

Module I

BASIC THERMODYNAMICS

REFERENCES:

***ENGINEERING THERMODYNAMICS* by P.K.NAG 3RD EDITION**



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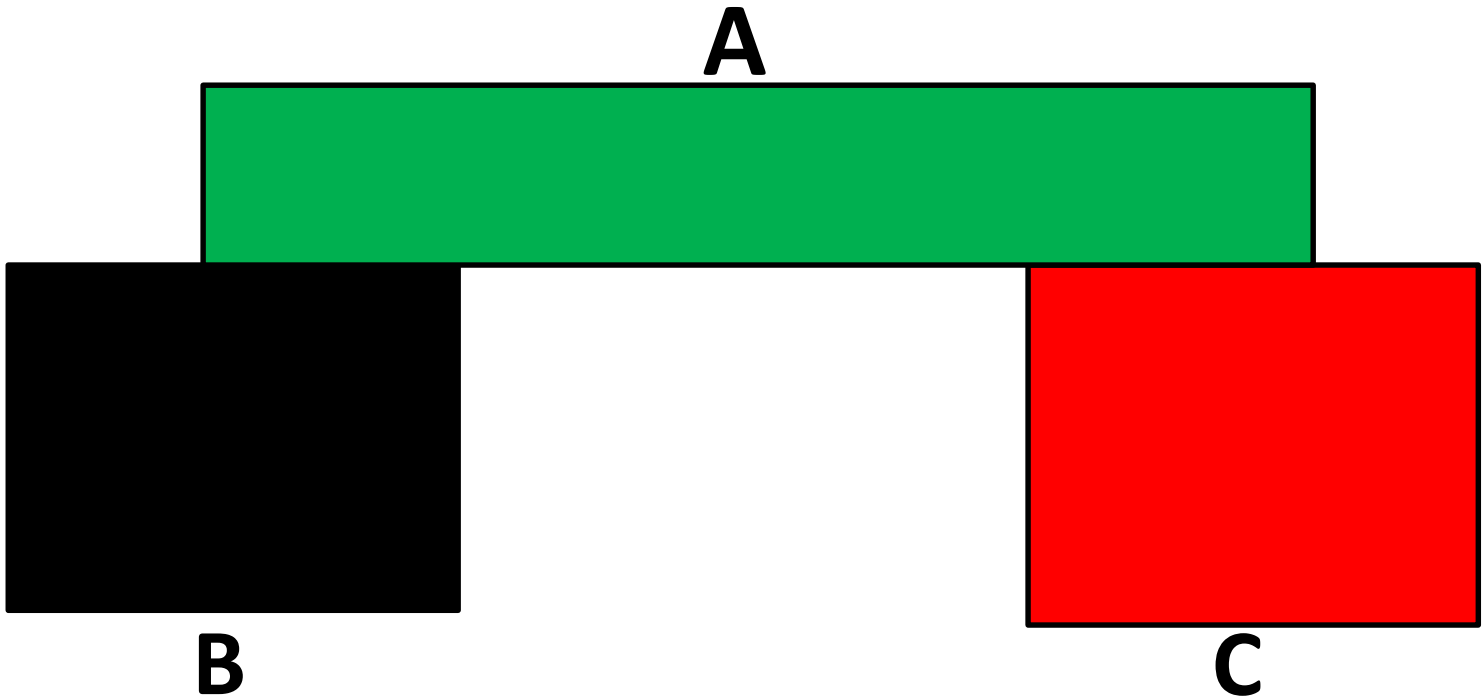
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LAWS OF THERMODYNAMICS

- **0th law** – when a body A is in thermal equilibrium with a body B, and also separately with a body C, then B and C will be in thermal equilibrium with each other.
- **Significance**- measurement of property called temperature.



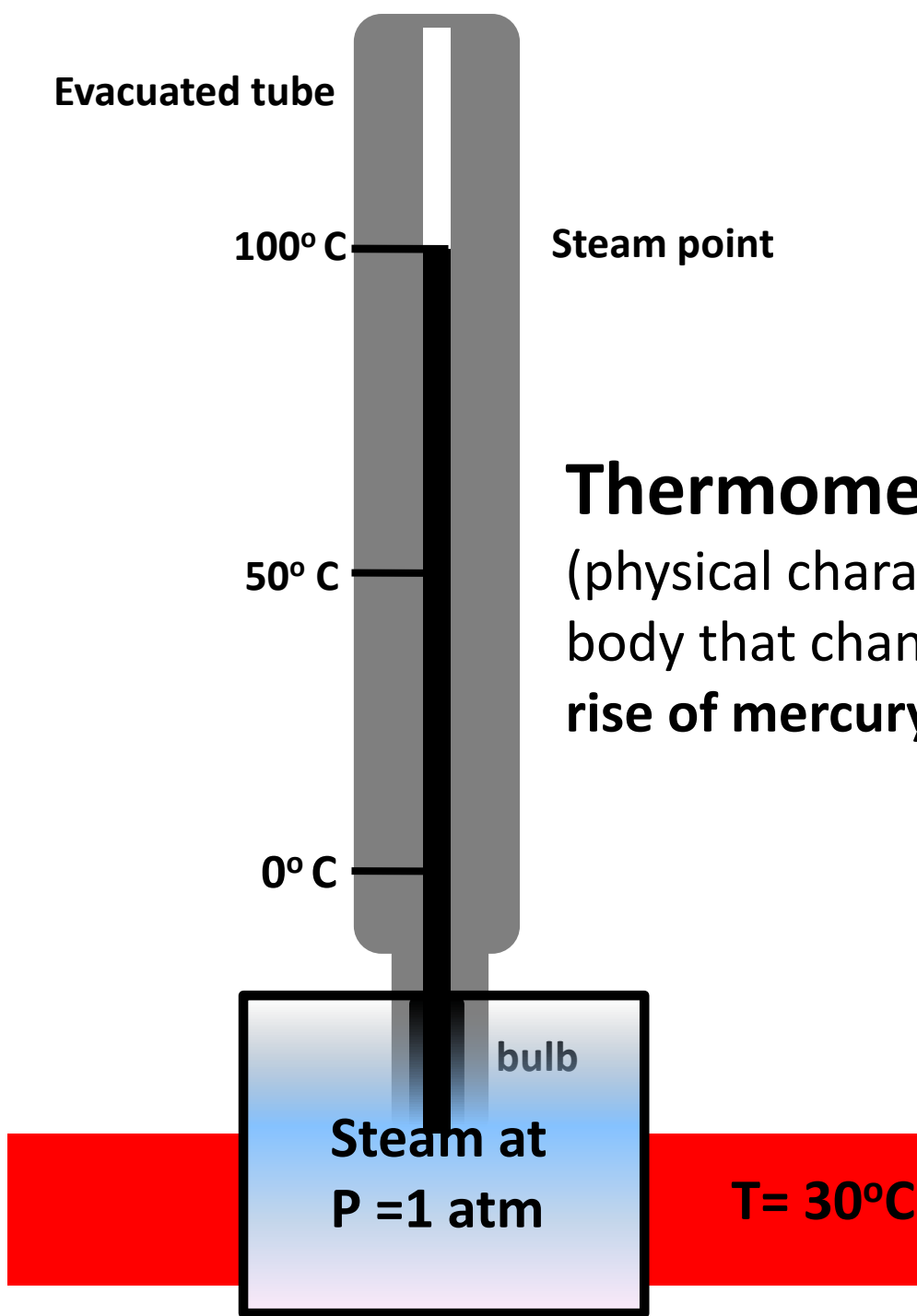
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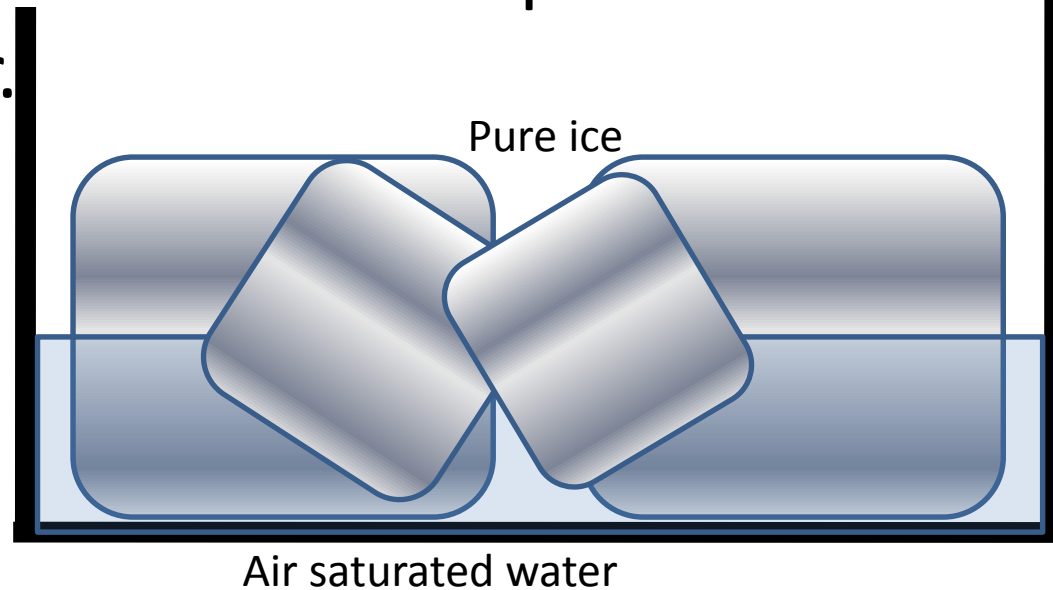




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REASONS FOR NOT TAKING ICE POINT AND STEAM POINT AS REFERENCE TEMPERATURES

- Ice melts fast so there is a difficulty in maintaining equilibrium between pure ice and air saturated water.



- Extreme sensitiveness of steam point with pressure



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TRIPLE POINT OF WATER AS NEW REFERENCE TEMPERATURE

- State at which ice liquid water and water vapor co-exist in equilibrium and is an easily reproducible state. This point is arbitrarily assigned a value 273.16 K
- i.e. $T \text{ in K} = 273.16 \frac{X}{X_{\text{triple point}}}$
- X- is any thermometric property like P,V,R, rise of mercury, thermo emf etc.



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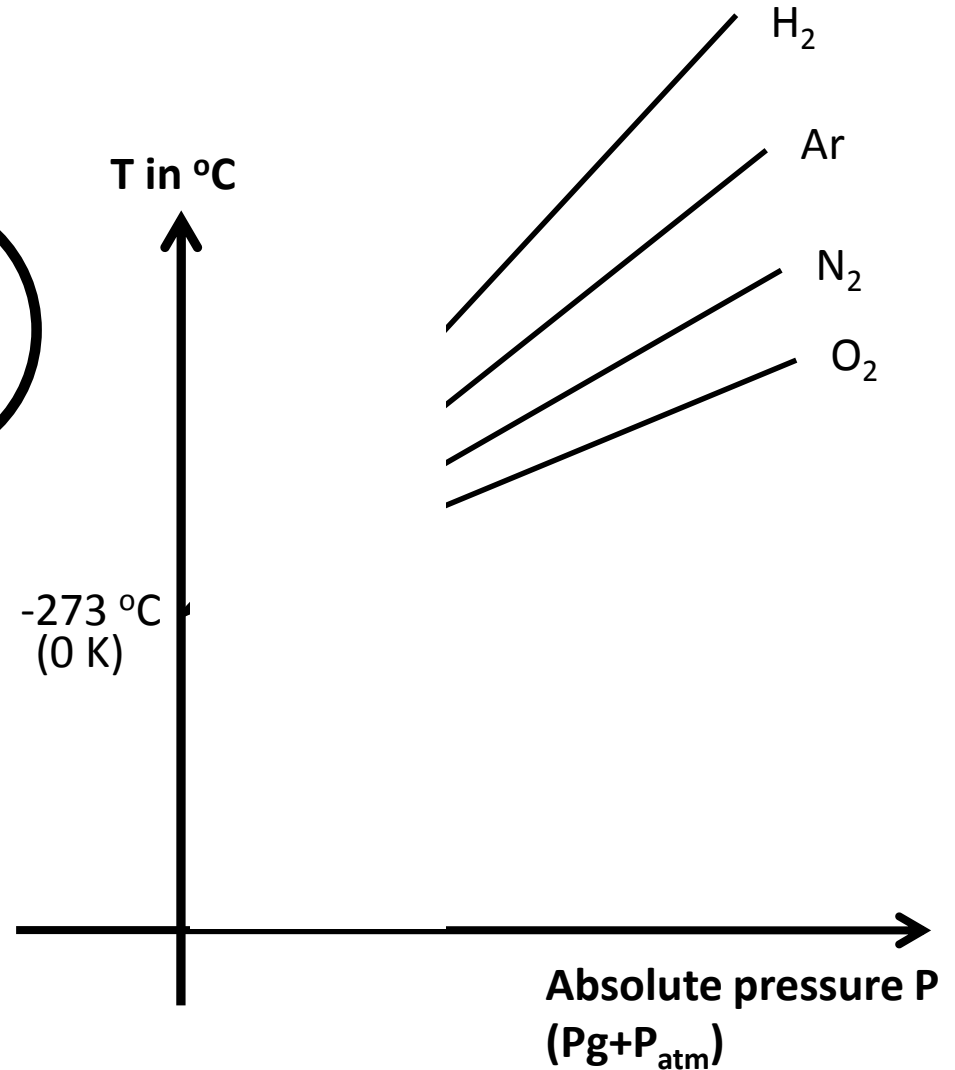
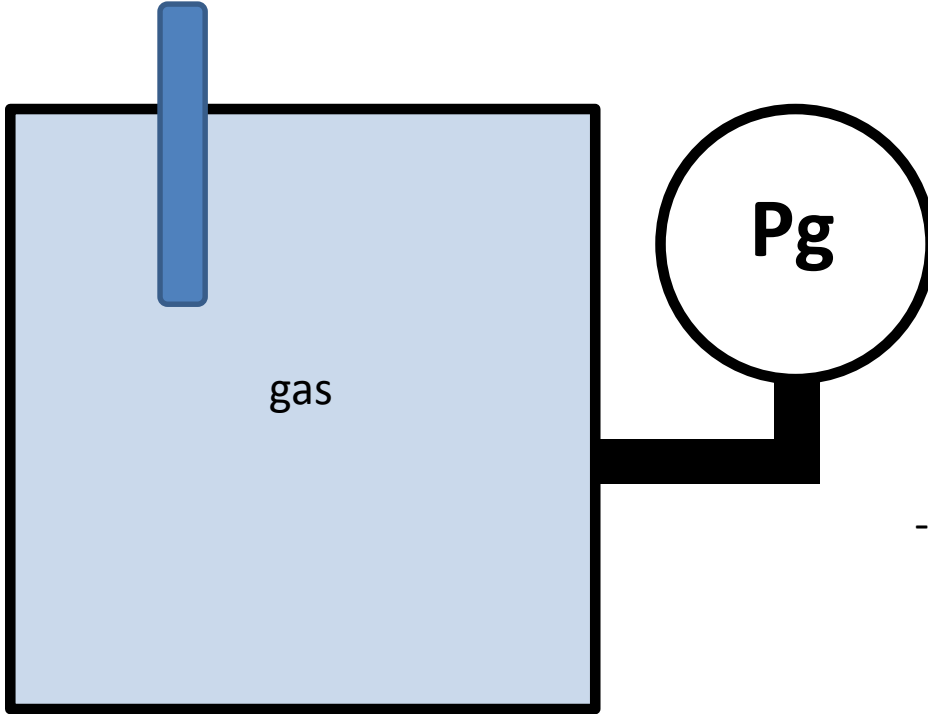
OTHER TYPES OF THERMOMETERS AND THERMOMETRIC PROPERTIES

- Constant volume gas thermometers-
pressure of the gas
- Constant pressure gas thermometers-
volume of the gas
- Electrical resistance thermometer-
resistance of the wire
- Thermocouple-
thermo emf



CELSIUS AND KELVIN (ABSOLUTE) SCALE

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Thermometer



This absolute 0K cannot be obtained since it violates third law.



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SYSTEMS, BOUNDARY AND SURROUNDING

Systems are any matter/ space on which our attention is focussed

Systems are of three types

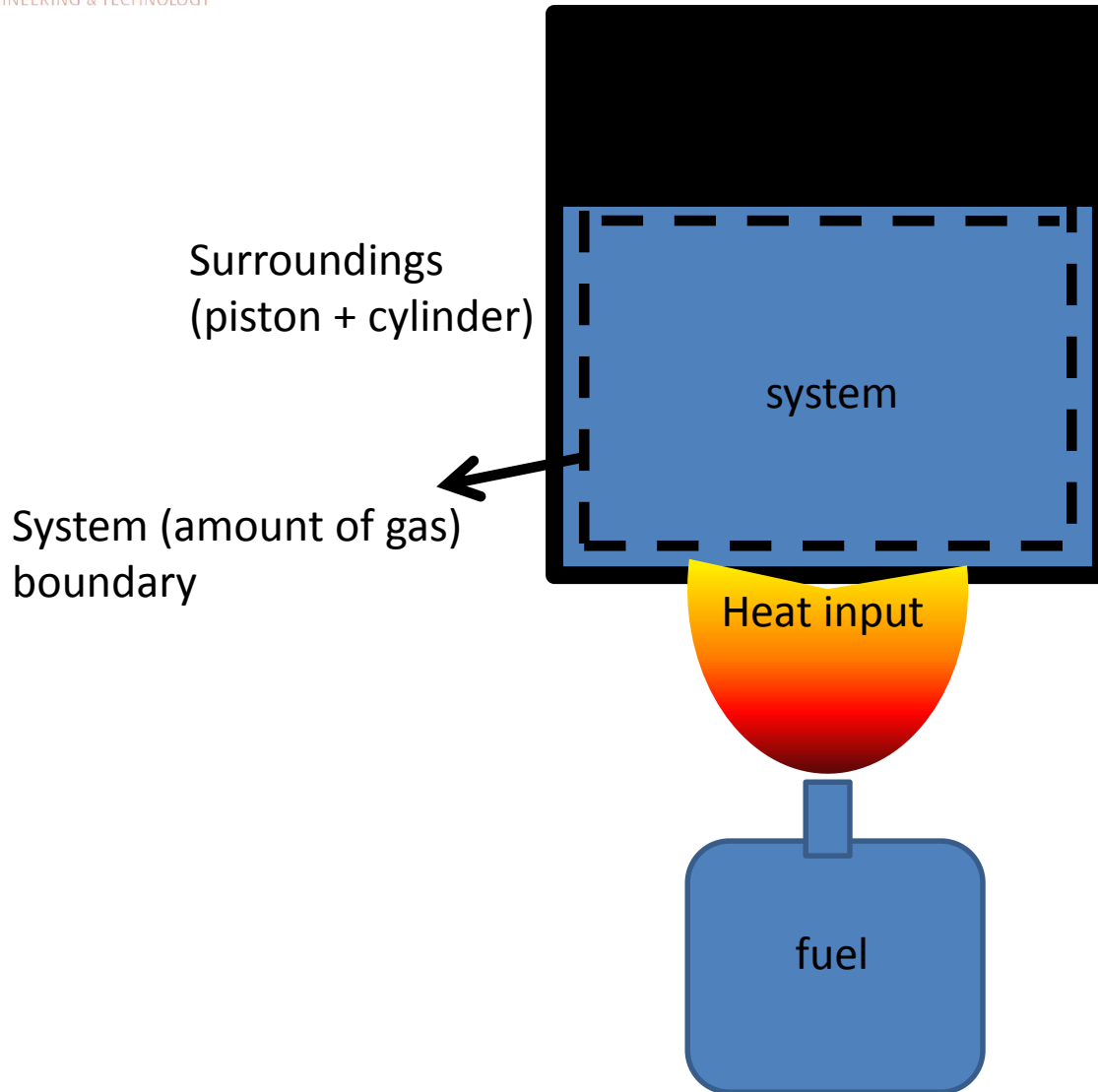
- closed system – no matter interaction with the system, but there is energy interaction.
- Open system – there is matter as well as energy interaction with the system.
- Isolated system- there is neither matter nor energy interaction with the system. System and surroundings together constitutes an isolated system.



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CONTROL MASS / CLOSED SYSTEM E.G.

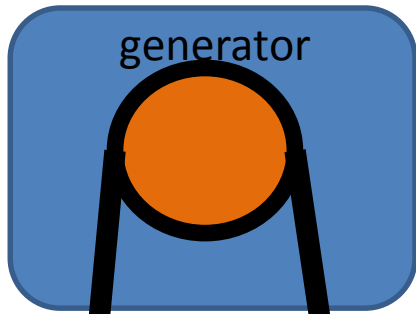
moving boundary work output





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OPEN SYSTEM E.G.

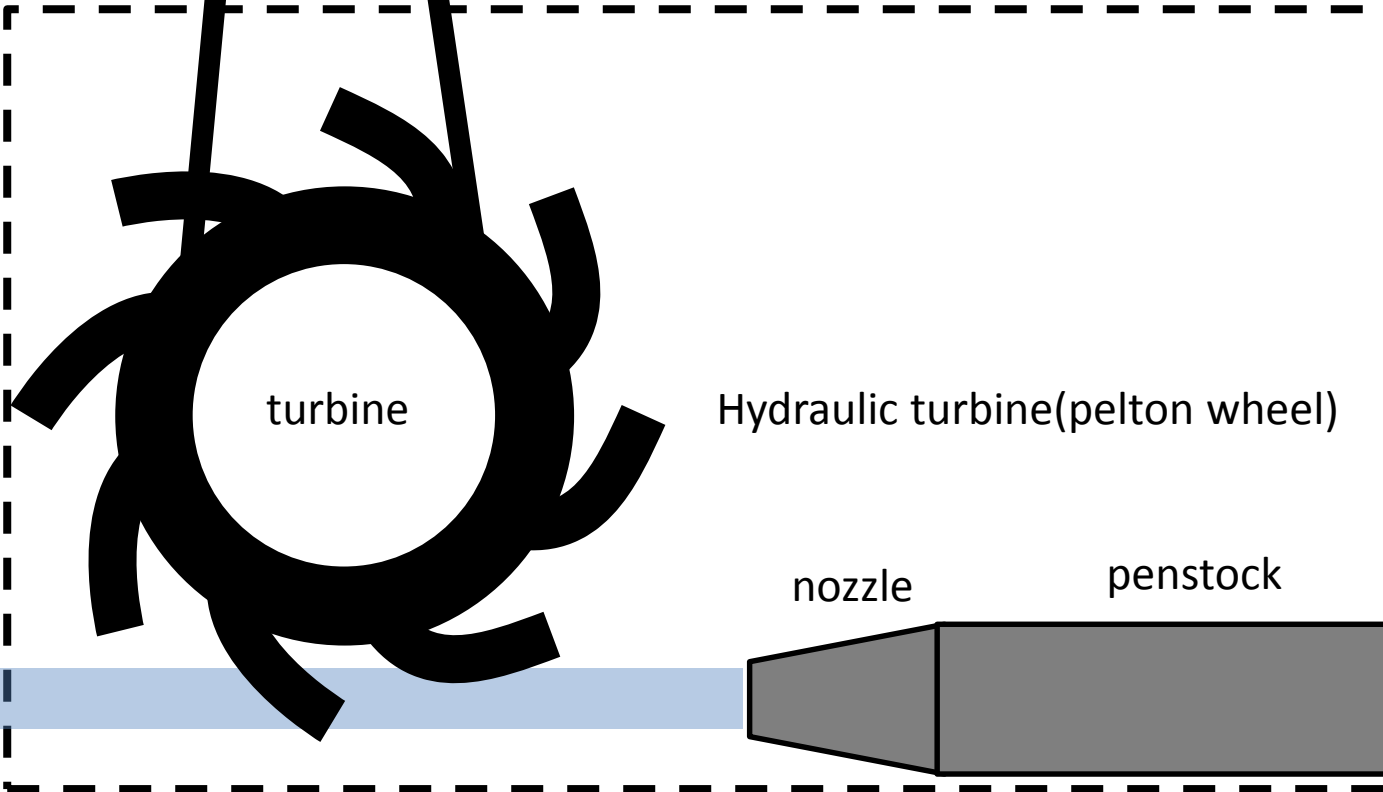


generator

Stationary boundary

Work output

System (stationary space) boundary



turbine

Hydraulic turbine(pelton wheel)

nozzle

penstock

Water + energy
input

Water + energy
output

Control volume/ open system

PROPERTIES OF A SYSTEM

- Characteristics of a system by which its physical condition may be described are called **properties of a system**. These are macroscopic in nature(physically measurable).

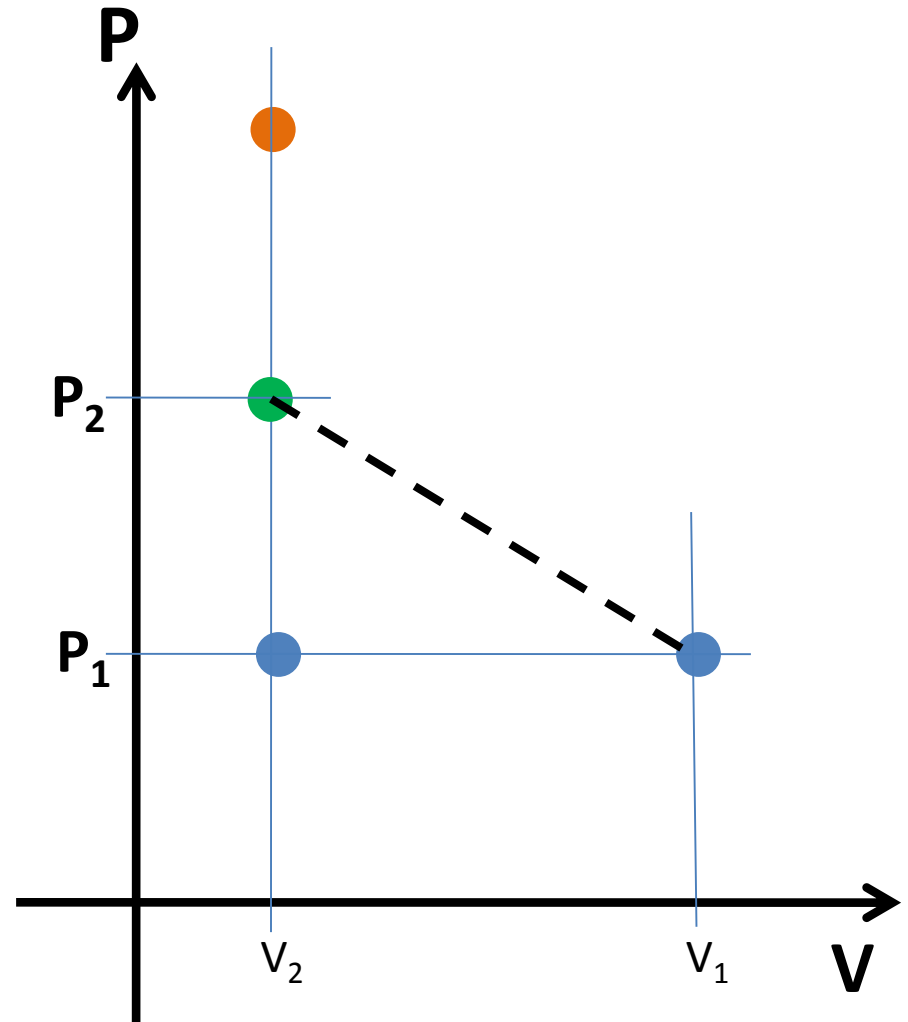
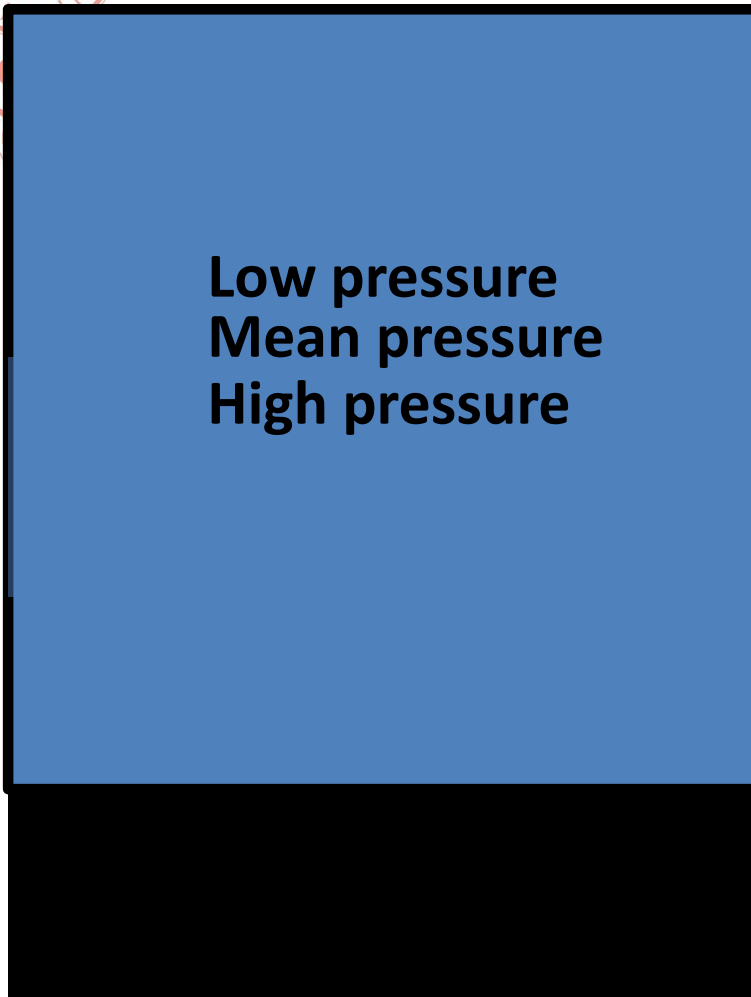
E.g. pressure, volume, temperature etc

- When all the **properties of a system have a definite value**, the system is said to exist at a **definite state**.

STATE OF A SYSTEM



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Any operation in which one or more of the properties of a system changes is called a change of state



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INTENSIVE AND EXTENSIVE PROPERTIES

- Intensive- independent of mass in the system
- Extensive- dependent of mass in the system

Mass= $m/2$

Pressure = P

Temp = T

Volume= $V/2$

Density,

Mass/Volume = ρ

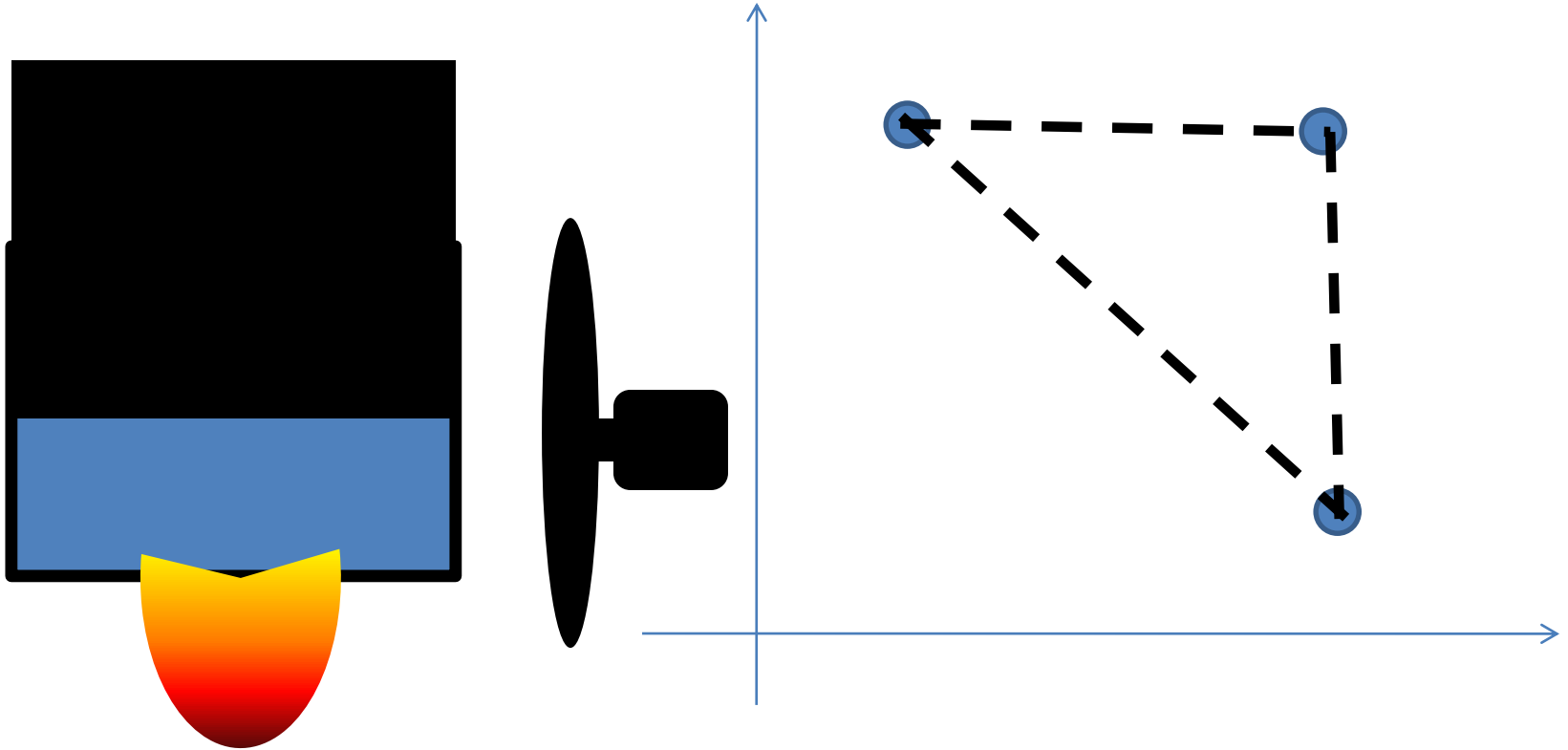
Specific volume,

Volume /mass = u

*Capital letter denotes Extensive property (except P and T)
and small letter denotes specific property(Extensive property per unit mass)*

THERMODYNAMIC CYCLE

- Cycle consists of a series of change of state such that final state is same as the initial state

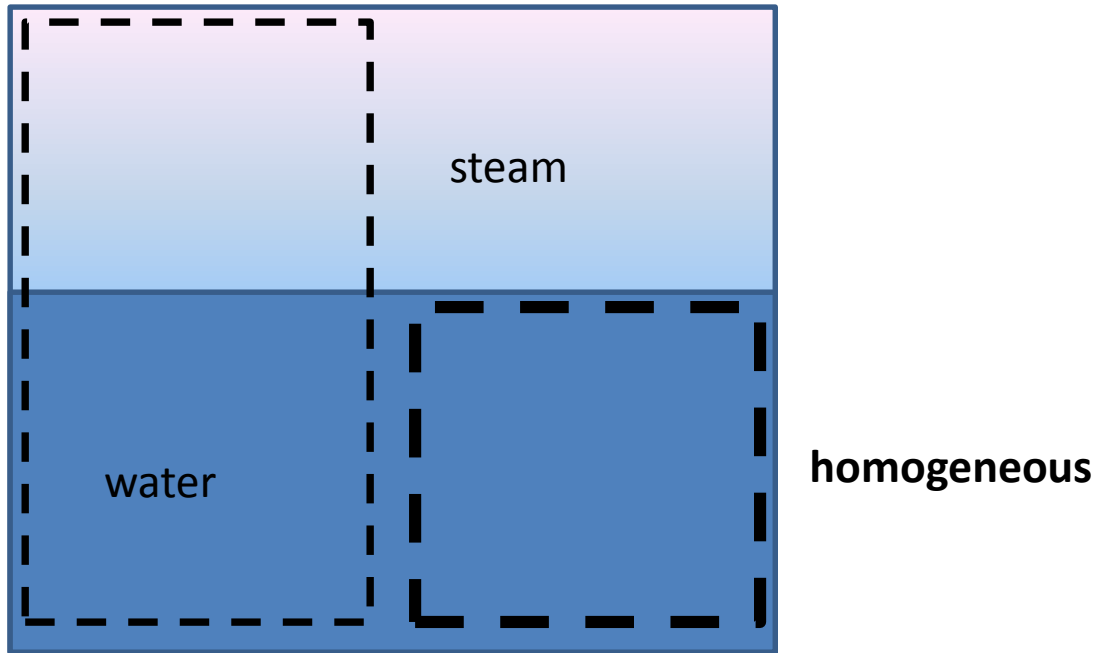




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Homogeneous and Heterogeneous systems

- A system consisting of only single phase is called homogeneous system



- A system consisting of more than one phase is heterogeneous system



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WORK

HEAT AND

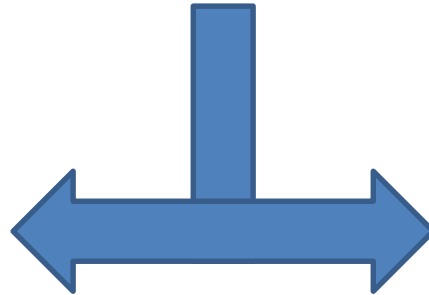
ENERGY



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ENERGY



ENERGY IN TRANSIT/MOTION

1. Energy that crosses the boundary of the system
2. Energy in the form of heat or work.
3. Specified as amount of energy transfer
e.g. amount of heat transferred, amount of work transferred.
4. They are **not properties of a system**.
5. They are **path function** i.e. amount of energy transfer depends on the path followed by the system during a process

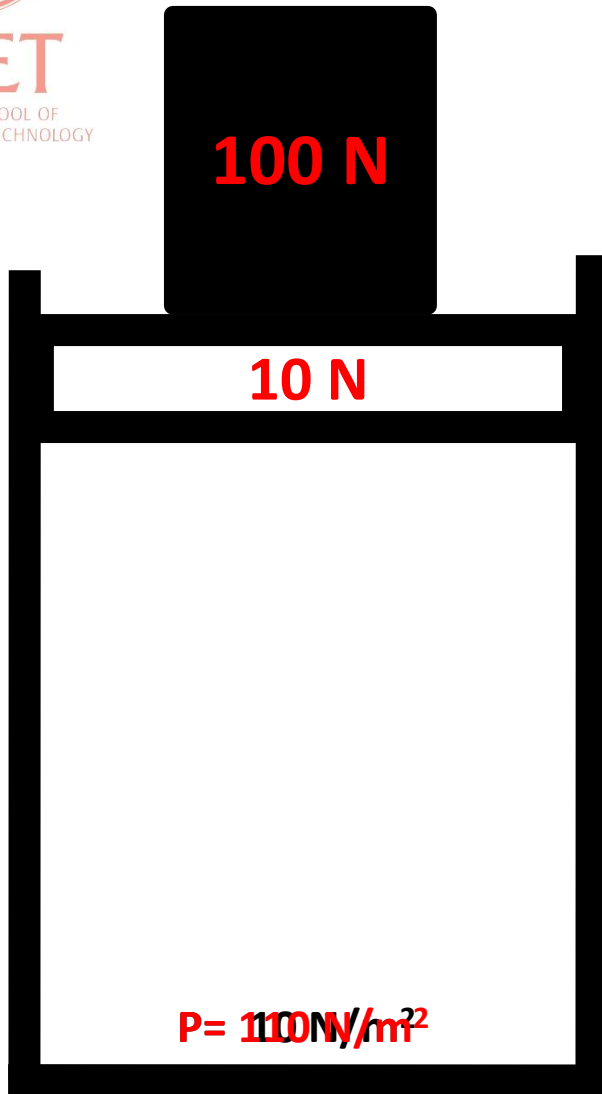
ENERGY IN STORAGE

1. Energy that is stored in the system
2. Energy in form of KE, PE, internal energy (sum of all forms of molecular energy)
3. Specify as change in energy e.g. Change in KE, PE, etc
4. These are **properties of a system** like T,P,V, mass etc
5. They are **point functions** i.e. they are independent of the path followed by the system during a process.

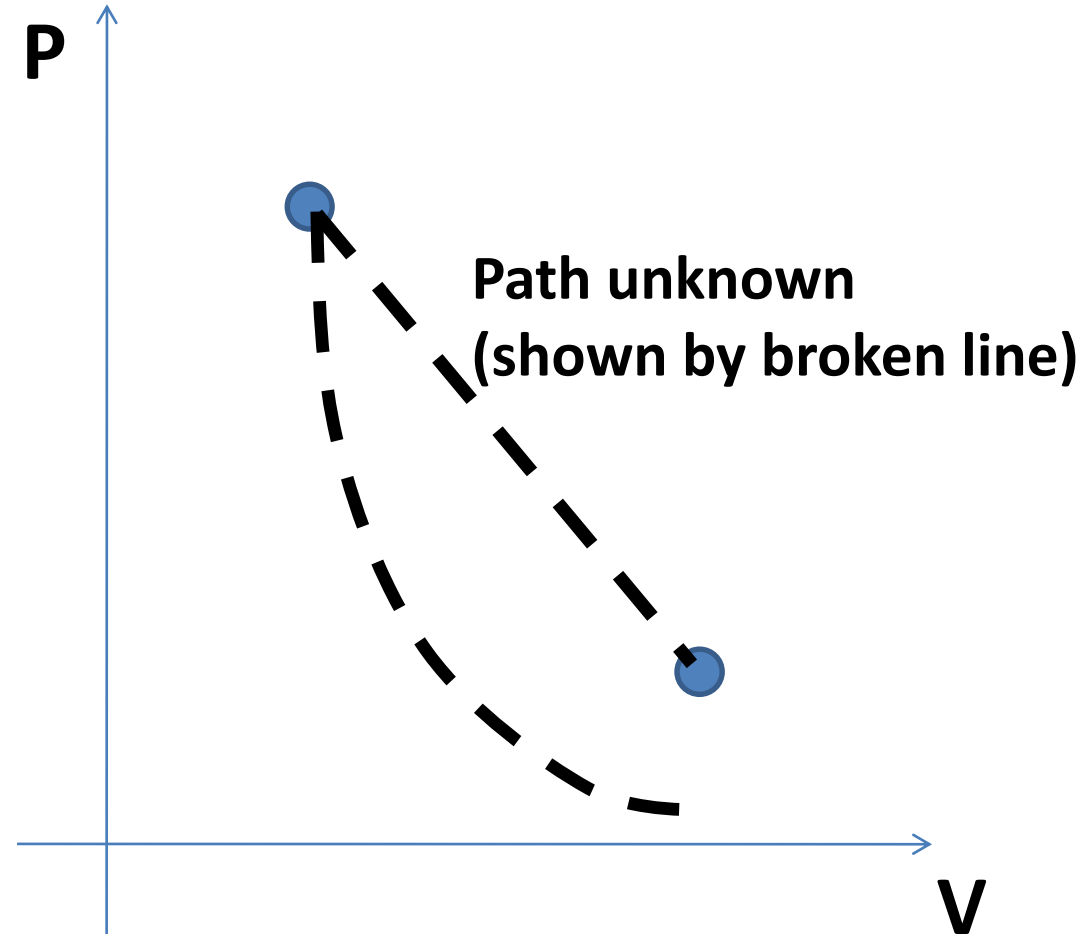


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DEFINING A PATH



Now the system and surroundings are in equilibrium



Now the system and surroundings are not in equilibrium



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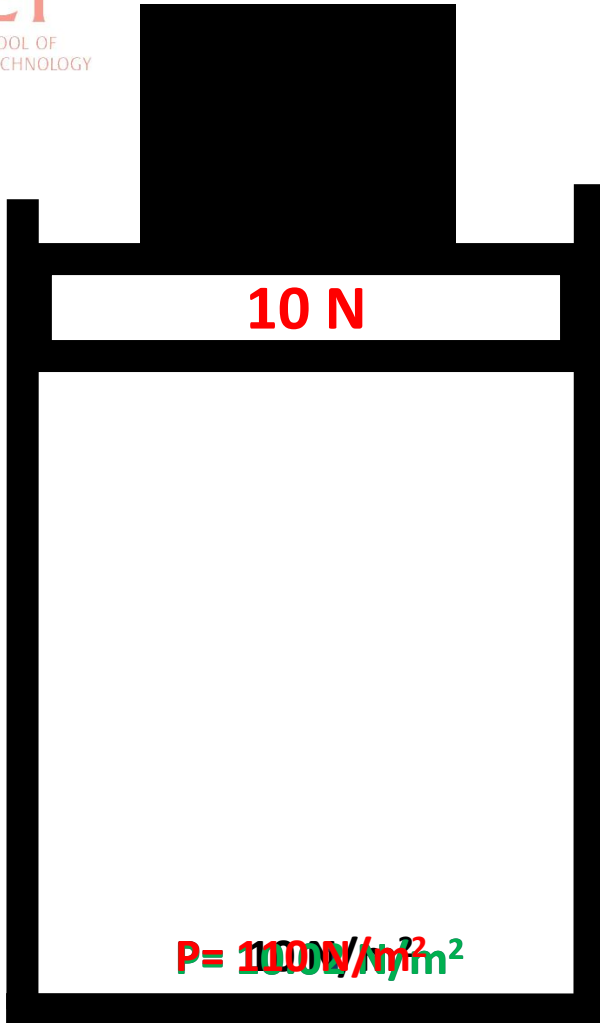
SPONTANEOUS PROCESS

- fast process
- Path cannot be defined
- There is dissipation effects like friction
- System or surroundings can be restored to their initial state.
- System may not follow the same path if we reverse the process
- Spontaneous process are also called irreversible process.



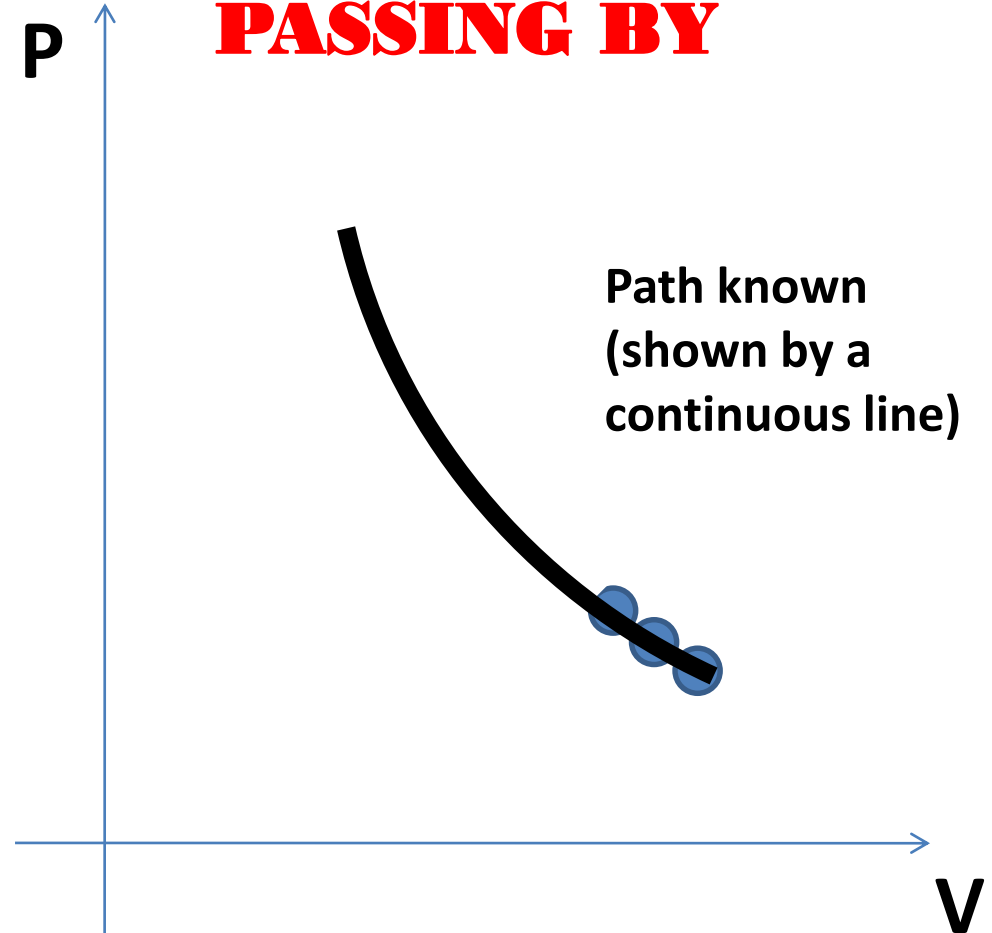
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DEFINING A PATH



Now the system and surroundings are in equilibrium

DECADES ARE
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Departure of states of the system from system thermodynamic equilibrium will be infinitesimally small.



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QUASI STATIC PROCESS

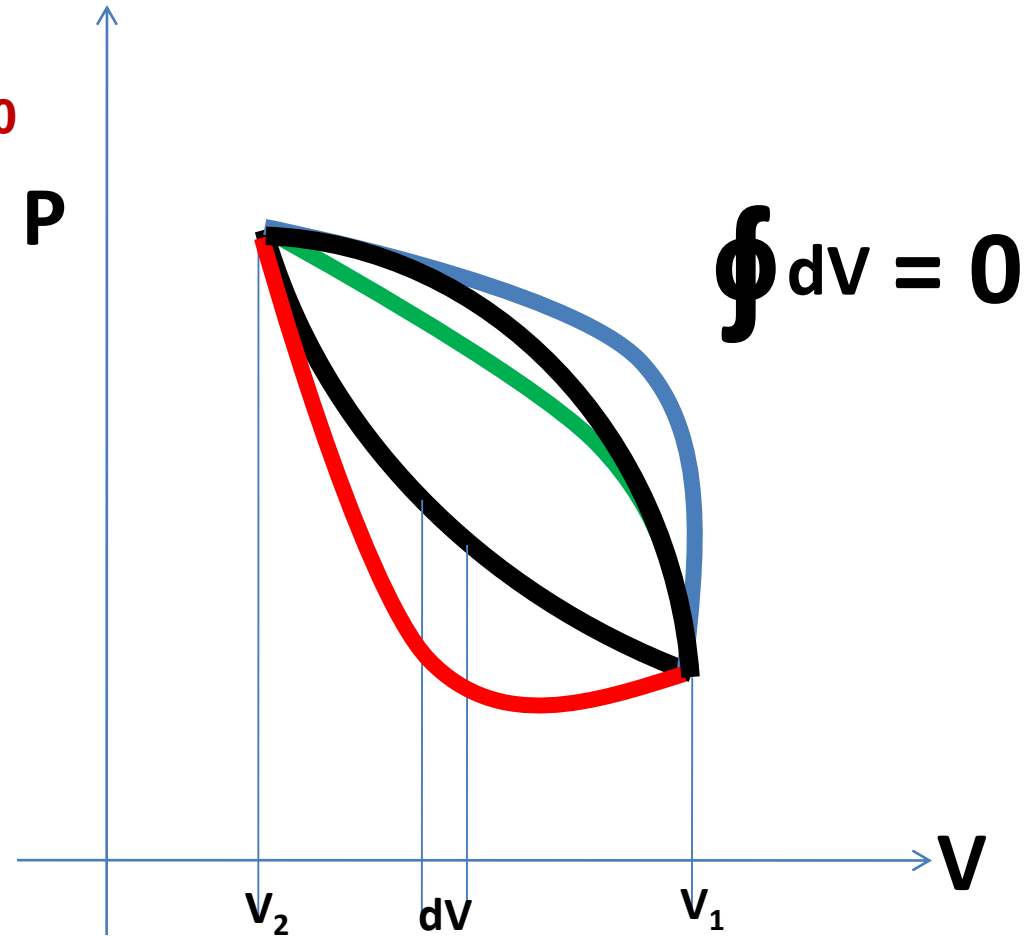
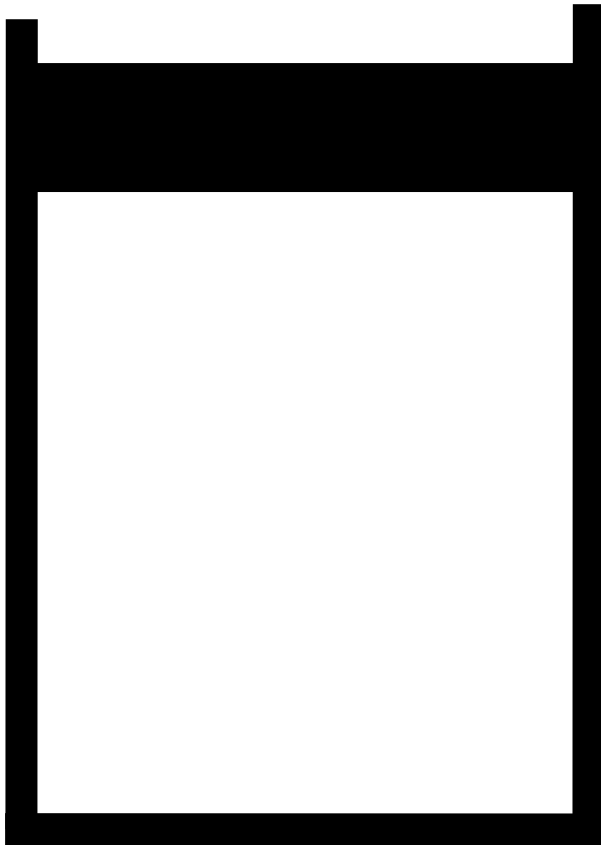
- Infinitely slow process
- Path can be defined
- There is no dissipation effects like friction
- Both System and surroundings can be restored to their initial state.
- System follows the same path if we reverse the process
- Quasi static process are also called reversible process



POINT FUNCTION/STATE FUNCTION

Cyclic integral (integral over a cycle)
of any point function (property) is = 0

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$$\int dV = V_2 - V_1 = \Delta V$$

$$\int dP = P_2 - P_1 = \Delta P$$

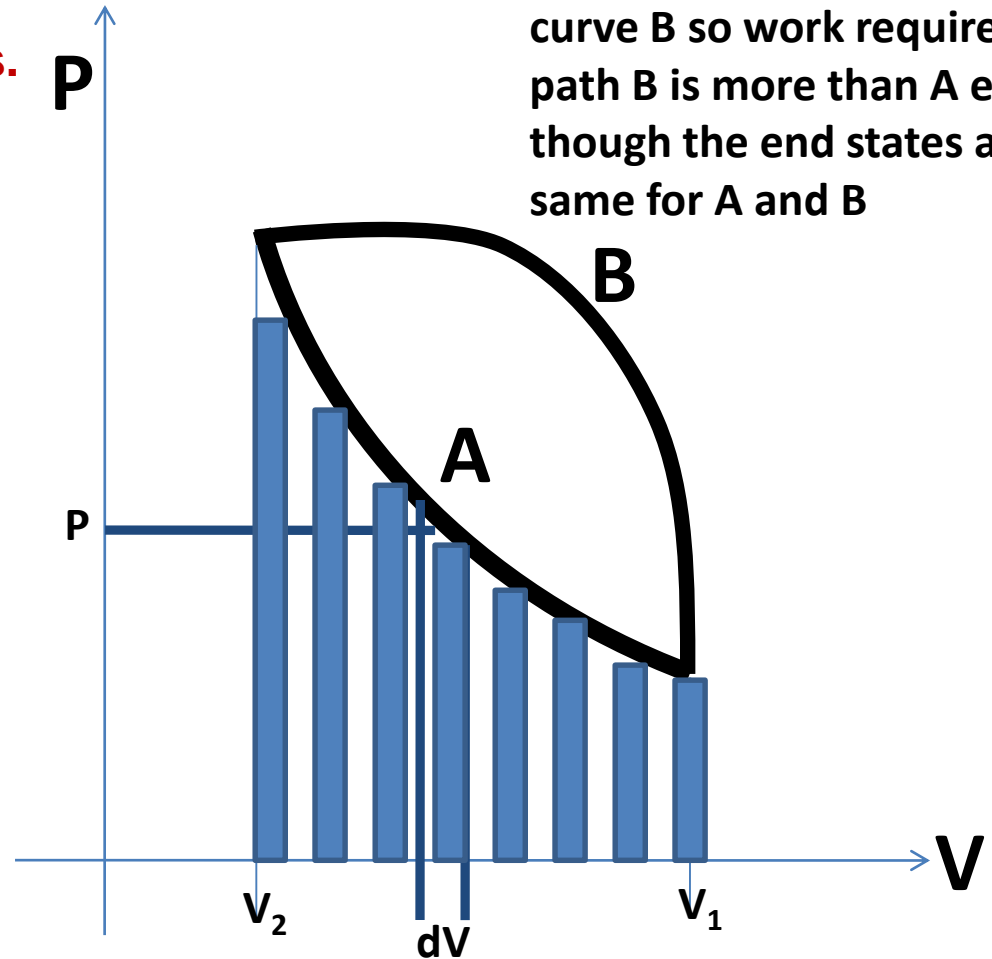
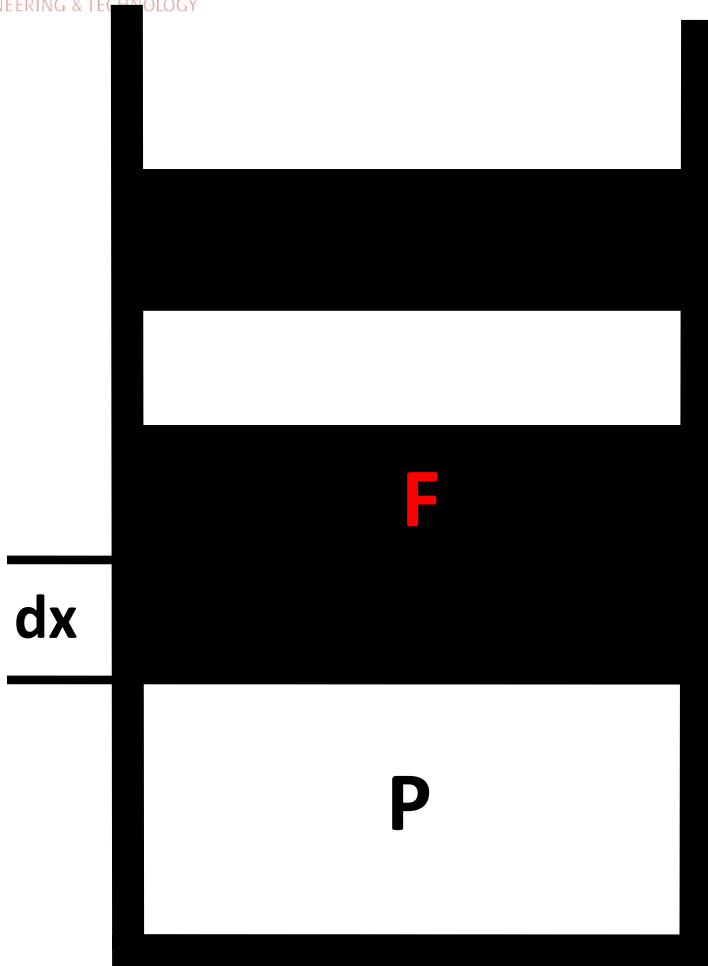
$$\int dT = T_2 - T_1 = \Delta T$$

These are called exact differential functions.



PATH FUNCTION

So heat and work are path functions.
Also they are not exact differentials



Path B has more area than curve A so work required in path B is more than A even though the end states are same for A and B

Then the total work required to move the piston from V_1 to V_2 , $W = \int P dV =$ area under PV curve

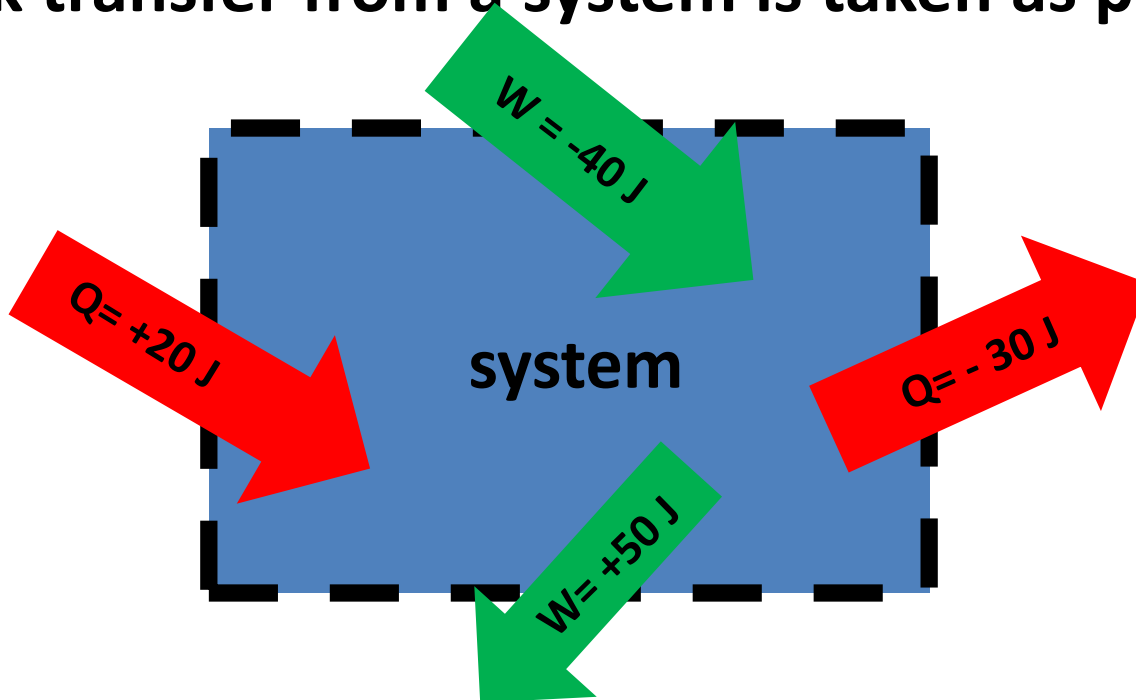
Small amount of work required to move the piston through a distance $dx = \delta W = F dx = P A dx = PdV$



Additional comments on heat and work transfer

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- Heat transfer to a system is taken as positive
- Heat transfer from a system is taken as negative
- Work transfer to a system is taken as negative
- Work transfer from a system is taken as positive





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FIRST LAW



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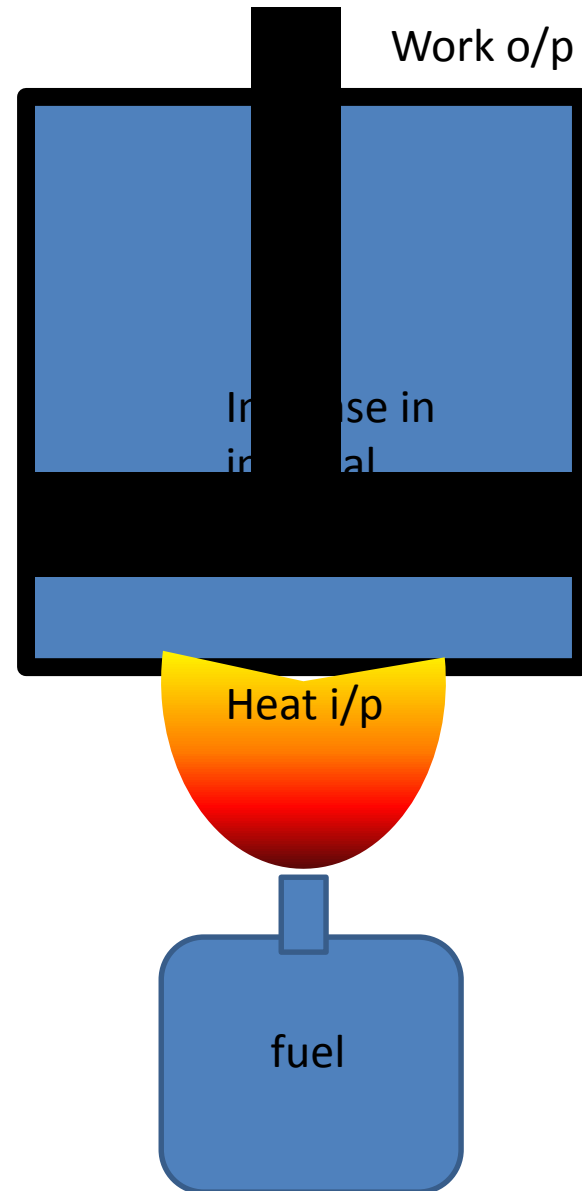
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- Law of conservation of energy-
Energy can neither be created
nor destroyed. It can only be
converted from one form to
another, here $Q = W + \Delta U$

$$Q - W = \Delta U$$

$$\delta Q - \delta W = dU$$

In differential form





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Specific heat (c)

- Defined as amount of heat required to raise the temperature of a unit mass of any substance through a unit degree. Its SI unit is J/kg K or J/kg°C
- i.e. $c = Q/m \Delta T$ or $c = \delta Q /m dT$
- $\delta Q = m c dT$
- $Q = m c \Delta T$



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Specific heat at constant volume(c_v)

- Defined as amount of heat required to raise the temperature of a unit mass of any substance through a unit degree in a constant volume process. Its SI unit is J/kg K or J/kg°C
- *i.e.* $c_v = Q/m \Delta T$ or $c_v = \delta Q /m dT$
- $\delta Q = m c_v dT$
- $Q = m c_v \Delta T$



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final

**internal
energy**

U_2

**Initial
internal
energy**

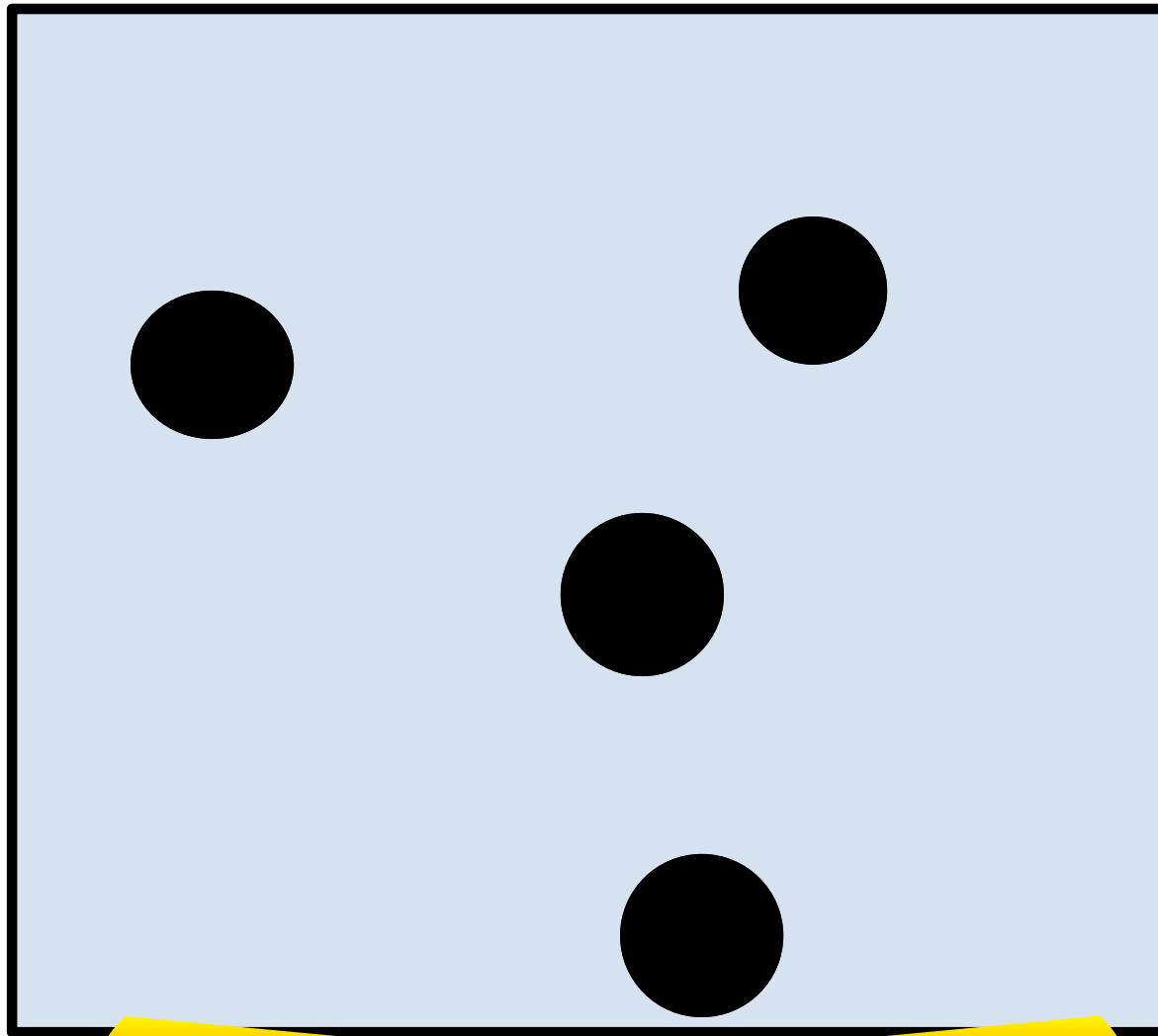
U_1

$$\delta Q - \delta W = dU$$

$$\delta Q = dU$$

$$m c_v dT = dU$$

$$c_v = (du/dT)_v$$



heat



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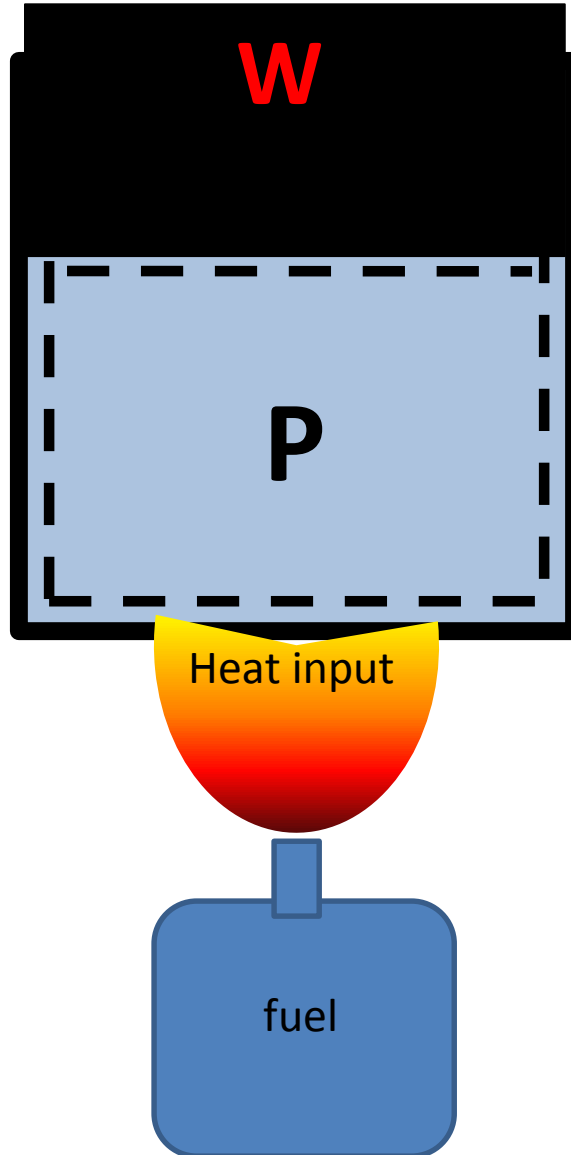
Specific heat at constant pressure(c_p)

- Defined as amount of heat required to raise the temperature of a unit mass of any substance through a unit degree in a constant pressure process. Its SI unit is J/kg K or J/kg°C
- *i.e. $c_p = Q/m \Delta T$ or $c_p = \delta Q /m dT$*
- $\delta Q = m c_p dT$
- $Q = m c_p \Delta T$



Specific heat at constant pressure (c_p)

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moving boundary work output
 $\delta W = PdV$

$$\delta Q - \delta W = dU$$

$$\delta Q - PdV = dU$$

$$m c_p dT = dU + PdV$$

$$\text{Enthalpy } H = U + PV$$

$$h = u + Pv$$

$$dh = du + d(pv)$$

In a constant pressure process

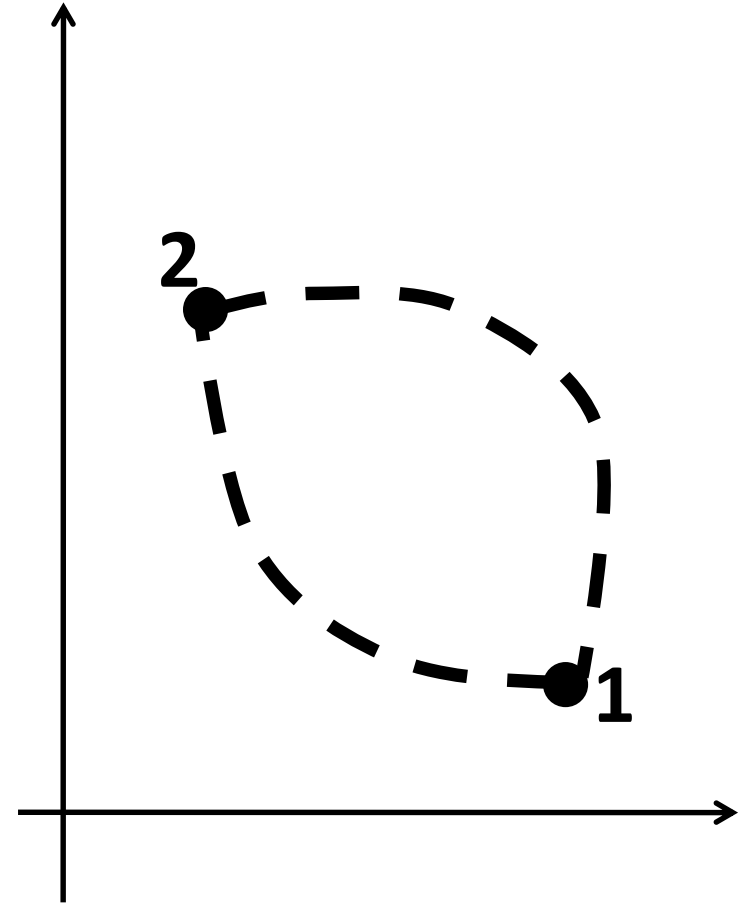
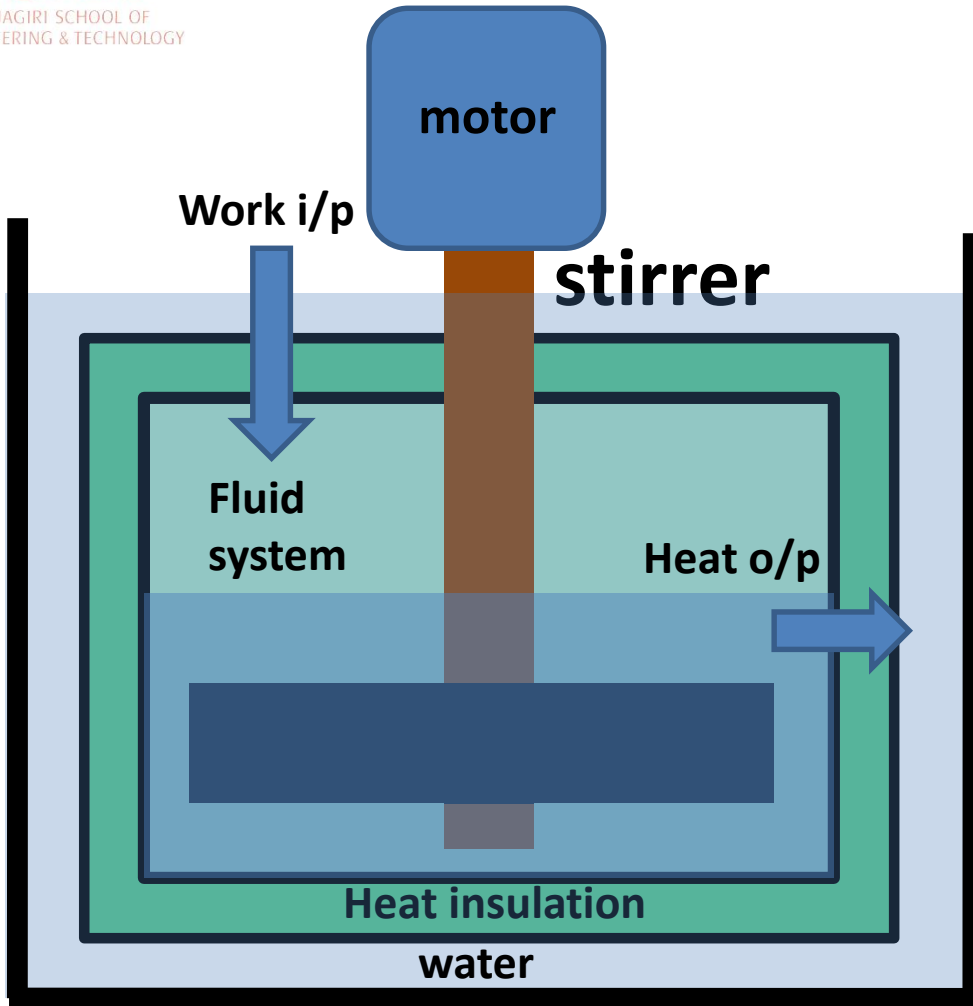
$$vdP = 0$$

$$\text{So } dh = du + pdv$$

$$c_p = (dh/dT)_p$$

AN EXPERIMENT BY JOULES ON FIRST LAW

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Joule found that heat output in process 2-1 was exactly equal to work input in process 1-2



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Joules experiment cont.

Process 1-2

- Work transfer = W_{1-2}
- heat transfer $Q_{1-2} = 0$ J (heat insulation wall)

Process 2-1

- Work transfer $W_{2-1} = 0$ J (no work done)
- Heat transfer = Q_{2-1}

- He found that $W_{1-2} = Q_{2-1}$
- I.e. in the cycle 1-2-1, $W_{1-2} + W_{2-1} = Q_{1-2} + Q_{2-1}$
- **in a cycle net work transfer = net heat transfer**

- **i.e. in a cycle $\Sigma W = \Sigma Q$**
- **In differential form , in a cycle**

$$\oint \delta W = \oint \delta Q$$



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INTERNAL ENERGY A PROPERTY?

From the first law we found
that,

In a cycle

$$\Sigma Q = \Sigma W$$

Consider cycle 1-A-2-B-1

$$Q_A + Q_B = W_A + W_B$$

$$Q_A - W_A = -Q_B + W_B$$

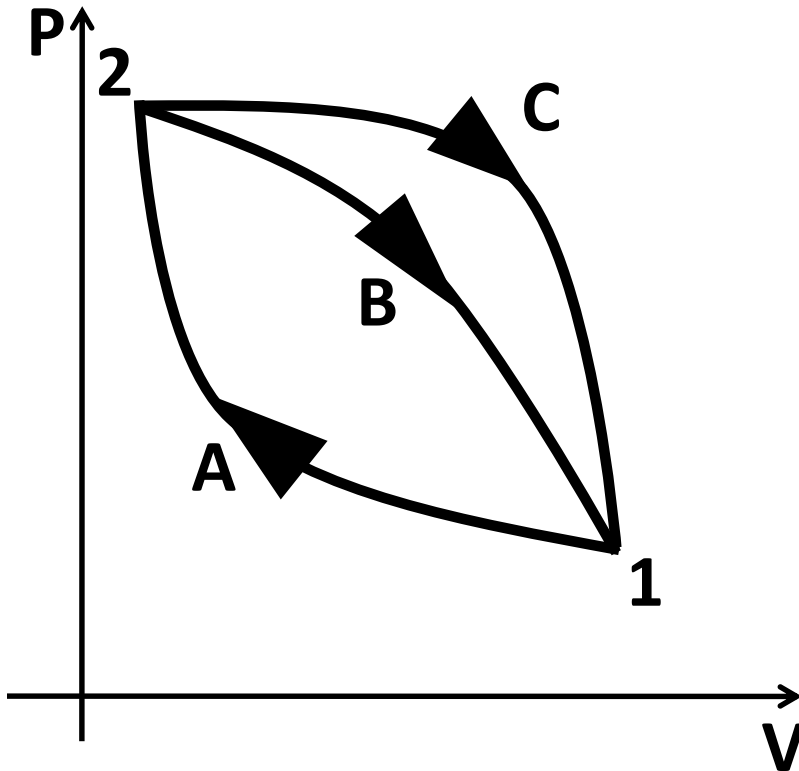
$$\Delta U_A = -\Delta U_B$$

Consider cycle 1-A-2-C-1

$$Q_A + Q_C = W_A + W_C$$

$$Q_A - W_A = -Q_C + W_C$$

$$\Delta U_A = -\Delta U_C$$



i.e. $\Delta U_B = \Delta U_C$

i.e. *U is independent of path followed, so U is a property*

Practice problem 1(p66)

- A stationary mass of gas is compressed without friction from an initial state of 0.3 m^3 and 0.105 MPa to a final state of 0.15 m^3 and 0.105 MPa . The pressure remaining constant during the process. There is a transfer of 37.6 kJ of heat from the gas during the process. How much does the internal energy of the gas change?

-21.85 kJ

Practice problem 2(p66)

- When a system is taken from state a to state b, in the fig along the path acb, 84 kJ of heat flows into the system and system does 32 kJ of work.
1. How much will the heat that flows into the system along the path adb be, if the work done is 10.5 kJ?
 2. When the system is returned from b to a along the curved path, the work done on the system is 21 kJ. Does the system absorb or liberate heat, and how much of the heat is absorbed or liberated?
 3. If $U_a = 0$ kJ and $U_d = 42$ kJ, find the heat absorbed in the process ad and db.

62.5 kJ

-73 kJ

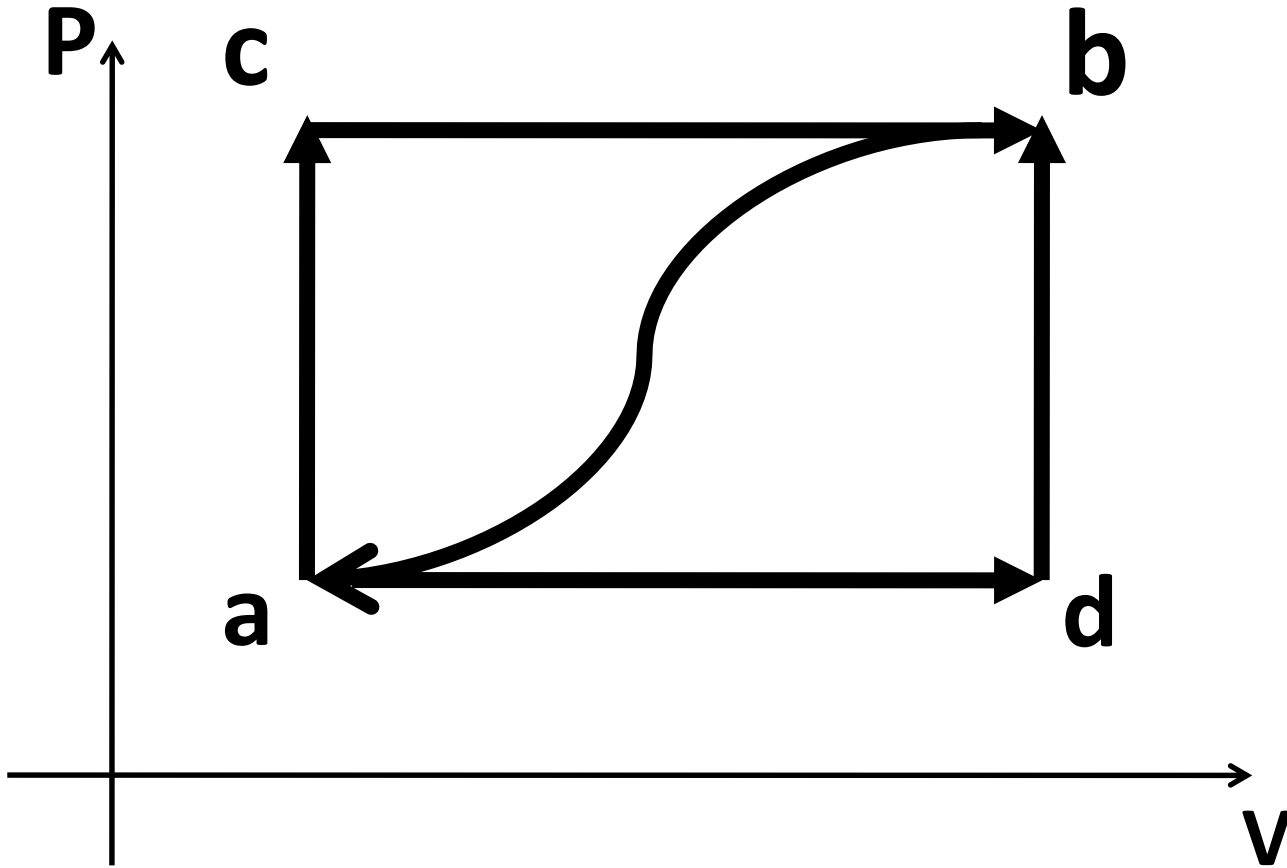
52.5 kJ

10 kJ



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Practice problem 3(p67)

- A piston and cylinder machine contains a fluid system which passes through a complete cycle of four processes. During a cycle, the sum of all heat transfer is -170 KJ. The system completes 100 cycles per minute. Complete the following table showing the method for each item, and compute the net rate of work input in KW.



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| <u><i>Process</i></u> | <u><i>Q(KJ/min)</i></u> | <u><i>W(KJ/min)</i></u> | <u><i>ΔE(KJ/min)</i></u> |
|-----------------------|-------------------------|-------------------------|--------------------------|
| a-b | 0 | 2170 | -2170 |
| b-c | 21000 | 0 | 21000 |
| c-d | -2100 | 34500 | -36600 |
| d-a | -35900 | -53670 | 17770 |

$$W_{net} = -283.3 \text{ kW}$$



Practice problem 4(p68)

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- Internal energy of a certain substance is given by the following eqn, ----- $u = 3.56 p v + 84$

Where u is in kJ/kg, P in kPa, v in m^3/kg .

A system composed of 3 kg of this substance expands from initial pressure of 500 kPa and a volume of 0.22 m^3 to a final pressure of 100 kPa in a process in which pressure and volume is related by $P v^{1.2} = \text{Constant}$.

- If the expansion is quasistatic find Q , ΔU and W for the process. **36.5 kJ 91 kJ 127.5 kJ**
- In another process the same system expands from same initial state to same final state as in previous part, but the heat transfer in this case is 30 kJ. Find the work transfer for this process. **121 kJ**
- Explain the difference in work transfer in both processes.

Practice problem 5(p69)

- A fluid is confined in a cylinder by a spring loaded, frictionless piston so pressure in the fluid is a linear function of volume ($P = a + bV$). The internal energy of the fluid is given by the equation

$$U = 34 + 3.15 PV$$

if the fluid changes from an initial state of 170 kPa, 0.03 m³ to final state of 400kPa, 0.06m³, with no work other than done on the piston, find the direction and magnitude of work and heat transfer.

$$W = 8.55 \text{ kJ}$$

$$Q = 68.05 \text{ kJ}$$



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Practice problem 6(p70)

- A stationary cycle goes through a cycle shown in the figure comprising the following processes.
- Process 1-2 isochoric (constant Volume) heat addition of 235KJ/kg.
- Process 2-3 adiabatic (no heat transfer) expansion to its original pressure with loss of 70 KJ/kg in internal energy.
- Process 3-1 isobaric (constant Pressure) compression to its original volume with heat rejection of 200 KJ/kg.
- Check whether this cycle follows **1st** law.

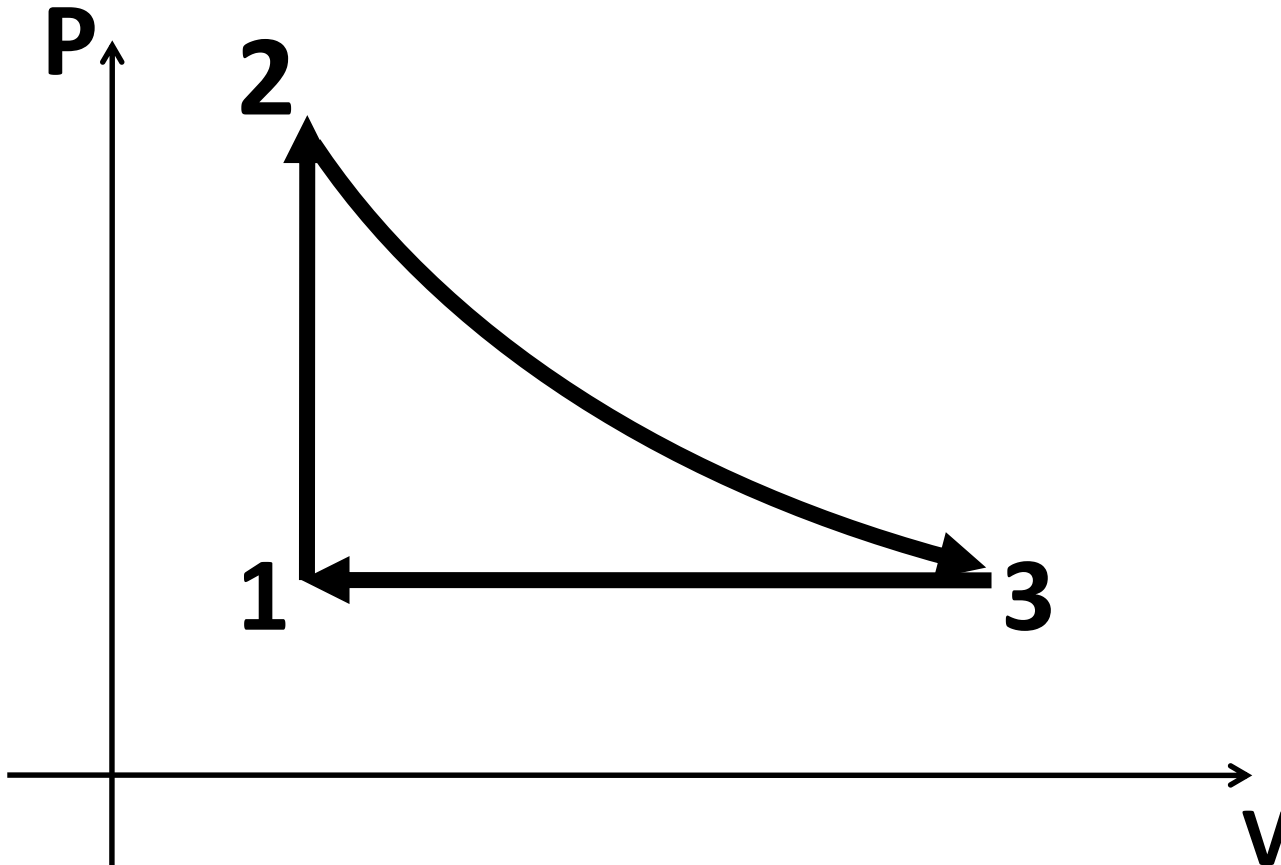
$$\text{Total } Q = \text{Total } W = 35 \text{ kJ/kg}$$



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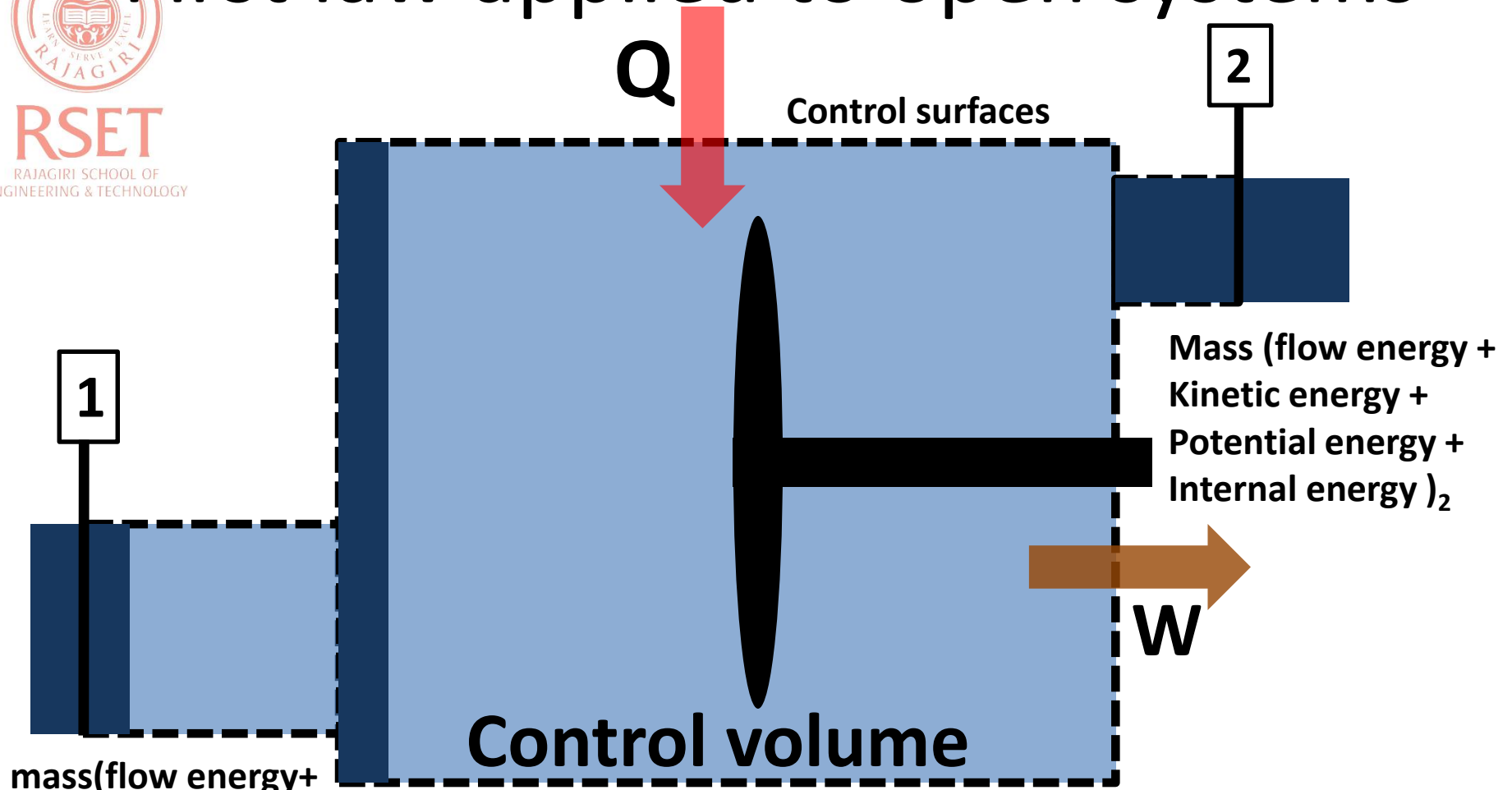
LENOIR CYCLE (PULSE JET ENGINE CYCLE)





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First law applied to open systems



mass(flow energy+
Kinetic energy +
potential energy +
internal energy)₁

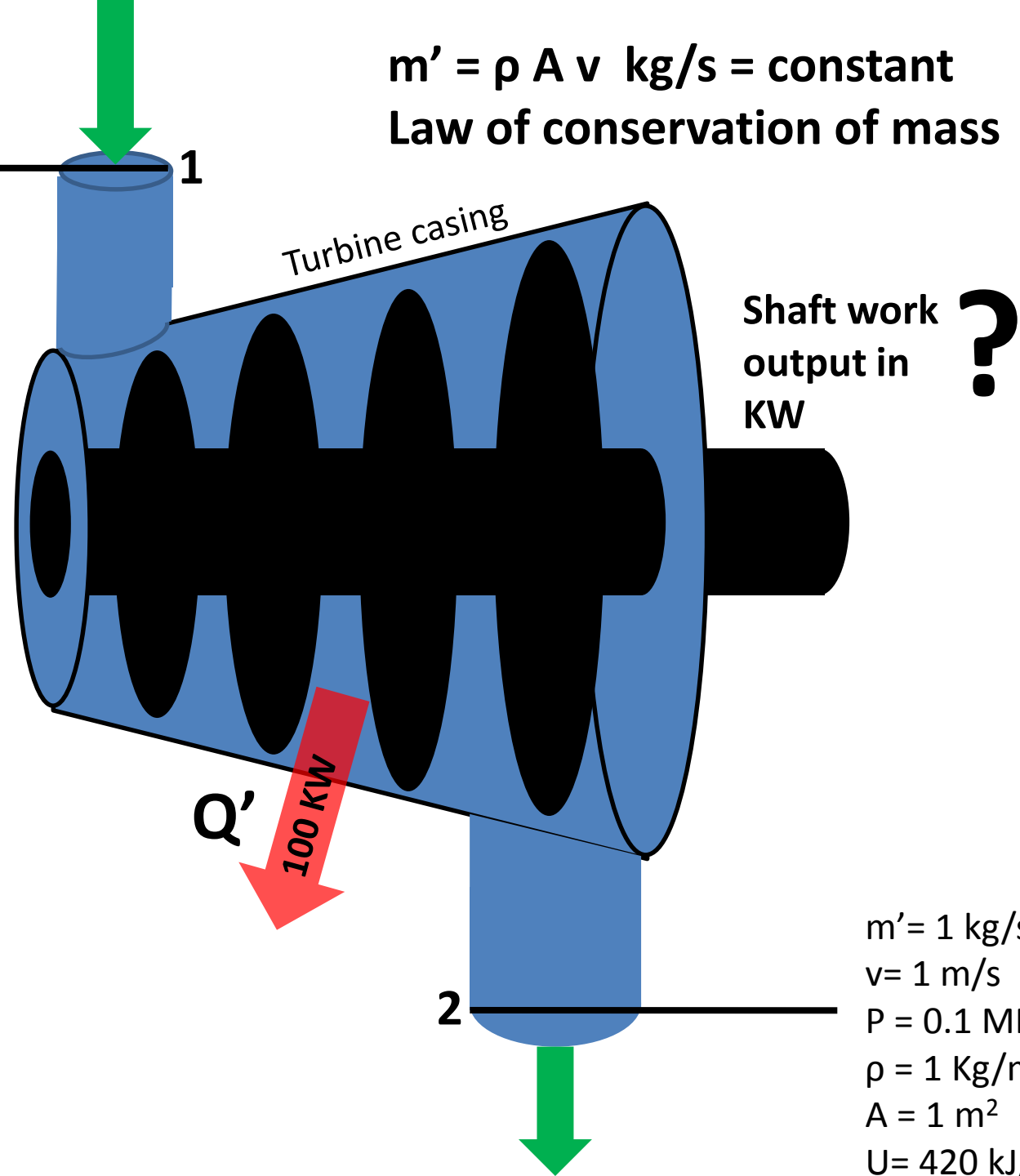
$$Q + m(FE + KE + PE + U)_1 = m(FE + KE + PE + U)_2 + W$$

In a continuous process let **m** be the amount of matter passing through the control volume in time **t** and **Q J** and **W J** be the amount of heat and work transfer in time **t**. then above equation becomes.

$$Q' + m'(FE+KE+PE+U)1 = m'(FE+KE+PE+U)2 + W' \text{ -----(SFEE)}$$

$m' = 1 \text{ kg/s}$
 $v = 2 \text{ m/s}$
 $P = 0.3 \text{ MPa}$
 $\rho = 1 \text{ Kg/m}^3$
 $A = 0.5 \text{ m}^2$
 $U = 1400 \text{ kJ/kg}$

$m' = \rho A v \text{ kg/s} = \text{constant}$
Law of conservation of mass



$m' = 1 \text{ kg/s}$
 $v = 1 \text{ m/s}$
 $P = 0.1 \text{ MPa}$
 $\rho = 1 \text{ Kg/m}^3$
 $A = 1 \text{ m}^2$
 $U = 420 \text{ kJ/Kg}$



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Practice problem 7(p88)

- Air flows steadily at a rate of 0.5 kg/s through an air compressor at 7 m/s velocity, 100 kPa pressure and $0.95 \text{ m}^3/\text{kg}$ volume and leaving at 5 m/s , 700 kPa and $0.19 \text{ m}^3/\text{kg}$. internal energy of air leaving is 90 kJ/kg greater than that of air entering. Cooling water in the compressor jackets absorbs heat from the air at the rate of 58 kW .
- Compute the rate of work input to the air in kW
- Find the ratio of inlet pipe diameter to outlet pipe diameter.



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Practice problem 8(p90)

- In a steady flow apparatus, 135 kJ of work is done by each kg of fluid. The specific volume of the fluid, pressure and velocity at the inlet are $0.37 \text{ m}^3/\text{kg}$, 600kPa and 16 m/s. The inlet is 32m above the floor and the discharge pipe is at the floor level. The discharge conditions are $0.62 \text{ m}^3/\text{kg}$, 100 kPa, and 270m/s. the total heat loss between inlet and discharge is 9kJ/kg of the fluid. In flowing through the apparatus, does the specific internal energy increases or decreases and by how much?

Practice problem 9(p90)

- In a steam power station steam flows steadily through a 0.2 m diameter pipeline from the boiler to the turbine. At the boiler end, the steam conditions are found to be, $P=4$ MPa, $T=400^{\circ}\text{C}$, h (*specific enthalpy, $u + P/\rho$*)= 3213.6 kJ/kg and $v= 0.084$ m³/kg. there is a heat loss of 8.5 kJ/kg from the pipeline. Calculate the steam flow rate.

Practice problem 10(p91)

- A certain water heater operates under steady flow conditions receiving 4.2 kg/s of water at 75°C temperature, enthalpy 313.93kJ/kg. the water is heated by mixing with steam which is supplied to the heater at temperature 100.2 °C and enthalpy 2676 kJ/kg. the mixture leaves the heater as liquid water at temperature 100°C and enthalpy 419 kJ/kg. how much steam must be supplied to the heater per hour?



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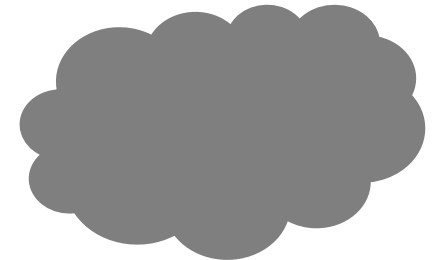
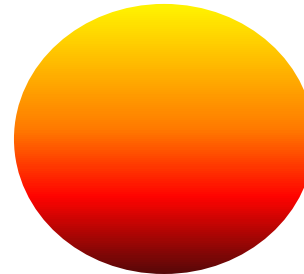
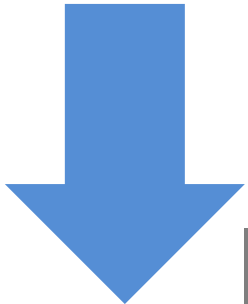
SECOND

LAW



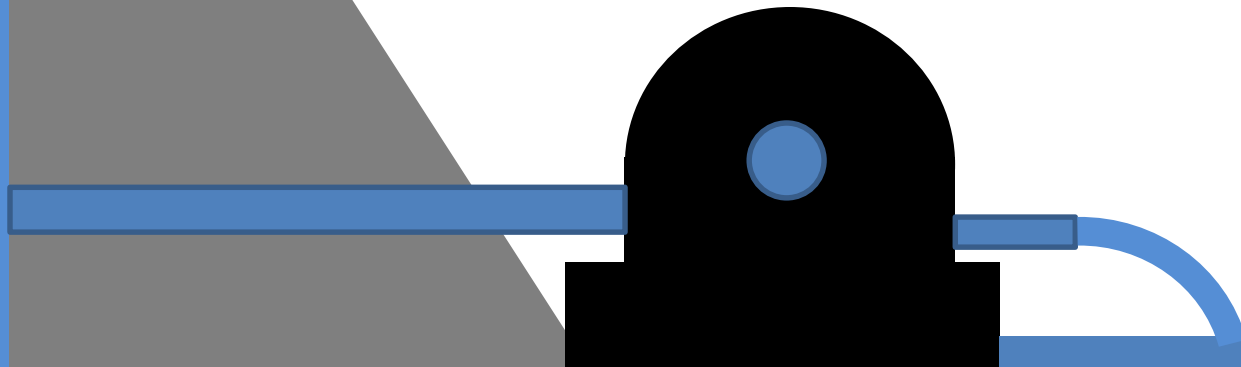
CYCLIC DEVICES

- **Heat engine**-- is a device **working in a cycle** in which there is a **net heat transfer to the system** and **net work transfer from the system**.
E.g. IC engines, power plants
- **Heat pump** – is a device **working in a cycle** in which there is a **net work transfer to the system** and **net heat transfer from the system**.



FOR CONTINUOUS HEAT OR WORK TRANSFER A DEVICE SHOULD WORK IN A CYCLE

Hydraulic turbine





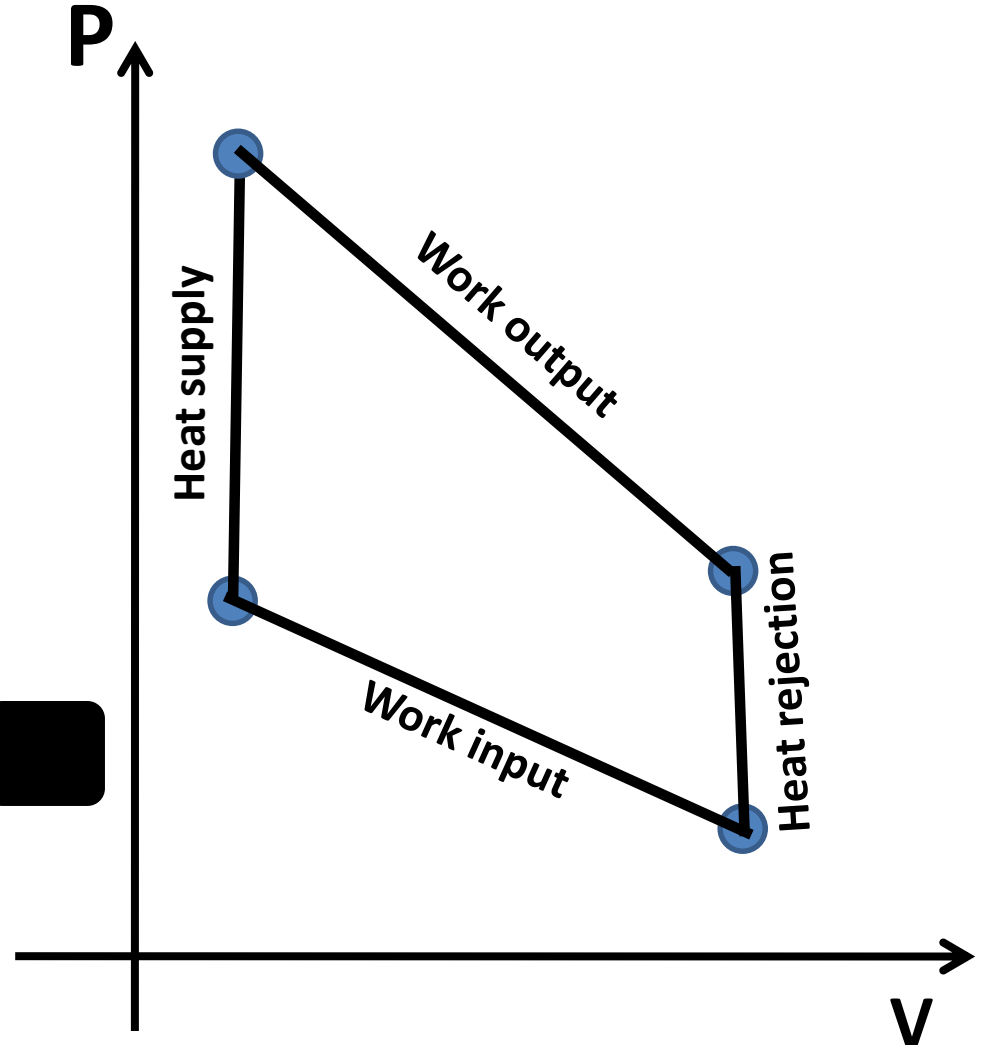
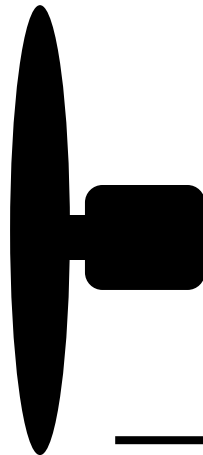
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HEAT ENGINE CYCLE e.g.

Heat sink (atm air) at
lower temperature T_2



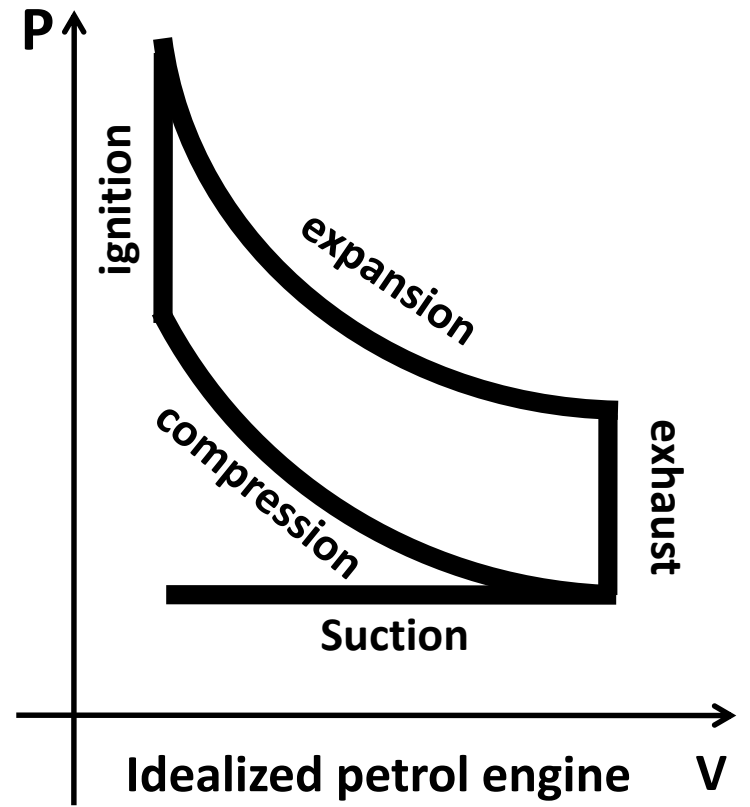
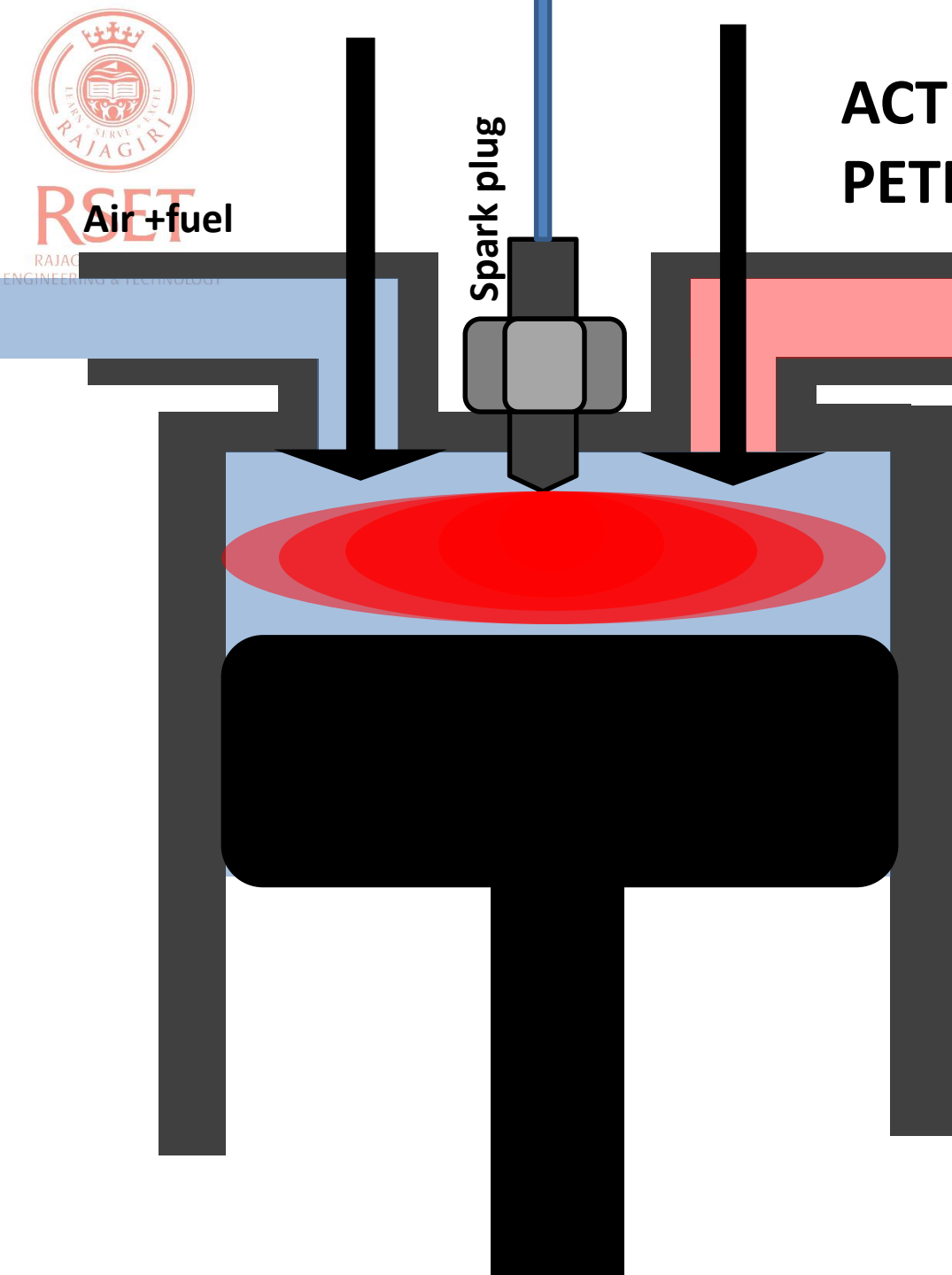
Heat source at higher temperature T_1





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ACTUAL OPERATION OF A PETROL ENGINE

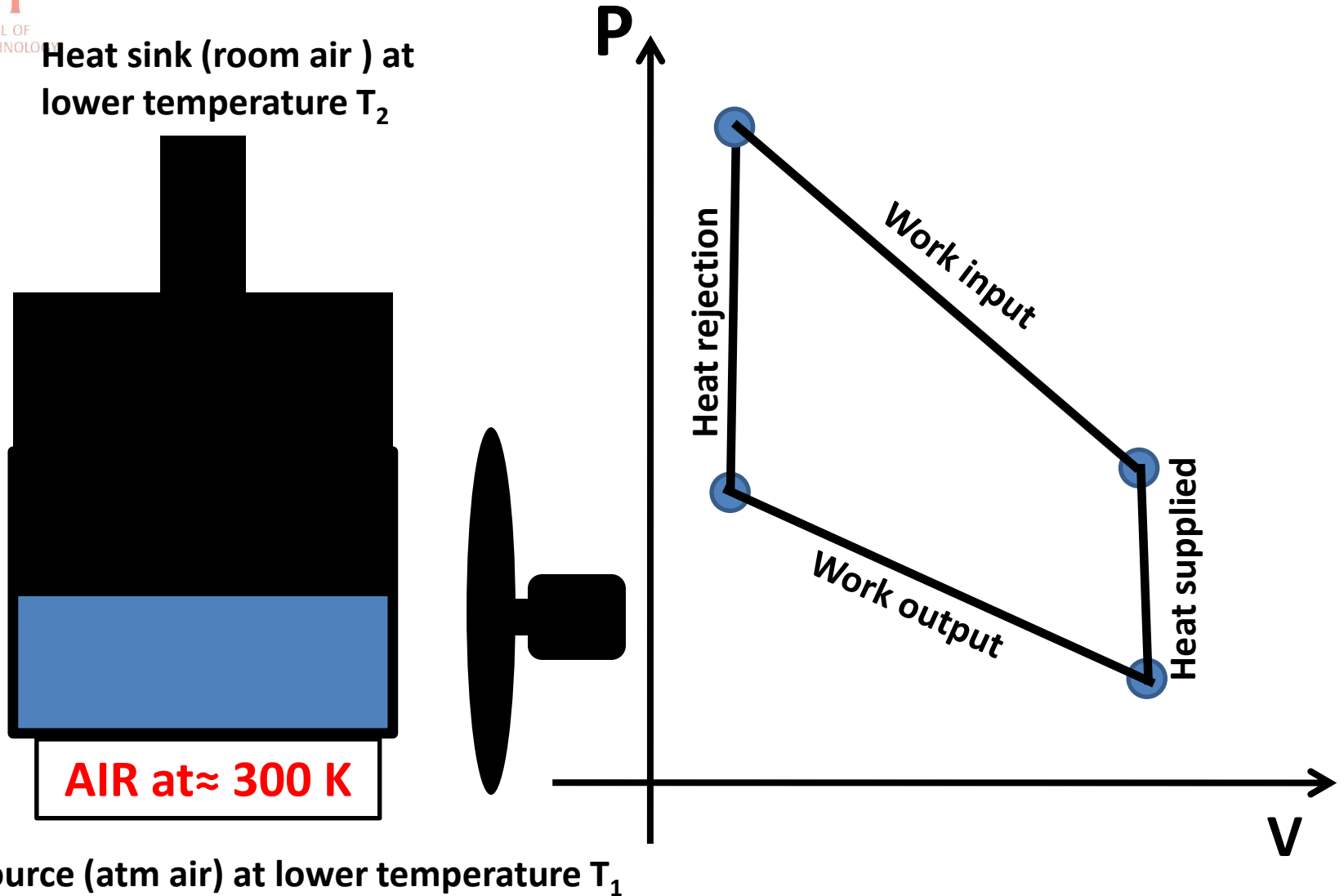


Idealized petrol engine
cycle (Otto cycle)



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HEAT PUMP CYCLE e.g.

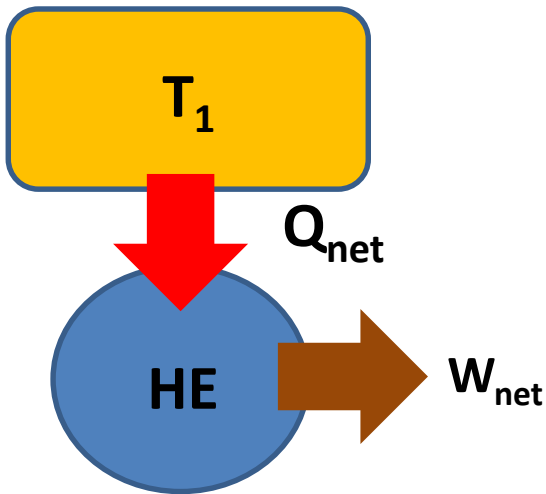




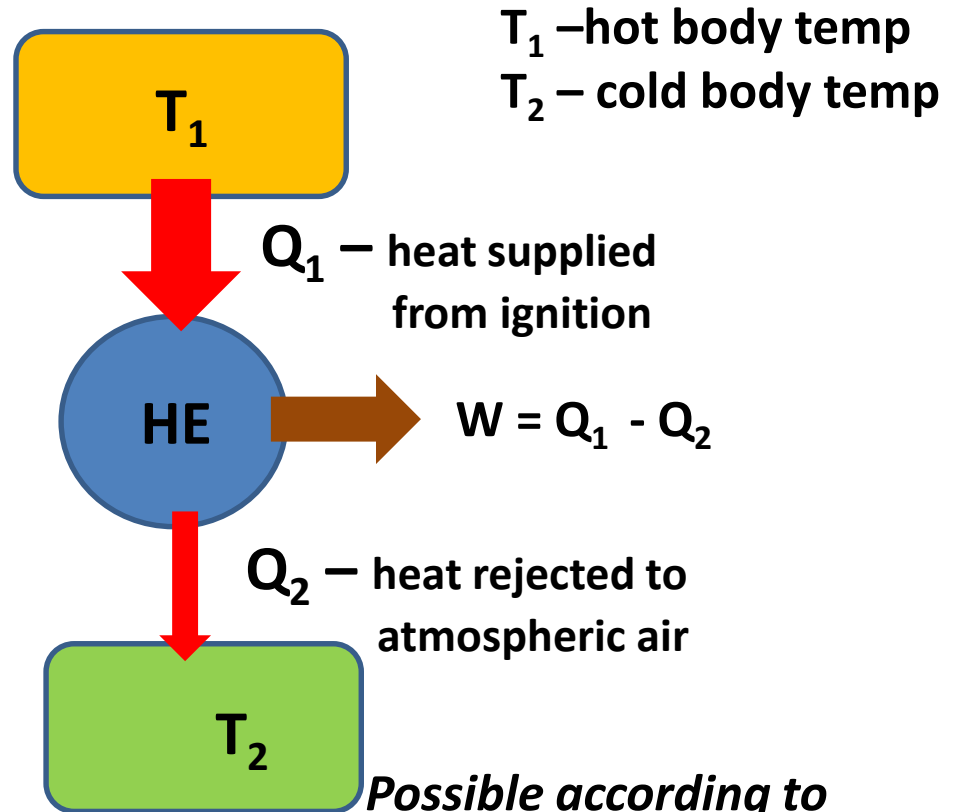
KELVIN PLANK STATEMENT OF SECOND LAW

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- It is impossible for a heat engine to produce net work in a complete cycle. If it exchanges heat only with bodies at a single fixed temperatures.***



***Impossible according to second law.
But possible according to the first law***



Possible according to second law as well as first law



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PERFORMANCE PARAMETER OF HEAT ENGINES

- Ratio of desired effect (net work output) to effort spent (heat supplied)
- Efficiency

$\eta =$ (net work output / heat supplied) in a cycle

$$= W / Q_1$$

$$= (Q_1 - Q_2) / Q_1 = 1 - Q_2 / Q_1$$

from this we find that no heat engine can have 100% efficiency.

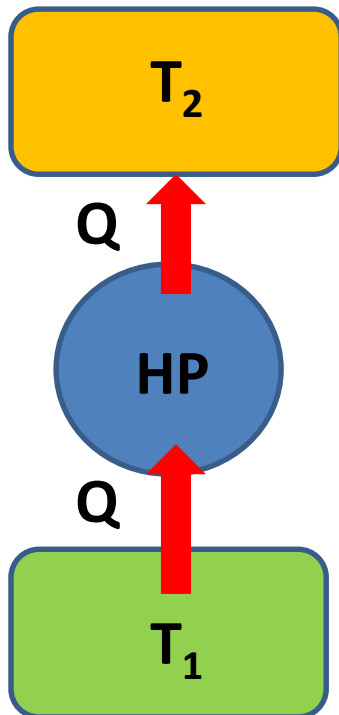
W is also called **available energy** i.e. maximum possible net work that can be obtained from an engine.



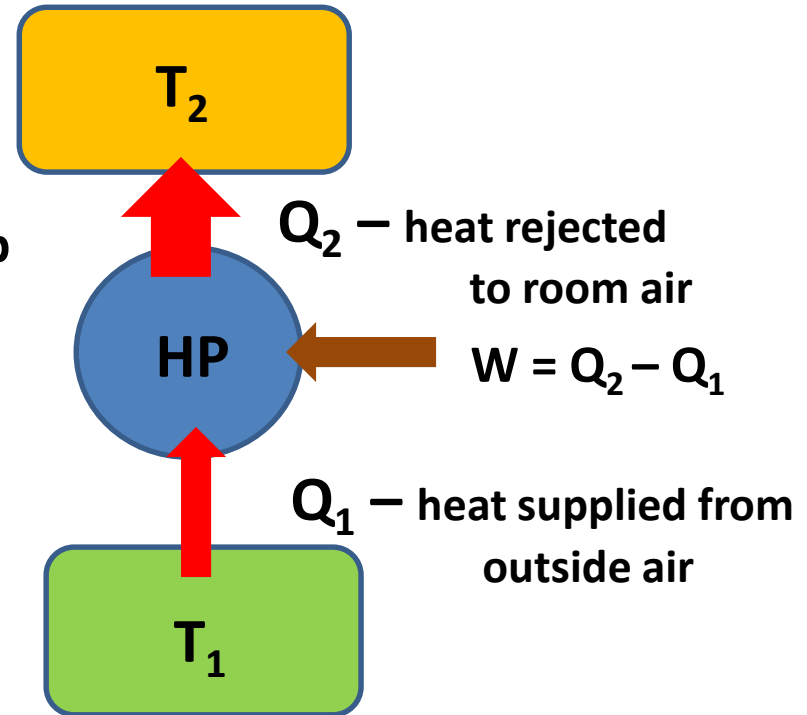
CLAUSIUS STATEMENT OF SECOND LAW

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- It is impossible to construct a device which, operating in a cycle, will produce no effect other than the transfer of heat from a cooler to a hotter body.



T_1 – cold body temp
 T_2 – hot body temp



*Impossible according to second law.
But possible according to the first law*

*Possible according to
second law as well as first law*



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PERFORMANCE PARAMETER OF HEAT PUMPS

- Ratio of desired effect (heat supplied to room) to effort spent (net work input)
- Coefficient of performance,
COP= (heat rejected by system/ net work input) in a cycle

$$= Q_2 / W$$

$$= Q_2 / (Q_2 - Q_1)$$

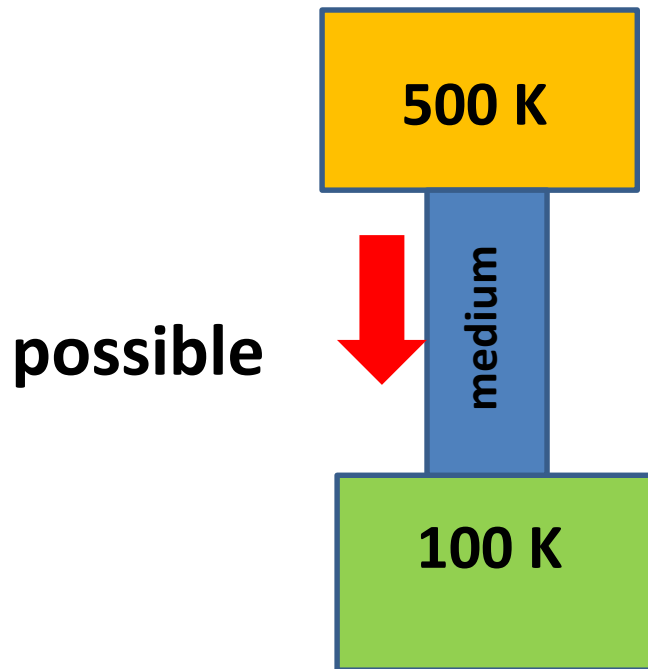
from this we find that COP of heat pumps is always greater than unity.



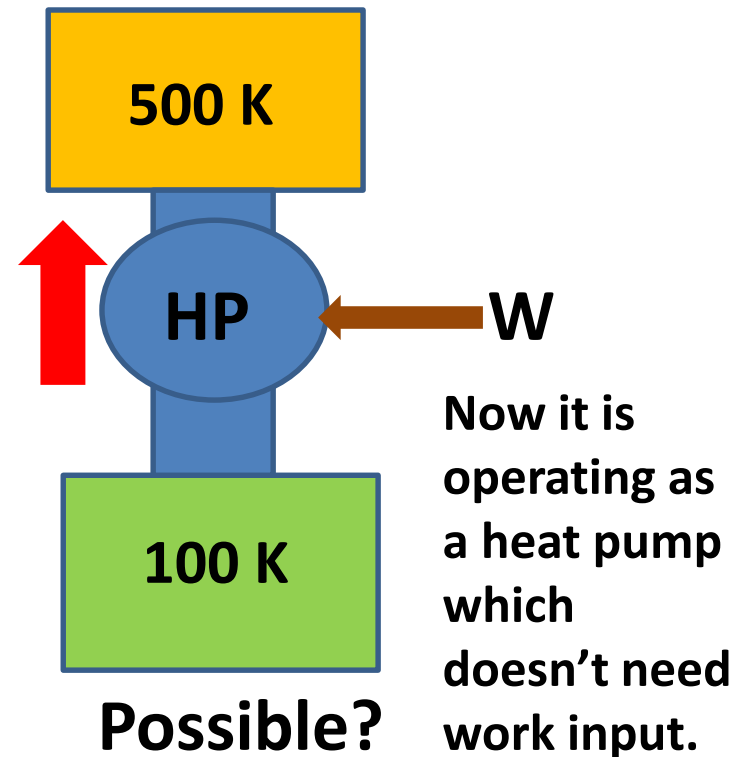
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EXPLAINING IRREVERSIBILITY USING SECOND LAW

- Heat transfer through a finite temperature difference.



So heat transfer through a finite temperature gradient is a spontaneous process

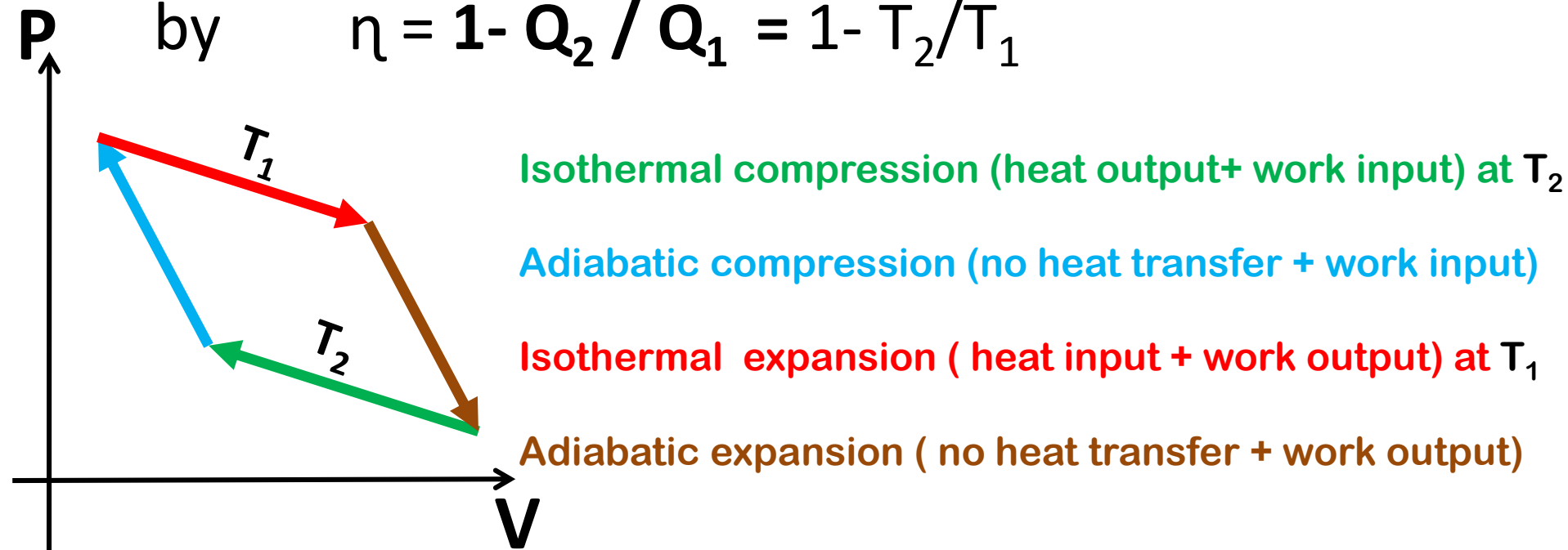




EFFICIENCY OF A CARNOT ENGINE CYCLE (A Reversible Cycle)

- Efficiency of a reversible heat engine in which heat is received *solely at temp T_1* from a heat source reservoir and heat is rejected *solely at temperature T_2* to a heat sink reservoir is given

by $\eta = 1 - Q_2 / Q_1 = 1 - T_2 / T_1$





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SOURCE RESERVOIRS AND SINK RESERVOIRS EXAMPLES

Heat Source reservoir - is defined as a large body of infinite heat capacity which is capable of supplying an unlimited quantity of heat without change in temperature

E.g. Sun



Heat Sink reservoir - is defined as a large body of infinite heat capacity which is capable of absorbing an unlimited quantity of heat without change in temperature

E.g. atmospheric air.

Practice problem 11(p130)

- A cyclic heat engine operates between a source temperature of 800°C and sink temperature of 30°C . What is the least rate of heat rejection per net output of the engine in KW ? ***0.392 kW***

Practice problem 12(p130)

- A domestic refrigerator maintains a temperature of -15°C . The ambient air temperature is 30°C . If the heat leaks into the freezer at a continuous rate of 1.75 kJ/s what is the least power necessary to pump this heat out continuously? ***0.31 kW***



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Practice problem 13

- It is proposed that solar energy can be used to warm a large collector plate. This energy would in turn be transferred as heat to a fluid within a heat engine, and the engine would reject energy as heat to atmosphere. Experiments indicate that about $1880 \text{ kJ/m}^2 \text{ h}$ of energy can be collected when the plate is operating at 90°C . Estimate the minimum collector area that would be required for a plant producing 1kW of useful shaft power. Atmospheric temperature may be assumed to be 20°C . **10 m^2**



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Practice problem 14

- A reversible heat engine in a satellite operates between a hot reservoir at T_1 . and a radiating panel at T_2 . The radiation from the panel is proportional to its area and to T_2^4 . For a given work output and value of T_1 show that the area of the panel will be minimum when $T_2/T_1 = 0.75$.
- Determine the minimum area of the panel for an output of 1 kW if the constant of proportionality is $5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$ and $T_1 = 1000\text{K}$.

0.1672 m²



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GRADES OF ENERGY

High Grade energy

Mechanical work

(Because in a heat pump all of the mechanical work can be converted to heat energy)

Electric energy

Water power

Wind power

Kinetic energy of a jet

Tidal power

Low grade energy

Heat or thermal

(because in a heat engine a portion of heat energy is available as net work- second law)

Heat derived from nuclear fission or fusion

Heat derived from the combustion of fossil fuels

**The bulk of high grade energy is obtained from sources of low grade energy
Complete conversion of low grade energy to high grade energy is impossible by
second law**



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ENTROPY

(Measure of irreversibility of process)

• **Efficiency of a Carnot cycle,**

$$\eta = 1 - Q_2 / Q_1 = 1 - T_2 / T_1$$

Q_1 - Heat supplied to engine

T_1 - Constant temperature

at which heat is supplied

Q_2 - Heat rejected by engine

T_2 - Constant temperature

at which heat is rejected

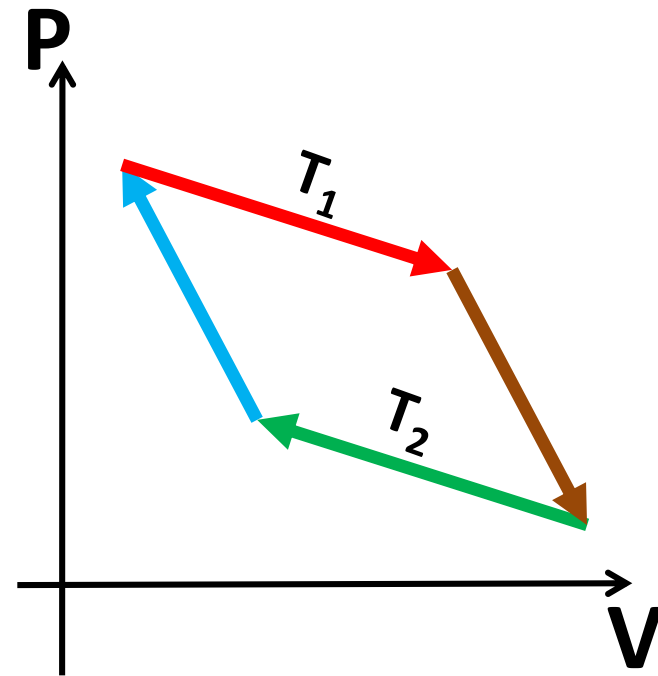
$$Q_2 / Q_1 = T_2 / T_1$$

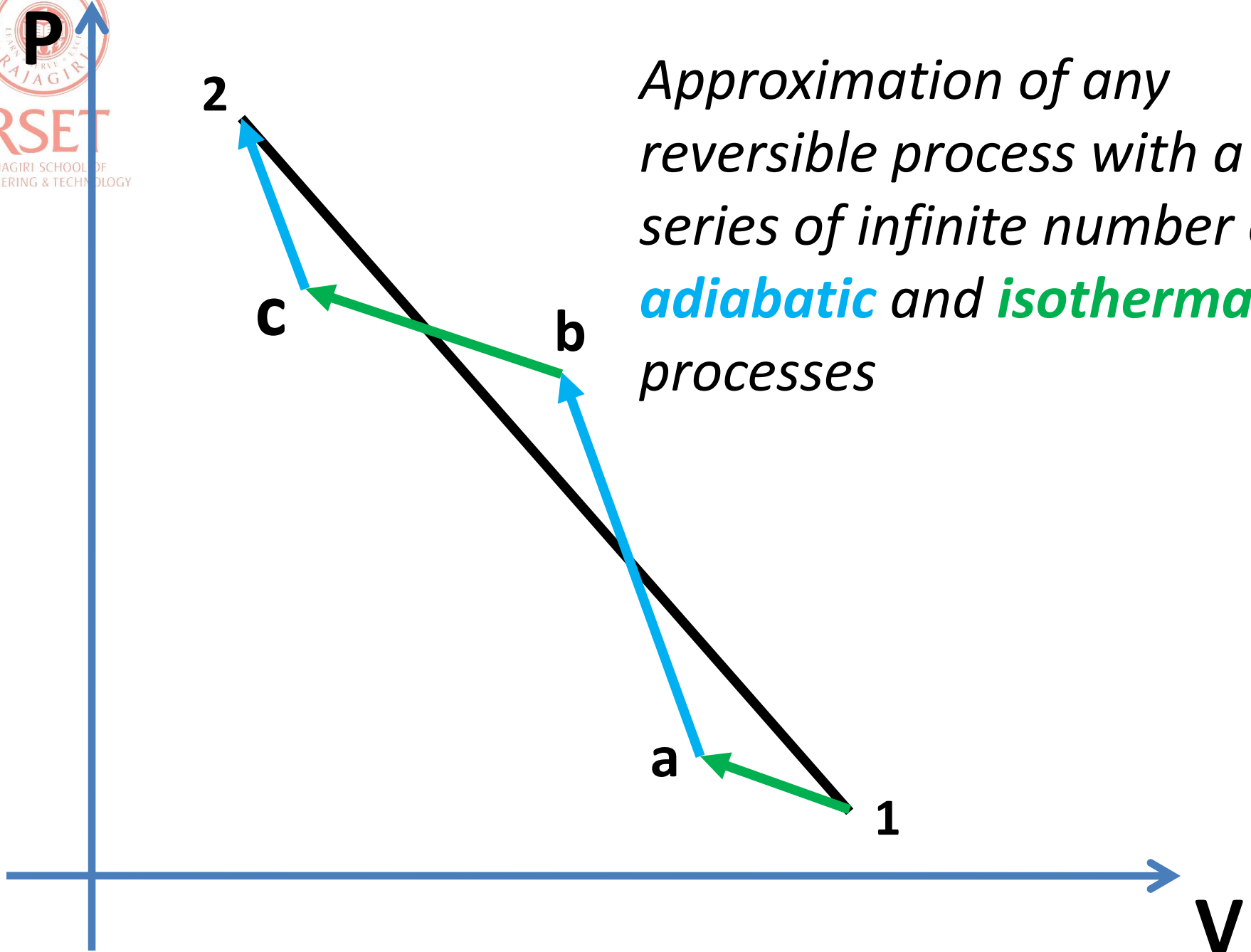
$$Q_1 / T_1 = Q_2 / T_2$$

$$Q_1 / T_1 - Q_2 / T_2 = 0$$

$\sum_{\text{cycle}} Q/T = 0$ for a Carnot engine cycle.

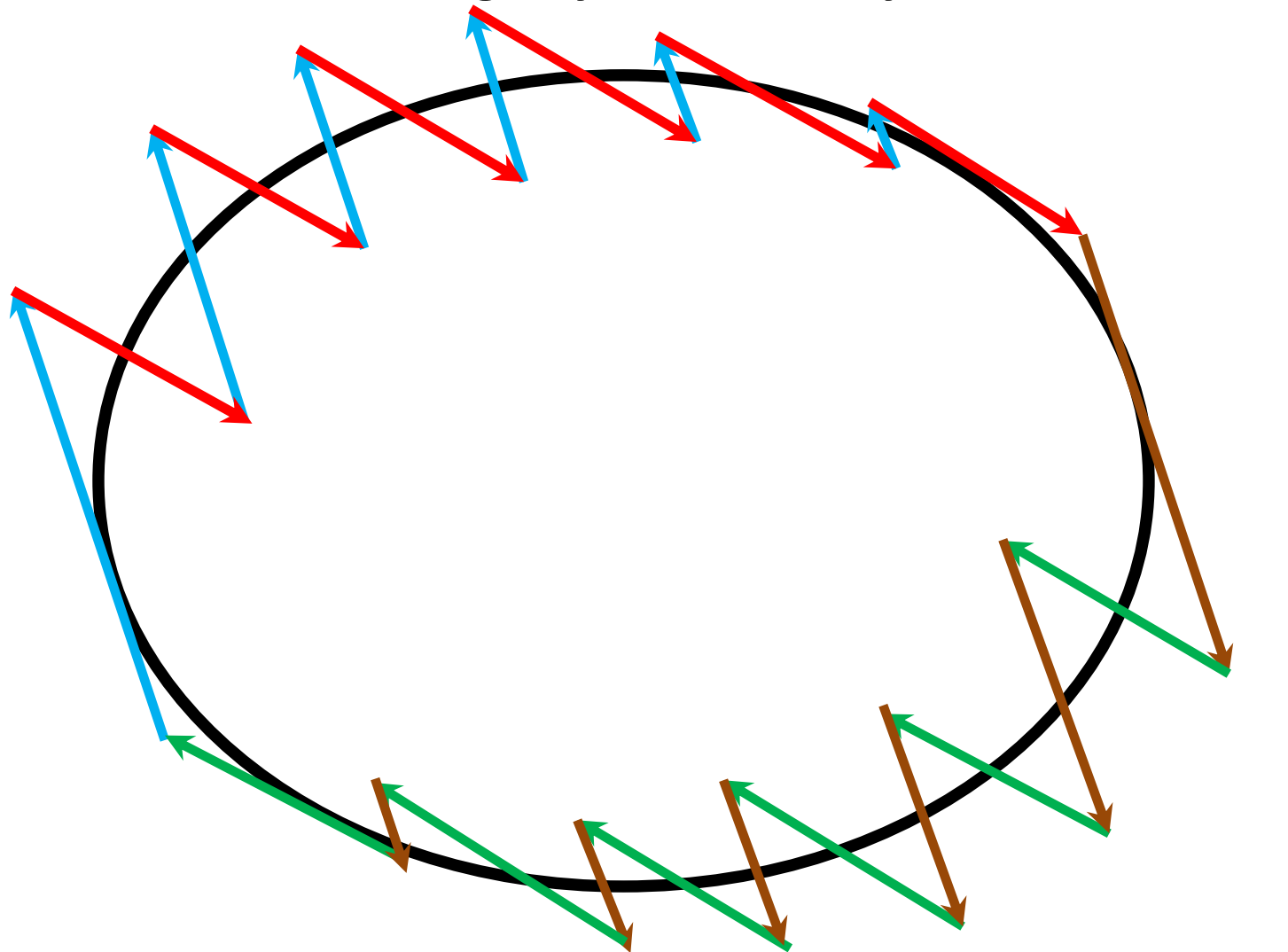
i.e. $\oint \frac{\delta Q}{T} = 0$ (for a Carnot engine cycle)





Approximation of any reversible process with a series of infinite number of **adiabatic** and **isothermal** processes

Considering any reversible cycle



Approximation of any cycle with a series of infinite number of adiabatic and isothermal processes

V



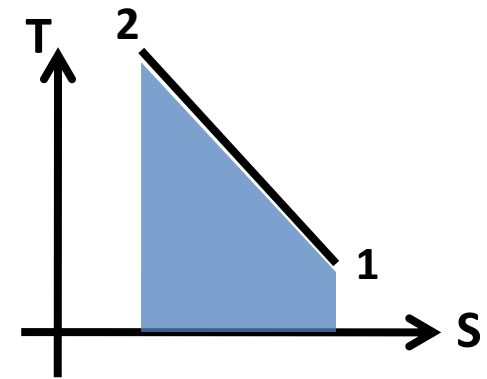
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- So for this reversible cycle also we can write

$$\oint \frac{\delta Q}{T} = 0 \quad (\text{for a reversible cycle})$$

- We know that cyclic integral of any property = 0
- So $\frac{\delta Q}{T}$ is a property, this property we call *Entropy S*.
- $\delta Q = T dS$
- $Q = \int T ds$ (area under *T-S* curve)
for a reversible process.



CLAUSIUS INEQUALITY

$$\oint \frac{\delta Q}{T} = 0 \quad (\text{for a reversible cycle})$$

$$\oint \frac{\delta Q}{T} < 0 \quad (\text{for an irreversible cycle})$$

$$\oint \frac{\delta Q}{T} > 0 \quad (\text{for an impossible cycle, since it violates second law})$$



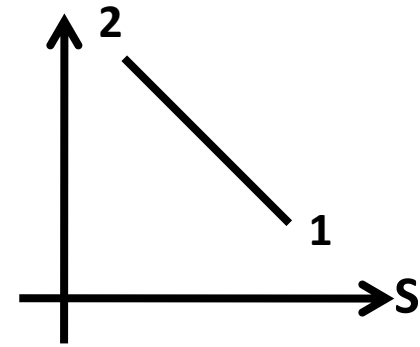
ENTROPY CHANGE DURING A PROCESS

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- For a reversible process,

$$S_2 - S_1 = \int \frac{\delta Q}{T}$$

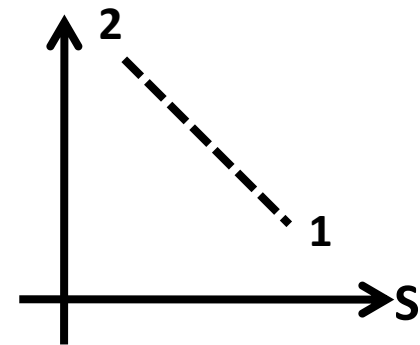
$$dS = \frac{\delta Q}{T}$$



- For an irreversible process,

$$S_2 - S_1 > \int \frac{\delta Q}{T}$$

$$dS > \frac{\delta Q}{T}$$



- For an impossible process,

$$S_2 - S_1 < \int \frac{\delta Q}{T}$$

$$dS < \frac{\delta Q}{T}$$

, since it violates second law)



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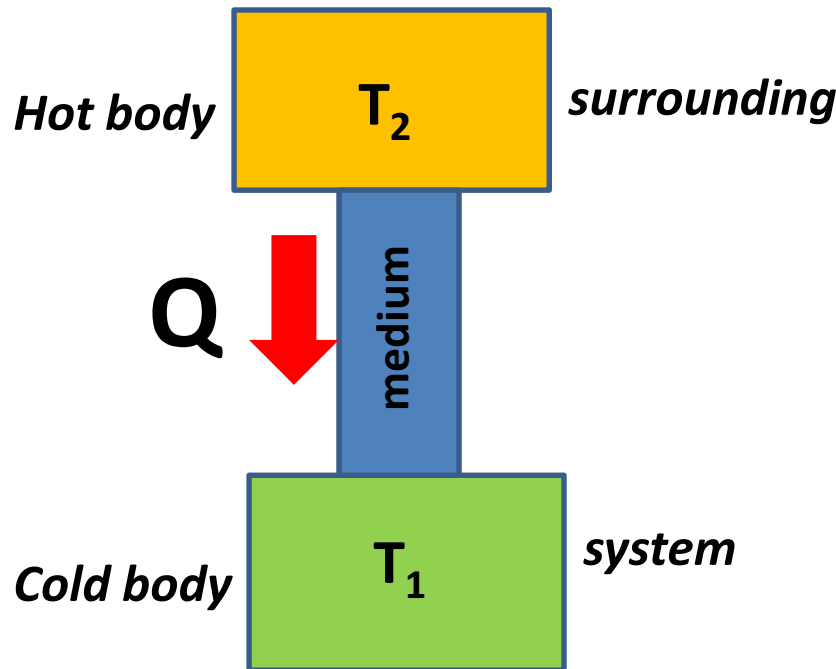
PRINCIPLE OF INCREASE OF ENTROPY

- For any process we can write $dS \geq \delta Q/T$
- For an isolated system, there is no energy transfer to or from the system so $\delta Q=0$
- So $dS \geq 0$ for an isolated system
- A system comprising of both **system** and **surrounding** is called isolated system or a universe
- i.e $(dS)_{universe} \geq 0$
- $(dS)_{system} + (dS)_{surrounding} \geq 0$
- $\Delta S_{system} + \Delta S_{surrounding} \geq 0$
- **i.e Entropy of an isolated system or universe will never decrease.**
- for a **reversible process** $(dS)_{universe} = 0$
i.e. $\Delta S_{system} + \Delta S_{surrounding} = 0$



EXPLAINING IRREVERSIBILITY USING ENTROPY PRINCIPLE

- Heat transfer through a finite temperature difference



So heat transfer through a finite temperature gradient is a spontaneous process

Entropy change of the system,

$$\Delta S_{\text{system}} = Q / T_1$$

Entropy change of the surrounding,

$$\Delta S_{\text{surroundings}} = -Q / T_2$$

Entropy change of the universe,

$$\Delta S_{\text{system}} + \Delta S_{\text{surroundings}} = Q (T_2 - T_1) / (T_1 T_2) > 0$$

Conversely if we consider Q flowing from T_1 to T_2 , we will get $\Delta S_{\text{universe}} < 0$ which makes it an impossible process



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Practice problem 15(p171)

- One kg of water is brought in contact with a heat reservoir at 373K. When the water has reached 373 K, find the entropy change of water, the heat reservoir and of the universe. (*take specific heat, c of the water as 4.187 kJ/kg K*) **0.183 kJ/K**
- If water is heated from 273 to 373 K by first bringing it in contact with a reservoir at 323 K and then with a reservoir at 373 K, what will the entropy change of the universe be? **0.098 kJ/K**
- How will you propose to heat the water from 273 to 373 K to make it a reversible process ?



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WHY WE ARE BOTHERED TO MAKE A PROCESS REVERSIBLE ?

- *Carnot's theorem- states that all heat engines operating between a given constant temperature source and a given constant temperature sink none has a higher efficiency than a reversible engine.*
- *Available work, W_{net} from a cyclic engine decreases with irreversibility.*



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AVAILABILITY

***(The reason we are bothered
about irreversibility)***



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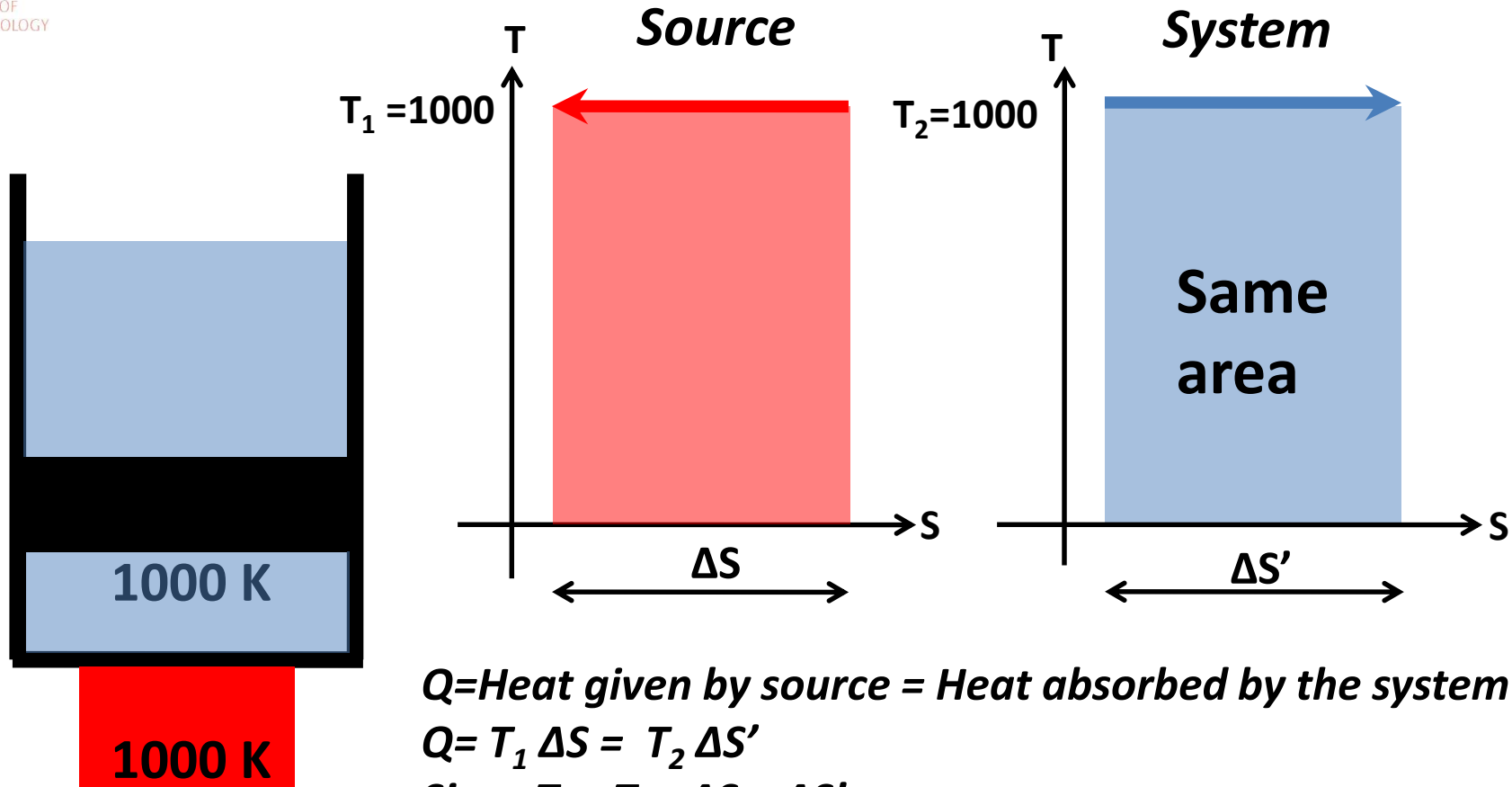
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RELATION BETWEEN AVAILABILITY AND ENTROPY



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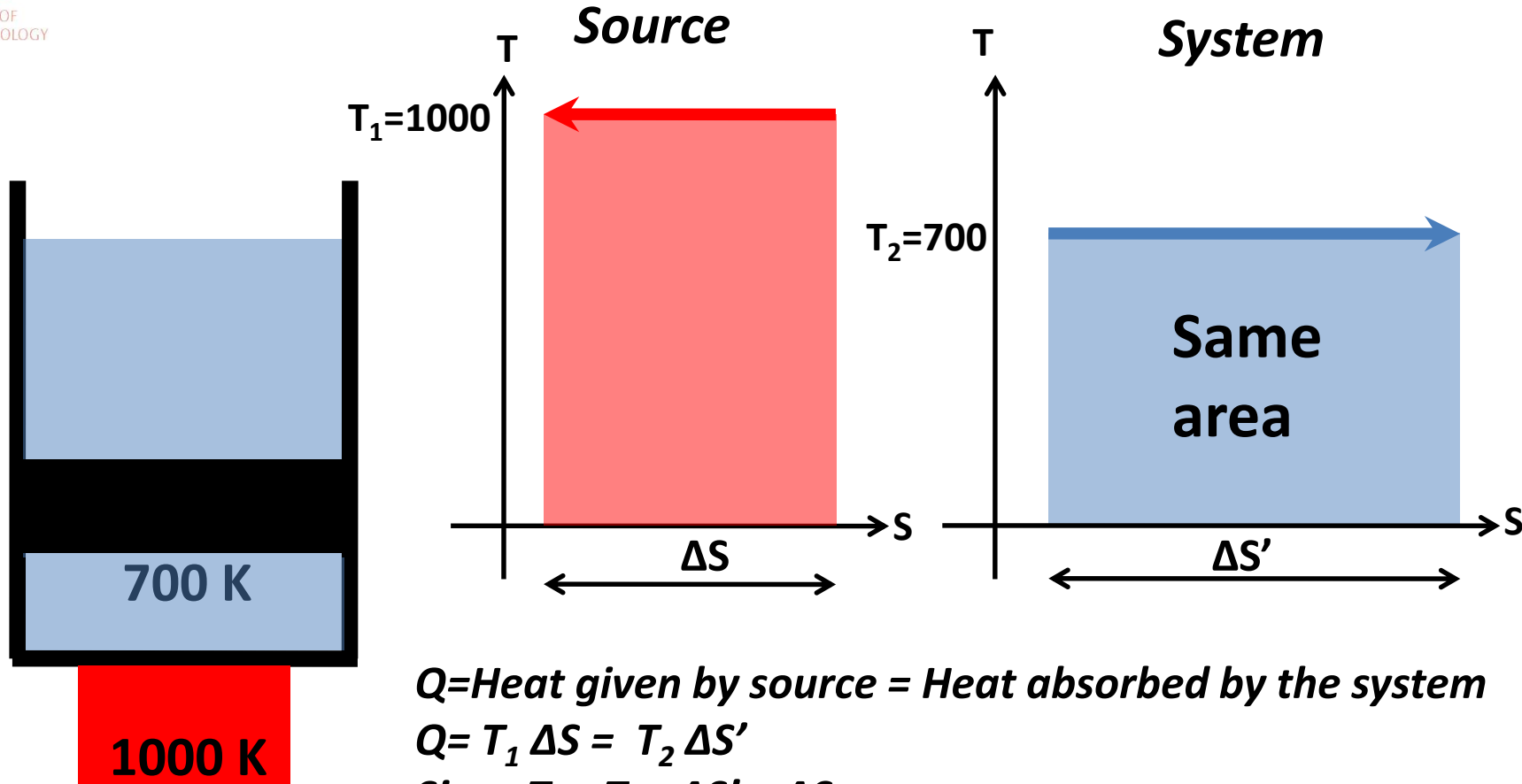
A REVERSIBLE ISOTHERMAL PROCESS





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AN IRREVERSIBLE ISOTHERMAL PROCESS

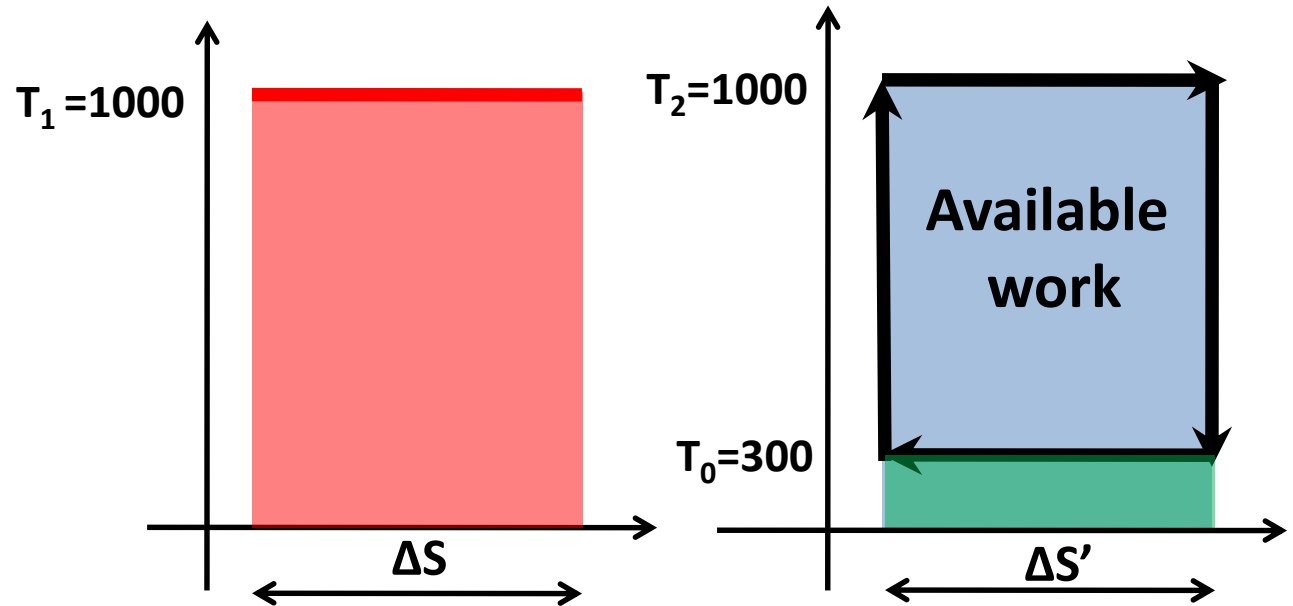
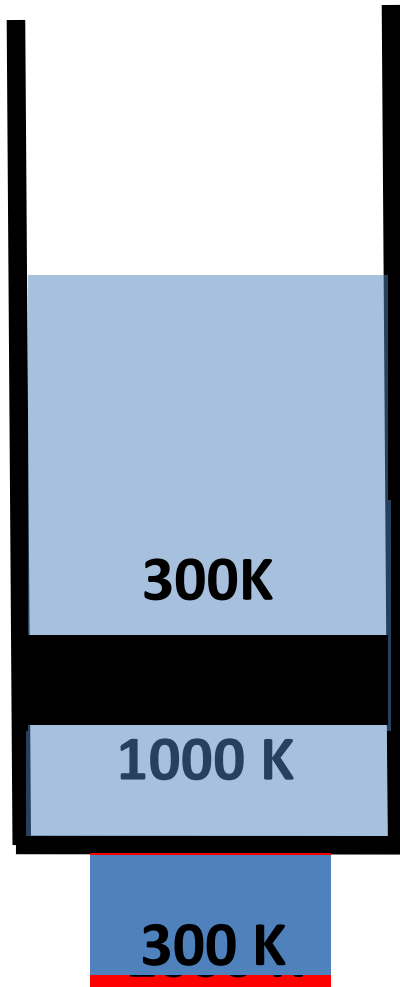




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AVAILABLE WORK FROM A REVERSIBLE CARNOT CYCLE



Let Heat given by source = Heat absorbed by the system
 $= Q_i = 14000 \text{ J}$

i.e. $Q_i = T_1 \Delta S = T_2 \Delta S' = 14000 \text{ J}$

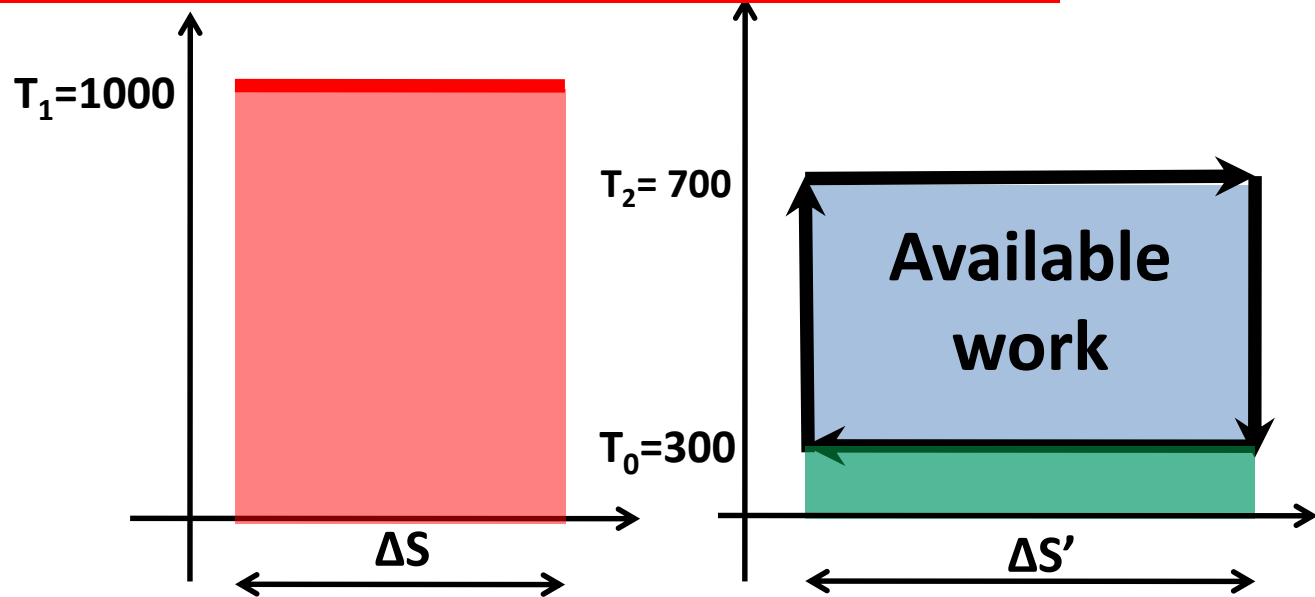
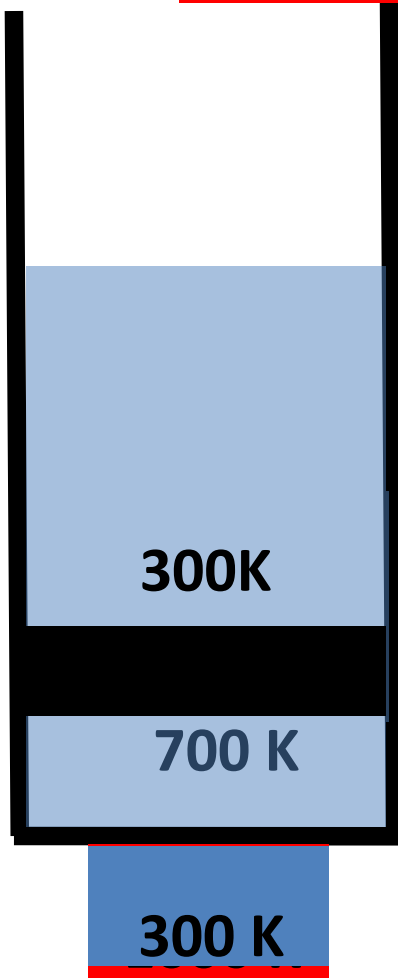
$\Delta S = 14 \text{ J/K}$ and $\Delta S' = 14 \text{ J/K}$

In this case heat rejected $Q_o = T_o \Delta S' = 4200 \text{ J}$

In this case $W = Q_i - Q_o = 14000 - 4200 = 9800 \text{ J}$

AVAILABLE WORK FROM AN IRREVERSIBLE CARNOT CYCLE

AVAILABILITY DECREASES WITH IRREVERSIBILITY



Let Heat given by source = Heat absorbed by the system
 $= Q_i = 14000 \text{ J}$

i.e. $Q_i = T_1 \Delta S = T_2 \Delta S' = 14000 \text{ J}$

$\Delta S = 14 \text{ J/K}$ and $\Delta S' = 20 \text{ J/K}$

In this case heat rejected $Q_o = T_o \Delta S' = 6000 \text{ J}$

In this case $W = Q_i - Q_o = 14000 - 6000 = 8000 \text{ J}$

Practice problem 16(p227)

- In a certain process, a vapor while condensing at 420°C , transfer heat to water evaporating at 250°C . The resulting steam is used in a power cycle which rejects heat at 35°C . What is the fraction of available energy in the heat transferred from the process vapor at 420°C that is lost due to irreversible heat transfer at 250°C ?
0.26



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IDEAL GAS AND REAL GAS EQUATIONS



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Ideal gas equation

Derived from experiments at macroscopic level

- Avogadro's law- Equal volumes of all gases under similar conditions of temperature and pressure contains equal no of molecules, (one mole of any gas at 1 atm and 273K occupies a volume of 22.4L)

$$V \propto n \text{ (at constant T and P)}$$

- Boyle's Law – $V \propto 1/P$ (at constant absolute T and n)
- Charle's Law – $V \propto T$ (at constant absolute P and n)
- i.e. $P V \propto n T$,
- $PV = n R' T$
- which leads to constant of proportionality, **R' - universal gas constant.**
- $R' = PV / nT = 1 \text{ atm } 22.4\text{L} / 1\text{mole } 273\text{K} = 8.314 \text{ kJ/kmole K}$
- **$Pv' = R'T$** where v' is molar specific volume m^3/kmol
- **$P V = m R T$** R-characteristic gas constant = $R'/\text{Molecular mass}$
- **A hypothetical gas which obeys the general gas equation at all ranges of temperatures and pressures is called an ideal gas.**



RSEP

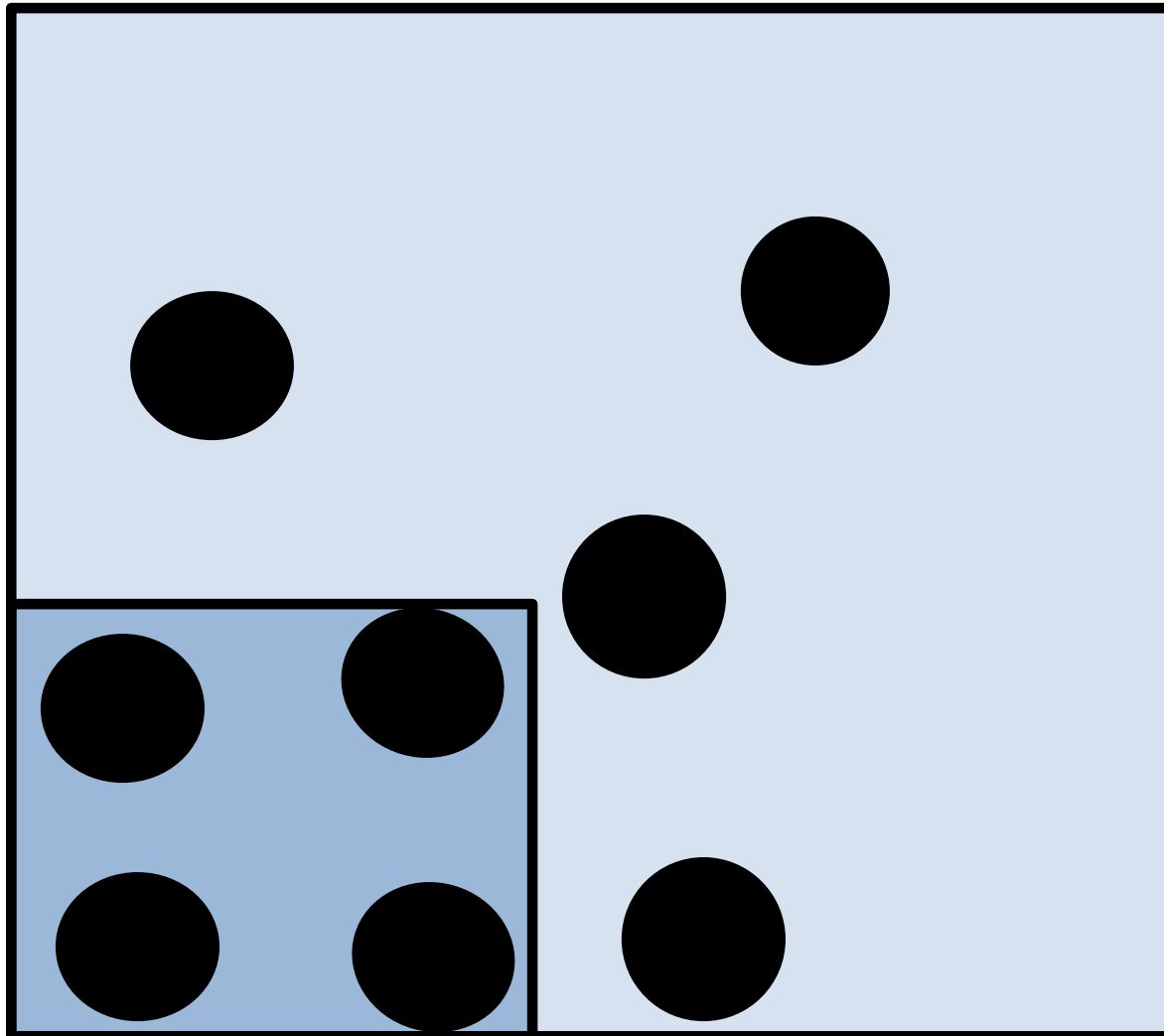
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KINETIC MOLECULAR(MICROSCOPIC) THEORY

FOR EXPLAINING IDEAL BEHAVIOR (FROM WIKIPEDIA)

- The gas consists of very small particles known as molecules. This smallness of their size is such that the total [volume](#) of the individual gas molecules added up is negligible compared to the volume of the smallest open ball containing all the molecules. This is equivalent to stating that the average distance separating the gas particles is large compared to their [size](#).
- These particles have the same [mass](#).
- The number of molecules is so large that statistical treatment can be applied.
- These molecules are in constant, [random](#), and rapid motion.
- The rapidly moving particles constantly collide among themselves and with the walls of the container. All these collisions are perfectly elastic. This means, the molecules are considered to be perfectly spherical in shape, and elastic in nature.
- Except during collisions, the [interactions](#) among molecules are negligible. (That is, they exert no [forces](#) on one another.)
- The average [kinetic energy](#) of the gas particles depends only on the [absolute temperature](#) of the [system](#). The kinetic theory has its own definition of temperature, not identical with the thermodynamic definition.
- The time during collision of molecule with the container's wall is negligible as compared to the time between successive collisions.
- Because they have mass, the gas molecules will be affected by gravity.

CAUSES OF DEVIATION OF A REAL GAS FROM IDEAL BEHAVIOR



At high temperature and low pressure

- *Total volume of individual molecules negligible*

- *Intermolecular attraction or repulsion negligible*

At high pressure and low temperature

- *Total volume of individual molecules significant*

- *Intermolecular attraction or repulsion significant*



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A REAL GAS EQUATION

Van der Waals gas equation

- $(P + a/v'^2)(v'-b) = R' T$ or $(P + a/v^2)(v-b) = R T$
- P is absolute pressure in Pa
- v' - molar specific volume $m^3/kmol$
- v - specific volume m^3/kg
- a/v'^2 - force of cohesion
- b - co-volume
- R' - universal gas constant-8.314 kJ/kmol K
- R - characteristic gas constant- $R' / \text{molecular mass in kg/kmol}$
- Real gas conforms more closely with van der Waals Equation of state, particularly at higher pressures, but is not obeyed at all ranges of pressure and temperatures.



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Practice problem

- *Atmospheric air at 1 atm pressure is having a density of 1 kg/m^3 , specific heat ratio of 1.4, and specific heat at constant pressure 1 kJ/kg*
- *Van der Waals gas constants for air is given by*
 $a=1.368 \text{ bar (m}^3/\text{kmol)}^2$ $b= 0.037 \text{ m}^3/\text{ kmol}$
- ***Find characteristic gas constant***
- ***Find the temperature of the air using ideal gas equation and real gas equation.***



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COMPRESSIBILITY FACTOR

- $Z = Pv'/R'T$
- Z- compressibility factor
- P- absolute pressure, Pa
- v' - molar specific volume, m^3/mol
- R' - universal gas constant, 8.314 J/mol K
- T- absolute temperature, K
- For an ideal gas $Z=1$
- But for real gas $Z \neq 1$,

Real gas equation can be used that time but we need detailed data like value of ***a*** and ***b***.

- when detailed data on a particular gas is not available we can use experiment data charts called "***Generalized Compressibility chart***".



GENERALIZED COMPRESSIBILITY CHART

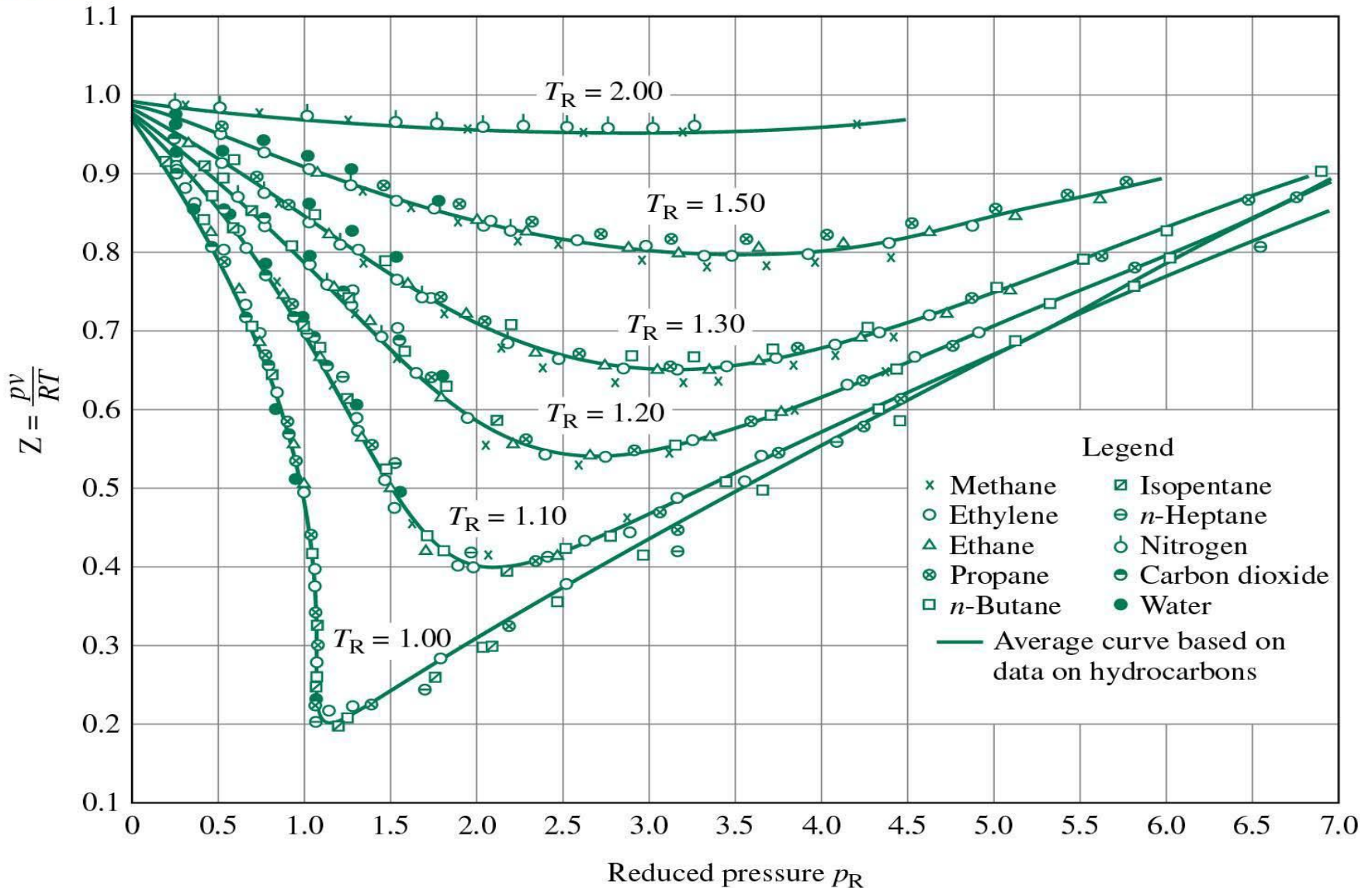
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- Reduced property of a substance is the ratio of a property to its critical property.
- Reduced pressure $P_r = P/P_c$
- Reduced temperature $T_r = T/T_c$
- Reduced molar specific volume $v'_r = v'/v'_c$
- Reduced specific volume $v_r = v/v_c$
- Where subscript C denotes critical point (pressure and temperature at which latent heat=0) which is a unique property for a substance.
- Compressibility factor **$Z = P v'/R' T$ or $Z = P v/R T$**
- Plot of **Z** versus **P_r** for different values of **T_r** for different gases is called Generalized compressibility chart.
- ***A single Generalized compressibility chart can be used for almost all gases.***



GENERALIZED COMPRESSIBILITY CHART

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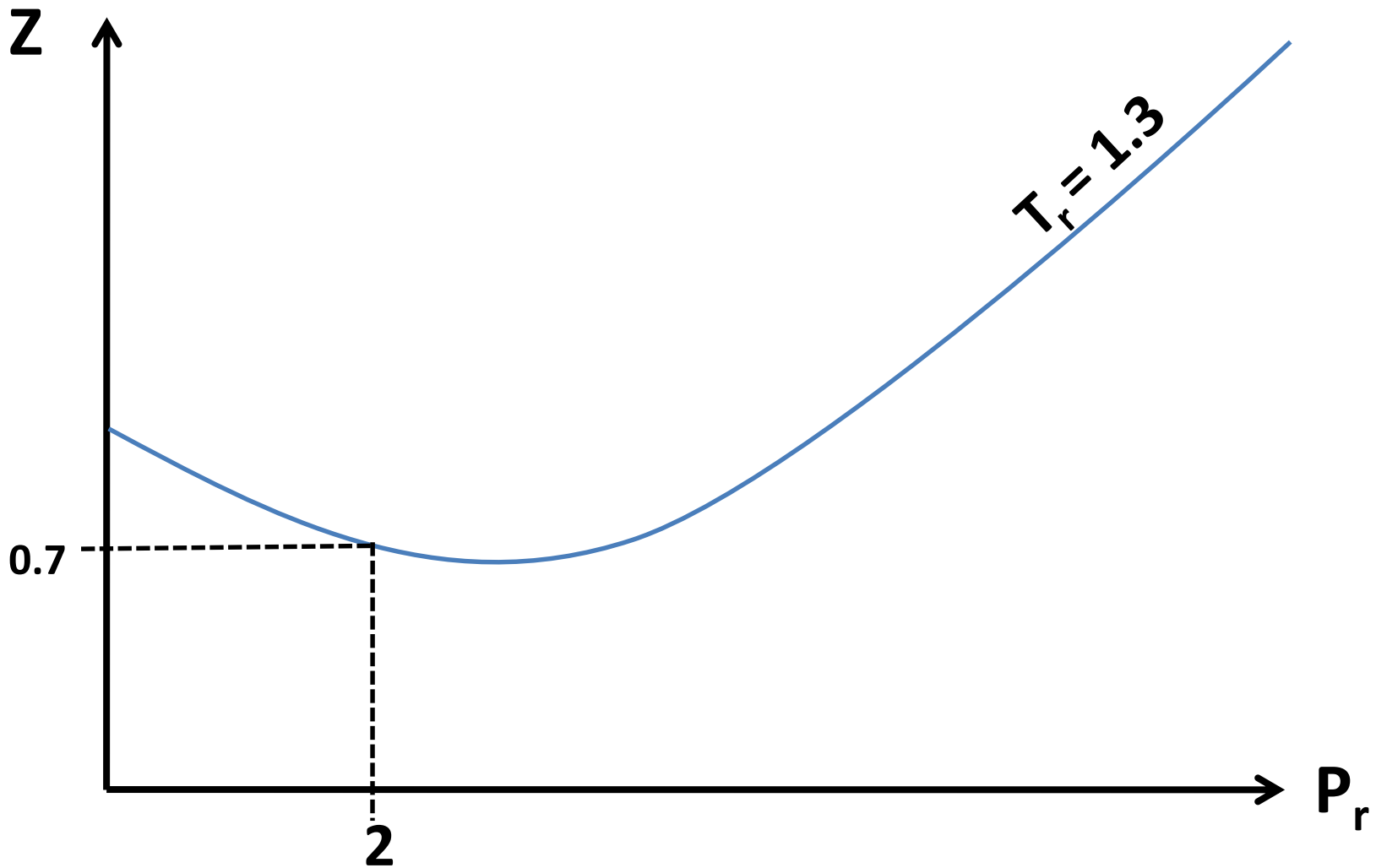
Practice problem 17(p346)

- A gas Neon has a molecular weight of 20.183 kg/kmol and its critical temperature, pressure and volume are 44.5 K, 2.73 MPa and 0.0416 m³/kg mol. [Reading from the compressibility chart given for a reduced pressure of 2 and a reduced temperature of 1.3, the compressibility factor Z is 0.7]. what are the corresponding specific volume, pressure, temperature and reduced volume?

$$P= 5.46 \text{ MPa}, T= 57.85 \text{ K}, v=3.05 \times 10^{-3} \text{ m}^3/\text{kg}, v_r=1.48$$



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INTERNAL ENERGY AND ENTHALPY OF AN IDEAL GAS

- Internal energy U and enthalpy H of an ideal gas is a function of temperature alone

- $U = f(T)$

given by, $U = m c_v T$ and $u = c_v T$

i.e. change in internal energy of an ideal gas,

$$\Delta U = m c_v \Delta T \quad \text{and} \quad \Delta u = c_v \Delta T$$

$$dU = m c_v dT \quad \text{and} \quad du = c_v dT$$

- $H = U + PV = m c_v T + m R T = f(T)$

given by, $H = m c_p T$ and $h = c_p T$

i.e. change in enthalpy of an ideal gas,

$$\Delta H = m c_p \Delta T \quad \text{and} \quad \Delta h = c_p \Delta T$$

$$dH = m c_p dT \quad \text{and} \quad dh = c_p dT$$

$$c_p / c_v = \gamma$$

$$c_p - c_v = R$$

$$c_v = R / (\gamma - 1)$$

$$c_p = \gamma R / (\gamma - 1)$$



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WORK DONE

HEAT TRANSFER

AND

CHANGE IN PROPERTIES

DURING A

REVERSIBLE PROCESS

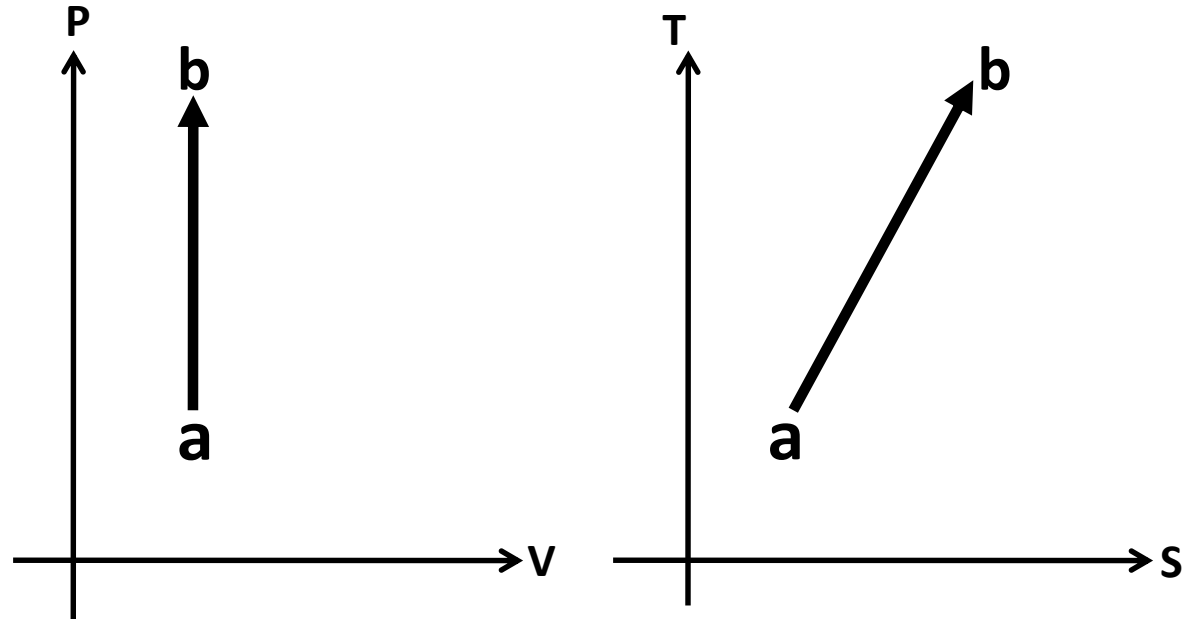
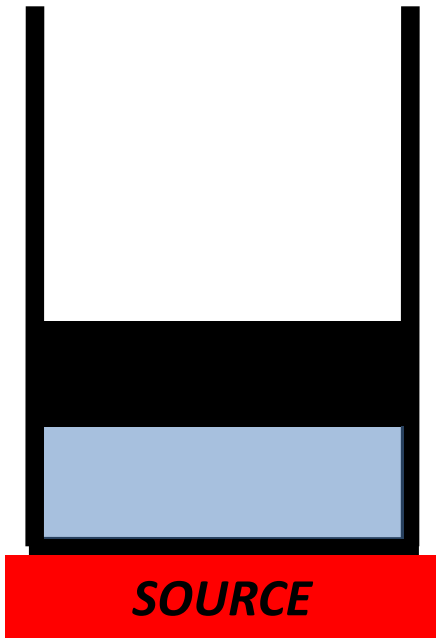
UNDERGONE BY AN

IDEAL GAS



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A CONSTANT VOLUME PROCESS (ISOCHORIC, $V=C$, $dV=0$)



$$P_a V_a / T_a = P_b V_b / T_b$$

$$P_a / P_b = T_a / T_b$$

Applying first law $\delta Q - \delta W = dU$

Here $\delta W = P dV = 0$, so $\delta Q = dU = m c_v dT$

$$Q_{ab} = m c_v (T_b - T_a)$$

$$T dS = m c_v dT$$

$$dS = m c_v dT / T$$

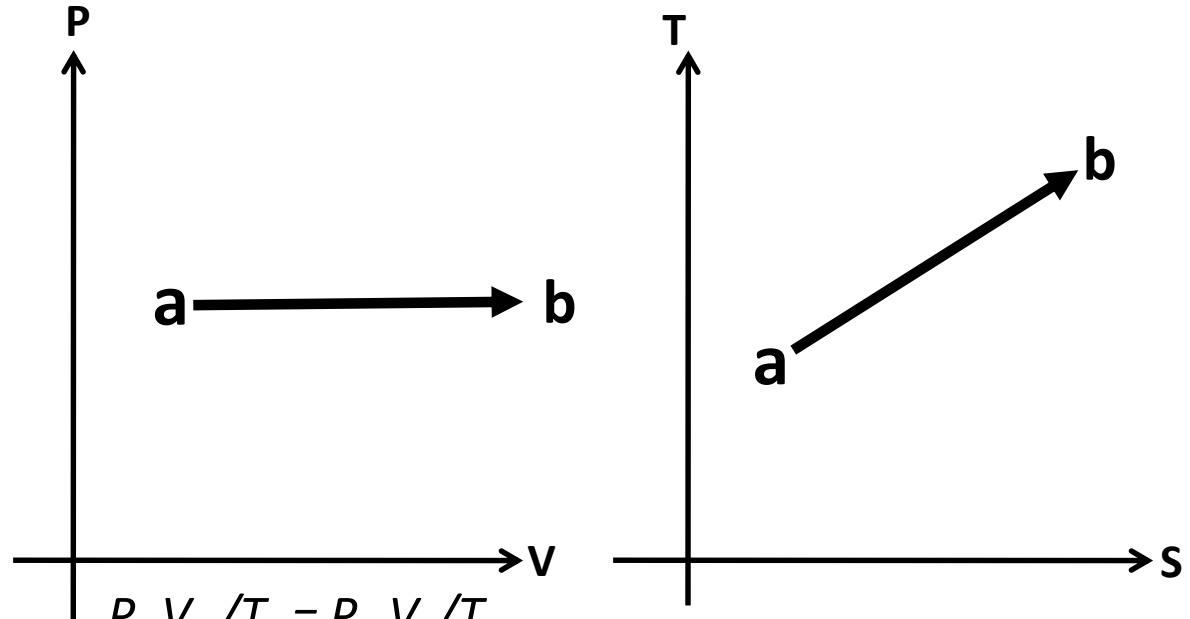
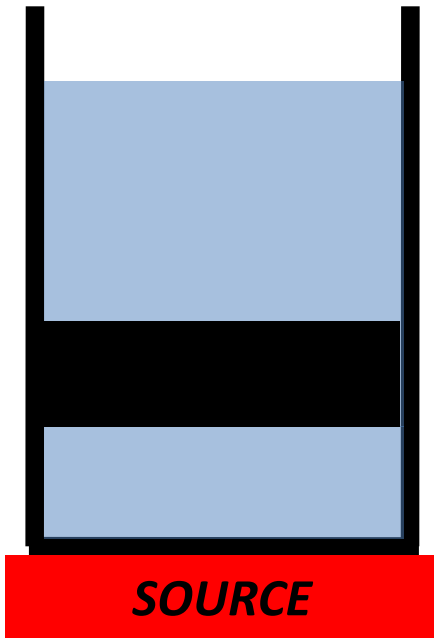
$$\text{i.e. } \Delta S = S_b - S_a = m c_v \ln (T_b / T_a)$$



A CONSTANT PRESSURE PROCESS

(*ISOBARIC*, $P=C$, $dP=0$)

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$$P_a V_a / T_a = P_b V_b / T_b$$

$$V_a / V_b = T_a / T_b$$

Applying first law $\delta Q - \delta W = dU$

$$\delta W = p dV \text{ i.e. } W_{ab} = P(V_b - V_a)$$

$$\delta Q = p dV + dU = dh = m c_p dT \text{ i.e. } Q_{ab} = m c_p (T_b - T_a)$$

$$T ds = m c_p dT$$

$$dS = m c_p dT / T$$

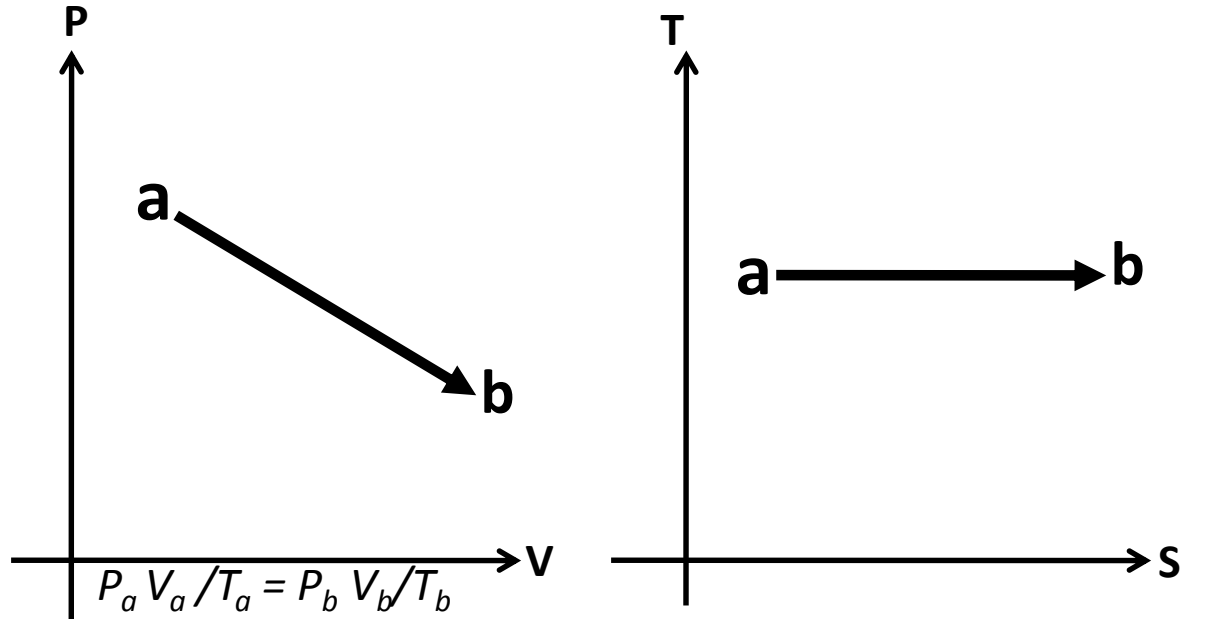
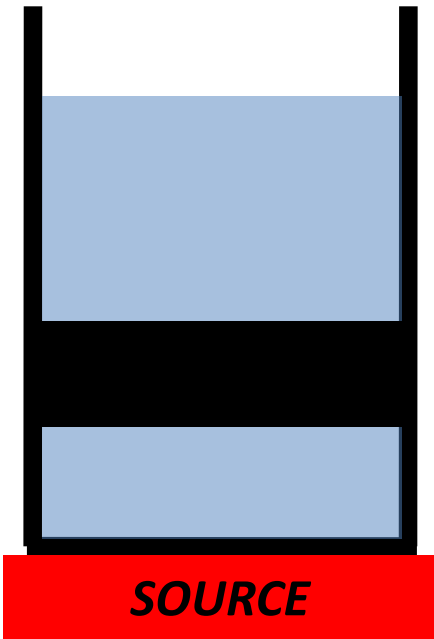
$$\text{i.e. } \Delta S = S_b - S_a = m c_p \ln (T_b / T_a)$$



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A CONSTANT TEMPERATURE PROCESS

(ISOTHERMAL, $T=C$, $dT=0$, $dU=0$)



Applying first law $\delta Q - \delta W = dU=0$

$$\delta W = PdV$$

$$\delta Q = PdV \text{ i.e. } Q_{ab} = C \int_{ab} dV/V = PV \ln(V_b/V_a) =$$

$$Q_{ab} = mRT \ln(V_b/V_a) = W_{ab}$$

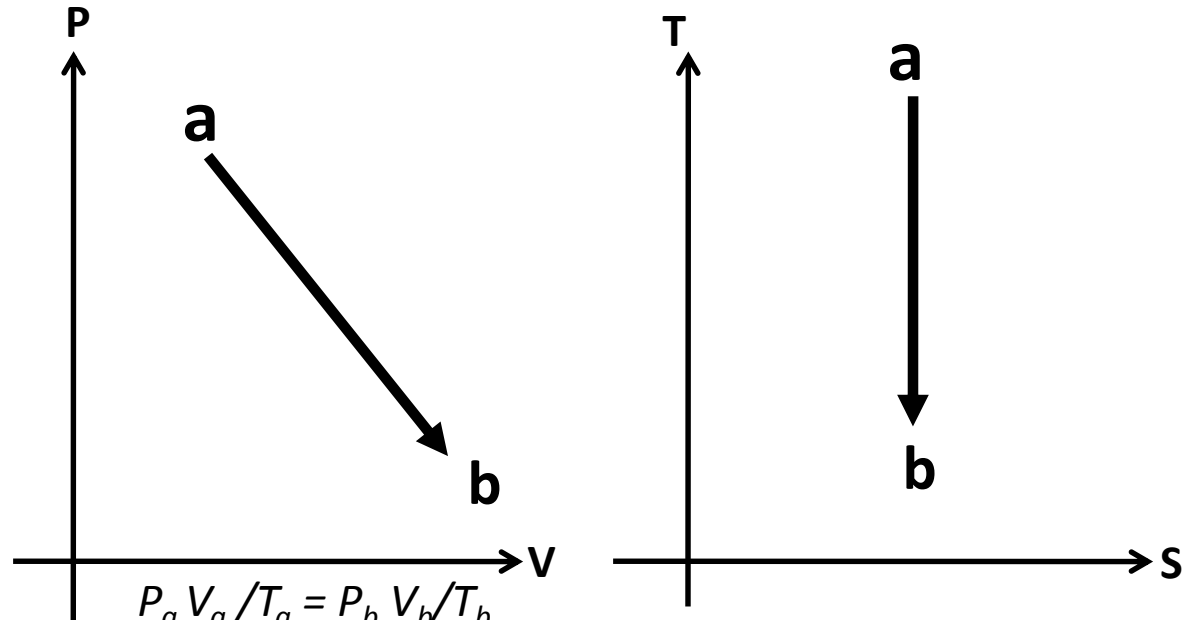
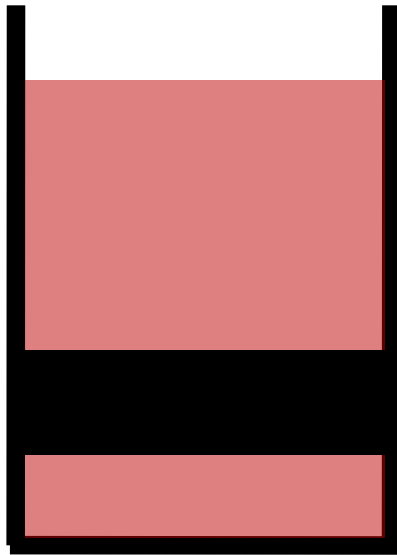
$$TdS = PdV = C dV/V$$

$$dS = C/T dV/V$$

$$\text{i.e. } \Delta S = S_b - S_a = mR \ln(V_b/V_a)$$



A CONSTANT ENTROPY PROCESS (ISENTROPIC, $S=C$, $dS=0$, $\delta Q=0$)



$$P_a V_a / T_a = P_b V_b / T_b$$

$$PV^\gamma = P_a V_a^\gamma = P_b V_b^\gamma = C \quad \text{i.e.} \quad P = V^\gamma / C$$

$$\text{Applying first law } \delta Q - \delta W = dU$$

$$\delta Q = 0$$

$$\delta W = PdV = dU \quad \text{i.e.} \quad W_{ab} = C \int_{ab} dV/V^\gamma = PV^\gamma (V_b^{-\gamma+1} - V_a^{-\gamma+1})$$

$$W_{ab} = mR (T_b - T_a)$$

$$TdS = 0$$

$$dS = 0$$

$$\text{i.e. } \Delta S = S_b - S_a = 0$$



IDEAL GAS P-V-T RELATIONSHIPS FOR

ANY REVERSIBLE PROCESS a – b

- Any reversible process can be represented by relation $PV^n = C$

- $P_a/P_b = (V_b/V_a)^n$

- From ideal gas relation, $P_a V_a/T_a = P_b V_b/T_b$

- $T_a/T_b = (P_a/P_b) (V_a/V_b)$

- i.e. $T_a/T_b = (V_b/V_a)^n (V_a/V_b) = (V_b/V_a)^{n-1}$

$$V_a/V_b = (T_b/T_a)^{1/(n-1)}$$

- Also $T_a/T_b = (P_a/P_b)^{(n-1)/n}$

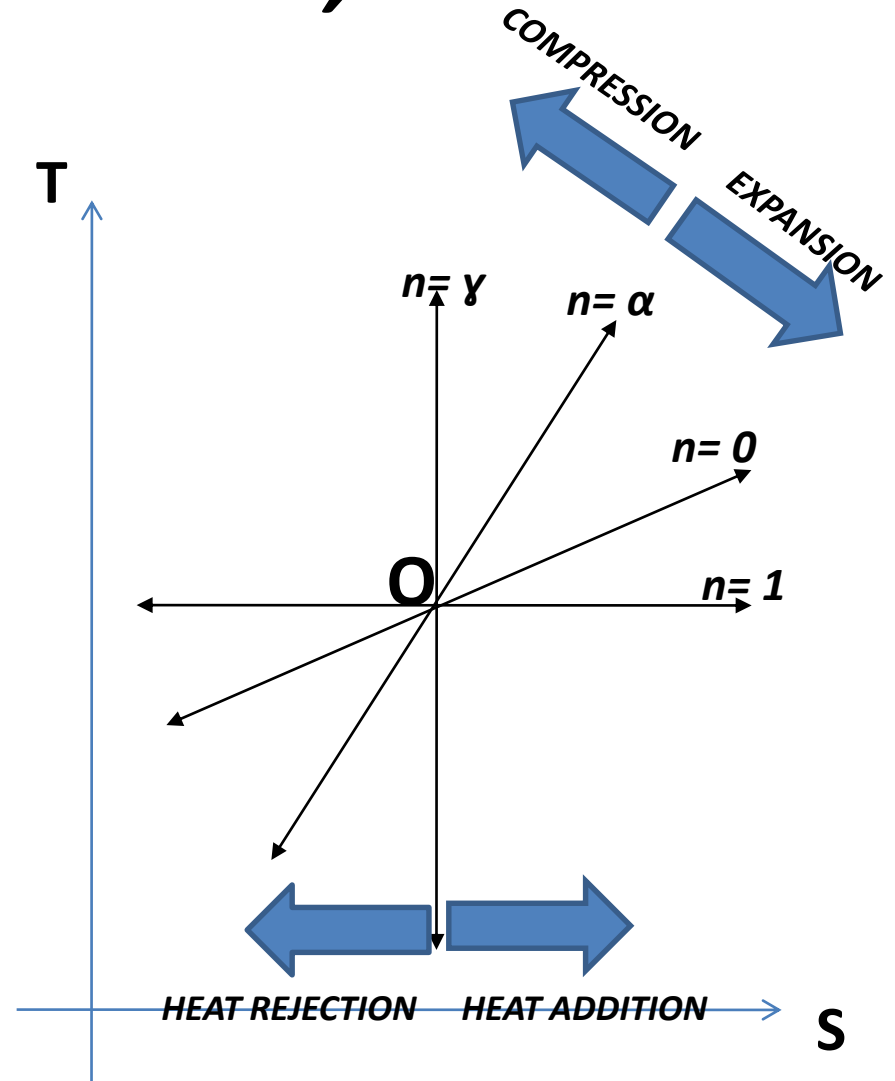
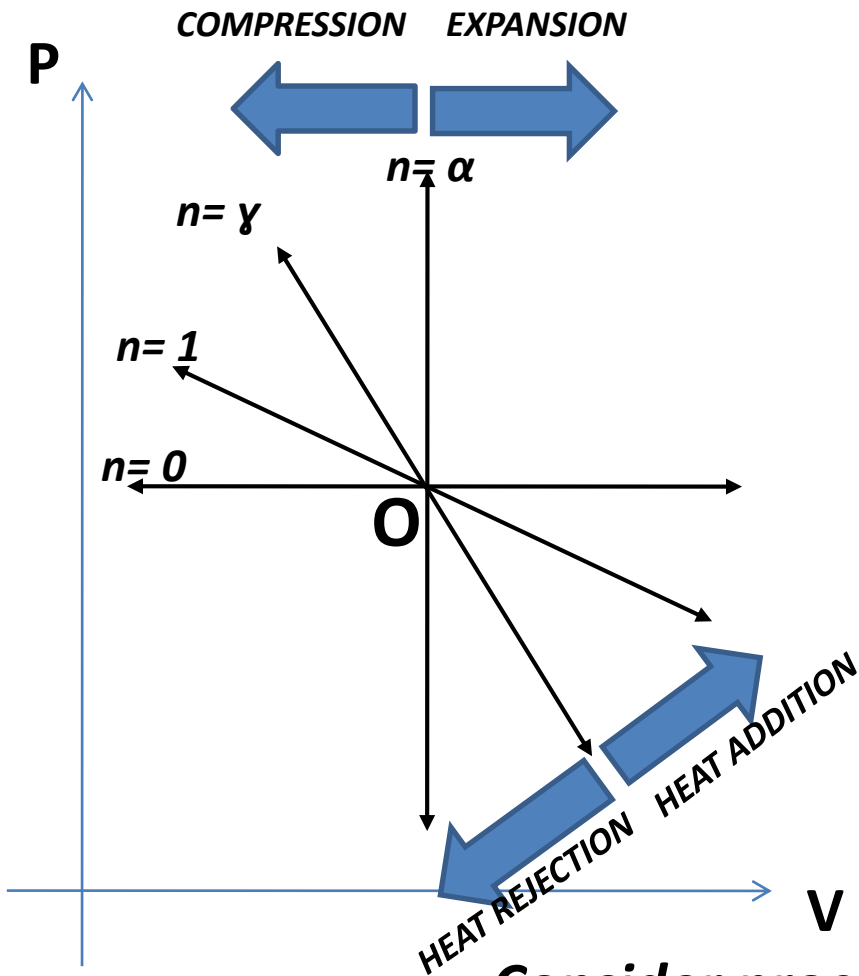
$$(P_a/P_b) = (T_a/T_b)^{n/(n-1)}$$

$n=0$, for isobaric process
 $n=1$, for isothermal process
 $n=\gamma$, for adiabatic(isentropic process)
 $n=\alpha$, for isochoric process



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P-V AND T-S DIAGRAM FOR VARIOUS REVERSIBLE PROCESSES, $PV^n = C$



Consider processes starting from O



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POLYTROPIC PROCESS $PV^n=C$ (generalized Process)

$$\text{Polytropic index, } n = (\log P_a - \log P_b) / (\log V_b - \log V_a)$$

- $PV^n = C$ $P_a V_a^n = P_b V_b^n$
- $P = C/V^n$

- $W_{ab} = \int_{ab} P dV = \int_{ab} C dV/V^n = C \int_{ab} dV/V^n = P V^n (V_b^{-n+1} - V_a^{-n+1}) / (1-n)$

i.e. $W_{ab} = m R (T_b - T_a) / (1-n)$ **n not=1**

- Applying first law $Q_{ab} - W_{ab} = \Delta U_{ab} = m c_v (T_b - T_a)$

- $Q_{ab} = W_{ab} + \Delta U_{ab} = m R (T_b - T_a) / (1-n) + m c_v (T_b - T_a)$

- For an ideal gas $c_v = R / (\gamma - 1)$

- i.e. $Q_{ab} = m R (T_b - T_a) / (1-n) + m R (T_b - T_a) / (\gamma - 1)$

- $= m R (T_b - T_a) [1 / (1-n) + 1 / (\gamma - 1)]$

i.e. $Q_{ab} = m R (\gamma - n) (T_b - T_a) / (1-n) (\gamma - 1)$ **n not=1**

$$\delta Q - \delta W = dU$$

- $\delta Q = \delta W + dU = PdV + m c_v dT$

- i.e. $TdS = PdV + m c_v dT$ i.e. $dS = PdV/T + m c_v dT/T = m R dV/V + m c_v dT/T$

- $\Delta S = S_b - S_a = m R \ln(V_b/V_a) + m c_v \ln(T_b/T_a)$

- $c_v = R / \gamma - 1$ also $V_b/V_a = (T_b/T_a)^{1/(1-n)}$

- So $\Delta S = S_b - S_a = m R \ln(T_b/T_a) / (1-n) + m R \ln(T_b/T_a) / (\gamma - 1) =$

- $m R \ln(T_b/T_a) [1 / (1-n) + 1 / (\gamma - 1)]$

i.e. $S_b - S_a = m R (\gamma - n) \ln(T_b/T_a) / (1-n) (\gamma - 1)$ **n not=1**

Practice problem 18(p337)

- *A certain gas has $c_p = 1.968$ and $c_v = 1.507$ kJ/kg K. find its molecular weight and characteristic gas constant.*
- *A constant volume chamber of 0.3 m^3 capacity contains 2 kg of this gas at 5°C . Heat is transferred to the gas until temperature is 100°C . Find the work done, the heat transferred, and the change in internal energy enthalpy and entropy.*

**$R = 0.461$ kJ/kg K, $M = 18.04$ kg/kg mol, $W = 0$, $Q = 286.33$ kJ, $\Delta U = 286.33$ kJ
 $\Delta H = 373$ kJ, $\Delta S = 0.921$ kJ/K**

Practice problem 19(p338)

- Show that for an ideal gas, the slope of the constant volume line on the T-S diagram is more than that of the constant pressure line.

Hint: $Tds = du + PdV = c_v dT + PdV$

i.e. $(dT/dS)_v = T/c_v$

$(dT/dS)_p = T/c_p$

since $c_v < c_p$

$(dT/dS)_v > (dT/dS)_p$

Practice problem 20(P339)

- 0.5 kg of air is compressed reversibly and adiabatically from 80kPa, 60°C to 0.4 Mpa, and is then expanded at constant pressure to the original volume. Sketch these processes on the P-V and T-S diagram. Compute the heat transfer and work transfer for the whole path.

$$W_{total} = 93.6 \text{ kJ}, \quad Q_{total} = 527.85 \text{ kJ}$$

Practice problem 21(p342)

- A mass of 0.25 kg of an ideal gas has a pressure of 300kPa, a temperature of of 80°C, and a volume of 0.07 m³. the gas undergoes an irreversible adiabatic process to a final pressure of 300 kPa and a final volume of 0.10 m³, during which the work done on the gas is 25 kJ. Evaluate the c_p and c_v of the gas and increase in entropy of the gas.*

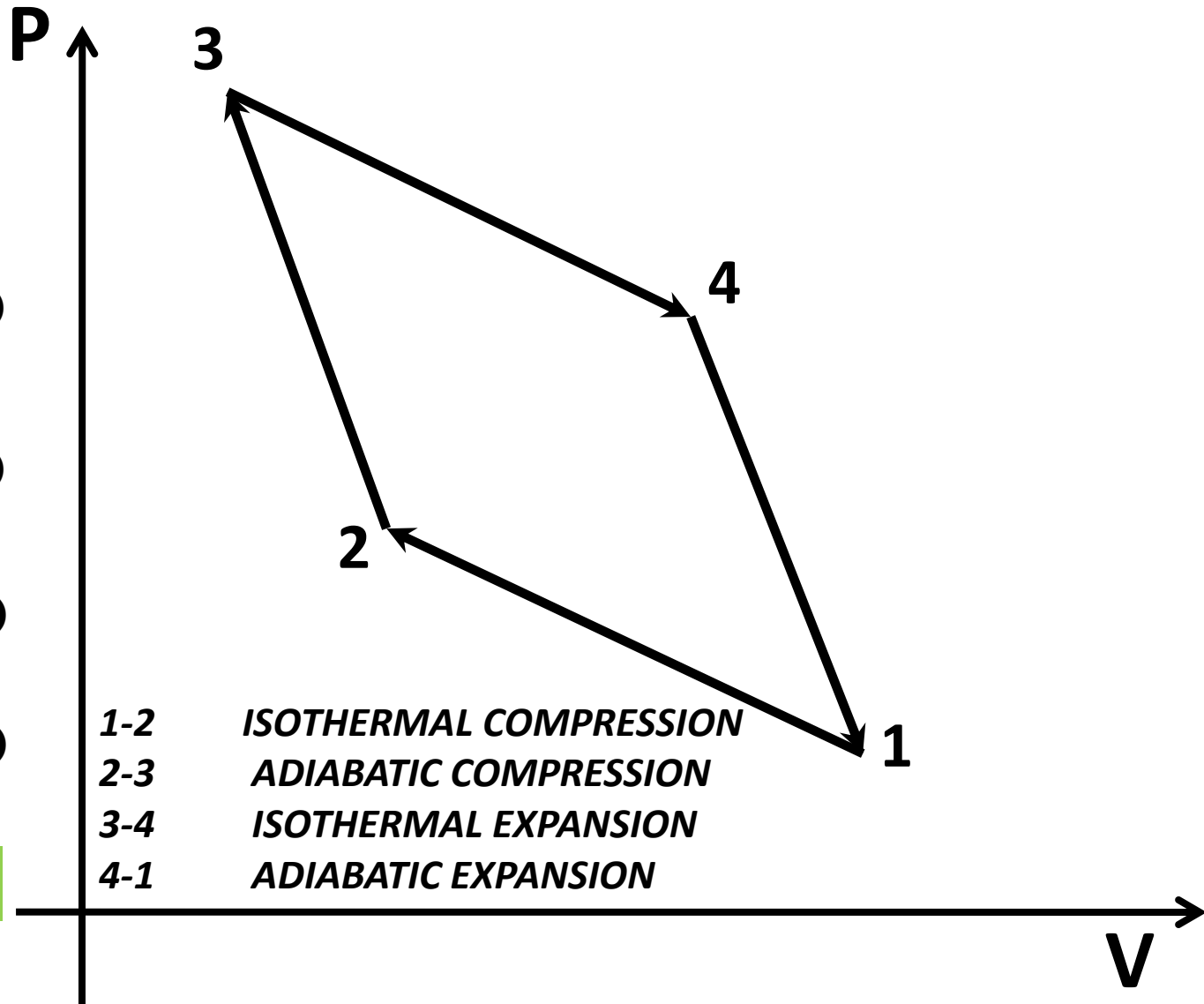
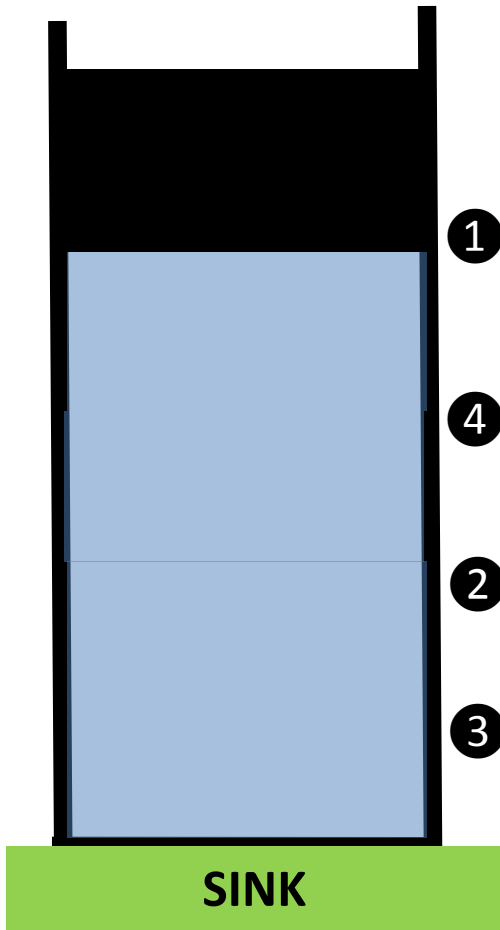
$$c_v = 0.658 \text{ kJ/kg K} \quad c_p = 0.896 \text{ kJ/kgK}$$

$$\Delta S = 0.08 \text{ kJ/kgK}$$



ANALYSIS OF CARNOT CYCLE AND EFFICIENCY

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EFFICIENCY OF A CARNOT CYCLE

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$$\begin{aligned}\bullet \eta &= W_{net}/Q_i = (Q_i + Q_o)/Q_i = 1 + Q_o/Q_i \\ &= 1 + [m R T_1 \ln(V_2/V_1)] / [m R T_3 \ln(V_4/V_3)] \\ &= 1 - [T_1 \ln(V_1/V_2)] / [T_3 \ln(V_4/V_3)]\end{aligned}$$

- In process 1-2 $T_1 = T_2$
- In process 2-3 $T_2/T_3 = (V_3/V_2)^{(\gamma-1)}$
- In process 3-4 $T_3 = T_4$
- In process 4-1 $T_1/T_4 = (V_4/V_1)^{(\gamma-1)}$
- i.e. $V_3/V_2 = V_4/V_1$ i.e. $V_1/V_2 = V_4/V_3$
- i.e. $\eta = 1 - T_1/T_3 = 1 - T_2/T_4$



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Practice Problem 22(p132)

• Which is the more effective way to increase the efficiency of a Carnot engine: to increase T_1 keeping T_2 constant ; or to decrease T_2 , keeping T_1 constant ?

• **HINT** : efficiency is given by $\eta = 1 - T_2/T_1$

Differentiating η keeping T_1 constant,

$$[d\eta/dT_2]_{T_1} = -1/T_1$$

i.e. as T_2 is decreased efficiency increases (-ve sign)

Differentiating η keeping T_2 constant,

$$[d\eta/dT_1]_{T_2} = T_2/T_1^2$$

i.e. as T_1 is increased efficiency increases

Since $T_1 > T_2$, $1/T_1 > T_2/T_1^2$

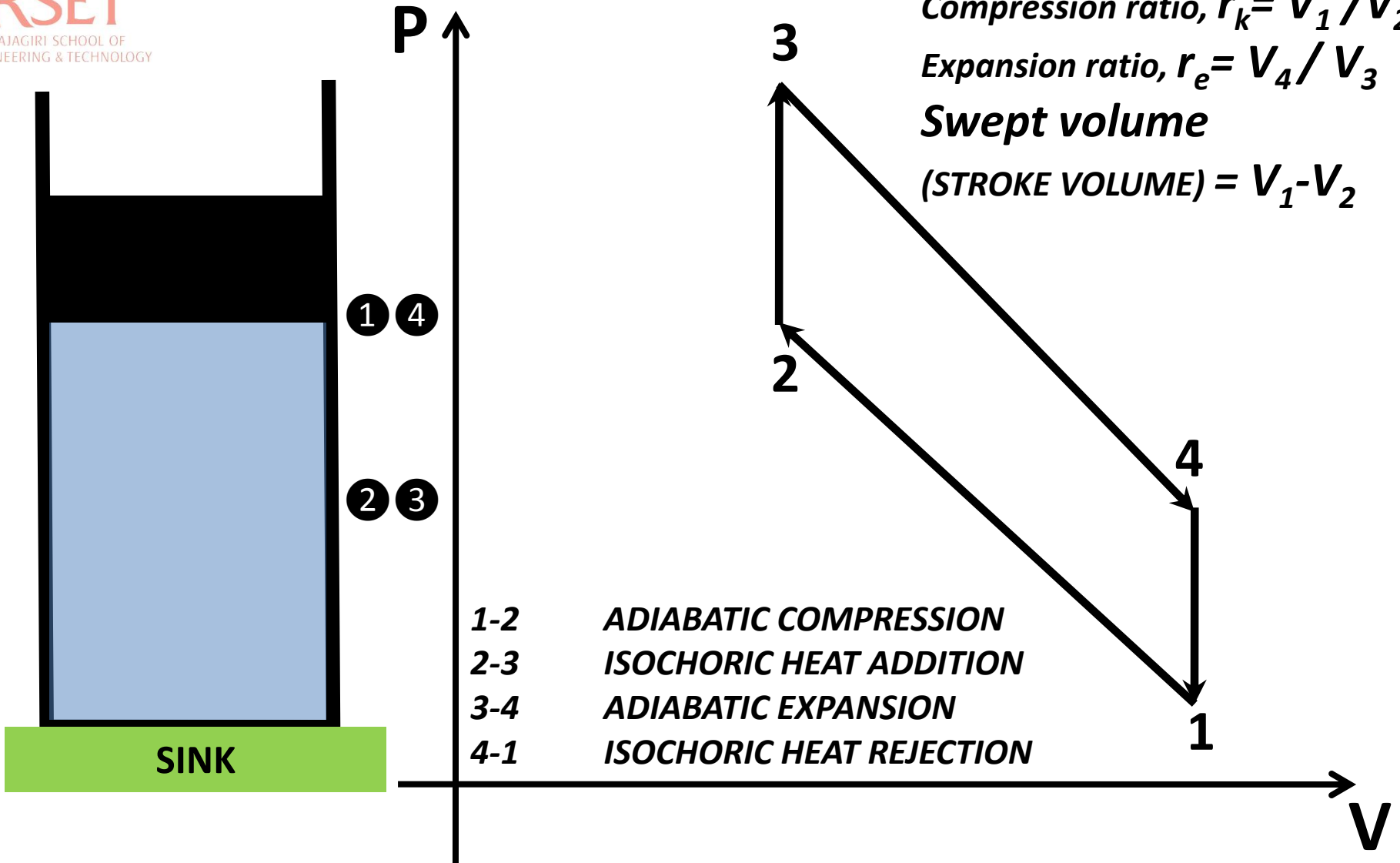
i.e. $[d\eta/dT_2]_{T_1} > [d\eta/dT_1]_{T_2}$

so more effective way for increasing efficiency of Carnot cycle is decrease T_2 , keeping T_1 constant.



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ANALYSIS OF OTTO CYCLE AND EFFICIENCY





EFFICIENCY OF AN OTTO CYCLE

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- $\eta = W_{net}/Q_i = (Q_i + Q_o)/Q_i = 1 + Q_o/Q_i$
 $= 1 + [m c_v (T_1 - T_4)/m c_v (T_3 - T_2)]$
 $= 1 + (T_1 - T_4)/(T_3 - T_2) = 1 - (T_4 - T_1)/(T_3 - T_2)$

- *Let us try to rewrite this equation in terms of compression OR expansion ratio*

$$\eta = 1 - (T_4/T_3) (1 - T_1/T_4)/(1 - T_2/T_3)$$

- *In process 1-2* $T_1/T_2 = (V_2/V_1)^{(\gamma-1)}$
- *In process 3-4* $T_3/T_4 = (V_4/V_3)^{(\gamma-1)} = (V_1/V_2)^{(\gamma-1)}$
- *i.e.* $T_1/T_2 = T_4/T_3$ *i.e.* $T_1/T_4 = T_2/T_3$
- $\eta = 1 - T_4/T_3 = 1 - (V_3/V_4)^{(1-\gamma)}$

- $\eta = 1 - 1/r_k^{(\gamma-1)}$

Mean effective pressure ,
 $P_m = W_{net} / \text{swept volume}$



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Practice problem 23(p523)

- An engine working on the Otto cycle is supplied with air at 0.1 MPa, 35°C. The compression ratio is 8. Heat supplied is 2100 kJ/kg. calculate the maximum pressure and temperature of the cycle, the cycle efficiency, and the mean effective pressure (for air $c_p = 1.005$ kJ/kg K, $c_v = 0.718$ kJ/kg K) ? Also draw T-S diagram for the cycle.*

$$P_{max} = 9.426 \text{ Mpa}$$

$$T_{max} = 3633 \text{ K}$$

$$\eta = 56.5 \%$$

$$P_m = 1.533 \text{ MPa}$$



ANALYSIS OF DIESEL CYCLE AND

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EFFICIENCY

Compression ratio $r_k = V_1/V_2$

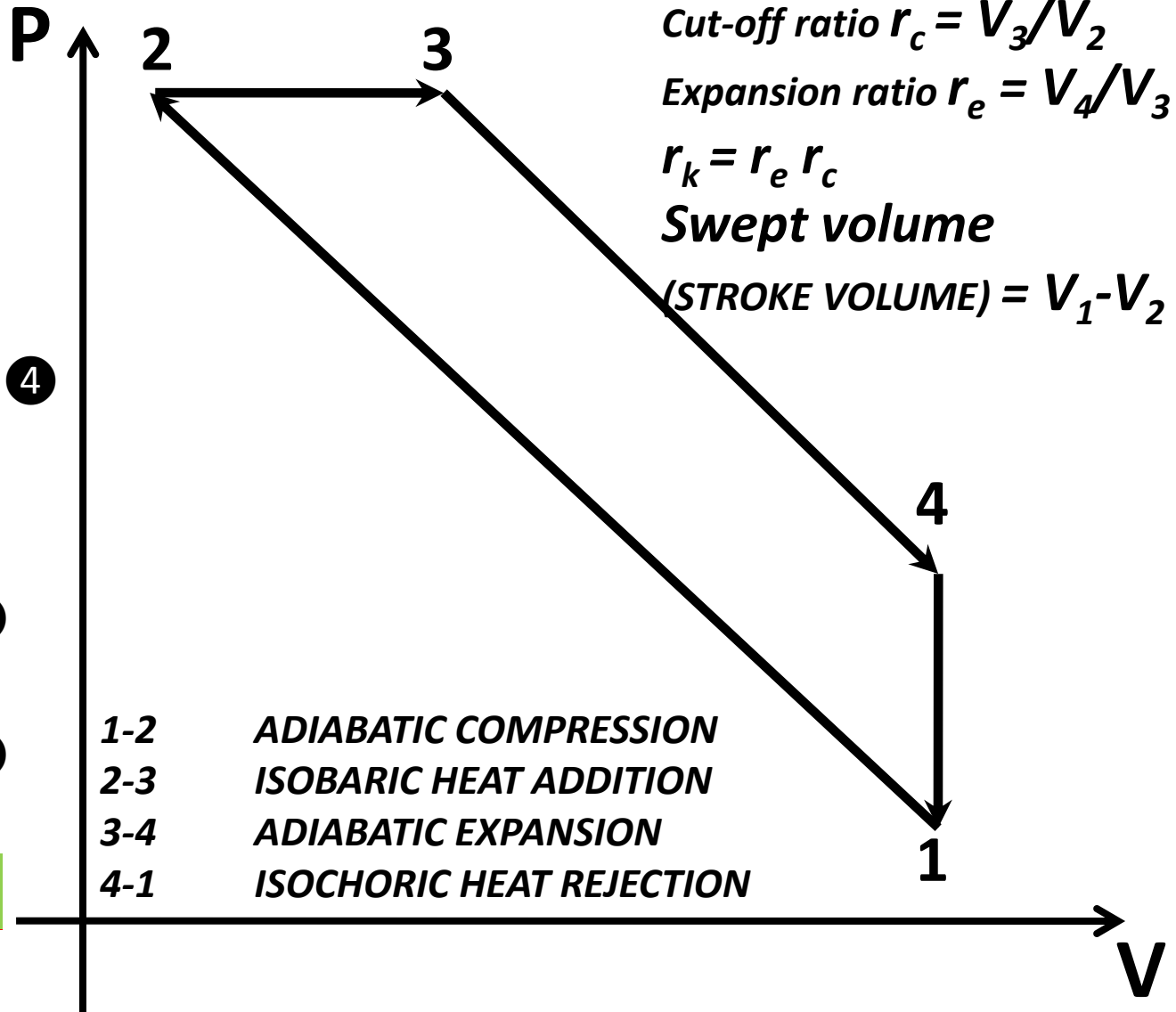
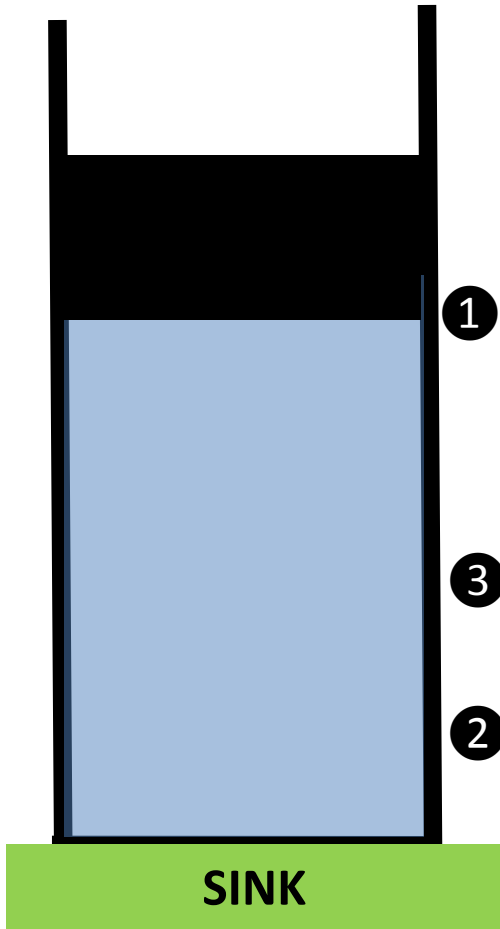
Cut-off ratio $r_c = V_3/V_2$

Expansion ratio $r_e = V_4/V_3$

$r_k = r_e r_c$

Swept volume

(STROKE VOLUME) = $V_1 - V_2$





EFFICIENCY OF A DIESEL CYCLE

- $\eta = W_{net}/Q_i = (Q_i + Q_o)/Q_i = 1 + Q_o/Q_i$
 $= 1 + [m c_v (T_1 - T_4) / m c_p (T_3 - T_2)] \quad c_p/c_v = \gamma$
 $= 1 + (1/\gamma) (T_1 - T_4)/(T_3 - T_2) = 1 - (1/\gamma) (T_4 - T_1)/(T_3 - T_2)$
- Let us try to rewrite this equation in terms of compression, expansion and cutoff ratios.
- In process 3-4 $T_4/T_3 = (V_3/V_4)^{(\gamma-1)} = 1/r_e^{(\gamma-1)}$
i.e. $T_4 = T_3/r_e^{(\gamma-1)} = T_3 r_c^{(\gamma-1)} / r_k^{(\gamma-1)}$
- In process 2-3 $T_2/T_3 = (V_2/V_3) = 1/r_c$
i.e. $T_2 = T_3/r_c$
- in process 1-2 $T_1/T_2 = (V_2/V_1)^{(\gamma-1)} = 1/r_k^{(\gamma-1)}$
i.e. $T_1 = T_2/r_k^{(\gamma-1)}$
i.e. $T_1 = T_3 / (r_c r_k^{(\gamma-1)})$ -----sub for T_2
- Now we got T_1 , T_2 and T_4 in terms of T_3 . substituting these values in η
- $\eta = 1 - (1/\gamma) [T_3 r_c^{(\gamma-1)} / r_k^{(\gamma-1)} - T_3 / (r_c r_k^{(\gamma-1)})] / [T_3 - T_3 / r_c]$
- Cancelling all T_3 , $\eta = 1 - (1/\gamma) [r_c^{(\gamma-1)} / r_k^{(\gamma-1)} - 1 / (r_c r_k^{(\gamma-1)})] / [1 - 1/r_c]$
- $\eta = 1 - [1/(\gamma r_k^{(\gamma-1)})] [r_c^\gamma - 1] / [r_c - 1]$

Practice problem 24(p524)

- A Diesel engine has a compression ratio of 14 and cut off takes place at 6% of the *stroke* (*max volume – min volume*) . Find the air standard efficiency. Also draw T-S diagram for the cycle.
- *If an Otto cycle engine(pertol engine) is used with same compression ratio, prove that efficiency of Otto cycle is more. (take $\gamma = 1.4$)*

Diesel = 60.5 %

Otto = 65.2 %

Practice problem 25(p525)

- In an air standard diesel cycle the compression ratio is 16 and at the beginning of isentropic compression the temperature is 15 °C and pressure is 0.1 MPa. Heat is added until the temperature at the end of the constant pressure process is 1480 °C .

- Calculate cutoff ratio

16

- Calculate heat supplied per kg of air

884.4 kJ/kg

- Calculate the cycle efficiency and MEP

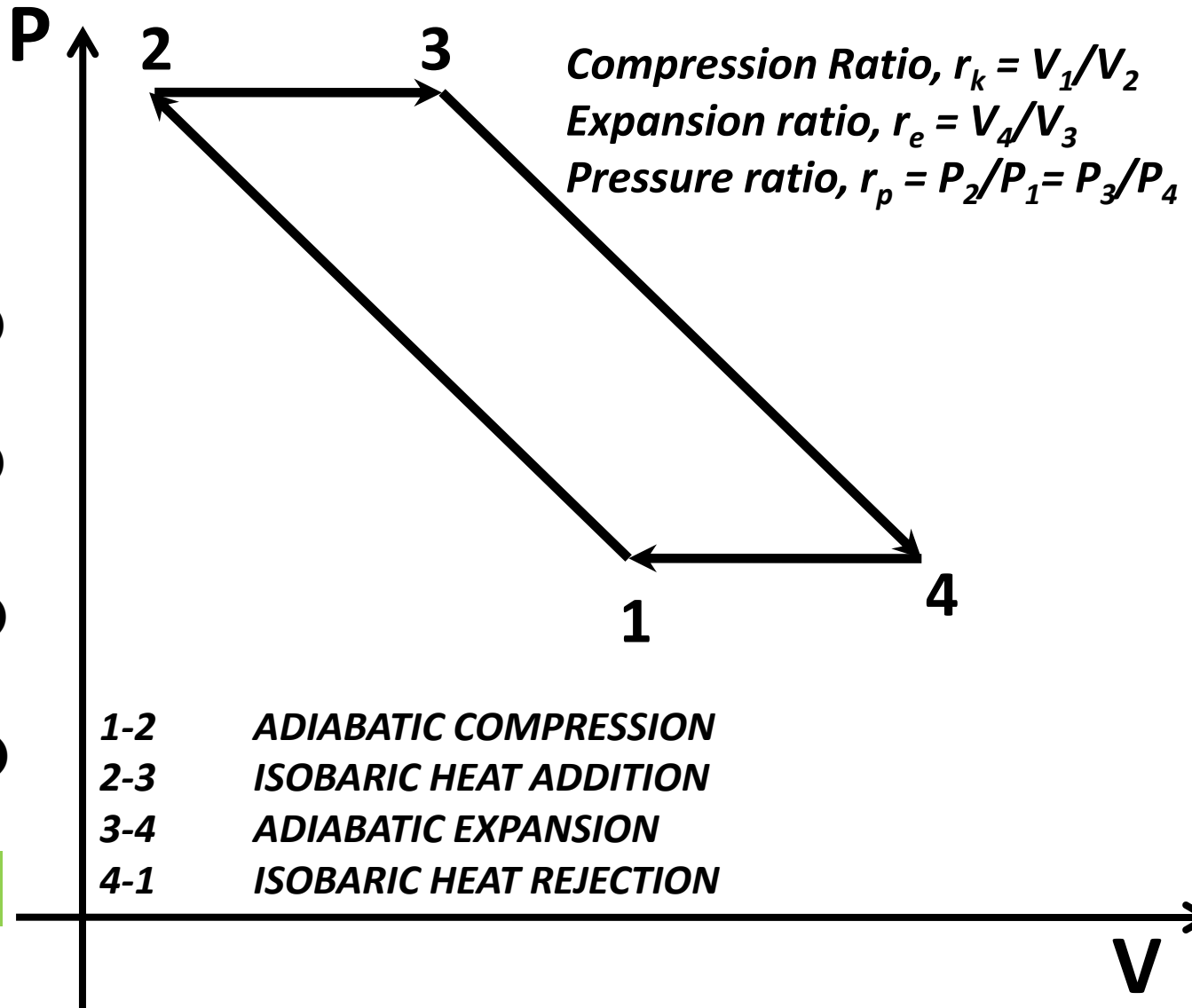
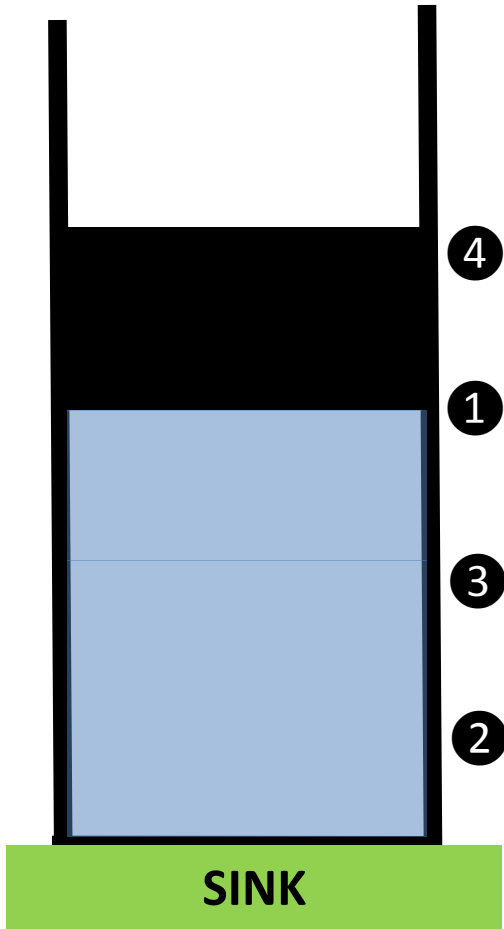
61.2 %

698.45 kPa



ANALYSIS OF BRAYTON CYCLE AND EFFICIENCY

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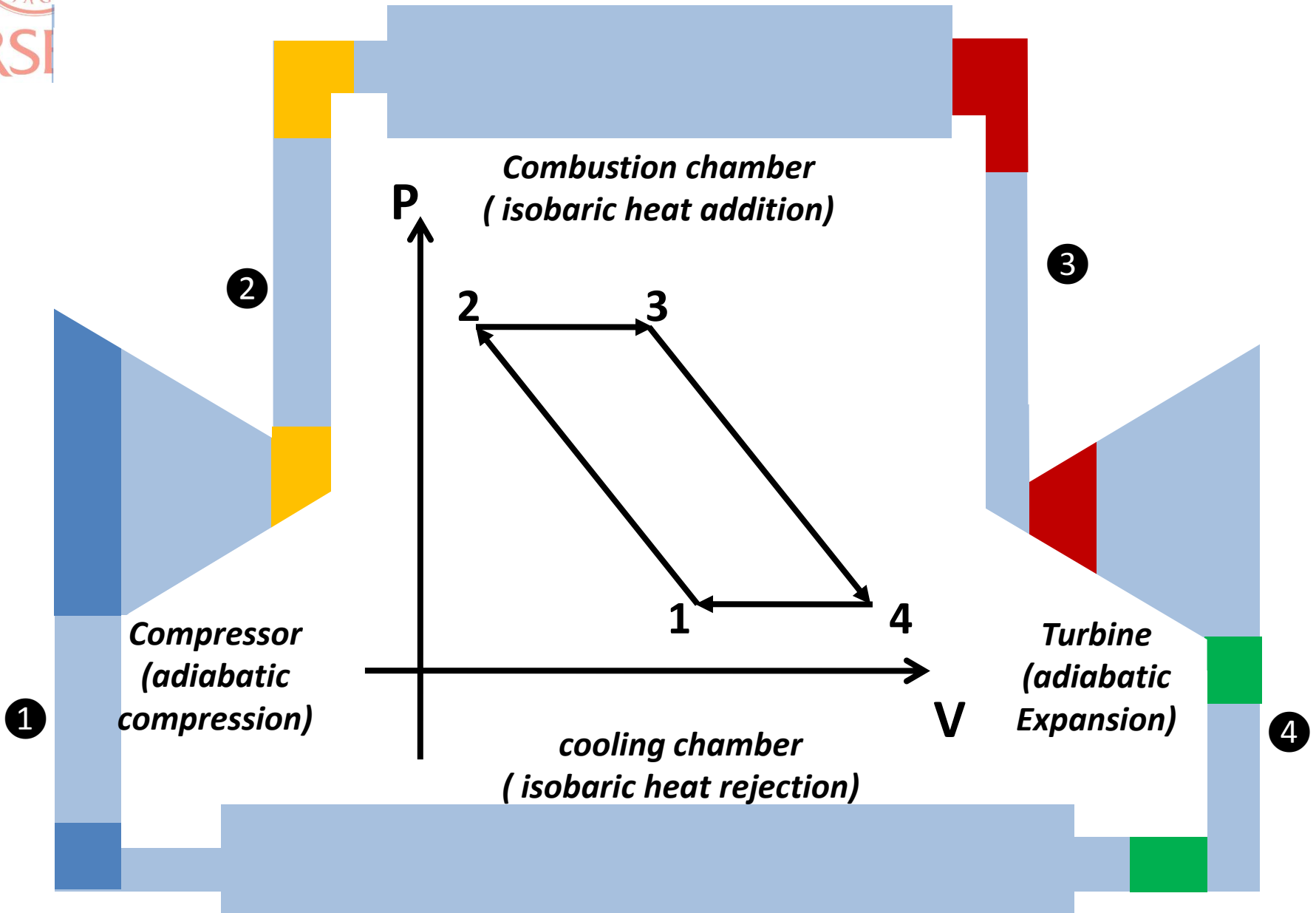
EFFICIENCY OF A BRAYTON CYCLE

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- $\eta = W_{net}/Q_i = (Q_i + Q_o)/Q_i = 1 + Q_o/Q_i$
 $= 1 + [m c_p (T_1 - T_4) / m c_p (T_3 - T_2)]$
 $= 1 + (T_1 - T_4) / (T_3 - T_2) = 1 - (T_4 - T_1) / (T_3 - T_2)$
- *Let us try to rewrite this equation in terms of compression, expansion and pressure ratios*
- *In process 1-2* $T_2/T_1 = (P_2/P_1)^{(\gamma-1)/\gamma}$
- *In process 3-4* $T_3/T_4 = (P_3/P_4)^{(\gamma-1)/\gamma} = (P_2/P_1)^{(\gamma-1)/\gamma}$
- *i.e.* $T_1/T_2 = T_4/T_3$ *i.e.* $T_1/T_4 = T_2/T_3$
- $\eta = 1 - T_4/T_3 = 1 - (P_4/P_3)^{(\gamma-1)/\gamma} = 1 - 1/r_p^{(\gamma-1)/\gamma} = 1 - (V_3/V_4)^{(1-\gamma)}$
- $\eta = 1 - 1/r_k^{(\gamma-1)}$
- $\eta = 1 - 1/r_p^{(\gamma-1)/\gamma}$

BRAYTON CYCLE POWER PLANT



Practice problem 26(p530)

- *In an ideal Brayton cycle air from the atmosphere at 1 atm, 300K is compressed to 6 atm and maximum cycle temperature is limited to 1100 K by using a large air fuel ratio. If the heat supplied is 100 MW find,*
- *Thermal efficiency of the cycle* **40.1%**
- *Work ratio= $(W_{turb} - W_{comp})/W_{turb}$* **0.545**
- *Power output* **40.1 MW**
- *Also draw the T-S diagram for the cycle*