Physics 262/266

George Mason University

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Course Info

http://complex.gmu.edu/www-phys/phys262/

First 5 weeks: Thermodynamics (Ch 17-20) **vol.1** (PHYS 262 & 266)

Mid 5 weeks: Optics (Ch 33-36) **vol. 2** (PHYS 262)

Last 5 weeks: Modern Physics (Ch 37-42) **vol. 3** (PHYS 262)
→Relativity
→Quantum Mechanics

Chapter 17: Temperature & Heat

Topics for Disscusion

- thermometers and temperature scales
- absolute zero and the Kelvin scale
- meaning of thermal equilibrium
- thermal expansion
- meaning of heat
- calorimetry calculations
- mechanisms of heat transfer

Description of Physical Systems

microscopic	macroscopic
→ properties of *atoms/molecules* that make up the system	→ *bulk* properties of the system
→ not directly associated with sense perceptions	→ directly associated with sense perceptions

Description of Physical Systems

microscopic

- → variables:

  $\vec{\mathbf{x}},\vec{\mathbf{v}},\vec{\mathbf{a}},\vec{\mathbf{p}},KE,PE,\ldots$

- → Theory: "Classical/Quantum Mechanics"
- Newton's Eqs,
- Maxwell's Eqs,
- Schrodinger's Eq (later)

macroscopic

- → variables:

  $T,P,V,U,S,\ldots$

- → Theory: "Thermodynamics"
- 0^{th} Law of Therm.
- 1^{st} Law of Therm.
- 2^{nd} Law of Therm.

"Statistical Mechanics"

(e.g. Kinetic Theory)

Temperature (T)

Physics definition: average KE of molecules (more on this next chapter)

Common usage: a measure of “hot” & “cold”

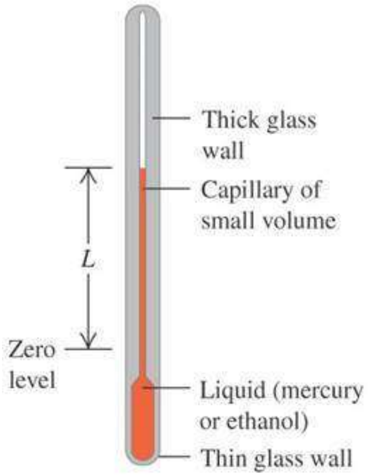
Physical changes associated with ΔT:

- Most materials expand when heated
- Pressure of gas (in a closed container) ↑ with ↑ T
- Electrical resistance changes with T
- Materials radiate at different λ at different T
- State of matter change with T

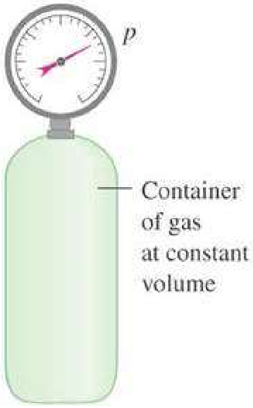
  Ice ←→ water ←→ steam

Measuring Temperature/Thermometer

(a) Changes in temperature cause the liquid's volume to change.



(b) Changes in temperature cause the pressure of the gas to change.



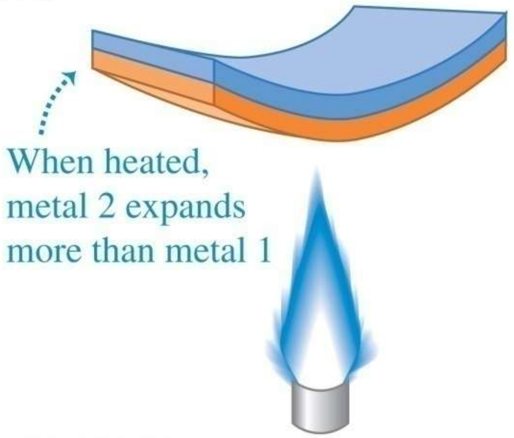
A small amount of liquid will typically increase in volume as temperatures rise. Mercury was chosen "early on" because it's dense; a small volume can record a large temperature range.

The pressure of a fixed volume of gas will rise if temperature rises.

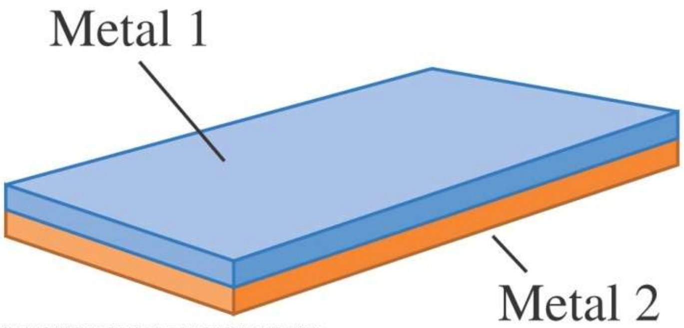
Measuring Temperature/Thermometer

Another commonly used measuring device relies on the *differential expansion* of a bimetal strip.

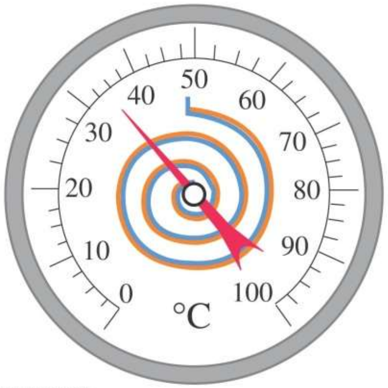
The strip bends when its temperature is raised.



A bimetallic strip

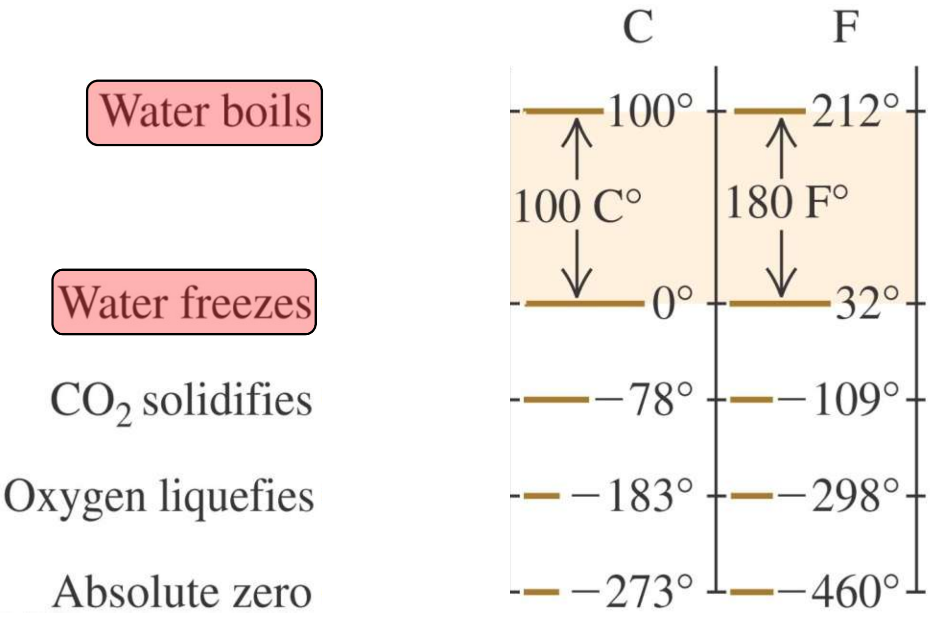


A bimetallic strip used in a thermometer



D bimetal strip
D infrared sensor

Temperature Scales

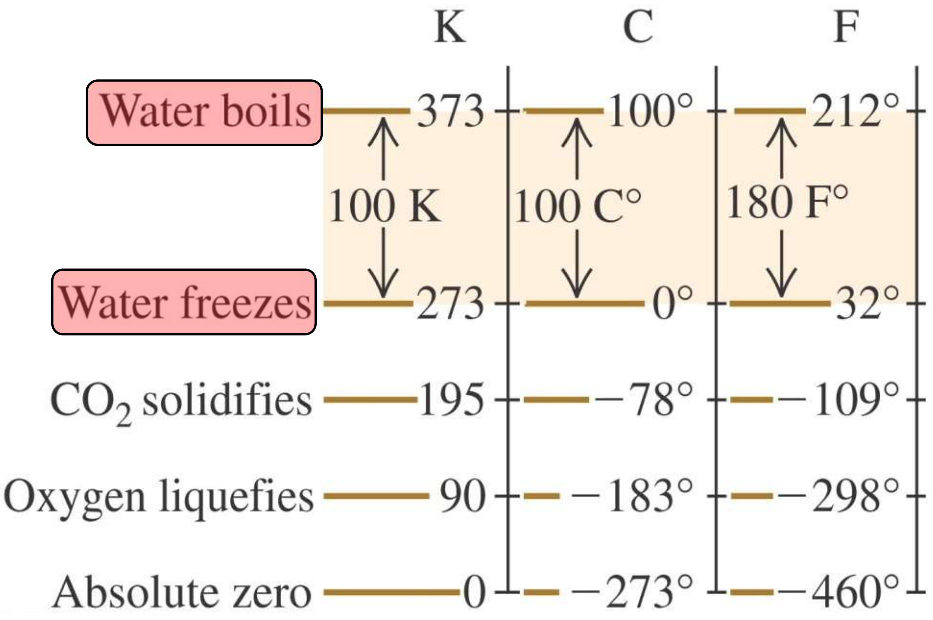


Celsius (°C) & Fahrenheit (°F) are traditionally defined with two readily reproducible reference states:

Freezing point & *Boiling* point of water at 1 atm.

$$\begin{cases} T_C = \frac{5}{9}\left[T_F - 32^o\right] \\ T_F = \frac{9}{5} T_C + 32^o \end{cases}$$

Temperature Scales



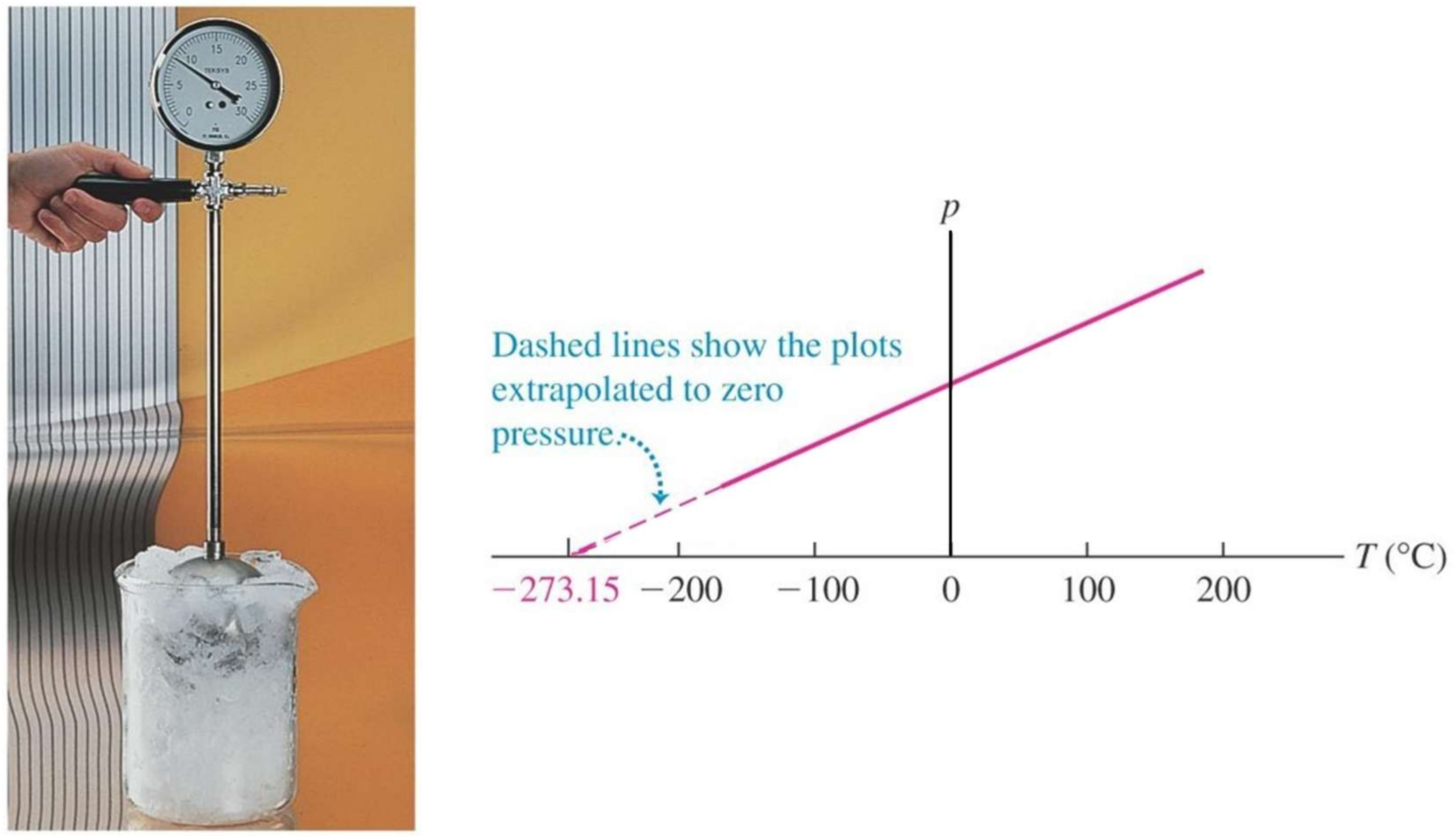
Celsius (°C) & Fahrenheit (°F) are traditionally defined with two readily reproducible reference states:

Freezing point & *Boiling* point of water at 1 atm.

(new)

$$\begin{cases} T_C = \frac{5}{9}\left[T_F - 32^o\right] \\ T_F = \frac{9}{5} T_C + 32^o \end{cases}$$

Absolute Zero and the Kelvin Scale (K)



(a) A constant-volume gas thermometer

(b) Graphs of pressure versus temperature at constant volume for three different types and quantities of gas

Dashed lines show the plots extrapolated to zero pressure.

A Gas Thermometer with sufficiently diluted gas (~Ideal Gas)

Absolute Zero and the Kelvin Scale (K)

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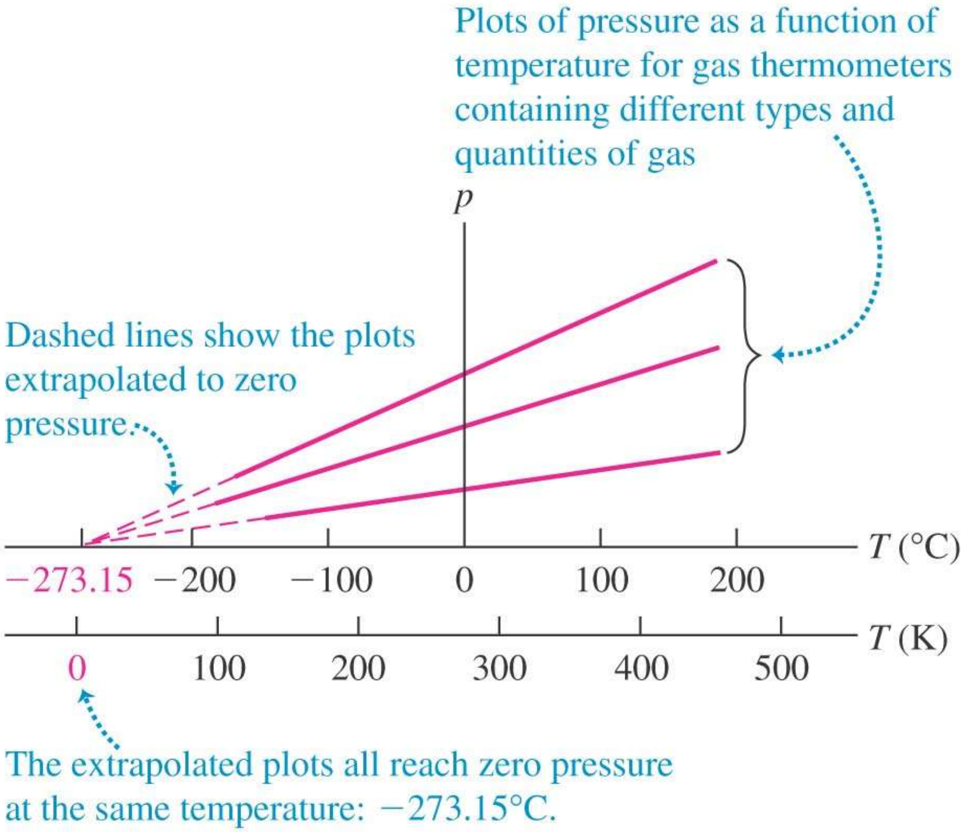


Plots of pressure as a function of temperature for gas thermometers containing different types and quantities of gas

Dashed lines show the plots extrapolated to zero pressure.

The extrapolated plots all reach zero pressure at the same temperature: −273.15°C.

A Gas Thermometer with sufficiently diluted gas (~Ideal Gas)

Absolute Zero and the Kelvin Scale (K)

Important Experimental Observations:

1. P vs. T relationship is linear for *all* dilute gases.
2. All curves extrapolate to a *single* zero point with zero pressure.

These imply…

→ There exists a **unique** "absolute zero" reference point and one can define an "absolute" temperature scale with it.

At this absolute zero point,

$$T_C = -273.15\ {}^oC$$

Kelvin T Scale (K)

$$T_K = T_C + 273.15$$

Thermal Expansion (linear)

- Objects such as these railroad tracks will thermal expand when T increases.
- The size of the change will depend on the material.

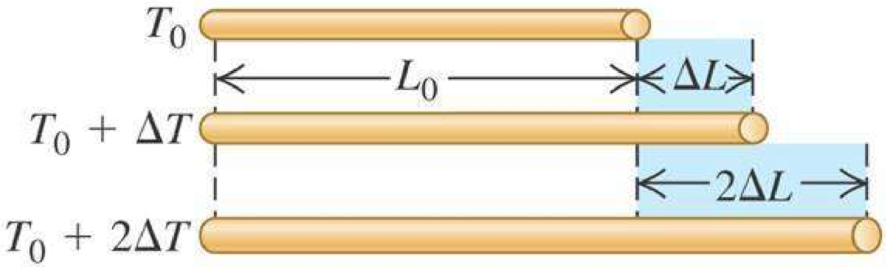
$$\Delta L = \alpha L_0 \Delta T$$

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

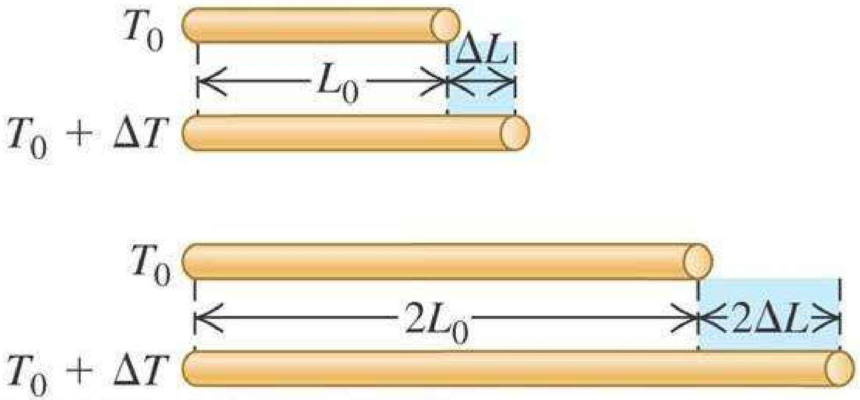
$$\Delta T = T - T_0$$

α is the coefficient of linear expansion

(a) For moderate temperature changes, ΔL is directly proportional to ΔT.

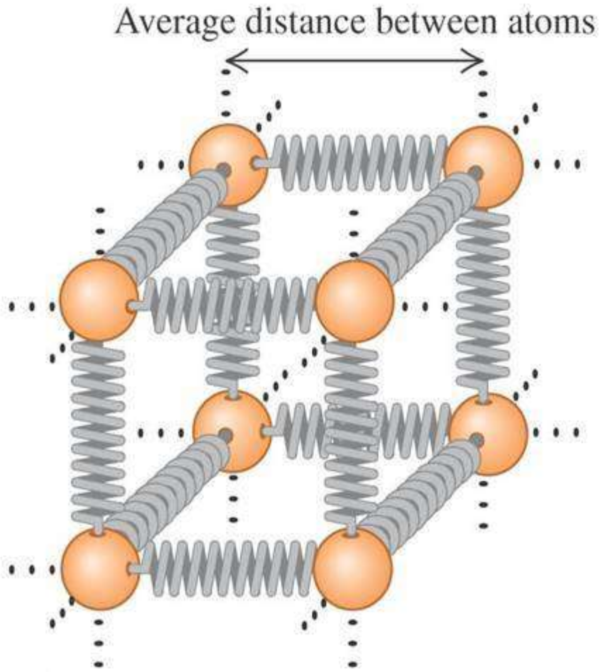


(b) ΔL is also directly proportional to L_0.



Thermal Expansion (volume)

Molecules can be visualized as spheres connected by springs. At a given temperature, these molecules vibrate according to the “spring” potential energy. Because of the asymmetry of this potential energy, the molecules average separation tends to increase with *T*.



One can approx. this volume expansion by:

$$\Delta V = \beta V_0 \Delta T$$

β is the coefficient of volume expansion

Coefficients of Expansion

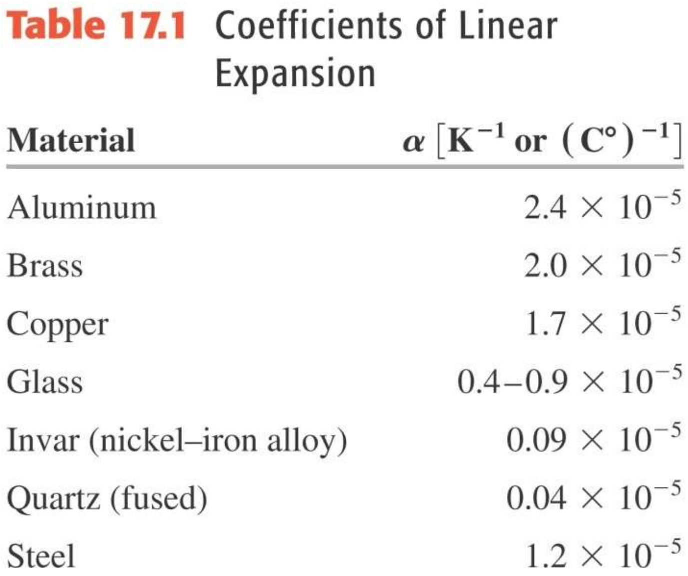


Table 17.1 Coefficients of Linear Expansion

Material	α [K^{-1} or $(C°)^{-1}$]
Aluminum	2.4×10^{-5}
Brass	2.0×10^{-5}
Copper	1.7×10^{-5}
Glass	$0.4–0.9 \times 10^{-5}$
Invar (nickel–iron alloy)	0.09×10^{-5}
Quartz (fused)	0.04×10^{-5}
Steel	1.2×10^{-5}

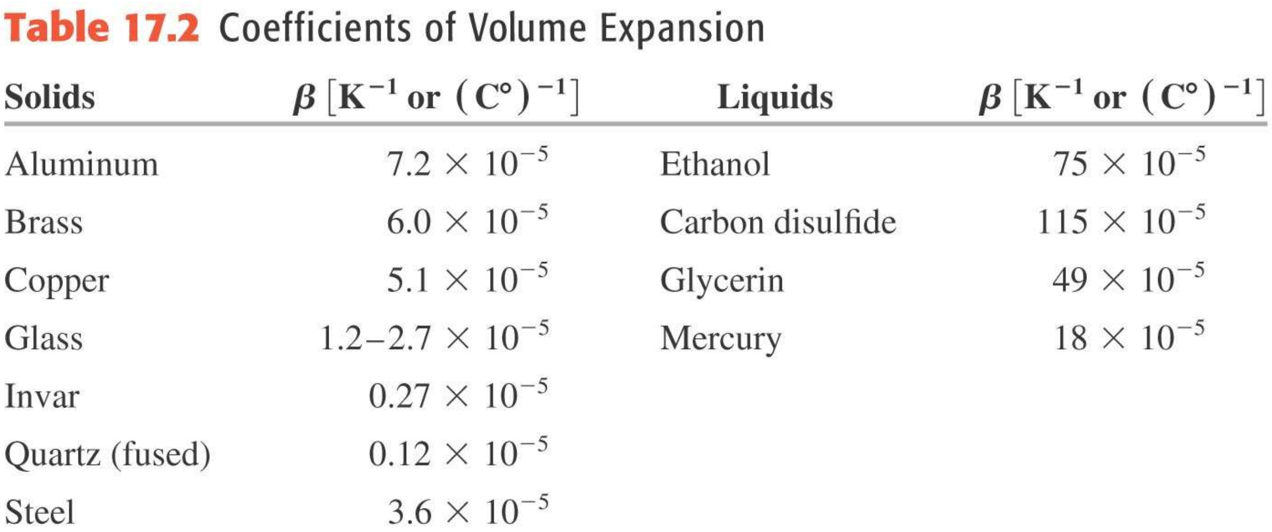


Table 17.2 Coefficients of Volume Expansion

Solids	β [K^{-1} or $(C°)^{-1}$]	**Liquids**	β [K^{-1} or $(C°)^{-1}$]
Aluminum	7.2×10^{-5}	Ethanol	75×10^{-5}
Brass	6.0×10^{-5}	Carbon disulfide	115×10^{-5}
Copper	5.1×10^{-5}	Glycerin	49×10^{-5}
Glass	$1.2–2.7 \times 10^{-5}$	Mercury	18×10^{-5}
Invar	0.27×10^{-5}		
Quartz (fused)	0.12×10^{-5}		
Steel	3.6×10^{-5}		

Notes:

1. These relations are approximately linear in a given range of *T* only.
2. α & β ~ constant in *T* range of interest.
3. Most substances have α & $\beta > 0$ but some are not, e.g. water.

Typically,

$$\boxed{\beta = 3\alpha}$$

Linear and Volume Expansion Rates

$$V = WHL$$

Each of the linear dimensions expands according to the Linear Thermal Expansion equation given previously.

$$W = W_o + \alpha W_o \Delta T, \quad H = H_o + \alpha H_o \Delta T, \quad L = L_o + \alpha L_o \Delta T$$

(assuming material to be “isotropic” – same in all directions)

$$V = (W_o + \alpha W_o \Delta T)(H_o + \alpha H_o \Delta T)(L_o + \alpha L_o \Delta T)$$

$$\cong W_o H_o L_o + W_0 \alpha H_o \Delta T L_o + \alpha W_o \Delta T H_o L_o + W_o H_o \alpha L_o \Delta T$$

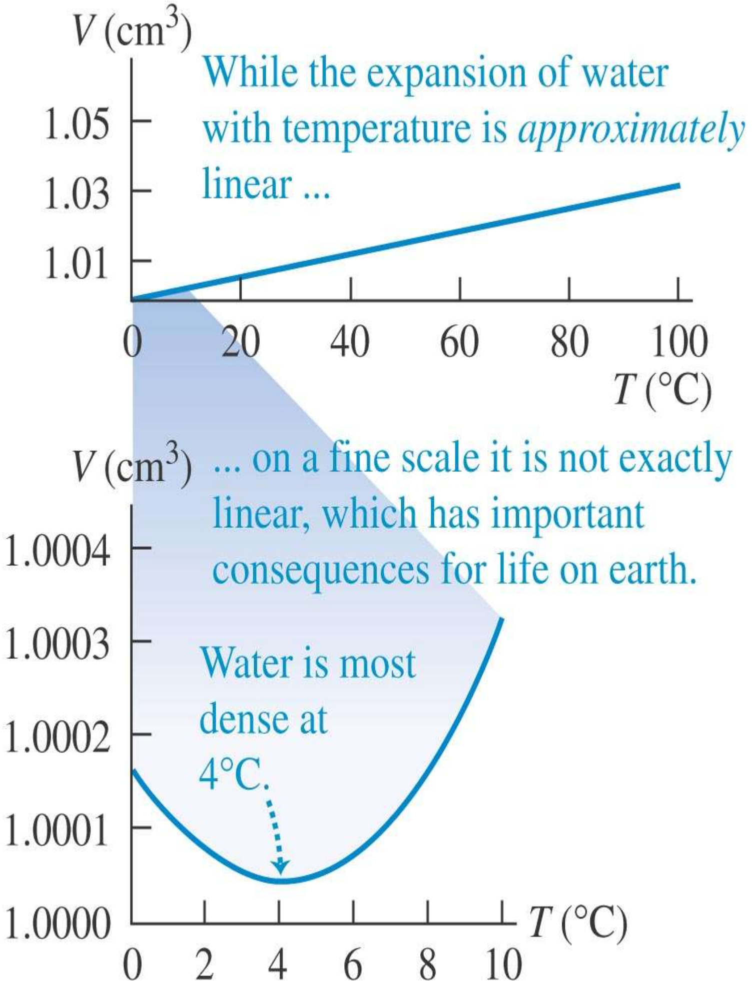
$$V = V_o + 3\alpha V_o \Delta T$$

(only terms up to Δ*T*)

Thermal Expansion of Water

National Geographic Magazine, July 2017

Thermal Expansion of Water

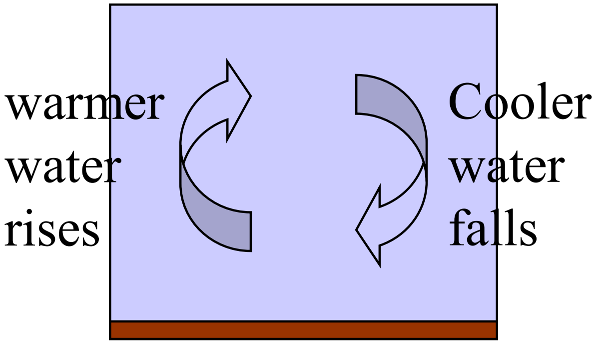


While the expansion of water with temperature is *approximately* linear ...

... on a fine scale it is not exactly linear, which has important consequences for life on earth.

Water is most dense at 4°C.

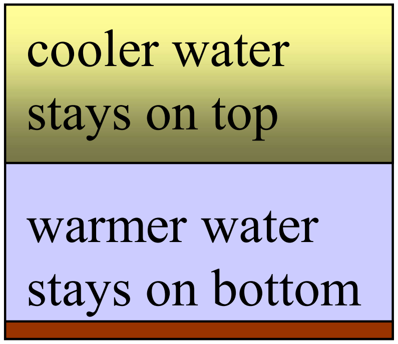
$T > 4^{o} C$



warmer water rises

Cooler water falls

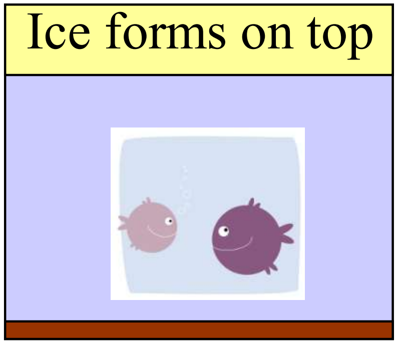
$0^{o} C < T < 4^{o} C$



cooler water stays on top

warmer water stays on bottom

$T < 0^{o} C$



Ice forms on top

- Ice is less dense than 4°C water
- Ice grows from top to bottom
- 4°C liquid water remain at bottom

Thermal Equilibrium

Observation:

When two objects at different T are brought "together", they will eventually reach the same temperature and the system reaches an *equilibrium* state when no further physical changes occur in the system.

e.g. warm soda cans in a cooler filled with ice

Thermal Equilibrium

Additional concepts…

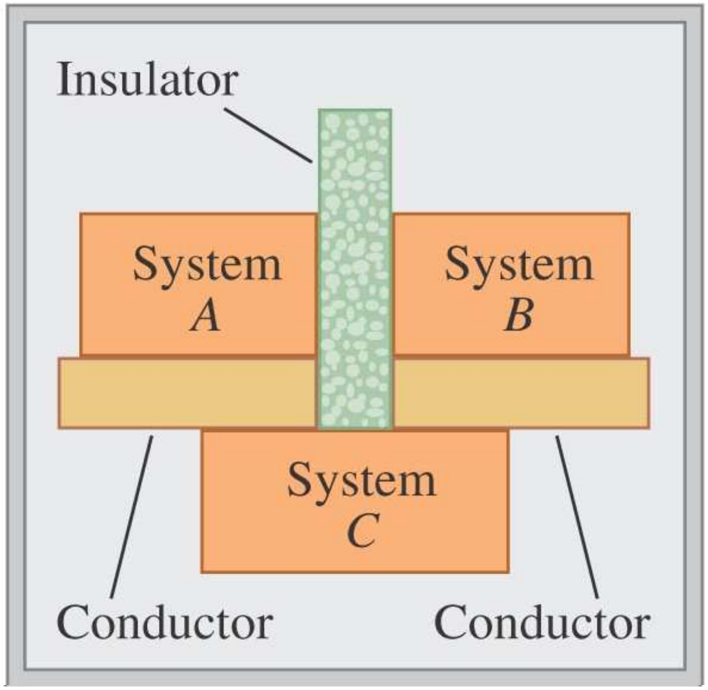
→ **Heat** (more on this later): the *transfer of energy* between objects with different *T*.

→ **Thermal Contact**: two objects are in thermal contact if heat can transfer between them (not necessary in physical contact).

→ **Thermal equilibrium**: the situation in which two objects in *thermal contact* cease to exchange energy by the process of *heat*.

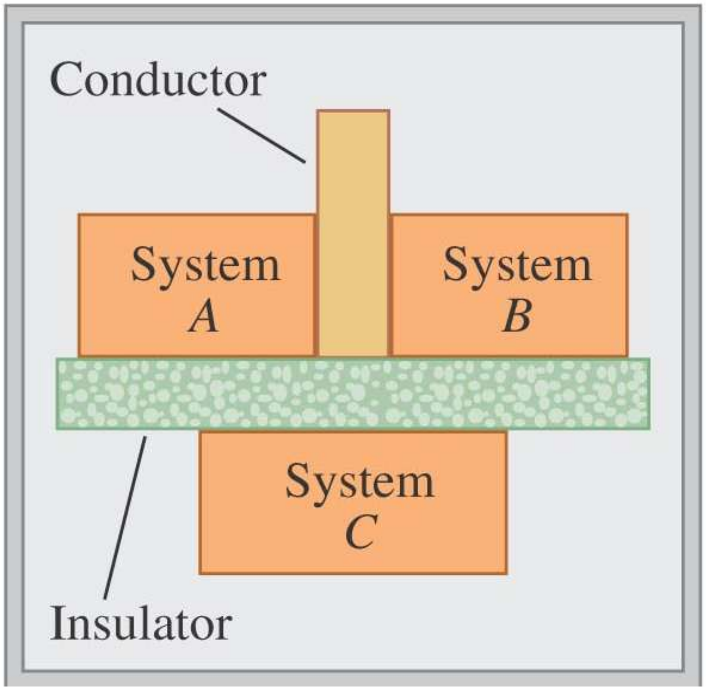
The 0th Law of Thermodynamics

(a) If systems A and B are each in thermal equilibrium with system C …



No heat flow between A-C and B-C.

(b) … then systems A and B are in thermal equilibrium with each other.



No heat flow between A-B.

Note: this *transitive* property is not true for all physical process, e.g. two pieces of iron with a magnet but the 0th Law have been shown to be true experimentally.

Heat

Caution: in everyday usage, **Temp & Heat** are usually interchangeable.

But, in physics, they are **not** the same!

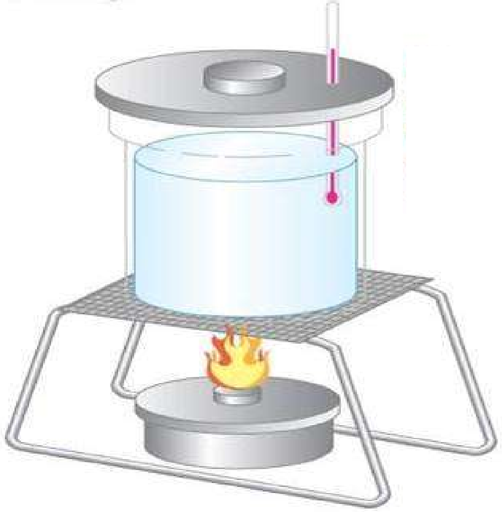
Temperature: a macroscopic state variable ~ avg. KE of molecules in the system (later).

Heat: the *transfer of energy* between bodies due to a temperature difference.

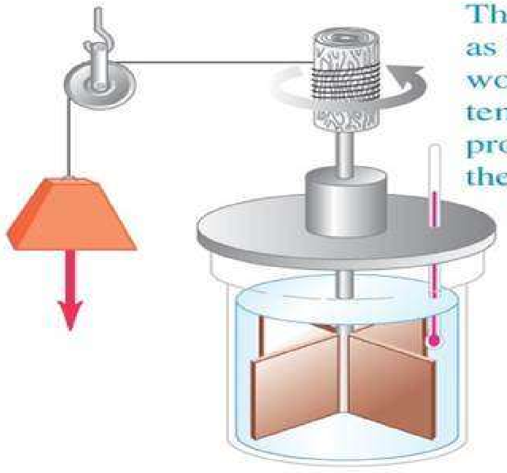
Mechanical Equivalent of Heat (Sir James Joules, 1818-1889)

- Joule found that he can raise the water temperature by the same amount with either providing heat or by doing mechanical work !
- His conclusion: *mechanical work* and *heat* are equivalent in raising the temperature of the water.

Raising the temperature of water by direct heating



Raising the temperature of water by doing work on it



The water warms as the paddle does work on it; the temperature rise is proportional to the amount of work done.

D colliding balls

Quantity of Heat

Energy transfer due to temp diff is called **heat**.

Historically, the unit of heat is defined in terms of temp changes of *water*:

1 calorie (cal) = amount of energy transfer (heat) needed to raise the temp of 1g of water from 14.5°C to 15.5°C.

From Joules experiment, we now know that this amount of heat is equivalent to 4.186 J amount of mechanical energy, i.e.,

$$1\text{cal} = 4.186\ \text{J}$$

Specific Heat/Heat Capacity

Different type of materials will need different amount of heat to raise its temp by $1^{o}C$ (or 1K).

We can quantify this using *specific heat c*:

$Q = mc\,\Delta T$ *or* $dQ = mc\,dT$

Q → quantity of heat needed to raise T from T_1 to T_2 $(\Delta T = T_2 - T_1)$

m → mass of the material

c → "specific heat" is characteristic of the type of material [$J/kg\cdot K$]

Specific Heat Values

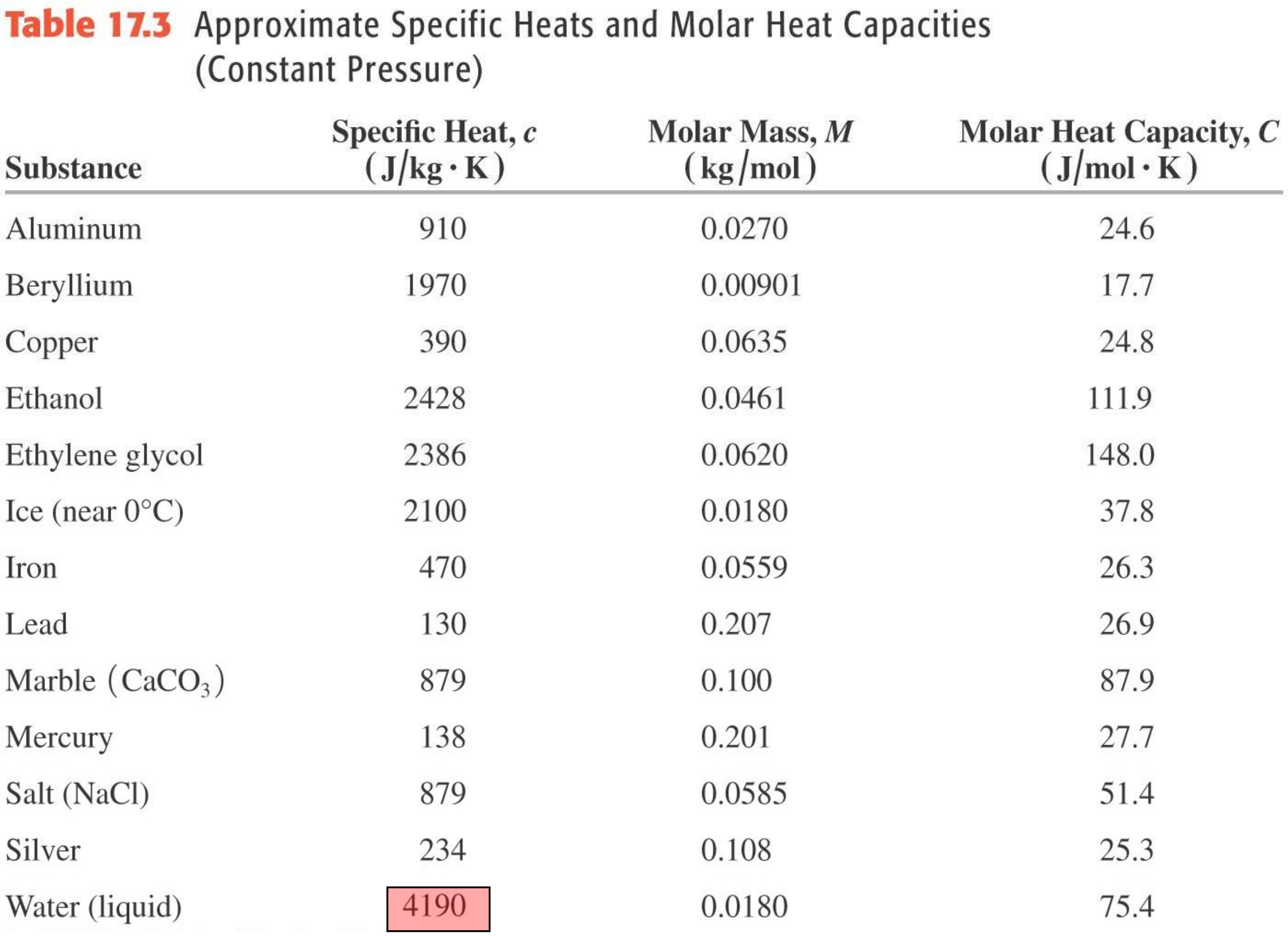


Table 17.3 Approximate Specific Heats and Molar Heat Capacities (Constant Pressure)

Substance	Specific Heat, c (J/kg·K)	Molar Mass, M (kg/mol)	Molar Heat Capacity, C (J/mol·K)
Aluminum	910	0.0270	24.6
Beryllium	1970	0.00901	17.7
Copper	390	0.0635	24.8
Ethanol	2428	0.0461	111.9
Ethylene glycol	2386	0.0620	148.0
Ice (near 0°C)	2100	0.0180	37.8
Iron	470	0.0559	26.3
Lead	130	0.207	26.9
Marble ($CaCO_3$)	879	0.100	87.9
Mercury	138	0.201	27.7
Salt (NaCl)	879	0.0585	51.4
Silver	234	0.108	25.3
Water (liquid)	4190	0.0180	75.4

Molar Specific Heat/Heat Capacity

- One can also specify the amount of materials by the number of molecules (or mole n) instead of its mass (m in kg). With $m=nM$,

$$Q = mc\,\Delta T = (nM)c\,\Delta T = nC\Delta T \qquad (note:\ cM = C)$$

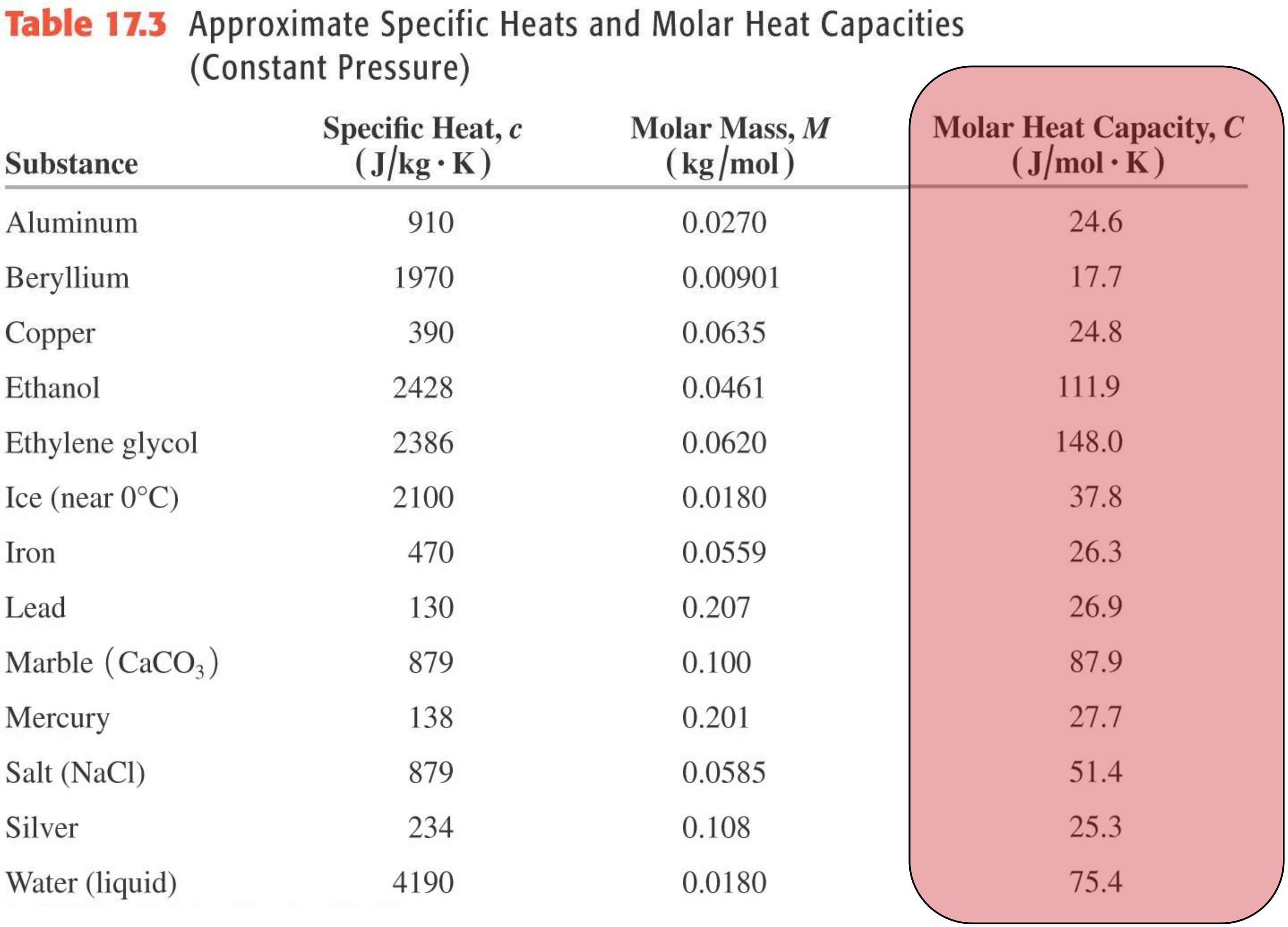
n → number of mole

M → molar mass (mass per mole)

C → molar specific heat (note upper case)

(1 mole $= 6.022\times10^{23}$ *particles*)

Specific Heat Values



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