

1 - Temperature and Heat

"Temperature" and "heat" have very different meanings (and should not be used interchangeably, regardless of how much it happens in regular language).

(Note that we will be focusing on large-scale or macroscopic objects).

Temperature and Thermal Equilibrium

The temperature is a measure of "hotness" or "coldness", using a constructed temperature scale (i.e. we use a measurable property of a material that varies with "hotness" or "coldness").

In a lab, we have two typical types of thermometers:

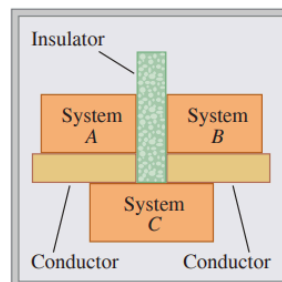
- A liquid mercury thermometer (changes in temperature causes the liquid's volume to change)
- A pressure thermometer (changes in temperature causes the gas' pressure to change)

Two systems are in thermal equilibrium if and only if they have the same temperature.

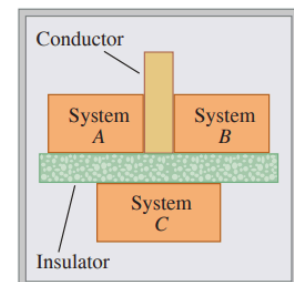
Consider three systems A, B, and C:

Figure 17.2 The zeroth law of thermodynamics.

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



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



Note that *A* and *B* are separated by an insulator. When $A = C$ and $B = C$, then $A = B$.

Zeroth Law of Thermodynamics

This is the zeroth law of thermodynamics. If *C* is initially in thermal equilibrium with both *A* and *B*, then *A* and *B* are in thermal equilibrium with each other.

Temperature Scales

- Celsius -> 0°C is the freezing point of pure water and 100°C is the boiling point

- Fahrenheit -> 32°F is freezing point of pure water and 212°F is the boiling point

Gas Thermometer and the Kelvin Scale

Ideally, we should define a temperature scale that does not depend on the properties of a particular material. A gas thermometer is close to ideal, as it uses the principle ($pV = nRT$) that the pressure of a gas at a constant volume increases with temperature

(a) A constant-volume gas thermometer



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

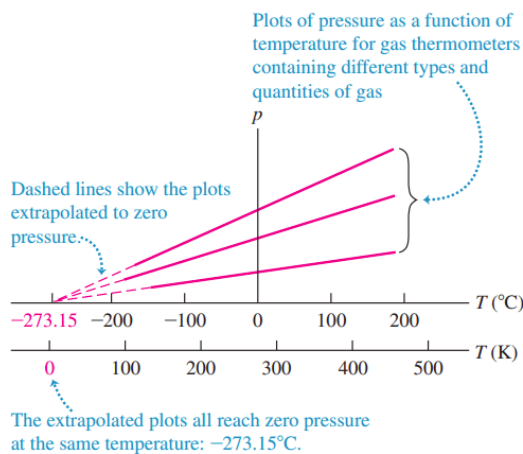


Figure 17.5 (a) Using a constant-volume gas thermometer to measure temperature. (b) The greater the amount of gas in the thermometer, the higher the graph of pressure p versus temperature T .

Note that all the pressure lines all intersect at one point (extrapolated to zero pressure), this is equivalent to 0 K (-273.15°C)

Remember that the Celsius scale has two fixed points --- normal freezing and boiling temperatures of H_2O . We define the Kelvin scale using a gas thermometer with only a single reference temperature.

We define the ratio of two temperatures T_1 and T_2 on the Kelvin scale as the ratio for the corresponding gas-thermometer pressures:

$$\frac{T_2}{T_1} = \frac{p_2}{p_1}$$

We specify the Kelvin temperature of a single specific state: triple point of water (pressure and temperature at which solid, liquid, and vapor water can all coexist). This occurs at 0.01°C (273.16 K) and water-vapor pressure of 610 Pa (~ 0.006 atm)

Temperature Conversions

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

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

$$T_K = T_C + 273.15$$

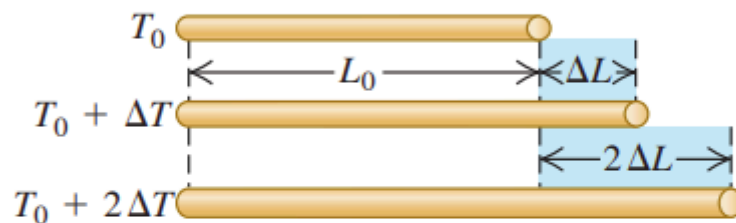
Thermal Expansion

Most materials tend to expand when their temperatures increases.

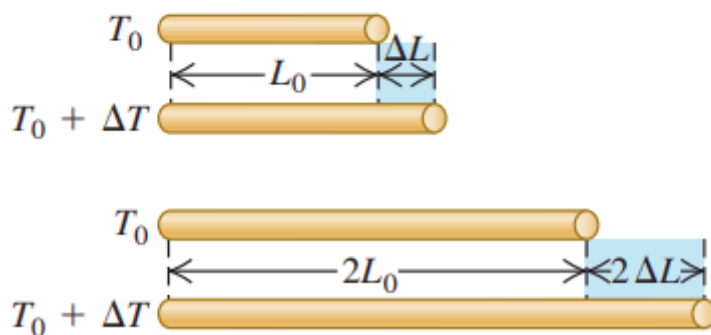
Consider a rod of length L_0 . Increasing the temperature of this rod causes it to expand, such that ΔT corresponds to ΔL .

Figure 17.8 How the length of a rod changes with a change in temperature. (Length changes are exaggerated for clarity.)

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



(b) ΔL is also directly proportional to L_0 .



The change in length is given by

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

where α is the coefficient of linear expansion of the material. Note that this is only an approximate relationship, such that it only holds for "small" ΔT ($\leq 100^\circ\text{C}$ or so)

Molecular model for Thermal Expansion

We can understand the linear expansion if we model the atoms as being held together by springs (interatomic forces modeled as spring forces). Each atom would vibrate about its equilibrium position, where the energy and amplitude of vibration increases with temperature. When the amplitude increases, the average distance between atoms also increases.

Volume Expansion

Thermal expansion also applies to liquid materials. If ΔT is not high, then the increase in volume ΔV is given by

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

There is a simple relationship between β and α for solid materials. Consider a cube of material with side length L and volume $V = L^3$.

At the initial temperature, $V = V_o$ and $L = L_o$. When temperature increases by dT , side length should increase by dL and the volume increases by an amount dV , such that

$$dV = \frac{dV}{dL} dL = 3L^2 dL$$

We replace L and V by their initial values such that dL is expressed as

$$dL = \alpha L_o dT$$

Since $V_o = L_o^3$, dV can also be expressed as

$$dV = 3L_o^2 \alpha L_o dT = 3\alpha V_o dT$$

This is consistent with $dV = \beta V_o dT$ only if

$$\beta = 3\alpha$$

Coefficients of Expansion

TABLE 17.1 Coefficients of Linear Expansion

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

Note that the coefficient has a unit of K^{-1} such that it is consistent with dimensional analysis.

Thermal Expansion of Water

Water is a special substance, because between 0°C and 4°C , water decreases in volume with increasing temperature (such that water is most dense at 4°C). Because of this behavior, lakes freeze from the top down instead of from the bottom up.

Thermal Stress

Consider an aluminium rod. If the temperature changes but is not allowed to expand or contract (e.g. clamped on both ends), then thermal stress develops.

Engineers account for thermal stresses when designing structures (e.g. for concrete highways, gaps are made to allow for expansion and contraction of concrete)

Calculating the Thermal Stress in a Clamped Rod

From the definition of Young's modulus:

$$Y = \frac{\frac{F}{A}}{\frac{\Delta L}{L_o}}$$

so

$$\left(\frac{\Delta L}{L_o}\right)_{\text{thermal}} = \frac{F}{AY}$$

If the length is to be constant, then the total fractional change in length must be zero such that

$$\left(\frac{\Delta L}{L_o}\right)_{\text{thermal}} + \left(\frac{\Delta L}{L_o}\right)_{\text{tension}} = \alpha\Delta T + \frac{F}{AY} = 0$$

Then the tensile stress needed to keep the length constant:

$$\frac{F}{A} = -Y\alpha\Delta T$$

Quantity of Heat

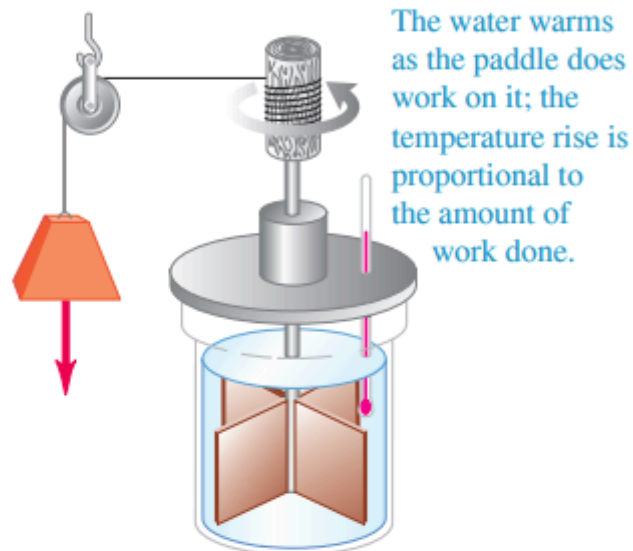
Energy transfer that takes place because of a temperature difference is called heat flow or heat transfer. Note that heat refers to the energy that is transferred or energy in transit due to a temperature difference, NOT the amount of energy contained within a particular system.

Meanwhile, temperature a quantitative description of the hotness and coldness of a material (a measure of the average translational kinetic energy associated with the disordered

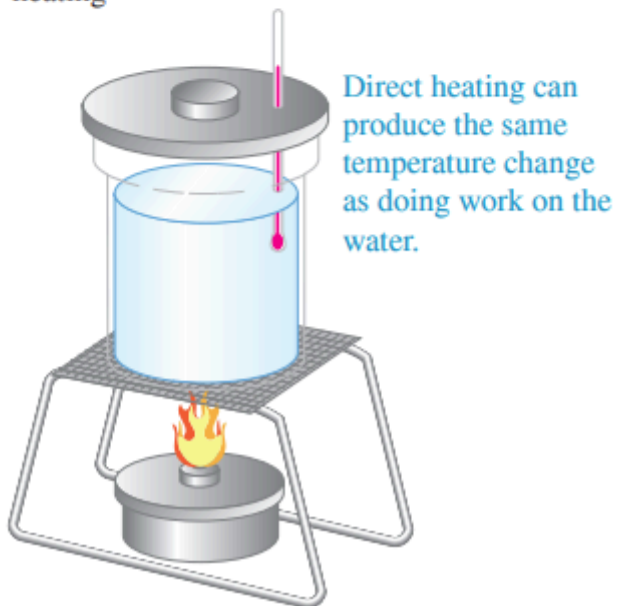
microscopic motion of atoms and molecules.)

Figure 17.15 The same temperature change of the same system may be accomplished by (a) doing work on it or (b) adding heat to it.

(a) Raising the temperature of water by doing work on it



(b) Raising the temperature of water by direct heating



The temperature of the body can be changed by either doing work on it or by adding heat to it.

Unit of Heat: calorie is defined as the amount of heat required to raise the temperature of 1 gram of water from 14.5°C to 15.5°C

Specific Heat

The heat required for temperature change ΔT of mass m is

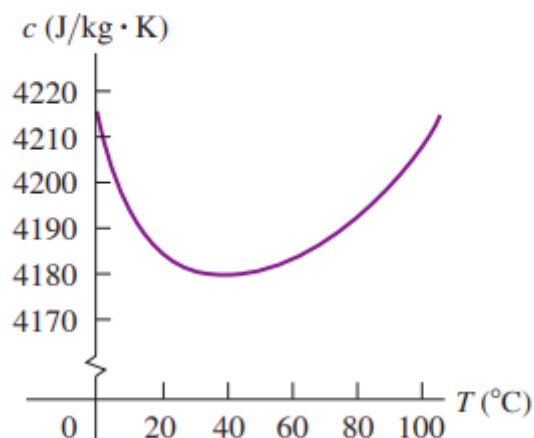
$$Q = mc\Delta T$$

where c is called the specific heat of the material.

For an infinitesimal temperature change dT and corresponding quantity of heat dQ :

$$dQ = mc \, dT$$

Figure 17.17 Specific heat of water as a function of temperature. The value of c varies by less than 1% between 0°C and 100°C.



Notice that the unit of c is J/kg K

The specific heat of water is approximately 4190 J/kg K or $1 \text{ cal/g } ^{\circ}\text{C}$.

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

Substance	Specific Heat, c ($\text{J/kg} \cdot \text{K}$)	Molar Mass, M (kg/mol)	Molar Heat Capacity, C ($\text{J/mol} \cdot \text{K}$)
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 Heat Capacity

Sometimes it is more convenient to describe a quantity of substance in terms of the number of moles n rather than the mass m of a material. The total mass m of a material is now given by

$$m = nM$$

where M is the molar mass (kg/mol) and n is the number of moles.

$$\begin{aligned} Q &= mc\Delta T = nMc\Delta T & (Mc = \text{molar heat capacity}) \\ Q &= nC\Delta T & (\text{for } n \text{ moles}) \end{aligned}$$

Phase Changes

A phase refers to the specific state of matter (solid, liquid, gas), and a phase change would then be a transition from one phase to another.

In any given pressure, it would take a specific temperature for phase change to start occurring.

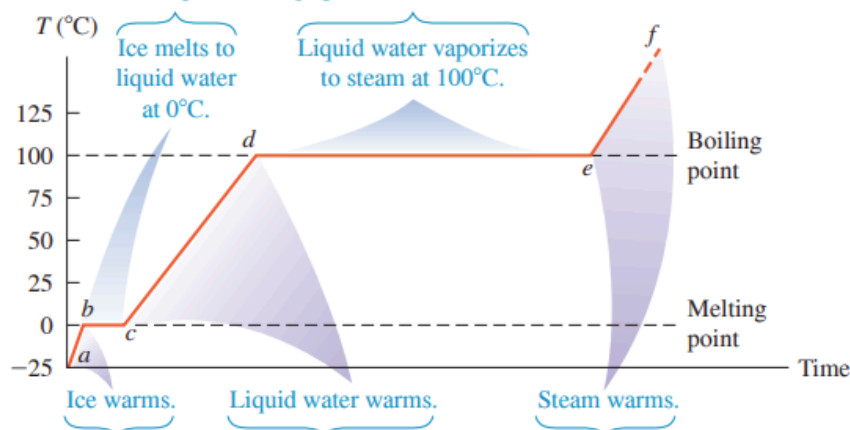
During a phase change, the temperature does not change until the phase change finishes, as the heat change is allocated to the phase change rather than to change the temperature.

This is defined through the heat of fusion and heat of vaporization:

- Heat of fusion, L_f - heat per unit mass that is transferred in a solid-liquid phase change
 - For H_2O at atm: $L_f = 3.34 \times 10^5 \text{ J/kg} = 79.6 \text{ cal/g}$
- Heat of vaporization, L_v - heat per unit mass that is transferred in a liquid-gas change.
 - For H_2O at atm: $L_v = 2.256 \times 10^6 \text{ J/kg} = 539 \text{ cal/g}$

Figure 17.20 Graph of temperature versus time for a specimen of water initially in the solid phase (ice). Heat is added to the specimen at a constant rate. The temperature remains constant during each change of phase, provided that the pressure remains constant.

Phase of water changes. During these periods, temperature stays constant and the phase change proceeds as heat is added: $Q = +mL$.



Temperature of water changes. During these periods, temperature rises as heat is added: $Q = mc\Delta T$.

$a \rightarrow b$: Ice initially at -25°C is warmed to 0°C .
 $b \rightarrow c$: Temperature remains at 0°C until all ice melts.
 $c \rightarrow d$: Water is warmed from 0°C to 100°C .
 $d \rightarrow e$: Temperature remains at 100°C until all water vaporizes.
 $e \rightarrow f$: Steam is warmed to temperatures above 100°C .

TABLE 17.4 Heats of Fusion and Vaporization

Substance	Normal Melting Point		Heat of Fusion, L_f (J/kg)	Normal Boiling Point		Heat of Vaporization, L_v (J/kg)
	K	$^\circ\text{C}$		K	$^\circ\text{C}$	
Helium	*	*	*	4.216	-268.93	20.9×10^3
Hydrogen	13.84	-259.31	58.6×10^3	20.26	-252.89	452×10^3
Nitrogen	63.18	-209.97	25.5×10^3	77.34	-195.8	201×10^3
Oxygen	54.36	-218.79	13.8×10^3	90.18	-183.0	213×10^3
Ethanol	159	-114	104.2×10^3	351	78	854×10^3
Mercury	234	-39	11.8×10^3	630	357	272×10^3
Water	273.15	0.00	334×10^3	373.15	100.00	2256×10^3
Sulfur	392	119	38.1×10^3	717.75	444.60	326×10^3
Lead	600.5	327.3	24.5×10^3	2023	1750	871×10^3
Antimony	903.65	630.50	165×10^3	1713	1440	561×10^3
Silver	1233.95	960.80	88.3×10^3	2466	2193	2336×10^3
Gold	1336.15	1063.00	64.5×10^3	2933	2660	1578×10^3
Copper	1356	1083	134×10^3	1460	1187	5069×10^3

*A pressure in excess of 25 atmospheres is required to make helium solidify. At 1 atmosphere pressure, helium remains a liquid down to absolute zero.