Lecture 1: Creating Sensors ESP3903

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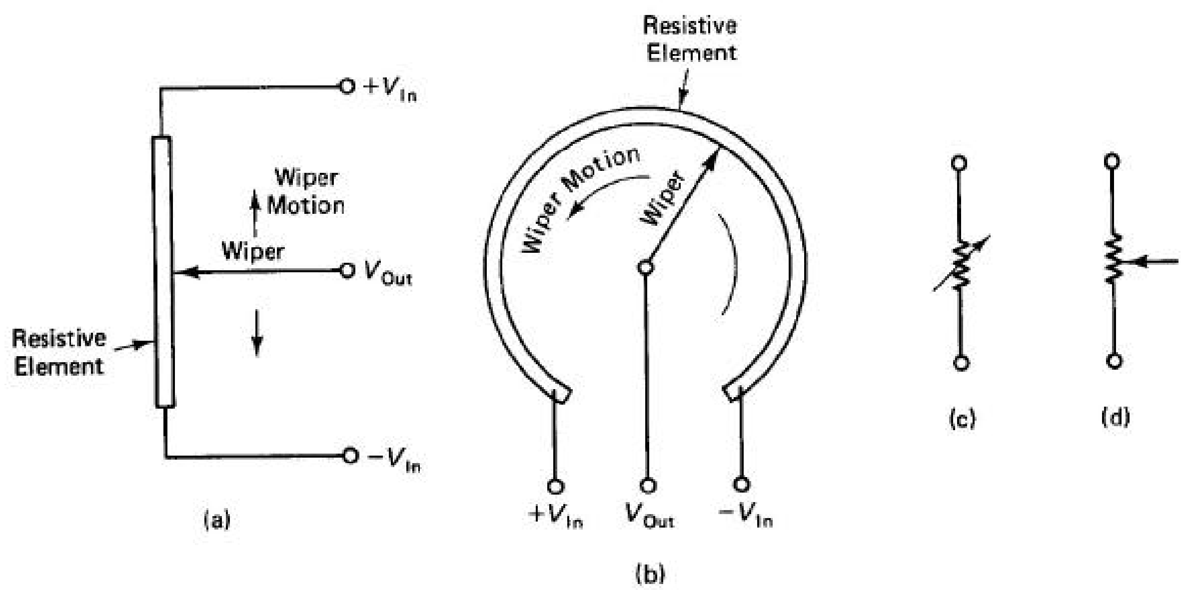
There are a wide variety of different sensors that can be made from simple readily available materials, you are free to choose/innovate. This lecture just gives an overview of some principles that might be useful to you. You may find it useful to take a look back at your ESP1104 Introduction to Electronics notes .

Resistance sensors

Can use a potential divider method for sensing position and angle

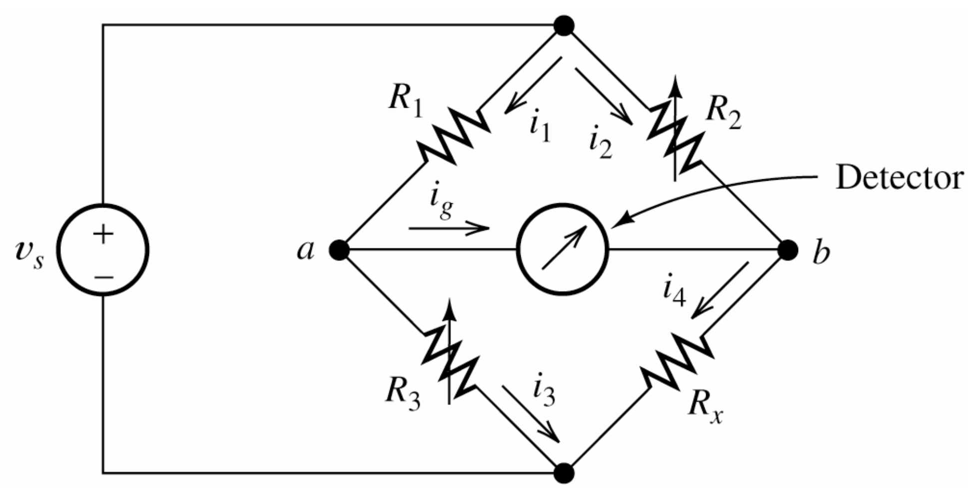


Many touch screens are also based upon the voltage divider principle. You can use the carbon paper and copper plates to make a simple touch screen sensor.

The Wheatstone bridge Resistance Circuits

The Null-Bridge

The Wheatstone bridge is a very powerful circuit used commonly with resistance sensitive sensors/transducers. Many types of sensors are based upon them changing their resistance as a function of an important parameter such as temperature or strain The Wheatstone bridge is a special type of circuit for detecting small changes in resistance, it consists of 4 resistors, two of which are usually fixed, as shown below. There is usually an unknown resistor (corresponding to the sensor), R_x.



The Wheatstone bridge. When the Wheatstone bridge is balanced, $i_g = 0$ and $v_{ab} = 0$.

Resistors R_2 and R_3 are varied until the detector current at the output is zero. At that condition, clearly

$$i_1 = i_3, \quad i_2 = i_4$$
$$v_a = R_3 i_3 = v_b = R_x i_4$$
$$R_1 i_1 = R_2 i_2$$

Therefore, at this “null condition”

$$\frac{R_3}{R_1} = \frac{R_x}{R_2} \Rightarrow R_x = R_2 \frac{R_3}{R_1}$$

The unknown resistance can then be obtained accurately, as long as R_2 and R_3 are known precisely. There are special high accuracy resistance boxes for doing this in which the resistance can be changed.

Deflection-bridge circuit

There are many ways of running a Wheatstone bridge, the way described above is the “balanced” approach. Another method is to fix $R_2 = R_1$ and select R_3 in such a way that the unknown resistance $R_x = R_3 + \Delta R$. Nominally, $R_x = R_3$, but then there is a change (say in temperature, strain etc), which causes a small perturbation ΔR in the resistance. It is easy to see that the output voltage, V_{ba}, is given by

$$V_{ba} = V_b - V_a = V_s \left(\frac{R_x}{R_x + R_2} - \frac{R_3}{R_1 + R_3} \right)$$

Substituting for R_x and using $R_2 = R_1$

$$V_{ba} == V_s\left(\frac{R_3+\Delta R}{R_3+\Delta R+R_2}-\frac{R_3}{R_2+R_3}\right)$$

Clearly when $\Delta R=0$, $V_{ab}=0$.

The using the binomial theorem and expanding, ignoring the second-order term in ΔR (ie, ΔR^2), we can prove

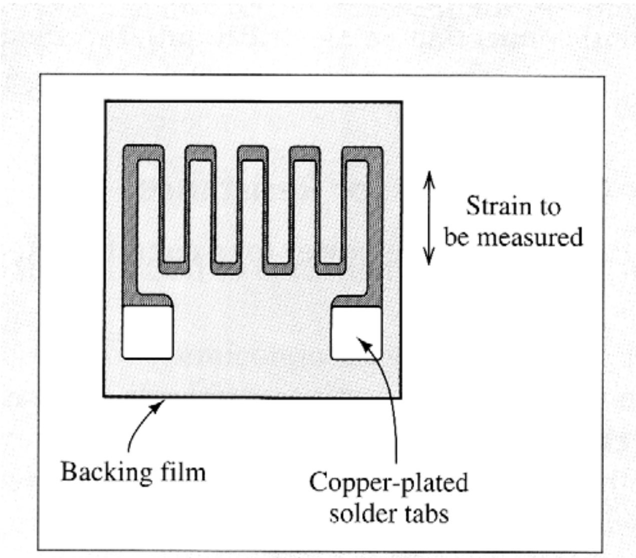
$$V_{ba} = V_s\left(\frac{R_3+\Delta R}{R_3+\Delta R+R_2}-\frac{R_3}{R_2+R_3}\right) \approx V_S\left(\frac{\Delta R}{R_3+R_2}-\frac{R_3\Delta R}{\left(R_3+R_2\right)^2}\right)$$

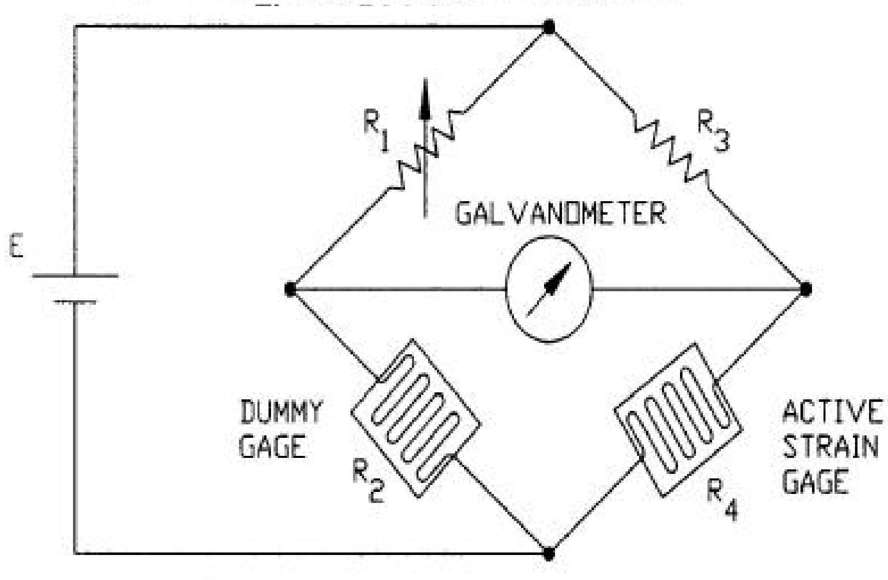
Often we make R_1, $R_2 >> R_3$, so it simplifies to a linear dependence on ΔR

$$\Delta V \approx V_S\left(\frac{\Delta R}{R_3+R_2}\right)$$

Note that in practice, the detector at the output, either in the null-bridge or deflector bridge mode will load the output and change it slightly. To calculate this loading effect, an equivalent Thevenin circuit for the Bridge network can be used.

Strain





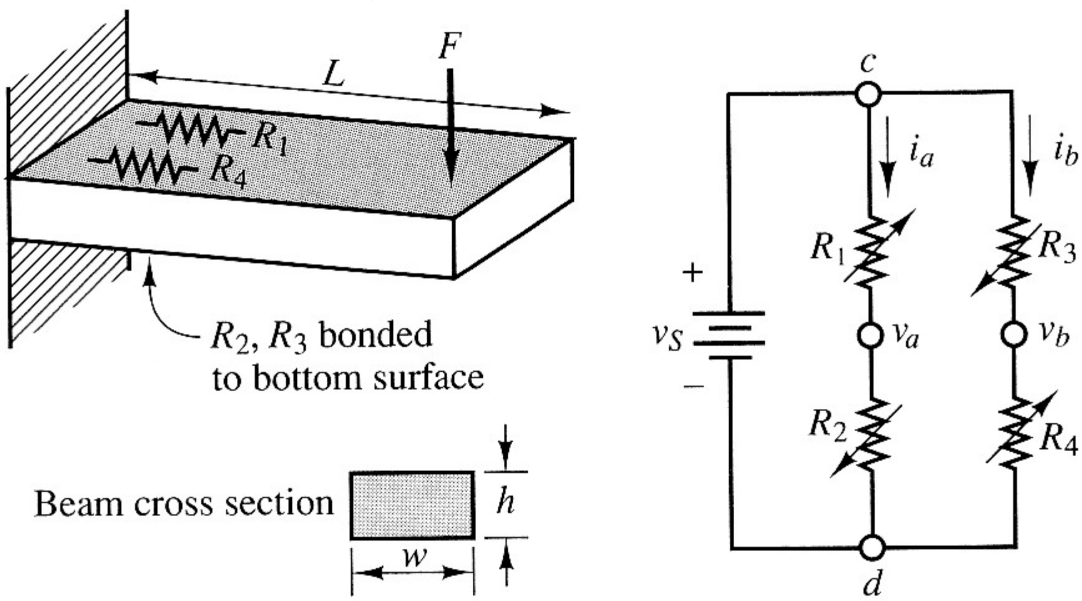
Thin conductors are bonded to a thin flexible plastic backing.

$$R = \frac{\rho L}{A}$$

$$G = \frac{\Delta R / R_0}{S}$$

Where R is the resistance, ρ is resistivity, L is total length, A is cross-sectional area. G is the Gauge factor which relates the strain S to change of relative change of resistance, $\Delta R/R_0$.

Force measurement with 4 strain gauges



Let R_1 and R_4 be the upper gauges and R_2 and R_3 the lower gauges. Thus, under the influence of the external force, we have

$$R_1 = R_4 = R_0 + \Delta R$$
$$R_2 = R_3 = R_0 - \Delta R$$

where R_0 is the zero strain resistance of the gauges. It can be shown from elementary statics that the relationship between the strain ϵ and a force F applied at a distance L for a cantilever beam is

$$\epsilon = \frac{6LF}{wh^2Y}$$

where h and w are as defined in Figure 2.45 and Y is the beam's modulus of elasticity.

In the circuit of Figure 2.45, the currents i_a and i_b are given by

$$i_a = \frac{v_S}{R_1 + R_2} \qquad \text{and} \qquad i_b = \frac{v_S}{R_3 + R_4}$$

The bridge output voltage is defined by $v_o = v_b - v_a$ and may be found from the following expression:

$$\begin{aligned} v_o = i_b R_4 - i_a R_2 &= \frac{v_S R_4}{R_3 + R_4} - \frac{v_S R_2}{R_1 + R_2} \\ &= v_S \frac{R_0 + \Delta R}{R_0 + \Delta R + R_0 - \Delta R} - v_S \frac{R_0 - \Delta R}{R_0 + \Delta R + R_0 - \Delta R} \\ &= v_S \frac{\Delta R}{R_0} = v_S GF \epsilon \end{aligned}$$

where the expression for $\Delta R / R_0$ was obtained in "Focus on Measurements: Resistance Strain Gauges." Thus, it is possible to obtain a relationship between the output voltage of the bridge circuit and the force F as follows:

$$v_o = v_S GF \epsilon = v_S GF \frac{6LF}{wh^2Y} = \frac{6 v_S GFL}{wh^2Y} F = kF$$

where k is the calibration constant for this force transducer.

Photo-conductive Cells - These photodevices vary their electrical resistance when subjected to light. Photoconductivity results from light hitting a semiconductor material which controls the current flow through it. Thus, more light increase the current for a given applied voltage. The most common photoconductive material is Cadmium Sulphide used in LDR photocells.

A **Photoconductive** light sensor does not produce electricity but simply changes its physical properties when subjected to light energy. The most common type of photoconductive device is the *Photoresistor* which changes its electrical resistance in response to changes in the light intensity. Photoresistors are **Semiconductor** devices that use light energy to control the flow of electrons, and hence the current flowing through them. The commonly used *Photoconductive Cell* is called the **Light Dependant Resistor** or **LDR**.

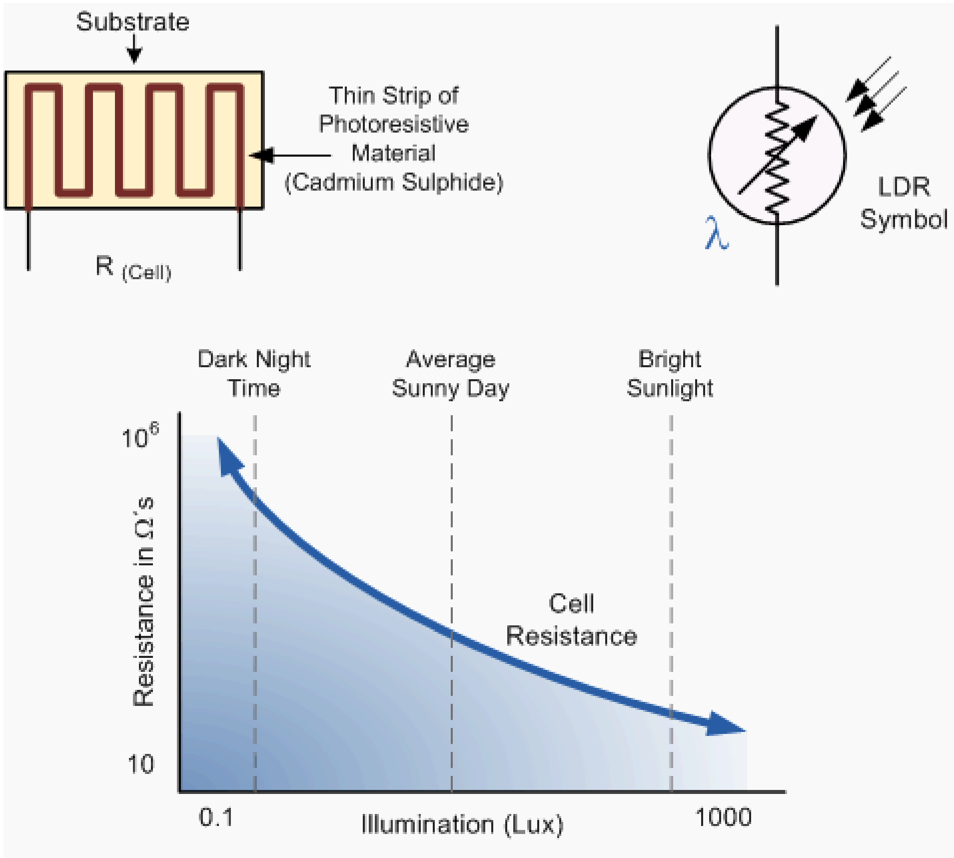
The Light Dependant Resistor

LDR

As its name implies, the **Light Dependant Resistor** (LDR) is made from a piece of exposed semiconductor material such as cadmium sulphide that changes its electrical resistance from several thousand Ohms in the dark to only a few hundred Ohms when light falls upon it by creating hole-electron pairs in the material. The net effect is an improvement in its conductivity with a decrease in resistance for an increase in illumination. Also, photoresistive cells have a long response time requiring many seconds to respond to a change in the light intensity.

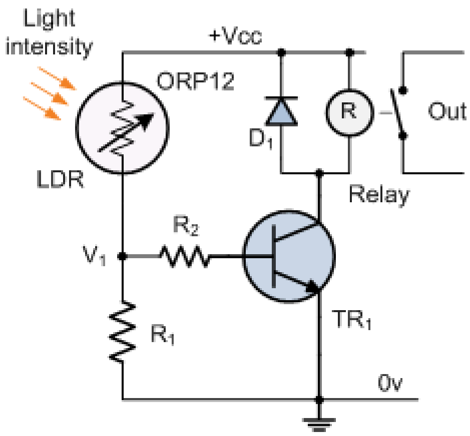
Materials used as the semiconductor substrate include, lead sulphide (PbS), lead selenide (PbSe), indium antimonide (InSb) which detect light in the infra-red range with the most commonly used of all photoresistive light sensors being **Cadmium Sulphide** (Cds). Cadmium sulphide is used in the manufacture of photoconductive cells because its spectral response curve closely matches that of the human eye and can even be controlled using a simple torch as a light source. Typically then, it has a peak sensitivity wavelength (λp) of about 560nm to 600nm in the visible spectral range.

The Light Dependant Resistor Cell



The most commonly used photoresistive light sensors is the **ORP12** Cadmium Sulphide photoconductive cell. This light dependant resistor has a spectral response of about 610nm in the yellow to orange region of light. The resistance of the cell when unilluminated (dark resistance) is very high at about 10MΩ's which falls to about 100Ω's when fully illuminated (lit resistance). To increase the dark resistance and therefore reduce the dark current, the resistive path forms a zigzag pattern across the ceramic substrate. The CdS photocell is a very low cost device often used in auto dimming, darkness or twilight detection for turning the street lights "ON" and "OFF", and for photographic exposure meter type applications.

One simple use of a Light Dependant Resistor, is as a light sensitive switch as shown below.



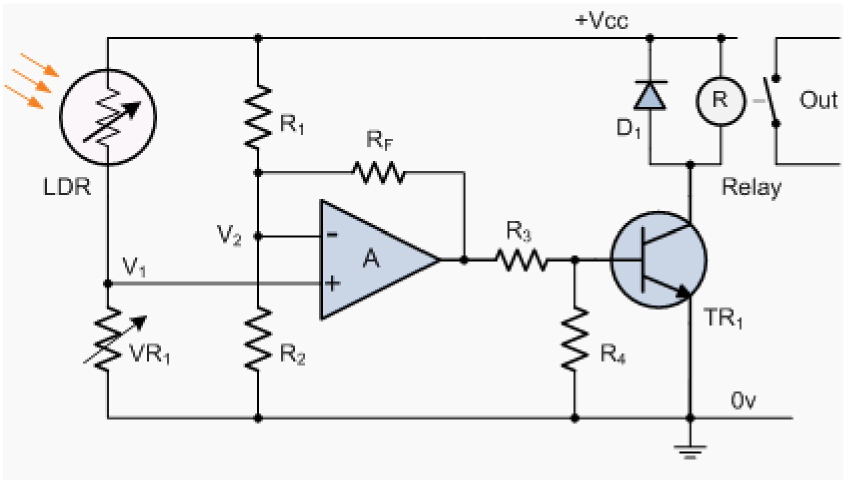
LDR Switch

This basic light sensor circuit is of a relay output light activated switch. A potential divider circuit is formed between the photoresistor, LDR and the resistor R1. When no light is present ie in darkness, the resistance of the LDR is very high in the Megaohms range so zero base bias is applied to the transistor TR1 and the relay is de-energised or "OFF".

As the light level increases the resistance of the LDR starts to decrease causing the base bias voltage at V1 to rise. At some point determined by the potential divider network formed with resistor R1, the base bias voltage is high enough to turn the transistor TR1 "ON" and thus activate the relay which in turn is used to control some external circuitry. As the light level falls back to darkness again the resistance of the LDR increases causing the base voltage of the transistor to decrease, turning the transistor and relay "OFF" at a fixed light level determined again by the potential divider network.

By replacing the fixed resistor R1 with a potentiometer VR1, the point at which the relay turns "ON" or "OFF" can be pre-set to a particular light level. This type of simple circuit shown above has a fairly low sensitivity and its switching point may not be consistent due to variations in either temperature or the supply voltage. A more sensitive precision light activated circuit can be easily made by incorporating the LDR into a "Wheatstone Bridge" arrangement and replacing the transistor with an **Operational Amplifier** as shown.

Light Level Sensing Circuit



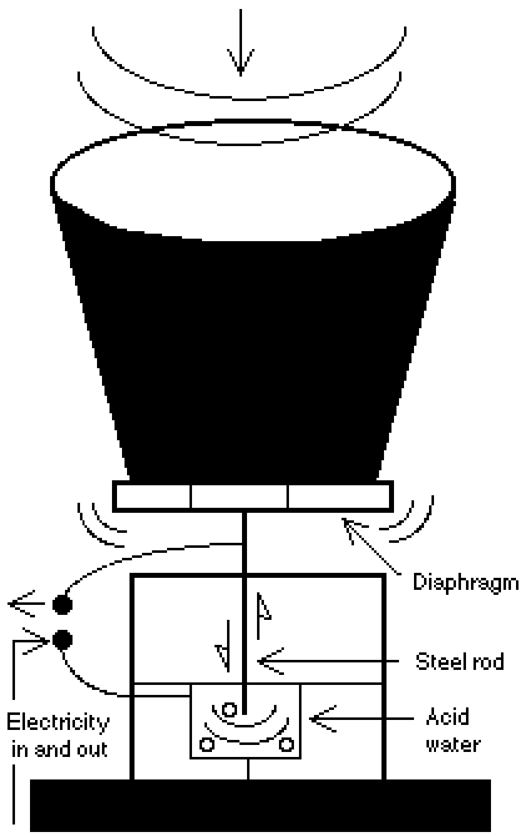
In this basic circuit the light dependant resistor, LDR1 and the potentiometer VR1 form one arm of a simple Wheatstone bridge network and the two fixed resistors R1 and R2 forming the other arm. Both sides of the bridge form potential divider networks whose outputs V1 and V2 are both connected to the inverting and non-inverting voltage inputs respectively of the operational amplifier. The configuration of the operational amplifier is as a **Differential Amplifier** also known as a voltage comparator with its output signal being the difference between the two input signals or voltages, V2 - V1. The feedback resistor Rf can be chosen to give a suitable amplifier voltage gain if required.

The resistor combination R1 and R2 form a fixed reference voltage input V2, set by the ratio of the two resistors and the LDR - VR1 combination a variable voltage input V1. As with the previous circuit the output from the operational amplifier is used to control a relay, which is protected by a free wheel diode, D1. When the light level sensed by the LDR and its output voltage falls below the reference voltage at V2 the output from the op-amp changes activating the relay and switching the connected load. Likewise as the light level increases the output will switch back turning "OFF" the relay.

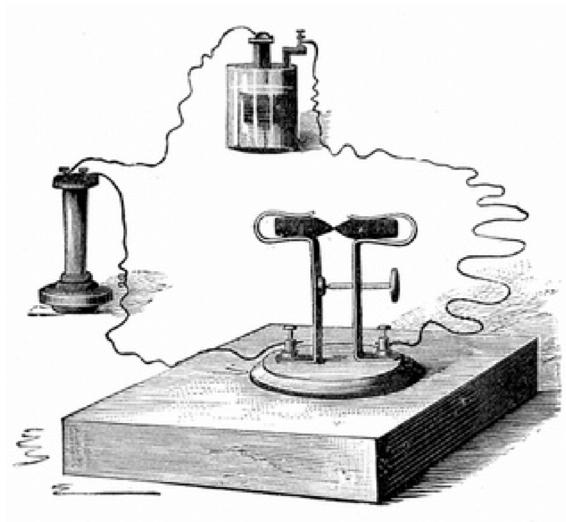
The operation of this type of circuit can also be reversed to switch the relay "ON" when the light level exceeds the reference voltage level and vice versa by reversing the positions of the light sensor LDR and the potentiometer VR1. The potentiometer can be used to "pre-set" the switching point of the differential amplifier to any particular light level making it ideal as a light sensor circuit.

Variable resistance microphones

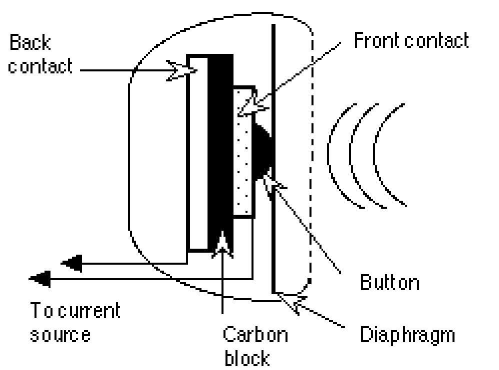
The world's first telephone transmitter (microphone) by Alexander Graham Bell (1876) was based upon variable resistance, see simplified diagram of Bell's liquid transmitter. The diaphragm vibrated with sound waves, causing a conducting rod to move up and down in a cup of acid water. Battery supplied power electrified the cup of acid. As the rod rose and fell it changed the circuit's resistance. This caused the line current to the receiver (not shown) to fluctuate, which in turn caused the membrane of the receiver to vibrate, producing sound.



Bell's first microphone (telephone transmitter) was followed by Edison's carbon transmitter, also based upon the variable resistance principle. Edison's carbon microphone was based upon an earlier Carbon microphone invented in 1878 by David Edward Hughes (1831-1900) English inventor



Two carbon rods make contact, but sound modulates how well the contact is made, effectively modulating the resistance in the circuit.



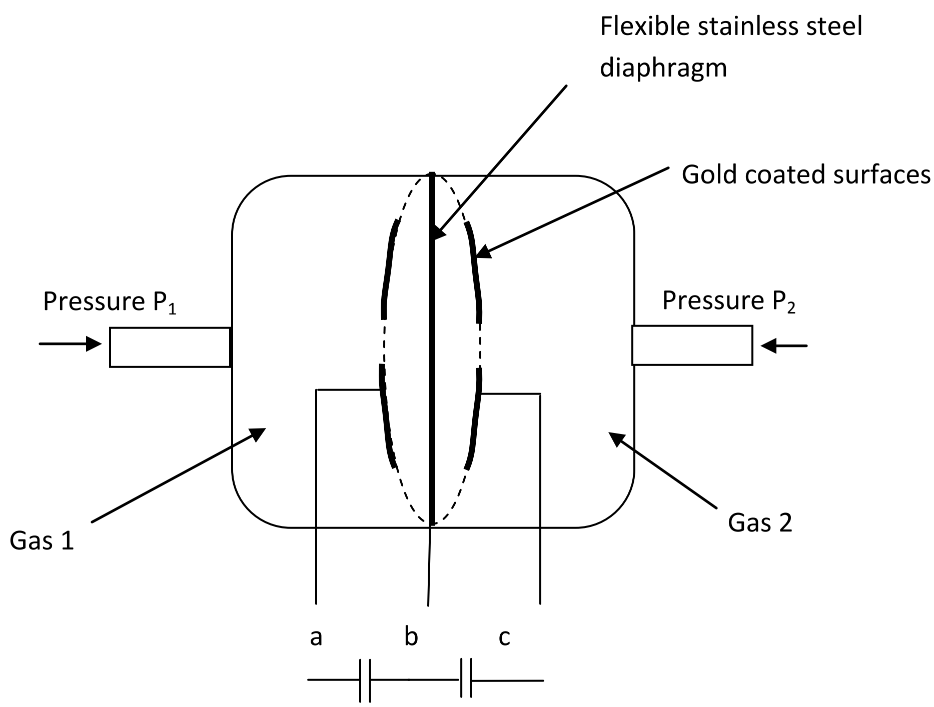
Edison's telephone transmitter

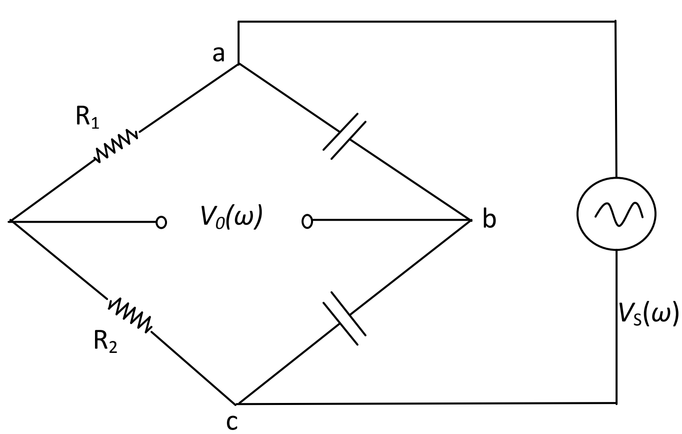
This is Edison's carbon block transmitter. It made the telephone practical. It relies on an unusual property of carbon: its conductivity to electricity varies with pressure.

A soft carbon button behind the diaprhagm presses against the front contact. This contact is attached to a line wire. Next comes the carbon and then the back contact. Battery current or line voltage is passed from one contact to another. The diaphragm moves under acoustic pressure, impinging on the front contact. This causes the circuit's resistance to vary, thus converting sound into a varying electrical current.

Capacitor and inductor Bridge Circuits

A differential pressure sensor uses changes in capacitance on either side of a flexible thin steel diaphragm, as shown below. The device consists of 3 terminals where the capacitances on either side relative to the centre terminal, C_{ab} and C_{bc} change as the diaphragm moves. The capacitances make up each leg of a Wheatstone bridge circuit, which is excited by an ac supply $V_S(\omega)$ as shown below, and the output voltage $V_0(\omega)$ varies according to the movement of the diaphragm.





Assume that the pressure is made of two parallel plate capacitors. If the undisplaced distance of the diaphragm to either side-plate is *d*, and the diaphragm is displaced from the centre in one direction by *x* (towards plate c), and R_1=R_2, it can be shown that the change in capacitor impedance caused by the displacement *x*, that the output voltage $V_0(\omega)$ is given by

$$V_0(\omega) = V_S(\omega)\frac{x}{2d}$$

The amplitude of the output is directly to proportional to the displacement *x*, and the whole system can be calibrated to measure pressure differences.

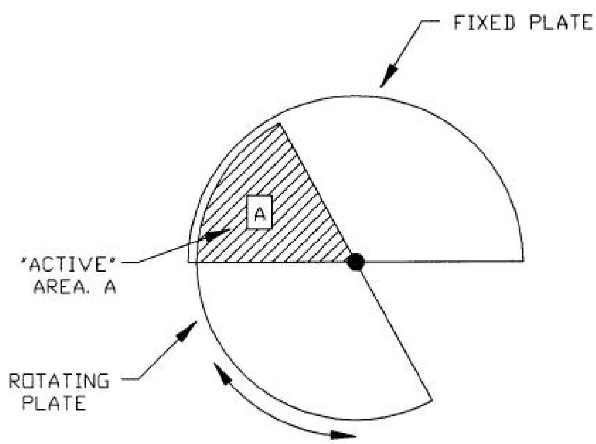
In order to prove the above formula, we need to consider the change in capacitance due to the central plate shifting *x* (to the right hand side), so

$C_{bc} = \dfrac{\varepsilon A}{d-x}, \quad C_{ab} = \dfrac{\varepsilon A}{d+x}$ where *A* is the area and *ε* is the dielectric

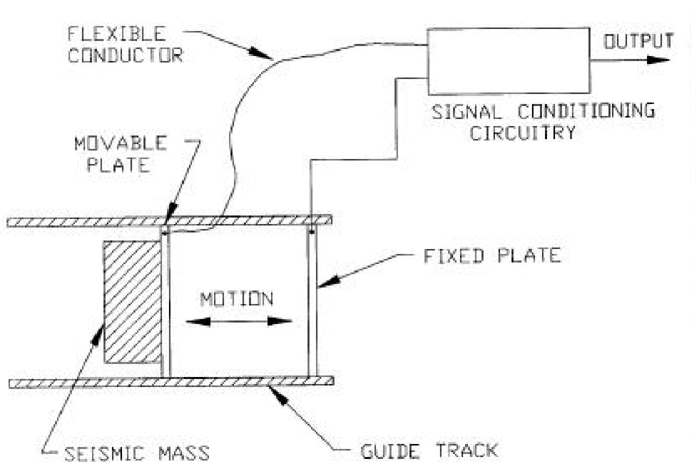
permittivity. The subsequent changes in impedances corresponding to each capacitor arm, Z_{bc} and Z_{ab} can be found, and the output voltage $V_0(\omega)$ is formulated in terms of the difference in voltage across two potential divider networks.

Capacitor sensors

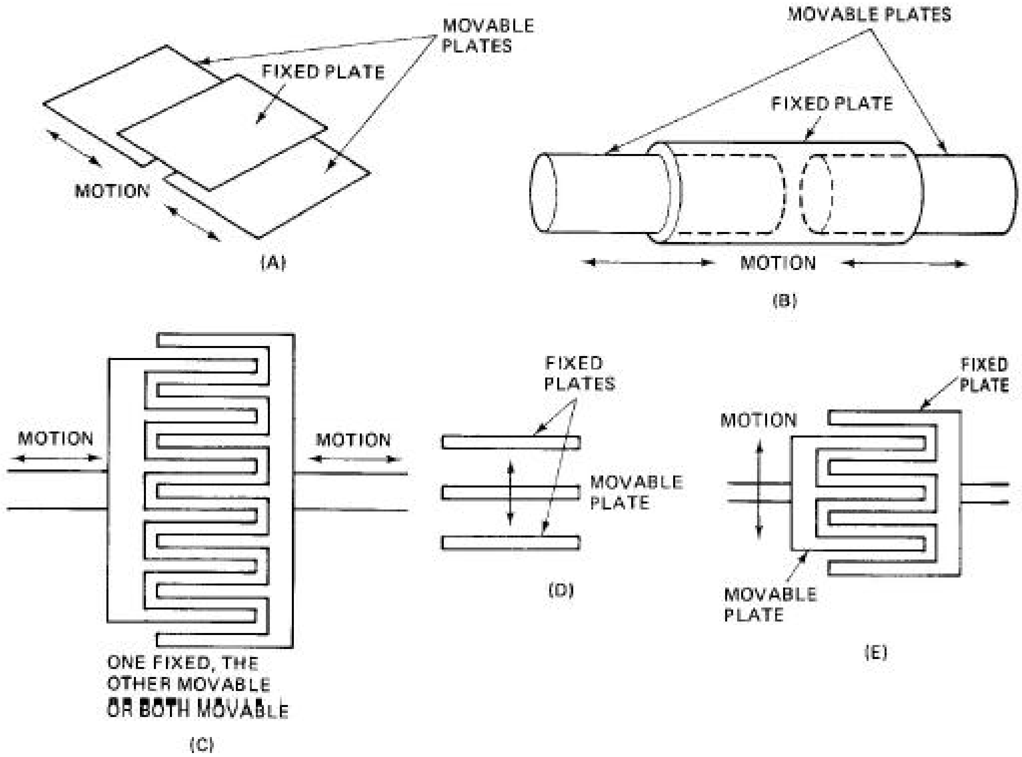
Variable overlap area between plates



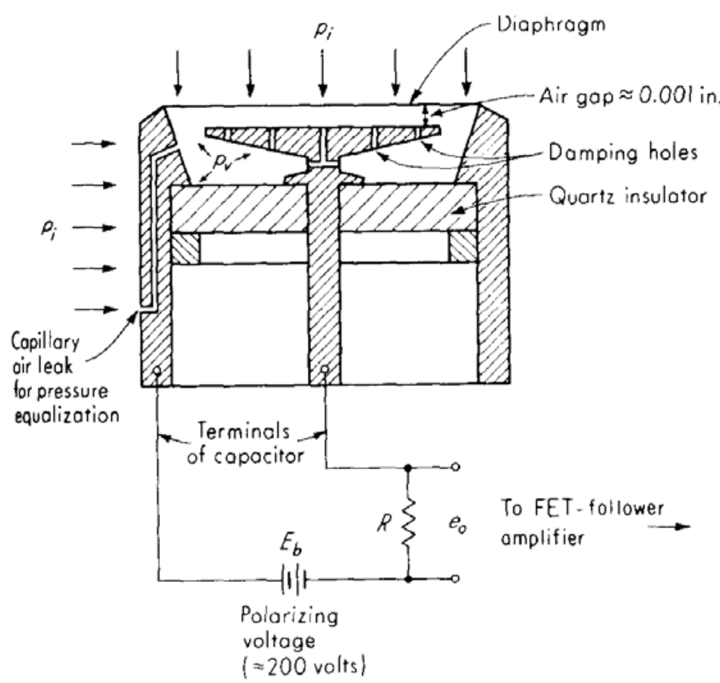
Variable distance between plates



Linear displacement detectors

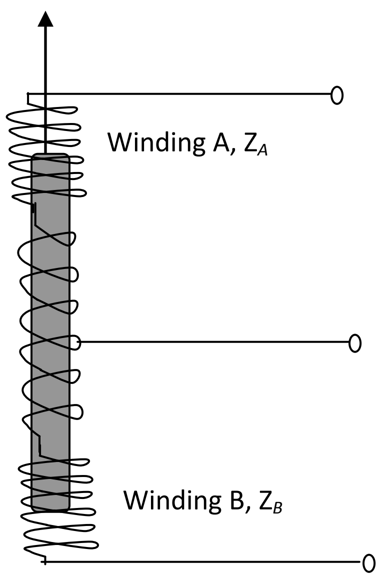


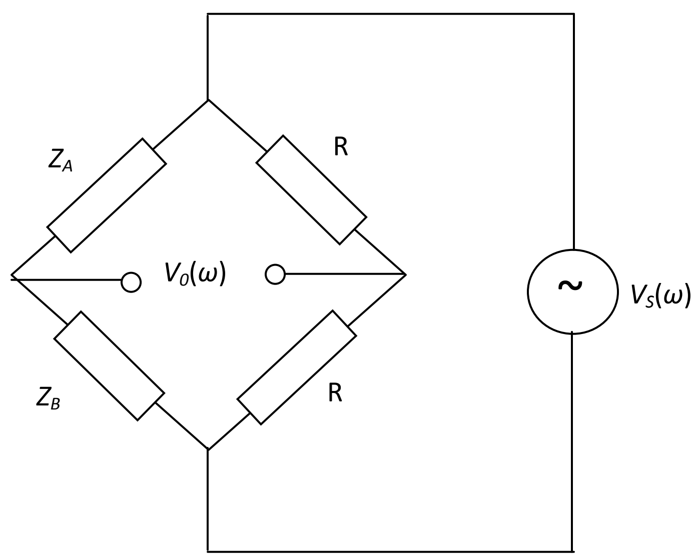
Condenser microphone



A variable-inductance position transducer

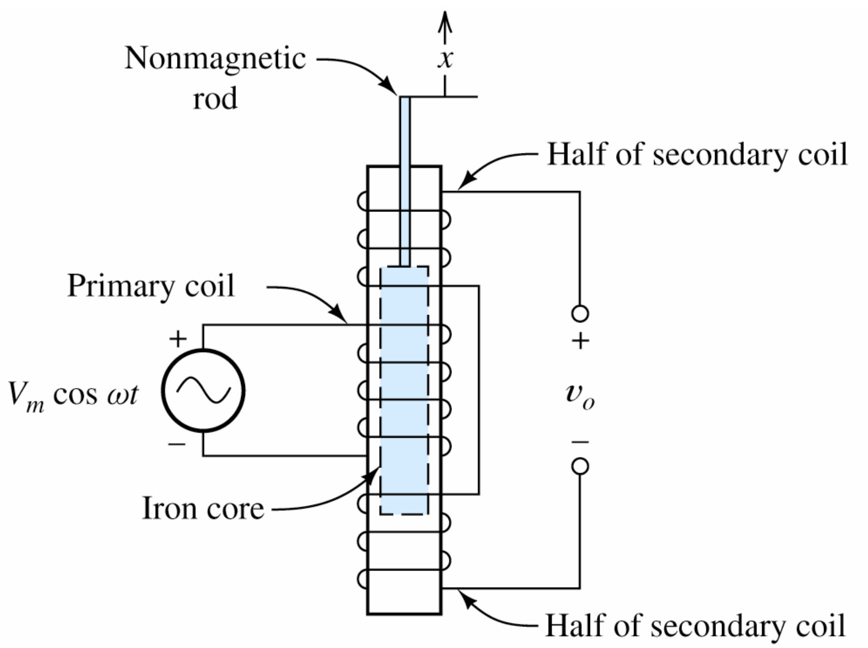
The following variable-inductance position transducer uses a Wheatstone bridge circuit. Here a single centre-tapped coil is wound symmetrically, as shown below.





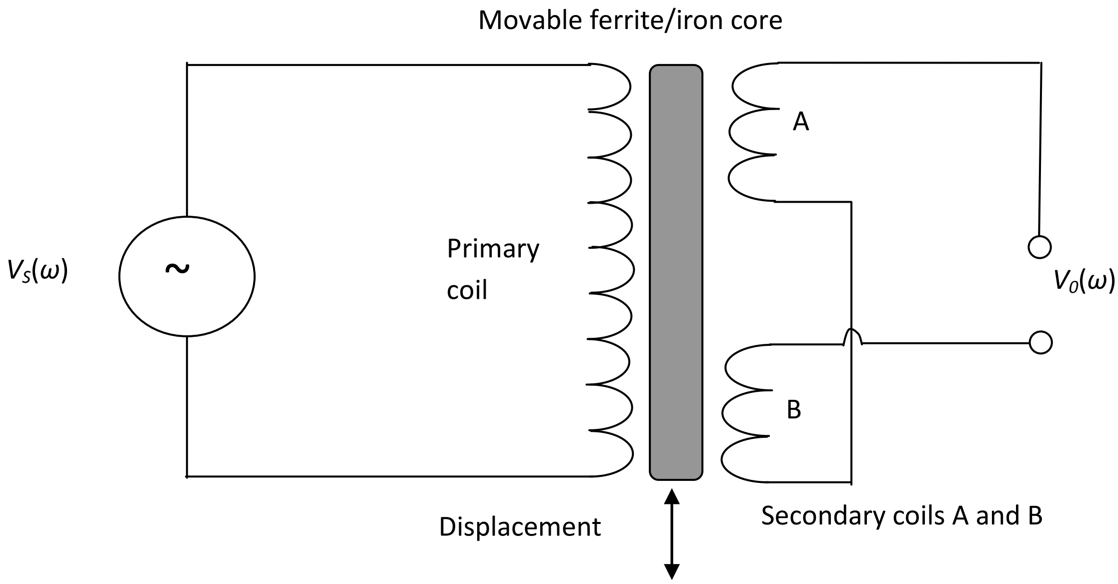
LVDT Position sensor

The linear variable differential transformer (LVDT) is widely used as a means of detecting position.



linear variable differential transformer used as a position transducer.

The LVDT consists of a transformer with a single primary winding and two secondary windings connected in the series opposing manner as shown below. The ferrite/iron core is free to move. The secondary coils are wound in a symmetric way over the primary winding and an ac source at a fixed frequency is used to excite it.



Let the coupling between the secondary and primary coils generate the voltages

$$V_a = K_a \sin(\omega t)$$
$$V_b = K_b \sin(\omega t)$$

where K_a and K_b depend on the degree of coupling, and hence on the position of the ferrite/iron core, for the core at the centre position, $K_a = K_b$, obviously

$$V_0 = V_a - V_b = 0$$

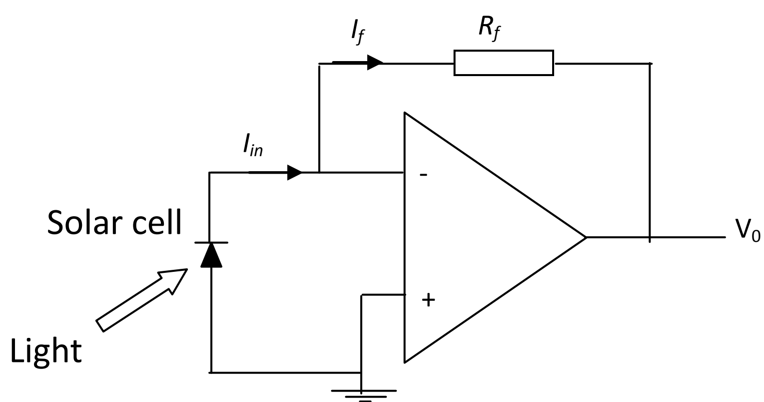
When the core is displaced, $K_a \neq K_b$, the output voltage is given by

$$V_0 = V_a - V_b = (K_a - K_b)\sin(\omega t) = Cx$$

Where C is a constant of proportionality linking the displacement distance x with the amplitude of the output voltage.

Light sensors

Consider the semiconductor solar cell (Photovoltaic cell), which is essentially a PN junction. When light falls on the PN junction, it creates free electron/hole pairs, and the internal electric field of the diode attracts free electrons created in the p-type material across the junction to the n-side. For the solar cell, we therefore need a current to voltage converting OP-Amplifier circuit. The simplest way to do this is to connect the solar cell across the input of an inverting OP-Amp circuit, one with a large feedback resistor, R_f as shown below.

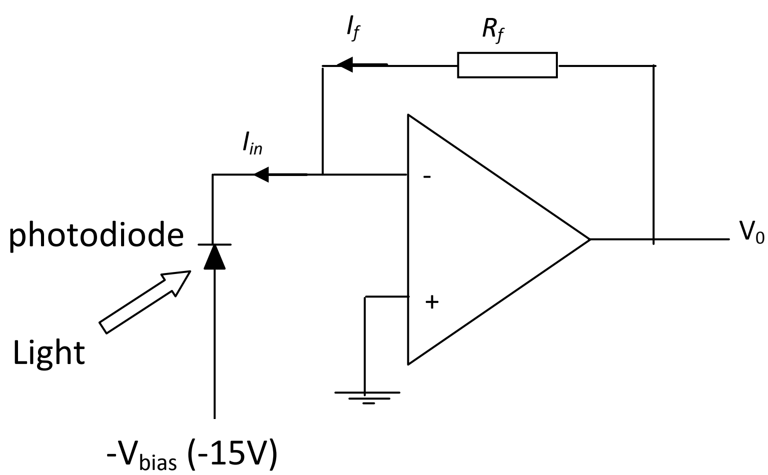


This circuit is sometimes called a trans-impedance amplifier, it converts current into voltage, the output voltage is obviously given by

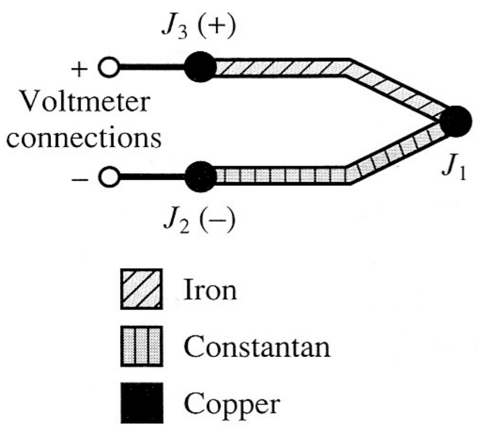
$$V_0 = -I_{in} \times R_f$$

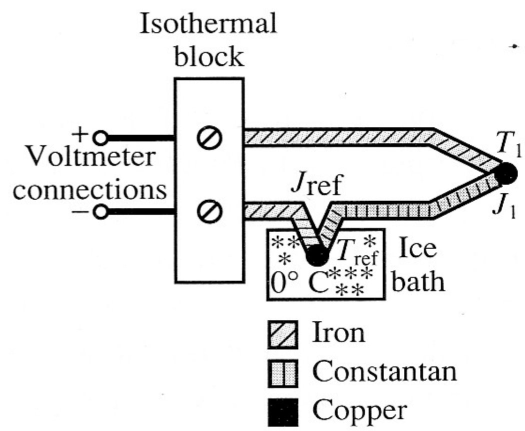
Generally the current is in the micro-ampere range, so the resistor R_f needs to be fairly large, typically of the order of mega-ohms. Normal office lighting gives around 100-200 μA

Photodiodes are diodes which when reverse biased, can produce a current if irradiated by light. The free carriers generated at the junction by the light, result in a greatly increased reverse saturation current. The detection OP-Amp circuit for photodiodes is given below, it is essentially the same current to voltage inverting OP-AMP circuit for solar cells, but now the input is biased negatively, as shown below.



Heat sensors - thermocouples





Type	Elements +/–	Seebeck coefficient (μV/°C)	Range (°C)	Range (mV)
E	Chromel/constantan	58.70 at 0°C	–270 to 1000	–9.835 to 76.358
J	Iron/constantan	50.37 at 0°C	–210 to 1200	–8.096 to 69.536
K	Chromel/alumel	39.48 at 0°C	–270 to 1372	–6.548 to 54.874
R	Pt(10%)—Rh/Pt	10.19 at 600°C	–50 to 1768	–0.236 to 18.698
T	Copper/constantan	38.74 at 0°C	–270 to 400	–6.258 to 20.869
S	Pt(13%)—Rh/Pt	11.35 at 600°C	–50 to 1768	–0.226 to 21.108

Need to connect the thermocouple to a differential/instrumentation amplifier.

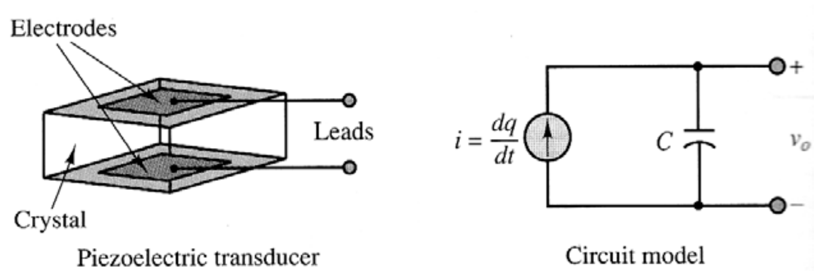
The Charge Amplifier

One of the most common transducers for the measurement of force, pressure, and vibrations is the **piezoelectric transducer**. It consists of a thin piezoelectric crystal (often quartz), which when subjected to a force (leading to deformation and displacement), generates an electric charge within the crystal. In general, if the external force produces a displacement x_i, then the charge produced, q, is given by

$$q = Kx_i$$

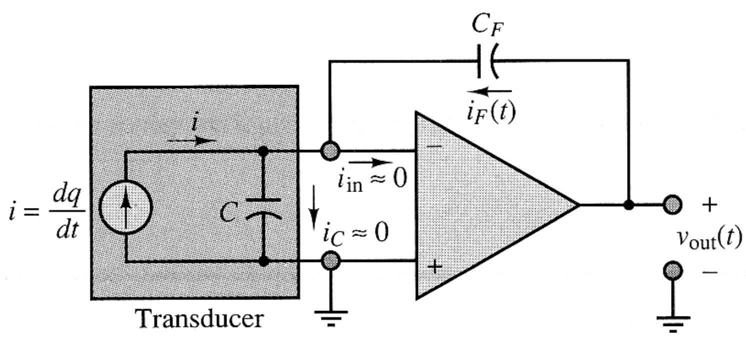
where K is a constant related to the material properties of the crystal.

The piezoelectric crystal can be modeled to be a current source in parallel with a crystal capacitance, where the current source represents the rate of change of the charge generated, as shown below.



Piezoelectric transducer

A Charge Amplifier is often used together with the piezoelectric crystal, as shown below. It is essentially an integrating circuit, with a capacitor in the feedback loop of an OP-Amp.



Charge amplifier

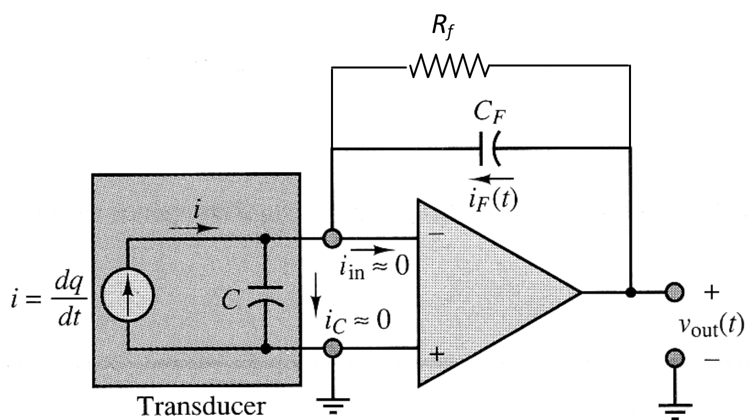
This Charge Amplifier circuit uses the very high input impedance of the OP-Amp to prevent the charge generated in the piezoelectric crystal from leaking to ground. The voltage difference across the piezoelectric crystal is effectively zero, since the OP-Amp operates to keep its input terminals at the same potential (zero volts in this case). The output voltage can be obtained by considering the current in the feedback loop, which is given by

$$i_f(t) = -i(t)$$

$$v_{out}(t) = \frac{1}{C_f}\int i_F(t)dt = -\frac{1}{C_f}\int \frac{dq}{dt}dt = -\frac{q}{C_f} = -\frac{Kx_i}{C_f}$$

So the output voltage is directly proportional to the displacement of the crystal. Note that the output voltage is independent of the crystal capacitance, and depends only on the capacitance used in the feedback loop of the OP-Amp. This is a very important advantage of the Charge Amplifier over other amplifiers. Often the cable connecting the piezoelectric transducer to the amplifier also has a capacitance, but this does not affect the output voltage of the Charge Amplifier. The Charge Amplifier has the desirable property of its output voltage being directly proportional to the crystal displacement, independent of other stray capacitances (in the crystal, cable etc).

In practice, a resistor in parallel with C_f needs to be used in the feedback loop, to avoid non-zero bias currents of the OP-Amp from steadily charging up the capacitor, driving the output voltage into saturation (clipped by the power supply voltage). A more practical version of the charge amplifier is therefore given below, which has the same advantages as already mentioned.

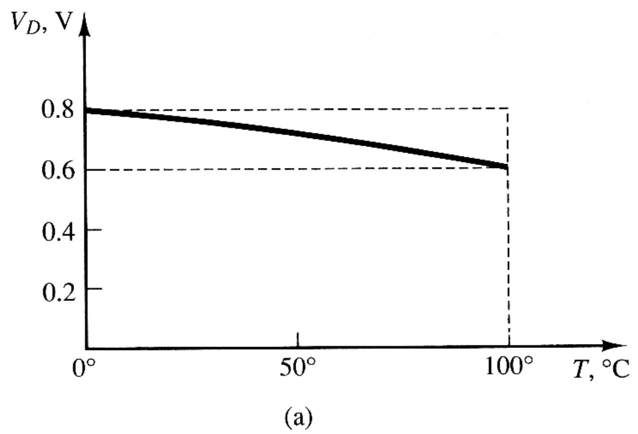


Charge amplifier

Typical values suitable for quartz crystals are C_f ranging from 10 to 100,000 pF, and R_f ranging from 10^{10} to 10^{12} Ω (for very slowly changing displacements).

A Diode Thermometer

Some electrical components such as transistors and diodes are already very sensitive to temperature variations, usually this is a problem and complicated circuits must be designed to suppress the temperature variation. On the other hand, in the present context, it is possible to use this effect as the basis of a thermometer. Consider the voltage across a diode, which varies as shown below.

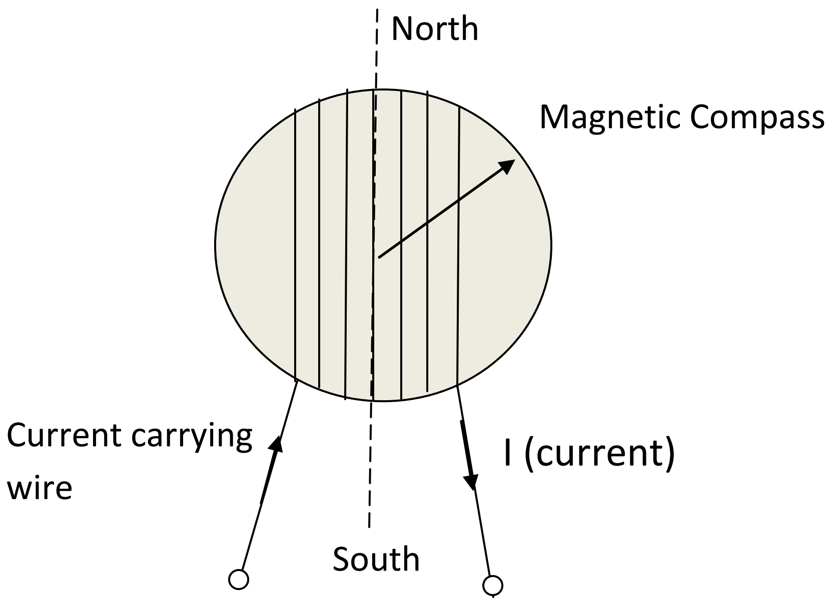


The well-known diode equation, in terms of the diode current, i_D, I_s the reverse bias saturation current, v_D the applied voltage across the diode is given below

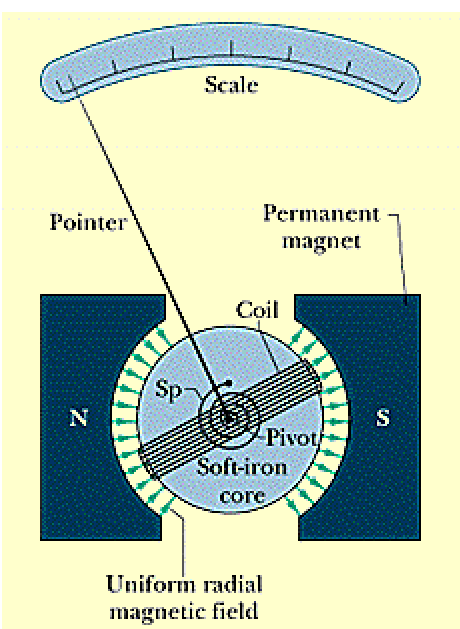
$$i_D = I_s\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right] \quad \text{where} \quad V_T = \frac{kT}{q}$$

V_T is known as the thermal voltage, a constant which depends on temperature, *k* = 1.38 × 10–23 J/K is Boltzmann's constant and *q* = 1.60 × 10–19 C is the magnitude of the electrical charge of an electron. At a temperature of 300 K, we have $V_T \approx 26$ mV. The diode can obviously be in series with a resistor energized by a DC source (voltage divider) at the terminals of an Op-Amp amplifier, and a sensitive temperature sensor can be made. It may also be possible to make a sensor array (from many diodes), since they can be small and cheap.

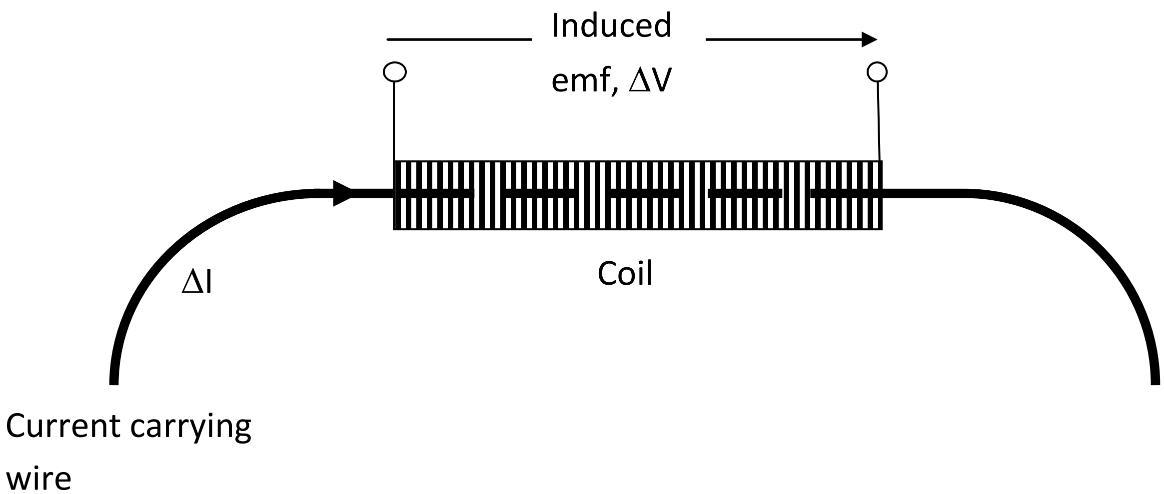
Measurement of DC current (Tangent galvanometer)



Modern Moving coil meters



AC current pickups



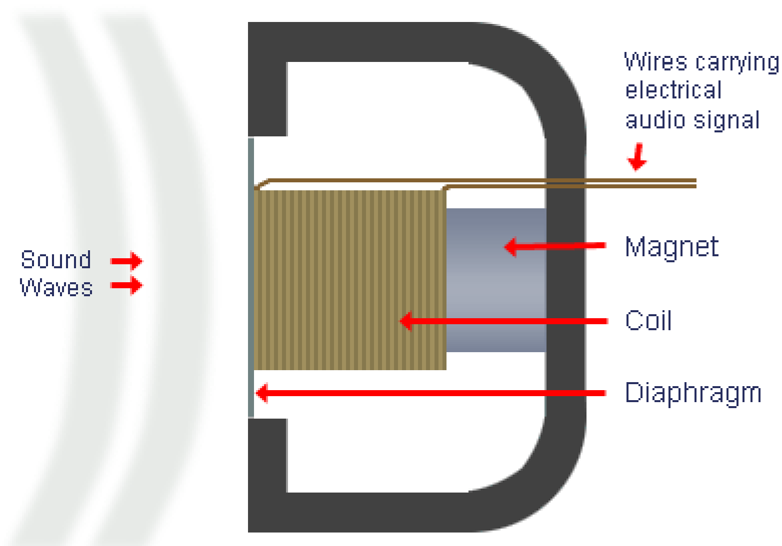
Electromagnetic pick-ups

There are many types of electromagnetic pick-ups, how does an electric guitar pick-up work?

Dynamic microphone

The diagram is attached to the coil. When the diaphragm vibrates in response to incoming sound waves, the coil moves backwards and forwards past the magnet. This creates a current in the coil which is channeled from the microphone along wires. A common configuration is shown below.

Cross-Section of Dynamic Microphone



Note that a headphone or a loudspeaker is not a sensor!

If you want to make a guitar pick-up/dynamic microphone, you must make all the associated electronic circuitry to go with it, and optimize it so that it functions similar to professional ones.