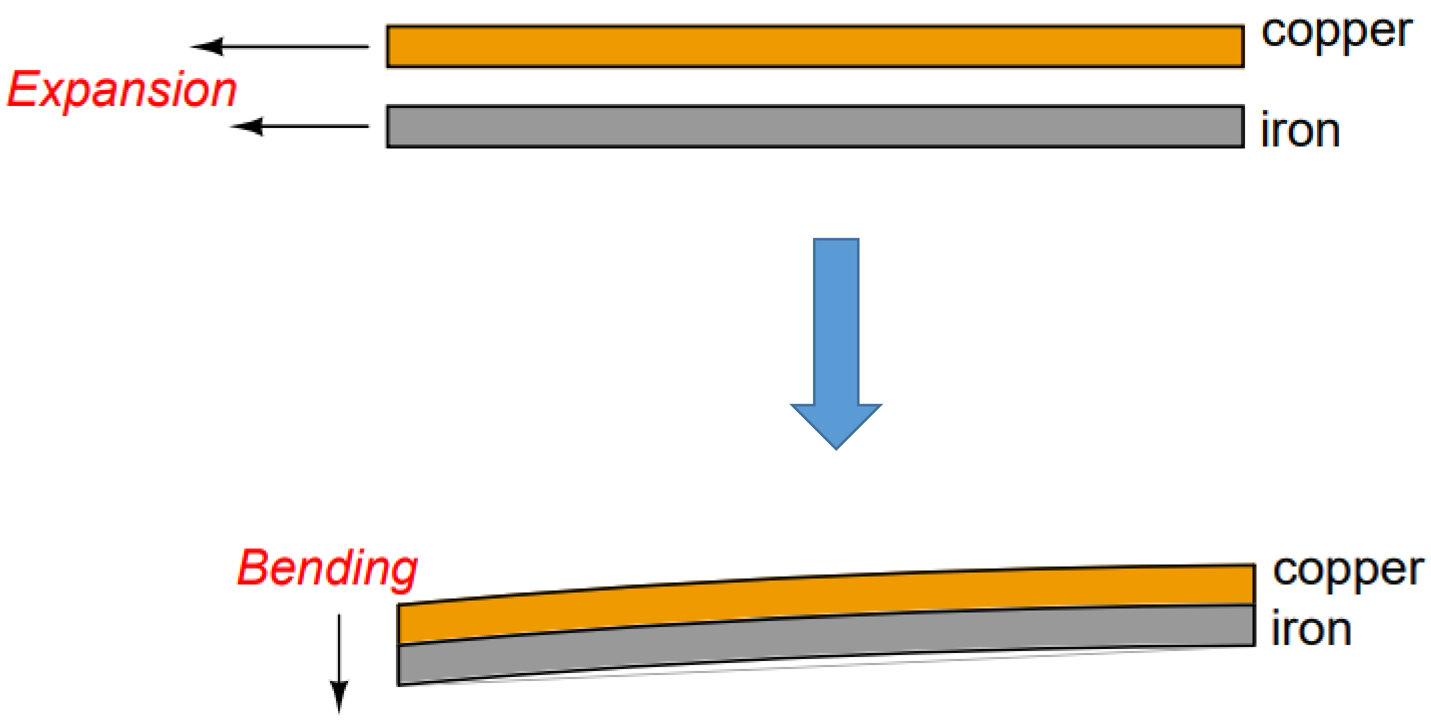
Instrumentation

Temperature Measurement

Course Instructor: Mohammad Reza Nayeri

Bi-Metal Sensor



$$l = l_0 (1 + \alpha \Delta T)$$

l = *Length of material after heating*
l_0 = *Original length of material*
α = *Coefficient of linear expansion*
ΔT = *Change in temperature*

- Aluminum = 25×10^{-6} per degree C
- Copper = 16.6×10^{-6} per degree C
- Iron = 12×10^{-6} per degree C
- Tin = 20×10^{-6} per degree C
- Titanium = 8.5×10^{-6} per degree C

Bi-Metal Sensor

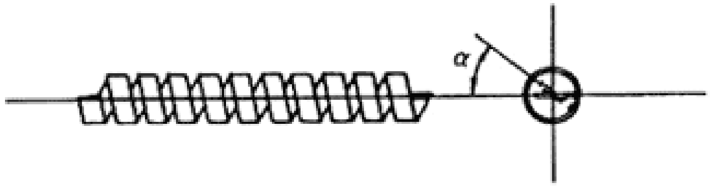
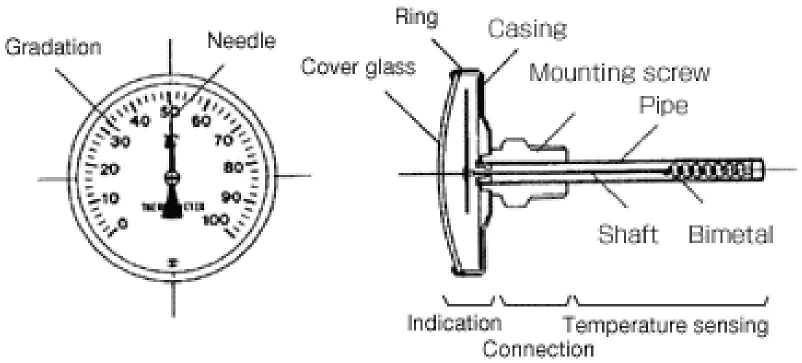
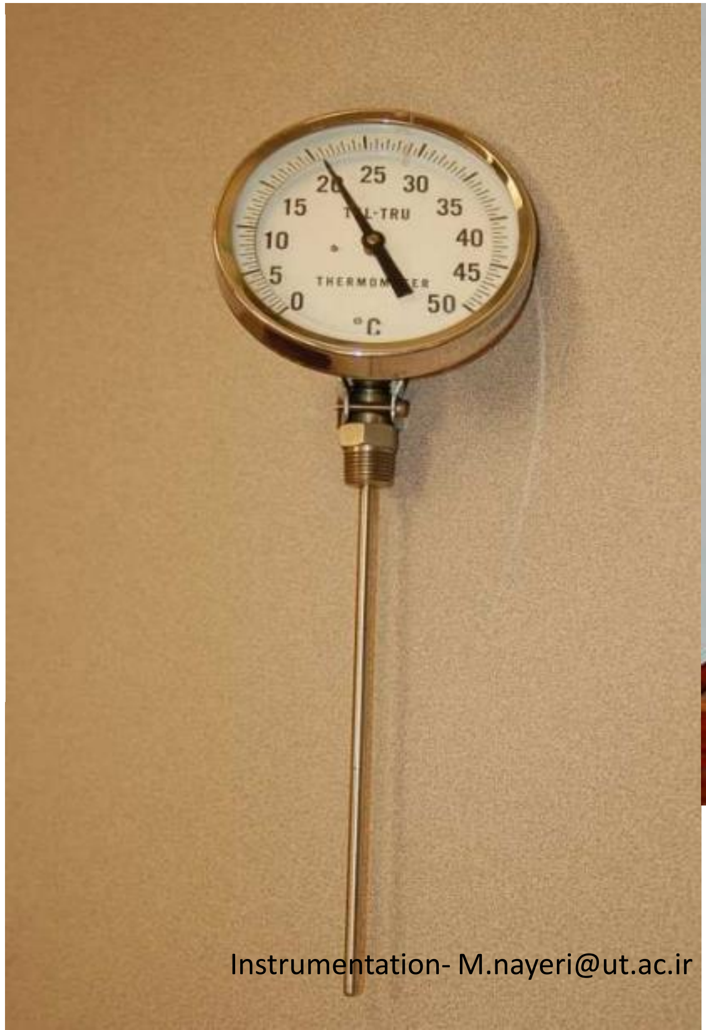
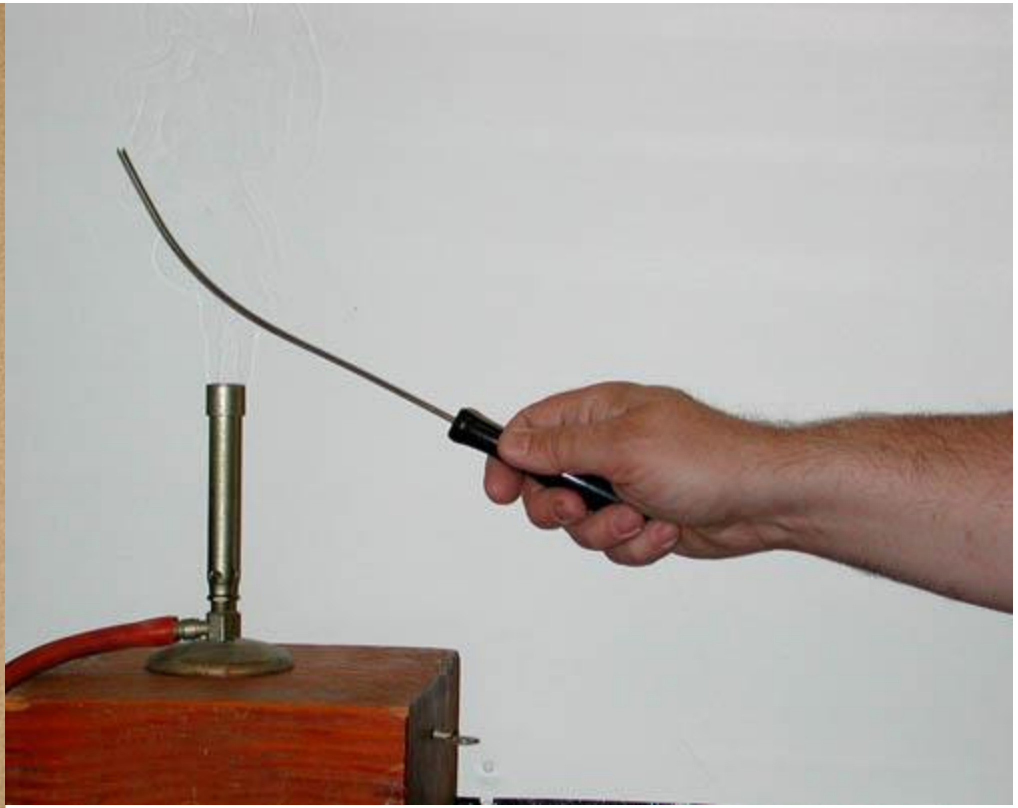
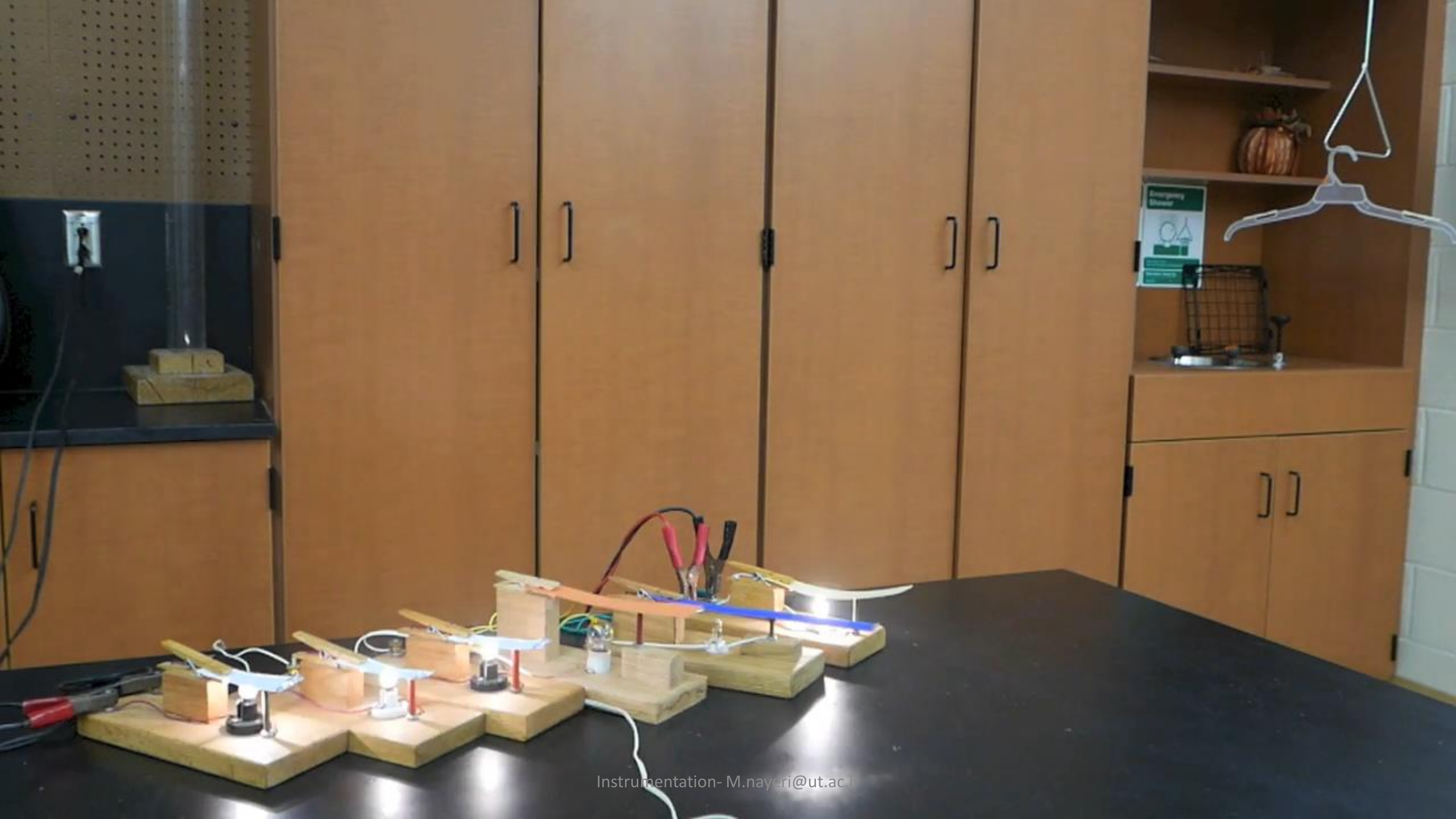


Fig. 3 Spiral bimetal



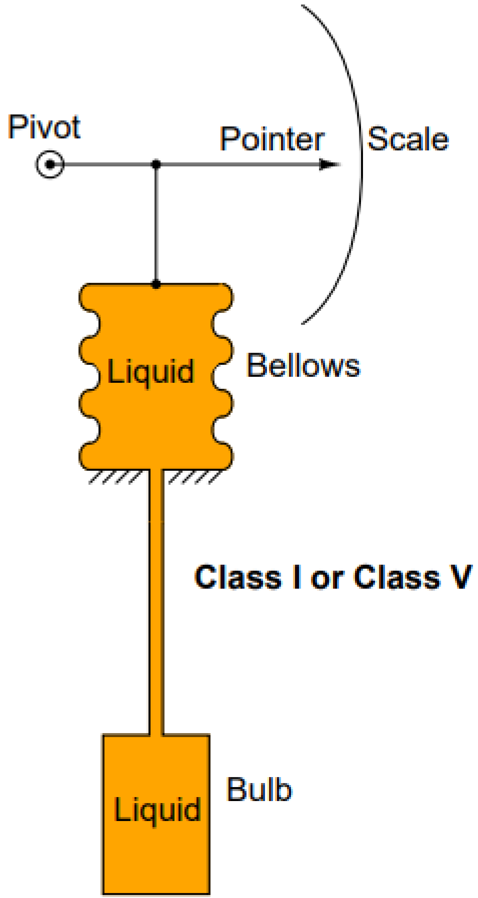


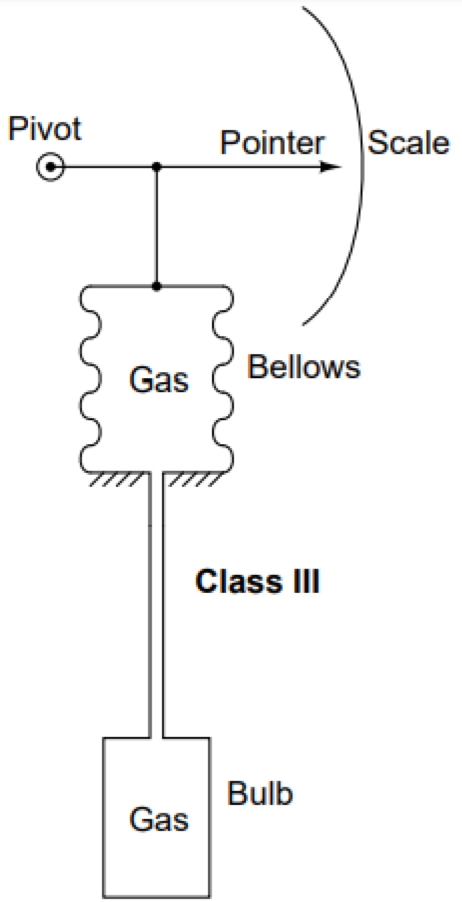




Filled-bulb

- Exploit the principle of fluid expansion to measure temperature.
- Class I and Class V systems use a liquid fill fluid (class V is mercury).
- Class III systems use a gas fill fluid instead of liquid.



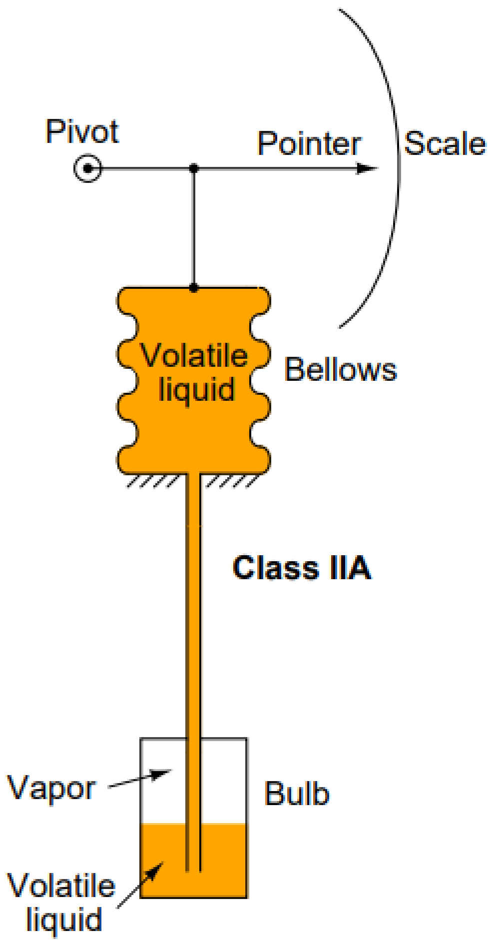


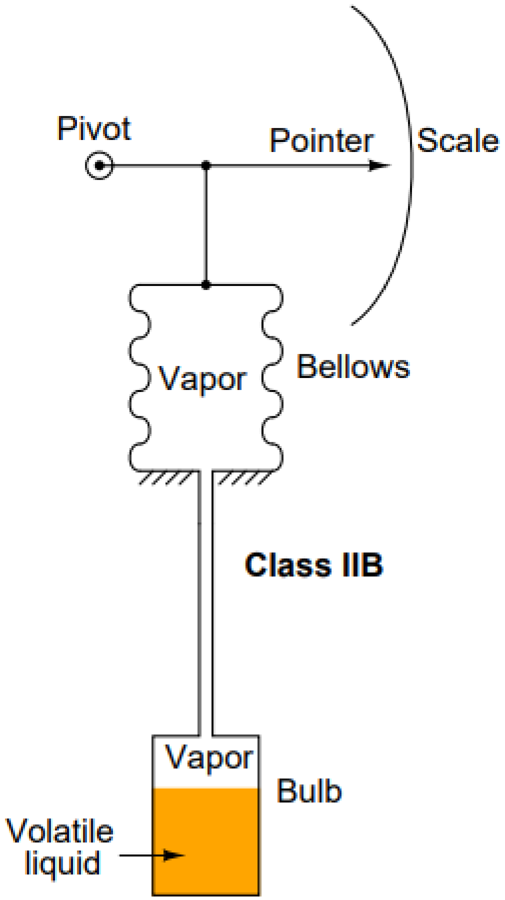
Filled-bulb

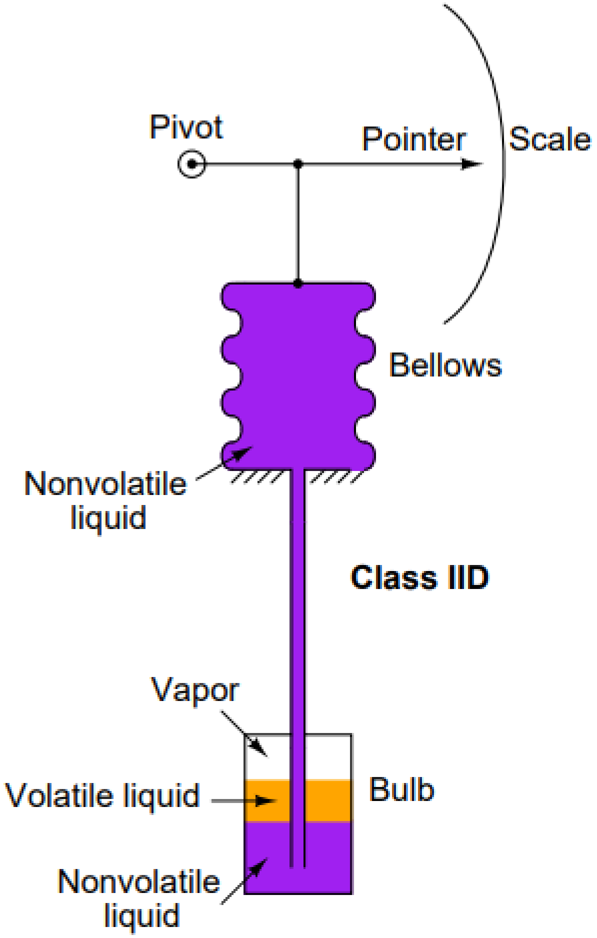
Filled-bulb

- A fundamentally different class of filled-bulb system is the Class II, which uses a volatile liquid/vapor combination to generate a temperature-dependent fluid expansion

- This makes the Class II system sensitive to temperature only at the bulb and nowhere else along the system’s volume.







Filled-bulb

- Pneumatic temperature transmitter using a filled-bulb as the sensing element
- Instead of directly actuating a pointer mechanism, the fluid pressure in this instrument actuates a self-balancing pneumatic mechanism to produce a 3 to 15 PSI air pressure signal representing process temperature.

Bi-Metal vs Filled-bulb

Thermistors

- A **thermistor** is a type of resistor whose resistance is dependent on temperature, more so than in standard resistors.
- The word is a combination of thermal and resistor.
- Thermistors are of two opposite fundamental types:

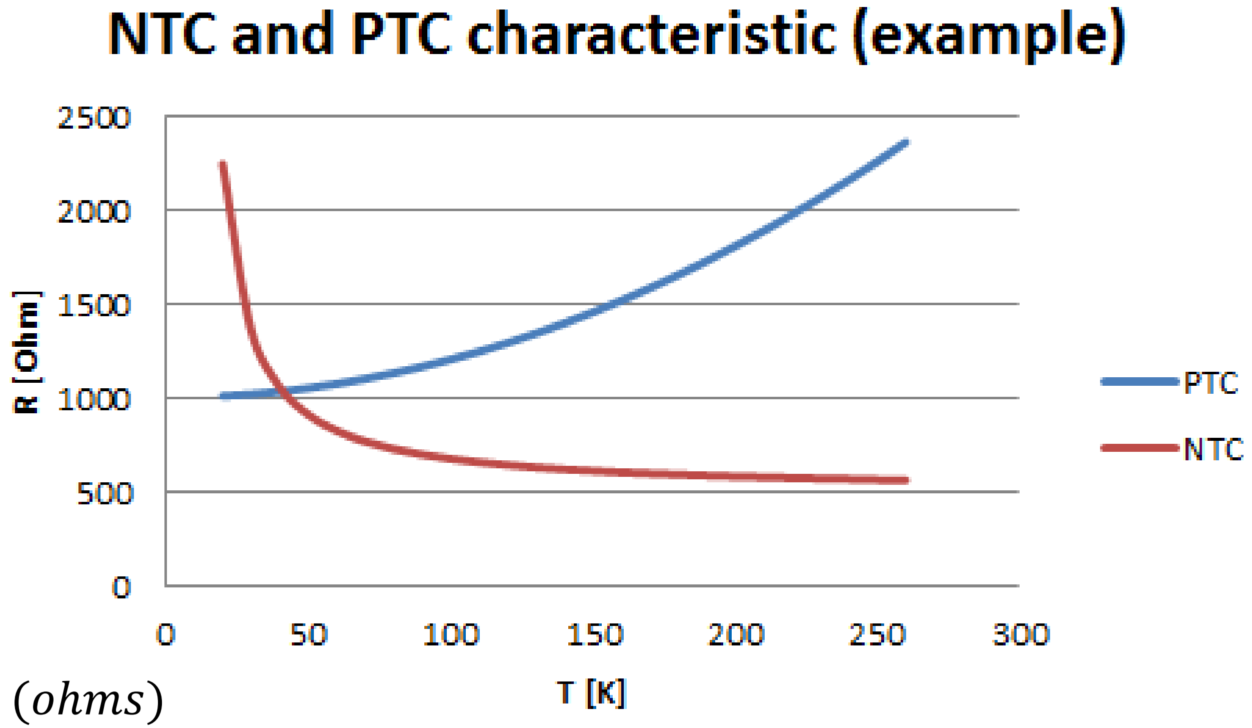
  - **NTC** (negative temperature coefficient)
  - **PTC** (positive temperature coefficient)

- NTC thermistors can now achieve accuracies over wide temperature ranges such as ±0.1 °C or ±0.2 °C from 0 °C to 70 °C with excellent long-term stability.

- The typical operating temperature range of a thermistor is −55 °C to +150 °C, though some glass-body thermistors have a maximal operating temperature of +300 °C.

Thermistors

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



$R\ =\ Resistance\ of\ thermistor\ at\ given\ temperature\ T\ (ohms)$
$R_0\ =\ Resistance\ of\ thermistor\ at\ the\ temperature\ T_0\ (ohms)$
$\beta\ =\ Temperature\ coefficient\ of\ thermistor$

$Note$:

- $The\ units\ of\ T\ and\ T_0\ are\ degree\ of\ kelvine\ (°K = ℃ + 273.15)$
- $The\ sign\ of\ \beta\ is\ positive\ and\ negative\ for\ NTC\ and\ PTC\ thermistors\ respectively.$

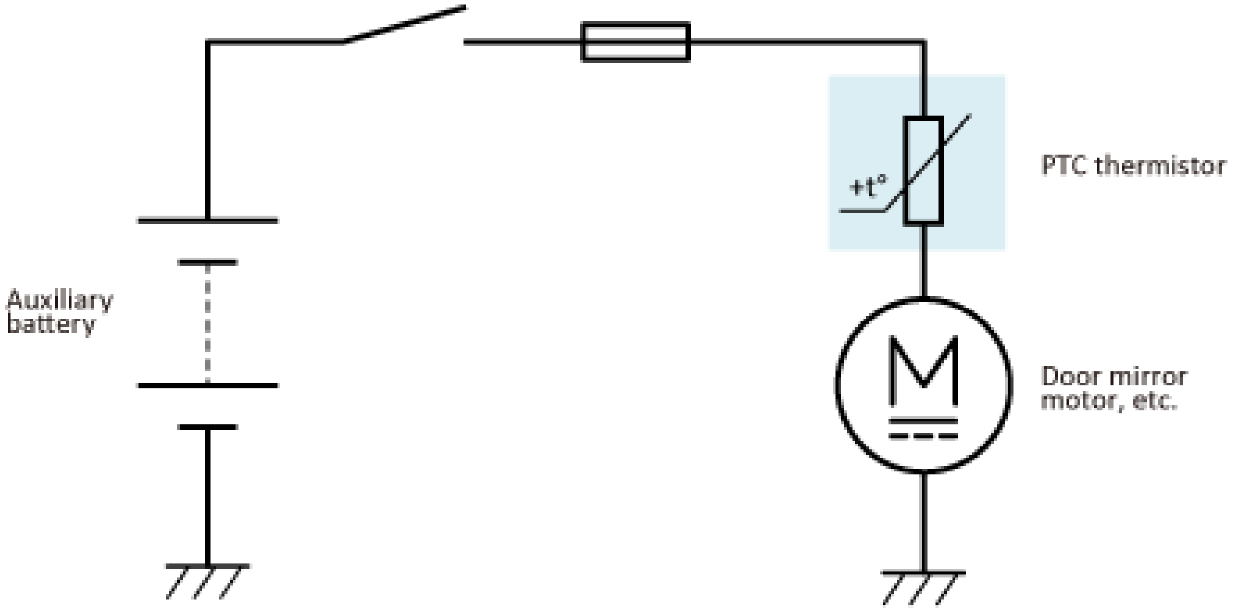
Thermistors

Applications:

PTC

- As current-limiting devices for circuit protection

PTC thermistor for
overcurrent protection

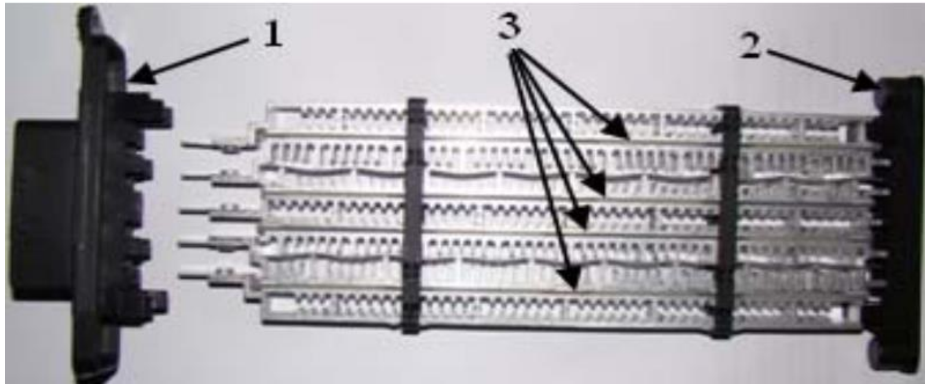


Thermistors

Applications:

PTC

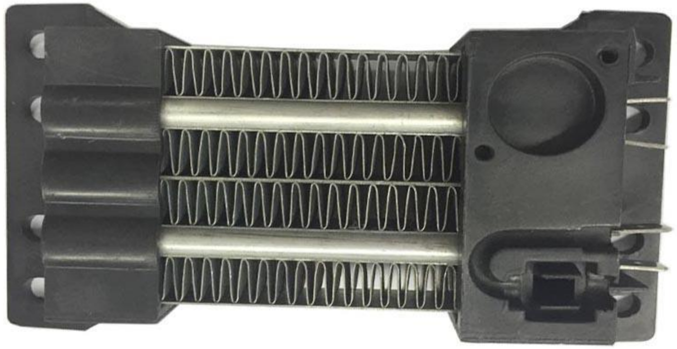
- As heater in automotive industry to provide additional heat inside cabin with diesel engine or to heat diesel in cold climatic conditions before engine injection.



(1) Electrical connector

(2) Heating resistive elements with fins

(3) The PTC heating resistive elements

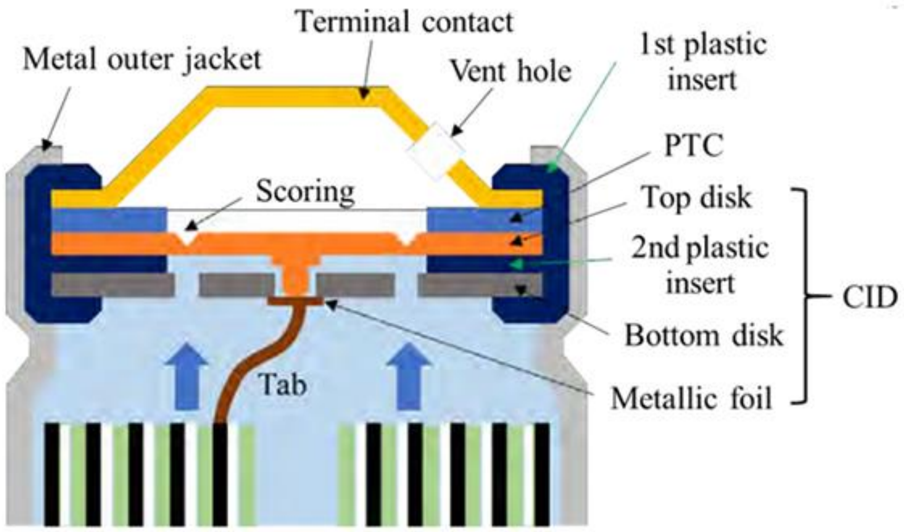


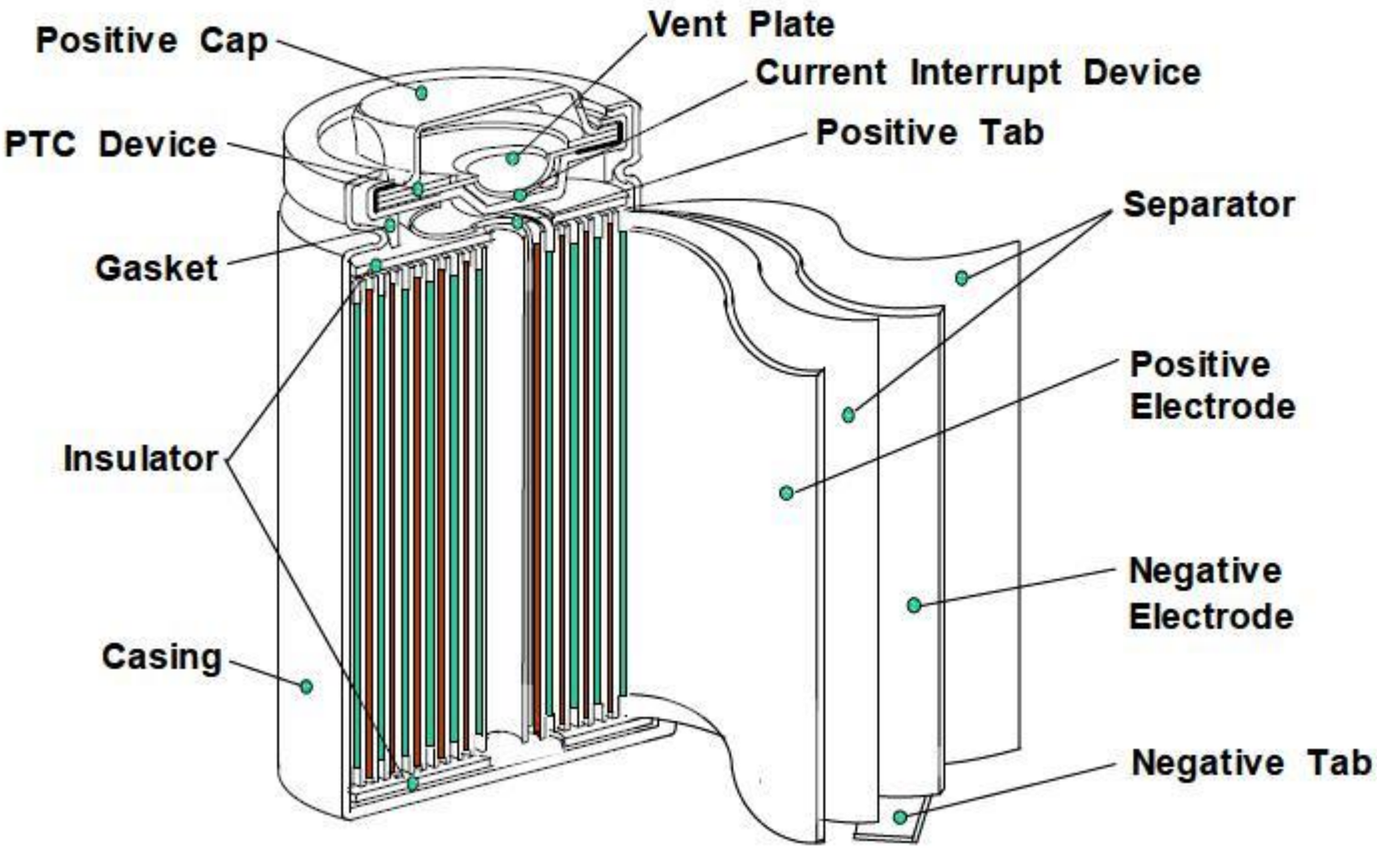
Thermistors

Applications:

PTC

- Lithium battery protection circuits



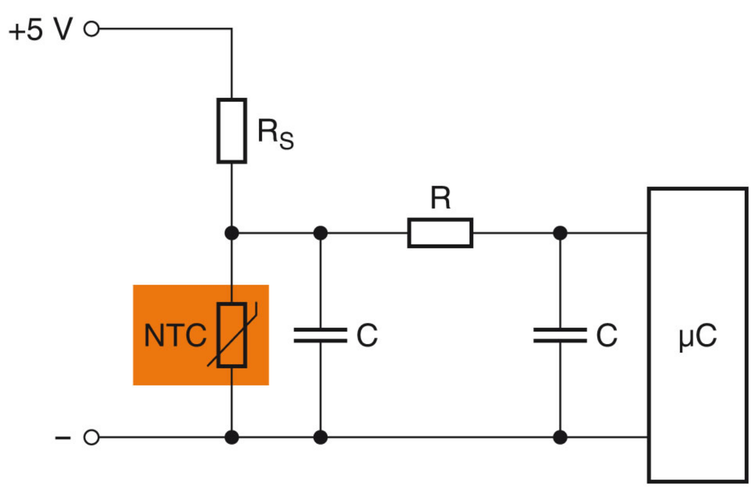


Thermistors

Applications:

NTC

- As a resistance thermometer for low-temperature measurements of the order of 10 K.
- As sensors in automotive applications to monitor fluid temperatures like the engine coolant, cabin air, external air or engine oil temperature



Resistive Temperature Detector (RTD)

- An RTD temperature sensor is a common device for temperature measurements in a wide range of industrial applications.

$$R_T = R_{ref}\,[1 + \alpha_1(T - T_{ref}) + \alpha_2(T - T_{ref})^2 + \cdots]$$

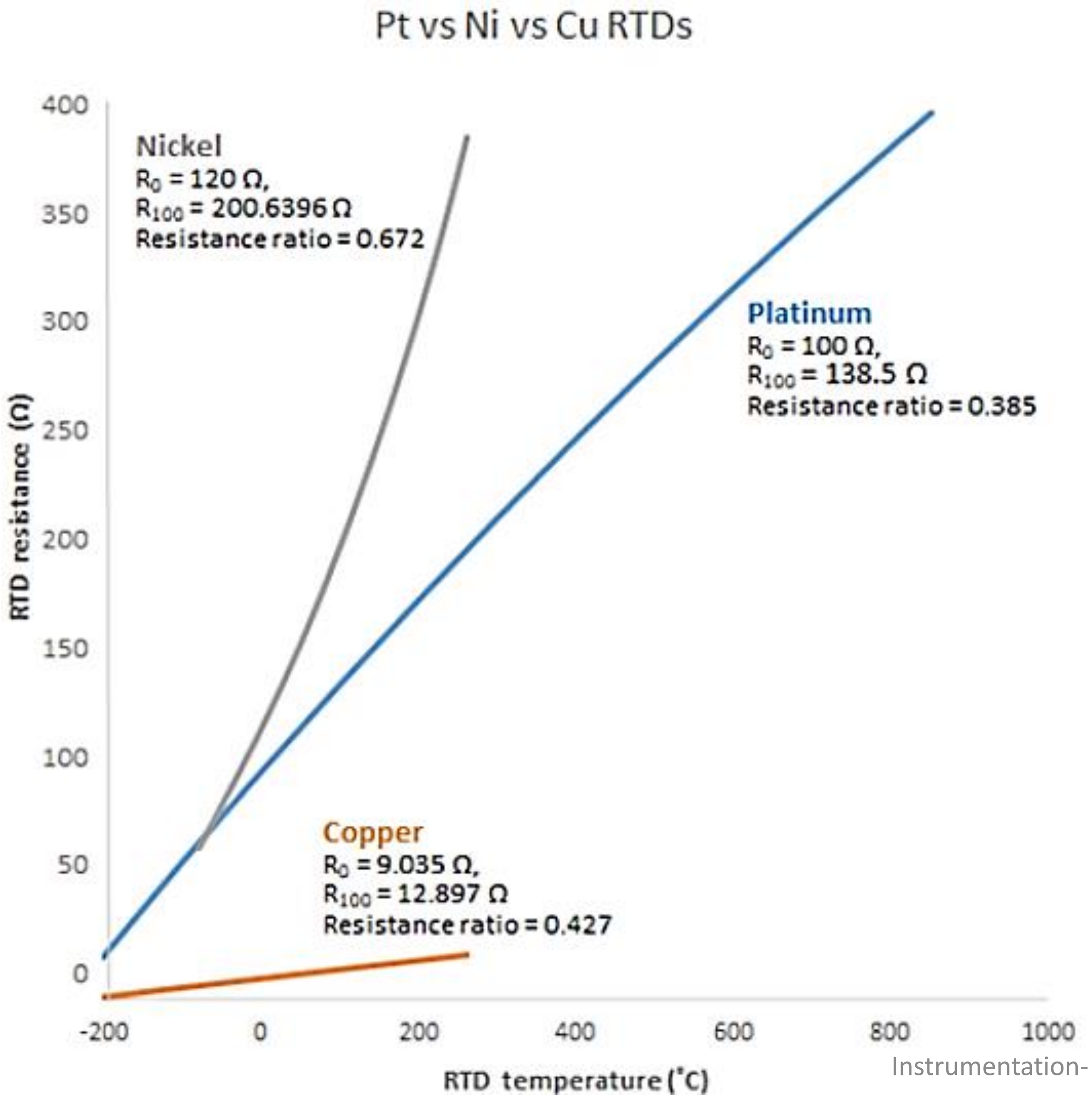
$R_T = Resistance\ of\ RTD\ at\ given\ temperature\ T\ (ohms)$
$R_{ref} = Resistance\ of\ RTD\ at\ the\ reference\ temperature\ T_{ref}\ (ohms)$
$\alpha_1 = Temperature\ coefficient\ of\ resistance\ (ohms\ per\ ohm/degree)$
$\alpha_2 = Square\ Temperature\ coefficient\ of\ resistance\ (ohms\ per\ ohm/degree^2)$

RTD

- Typically, RTDs contain either platinum, nickel, or copper wires, as these materials have a positive temperature coefficient.

RTD type	Maximum measurement range	Long term stability	Corrosion resistance	Temperature vs. resistance linearity	Typical resistance at 0 °C	Typical resistance at 100 °C	Change in resistance 0... 100 °C	Resistance Ratio $(R_{100}-R_0)/R_0$
Platinum	-200... 850 °C	Excellent	Excellent	Good	100 Ω	138.5 Ω	38.5 Ω	0,385
Nickel	-80... 260 °C	Fair	Good	Fair	120 Ω	200.64 Ω	80.64 Ω	0,672
Copper	-200... 260 °C	Good	Fair	Excellent	9.035 Ω	12.897 Ω	3.86 Ω	0,427

RTD



RTD type	Resistance Ratio $(R_{100}-R_0)/R_0$	Alpha, (α) $(R_{100}-R_0)/(100 \times R_0)$
Platinum	0,385	0,00385
Nickel	0,672	0,00672
Copper	0,427	0,00427

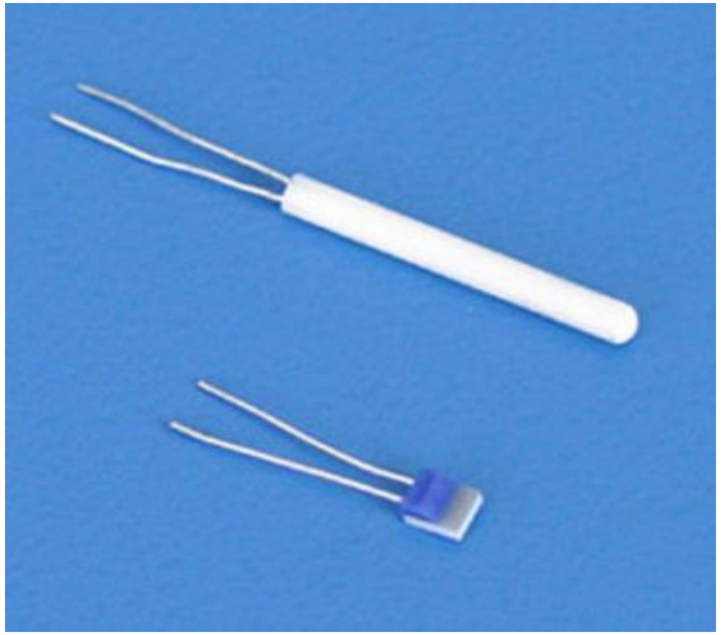
PT100 CU10 NI100

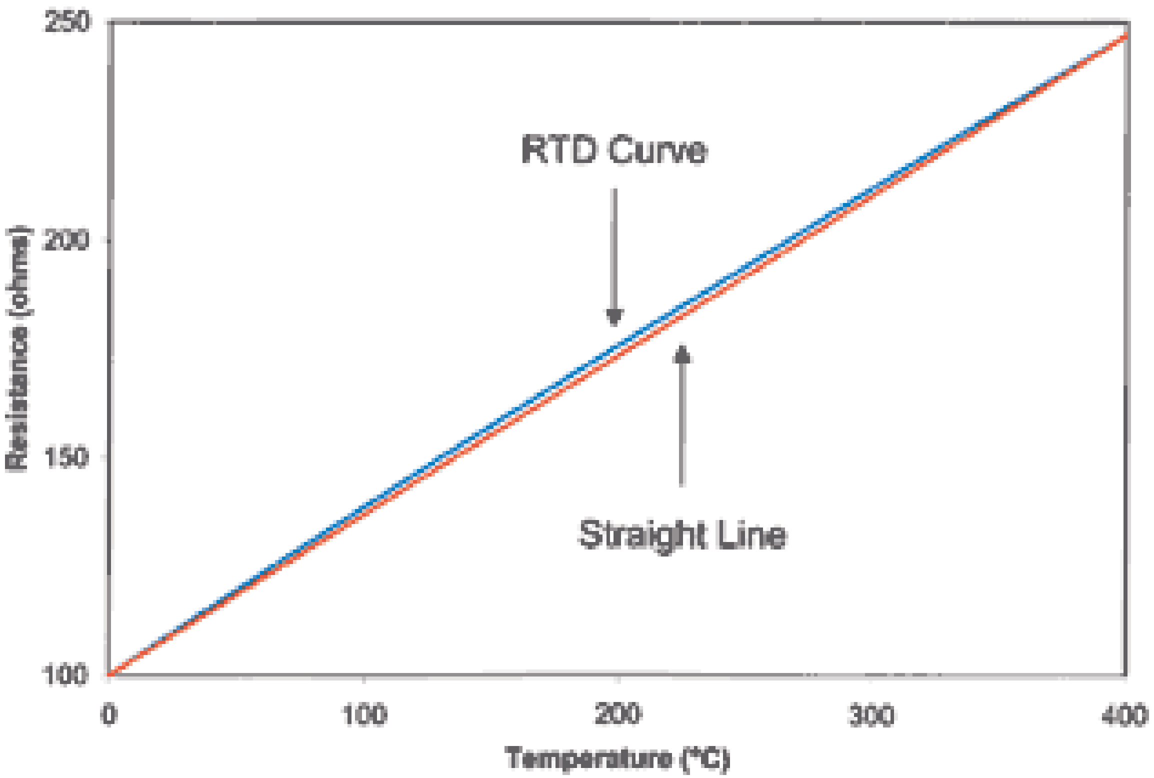
PT200 CU100 NI120

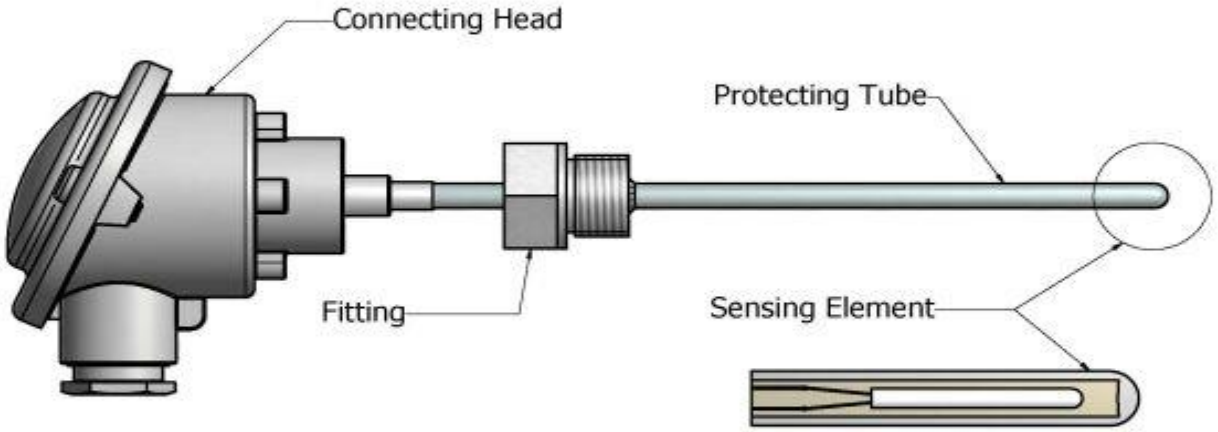
PT500

PT1000

RTD





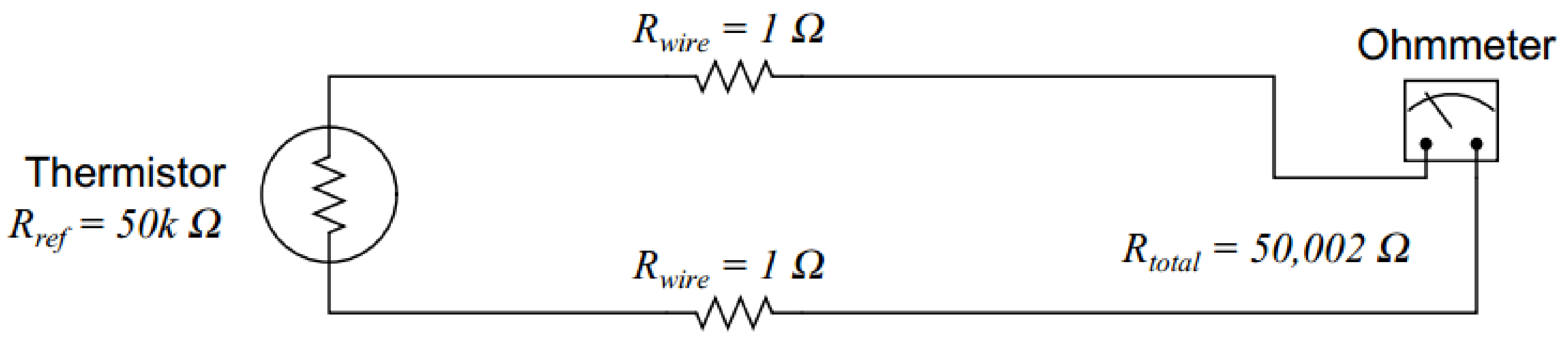


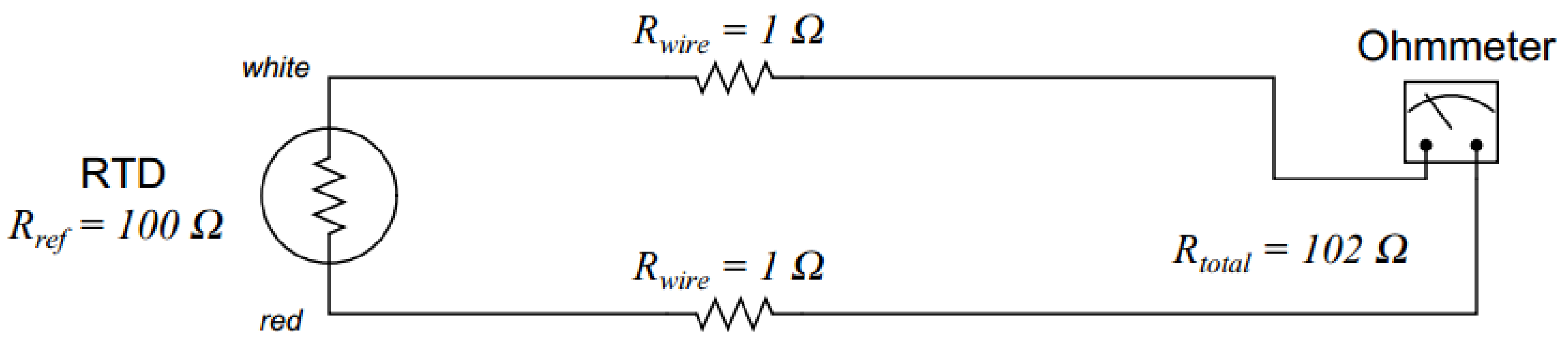
$$R = R_0(1 + \alpha_1 T + \alpha_2 T^2)$$

$PT100 \rightarrow$

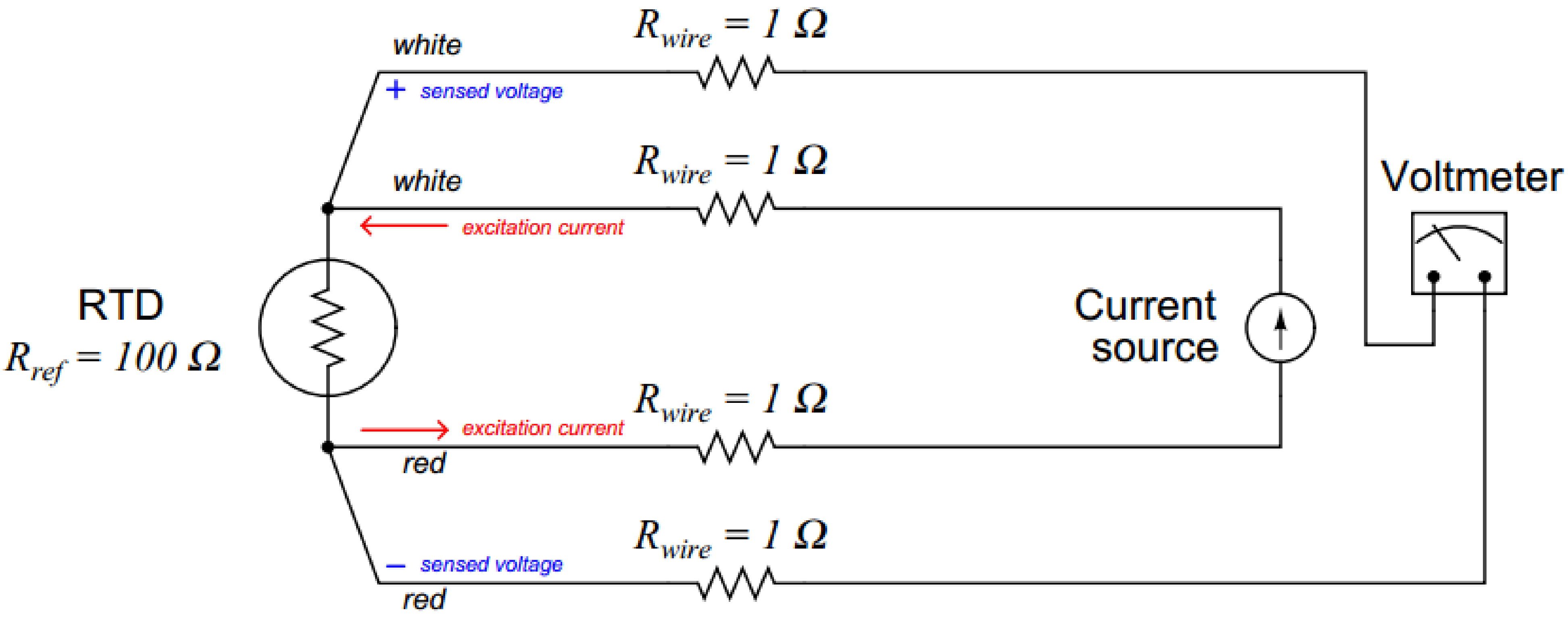
$$R_0 = 100$$
$$\alpha_1 = 3.85 \times 10^{-3}$$
$$\alpha_2 = 5.77 \times 10^{-7}$$

Two Wire RTD

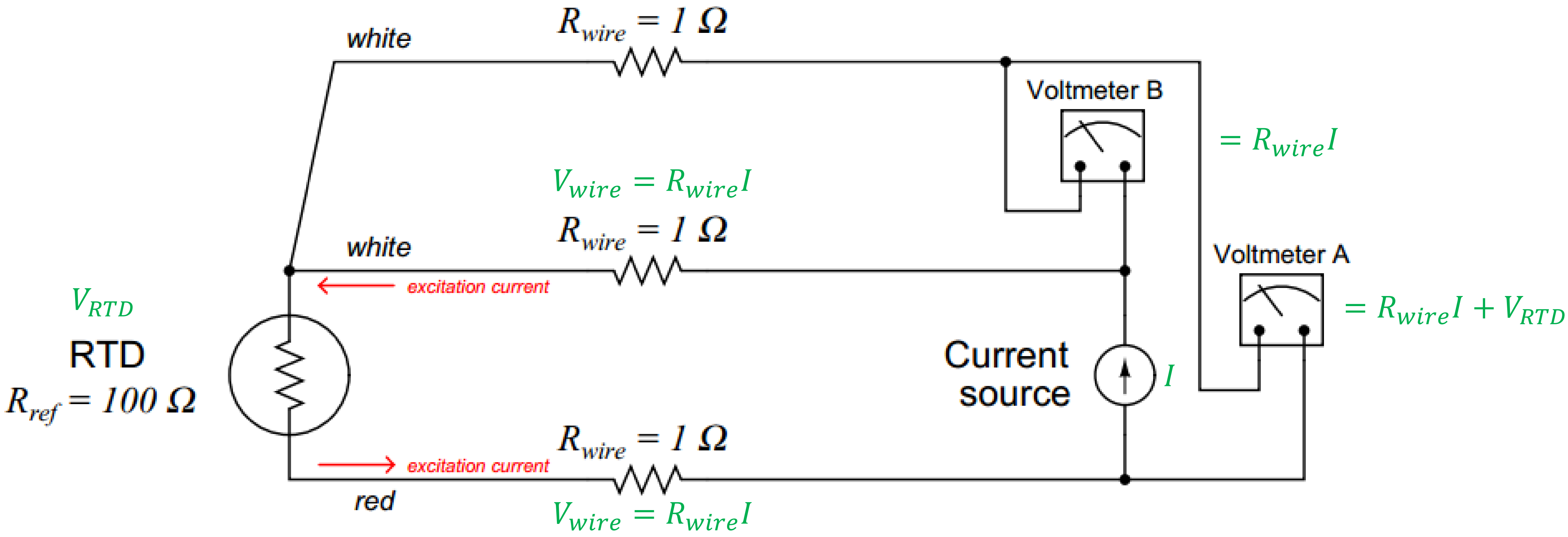

$R_{wire} = 1\ \Omega$
Ohmmeter
Thermistor
$R_{ref} = 50k\ \Omega$
$R_{wire} = 1\ \Omega$
$R_{total} = 50{,}002\ \Omega$


$R_{wire} = 1\ \Omega$
Ohmmeter
white
RTD
$R_{ref} = 100\ \Omega$
$R_{wire} = 1\ \Omega$
$R_{total} = 102\ \Omega$
red

Four Wire RTD



Three Wire RTD



$$V_{RTD} = V_{\mathrm{meter(A)}} - V_{\mathrm{meter(B)}}$$

Self Heating Problem

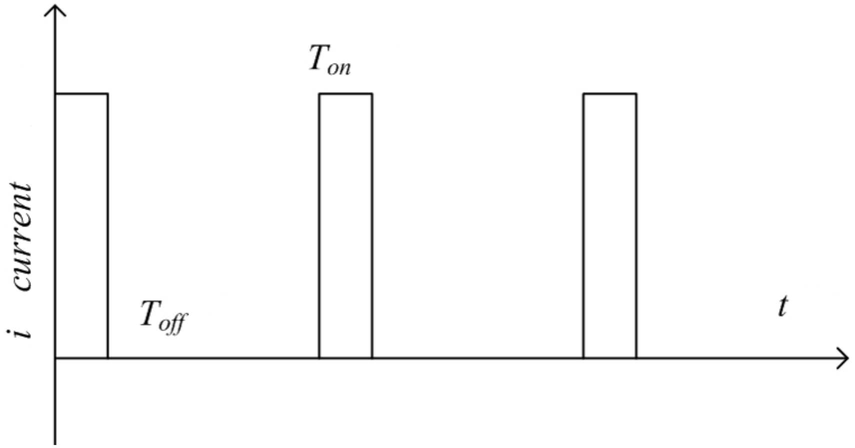
- When a current flows through a thermistor or a RTD, it generates heat, which raises the temperature of the thermistor or RTD above that of their environment.

$$P_E = RI^2$$

- This electrical heating may introduce a significant error if a correction is not made

- The effect may be minimized by limiting excitation current to a bare minimum, but this results in less voltage dropped across the device.

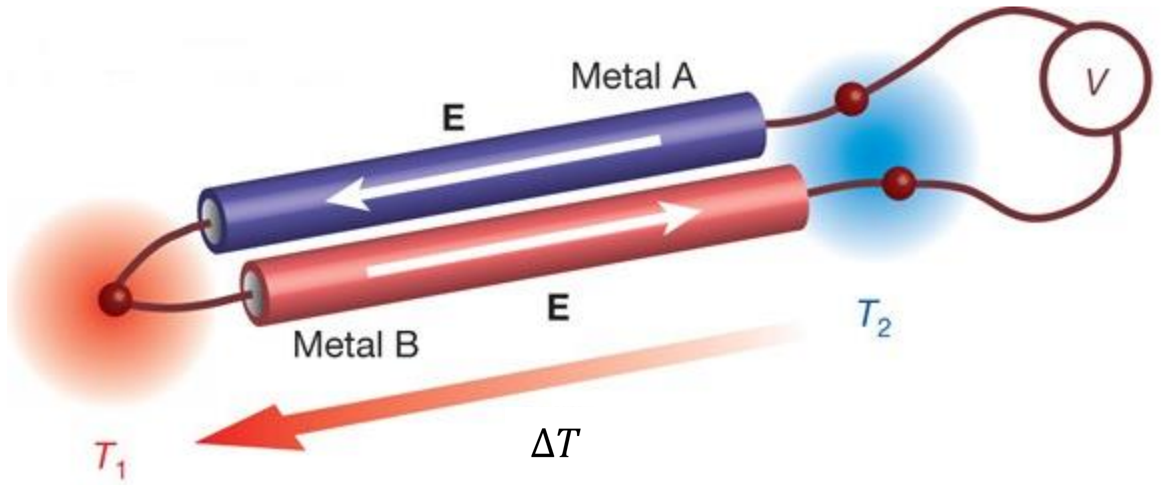
- One clever way to circumvent the self-heating problem without diminishing excitation current to the point of uselessness is to *pulse current* through the resistive sensor and digitally sample the voltage only during those brief time periods while the thermistor or RTD is powered.

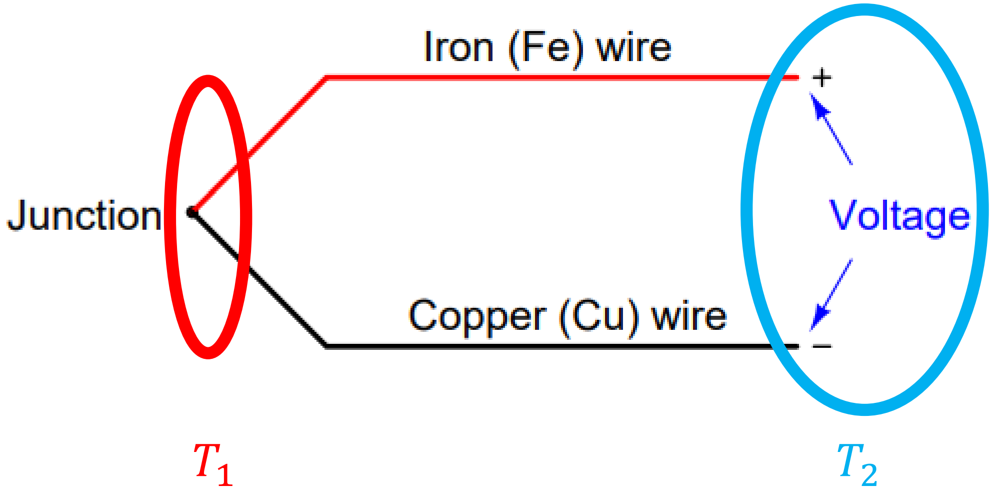


- This technique works well when we are able to tolerate slow sample rates from our temperature instrument, which is often the case because most temperature measurement applications are slow-changing by nature.

Thermocouple

Seebeck Effect

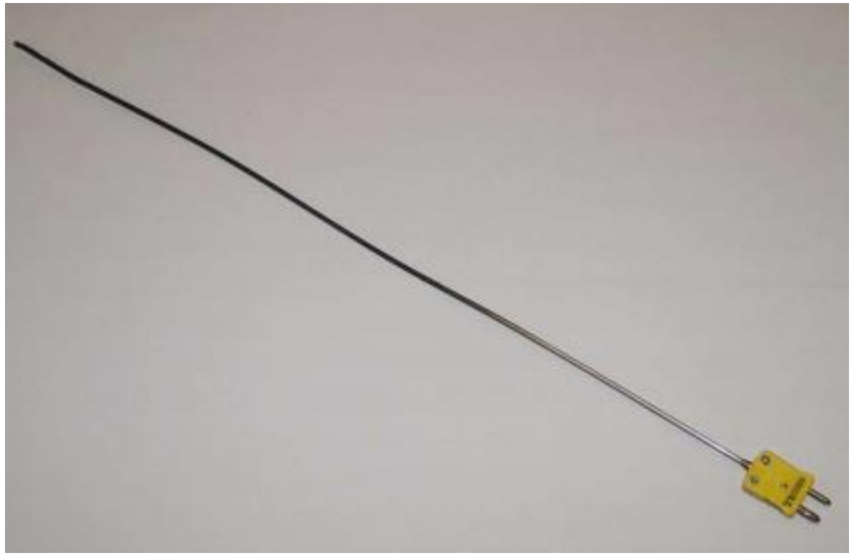




$$V \propto \Delta T$$

$$V = \alpha(T_1 - T_2) = \alpha\Delta T$$

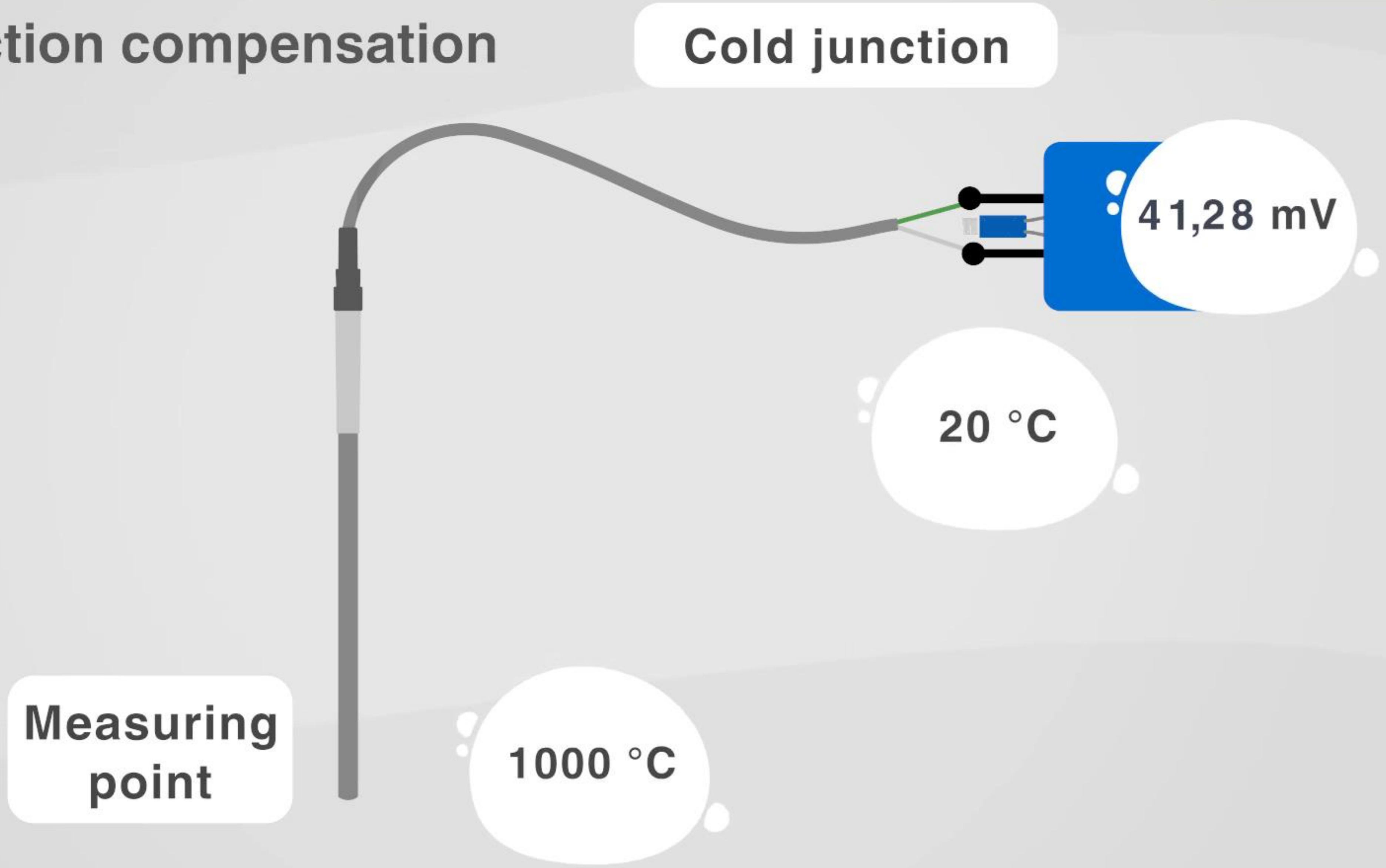
Thermocouple



All Type of Thermocouples

ANSI/ASTM	Symbol Single	Generic Names	Color Coding	
			Individual Conductor	Overall Jacket Extension Grade Wire
T	TP TN	Copper Constantan, Nominal Composition: 55% Cu, 45% Ni	Blue Red	Blue
J	JP JN	Iron Constantan, Nominal Composition: 55% Cu, 45% Ni	White Red	Black
E	EP EN	Chromel®, Nominal Composition: 90% Ni, 10% Cr Constantan, Nominal Composition: 55% Cu, 45% Ni	Purple Red	Purple
K	KP KN	Chromel, Nominal Composition: 90% Ni, 10% Cr Alumel®, Nominal Composition: 95% Ni, 2% Mn, 2% Al	Yellow Red	Yellow
N	NP NN	Nicrosil®, Nominal Compositions: 84.6% Ni, 14.2% Cr, 1.4% Si Nisil®, Nominal Composition: 95.5% Ni, 4.4% Si, 1% Mg	Orange Red	Orange
S	SP SN	Platinum 10% Rhodium Pure Platinum	Black Red	Green
R	RP RN	Platinum 13% Rhodium Pure Platinum	Black Red	Green
B	BP BN	Platinum 30% Rhodium Platinum 6% Rhodium	Gray Red	Gray
C*	P N	Tungsten 5% Rhenium Tungsten 26% Rhenium	Green Red	Red

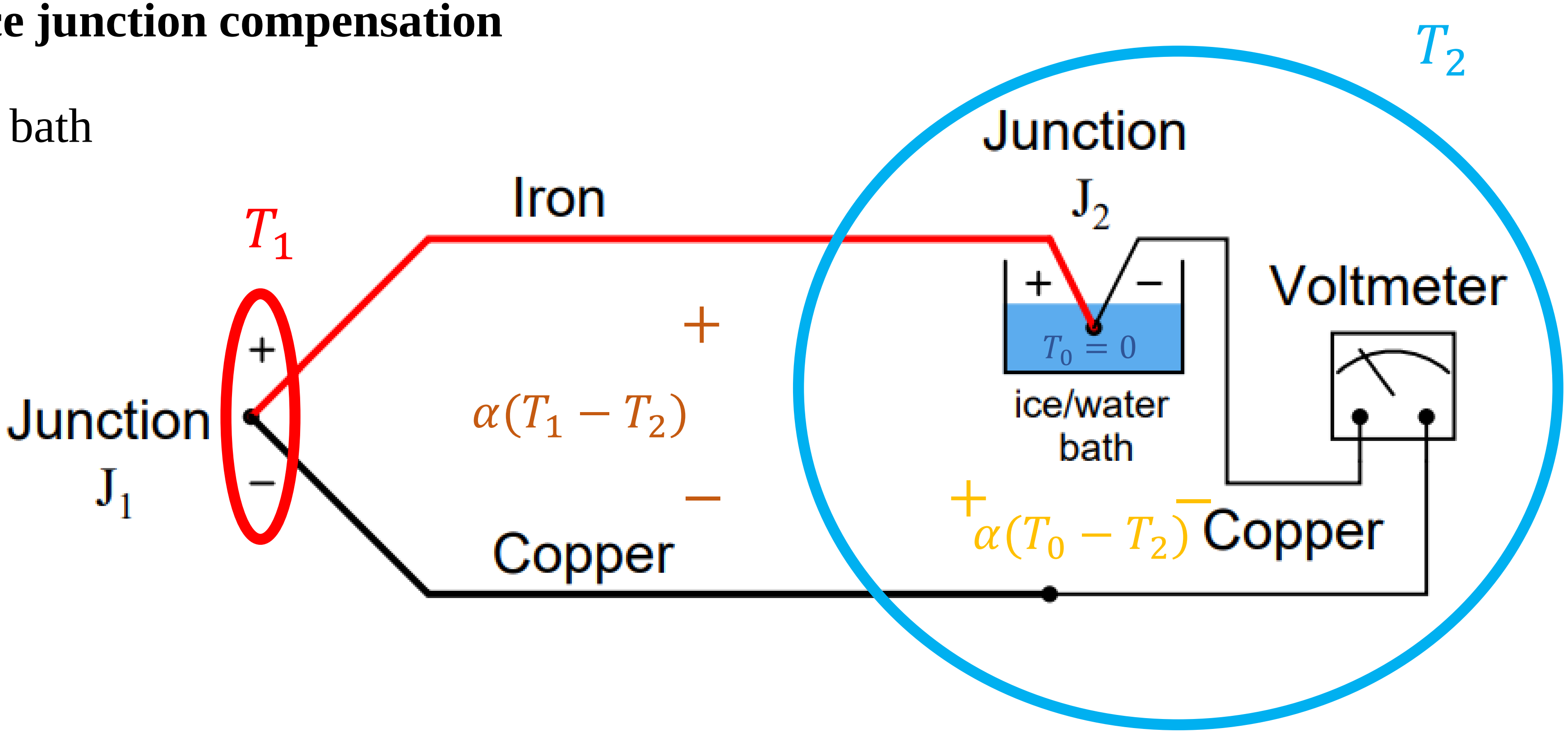
Cold junction compensation



Thermocouple

Reference junction compensation

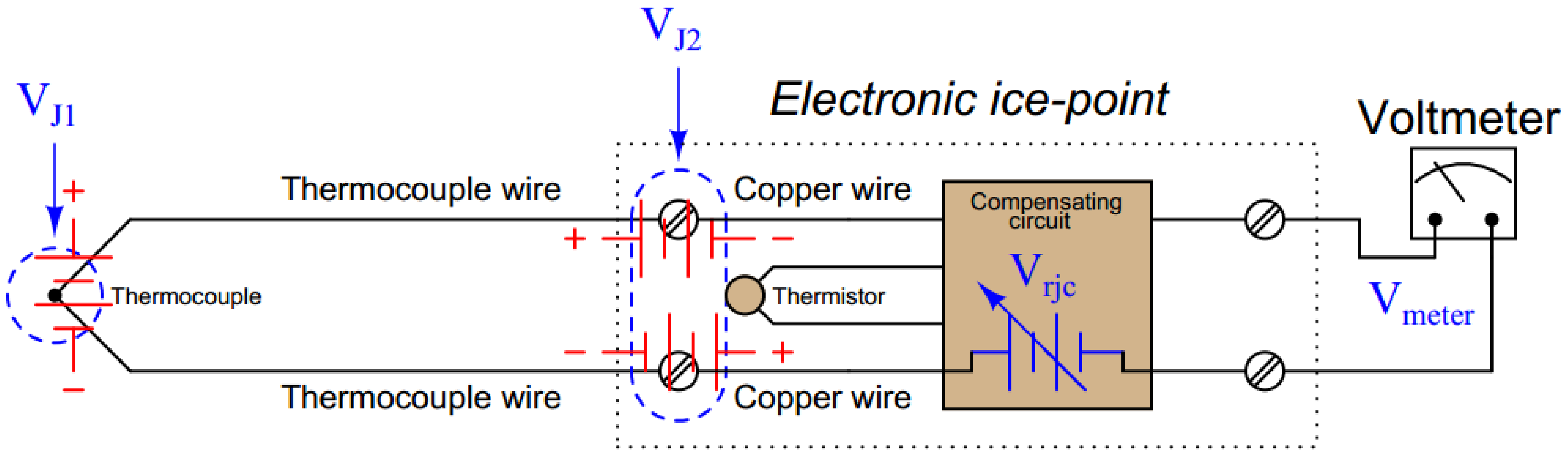
Ice/water bath

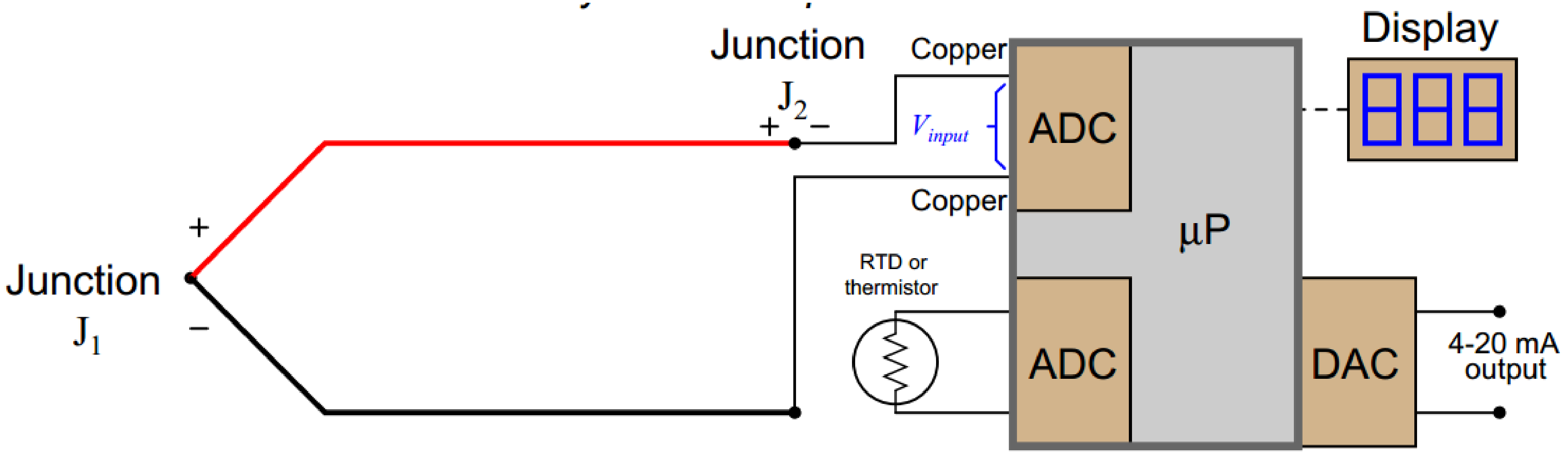


$$V_{Voltmeter} = \alpha(T_1 - T_2) - \alpha(T_0 - T_2) = \alpha(T_1 - T_0) = \alpha T_1$$

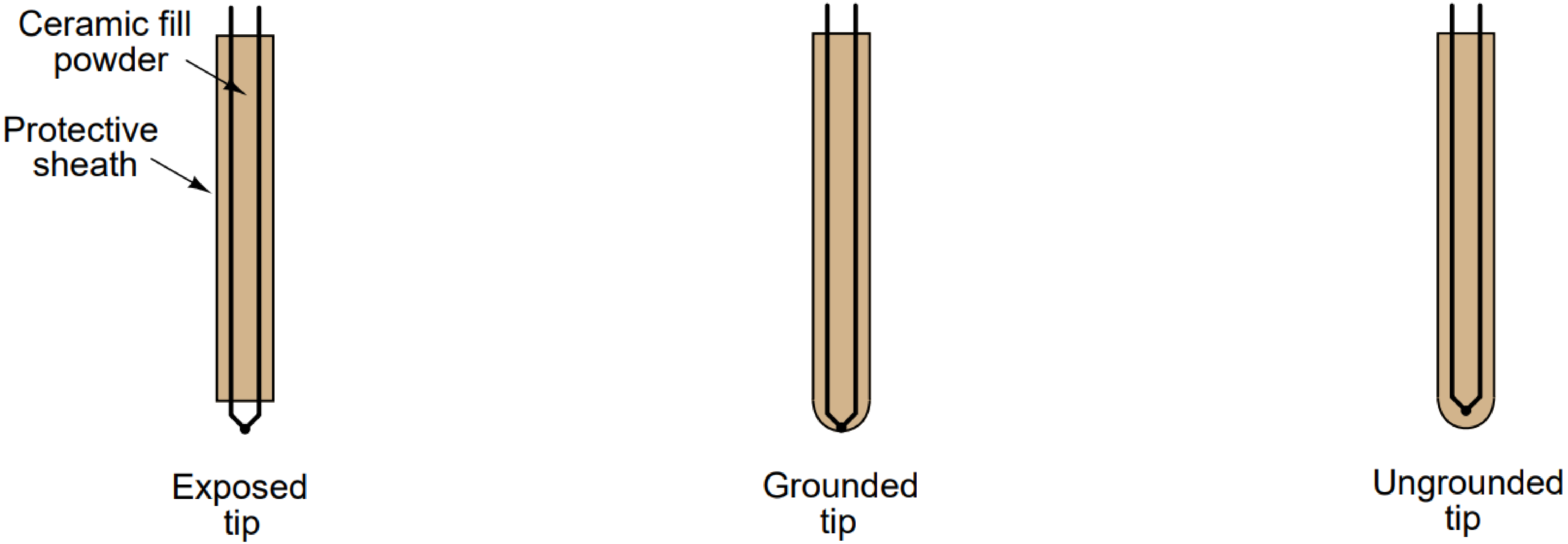
Thermocouple

Reference junction compensation





Thermocouple

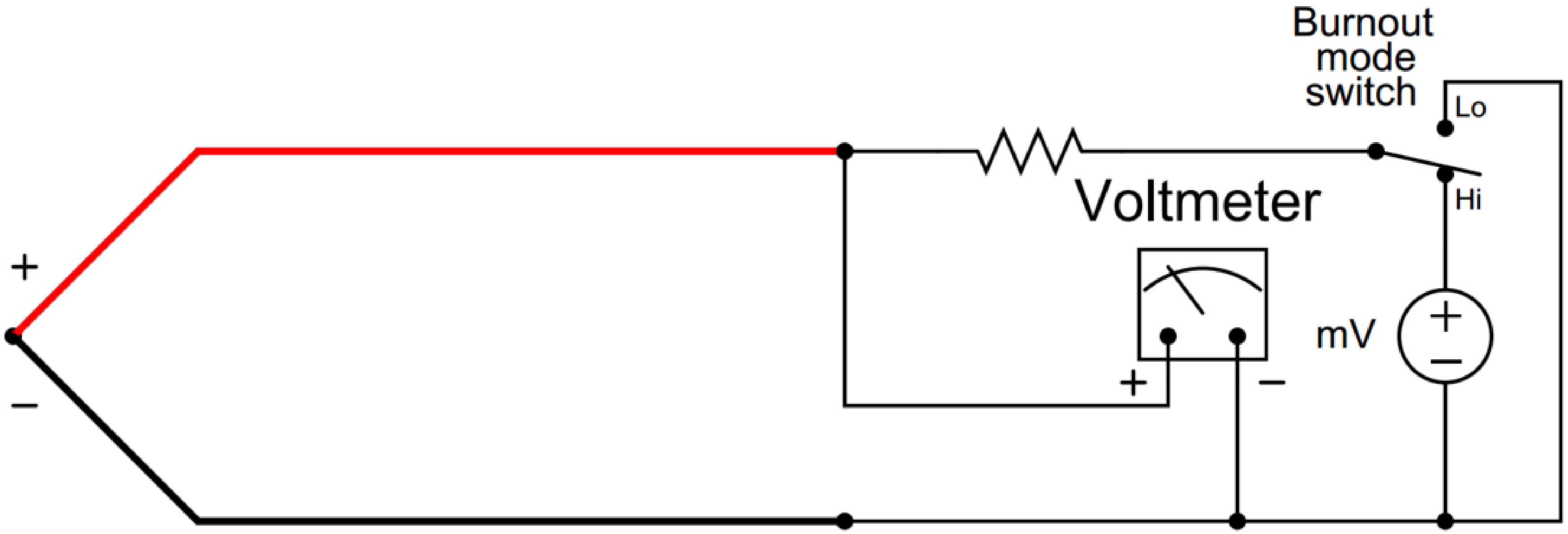


- Maximum sensitivity
- Fastest response time
- More fragile

- Fast response times
- Great sensitivity
- Vulnerable to ground loops

Burnout detection

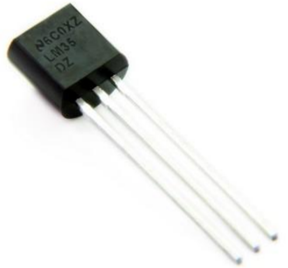
- The most common failure mode for thermocouples is to fail open, otherwise known as "**burning out**".
- The resistor in this circuit provides a connection to a stable voltage in the event of an open thermocouple.
- It is sized in the mega-ohm range to minimize its effect during normal operation when the thermocouple circuit is complete.

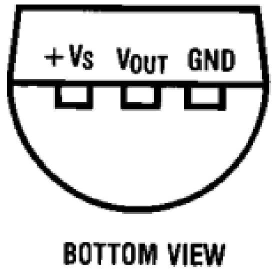


Semiconductor Temperature Sensors

LM35

- Calibrated directly in § Celsius (Centigrade)
- Linear a 10.0 mV/§C scale factor
- 0.5§C accuracy guaranteeable (at a25§C)
- Rated for full -55§ to a150§C range
- Operates from 4 to 30 volts
- Less than 60 mA current drain





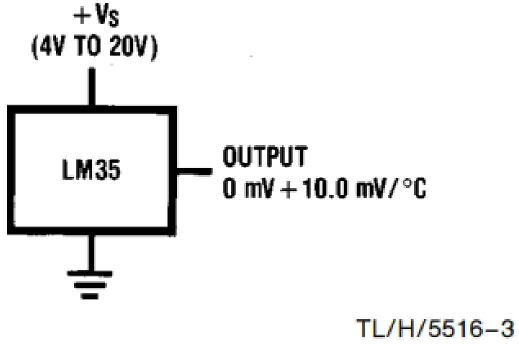
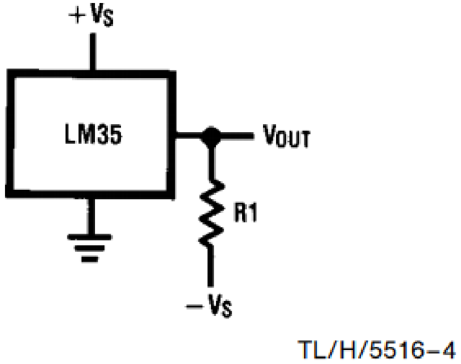


FIGURE 1. Basic Centigrade Temperature Sensor (+2°C to +150°C)



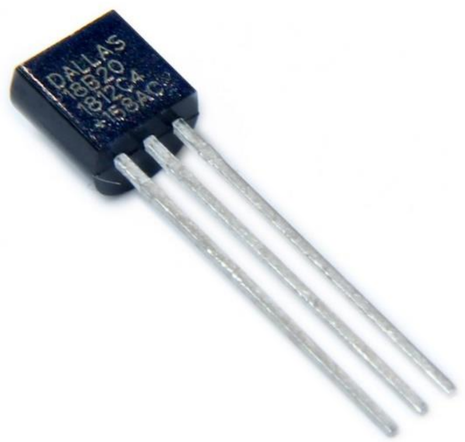
Choose $R_1 = -V_S/50\ \mu A$

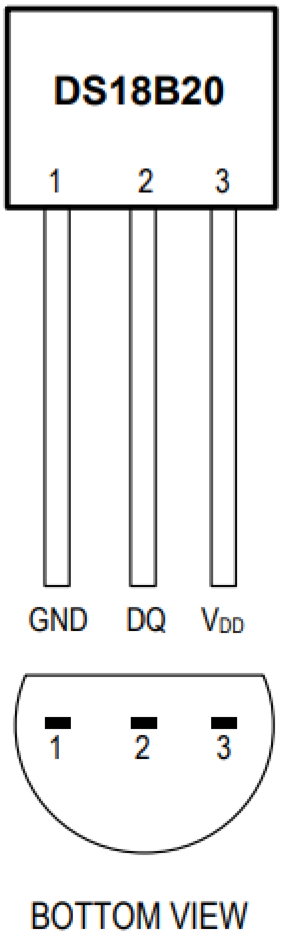
$V_{OUT} = +1{,}500$ mV at $+150°C$
$= +250$ mV at $+25°C$
$= -550$ mV at $-55°C$

FIGURE 2. Full-Range Centigrade Temperature Sensor

Semiconductor Temperature Sensors

DS18B20



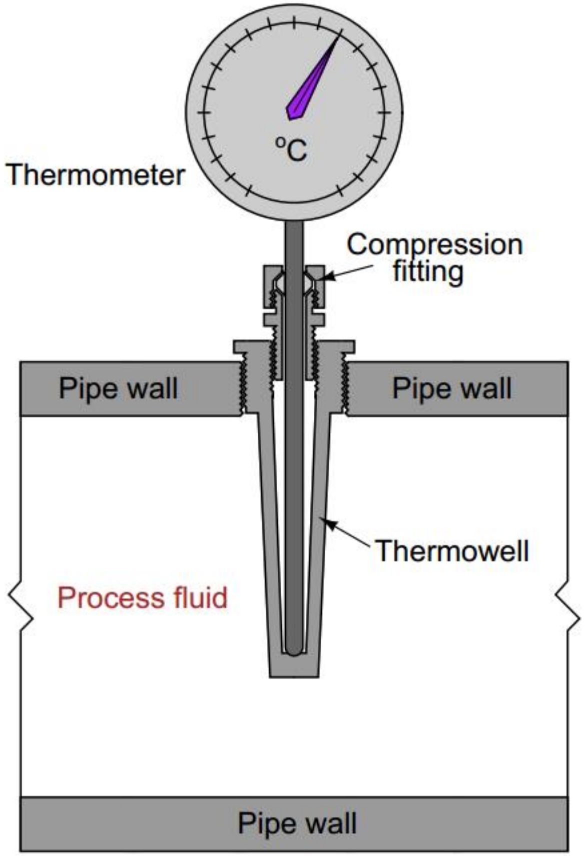


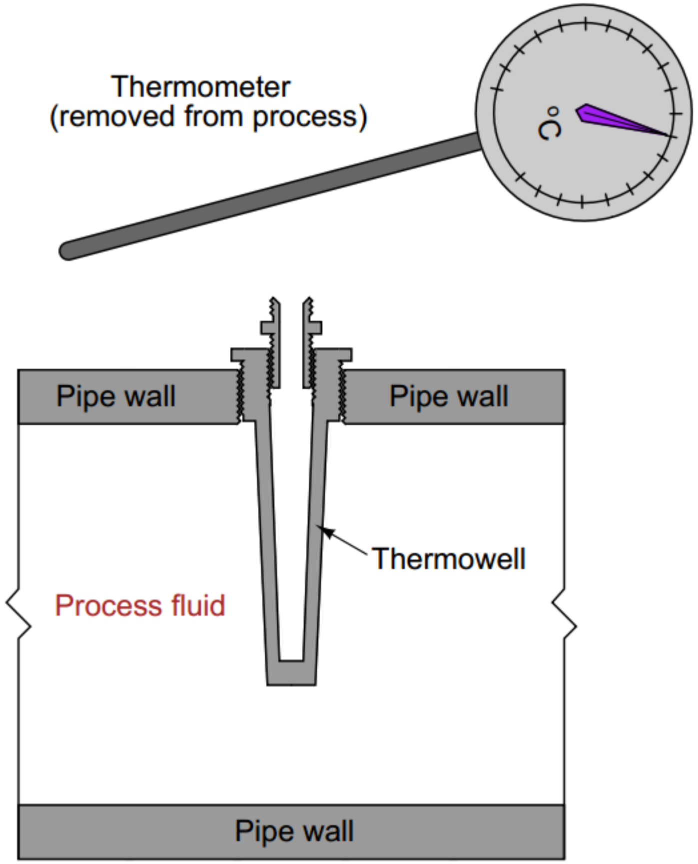
- Provides 9-bit to 12-bit Celsius temperature measurements
- Unique 1-Wire® Interface Requires Only One Port Pin for Communication
- Reduce Component Count with Integrated Temperature Sensor and EEPROM
- Measures Temperatures from -55°C to +125°C
- ±0.5°C Accuracy from -10°C to +85°C

Typical Temperature Sensor Characteristics

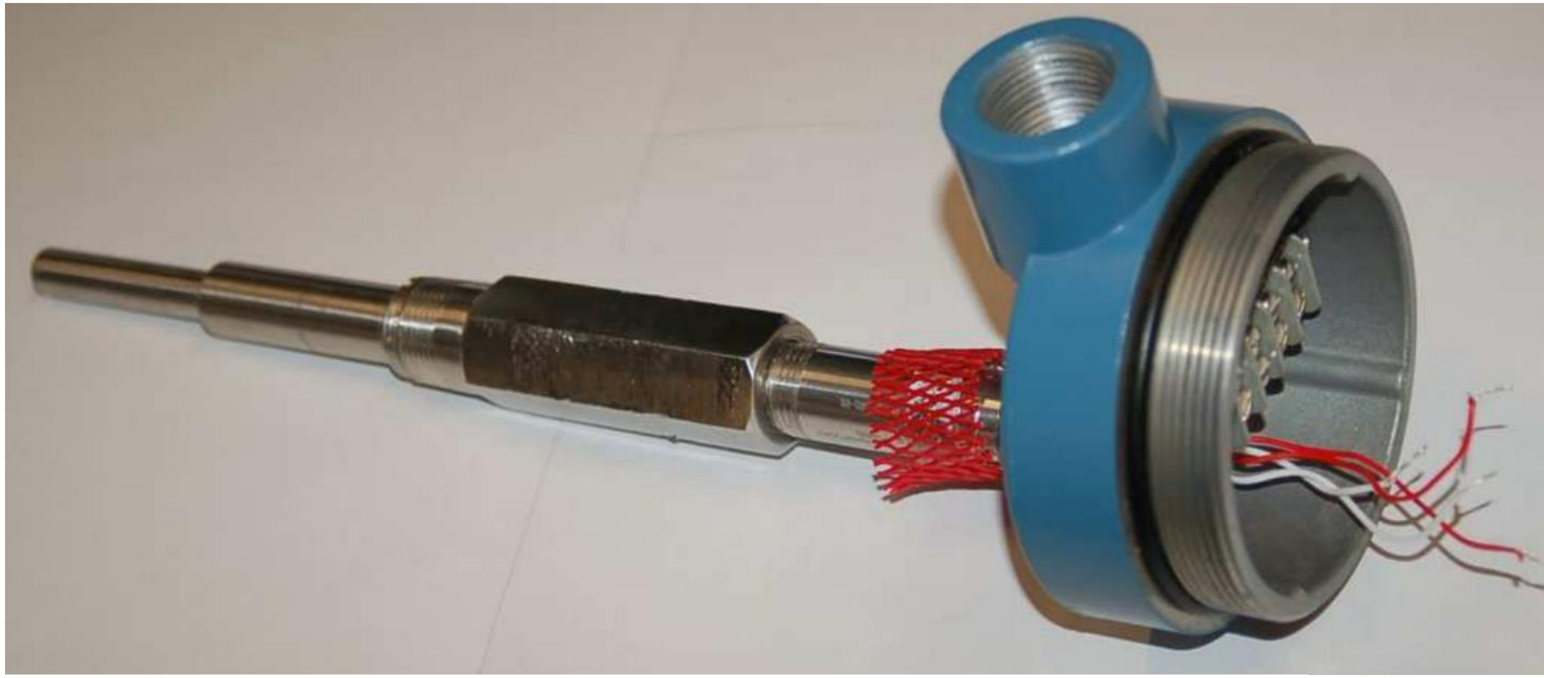
Typical Charac-teristics	Thermistors General Purpose	Resistance Temperature Devices (RTDs)	Thermocouples (TCs)	Semiconductor Temperature Sensors
Temperature Range	- 55°C to + 125°C	- 200°C to + 850°C	-600°C to +2000°C	-50°C to +150°C
Linearity	Exponential	Fairly linear	Fairly Linear	Best
Sensitivity	High	Low	Medium	Highest
Response Time	Fast	Slow	Fast to Slow (depends on construction)	Slow
Excitation or power	Needed	Needed	Not Needed	Needed
Long-Term Stability	Low	High	High	Medium
Self-heating	Yes	Yes	No	Yes
Cost	Low	Low (film) High (wire wound)	Moderate to High: (depends on construction)	Low to Moderate

Temperature Accessories





Temperature Accessories



تاخیر در انتقال گرما

اتلاف گرما

منبع گرما (سیال) → ترموول → فاصله هوایی بین ترموول و حسگر دما → حسگر دما

خازن گرمایی

مقاومت گرمایی

Temperature Transmitter

- A temperature transmitter is a device that connects to a temperature sensor to transmit the signal elsewhere for monitoring and control purposes. Typically, the temperature sensor is either an RTD, Thermistor or Thermocouple type sensor and will interface with a PLC, DCS, data logger or display hardware.

- The temperature transmitter's role is to isolate the temperature signal, *filter any EMC noise*, *amplify* and *convert the temperature sensor's signal to a 4-20mA or 0-10V DC range* for further use.

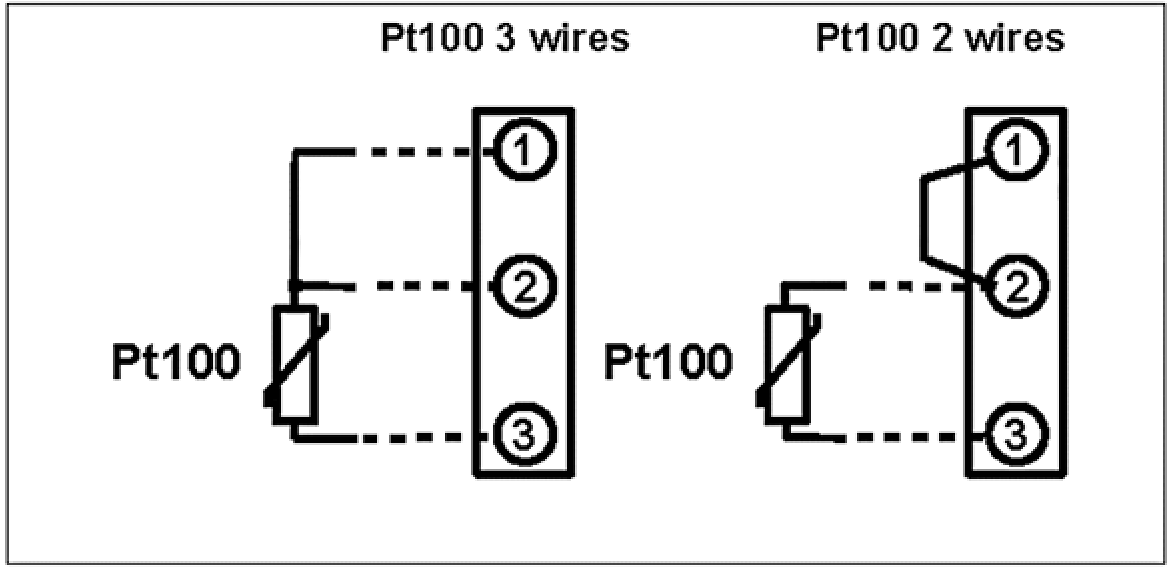
$$T \in [T_{min}, T_{max}] \longrightarrow \begin{matrix} I \in [4\,, 20]\; mA \\ V \in [0\,, 10] V \end{matrix}$$

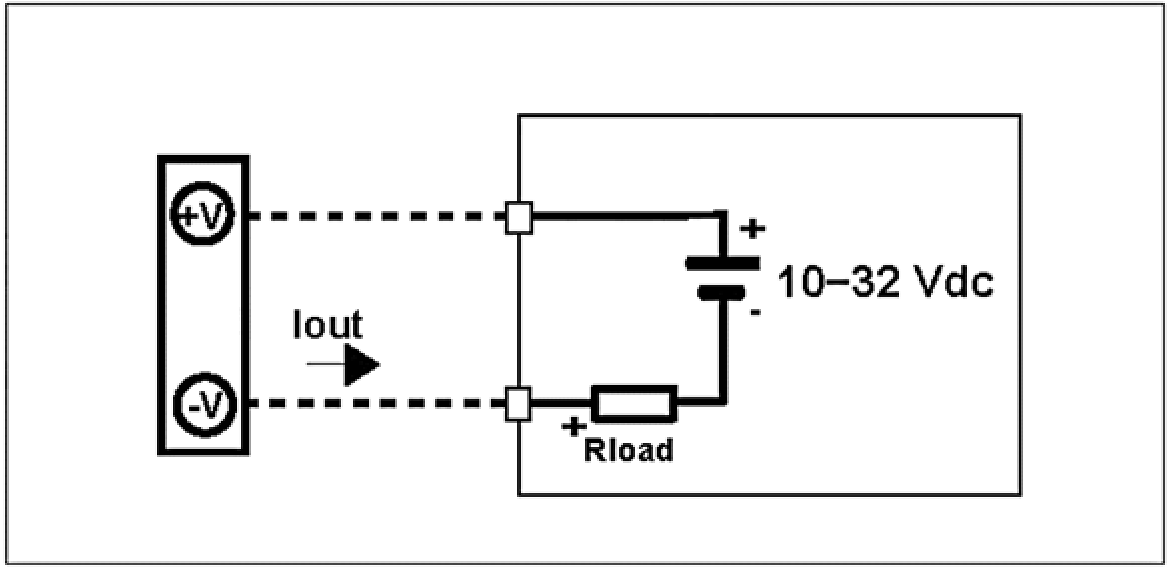
$$R \in [R_{min}, R_{max}]\Omega$$

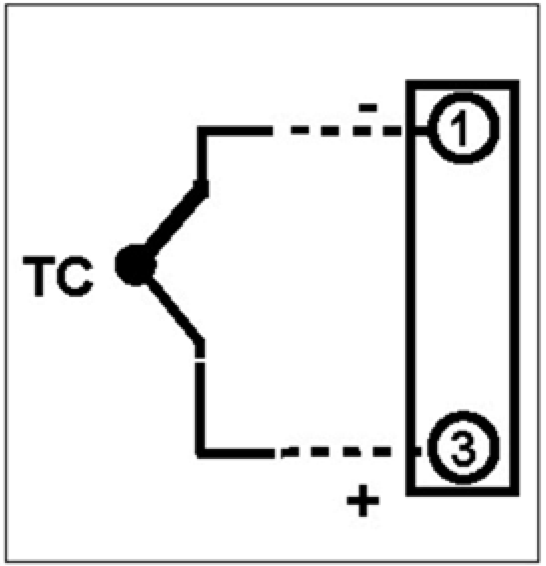
$$V \in [V_{min}, V_{max}] mV$$

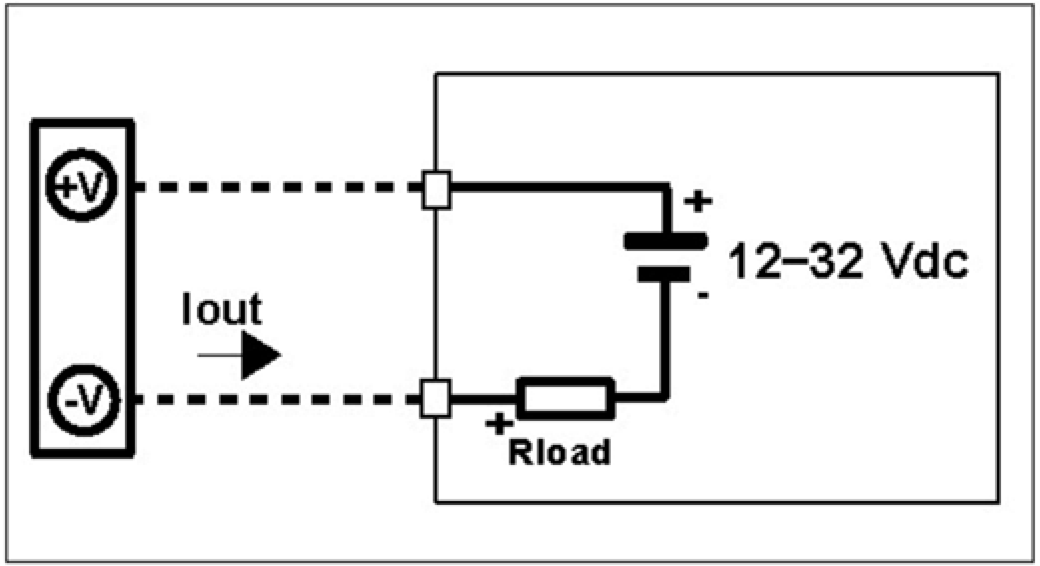
Analog Transmitter

Analog Transmitter

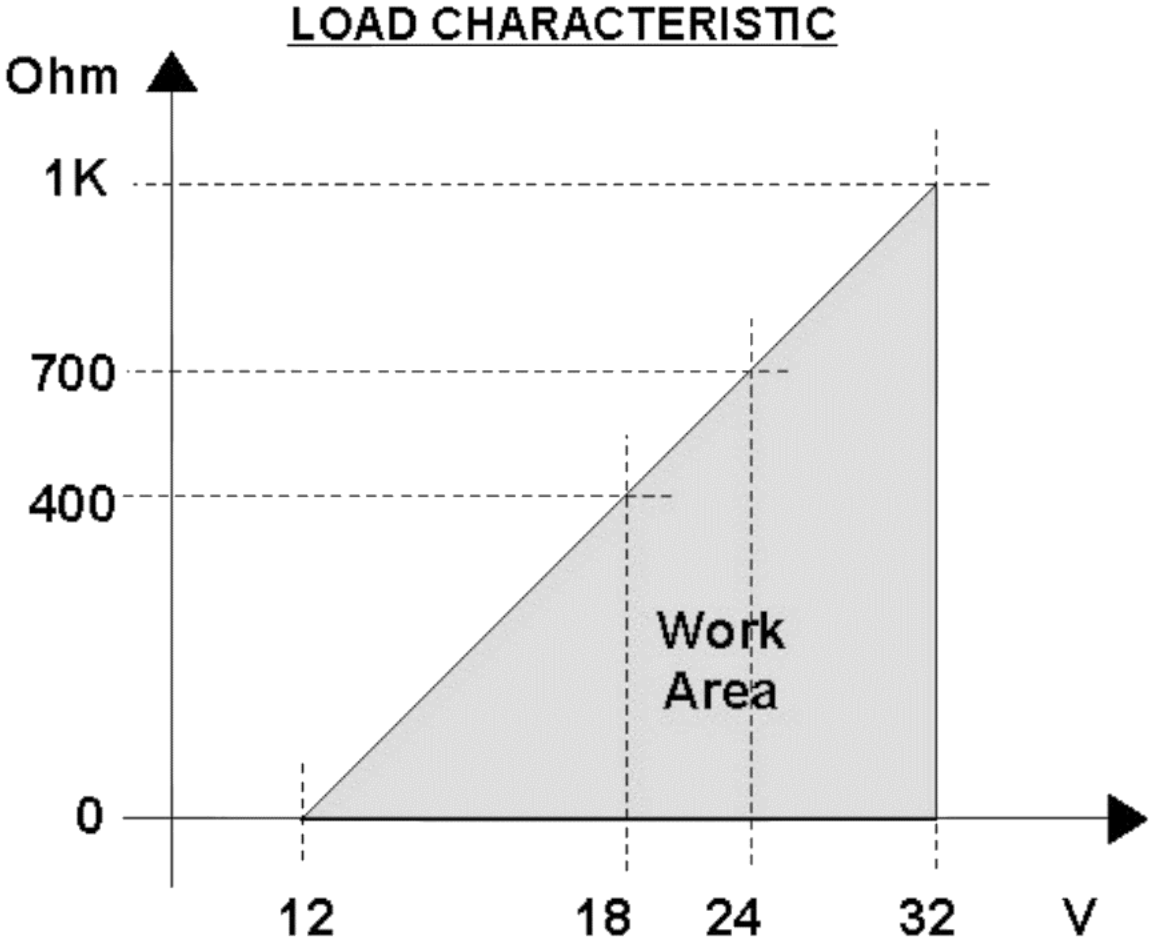








Analog Transmitter



Analog Transmitter Calibration

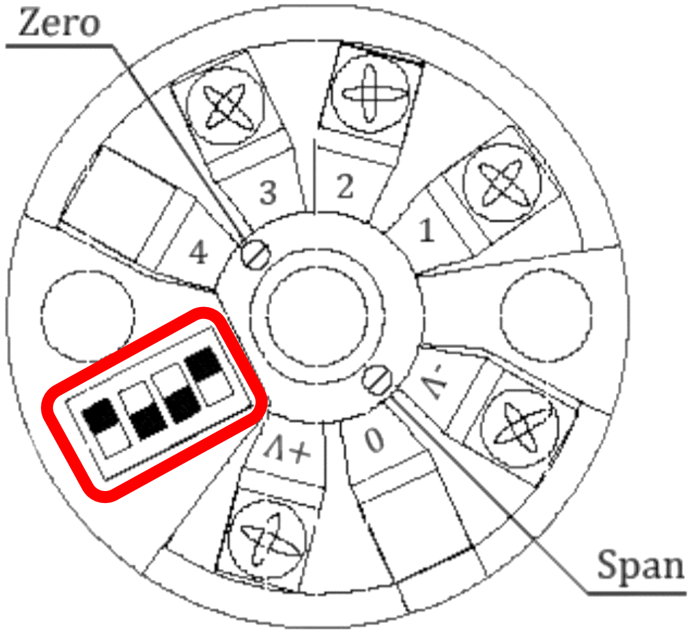
$$T \in [T_{min}, T_{max}]$$
$$or$$
$$R \in [R_{min}, R_{max}]$$

$$I \in [4mA, 20mA]$$

$T \in [20,250]$°C

ZERO   *ZERO + SPAN*

INPUT		SWITCH			
SPAN	ZERO	1	2	3	4
< 80°C (176°F)	- 50 – -15°C(-58–5°F)			●	
< 80°C (176°F)	- 15 – 15°C(5–59°F)	●		●	
< 80°C (176°F)	15 – 50°C(59–122 °F)	●	●	●	
80–200°C(176–392°F)	- 50 – -15°C(-58–5°F)			●	●
80–200°C(176–392°F)	- 15– 15°C(5–59°F)	●		●	●
80–200°C(176–392°F)	15 – 50°C(59–122 °F)	●	●	●	●
200–250°C(392–482°F)	- 50–50°C(-58–122°F)				
250–650°C(482–1202°F)	- 50–50°C(-58–122°F)				●



Analog Transmitter Calibration

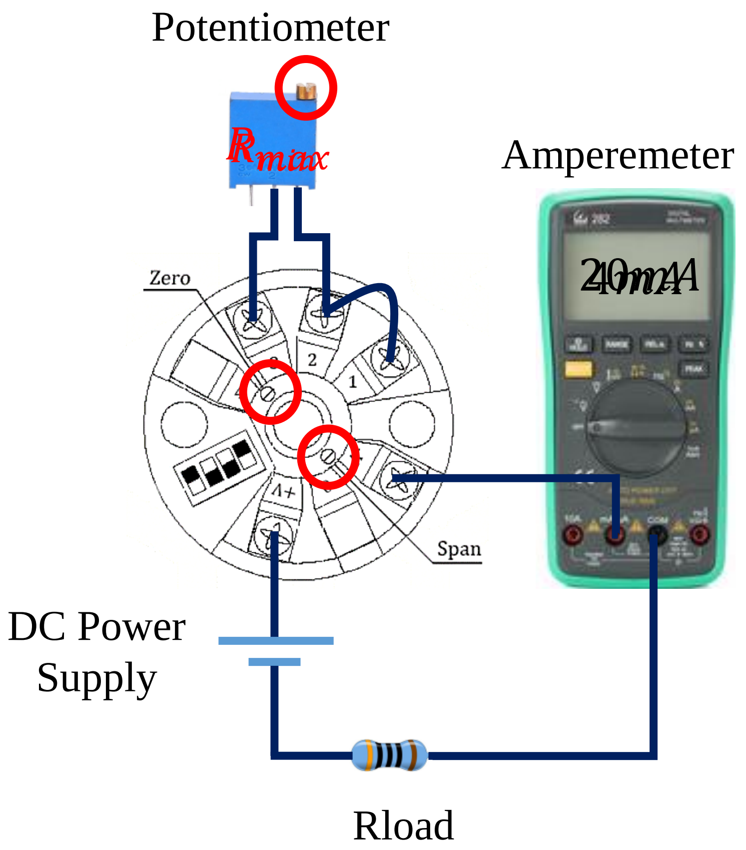
$$T \in [T_{min}, T_{max}] \longrightarrow I \in [4mA, 20mA]$$

Step1: Rotate the potentiometer screw so that the value of resistance is equal R_{min} correspond to T_{min}.

Step2: Rotate *Zero* screw so that the value of Amperemeter is equal $4mA$.

Step3: Rotate the potentiometer screw so that the value of resistance is equal R_{max} correspond to T_{max}.

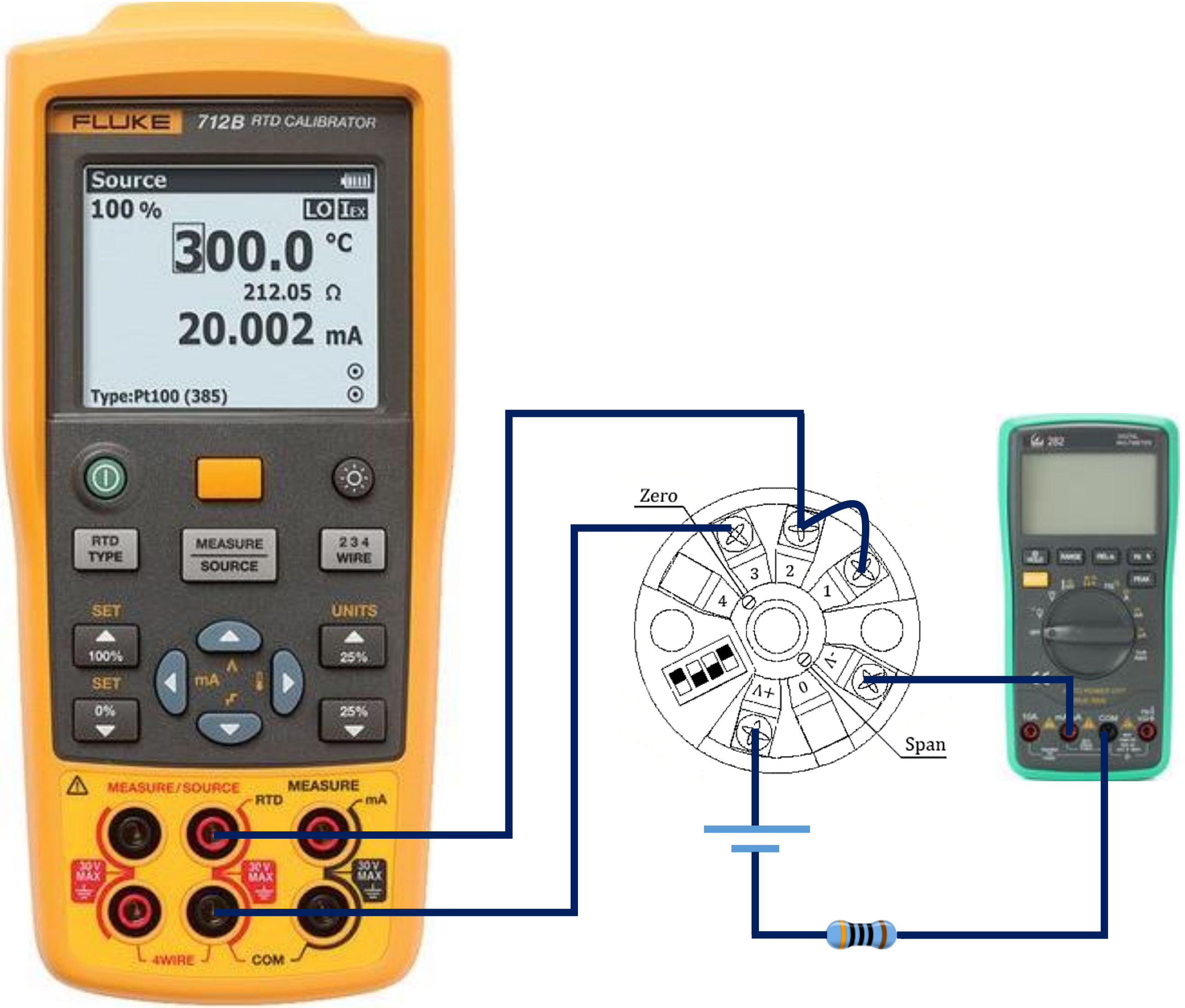
Step4: Rotate *Span* screw so that the value of Amperemeter is equal $20mA$.



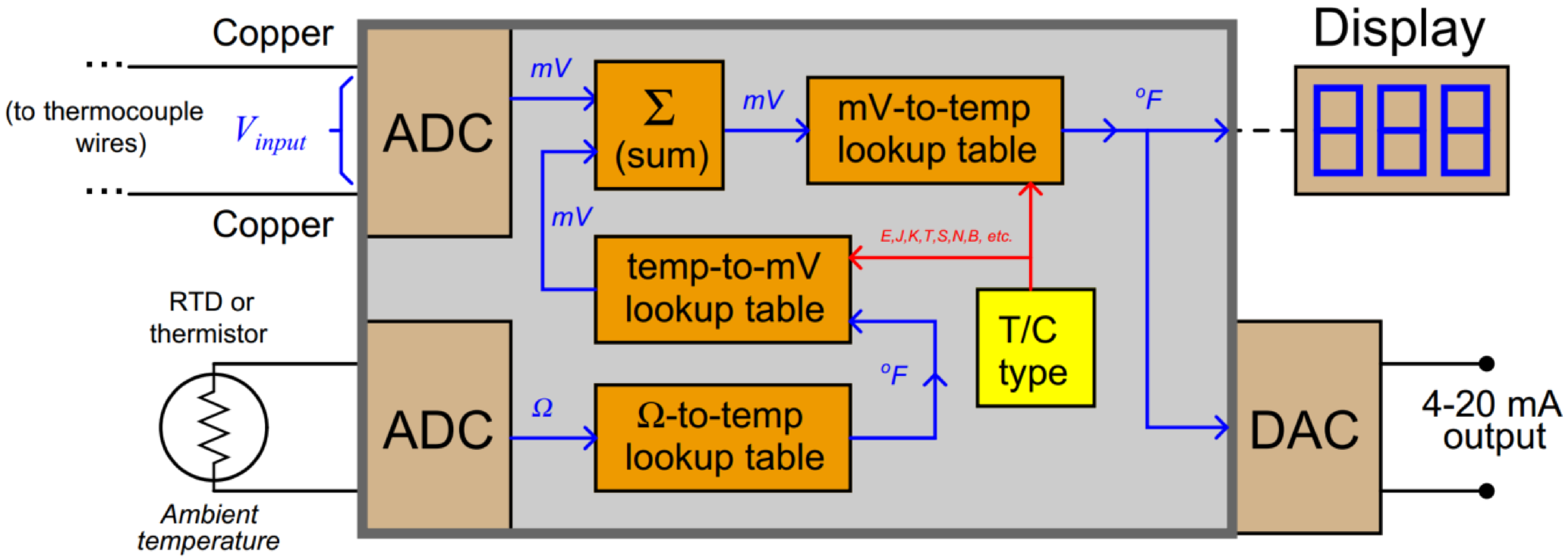
The internal circuits of *Zero* screw and *Span* screw are interconnected. So repeat steps 1 to 4 several times.

Analog Transmitter Calibration

A **temperature calibrator** is a device that can measure and/or simulate **temperature** sensor signals, not containing any heat course. These sensor signals are typically resistance (for RTD sensors) or voltage (for thermocouples).



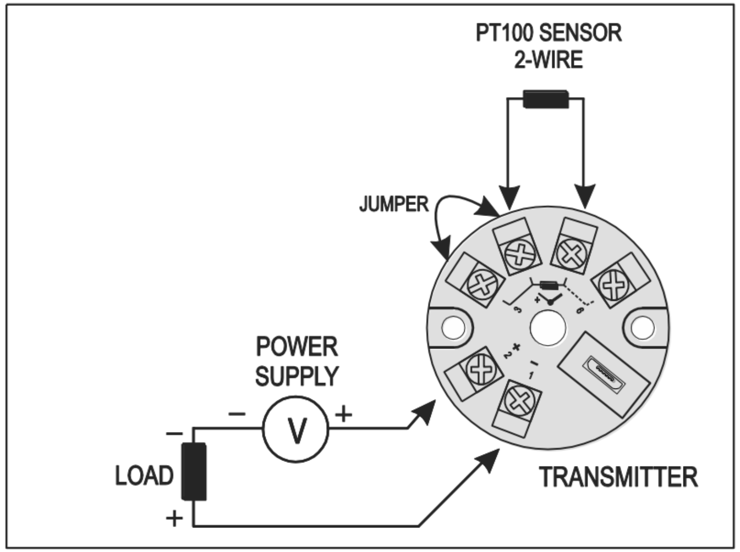
Digital Transmitter

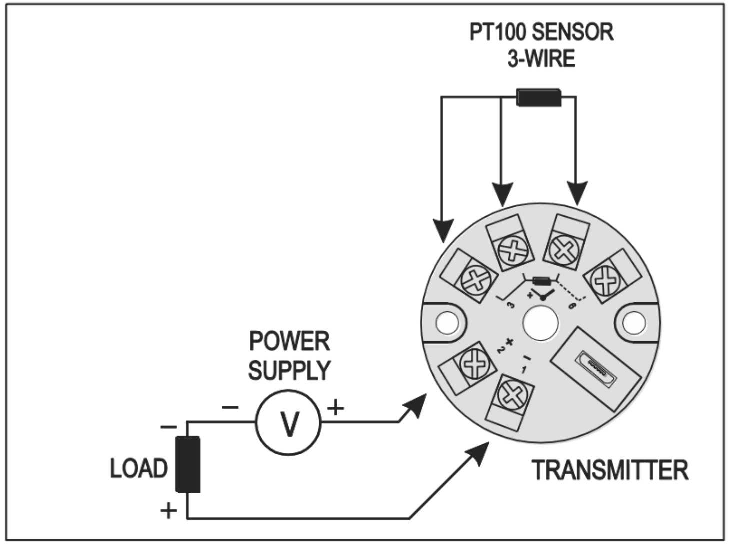


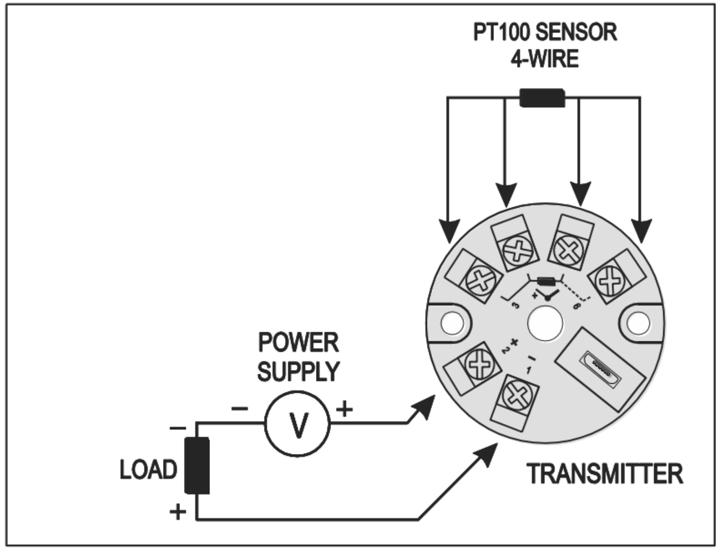
Digital Transmitter

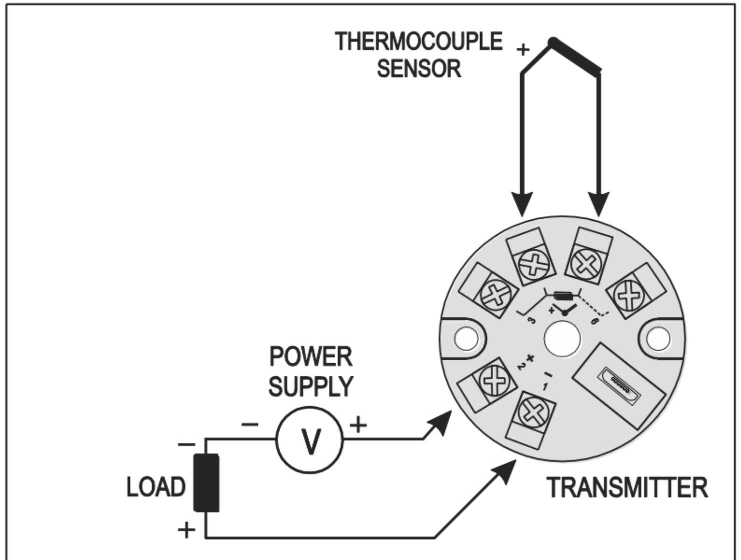
Sensor Type	Maximum Measurement Range	Minimum Measurement Range
Voltage	0 to 50 mV	5 mV
Thermocouple K	-150 to 1370 °C	100 °C
Thermocouple J	-100 to 760 °C	100 °C
Thermocouple R	-50 to 1760 °C	400 °C
Thermocouple S	-50 to 1760 °C	400 °C
Thermocouple T	-160 to 400 °C	100 °C
Thermocouple N	-270 to 1300 °C	100 °C
Thermocouple E	-90 to 720 °C	100 °C
Thermocouple B	500 to 1820 °C	400 °C
Pt100	-200 to 650 °C	40 °C
Pt1000	-200 to 650 °C	40 °C
NTC	-30 to 120°C	40 °C

Digital Transmitter





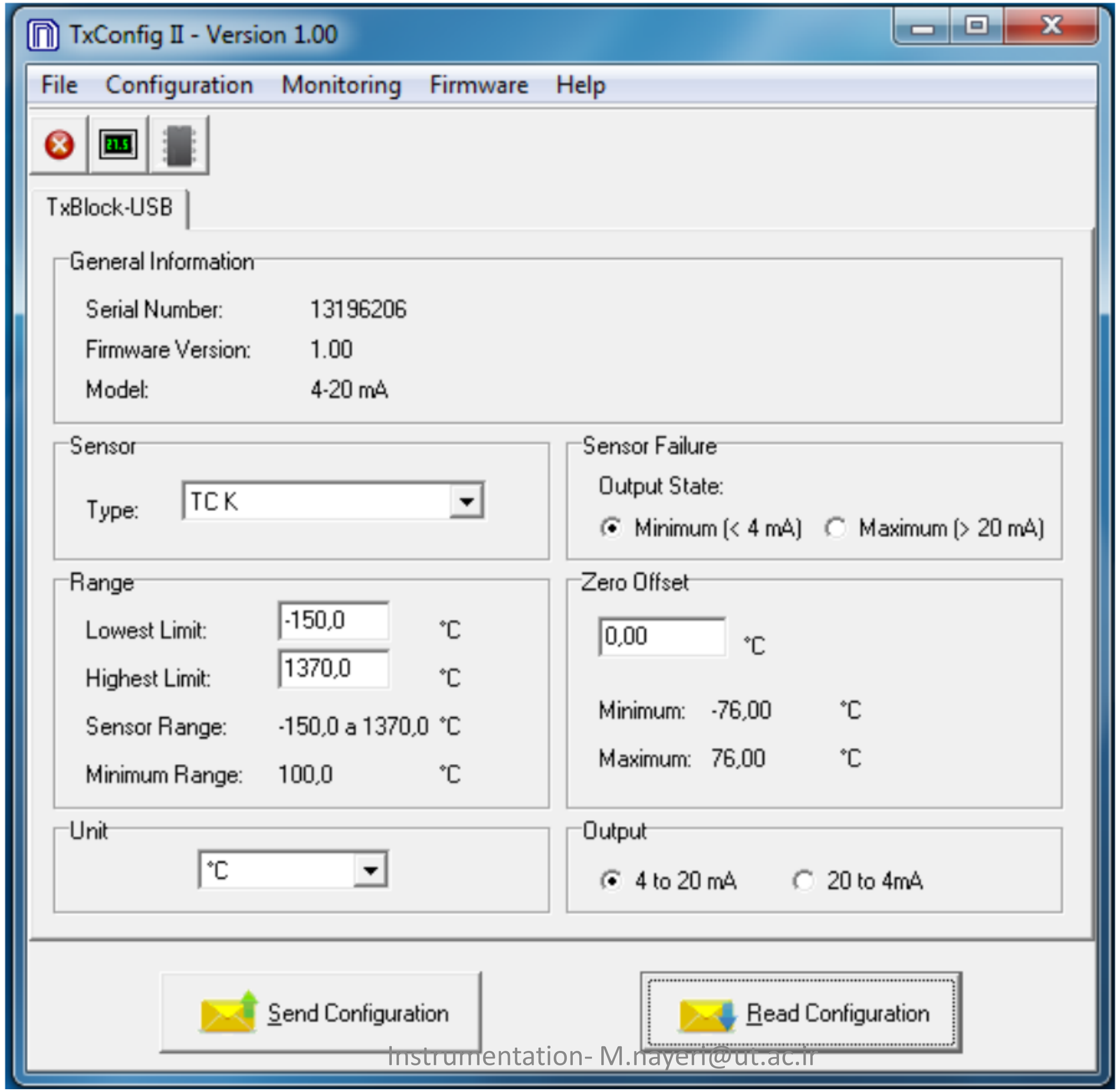




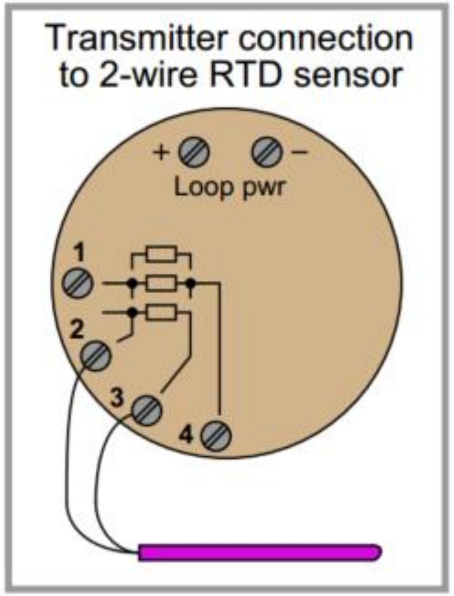
Power supply: 10 to 35 Vdc, across the transmitter;

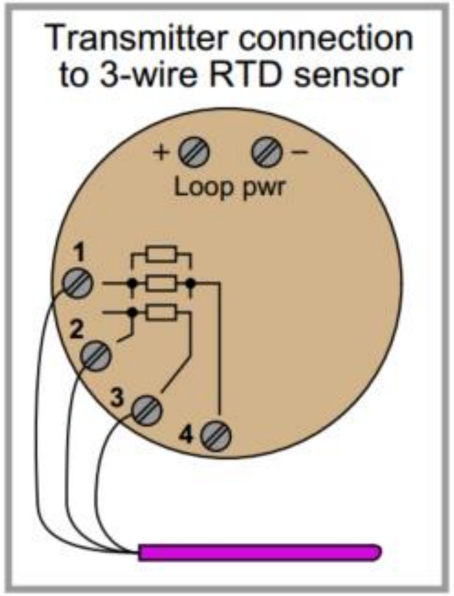
Maximum load (RL): RL (max.) = (Vdc – 10) / 0.02 [Ω]
Where: Vdc= Power supply voltage (10-35 Vdc)

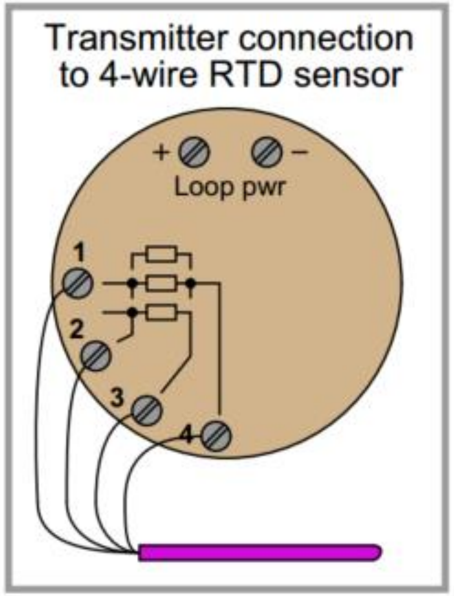
Digital Transmitter



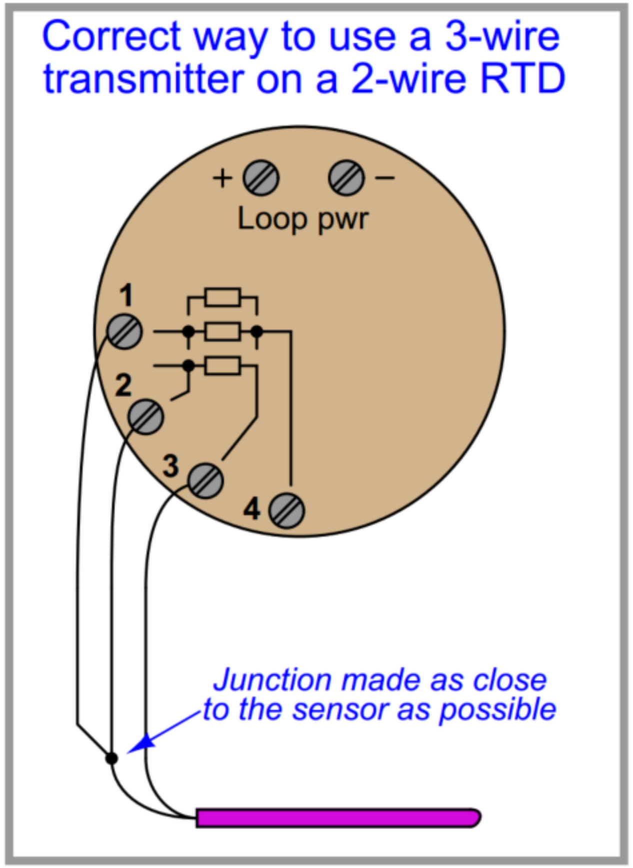
Transmitter

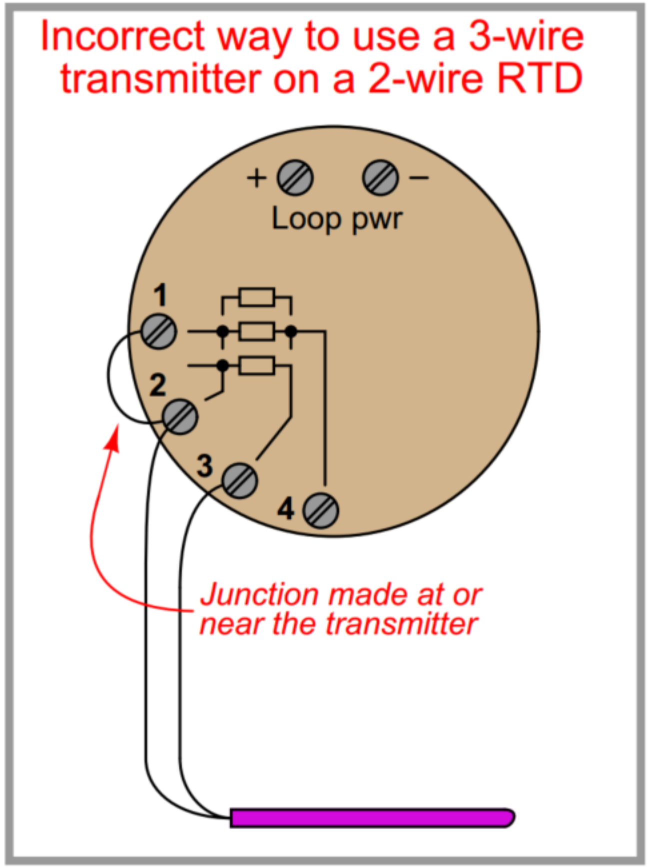




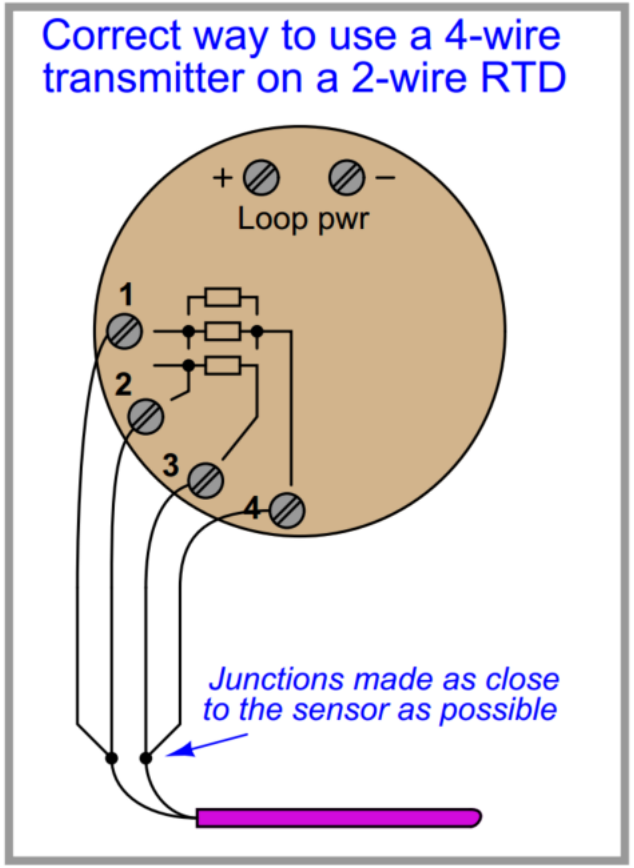


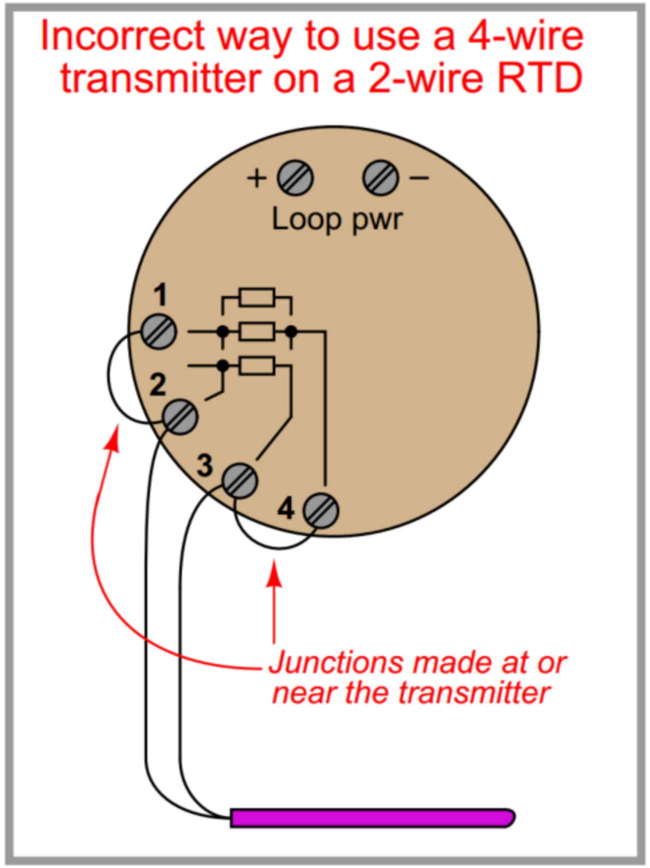
Transmitter



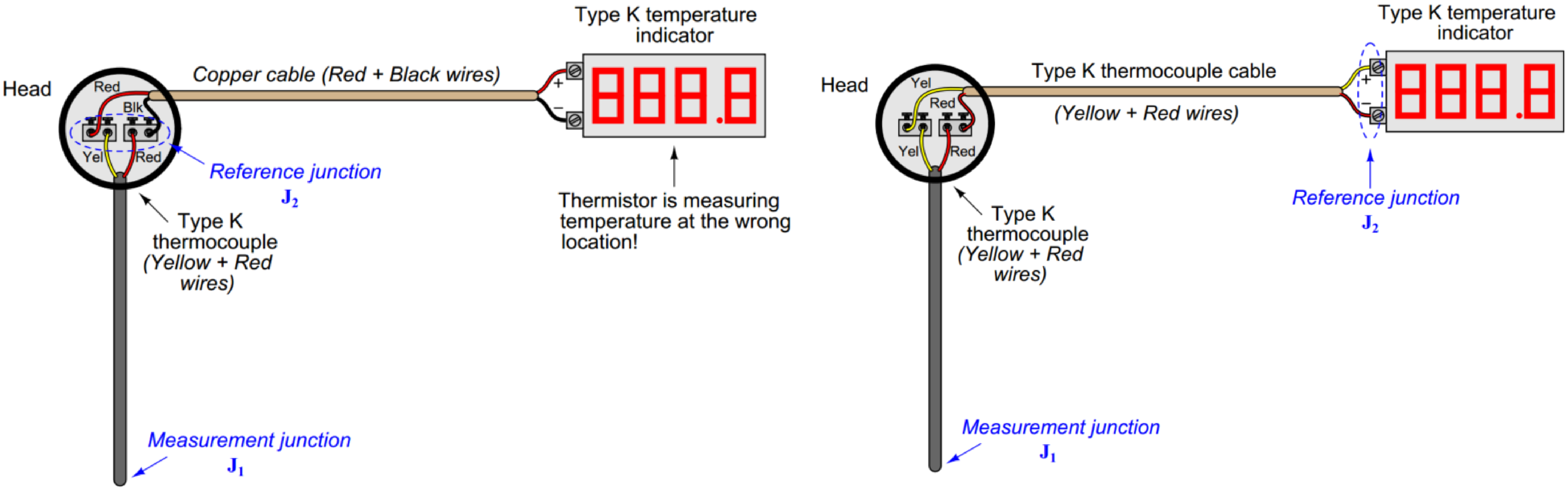


Transmitter





Transmitter



Non-contact Temperature Sensors

- Virtually any mass above absolute zero temperature emits electromagnetic radiation (photons, or light) as a function of that temperature.

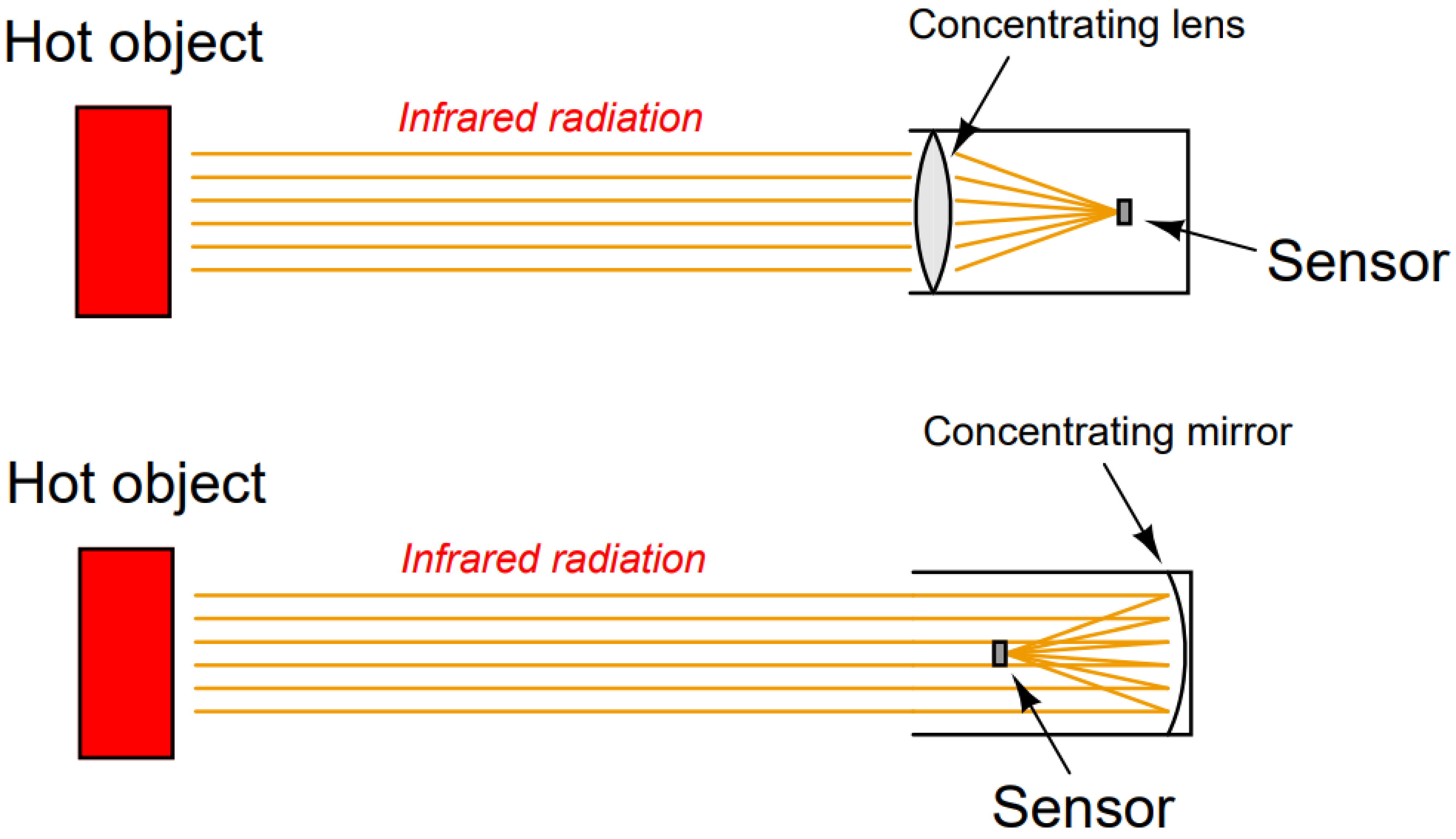
- This basic fact makes possible the measurement of temperature by analyzing the light emitted by an object.

- The Stefan-Boltzmann Law of radiated energy quantifies this fact:

$$\frac{dQ}{dt} = e\sigma A T^4$$

$$\frac{dQ}{dt} = \text{ } Radiant\ heat\ loss\ rate\ (watts)$$
$$e \ = \ Emissivity\ factor\ (unitless)$$
$$\sigma = \ Stefan - Boltzmann\ constant\ (5.67 \ \times \ 10^{-8} \frac{W}{m^2 \times {}^\circ K^4})$$
$$A \ = \ Surface\ area\ (square\ meters)$$
$$T \ = \ Absolute\ temperature\ (Kelvin)$$

Non-contact Temperature Sensors

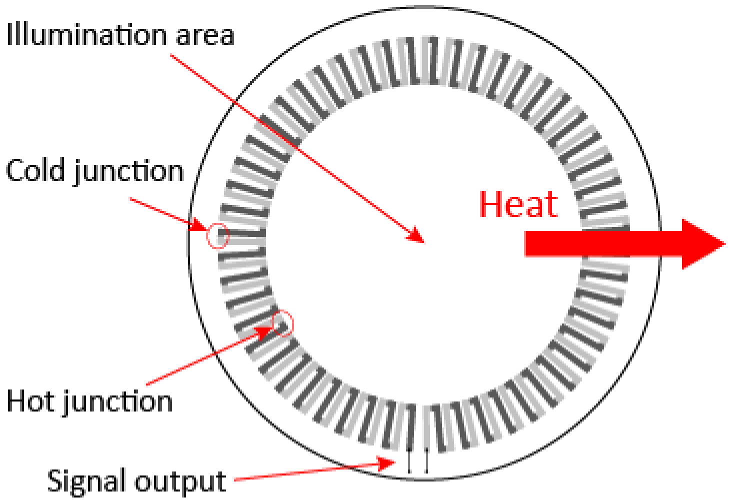


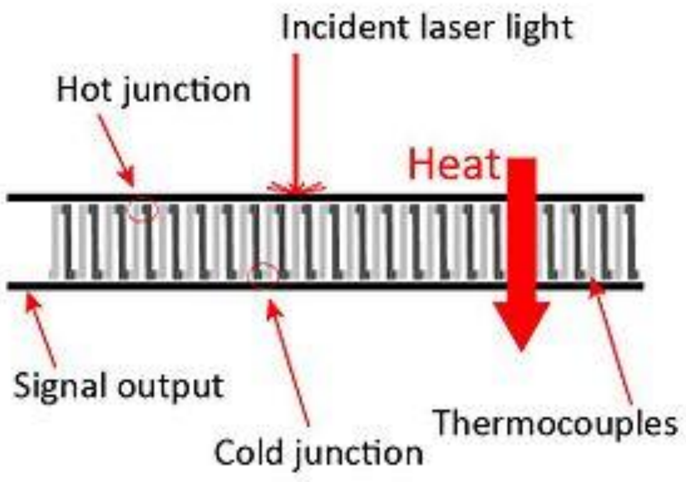
Non-contact Temperature Sensors

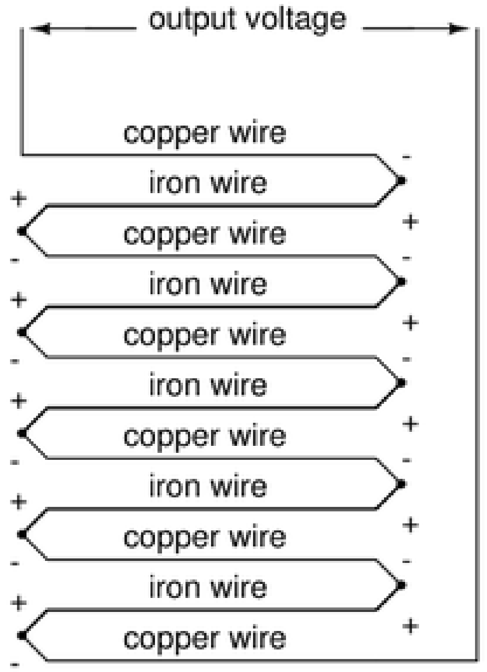
- Thermocouples were the first type of sensor used in non-contact pyrometers, and they still find application in modern versions of the same technology.

- Since the sensor does not become nearly as hot as the target object, the output of any single thermocouple junction at the sensor area will be quite small.

- instrument manufacturers often employ a series-connected array of thermocouples called a **thermopile** to generate a stronger electrical signal.

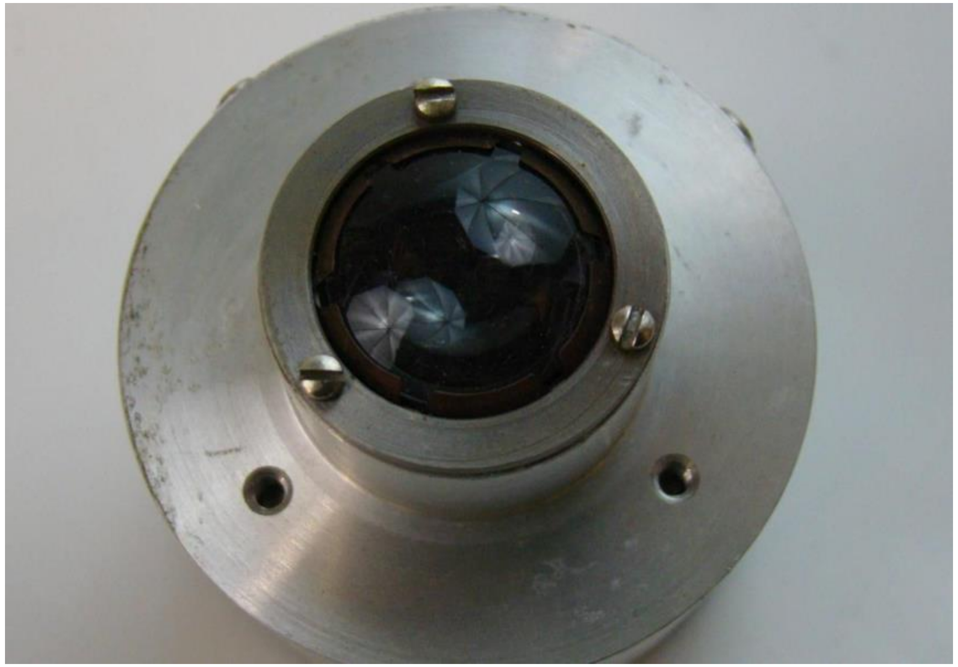






Non-contact Temperature Sensors

Radiamatic




Surface temp
28.3
Non-Contact
Model:HTD8808
MODE

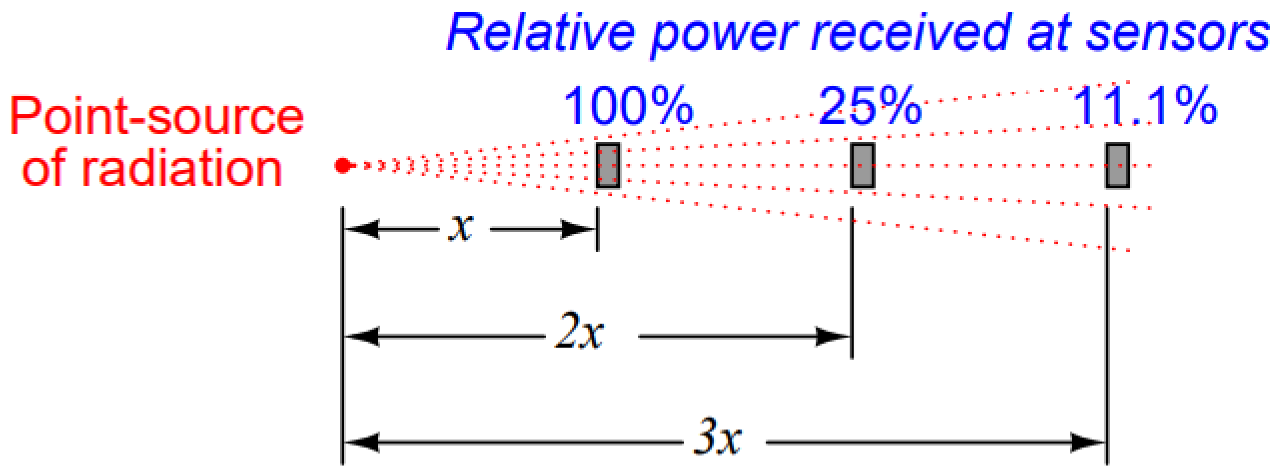

36.8
MODE

Non-contact Temperature Sensors

Distance considerations

Inverse square law

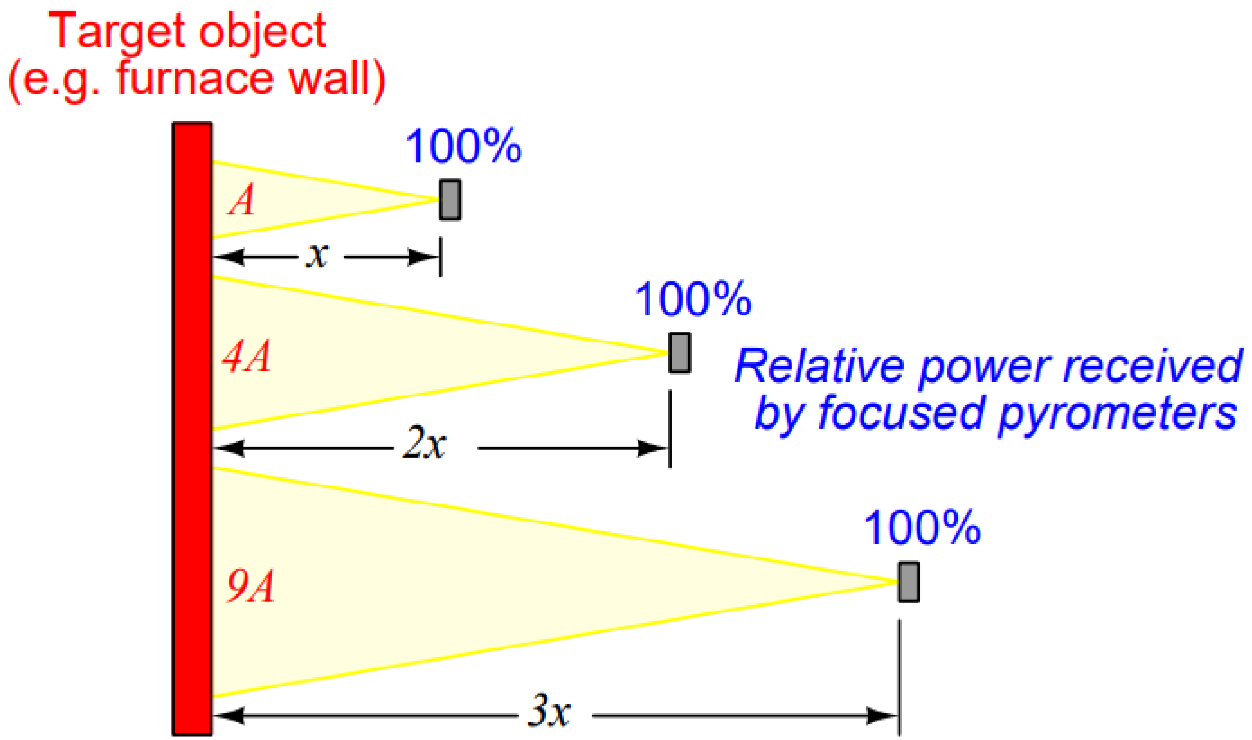
- The intensity of radiation falling on an object from a point-source decreases with the square of the distance separating the radiation source from the object.



Non-contact Temperature Sensors

Distance considerations

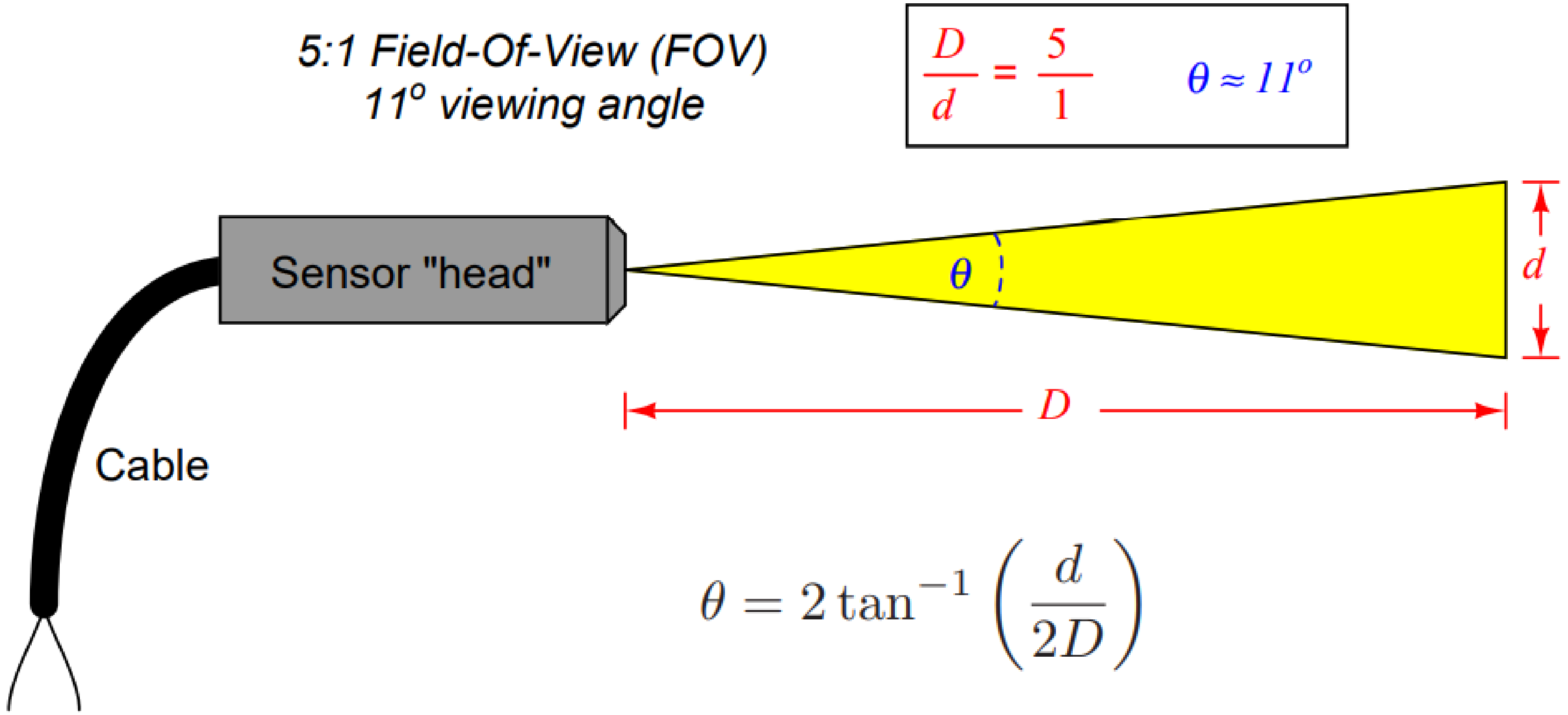
- Non-contact pyrometers are focused-optic devices, with a definite field of view, and that field of view should always be completely filled by the target object (assumed to be at a uniform temperature).



Non-contact Temperature Sensors

Distance considerations

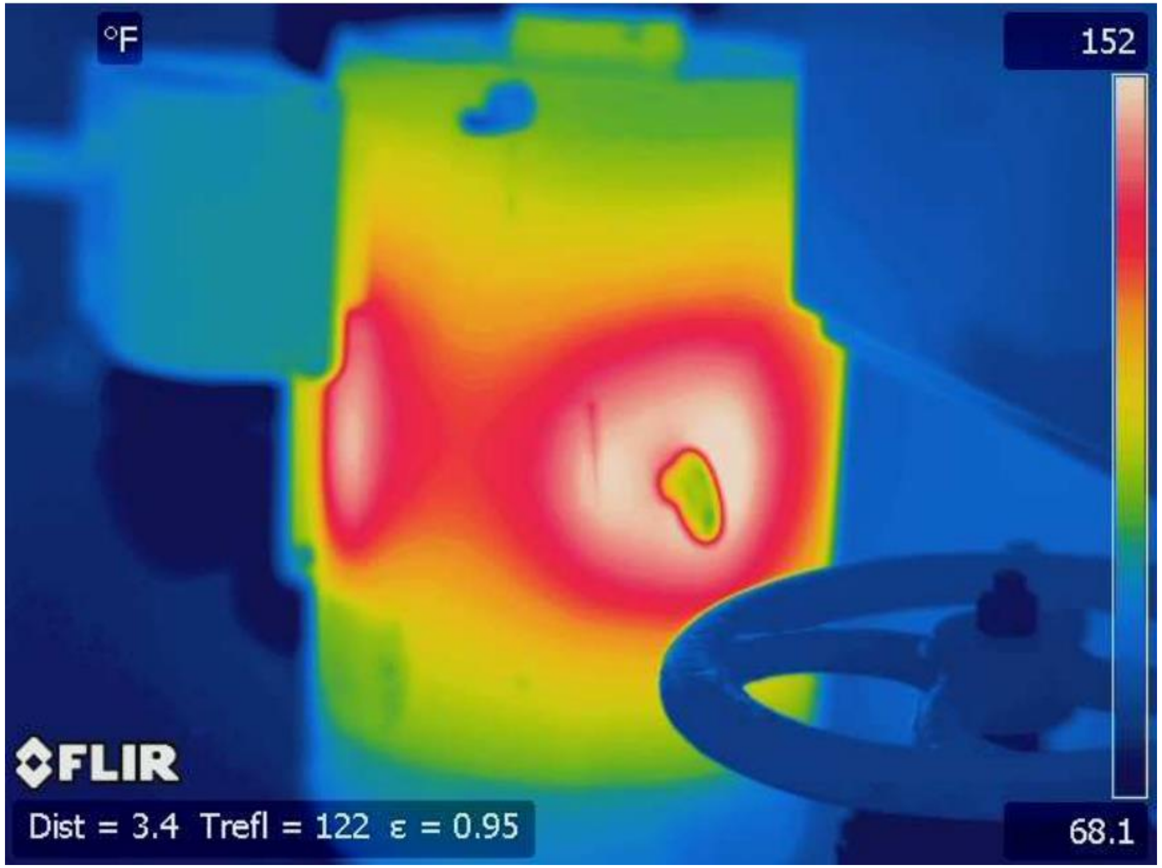
- Non-contact sensor fields-of-view are typically specified either as an angle, as a distance ratio, or both.



$$\theta = 2\tan^{-1}\left(\frac{d}{2D}\right)$$

Distance ratio	Angle (approximate)
1:1	53^o
2:1	30^o
3:1	19^o
5:1	11^o
7:1	8^o
10:1	6^o

Thermal Imaging



MLX90615 Infra Red Thermometer

- Factory calibrated in wide temperature range: -40…85˚C for sensor temperature
- High accuracy of 0.5°C over wide temperature range
- Measurement resolution of 0.02°C
- 3V supply voltage