Objectives

Ch 18 : Temperature, heat, and the first Law of themodynamics

18.1 Temperature

18.2 The Celsius and Fahrenheit scales

18.3 Thermal expansion

18.4 Absorption of heat

18.5 The first law of thermodynamics

18.6 Heat transfer mechanisms

18-1 Temperature

Thermodynamics is the study of thermal energy (internal energy) of systems.

Zeroth Law of thermodynamics

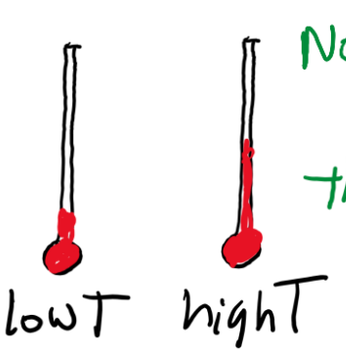
If two objects are in thermal equilibrium, their temperatures are equal. And vice versa.

A B thermal equilibrium $\Longleftrightarrow T_A = T_B$

Temperature can change some properties of an object.
you can use these properties to measure temperature.

Example:

Volume of liquids



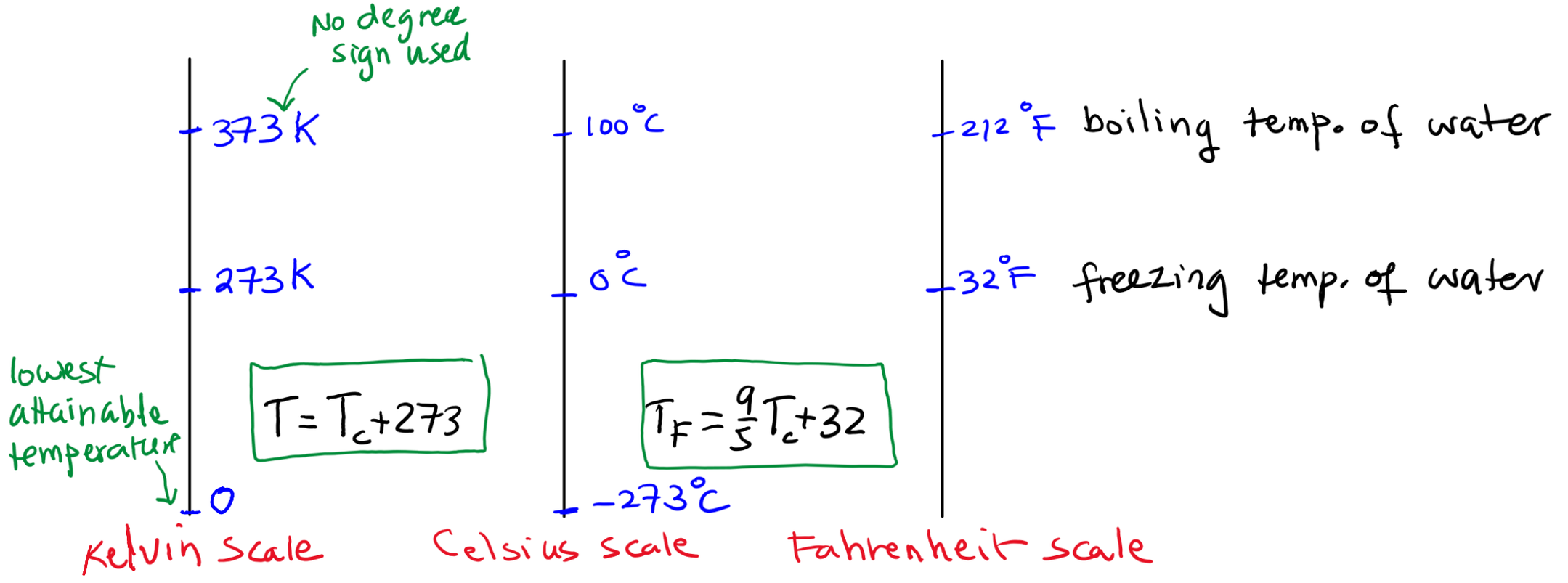
Not calibrated

thermoscope

calibrated

thermometer

18-2 Celsius and Fahrenheit scales



Temperature difference

$\Delta T = \Delta T_c$

5 K = 5 C° ← for difference, use ° after letter

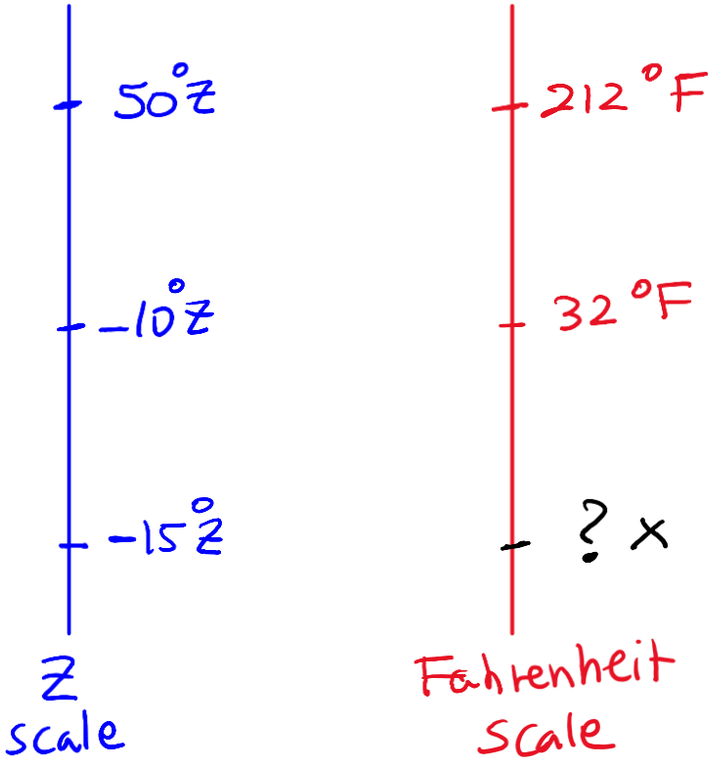
Five degrees difference in Kelvin = Five degrees diffence in Celsius

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

5 C° = 9 F°

Five degrees difference in Celsius = nine degrees diffence in Fahrenheit

Example

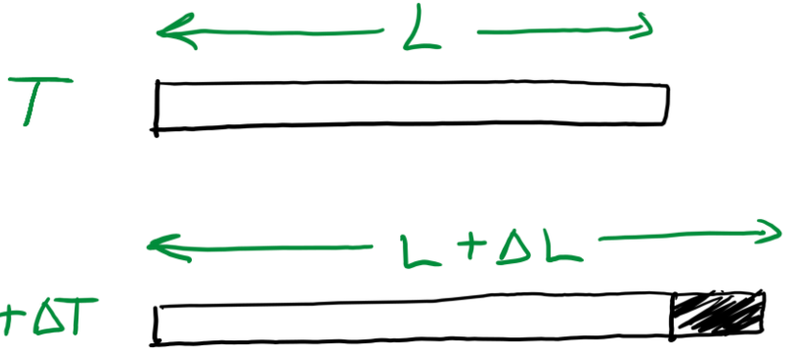


$$\frac{x - 32^\circ F}{-15^\circ Z - (-10^\circ Z)} = \frac{32^\circ F - 212^\circ F}{-10^\circ Z - 50^\circ Z}$$

$$x - 32^\circ F = \frac{-5}{-60}(-180\ F^\circ)$$

$$x = -15\ F^\circ + 32\ F^\circ = 17^\circ F$$

13-3 Thermal Expansion



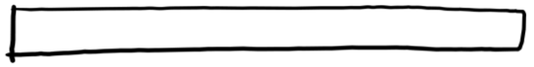
Increase the temperature by ΔT

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

α: Gefficient of Linear expansion

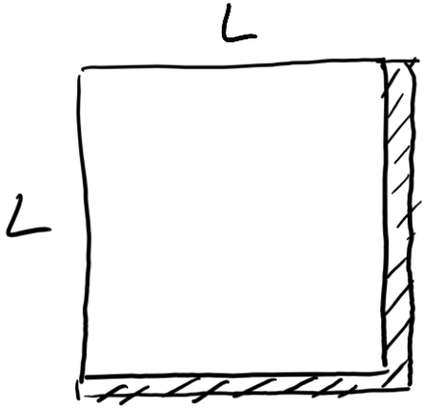
L: original length

For aluminium $\alpha = 23 \times 10^{-6} / C^{\circ}$



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

α coefficient of linear expansion

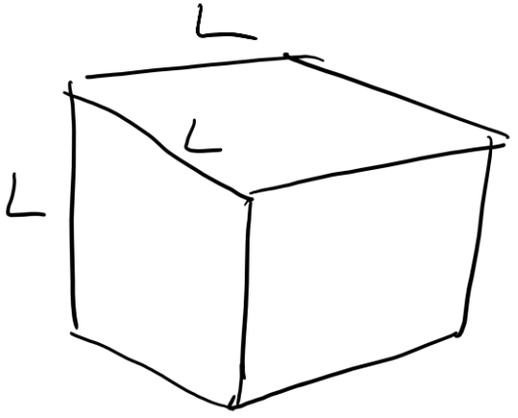


$$A = L^2 \Rightarrow \Delta A = (L + \Delta L)^2 - L^2$$

$$\Delta A = L^2 + 2L\Delta L + \Delta L^2 - L^2$$

ignore. too small

$$\Delta A = 2\alpha A \Delta T$$



$$V = L^3 \Rightarrow \Delta V = (L + \Delta L)^3 - L^3$$

$$\Delta V = L^3 + 3L^2\Delta L + 3L\Delta L^2 + \Delta L^3 - L^3$$

ignore. Too small

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

V ← original volume

β Coefficient of volume expansion

Example

A truck loaded with 40,000 L of desiel moves from hot to cold weather. The change in temperature is 20 K. How many liters are remaining?

The coefficient of volume expansion for desiel = $10^{-3}/C^{\circ}$

$$\Delta T = T_f - T_i$$

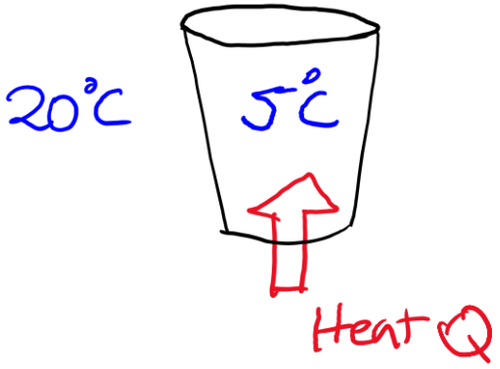
$$\Delta V = \beta V \Delta T = 10^{-3}(40{,}000)(-20) = -800\,L$$

$$\Delta V = V_f - V_i = -800 \Rightarrow V_f = V_i - 800 = 39{,}200\,L$$

remaining

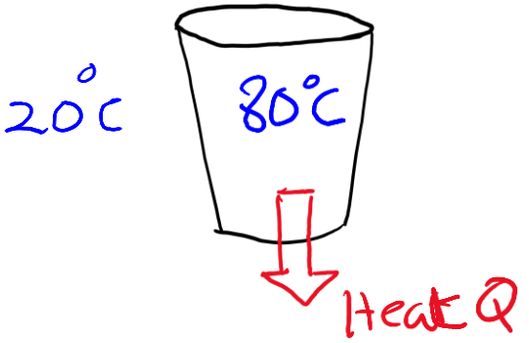
18-4 Absorption of heat

Heat Q is the energy transferred between two objects because of a temperature difference between them.



Heat absorbed (gained)

$Q > 0$

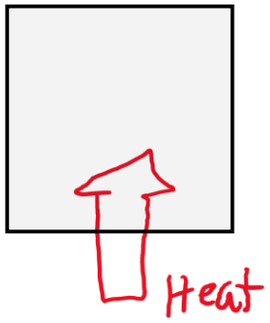


Heat released (lost)

$Q < 0$

SI unit for heat: Joule (J)

1 cal = 4.2 J



change
- Temperature (same state)
- State (same temperature)
  - (solid → liquid)
  - (Liquid → gas)

Changing temperature

$$Q = C\,\Delta T$$

Q: Heat

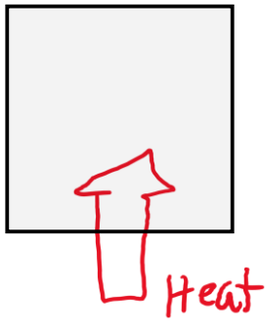
C: heat capacity of the object

$$c = \frac{C}{m}$$

c: specific heat of the material

m: mass

$$Q = mc(T_f - T_i)$$



change → Temperature (same state)

change → State (same temperature)

(solid → liquid)

(Liquid → gas)

Changing state

$Q = L\,m$ ← mass

Q: Heat

L: heat of transformation

Heat of transformation

= heat per unit mass to change a substance from one state to another

Solid → Liquid $\quad Q = L_f m$

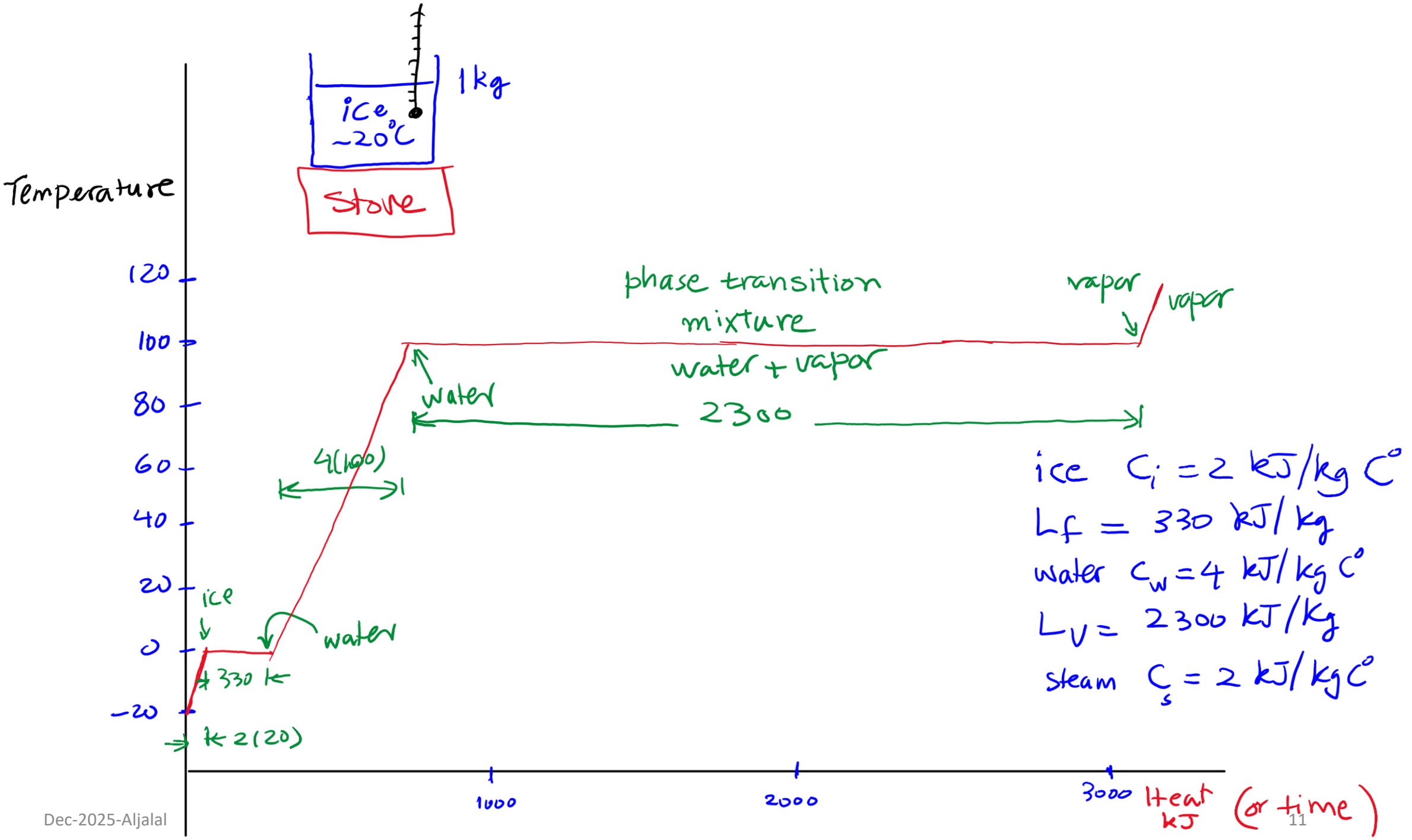
Liquid → solid $\quad Q = -L_f m$

L_f: heat of fusion

Liquid → gas $\quad Q = L_v m$

gas → Liquid $\quad Q = -L_v m$

L_v: heat of vaporization


1 kg
ice
-20°C
stove
Temperature
120
100
80
60
40
20
0
-20
phase transition
mixture
water + vapor
vapor
vapor
water
2300
4(100)
ice
water
330
2(20)
1000
2000
3000
Heat
kJ
(or time)
ice $C_i = 2$ kJ/kg C°
$L_f = 330$ kJ/kg
water $C_w = 4$ kJ/kg C°
$L_V = 2300$ kJ/kg
steam $C_s = 2$ kJ/kg C°

Example

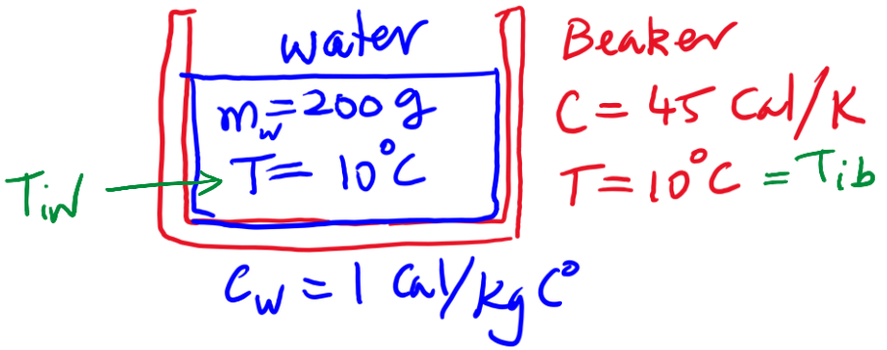
$m_c = 100\,g$

$T = 300^\circ C = T_{ic}$

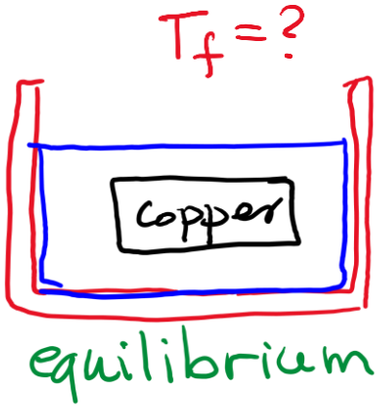
copper

$c_c = 0.09\ Cal/Kg\,C^\circ$

The System is isolated



$\Longrightarrow$



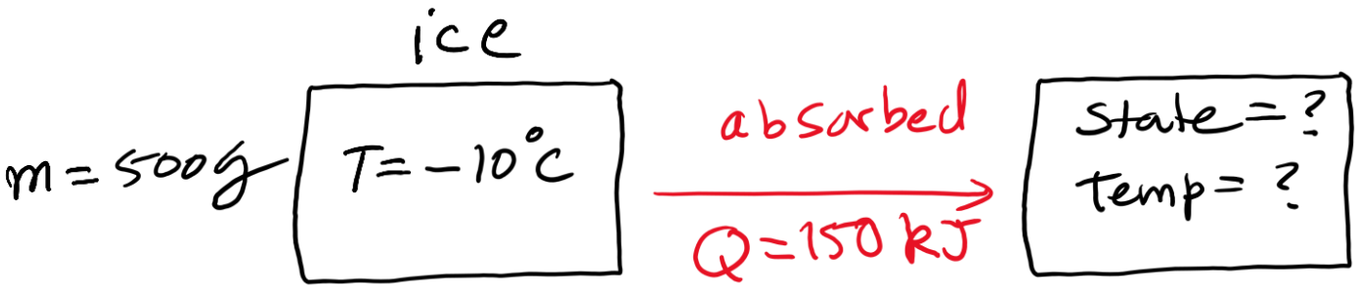
System is isolated $\Longrightarrow$ total energy does not change

$$Q_{copper} + Q_{water} + Q_{beaker} = 0$$

$$c_c m_c (T_f - T_{ic}) + c_w m_w (T_f - T_{iw}) + C_b (T_f - T_{ib}) = 0$$

$$T_f = \frac{c_c m_c T_{ic} + c_w m_w T_{iw} + C_b T_{ib}}{c_c m_c + c_w m_w + C_b} = \ldots$$

Example



$C_i = 2$ kJ/kg K

$L_f = 330$ kJ/kg

$Q_1 = mc_i\Delta T = (0.5)(2)(10) = 10$ kJ

$Q_2 = mL_f = (0.5)(330) = 165$ kJ

$Q_1 < Q$ you can complete ①

$Q_1 + Q_2 > Q$ you cannot complete ②

after ① the remaining heat $Q_{rem} = Q - Q_1 = 140$ kJ

you can melt $m_w = \frac{Q_{rem}}{L_f} = \frac{140}{330} = 0.42$ kg (water)

$m_i = 0.5 - 0.42 = 0.08$ kg (ice)

Final state = mixture of water and ice at $T_f = 0^\circ C$

18-5 Fist Law of thermodynamics

$$\Delta E_{int} = Q - W$$

- ΔE_{int}: Change in interal energy of a system
- Q: heat transferred to the system
- W: work done by the system

Work done by the gas

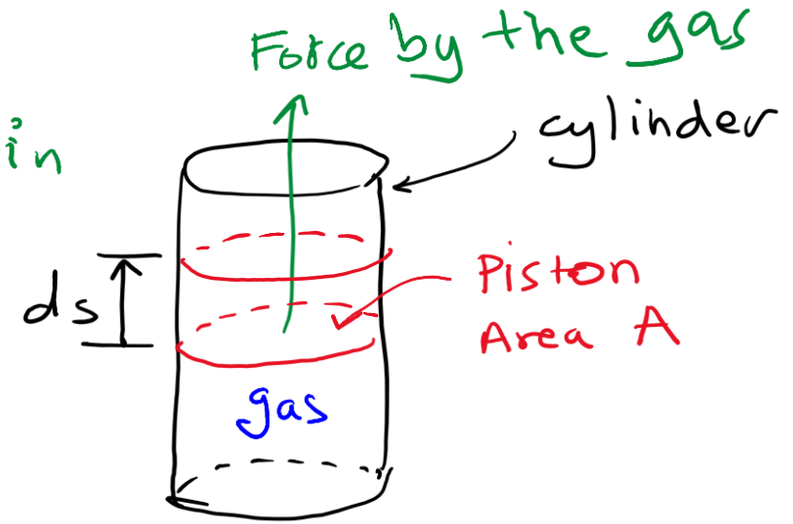
$$dW = Fds$$

$$dW = PAds$$

- Ads: Change in Volume dV
- P: pressure of the gas

$$dW = PdV$$

$$W = \int_{V_i}^{V_f} P\,dV$$

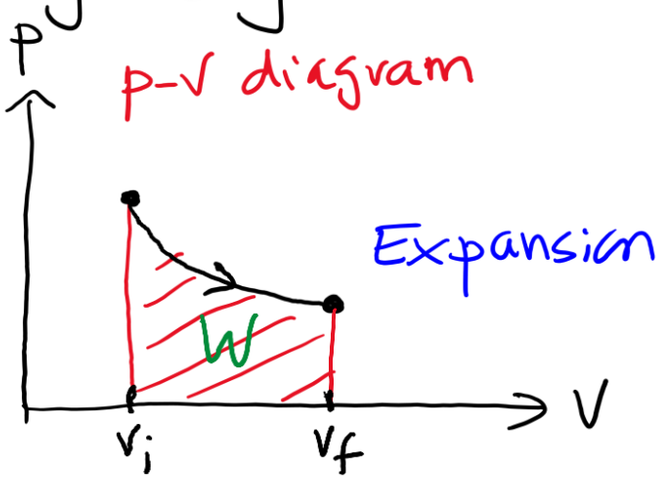


$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$F = PA$$

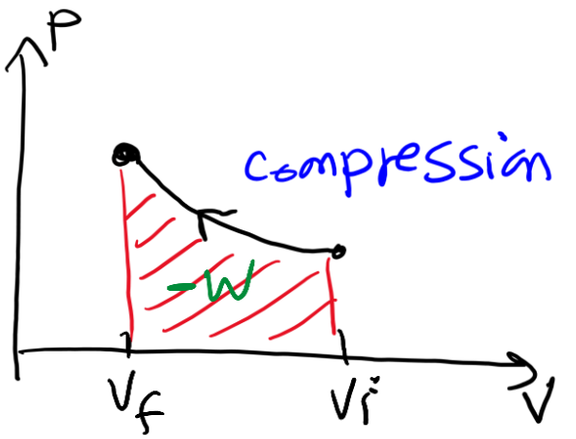
Work done by the gas

$$W = \int_{V_i}^{V_f} p\,dV$$



W = area under the curve

W > 0



W = −area under the curve

W < 0

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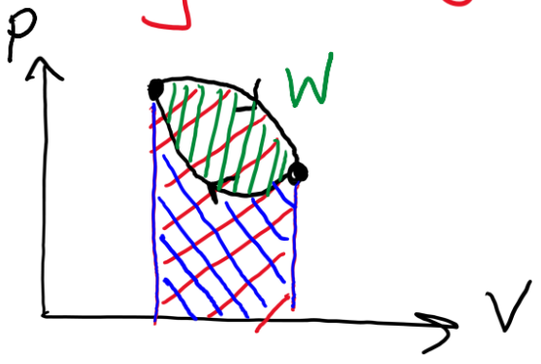
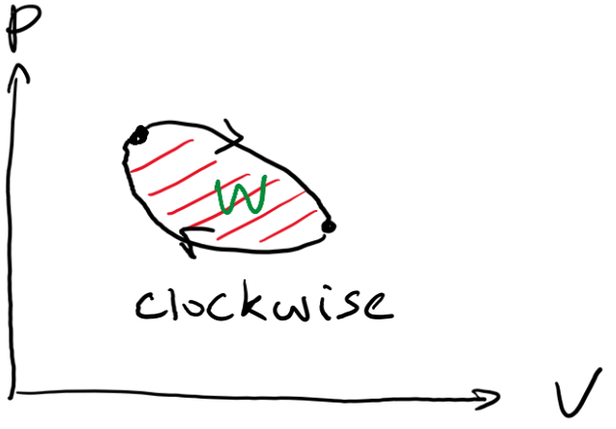
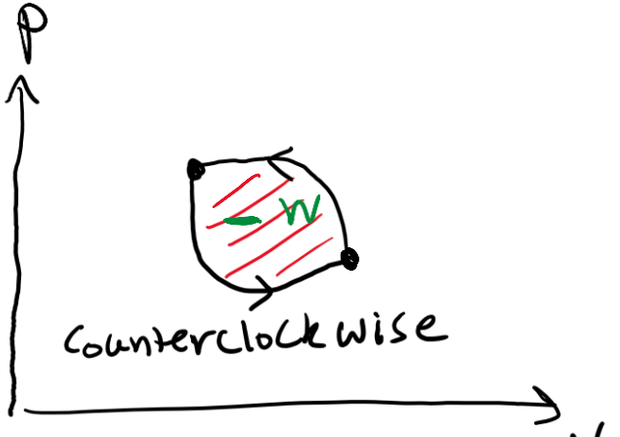
thermodynamic cycle





W = area of the loop

W > 0



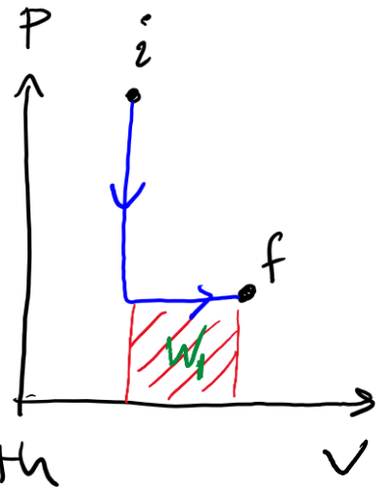
W = − area of the loop

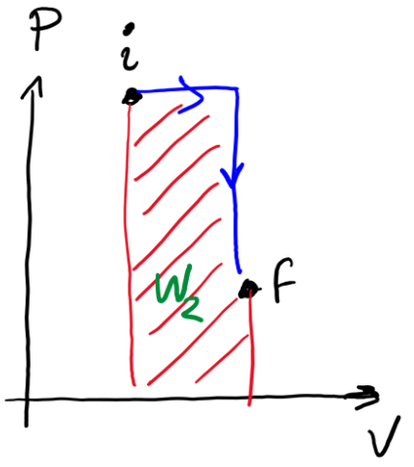
W < 0

$W_1 < W_2$ Work depends on path

$Q_1 < Q_2$ Heat depends on path

$Q_1 - W_1 = Q_2 - W_2$ does not depend on path





$\Delta E_{int,1} = \Delta E_{int,2}$ ΔE_{int} change in internal energy does not depend on path.

It depends on the state (P, V) of the system.

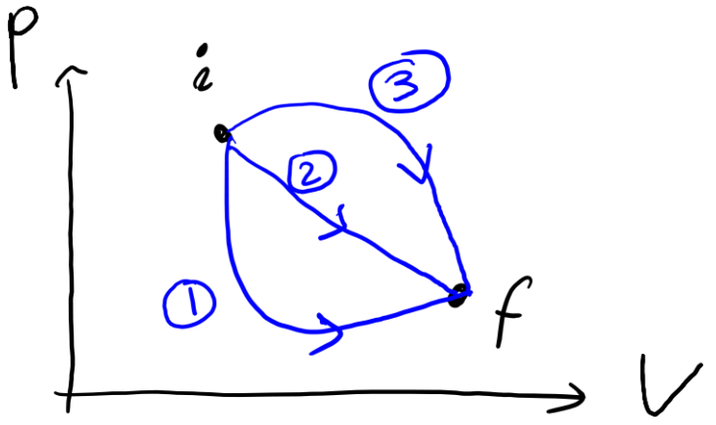
First law of thermodynamics

$\Delta E_{int} = Q - W$ ← work done by the system

↑ change in internal energy of a system

↑ Heat transferred to the system

Question



compare ΔE_{int} for paths : $\Delta E_{int,1} = \Delta E_{int,2} = \Delta E_{int,3}$

↑ does not depend on path

compare W for paths : $W_3 > W_2 > W_1$

↑ area under the curve

compare Q for paths : $Q_3 > Q_2 > Q_1$

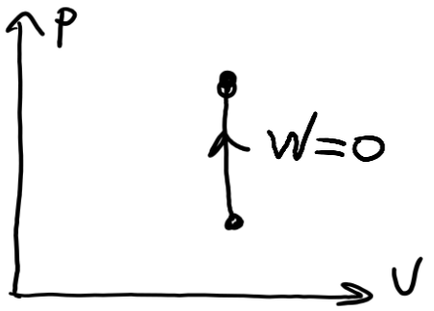
$$\Delta E_{int} = Q - W$$

$$Q = \underbrace{\Delta E_{int}}_{\text{same}} + W$$

$\Delta E_{int} = Q - W$

Constant-volume process

$W = 0$



$\Delta E_{int} = Q$

Cyclical process

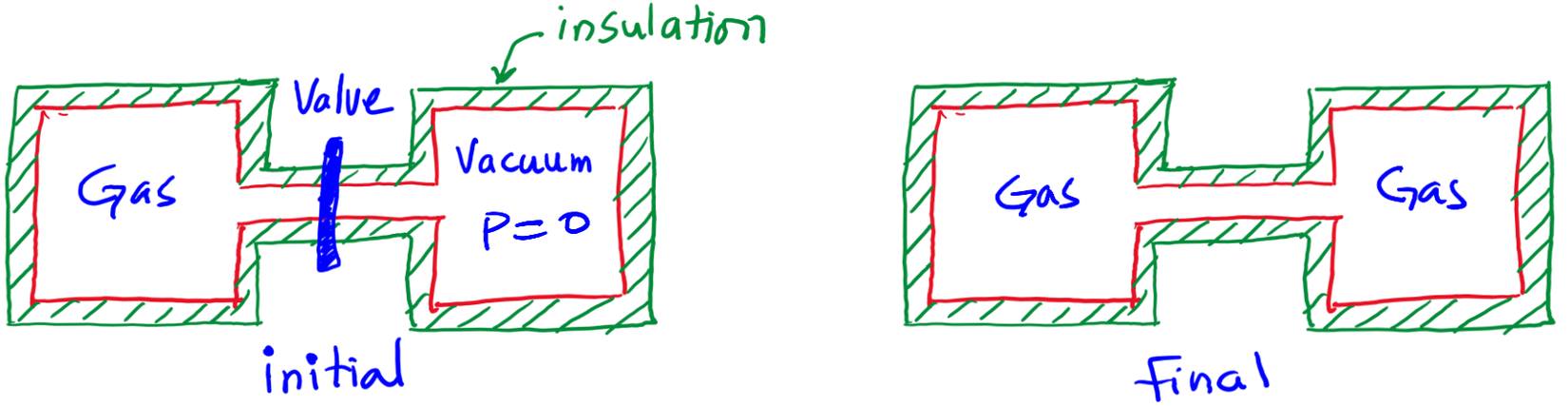
$\Delta E_{int} = 0$

$Q = W$

Adiabatic process $\quad Q = 0$ $\quad \Delta E_{int} = -W$

Free-expansion process $\quad W = 0$, $Q = 0$ $\quad \Delta E_{int} = 0$

Free expansion

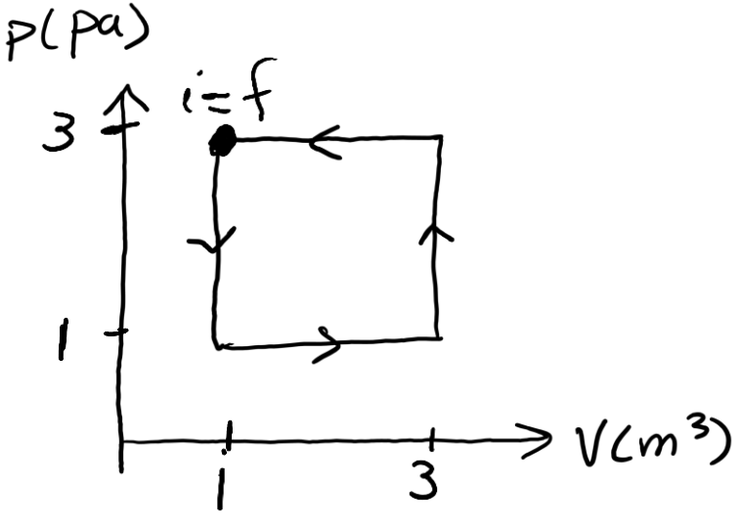


system is insulated $\Rightarrow$ $Q = 0$

$W = \int_0 P\,dV$ $\Rightarrow$ $W = 0$

$\Rightarrow \Delta E_{int} = 0$

Question



$$\Delta E_{int} = 0$$

$$W = -4\ J$$

$$Q = \Delta E_{int} + W = -4\ J$$

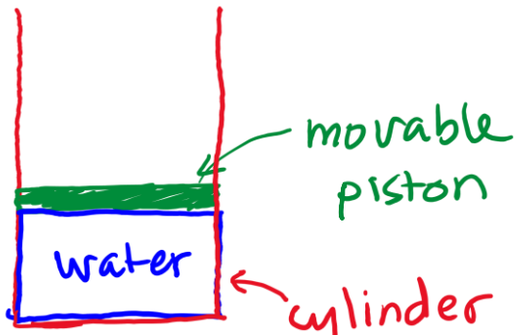
Example

$p = 1$ atm

$V_i = 1 \times 10^{-3}\ m^3$

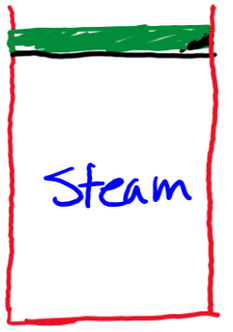
$T = 100^{\circ}C$

$m = 1$ kg



initial

Q ⟹



final

$p = 1$ atm

$V_f = 2\ m^3$

$T_f = 100^{\circ}C$

1.0×10^5 pa

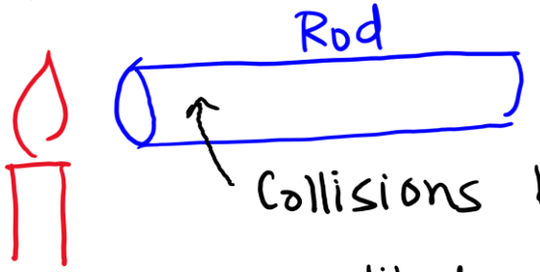
$$W = \int_{V_i}^{V_f} p\, dV = p\,\Delta V = 1.0 \times 10^5 (2 - 1 \times 10^{-3}) = 200\ kJ$$

$$Q = L_v m = (2300 \times 10^3)(1) = 2300\ kJ$$

$$\Delta E_{int} = Q - W = 2100\ kJ$$

18-6 Heat transfer mechanisms

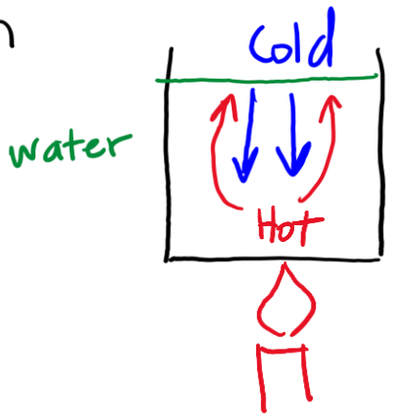
1. Conduction



At high temperature, molecules have large vibration amplitudes.

Collisions between adjacent molecules cause the amplitudes to move from one region to another

2. Convection



Water expands with temperature

⇒ water has lower density

⇒ water moves up because of buoyant forces.

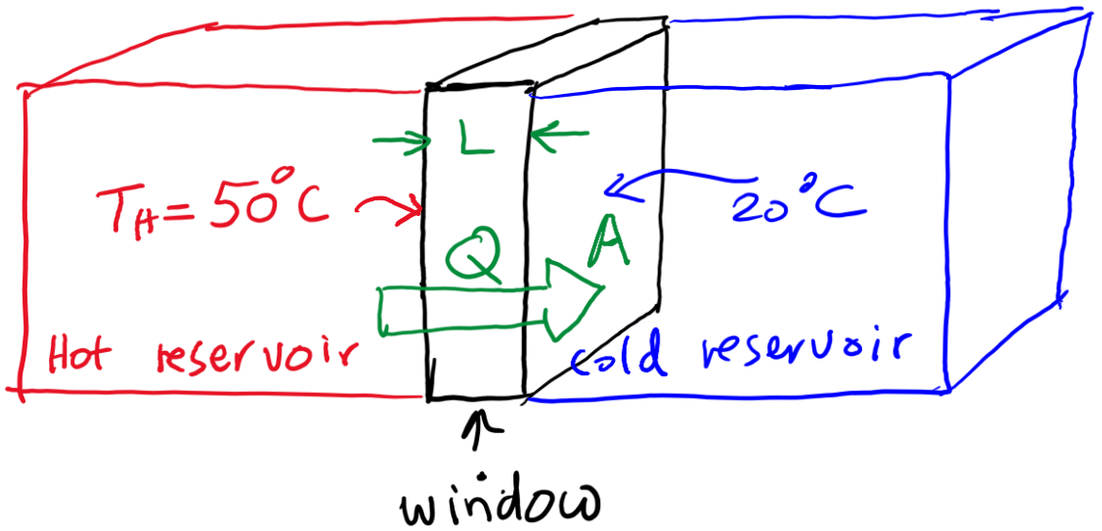
3. Radiation

Electromagnetic waves

Conduction

thermal equilibrium: All parts have the same temperature.

Steady state: temperature does not change with time.



Thermal Resistance (R-value)

$$R \equiv \frac{L}{k}$$

higher R → better insulation

At steady state:

Conduction rate

$$P_{cond} = \frac{Q}{t} = kA\frac{T_H - T_C}{L}$$

- Q: heat
- T_H: Hot reservoir temperature
- T_C: cold reservoir temperature
- t: time
- A: area
- L: thickness
- k: thermal conductivity depends on material

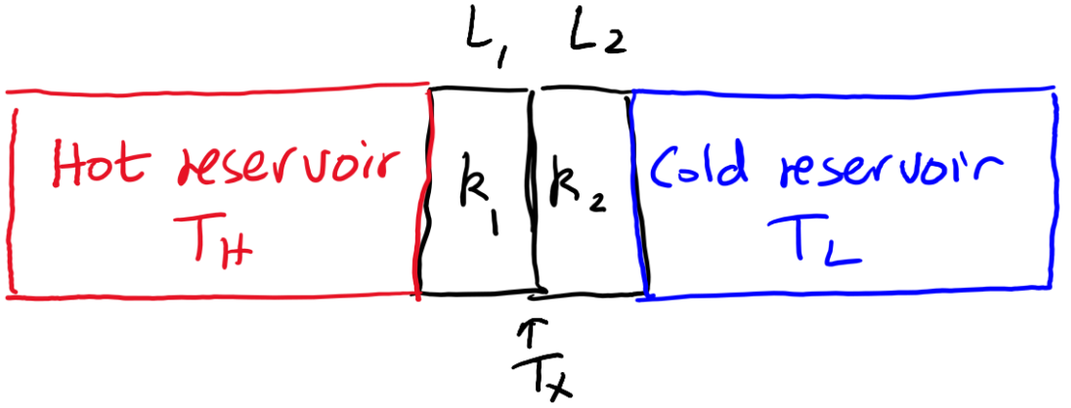
k

air = 0.03 $\frac{W}{mK}$

glass = 1 $\frac{W}{mK}$

copper = 400 $\frac{W}{mK}$

Composite slab



In the steady state, the conduction rates through the two slabs are equal.

$$P_{cond} = k_1 A \frac{T_H - T_x}{L_1} = k_2 A \frac{T_x - T_c}{L_2}$$

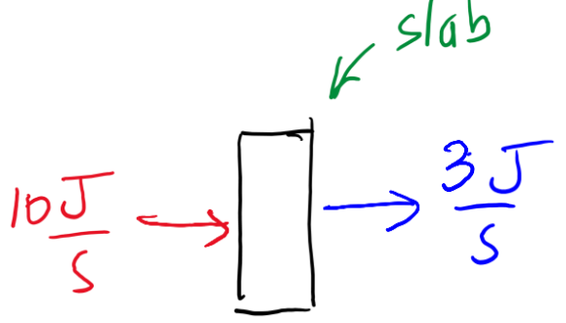
Solve for T_x, then substitute T_x

$$P_{cond} = A \frac{T_H - T_c}{\frac{L_1}{k_1} + \frac{L_2}{k_2}} = A \frac{T_H - T_c}{R_1 + R_2}$$

$R \equiv \frac{L}{k}$

For more slabs

$$P_{cond} = A \frac{T_H - T_c}{R_1 + R_2 + \cdots}$$



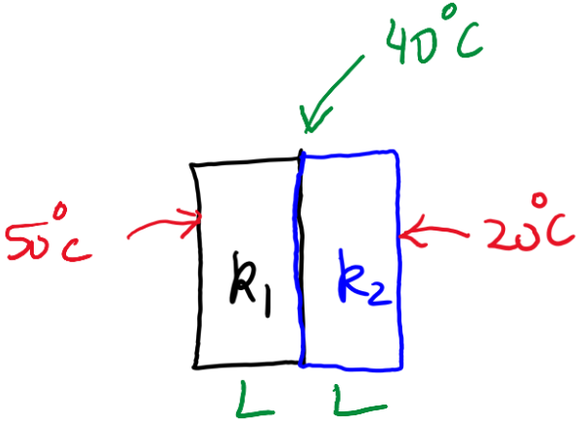
$\Rightarrow$ The slab absorbs 7 J/s.

$Q = m c \Delta T$

$\Rightarrow$ its temperature increases.

$\Rightarrow$ Not a steady state.

Example



Heat transfer is steady.

The two slabs have the same thickness and the same area.

Compare k_1 and k_2?

In the steady state,

the heat conduction rates through the two slabs are equal.

$$P_{cond,1} = P_{cond,2}$$

$$k_1 A \frac{50-40}{L} = k_2 A \frac{40-20}{L}$$

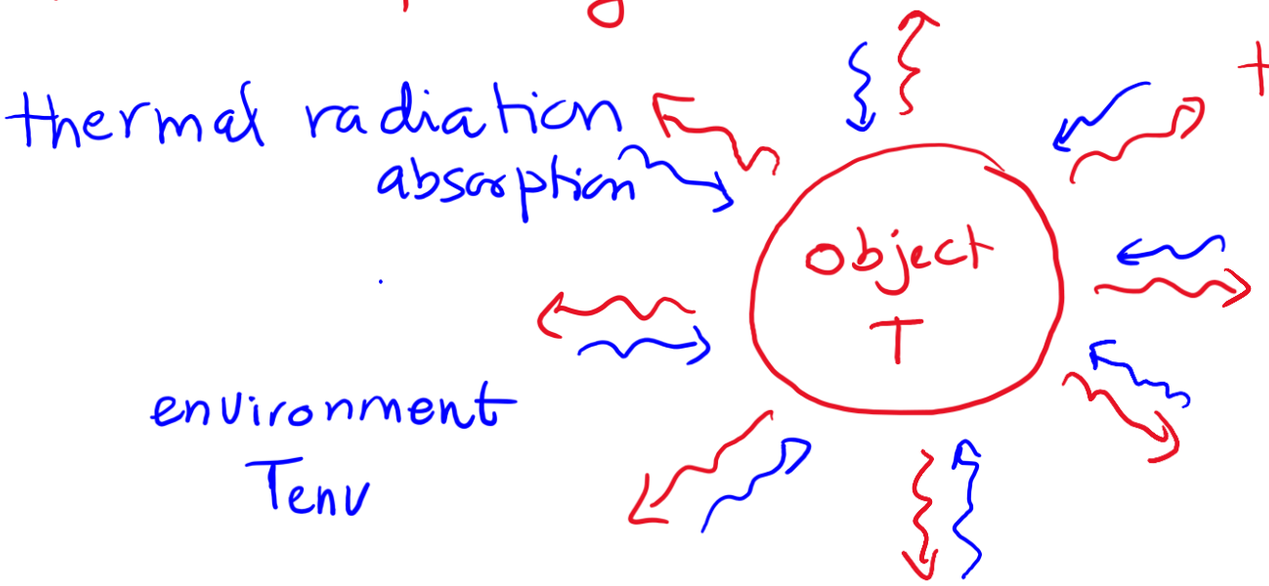
bigger

$$k_1(10) = k_2(20)$$

$$k_1 \Delta T_1 = k_2 \Delta T_2$$

smaller $\Delta T \Rightarrow$ bigger k.

Heat transfer by radiation



surface area of the object

Temperature of the object in Kelvins.

Rate of thermal radiation emission $P_{rad} = \sigma \varepsilon A T^4$

Temperature of the environment in kelvins.

Rate of thermal radiation absorption $P_{abs} = \sigma \varepsilon A T_{env}^4$

Net rate of energy exchange due to thermal radiation

$$P_{net} = P_{abs} - P_{rad} = \sigma \varepsilon A (T_{env}^4 - T^4)$$

Stefan-Boltzmann constant $\sigma = 6 \times 10^{-8}\ W/m^2K^4$

emissivity ε

0 ← White shiny

→ 1 Black