


A Summary of Thermodynamic Processes

Process	Basic Idea	Work (W)	ΔU	Heat (Q)
Isochoric (Constant Volume)	$W = 0$ $P/T = \text{const}$	0	$n C_V \Delta T$	$Q = \Delta U$
Isothermal (Constant Temp.)	$\Delta T = \Delta U = 0$; $PV = \text{const}$	$nRT \ln\left(\frac{V_f}{V_i}\right)$	0	$Q = W$
Adiabatic (No Heat)	$Q = 0$	$-n C_V \Delta T$	$n C_V \Delta T$	0
Free Expansion	$Q = \Delta T = 0$; $P_i V_i = P_f V_f$	0	0	0
Isobaric (Constant Pressure)	no zeroes! $V/T = \text{const}$	$P\Delta V = nR \Delta T$	$n C_V \Delta T$	$n C_P \Delta T$



molar!

Sample Problem

A container of monatomic ideal gas contains just the right number of moles so that $nR = 20 \text{ J/K}$. The gas is in state 1 such that: $P_1 = 20 \text{ kPa}$ $V_1 = 100 \times 10^{-3} \text{ m}^3$

(a) What is the temperature T_1 of the gas?

Use the ideal gas law: $PV = nRT$, so:

$$T_1 = P_1 V_1 / nR = 2000 / 20 = 100 \text{ K}$$

(b) If $Q = 2500 \text{ J}$ of heat is added to the gas, and the gas expands at constant pressure, the gas will reach a new equilibrium state 2. What is the final temperature T_2 ?

We've already seen that, at constant pressure for a monatomic ideal gas: $Q = \Delta U + W = (3/2)nR\Delta T + nR\Delta T = (5/2)nR\Delta T$

Therefore $\Delta T = (2/5)Q/nR = 1000/20 = 50 \text{ K}$.

$$T_2 = T_1 + \Delta T = 100 + 50 = 150 \text{ K}$$

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(a) What is the temperature T_1 of the gas?

$$P_1 V_1 = n R T_1 \quad ; \quad \cancel{20 \cdot 10^3} = 100 \cdot \cancel{10^{-3}} = 20 \cdot T_1 \quad i=3$$

(b) If $Q = 2500 \text{ J}$ of heat is added to the gas, and the gas expands at constant pressure, the gas will reach a new equilibrium state 2. What is the final temperature T_2 ?

$$T_1 = 100 \text{ K}$$

$$2500 \text{ J} = Q = \Delta U + W = \frac{3}{2} n R \Delta T + P \Delta V$$

$PV = nRT$

$$U = \frac{i}{2} n R T$$

$T_2 - T_1 = \Delta T$

$$Q = c m \Delta T$$
$$Q = c \cdot n \cdot \Delta T$$

(c) How much work was done by the gas during the expansion?

(d) What is the final volume V_2 ?

(e) What is the change in the internal energy?

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$$T_2 = T_1 + \Delta T = 100 + 50 = 150 \text{ K}$$

$$PV_1 = nRT_1$$

$$PV_2 = nRT_2$$

$$W = P\Delta V = P(V_2 - V_1) =$$

$$= PV_2 - PV_1 = nRT_2 - nRT_1 = nR\Delta T$$

(c) How much work was done by the gas during the expansion?

$$W = nR\Delta T = 20 * 50 = 1000 \text{ J}$$

(This equation is true only for a constant pressure process)

(d) What is the final volume V_2 ?

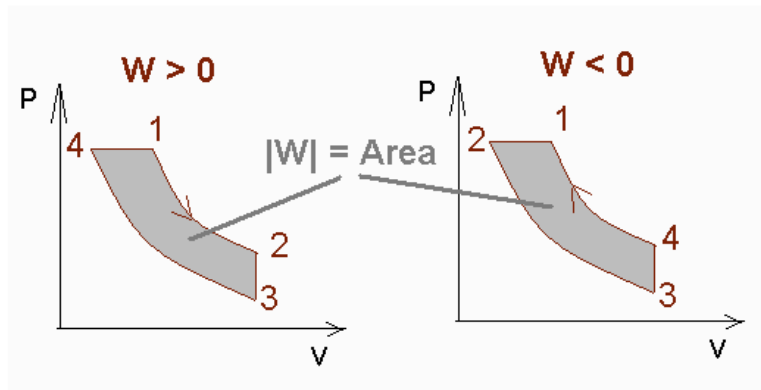
One approach is to bring in the ideal gas law again:

$$V_2 = nRT_2/P_2 = 20(150)/20 \times 10^3 = 150 \times 10^{-3} \text{ m}^3$$

A cyclic process

In a cyclic process, the system starts in a particular state and returns to that state after undergoing a few different processes.

The net work involved is the enclosed area on the P-V diagram.



If the cycle goes clockwise, the system does work. This is the case for an engine.

If the cycle goes counter-clockwise, work is done on the system. An example of such a system is a refrigerator or air conditioner.

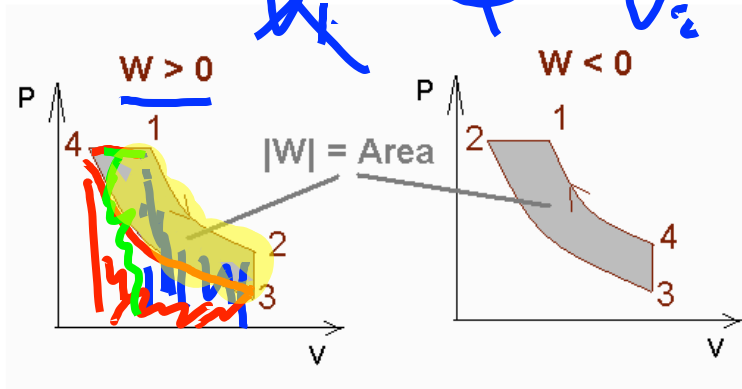
When the system returns to its initial state ($T_i = T_f$) there is no change in internal energy after going around the cycle $\Delta U = 0$,

Hence: $Q_{\text{cycle}} = W_{\text{cycle}} = \text{Area}_{\text{cycle}}$

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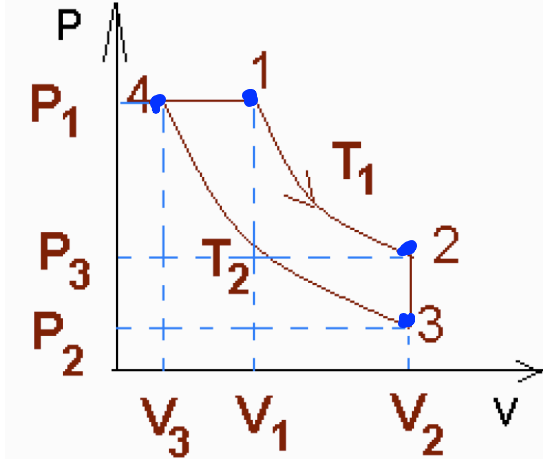
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$$P_1 V_1 = n R \cdot T_1$$

Sample Process



Let's say our sample process consists of the following four steps:

1. Expansion at constant temperature (T_1).
2. Removing heat at constant volume (V_2).
3. Compression at constant temperature (T_2).
4. Expansion at constant pressure (P_1).

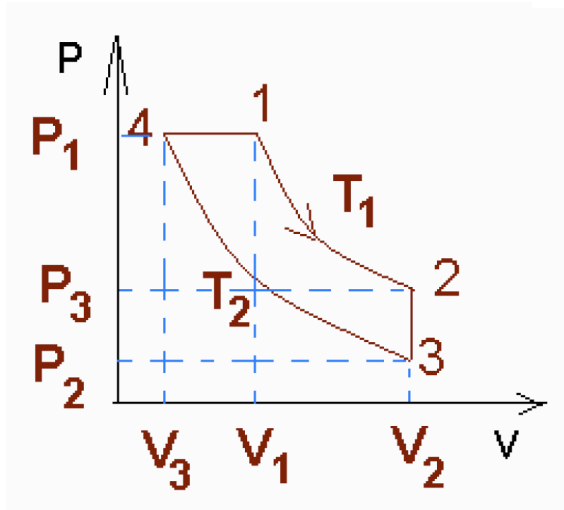
$$Q_{12} + Q_{23} + Q_{34} + Q_{41} = \Delta U = 0$$

Because the amount of matter is constant, $n = \text{const}$, from the ideal gas law we have: $PV/T = nR = \text{const}$ or

$$P_1 V_1 / T_1 = P_2 V_2 / T_1 = P_3 V_2 / T_2 = P_1 V_3 / T_2$$

Isothermal compression

$$(T = \text{const}) \quad Q_{34} = \Delta U_{34} + W_{34}$$



The work W_{34} done by the system is negative, $W_{34} < 0$, or $W_{34} = -|W_{34}|$ but of smaller magnitude than W_{12} .

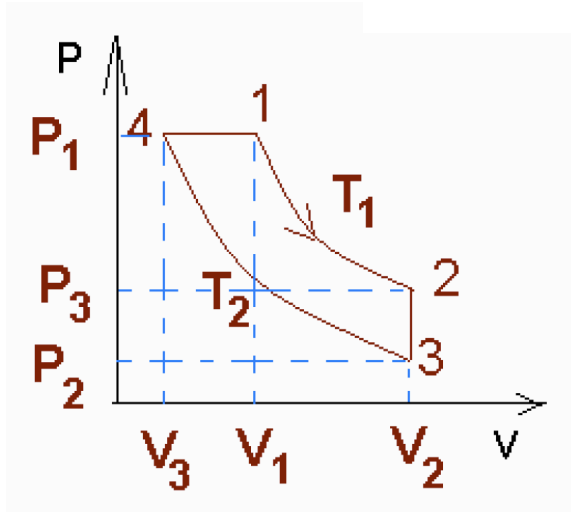
The area under the PV curve is clearly less now than that involved in step 1. $|W_{34}| < |W_{12}|$

The internal energy does not change, $\Delta U_{34} = 0$, so,

$$Q_{34} = W_{34} < 0 \text{ (heat is removed from the system).}$$

Isobaric expansion

$$(P = \text{const}) \quad Q_{41} = \Delta U_{41} + W_{41}$$

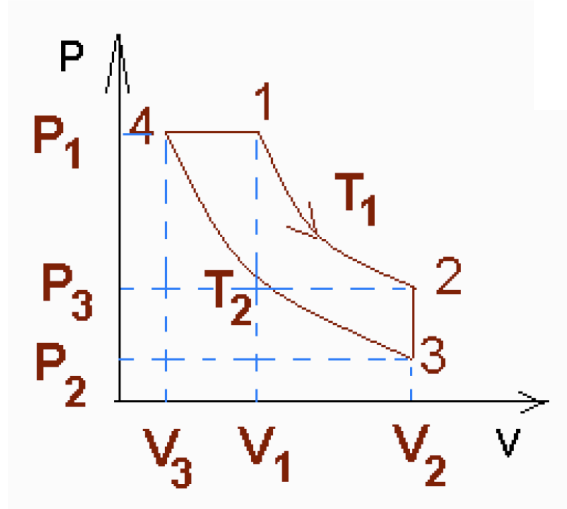


When the system goes from the state 4 to the state 1 the temperature is increasing ($T_i = T_2 < T_1 = T_f$), so $\Delta U_{41} > 0$

Also the volume is increasing: $V_i = V_3 < V_1 = V_f$ so,
 $W_{41} = P_1 \Delta V > 0$

$$\text{So,} \quad Q_{41} = \Delta U_{41} + W_{41} > 0$$

For the cycle or any part of it: $Q = \Delta U + W$



Isothermal expansion

$$(T = \text{const}) \quad Q_{12} = \Delta U_{12} + W_{12}$$

The system does work $W_{12} > 0$ which must be equal to the heat Q_{12} added to the system in the expansion, because the internal energy does not change $\Delta U_{12} = 0$.

Isochoric process ($V = \text{const}$) $Q_{23} = \Delta U_{23} + W_{23}$

The work done in this step is $W_{23} = 0$. An amount of heat Q_{23} is removed from the system because the internal energy decreases (the temperature changes from T_1 to T_2). $Q_{23} = \Delta U_{23} < 0$

Cycle Summary

Because $W_{23} = 0$, the net work done is

$$W_{\text{net}} = W_{12} + W_{34} + W_{41} = W_{12} - |W_{34}| + W_{41} > 0$$

The net heat added to the system is ($\Delta U_{\text{net}} = 0$)

$$\underline{Q_{\text{net}} = W_{\text{net}} > 0}$$

Because $\Delta U_{\text{net}} = 0$, we can connect ΔU_{23} and ΔU_{41} (ΔU_{12} and ΔU_{34} both = 0).

$$\Delta U_{\text{net}} = 0 = \Delta U_{12} + \Delta U_{23} + \Delta U_{34} + \Delta U_{41} = \Delta U_{23} + \Delta U_{41}$$

Hence, $\Delta U_{23} = -\Delta U_{41}$

We can take this analysis further and state the net work in terms of T_1 , T_2 , V_1 , and V_2 .

For $T = \text{const}$: ($V_2 > V_1$)

$$W_{12} = nRT_1 \ln\left(\frac{V_2}{V_1}\right)$$

$$W_{34} = nRT_2 \ln\left(\frac{V_1}{V_2}\right)$$

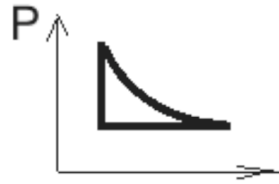
For $P = \text{const}$: ($V_1 > V_3$)

$$W_{41} = P_1(V_1 - V_3)$$

The net work:

$$W_{\text{net}} = W_{12} + W_{34} + W_{41}$$

Temperature, heat, gas: $T_k = T_c + \underline{273}$



$$Q = cm\Delta T \quad Q = \pm mL \quad \Sigma Q = 0$$

$$\frac{N}{N_A} = \frac{m}{\mu} = n \quad PV = NkT = nRT \quad E_{kav} = \frac{i}{2}kT$$

$$R = kN_A \quad U = \frac{i}{2}kNT = \frac{i}{2}nRT \quad i = 3, 5, 6.$$

$$W = \text{Area}(P_{\text{vs.}} V) \quad V \uparrow \Rightarrow W > 0 \quad V \downarrow \Rightarrow W < 0$$

$$\frac{PV}{nT} = R = \text{const} \Rightarrow n = \text{const} \Rightarrow \frac{PV}{T} = nR = \text{const} \Rightarrow \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$Q = W + \Delta U \quad \Delta U_{\text{cycle}} = 0 \quad Q_{\text{cycle}} = W_{\text{cycle}}$$

$$P = \text{const}: \frac{V_1}{T_1} = \frac{V_2}{T_2} \quad W = P\Delta V = nR\Delta T \quad \Delta U = \frac{i}{2}nR\Delta T \quad Q = \frac{i+2}{2}nR\Delta T$$

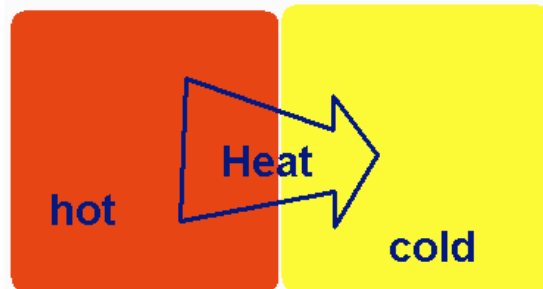
$$V = \text{const} \Rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2} \quad W = 0 \quad \Delta U = \frac{i}{2}nR\Delta T \quad Q = \Delta U = \frac{i}{2}nR\Delta T$$

$$T = \text{const} \Rightarrow P_1V_1 = P_2V_2 \quad Q = W \quad \Delta U = 0$$

Heat Transfer

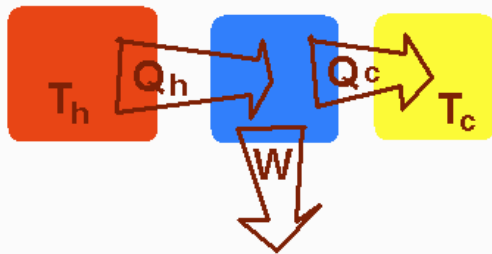
Heat is transferred naturally from a higher-temperature region to a lower-temperature region. That means, if we let a system alone, it is going to cool down or heat up until the temperature of the system becomes equal to the temperature of the surrounding matter.

Heat is not transferred naturally in the other direction. To reverse the process we have to act on a system.



A Heat Engine

The higher temperature causes the system to expand, doing work, and the lower temperature re-sets the engine so another cycle can begin.



In a full cycle of a heat engine, three things happen:

1. Heat Q_h is added at a relatively high temperature T_h .
2. Some of the energy from the input heat is used to do work W .
3. The rest of the energy is removed as heat Q_c at a relatively low temperature T_c .

The conservation of energy, for a cycle: $|Q_h| = W + |Q_c|$

Efficiency

The efficiency of an engine tells us how much of the input energy ends up doing useful work.

The efficiency is defined as:

$$e = \frac{W}{|Q_h|} = \frac{|Q_h| - |Q_c|}{|Q_h|} = 1 - \frac{|Q_c|}{|Q_h|} \quad \propto \underline{\underline{100\%}}$$

This is the maximum possible efficiency of an engine. In practice losses from friction and other sources reduce the efficiency.

An Ideal (Carnot) Engine

Carnot's Principle: An engine achieves *maximum* efficiency when it uses *reversible* processes.

(In other words the efficiency of an engine using irreversible processes can be no greater than the efficiency of an engine using reversible processes that is working between the same temperatures. This is named for Sadi Carnot, a French engineer).

Carnot showed that for an *ideal* (or Carnot) engine, operating between temperatures T_h and T_c , the efficiency is:

$$e_c = 1 - \frac{T_c}{T_h}$$

A heat engine is designed to operate between 20°C and 30.0°C . Neglecting all possible energy loss, what amount of heat Q do we need supply to it in order to get out 2000 J of work?

$$2000 = W = Q_h - |Q_c|$$

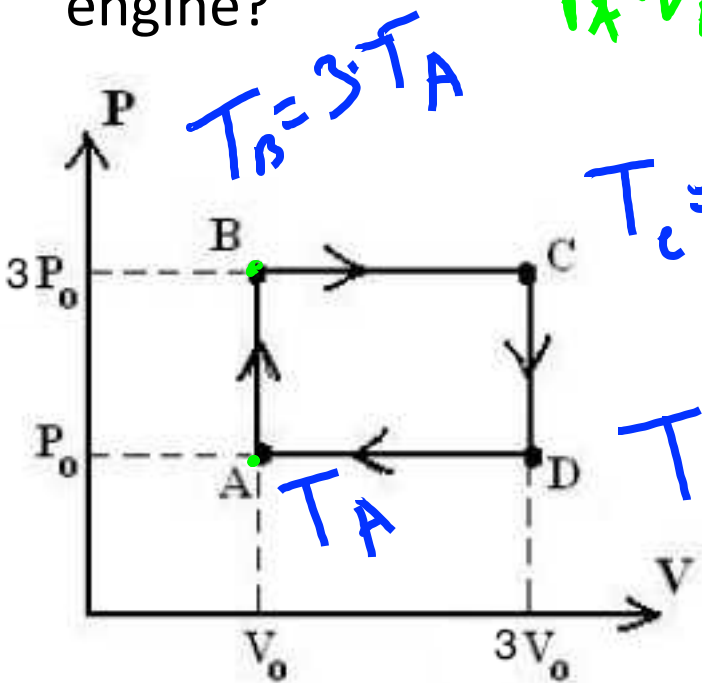
$$e_c = 1 - \frac{T_c}{T_h} = 1 - \frac{|Q_c|}{|Q_h|}$$

$$e = 1 - \frac{293}{303} = 1 - \frac{Q_h - 2000}{Q_h}$$

$$T_c = 273 + 20$$

$$T_h = 273 + 30$$

A diatomic ideal gas is the working substance for an engine that undergoes the cyclic process (ABCD) shown in the PV diagram. What is the efficiency of this engine?



$$P_A \cdot V_A = n \cdot R \cdot T_A$$

$$T_A = \frac{P_0 \cdot V_0}{nR}$$

$$T_C = 9 \cdot T_A$$

$$T_B = \frac{3P_0 \cdot V_0}{nR}$$

$$T_D = 3 \cdot T_A$$

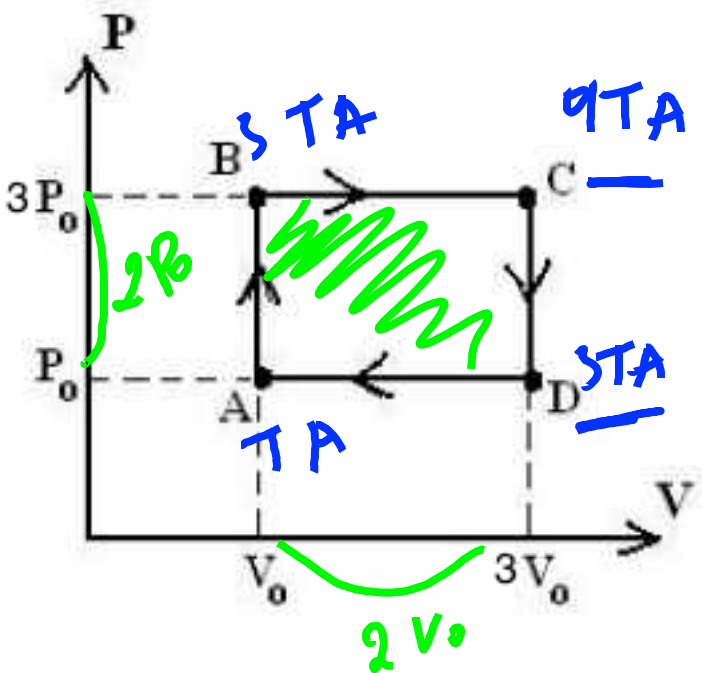
$$T_C = \frac{3P_0 \cdot 3V_0}{nR}$$

$$\underline{T_C > T_B = T_D > T_A} \quad T_D = \frac{P_0 \cdot 3V_0}{nR}$$

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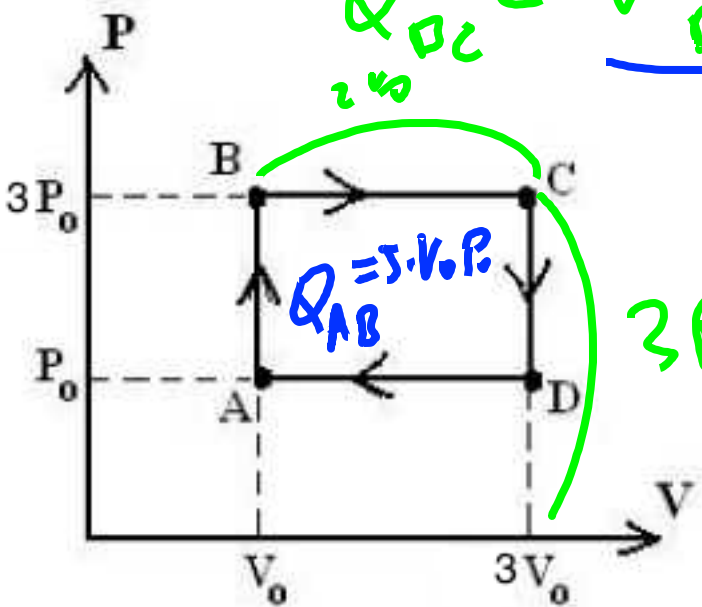
~~$e = 1 - \frac{T_c}{T_h}$~~

$$e = 1 - \frac{|Q_c|}{|Q_h|} = \frac{W}{|Q_h|} ; W = 2 P_0 \cdot 2 V_0 = 4 P_0 \cdot V_0$$



$$\begin{aligned} Q_{AB} &= \Delta U_{AB} + \cancel{W_{AB}} \\ &= U_B - U_A = \frac{5}{2} n R T_B - \frac{5}{2} n R T_A \\ &= \frac{5}{2} \cdot P_B \cdot V_B - \frac{5}{2} P_A \cdot V_A \\ &= \frac{5}{2} \cdot 3 P_0 \cdot V_0 - \frac{5}{2} P_0 \cdot V_0 = 5 P_0 \cdot V_0 > 0 \end{aligned}$$

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1. 21

2. ~~21~~

$$Q = Q_{AB} + P_{BC} \Delta V_{BC} = 26 P_0 V_0$$

$$Q_{BC} = \underbrace{U_{BC}}_{2V_0} + \underbrace{P \Delta V_{BC}}_{2V_0 \cdot 3P_0} + Q_c = |Q_{AB}^+ + Q_{DA}^+|$$

$$+ \frac{5}{2} P_c V_c - \frac{5}{2} P_B V_0 =$$

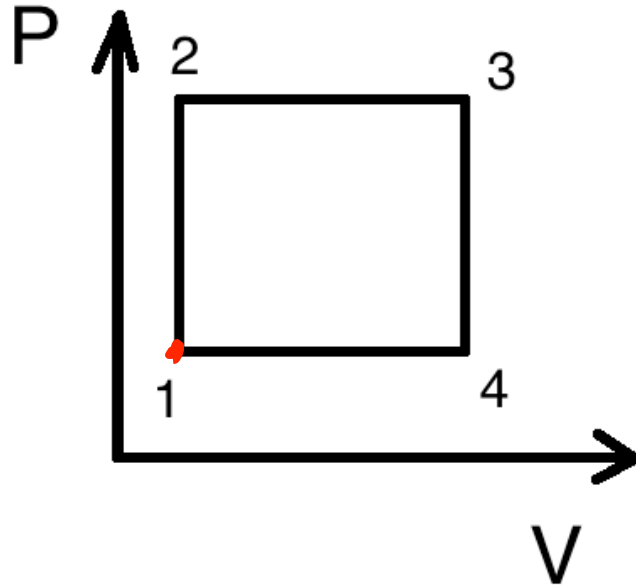
$$= \underline{6 V_0 P_0} + \underline{\frac{5}{2} 3 P_0 \cdot 3 V_0} - \frac{5}{2} 3 P_0 \cdot V_0 = \underline{21 P_0 V_0}$$

$$Q_{CD} = 0 + U_D - U_C < 0$$

$$Q_{DA} = U_A + U_A - U_D < 0$$

$$e = \frac{W}{Q_h} = \frac{4 \text{ kJ}}{76 \text{ kJ}} \cdot 100\% =$$
$$=$$

A square cycle



$$\underline{nR} = 100 \text{ J/K}$$

$$P_1 = 200 \text{ kPa}$$

$$P_3 = 400 \text{ kPa}$$

$$V_1 = 10 \text{ L}$$

$$V_2 = 20 \text{ L}$$

Monatomic gas

$$= 200 \cdot 10^3 \text{ Pa}$$

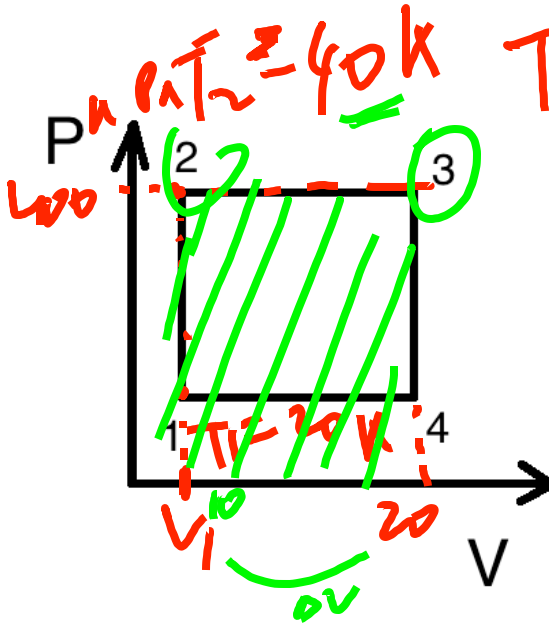
$$= 400 \cdot 10^3 \text{ Pa}$$

$$= 10 \cdot 10^{-3} \text{ m}^3$$

$$= 20 \cdot 10^{-3} \text{ m}^3$$

$$f = 3$$

Find everything



A square cycle

$nR = 100 \text{ J/K}$ $P_1 = 200 \text{ kPa}$
 $P_3 = 400 \text{ kPa}$ $V_1 = 10 \text{ L} = 10 \cdot 10^{-3} \text{ m}^3 = 200 \cdot 10^3 \text{ Pa}$
 $V_2 = 20 \text{ L}$ Monatomic gas

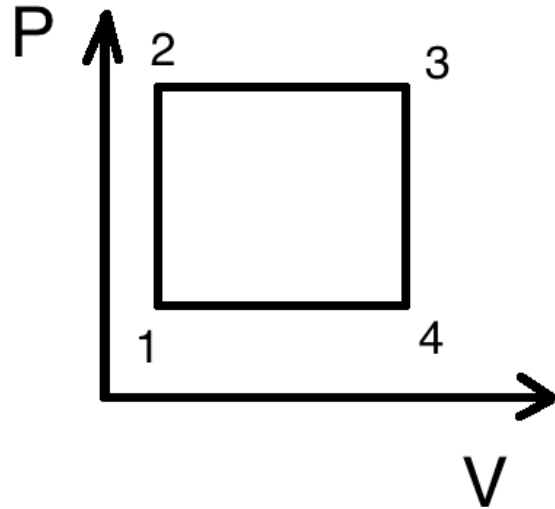
$PV = nRT$
 $200 \cdot 10 = 100 \cdot T_1$
 $T_2 = \frac{P_2 V_2}{100} = \frac{400 \cdot 10}{100}$

$T_3 = \frac{P_3 V_3}{100} = \frac{400 \cdot 20}{100}$
 $U = \frac{i}{2} nRT$ $Q = \Delta U + W_{\text{gas}}$
 $P = \text{AREA}_{PV}$
 $U = \frac{3}{2} \cdot 100 \cdot T$

Process	P	T	V	Q	ΔE_{int}	W
1 → 2	→	→	→			
2 → 3	→	→	→			
3 → 4	→	→	→			
4 → 1	→	→	→			
Complete cycle						

$Q_{23} = W_{23} + \Delta U_{23} = 400 \cdot 10 + U_3 - U_2 = 4000 + \frac{3}{2} \cdot 100 \cdot 80 - \frac{3}{2} \cdot 100 \cdot 40$

A square cycle



$$nR = 100 \text{ J/K}$$

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$$V_1 = 10 \text{ L}$$

$$V_2 = 20 \text{ L}$$

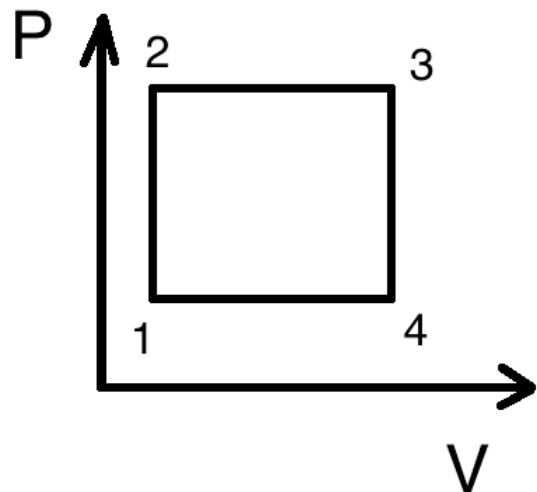
Monatomic gas

$$PV = nRT \quad Q = \Delta U + W_{\text{gas}}$$

$$U = (i/2)nRT \quad P = \text{AREA}_{PV}$$

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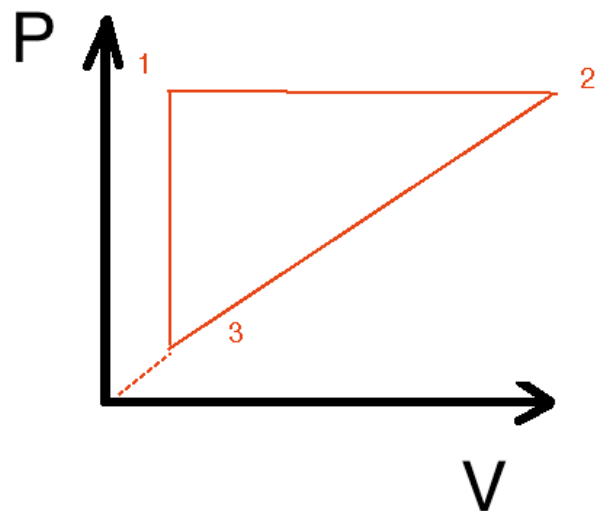
$$V_2 = 20 \text{ L}$$

Monatomic gas

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$$U = (i/2)nRT \quad P = \text{AREA}_{PV}$$

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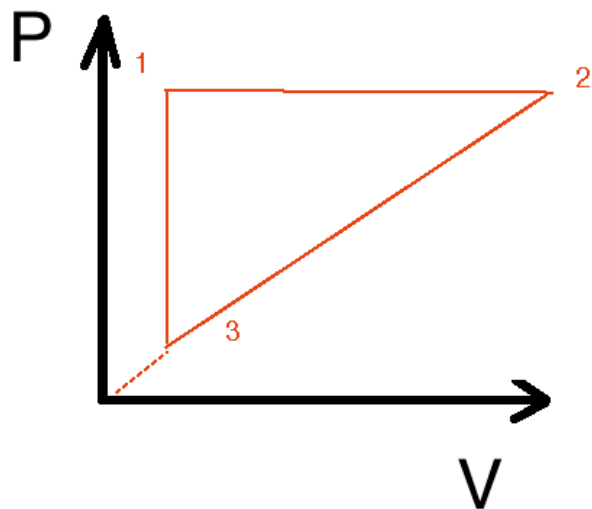


$nR = 300 \text{ J/k}$
 $P_1 = 600 \text{ kPa}$
 $V_1 = 40 \text{ L}$
 $V_2 = 120 \text{ L}$
 diatomic gas

$$PV = nRT \quad Q = \Delta U + W_{\text{gas}}$$

$$U = (i/2)nRT \quad W_{\text{gas}} = \text{AREA}_{PV}$$

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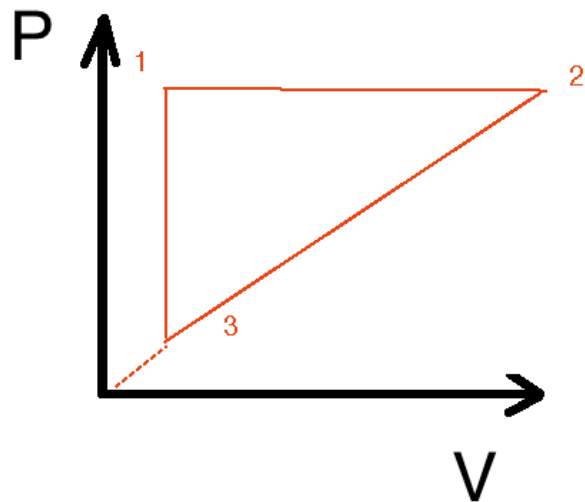


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1 → 2	→	→	→			
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3 → 1	→	→	→			
Complete cycle						

Worksheet Filling in the Table

The P-V diagram shows the cycle made of three processes:

1 – 2 is the adiabatic process

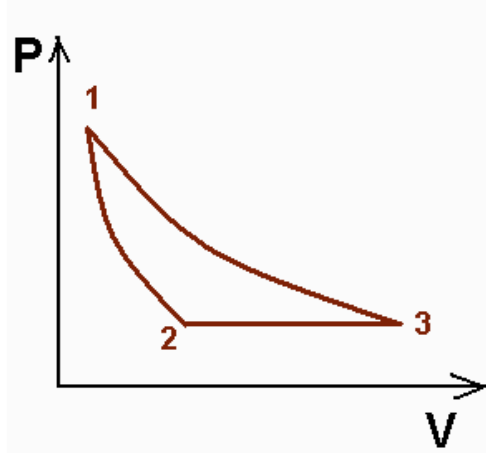
2– 3 is isobaric process

3 – 1 is isothermal process

The gas consists of diatomic molecules.

The number of moles is such that $nR = 100 \text{ J/K}$

$$P_2 = P_3 = 100 \text{ kPa} \quad V_3 = 0.5 \text{ m}^3$$



The system does 20kJ of work when making the process 2 -3

The total work done by the system in the cycle is -19400 J

Find everything you can.

$$PV = nRT$$

$$Q = \Delta U + W$$

$$\Delta U = (i/2)nR\Delta T$$

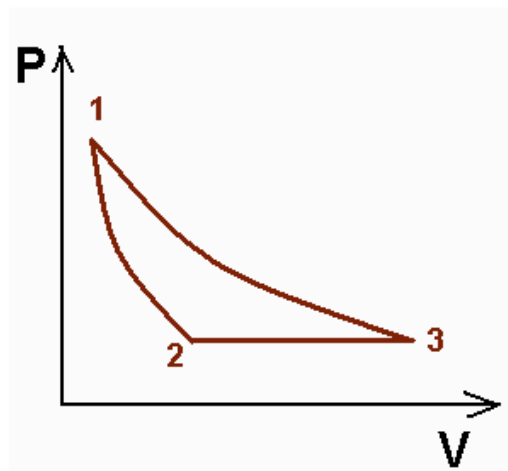
$$W_{T=\text{const}} = nRT \ln(V_f/V_i)$$

$$W_{P=\text{const}} = P(V_f - V_i)$$

$$Q_{\text{net}} = W_{\text{net}}$$

$$\Delta U_{\text{net}} = 0 \quad i = 5$$

Let's make a table



diatomic gas

$$nR = 100 \text{ J/K}$$

$$P_3 = 100 \text{ kPa}$$

$$V_3 = 0.5 \text{ m}^3$$

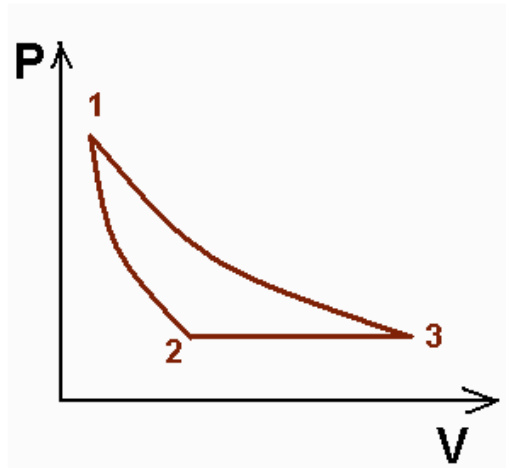
20kJ of work done in the process 2 -3

The total work -19400 J

Process	Q	ΔE_{int}	W	P	V	T
1 to 2						
2 to 3						
3 to 1						
Complete cycle						

Let's make a table

$$nR = 100 \text{ J/K}$$



diatomic gas

$$nR = 100 \text{ J/K}$$

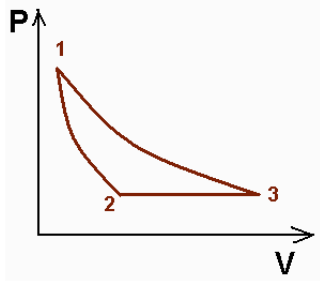
$$P_3 = 100 \text{ kPa}$$

$$V_3 = 0.5 \text{ m}^3$$

20kJ of work done in
the process 2 -3

The total work -19400 J

Process	Q	ΔE_{int}	W	P	V	T
1 to 2				P_1	V_1	T_1
2 to 3			20000 J	$P_2 = 100 \text{ kPa}$	V_2	T_2
3 to 1				$P_3 = 100 \text{ kPa}$	$V_3 = 0.5 \text{ m}^3$	T_3
Complete cycle			-19400 J			



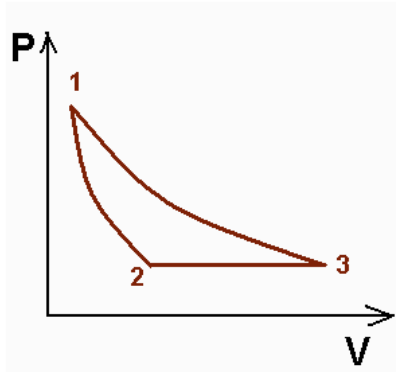
$$nR = 100 \text{ J/K}$$

Process	Q	ΔE_{int}	W	P	V	T
1 to 2				P_1	V_1	T_1
2 to 3			20000 J	$P_2 = 100 \text{ kPa}$	V_2	T_2
3 to 1				$P_3 = 100 \text{ kPa}$	$V_3 = 0.5 \text{ m}^3$	T_3
Complete cycle			-19400 J	n/a		

Equations: $PV = nRT$, $Q = \Delta U + W$, $\Delta U = (i/2)nR\Delta T$

$$W_{T=\text{const}} = nRT \ln(V_f/V_i) \quad W_{P=\text{const}} = P(V_f - V_i)$$

$$Q_{\text{net}} = W_{\text{net}} \quad \Delta U_{\text{net}} = 0 \quad i = 5$$



Equations: $PV = nRT$, $Q = \Delta U + W$,
 $\Delta U = (5/2)nR\Delta T$ $W_{T=\text{const}} = nRT \ln(V_f/V_i)$
 $W_{P=\text{const}} = P(V_f - V_i)$ $nR = 100 \text{ J/K}$
 $Q_{\text{net}} = W_{\text{net}}$ $\Delta U_{\text{net}} = 0$

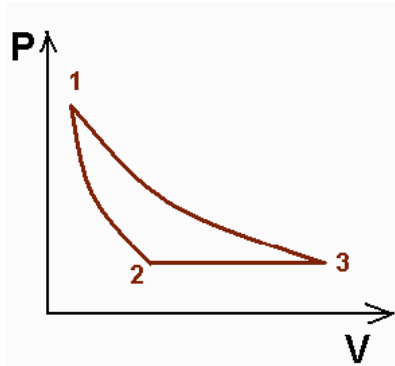
Let's first write all the zeros:

Process	Q	ΔE_{int}	W	P	V	T
1 to 2	0			P_1	V_1	T_1
2 to 3			20000 J	$P_2 = 100 \text{ kPa}$	V_2	T_2
3 to 1		0		$P_3 = 100 \text{ kPa}$	$V_3 = 0.5 \text{ m}^3$	T_3
Complete cycle		0	-19400 J	n/a		

$$\Delta E_{\text{int-cycle}} = \Delta U_{\text{net}} = 0$$

$$\Delta E_{\text{int-31}} = \Delta U_{T=\text{const}} = 0$$

$$Q_{12} = Q_{\text{adiab}} = 0$$



Equations: $PV = nRT$, $Q = \Delta U + W$,
 $\Delta U = (5/2)nR\Delta T$ $W_{T=\text{const}} = nRT \ln(V_f/V_i)$
 $W_{P=\text{const}} = P(V_f - V_i)$ $nR = 100 \text{ J/K}$
 $Q_{\text{net}} = W_{\text{net}}$ $\Delta U_{\text{net}} = 0$

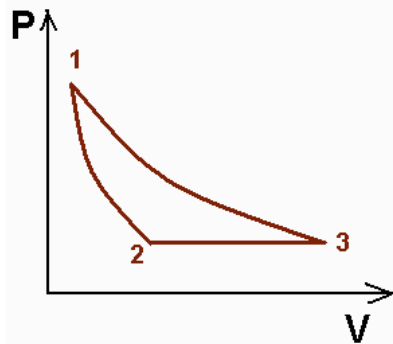
Process	Q	ΔE_{int}	W	P	V	T
1 to 2	0			P_1	V_1	500 K
2 to 3			20000 J	$P_2 = 100 \text{ kPa}$	V_2	T_2
3 to 1		0		$P_3 = 100 \text{ kPa}$	$V_3 = 0.5 \text{ m}^3$	500 K
Complete cycle		0	-19400 J	n/a		

Now let's apply $PV = nRT$ to all the states (1, 2 and 3):

$$P_1V_1 = nRT_1 \quad P_2V_2 = nRT_2 \quad P_3V_3 = nRT_3 \quad \text{In addition: } T_1 = T_3$$

$$\Rightarrow \quad P_1V_1 = 100T_1 \quad 10^5 * V_2 = 100T_2 \quad 10^5 * 0.5 = 100T_3$$

We can find $T_3 = T_1 = 500 \text{ K}$



Equations: $PV = nRT$, $Q = \Delta U + W$,
 $\Delta U = (5/2)nR\Delta T$ $W_{T=\text{const}} = nRT \ln(V_f/V_i)$
 $W_{P=\text{const}} = P(V_f - V_i)$ $nR = 100 \text{ J/K}$
 $Q_{\text{net}} = W_{\text{net}}$ $\Delta U_{\text{net}} = 0$

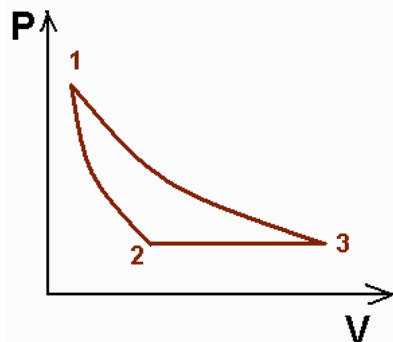
Process	Q	ΔE_{int}	W	P	V	T
1 to 2	0			P_1	V_1	500 K
2 to 3			20000 J	$P_2 = 100 \text{ kPa}$	V_2	T_2
3 to 1		0		$P_3 = 100 \text{ kPa}$	$V_3 = 0.5 \text{ m}^3$	500 K
Complete cycle	-19400 J	0	-19400 J	n/a		

Now let's apply $Q = \Delta U + W$ to all the process:

$$Q_{12} = \Delta U_{12} + W_{12} = 0 \quad Q_{23} = \Delta U_{23} + W_{23}$$

$$Q_{31} = \Delta U_{31} + W_{31} = W_{31}$$

$$Q_{\text{net}} = \Delta U_{\text{net}} + W_{\text{net}} = W_{\text{net}} = -19400 \text{ J}$$



Equations: $PV = nRT$, $Q = \Delta U + W$,
 $\Delta U = (5/2)nR\Delta T$ $W_{T=\text{const}} = nRT \ln(V_f/V_i)$
 $W_{P=\text{const}} = P(V_f - V_i)$ $nR = 100 \text{ J/K}$
 $Q_{\text{net}} = W_{\text{net}}$ $\Delta U_{\text{net}} = 0$

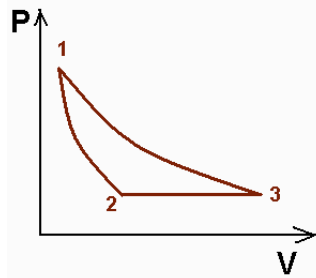
Process	Q	ΔE_{int}	W	P	V	T
1 to 2	0			P_1	V_1	500 K
2 to 3			20000 J	$P_2 = 100 \text{ kPa}$	V_2	300 K
3 to 1		0		$P_3 = 100 \text{ kPa}$	$V_3 = 0.5 \text{ m}^3$	500 K
Complete cycle	-19400 J	0	-19400 J	n/a		

Now let's apply $W_{P=\text{const}} = P(V_f - V_i)$ and $PV = nRT$

$$W_{P=\text{const}} = P(V_f - V_i) = PV_f - PV_i = nRT_f - nRT_i = nR\Delta T$$

$$W_{23} = nR\Delta T_{23} \quad 20000 = 100 * \Delta T_{23} \quad \Delta T_{23} = 200 = 500 - T_2$$

$$T_2 = 300 \text{ K}$$



Equations: $PV = nRT$, $Q = \Delta U + W$,
 $\Delta U = (5/2)nR\Delta T$ $W_{T=\text{const}} = nRT \ln(V_f/V_i)$

$$W_{P=\text{const}} = P(V_f - V_i) \quad nR = 100 \text{ J/K}$$

$$Q_{\text{net}} = W_{\text{net}} \quad \Delta U_{\text{net}} = 0$$

Process	Q	ΔE_{int}	W	P	V	T
1 to 2	0	-50000 J	50000 J	P_1	V_1	500 K
2 to 3	70000 J	50000 J	20000 J	$P_2 = 100 \text{ kPa}$	V_2	300 K
3 to 1	-89400 J	0	-89400 J	$P_3 = 100 \text{ kPa}$	$V_3 = 0.5 \text{ m}^3$	500 K
Cycle	-19400 J	0	-19400 J	n/a		

Now we can find everything. $\Delta U_{23} = (5/2)nR\Delta T_{23} = 50000 \text{ J}$

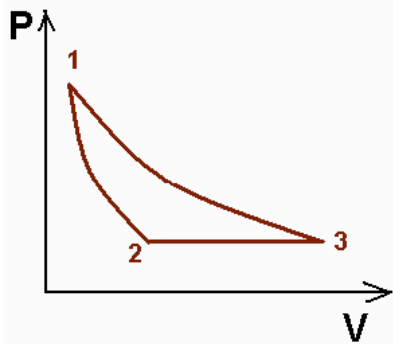
$$Q_{23} = \Delta U_{23} + W_{23} = 70000 \text{ J}; \quad Q_{31} = -89400 \text{ J} \quad \text{because}$$

$$Q_{\text{net}} = Q_{12} + Q_{23} + Q_{31} \quad \text{and} \quad -19400 = 0 + 70000 + Q_{31}$$

$$W_{31} + 0 = Q_{31} = -89400 \text{ J}; \quad W_{12} = 50000 \text{ J} \quad \text{because}$$

$$W_{\text{net}} = W_{12} + W_{23} + W_{31} \quad \text{and} \quad -19400 = W_{12} + 20000 - 98400$$

$$Q_{12} = \Delta U_{12} + W_{12} \quad \text{leads to} \quad 0 = \Delta U_{12} + 50000; \quad \Delta U_{12} = -50000 \text{ J}$$



Equations: $PV = nRT$, $Q = \Delta U + W$,
 $\Delta U = (5/2)nR\Delta T$ $W_{T=\text{const}} = nRT \ln(V_f/V_i)$
 $W_{P=\text{const}} = P(V_f - V_i)$ $nR = 100 \text{ J/K}$
 $Q_{\text{net}} = W_{\text{net}}$ $\Delta U_{\text{net}} = 0$

Process	Q	ΔE_{int}	W	P	V	T
1 to 2	0	-50000 J	50000 J	597749 Pa	0.084 m ³	500 K
2 to 3	70000 J	50000 J	20000 J	P ₂ = 100 kPa	V ₂ = 0.3 m ³	300 K
3 to 1	-89400 J	0	-89400 J	P ₃ = 100 kPa	V ₃ = 0.5 m ³	500 K
Cycle	-19400 J	0	-19400 J	n/a		

Now we can find everything. $P_1 V_1 = 100 T_1$ $10^5 * V_2 = 100 T_2$

Hence: $10^5 * V_2 = 100 * 300$ and $V_2 = 0.3 \text{ m}^3$

$W_{31} = nRT_3 \ln(V_1/V_3)$ hence $-89400 = 100 * 500 * \ln(V_1/0.5)$

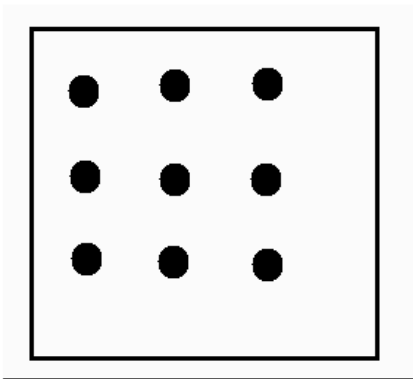
That gives: $V_1 = 0.5/e^{1.788} \approx 0.084 \text{ m}^3$ $P_1 = 100 * 500 / 0.084$

Entropy

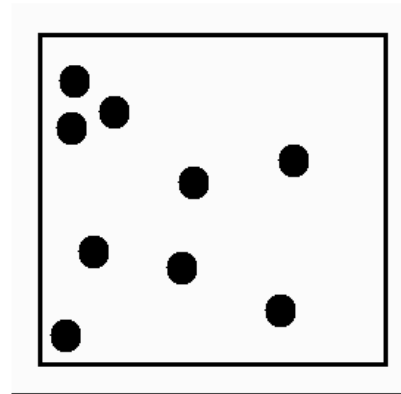
Entropy is a measure of *disorder* in a system.

Entropy is “proportional” to a chaos in the system: the more chaos => the more entropy

Order => low entropy

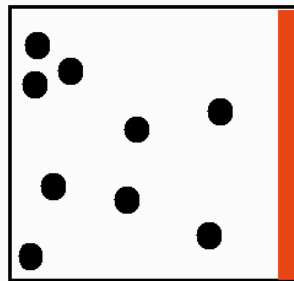
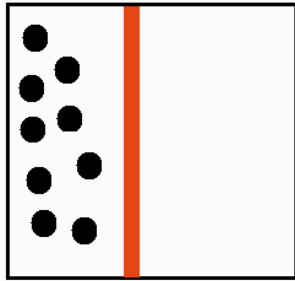


Chaos => high entropy



The symbol for entropy is S , and the units are J/K.

When a closed system is *not* in equilibrium, it is *not* in the *most* chaotic (*least* order) state, and the system tries to reach the most chaotic state, and the entropy of the system is increasing; $S_f > S_i$; $\Delta S > 0$



For example: if we collect all the particles in one half of a container and then release them, the particles eventually fill up the whole

container, and the system will reach the least ordered state.

The opposite process requires *an external force* acting on the system, in that case the system is *not* close.

The Second Law of Thermodynamics

In *any* process the entropy of a closed system either increases or stays the same, *it never decreases*. Hence, the change in entropy of a closed system is *never* negative!

$$\Delta S \geq 0$$

When a closed system is in equilibrium, it is in the *most* chaotic (*least* ordered) state, and the entropy of the system cannot be any higher, hence stays the same: change in entropy is zero:

$$\Delta S = 0$$

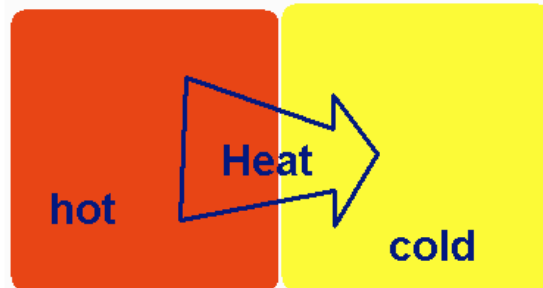
For example, a gas in equilibrium has randomly and uniformly distributed particles.

Heat Transfer

Heat is transferred naturally from a higher-temperature region to a lower-temperature region. That means, if we let a system alone, it is going to cool down or heat up until the temperature of the system becomes equal to the temperature of the surrounding matter.

Heat is not transferred naturally in the other direction. To reverses the process we have to act on a system.

An example of an irreversible process.



$$\Delta S > 0$$

Reversible and Irreversible Processes

Let's say you drop a glass of milk and the glass smashes into 27 pieces and milk spills all over the floor. If you videotaped this and ran the film backwards it would be obvious to you that the film was running backwards.

Why?

The process violates:

- 1) The Law of Conservation of Energy
- 2) The Law of Conservation of Momentum
- 3) The Second Law of Thermodynamics (Entropy Never Decreases)
- 4) All of the above

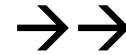
C. Only the Second Law of Thermodynamics would be violated - this is why entropy is sometimes called time's arrow.

Time moves in the direction of increasing entropy (in a physical world).

These are examples of an irreversible process.

In all the examples the transition from an order to a chaos is happening.

A).



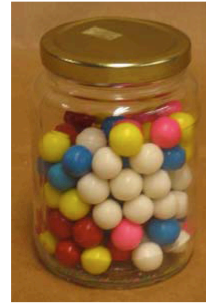
B). A process is irreversible if *energy is lost to friction*, or

C). if energy is lost as *heat flows from a hot region to a cooler region*.

Reversible process vs. irreversible process

A *reversible* process is one in which there is *no* change in entropy, and the system *and the surroundings* can be returned to the initial state.

**Irreversible
process**



$$\Delta S > 0$$

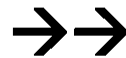
Ordered state

or

Chaotic state

(slide it carefully!)

**Reversible
process**



$$\Delta S = 0$$

The ice bomb

The entropy of the system ...

1. Did not change

2. Increased

3. Decreased

4. We do not know