Xi'an Jiaotong-Liverpool University
西交利物浦大学

MEC208 Instrumentation and Control System

2024-25 Semester 2

Dr. Yuqing Chen

Email: Yuqing.chen@xjtlu.edu.cn

Office: EB330

Department of Mechatronics and Robotics

School of Advanced Technology

Lecture 4

Outline

Signal Conditioning

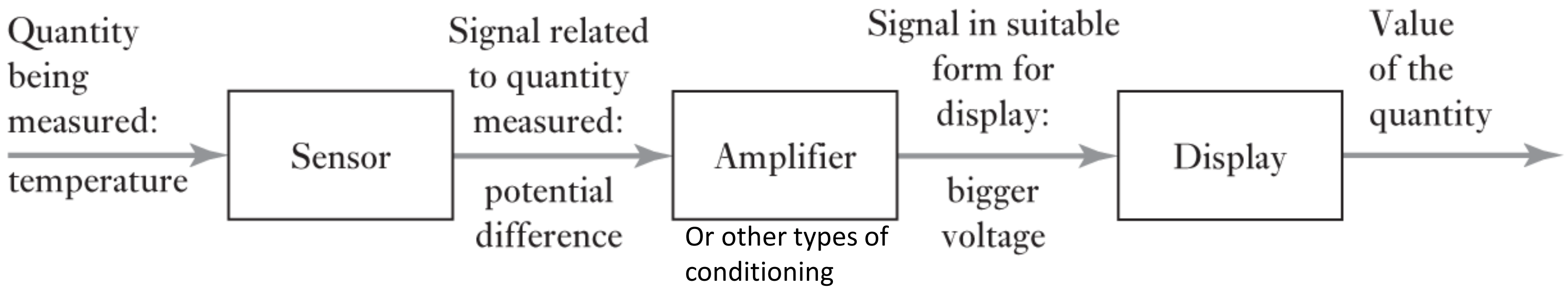
- ❑ **What is Signal Condition**
- ❑ **Wheatstone Bridge**
  - Basics
  - Temperature Compensation
- ❑ **Amplifiers**
- ❑ **Protection Circuit**
- ❑ **Filters**

What is Signal Conditioning?

The output signal from the sensor of a measurement system has generally to be processed in some way to make it suitable for the next stage of the operation. The signal may be, for example,

- too small and have to be amplified,
- contain interference, 干涉
- be non-linear and require linearization,
- be analogue and have to be made digital,
- be a resistance change and have to be made into a voltage change etc.

All these changes can be referred to as **signal conditioning**.



Signal Conditioning Elements

Signal conditioning can involve protection to prevent damage to the next element in a system, getting a signal into the form required, getting the level of a signal right, reducing noise, manipulating a signal to perhaps make it linear.

Commonly used signal conditioning elements are:

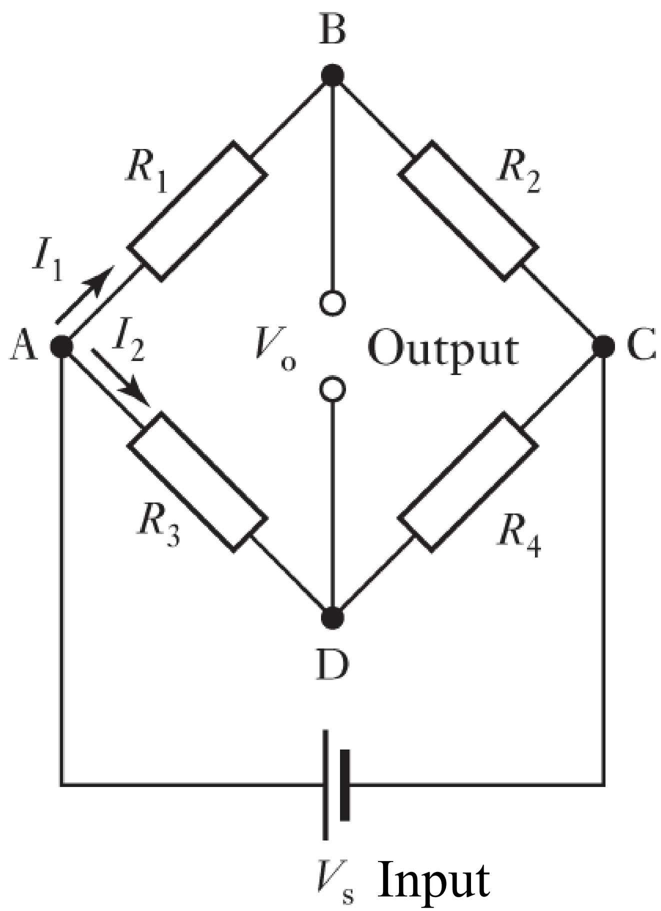
- *Wheatstone bridge*
- *Protection elements*
- *Filters*
- *Operational amplifiers*
- *Signal modulators*

Outline

Signal Conditioning

- ❑ **What is Signal Condition**
- ❑ **Wheatstone Bridge**
  - **Basics**
  - Temperature Compensation
- ❑ **Amplifiers**
- ❑ **Protection Circuit**
- ❑ **Filters**

Wheatstone Bridge



The **Wheatstone bridge** can be used to convert a resistance change to a voltage change and can detect very small changes in resistance.

The bridge is said to be balanced if:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

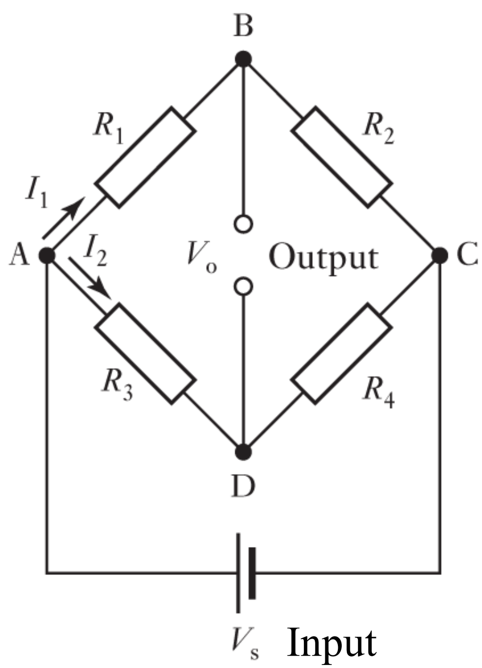
Then the output voltage

$$V_o = V_B - V_D = V_s\left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4}\right)$$

$$= 0.$$

Wheatstone Bridge Application

Consider R_2 to be a sensor which has a resistance change. A change in resistance from R_2 to $R_2 + \delta R$ gives a change in output from V_o to $V_o + \delta V_o$:



$$V_o + \delta V_o = V_s\left(\frac{R_2 + \delta R}{R_1 + R_2 + \delta R} - \frac{R_4}{R_3 + R_4}\right)$$

$$\delta V_o = V_s\left(\frac{R_2 + \delta R}{R_1 + R_2 + \delta R} - \frac{R_2}{R_1 + R_2}\right)$$

If δR is much smaller than R_2, then the above equation approximates to:

$$\delta V_o \approx V_s\left(\frac{\delta R}{R_1 + R_2}\right)$$

With this approximation, the change in output voltage is thus proportional to the changes in the resistance of the sensor (when there is no load resistance across the output. If there is such a resistance then the loading effect has to be considered).

Bridge Balancing

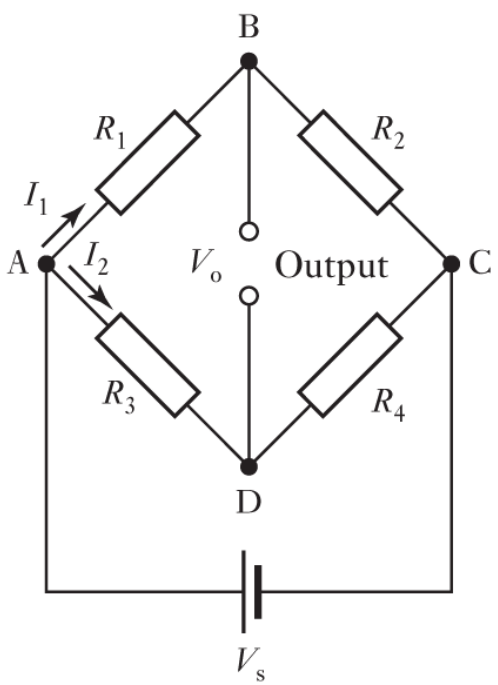
When a bridge is installed, it is very unlikely that the bridge will output exactly zero volts when no strain/temperature change is applied. Rather, slight variations in resistance among the bridge arms and lead resistance will generate some nonzero initial offset voltage.

There are a few different ways that a system can handle this initial offset voltage:

- **Software Compensation**: compensates for the initial voltage in software. If the offset is large enough, it limits the amplifier gain that can be applied to the output voltage, thus limiting the dynamic range of the measurement;
- **Offset-Nulling Circuit**: uses an adjustable resistance, or potentiometer, to physically adjust the output of the bridge to zero;
- **Buffered Offset Nulling**: a nulling circuit adds an adjustable DC voltage to the output of the instrumentation amplifier.

Example 5.1

Consider a platinum resistance temperature sensor which has a resistance at 0°C of 100 Ω and forms one arm of a Wheatstone bridge (supply voltage: 6.0 V). The bridge is balanced, at this temperature, which each of the other arms also been 100 Ω. If the temperature coefficient of resistance of platinum is 0.0039/K, what will be the output voltage per degree change in temperature if the load across the output can be assumed to be infinite?



The variation of the resistance of the platinum with temperature:

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

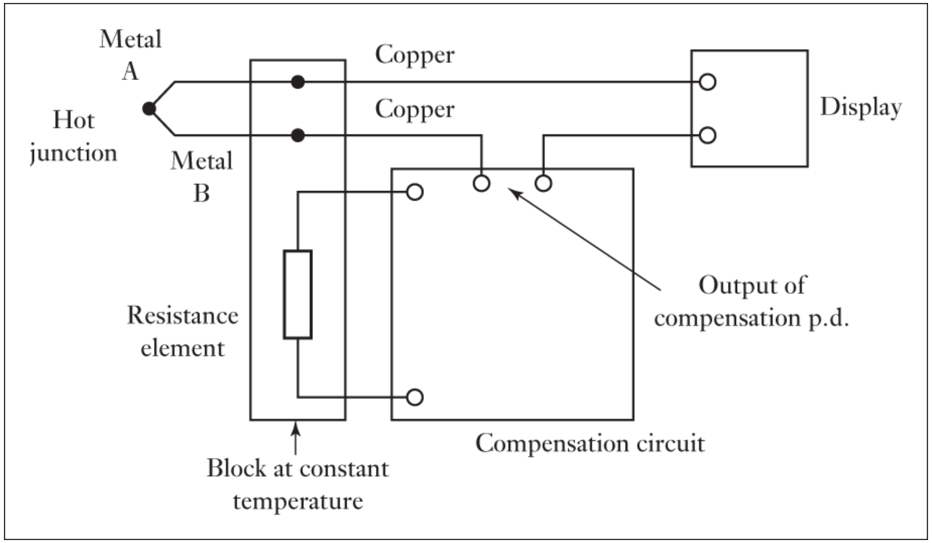
Thus change in resistance caused by per degree change refer to the 1st order derivative:

$$\frac{dR_T}{dT} = R_0\alpha = 100 \times 0.0039 = 0.39\Omega/K$$

Since the resistance change is small compared with the 100 Ω, the approximate equation can be used, hence:

$$\frac{d\ \delta V_0}{dT} \approx V_s\left(\frac{d\ \delta R/dT}{R_1 + R_2}\right) = \frac{6.0 \times 0.39}{100 + 100} = 0.012V/K$$

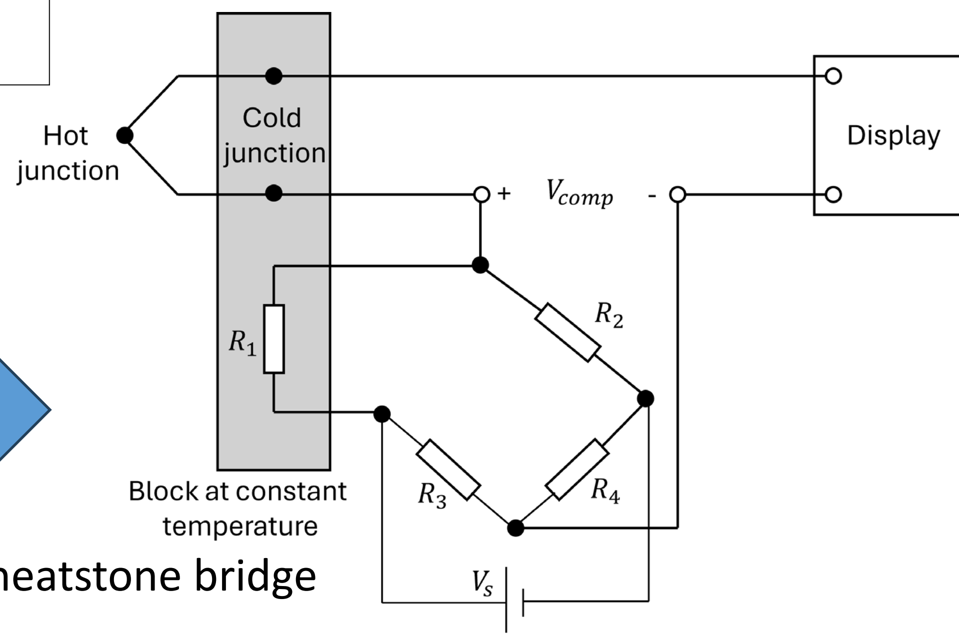
Cold Junction Compensation



Received by display   Compensated by circuit

$$E_{T,0} = E_{T,I} - E_{I,0}$$

Measured from thermocouple



The output of Wheatstone bridge should be $E_{I,0}$

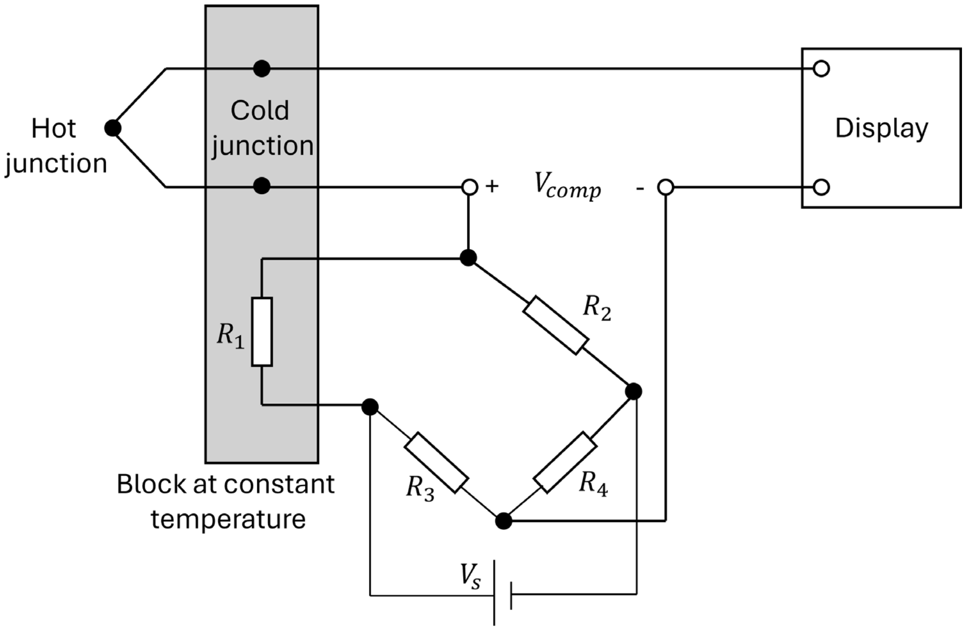
Cold Junction Compensation

- Choose RTD as the temperature detector

$$R_1 = R(1 + \alpha T_c) \Rightarrow \delta R = \alpha R T_c$$

- Output of the Wheatstone bridge

$$V_{comp} \propto \delta R \Rightarrow V_{comp} \propto T_c$$

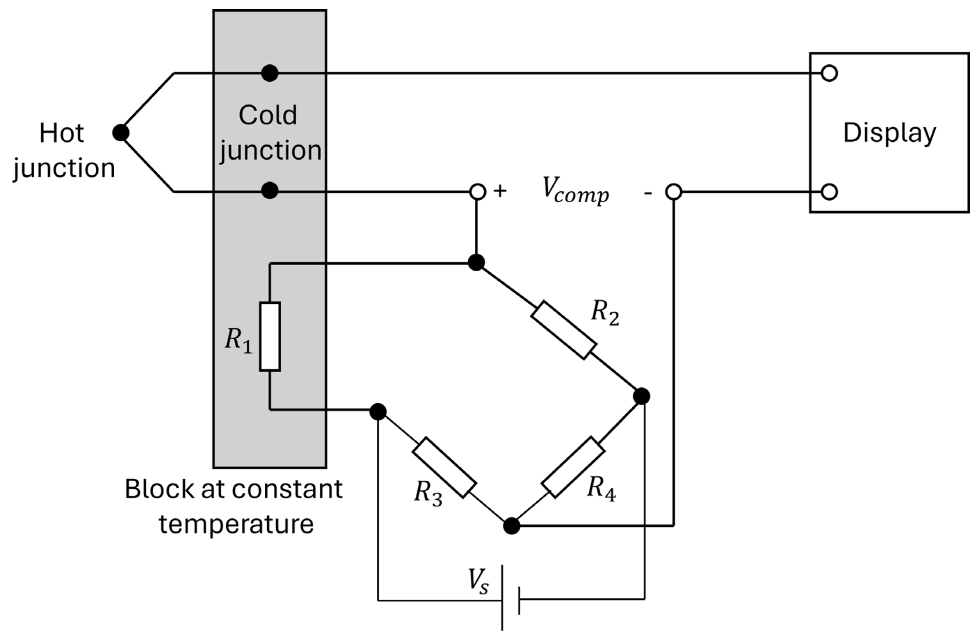


Cold Junction Compensation

- Desired output of Wheatstone bridge should be $E_{I,0}$

$$E_{I,0} = kT_c$$

- We can establish equality between $E_{I,0}$ and V_{comp}, and adjust the bridge to setup the compensation circuit



Outline

Signal Conditioning

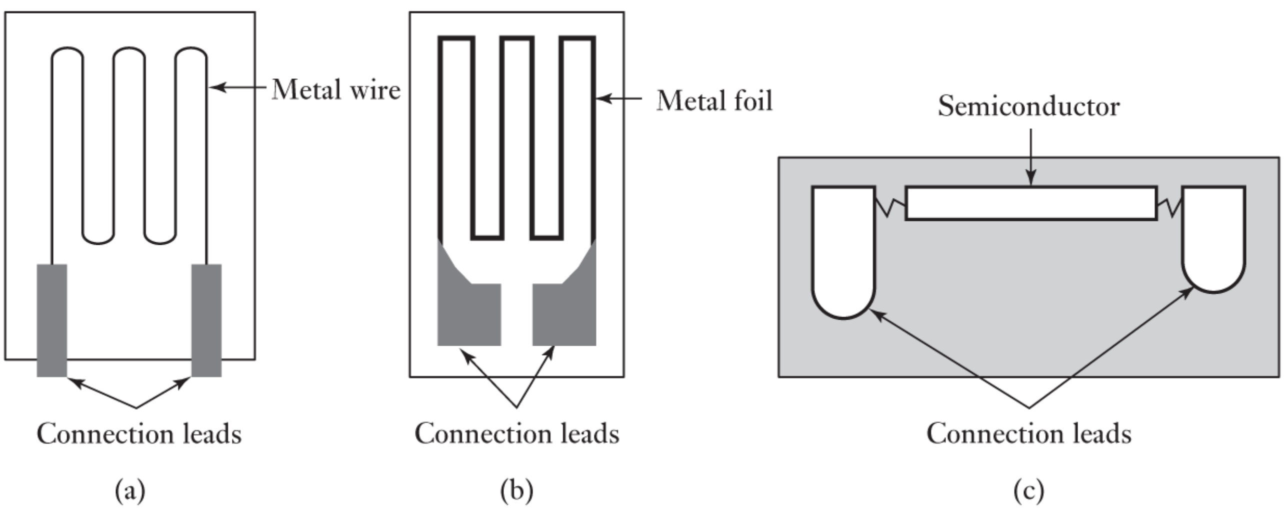
- ❑ **What is Signal Condition**
- ❑ **Wheatstone Bridge**
  - Basics
  - **Temperature Compensation**
- ❑ **Amplifiers**
- ❑ **Protection Circuit**
- ❑ **Filters**

Temperature Compensation for Strain Gauge

Recall of **Strain gauge**: sensor used to measure very small strain.

The major **problem**: gauge resistance changes not only with stain, but also with temperature. Especially for semiconductor strain gauges, which have a great sensitivity to temperature.

Fig. Three types of strain gauges.



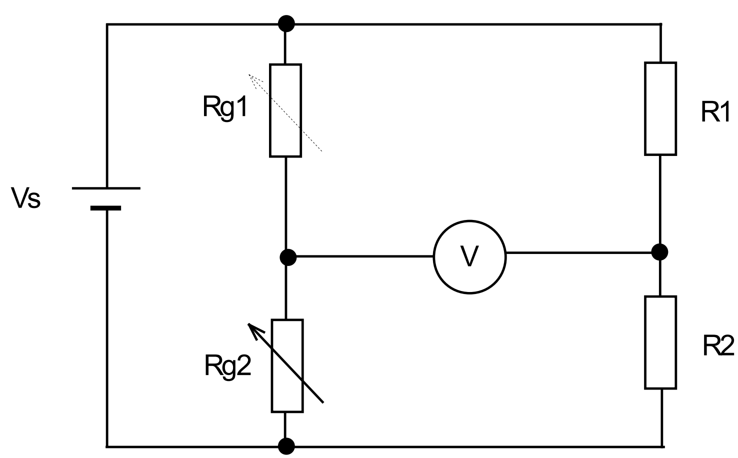
$$\frac{\Delta R}{R} = G\varepsilon$$

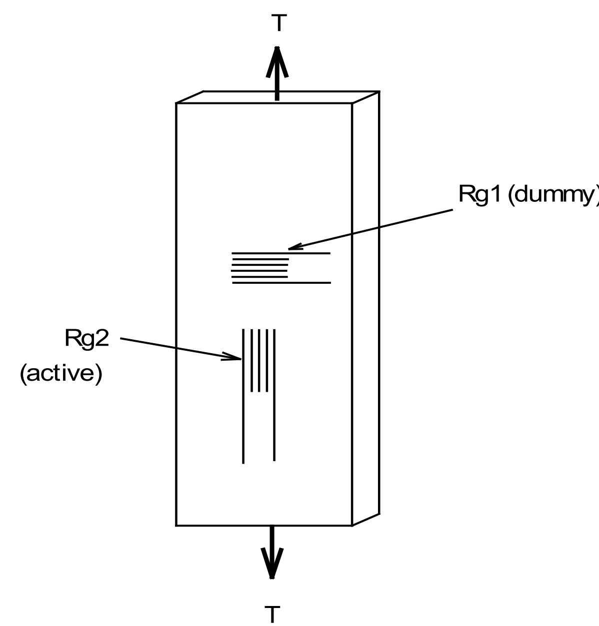
Temperature Compensation for Strain Gauge

One way of eliminating the temperature effect is to use a **dummy** strain gauge.

伪

- This dummy strain gauge is identical to the one under strain, i.e., the active gauge, and is mounted on the same material but is **NOT** subject to the strain.
- The dummy strain gauge is positioned close to the active gauge so that it is suffered from the same temperature change.
- The active gauge is mounted in one arm of the Wheatstone bridge, and the dummy gauge in the other arm, so the effects of temperature-induced resistance changes cancel out.

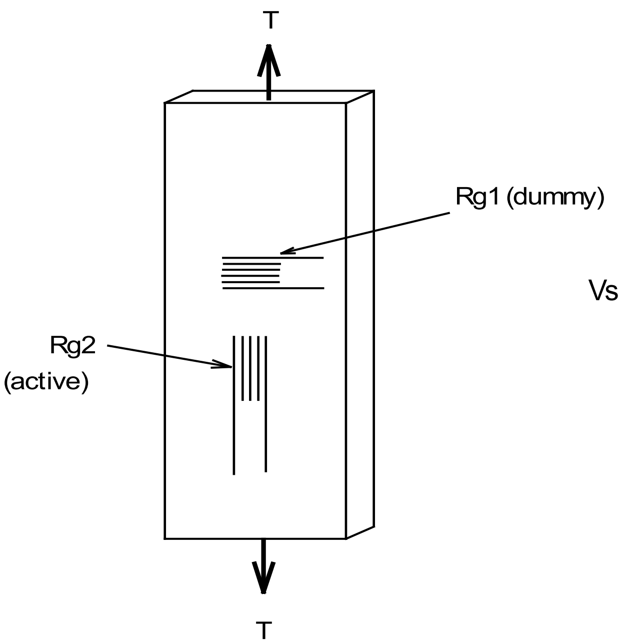


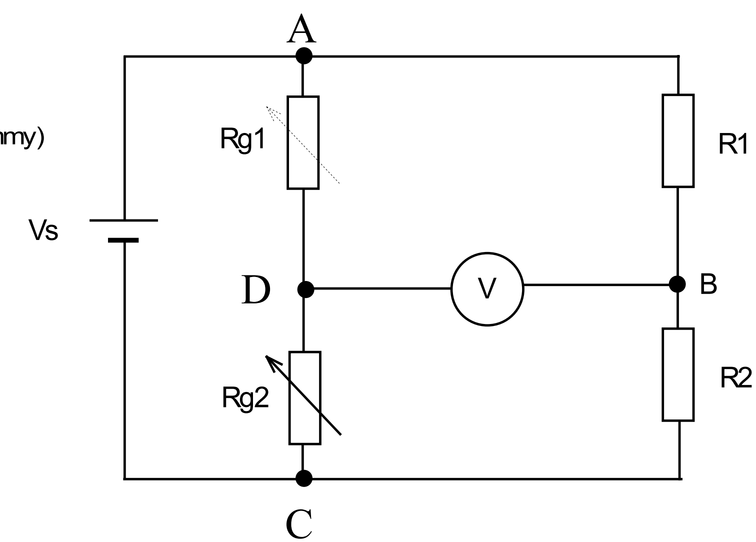


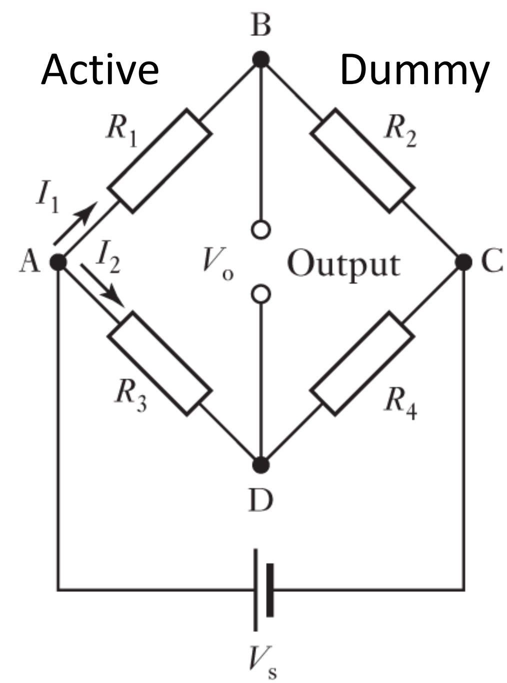
Temperature Compensation for Strain Gauge

Single active gauge plus one 'dummy' gauge

Used to measure tensile strain and provide temperature compensation

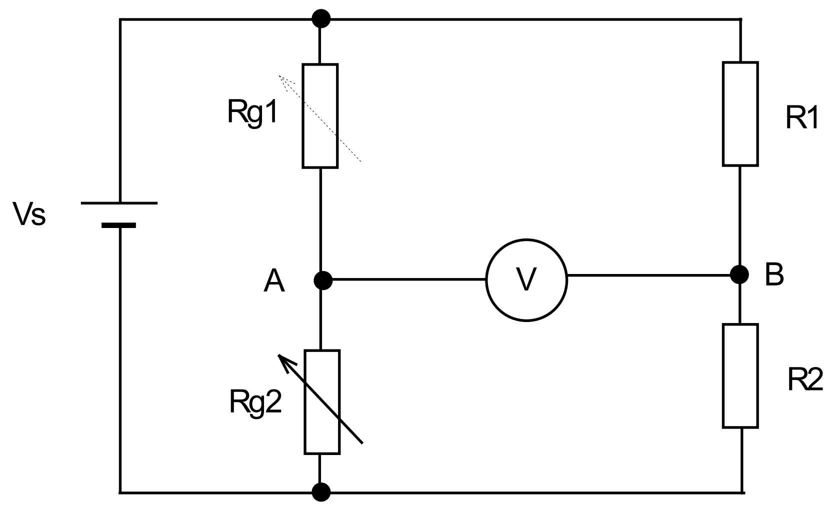






Note that temperature changes affect both gauges but this does not affect the bridge balance. Longitudinal strain however, only affects $Rg2$ and this produces an out of voltage from the bridge.

Analysis



No strain change:

$$V_{out} = V_A - V_B$$

$$= V_s\left(\frac{Rg2}{Rg1+Rg2} - \frac{R2}{R1+R2}\right)$$

$$= 0$$ at original balance.

Analysis

Note that a temperature change will cause the same fractional change to both Rg1 and Rg2 so that the ratio $\frac{Rg2}{Rg1+Rg2}$ is unaffected.

However, when subjected to strain, only Rg2 becomes:

$$Rg2 + \Delta Rg2 = Rg2\left(1 + \frac{\Delta Rg2}{Rg2}\right) = Rg2(1 + G\varepsilon)$$

$Note: \frac{\Delta R}{R} = G\varepsilon$

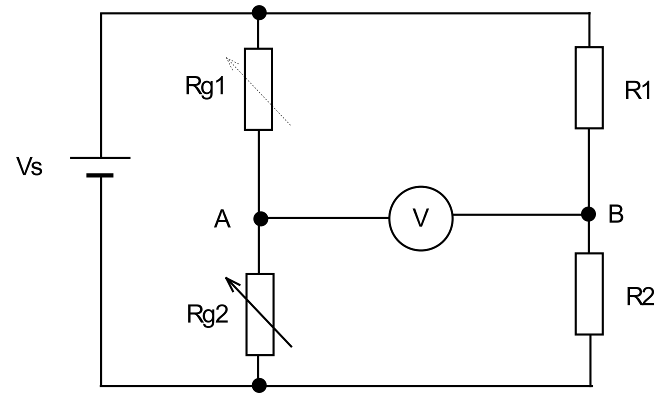
where ε = strain = $\Delta L/L$.

Therefore,

$$V_{out} = V_s\left(\frac{Rg2(1 + G\varepsilon)}{Rg1 + Rg2(1 + G\varepsilon)} - \frac{R2}{R1 + R2}\right)$$

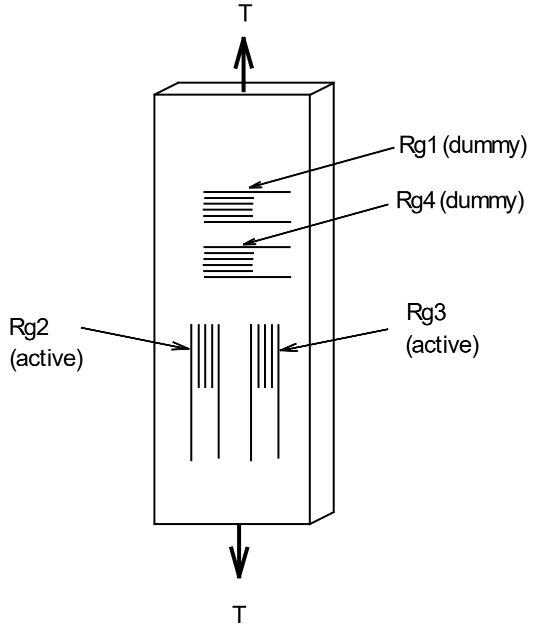
so if $Rg1 = Rg2 = Rg$ and $R1 = R2$, then

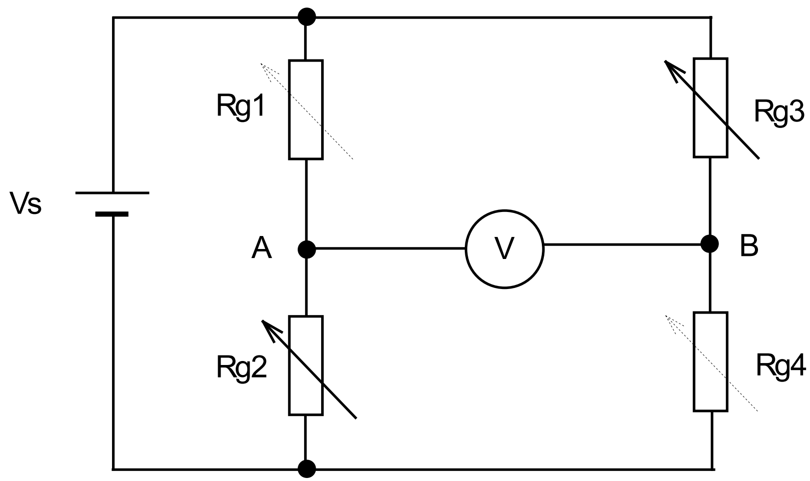
$$\begin{aligned} V_{out} &= V_s\left(\frac{Rg(1 + G\varepsilon)}{Rg + Rg(1 + G\varepsilon)} - \frac{1}{2}\right) \\ &= V_s\left(\frac{(1 + G\varepsilon)}{1 + (1 + G\varepsilon)} - \frac{1}{2}\right) \\ &= V_s\left(\frac{G\varepsilon}{2(2 + G\varepsilon)}\right) \approx V_s\frac{G\varepsilon}{4} \end{aligned}$$



2 Active + 2 Dummy Gauges

Two active gauges and two 'dummy' gauges





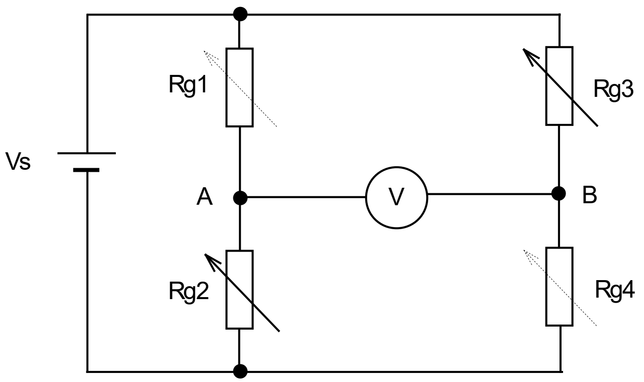
Note the position of the gauges in the bridge are chosen so that :

1) their effects reinforce one another to give double the output voltage of a single active gauge bridge

$$V_o = V_s \frac{G\varepsilon}{2}$$

2) Temperature compensation is achieved.

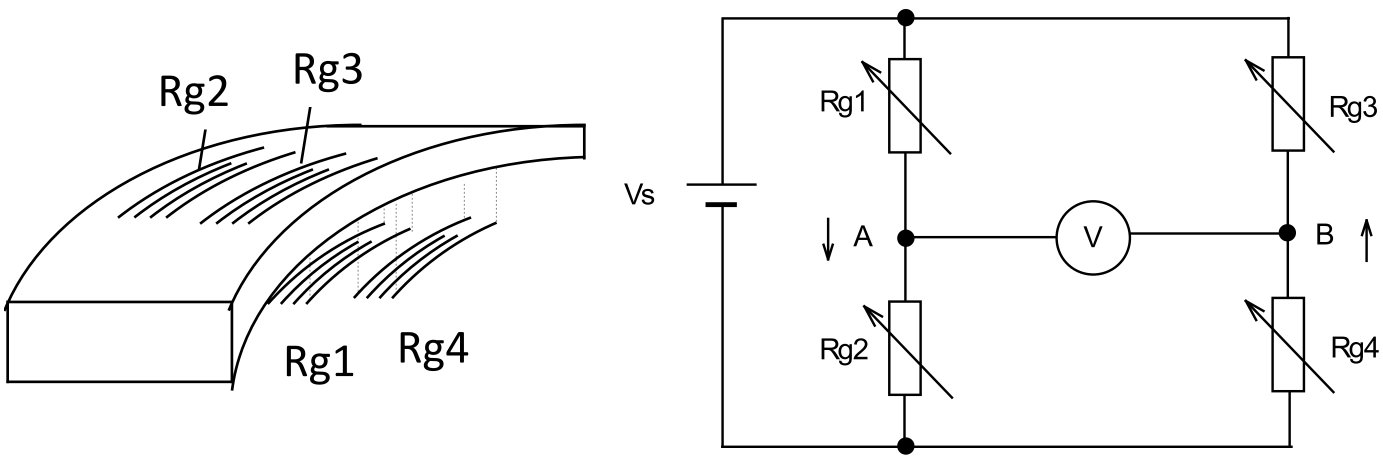
Analysis



$$V_o = V_s \frac{G\varepsilon}{2}$$

4 Active Gauges

Four active gauges - Bending strain



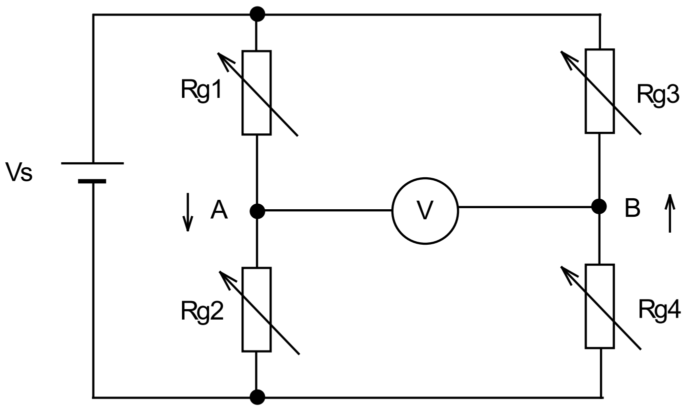
Note the position of the gauges in the bridge are chosen so that :

1) their effects reinforce one another to give four times the output voltage of a single active gauge bridge

$$V_{out} = V_s G \varepsilon$$

2) Temperature compensation is achieved.

Analysis



$$V_{out} = V_s G \varepsilon$$

Amplification of the Bridge Output Voltage

Note the even the four active gauge bridge typically only produces a very small output voltage.

For example, for a four active gauge bridge, $V_{out} = V_s G\varepsilon$

If ε = 1μ (strain = 10^{-6}), V_s = 10 volts , G = 2.2 , then

$$V_{out} = 2.2 \times 10^{-5}\ \text{V}$$

Typically the elastic limit of metals might be reached by around 10000μ strain so even then the output is only 0.22 volts

Note that there is a limit to the size of the supply voltage V_S that can be used because of the power dissipation in the strain gauges.

Typically the resistance of the gauge is 200Ω, so if V_s = 10 volts , the power dissipation in the gauge is $V^2/R = (10/2)^2/200 = 0.125$ watts.

Amplifier is required

Outline

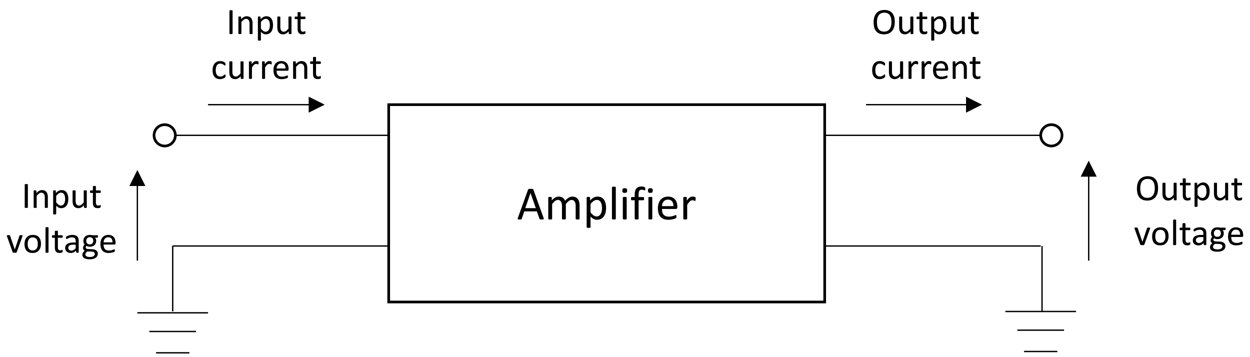
Signal Conditioning

- ❑ **What is Signal Condition**
- ❑ **Wheatstone Bridge**
  - Basics
  - Temperature Compensation
- ❑ ***Amplifiers***
- ❑ **Protection Circuit**
- ❑ **Filters**

The Operational Amplifier (Op-Amp)

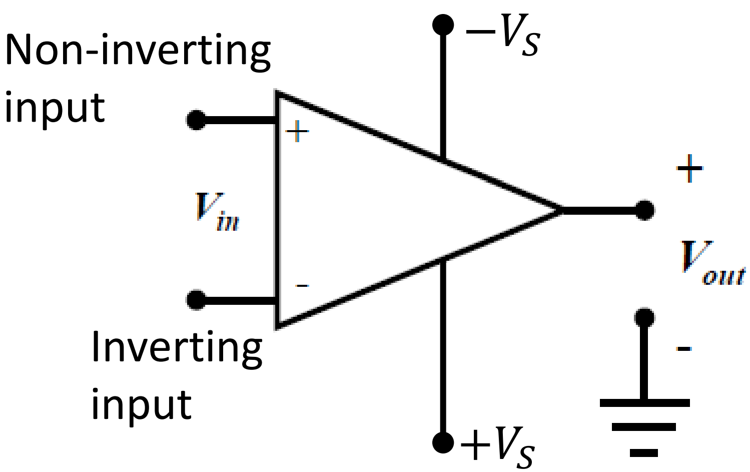
- An amplifier can be considered to be essentially a system which has an input and an output, the voltage gain of the amplifier being the ratio of output and input voltages when each is measured relative to earth.

- The basis of many signal conditioning modules is the operational amplifier. It is a high-gain DC amplifier, the gain typically being of the order of 1×10^5 or more.

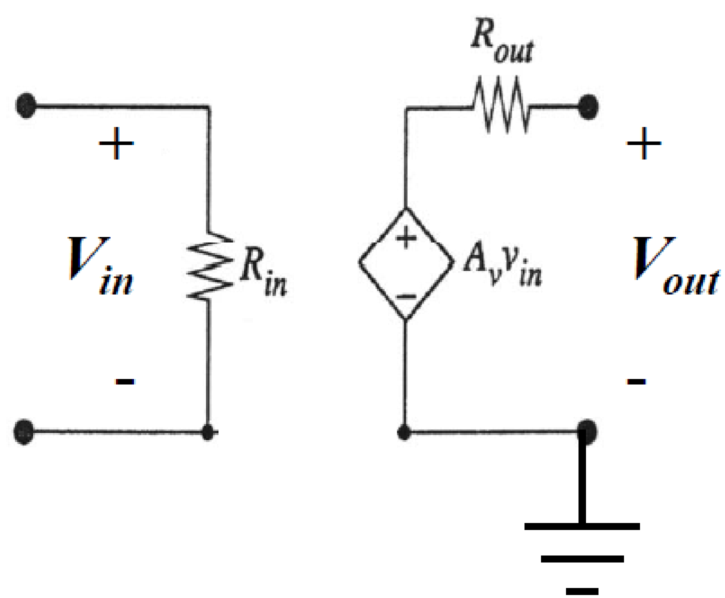


The Operational Amplifier (Op-Amp)

Circuit Symbol



Model



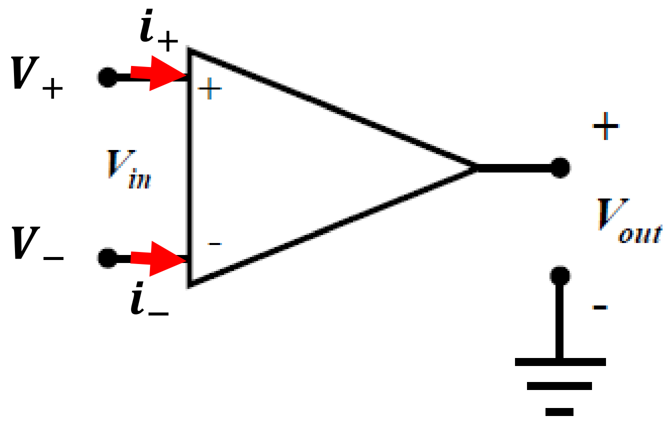
Supply voltage $\pm V_S$ of amplifier could be neglected in symbol

Ideal Operational Amplifier

The ideal model for an amplifier is

- Infinite gain $\boxed{V_{out} = A_v(V_+ - V_-), A_v \to \infty}$
- Infinite input impedance: R_{in} = Infinity
- Zero output impedance: $R_{out} = 0$;

Circuit Symbol



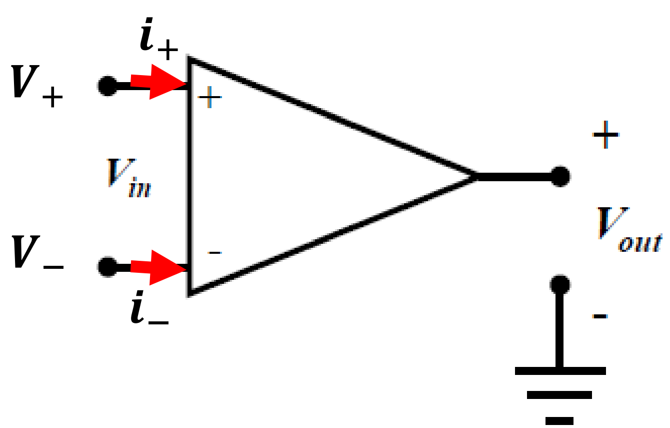
- Infinite gain means that the device is useless without adding "Feedback" to control the overall gain to a finite value.
- The output depends on the connections made to the inputs

Ideal Operational Amplifier

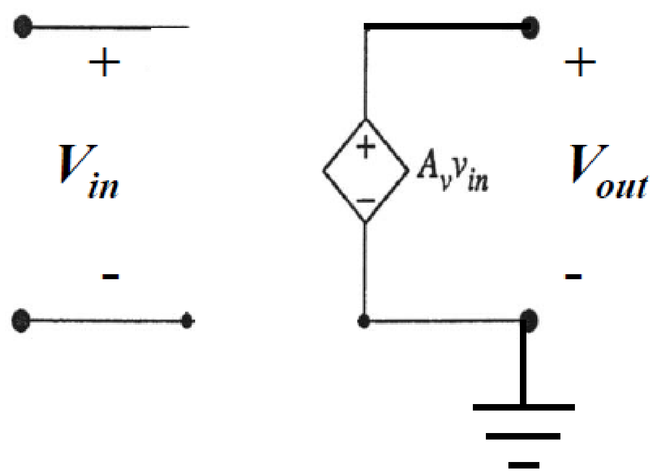
- R_{in} = Infinity;
- Voltage Gain: A_v=Infinity at all frequencies;
- $R_{out} = 0$;
- $\boxed{i_+ = i_- = 0;}$
- $\boxed{V_+ = V_-.}$

Main tools to analyze amplifier

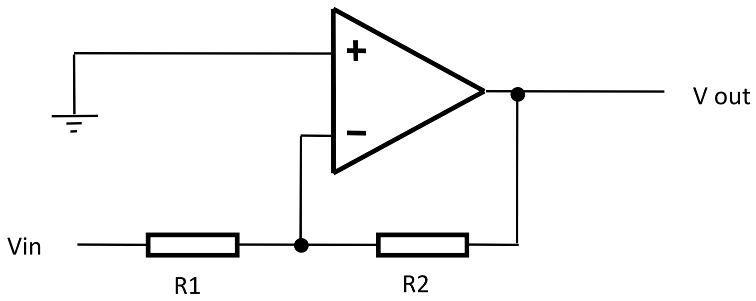
Circuit Symbol



Model



Inverting Amplifier



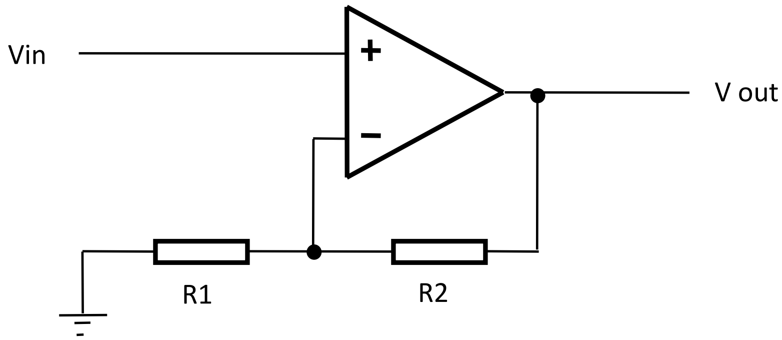
Voltage gain $= -\frac{R_2}{R_1}$

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

$$V_- = V_+ = 0$$

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

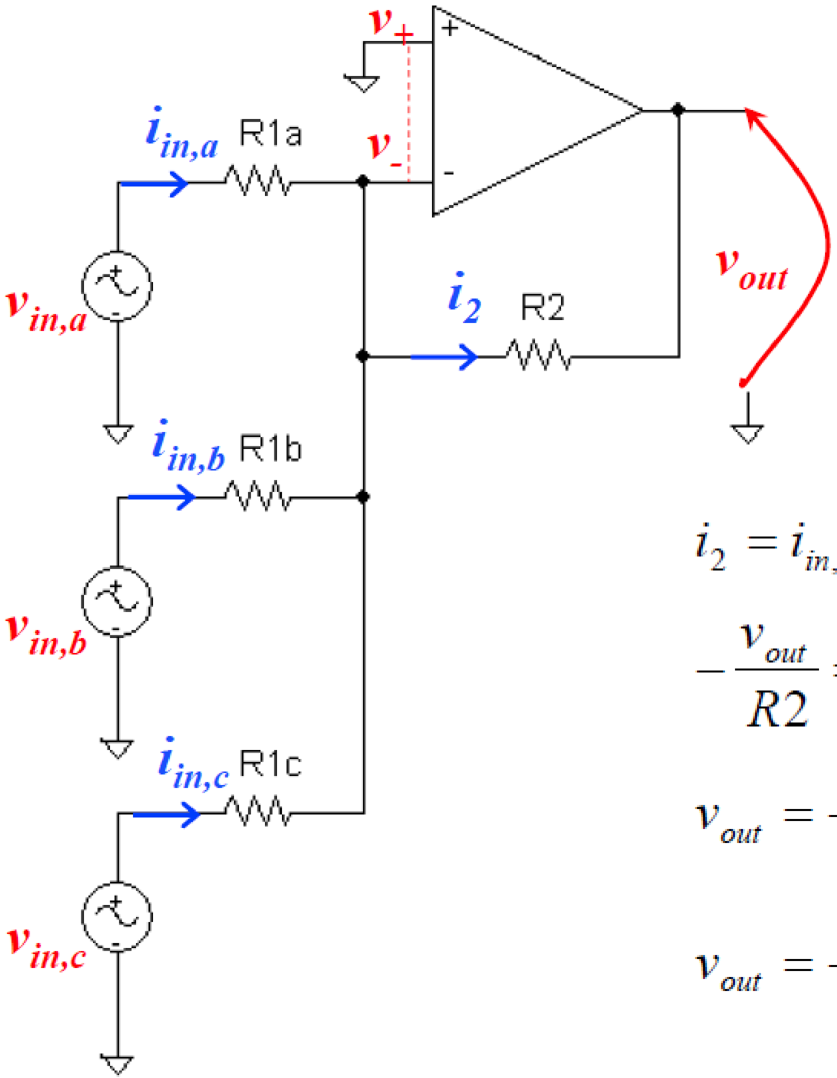
Non-inverting Amplifier



Voltage gain $= 1 + \dfrac{R_2}{R_1}$

$$\left.\begin{aligned} \frac{V_{out} - V_-}{R_2} &= \frac{V_- - 0}{R_1} \\ V_- = V_+ &= V_{in} \end{aligned}\right\} \qquad \frac{V_{out}}{V_{in}} = \left(1 + \frac{R_2}{R_1}\right)$$

Summing Amplifier



- Output is a scaled sum of inputs.
- Scaling can be controlled by ratios of resistors.

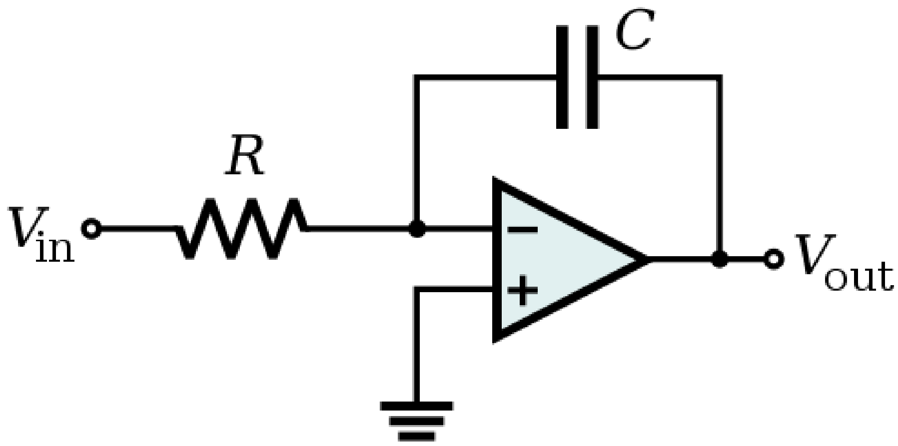
$$i_2 = i_{in,a} + i_{in,b} + i_{in,c}$$

$$-\frac{v_{out}}{R2} = \frac{v_{in,a}}{R1a} + \frac{v_{in,b}}{R1b} + \frac{v_{in,c}}{R1c}$$

$$v_{out} = -v_{in,a}\frac{R2}{R1a} - v_{in,b}\frac{R2}{R1b} - v_{in,c}\frac{R2}{R1c}$$

$$v_{out} = -\left(v_{in,a}\frac{R2}{R1a} + v_{in,b}\frac{R2}{R1b} + v_{in,c}\frac{R2}{R1c}\right)$$

Integrating Amplifier



Capacitor U-I relation:

$$I = C\frac{dU}{dt}$$

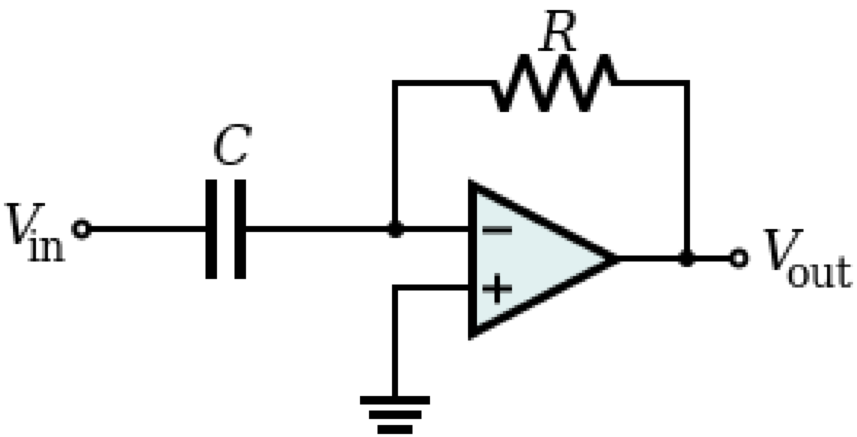
$$U = \frac{1}{C}\int I dt$$

$$\frac{V_{in} - 0}{R} = C\frac{d(0 - V_{out})}{dt} = -C\frac{dV_{out}}{dt}$$

$$dV_{out} = -\frac{1}{RC}V_{in}\mathrm{dt}$$

$$V_{out}(t_2) - V_{out}(t_1) = -\frac{1}{RC}\int_{t_1}^{t_2} V_{in}\mathrm{dt}$$

Differentiating Amplifier



Capacitor U-I relation:

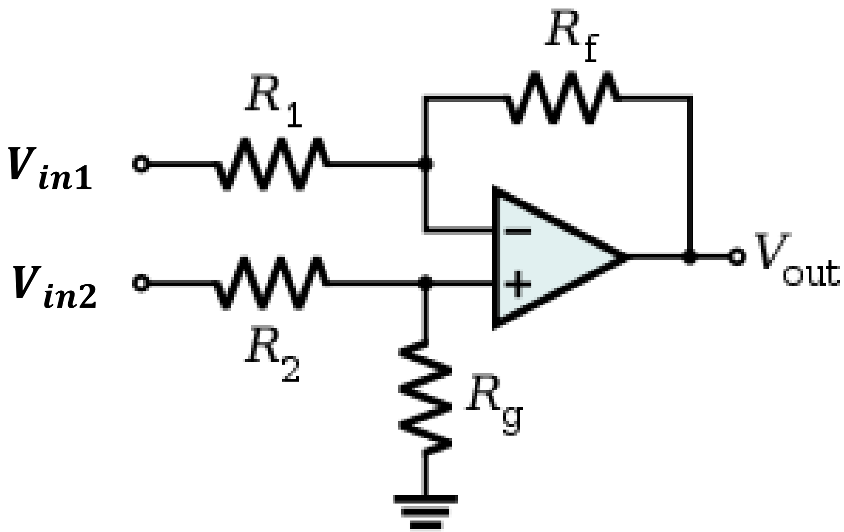
$$I = C\frac{dU}{dt}$$

$$U = \frac{1}{C}\int Idt$$

$$\frac{V_{out} - 0}{R} = C\frac{d(0 - V_{in})}{dt} = -C\frac{dV_{in}}{dt}$$

$$V_{out} = -RC\frac{dV_{in}}{dt}$$

Difference Amplifier



$$\frac{V_{out} - V_-}{R_f} = \frac{V_- - V_{in1}}{R_1}$$

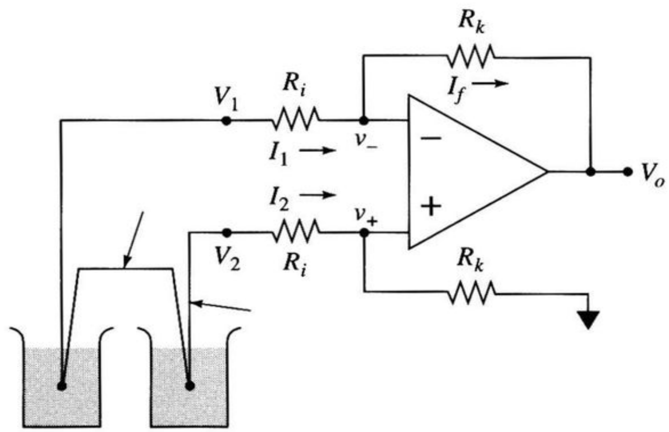
$$V_- = V_+ = V_{in2}\frac{R_g}{R_2 + R_g}$$

assume: $\frac{R_1}{R_f} = \frac{R_2}{R_g}$

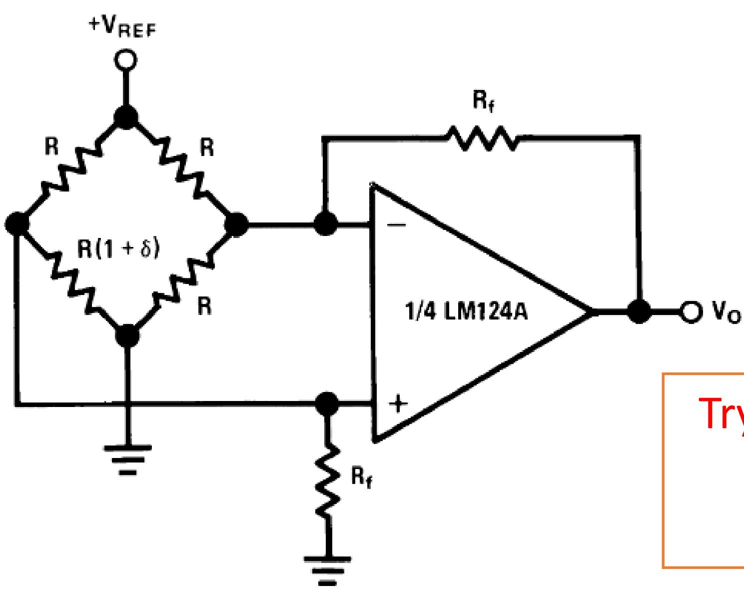
$$V_{out} = \frac{R_f}{R_1}(V_{in2} - V_{in1})$$

Typical Applications of Difference Amplifiers

- **Thermocouple**



- **Wheatstone Bridge**



Try to derive the relations by yourself

Outline

Signal Conditioning

- ❑ **What is Signal Condition**
- ❑ **Wheatstone Bridge**
  - Basics
  - Temperature Compensation
- ❑ **Amplifiers**
- ❑ ***Protection Circuit***
- ❑ **Filters**

Protection Circuit

There are many situations where the connection of a sensor to the next unit, e.g. a microprocessor, can lead to the possibility of damage as a result of perhaps a high current or high voltage.

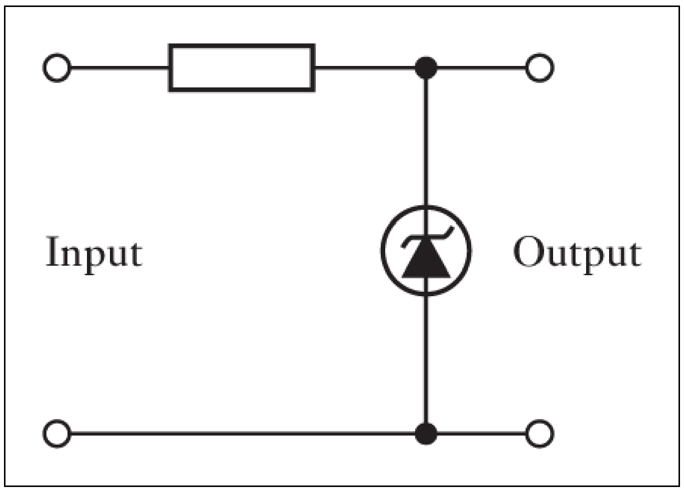


Fig. Zener diode protection circuit.

- Protection from high current by:
  - incorporating in the input line of a series resistor to limit the current to an acceptable level.
- Protection from high voltage by:
  - using a Zener diode circuit. Zener diodes behave like ordinary diodes up to some breakdown voltage when they become conducting. Its resistance drop to a very low value when voltage exceeds some threshold, say 5V.

Outline

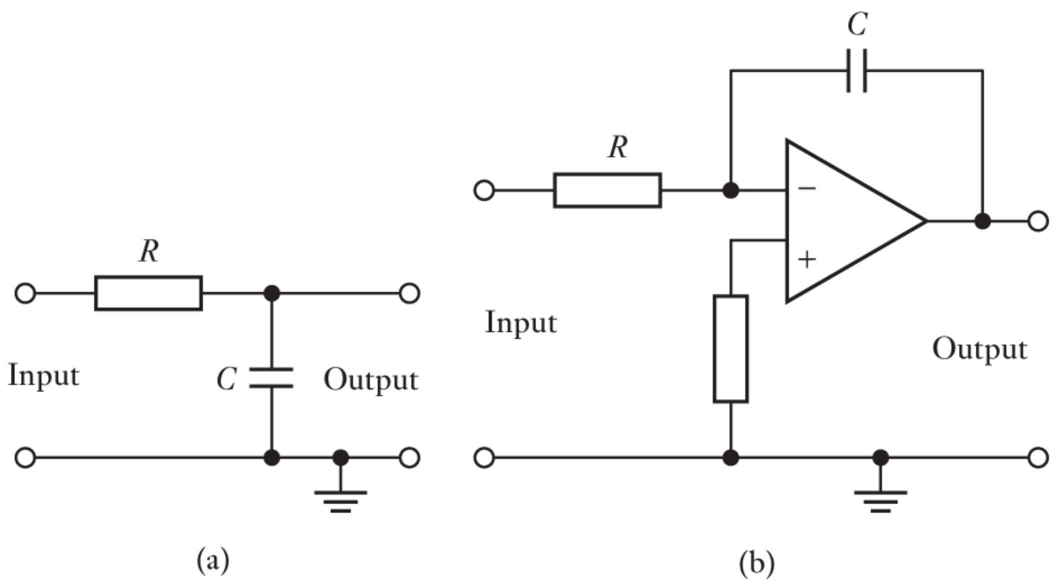
Signal Conditioning

- ❑ **What is Signal Condition**
- ❑ **Wheatstone Bridge**
  - Basics
  - Temperature Compensation
- ❑ **Amplifiers**
- ❑ **Protection Circuit**
- ❑ ***Filters***

Filtering

The term **filtering** is used to describe the process of removing a certain band of frequencies from a signal and permitting others to be transmitted.

- Passive filter: made up using only resistors, capacitors and inductors;
- Active filter: made up using amplifiers in addition to resistors, capacitors and inductors.



Only need to understand the concept

Fig. Low-pass filter: (a) passive, (b) active using an operational amplifier.

Characteristics of Ideal Filters

Cutoff frequency: the frequency at which the output voltage is 70.7% or attenuated by 3dB of that in the pass band.

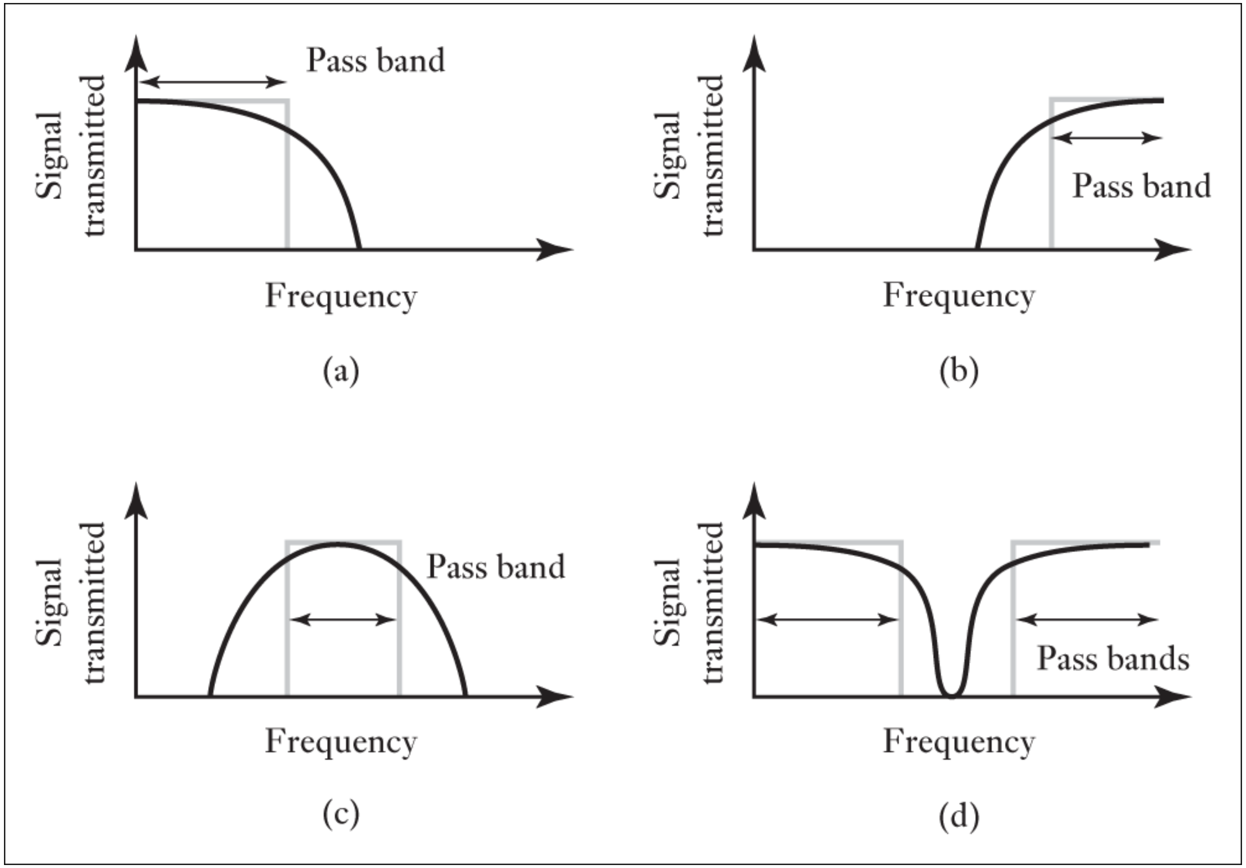


Fig. Filters (a) low-pass, (b) high-pass, (c) band-pass, (d) band-stop.

Outline

Signal Conditioning

- ❑ **What is Signal Condition**
- ❑ **Wheatstone Bridge**
  - Basics
  - Temperature Compensation
- ❑ **Amplifiers**
- ❑ **Protection Circuit**
- ❑ **Filters**
- ❑ ***Interference and Noise***

Interference and Noise

Transducers often produce only small amplitude signals that have to be connected to a display device some distance away from the point of measurement. This must be done with care to avoid 'picking up' unwanted noise signal (interference and natural noise) that can corrupt or obscure the required signal.

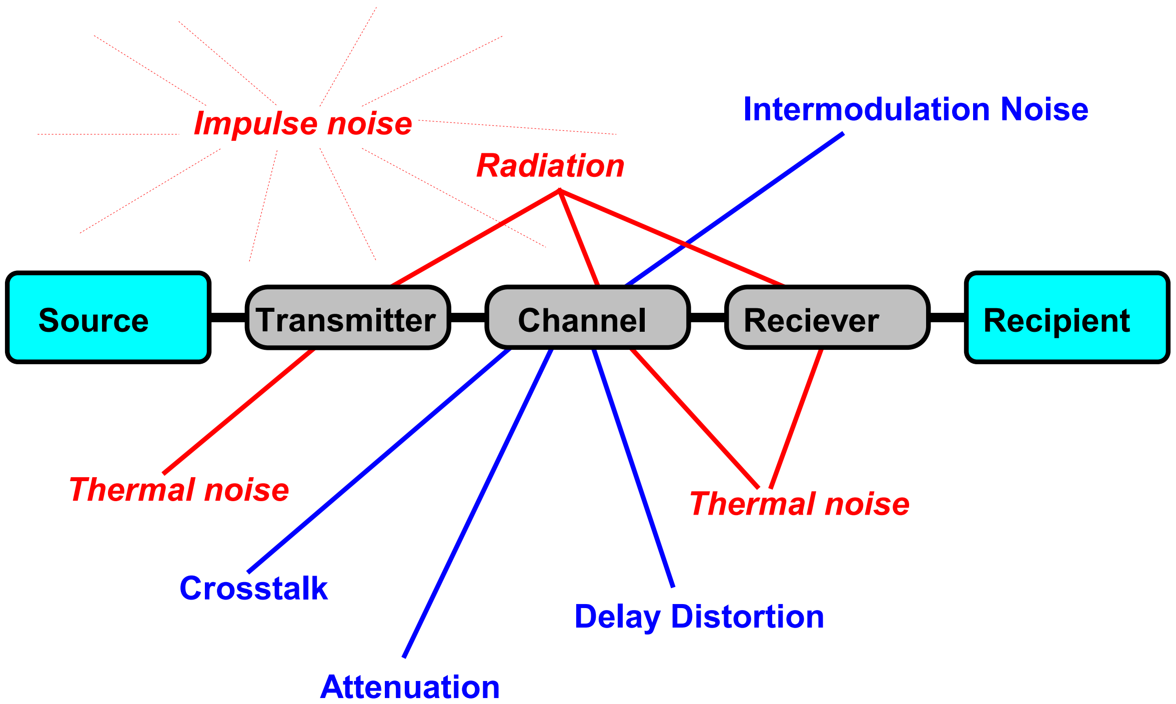
Signal-to-Noise Ratio:
SNR = Signal Power / Noise Power

It is better to prevent the noise being picked up than to try to eliminate it afterwards.

Signal processing techniques can be used to effectively to improve SNR:

- i.e., signal averaging is particularly useful when the required signal occupies a range of frequencies, but it works only if the noise is uncorrelated with the required signal.

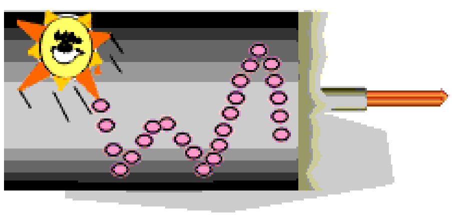
Sources of Noise

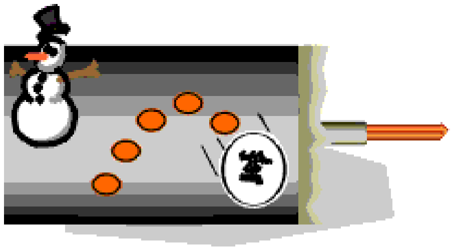


- Unwanted electric signals come from a variety of sources, generally classified as either human interference or naturally occurring noise.
- Noise (unlike distortion) is not correlated with the desired signal.
- Human interference: other electrical apparatus, channel crosstalk etc.
- Natural noise: atmospheric disturbance, extra-terrestrial radiation, random electron motion etc.

Thermal Noise

- Thermal noise is the noise produced by the random motion of charged particles (usually electrons) in conducting media.
- Thermal noise *can be reduced* by cooling the noise source (being applied in some radio receivers using cryogenic coolers, to improve the receiver sensitivity)
- *Cannot be eliminated.*

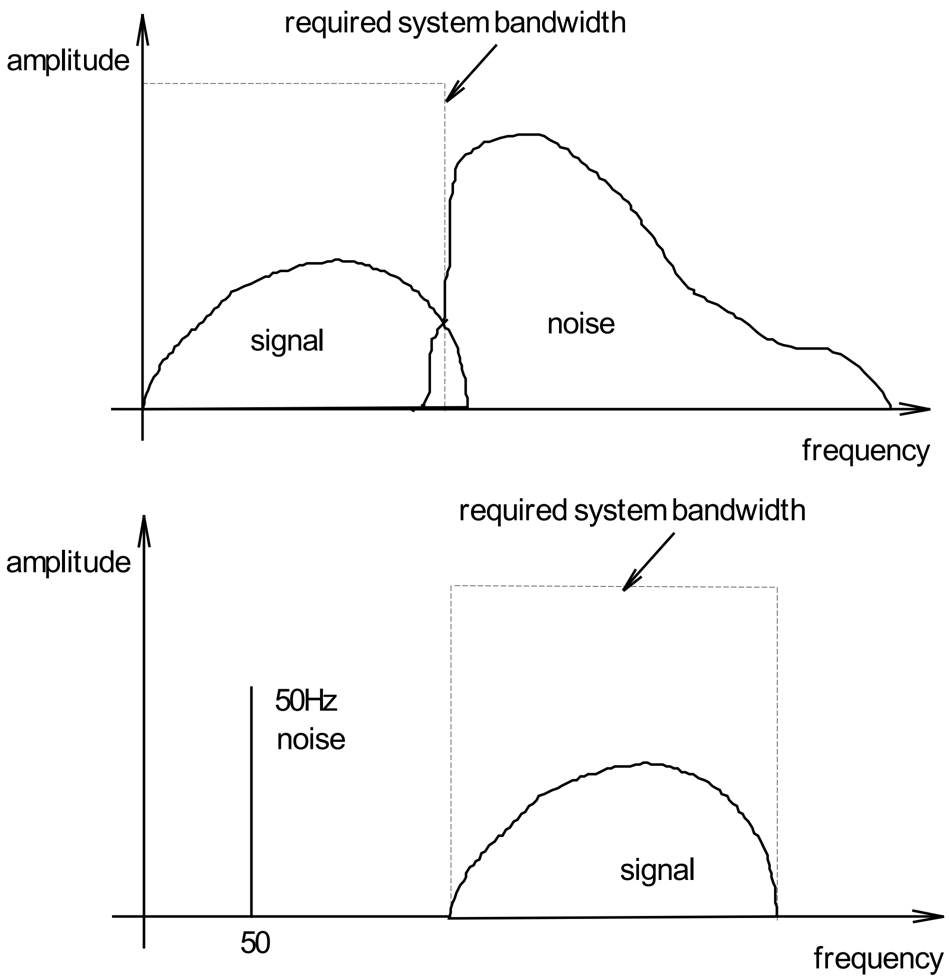




❖ Generally thermal noise can be modeled as a zero mean Gaussian WSS (wide-sense stationary) random process.

❖ The noise is called **White Noise** since all frequency components appear with equal power (white is used in white light for a similar reason).

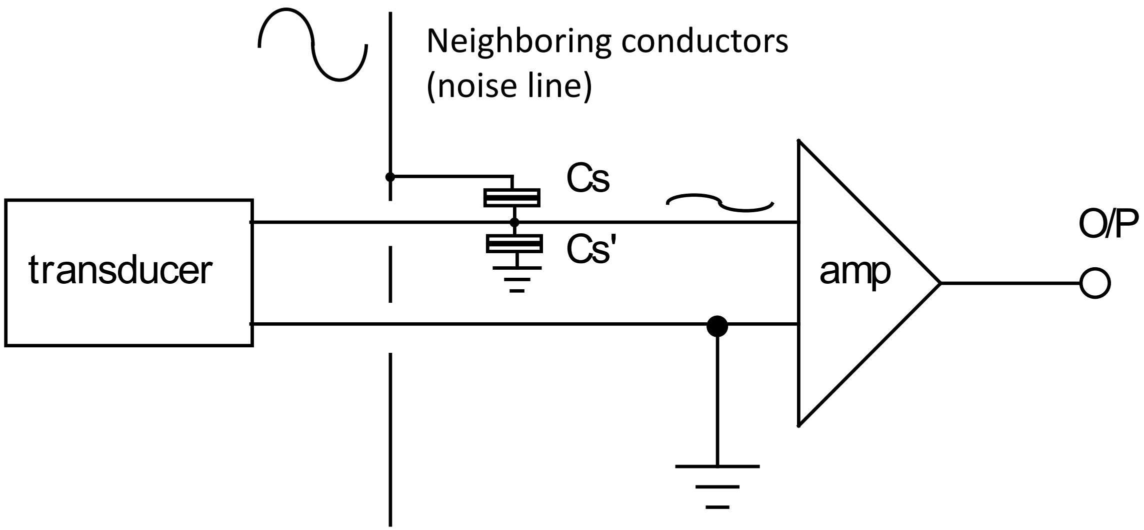
Noise Elimination – Bandwidth Limiting



Avoiding Noise ‘pick-up’

Noise is often inadvertently 'picked up' for three main reasons:

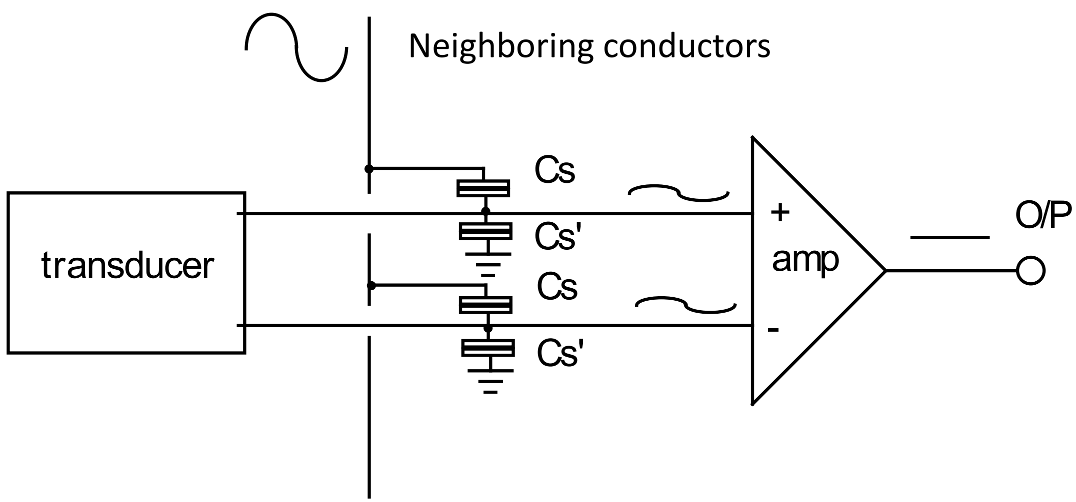
1) ***Noise pick-up by capacitive coupling***



Avoiding Noise 'pick-up'

Avoid capacitive coupling – (i) balance the input

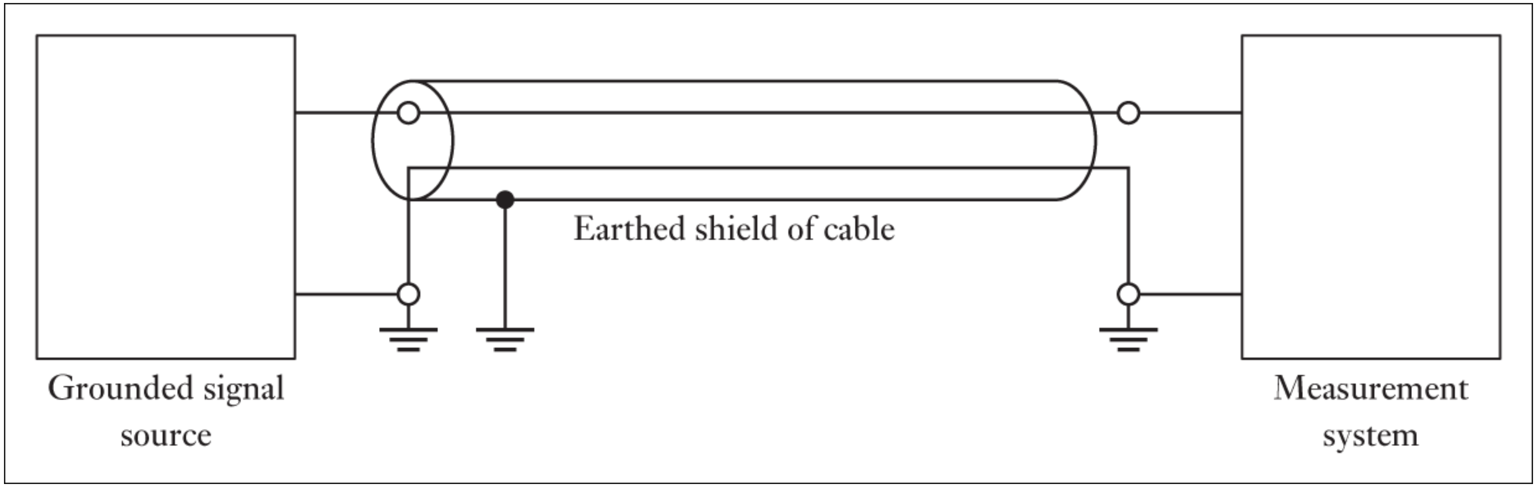
Minimise this problem by using a difference amplifier with high common mode rejection and with both input lines isolated from ground. Then the noise 'pick up' links equally to both inputs and cancels because the amplifier only amplifies *differential* signals and does not amplify common mode signals (ideally).



Avoiding Noise ‘pick-up’

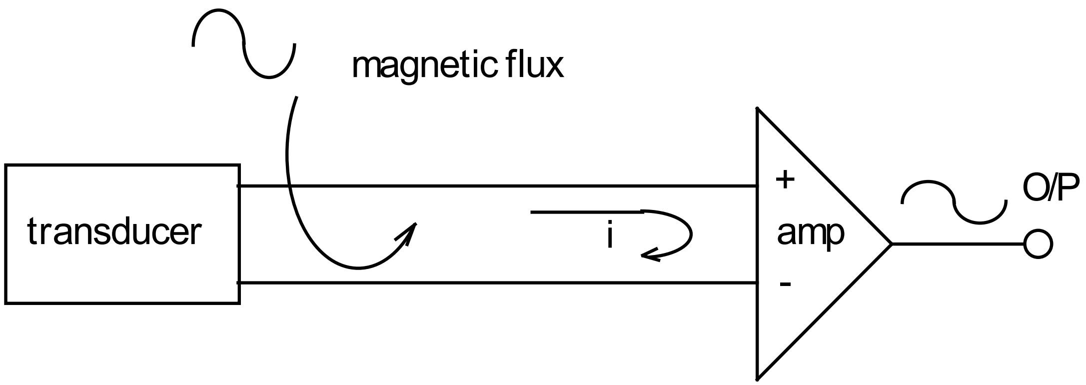
Avoid capacitive coupling – (ii) screen with co-axial cable

Alternatively use screened co-axial cable with the outer sheath grounded. This protects the inner cable from capacitively linking with the noise line.



Avoiding Noise ‘pick-up’

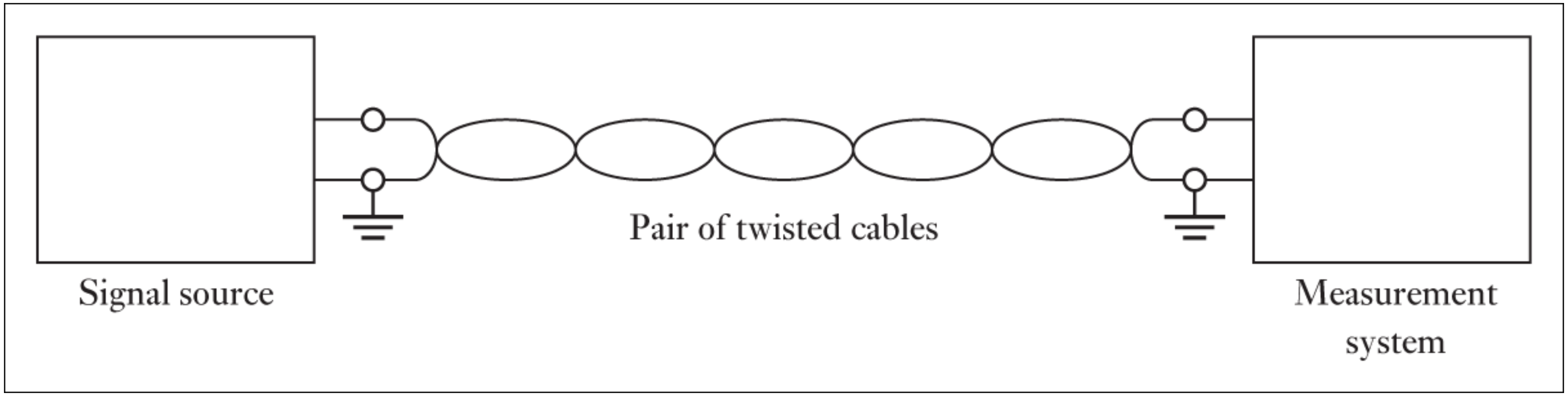
*2) **Noise pick-up by electromagnetic coupling***



Avoiding Noise 'pick-up'

Avoid Electromagnetic coupling – twist the wires

Minimise this pick-up noise by twisting the input lines together.

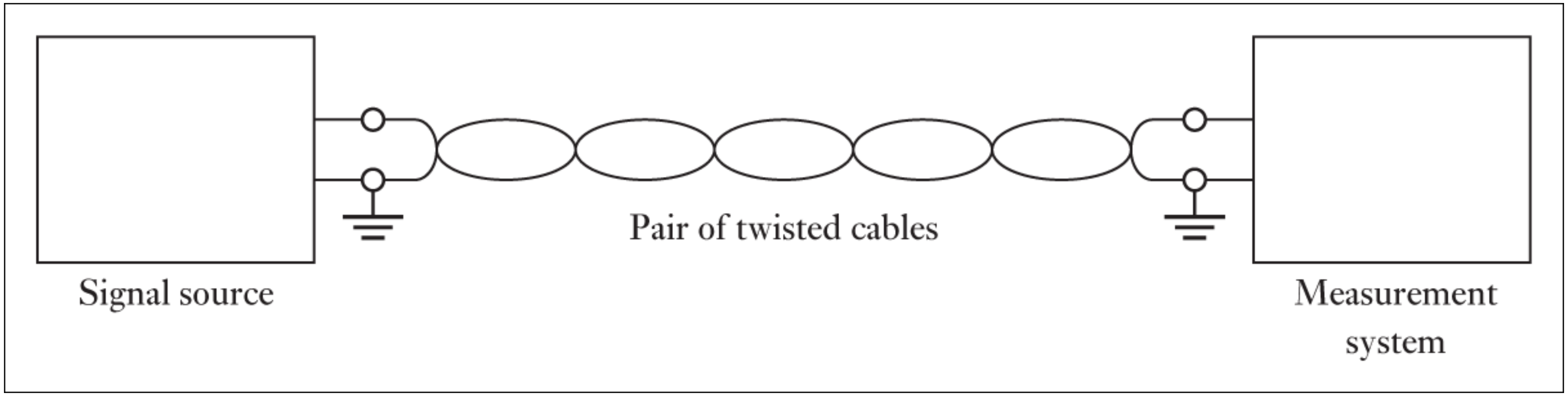


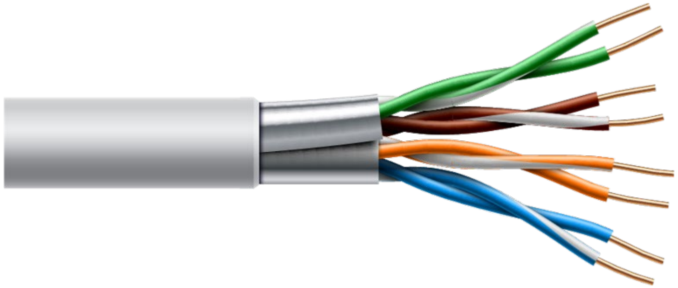
The induced voltages in each loop are reduced by the small area of each loop and are of opposite polarity in each loop and so cancelled.

Avoiding Noise 'pick-up'

Avoid Electromagnetic coupling – twist the wires

Minimise this pick-up noise by twisting the input lines together.

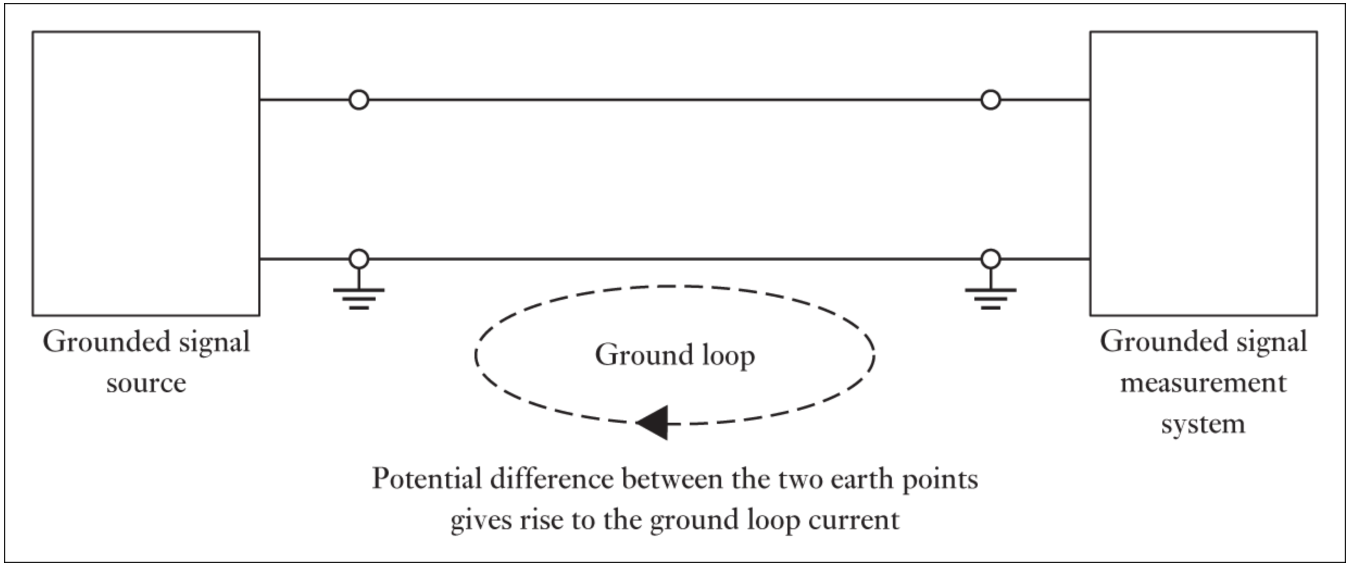




Avoiding Noise ‘pick-up’

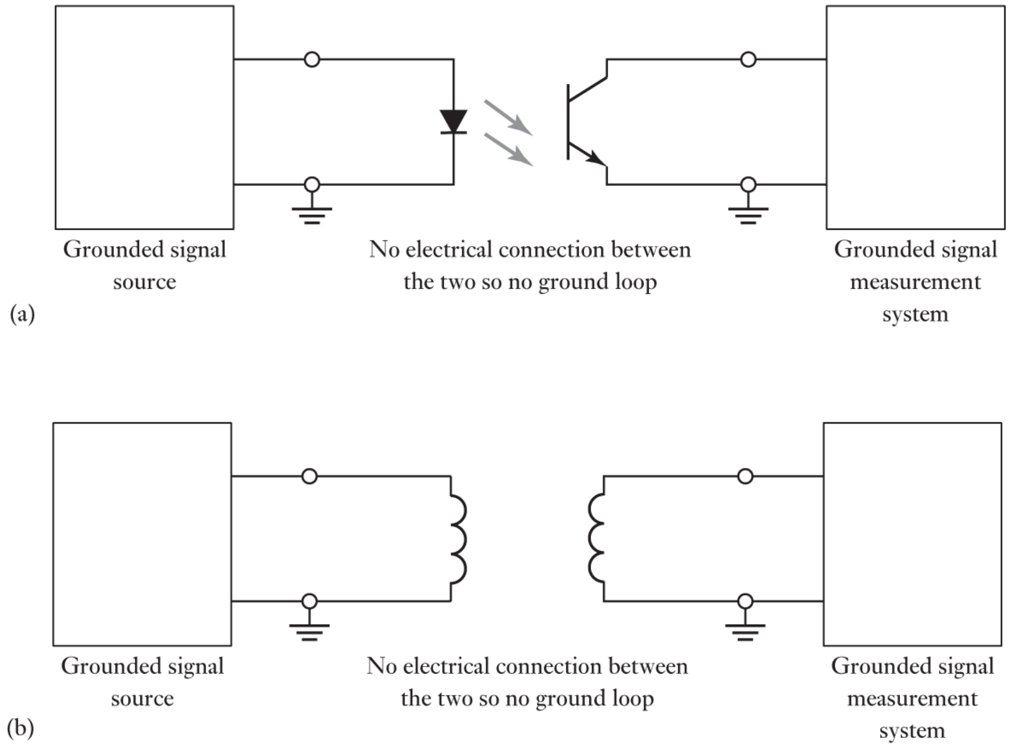
3) Noise pick-up by Ground loops

Problems can arise with systems when a circuit has several grounding points. In a large system, multiple grounding is largely inevitable. Unfortunately, there may be potential difference between the two grounding points and thus significant currents (ground-loop currents) can flow between the grounding points through the low but finite ground resistance.



Avoiding Noise 'pick-up'

Avoid Ground loop coupling – electrical isolation

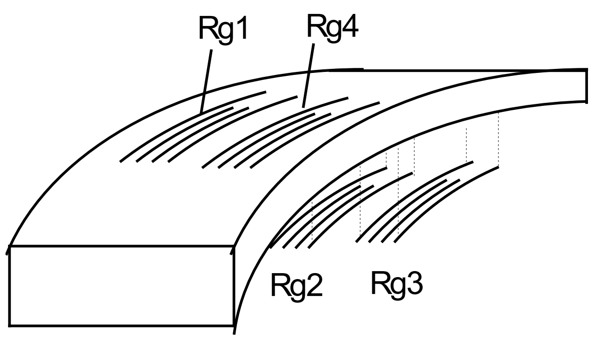


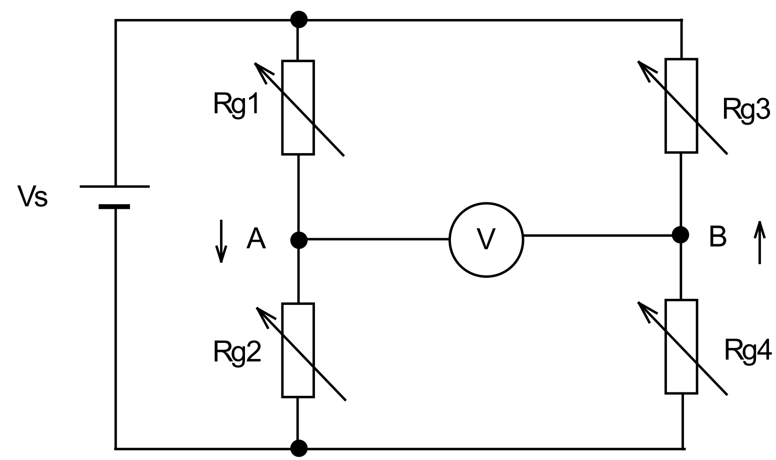
✓ Besides, ground loops from multiple point grounding can be minimized if the multiple earth connections are made close together and the common ground has a resistance small enough to make the voltage drops between the earth points negligible.

Quiz 4.1

The strain in a beam subject to tensile stress is to be measured using four strain gauges. The supply voltage to the bridge Vs is 6V, the gauge factor G=2.3, the gauges have a resistance of 200Ω each, Young's modulus of the beam is 250 x 10^9 Newtons/m^2. (hint: Young's modulus=stress/strain)

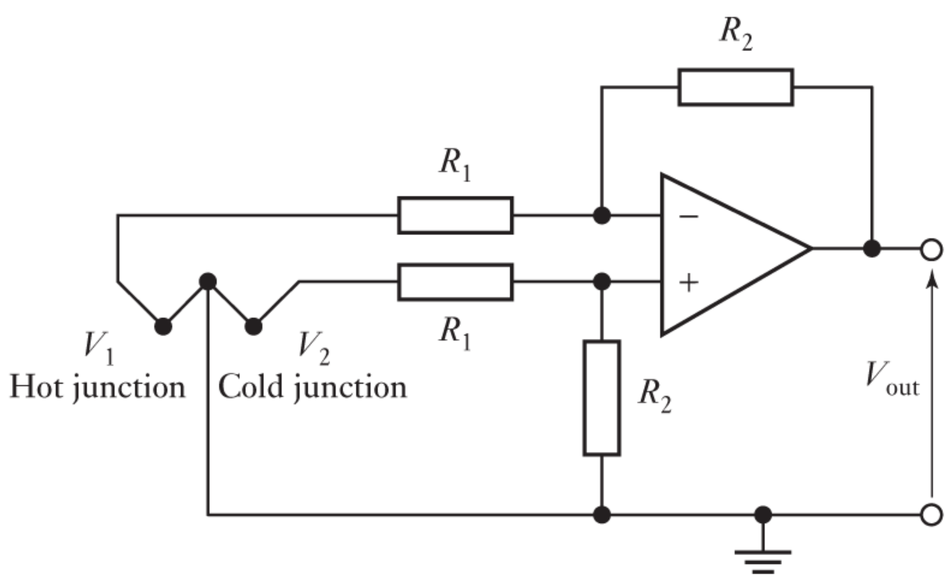
Suppose the measured output voltage from the bridge is 80μV, determine the corresponding strain and stress.





Quiz 4.2

A differential amplifier is used with a copper-constantan thermocouple sensor with sensitivity of $43\mu V/^{o}C$. Suppose $R_1 = 1k\Omega$ and $R_2 = 2.32k\Omega$, the temperature difference between the two thermocouple junctions is 100^{o}C. Find the output voltage of the circuit.



Thank You！