# Temperature, and Temperature Dependent on Physical Properties

Physics Enhancement Programme

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# Temperature Scales

- The Celsius, Fahrenheit, and Kelvin Temperature Scales:

$$T_F = \frac{9}{5}T_C + 32^\circ\mathrm{F}$$

$$T = T_C + 273.15$$

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# Temperature Scale

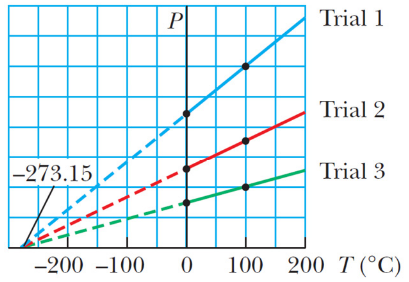

**Figure 19.5** Pressure versus temperature for experimental trials in which gases have different pressures in a constant-volume gas thermometer. Notice that, for all three trials, the pressure extrapolates to zero at the temperature −273.15°C.

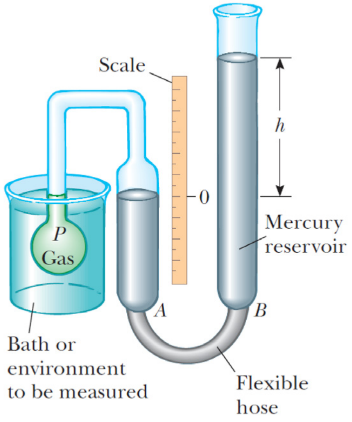

**Figure 19.3** A constant-volume gas thermometer measures the pressure of the gas contained in the flask immersed in the bath. The volume of gas in the flask is kept constant by raising or lowering reservoir *B* to keep the mercury level in column *A* constant.

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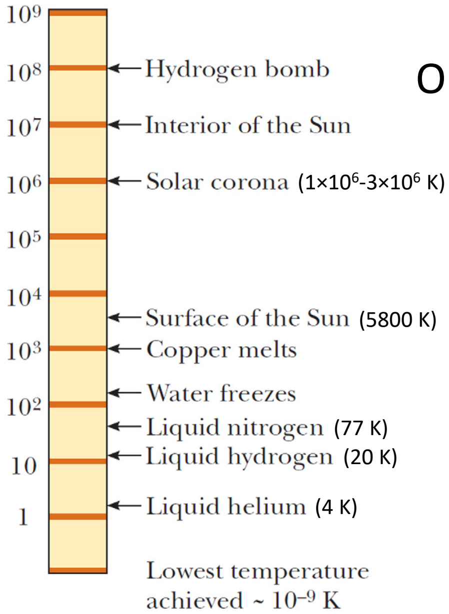
# Temperature

- Concept of temperature – A feeling of how hot or cold an object is.
- Our senses provide us the feeling of temperature.
- Our senses may be unreliable.
- Need reliable, qualitative, and reproducible methods for measuring the hotness or coldness of an object.
- Need a technical definition of temperature.

# Examples of Object Temperatures



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# Thermal Contact

- Two objects are in thermal contact with each other if energy can be exchanged between the 2 objects.
  - The exchanges is in the form of heat or electromagnetic radiation.
  - The energy is exchanged due to a temperature difference.

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# Quick Quiz on Thermal Contact

Two objects, with different sizes, masses, temperatures, and potential energy are placed in thermal contact. In which direction does the energy travel?

a) Energy travels from the larger object to the smaller object.
b) Energy travels from the object with more mass to the one with less mass.
c) Energy travels from the object at higher temperature to the object at lower temperature.
d) Energy travels from the object with higher potential energy to the object with lower potential energy.

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# Quick Quiz

Consider the following pairs of materials. Which pair represents two materials, one of which is twice as hot as the other?

(a) boiling water at 100°C, a glass of water at 50°C;
(b) boiling water at 100°C, frozen methane at -50°C;
(c) an ice cube at -20°C, flames from a circus fire-eater at 233°C;
(d) none of these pairs.

Answer:

# Thermal Equilibrium

- Thermal equilibrium is a situation in which two objects would not exchange energy by heat or electromagnetic radiation if they were placed in thermal contact.
- The thermal contact does not have to also be physical contact.

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# Quick Quiz on Thermal Equilibrium

Is it possible for two objects to be in thermal equilibrium if they are not in contact with each other? Explain.

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# Zeroth Law of Thermodynamics

- If objects A and B are separately in thermal equilibrium with a third object C, then A and B are in thermal equilibrium with each other.
- Since they are in thermal equilibrium with each other, there is no energy exchanged between them.

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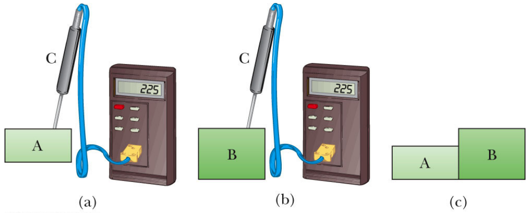
# Zeroth Law of Thermodynamics



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- Object C (thermometer) is placed in contact with A until they achieve thermal equilibrium.
  - The reading on C is recorded.
- Object C is then placed in contact with object B until they achieve thermal equilibrium.
  - The reading on C is recorded again.
- If the two readings are the same, A and B are also in thermal equilibrium.

# Definition of Temperature

- Temperature can be thought of: the property that determines whether an object is in thermal equilibrium with other objects.
- Two objects in thermal equilibrium with each other are at the same temperature.
- If two objects have different temperatures, they are not in thermal equilibrium with each other.

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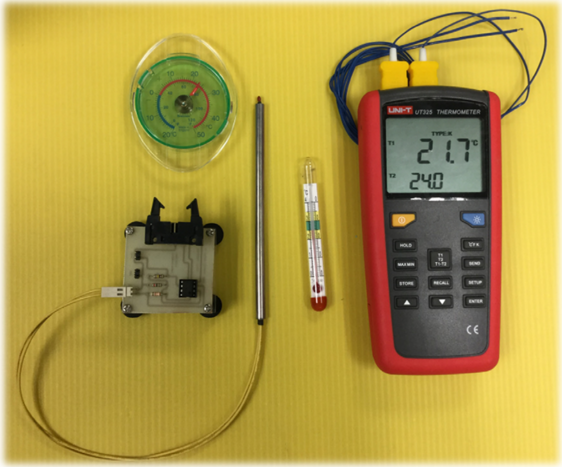
# Demonstration: Temperature Sensors

Can you identify the types of temperature sensing?



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# Temperature Measurements

- There are many types of sensors used to measure temperature.
- For different temperature scales, different measurement technique are established as standards.
- Common types used in physical experiments:
  - Thermometer
  - Resistance-temperature-detectors RTD (resistive elements)
  - Thermistors (semiconductor resistive elements)
  - Thermocouples (thermoelectric elements)
  - Infrared thermometer (thermal radiation)

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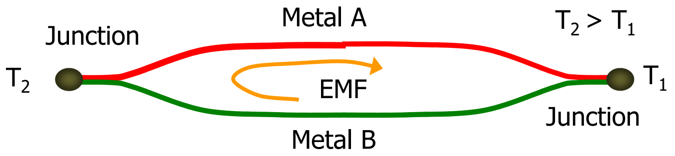
# Thermal Imager

Measured Temperature = 34.9°C
Background = 22°C

# Thermocouple

- Thermocouples consist of 2 different metals joined together.
- Seebeck Effect

  When the junctions of 2 dissimilar metals have different temperatures an EMF is generated in the loop ∝ ΔT.



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# Thermocouple

- The electromotive force (EMF) is:

$$\mathrm{EMF} \propto (T_2 - T_1)$$

$$\mathrm{EMF} = \int_{T_1}^{T_2} (K_A - K_B)\, dT$$

$$\mathrm{EMF} = e_{T_2,T_1} = \alpha (T_2 - T_1)$$

$K_A$ and $K_B$ are thermal transportation constants, and
$\alpha$ is a constant of the metal pair combination ($V^\circ\ C^{-1}$)

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# Standard Thermocouple

| Type | Metal A | Metal B | Temperature Range |
|---|---|---|---|
| J | Iron | Constantan ($Cu_{57}Ni_{43}$) | -190–760 °C |
| T | Copper | Constantan ($Cu_{57}Ni_{43}$) | -200–370 °C |
| K | Chromel ($Ni_{90}Cr_{10}$) | Alumel ($Ni_{94}Mn_3Al_2Si_1$) | -190–1260 °C |
| E | Chromel ($Ni_{90}Cr_{10}$) | Constantan ($Cu_{57}Ni_{43}$) | -200–1260 °C |
| S | Platinum-Rhodium ($Pt_{90}Rh_{10}$) | Platinum | 0–1450 °C |
| R | Platinum-Rhodium ($Pt_{87}Rh_{13}$) | Platinum | 0–1450 °C |

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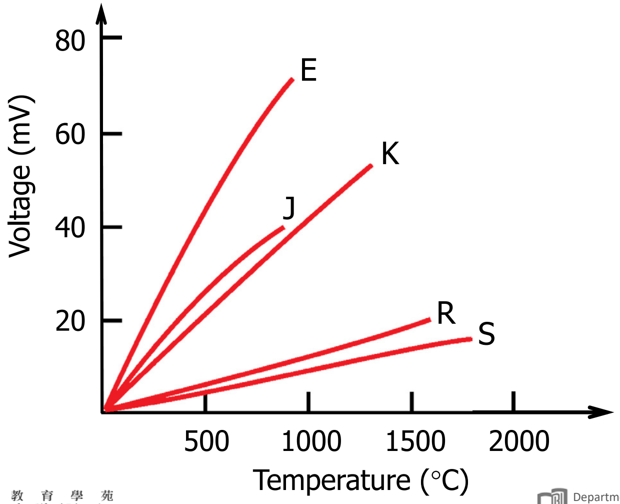
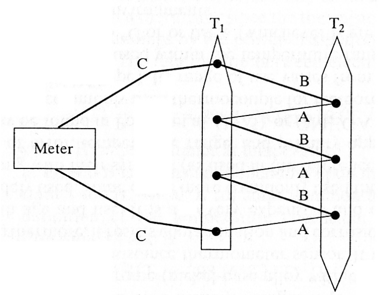
# Standard Thermocouple Curves

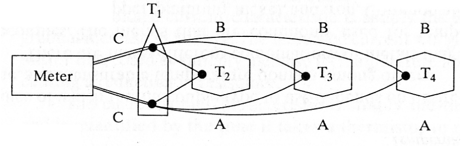


# Common Configurations of Thermocouple

In Series:



In Parallel:



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# Thermocouple Characteristics

- The potential generated is small ~ $\mu V\ ^\circ C^{-1}$.
- The potential is only dependent upon the $\Delta T$ of the junctions.
- That is, a junction temperature must be known in order to determine the other junction's temperature.

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# Thermocouple Characteristics

- The potential generated by a thermocouple is:

$$e_{T_2,T_1} = \alpha\left(T_2 - T_1\right) + \beta\left(T_2^2 - T_1^2\right) + \gamma\left(T_2^3 - T_1^3\right) + \cdots$$

- For $T_1 = 0$ (reference temperature at 0°C),

$$e_{T_2,T_1} = \alpha T_2 + \beta T_2^2 + \gamma T_2^3 + \cdots$$

or

$$e_{T_2,T_1} = \alpha T + \beta T^2 + \gamma T^3 + \cdots$$

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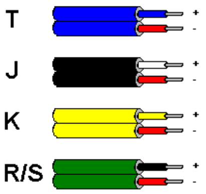
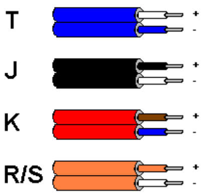
# Thermocouple – Commercial Standards

US Standard



British Standard

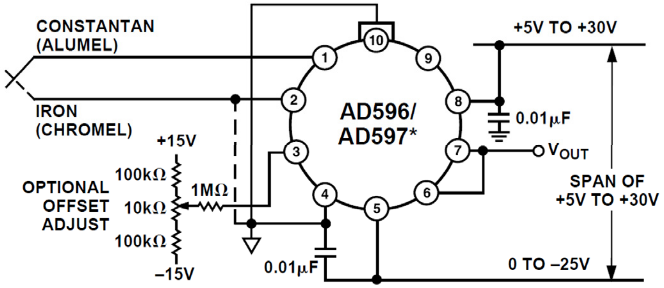


Connectors

# Thermocouple Conditioner

FEATURES

- Operates with Type J (AD596) or Type K (AD597) Thermocouples
- Built-In Ice Point Compensation
- Temperature Proportional Operation: 10 mV/°C
- High Impedance Differential Input



# Resistance-Temperature-Detectors

- Resistance thermometers work on the principle that the electrical resistance of a material varies with temperature.

$$R_T = R_{T=0^\circ\mathrm{C}}\left[1+\alpha\left(\Delta T\right)\right]$$

For higher accuracy, second order term can also be used:

$$R_T = R_{T=0^\circ\mathrm{C}}\left[1+\alpha\left(\Delta T\right)+\beta\left(\Delta T\right)^2\right]$$

where $\alpha$ and $\beta$ are the first and second order temperature coefficients, respectively.

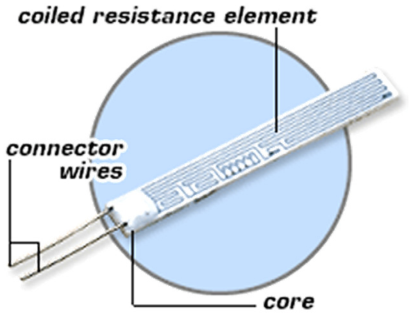
# Resistance-Temperature-Detectors

- Resistance elements are commonly calibrated by determining their resistance at 0°C, 100°C, and -78.51°C (sublimation point of $CO_2$).

# Resistance-Temperature-Detectors

Construction:

- Most RTD probes consist of a length of coiled wire wrapped around a ceramic or glass core.



http://www.omega.com/prodinfo/rtd.html

# Resistance-Temperature-Detectors

Construction

- Long thin piece wire coiled and protected by glass or insulated stainless steel tube.
- Typical resistance R ~ 100's Ω at room temperature.
- Platinum is general used even though it is expensive.
- Platinum is chemically inert and that it produces very repeatable measurements.

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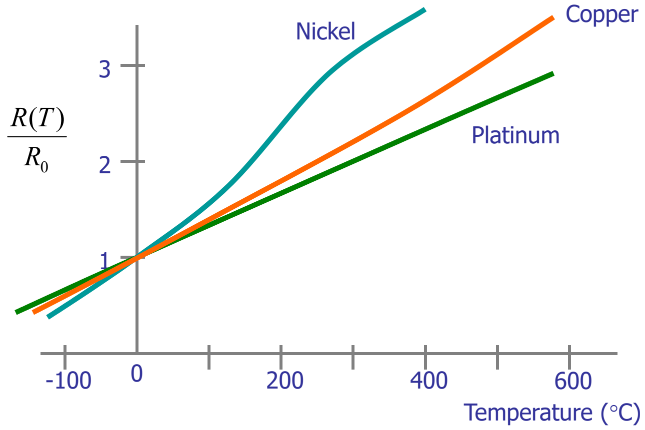
# Resistance-Temperature-Detectors

- Typical resistance curves of some common RTD:



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# Resistance-Temperature-Detectors

- Common metals are platinum, copper and nickel.

| Metal | α (°C$^{-1}$) Between 0-100°C |
|---|---|
| Platinum | 0.0039 |
| Copper | 0.0043 |
| Nickel | 0.0068 |

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# Resistance-Temperature-Detectors

Self-heating Effect

- RTD operates by current passing through the sensor.
- The current will introduce the self-heating effect, which causes a rise in temperature ΔT:

$$\Delta T = \frac{P}{P_D}$$

where P is the Actual Power Dissipated,
$P_D$ is the Dissipation Constant. Typically, $P_D$ ~ 25 mW °C$^{-1}$.

# Resistance-Temperature-Detectors

Self-heating Effect

- For example, current i = 10 mA passing through a 300 Ω RTD, the temperature rise will be:

$$\begin{aligned}\Delta T &= \frac{i^2 R}{P_D}\\ &= \frac{\left(10\times10^{-3}\right)^2(300)}{25\times10^{-3}}\\ &= 1.2^{\circ}\mathrm{C}\end{aligned}$$

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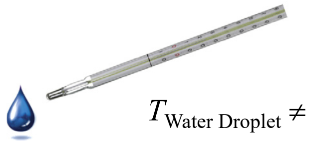
# Resistance-Temperature-Detectors

- Thermal Shunting – Altering the measurement temperature by inserting a sensor or transducer.

- Example: Temperature Measurement of a Drop of Water.
- If we insert a thermometer into a drop of water and try to measure the temperature, the thermometer will definitely alter the water droplet temperature.



$T_{\text{Water Droplet}} \neq T_{\text{Thermometer}}$

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# Resistance-Temperature-Detectors

| Small RTD | Large RTD |
|---|---|
| Fast Response Time | Slow Response Time |
| Low Thermal Shunting | Poor Thermal Shunting |
| High Self-Heating Effect | Low Self-Heating Effect |

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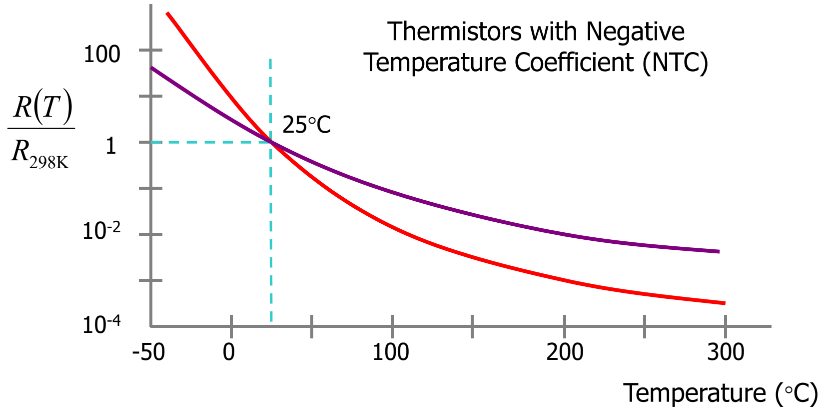
# Thermistor

- Thermistors are resistive semiconductor devices.
- Thermistors have a very large negative temperature coefficient (NTC).
- The electrical resistance $R$ (in Ω) and temperature $T$ (in K) is:

$$R(T) = R_o \exp\left[\beta\left(\frac{1}{T}-\frac{1}{T_o}\right)\right]$$

where $R_o$ is resistance at reference temperature $T_o$.
$\beta$ is the resistance temperature, typical value ~ 4000.

# Thermistor with NTC



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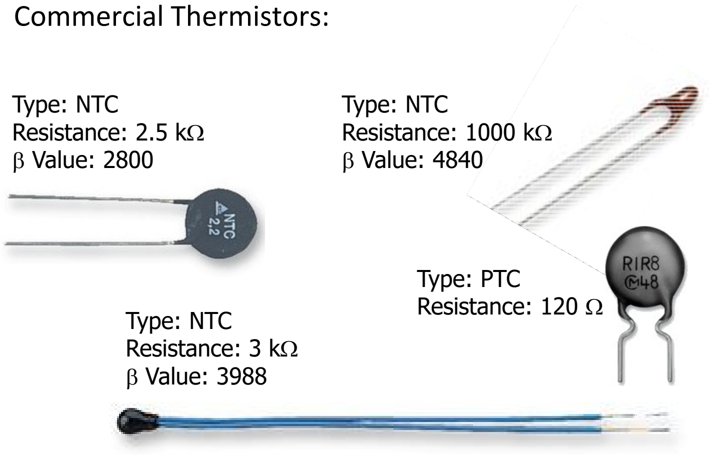
# Thermistor

- Commercial Thermistors:



Type: NTC
Resistance: 2.5 kΩ
β Value: 2800

Type: NTC
Resistance: 1000 kΩ
β Value: 4840

Type: PTC
Resistance: 120 Ω

Type: NTC
Resistance: 3 kΩ
β Value: 3988

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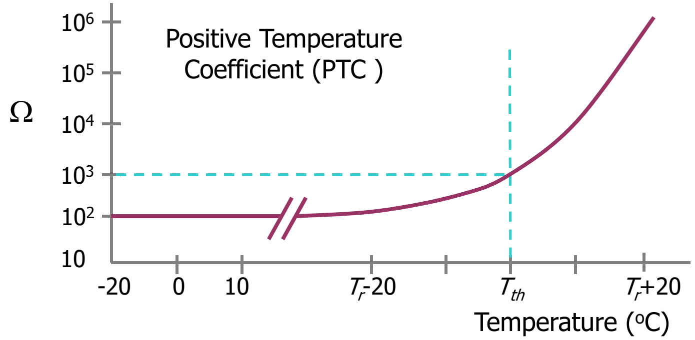
# Thermistor with PTD

- Positive temperature coefficient (PTC) thermistors are available, but they have short temperature spans.
- Typically $T_{max} \sim T_{th} + 100°C$ ($T_{th}$ is the threshold temperature)



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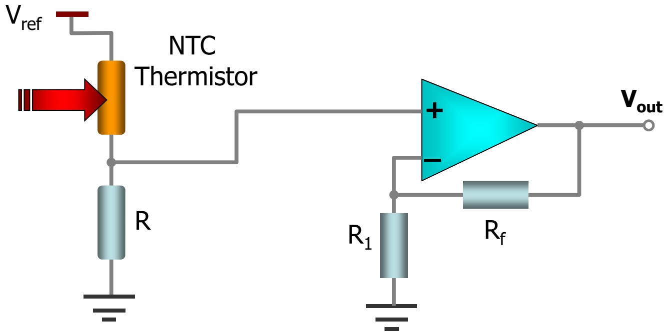
# Thermistor – Signal Conditioning

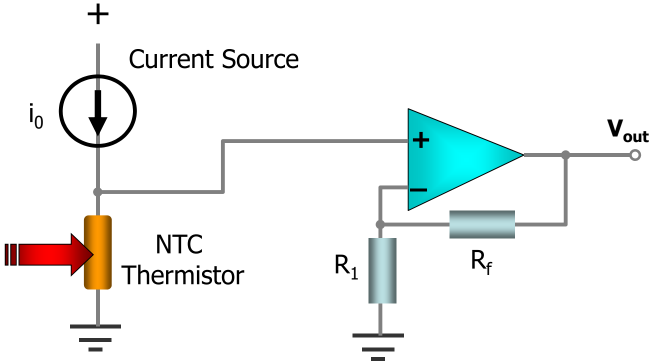
- Two common signal conditioning methods for thermistor:

Potential Divider Method



# Thermistor – Signal Conditioning

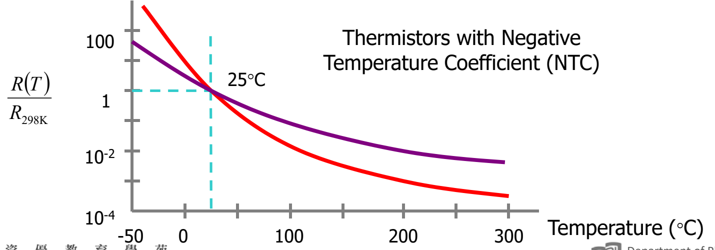
Current Source Method



# Thermistor – Practical Application

NTC Thermistor:

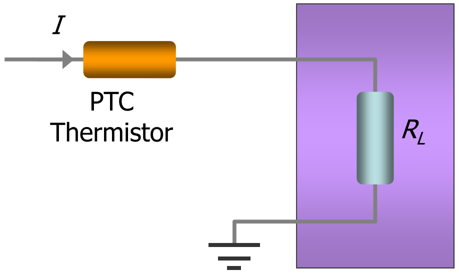
- Temperature measurements.
- Needs microprocessor to linearize measurements.
- Self-heating effect is a big problem. Self-heating reduces the thermistor resistance, results in higher current flowing through the thermistor.



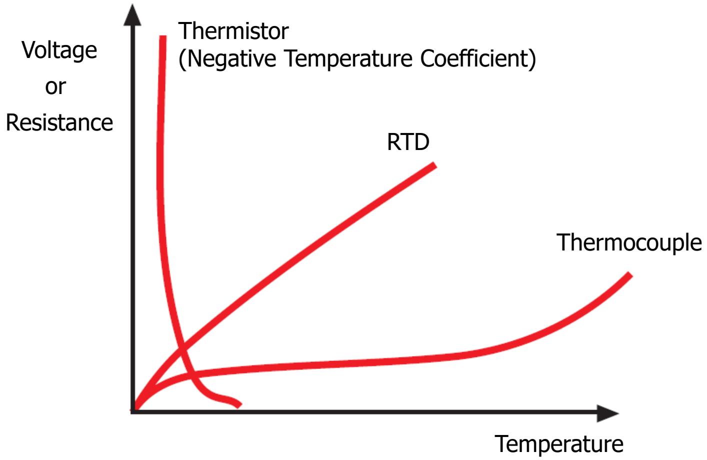
# Thermistor – Practical Application

PTC Thermistor:

- PTC thermistors are used for circuit protection against excessive $I^2R$ in the event of malfunction or short circuit.



# Comparison



# Thermal Expansion

- Thermal expansion:
  - Increase in the size of an object with an increase in its temperature.
  - Consequence of the change in the average separation between the atoms in an object.
  - If the expansion is small relative to the original dimensions of the object, the change in any dimension is, to a good approximation, proportional to the first power of the change in temperature.

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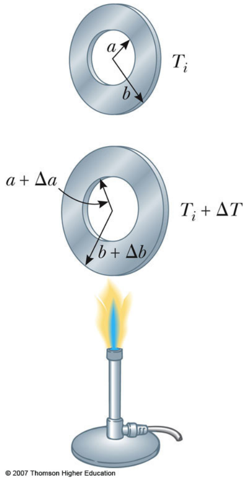
# Thermal Expansion

- Temperature increases, all the dimensions will increase.
- A cavity in a piece of material expands in the same way as if the cavity were filled with the material



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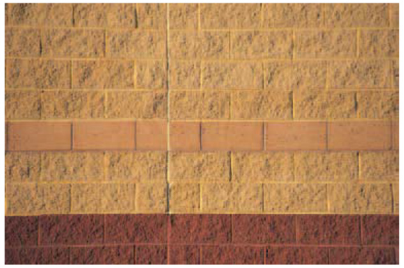
# Thermal Expansion

Examples to Compensate Solid and Liquid Thermal Expansion:

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# Linear Expansion

- An object with an initial length *L.*
- Suppose that the length increases by $\Delta L$ in response to a temperature change by $\Delta T$.
- The coefficient of linear expansion is defined as:

$$\alpha = \frac{\Delta L / L}{\Delta T}$$

- Rearrange: $\Delta L = \alpha L \Delta T$

# Linear Expansion

- Some materials expand along one dimension, but contract along another as the temperature increases.
  - Example: Calcite ($CaCO_3$), which expands along one dimension (positive $\alpha$), but contract along another (negative $\alpha$).
- Since the linear dimensions change, it follows that the surface area and volume also change with a change in temperature.
- A cavity in a piece of material expands in the same way as if the cavity were filled with the material.

---

# Area Expansion

- The change in area is proportional to the original area and to the change in temperature:

$$\beta = \frac{\Delta A / A}{\Delta T}$$

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# Volume Expansion

- The change in volume is proportional to the original volume and to the change in temperature.

$$\gamma = \frac{\Delta V / V}{\Delta T}$$

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# On-Class Exercise: Thermal Expansion

Find the coefficient of area expansion ($\beta$) and the coefficient of volume expansion ($\gamma$). Express your answers in terms of coefficient of linear expansion ($\alpha$).

# Expansion Coefficients

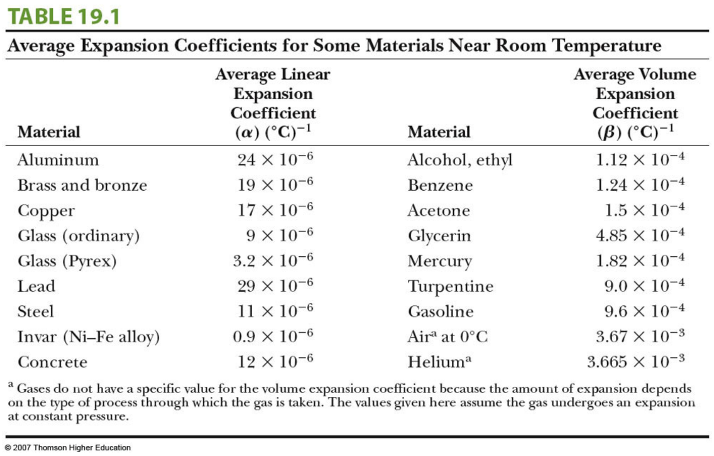

**TABLE 19.1**

**Average Expansion Coefficients for Some Materials Near Room Temperature**

| Material | Average Linear Expansion Coefficient ($\alpha$) $(°\mathrm{C})^{-1}$ | Material | Average Volume Expansion Coefficient ($\beta$) $(°\mathrm{C})^{-1}$ |
|---|---|---|---|
| Aluminum | $24 \times 10^{-6}$ | Alcohol, ethyl | $1.12 \times 10^{-4}$ |
| Brass and bronze | $19 \times 10^{-6}$ | Benzene | $1.24 \times 10^{-4}$ |
| Copper | $17 \times 10^{-6}$ | Acetone | $1.5 \times 10^{-4}$ |
| Glass (ordinary) | $9 \times 10^{-6}$ | Glycerin | $4.85 \times 10^{-4}$ |
| Glass (Pyrex) | $3.2 \times 10^{-6}$ | Mercury | $1.82 \times 10^{-4}$ |
| Lead | $29 \times 10^{-6}$ | Turpentine | $9.0 \times 10^{-4}$ |
| Steel | $11 \times 10^{-6}$ | Gasoline | $9.6 \times 10^{-4}$ |
| Invar (Ni–Fe alloy) | $0.9 \times 10^{-6}$ | Air[a] at 0°C | $3.67 \times 10^{-3}$ |
| Concrete | $12 \times 10^{-6}$ | Helium[a] | $3.665 \times 10^{-3}$ |

[a] Gases do not have a specific value for the volume expansion coefficient because the amount of expansion depends on the type of process through which the gas is taken. The values given here assume the gas undergoes an expansion at constant pressure.

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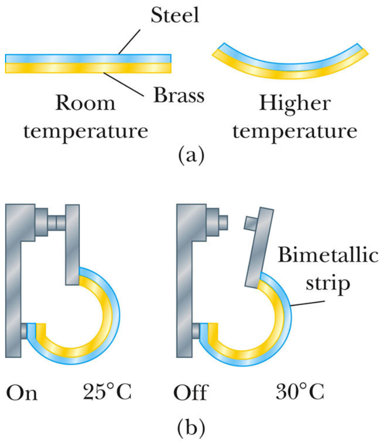
# Application: Bimetallic Strip

- Different substances have different characteristic average coefficient of expansion.
- This physical property can be used to fabricate devices, which are called bimetallic strip.



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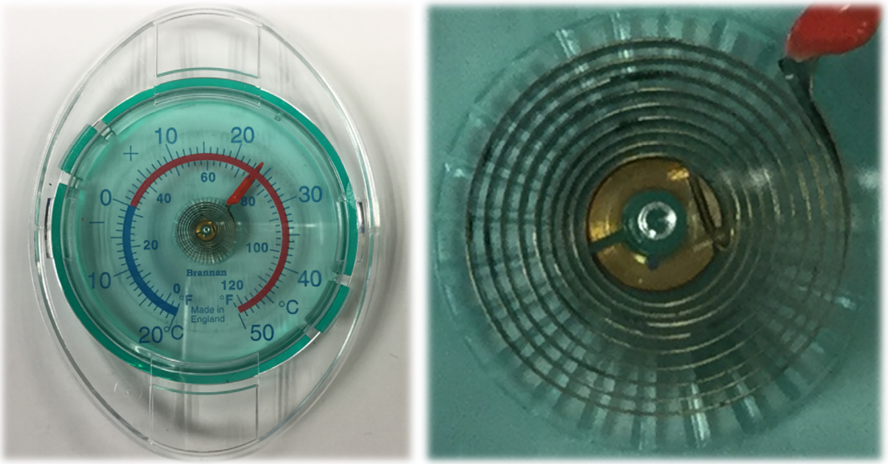
# Demonstration: Application of Bimetallic Strip



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# Pressure

- Pressure: Normal force exerted by a fluid per unit area.
- Unit of Pressure: Force per unit area

$$[\ \mathrm{N/m^2}\ ] \Leftrightarrow [\ \mathrm{Pa}\ ]$$

$$1\ \mathrm{Pa} = 1\ \mathrm{N/m^2}$$

- Other commonly used pressure units:

Bar, and Standard Atmosphere

$$1\ \mathrm{bar} = 10^5\ \mathrm{Pa} = 0.1\ \mathrm{MPa} = 100\ \mathrm{kPa}$$

$$1\ \mathrm{atm} = 101{,}325\ \mathrm{Pa} = 101.325\ \mathrm{kPa} = 1.01325\ \mathrm{bars}$$

$$\begin{aligned} 1\ \mathrm{kgf/cm^2} = 9.807\ \mathrm{N/cm^2} &= 9.807 \times 10^4\ \mathrm{N/m^2} = 9.807 \times 10^4\ \mathrm{Pa} \\ &= 0.9807\ \mathrm{bar} \\ &= 0.9679\ \mathrm{atm} \end{aligned}$$

# Pressure

- Absolute Pressure: Relative to absolute vacuum (absolute zero pressure).
- Gage Pressure: Relative to atmospheric pressure.
  - Most pressure-measuring devices are calibrated to read zero in the atmosphere.
- Vacuum Pressure: Pressures below atmospheric pressure.

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# Pressure

- Absolute, gage, and vacuum pressures are all positive quantities and are related by:

$$P_{\text{gage}} = P_{\text{abs}} - P_{\text{atm}}$$

$$P_{\text{vac}} = P_{\text{atm}} - P_{\text{abs}}$$

- In thermodynamic relations and tables, absolute pressure is almost always used.

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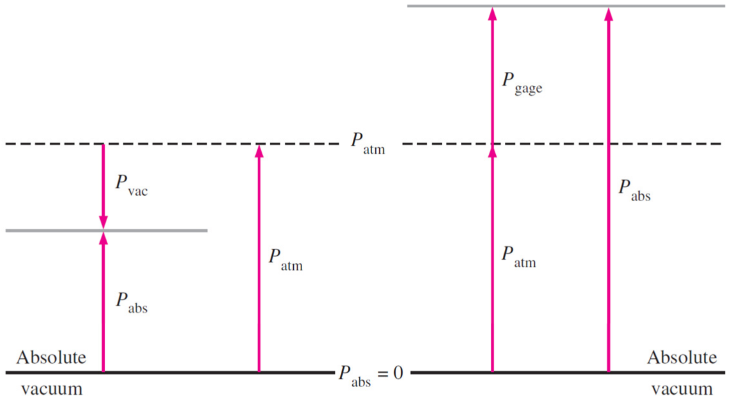
# Pressure

- Illustrations of Absolute, gage, and vacuum pressures.



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# Variation of Pressure with Depth

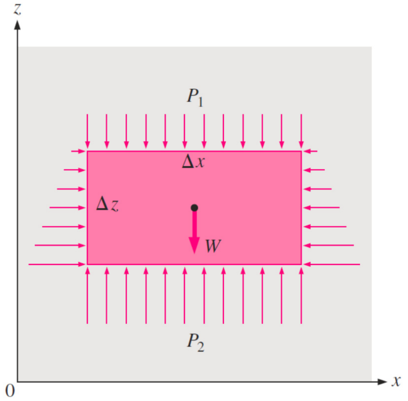
- Consider a rectangular fluid element (height Δz, length Δx, and unit depth into the page) in equilibrium.
- Assume ρ=constant, force balance in the z-direction:

$$\sum F_z = ma_z = 0$$

$$P_2\Delta x - P_1\Delta x - \rho g\Delta x\Delta z = 0$$

$$W = mg = \rho g\Delta x\Delta z$$

$$\Delta P = P_2 - P_1 = \rho g\Delta z$$

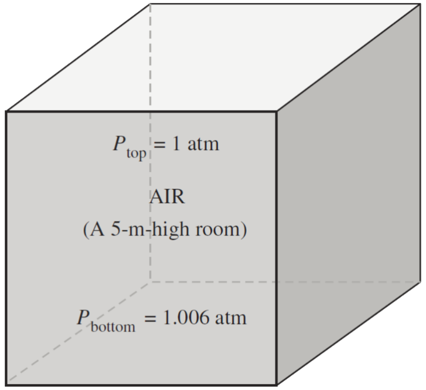


# Variation of Pressure with Depth

$$P = P_{\text{atm}} + \rho g h$$

or

$$P_{\text{gage}} = \rho g h$$



In a room filled with a gas, the variation of pressure with height is negligible.

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# Variation of Pressure with Depth

- For fluids whose density changes significantly with elevation:

$$\frac{dP}{dz} = -\rho g$$

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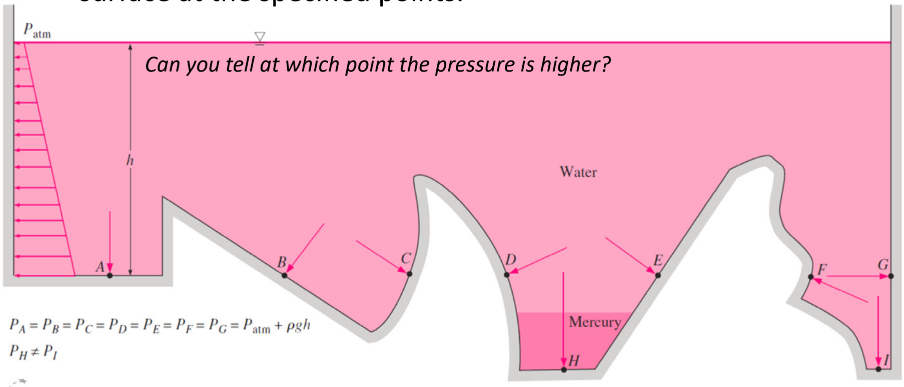
- Pressure in a fluid at rest is independent of the shape or cross section of the container.
- Pressure is the same at all points on a horizontal plane in a given fluid.
- Pressure force exerted by the fluid is always normal to the surface at the specified points.



*Can you tell at which point the pressure is higher?*

$P_A = P_B = P_C = P_D = P_E = P_F = P_G = P_{\text{atm}} + \rho g h$

$P_H \neq P_I$

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# Exercise: Hydrostatic Pressure on Solar Pond

Solar ponds are used to store solar thermal energy. The rise of heated water to the surface is prevented by adding salt at the pond bottom. In a typical salt gradient solar pond, the density of water increases in the gradient zone, and the density (ρ) can be expressed as:

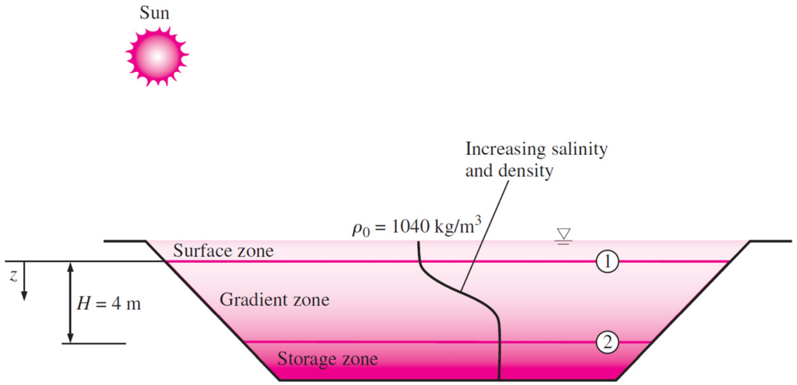
$$\rho = \rho_o \sqrt{1 + \tan^2\left(\frac{\pi}{4}\frac{z}{H}\right)}$$

$\rho_o$ = density on the water surface
$z$ = vertical distance from water surface
$H$ = thickness of the gradient zone

Suppose $H$ = 4 m, $\rho_o$ = 1040 kg/m$^3$, surface zone thickness = 0.8 m, calculate the gage pressure at the bottom of the gradient zone.

Hint: $\int \sqrt{1 + \tan^2(ax)}\, dx = \frac{1}{a}\sinh^{-1}\left[\tan(ax)\right] + C$

# Exercise: Hydrostatic Pressure on Solar Pond



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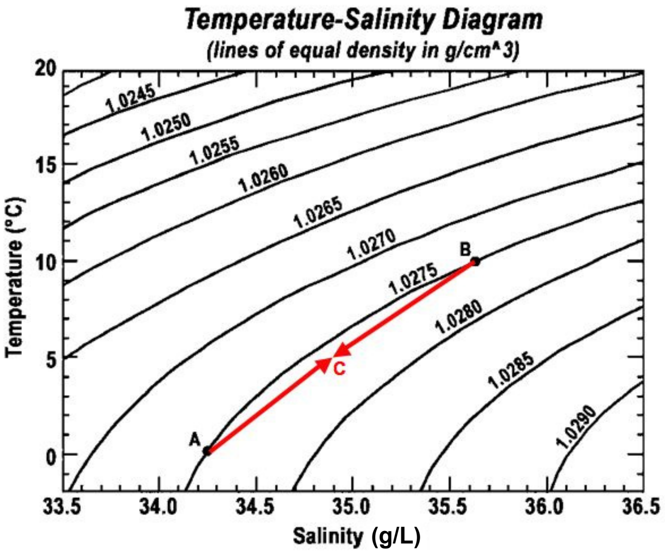

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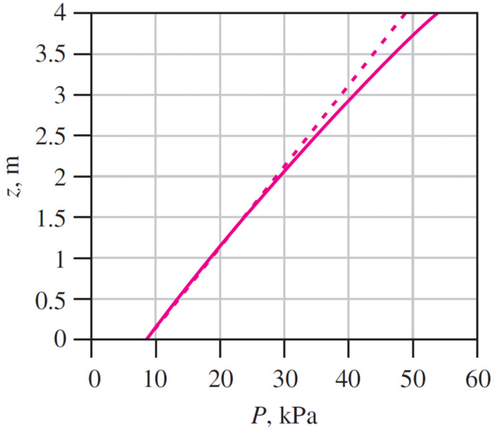
# Exercise: Hydrostatic Pressure on Solar Pond



Variation of gage pressure with depth in the gradient zone of the solar pond.
Dashed line: hydrostatic pressure for the case of constant density at 1040 kg/m$^3$ (for reference).
Variation of pressure with depth is not linear when density varies with depth.

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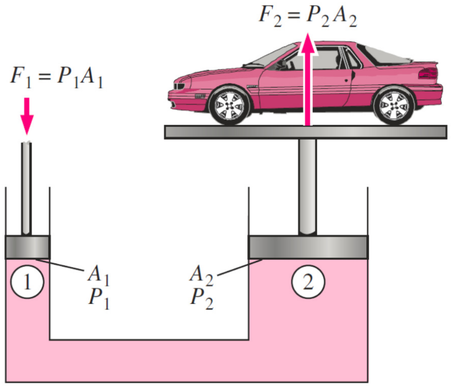
# Hydraulic Lifting

$$P_1 = P_2$$

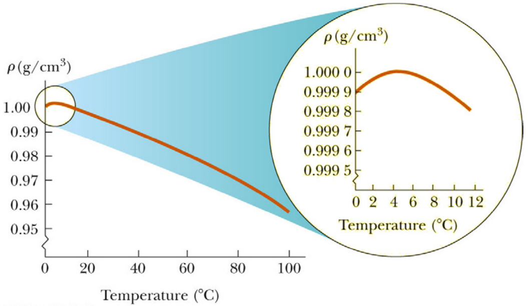
$$\Downarrow$$

$$\frac{F_1}{A_1} = \frac{F_2}{A_2}$$



# Physical Properties: Water

- As temperature increases from 0°C to 4°C, water contracts (density increases).
- Above 4°C, water expands with increasing temperature (density decreases).
- The maximum density of water (1 g/cm$^3$) occurs at 4°C.



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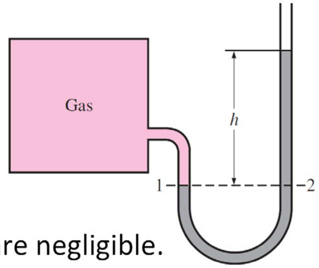
# Manometer



A basic manometer

- Assume: gravitational effects of gases are negligible.
- Pressure anywhere in the tank and at position 1 has the same value.
- Pressure does not vary in the horizontal direction within a fluid, $P_2 = P_1$.
- Pressure is determined directly by $P_2 = P_{atm} + \rho gh$.
- the diameter of the tube should be large enough (> a few mm) to ensure that the surface tension effect and thus the capillary rise is negligible.

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# Manometer

- Some manometers involve multiple immiscible fluids of different densities stacked on top of each other.
- Such systems can be analyzed by:
  - Pascal's law;
  - pressure change across a fluid column (height h) is $\Delta P = \rho gh$;
  - pressure increases downward in a given fluid and decreases upward (i.e., $P_{bottom} > P_{top}$); and
  - two points at the same elevation in a continuous fluid at rest are at the same pressure.

Pascal's Law: A change in pressure at any point in an enclosed fluid at rest is transmitted undiminished to all points in the fluid.

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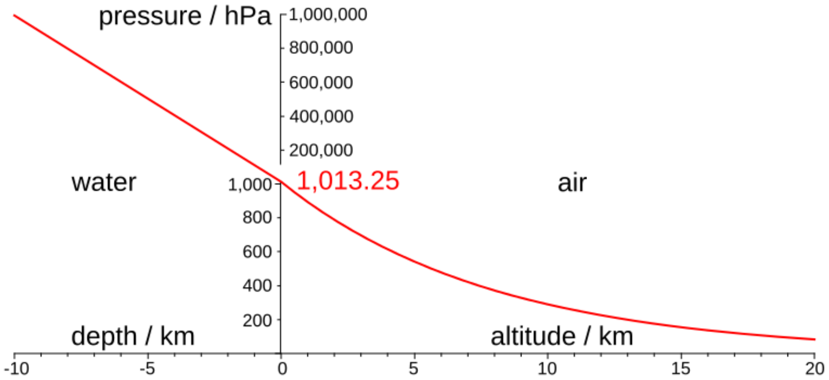
# Pascal's Law



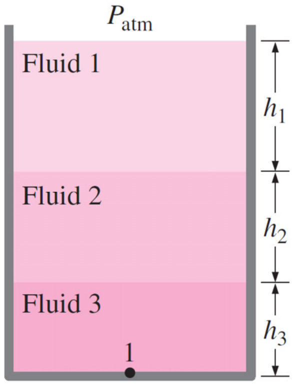
Pressure in water and air.
Pascal's law applies only for fluids.

Illustration Source: Wikipedia

# Manometer

## Multiple Immiscible Fluids of Different Densities

$$P_{\text{atm}} + \rho_1 g h_1 + \rho_2 g h_2 + \rho_3 g h_3 = P_1$$



In stacked-up fluid layers, the pressure change across a fluid layer of density ρ and height *h* is ρ*gh*.

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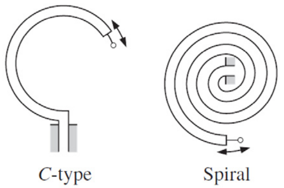
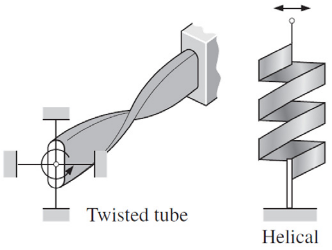
# Other Pressure Measurement Devices

- Bourdon tube
- Strain-gage pressure transducers
- Piezoelectric transducers
- Digital Pressure Meter





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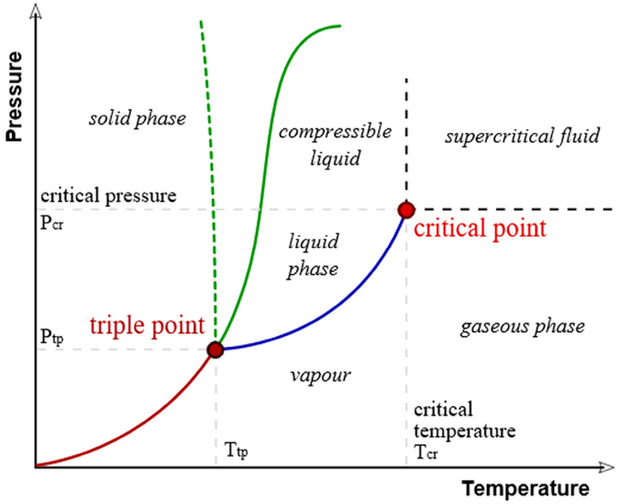
# Water Phase Diagram



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# Exercise

The pendulum of a certain pendulum clock is made of brass. When the temperature increases, does the period of the clock increase, decrease, or remain the same? Give reasons.

Solution:

# What we will learn: The Balance Equations

*Mass balance:*

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}}$$

*Energy balance:*

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}}$$

*Entropy balance:*

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy}\\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change}\\ \text{in entropy}}}$$

*Exergy balance:*

$$\underbrace{X_{\text{in}} - X_{\text{out}}}_{\substack{\text{Net exergy transfer}\\ \text{by heat, work, and mass}}} - \underbrace{X_{\text{destroyed}}}_{\substack{\text{Exergy}\\ \text{destruction}}} = \underbrace{\Delta X_{\text{system}}}_{\substack{\text{Change}\\ \text{in exergy}}}$$