Lecture 40

(CH12:1)

Thermodynamics & Temperature

- **Mechanics**: mechanical energy of systems governed by Newton's laws

- **Thermodynamics:** internal energy of bodies – *thermal energy*

- **Temperature**: central concept - sometimes a measure of the internal energy

    - Kelvin temperature - absolute temperature (see Fig 18-1)

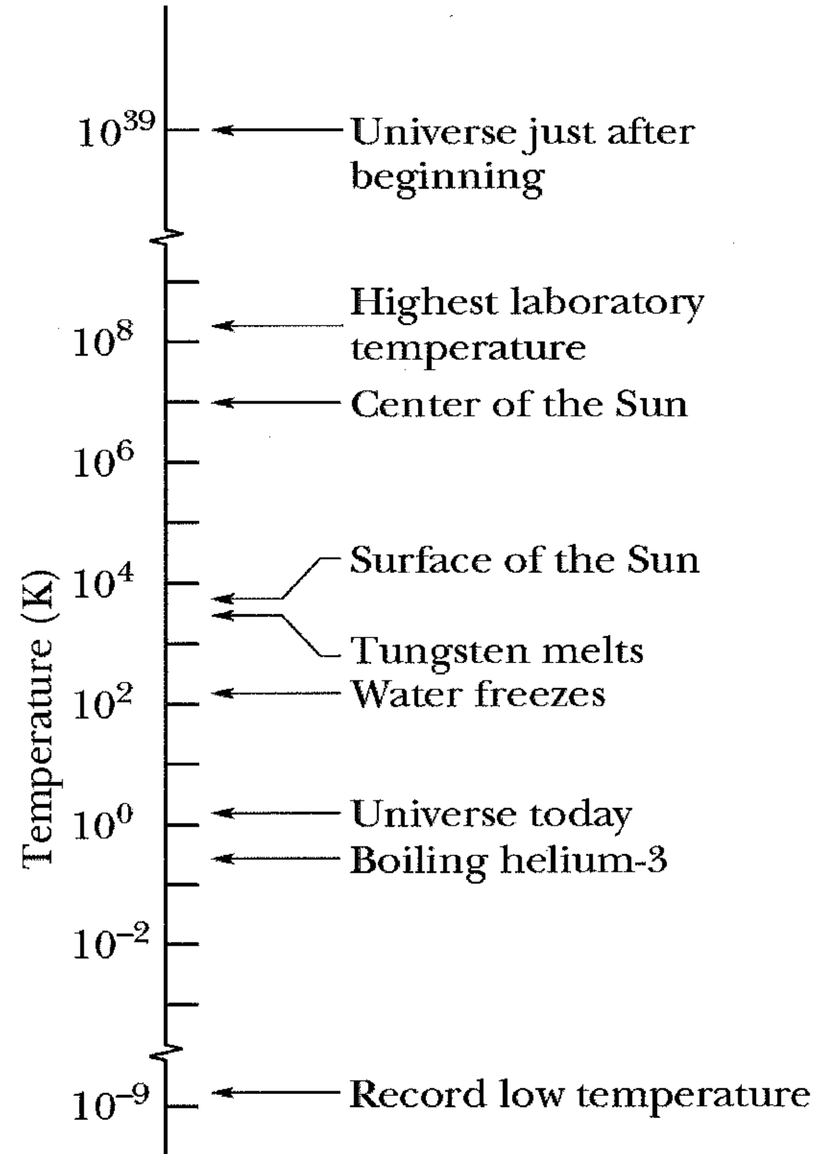
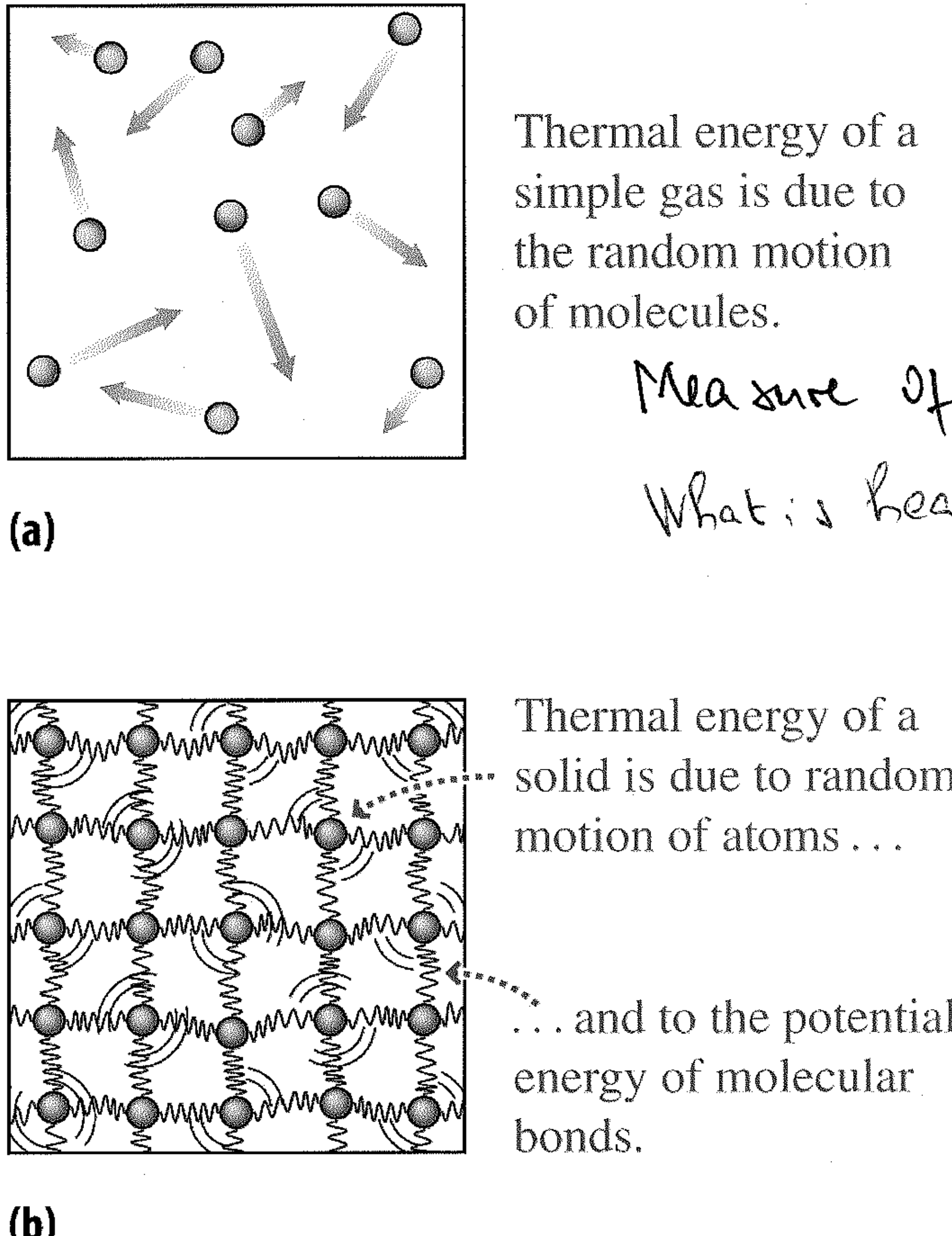


Figure 12.1

What is temperature?



Measure of thermal energy

What is heat? → Process

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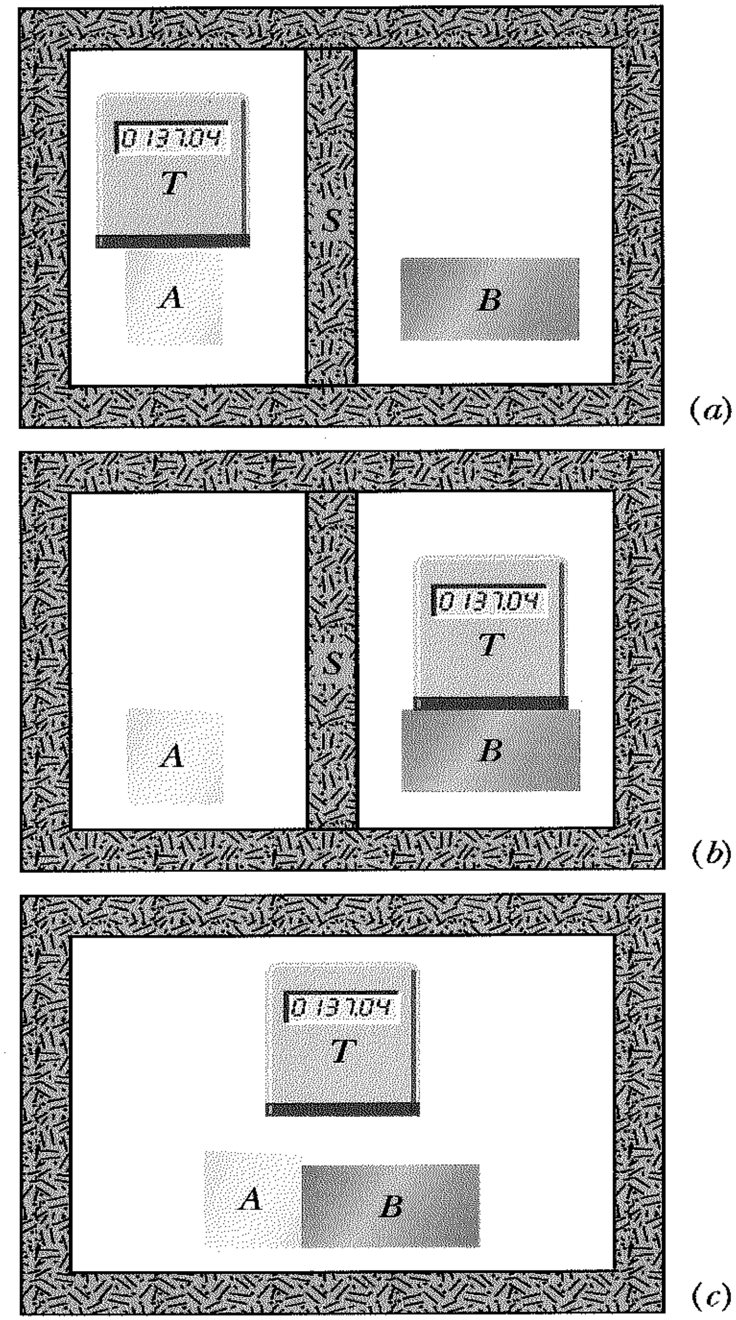
The Zeroth Law of Thermodynamics

- **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* <u>temperature</u>

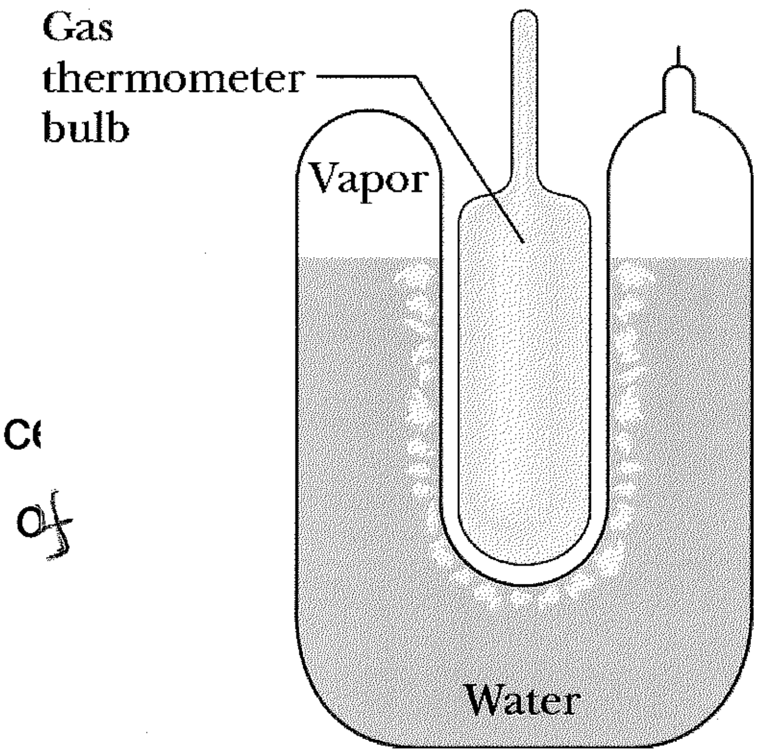


Measuring Temperature

- 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

$$T_3 = 273.16\ K$$



Celsius and Fahrenheit Scales

- Celsius scale: used worldwide

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

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

- Fahrenheit scale: used in United States

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

0° C => 32° F

10° C => 36.5 ° F

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

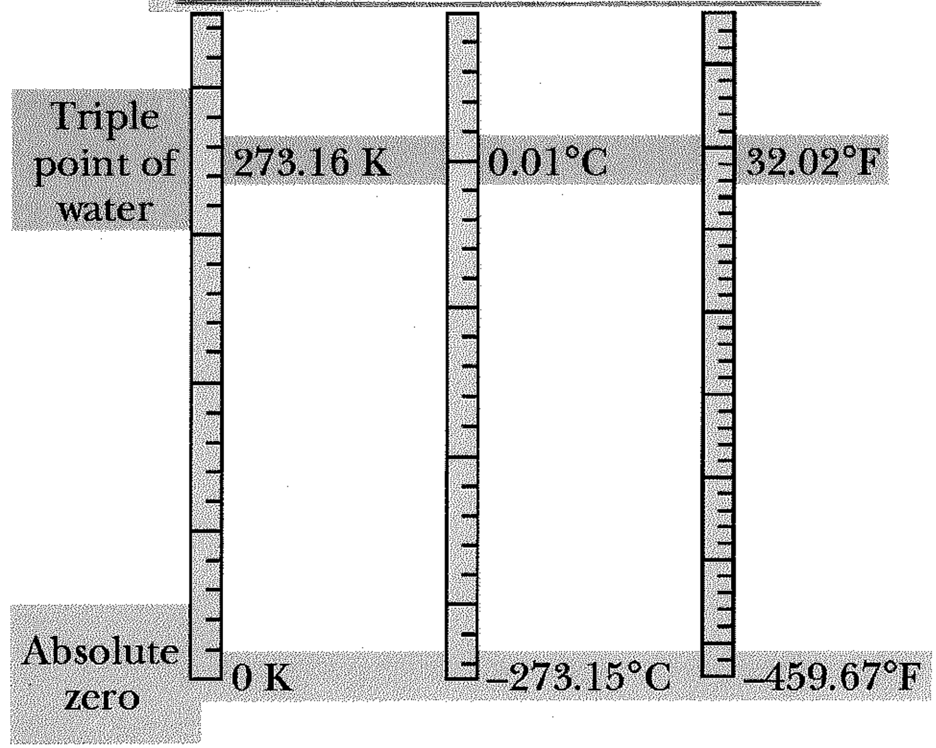
$T_C = \frac{5}{9}(T_F - 32°)$

$T_K = T°C + 273.15$

$T_K = \frac{9}{5}(T°F - 459.67)$

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



T = 5°F , T → °C = ?

25. ORGANIZE AND PLAN We convert °F to °C using:

$$T(^\circ C)=\frac{5}{9}\left(T(^\circ F)-32^\circ\right)$$

SOLVE $T(^\circ C)=\frac{5}{9}\left(5^\circ F-32^\circ\right)=-15^\circ C$

REFLECT 32°F corresponds to 0°C, the temperature at which water freezes.

"0" = ?

32. ORGANIZE AND PLAN We use the equations to convert from K and °C to °F, and set the temperature to 0 K:

$$T(\text{K}) = T(^\circ\text{C}) + 273.15$$

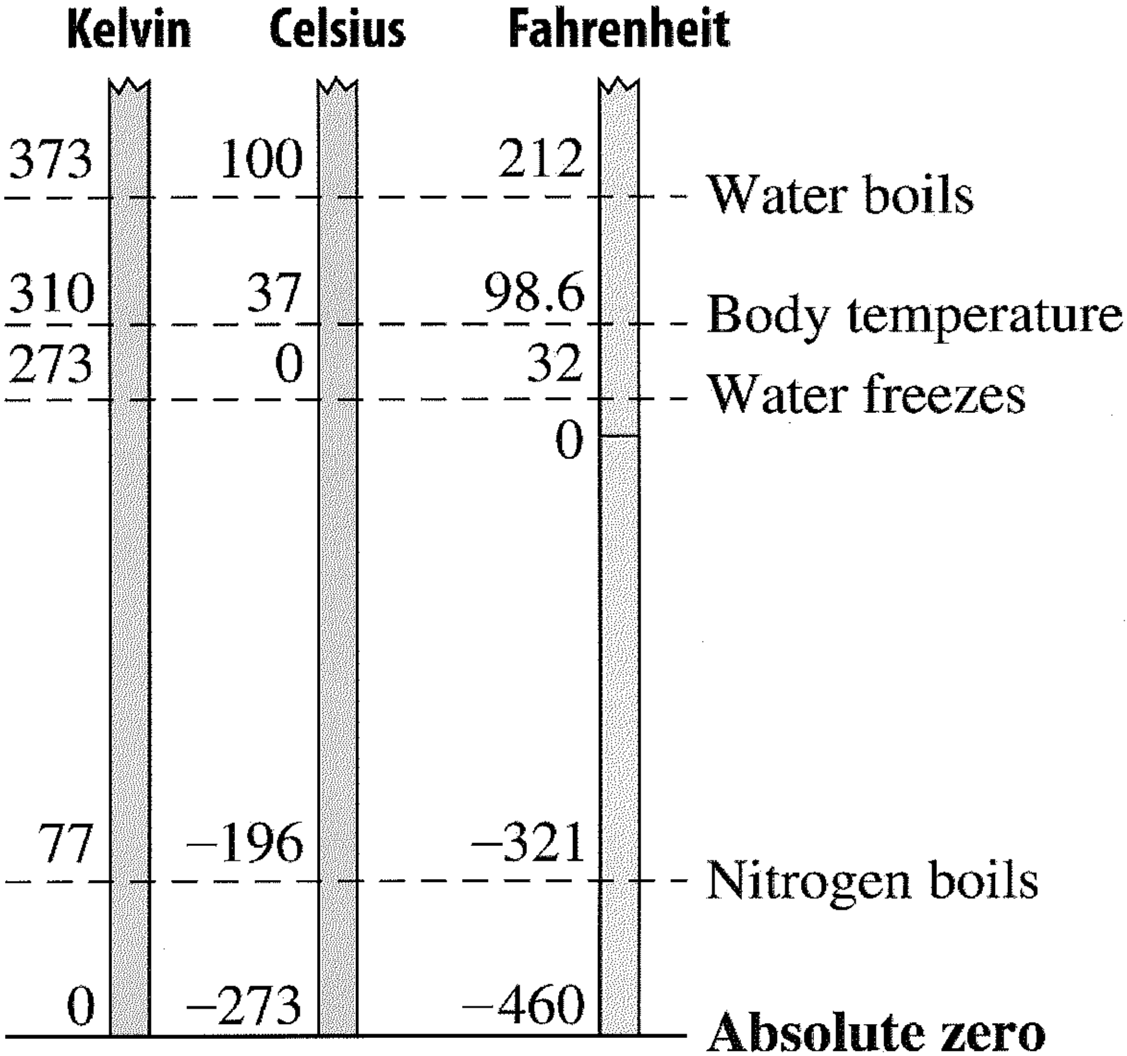
SOLVE

$$0\ \text{K} = T(^\circ\text{C}) + 273.15$$
$$T(^\circ\text{C})_0 = -273.15^\circ\text{C}$$

Temperature for storage of some delicate equipment is 78 K. Express this temperature in Celsius ?

$$T\ [K] = T\ ^{\circ}C + 273.15$$

$$\text{So } T\ ^{\circ}C = T\ [K] - 273.15 = -195.15\ ^{\circ}C$$



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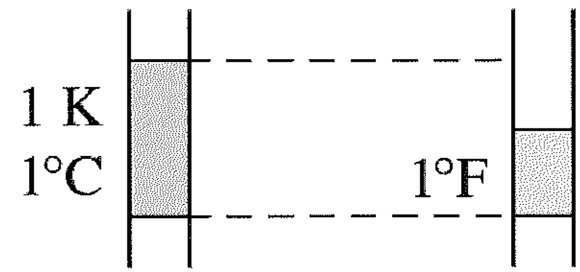


$$\frac{1\text{ K (or }1^\circ\text{C)}}{1^\circ\text{F}} = \frac{9}{5}$$

35. ORGANIZE AND PLAN For part (a), we use the equation to convert from °F to °C and set both sides of the equation equal by replacing the temperatures with a variable, i.e., x, and Solve for *x*. To answer (b), we use the equation to convert °C to K.

SOLVE

(a)

$$T(^\circ\mathrm{C}) = \frac{5}{9}\left(T(^\circ\mathrm{F}) - 32\right)$$

$$x = \frac{5}{9}(x - 32) = \frac{5}{9}x - \frac{5}{9}32$$

$$x - \frac{5}{9}x = -\frac{5}{9}32$$

$$x = -40$$

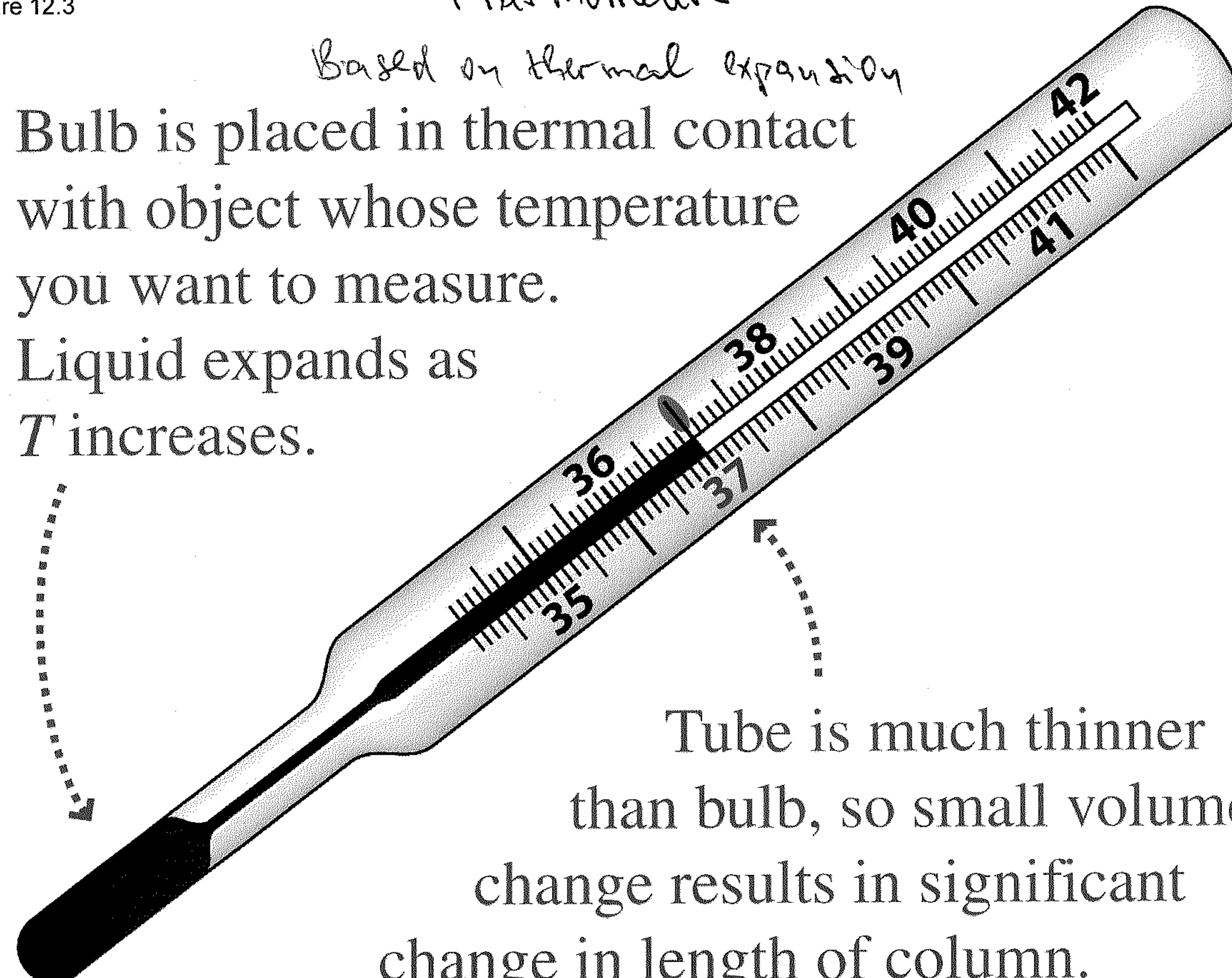
(b)

$$T(\mathrm{K}) = T(^\circ\mathrm{C}) + 273.15 = (-40^\circ\mathrm{C}) + 273.15 = 233.15\ \mathrm{K}$$

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.

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Measuring Temperature

- The Constant-Volume Gas Thermometer

  - Device to measure temperature (see Fig. 18-5 =>)

$$T = Cp \qquad p = p_0 - \rho g h$$

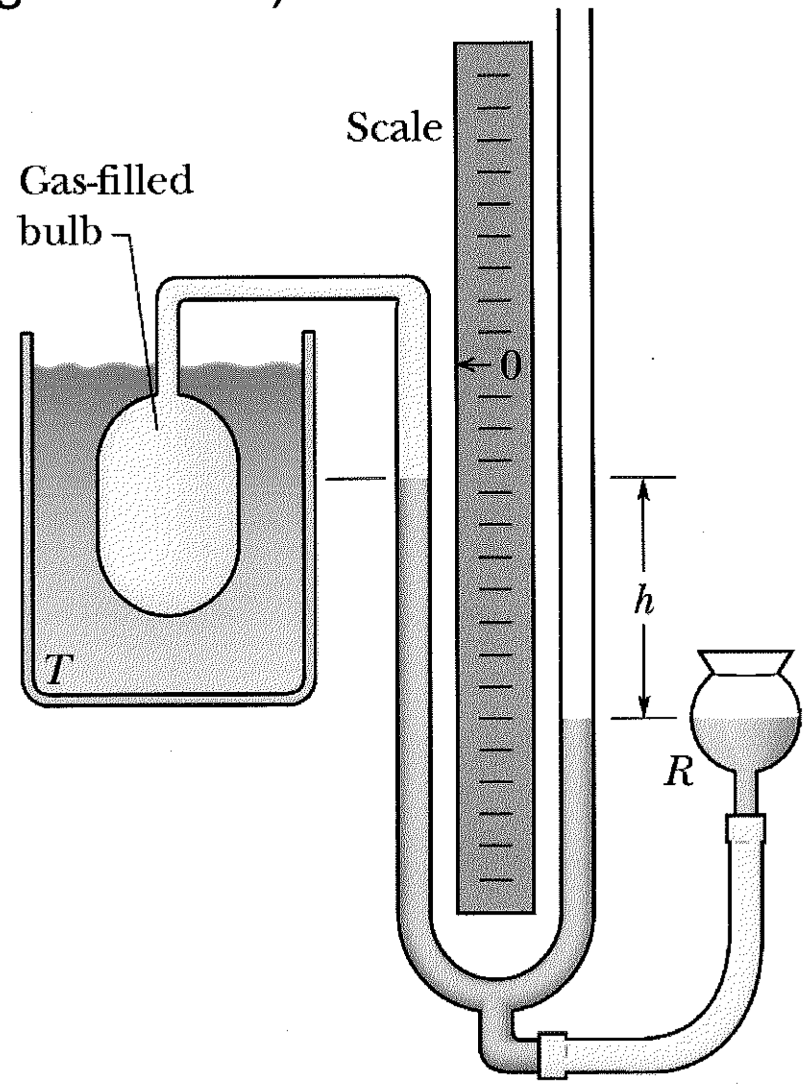
  - Reminder: units for pressure

$$1\,atm = 1.01 \cdot 10^5\,Pa = 760\,torr = 14.7\,lb/in.^2$$

  - At the triple point:

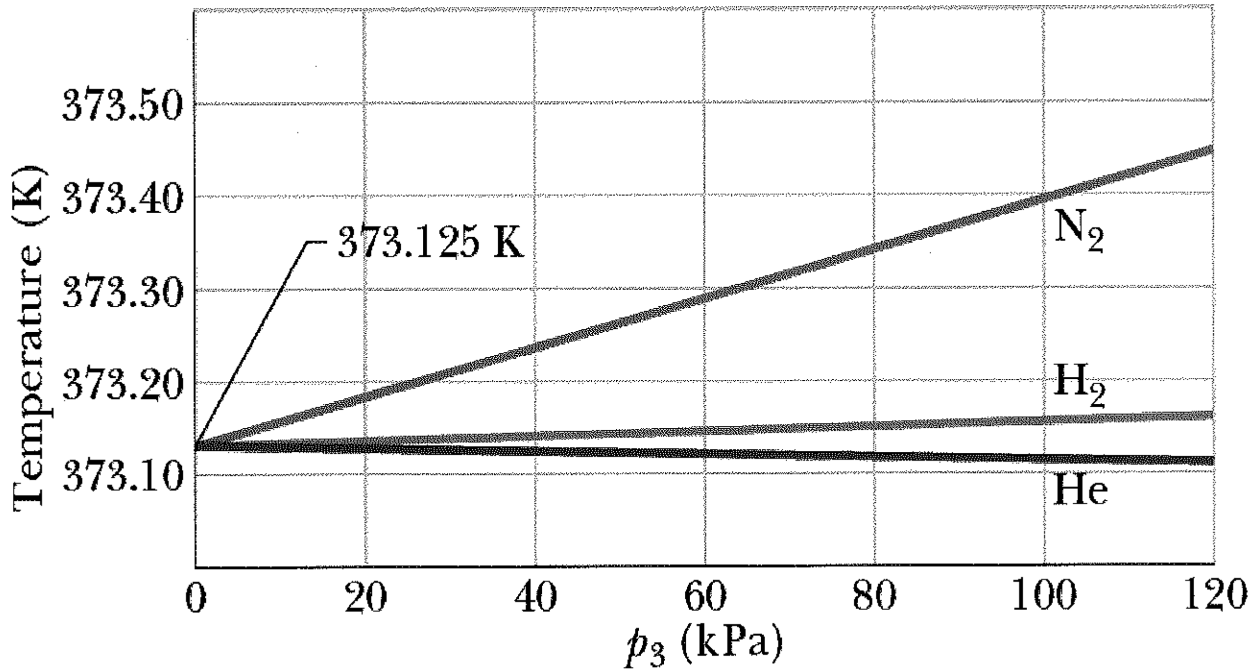
$$T_3 = Cp_3 \rightarrow \frac{T}{T_3} = \frac{p}{p_3}$$

$$T = T_3\left(\frac{p}{p_3}\right)$$



- Slight dependence on the gas density:
- Fig. 18-6

$$T = (273.16)\left(\lim_{m\to 0}\frac{p}{p_3}\right)$$

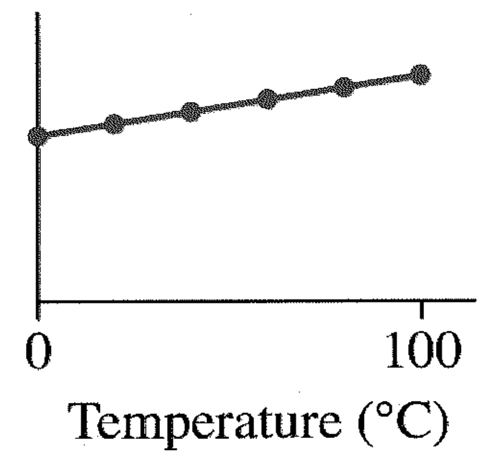


- Practical recipe to measure temperature: measure ratio (p/p3) twice and extrapolate to p3=0.
- *Ideal gas temperature*: measure by the constant-volume gas thermometer.

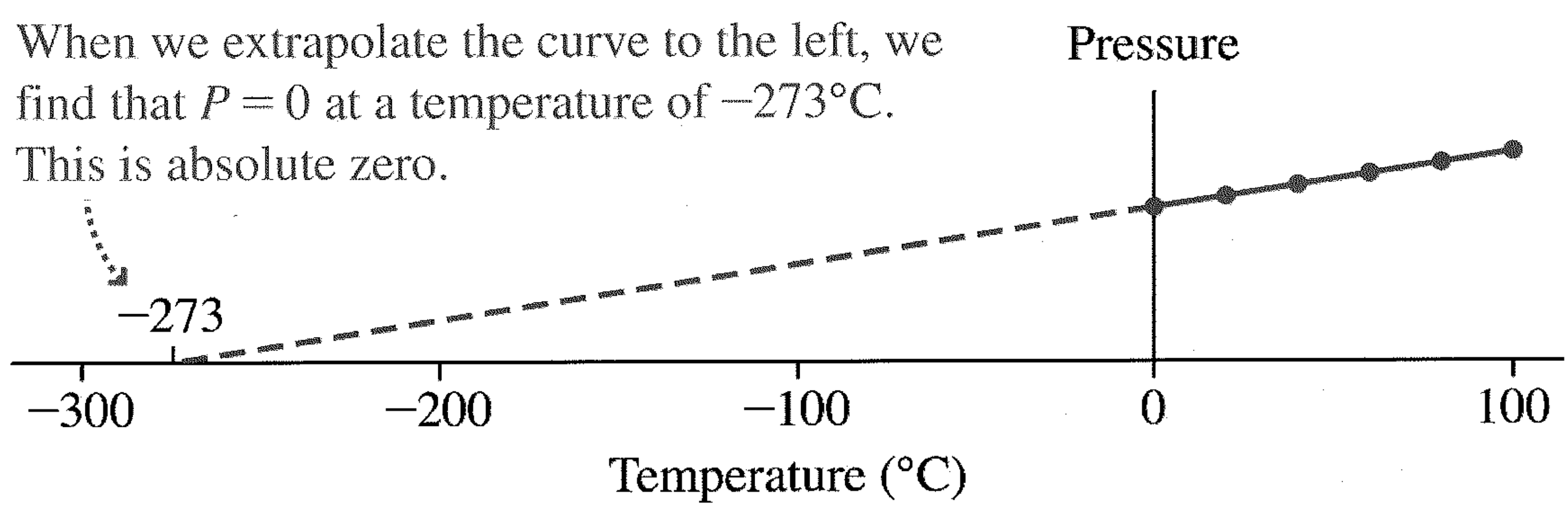
Figure 12.9

Gas Thermometers

V = const



(a)



(b)

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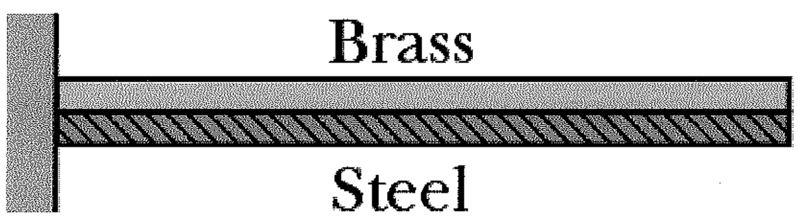
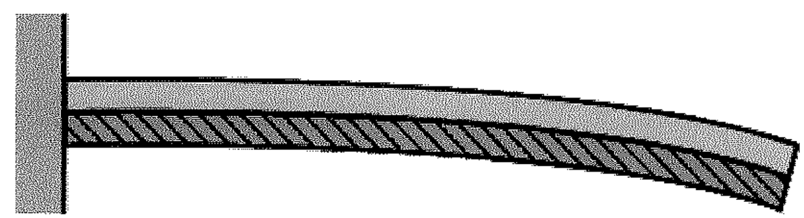
Thermal Expansion

- 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*)

- **Linear expansion**

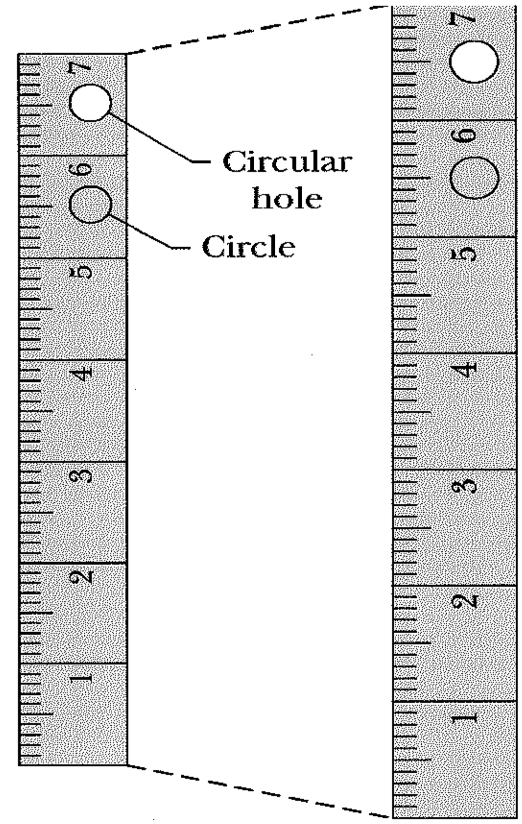
$$\Delta L = L_0 \alpha \Delta T$$

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

  - ***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



(a) (b)

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."

Table 12-1

TABLE 12.1 Thermal Expansion Coefficients*

Material	Coefficient of linear expansion ($°C^{-1}$)	Coefficient of volume expansion ($°C^{-1}$)
Solids		
Aluminum	2.4×10^{-5}	7.2×10^{-5}
Brass	2.0×10^{-5}	6.0×10^{-5}
Copper	1.7×10^{-5}	5.1×10^{-5}
Concrete	1.2×10^{-5}	3.6×10^{-5}
Glass (common)	4.0×10^{-6} to 9.0×10^{-6}	1.2×10^{-5} to 2.7×10^{-5}
Glass (Pyrex)	3.3×10^{-6}	9.9×10^{-6}
Lead	2.9×10^{-5}	8.7×10^{-5}
Quartz	4.0×10^{-7}	1.2×10^{-6}
Silver	1.9×10^{-5}	5.7×10^{-5}
Steel (typical)	1.2×10^{-5}	3.6×10^{-5}
Liquids		
Ethanol		7.5×10^{-4}
Glycerin		4.9×10^{-4}
Mercury		1.8×10^{-4}
Methanol		1.2×10^{-3}
Water (1°C)		-4.8×10^{-5}
Water (20°C)		2.1×10^{-4}
Water (50°C)		5.0×10^{-4}

*at 20°C unless otherwise noted.

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50 m steel at 20°C
L = ? 32°C and −10°C

37. **ORGANIZE AND PLAN** We use the equation for linear expansion, $\frac{\Delta L}{L} = \alpha \Delta T$, **solved** for ΔL, and with the expansion coefficient of steel, α, from Table 12.1, to calculate the change in length due to the different temperature. The temperature difference ΔT can be positive or negative. Then we add the change in length to the original length.

SOLVE

(a)

$$\Delta L = \alpha\ \Delta TL = \left(1.2\times10^{-5}\,{}^\circ\text{C}^{-1}\right)\times\left(12\,{}^\circ\text{C}\right)\times\left(50\text{ m}\right) = 0.0072\text{ m}$$

$$L\left(32\,{}^\circ\text{C}\right) = 0.0072\text{ m} + 50\text{ m} = 50.0072\text{ m}$$

(b)

$$\Delta L = \alpha\Delta TL = \left(1.2\times10^{-5}\,{}^\circ\text{C}^{-1}\right)\times\left(-30\,{}^\circ\text{C}\right)\times\left(50\text{ m}\right) = -0.018\text{ m}$$

$$L\left(-10\,{}^\circ\text{C}\right) = -0.018\text{ m} + 50\text{ m} = 49.982\text{ m}$$

REFLECT Using the tape at temperatures significantly different from 20°C can result in relevant measuring errors.

Boom 246 m $\Delta L = ?$ (40 °C → −20 °C)

38. ORGANIZE AND PLAN We use the equation for linear expansion, $\frac{\Delta L}{L} = \alpha \Delta T$, solved for ΔL, and with the expansion coefficient of steel, α, from Table 12.1.

SOLVE $\Delta L = \alpha \Delta T L = (1.2 \times 10^{-5}\,^{\circ}\mathrm{C}^{-1}) \times (60\,^{\circ}\mathrm{C}) \times (246\ \mathrm{m}) = 0.177\ \mathrm{m}$

REFLECT The building height differs by about 18 cm!

Booe  100 ml; 98 ml ethanol at 25°C | T = ? ; 98 ml -> 100 ml

44. ORGANIZE AND PLAN We use the equation for volume thermal expansion, $\frac{\Delta V}{V} = \beta\,\Delta T$, and solve for the higher temperature in ΔT. ΔV is given by the difference between the overflow volume and the fill volume.

SOLVE

$$\frac{\Delta V}{V} = \beta\,\Delta T = \beta\,(T_h - T_l) = \beta . T_h - \beta . T_l \;,\quad T_h = \frac{\Delta V}{V . \beta} + T_l$$

$$T_h = \frac{\Delta V}{V\beta} + T_l = \frac{(0.2\text{ ml})}{(98\text{ ml})\times(7.5\times10^{-4}\,°\text{C}^{-1})} + (25°\text{C}) = 27.72°\text{C}$$

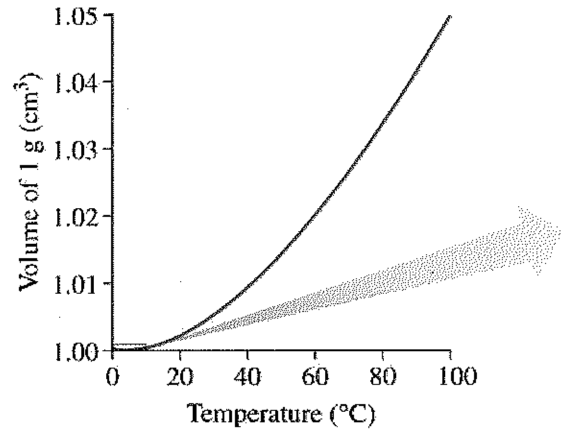
REFLECT In general, liquids have expansion coefficients about an order of magnitude higher than metals, resulting in relatively large volume changes for relatively small temperature changes.

Figure 12.6

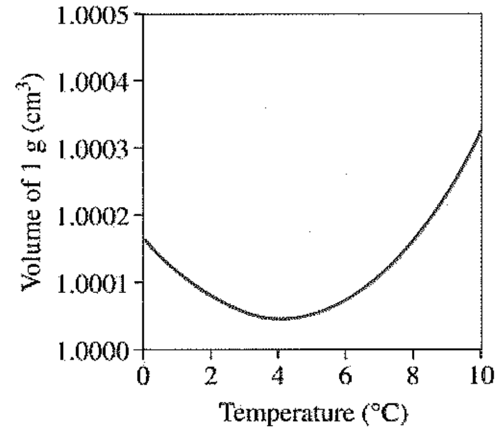
Thermal expansion of H_2O

Temperature (°C)	Volume of 1 g of water (cm^3)	Density (g/cm^3)
0	1.0002	0.9998
4	1.0000	1.0000
10	1.0003	0.9997
20	1.0018	0.9982
50	1.0121	0.9881
75	1.0258	0.9749
100	1.0434	0.9584

(a) Volume of 1 g of water as a function of temperature



(b) Large-scale graph of the volume of 1 g of water as a function of temperature



(c) Enlarged and rescaled detail of the lower-left end of the curve in (a)

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