Ch4: Sensors – Part 2

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Stress, Strain, and Force

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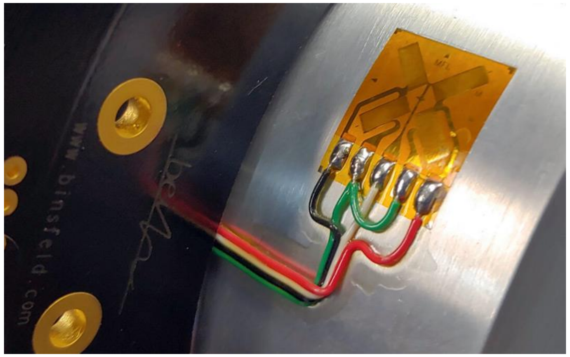
Stress, Strain, and Force

Stress & Strain Measurement

- **Measurement of stress** in a mechanical component is important when **assessing** whether the component is subjected to **safe load levels**.

- **Experimental stress analysis** (e.g., with strain gages) and **analytical or numerical** stress analysis (e.g., with finite element analysis) are both important and **complementary** to design reliable mechanical parts.

- **Stress and Strain** measurements can also be used to **indirectly** measure other physical quantities such as **force** (by measuring strain of a flexural element), **pressure** (by measuring strain in a flexible diaphragm), **temperature** (by measuring thermal expansion of a material), and **displacement**.

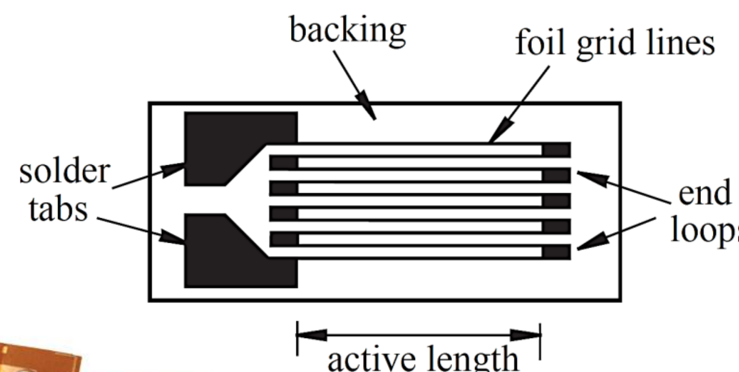


Strain Gage (Metal Foil Type)

Electrical Resistance Strain Gage is the most common sensor used to measure strain. It consists of a **thin foil of metal** (usually Constantan) deposited as a grid pattern onto a thin plastic backing material (usually polyimide). The foil pattern is terminated at both ends with large metallic pads that allow leadwires to be easily attached with solder.

- The gage is adhesively bonded directly to the component (usually with epoxy).

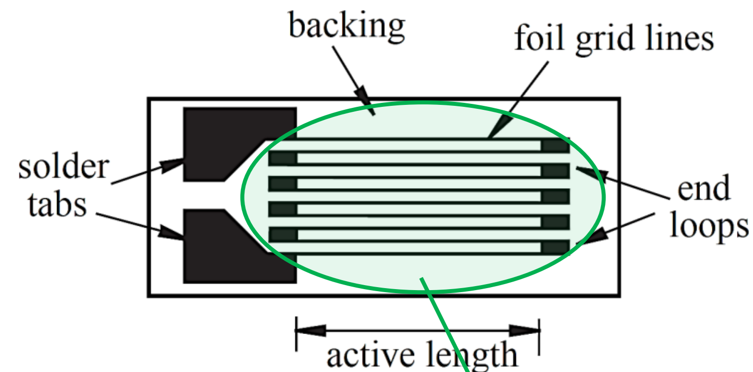
- When the component is loaded, the metal foil **deforms**, and the **resistance changes**. If this resistance change is measured accurately, the **average** of the strain on the **small surface** of the component can be determined.



- Making measurements where **stress gradients are large** (e.g., stress concentration) can yield **poor results**.

Strain Gage (Metal Foil Type)

The **metal foil** grid lines in the **active portion** of the gage can be approximated by a **single** rectangular conductor (effects of gage end loops and solder tabs are negligible). Thus, total resistance:

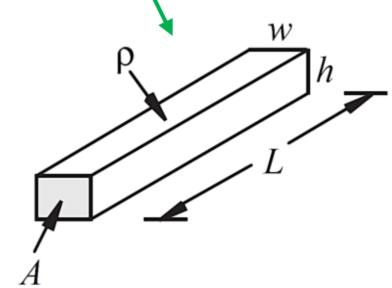


$$R = \rho \frac{L}{A} \quad \Rightarrow \quad \frac{\mathrm{d}R/R}{\varepsilon_{\text{axial}}} = \underbrace{1 + 2\nu}_{} + \underbrace{\frac{\mathrm{d}\rho/\rho}{\varepsilon_{\text{axial}}}}_{}$$

ρ: foil metal resistivity
ν: Poisson's ratio

Change in R due to increased L and decreased A

Change in R due to **piezoresistive effect*** in the material



All three terms are approximately constant over the operating range of typical strain gage metal foils:

Gage Factor (GF) ≅ 2

$$\Rightarrow \quad GF = \frac{\mathrm{d}R/R}{\varepsilon_{\text{axial}}}$$

* **Piezoresistive Effect** is a change in the electrical **resistivity** of a semiconductor or metal when mechanical strain is applied.

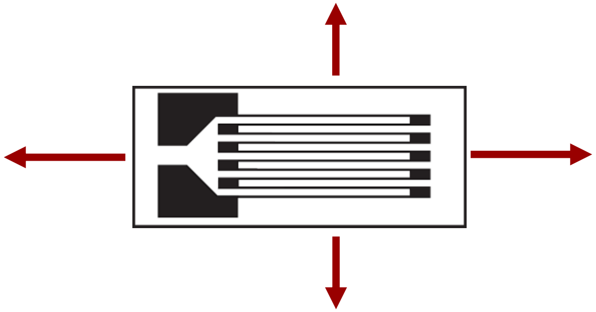
Strain Gage (Metal Foil Type)

- If a 120Ω strain gage with gage factor 2.0 is used to measure a strain of 100 με (microstrain), how much does the resistance of the gage change from the unloaded state to the loaded state?

$$\Delta R = R \cdot GF \cdot \varepsilon$$
$$\Delta R = 120(\Omega) \times 2.0 \times 0.000100 = 0.024\ \Omega$$

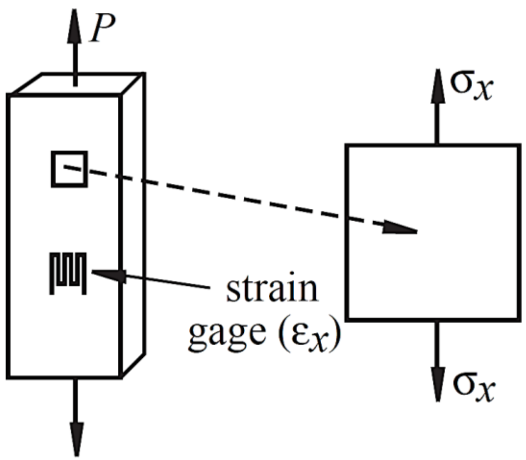
- Strain gage suppliers also report a **Transverse Sensitivity** for the gage, which is a number that predicts the gage's sensitivity to **transverse strains** (those perpendicular to the measuring axis of the gage). The transverse sensitivity is usually close to 1%.

For example, a gage experiencing 50 με in the axial direction and 100 με in the transverse direction with a transverse sensitivity of 1% will sense 51 με (50+1% of 100).



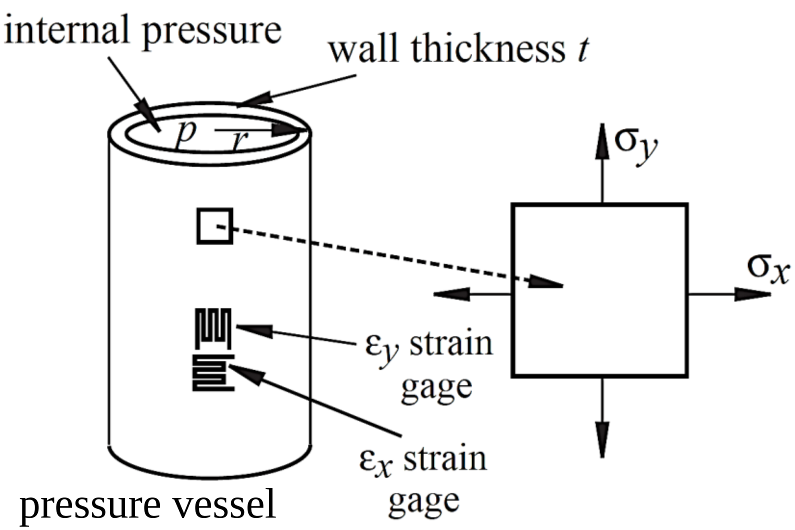
Strain Gage in Uniaxial & Biaxial Loading

Uniaxial Loading



$$\sigma_x = E\varepsilon_x$$

Biaxial Loading (loading in two orthogonal directions)

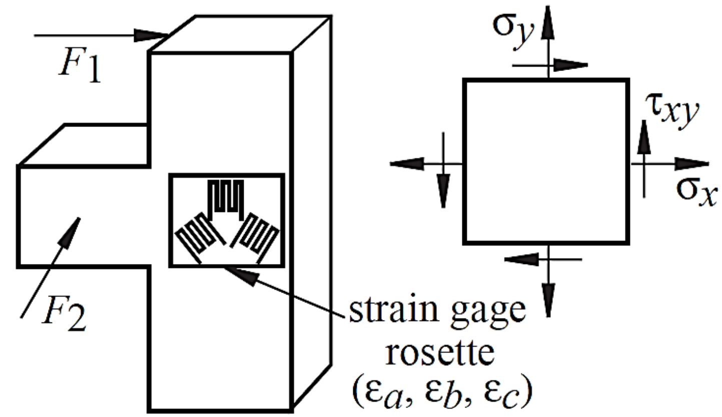


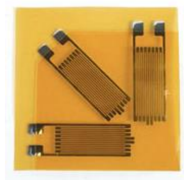
$$\varepsilon_x = \frac{\sigma_x}{E} - v\frac{\sigma_y}{E} \qquad \varepsilon_y = \frac{\sigma_y}{E} - v\frac{\sigma_x}{E}$$

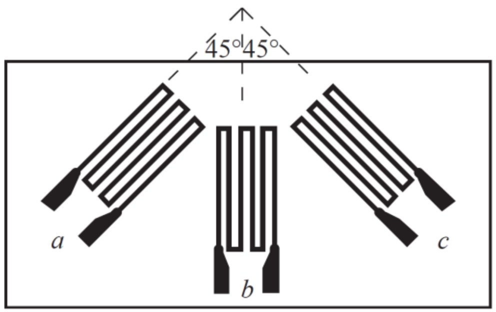
Strain Gage in Complex Loading & Geometry

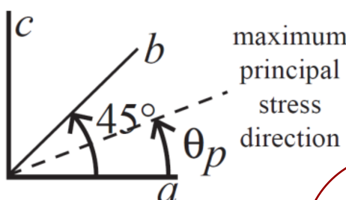
For **Complex Loading and Geometry**, three gages (known as strain gage **rosette**) is mounted in three different directions to find the magnitude and direction of the **Principal Stresses** ($\sigma_{\max,\min}$, $\tau_{\max}$).

- The most common rosette patterns is rectangular strain gage:





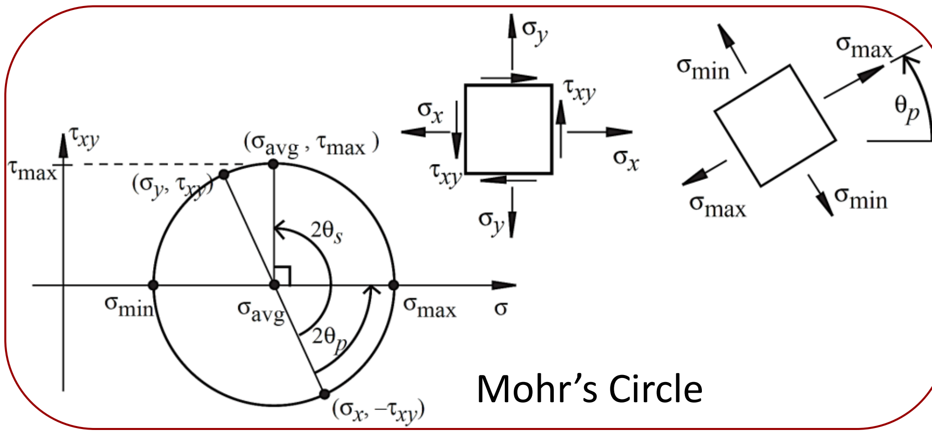




$$\sigma_{\max,\min} = \frac{E}{2}\left[\frac{\varepsilon_a+\varepsilon_c}{1-\nu} \pm \frac{1}{1+\nu}\sqrt{2(\varepsilon_a-\varepsilon_b)^2+2(\varepsilon_b-\varepsilon_c)^2}\right]$$

$$\tau_{\max} = \frac{E}{2(1+\nu)}\sqrt{2(\varepsilon_a-\varepsilon_b)^2+2(\varepsilon_b-\varepsilon_c)^2}$$

$$\tan 2\theta_p = \frac{2\varepsilon_b-\varepsilon_a-\varepsilon_c}{\varepsilon_a-\varepsilon_c}$$

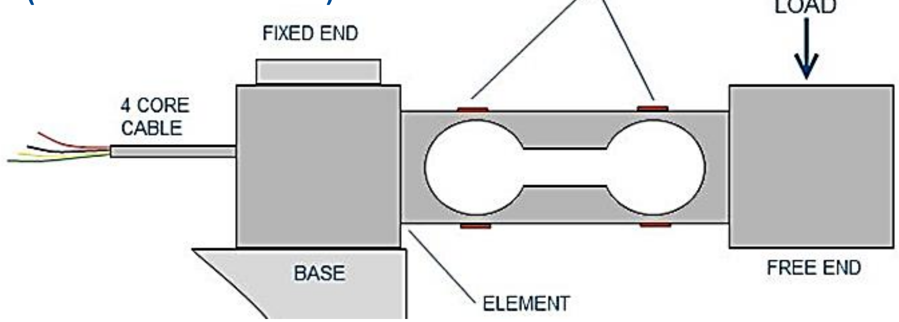


Mohr's Circle

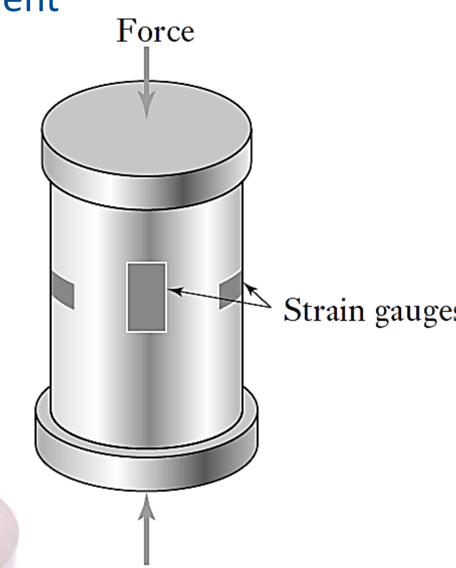
Force Sensor Using Strain Gage

Load Cell is a sensor used to measure **force**. It contains an internal **flexural or compressional element**, usually with several **strain gages** mounted on its surface. The flexural element's shape is designed so that the strain gage outputs can be easily related to the applied **force**. Load cells are also used in **weight scales**.

Flexural element
(small forces: 50 KN)

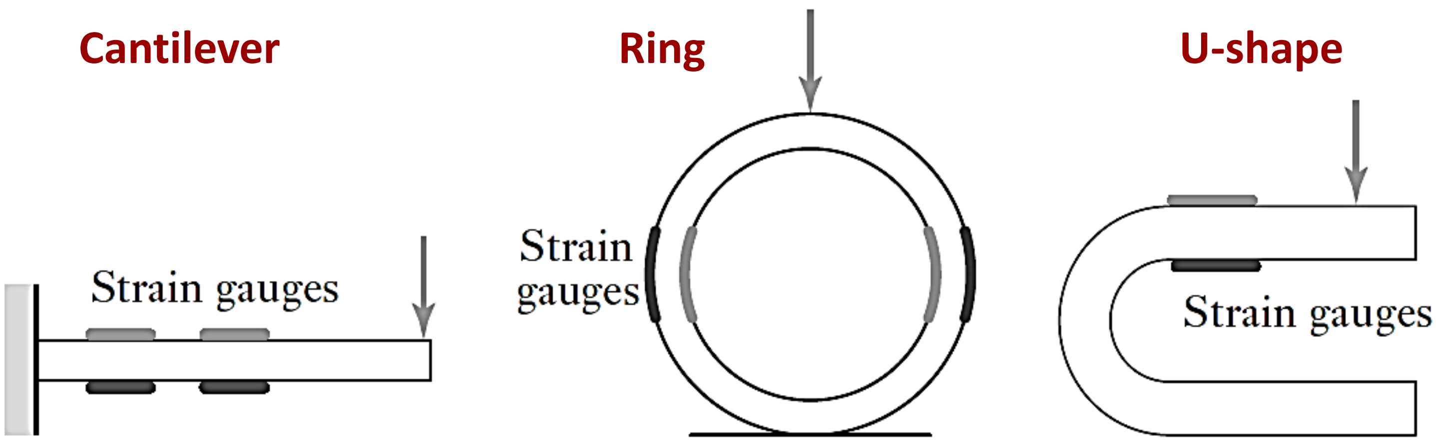


Compressional element
(large forces: 10 MN)



Displacement Sensor Using Strain Gage

Displacement can be measured by attaching strain gauges to flexible elements in the form of **Cantilevers**, **Rings**, or **U-shapes**.

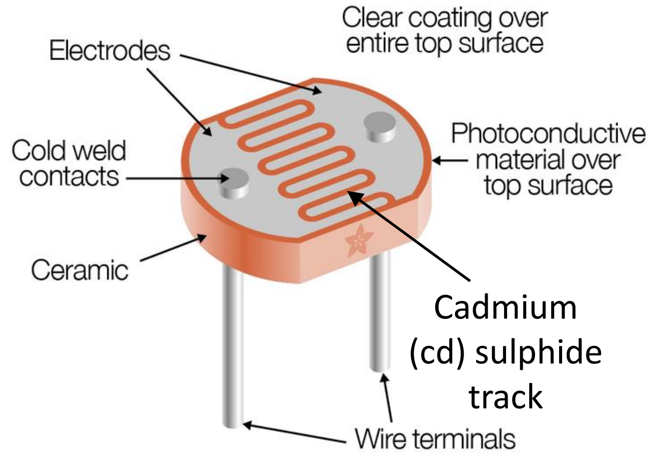


- When the flexible element is bent or deformed, the resistance of strain gauges change. This change is a measure of the displacement or deformation of the flexible element.

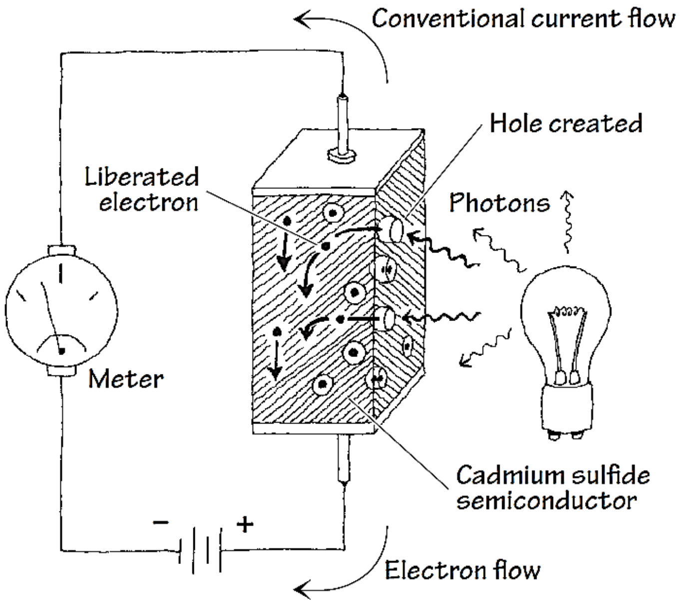
Light Sensors

Photoresistor

A **Photoresistor** is a light-controlled variable resistors whose resistance depends on the **intensity of the light** falling on it, **decreasing linearly** as the intensity **increases**. The sensitivity depends on the **wavelength** of the light.



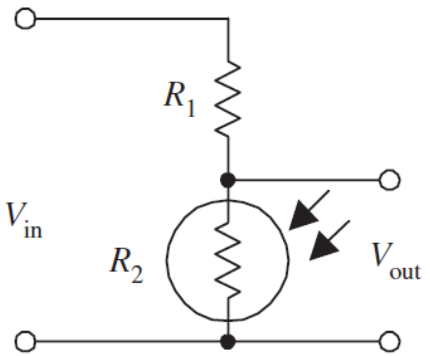
(Symbol)

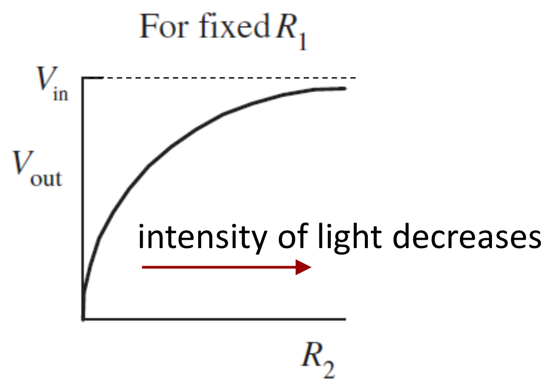


Photoresistors are made from a special kind of **semiconductor** crystal, such as Cadmium sulfide (for **light**) or Lead sulfide (for **infrared**). When this semiconductor is placed in the dark, electrons within its structure do not want to flow through the resistor. However, when illuminated, incoming photons of light collide with the **bound electrons**, stripping them from the binding atom, thus creating a hole in the process. These liberated electrons can now contribute to the current flowing through the device (the resistance goes down).

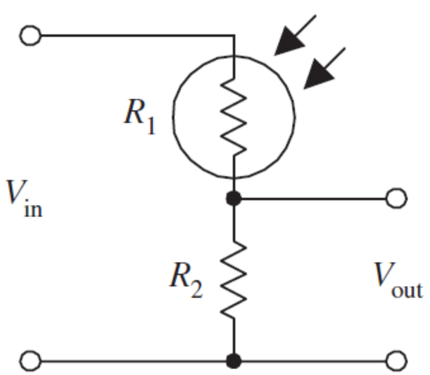
Application: Light-Sensitive Voltage Divider

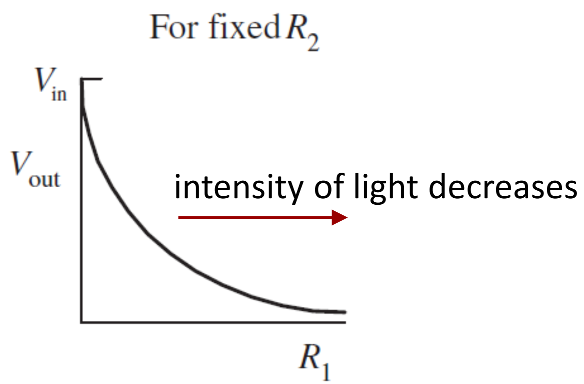
A voltage divider is usually used when using the photoresistor with a microcontroller.





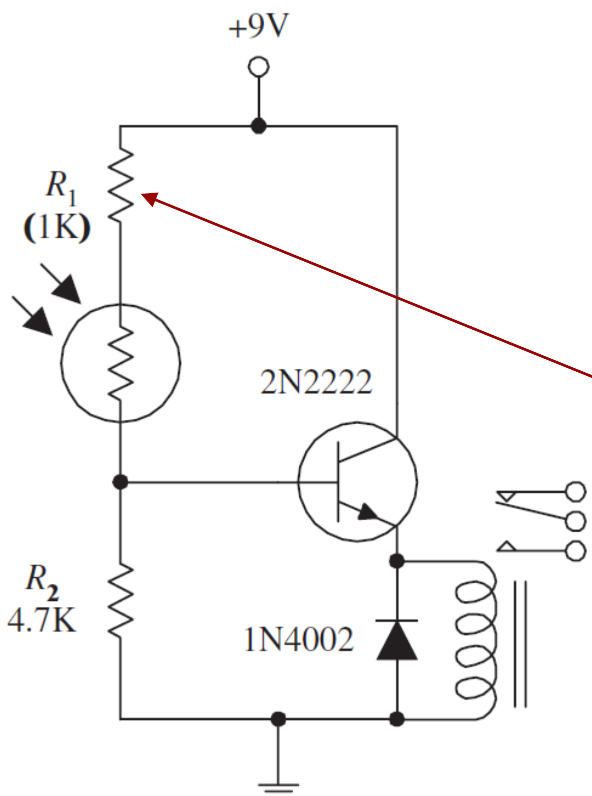
$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in}$$



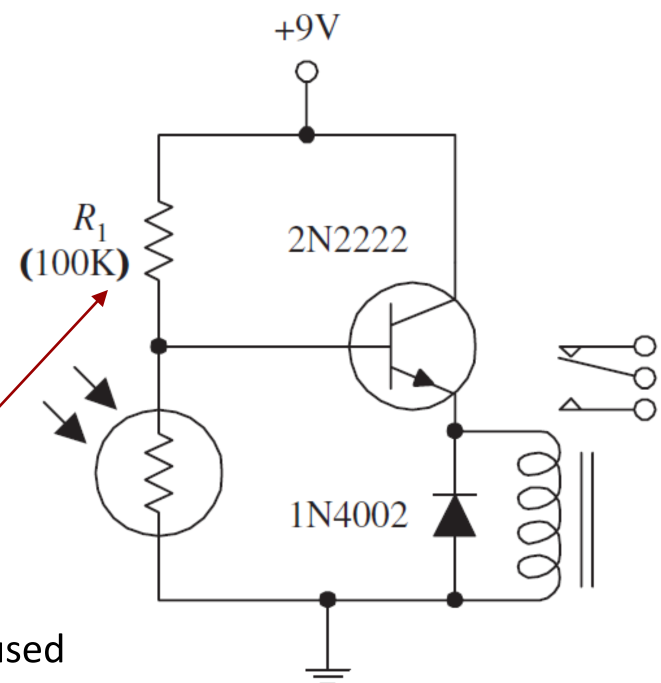


Application: Light/Dark-Activated Relay

Light-Activated Circuit



Dark-Activated Circuit

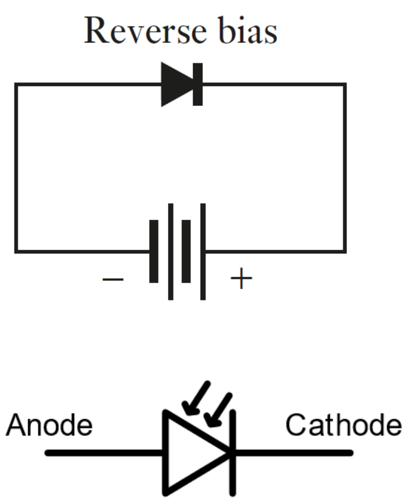


The **potentiometer** is used to adjust the sensitivity by controlling current flow through the transistor.

Photodiode

Photodiode is **semiconductor junction diode** which is always connected into a circuit in **reverse bias mode**, hence, it have a wide depletion region.

- Photodiodes are designed to detect photons and can be used in circuits to sense light.
- With no incident light, the reverse current is almost negligible and is called the **dark current**. When light (photon) falls on the junction, extra hole–electron pairs are produced and there is an increase in the reverse current.



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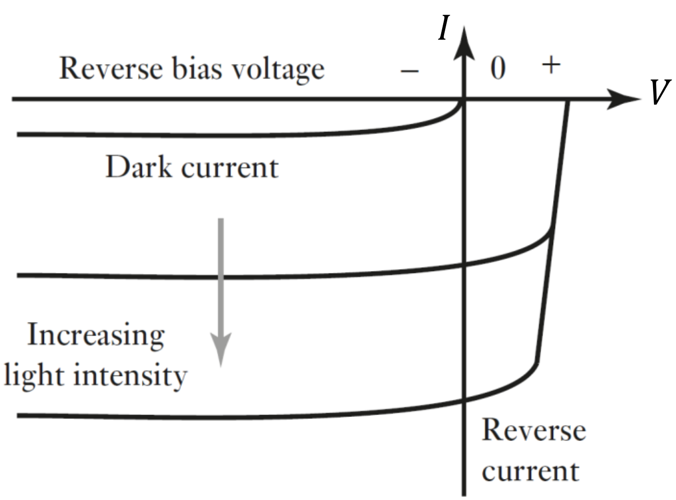
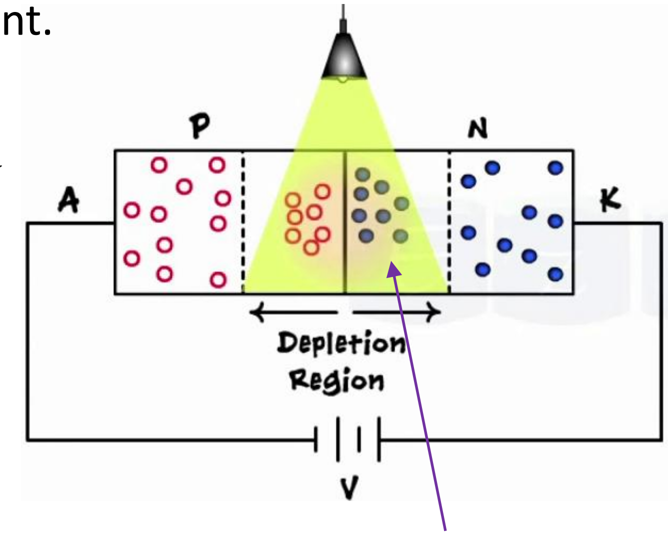
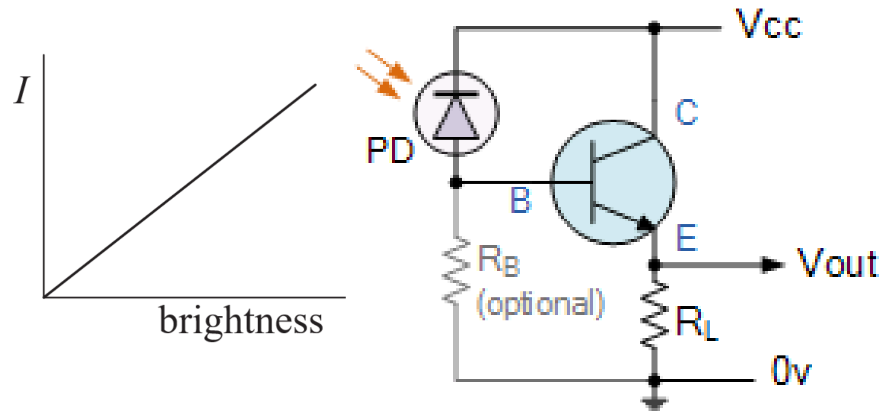




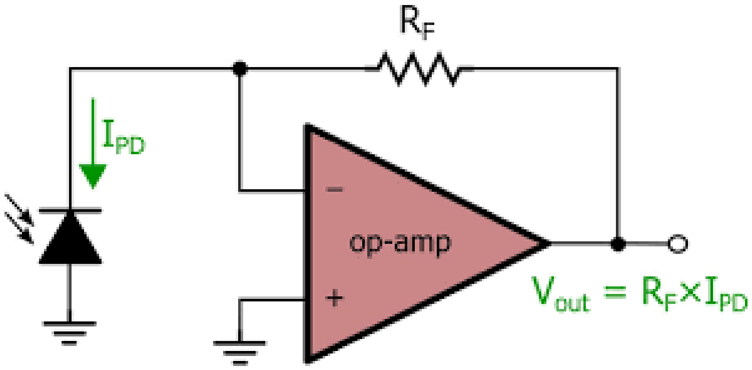
Generated hole–electron pairs which attract to + and - sides.

Photodiode

- The reverse current is **linearly proportional** to the intensity of the light.
- They have very **fast response** to light.



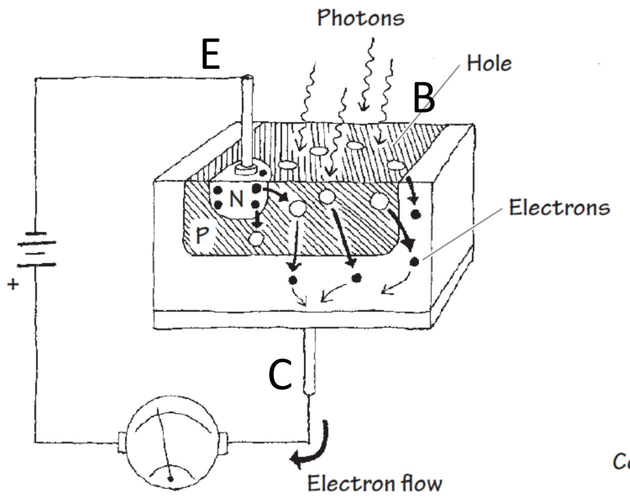
- **Amplification** is required as the current is very small.

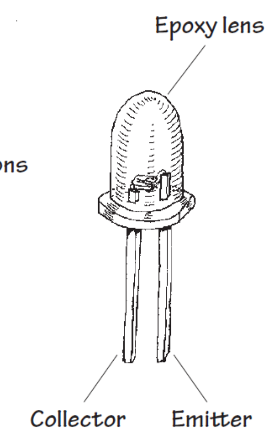


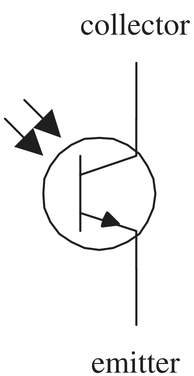
Phototransistor

Phototransistors are light-sensitive transistors.

- A bipolar phototransistor resembles a **BJT** with its Base lead (B) removed and replaced with a light-sensitive surface area (a large **p-type** semiconductor).
- When this surface area is kept dark, there is a very small collector-to-emitter current. However, when this surface area is exposed to light, a small base current is generated that is directly proportional to the light intensity and controls a much larger current flows through the collector-to-emitter region.
- Phototransistor can be **more sensitive** than photodiodes, although it is **slower to respond**.

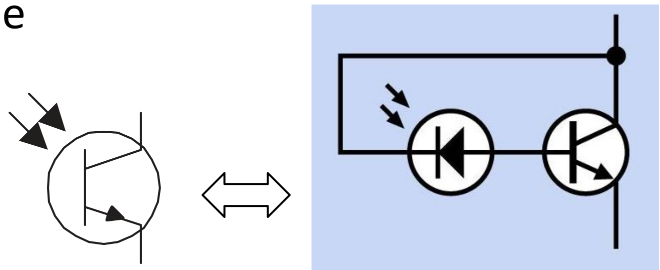




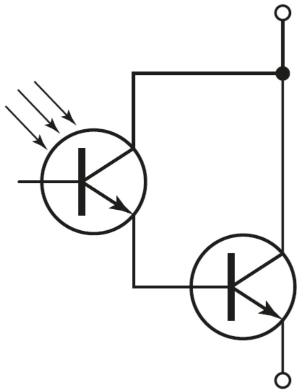


Phototransistor

- A phototransistor is functionally similar to a photodiode controlling an ordinary transistor.



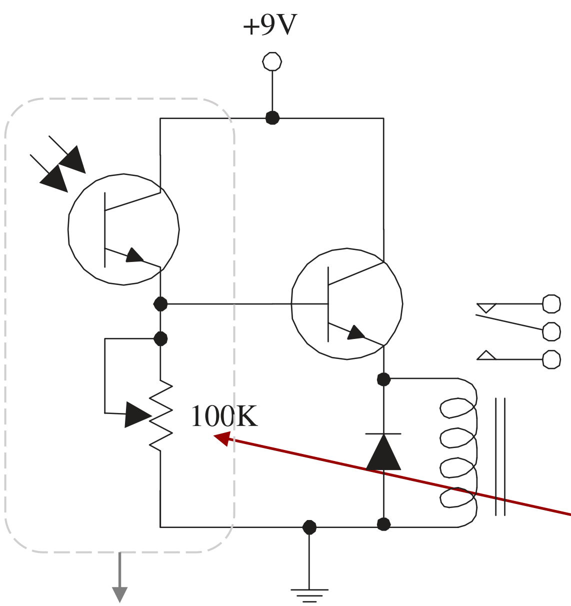
- **Photodarlington** is a phototransistor connected in a Darlington arrangement with a conventional transistor in an integrated package.
  - They give a **higher collector current** for a given light intensity.
  - They are much **more sensitive** to light than ordinary phototransistors.
  - They tend to have **slower response** times.
  - These devices may or may not come with a base lead.

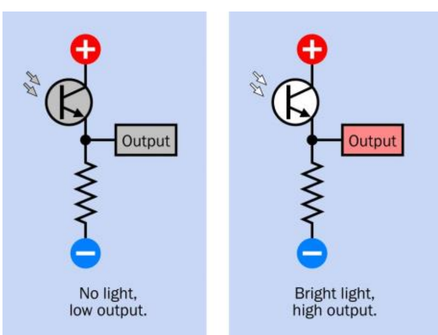


Other Kinds of Phototransistors are **Three-Lead Phototransistor** and **PhotoFETs**.

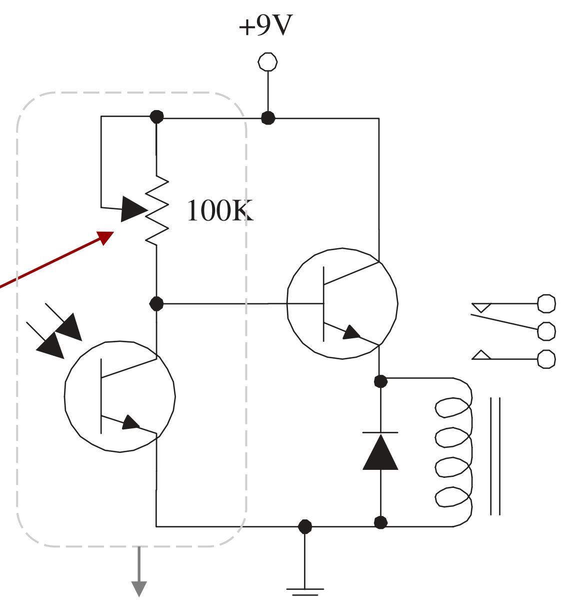
Application: Light/Dark-Activated Relay

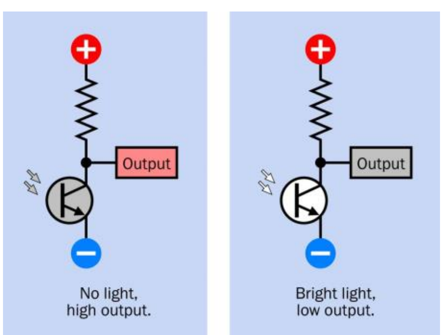
Light-Activated Circuit





Dark-Activated Circuit

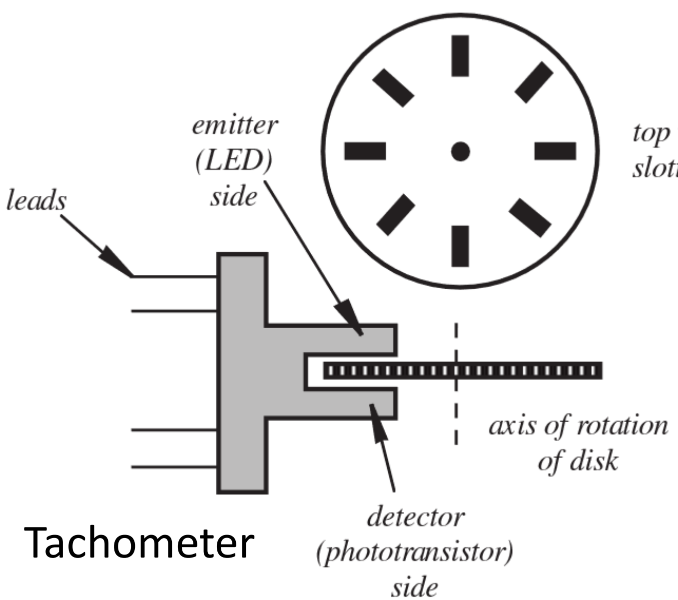


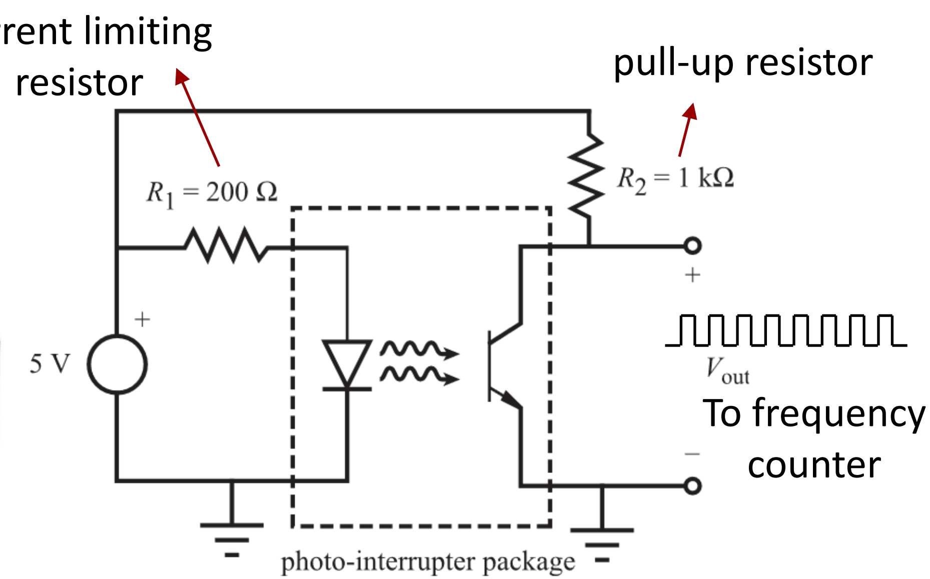


The 100k **potentiometer** is used to adjust the sensitivity by controlling current flow through the phototransistor.

Application: Simple Encoder

To track the **angular position or velocity** of shaft of a motor, a slotted disk connected to the shaft and an **LED-phototransistor pair** is used. The LED produces a beam of light to trigger the phototransistor into conduction and it can be broken or interrupted by rotation of the disk. Each slot in the disk provides a digital pulse as it interrupts the light beam during rotation. A **frequency counter** is used to count the number of electrical pulses generated. The number of pulses provides the measure of rotation.





Temperature

Temperature Measurement

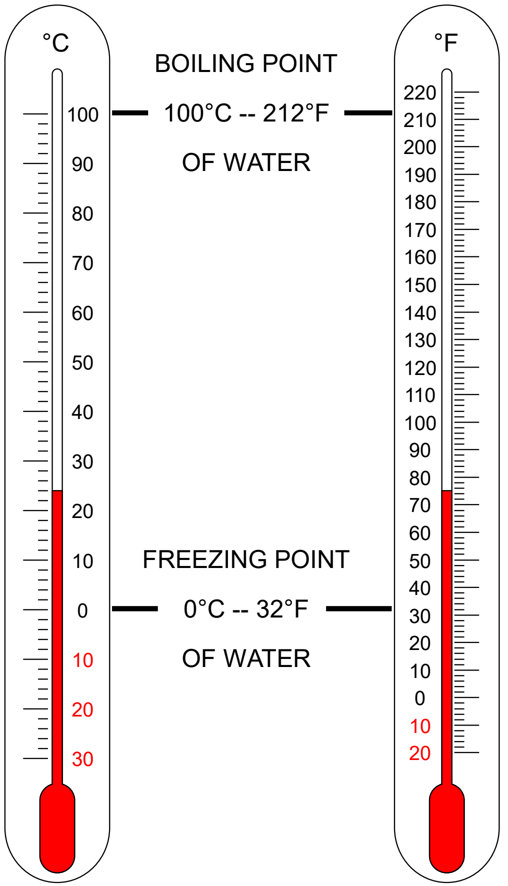
Temperature can be measured by measuring quantities such as expansion or contraction of solids, liquids, or gases, electrical resistance of conductors and semiconductors, thermoelectric EMFs, strain, pressure, and volume.

Temperature units:
Celsius (°C), Kelvin (K), Fahrenheit (°F), Rankine (°R)
(SI) (SI) (USCS) (USCS)

$$T_C = T_K - 273.15$$

$$T_F = (9/5)T_C + 32$$

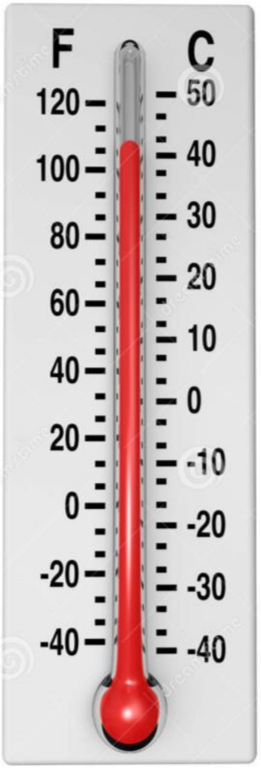
$$T_R = T_F + 459.67$$



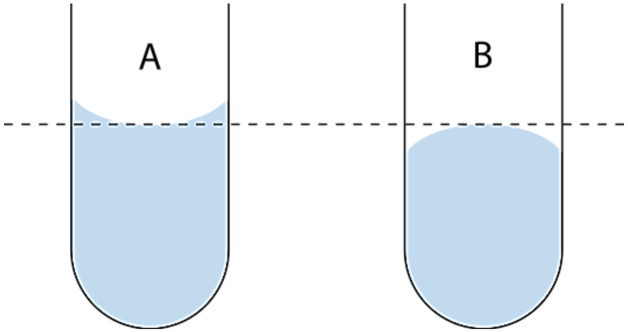
CELSIUS FAHRENHEIT

Liquid-in-Glass Thermometer

It is simple **nonelectrical** temperature-measuring device. It typically uses **alcohol** or **mercury** (Hg) as the working fluid, which expands and contracts relative to the glass container.

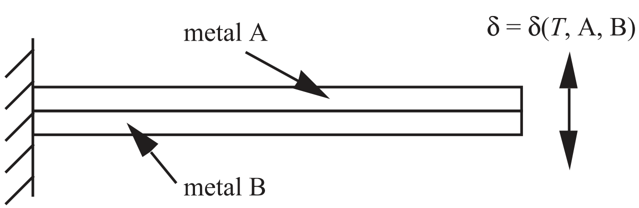


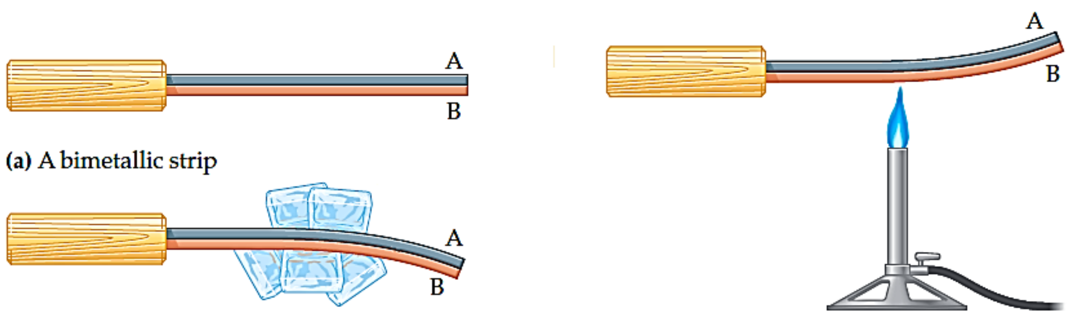
- The upper range is usually on the order of 300°C (600°F).
- Because readings are made visually, and there can be a meniscus at the top of the working fluid, measurements must be made carefully.



Bimetallic Strip

Bimetallic Strip is a **nonelectrical** temperature-measuring device that is composed of two or more metal layers having different **coefficients of thermal expansion** and permanently bonded together. Due to the difference in the thermal expansions of the metal layers, the structure will deform when the temperature changes.



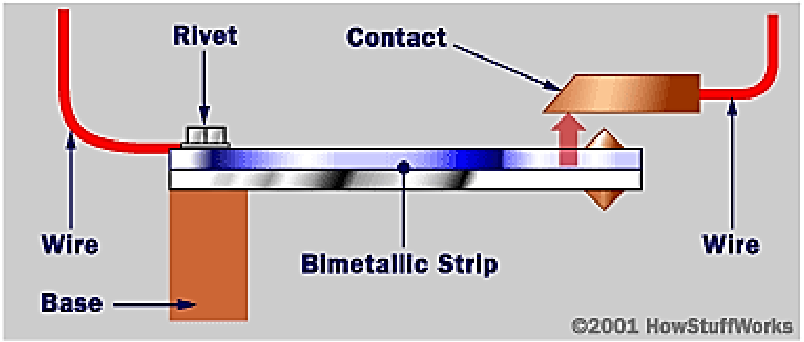


(a) A bimetallic strip

(b) Chilling the strip

(c) Heating the strip

- Bimetallic strips are used as a **temperature-controlled switch** in **thermostats** where the mechanical motion of the strip makes or breaks an electrical contact.



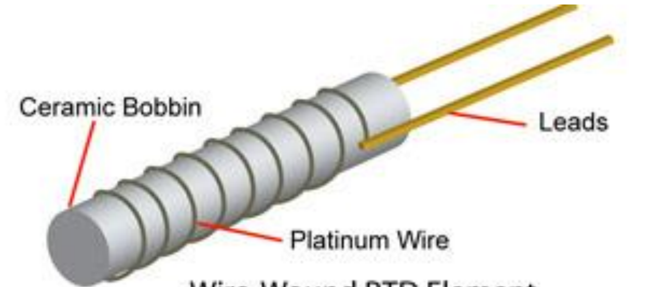
Resistance Temperature Detector (RTD)

RTD is constructed of **metallic** wire wound around a ceramic or glass core and hermetically sealed.

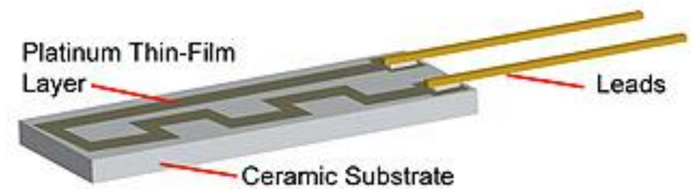
- The resistance of the metallic wire increases with temperature.

$$R = R_0[1 + \alpha(T - T_0)]$$

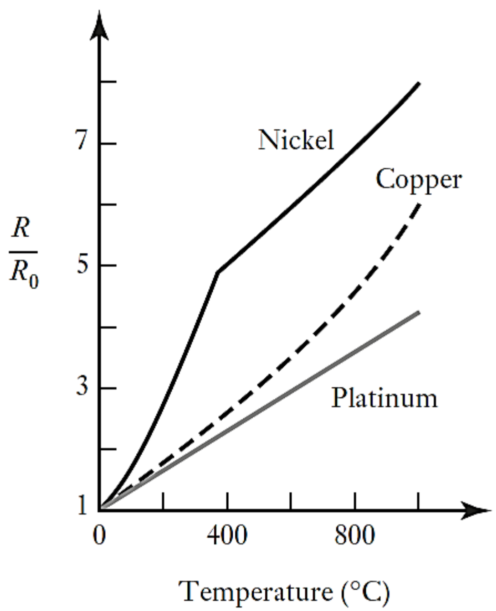
T_0: reference temperature (usually 0°C),
R_0: resistance at T_0, α: calibration constant



Wire-Wound RTD Element



Thin-Film RTD Element



- The most common metal is **Platinum** (Pt) because of its high melting point, resistance to oxidation, predictable temperature characteristics, and stable calibration values [Operating range: -220 °C to 750 °C]. (linear)
- Lower cost **Nickel** (Ni) and **Copper** (Cu) types are also available, but they have narrower operating ranges. (nonlinear: 2^{nd} or 3^{rd} order polynomial)

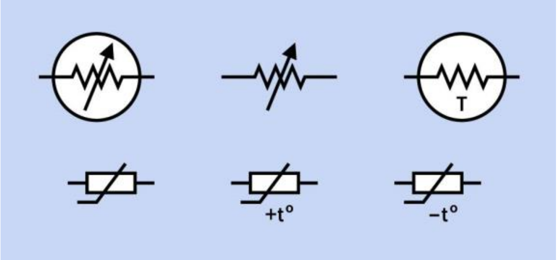
Thermistor

A **Thermistor** is a **semiconductor** device whose resistance changes **exponentially** with temperature.

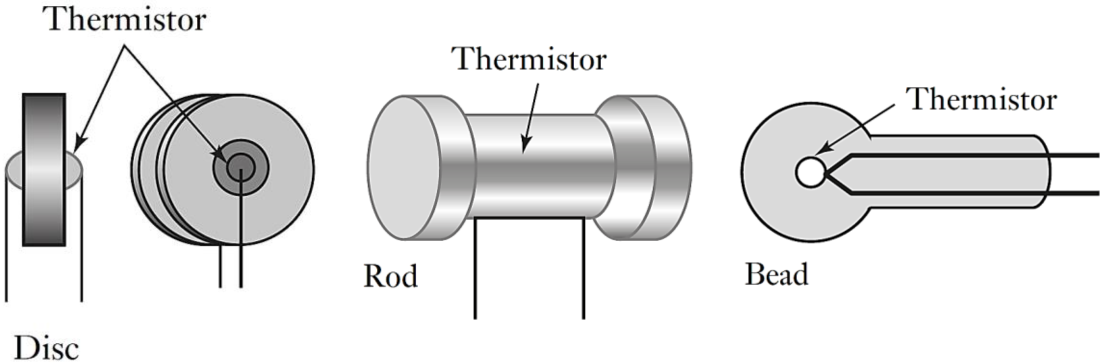
$$R = R_0 \, e^{\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]}$$

T_0: reference temperature,
R_0: resistance at T_0,
β: calibration constant (characteristic temperature)

Symbol



More common forms: bead, disc, and rod.



Thermistor

Thermistors are of two opposite fundamental types:

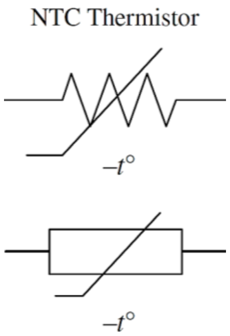
- **NTC** (**N**egative **T**emperature **C**oefficient): Resistance decreases as temperature rises.
- **PTC** (**P**ositive **T**emperature **C**oefficient): Resistance increases as temperature rises.

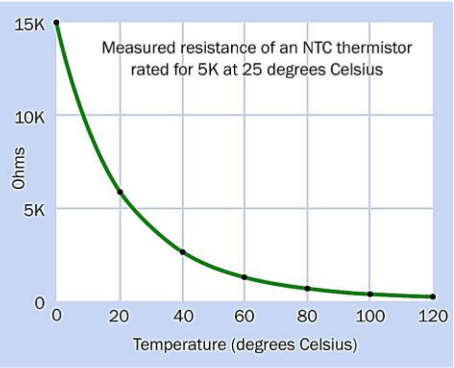
Advantages of Thermistors:

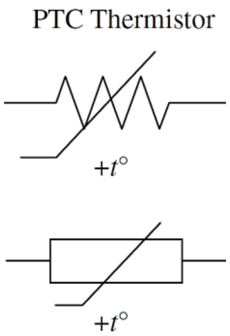
- A well-calibrated thermistor can be more accurate than a typical RTD.
- They are rugged and can be very small.
- They respond very rapidly to changes in temperature.

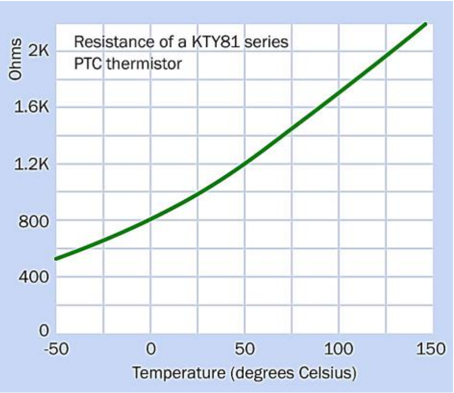
Disadvantages of Thermistors:

- They give very large changes in resistance per degree change in temperature (non-linearity).
- They have much narrower operating ranges than RTDs.







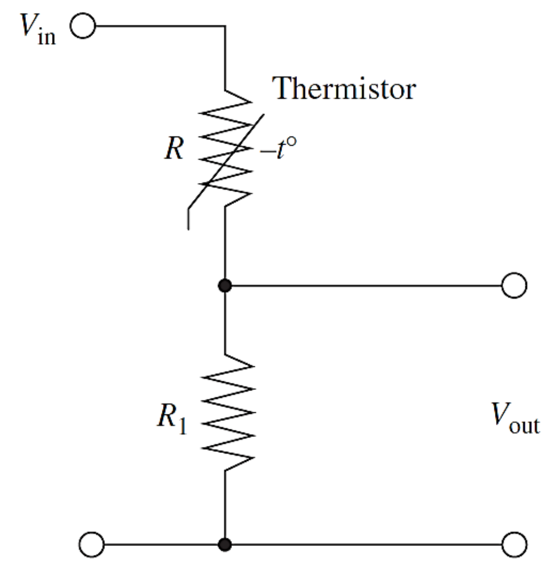


Using Thermistors & RTDs

To use a thermistor or RTD as a thermometer for input to a microcontroller, a voltage is required that can be measured by the analog-to-digital converter (ADC) of the microcontroller.

- A typical circuit is using a voltage divider with a fixed-value resistor of the same value as R_0.

$$V_{out} = \frac{R_1}{R_1 + R} V_{in}$$

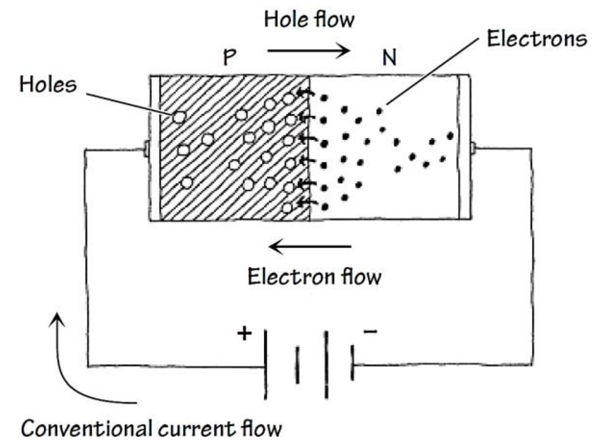


Thermodiode

In a **Thermodiode**, when the temperature of doped semiconductors changes, the mobility of their **charge carriers** changes, and this affects the rate at which electrons and holes can diffuse across a p–n junction.

$$I_D = I_0\left(e^{\frac{qV_D}{kT}} - 1\right)$$

k Boltzmann's constant,
q charge of one electron,
I_0 reverse saturation current,
I_D current through the junction,
V_D forward bias voltage across the junction,
T absolute temperature of the junction (Kelvin).

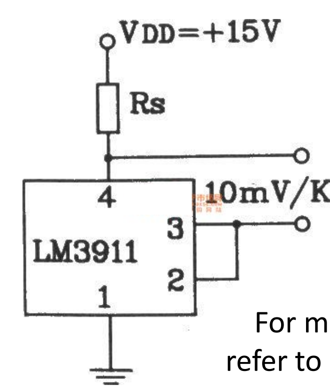


By taking logarithms:

$$V_D = \frac{kT}{q}\ln\left(\frac{I_D}{I_0} + 1\right)$$

For a constant current, V_D is linearly proportional to T (Kelvin).

- Diodes for use as temperature sensors, together with the necessary signal conditioning, are supplied as ICs, e.g., LM3911.

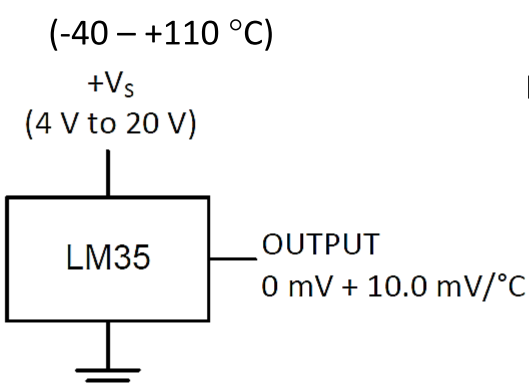


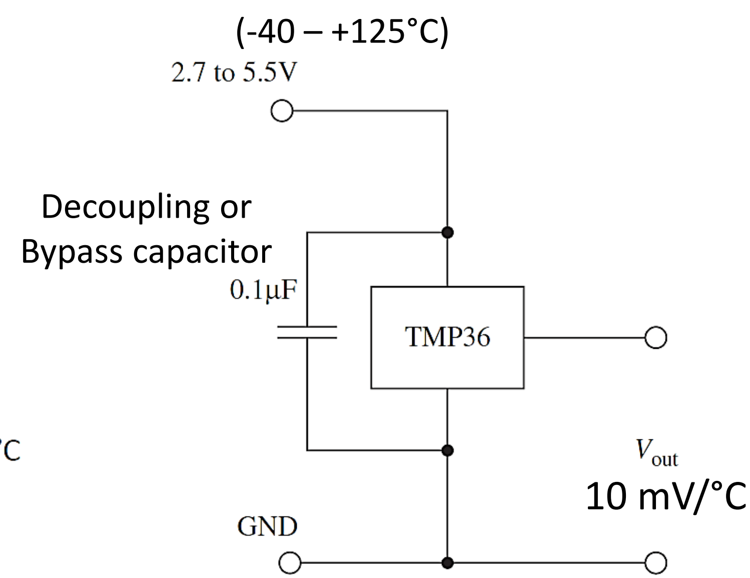
For more info refer to datasheet

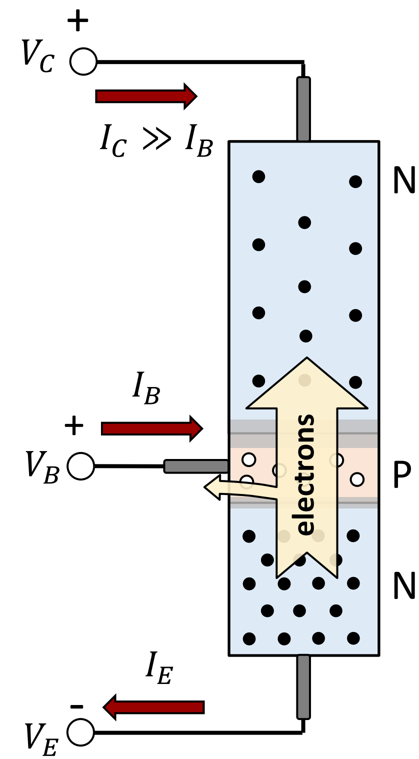
Thermotransistor

In a **Thermotransistor**, the voltage across the junction between the **base** and the **emitter** depends on the temperature and can be used as a measure of temperature.

- Transistors for use as temperature sensors, together with the necessary signal conditioning, are supplied as ICs, e.g., LM35, and TMP36.

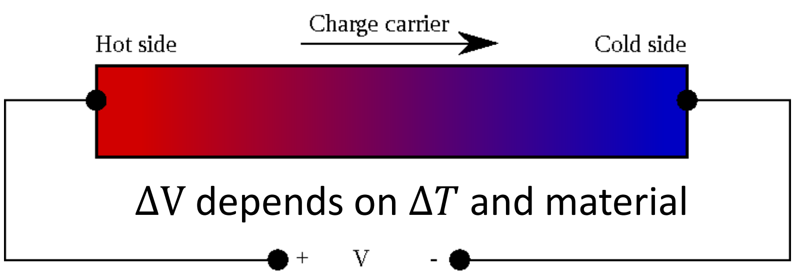




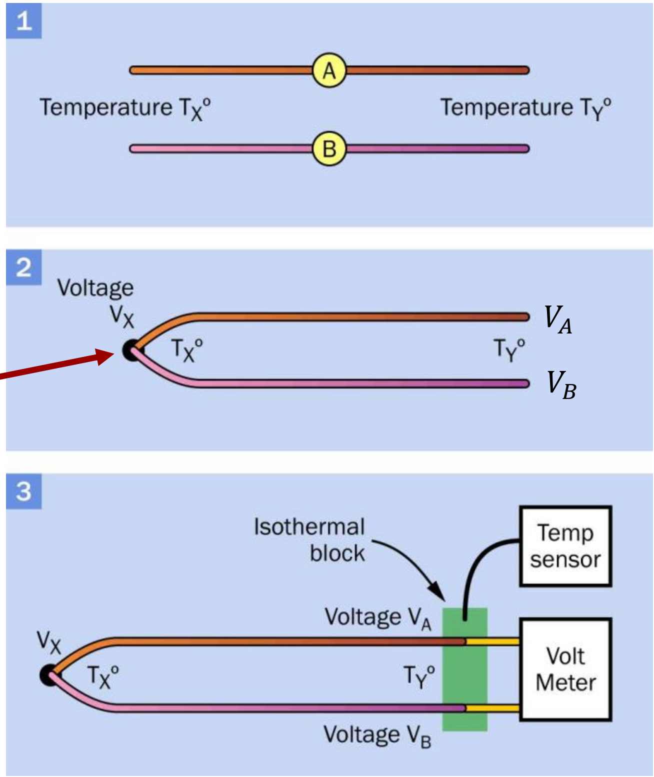


Thermocouple

When one end of a piece of metallic wire is maintained at a temperature (T_x) that is different from the other end (T_y), the temperature gradient along the wire creates a small electromotive force (EMF) that causes a difference in electrical potential between two ends of the wire. This is known as **Seebeck Effect**.



Two dissimilar metals in contact form a **thermoelectric junction**.



- Basic principles of a thermocouple:

$$V_x - V_A = \alpha_A \Delta T$$
$$V_x - V_B = \alpha_B \Delta T$$
$$V_B - V_A = (\alpha_A - \alpha_B)\Delta T$$

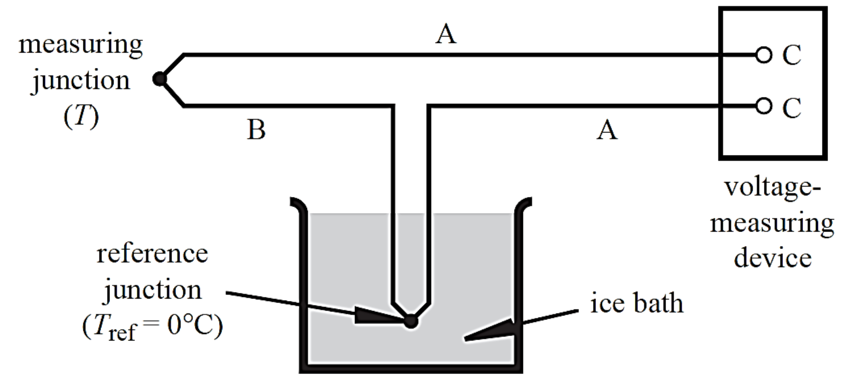
$$T_x = \Delta T + T_y$$
$$T_x = \frac{V_B - V_A}{\alpha_A - \alpha_B} + T_y$$

α_A, α_B: Seebeck coefficients

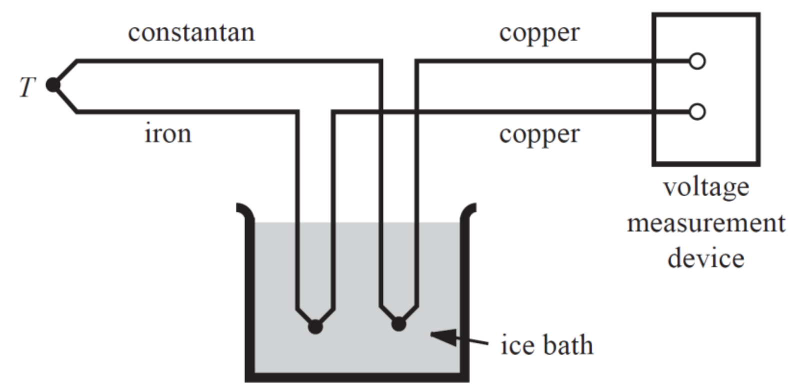
Thermocouple Configurations for Measurements

Standard Configuration: It consists of wires of two metals, A and B, attached to a voltage-measuring device with terminals made of metal C and at the same temperature. A convenient reference temperature is 0°C (ice-water mixture).

- An alternative to using an ice bath is a **semiconductor reference** (e.g., a **thermistor**), which electrically establishes the reference temperature.

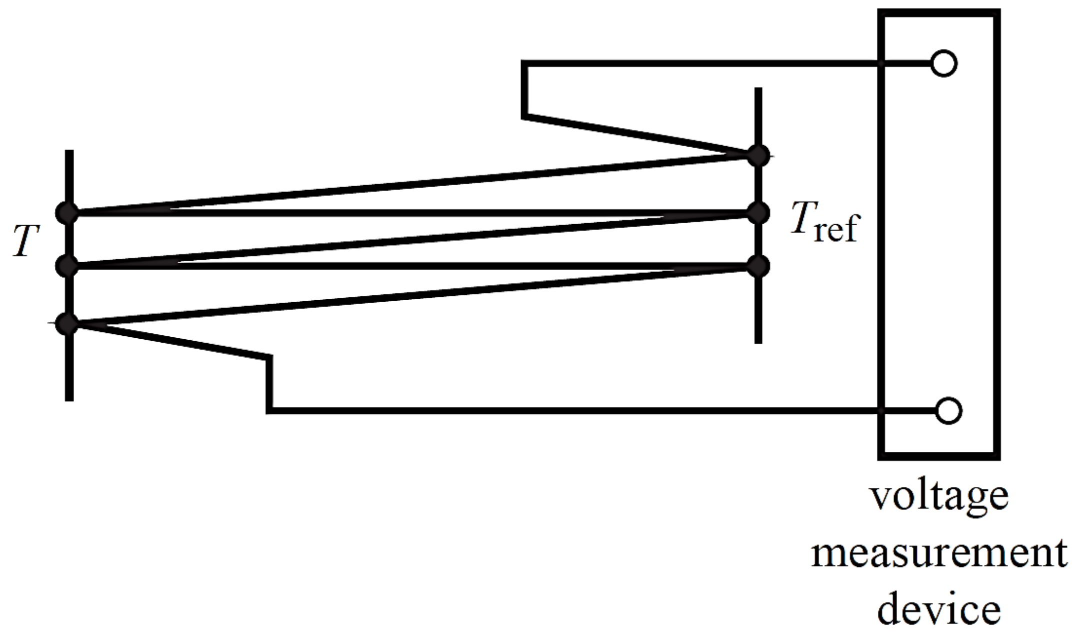


Two-reference junction configuration: It allows independent choice of the leadwire metal. Copper is a good choice for leadwires, since it is inexpensive.



Thermopile

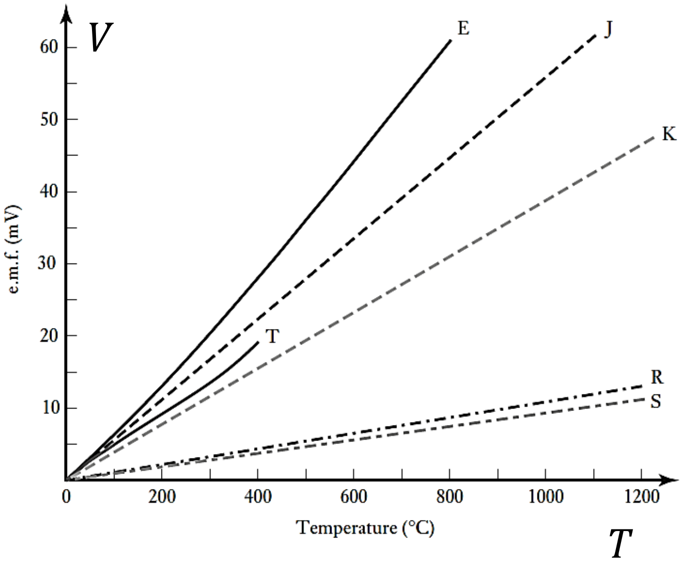
Thermopile combines N pairs of junctions, resulting in a voltage N times that of a single pair. If the measuring junctions (at T) are at different temperatures, the output would represent the **average** of these temperatures.



Common Thermocouples

The six most commonly used thermocouple metal pairs have different ranges and sensitivities are denoted by the letters **E**, **J**, **K**, **R**, **S**, and **T**. The 0°C reference junction calibration for each of the types is **nonlinear** and can be approximated with a polynomial.

$$V = kT + bT^2 \quad \text{or} \quad T = \sum_{i=1}^{9} c_i V^i$$



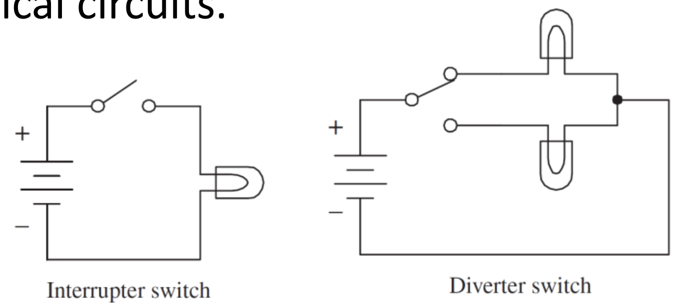
Thermocouples are generally mounted in a sheath to give them mechanical and chemical protection. However, the sheath reduces the response time of the thermocouple.

Ref.	Materials	Range (°C)	(μV/°C)
B	Platinum 30% rhodium/platinum 6% rhodium	0 to 1800	3
E	Chromel/constantan	−200 to 1000	63
J	Iron/constantan	−200 to 900	53
K	Chromel/alumel	−200 to 1300	41
N	Nirosil/nisil	−200 to 1300	28
R	Platinum/platinum 13% rhodium	0 to 1400	6
S	Platinum/platinum 10% rhodium	0 to 1400	6
T	Copper/constantan	−200 to 400	43

Inputting Data by Switches

Mechanical Switches

Mechanical Switches consist of one or more pairs of contacts which can be **mechanically** closed or opened and in doing so make or break electrical circuits.



Momentary-Contact switches (like pushbutton switches) are used when it is necessary to only **momentarily** open or close a connection. These switches come in either **Normally Closed** (**NC**) or **Normally Open** (**NO**) forms

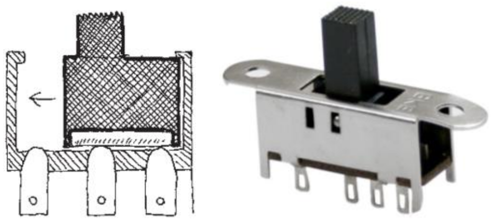
- NC switch acts as a **closed circuit** when left **untouched**.
- NO switch acts as an **open circuit** when left **untouched**.

Switches can be classified based on their **shape** or **number of Poles and Throws**.

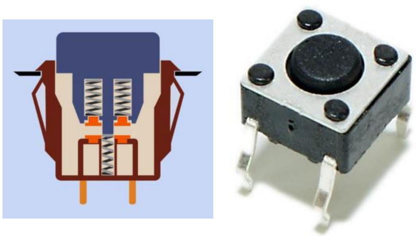
- **Pole (P)**: Number of **separate circuits** that can be completed by the **same switching action**.
- **Throw (T)**: Number of **individual contacts** for **each pole**.

Switch Types Based on Shape

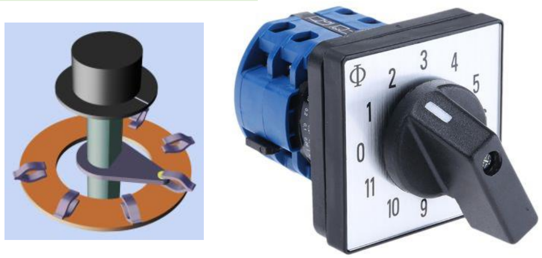
Slide Switch



Pushbutton Switch

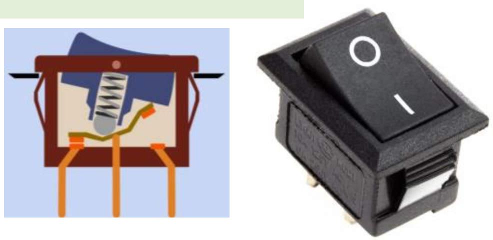


Rotary Switch

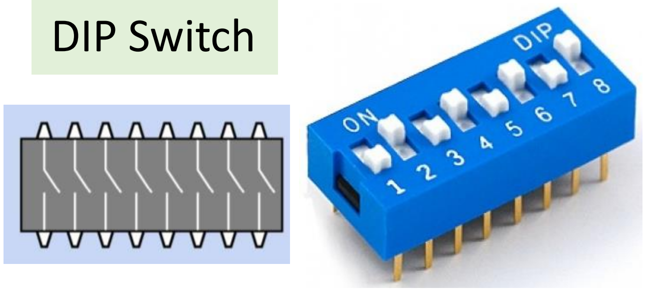


Toggle Switch

Rocker Switch



DIP Switch



Binary-Coded Switch

Switch Position	Pin 1	Pin 2	Pin 3	Pin 4
0	●	●	●	●
1	🔴	●	●	●
2	●	🔴	●	●
3	🔴	🔴	●	●
4	●	●	🔴	●

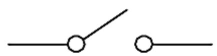
⋮

Center-Off Position Switch

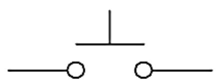
It has an additional "off" position located between the two "on" positions.

Switch Types Based on P & T

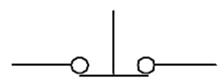
SPST (Single-Pole, Single-Throw)



Throw switch

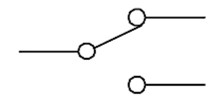


Normally open push-button

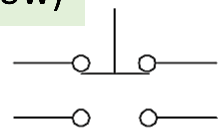


Normally closed push-button

SPDT (Single-Pole, Double-Throw)

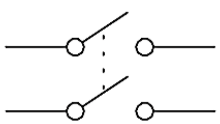


Throw switch

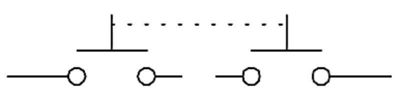


Normally open/closed push-button

DPST (Double-Pole, Single-Throw)

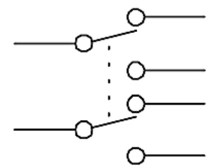


Throw switch

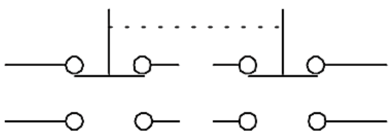


Normally open push-button

DPDT (Double-Pole, Double-Throw)

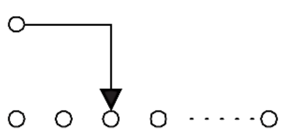


Throw switch

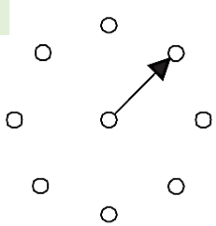


Normally open/closed push-button

SP(n)T

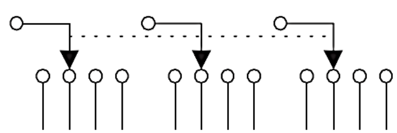


Multiple contact slider switch

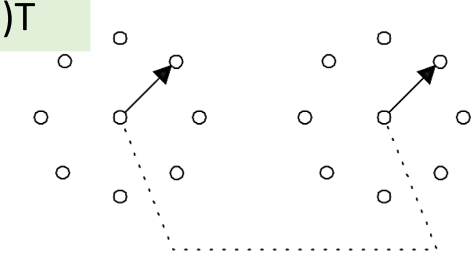


Multiple contact rotary switch (SP8T)

(n)P(m)T



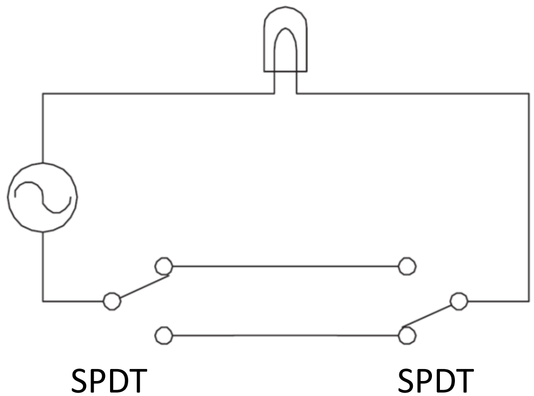
3P4T



2-deck rotary (DP8T)

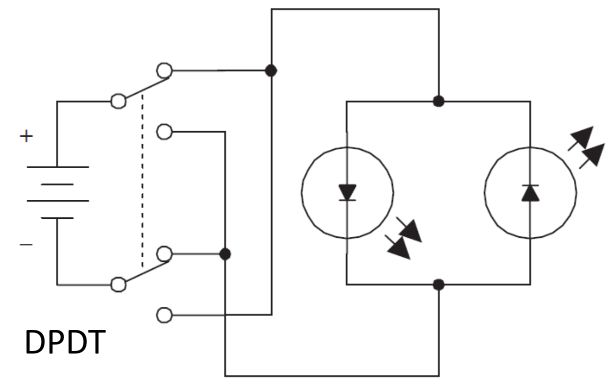
Simple Applications

Dual-Location On/Off Switching Network

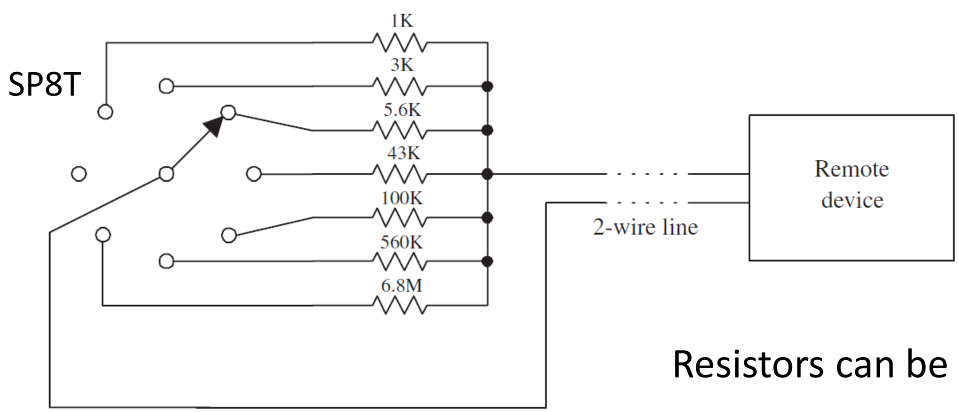


This setup is frequently used in household wiring applications.

Current-Flow Reversal



Multiple Selection Control of a Voltage-Sensitive Device via a Two-Wire Line



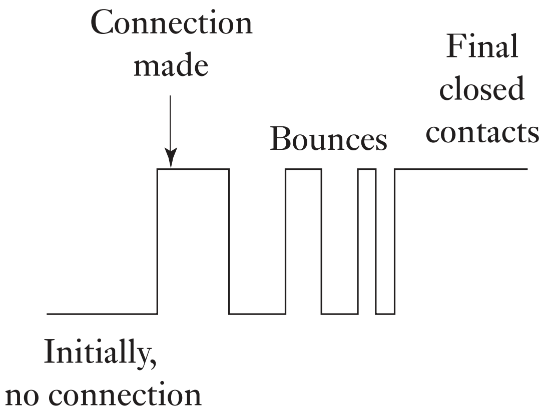
Resistors can be part of a voltage divider.

Switch Bounce

When two metal contacts extremely rapid in a mechanical switch (e.g., in a momentary-contact switch), **microscopic vibrations** occur that cause brief interruptions before the contacts settle (after about some 20 ms). While this phenomenon is not perceptible to human senses, it can be perceived as a series of multiple pulses by a **logic chip** (e.g., microprocessor). Similarly, when a mechanical switch is opened, bouncing can occur. To overcome this problem either **hardware** solutions or **software** solutions can be used to **debounce a switch** that drives a logic input.

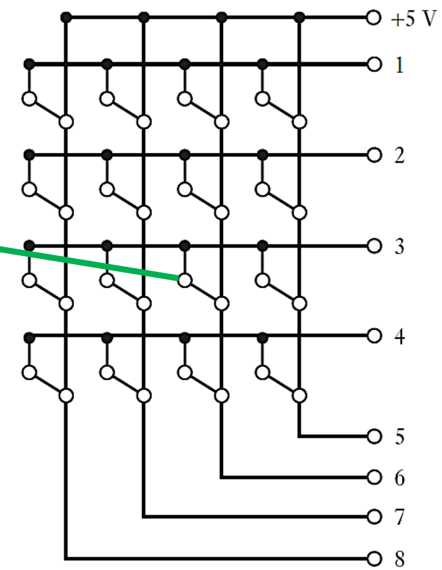
A piece of code in the Microcontroller

SR flip-flop
D flip-flop
Schmitt trigger



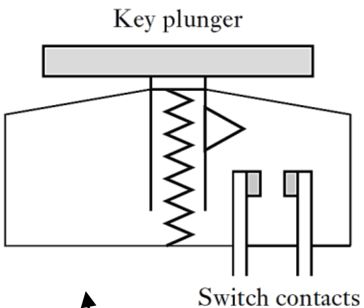
Keypad

- A **Keypad** is **an array of switches.**
- Switches can be **contact-type**, **membrane**, or **piezoelectric**.

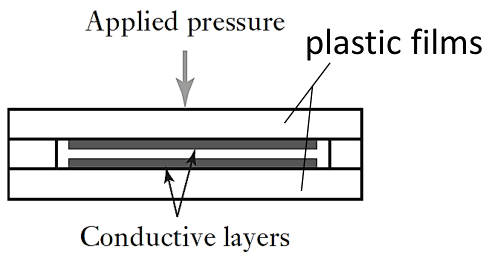


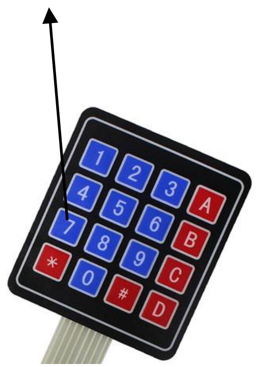
By pressing, 3 & 6 become 5V

Contact-type Key

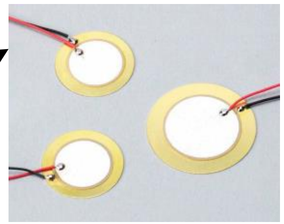


Membrane Key





Piezoelectric Key



Selection of Sensors

Factors To Be Considered

(1) Nature of Sensor Input and Measurement Requirement (variable to be measured, its nominal value, values range, required accuracy, measurement speed, reliability, resolution, environmental conditions [temperature, pressure, moist, corrosion, EM interferences, etc.]).

(2) Nature of Sensor Output (required signal conditioning, communication protocol, data acquisition card, signal level, data presentation system).

(3) Possible Sensors (direct or indirect measurements, active or passive sensors, sensor range, accuracy, linearity, response time, error, sensitivity, reliability, durability, maintainability, lifetime, wear, service, physical size, weight, implementation complexity, power supply requirements [battery, 110/220 V AC, USB-port], availability, supplier, cost).