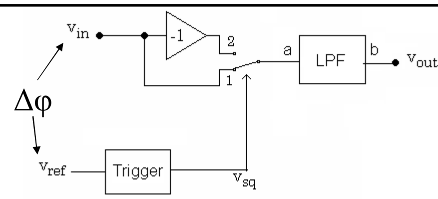
Phase-sensitive detector



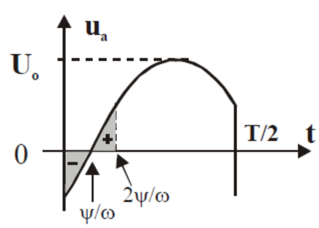
$$u_{in} = U_o \sin(\omega t - \psi) = U_o \sin\left[\omega\left(t - \frac{\psi}{\omega}\right)\right]$$



Phase-sensitive detector



$$u_{in} = U_o \sin(\omega t - \psi) = U_o \sin\left[\omega\left(t - \frac{\psi}{\omega}\right)\right]$$



After tle LPF:

$$U_b = \frac{1}{\frac{T}{2}} \int_0^{\frac{T}{2}} U_o \sin\left[\omega\left(t - \frac{\psi}{\omega}\right)\right] dt = \frac{2}{T} \int_{2\frac{\psi}{\omega}}^{\frac{T}{2}} U_o \sin\left[\omega\left(t - \frac{\psi}{\omega}\right)\right] dt \xrightarrow[\text{Change the variable}]{\boxed{\tau = t - \frac{\psi}{\omega}}}$$

$$\longrightarrow U_b = \frac{2}{T} \int_{\frac{\psi}{\omega}}^{\frac{T}{2} - \frac{\psi}{\omega}} U_o \sin \omega\tau \cdot d\tau \Rightarrow \boxed{U_b = \frac{2U_o}{\pi} \cos\psi}$$

Phase-sensitive detector
CONCLUSIONS

$$\boxed{U_b = \frac{2U_o}{\pi}\cos\psi}$$

When $\Delta\varphi = \Psi = 0$ (synchronous detection)

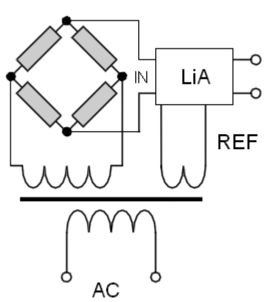
$$U_b = \frac{2U_0}{\pi}$$

When $\Psi = 90°$ $\quad U_b = 0$

•In the lock-in amplifiers a phase sensitive detector is used as the *selective element*.
•This detector *selects* from the input signal only:
  •these components that have the same frequency as the reference voltage.
  •these signals that are in phase with the reference signal.
• Noise having a random frequency will be strongly attenuated.

•The phase problems (they appear due to the physical problems, connections, etc) are resolved by the phase shifter.

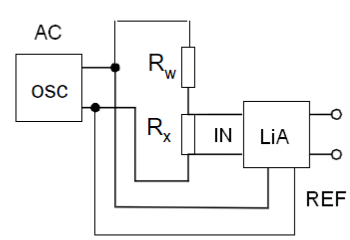
Lock-in Amplifier (LiA)- applications



The measurement of **small variations of the resistance** – strain-gauge bridge

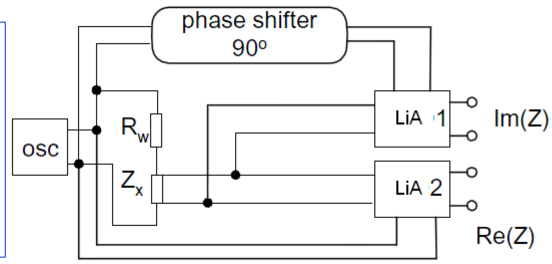
From the signal (μV) with noises we can separate only the signal of the frequency the same as supply voltage
(bridge= modulator device)

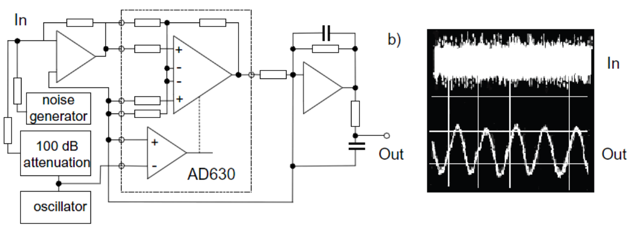
The measurement of **small resistances** (micro-ohm-meter) = the measurement of very small voltage drop across the unknown resistance



Lock-in Amplifier (LiA)- applications

- We can separate both components of the vector signal – in phase and shifted by 90°.
- We can analyze the **impedance components *Re(Z)* and *Im(Z)*,**
- We can determine the phase shift
- We can perform spectral analysis





Lock-in amplifier based on the AD630 device of Analog Devices