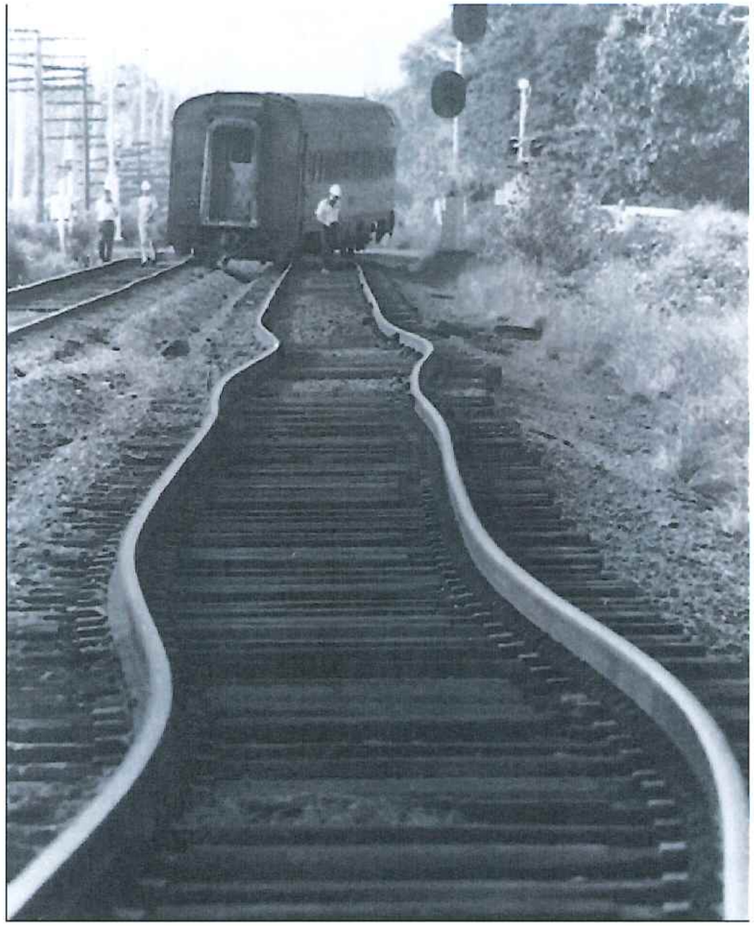
LECTURE 32

(Ch10: 1-2)

Topic 10: Thermal Physics



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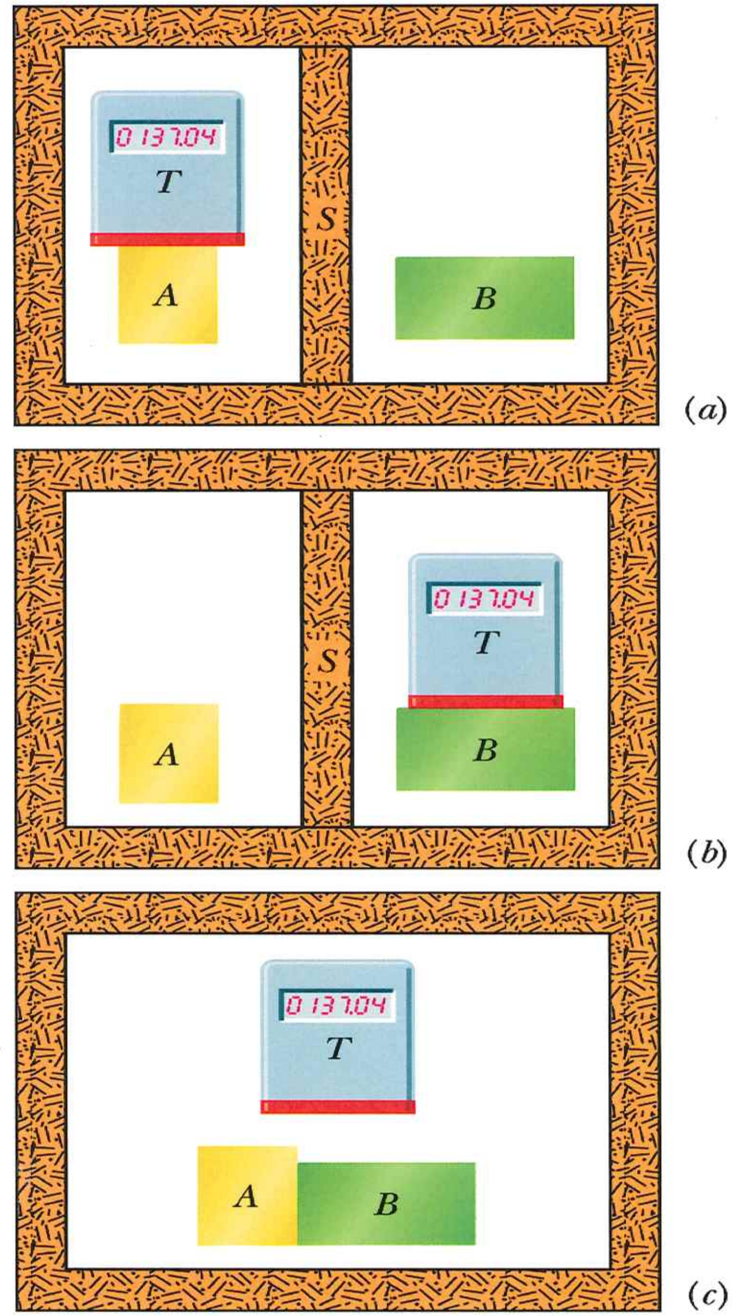
The Zeroth Law of Thermodynamics

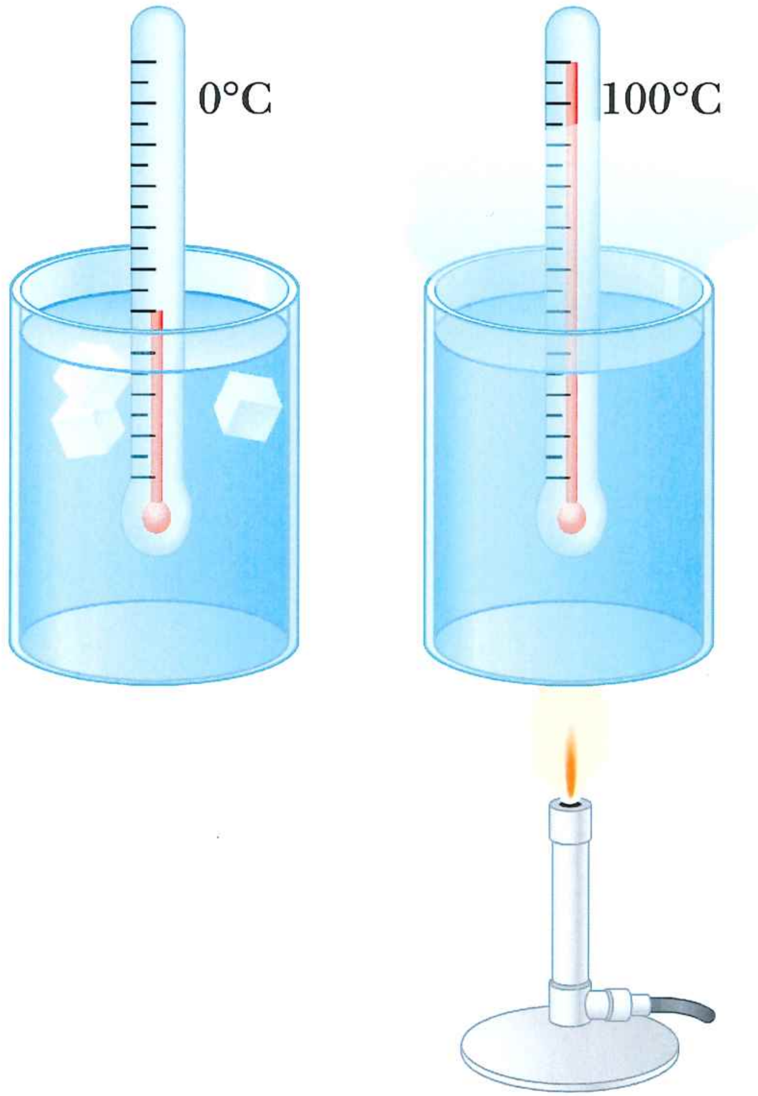
- **Thermal equilibrium**: no net exchange of thermal energy

- **Thermoscop** (see Fig. 18-2)

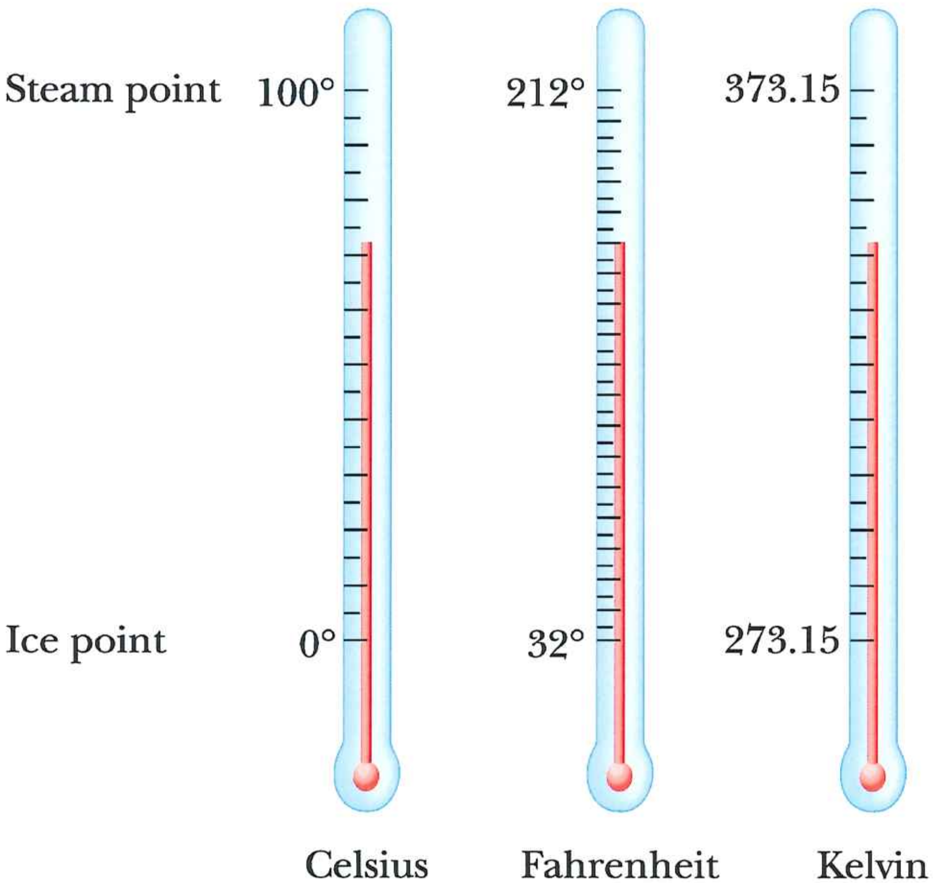
- **Zeroth Law** (see Fig 18-3 =>):
  - *If bodies A and B are each in thermal equilibrium with a third body T, then A and B are in equilibrium with each other*
  - *Each body characterized by its* temperature



Thermometers and Temperature Scales



The Celsius, Kelvin, and Fahrenheit Temperature Scales



$$T_C = T - 273.15$$

$$T_F = \frac{9}{5} T_C + 32$$

$$T_C = \frac{5}{9}\left(T_F - 32\right)$$

$$\Delta T_F = \frac{9}{5} \Delta T_C$$

Celsius and Fahrenheit Scales

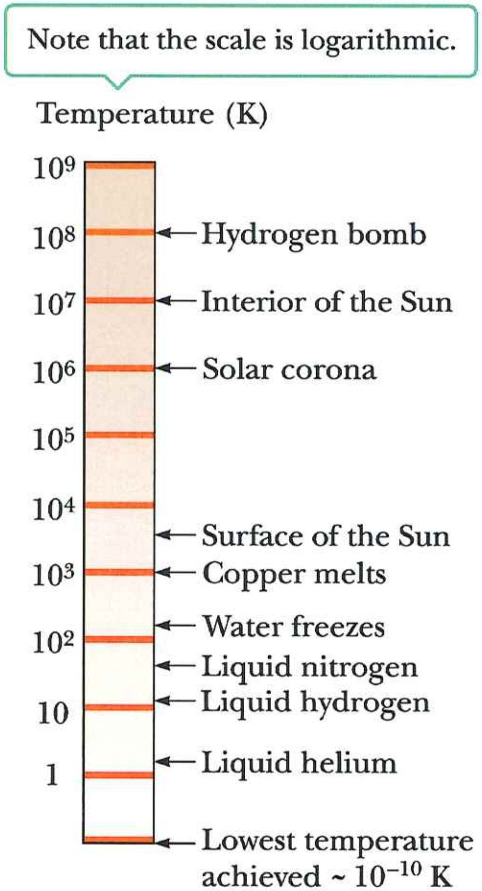
- Celsius scale: used worldwide

$$T_C = T - 273.15\,K$$

  - 1^o C = 1 K
  - 0^o C => ice-water phase transition, normal pressure
  - 100^o C => water-vapor phase transition
  - 37^o C => normal human body temperature
  - 20^o C => normal room temperature (68^o F)

The Constant-Volume Gas Thermometer and the Kelvin Scale

Kelvin: defined as $\frac{1}{273.16}$ of temperature of the triple point of water



- Fahrenheit scale: used in United States

$$T_F = \frac{9}{5} T_C + 32$$

0º C => 32º F

10º C => 36.5 º F

– Some corresponding temperatures (Table 18-1 and Fig 18-7)

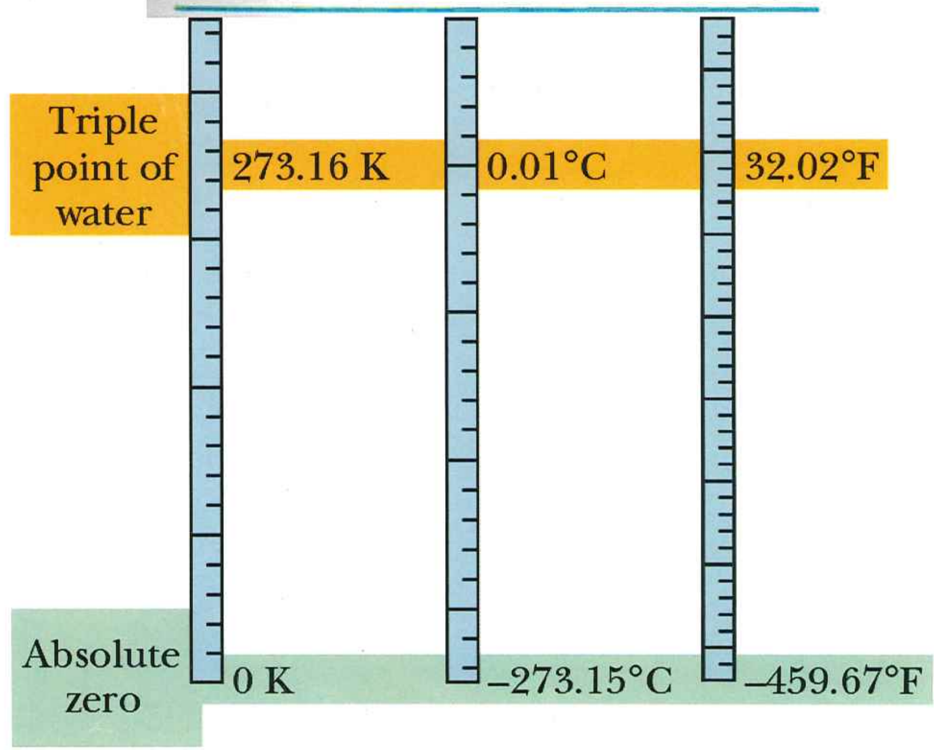
$$T_C = \frac{5}{9}(T_F - 32^\circ)$$

$$T_K = T^\circ C + 273.15$$

$$T_K = \frac{9}{5}(T^\circ F - 459.67)$$

TABLE 19-1 Some Corresponding Temperatures

Temperature	°C	°F
Boiling point of water[a]	100	212
Normal body temperature	37.0	98.6
Accepted comfort level	20	68
Freezing point of water[a]	0	32
Zero of Fahrenheit scale	≈ −18	0
Scales coincide	−40	−40

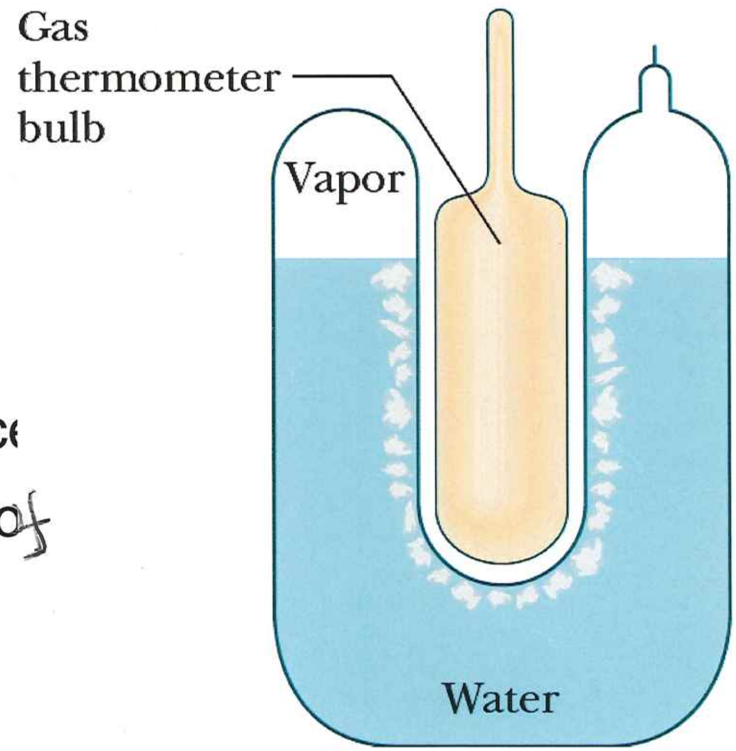


Measuring Temperature

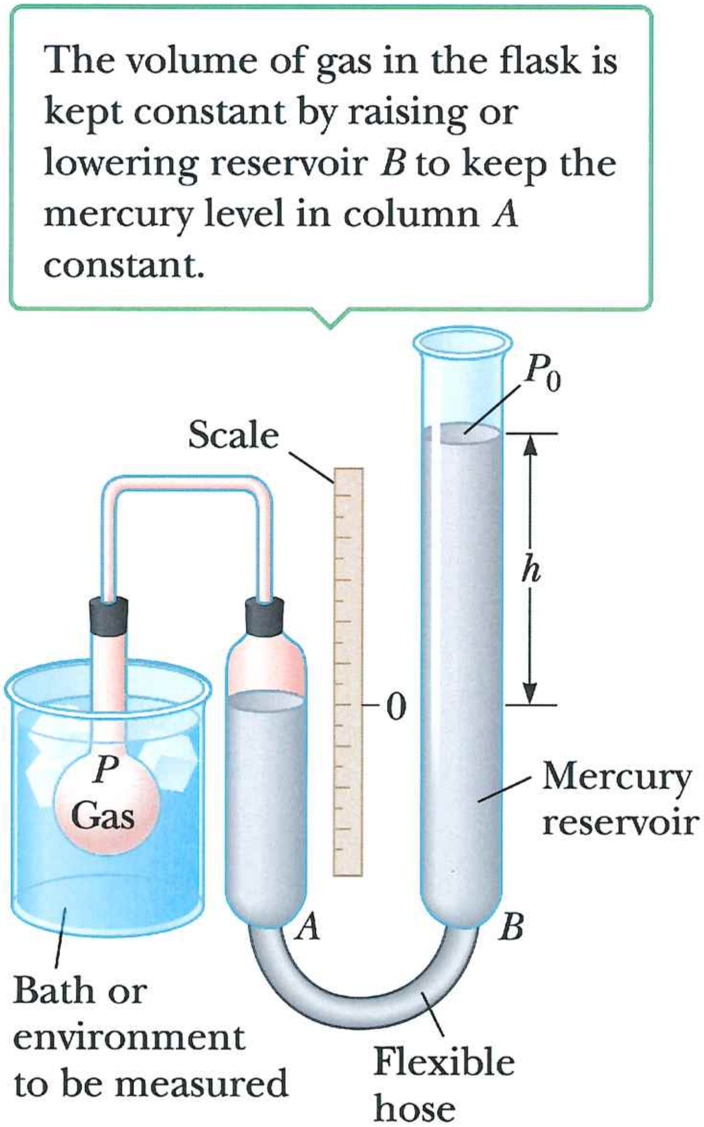
- The triple point of water
  - Triple point: ice, water and vapor coexist
  - *Standard fixed point*: triple point of water

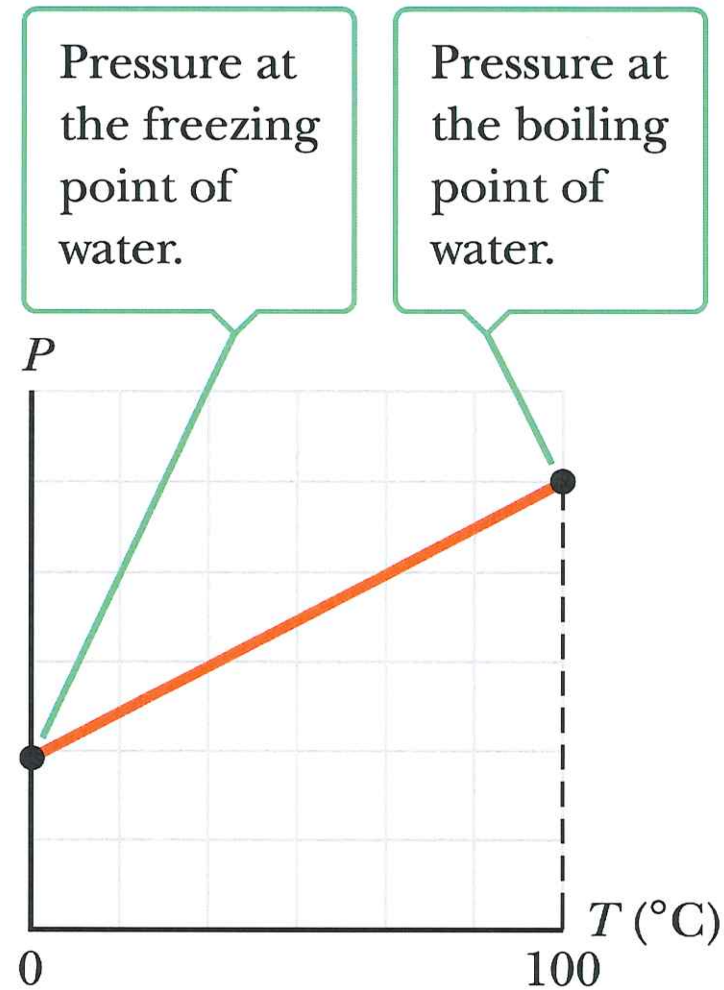
  - *A degree Kelvin* is 1/273.16 of the difference between absolute zero and the triple point of water

$$T_3 = 273.16\ K$$

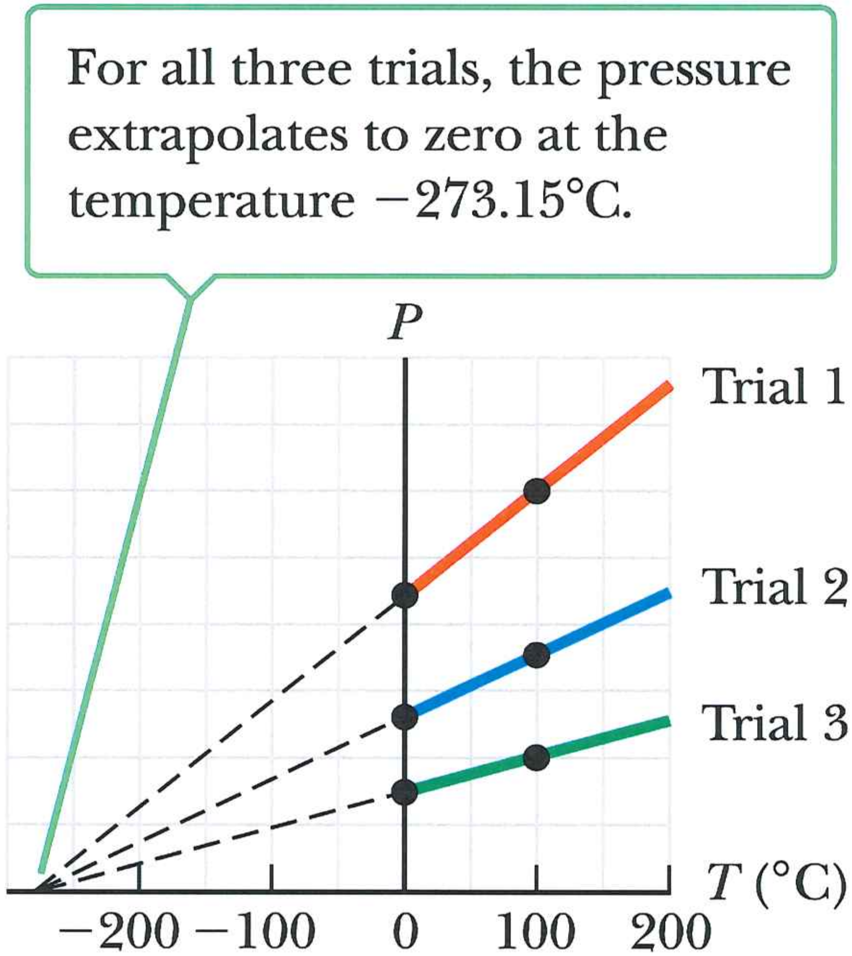


The Constant-Volume Gas Thermometer and the Kelvin Scale





The Constant-Volume Gas Thermometer and the Kelvin Scale



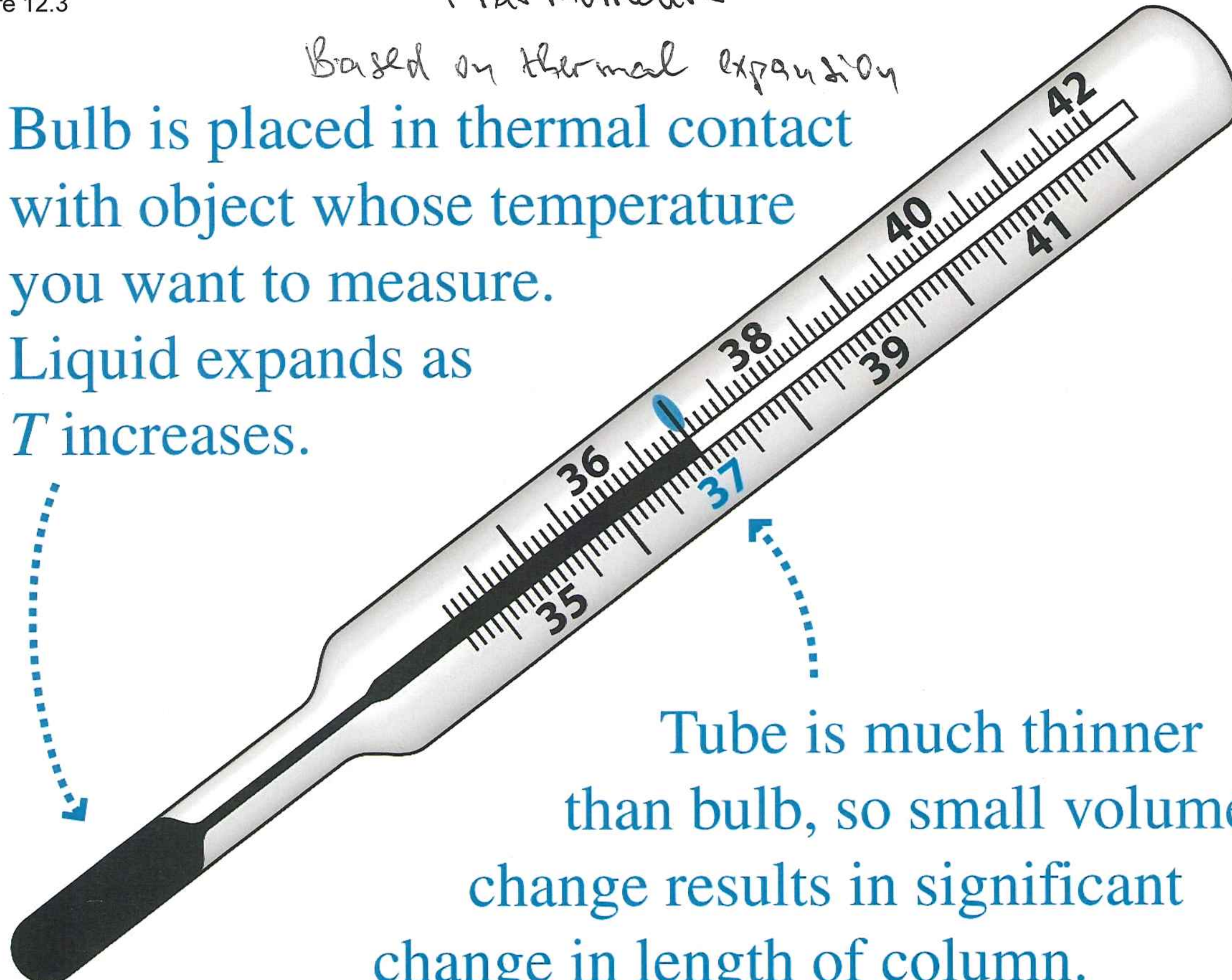
$$T_C = T - 273.15$$

Figure 12.3

Thermometers

Based on thermal expansion

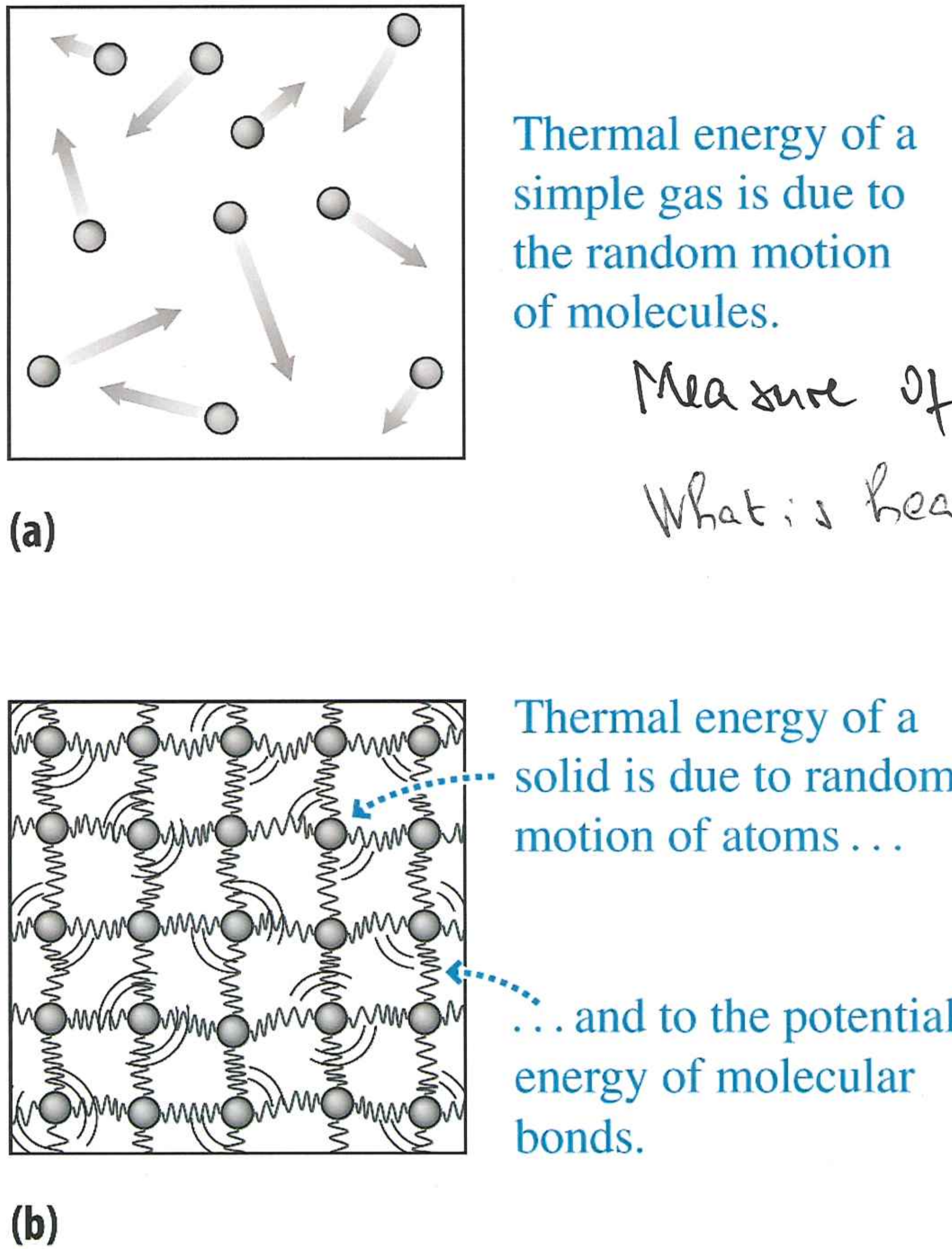
Bulb is placed in thermal contact with object whose temperature you want to measure. Liquid expands as *T* increases.



Tube is much thinner than bulb, so small volume change results in significant change in length of column.

What is temperature?

Figure 12.1



Measure of thermal energy

What is heat? → Process

1. For each of the following temperatures, find the equivalent temperature on the indicated scale:

   a. $-273.15^\circ C$ on the Fahrenheit scale,

   Answer

   b. $98.6^\circ F$ on the Celsius scale, and

   Answer

   c. 1.00×10^2 K on the Fahrenheit scale.

10.1 **(a)** $T_F = \frac{9}{5}T_C + 32 = \frac{9}{5}(-273.15) + 32 = \boxed{-460^\circ F}$

(b) $T_C = \frac{5}{9}(T_F - 32) = \frac{5}{9}(98.6 - 32) = \boxed{37^\circ C}$

(c) $T_F = \frac{9}{5}T_C + 32 = \frac{9}{5}(T_K - 273.15) + 32 = \frac{9}{5}(-173.15) + 32 = \boxed{-280^\circ F}$

5. On January 22, 1943, in Spearfish, South Dakota, the temperature rose from $-4.00°F$ to $45.0°F$ over the course of two minutes (the current world record for the fastest recorded temperature change). By how much did the temperature change on the Kelvin scale?

10.5 Use the relations $T_C = T - 273.15$ and $T_C = \frac{5}{9}(T_F - 32)$ to see that $\Delta T = \frac{5}{9}\Delta T_F$

(where T is the Kelvin temperature and T_F is the Fahrenheit temperature).

Substitute $\Delta T_F = T_{Ff} - T_{Fi} = 45.0°F - (-4.00°F) = 49.0°F$ to find that

$$\Delta T = \frac{5}{9}\Delta T_F = \frac{5}{9}(49.0°F) = \boxed{27.2 \text{ K}}$$

7. **BIO** A person's body temperature is 101.6°F, indicating a fever of 3.0°F above the normal average body temperature of 98.6°F. How many degrees above normal is this body temperature on the Celsius scale?

10.7 Use the relation $T_C = \frac{5}{9}(T_F - 32)$ to realize that $\Delta T_C = \frac{5}{9}\Delta T_F$. For $\Delta T_F = 3.0°\text{F}$,

$\Delta T_C = \boxed{1.67°\text{C}}$. Alternatively, calculate that 98.6°F = 37.0°C and 101.6°F =

38.67°C so that $\Delta T_C = 1.67°\text{C}$ as before.

8. The temperature difference between the inside and the outside of a home on a cold winter day is 57.0°F. Express this difference on

   a. the Celsius scale and

   b. the Kelvin scale.

10.8 **(a)** As in the solution to Problem 10.7 above,

$$\Delta T_C = \frac{5}{9}(\Delta T_F) = \frac{5}{9}(57.0)°C = \boxed{31.7°C}$$

(b) $\Delta T_K = \frac{5}{9}\left(T_{C,out} + 273.15\right) - \left(T_{C,in} + 273.15\right) = \left(T_{C,out} - T_{C,in}\right) = \Delta T_C = \boxed{31.7\ K}$

- **Linear expansion**

$$\Delta L = L_0 \alpha \Delta T$$

$$L = L_0(1+\alpha\Delta T)$$

  - ***Coefficient of linear expansion***

$$\alpha = \frac{\Delta L / L_0}{\Delta T}$$

  - Units of α :
  - 1/T, “per degree”,
  - “per Kelvin”
  - (see Table 18-2)
  - Holes expands as well

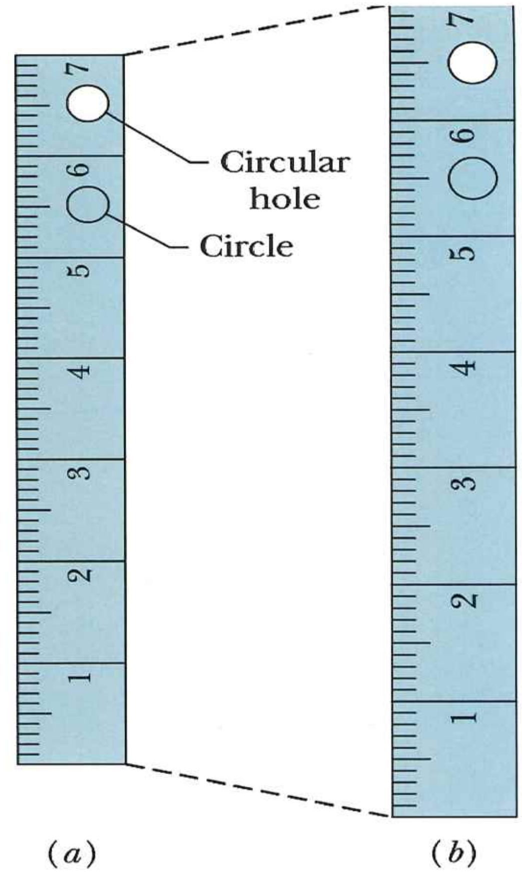


TABLE 19-2 Some Coefficients of Linear Expansion[a]

Substance	α (10^{-6}/C°)	Substance	α (10^{-6}/C°)
Ice (at 0°C)	51	Steel	11
Lead	29	Glass (ordinary)	9
Aluminum	23	Glass (Pyrex)	3.2
Brass	19	Diamond	1.2
Copper	17	Invar[b]	0.7
Concrete	12	Fused quartz	0.5

[a]Room temperature values except for the listing for ice.

[b]This alloy was designed to have a low coefficient of expansion. The word is a shortened form of “invariable.”

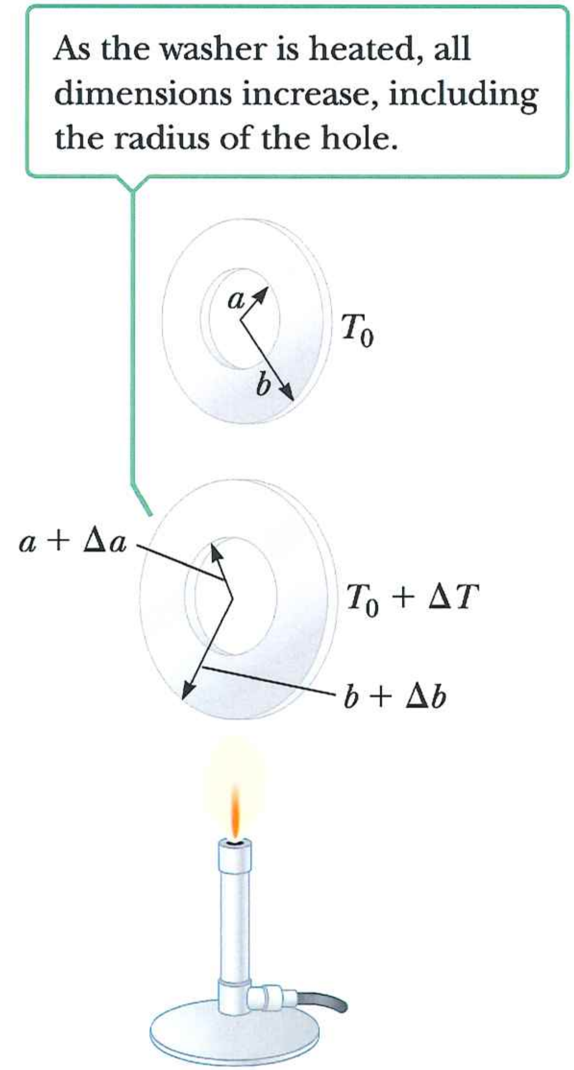
Thermal Expansion of Solids and Liquids

Table 10.1 Average Coefficients of Expansion for Some Materials Near Room Temperature

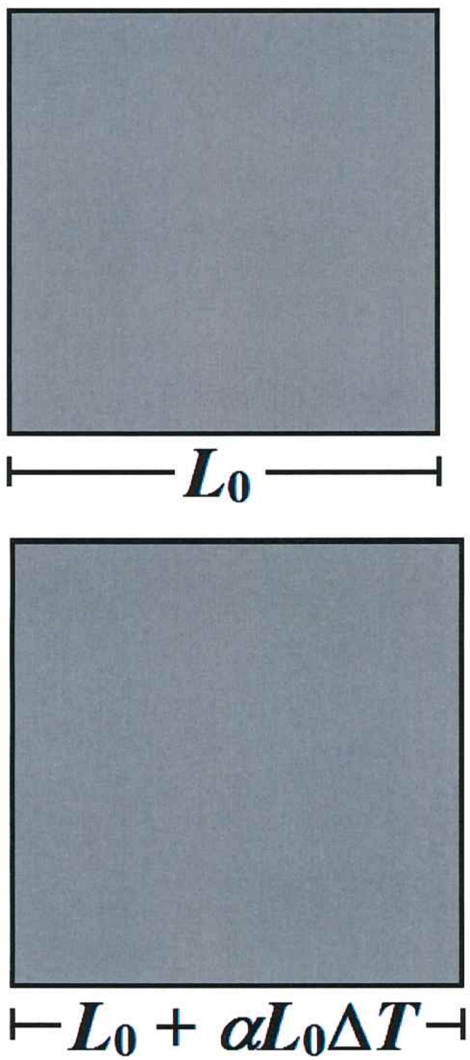
Material	Average Coefficient of Linear Expansion $[(°C)^{-1}]$	Material	Average Coefficient of Volume Expansion $[(°C)^{-1}]$
Aluminum	24×10^{-6}	Acetone	1.5×10^{-4}
Brass and bronze	19×10^{-6}	Benzene	1.24×10^{-4}
Concrete	12×10^{-6}	Ethyl alcohol	1.12×10^{-4}
Copper	17×10^{-6}	Gasoline	9.6×10^{-4}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

Thermal Expansion of Solids and Liquids



Thermal Expansion of Solids and Liquids



$$A_0 = L_0^{\,2}$$

$$A = L^2 = \left(L_0 + \alpha L_0 \Delta T\right)\left(L_0 + \alpha L_0 \Delta T\right)$$

$$= L_0^{\,2} + 2\alpha L_0 \Delta T + L_0^{\,2}\left(\alpha \Delta T\right)^2$$

$$A = L_0^{\,2} + 2\alpha L_0^{\,2} \Delta T$$

$$= A_0 + 2\alpha A_0 \Delta T$$

$$\Delta A = A - A_0 = \gamma A_0 \Delta T$$

Thermal Expansion of Solids and Liquids

$$\Delta V = \beta V_0 \Delta T \quad \beta = 3\alpha$$

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Invar (Ni–Fe alloy)	0.9×10^{-6}	Turpentine	9.0×10^{-4}
Lead	29×10^{-6}	Air[a] at 0°C	3.67×10^{-3}
Steel	11×10^{-6}	Helium	3.665×10^{-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.

11. The New River Gorge bridge in West Virginia is a 518-m-long steel arch. How much will its length change between temperature extremes of $-20.0°C$ and $35.0°C$?

10.11 The increase in temperature is $\Delta T = 35°C-(-20°C) = 55°C$.

Thus, $\Delta L = \alpha L_0(\Delta T) = [11 \times 10^{-6}\,(°C)^{-1}](518\text{ m})(55°C) = 0.31\text{ m} = \boxed{31\text{ cm}}$

13. A pair of eyeglass frames are made of epoxy plastic $\left(\text{coefficient of linear expansion} = 1.30 \times 10^{-4}\ (^{\circ}\text{C})^{-1}\right)$. At room temperature (20.0°C), the frames have circular lens holes 2.20 cm in radius. To what temperature must the frames be heated if lenses 2.21 cm in radius are to be inserted into them?

10.13 We choose the radius as our linear dimension. Then, from $\Delta L = \alpha L_0(\Delta T)$,

$$\Delta T = T_C - 20.0^{\circ}\text{C} = \frac{L - L_0}{\alpha L_0} = \frac{2.21 - 2.20\ \text{cm}}{\left[1.30 \times 10^{-4}\ (^{\circ}\text{C})^{-1}\right](2.20\ \text{cm})} = 35.0^{\circ}\text{C}$$

or $\boxed{T_C = 55.0^{\circ}\text{C}}$

16. A wire is 25.0 m long at 2.00° C and is 1.19 cm longer at 30.0° C. Find the wire's coefficient of linear expansion.

10.16 Use the defining equation for linear expansion to find

$$\Delta L = \alpha L_0 \Delta T \quad \rightarrow \quad \alpha = \frac{\Delta L}{L_0 \Delta T} = \frac{1.19 \times 10^{-2}\ \text{m}}{(25.0\ \text{m})(30.0°\text{C} - 2.00°\text{C})}$$

$$\alpha = \boxed{1.70 \times 10^{-5}\ (°\text{C})^{-1}}$$

23. The band in Figure P10.23 is stainless steel (coefficient of linear expansion $= 17.3 \times 10^{26}$ $(°C)^{-1}$; Youngns modulus $= 18 \times 10^{10}$ N/m^2). It is essentially circular with an initial mean radius of 5.0 mm, a height of 4.0 mm, and a thickness of 0.50 mm. If the band just fits snugly over the tooth when heated to a temperature of 80.0° C, what is the tension in the band when it cools to a temperature of 37° C?

Figure P10.23

10.23 If allowed to do so, the amount the band (with initial length L_0)would contract as it cools to 37°C is $\Delta L = \alpha L_0 |\Delta T|$. Since the band is not allowed to contract, it will develop a tensile stress given by

$$Stress = Y\left(\frac{\Delta L}{L_0}\right) = Y\left(\frac{\alpha L_0 |\Delta T|}{L_0}\right) = Y\alpha |\Delta T|$$

If A = (height · thickness) = (4.0 mm)(0.50 mm) = 2.0×10^{-6} m^2 is the cross-sectional area of the band, the tension in the band will be

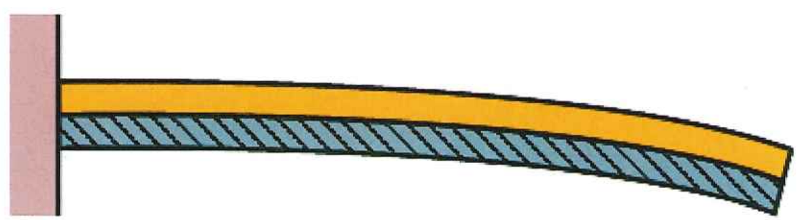
$$F = A \cdot (Stress)$$
$$= (2.0 \times 10^{-6}\ \text{m}^2)\left(18 \times 10^{10}\ \frac{\text{N}}{\text{m}^2}\right)(17.3 \times 10^{-6}\ °\text{C}^{-1})(80°\text{C} - 37°\text{C})$$
$$= \boxed{2.7 \times 10^2\ \text{N}}$$

Thermal Expansion

- Solids, liquids and gases expand with temperature in almost all conditions.
- Exception: water between 0° C and 4° C.
- Undesirable effects: railroads, bridges, etc
- Useful effects: thermometers, thermostats:
  - liquid expansions: alcohol, Hg
  - bimetal expansion: brass-steel strip

$T = T_0$

(*a*)



$T > T_0$

(*b*)