Module 5

SIGNAL CONDITIONING

AMPLIFICATION, FILTERING, MULTIPLEXING, CONVERSION TECHNIQUES, SENSOR INTERFACE DESIGN: WHEATSTONE BRIDGE AND OPERATIONAL AMPLIFIER CIRCUITS FOR VARIOUS APPLICATIONS

Signal Conditioning

Signal conditioning is the operation performed on the signal to convert it to a form suitable for interfacing with other elements in the system.

Example of signal conditioning:

- **Signal-range and offset changes**

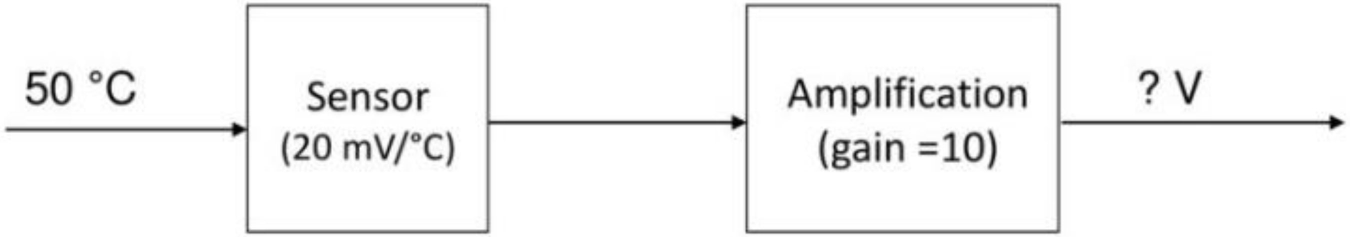
  i.e. amplification and zero adjustment
- **Conversions**

  e.g. current to voltage and voltage to current
- **Filtering**

  removing unwanted frequencies

Example 1

An amplifier outputs a voltage that is 10 times the voltage on its input terminals. It has an input resistance of 10 kΩ. A sensor outputs a voltage proportional to temperature with a transfer function of 20 mV/°C. The sensor has an output resistance of 5.0 kΩ. If the temperate is 50 °C, find the amplifier output.

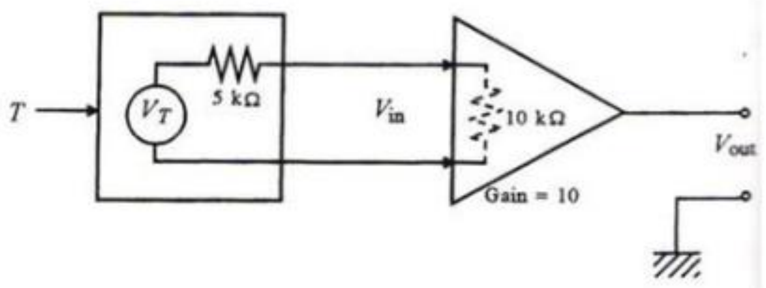


Answer

- The sensor output V_T = (50°C)*(20 mV/°C) = 1V.
- Due to non-zero sensor output resistance (5kΩ) and finite amplifier input resistance (10kΩ), the sensor delivers only

$$V_{in} = \frac{10}{5+10} \times V_T = \frac{10}{5+10} \times 1 = 0.667$$

- This is amplified 10 times to give V_{out} = **6.67V**.
- **Note:** if the sensor o/p impedance is zero or the amplifier i/p impedance is infinite, V_{out} = **10V**.



Loading Effect

When an instrument of lower sensitivity is used with a heavier load, the measurement it makes is incorrect, this effect is called the loading effect

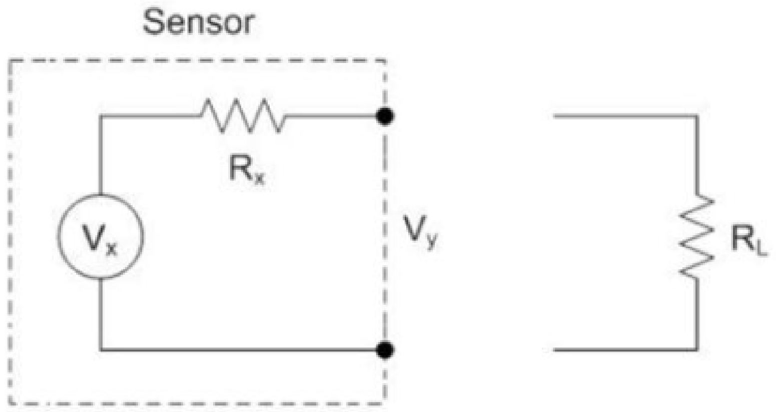
Example :

Loading effect in a Voltmeter:

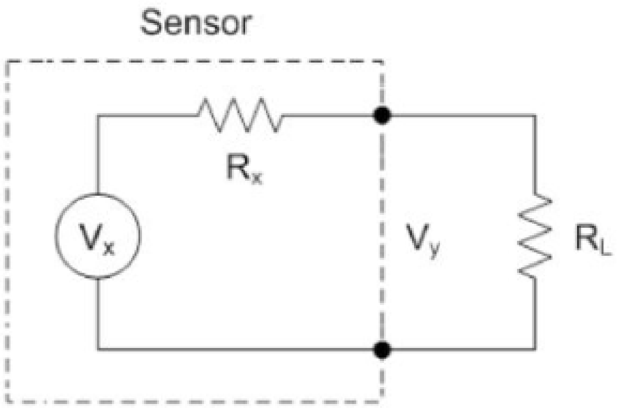
- When a Voltmeter is connected across a resistor to measure voltage, the Voltmeter draws current for its working
- As the Voltmeter's resistance is parallel with the resistance of the load to be measured, the resultant resistance decreases
- Thus, the Voltmeter reads less value than the actual value. This is due to loading effect
- To reduce loading effect in Voltmeters, high sensitivity Voltmeters are used

Effect of Loading

Connecting a sensor or circuit to a load introduces uncertainty in the measurement (i.e. in the amplitude of the output voltage) as shown below.



without load: $V_y = V_x$



With load: $V_y < V_x$

- The output voltage is calculated using voltage division as

$$V_y = \frac{R_L}{R_L + R_x} V_x$$

- The output voltage is reduced by the voltage drop over the internal resistance of the sensor R_X.

- To reduce the uncertainty (i.e. to keep $\boldsymbol{V_y \approx V_x}$), the internal resistance (the sensor output resistance), R_x, should be much smaller than the load resistance

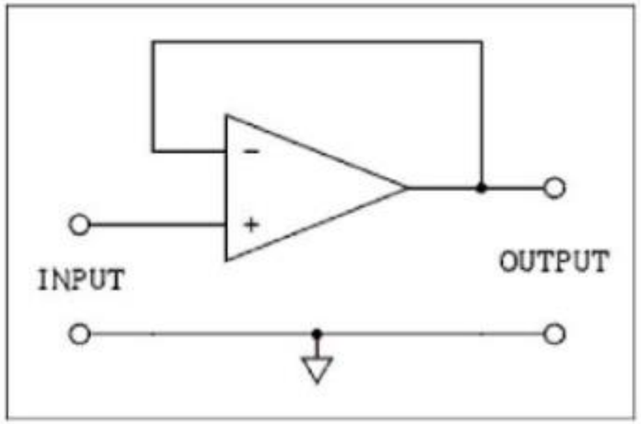
$$R_L >> R_x$$

The buffer circuit

- To minimize the loading effect, we must look for a circuit that has *very large input impedance* to obtain the whole sensor output voltage.

- Furthermore, as this circuit is probably going to drive other circuits, it should have *very small output impedance*.

- A device having these two properties is called a buffer. One example of buffer is the *voltage follower*:



$$V_{out} = V_{in}$$

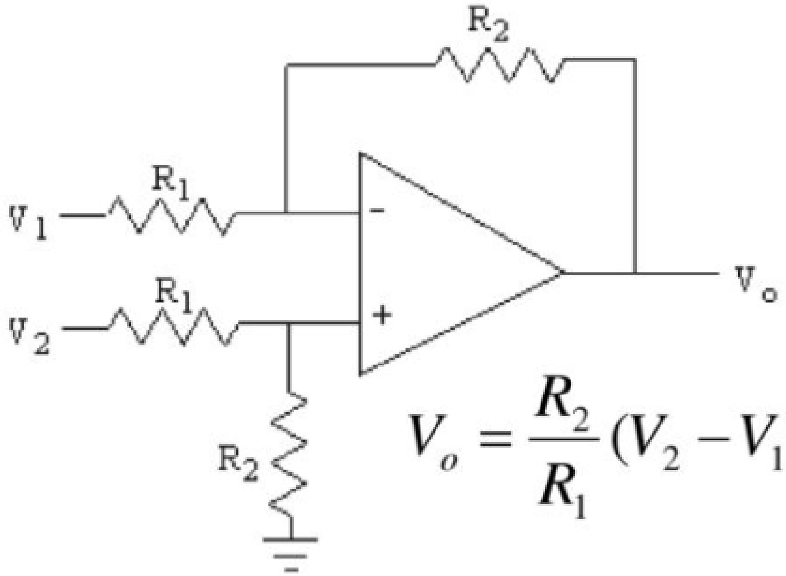
To avoid loading effect, it has been made a fundamental rule amongst engineers to *always* ensure that the *input resistance* of each network is as high as possible, so that when it comes in parallel with its previous part, it does not significantly change the overall resistance

This is what a *voltage buffer* would do: pick the voltage out of the sensor, with minimal loading.

The buffer, then is capable of driving a much *lower* output impedance, which results in much larger current capability

Difference Amplifier

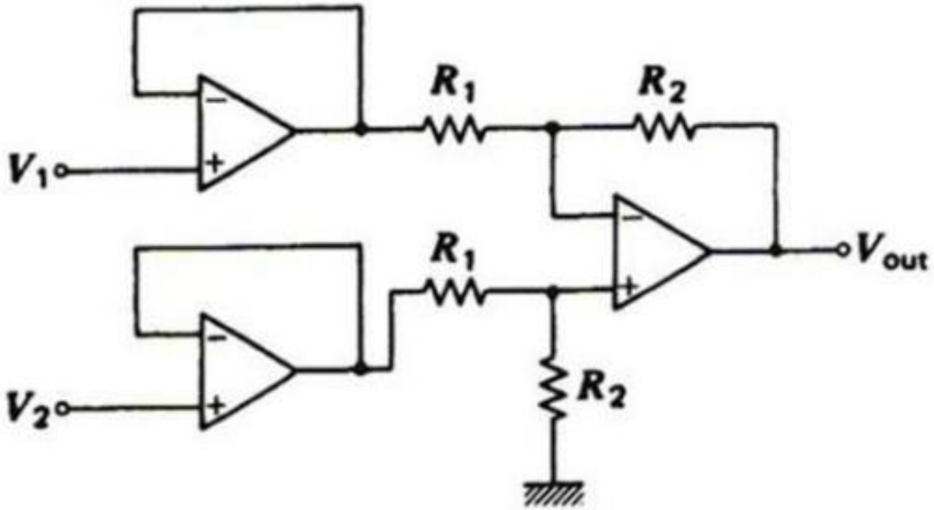
In signal conditioning, it is sometimes required to find the difference between two signals. This can be achieved using the following difference amplifier circuit.



$$V_o = \frac{R_2}{R_1}(V_2 - V_1)$$

The instrumentation amplifier

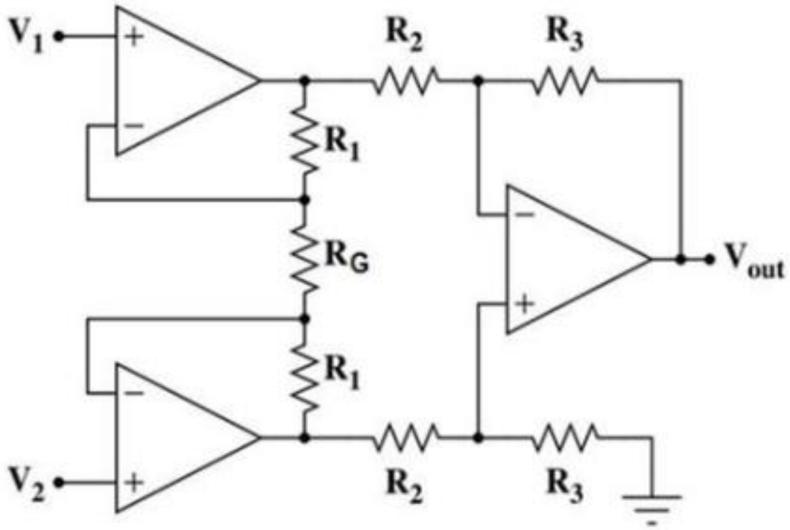
- The input impedances of the difference amplifier can be relatively low and, hence, tend to load the sensor output.
- To have high input impedance, the difference amplifier is preceded by two voltage follower circuits to form the so-called *instrumentation amplifier*.



$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$

The instrumentation amplifier

- One disadvantage of the previous differential circuit is that in order to change the gain, 2 pairs of resistors need to be changed.
- A more common differential amplifier in which the gain can be adjusted using one resistor (R_G) is shown below.



$$V_{out} = \left(1 + \frac{2R_1}{R_G}\right)\left(\frac{R_3}{R_2}\right)(V_2 - V_1)$$

INTRODUCTION

➢ *The term "**operational amplifier**" denotes a special type of amplifier that, by proper selection of its external components, could be configured for a variety of operations.*

HISTORY

➢ *First developed by **John R. Ragazzine** in **1947** with vacuum tube.*

➢*In 1960 at **FAIRCHILD SEMICONDUCTOR CORPORATION**, **Robert J. Widlar** fabricated op amp with the help of IC fabrication technology.*

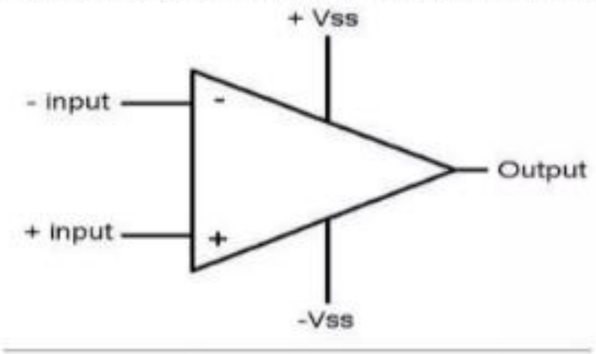
➢ *In 1968 FAIRCHILD introduces the **op-amp** that was to become the industry standard.*

WHAT IS OP-AMP?

✓*An operational amplifier (op-amp) is a DC-coupled high-gain electronic voltage amplifier*

✓ *Direct- coupled high gain amplifier usually consisting of one or more differential amplifiers*

✓*Output stage is generally a push-pull or push-pull complementary-symmetry pair.*



✓*Op amps are differential amplifiers, and their output voltage is proportional to the difference of the two input voltages. The op amp's schematic symbol is shown in the above figure*

✓*The two input terminals, called the inverting and non-inverting, are labeled with - and +,*
respectively.

CIRCUIT SYMBOL

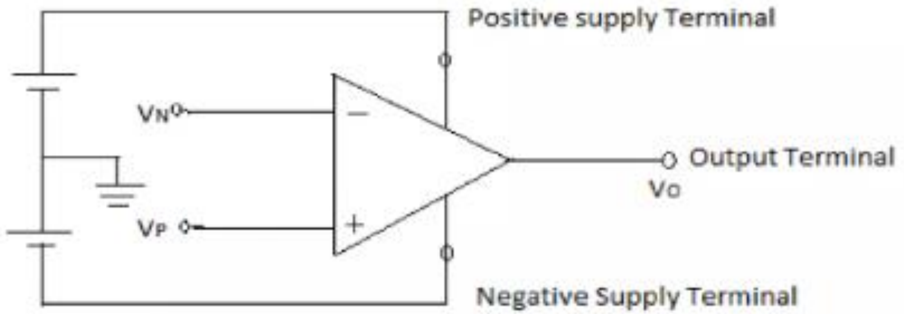


Fig.. Ckt symbol for general purpose op-amp

Figure shows the symbol of **op-amp** & the power supply connections to make it work. The input terminal identified by the '-' and "**+**" symbols are designated inverting & non-inverting. Their voltage w.r.t ground are denoted as $\mathbf{V_N}$ & $\mathbf{V_P}$ and output voltage as $\mathbf{V_O}$. Op-amp do not have a zero volt ground terminal Ground reference is established externally by the power supply common.

Operational Amplifiers picture

Figure: The Philbrick Operational Amplifier.

Figure : What an Op-Amp looks like in today's world

Op-amp pin diagram

There are 8 pins in a common Op-Amp, like the 741 which is used in many instructional courses.

Pin 1: Offset null

- Pin 2: Inverting input terminal
- Pin 3: Non-inverting input terminal

Pin 4: –VCC (negative voltage supply)

Pin 5: Offset null

- Pin 6: Output voltage

Pin 7: +VCC (positive voltage supply)

Pin 8: No Connection

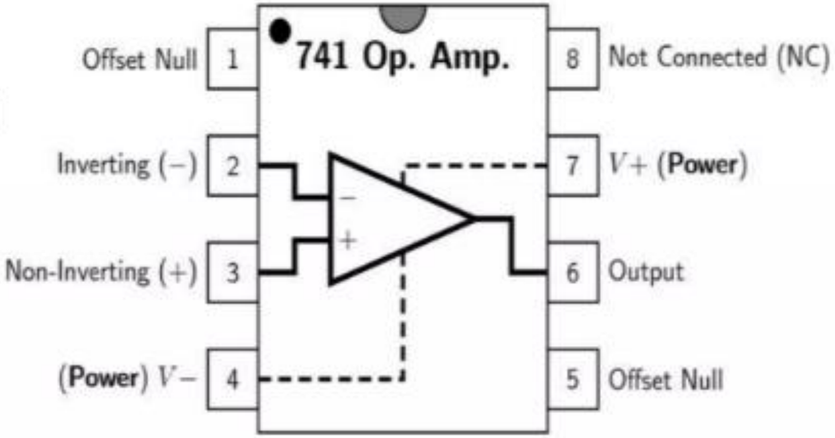
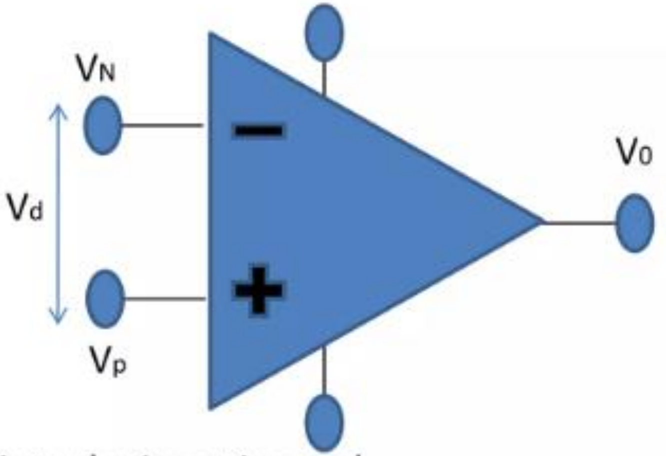


Figure : Pin connection, LM741.

Important terms and equation



a = gain of amplifiers.
V_d= difference between the voltage.
V_0= gain of voltage.
The equation :

$$V_0 = a\,(V_P - V_N)$$

Electrical parameter :

1.Input bias current(I_b): average of current that flows into the inverting and non-inverting input terminal of op-amp.

2. I/p and o/p impedance: It is the resistance offered by the inputs and the output terminals to varying voltages. The quantity is expressed in Ohms.

3. Open Loop Gain: It is the overall voltage gain or the amplification.

4. Input offset voltage : It is a voltage that must be applied between the two terminal of an op-amp to null the o/p.

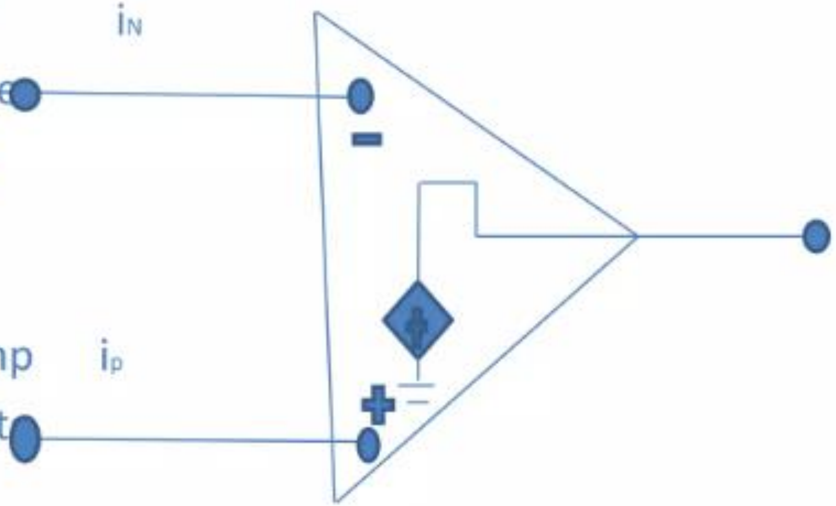
5. Input offset current (I_i): The algebraic different between the current in to the inverting and Non-inverting terminal.

IDEAL OP-AMP

We know to minimize loading , a well designed voltage amplifier must draw negligible current from the input source and must present negligible resistance To the output load . Op-amp are no

V_O

exception so we define the ideal op-amp as an ideal voltage amplifier with infinite open loop gain.



$a \longrightarrow$ infinity

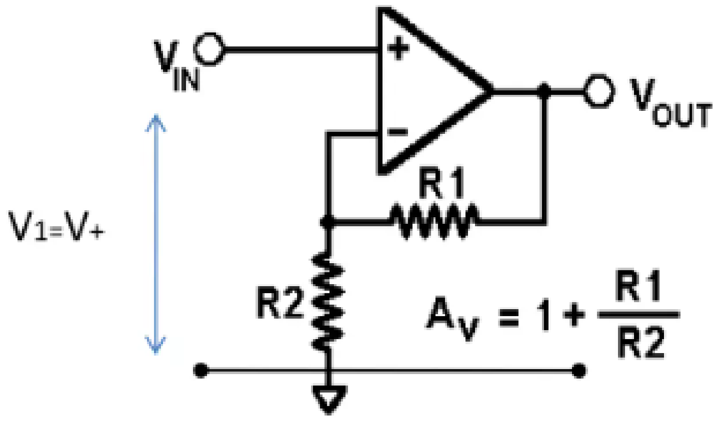
Its ideal terminal condition are

r_d =infinity , $r_o = 0$, $i_p = i_n = 0$

IDEAL OP-AMP FOLLOWS THE GIVEN PROPERTY

1. Infinite voltage gain a
2. Infinite input resistance r_d so that almost any signal source can drive it and there loading of the preceding stage.
3. Zero output resistance r_o so that the output can drive an infinite number of other device.
4. Zero output voltage when input is zero.
5. Infinite common mode rejection ratio so that the output common mode noise vo is zero.
6. Infinite slew rate so that output voltage changes occurs simultaneously with input voltage changes.

Non -ideal op-amp



1. This is opposite to the ideal op-amp only the positive and Negative terminal are change there position.

2. There is a single external input signal $V_1=V_+$ that is applied to the +Ve pin of op-amp.

3. A signal is also made to appear at the -Ve input terminal, But this is derived from resistors R_1 and R_2.

CHARACTERISTICS OF IDEAL OP-AMP

- Infinite input impedance(about 2Mohm)
- Low output impedance(about 200 ohm)
- Very large voltage gain at low frequency
- Thus,small changes in voltages can be amplified byusing an op-amp
- Infinte bandwidth(all frequencies are amplified by same factor

❑Infinite Common-mode rejection ratio

❑Infinite Power supply rejection ratio.

Applications of OPAMP

- Operational Amplifier (OPAMP) is a very high gain amplifier fabricated on Integrated Circuit (IC)
- Finds application in
  - Audio amplifier
  - Signal generator
  - Signal filters
  - Biomedical Instrumentation
    - And numerous other applications

Advantages of OPAMP

- Advantages of OPAMP over transistor amplifier
  - Less power consumption
  - Costs less
  - More compact
  - More reliable
  - Higher gain can be obtained
  - Easy design

Drawbacks of OPAMP

- Most OPAMPs are designed for low power operation. For high output, OPAM has to be specifically designed for that application
- Limited Common Mode Rejection Ratio
- Slew rate Limitation

FILTERS

- Filters are circuits that are capable of *passing signals within a band* of frequencies while *rejecting or blocking* signals of frequencies *outside this band*. This property of filters is also called “frequency selectivity”.
- Filter can be passive or active filter.

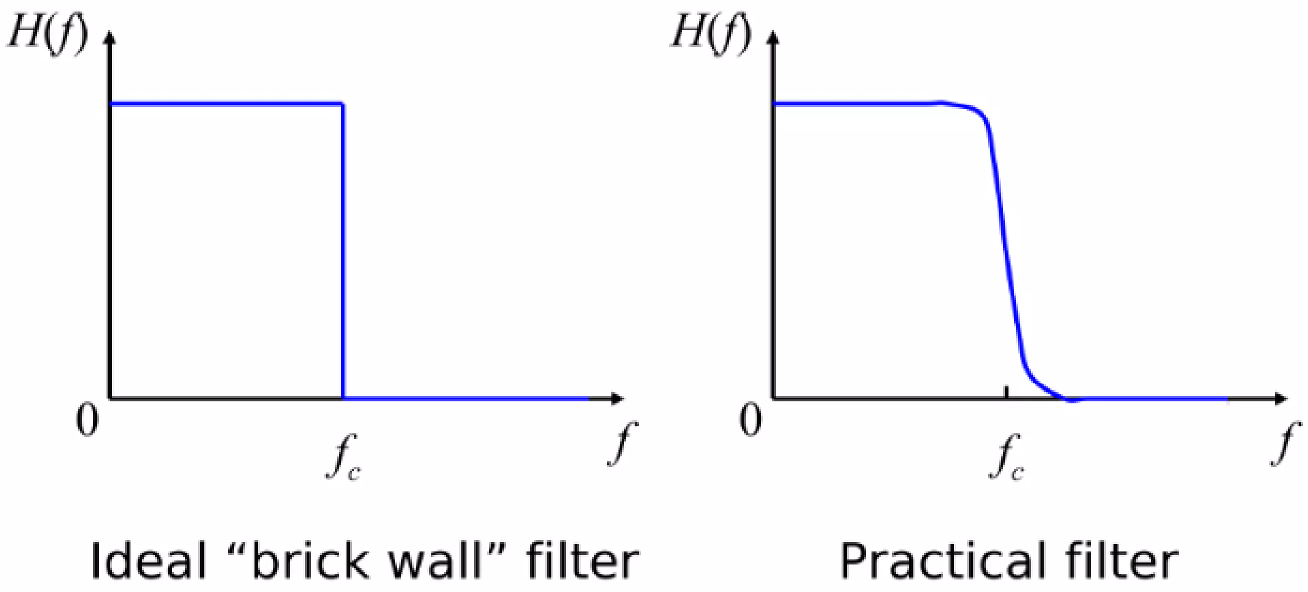
Passive filters: The circuits built using RC, RL, or RLC circuits.

Active filters : The circuits that employ one or more op-amps in the design an addition to resistors and capacitors

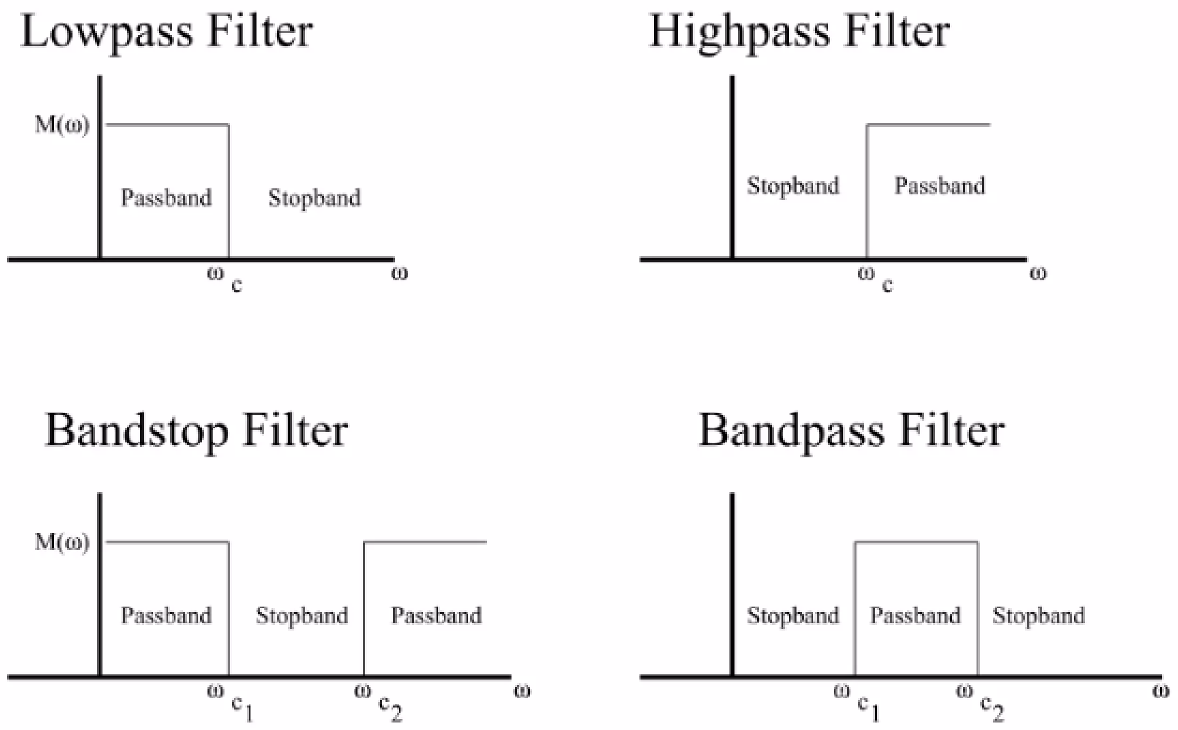
Types of Filters

- There are two broad categories of filters:
  - An *analog filter* processes continuous-time signals
  - A *digital filter* processes discrete-time signals.
- The analog or digital filters can be subdivided into four categories:
  - Low pass Filters
  - High pass Filters
  - Band stop Filters
  - Band pass Filters

Analog Filter Responses



Ideal Filters



Passive Filters

- Made up of passive components - resistors, capacitors and inductors
- No amplifying elements (transistors, op-amps, etc)
- No signal gain
- 1st order - design is simple (just use standard equations to find resonant frequency of the circuit)
- 2nd order - complex equations
- Require no power supplies
- Buffer amplifiers might be required
- Desirable to use inductors with high quality factors

Inductor – a Big Problem!

- Physical size, and large inductance values are required.
- Tuning inductors to the required values is time-consuming and expensive for larger quantities of filters.
- Often prohibitively expensive.
- Difficult to implement at frequencies below 1 kHz.
- Lossy

Active Filters

- No inductors
- Made up of op-amps, resistors and capacitors
- Provides arbitrary gain
- Generally easier to design
- High input impedance prevents excessive loading of the driving source
- Low output impedance prevents the filter from being affected by the load
- Easy to adjust over a wide frequency range without altering the desired response

Applications of Active Filter

- Active filters are mainly used in communication and signal processing circuits.
- They are also employed in a wide range of applications such as entertainment, medical electronics, etc.

Advantages of Active Filters

- Advantages of active RC filters include:
  - Reduced size and weight
  - Increased reliability and improved performance
  - Simpler design than for passive filters and can realize a wider range of functions as well as providing voltage gain
  - In large quantities, the cost of an IC is less than its passive counterpart

Drawbacks of Active Filters

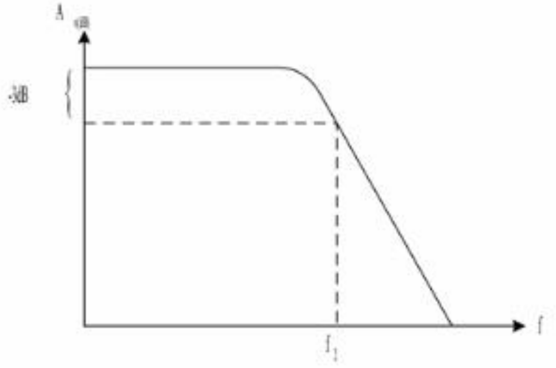
- Active RC filters also have some disadvantages:
  - limited bandwidth of active devices limits the highest attainable pole frequency and therefore applications nearby 100 kHz (passive RLC filters can be used up to 500 MHz)
  - require power supplies (unlike passive filters)
  - increased sensitivity to variations in circuit parameters caused by environmental changes compared to passive filters.

- For many applications, particularly in voice and data communications, the economic and performance advantages of active RC filters far outweigh their disadvantages.

Categories of Filters

Low Pass Filters:

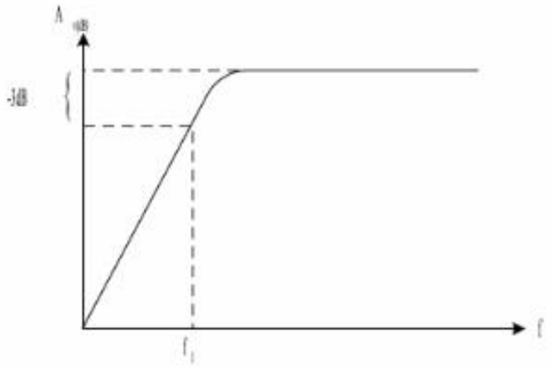
Pass all frequencies from dc up to the upper cutoff frequency.



Low-pass response

High Pass Filters:

Pass all frequencies that are above its lower cutoff frequency

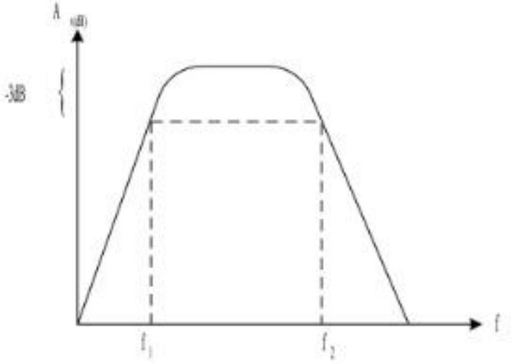


High-pass response

Categories of Filters

Band Pass Filters:

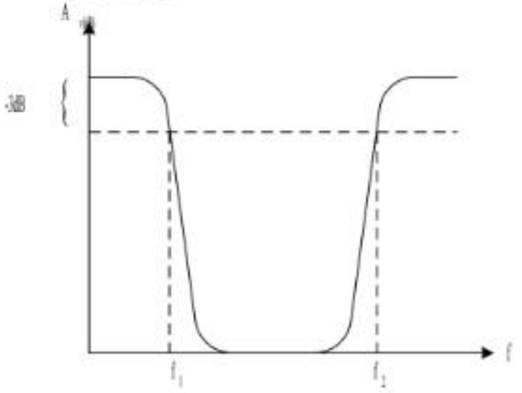
Pass only the frequencies that fall between its values of the lower and upper cutoff frequencies.



Band Pass Response

Band Stop (Notch) Filters:

Eliminate all signals within the stop band while passing all frequencies outside this band.

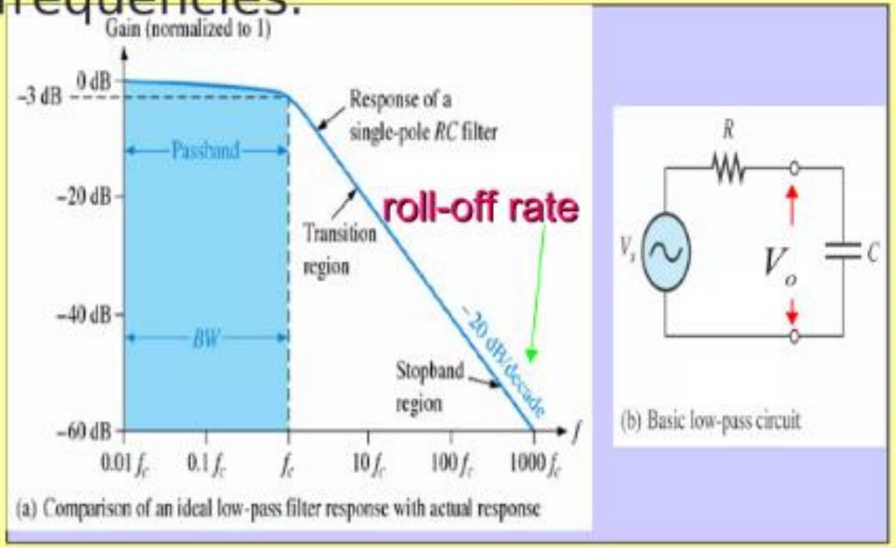


Band Stop Response

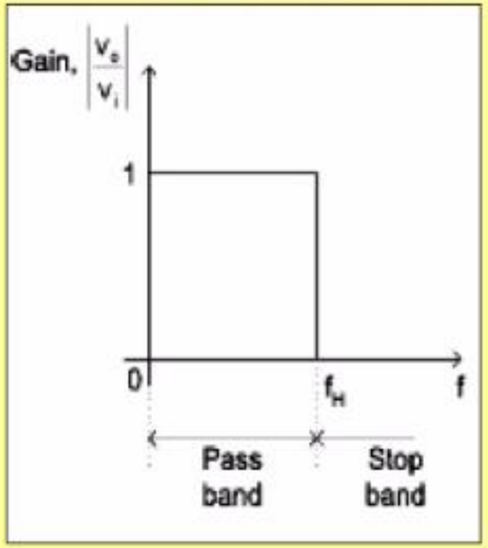
Basic Filter Response

Low-Pass Filter Response

➢ A **low-pass filter** is a filter that passes frequencies from 0Hz to critical frequency, f_c and significantly attenuates all other frequencies.



Actual response

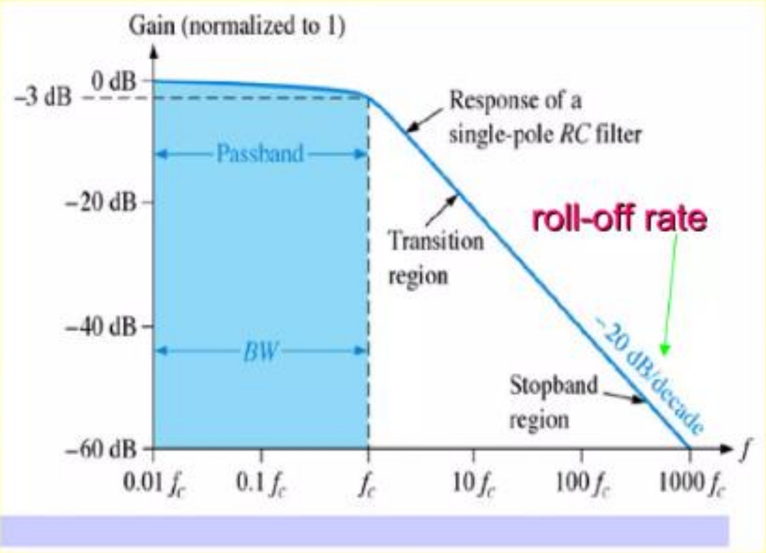


Ideal response

Ideally, the response drops abruptly at the critical frequency

Passband of a filter is the range of frequencies that are allowed to pass through the filter with minimum attenuation (usually defined as less than -3 dB of attenuation).

Transition region shows the area where the fall-off occurs.



Stopband is the range of frequencies that have the most attenuation.

Critical Frequency (also called cut-off frequency):

It is defined as the end of the passband and normally specified at the point where the response drops -3dB (70.7%) from the passband response.

- The **bandwidth** of an **ideal** low-pass filter is equal to f_c:

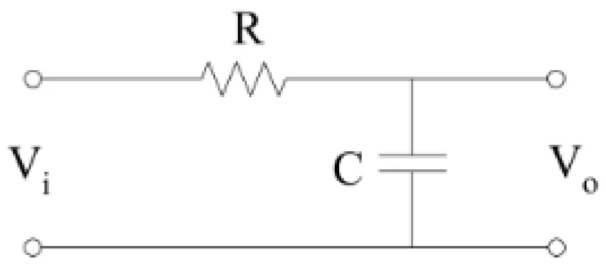
$$BW = f_c$$

- The critical frequency of a low-pass RC filter occurs when

  $X_c = R$ and can be calculated using the formula below:

$$f_c = \frac{1}{2\pi RC}$$

Passive single pole low pass filter



$$V_o = \frac{X_C}{X_C + R} V_i$$

$$V_o = \frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C} + R} V_i = \frac{1}{1 + j\omega CR} V_i$$

$$H(j\omega) = \frac{1}{1 + j\frac{\omega}{\omega_0}} \quad \text{where} \quad \omega_o = \frac{1}{RC}$$

or

$$H(s) = \frac{\omega_0}{s + \omega_0}$$

where

$$s = j\omega$$

$$\varphi(\omega) = -\tan^{-1}\left(\frac{\omega}{\omega_0}\right)$$

$$H(j\omega)=\frac{1}{1+j\omega CR}$$

$$V_o=\frac{1}{1+j\omega CR}V_i$$

$$\omega=\frac{1}{RC} \qquad \Rightarrow |V_o| = ??$$

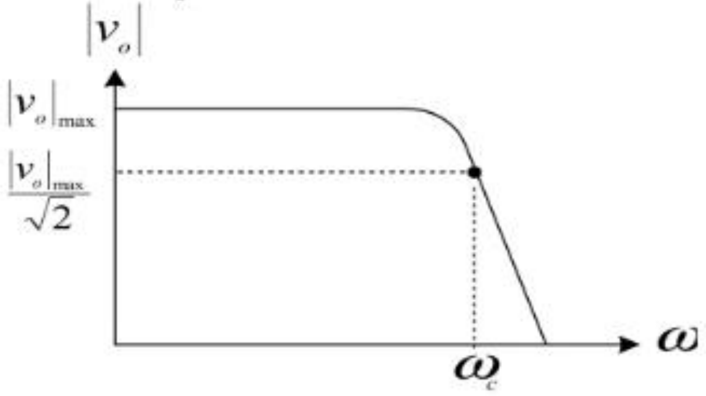
$$V_o=\frac{1}{1+j}V_i$$

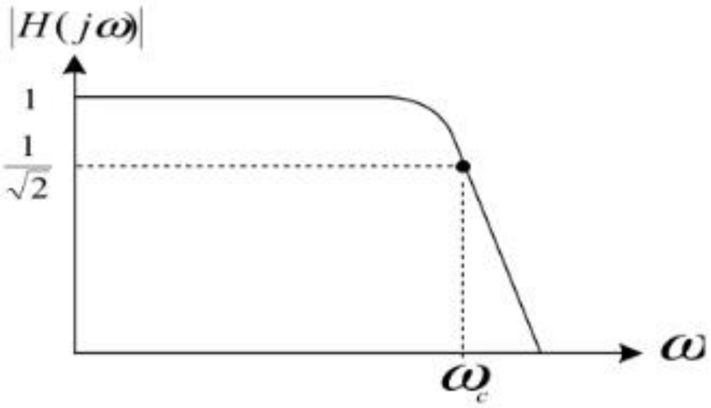
$$|V_o|=\frac{1}{\sqrt{1^2+1^2}}|V_i|=\frac{1}{\sqrt{2}}|V_i|$$

$$\omega_c=\omega_o=\frac{1}{RC} \quad \text{(cut-off frequency)}$$

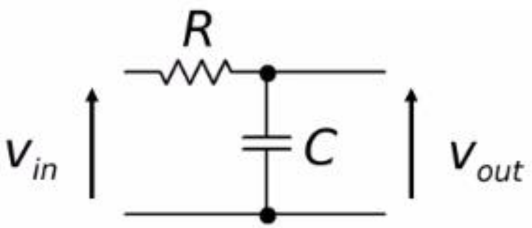
$\omega \to 0 \Rightarrow |V_o| = |V_i| \leftarrow$ max. value

$\omega \to \infty \Rightarrow |V_o| = 0 \leftarrow$ min. value





Single Pole Passive Filter

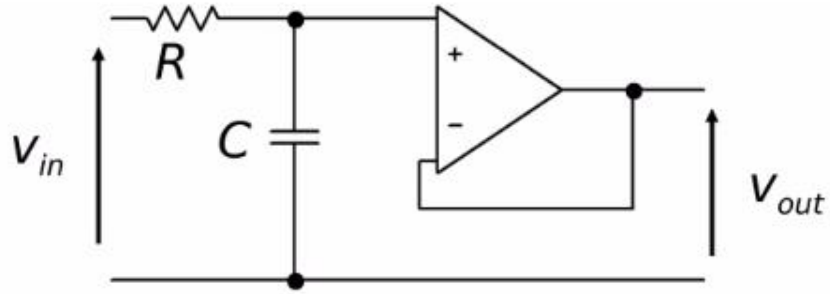


$$\frac{v_{out}}{v_{in}} = \frac{Z_C}{R+Z_C} = \frac{1/sC}{R+1/sC}$$

$$¿\frac{1}{sCR+1} = \frac{1/RC}{s+1/RC}$$

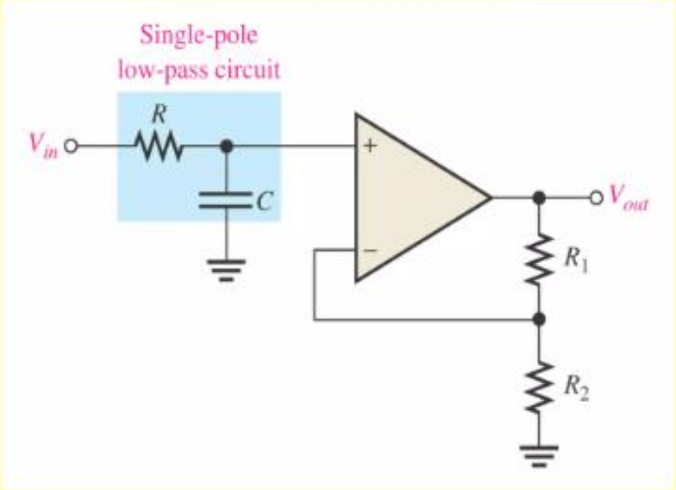
- First order low pass filter
- Cut-off frequency = $1/RC$ rad/s
- Problem : Any load (or source) impedance will change frequency response.

Single Pole Active Filter



- Same frequency response as passive filter.
- Buffer amplifier does not load RC network.
- Output impedance is now zero.

Critical Frequency and Roll-off Rate

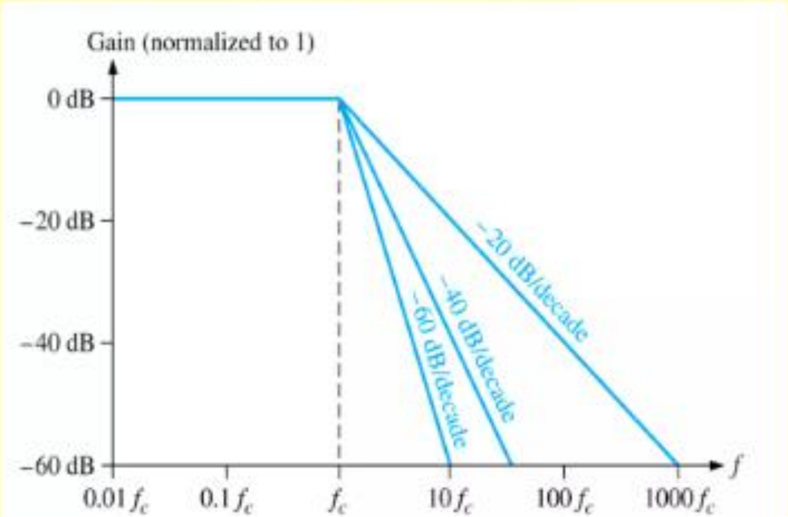


One-pole (first-order) low-pass filter.

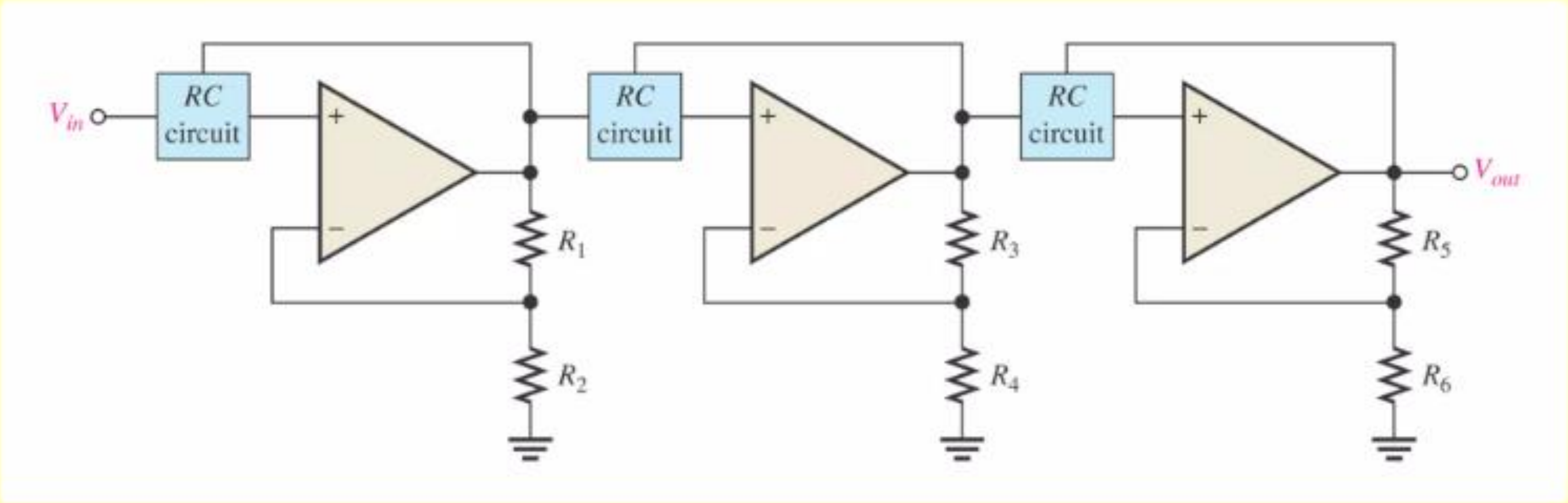
- The **critical frequency**, f_c is determined by the values of **R** and **C** in the frequency-selective RC circuit.
- Each **RC** set of filter components represents a **pole**.
- **Greater roll-off rates** can be achieved with **more poles**.

➢ The number of poles determines the roll-off rate of the filter. For example, a Butterworth response produces -20dB/decade/pole.
This means that:

- **One-pole (first-order)** filter has a roll-off of -20 dB/decade
- **Two-pole (second-order)** filter has a roll-off of -40 dB/decade
- **Three-pole (third-order)** filter has a roll-off of -60 dB/decade



➢ The number of filter poles can be increased by ***cascading***. To obtain a filter with three poles, cascade a two-pole with one-pole filters.

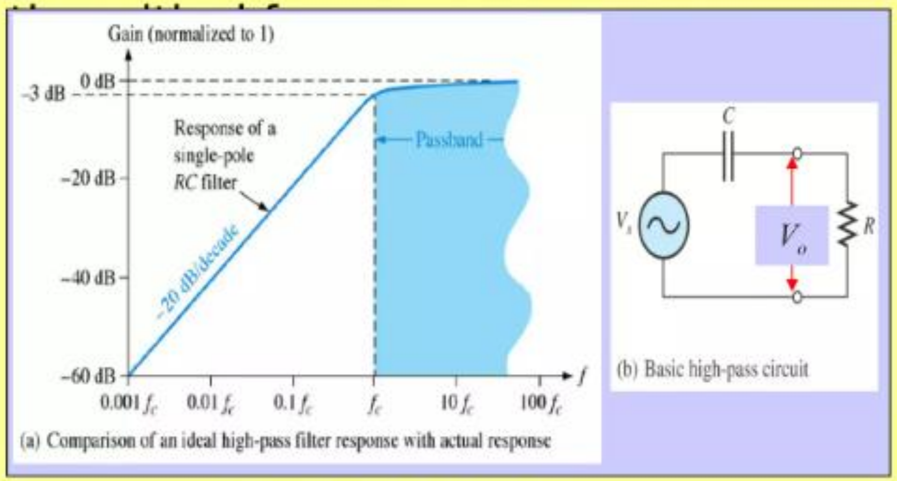


Three-pole (third-order) low-pass filter.

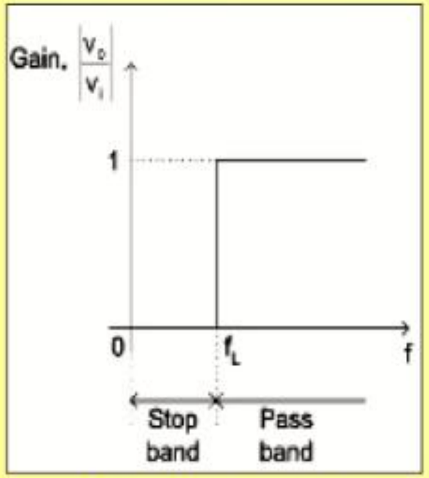
High Pass Filter Response

➢ A **high-pass filter** is a filter that significantly attenuates or rejects all frequencies **below** f_c and passes all frequencies **above** f_c.

➢ The passband of a high-pass filter is all frequencies above



Actual response



Ideal response

Ideally the response rises abruptly at the critical frequency

Advantages of Active Filters

Advantages of active filters over passive filters

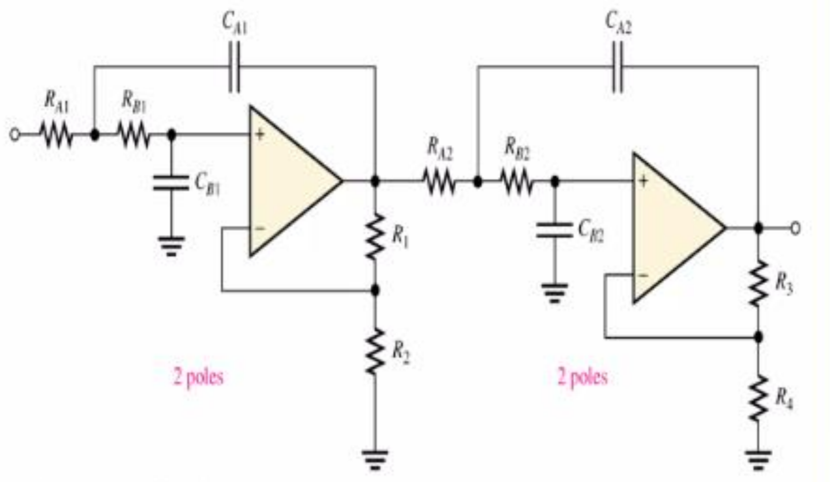
1. By containing the op-amp, active filters can be designed to provide required gain, and hence **no signal attenuation** as the signal passes through the filter.

2. **No loading problem**, due to the high input impedance of the op-amp prevents excessive loading of the driving source, and the low output impedance of the op-amp prevents the filter from being affected by the load that it is driving.

3. **Easy to adjust over a wide frequency range** without altering the desired response.

Numerical

- Determine the capacitance values required to produce a critical frequency of 2680 Hz if all resistors in RC low pass circuit is 1.8kΩ



(b) Fourth-order configuration

$$f_c = \frac{1}{2\pi RC}$$

$$C = \frac{1}{2\pi f_c R} = 0.033\ \mu F$$

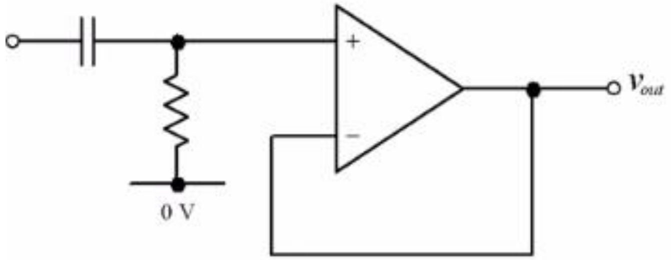
$C_{A1}=C_{B1}=C_{A2}=C_{B2}=0.033$ µf

Both stages must have the same cut-off frequency.

So, assume equal-value of capacitors.

Low Pass and High Pass Design

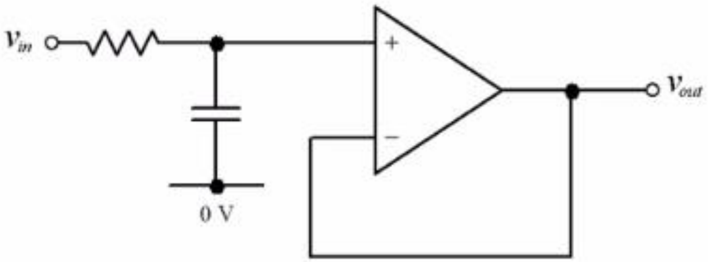
High Pass



$$\frac{v_{out}}{v_{in}} = \frac{1}{\frac{1}{sCR}+1} = \frac{1}{\frac{1+sRC}{sCR}}$$

$$\frac{sRC}{RC\left(s+1/RC\right)} = \frac{s}{\left(s+1/RC\right)}$$

Low Pass



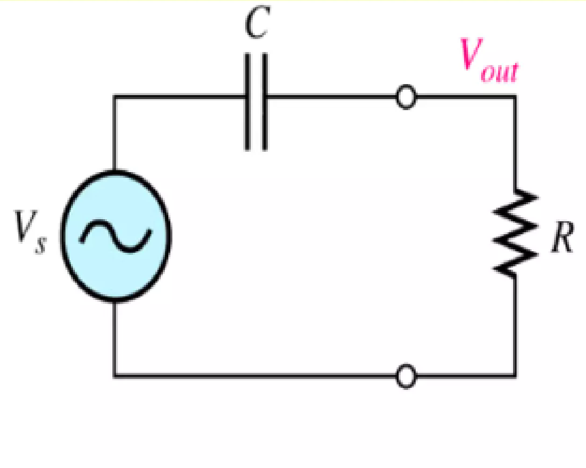
$$\frac{v_{out}}{v_{in}} = \frac{1/RC}{s+1/RC}$$

- The critical frequency of a high-pass RC filter occurs when

  X_C = R and can be calculated using the formula below:

$$f_c = \frac{1}{2\pi RC}$$

- Figure below shows the basic High-Pass filter circuit :



(b) Basic high-pass circuit

At critical frequency,

Resistance = Capacitance

$$R = X_c$$

$$R = \frac{1}{\omega_c C}$$

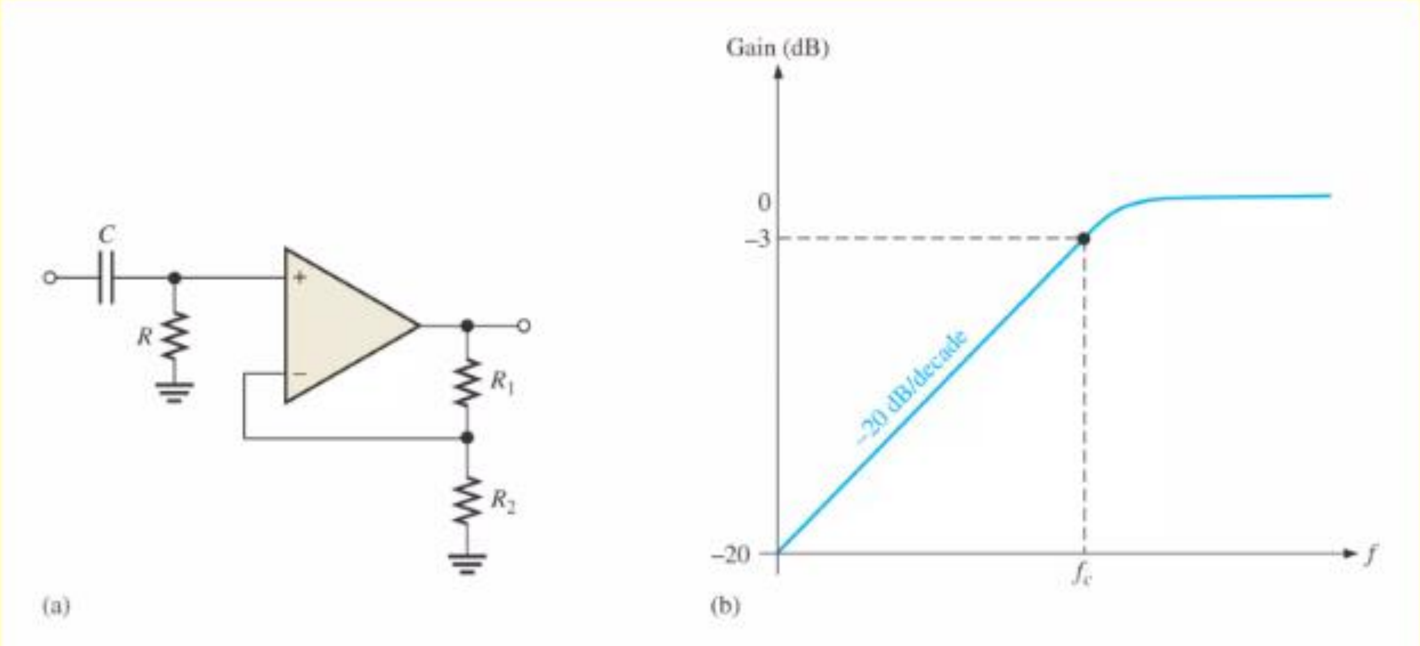
$$R = \frac{1}{2\pi f_c C}$$

Critical Frequency:

$$f_c = \frac{1}{2\pi RC}$$

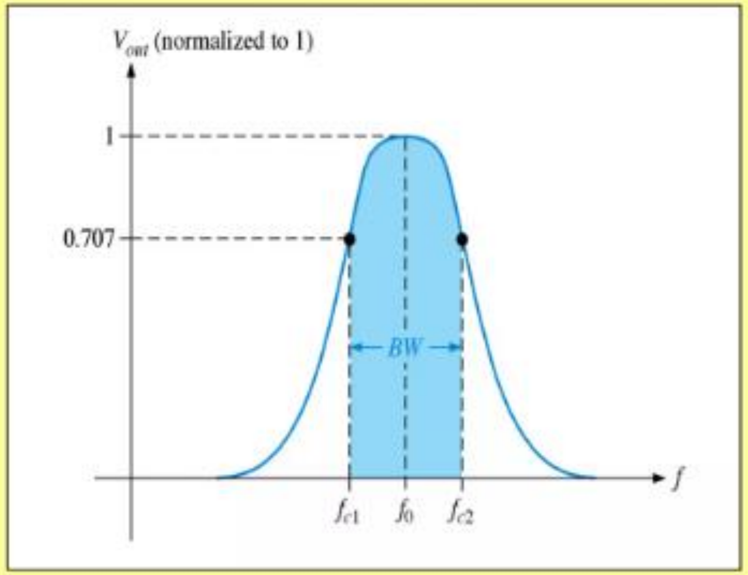
Single-Pole Active High Pass Filter

- In high-pass filters, the roles of the capacitor and resistor are reversed in the RC circuits as shown from Figure (a). The negative feedback circuit is the same as for the low-pass filters.
- Figure (b) shows a high-pass active filter with a -20dB/decade roll-off

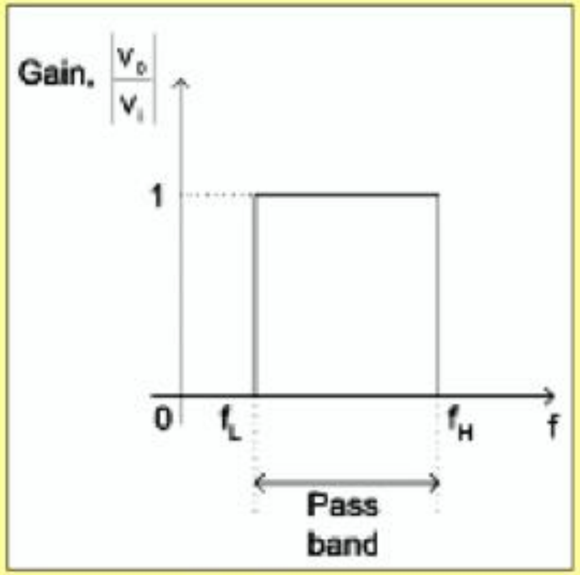


Band Pass Filter Response

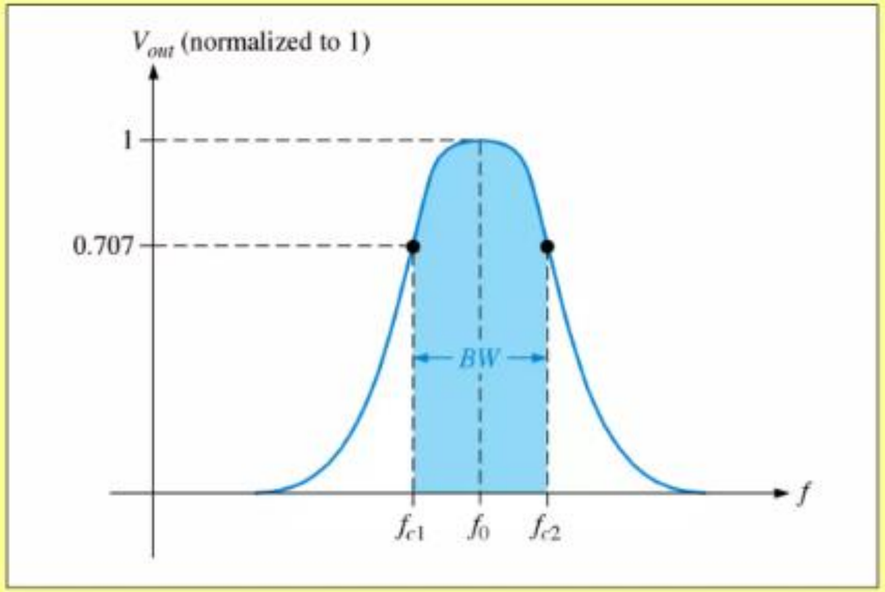
- A **band-pass filter** passes all signals lying within a band between a **lower-frequency limit** and **upper-frequency limit** and essentially rejects all other frequencies that are outside this specified band.



Actual response



Ideal response



➢ The **bandwidth (BW)** is defined as the **difference** between the **upper critical frequency (f_{c2})** and the **lower critical frequency (f_{c1})**.

$$BW = f_{c2} - f_{c1}$$

➢ The frequency about which the pass band is centered is called the ***center frequency***, ***f_o*** and defined as the geometric mean of the critical frequencies.

$$f_0 = \sqrt{f_{c1} f_{c2}}$$

- The ***quality factor (Q)*** of a band-pass filter is the ratio of the center frequency to the bandwidth.

$$Q = \frac{f_o}{BW}$$

- The higher value of Q, the narrower the bandwidth and the better the selectivity for a given value of $f_{o.}$
- (Q>10) as a narrow-band or (Q<10) as a wide-band
- The quality factor (Q) can also be expressed in terms of the damping factor (DF) of the filter as :

$$Q = \frac{1}{DF}$$

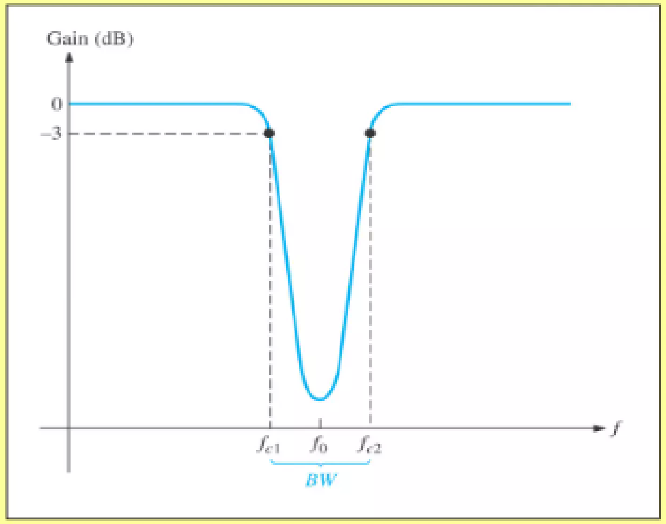
Opamp Bandpass Filter

A bandpass filter consists of three separate components

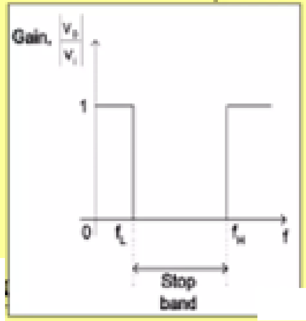
1. A unity-gain low-pass filter whose cutoff frequency is w_{c2}, the larger of the two cutoff frequencies
2. A unity-gain high-pass filter whose cutoff frequency is w_{c1}, the smaller of the two cutoff frequencies
3. A gain component to provide the desired level of gain in the passband.

These three components are cascaded in series. The resulting filter is called a **broadband** bandpass filter, because the band of frequencies passed is wide.

Band Stop Filter Response



Actual response



- **Band-stop filter** is a filter which its operation is **opposite** to that of the band-pass filter because the frequencies **within** the bandwidth are **rejected**, and the frequencies above f_{c1} and f_{c2} are **passed**.

- For the band-stop filter, the **bandwidth** is a band of frequencies between the 3 dB points, just as in the case of the band-pass filter response.

Opamp Bandstop Filter

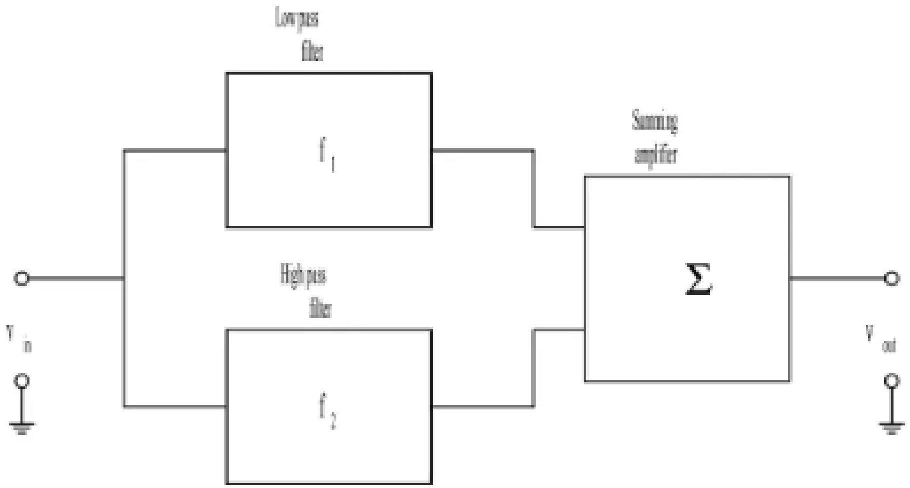
Like the bandpass filters, the bandreject filter consists of three separate components

- The unity-gain low-pass filter has a cutoff frequency of w_{c1}, which is the smaller of the two cutoff frequencies.
- The unity-gain high-pass filter has a cutoff frequency of w_{c2}, which is the larger of the two cutoff frequencies.
- The gain component provides the desired level of gain in the passbands.

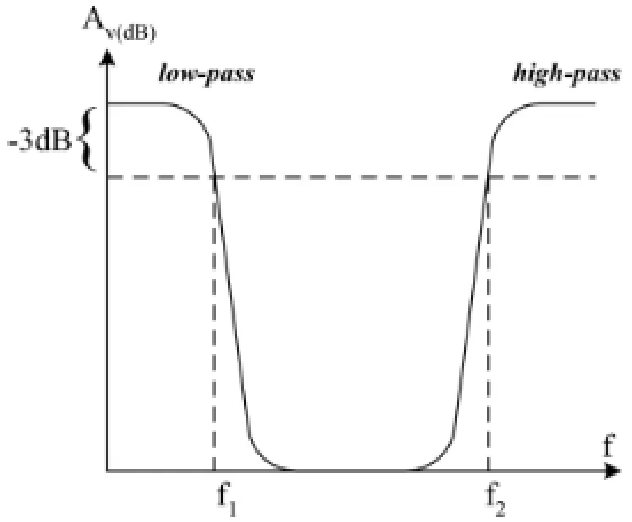
The most important difference is that these components are connected in parallel and using a summing amplifier.

Band-Stop (Notch) Filter

The notch filter is designed to block all frequencies that fall within its bandwidth. The circuit is made up of a ***high pass filter***, a ***low-pass filter*** and a ***summing amplifier***. The summing amplifier will have an output that is equal to the sum of the filter output voltages.



Block diagram



Frequency response

Multiplexed and Distributed sensors

1. ***Basic sensor array topologies***

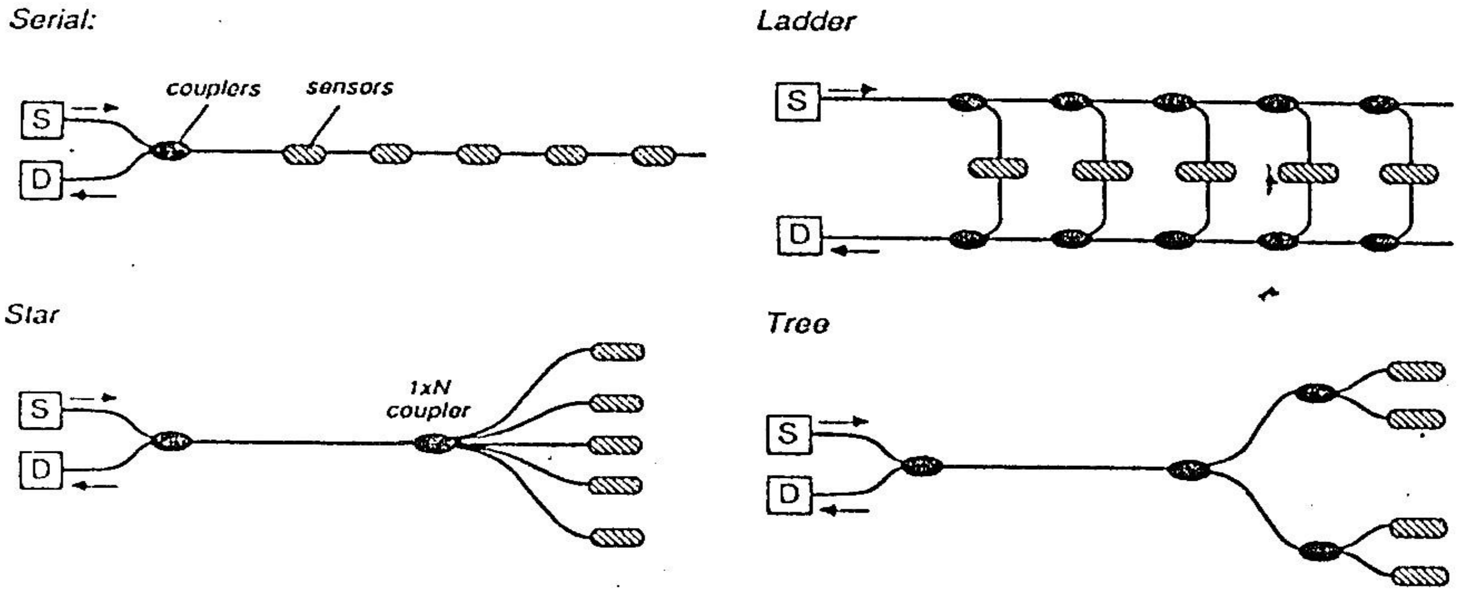
2. ***Time division multiplexing (TDM)***

3. ***Wavelength division multiplexing (WDM)***

4. ***Optical time domain reflectometry (OTDR)***

5. ***Optical low coherence reflectometry (OLCR)***

Basic Sensor Array Topologies



Advantages of Multiplexing:

(1) Many sensors share the same source/detector and processing electronics and this helps to reduce the cost of the system.

(2) Lower fiber count in telemetry cables and ease of E/O interfacing

History behind Multiplexing

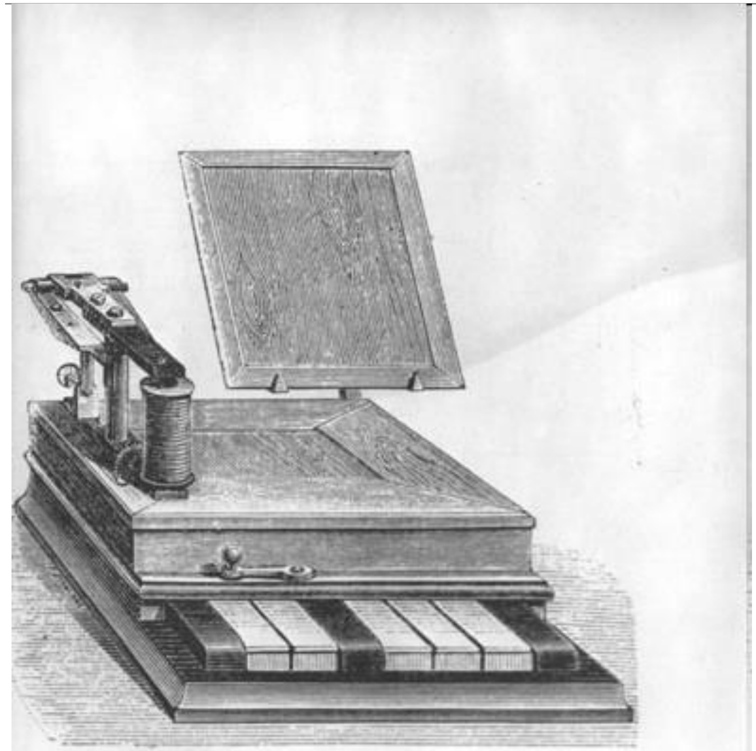


FIGURE 51.—Baudot's multiplex telegraph transmitter keyboard. The cadence counter on top of the case enabled the operator to transmit at the correct speed. From *La*

- 1894
- Baudot's multiplex telegraph

History

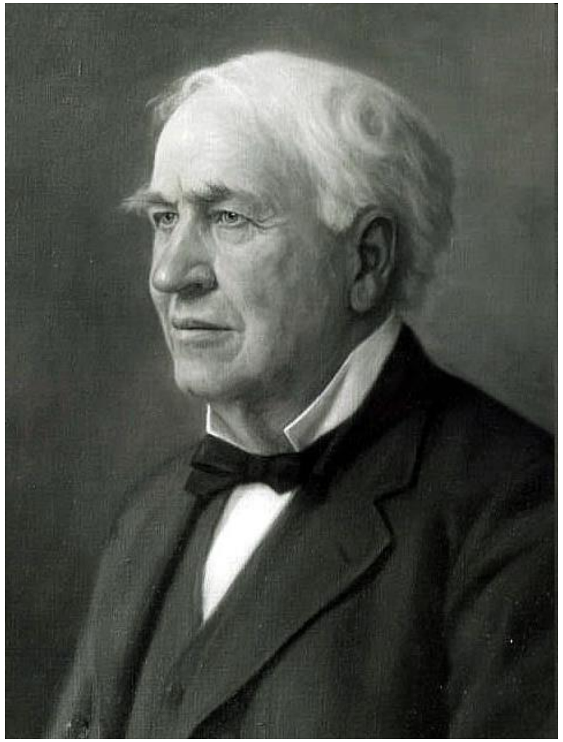
Western Union problem

Thomas Edison:

- Wavelength strength
- Polarity

Western Union

- electrical-mechanical multiplexing device
  - 8 messages in 1913
  - 72 messages in 1936

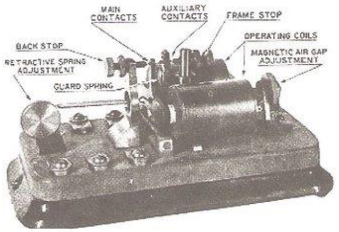


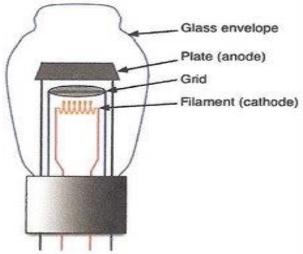
Data Transmission Speeds

- Characters Per Minute (CPM)
- Words Per Minute (WPM)
  - 5 characters and space
- Bits Per Second (bps)
  - 1950s → 1200 bps
  - Currently → 10 Gbps

Multiplexing Devices Development

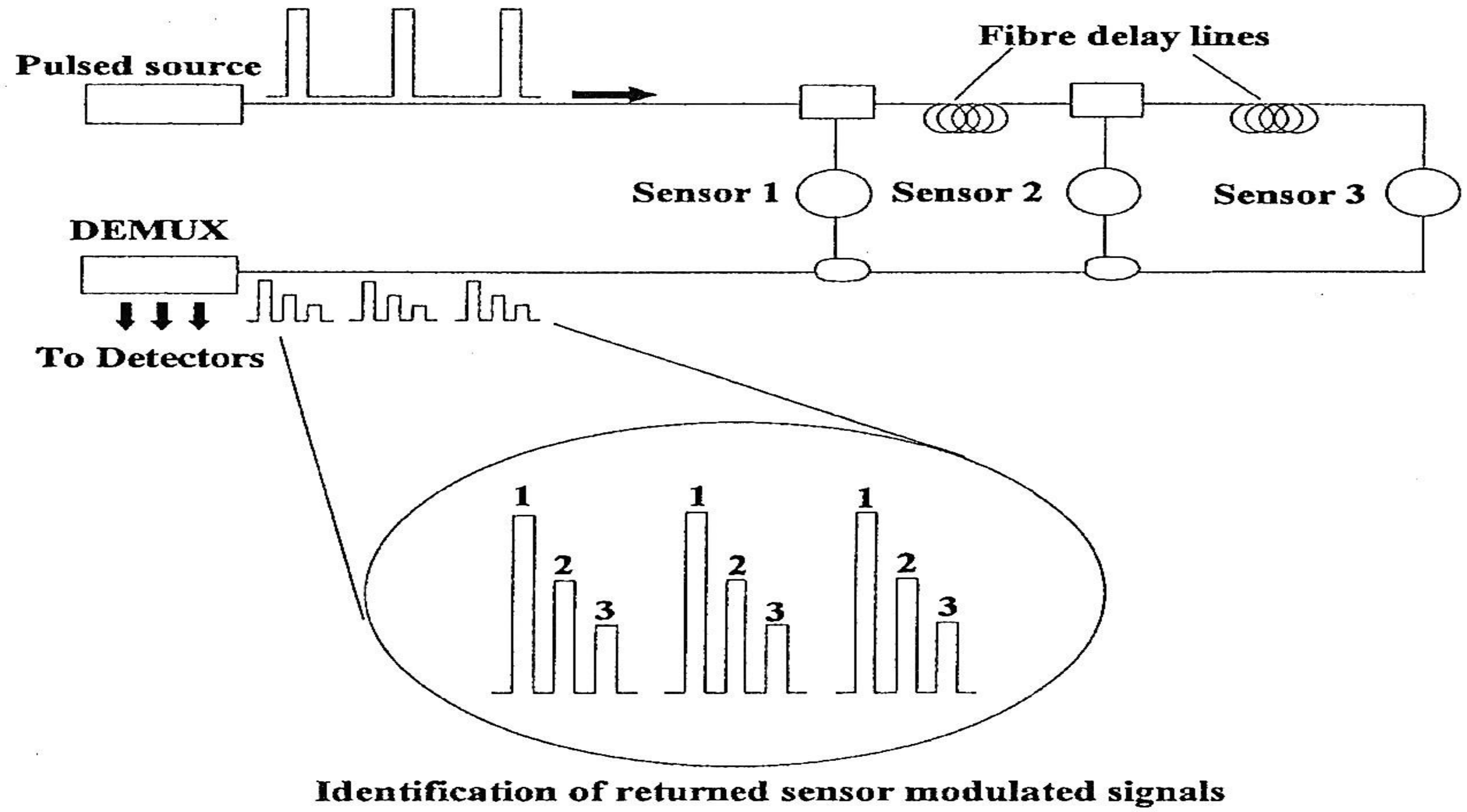
- Telegraph lines utilized DC
- Vacuum Tubes allowed AC in 1930s
- Transistors replaced Vacuum Tubes in1960s
- Integrated Circuits



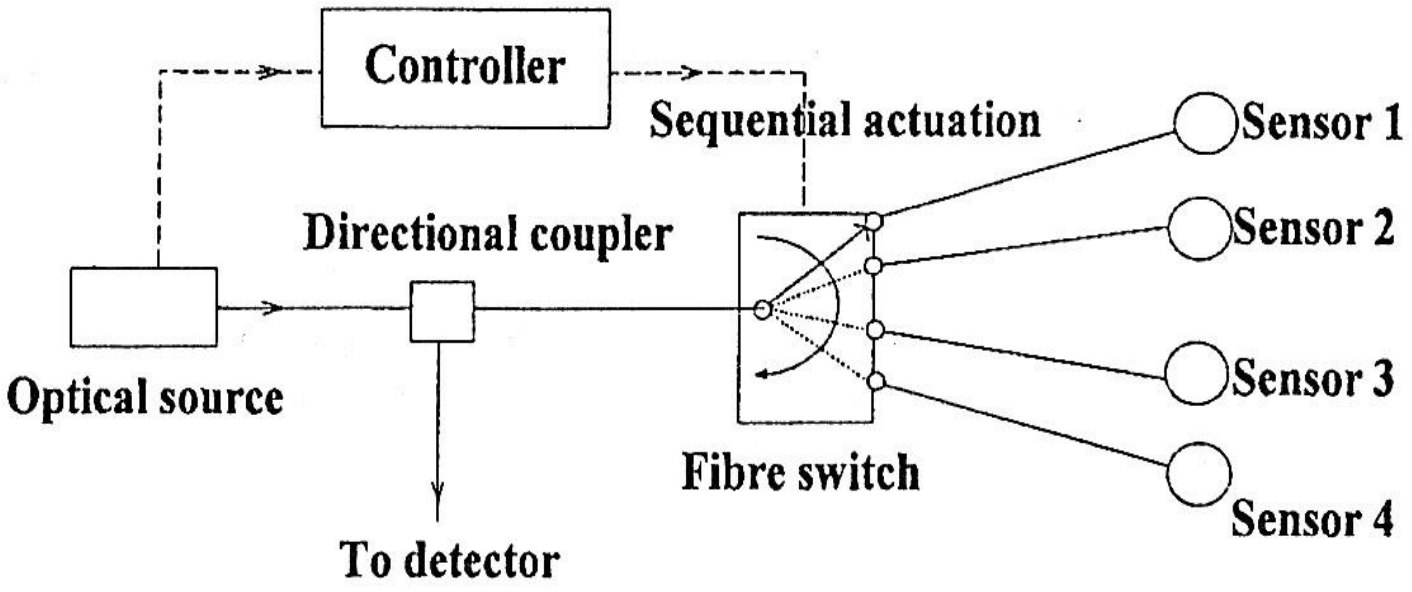


Time Division Multiplexing (TDM)

TDM ladder network

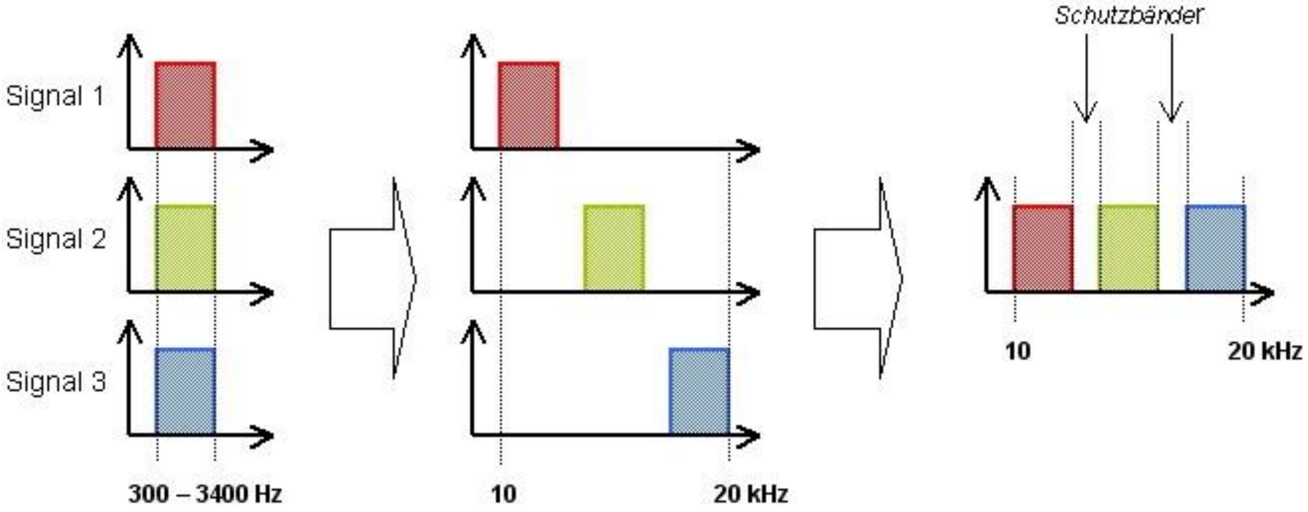


TDM Star Network



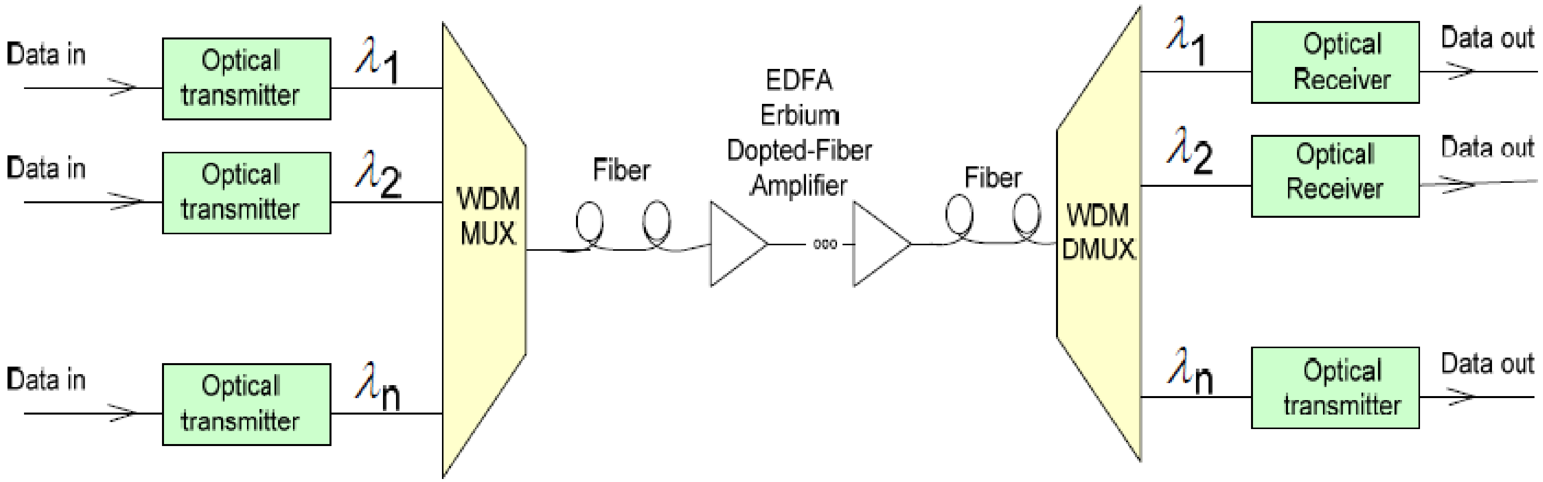
Frequency-Division Multiplexing (FDM)

- All signals are sent simultaneously, each assigned its own frequency
- Using filters all signals can be retrieved

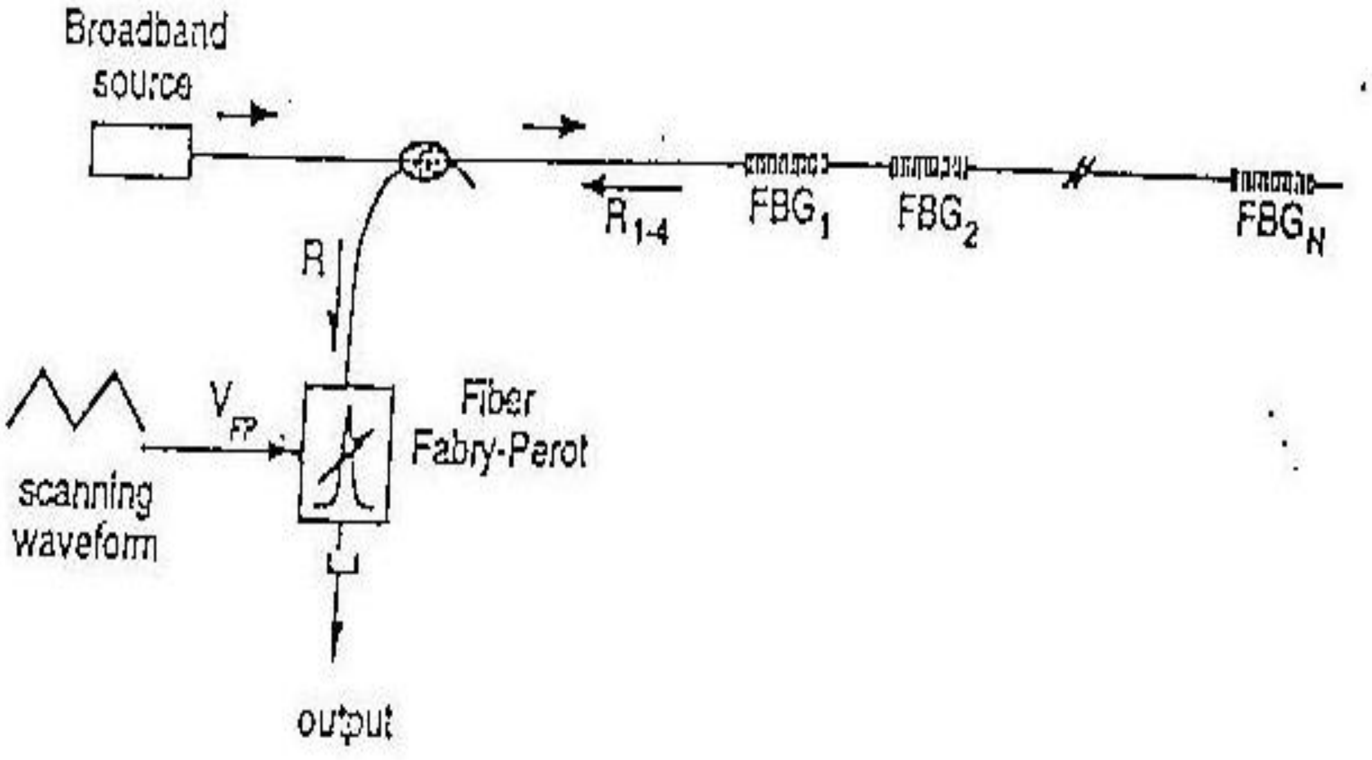


Wavelength-Division Multiplexing (WDM)

WDM is the combining of light by using different wavelengths



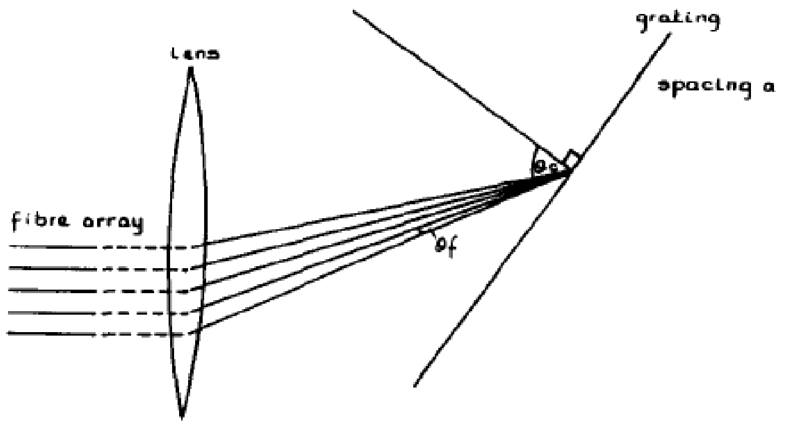
Wavelength Division Multiplexing



Grating Multiplexer

Lens focuses all signals to the same point

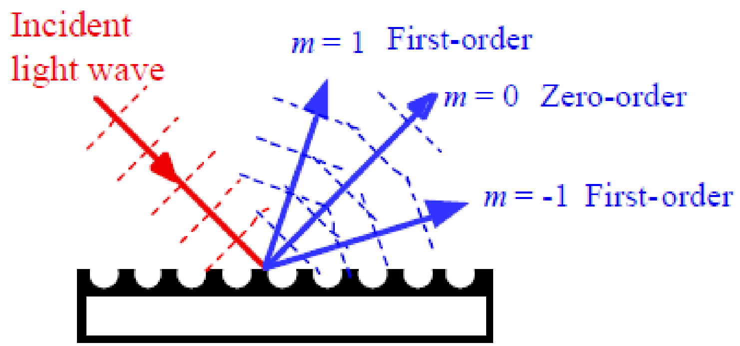
Grating reflects all signals into one signal



$$a(\sin\theta_i + \sin\theta_o) = m\lambda$$

Grating Multiplexer

Reflection off of grating is dependent on incident angle, order, and wavelength

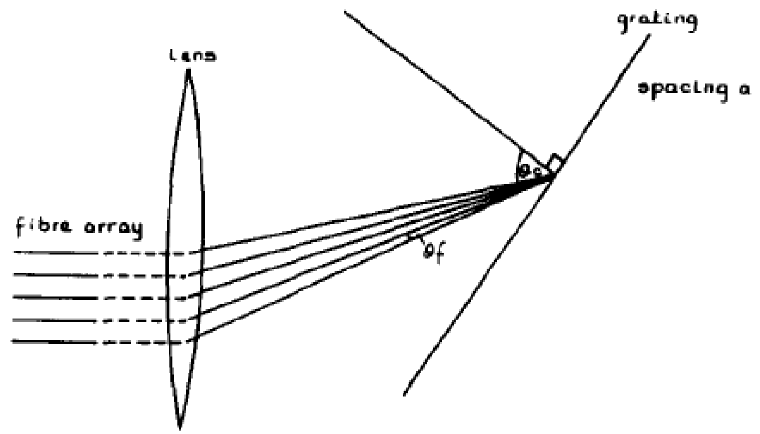


$$d(\sin\theta_i + \sin\theta_o) = m\lambda$$

Grating Multiplexer

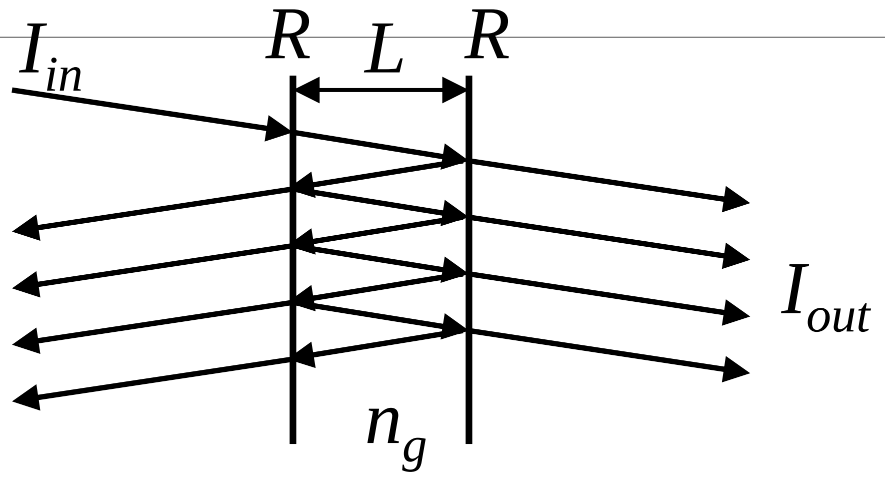
- Multiplexer is designed such that each λ and θ_i are related

- Results in one signal that can then be coupled into a fiber optic cable



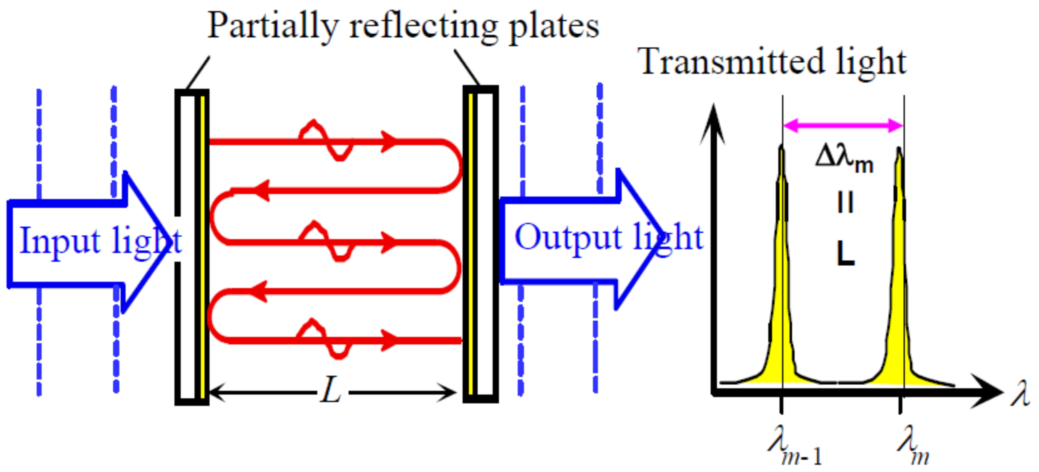
$$a(\sin\theta_i+\sin\theta_o)=m\lambda$$

Fabry-Perot Filter



Transmitted light:
$\lambda_m = 2L/m$
where m = 1, 2, 3,….

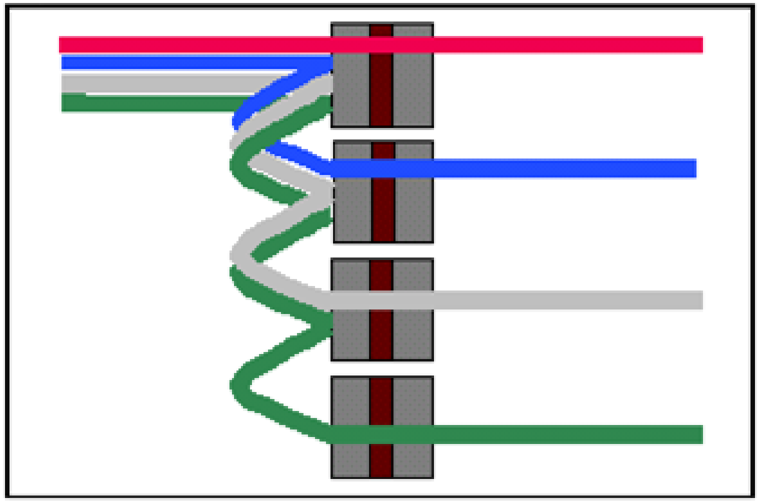
Separation of the modes:
$\Delta\lambda_m = L$



Fabry-Perot Multiplexer

Separates based on wavelength = demux

Can be reversed for multiplexer



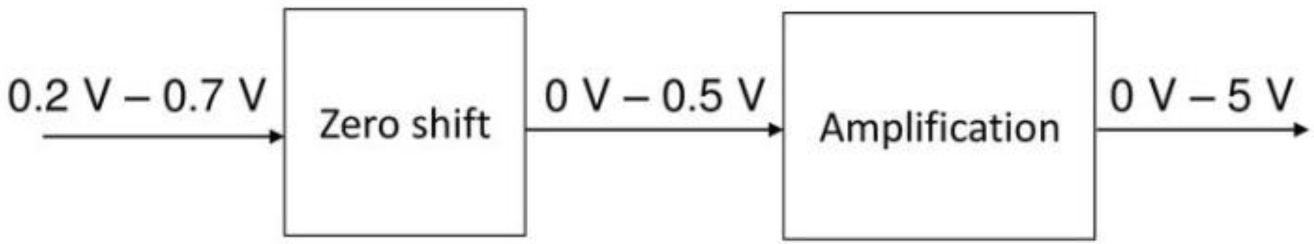
Signal-range and offset (bias)

Example

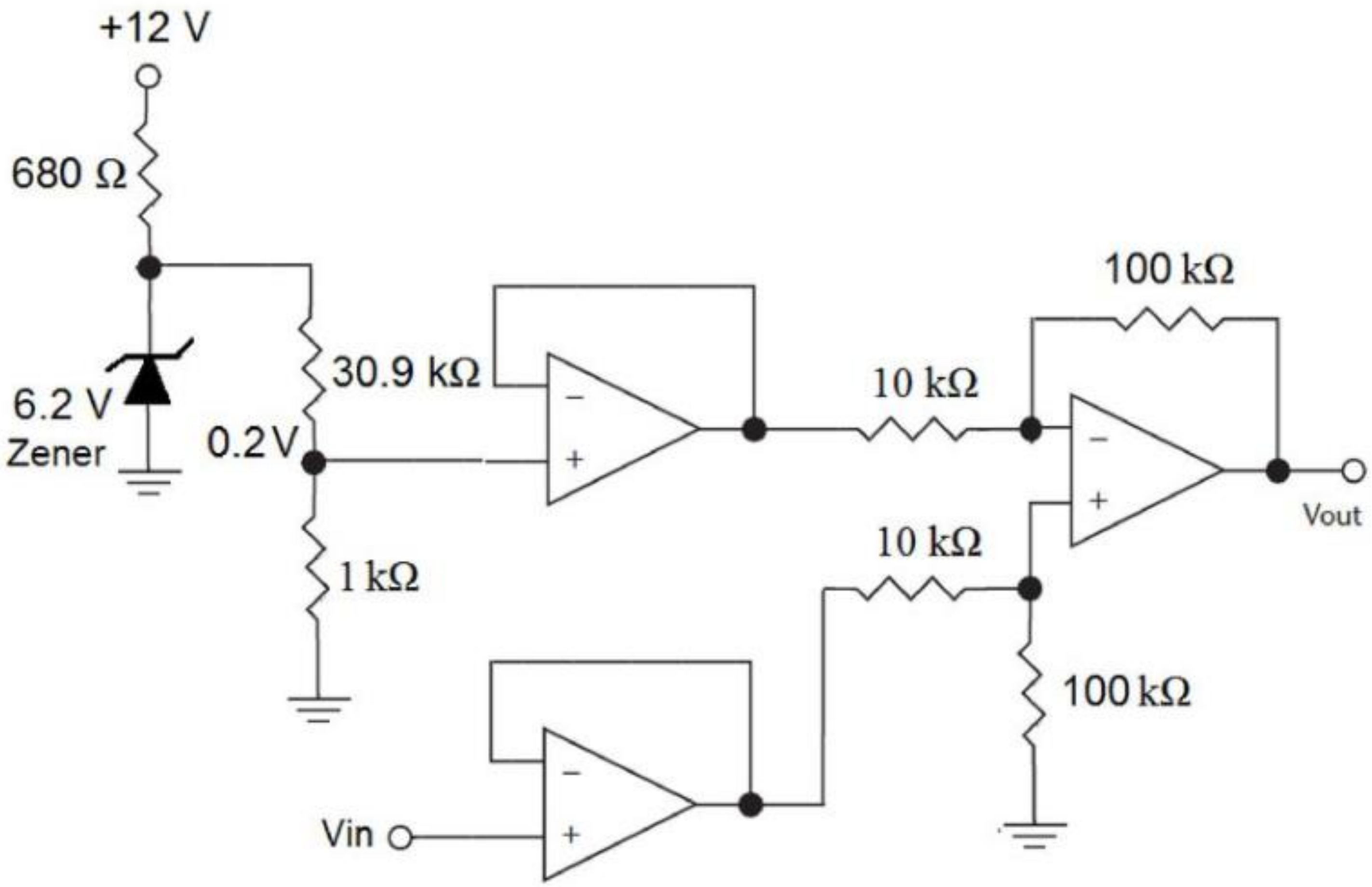
Design a circuit to achieve the following voltage conversion.

Answer

- It is clear that we need to subtract 0.2V, then multiply the signal by 10.



- This looks like a differential amplifier with a gain of 10 and a fixed input of 0.2 volts to the inverting side. The following circuit shows how this could be done using an instrumentation amplifier.



Note that a voltage divider is used to provide the 0.2V offset. The zener diode is used to keep the bias voltage (i.e. the 0.2V) constant against changes of the supply.

Example

A sensor outputs a voltage in the range of 20 to 250 mV. Develop signal conditioning so that this become 0 to 5 V. The circuit must have very high input impedance.

Answer

Let us develop an linear equation for the output in terms of the input

$$V_{out} = aV_{in} + b$$

where *a* and *b* are to be found.

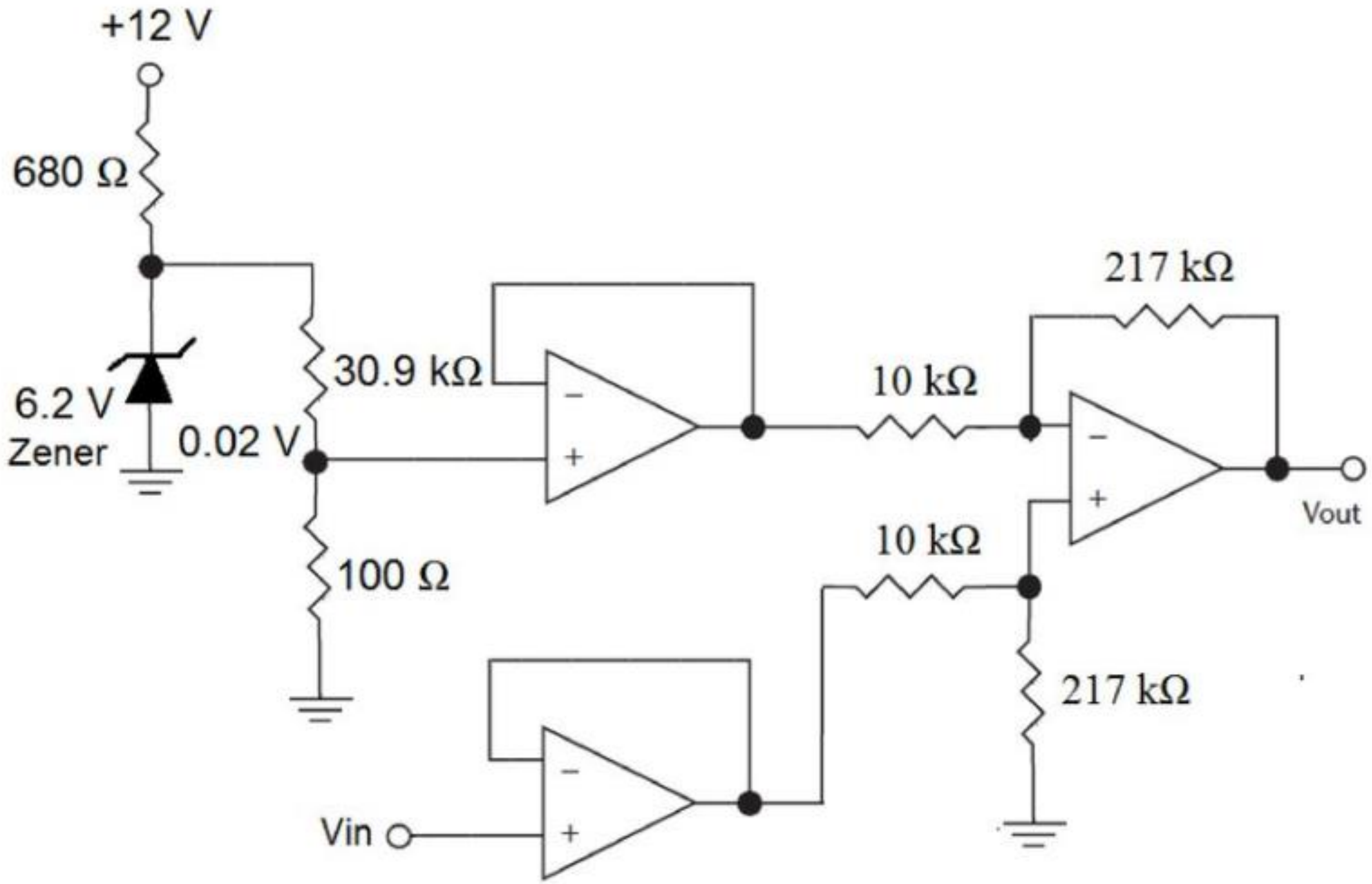
- For the given two conditions we can write

$$\left.\begin{aligned} 0 &= a(0.020) + b \\ 5 &= a(0.250) + b \end{aligned}\right\} \Rightarrow \quad a = 21.7, \quad b = -0.434$$

- Hence, the required equation is

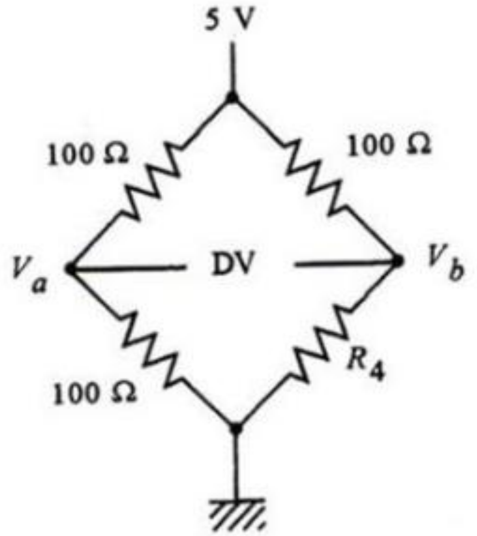
$$\begin{aligned} V_{out} &= 21.7V_{in} - 0.434 \\ &= 21.7(V_{in} - 0.02) \end{aligned}$$

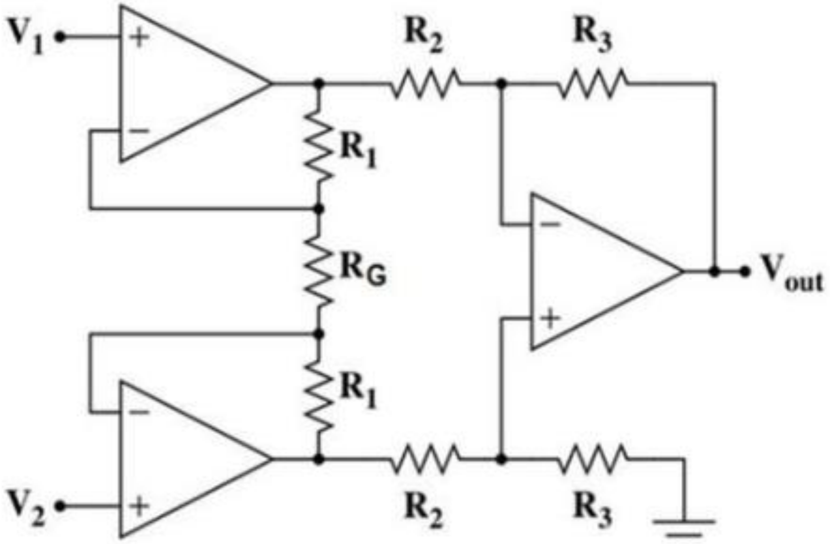
- Therefore we need a differential amplifier with a gain of 21.7 and a fixed input of 0.02V to the inverting side. The following circuit shows how this could be done using an instrumentation amplifier.


+12 V
680 Ω
6.2 V
Zener
30.9 kΩ
0.02 V
100 Ω
10 kΩ
217 kΩ
10 kΩ
217 kΩ
Vout
Vin

Example

A bridge circuit for which R_4 varies from 100Ω to 102Ω is shown below. Show how this bridge could be connected to the given instrumentation amplifier to provide an output of 0 to 2.5V for that change in R_4. Assume that, in the instrumentation amplifier circuit, $R_2 = R_3 = 1\ k\Omega$ and $R_1 = 100\ k\Omega$.





Answer

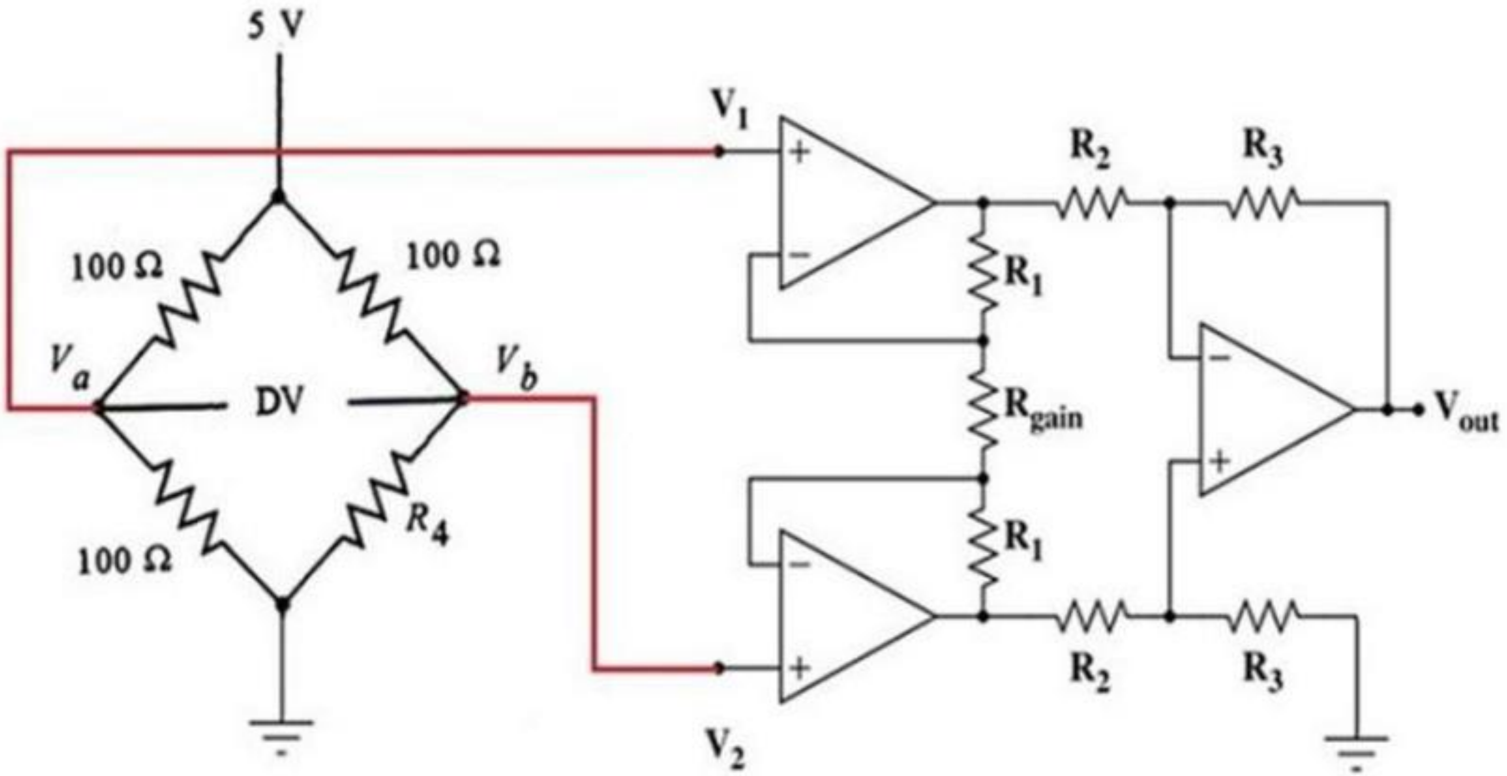
- Clearly, the bridge nulls when R_4=100 Ω. **So, we do not need zero adjustment.**
- When R_4 = 102Ω the bridge offset voltage is found as

$$\Delta V = V_b - V_a = 5\left(\frac{102}{100+102} - \frac{100}{100+100}\right) = 24.75 \text{ mV}.$$

- To get an output of 2.5V at 102Ω we need a differential gain of (2.5 V/24.75 mV) = 101.
- For the given instrumentation amplifier we have

$$V_{out} = \left(1 + \frac{2R_1}{R_G}\right)\left(\frac{R_3}{R_2}\right)(V_2 - V_1) \quad \Rightarrow \quad 101 = \left(1 + \frac{2(100)}{R_G}\right)\left(\frac{1}{1}\right)$$

$$\Rightarrow \quad R_G = 2k\Omega$$



5 V
100 Ω
100 Ω
V_a
DV
V_b
100 Ω
R_4
V_1
V_2
R_1
R_{gain}
R_1
R_2
R_3
R_2
R_3
V_{out}

Conversion

- In many situations it is required to convert one form of signal or physical value into another form such as
  - resistance to voltage
  - voltage-to-current
  - current-to-voltage

- For example, a typical standard in process control systems is to use current signals in the range 4 to 20 mA for transmission. This requires conversion from voltage to current at the sending end and a conversion from current to voltage at the receiving end.

Current to voltage converter

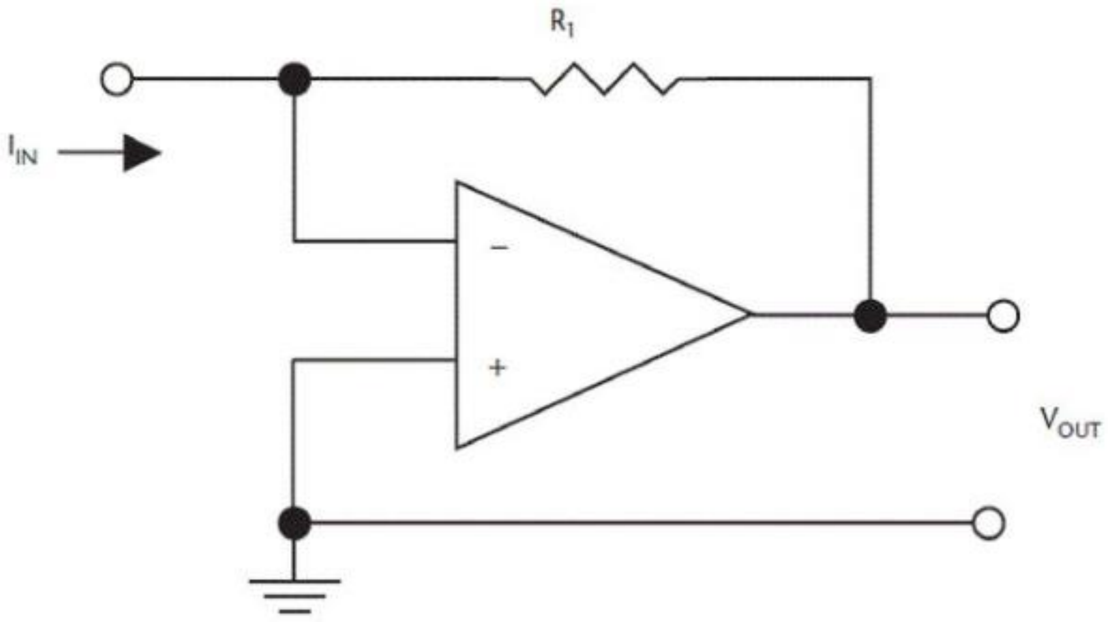
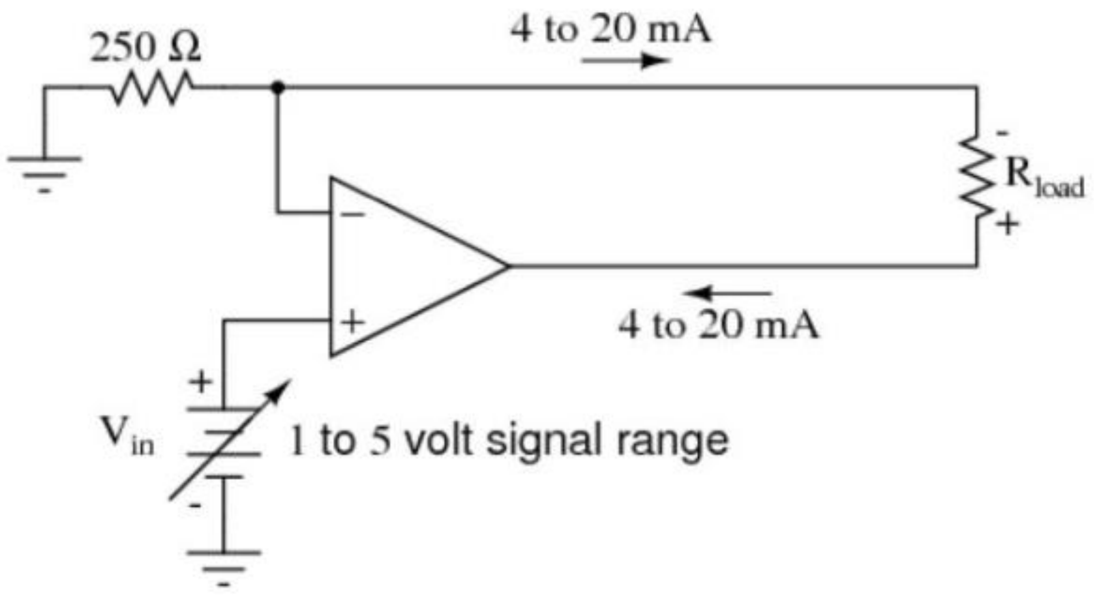


Figure 4.10 Current to voltage converter.

$$V_{out} = -R_1 I_{IN}$$

Voltage to current converter

In the following circuit, the current through the load resistor $\boldsymbol{R_{Load}}$ is equal to $V_{in}/(250\Omega)$. No matter what value of $\boldsymbol{R_{Load}}$ is, the current through it will be function of V_{in} only.



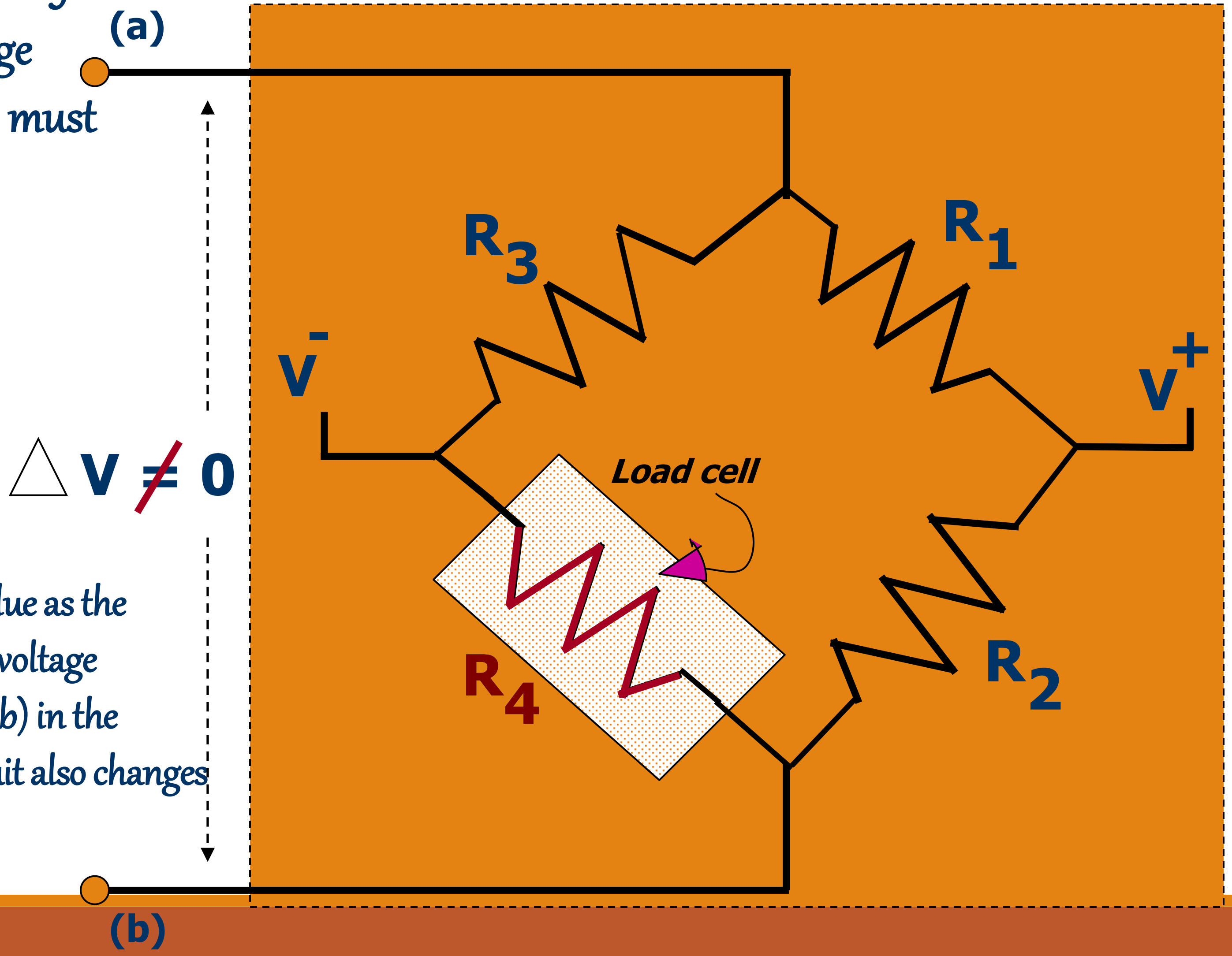
Sensor Interface Design: Wheatstone bridge

With strain gauge sensors, a Wheatstone bridge may not bridge the gap

Sensor Interface Design: Wheatstone bridge

This resistance change must become an amplified voltage signal if the resistance change is to be used in an instrumentation system to control the amount of mass on the load cell.

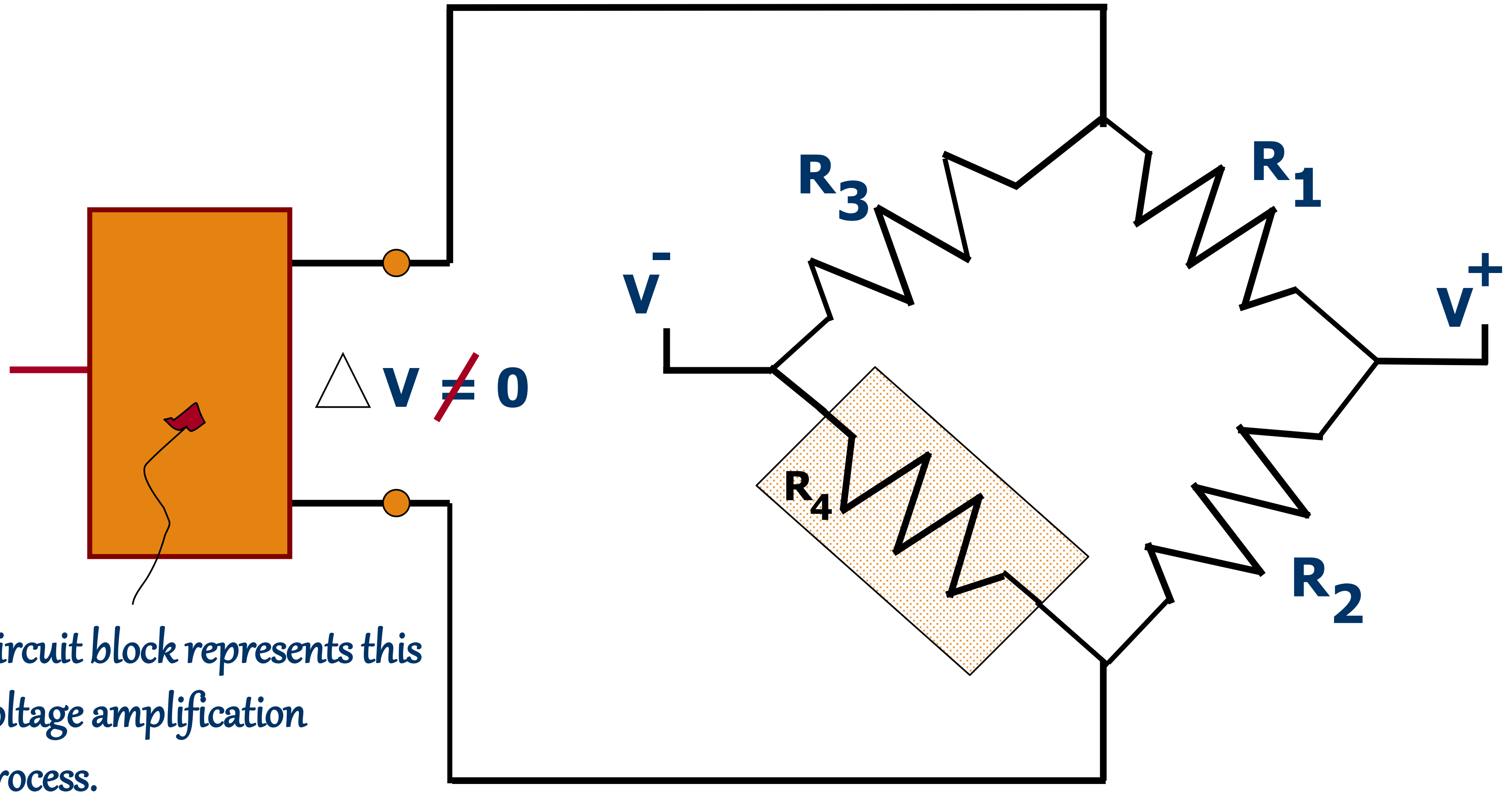
Often this voltage difference value must be amplified.



R_4 changes in resistance value as the weight changes and the voltage between points (a) and (b) in the Wheatstone bridge circuit also changes proportionally.

Amplifying Wheatstone bridge output

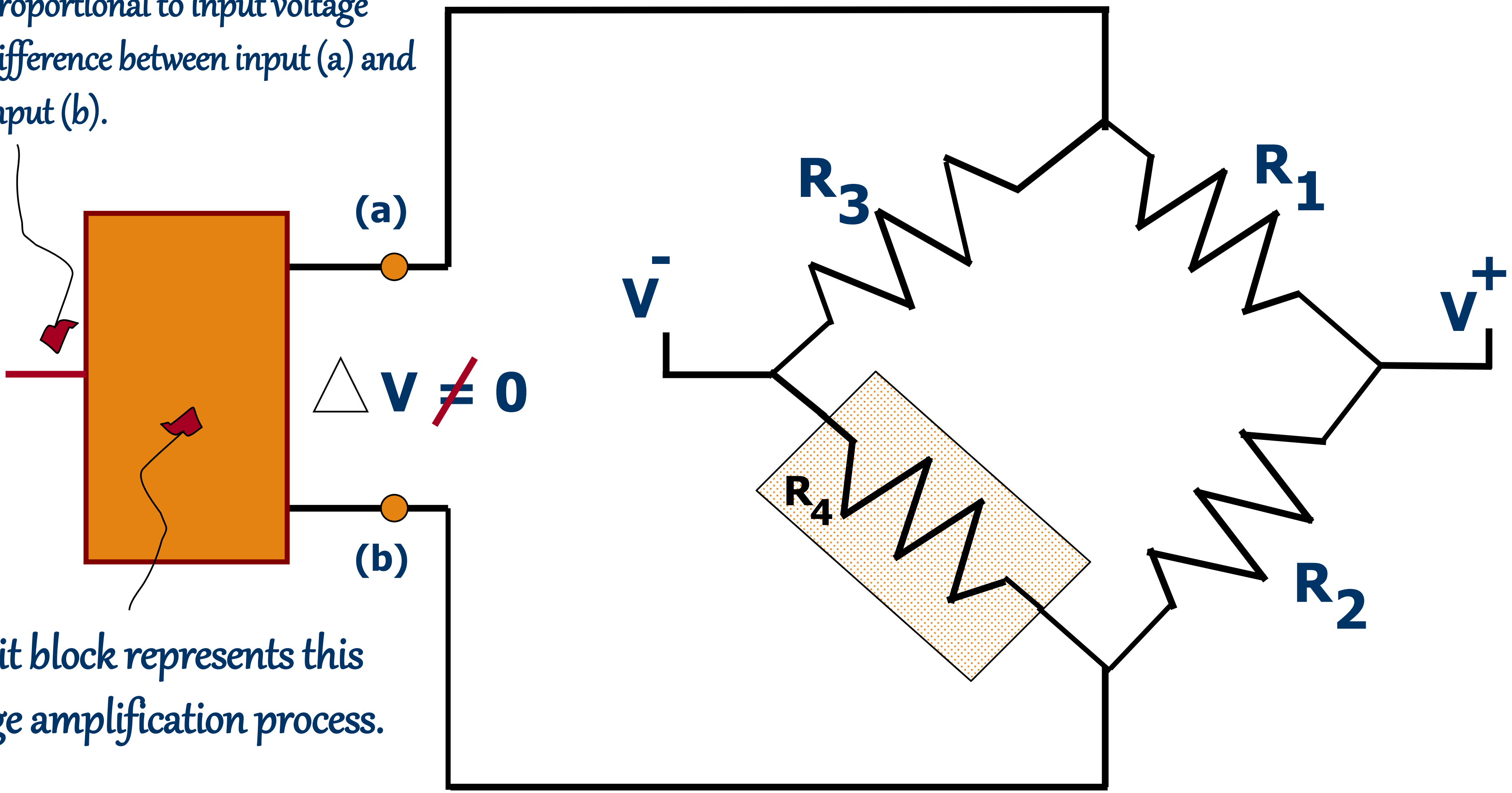
Circuits can be built to amplify the resistance change when the weight monitored by the load cell (R_4) changes.



Circuit block represents this voltage amplification process.

Amplifying Wheatstone bridge output

This output voltage signal is proportional to input voltage difference between input (a) and input (b).



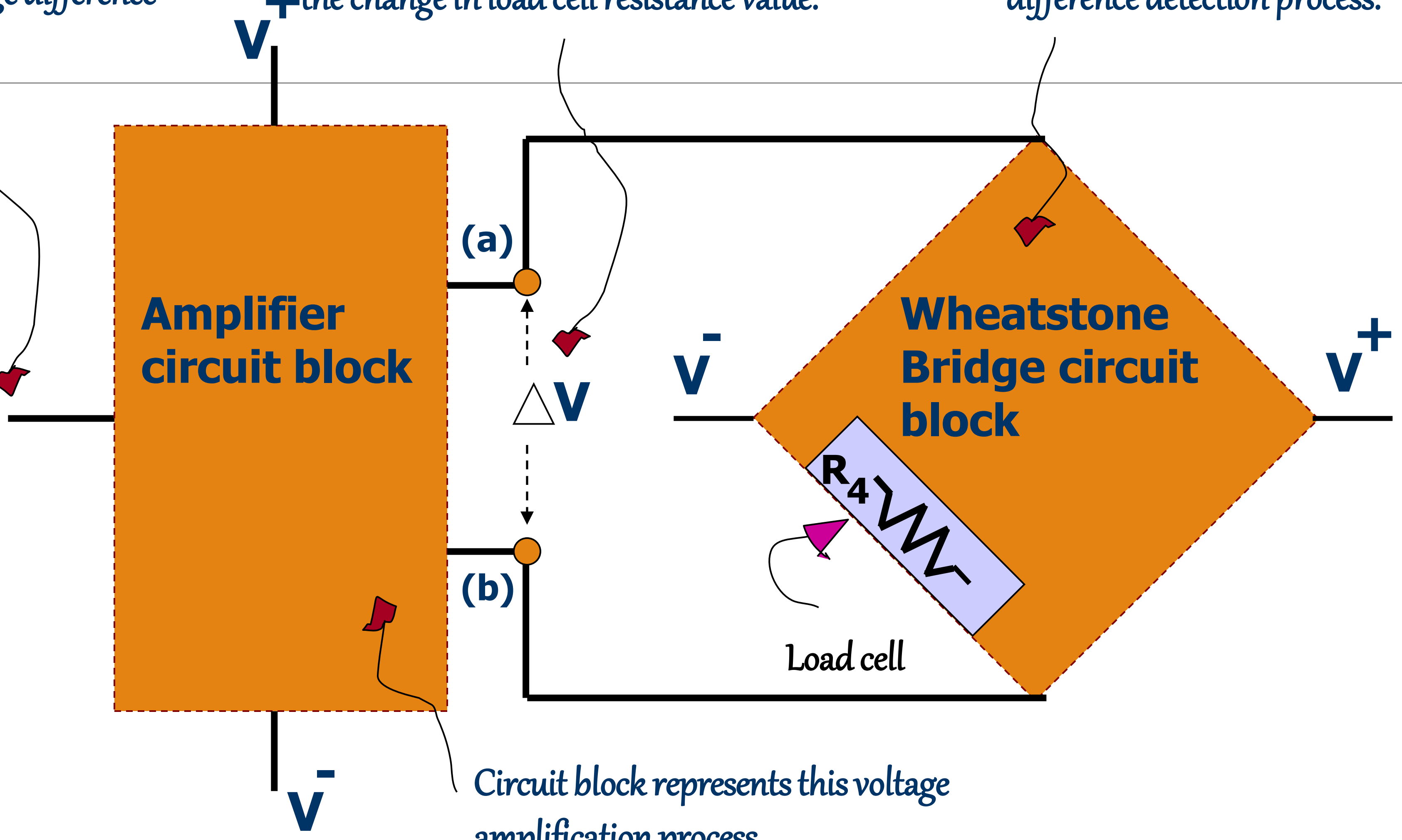
Circuit block represents this voltage amplification process.

Interfacing Circuit

This high magnitude output voltage signal is proportional to input voltage difference value.

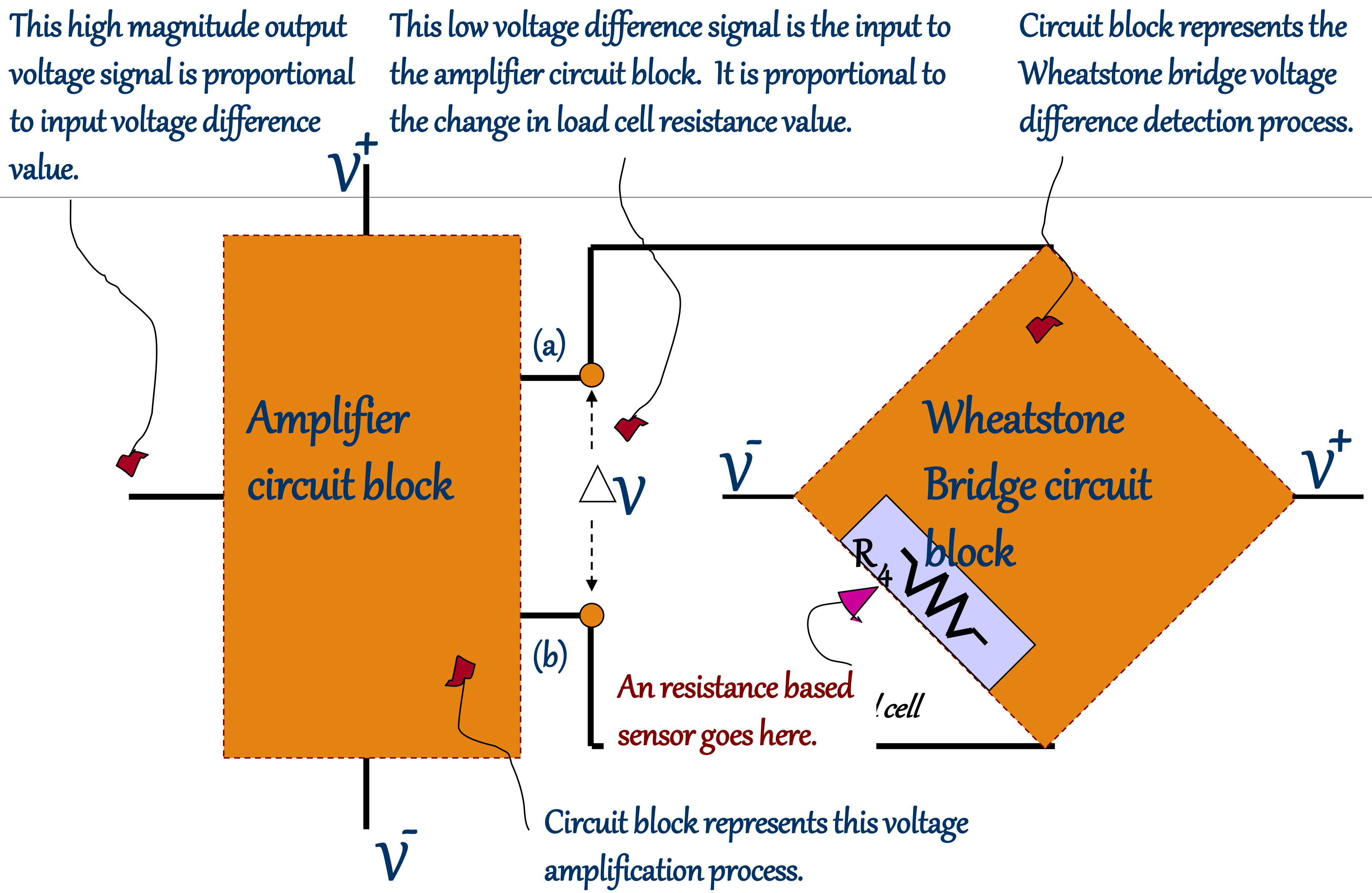
This low voltage difference signal is the input to the amplifier circuit block. It is proportional to the change in load cell resistance value.

Circuit block represents the Wheatstone bridge voltage difference detection process.



Circuit block represents this voltage amplification process.

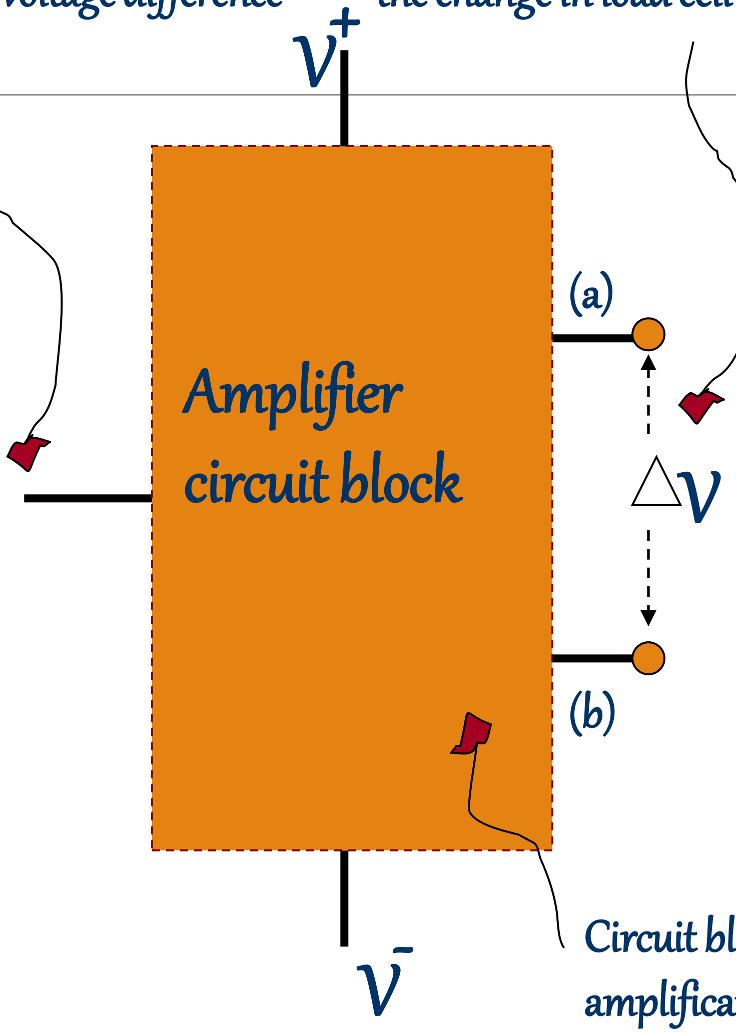
Interfacing Circuit



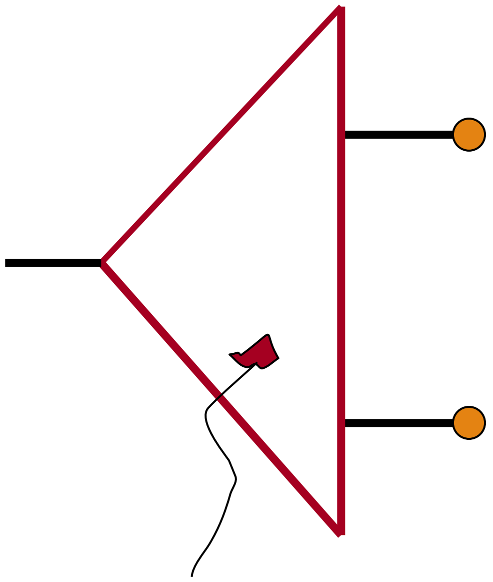
Interfacing Circuit

This high magnitude output voltage signal is proportional to input voltage difference value.

This low voltage difference signal is the input to the amplifier circuit block. It is proportional to the change in load cell resistance value.



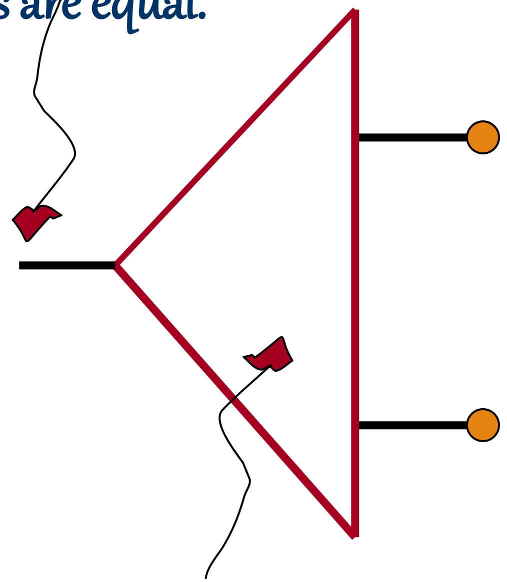
Circuit block represents this voltage amplification process.



Circuit icon for Operational Amplifier

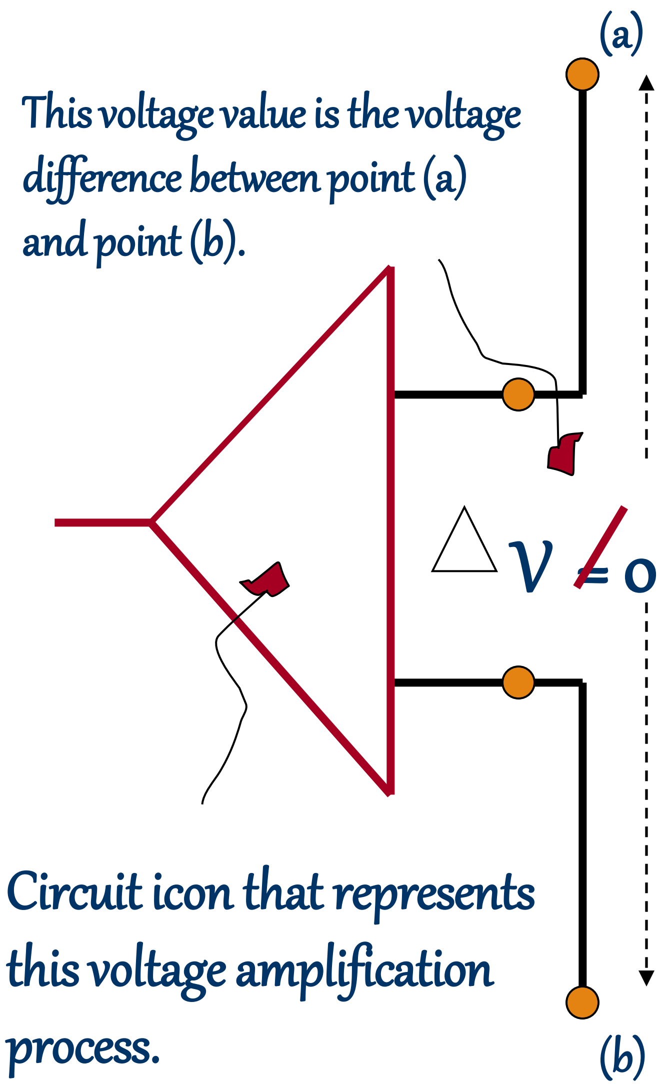
Operational Amplifier
Operational Rule

Output voltage is equal to zero only when both input signals are equal.



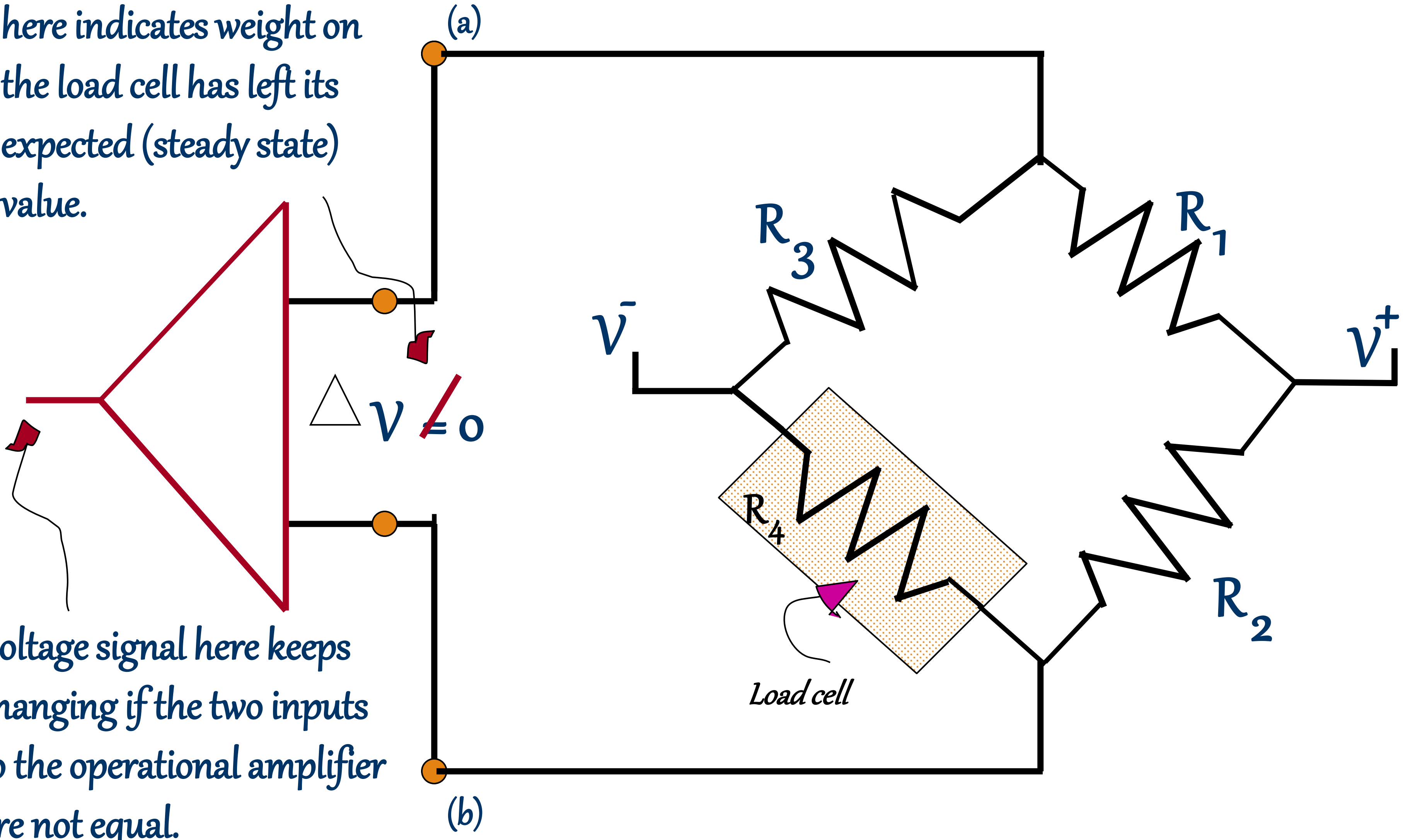
Circuit icon for Operational Amplifier

Operational Amplifier Operational Rule



Operational Amplifier interface to load cell sensor Wheatstone bridge

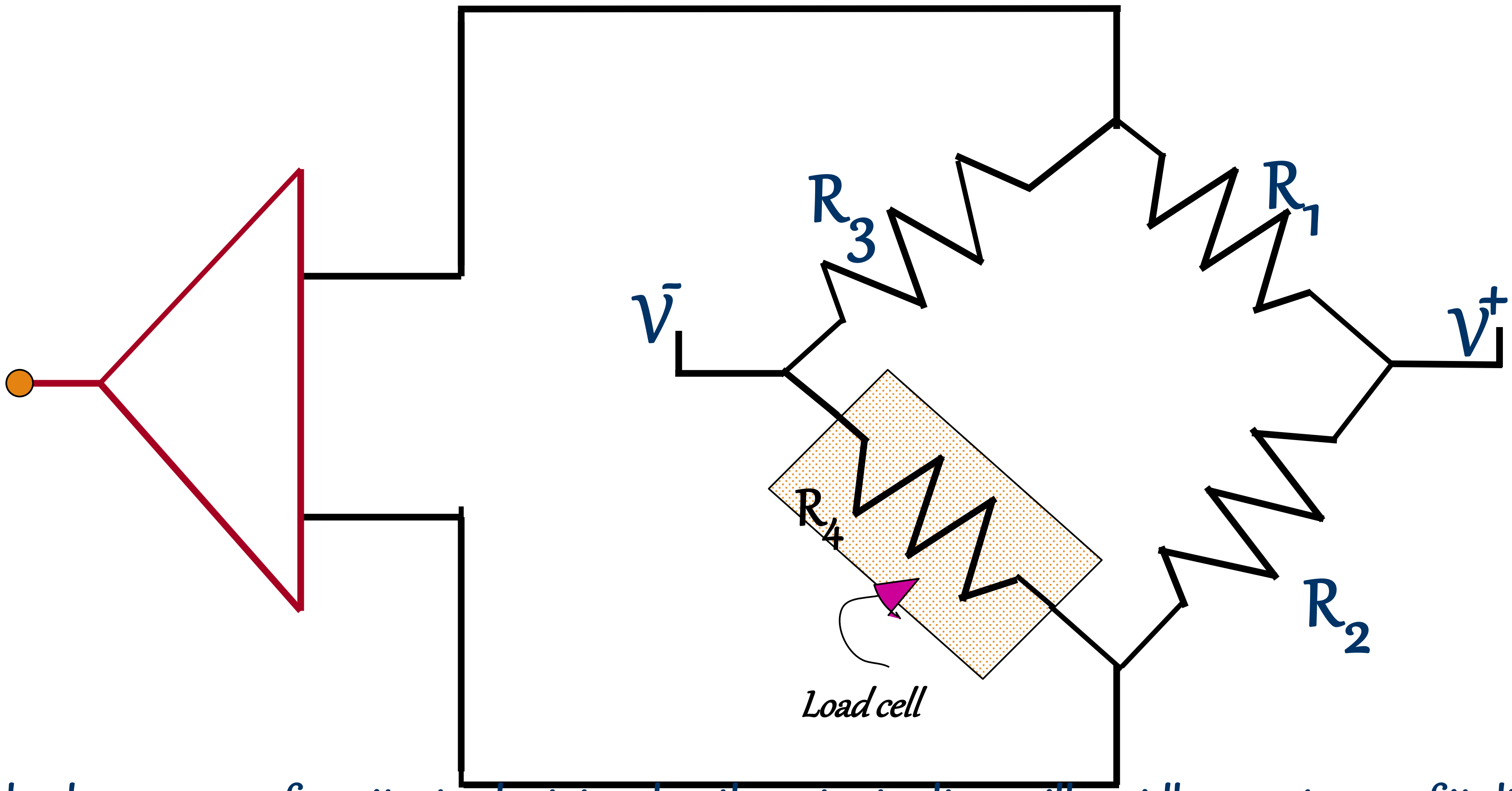
A non zero voltage value here indicates weight on the load cell has left its expected (steady state) value.



Voltage signal here keeps changing if the two inputs to the operational amplifier are not equal.

Operational Amplifier interface to load cell sensor Wheatstone bridge

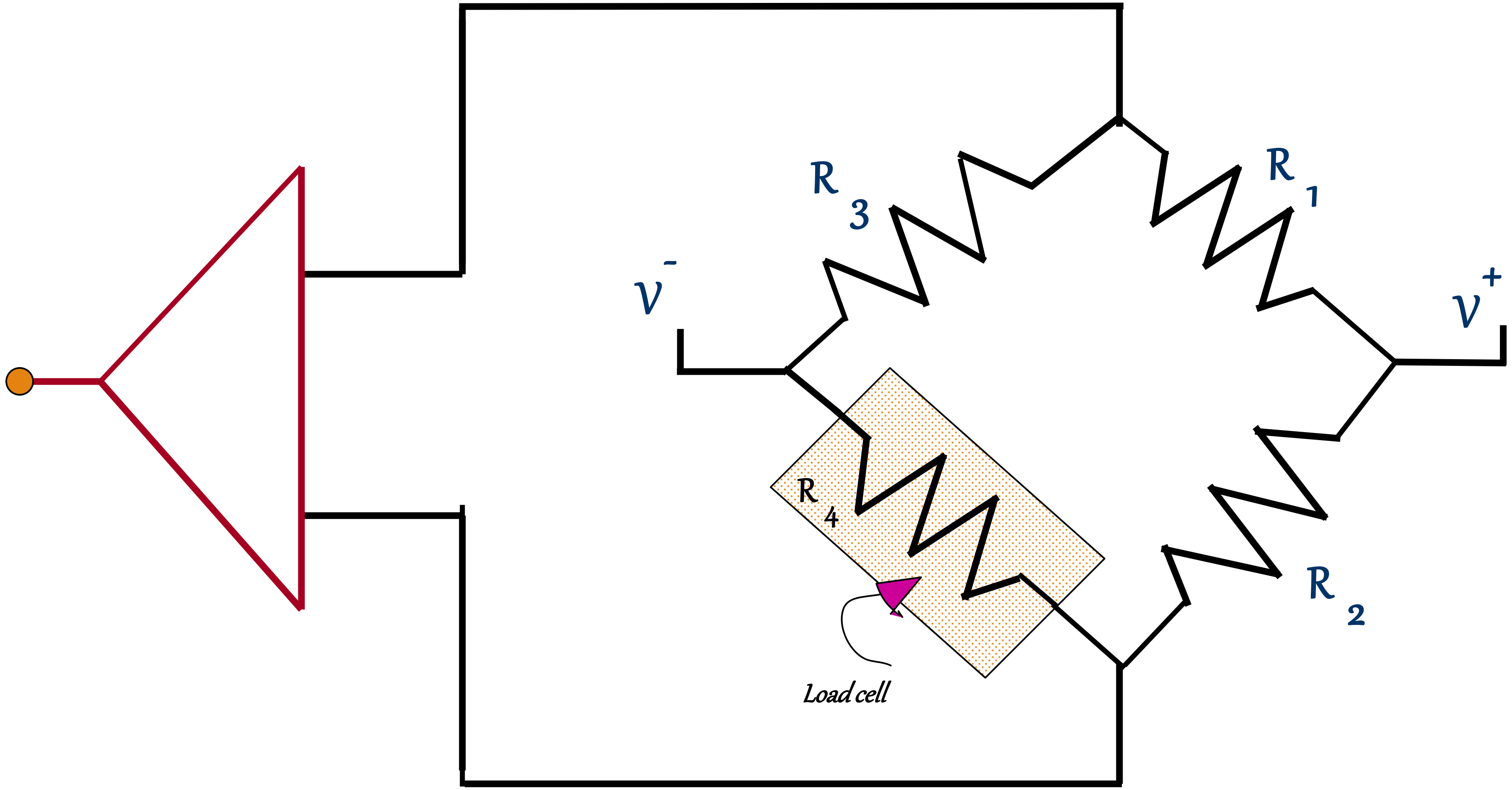
The Wheatstone bridge is "balanced" (output of operational amplifier is zero volts) when the weight on the load cell is at its steady state value.



If the weight of the load moves away from its steady state value, the output voltage will rapidly move to one of its limit saturation voltage values.

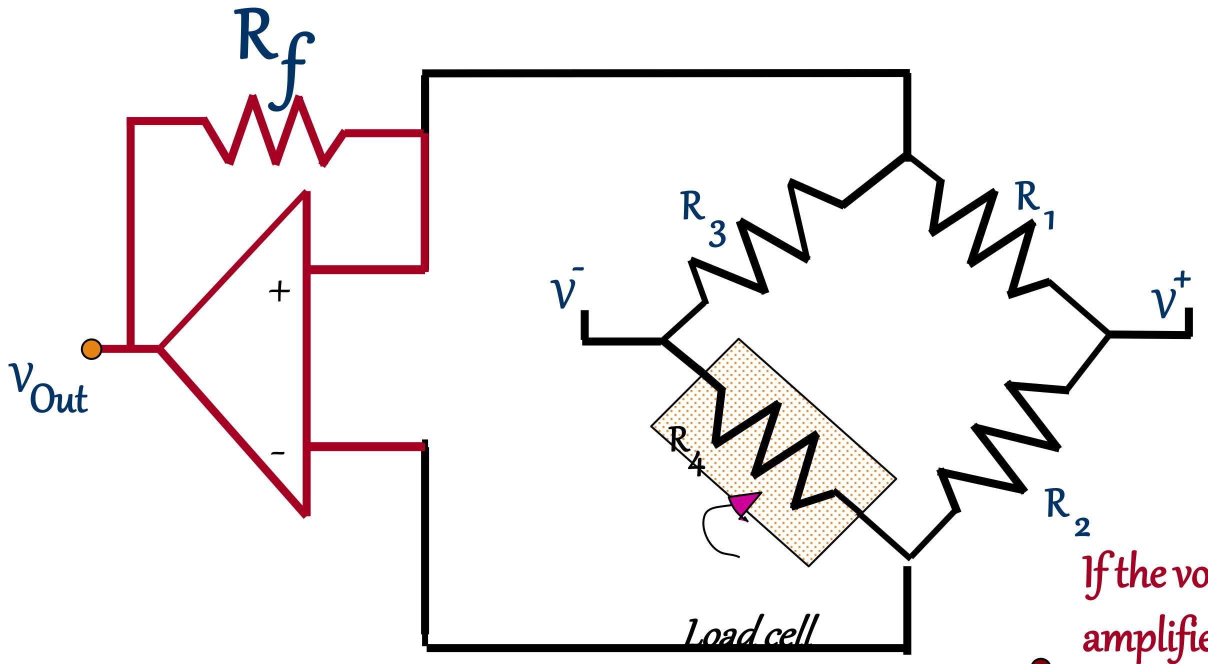
Operational Amplifier interface to load cell sensor Wheatstone bridge

A feedback circuit from the output terminal of the amplifier to one of the input terminals of the amplifier is used to stabilize the output signal at a value that is between zero volts and a maximum (a saturation) value.



Operational Amplifier interface to load cell sensor Wheatstone bridge

A feedback circuit from the output terminal of the amplifier to one of the input terminals of the amplifier is used to stabilize the output signal at a value that is between zero volts and a maximum (a saturation) value.

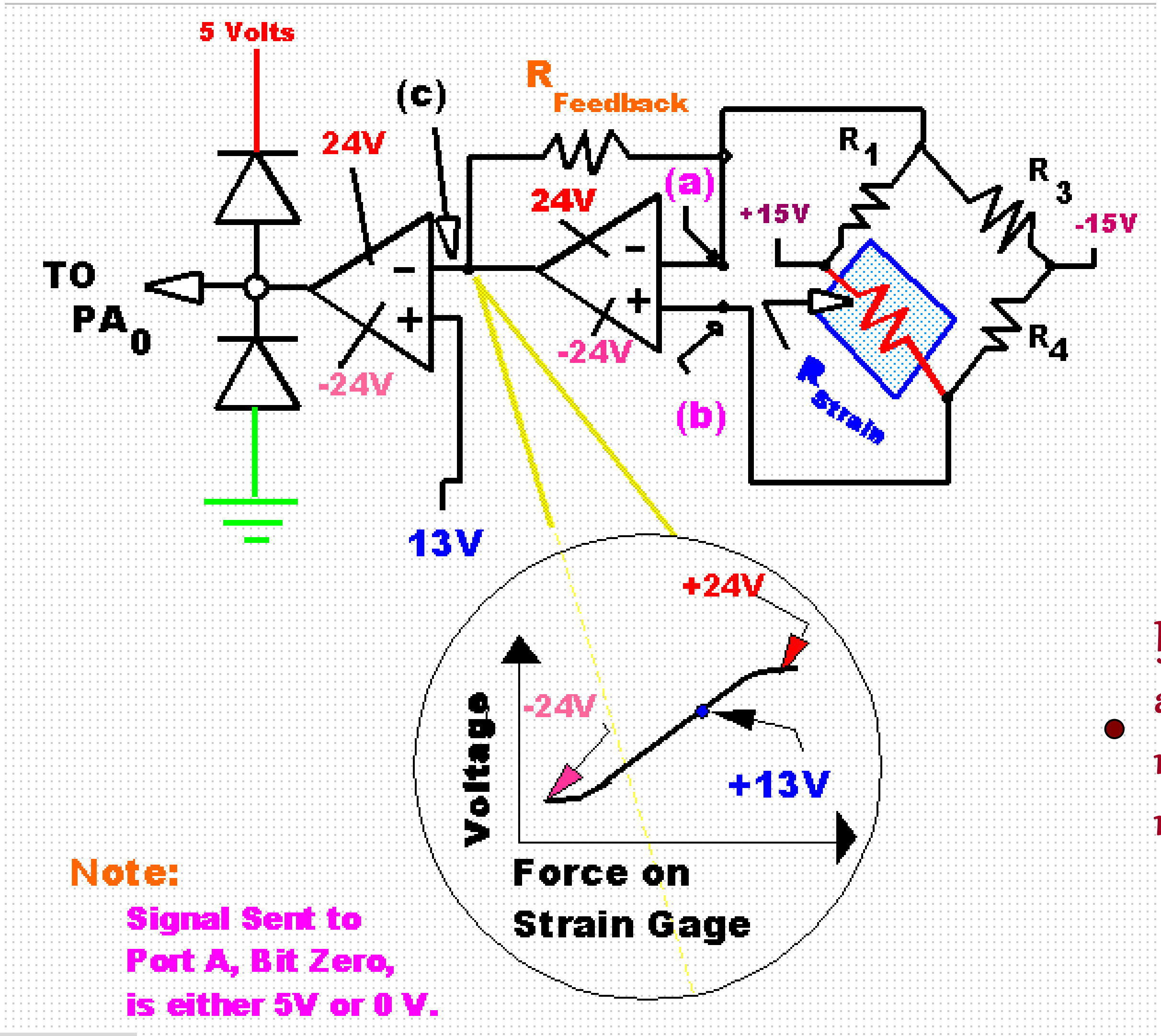


- If the voltage difference across the amplifier inputs increases (becomes more positive) the output signal increases (becomes more positive).

$$V_{out}\ a\ \frac{R_f + \triangle R_4}{\triangle R_4}$$

There are several possible feedback circuit arrangements.

This operation amplifier configuration selection is known as a non-inverting amplifier.



7 Strain Gage Op Amp Application

Strain gauge sensor interface example

- If the voltage difference across the amplifier inputs increases (becomes more positive) the output signal moves to its maximum negative value.

There are several possible feedback circuit arrangements.
This operation amplifier configuration selection is known as an inverting amplifier.

OPAMP Applications

Operational Amplifiers

Properties

- open-loop gain: ideally infinite: practical values 20k-200k
  - high open-loop gain → virtual short between + and - inputs
- input impedance: ideally infinite: CMOS opamps are close to ideal
- output impedance: ideally zero: practical values 20-100Ω
- zero output offset: ideally zero: practical value <1mV
- gain-bandwidth product (GB): practical values ~MHz
  - frequency where open-loop gain drops to 1 V/V

Commercial opamps provide many different properties

low noise

low input current

low power

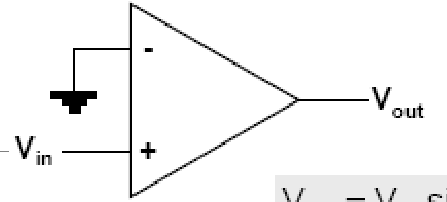
high bandwidth

low/high supply voltage

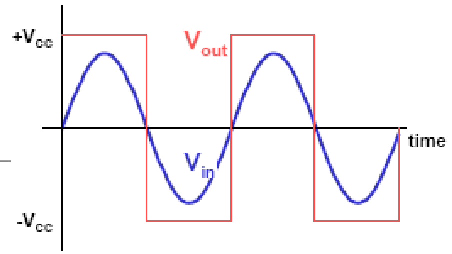
special purpose: comparator, instrumentation amplifier

Basic OPAMP Configuration

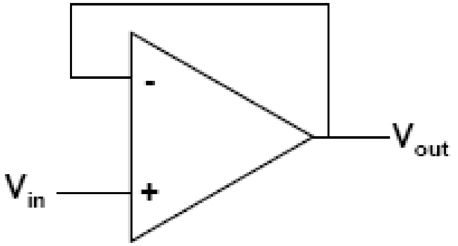
- Voltage Comparator
  - *digitize input*



$$V_{out} = V_{CC}\,\mathrm{sign}(V_{in})$$

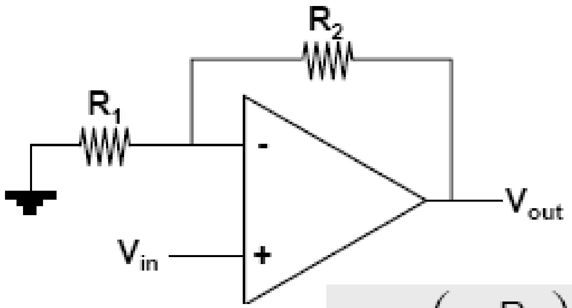


- Voltage Follower
  - *buffer*



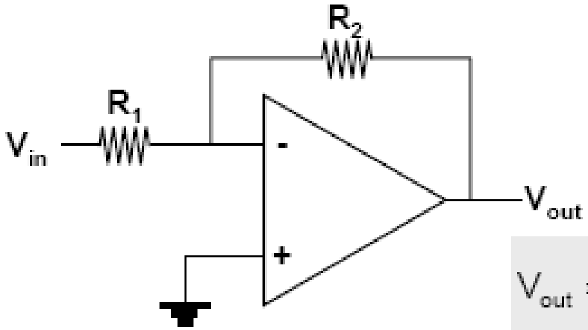
$$V_{out} = V_{in}$$

- Non-Inverting Amp



$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

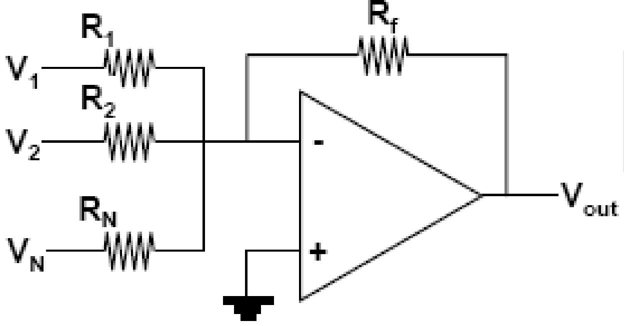
- Inverting Amp



$$V_{out} = -\frac{R_2}{R_1} V_{in}$$

More OPAMP Configurations

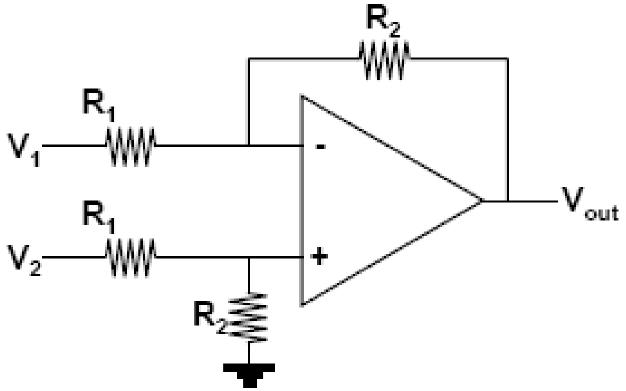
Summing Amp



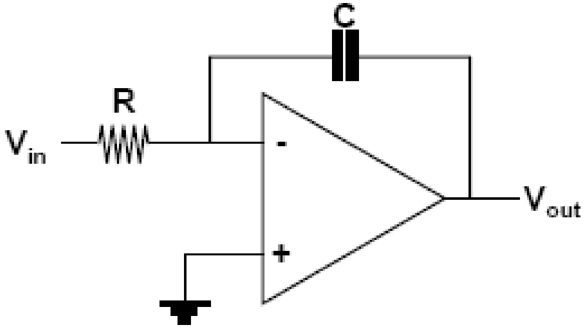
$$V_{out} = -\left(V_1 \frac{R_f}{R_1} + V_2 \frac{R_f}{R_2} + \cdots + V_N \frac{R_f}{R_N}\right)$$

Differential Amp

$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$



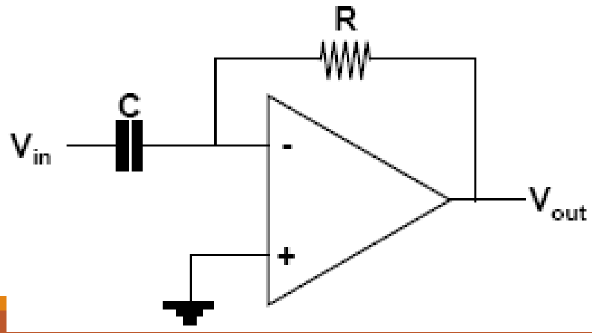
Integrating Amp



$$V_{out} = -\frac{1}{j\omega CR} V_{in} = -\frac{1}{RC}\int V_{in}\,dt$$

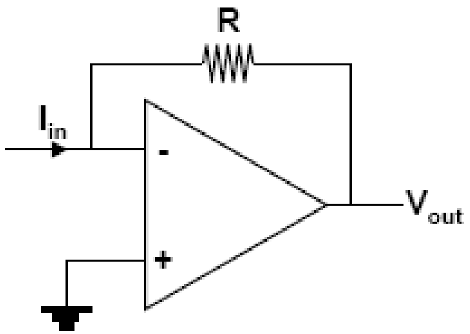
Differentiating Amp

$$V_{out} = -\frac{R}{\frac{1}{j\omega C}} V_{in} = -RC\frac{dV_{in}}{dt}$$



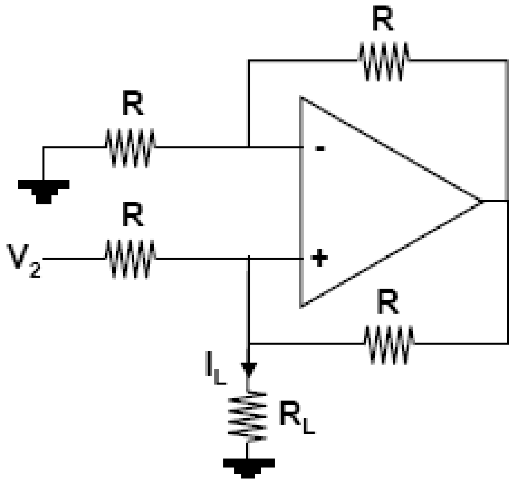
Converting Configuration

Current-to-Voltage



$$V_{out} = -I_{in}R$$

Voltage-to-Current

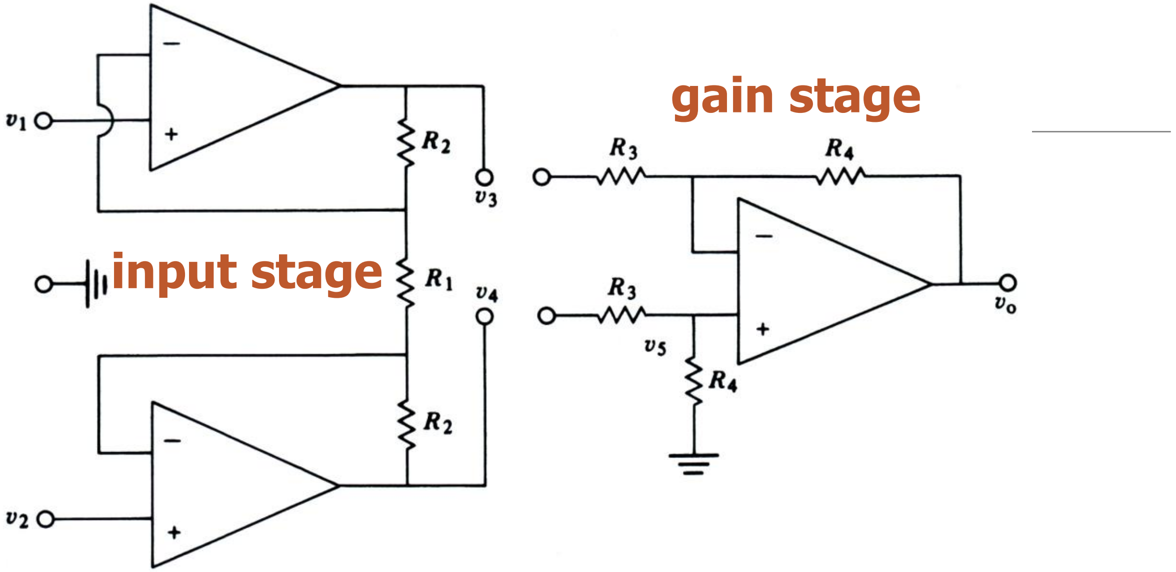


$$I_L = \frac{V_{in}}{R}$$

Instrumentation Amplifier

Robust **differential**

gain amplifier



Input stage
- high input impedance
  - buffers gain stage
- no common mode gain
- can have differential gain

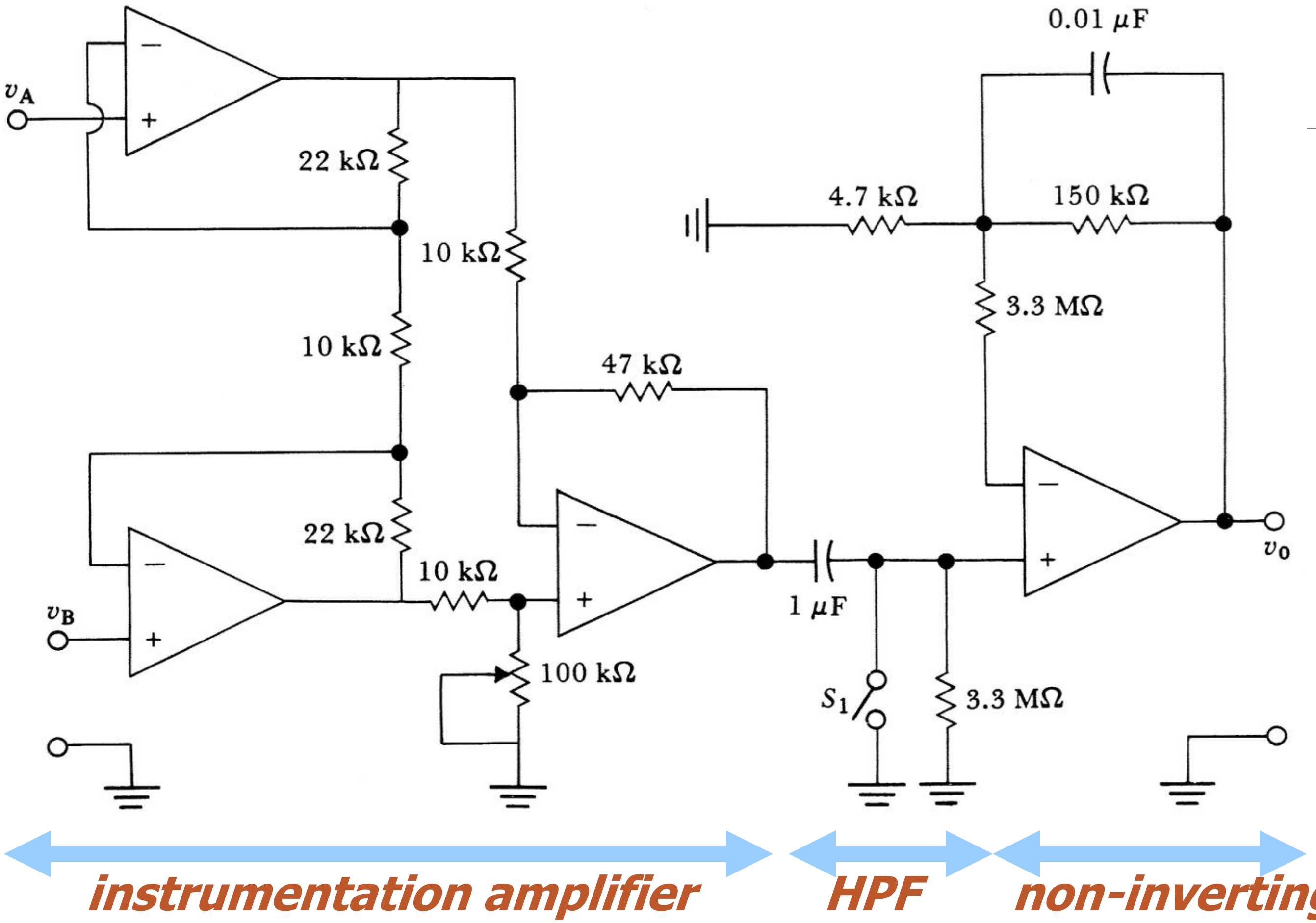
Gain stage
- differential gain, low input impedance

Overall amplifier
- amplifies only the differential component
  - high common mode rejection ratio
- high input impedance suitable for biopotential electrodes with high output impedance

Total differential gain

$$G_d = \frac{2R_2 + R_1}{R_1}\left(\frac{R_4}{R_3}\right)$$

Instrumentation Amplifier



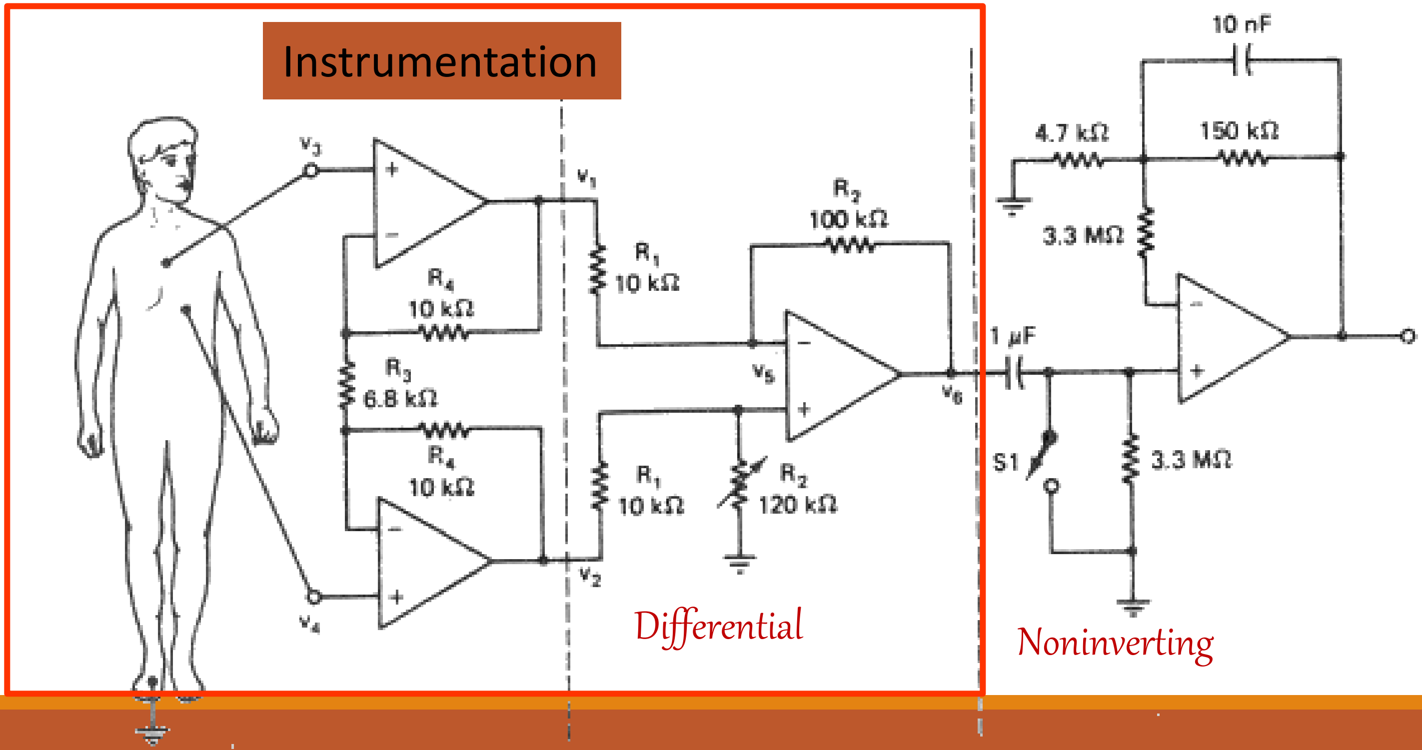
With 776 op amps, the circuit was found to have a CMRR of 86 dB at 100 Hz and a noise level of 40 mV peak to peak at the output. The frequency response was 0.04 to 150 Hz for ±3 dB and was flat over 4 to 40 Hz. The total gain is 25 (instrument amp) x 32 (non-inverting amp) = 800.

Differential Amplifiers

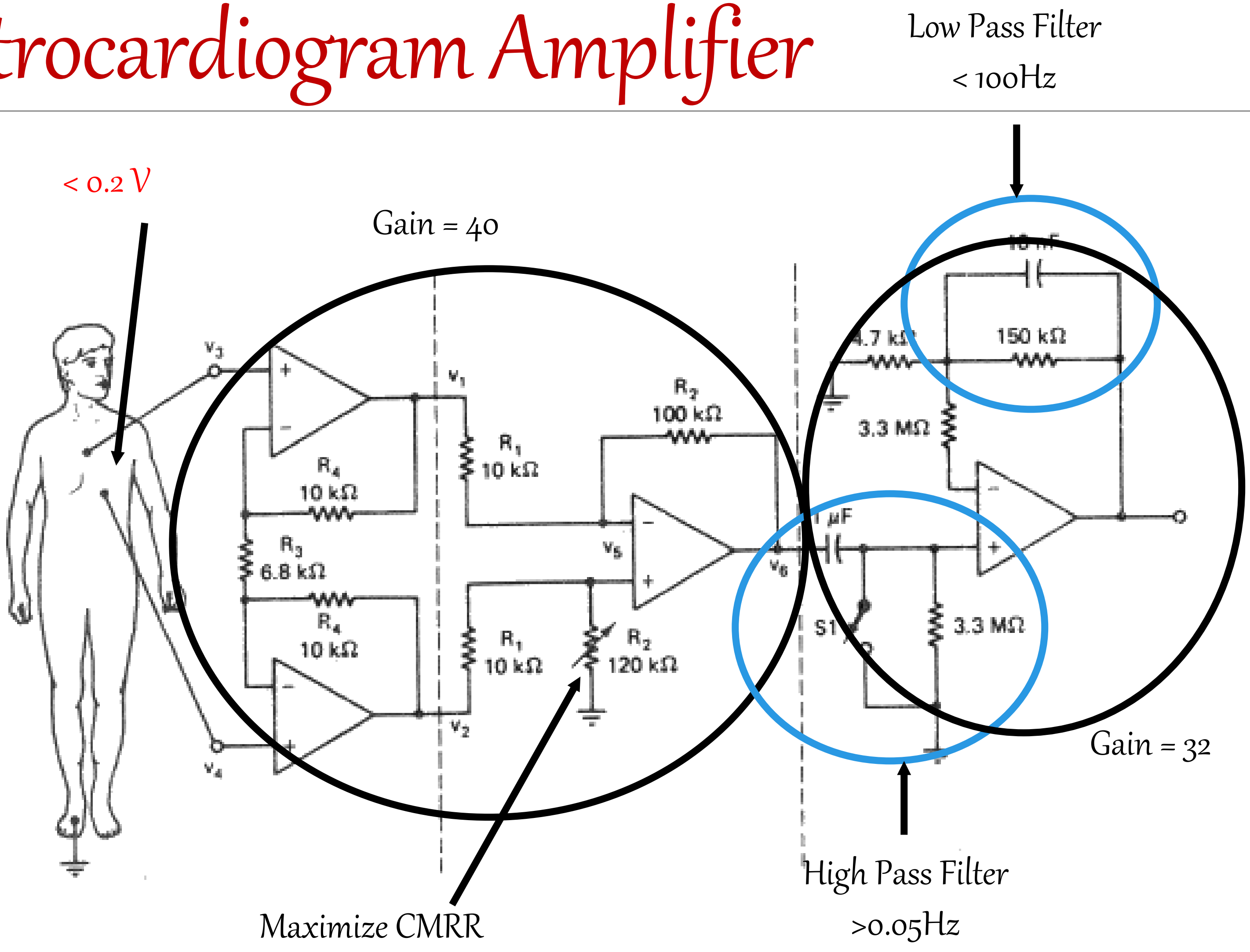
Combination of Inverting and Noninverting Amp

Can reject 60Hz interference

Electrocardiogram amplifier

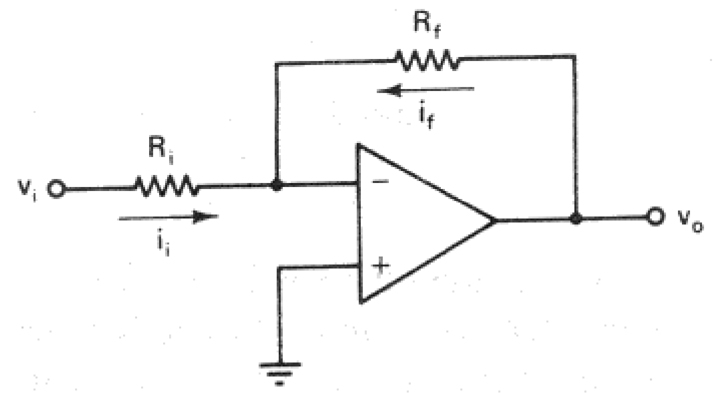


The Electrocardiogram Amplifier



Inverter and Scale Changer

Inverting Amp with Gain = - Rf / Ri



Inverter

- Rf / Ri = 1

Inverter and Scale Changer

- Proper choice of Rf / Ri

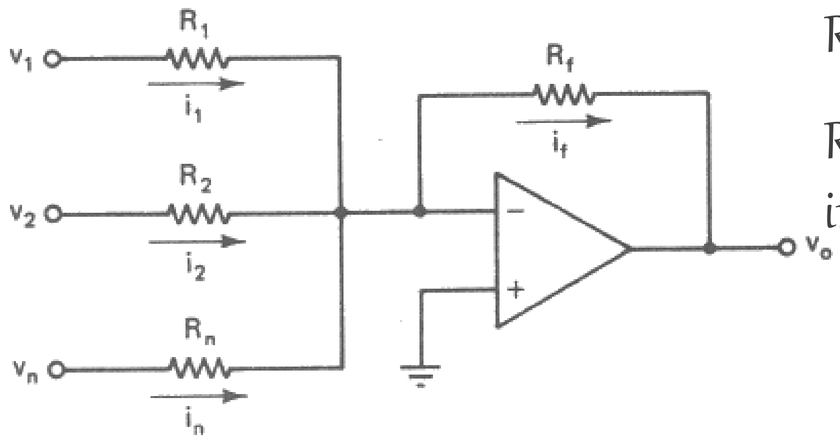
Application

- Use of inverter to scale the output of DAC

Adders (Summing Amplifiers)

Adder

- Inverter with Several inputs



$V_o = -R_f(V_1/R_1 + V_2/R_2 + \ldots + V_n/R_n)$

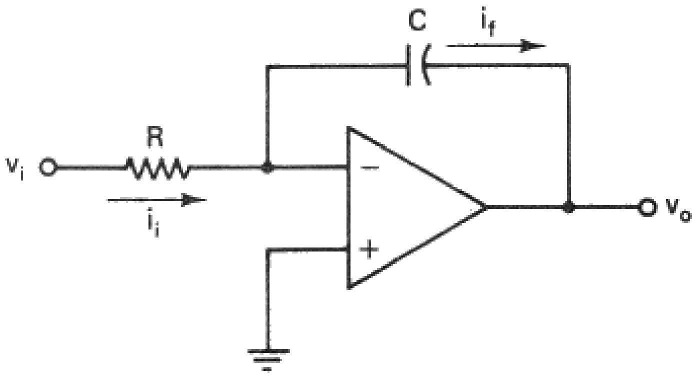
- $I_f = I_1 + I_2 + I_n$
- $I_1 = V_1/R_1, \ldots$
- $V_o = -I_f * R_f$

R_f determines overall Gain

R_i determines the weighting factor and input impedance

Integrator

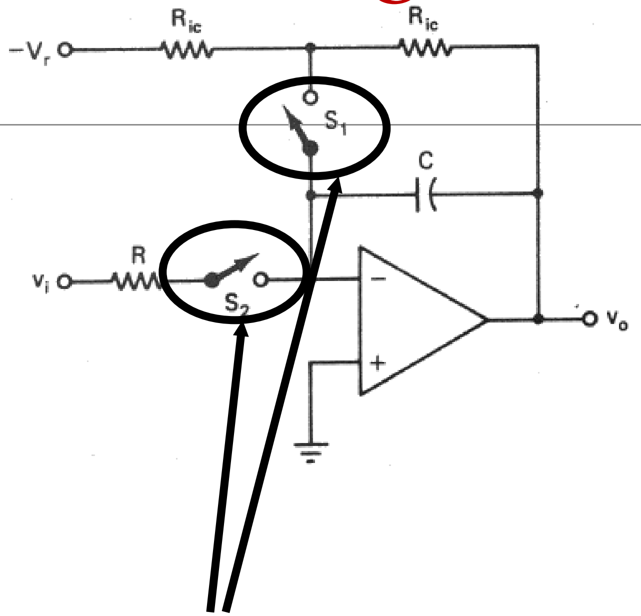
$$v_0 = \frac{-1}{RC}\int_0^{t_1} v_i\,dt + v_{ic}$$



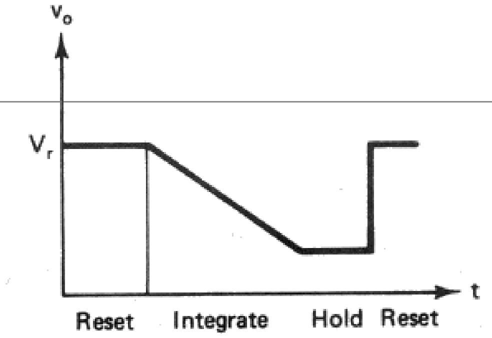
Drawbacks

- Vo will reach saturation voltage, if Vi is left connected indefinitely
  - Integrator operates as an open-loop amplifier for DC inputs

Practical Integrator



Controlled By
Relay or
Solid State Switch or
Analog Switch



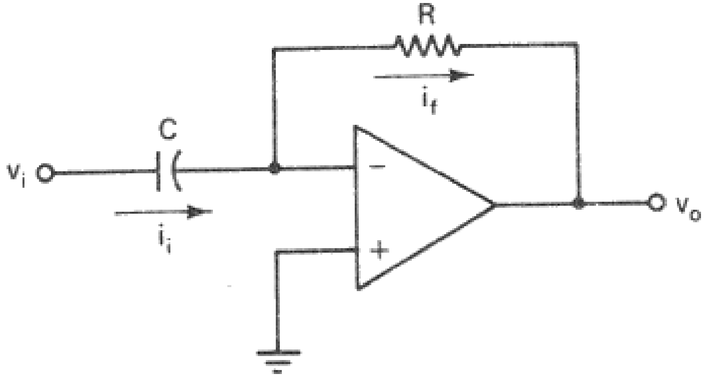
Reset
- S1 Closed, S0 Open
  - Inverter
  - C is initialized to Vr

Integrate
- S1 Open, S0 Closed

Hold
- S1 Open, S0 Open
- Keeps Vo constant
  - Read and Process

Differentiators

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



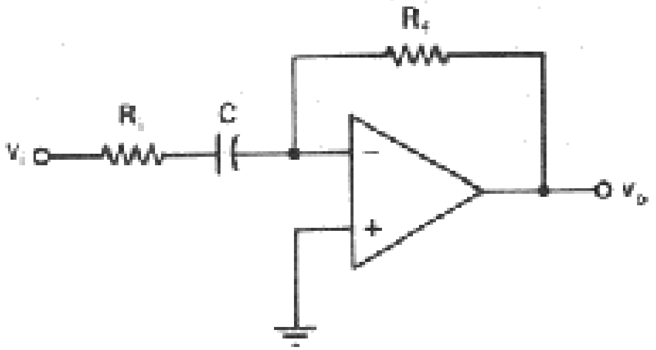
Drawbacks

- Instability at High frequencies

Practical Differentiator

- Stable

$$R_i = \sqrt{\frac{R}{A_0\omega_0 C}}$$



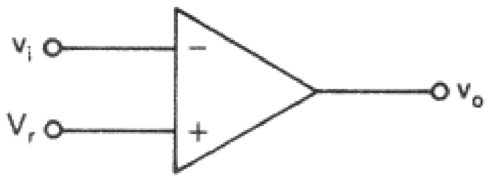
Comparators

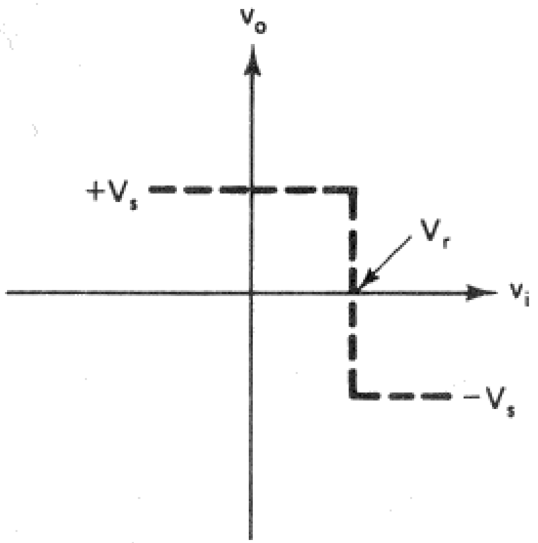
Compare Two Inputs

- $V_i > V_r$
  - $V_o = -V_s$
- $V_i < V_r$
  - $V_o = V_s$

Drawbacks

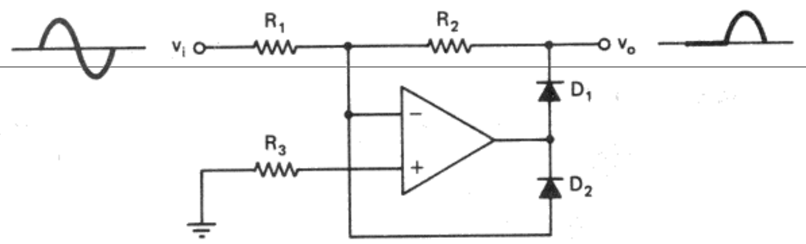
- If $V_i = V_r$ + small noise
  - Rapid fluctuation between $\pm V_s$



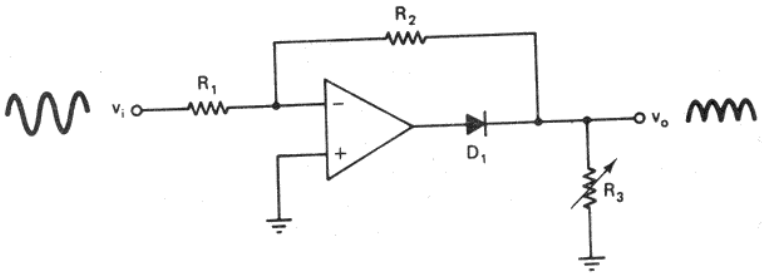


Rectifiers

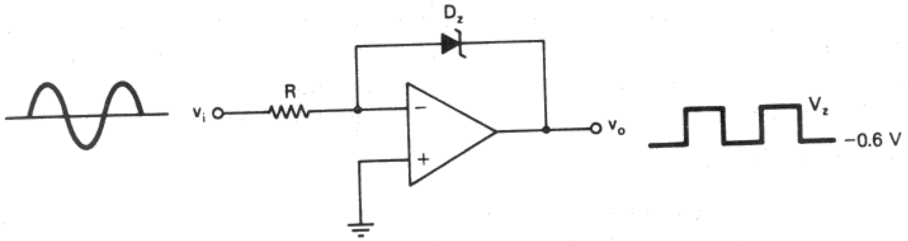
Precision Half Wave Rectifier



Precision Full Wave Rectifier

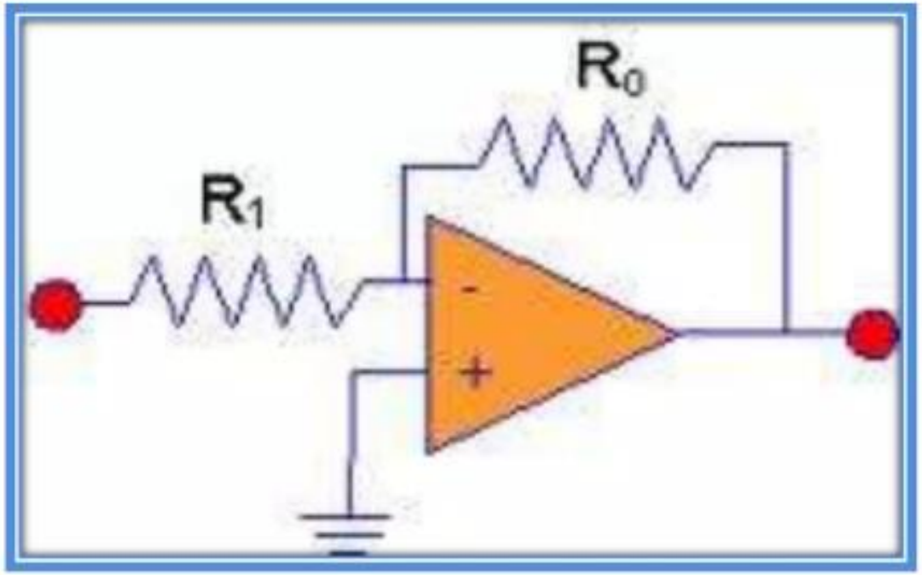


Limiters



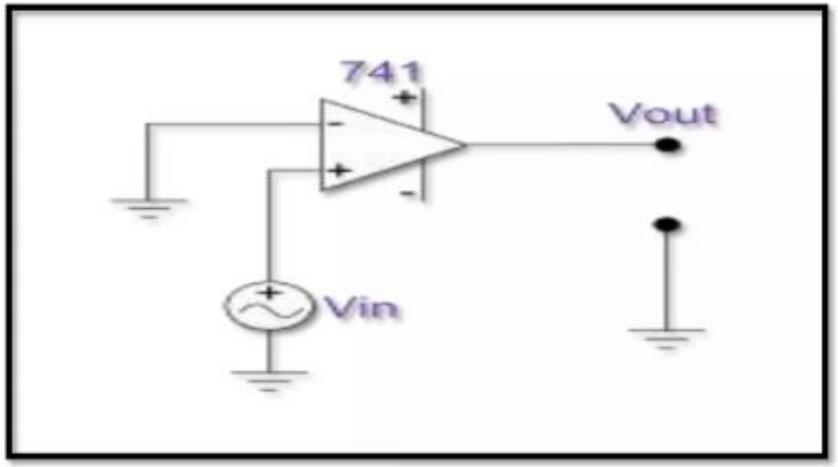
OPAMP as a Current Source

A current source can be made from an inverting amplifier as shown in figure. The current in the load resistor, R_0 must be equal to the current in R_1. The current is then obtained by dividing the input voltage by R_1.



OPAMP as a Zero Crossing Detector

ZCD circuit can be used to check whether the op-amp is in good condition. Zero crossing detectors can be used as frequency counters and for switching purposes in power electronics circuits. ZCD is a basic op amp circuit.



Module 5 ends!