The First Law of Thermodynamics

Q and W are **process (path)-dependent**.

$(Q - W) = \Delta E_{int}$ is **independent of the process**.

$$\Delta E_{int} = E_{int,f} - E_{int,i} = Q - W \quad \text{(first law)}$$

Q: "+" heat into the system; "–" heat lost from the system

W: "+" work done by the system. "–" work done on the system

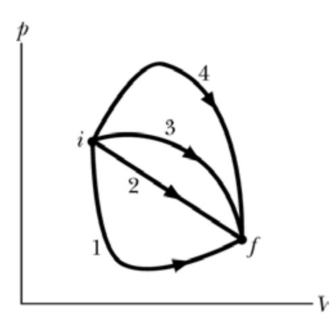
First law of thermodynamics is an extension of the principle of energy conservation to systems that are not isolated.

Problem

The figure here shows four paths on a *p*-*V* diagram which a gas can be taken from state *i* to state *f*. Rank the paths according to the following parameters, greatest first.

A) the change ΔE_{int}

All paths start at i and end at f, therefore all paths have the same change in internal energy, ΔE_{int}



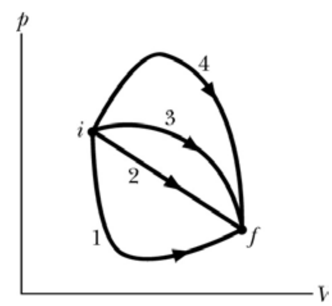
Problem

The figure here shows four paths on a *p*-*V* diagram which a gas can be taken from state *i* to state *f*. Rank the paths according to the following parameters, greatest first.

B) the greatest work *W* done by the gas

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

Path 4 has the maximum area under the p-V curve.



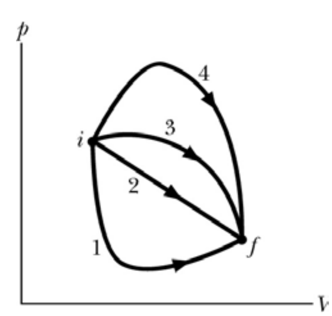
Problem

The figure here shows four paths on a *p*-*V* diagram which a gas can be taken from state *i* to state *f*. Rank the paths according to the following parameters, greatest first.

C) the magnitude of the energy transferred as heat *Q*.

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

$$\Rightarrow Q = \Delta E_{int} + W$$



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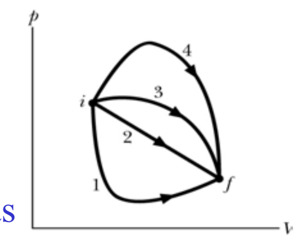


A) the change ΔE_{int}

All paths start at i and end at f, therefore all paths have the same change in internal energy, ΔE_{int}

B) the greatest work *W* done by the gas

$W = \int dW = \int_{V_i}^{V_f} p\,dV$ Path 4 has the maximum area under the p-V curve.

C) the magnitude of the energy transferred as heat *Q*.

$Q = \Delta E_{int} + W$ W is greatest for path 4 => Q_4 is greatest.

Some special cases of the First Law of Thermodynamics

Adiabatic processes: system insulated, no heat transfer

$Q = 0$ therefore $\Delta E_{int} = Q - W = - W$

Constant-volume process: V is fixed

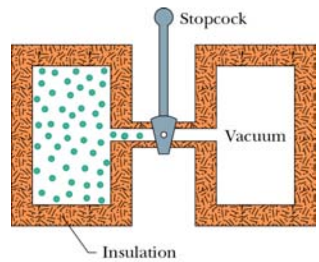
$dW = pdV = 0, \; W = 0$ therefore $\Delta E_{int} = Q - W = Q$

Cyclic processes: System goes back to the initial state

$\Delta E_{int} = 0$ therefore $Q = W$

Some special cases of the First Law of Thermodynamics

Free expansion:

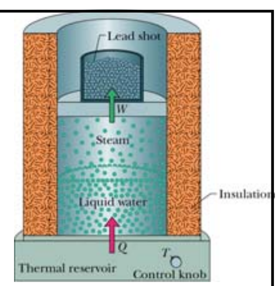


insulated => no heat transfer
=> $Q = 0$,

expands into vacuum without pushing something to change its volume
=> $W = 0$,

Therefore: $\Delta E_{int} = Q - W = 0 - 0 = 0$

Let 1.00 kg of liquid water at 100ºC be converted to steam at 100ºC by boiling at standard atmospheric pressure (1 atm) as shown. The volume of that water changes from an initial value of 1.00 x$10^{-3}$$m^3$ as a liquid to 1.671 m^3 as steam.



A) How much work is done by the system during this process?

$$W = \int dW = \int_{V_i}^{V_f} p\,dV = (1.01\text{x}10^5)(1.671 - 0.001)\text{J} = 169.0\text{ kJ}$$

B) How much energy is transferred as heat during the process?

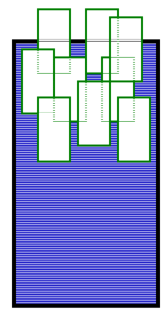
$$Q = m\,L_V = (1.00)(2256) = 2256\text{ kJ}$$

C) What is the change in the system's internal energy during the process?

$$\Delta E_{int} = Q - W = 2256\text{ kJ} - 169\text{ kJ} = 2087\text{ kJ}$$

Daily Quiz, November 17, 2004

50 grams of ice at –20°C is placed in a glass containing 100 grams of liquid water at 10°C. Assume that there is no heat transfer from the water to the glass or to the environment. What is the state when the ice/water mixture has come to thermal equilibrium?



$L_F = 333$ J/g $c_{ice} = 2.22$ J/g°C $c_{water} = 4.190$ J/g°C

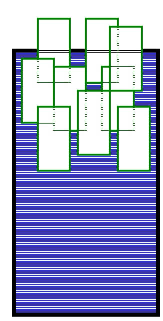
1) all ice at 0°C
2) all liquid water at 6.4°C
3) some ice, some liquid water at 0°C
4) none of the above

Daily Quiz, November 17, 2004

First: find how much energy is available in cooling the water to 0°C.

$$Q_{water} = m_{water}c_{water}(\Delta T_{water}) = (100\text{g})(4.190 \text{ J/g°C})(10°\text{C}) = 4{,}190 \text{ J}$$

50 grams of ice at -20°C is placed in a glass containing 100 grams of liquid water at 10°C. Assume that there is no heat transfer from the water to the glass or the environment. What is the state when the ice/water mixture has come to thermal equilibrium?



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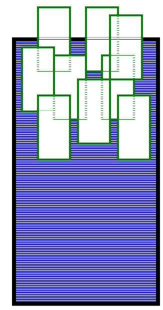
2) all liquid water at 6.4°C
3) some ice, some liquid at 0°C
4) none of the above

Daily Quiz, November 17, 2004

Second: find how much energy is needed to warm the ice to 0°C.

$Q_{ice} = m_{ice}c_{ice}(\Delta T_{ice}) = (50g)(2.22\ J/g^{o}C)(20^{o}C) = 2{,}220\ J$

50 grams of ice at -20°C is placed in a glass containing 100 grams of liquid water at 10°C. Assume that there is no heat transfer from the water to the glass or the environment. What is the state when the ice/water mixture has come to thermal equilibrium?



$L_F = 333\ J/g \quad c_{ice} = 2.22\ J/g^{o}C \quad c_{water} = 4.190\ J/g^{o}C$

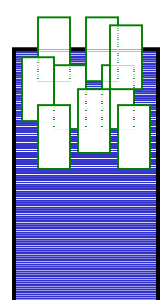
1) all ice at 0°C 2) all liquid water at 6.4°C
3) some ice, some liquid at 0°C
4) none of the above

Daily Quiz, November 17, 2004

Third: find how much energy is needed to melt all of the ice.

$Q_{melt} = m_{ice}L_F = (50g)(333\ J/g) = 16{,}650\ J$

50 grams of ice at -20°C is placed in a glass containing 100 grams of liquid water at 10°C. Assume that there is no heat transfer from the water to the glass or the environment. What is the state when the ice/water mixture has come to thermal equilibrium?



$L_F = 333\ J/g \quad c_{ice} = 2.22\ J/g^{o}C \quad c_{water} = 4.190\ J/g^{o}C$

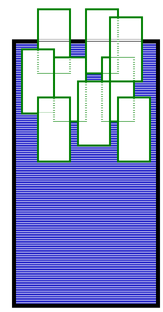
1) all ice at 0°C 2) all liquid water at 6.4°C
3) some ice, some liquid at 0°C
4) none of the above

Daily Quiz, November 17, 2004

Clearly, enough energy is available to raise the temperature of the ice (Q_{water} = 4,190J) > (Q_{ice} = 2,220J) to 0°C

... but not enough to melt all of the ice (Q_{melt} = 16,650J).

50 grams of ice at -20°C is placed in a glass containing 100 grams of liquid water at 10°C. Assume that there is no heat transfer from the water to the glass or the environment. What is the state when the ice/water mixture has come to thermal equilibrium?



L_F = 333 J/g c_{ice} = 2.22 J/g°C c_{water} = 4.190 J/g°C

1) all ice at 0°C
2) all liquid water at 6.4°C
3) some ice, some liquid at 0°C
4) none of the above

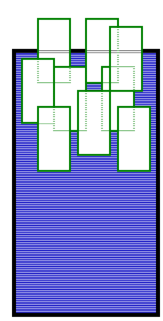
Daily Quiz, November 17, 2004

How much ice melted?

(Q_{water} = 4,190J) – (Q_{ice} = 2,220J) = 1,970J available to melt ice.

$Q_{melt} = m_{melt}L_F$ => $m_{melt} = Q_{melt}/L_F$ = (1970J)/(333J/g) = 5.9g

Final state: 44.1grams of ice at 0°C and 105.9 grams of liquid water at 0°C.



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1) all ice at 0°C
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Heat Transfer Mechanisms

There are three heat transfer mechanisms:

Conduction: heat transfer through direct contact.

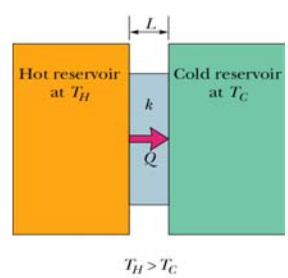
Convection: Convection happens when a fluid comes in contact with an object whose temperature is higher than that of the fluid. Heat is transferred through the flow of the fluid.

Radiation: Heat can be exchanged via electromagnetic waves, called thermal radiation. It does not need a medium.

Heat Transfer Mechanisms

Conduction: heat transfer through direct contact.

$$Q = kA\frac{T_H - T_L}{L}t$$



k: thermal conductivity, different for different material. The higher the k value, the better a thermal conductor it is.

e.g. Aluminum: k = 235; window glass: k = 1   (unit: W/m·K)

Conduction rate: $P_{cond} = Q/t = kA\,(T_H - T_L)\,/L$

Thermal resistance of a slab of thickness L:

$$R = L / k$$

The higher the R-value, the better a thermal insulator it is.

e.g. R-13 fiberglass insulation for the house: $R = 13\ \mathrm{ft^2\,{}^oF\cdot h/Btu}$

How much heat is lost through 1 ft^2 of this fiberglass in 24 hr period when $T_{outside} = 32^oF$ and $T_{inside} = 72^oF$?

$$Q = kA\left(\frac{T_H - T_L}{L}\right)t = A\left(\frac{T_H - T_L}{R}\right)t$$

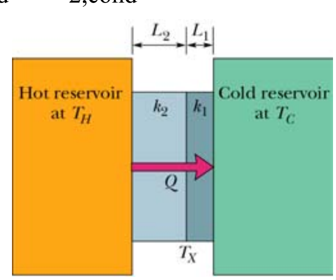
$$= (1\,\mathrm{ft}^2)\left(\frac{72^o\mathrm{F} - 32^o\mathrm{F}}{13\,\mathrm{ft}^2\,{}^o\mathrm{Fh/Btu}}\right)(24\mathrm{h}) = 73.8\,\mathrm{Btu}$$

Between R-11 and R-13 fiberglass material for insulation, which one will you pick for your house?

Conduction through a composite Slab

The energy transferred through one material in a certain time must be equal to that transferred through the other material in the same time. i.e. $P_{1,cond} = P_{2,cond}$

$$P_{cond} = \frac{k_2 A(T_H - T_X)}{L_2} = \frac{k_1 A(T_X - T_C)}{L_1}$$



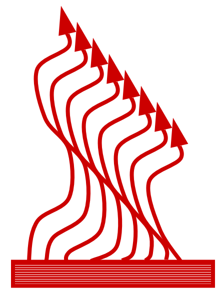
solve for T_X: $$P_{cond} = \frac{A(T_H - T_C)}{L_1/k_1 + L_2/k_2}$$

For n layers: $$P_{cond} = \frac{A(T_H - T_C)}{\sum_{i=1}^{n}(L_i / K_i)}$$

examples: “dry wall + insulation +outside wall” for your house, and “shirt + sweater + coat” for your body in the winter.

Convection: Convection happens when a fluid comes in contact with an object whose temperature is higher than that of the fluid. Heat is transferred through the flow of the fluid.

Think of warm air rising from a heat register



Radiation: Heat can be exchanged via electromagnetic waves, called thermal radiation. It does not need a medium.

$$P_{rad} = \sigma \varepsilon A T^4$$

$\sigma = 5.6703 \times 10^{-8}\ W/m^2 \cdot K^4$ (Stefan-Boltzmann constant)

ε: emissivity, a value between 0 and 1

A: surface area

T: temperature of the surface in Kelvin

(Classical Approximation -- corrected by Quantum Mechanics)