PHYSICS 2: FLUID MECHANICS AND THERMODYNAMICS

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Chapter 2 Heat, Temperature, and the First Law of Thermodynamics

2.1. Temperature and the Zeroth Law of Thermodynamics

2.2. Thermal Expansion

2.3. Heat and the Absorption of Heat by Solids and Liquids

2.4. Work and Heat in Thermodynamic Processes

2.5. The First Law of Thermodynamics and Some Special Cases

2.6. Heat Transfer Mechanisms

Overview

- Thermodynamics that is one of the main branches of physics and engineering is the study and application of the thermal energy (commonly called the internal energy) of systems.
- These systems exist in various phases: solid, liquid and gas.
- Temperature is one of the central concepts of thermodynamics.
- Examples of the application of thermodynamics in our life are countless:
  - The heating of a car engine.
  - The proper heating and cooling of foods.
  - The transfer of thermal energy in an El Nino event.
  - The discrimination in temperature of patients between a benign viral infection and a cancerous growth.

Heat Transfer [Conduction, Convection, and Radiation]

https://www.youtube.com/watch?v=kNZi12OV9Xc&t=64s

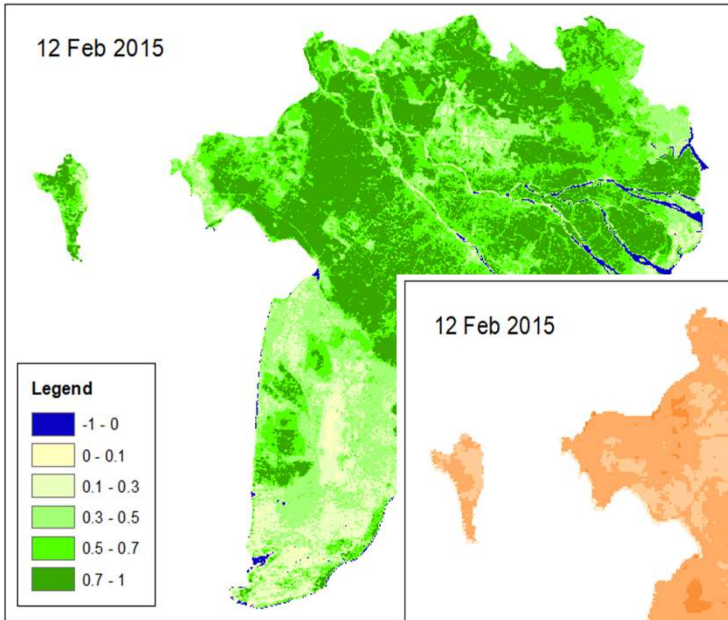
NASA MODIS-Terra Level 3 Thermal-IR 8-Day 4km Daytime SST V2019.0 (2000-2020)

https://www.youtube.com/watch?v=FpgdrAP-hNQ

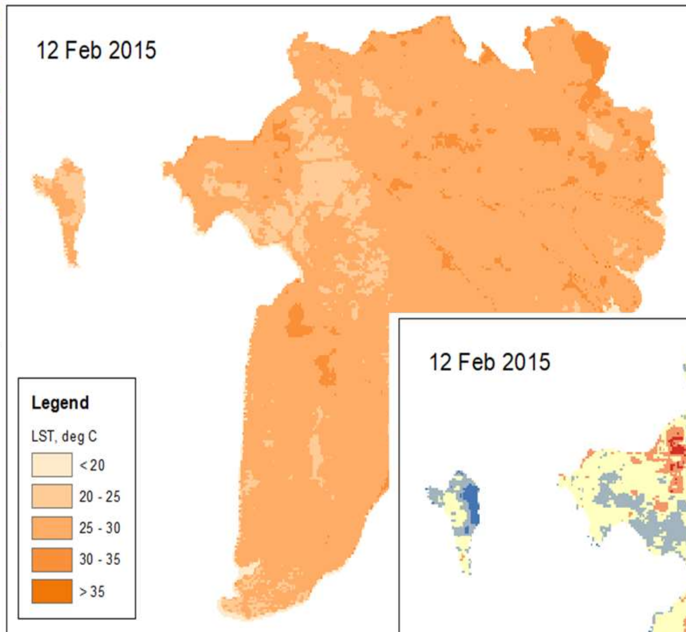
What are El Niño and La Niña?

https://oceanservice.noaa.gov/facts/ninonina.html

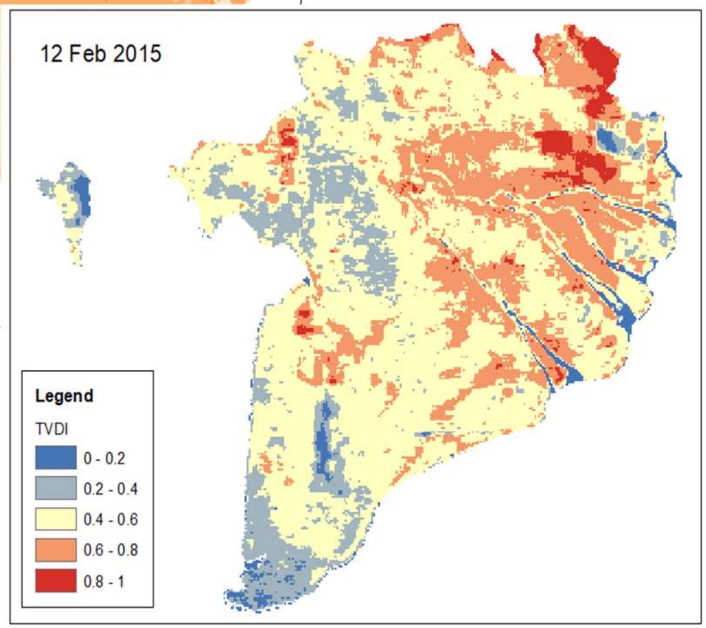
Spatiotemporal pattern of drought in the 2001 - 2015 dry seasons in the Mekong River Delta from MODIS satellite data



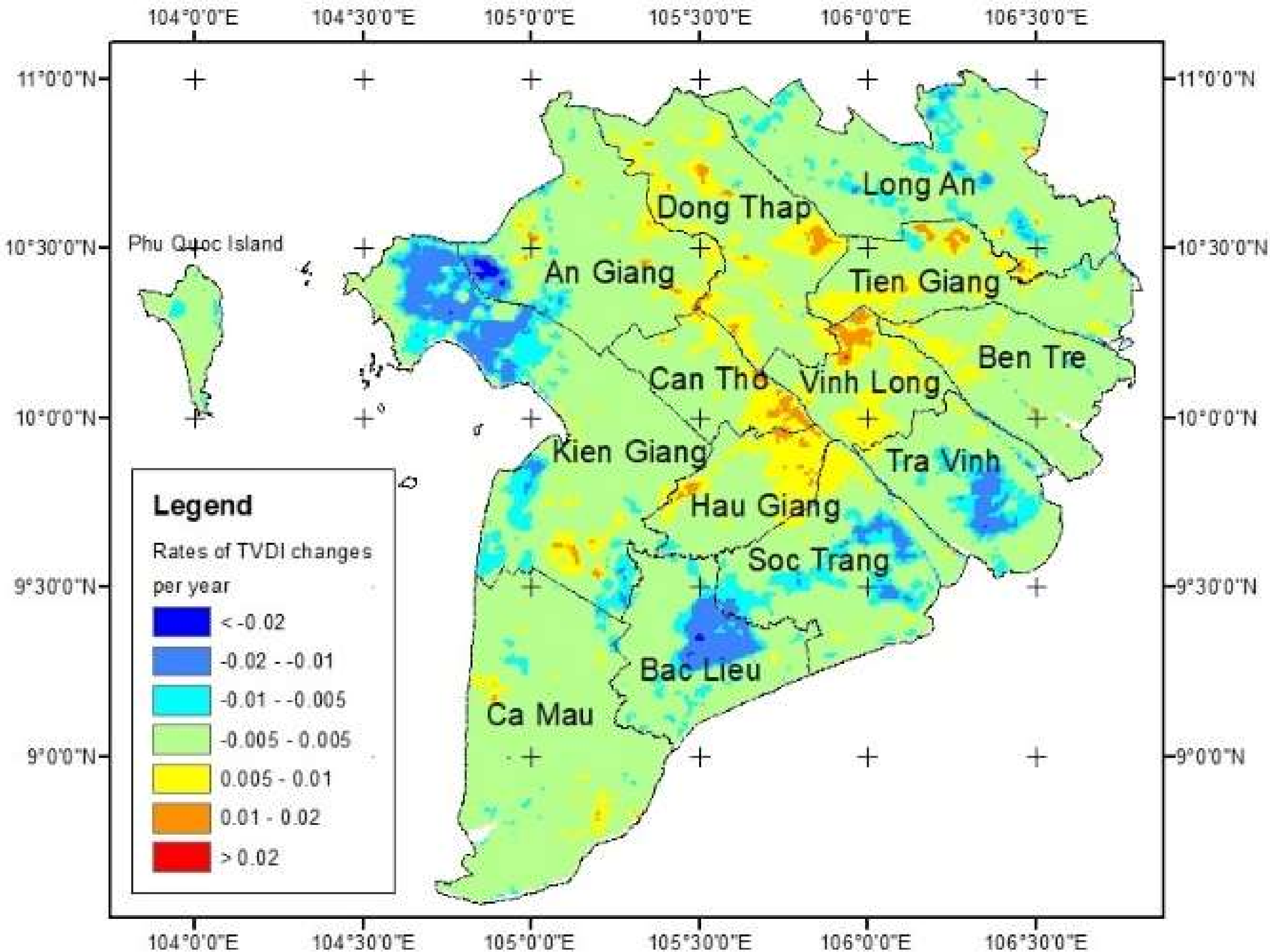
Normalized Different Vegetation Index (NDVI)



Land Surface Temperature (LST)



Drought Index (TDVI)

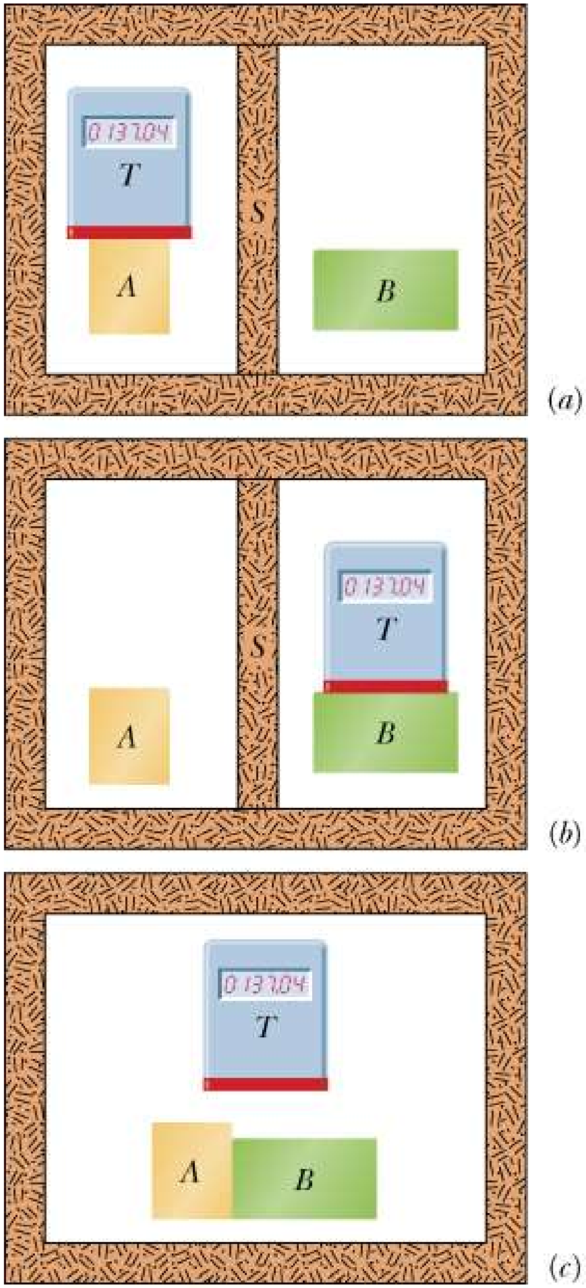


Phan et al., 2020

2.1. Temperature and the Zeroth Law of Thermodynamics

A. Temperature:

- Temperature is one of the seven SI base quantities. Unit: Kelvin
- The temperature of a body does have a lower limit of 0 K.
- The temperature of our Universe is about 3 K.



B. The Zeroth Law of Thermodynamics:

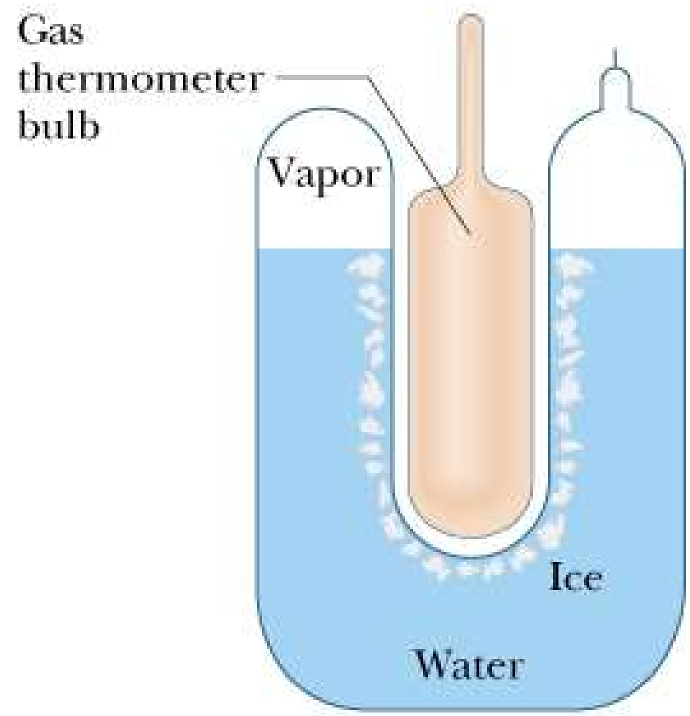
Thermal equilibrium is the condition under which two objects in thermal contact with each other exchange no heat energy. These two objects have the same temperature.

> If bodies A and B are each in thermal equilibrium with a third body T, then A and B are in thermal equilibrium with each other.

(T is a thermoscope, which is thermally sensitive)

C. Measuring Temperature:

- To set up a temperature scale, we need to select a standard fixed point and give it a standard fixed-point temperature.
- The triple point of water: Liquid water, solid ice, and water vapor can coexist in thermal equilibrium, at only one set of values of pressure and temperature. This triple point has been assigned a value of 273.16 K.



- The constant-Volume Gas Thermometer:
  - The temperature of any body in thermal contact with the bulb:

$$T = C\,p$$

- If we next put the bulb in a triple-point cell:

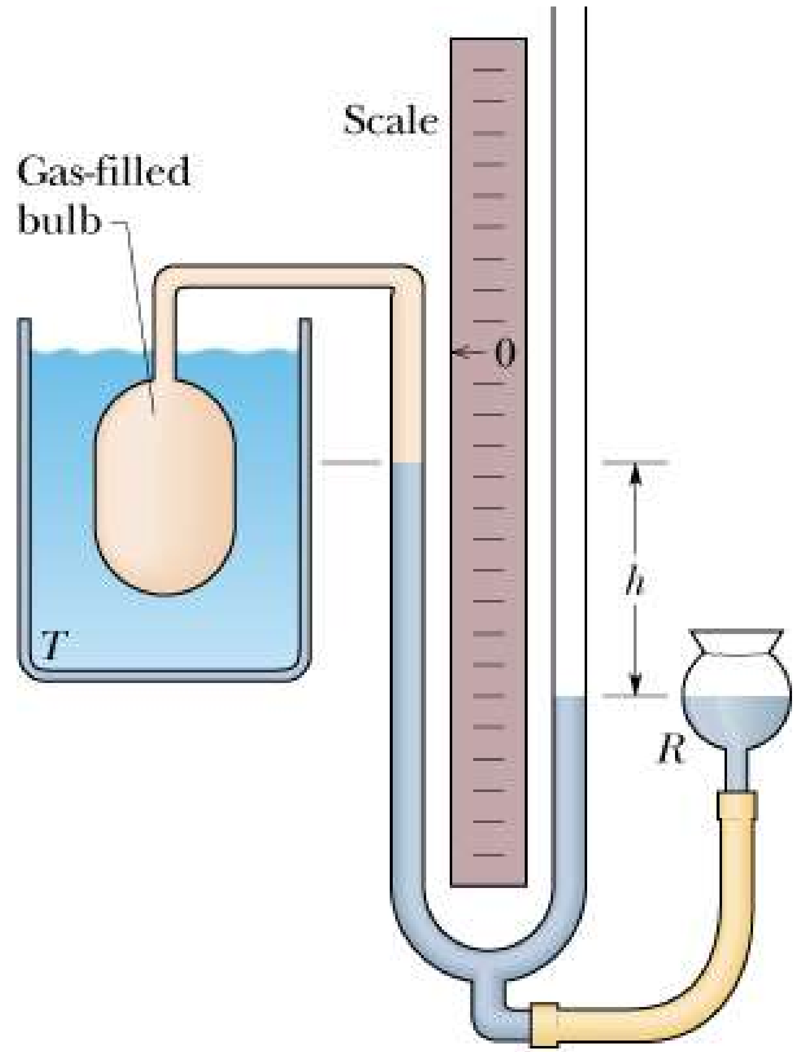
$$T_3 = C\,p_3$$

$$T = T_3\left(\frac{p}{p_3}\right) = 273.16 \times \left(\frac{p}{p_3}\right)\ (\mathrm{K})$$

T is measured in Kelvins,

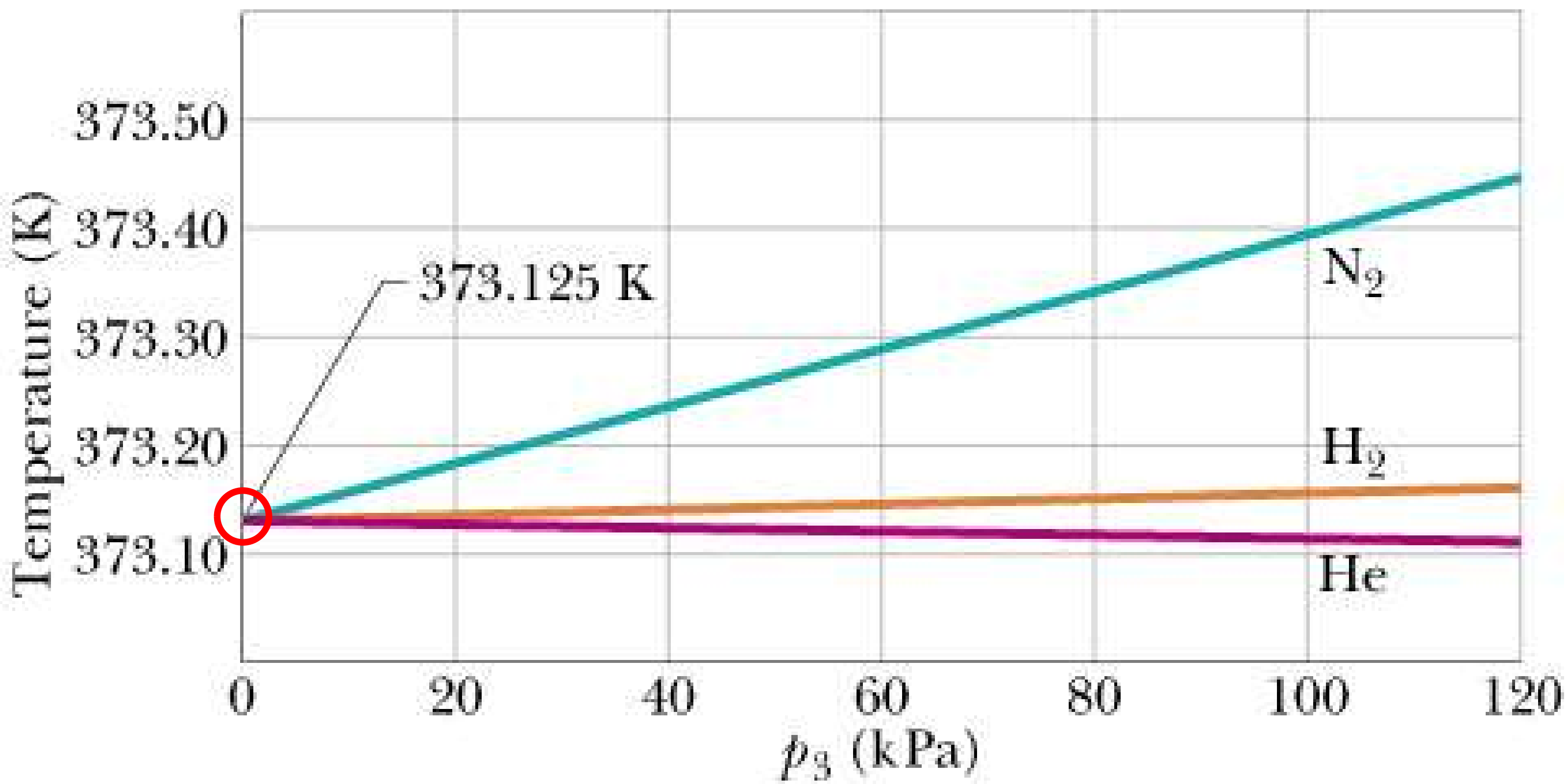
p_3 and p are the pressures of the gas at 273.16 K and the measured temperature, respectively.

→ T slightly depends on the nature of gas



- If very small amount of gas is used:

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



→ The boiling point of water nicely converge to a single point if very small amount of gas used

D. The Celsius and Fahrenheit Scales:

- The zero of the Celsius scale is computed by:

$$\boxed{T_C = T - 273.15^0}$$

- The relation between the Celsius and Fahrenheit (used in US) scales is:

$$\boxed{T_F = \frac{9}{5} T_C + 32^0}$$

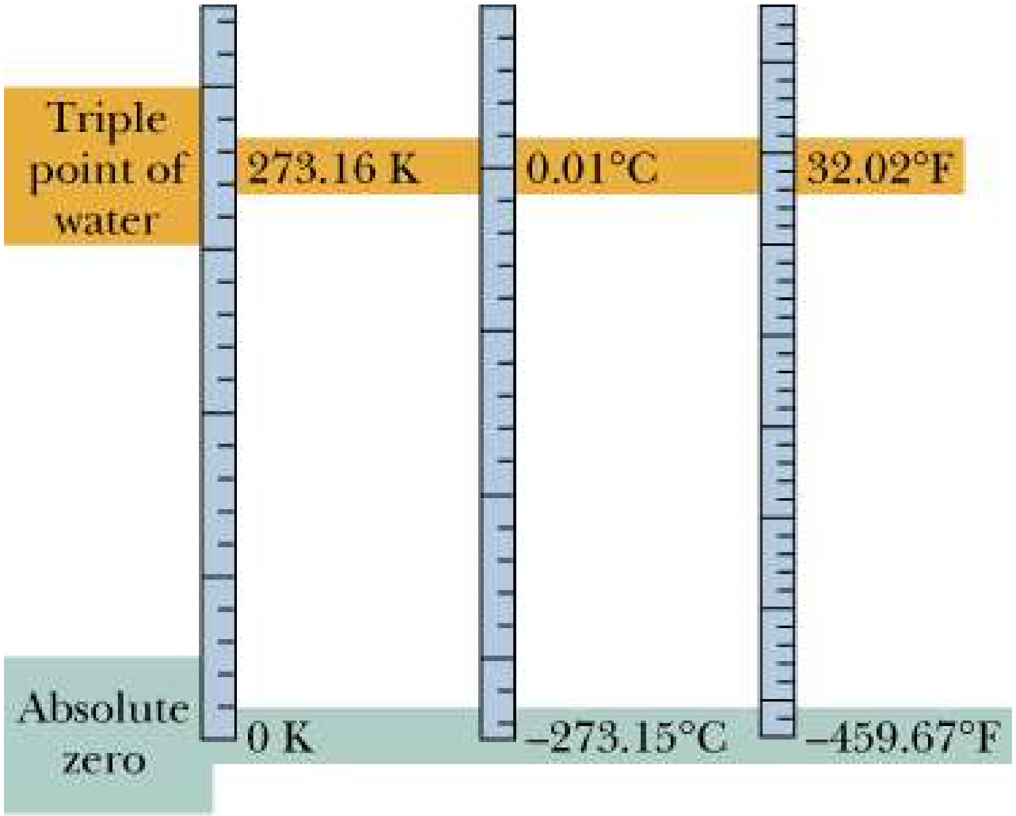
- 0^0 on the Celsius scale measures the same temperature as 32^0 on the Fahrenheit scale:

$$0^0C = 32^0F$$

- A temperature difference of 5 Celsius degrees is equivalent to a temperature difference of 9 Fahrenheit degrees:

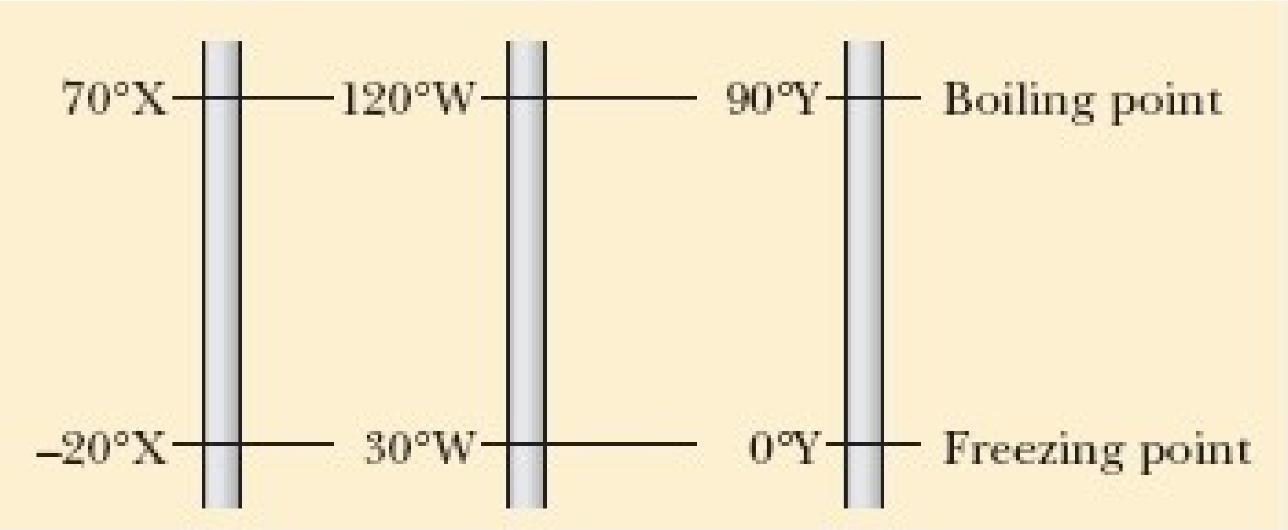
$$5\ C^0 = 9\ F^0$$

Note: the degree symbol that appears after C or F means temperature differences.

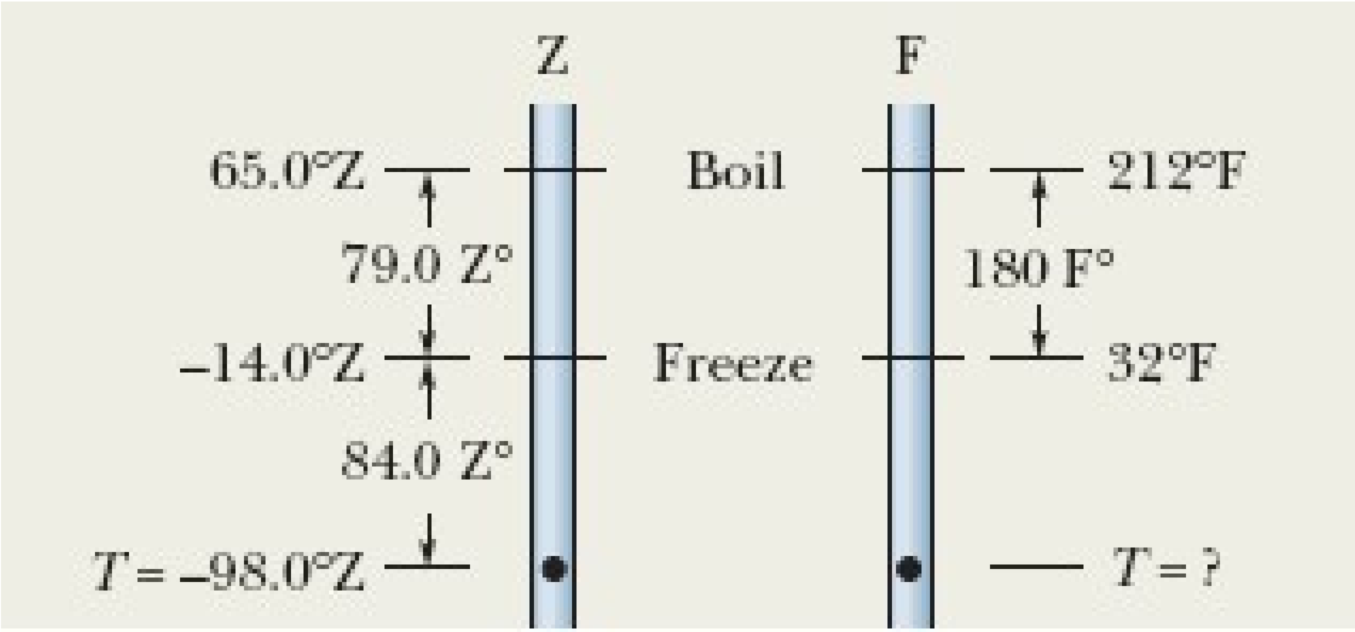


The Kelvin, Celsius, and Fahrenheit temperature scales are compared.

Checkpoint: The figure here shows three linear temperature scales with the freezing and boiling points of water indicated. (a) Rank the degrees on these scales by size, greatest first. (b) Rank the following temperatures, highest first: 50°X, 50°W, and 50°Y.



Sample: Suppose you come across old scientific notes that describe a temperature scale called Z on which the boiling point of water is 65.0°Z and the freezing point is –14.0°Z. To what temperature on the Fahrenheit scale would a temperature of T = –98.0°Z correspond? Assume that the Z scale is linear; that is, the size of a Z degree is the same everywhere on the Z scale.



S1: Difference in Z^0 and F^0 scales

$79\ Z^0 \rightarrow 180\ F^0$
$1\ Z^0 \rightarrow ? \quad = 180/79$

$84\ Z^0 \rightarrow 84*(180/79)\ F^0$

$T = 32^0F - 84Z^0.(180F^0/79Z^0)$
$T = -159.5\ ^0F$

S2: For linear scales, the relationship between X (^{0}Z) and Y (^{0}F) can be written by:

$$y = ax + b$$

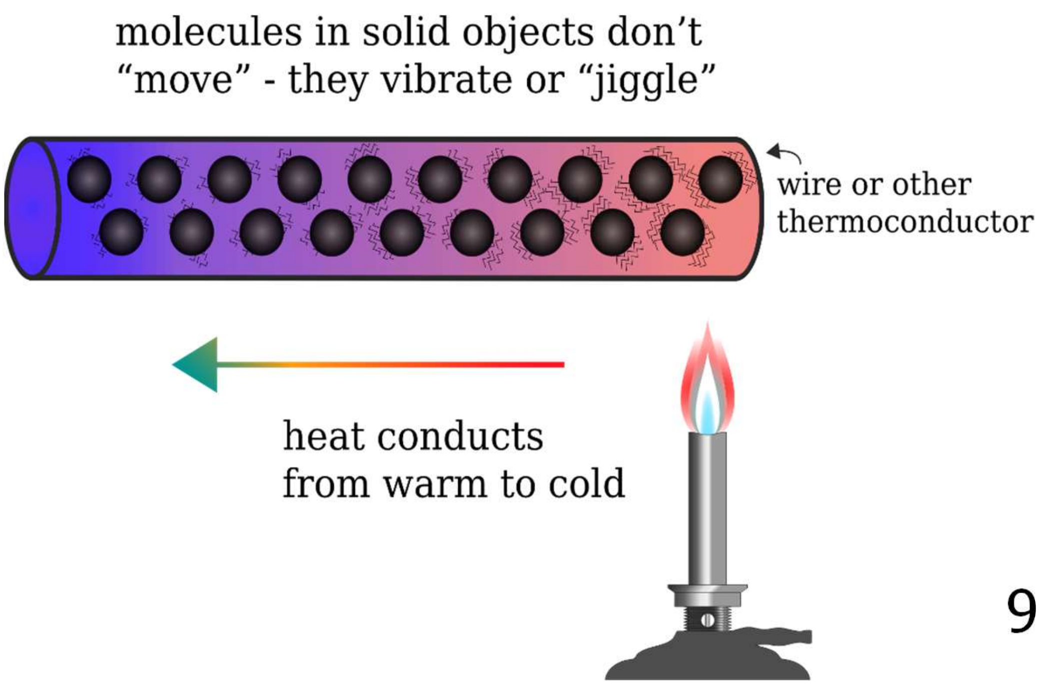
$212\ ^0F = a\ (65\ ^0Z) + b$
$32\ ^0F = a\ (-14\ ^0Z) + b$

$\rightarrow a = 2.3,\ b = 63.9$

$x = -98\ ^0Z \rightarrow y = T = 159.5\ ^0F$

2.2. Thermal Expansion

The change in volume of materials in response to a change in temperature is called thermal expansion. Under the microscopic view as the temperature increases, the particles (atoms and molecules) jiggle more rapidly, atoms are pushed away from each other, leading to an expansion.



When a Concorde flew faster than the speed of sound, thermal expansion due to the rubbing by passing air increased the aircraft’s length by about 12.5 cm. (V_s in air is 331.5 m/s at 0 °C)

There are three types of thermal expansion:

- Linear expansion: (solids)

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

α: the coefficient of linear expansion
unit: $1/C^0$ or 1/K

- Area expansion: (solids)

$$\Delta A = A\alpha_A\Delta T$$

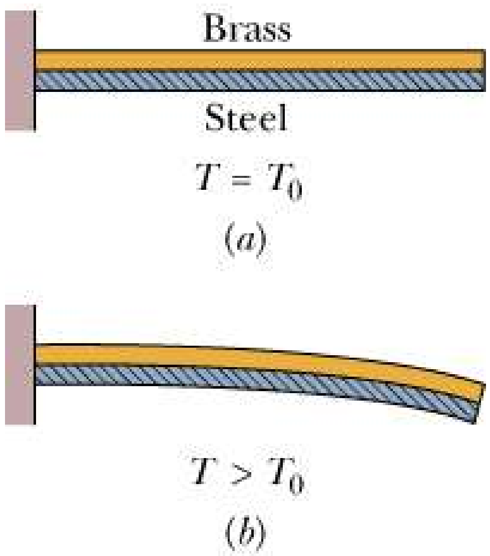
α_A: the coefficient of area expansion

For isotropic materials: $\alpha_A = 2\alpha$

Why are gaps left between railway tracks?

https://www.youtube.com/watch?v=9JuKqkZVgTU

A bimetal strip



→ Different amounts of expansion or contraction can produce bending

- Volume expansion: (solids and liquids)

$$\Delta V = V\beta\Delta T$$

β: the coefficient of volume expansion

For isotropic materials: $\beta = 3\alpha$

$$\beta = \frac{1}{V}\frac{\partial V}{\partial T} = \frac{1}{L^3}\frac{\partial L^3}{\partial T} = \frac{1}{L^3}\frac{\partial L^3}{\partial L}\frac{\partial L}{\partial T} = 3\frac{1}{L}\frac{\partial L}{\partial T} = 3\alpha$$

Special case of water:

+ $0^0C < T < 4^0C$: water contracts as the temperature increases.

+ $T > 4^0C$: water expands with increasing temperature.

+ The density of water is highest at about 4^0C.

Hydrogen Bonds

https://www.youtube.com/watch?v=RSRiywp9v9w

Table 18-2 Some Coefficients of Linear Expansion[a]

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

Question: The initial length L, change in temperature ΔL of four rods are given in the following table. Rank the rods according to their coefficients of thermal expansion, greatest first.

Rod	L (m)	ΔT (^{0}C)	ΔL (10^{-4}m)
a	2	10	4
b	1	20	4
c	2	10	8
d	4	5	4

Problem 10. An aluminum flagpole is 33m high. By how much does its length increase as the temperature increases by 15 C^0?

α = $23 \times 10^{-6}/C^0$ is the coefficient of linear expansion of aluminum (Table 18-2).

For a linear expansion:

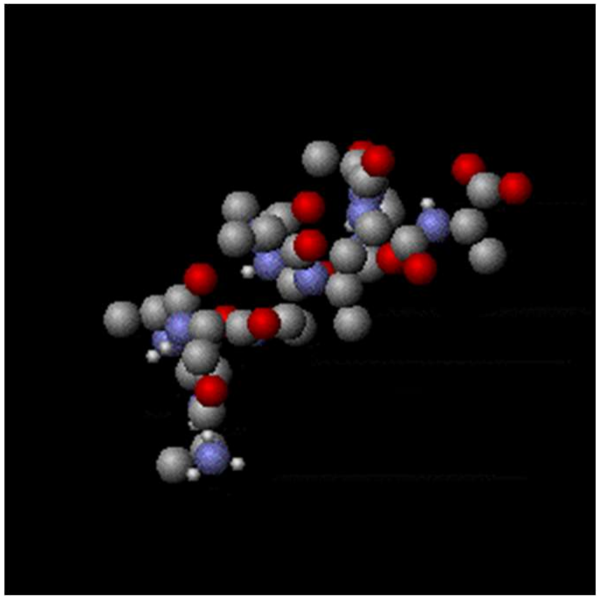
$$\Delta L = L\alpha\Delta T = 33 \times 23 \times 10^{-6} \times 15 = 0.011\,(m)$$

$$\Delta L = 1.1\,\text{cm}$$

2.3. Heat and the Absorption of Heat by Solids and Liquids

A. Temperature and Heat

Recall: Thermal energy is an internal energy that consists of the kinetic and potential energies associated with the random motions of the atoms, molecules, and other microscopic bodies within an object.



Thermal motion of a segment of protein alpha helix.

Experiment: Leave a cup of hot coffee in a cool room → the temperature of the cup will fall until it reaches the room temperature.

Heat (symbolized **Q**) is the energy transferred between a system and its environment because of a temperature difference that exists between them.

- $T_S>T_E$: energy transferred from the system to the environment, $Q<0$.

  $T_S<T_E$: system ← environment, $Q>0$.

  $T_S=T_E$: no transferred energy, $Q=0$.

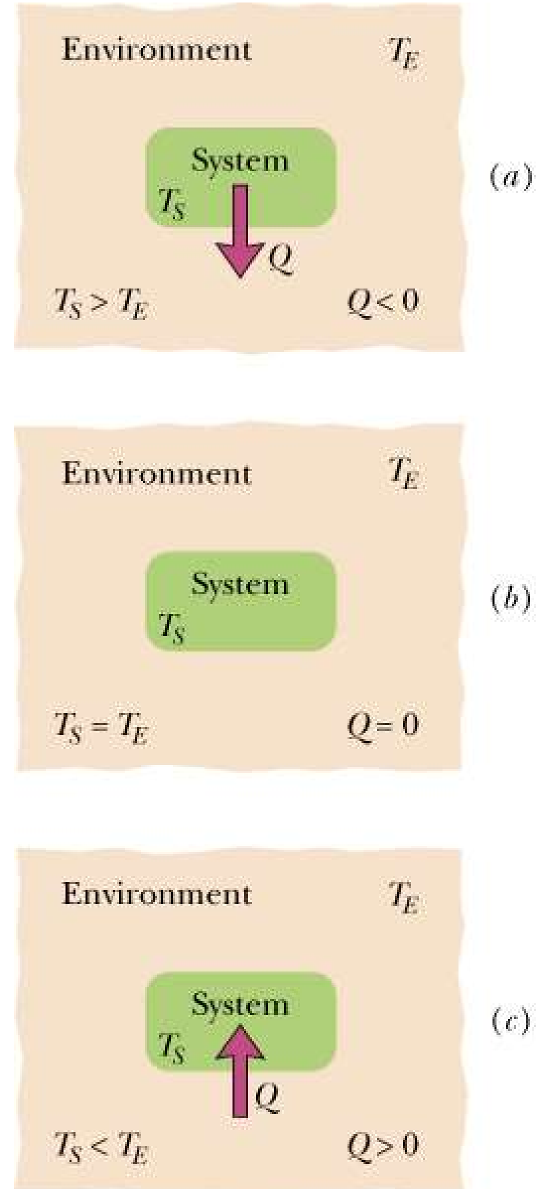
<u>Unit:</u> - SI: joule (J);

- CGS: erg, 1 erg=1 $g.cm^2/s^2$

  10^7 ergs = 1 joule

- Calorie (cal): the amount of heat is needed to raise the temperature of 1 g of water from 14.5^0C to 15.5^0C.

  1 cal = 4.1868 J; 1 food calorie = 1 kcal



B. The Absorption of Heat by Solids and Liquids

B1. Heat capacity: The heat capacity **C** of an object is the amount of energy needed to raise the temperature of the object by 1 degree.

$$Q = C\,\Delta T = C\,(T_f - T_i)$$

T_f and T_i are the final and initial temperatures of the object, respectively.

Unit: J/K or J/C^0; or cal/K or cal/C^0

B2. Specific Heat: The specific heat **c** of a material is the heat capacity of the material per unit mass.

$$Q = cm\,\Delta T = cm\,(T_f - T_i)$$

m: the mass of the object

Unit: $\dfrac{\text{cal}}{\text{g}\,\text{C}^0}$ or $\dfrac{\text{J}}{\text{kg}\,\text{K}}$

B3. Molar Specific Heat:

Why do we need to use the mole? In many instances, the mole is the most convenient unit for specifying the amount of a substance:

$$\boxed{1 \text{ mol} = 6.02 \times 10^{23} \text{ elementary units}}$$

Elementary unit: atom or molecule

Examples:

1 mol of aluminum (Al) means 6.02×10^{23} atoms

1 mol of aluminum oxide (Al_2O_3) means 6.02×10^{23} molecules

→ The molar specific heat is the heat capacity per mole.

B4. Heats of transformation:

- Phase change: When heat is absorbed or released by a solid, liquid, or gas, the **temperature** of the sample **does not change** but the **sample** may **change** from one phase (or state) to another.
- Three common states of matter: solid, liquid, gas (vapor).

- melting: solid → liquid; freezing is the reverse of melting
- vaporizing: liquid → gas (vapor); condensing is the reverse of vaporizing
- The amount of energy per unit mass that is transferred as heat when a sample of mass m completely undergoes a phase change is called the heat of transformation **L**:

$$Q = Lm$$

Q is also called "latent heat";

L: specific latent heat

Latent means "hidden"

- Phase change from liquid to gas: the heat of vaporization L_V (or specific latent heat of vaporization)
- Phase change from solid to liquid: the heat of fusion L_F (or specific latent heat of fusion)

Table 18-3 Some Specific Heats and Molar Specific Heats at Room Temperature

Substance	Specific Heat $\frac{cal}{g \cdot K}$	Specific Heat $\frac{J}{kg \cdot K}$	Molar Specific Heat $\frac{J}{mol \cdot K}$
Elemental Solids			
Lead	0.0305	128	26.5
Tungsten	0.0321	134	24.8
Silver	0.0564	236	25.5
Copper	0.0923	386	24.5
Aluminum	0.215	900	24.4
Other Solids			
Brass	0.092	380	
Granite	0.19	790	
Glass	0.20	840	
Ice (–10°C)	0.530	2220	
Liquids			
Mercury	0.033	140	
Ethyl alcohol	0.58	2430	
Seawater	0.93	3900	
Water	1.00	4187	

Table 18-4 Some Heats of Transformation

	Melting		Boiling	
Substance	Melting Point (K)	Heat of Fusion L_F (kJ/kg)	Boiling Point (K)	Heat of Vaporization L_V (kJ/kg)
Hydrogen	14.0	58.0	20.3	455
Oxygen	54.8	13.9	90.2	213
Mercury	234	11.4	630	296
Water	273	333	373	2256
Lead	601	23.2	2017	858
Silver	1235	105	2323	2336
Copper	1356	207	2868	4730

Sample: (a) How much heat must be absorbed by ice of mass m=720 g at -10^{0}C to take it to liquid state at 15^{0}C? (b) If we supply the ice with a total energy of only 210 kJ (as heat), what then are the final state and temperature of the water?

(a) Key idea: heating process from -10^{0}C to 0^{0}C, then melting of all the ice, and finally heating of water from 0^{0}C to 15^{0}C.

- First, we compute the heat Q_1 needed to increase the ice temperature from -10^{0}C to the melting point of water (0^{0}C):

$$Q_1 = c_{ice} m \left(T_f - T_{init}\right) \rightarrow \quad Q_1 \approx 15.98 \text{ kJ}$$

c_{ice}: the specific heat of ice, 2220 J kg^{-1} K^{-1} (see Table 18-3)

- Second, the heat Q_2 is needed to completely melt the ice:

$$Q_2 = L_F m \qquad \rightarrow \quad Q_2 \approx 239.8 \text{ kJ}$$

L_F: the heat of fusion of ice, 333 kJ kg^{-1} (see Table 18-4)

- Finally, the heat Q_3 is needed to increase the liquid water of 0^0C to 15^0C:

$$Q_3 = c_{liquid} m (T_f' - T_{init}) \rightarrow Q_3 \approx 45.25 \text{ kJ}$$

c_{liquid}: the specific heat of water, 4190 J kg^{-1} K^{-1} (see Table 18-3)

(b) When we supply the ice with a total energy of only 210 kJ (as heat):

$$Q_1 < Q_{supply} < Q_1 + Q_2$$

- The final state is a mixture of ice and liquid, the mass of water m_{water} (=the mass of melted ice) is:

$$m_{water} = \frac{Q_{supply} - Q_1}{L_F} \rightarrow m_{water} \approx 583 \text{ g}$$

- The mass of remaining ice: 137 g
- The temperature of the mixture is 0^0C

Homework:

Problems 2, 3, 5, 6, 11, 15, 19, 21, 29, 30, 32, 35, 36, 37, 38, 39, 40 (in Chapter 18, textbook)