DIPARTIMENTO di ELETTRONICA, INFORMAZIONE e BIOINGEGNERIA

POLITECNICO DI MILANO

Lecture 7
Conditioning of resistive sensors

General equation of a variable resistance :

$$R = R_0\, f(x), \text{ con } f(0) = 1$$

For **linear** sensors we have:

$$R = R_0\,(1+x)$$

The value x depends strongly on sensor type:

Linear potentiometers	from 0 to -1
Strain gauges	from 10^{-5} to 10^{-2}
LDR, humistors	>1000
Gas sensors, liquid conductivity sensors	<100
PTC switching (above T_{critic})	>10000

Conditioners for resistive sensors

- they must drive the sensor with an electric voltage or current in order to obtain an output signal, because a change in resistance is not by itself a signal
- this supply, whose magnitude affects that of the output signal, is limited by sensor self-heating, which must be avoided unless the sensing principle uses sensor self-heating, as in some flowmeters and liquid level meters

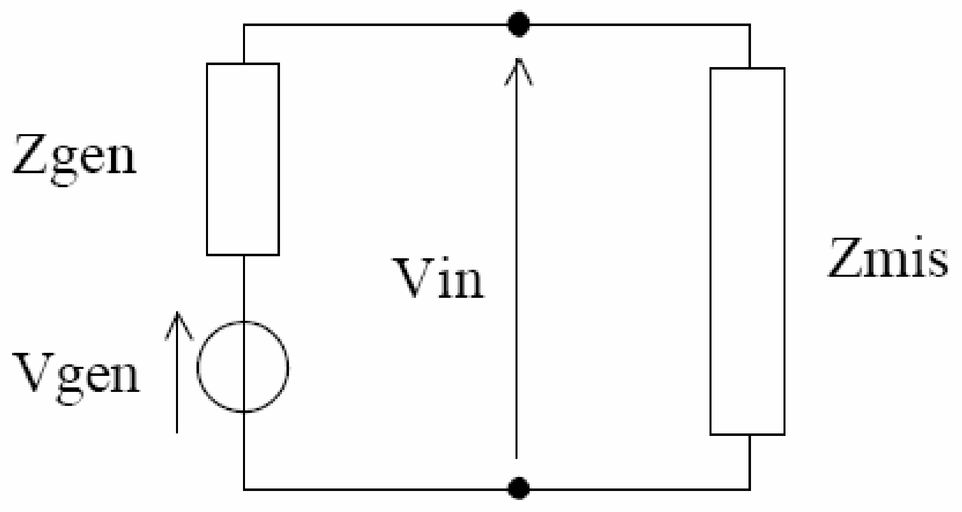
Alternative expressions for **linear sensors**

$$R = R_o\,(1+x) \;\Leftrightarrow\; R = R_o + \Delta R$$

$$\Rightarrow x \cdot R_o = \Delta R$$

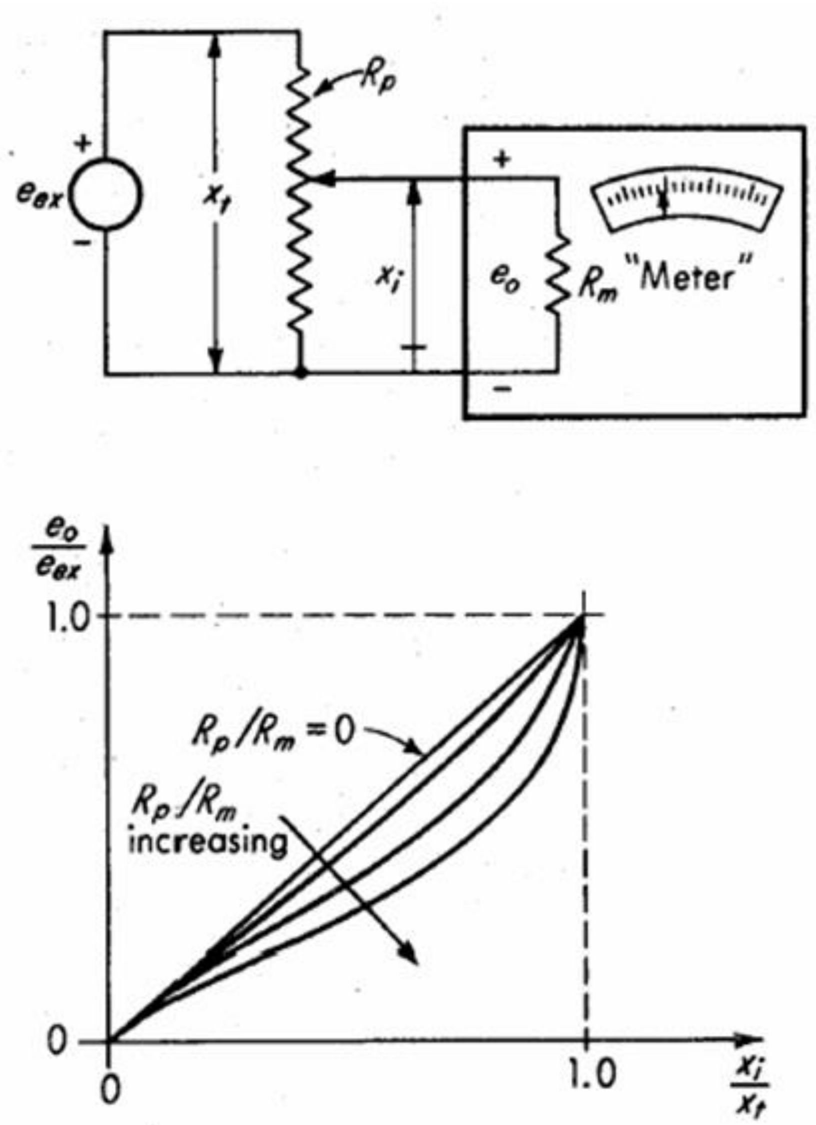
$$\Rightarrow x = \Delta R / R_o$$

Impedance matching

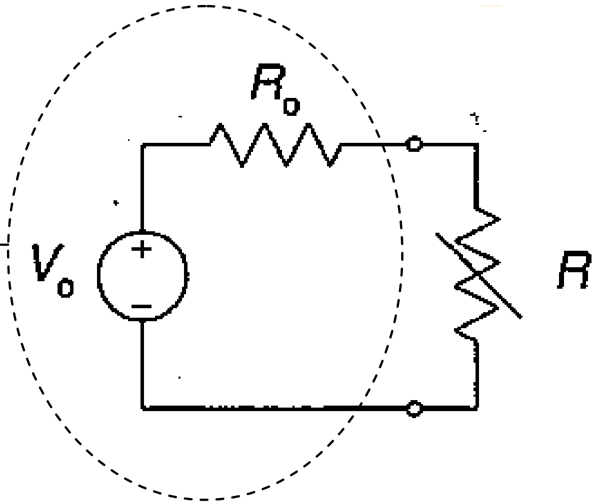


$$\frac{Vin}{Vgen} = \frac{1}{\frac{Zgen}{Zmis}+1}$$

Impedance matching



Thevenin Equivalent Circuit (seen by the sensor)



Power P absorbed by the sensor is :

$$P = \left(\frac{V_0}{R_0 + R} \right)^2 R$$

The Maximum value of P as a function of R is :

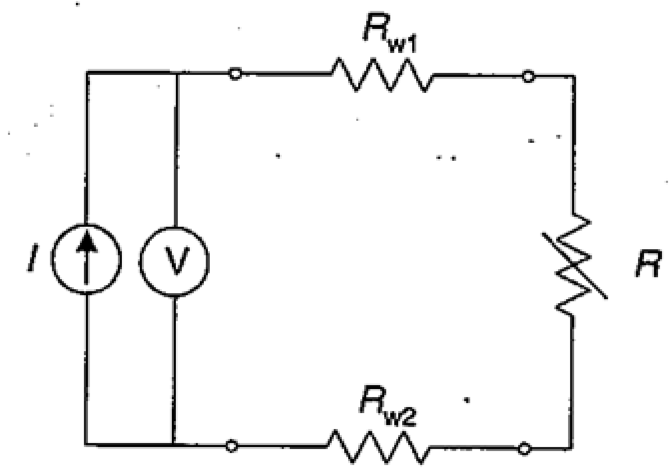
$$\frac{dP}{dR} = 2\frac{V_0}{R_0 + R}\frac{-V_0}{(R_0 + R)^2}R + \left(\frac{V_0}{R_0 + R} \right)^2 = \left(\frac{V_0}{R_0 + R} \right)^2 \frac{R_0 - R}{R_0 + R} = 0$$

$$R = R_0; \qquad P_{max} = \left(\frac{V_0}{R_0 + R_0} \right)^2 R_0 = \frac{V_0^2}{4R_0}$$

Sensitivity to the length of connecting wires: two-wire circuit

Conditioners for remote sensors must be insensitive to connecting lead resistance or compensate for it.

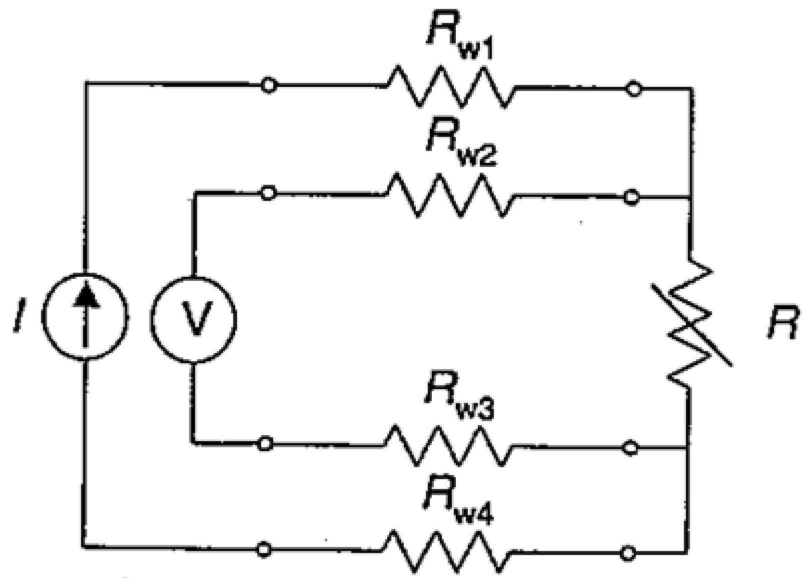
$$V = I\left(R + R_{w1} + R_{w2}\right)$$



If R=0Ω $\Rightarrow$ V(0) ≠ 0V (offset error)

(ex.: 10 m. of AWG wire n. 20 adds 0.333 mΩ to R, which is the variation in resistance of a Pt100 sensor for 1°C)

Sensitivity to connecting lead resistance: four-wire Kelvin circuit



- It is hypothesized that the voltage measurement circuit V has a very high input impedance
- in such conditions, V is insensible to connecting lead resistance

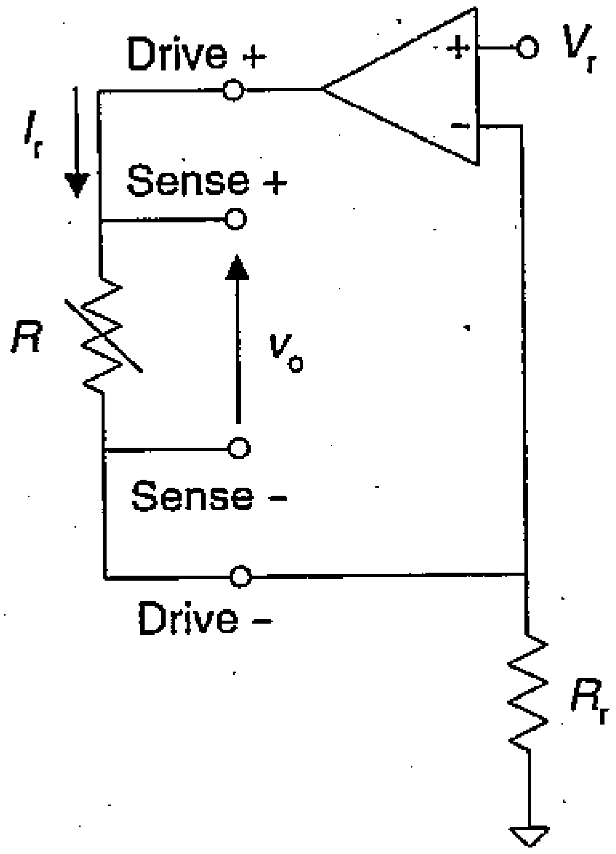
TABLE 3.1 Copper Conductor Data[a]

AWG[b]	Stranding	Diameter (mm)	Dc Resistance[c] (Ω/km)
10	Solid	2.600	3.28
	37/26	2.921	3.64
	49/27	2.946	3.58
20	Solid	0.813	33.20
	10/30	0.899	33.86
	26/34	0.914	32.97
30	Solid	0.254	340.00
	7/38	0.305	338.58

[a] Solid wire data are from Spectra-Strip, and stranded conductor data are from Alpha Wire. There is additional information at http://www.brimelectronics.com/AWGchart.htm.

AWG stands for **American Wire Gauge**, also known as B&S gauge (from Brown and Sharp),which is a diameter specification. Metric gauge numbers correspond to 10 times the diameter in millimeters. For example, a metric wire No. 6.0 is 0.6 mm in diameter. AWG numbers do not correspond to diameter sizes proportionally; and the higher the gauge number, the smaller the diameter. Typical household wiring is AWG number 12 or 14. Telephone wire is usually 22, 24, or 26. Strand number n/m means that taking n strands of wire number m makes the desired wire number. For example, 10 strands of 30AWG or 26 strands of 34AWG make a 20AWG wire

Signal conditioner for a resistive sensor based on current excitation



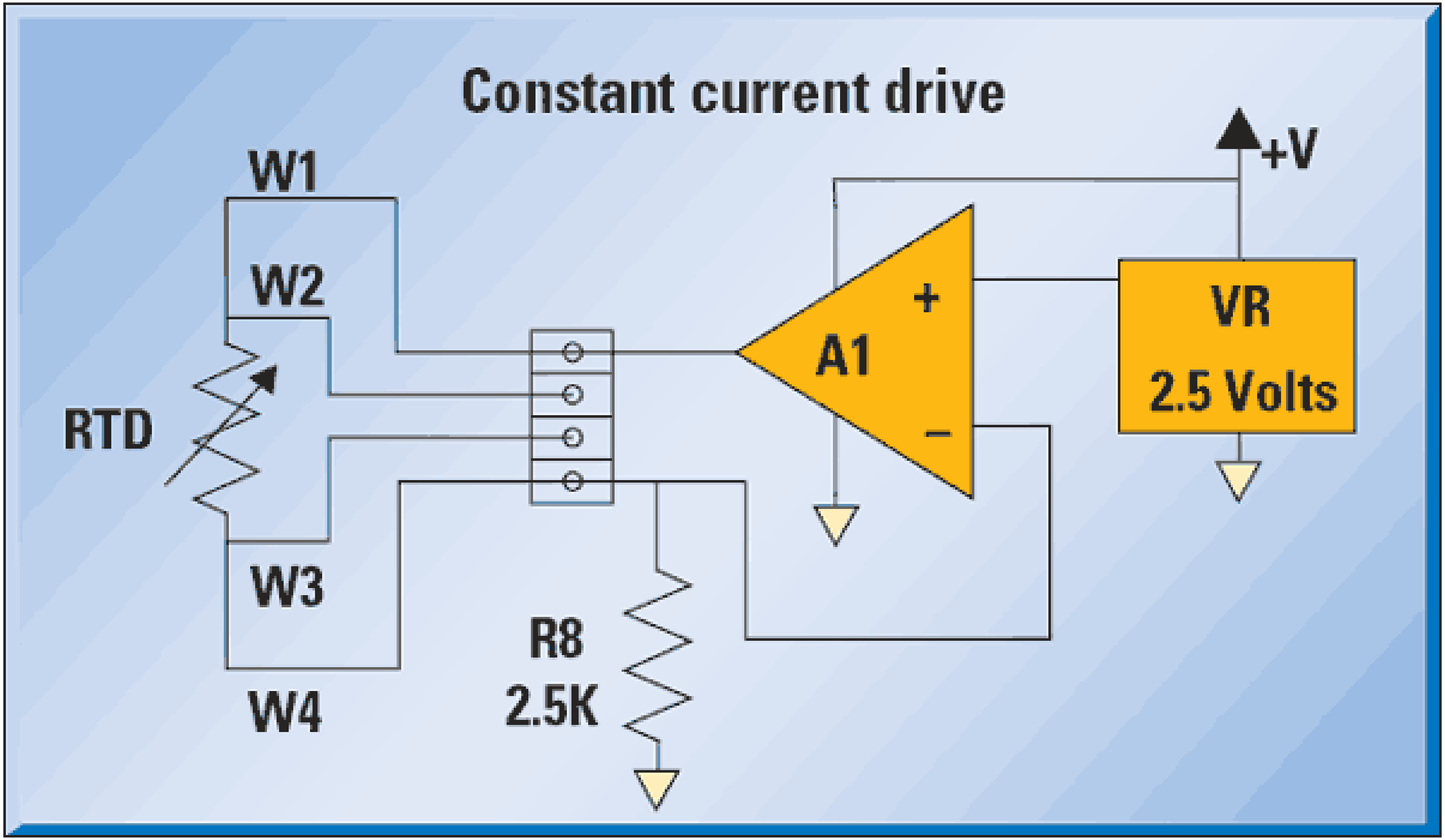
$$v_0 = I_r R = \frac{V_r}{R_r} R_0(1+x) \quad \textit{(linear relationship)}$$

If $R_r = R_0$, subtracting the drop in voltage across R_r from v_0, yields

$$v_s = v_0 - I_r R_r = V_r(1+x) - V_r = V_r x$$

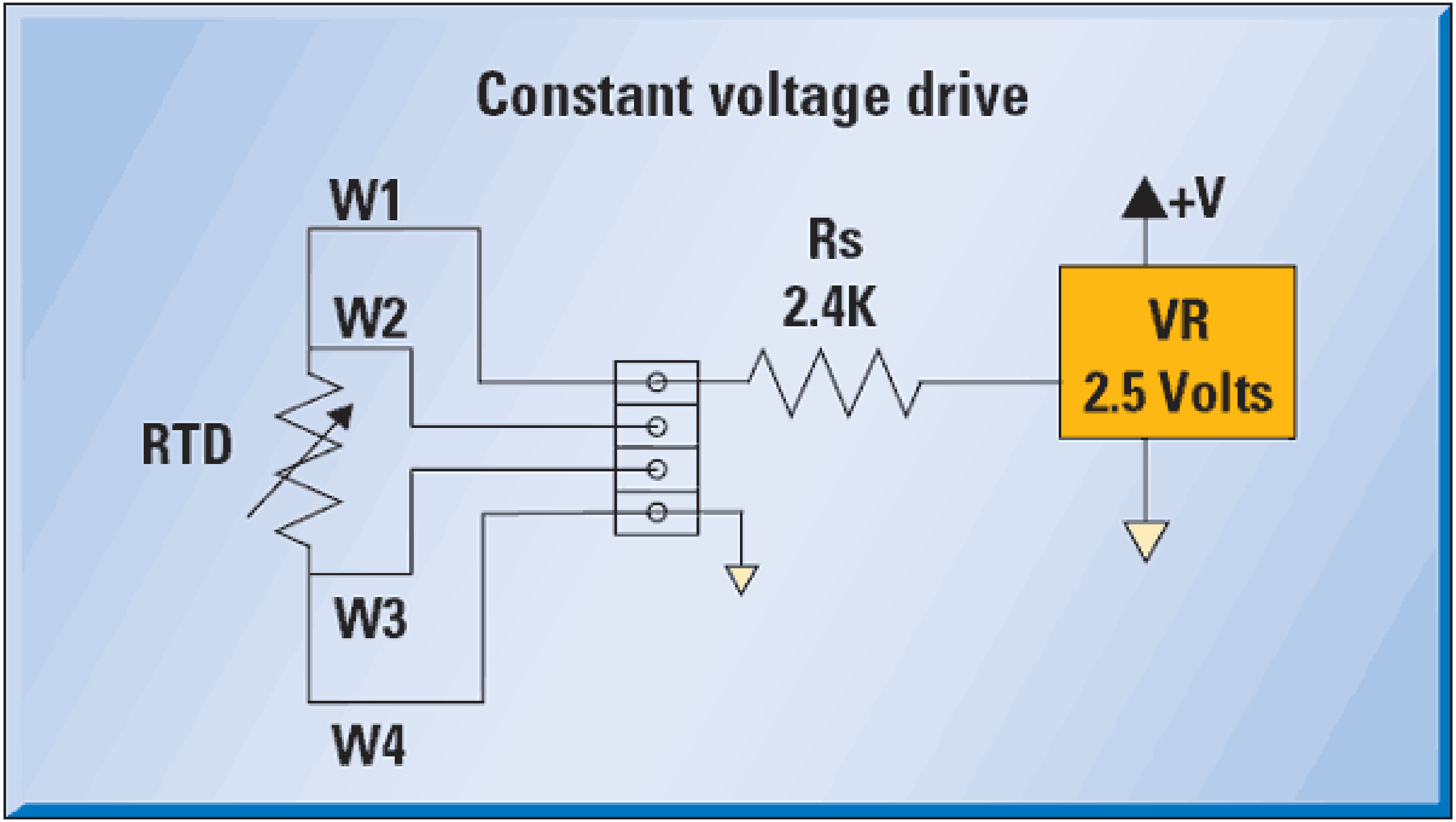
Which is 0 for x=0

Example: conditioning of a RTD sensor (National Semiconductor)



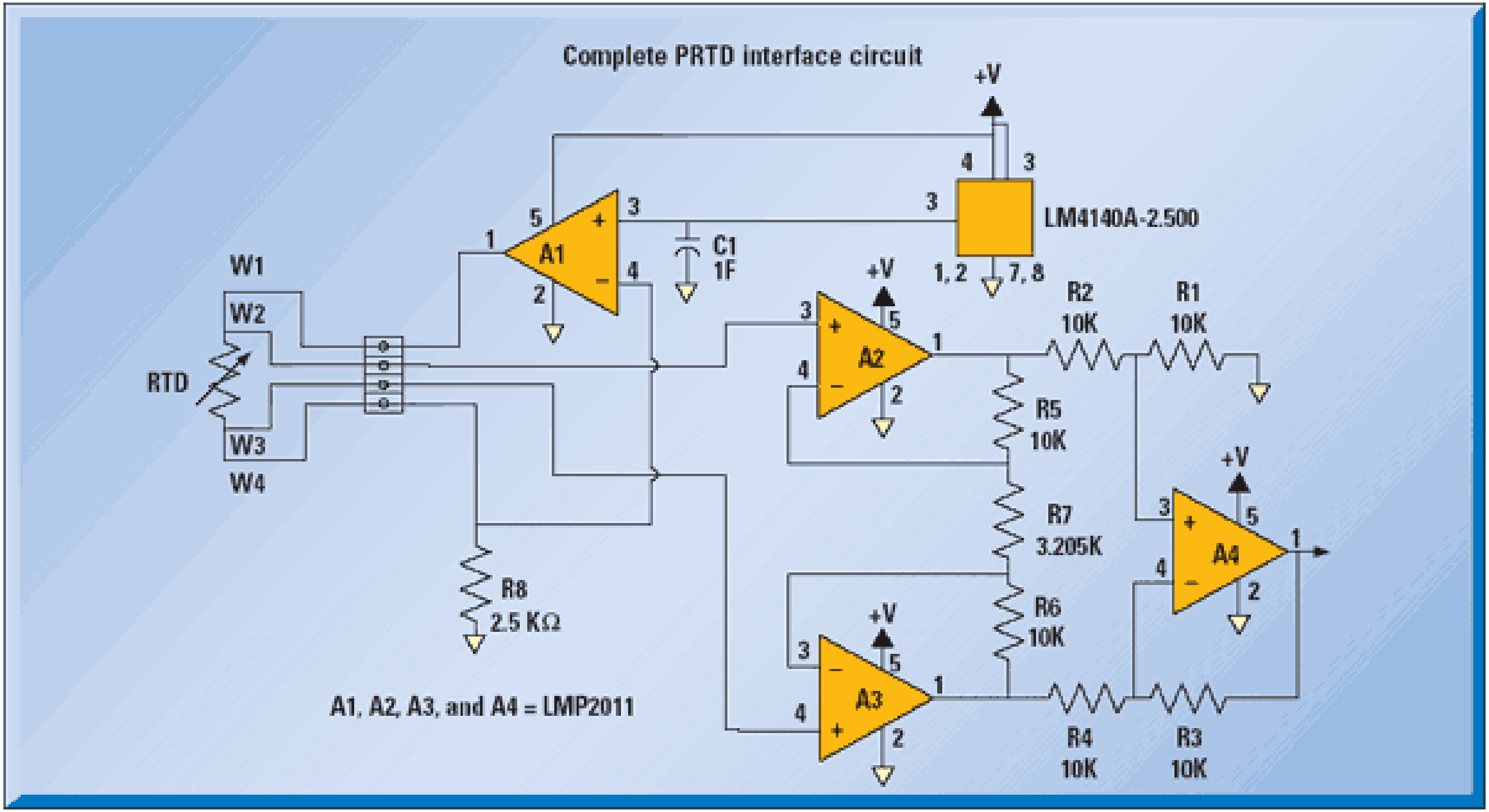
http://www.national.com/nationaledge/dec04/article.html

Example: conditioning of a RTD sensor (National Semiconductor)



http://www.national.com/nationaledge/dec04/article.html

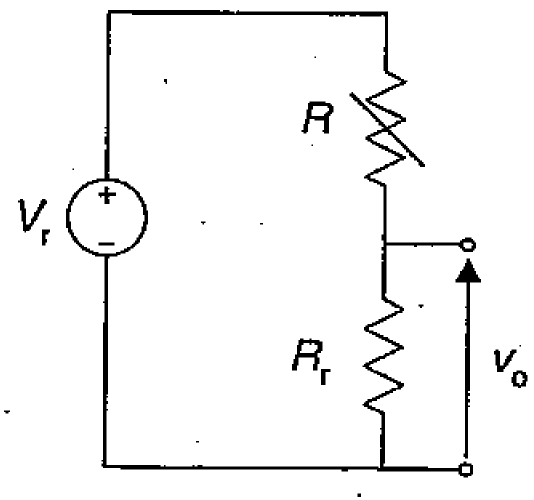
Example: conditioning of a RTD sensor (National Semiconductor)



http://www.national.com/nationaledge/dec04/article.html

Voltage dividers

Are typically used to measure high values of resistance

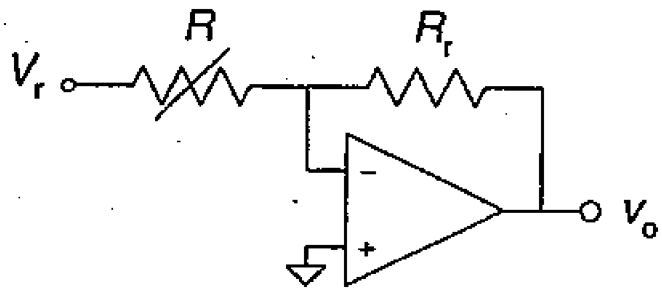


$$v_0 = \frac{V_r}{R_r + R} R_r$$

From this relationship it is obtained the unknown resistance R:

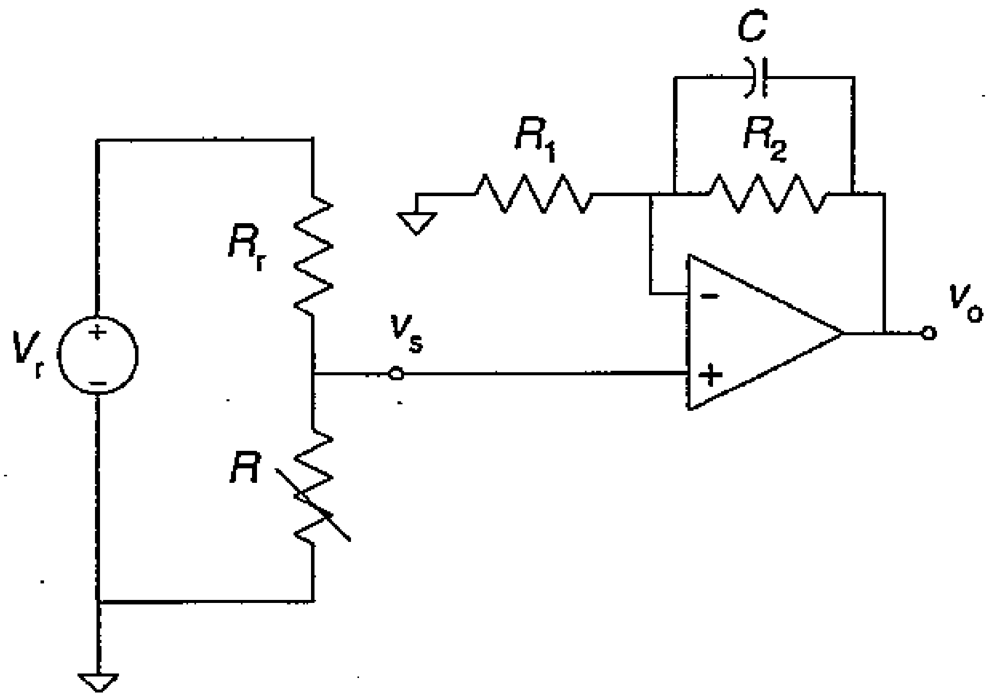
$$R = R_r \frac{V_r - v_0}{v_0}$$

By adding an op-amp to the voltage divider we obtain a circuit in which the output voltage is inversely proportional to the unknown resistance.



Amplifier for voltage divider

Voltage dividers need voltage measurement systems with high input impedance.
The following example shows a non-inverting amplifier with high-impedance input and a gain equal to 1 + R_2/R_1

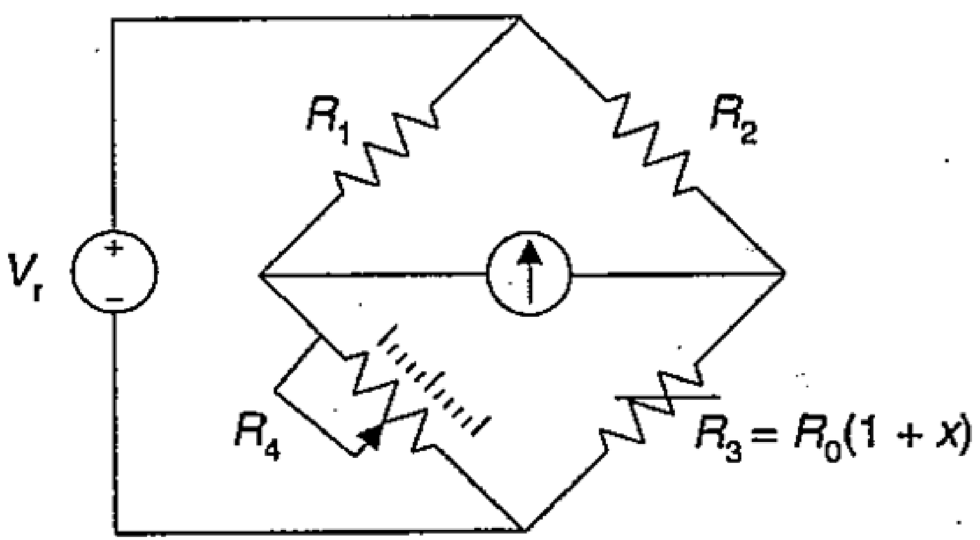


Wheatstone bridge circuits

The Wheatstone bridge measurement method was first proposed by S. H.Christie in 1833 and reported by Sir Charles Wheatstone to the Royal Society (London) in 1858 as a method to measure small resistances. It is based on a feedback system, either electric or manual, in order to adjust the value of a standard resistor until the current through the galvanometer or other null indicator is zero.

Once the balance condition has been achieved we have

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

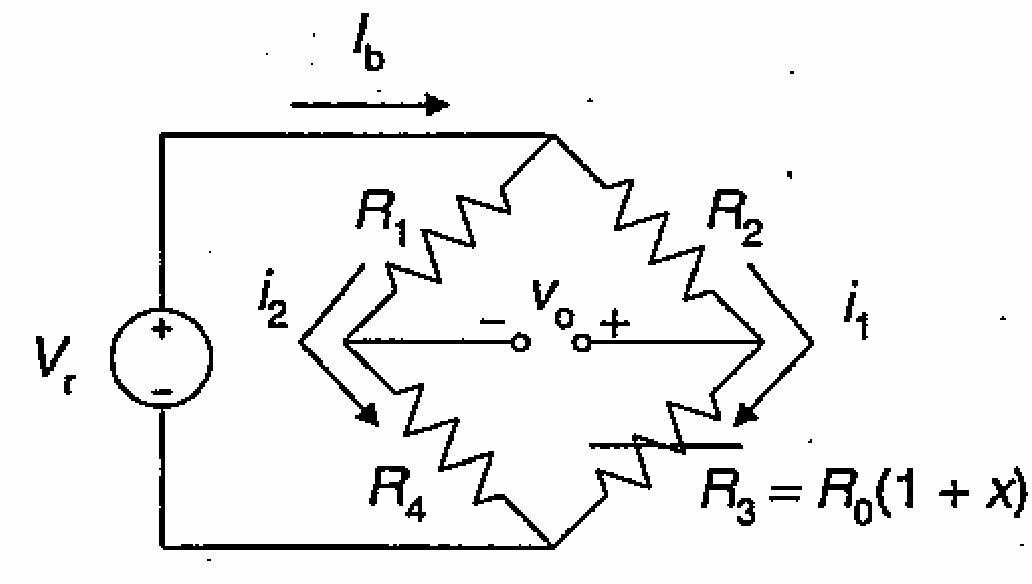


That is, changes in R_3 are directly proportional to the corresponding changes we have to produce in R_4 in order to balance the bridge.

This measurement method can be also used as a polarity detector because the output is positive or negative, depending on whether x is greater or less than a given threshold.

Wheatstone bridge circuits "deflection" mode

Wheatstone bridges are often used in the deflection mode. Instead of measuring the action needed to restore balance on the bridge, this method measures the voltage difference between both voltage dividers or the current through a detector bridging them.



If the bridge is balanced when x=ˆ0, which is the usual situation, we define a parameter

$$k = \frac{R_1}{R_4} = \frac{R_2}{R_0}$$

The voltage difference between both branches is

$$v_0 = V_r\left(\frac{R_3}{R_2 + R_3} - \frac{R_4}{R_1 + R_4}\right) = V_r \frac{kx}{(k+1)(k+1+x)} \qquad (1)$$

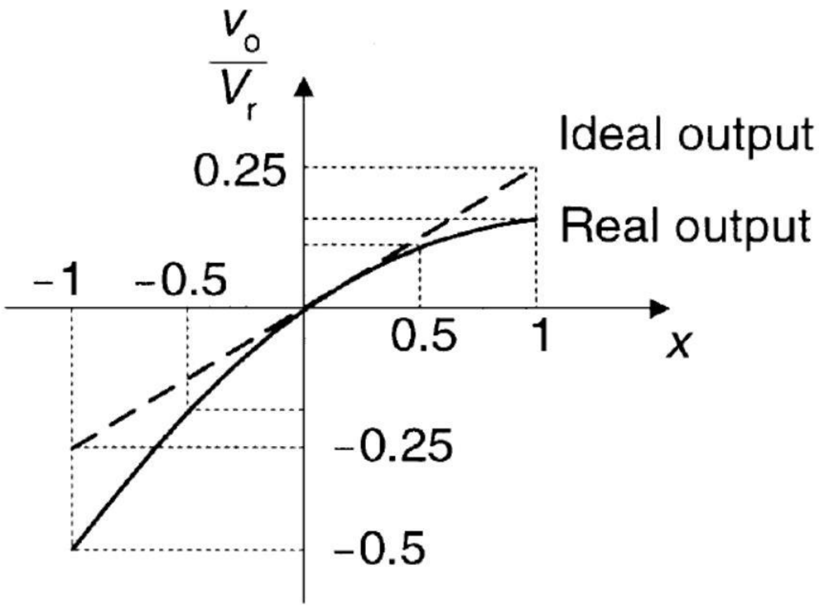
Thus the output voltage is proportional to the changes in R_3 only when x<<k+1; that is, the sensitivity depends on x (and k and V_r)

For x=ˆ0, the sensitivity is

$$S_0 = \left.\frac{dv_o}{d(xR_0)}\right|_{x=0} = \frac{V_r k}{R_0}\frac{1}{(k+1)^2} \qquad (2)$$

The maximal sensitivity as a function of k is obtained by setting dS_0/dk=ˆ 0, which yields k=1. By calculating the second derivative we can verify that this point is a maximum.
On the other hand, from the relationship 1 (see above) we infer that k= 1 yields a nonlinear output unless x<<2.

The actual output departs from a straight line through the origin for k ≙1:



If the bridge is supplied by a **constant current I_r**, the output voltage is

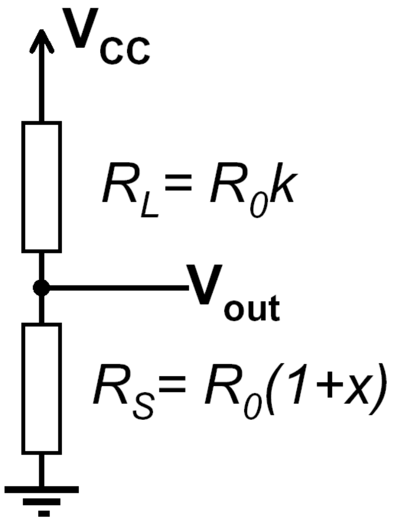
$$v_o = I_r R_0 \frac{kx}{2(k+1)+x}$$

To have an approximately linear output we need x<<2(k+1),†and x<<4 when K=1. Linearity is not necessary to achieve good accuracy. What matters is the repeatability of the results. But the output is easily interpreted when it is proportional to the measurand.

For metal strain gages, x seldom exceeds 0.02. Therefore, usually k= 1 to improve sensitivity and, unless a very high linearity is desired, the presence of x in the denominator of equations (1) and (2) is ignored. Alternatively, the actual x can be calculated from the output voltage or current by solving for x in those equations. For example, for a bridge supplied by constant voltage and k=1, from (1) we obtain

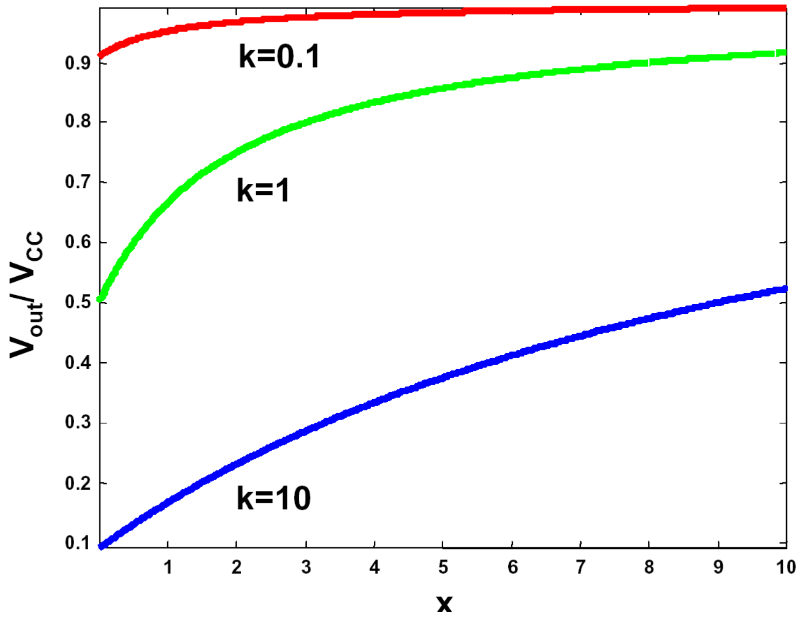
$$x = \frac{4v_o}{V_r} \frac{1}{1 - \dfrac{2v_o}{V_r}}$$

Voltage divider



$$V_{out} = V_{CC}\frac{R_S}{R_S + R_L} =$$

$$= V_{CC}\frac{R_0(1+x)}{R_0(1+x)+R_0 k} = V_{CC}\frac{1+x}{1+x+k}$$

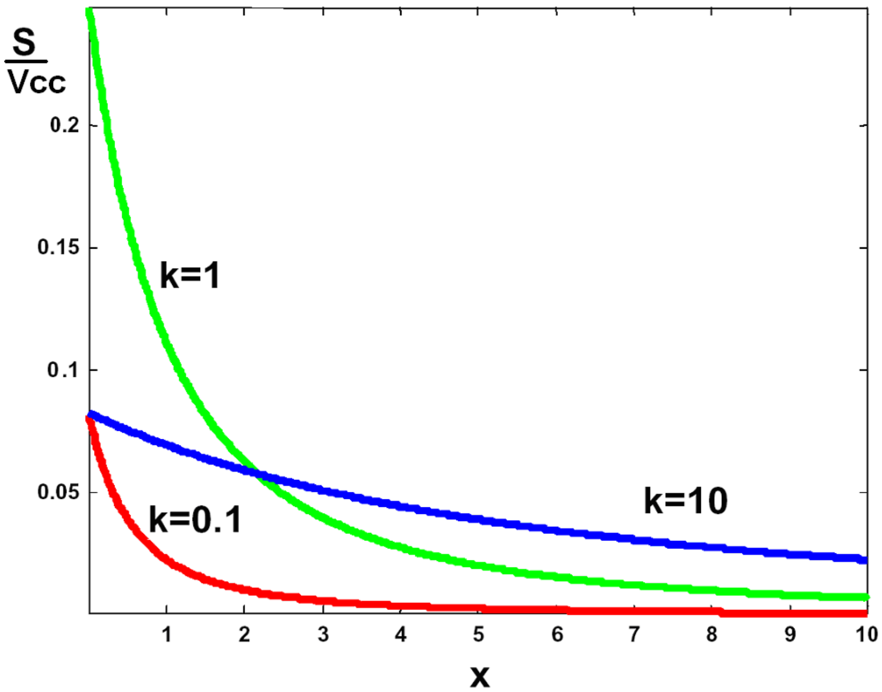


Voltage divider: sensitivity

$$S = \frac{dV_{out}}{dx} = \frac{d}{dx}\left(V_{CC}\frac{1+x}{1+x+k}\right) =$$

$$= V_{CC}\frac{(1+x+k)-(1+x)}{(1+x+k)^2} =$$

$$= V_{CC}\frac{k}{(1+x+k)^2}$$

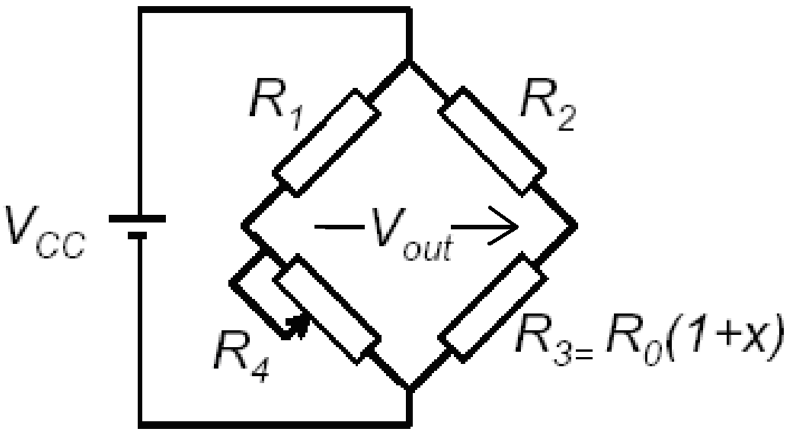


$$\frac{dS}{dk} = 0 \Rightarrow \frac{d}{dk}\left(V_{CC}\frac{k}{(1+x+k)^2}\right) = 0$$

$$\Rightarrow \frac{(1+x+k)^2 - k2(1+x+k)}{(1+x+k)^4} = 0 \Rightarrow \mathbf{k = 1 + x}$$

Maximal sensitivity for $R_L = R_S$

Wheatstone bridge



"deflection" mode:

$$V_{out} = V_{CC}\left(\frac{R_3}{R_2+R_3} - \frac{R_4}{R_1+R_4}\right)$$

By operating close to the equilibrium condition :

$$k = \frac{R_1}{R_4} = \frac{R_2}{R_0}$$

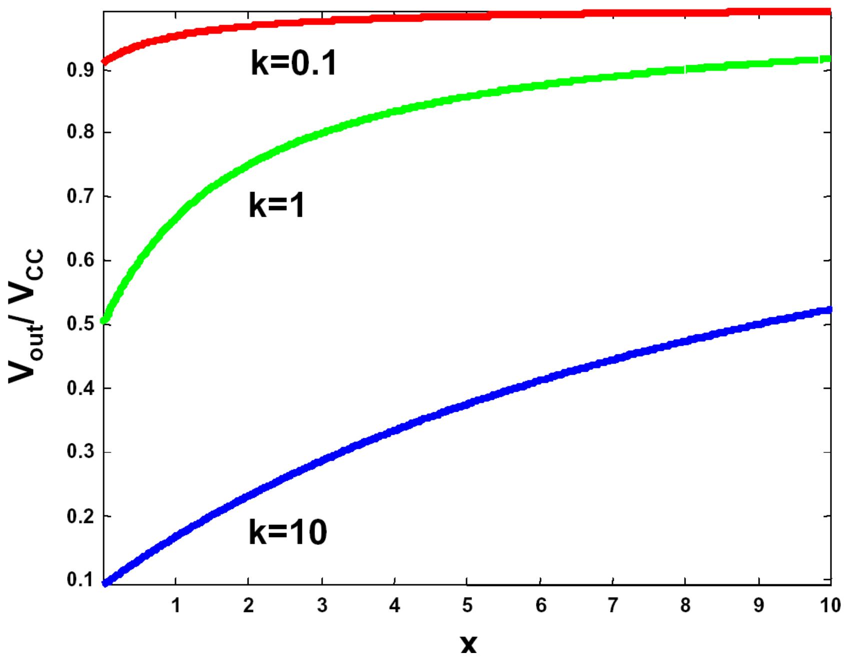
therefore:

$$V_{out} = V_{CC}\left(\frac{R_0(1+x)}{R_0k+R_0(1+x)} - \frac{R_4}{R_4k+R_4}\right) =$$

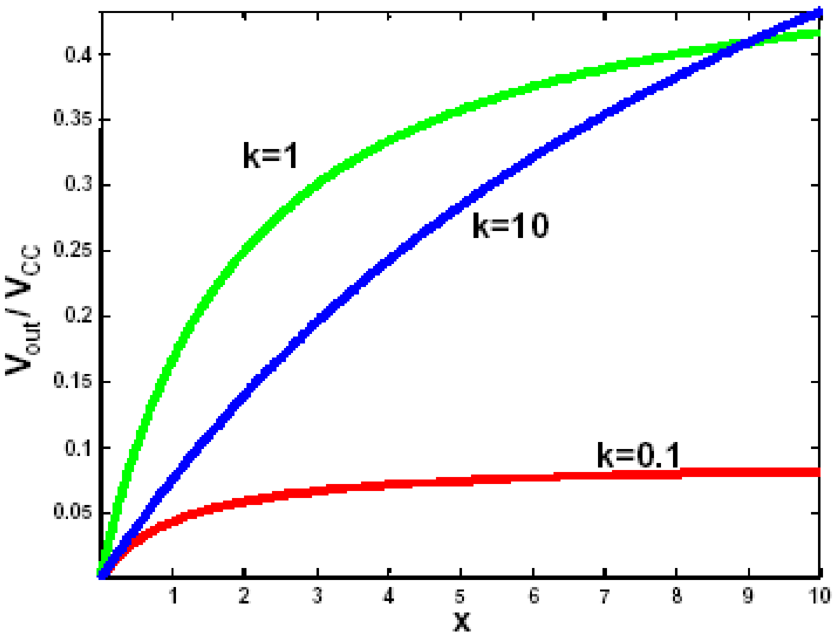
$$= V_{CC}\left(\frac{(1+x)}{k+(1+x)} - \frac{1}{k+1}\right) = V_{CC}\frac{kx}{(1+k)(1+k+x)}$$

Voltage divider vs Wheatstone bridge: output

Partitore di tensione



Ponte di Wheastone



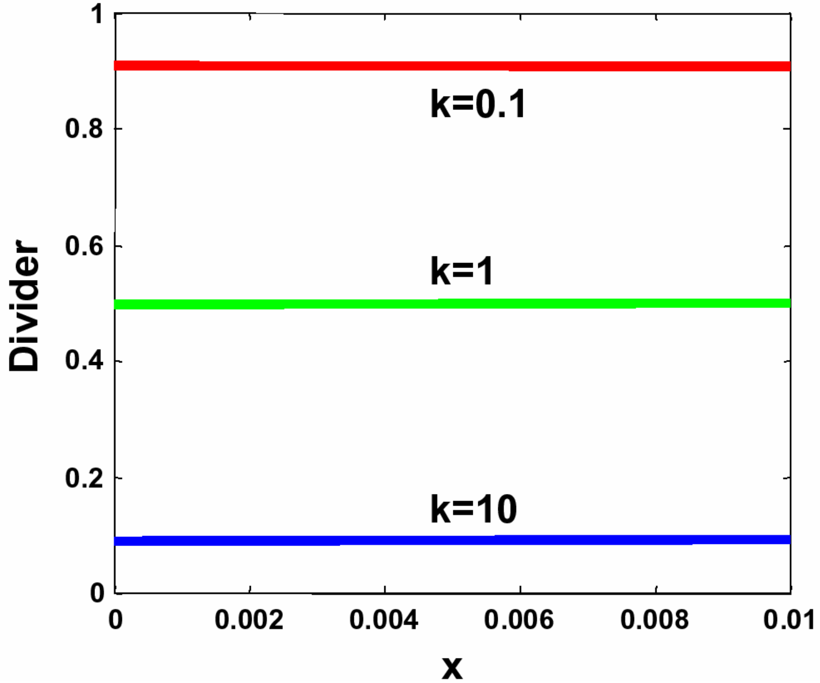
Wheatstone bridge: sensitivity

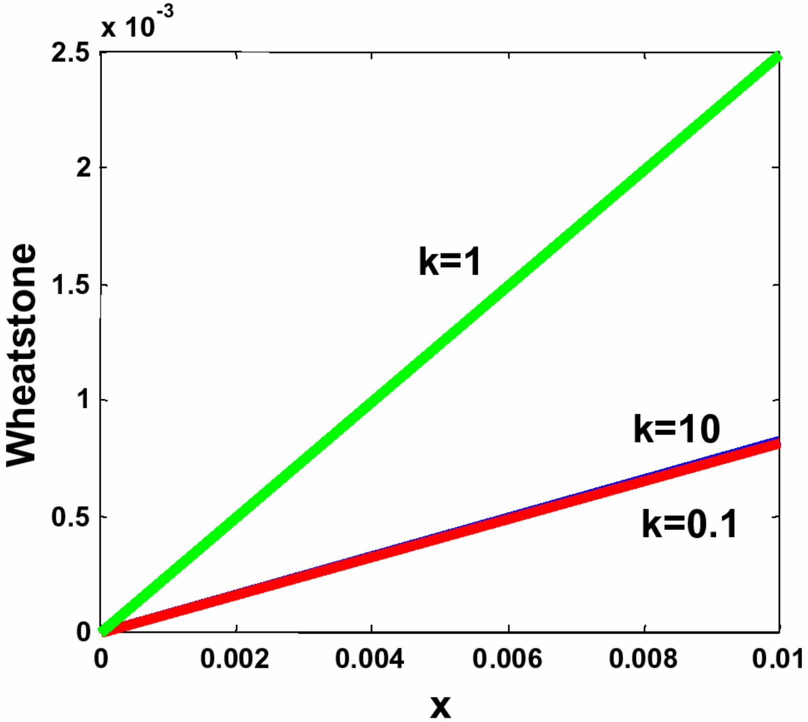
$$S = \frac{dV_{out}}{dx} = V_{CC}\frac{d}{dx}\left(\frac{kx}{(1+k)(1+k+x)}\right) =$$

$$= V_{CC}\frac{k(1+k)(1+k+x) - kx(1+k)}{(1+k)^2(1+k+x)^2} =$$

$$= V_{CC}\frac{k}{(1+k+x)^2}$$

Voltage divider vs Wheatstone bridge: sensitivity

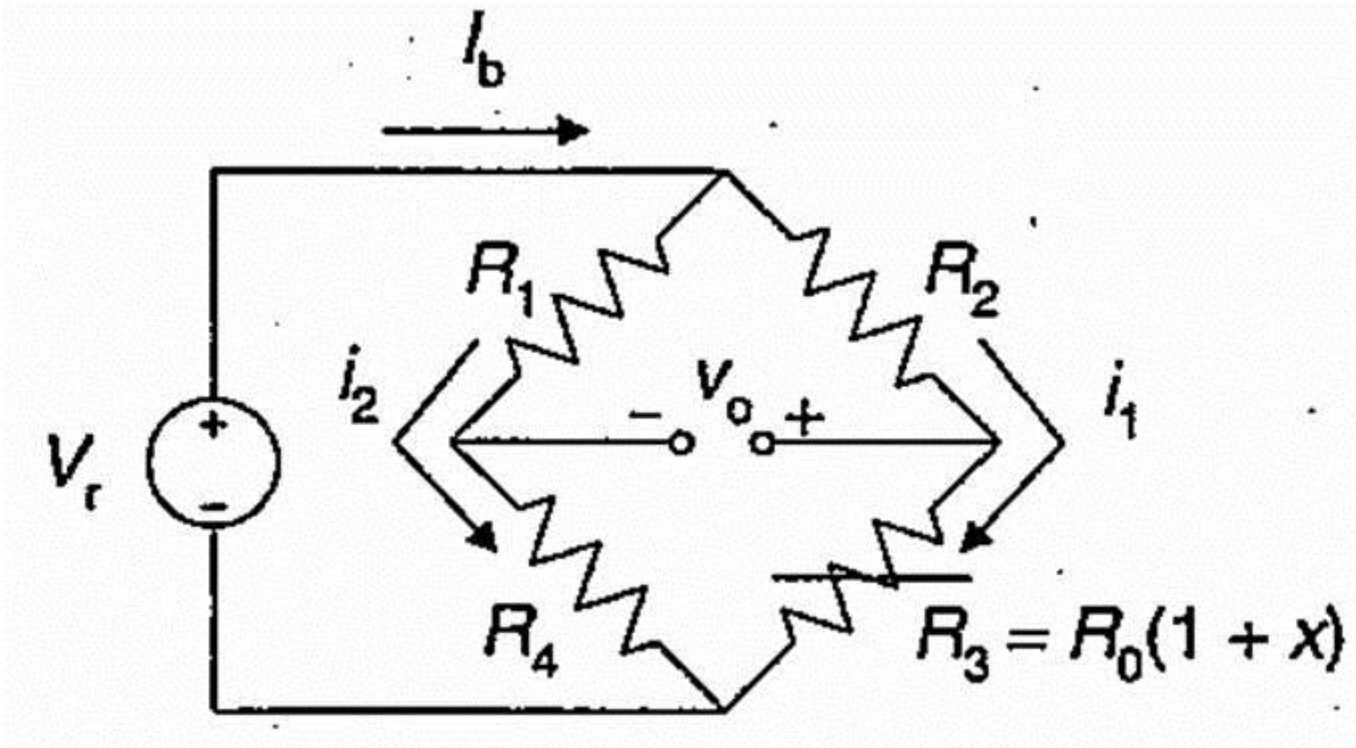


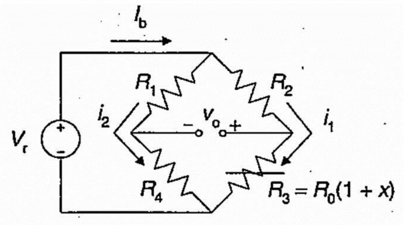


The voltage divider has a great offset compared with voltage changes, and this makes the curves ‘flat’ close to x=0.

The sensitivity of the two circuits is the same, but the sensitivity of the Wheatstone bridge can be increased by an amplifier stage

Wheatstone bridge: different configurations ("quarter bridge", "half bridge", "full bridge")





R_1	R_2	R_3	R_4	v_0 (const. Vr)	v_0 (const. I)
R_0	R_0	$R_0(1+x)$	R_0	$V_r \frac{x}{2(2+x)}$	$IR_0 \frac{x}{4+x}$
$R_0(1+x)$	R_0	$R_0(1+x)$	R_0	$V_r \frac{x}{2+x}$	$IR_0 \frac{x}{2}$
R_0	R_0	$R_0(1+x)$	$R_0(1-x)$	$V_r \frac{2x}{(4-x^2)}$	$IR_0 \frac{x}{2}$
R_0	$R_0(1-x)$	$R_0(1+x)$	R_0	$V_r \frac{x}{2}$	$IR_0 \frac{x}{2}$
$R_0(1-x)$	R_0	$R_0(1+x)$	R_0	$V_r \frac{-x^2}{(4-x^2)}$	$IR_0 \frac{-x^2}{4}$
$R_0(1+x)$	$R_0(1-x)$	$R_0(1+x)$	$R_0(1-x)$	$V_r x$	$IR_0 x$

$V_r \dfrac{x}{2(2+x)}$	$IR_0 \dfrac{x}{4+x}$
$V_r \dfrac{x}{2+x}$	$IR_0 \dfrac{x}{2}$
$V_r \dfrac{2x}{(4-x^2)}$	$IR_0 \dfrac{x}{2}$
$V_r \dfrac{x}{2}$	$IR_0 \dfrac{x}{2}$
$V_r \dfrac{-x^2}{(4-x^2)}$	$IR_0 \dfrac{-x^2}{4}$
$V_r x$	$IR_0 x$

$\Rightarrow$ Bridges supplied by constant current are generally more linear than bridges supplied by constant voltage

$\Rightarrow$ “full bridge” configurations are much used with strain gauges.

Thermal compensation by Wheatstone bridge

Strain gauges are sensible to temperature changes too.

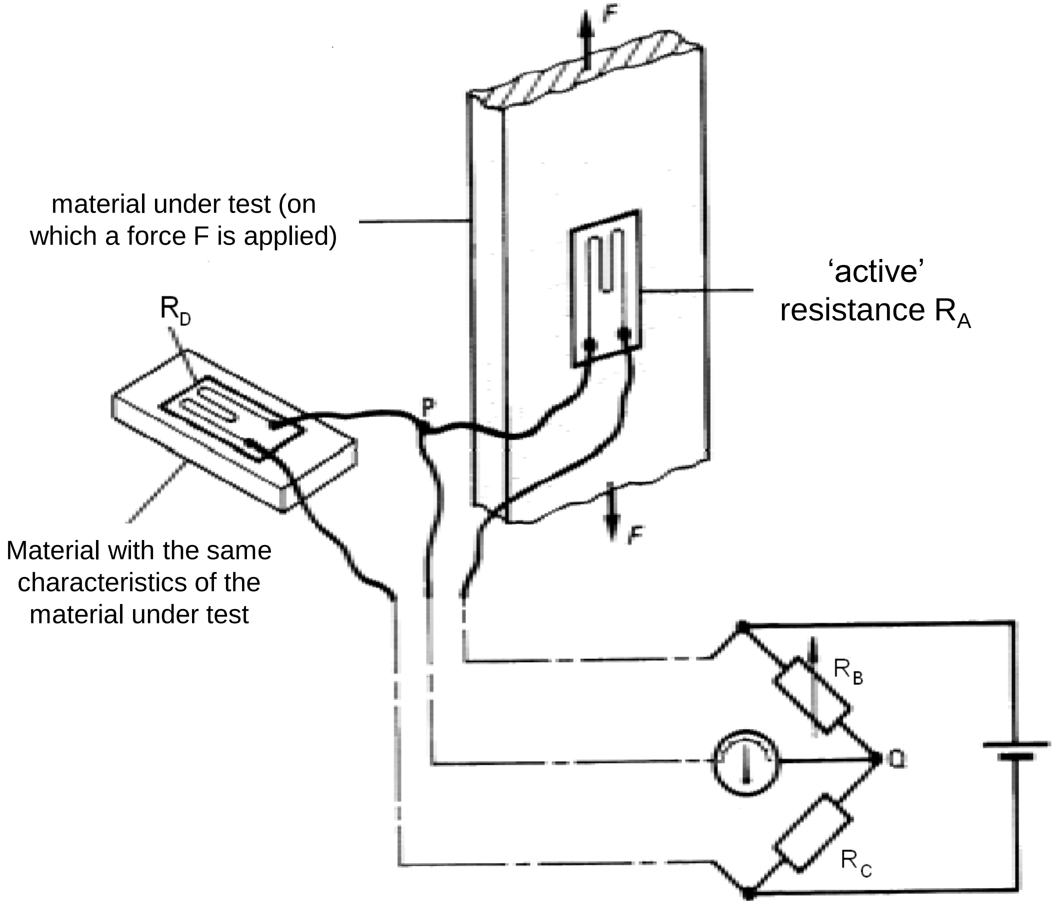
Wheastone bridge configuration can be useful to compensate this effect.

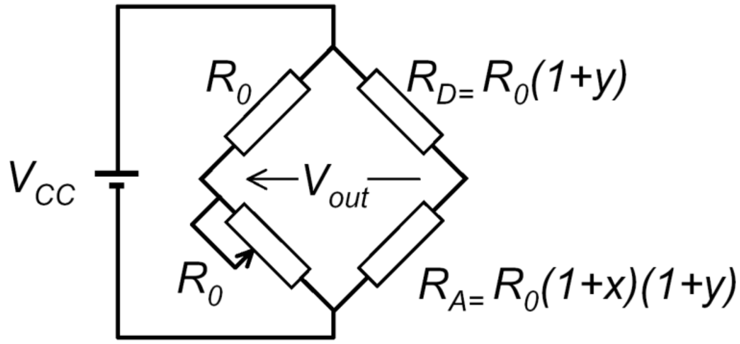
Assume the following setup:

- An “active” resistance R_A submitted to both temperature (y) and mechanical (x) variations;

- A ‘dummy’ resistance R_D, positioned close to the active one, submitted ONLY to temperature variations;

Thermal compensation by Wheatstone bridge

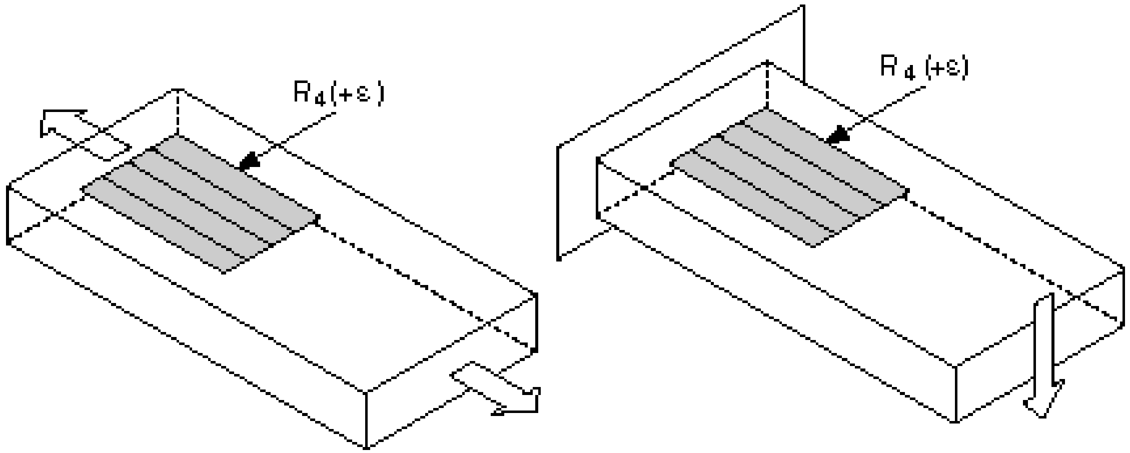




⇒ The effect of (1+y) is cancelled

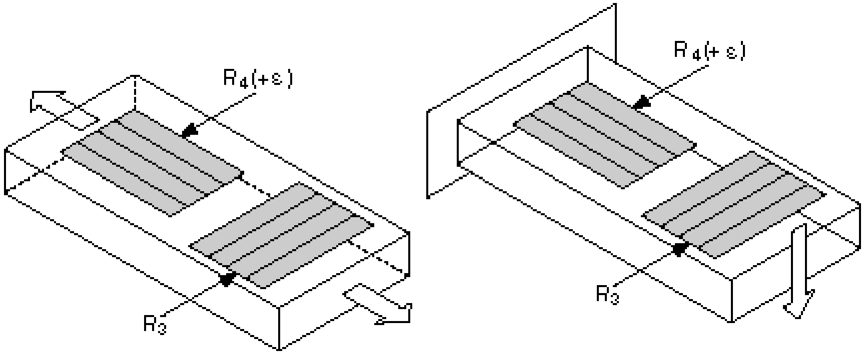
Quarter-Bridge Strain Gauge - Configuration Type I

- Measures **axial or bending strai**n
- Requires a passive quarter-bridge completion resistor known as a dummy resistor
- Requires half-bridge completion resistors to complete the Wheatstone bridge
- R4 is an active strain gauge measuring the tensile strain (+ε)



Quarter-Bridge Strain Gauge - Configuration Type II

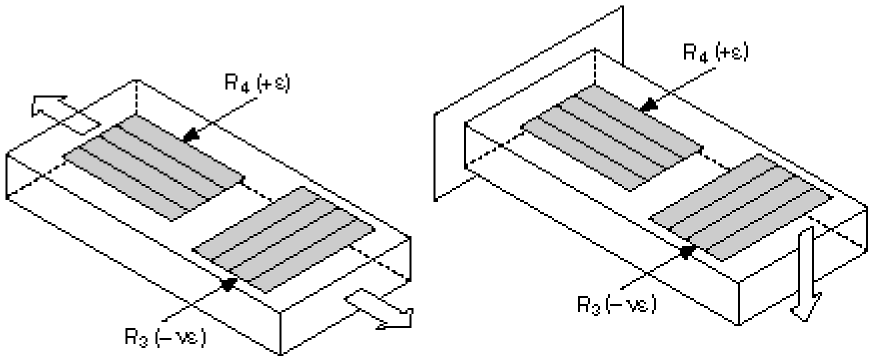
Ideally, the resistance of the strain gauge should change only in response to applied strain. However, strain gage material, as well as the specimen material to which the gage is applied, also responds to changes in temperature.

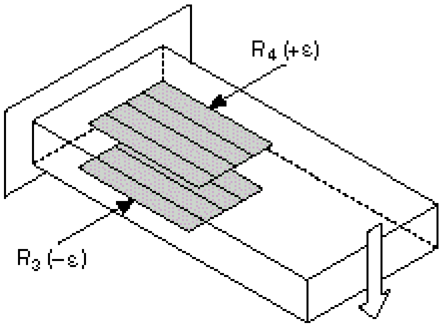


The quarter-bridge strain gage configuration type II helps further minimize the effect of temperature by using two strain gages in the bridge. As shown in the figure, typically one strain gauge (R4) is active and a second strain gauge (R3) is mounted in close thermal contact, but not bonded to the specimen and placed transverse to the principal axis of strain.

Therefore the strain has little effect on this dummy gage, but any temperature changes affect both gauges in the same way. Because the temperature changes are identical in the two strain gauges, the ratio of their resistance does not change, the output voltage (V_o) does not change, and the effects of temperature are minimized.

Half-Bridge Strain Gauge -
→ double the bridge's sensitivity





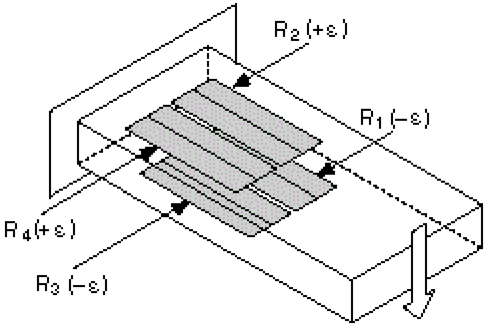
Configuration Type I

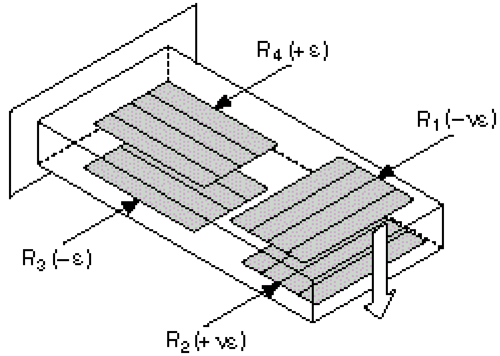
- Measures **axial or bending strain**
- Requires half-bridge completion resistors to complete the Wheatstone bridge
- R4 is an active strain gage measuring the tensile strain (+ε)
- R3 is an active strain gage compensating for Poisson's effect (-νε)
- This configuration is commonly confused with the quarter-bridge type II configuration, but type I has an active R3 element that is bonded to the strain specimen.

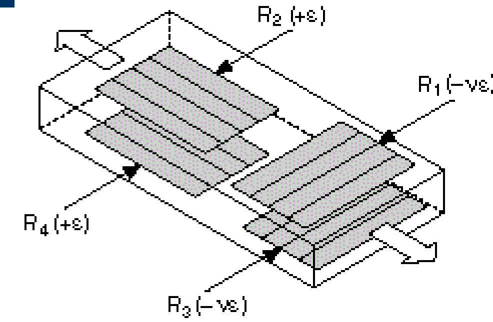
Configuration Type II

- Measures **bending strain only**
- Requires half-bridge completion resistors to complete the Wheatstone bridge
- R4 is an active strain gage measuring the tensile strain (+ε)
- R3 is an active strain gage measuring the compressive strain (-ε)

Full-Bridge Strain Gauge







Configuration Type I

- Highly sensitive to **bending strain only**
- R1 and R3 are active strain gages measuring compressive strain (–ε)
- R2 and R4 are active strain gages measuring tensile strain (+ε)

Configuration Type II

- Sensitive to **bending strain only**
- R1 is an active strain gage measuring the compressive Poisson effect (–νε)
- R2 is an active strain gage measuring the tensile Poisson effect (+νε)
- R3 is an active strain gage measuring the compressive strain (–ε)
- R4 is an active strain gage measuring the tensile strain (+ε)

Configuration Type III

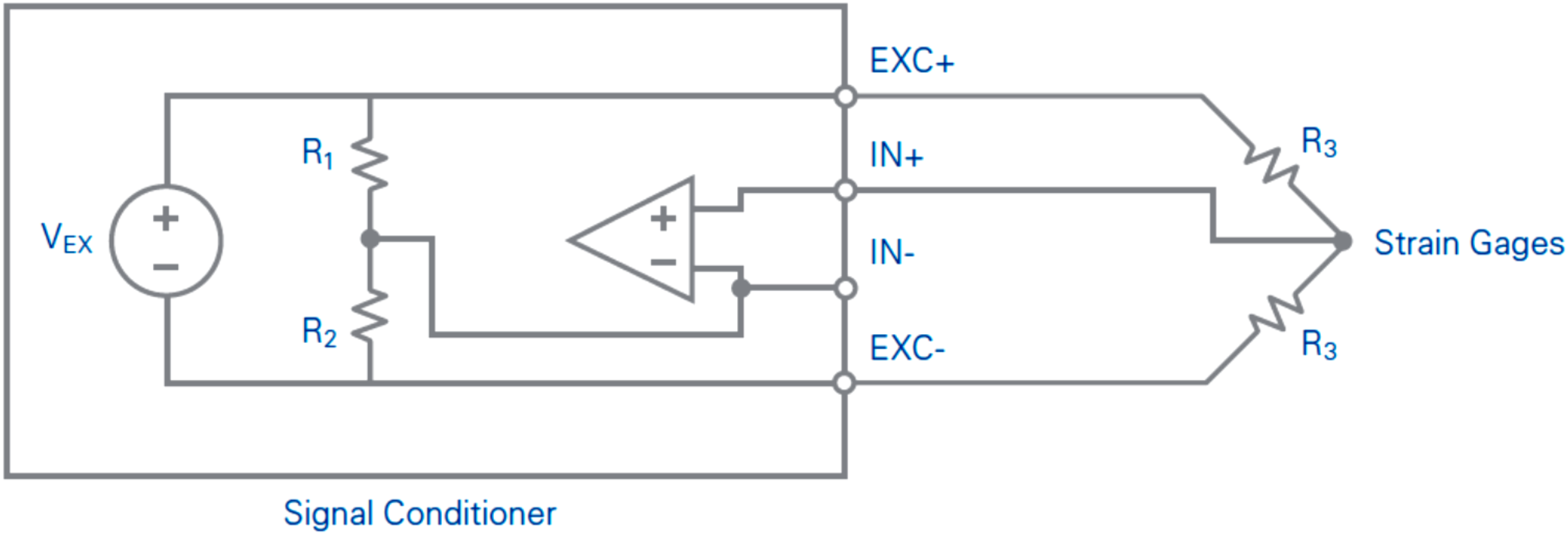
- Measures **axial strain**
- R1 and R3 are active strain gages measuring the compressive Poisson effect (–νε)
- R2 and R4 are active strain gages measuring the tensile strain (+ε)

Bridge Configurations for Strain Gages – Summary

Measurement Type	Quarter Bridge		Half-Bridge		Full-Bridge		
	Type I	Type II	Type I	Type II	Type I	Type II	Type III
Axial Strain	Yes	Yes	Yes	No	No	No	Yes
Bending Strain	Yes	Yes	Yes	Yes	Yes	Yes	No
Compensation							
Transverse Sensitivity	No	No	Yes	No	No	Yes	Yes
Temperature	No	Yes	Yes	Yes	Yes	Yes	Yes
Sensitivity							
Sensitivity at 1000 με	~0.5 mV/V	~0.5 mV/V	~0.65 mV/V	~1.0 mV/V	~2.0 mV/V	~1.3 mV/V	~1.3 mV/V
Installation							
Number of Bonded Gages	1	1*	2	2	4	4	4
Mounting Location	Single Side	Single Side	Single Side	Opposite Sides	Opposite Sides	Opposite Sides	Opposite Sides
Number of Wires	2 or 3	3	3	3	4	4	4
Bridge Completion Resistors	3	2	2	2	0	0	0

*A second strain gage is placed in close thermal contact with structure but is not bonded.

Signal conditioner for a half-bridge strain gage circuit



a) Power supply

Bridge-based sensors require a constant voltage to power the bridge. Bridge signal conditioners typically include a voltage source. No standard voltage level is recognized industry wide, but excitation voltage levels of around 3 V and 10 V are common. Though a higher excitation voltage generates a proportionately higher output voltage, it can also cause larger errors because of self-heating (that changes a bridge's resistivity and sensitivity and the adhesive's ability to transfer strain). Similarly, small fluctuations in the excitation voltage due to unstable excitation sources can affect the accuracy of your measurements.

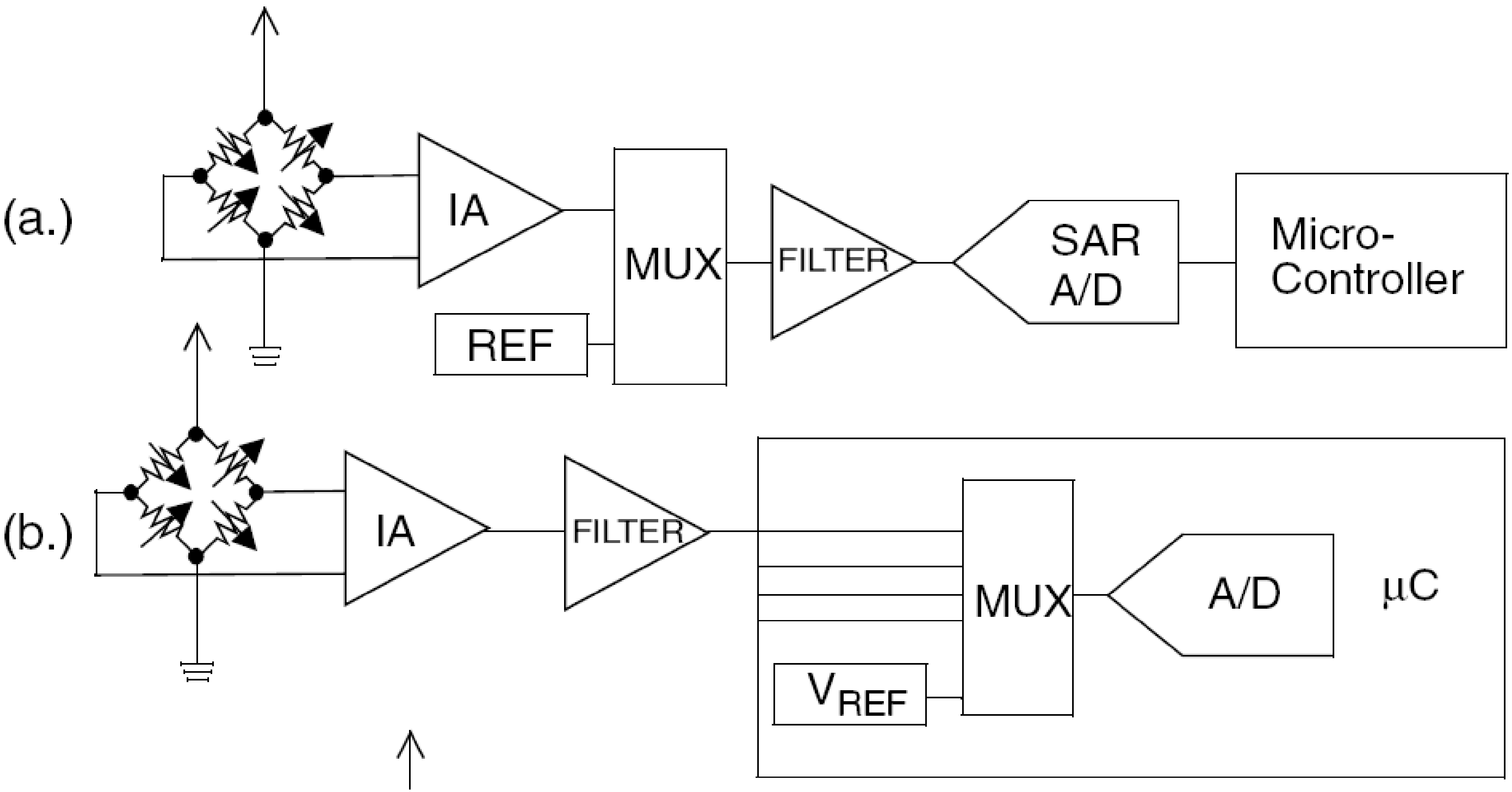
→ The optimum excitation voltage is best determined by an experimental procedure. With no load applied, one should examine the zero point of the channel while progressively raising the excitation level. When instability is seen in the zero reading, excitation is then lowered until stability returns. This experiment should be performed at the highest temperature over which measurements are supposed to be done. In noisy environments, low excitation levels can be used by properly shielding the lead wires and placing the measurement device close to the sensors.

The optimum excitation voltage is best determined by an experimental procedure. With no load applied, you should examine the zero point of the channel while progressively raising the excitation level. When you see instability in the zero reading, you should lower the excitation until stability returns. You should perform this experiment at the highest temperature over which you are taking measurements. In noisy environments, you can still use low excitation levels by properly shielding the lead wires and placing the measurement device close to the sensors.

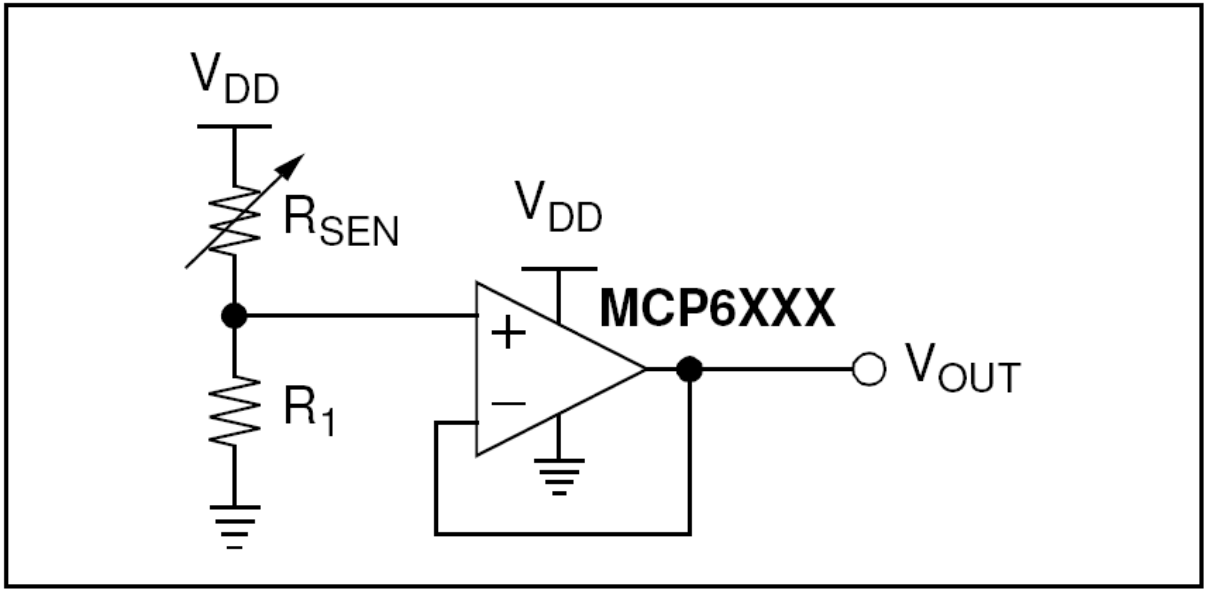
b) Amplification

The output of strain gages is relatively small. For example, most strain gage bridges output less than 10 mV/V, or 10 millivolts of output per volt of excitation voltage. With 10 V excitation, the output signal is 100 mV. Therefore, signal conditioners for bridge-based sensors usually include amplifiers to boost the signal level, increase measurement resolution, and improve signal-to-noise ratios. Load, pressure, and torque sensors can output low- or high-level voltages, depending on its excitation requirements. Low-level sensors are typically powered by a measurement device and output millivolt signals. High-level sensors (or conditioned sensors) require higher external power sources to operate, and output ±5 V, ±10 V, or 4–20 mA signals.

Wheatstone bridges output stages



1. Resistance-to-voltage conversion: a) voltage divider



The voltage divider (R_{SEN} and R_1) converts the sensor resistance to a voltage. The op-amp buffers the voltage divider for further signal processing.

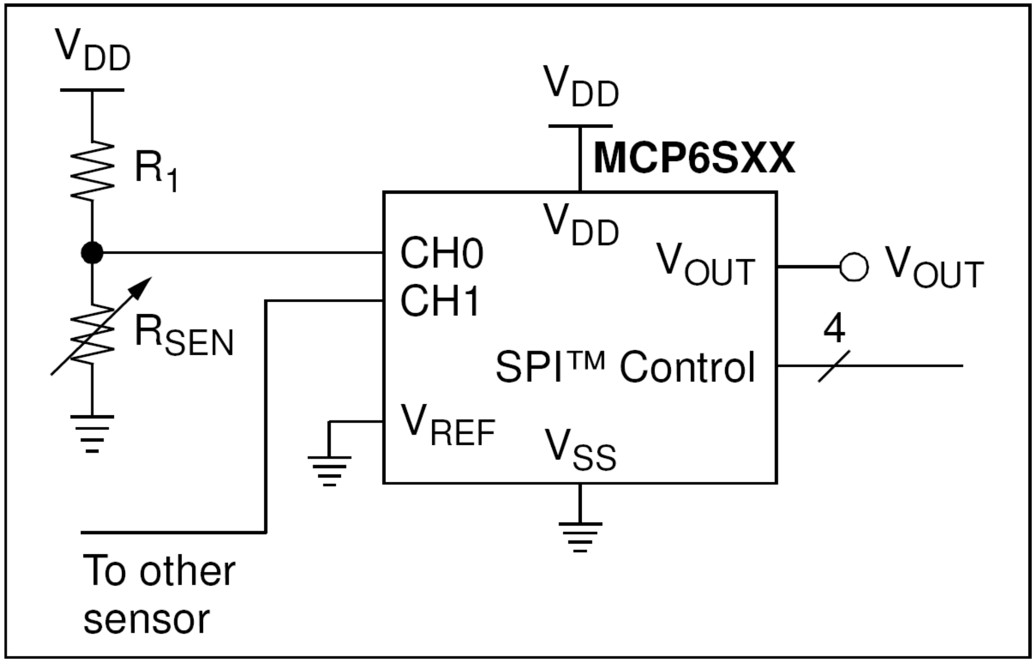
Advantages
- Simplicity
- Ratiometric output* (with an Analog-to-Digital Converter (ADC) using V_{DD} as its reference voltage)
- Detection of open sensor (failure)

Disadvantages
- Poor common mode noise rejection
- Voltage is a non-linear function of resistance

Sensor Examples
- Thermistor
- RTD
- Magneto-resistive sensor

** the output is proportional to the supply voltage*

1. Resistance-to-voltage conversion: b) Voltage Divider and Variable Gain



The voltage divider (R_{SEN} and R_1) converts the sensor resistance to a voltage. The MCP6Sxx (a PGA, programmable gain amplifier) buffers the voltage divider for further signal processing and can be set to different gains when the sensor is non-linear.

Advantages

- Linearization of non-linear sensors
- Ratiometric output (with an ADC using V_{DD} as its reference voltage)
- Multiplexing several sensors
- Detection of open sensor(failure)

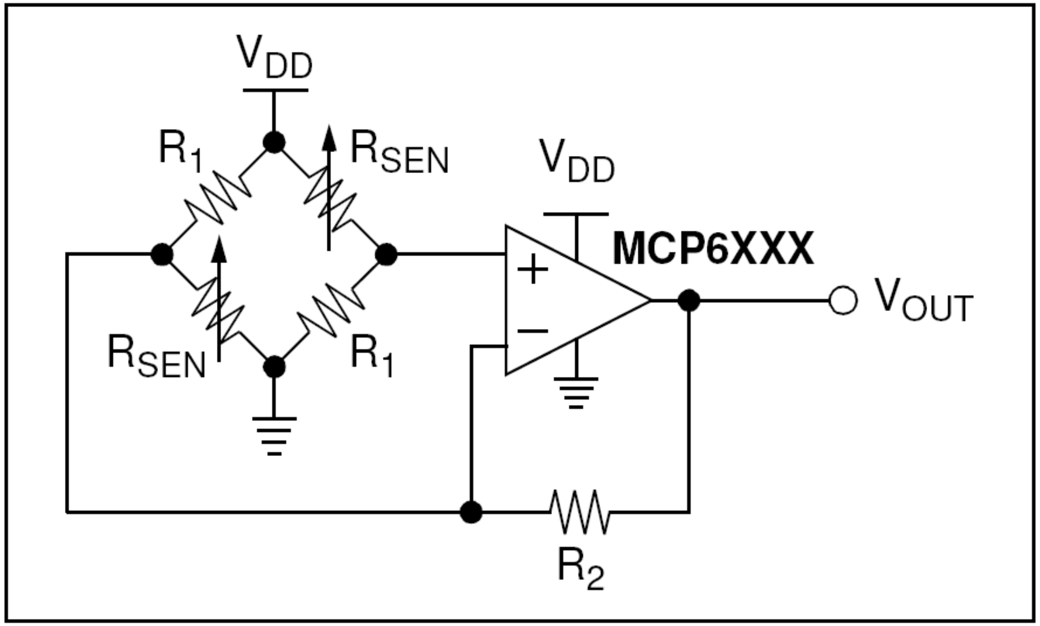
Disadvantages

- Poor common mode noise rejection
- Voltage is a non-linear function of resistance
- Needs a controller and firmware

Sensor Examples

- Thermistor

1. Resistance-to-voltage conversion: c) Wheatstone Bridge



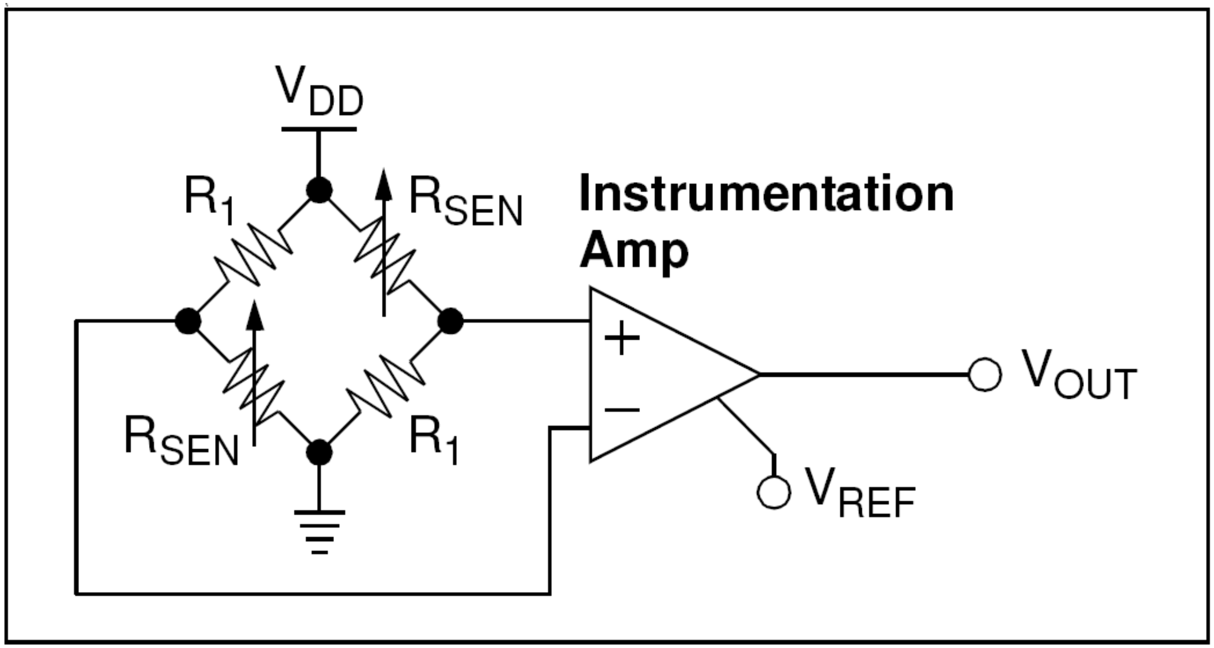
A Wheatstone bridge converts a change in resistance to a change in differential voltage.
The op amp amplifies the difference voltage.

Advantages
- Good rejection of common mode noise
- Ratiometric output (with an ADC using V_{DD} as its reference voltage)
- Simplicity
- Detection of open sensor(failure)

Disadvantages
- Gain is a function of R_{SEN}
- Needs a controller and firmware to correct
- Voltage is a non-linear function of resistance

Sensor Examples
- Strain gage
- Pressure sensor
- Magneto-resistive sensor

1. Resistance-to-voltage conversion: d) Wheatstone Bridge and INA



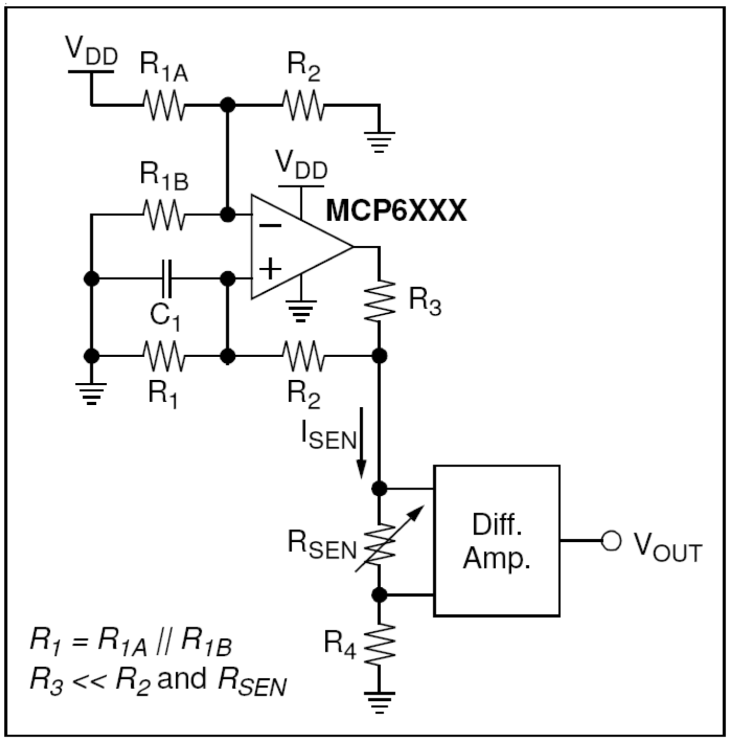
In this Wheatstone bridge circuit the instrumentation amplifier amplifies the bridge's difference voltage and gives excellent rejection of common mode noise.

Advantages
- Excellent common mode noise rejection
- Ratiometric output (with an ADC using V_{DD} as its reference voltage)
- Detection of open sensor failure)

Disadvantages
- Cost
- Voltage is a non-linear function of resistance

Sensor Examples
- Strain gage
- Pressure sensor
- Magneto-resistive sensor

1. Resistance-to-voltage conversion: e) Floating Current Source



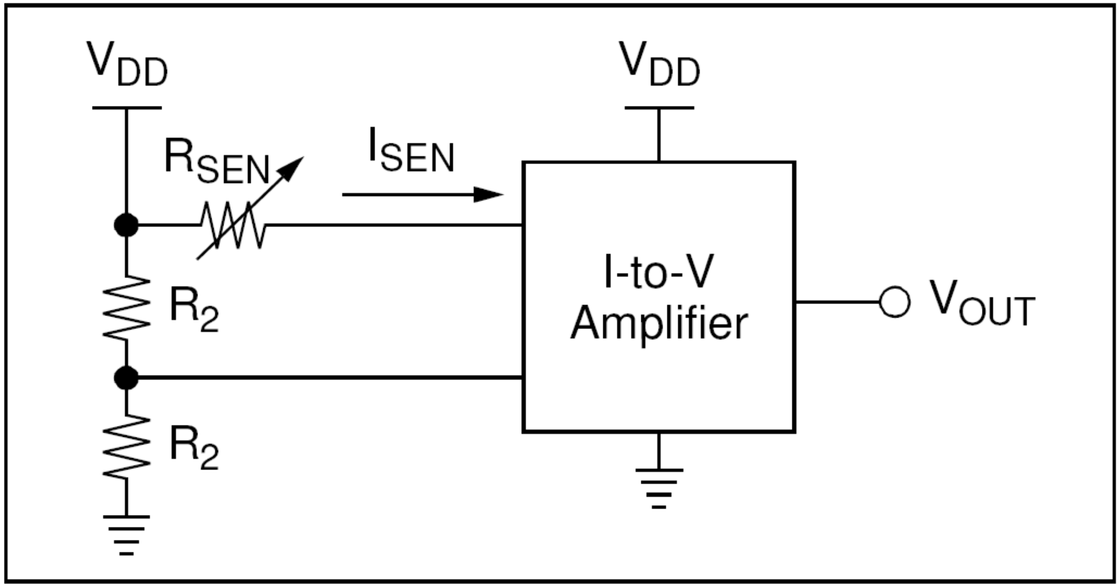
This circuit provides a current source (I_{SEN}) that accurately converts resistance to voltage. R_{1A}, R_{1B}, R_1, R_2, R_3 and the op amp form a current source (Howland current pump). C_1 stabilizes this current source and reduces noise. R_4 provides isolation from ground for remote sensors. The voltage across R_{SEN} is amplified by a difference amplifier which also rejects common mode noise. The voltage on top of R_4 can be used to detect an open (failed) sensor.

Advantages
- Linearity of resistance to voltage conversion
- Ratiometric output (with an ADC using V_{DD} as its reference voltage)

Disadvantages
- Cost
- Requires accurate resistors

Sensor Examples
- Thermistor
- RTD
- Hot-wire anemometer

2. Resistance-to-current conversion



The second strategy for conditioning a resistive sensor is to produce a current that is a function of the resistance.
The basic strategy is to use a "I-to-V Amplifier" which can be a transimpedance amp or a logarithmic amp.

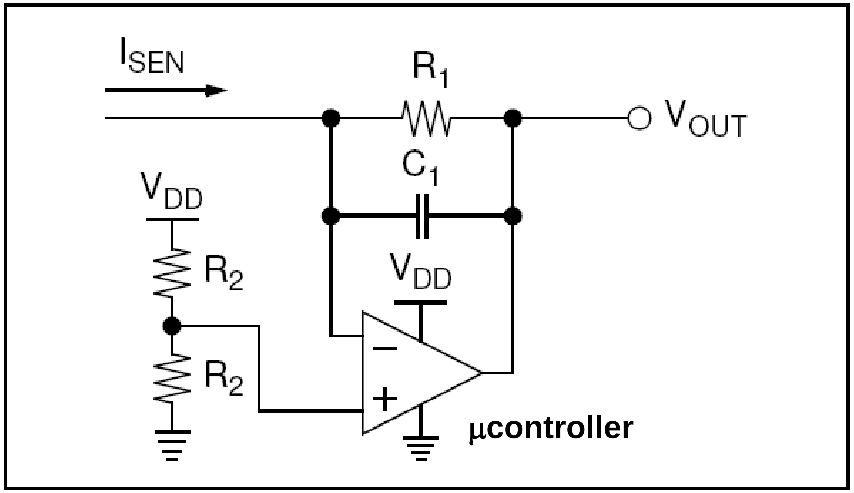
Advantages
- Linearity of resistance to voltage conversion
- Ratiometric output (with an ADC using V_{DD} as its reference voltage)

Disadvantages
- Cost
- Requires accurate resistors

Sensor Examples
- Thermistor
- RTD
- Hot-wire anemometer

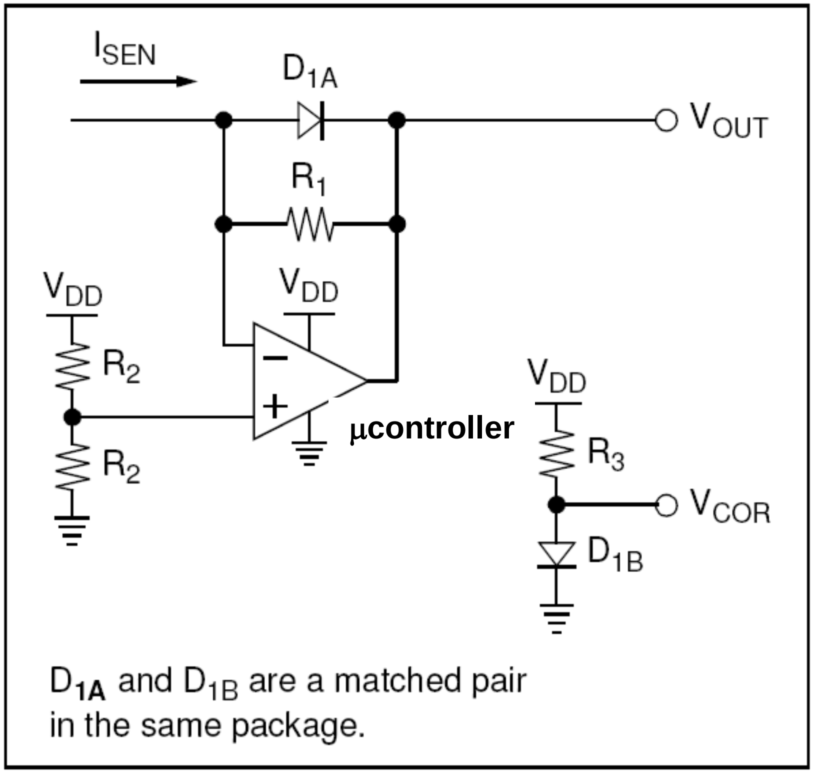
I-to-V amplifiers

Transimpedance Amplifier



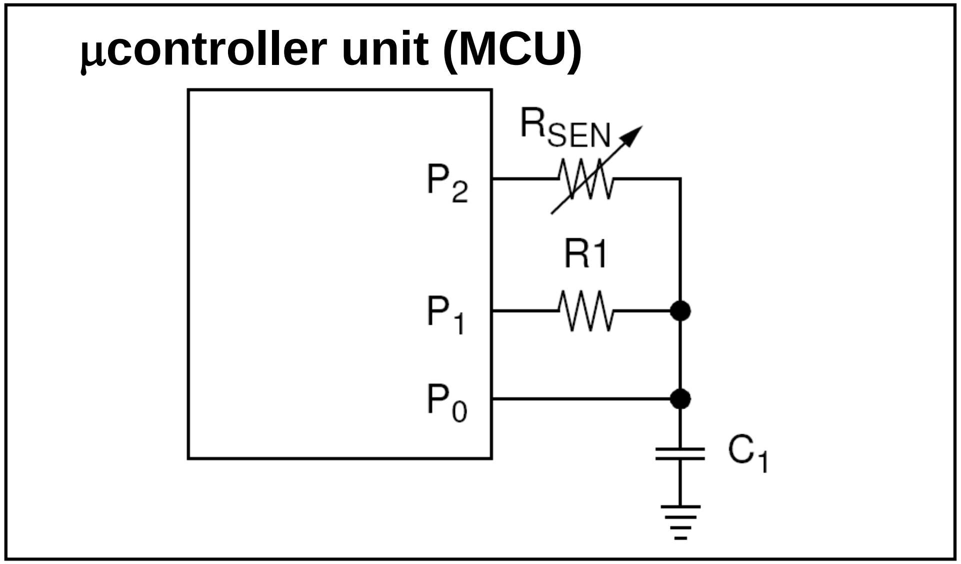
a transimpedance amplifier (R_1 and the op amp) converts the sensor current (I_{SEN}) to a voltage. The capacitor C_1 is sometimes needed to stabilize the amplifier when the source has a large capacitance

Logarithmic Amplifier



a logarithmic amplifier (D_{1A} and the op amp) converts the sensor current (I_{SEN}) to a voltage proportional to the logarithm of the current. R_1 maintains negative feedback when I_{SEN} is small or negative. D_{1B} is used to correct D_{1A} for temperature changes.

3. RC decay



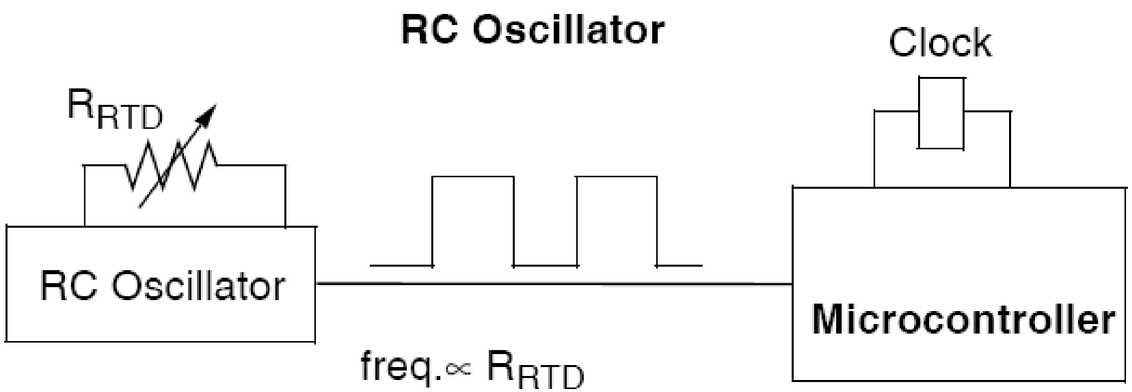
The third strategy for conditioning a resistive sensor is to produce a voltage with a RC decay (single pole response to a step). The time it takes for the voltage to decay to a threshold is a measure of the resistance. The figure shows a circuit using a MCU circuit that sets a ratiometric threshold (proportional to V_{DD}). The time is measured for both R_1 and R_{SEN} separately in order to correct for V_{DD}, C_1, and temperature errors. The MCU provides the switching and control needed.

Advantages
- Ratiometric correction of V_{DD}, C_1 and temperature errors
- Accurate
- Simple timing measurement

Disadvantages
- MCU timing resolution
- Digital noise
- Threshold must be ratiometric

Sensor Examples
- Thermistor

4. Oscillator frequency



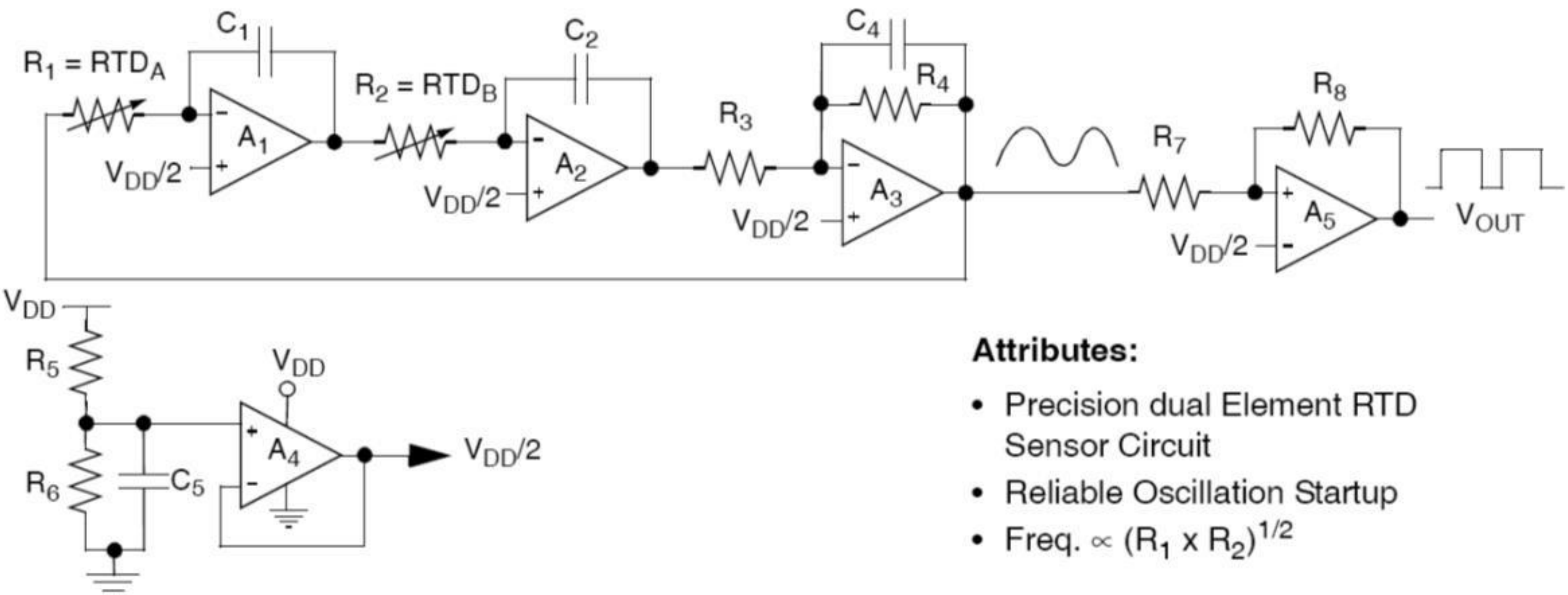
The fourth strategy for conditioning a resistive sensor is to measure a change in oscillation frequency. Oscillator circuits can be used to provide accurate temperature measurement with Resistive Temperature Detector (RTD) sensors. Oscillators provide a frequency output that is proportional to temperature and are easily integrated into a microcontroller system.

Advantages
- Does not require ADC or V_{REF}
- Excellent noise immunity
- Accuracy proportional to quality of microcontroller clock

Disadvantages
- Cost
- Design complexity

Sensor Examples
- RTD
- hot-wire anemometer

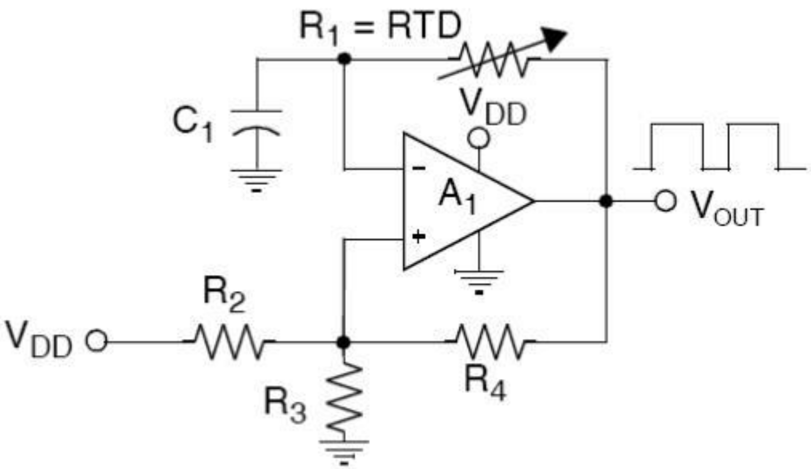
4. Oscillator frequency: a) State variable oscillator



Attributes:

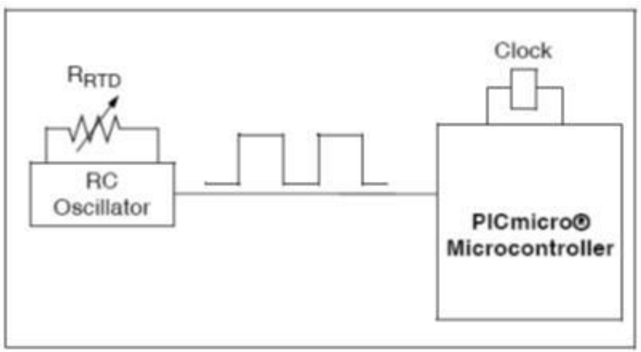
- Precision dual Element RTD Sensor Circuit
- Reliable Oscillation Startup
- Freq. $\propto (R_1 \times R_2)^{1/2}$

4. Oscillator frequency:
b) Relaxation oscillator



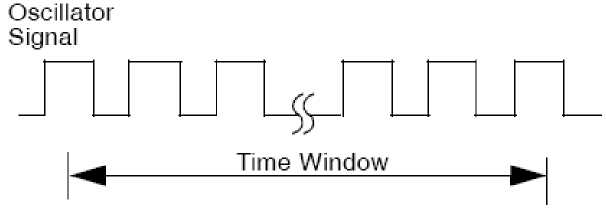
Attributes:

- Low Cost Solution
- Single Comparator Circuit
- Square Wave Output
- Freq. = 1/ (1.386 x R_1 x C_1)



Fixed time method

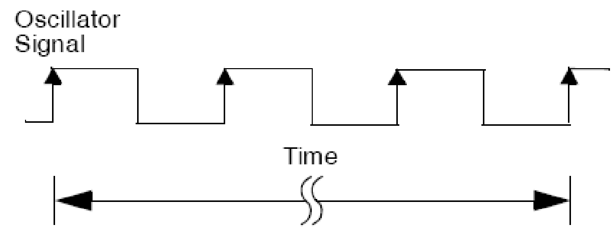
Algorithm:
Count the number of clock pulses in a time window.



Example: Measure the number of oscillation pulses in a 100 ms window and multiply by 10 to determine the frequency.

Fixed cycle method

Algorithm:
Determine the time between a fixed number of oscillation pulses.



Example: Measure time between four rising edges of the oscillation signal.