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MIT WORLD PEACE UNIVERSITY | PUNE
TECHNOLOGY, RESEARCH, SOCIAL INNOVATION & PARTNERSHIPS

# MEE 105B– Basic Mechanical Engineering

# Unit 4: Thermal Engineering

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# Syllabus Unit 4: Thermal Engineering

- Introduction to Thermodynamics
- Basic Concepts and Terminology
- Heat and Work
- Thermodynamics Laws with examples – Zero$^{th}$ law and First law
- Limitation of First Law,
- Concept of Heat Engine, Heat Pump, Refrigerator,
- 2$^{nd}$ law of thermodynamics statement (Kelvin Plank, Clausius),
- Numericals on 2$^{nd}$ law only
- Introduction to Heat Transfer
- Modes of Heat Transfer

# Thermodynamics

- Thermodynamics is a science of energy transfer and its effect on various physical properties of matter
- Thermodynamics is mostly concerned with heat and its conversion into work
- Thermodynamics Deals with
  - Transfer of Energy
  - Transformation of Energy
  - Effect of Transfer and transformation of energy on surrounding
- It defines macroscopic variables, such as internal energy, entropy, and pressure that partly describe a body of matter

*"Thermodynamics is a funny subject. First time you go through it you don't understand it at all. The second time you go through it, you think understand it except for one or two points. Third time you go through it, you know you don't understand it but by that time you are so used to the subject that it doesn't bother you anymore !! "*

-Arnold Sommerfeld (One of the founder of Quantum Mechanics)

# Thermodynamics: Introduction

- Thermodynamics is based on four laws. These laws are empirical in nature and till today no evidence of violation has observed
  - **Zeroth law**: Defines Temperature(T)
  - **First law**: Defines Internal Energy (U)
  - **Second law**: Defines Entropy (S)
  - **Third law**: Provides absolute value of entropy
- Applications of Thermodynamics:
  - All power producing devices such as turbines, steam engines, Internal combustion engines, Jet engines
  - Power consuming devices such as compressors, pumps, home appliances etc.

# Application areas of Thermodynamics

The human body

Air conditioning systems

Airplanes

Car radiators

Power plants

Refrigeration systems

# Thermodynamic Approach

## Macroscopic and Microscopic Approaches

Behaviour of matter can be studied by these two approaches.

**In macroscopic** approach, certain quantity of matter is considered, without a concern on the events occurring at the molecular level. These effects can be perceived by human senses or measured by instruments.

eg: pressure, temperature

**In microscopic** approach, the effect of molecular motion is Considered.

eg: At microscopic level the pressure of a gas is not constant, the temperature of a gas is a function of the velocity of molecules. Most microscopic properties cannot be measured with common instruments nor can be perceived by human senses

# Thermodynamic Approach

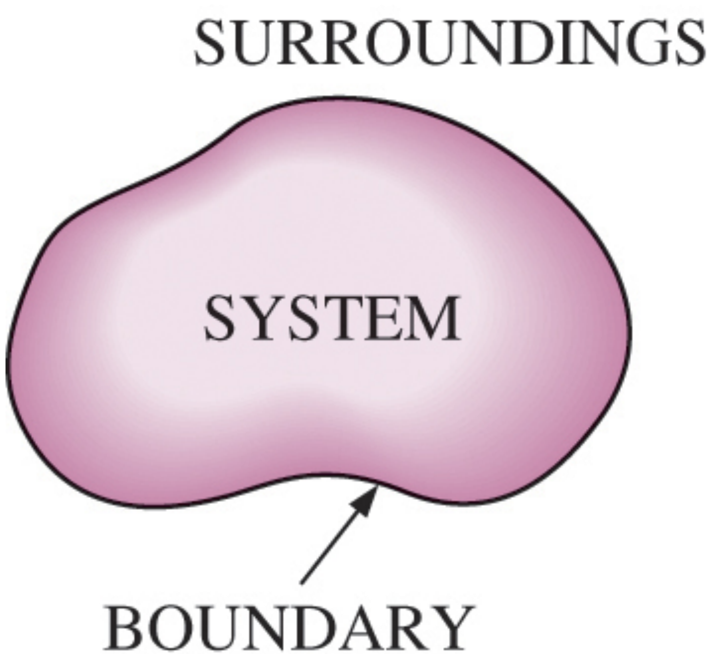
| Macroscopic approach | Microscopic approach |
|---|---|
| In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level . In other words this approach to thermodynamics is concerned with gross or overall behavior . This is known as classical thermodynamics | This approach considers that the systems is made up of a very large numbers of the discrete particle known as molecules. These molecules have different velocities and energies. The values of these energies are constantly changing with time. |
| The analysis of macroscopic systems requires simple mathematical formulae. | The behavior of the system is found by using statistical method as the number of molecules is very large. So advanced statistical and mathematical methods are needed to explain the changes in the system. |
| The values of the properties of system are their average values. For example consider a sample of a gas in a closed container. The pressure of the gas is the average value of the pressure exerted by millions of individual molecules . | The properties like velocity, momentum, impulse, kinetic energy, force of impact, etc which describe the molecule cannot be easily measured by instruments . Our senses cannot feel them . |
| In order to describe such a system only a few properties are needed . | Large number of variables are needed to describe such a system . So the approach is complicated . |

# Thermodynamics: Basic Concepts

- System
- Closed System
- Open System
- Isolated System
- Property
- Intensive Property
- Extensive Property
- State
- Process
- Reversible Process
- Irreversible Process
- Carnot Cycle

# Basic Concepts: System

- System: A quantity of matter or a region in space chosen for study.
- Surroundings: The mass or region outside the system
- Boundary: The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable*.



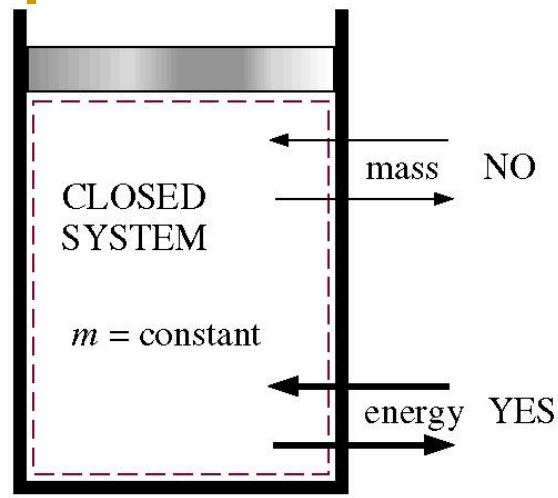
# Basic Concepts: System

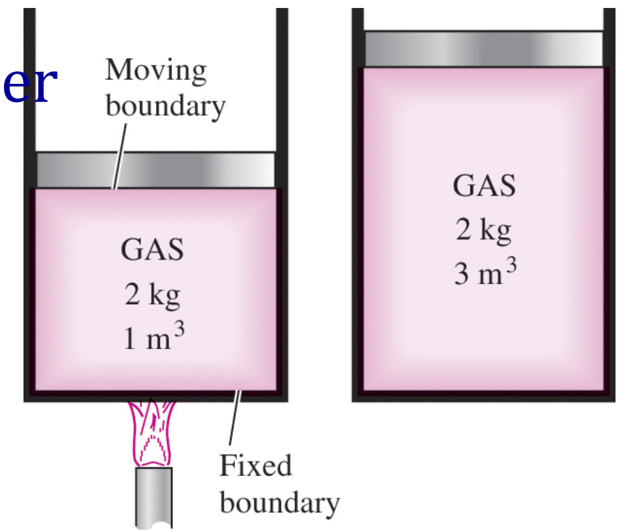
- **Systems may be considered to be *closed, open and Isolated***

## 1) Closed System(control mass)

- Consists of a fixed amount of mass
- Mass can NOT cross the boundary
- Energy CAN cross the boundary
- Volume does not have to be fixed

  e.g. Gas being heated in a closed cylinder



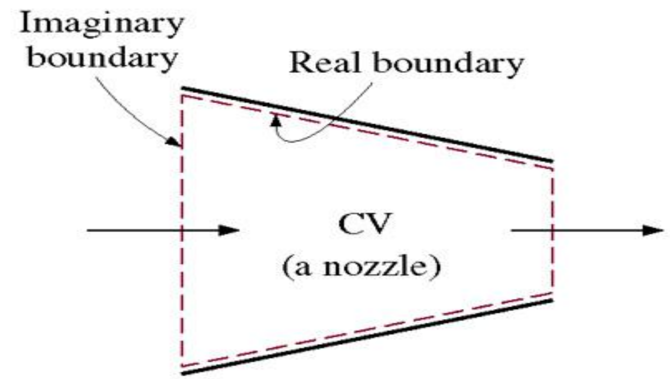
# Basic Concepts: System

## 2) Open System(control volume):

- Mass CAN cross the boundary
- Energy CAN cross the boundary
- Control volume can have fixed

  as well as moving boundary

  e.g. Nozzle, Pressure Cooker

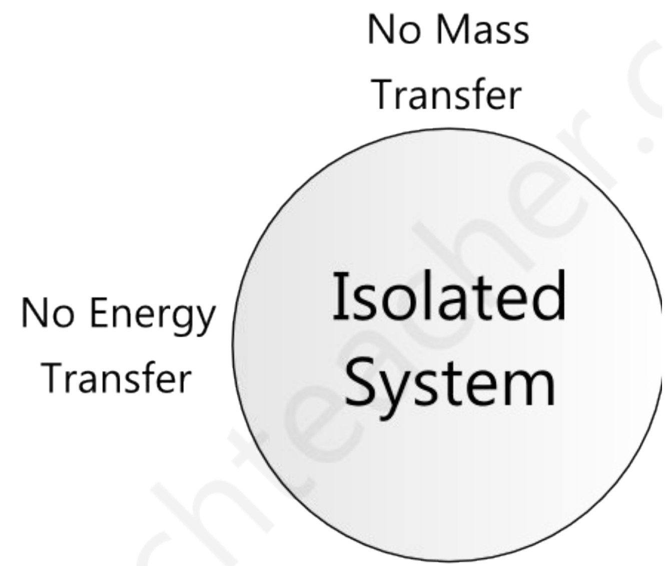



(*a*) A control volume with real and imaginary boundaries

## 3) Isolated System:

- Mass can NOT cross the boundary
- Energy can NOT cross the boundary

  e.g. Thermos Flask, Calorimeter



# Basic Concepts: System

| Type of boundary | Interactions |
|---|---|
| Open | All interactions possible (Mass, Work, Heat) |
| Closed | Matter cannot enter or leave |
| Isolated | No interactions are possible |
| Insulated | Heat cannot enter or leave |
| Rigid | Mechanical work cannot be done |

# Basic Concepts: Property

- **Thermodynamic Property:** The physical entity which gives information about thermodynamic system is called its property

  e.g. Pressure, Temperature, Volume, Internal Energy, Enthalpy, Entropy, Heat Capacity

- **Intensive Properties:** Thermodynamic properties which do not depend upon mass within the system are called intensive properties

  e.g. Pressure, Temperature, Density, Coefficient of linear expansion

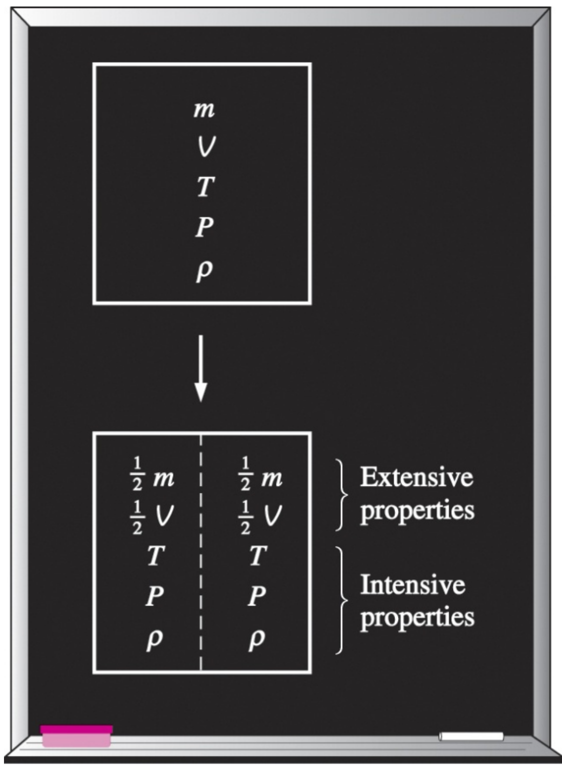
- **Note:** All specific(property per unit mass) and molar (property per unit mole) properties are intensive properties

  e.g. Specific volume, Specific enthalpy, Molar heat capacity, Universal gas constant

# Basic Concepts: Property

- **Extensive Properties:** Thermodynamic properties which depend upon mass within the system are called extensive properties

  e.g. Volume, Internal Energy, Enthalpy, Entropy, Mass




Partition Method For Identification of Intensive and Extensive Properties

# Basic Concepts: State

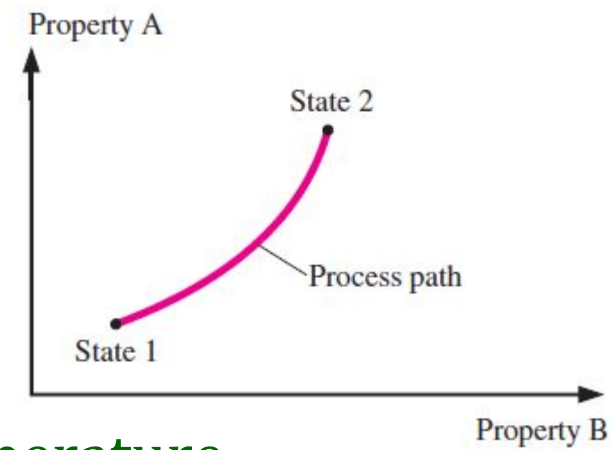
- **State of a system:** A complete set of all properties of a system under given condition is called state of a system

  e.g. Consider air inside a closed room as system, the air will have definite value for Temperature, Pressure, Volume, Internal Energy and so on. A collective set of all those values is called state of a system in that condition.

  **Note:** Change in any one state variable(property) is sufficient to change the state of a system

# Basic Concepts: Process

- **Process**: Any change that a system undergoes from one equilibrium state to another is called a process, and the series of states through which a system passes during a process is called the path of the process

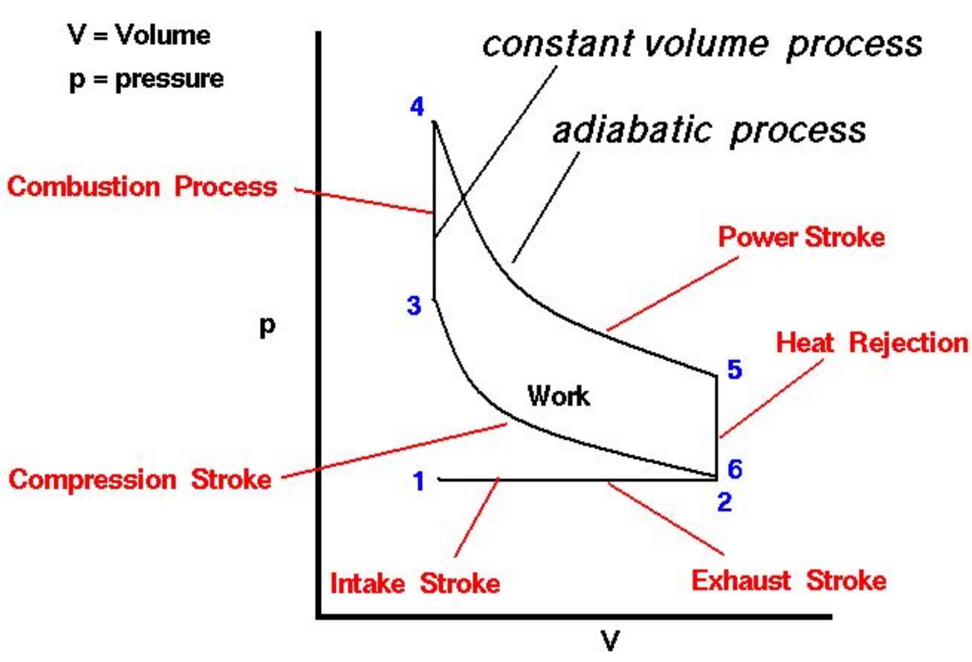



- **Isothermal Process**: No change in temperature
- **Isobaric Process**: No change in pressure
- **Isochoric Process**: No change in volume
- **Adiabatic Process**: No exchange of heat between system and surrounding

- **Here is a brief listing of a few kinds of processes, which we will encounter in TD:**
- **Isothermal process** → the process takes place at constant temperature *(e.g. freezing of water to ice at –10°C)*
- **Isobaric** → constant pressure *(e.g. heating of water in open air→ under atmospheric pressure)*
- **Isochoric** → constant volume *(e.g. heating of gas in a sealed metal container)*
- **Reversible process** → the system is close to equilibrium at all times (and infinitesimal alteration of the conditions can restore the universe (system + surrounding) to the original state.
- **Cyclic process** → the final and initial state are the same. However, q and w need not be zero.
- **Adiabatic process** → $dq$ is zero during the process (no heat is added/removed to/from the system)
- **A combination of the above are also possible: e.g. 'reversible adiabatic process'.**

# Basic Concepts: Thermodynamic Cycle

- **Thermodynamic Cycle**: If system undergoes a series of state changes in such a way that it returns back to its original state then the process is known as thermodynamic cycle
  - If all the processes in the cycle are reversible then the cycle is called reversible cycle
  - Analysis of reversible cycles is important because working of power producing devices such as steam power plant, Diesel/Petrol Engine, Gas turbine can be approximated using reversible cycles




The diagram shows idealized Otto cycle which is basis for petrol engines.

# Basic Concepts: Equilibrium

- **Thermodynamics deals with *equilibrium* states.**
- The word equilibrium implies a state of balance.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system
- **Thermal Equilibrium**: No change in temperature within the system w.r.t. time
- **Mechanical Equilibrium:** No change in pressure within the system
- **Chemical Equilibrium:** No change in chemical composition within the system w.r.t. time
- **Thermodynamic Equilibrium:** If all above three equilibriums coexist together then the system is in thermodynamic equilibrium

# Basic Concepts: Reversible Process

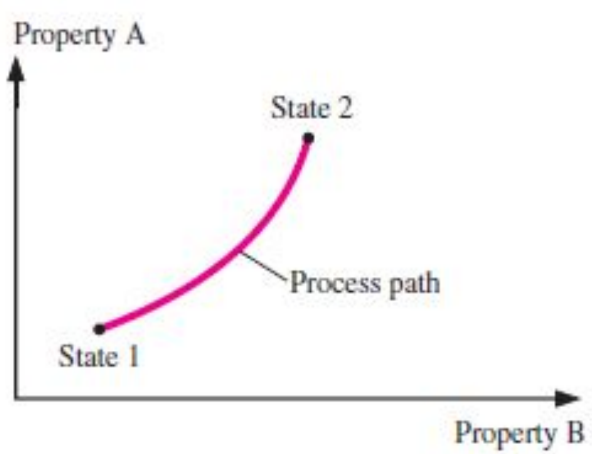
- A reversible process is defined as a process that can be reversed without leaving any trace on the surroundings. It means both system and surroundings are returned to their initial states at the end of the reverse process.
- A reversible process is a thermodynamic process which once having taken place, can be reversed by slight change of driving potential and while doing so the system undergoes through exactly same states as that of the forward states
  - The necessary condition for reversibility is equilibrium. There has to be equilibrium within the system and in between system and surrounding during the process.
  - In order to achieve equilibrium the process must be slow hence reversible process also known as quasi static process
  - After reversing the process the system as well as surroundings will return to the same original conditions

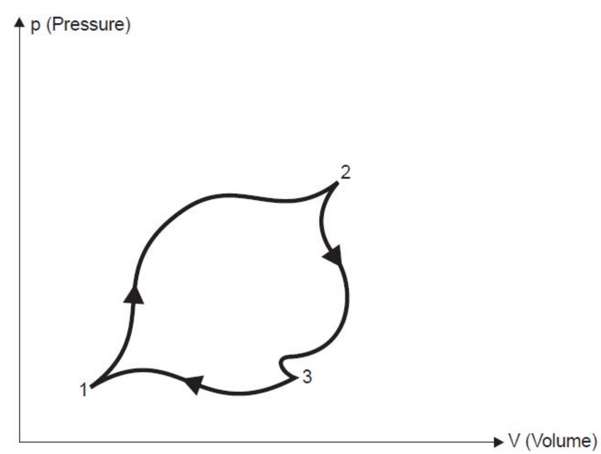
# Cycles

**State:**
It is the condition of a system as defined by the values of all its properties. It gives a complete description of the system. Any operation in which one or more properties of a system change is called a **change of state**.

**Path**: The succession of states passed through during a change of state is called the **path** of the system. A system is said to go through a **process** if it goes through a series of changes in state.

**Process**: Any process or series of processes whose end states are identical is termed a **cycle.**



# Basic Concepts: Reversible Process

- All real life processes are irreversible as **they are only idealizations of actual processes** but still we study reversible process because
  - Reversible processes are easier to analyze
  - **They serve as limits (idealized models) to which the actual processes can be compared.**
  - Work producing devices (such as steam turbine) produce maximum work and work consuming devices(such as compressor) consume least work if all processes are reversible hence engineers try to strive for reversible processes

# Basic Concepts: Irreversible Process

**Irreversible Process**: The process once having taken place cannot be reversed to its original state without leaving any traces on surroundings is called irreversible process

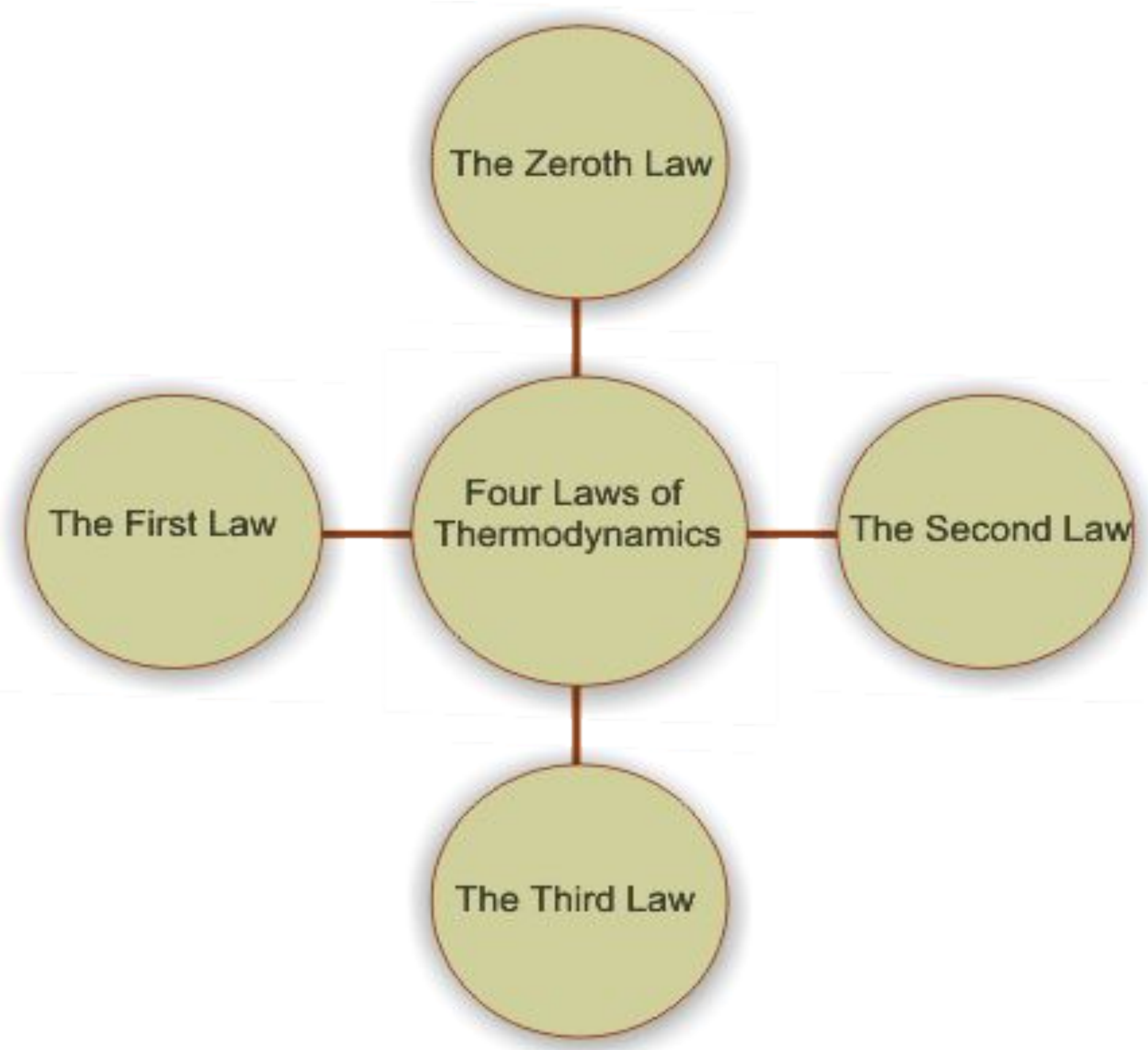
- The system will not go through the same states during forward and reverse process

**Factors Responsible for Irreversibility:**

- Friction because work done against the friction in forward cannot be recovered in reverse process
- Condition of non equilibrium
- Heat transfer through finite temperature difference
- Mixing of two different gases
- Unrestrained expansion and compression
- Heat transfer (finite $\Delta T$)
- Chemical reactions

# Laws of Thermodynamics

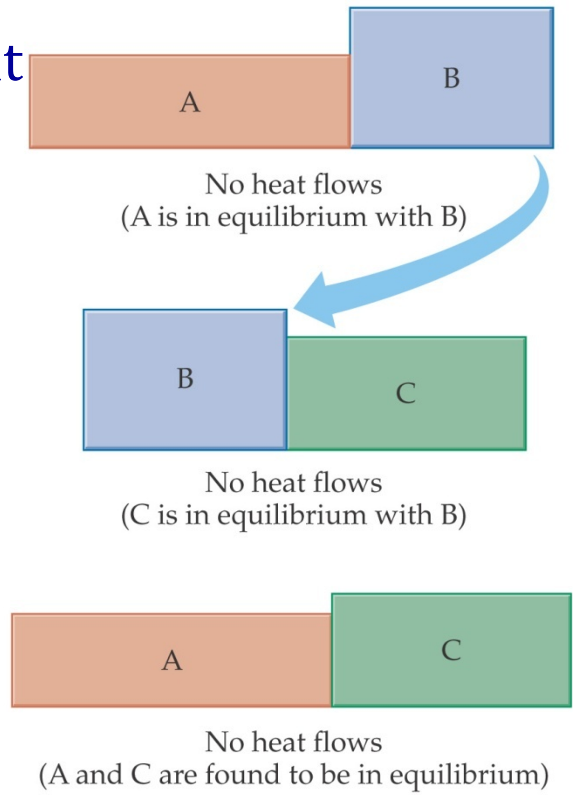
Thermodynamics, basically depends on four laws – Zeroth, first, second and third law of thermodynamic.



# Zeroth Law of Thermodynamic

## Statement:

- *If two bodies are in thermal equilibrium with third body then they are in thermal equilibrium with each other as well*
  - Zeroth law was invented after first and second law but it is so basic that it was named ahead of these laws
  - Even though zeroth law appears unimportant the conclusion obtained from zeroth law cannot be obtained from any other law of thermodynamics
  - Zeroth law introduces new state variable, temperature. It is a basis for temperature measurement

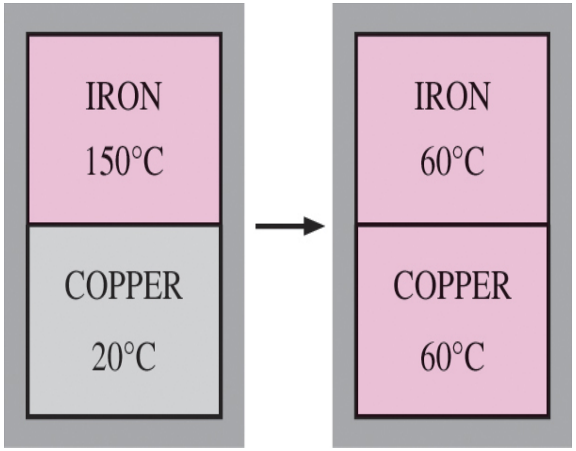


# TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

- **The zeroth law of thermodynamics: If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.**

- **By replacing the third body with a thermometer, the zeroth law can be restated as *two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact*.**

Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.



# Heat : Q
# Energy caused by temperature difference

**Heat**

- is the amount of internal energy entering or leaving a system
- occurs by conduction, convection, or radiation.
- causes a substance's temperature to change
- is not the same as the internal energy of a substance
- is positive if thermal energy flows into the substance
- is negative if thermal energy flows out of the substance
- is measured in joules (J)

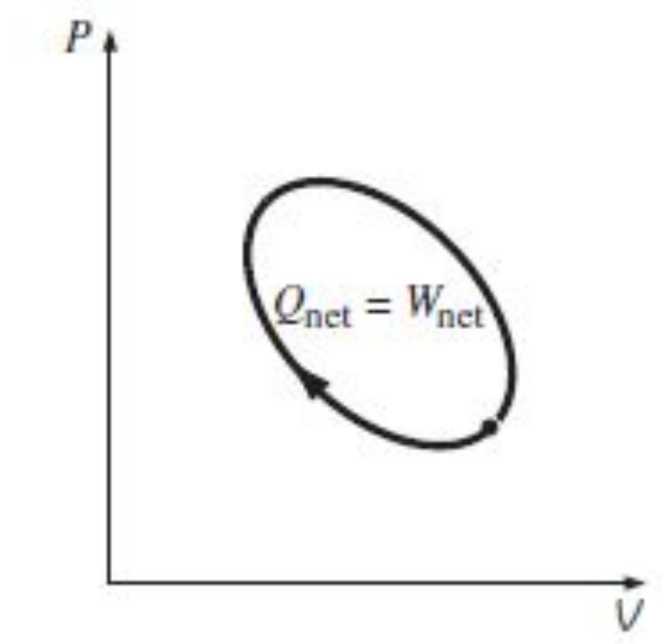
# Work : W
# Energy caused by physical motion

- Work can be defined as transfer of energy. In physics we say that work is done on an object when you transfer energy to that object.
- Work is done when the point of application of force moves in the direction of force.
- W is positive if work is done by system.
- W is negative if work is done on the system.
- W = F x d , Pressure (P) = Force/Area or  F = P A
- Volume (V) = L x W x H or A x d, d= V/A
- W= F x V/A ,W= P V

# <u>First law of Thermodynamics</u>

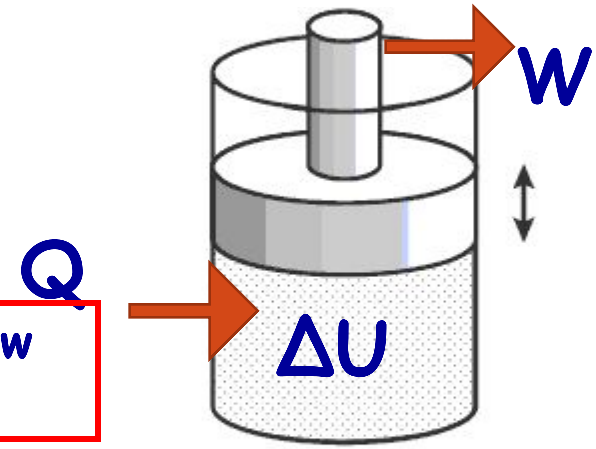
- The *first law of thermodynamics* is simply an expression of the conservation of energy principle, and it asserts that *energy* is a thermodynamic property.
- **<u>First law for cyclic process</u>**: “ For a closed system under going a cyclic change, algebraic sum of work transfer is equal to algebraic sum of heat transfer.”
  - Till today no evidence of violation of first law of thermodynamics is observed

$$\oint dW = \oint dQ$$



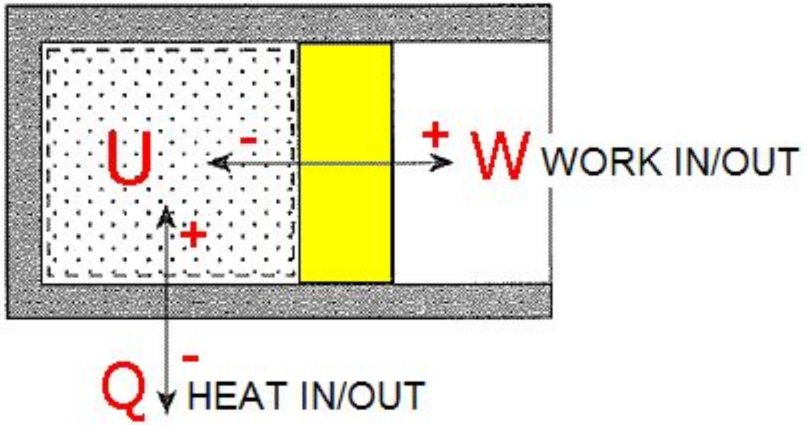
# First law of Thermodynamics

- **First law for non cyclic process**: " For a closed system under going a state change, thermal energy supplied to the system is equal to algebraic sum of work done by the system and change in internal energy ."
- **$Q = \Delta U + W$**




**Note: The first law of thermodynamics and law of conservation of energy are one and same**

- **Notations:**
  - Heat supplied to the system: +ve
  - Heat removed from the system: -ve
  - Work done by the system: +ve
  - Work done on the system: -ve



# Form of Energy

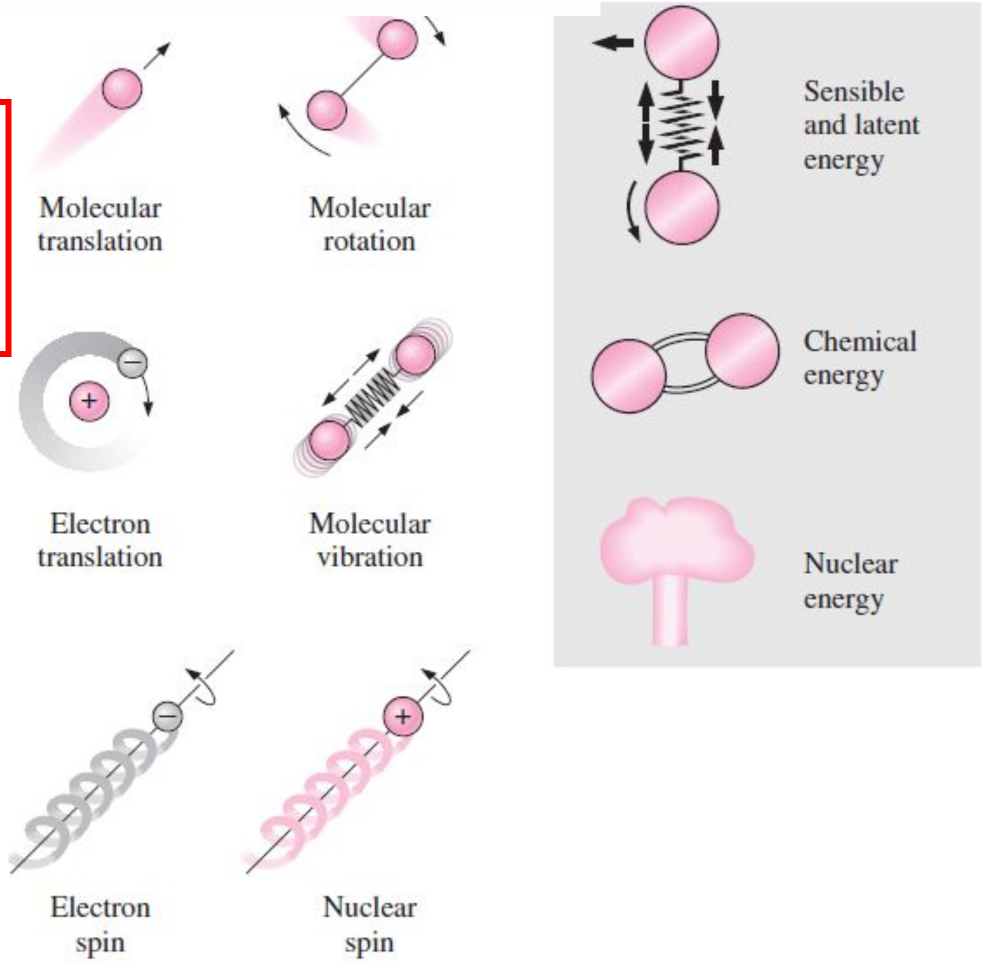
- The sum of all forms of energy of a system is called ***Total Energy***, which is considered to consist of internal, kinetic, and potential energies. $E = U + mV^2/2 + mgz$
- ***Internal energy*** represents the molecular energy of a system and may exist in sensible, latent, chemical, and nuclear forms. Represented by symbol, ***U***.
- ***Kinetic Energy*** is the energy that a system possesses as a results of its motion relative to some reference frame. $KE = mV^2/2$
- **Potential Energy** is the energy that a system possesses as a results of its elevation in a gravitational field. $PE = mgz$

# Internal Energy

- **Internal Energy**: Internal energy is a collective term used for types of energies that system can posses

$$\varepsilon = \varepsilon_{trans} + \varepsilon_{rot} + \varepsilon_{vib} + \varepsilon_{chem} + \varepsilon_{electronic} + \varepsilon_{nuclear}$$

**Note: Internal energy is valid state variable something similar to temperature, pressure and volume.**



# Enthalpy

- Enthalpy of fluid is defined as algebraic sum of internal energy and flow work

  **i. e. h=u+Pv**

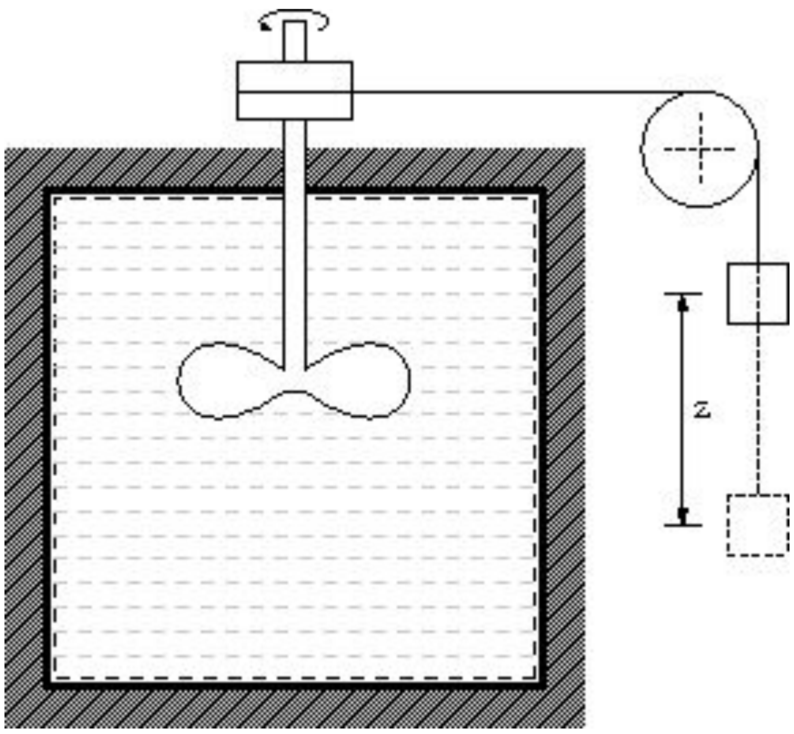
- Generally kinetic and potential energy of fluid will be negligible as compared internal energy and flow energy. Therefore enthalpy can be considered as energy of a flowing fluid whereas internal energy can be considered as energy of a stationary fluid
- Since all of u, P, v, are properties of a system enthalpy is also property of a system
- For an ideal gas enthalpy is also function of temperature alone

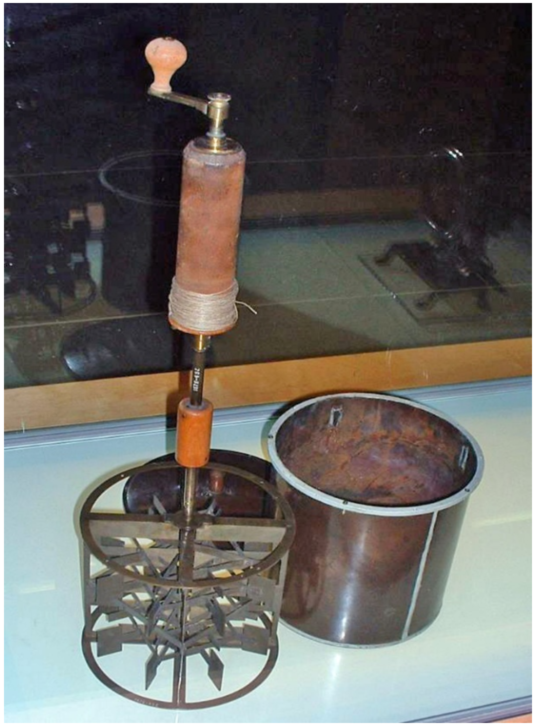
$$\begin{aligned} h &= u + Pv \\ &= C_v T + RT \\ &= C_p T \end{aligned}$$

# Joule's Experiment -I

A series of Experiments carried out by Joule between 1843 and 1848 from the basis for the **First Law of Thermodynamics .**

The following are the observations during the Paddle Wheel experiment shown in Fig



# Joule's Experiment -I

- Joule observed that churning action of pedal wheel causes increase in temperature of water inside the calorimeter.
- He also found that decrease in potential energy of weight driving the pedal wheel equals increase in thermal energy of water inside the calorimeter
- **Conclusion**: "Mechanical work can be completely converted into heat"

$$mgz = mC\Delta T$$

# The First Law of Thermodynamics

- Heat and work are equivalent
- Energy is conserved in any transformation
- The change of energy of a system is independent of the path taken

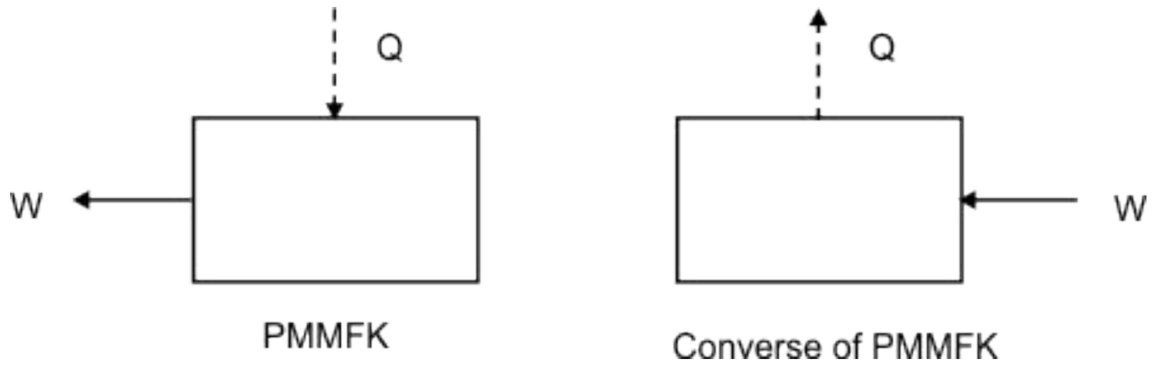
*Energy can be neither created nor destroyed*

$DE = q - w$ or $dE = dq - dw$

$E$ = internal energy
$q$ = heat
$w$ = work

# A Perpetual Motion Machine of First Kind (PMM-I)

Thermodynamics originated as a result of man's Endeavour to convert the disorganized form of energy (internal energy) into organized form of energy (work).




An imaginary device which would produce work continuously without absorbing any energy from its surroundings is called a **Perpetual Motion Machine of the First kind**, (PMMFK). A PMMFK is a device which violates the first law of thermodynamics. It is impossible to develop a PMMFK (Figure

# Limitations of First law of Thermodynamics

- The first law places **no restriction on the direction of a process**, but satisfying the first law does not ensure that the process can actually occur.
  - ✔ The second law determines the *theoretical limits for the performance of commonly used engineering systems*

- *The first law is concerned with the* ***quantity*** **of energy** and the **transformations of energy** from one form to another with no regard to its quality. –
  - ✔ *The second law also asserts that energy has quality as well as quantity*

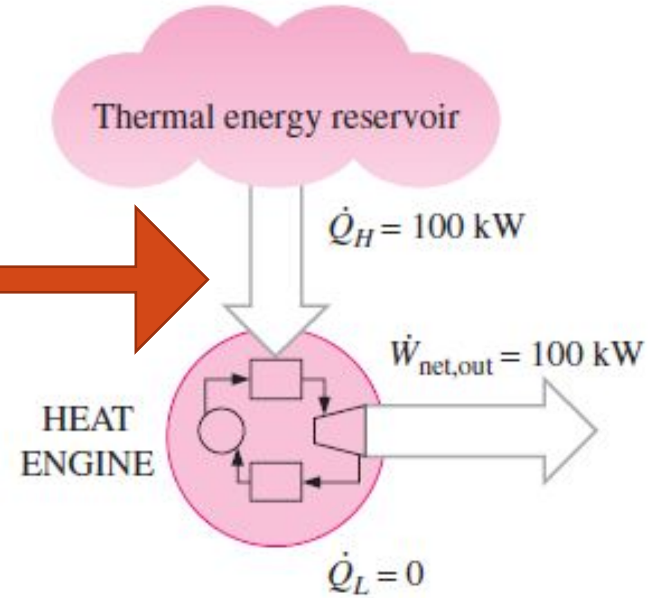
- Does not specify the **feasibility of the reaction**: first law does not specify that process is feasible or not
  - ✔ second law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process

- Practically it **is not possible to convert the heat energy into an equivalent amount of work**.
  - ✔ The second law predicts the *degree of completion of chemical reactions.*

# Second Law of Thermodynamics

- **Kelvin-Plank Statement:** It is impossible to construct a device which when operates in a thermodynamic cycle, converts all the heat energy supplied to it in to an equivalent amount work.
- In other words the second law states that it impossible to convert heat completely into mechanical work.
- Therefore, to operate HE at least two thermal reservoirs at different temp. are requried.

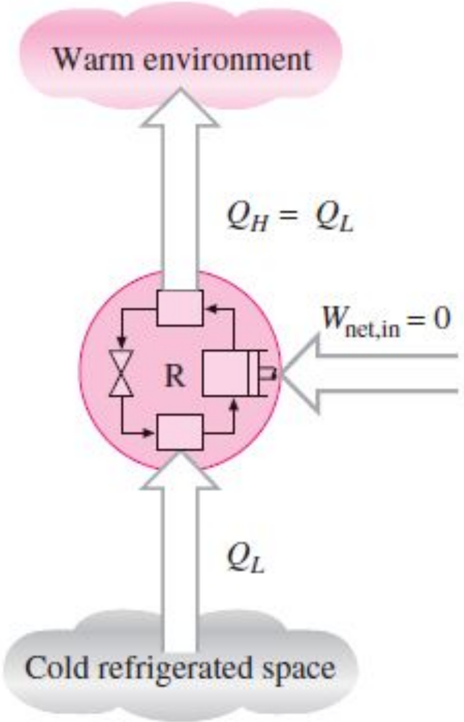
**Not Possible**



# Second Law of Thermodynamics

- **Clausius Statement:** It is impossible to construct a device that operates on a thermodynamic cycle whose sole(only) effect is transfer of heat from lower temperature to higher temperature
- In other words transfer of heat from lower temperature to higher temperature is not possible without providing some work input.

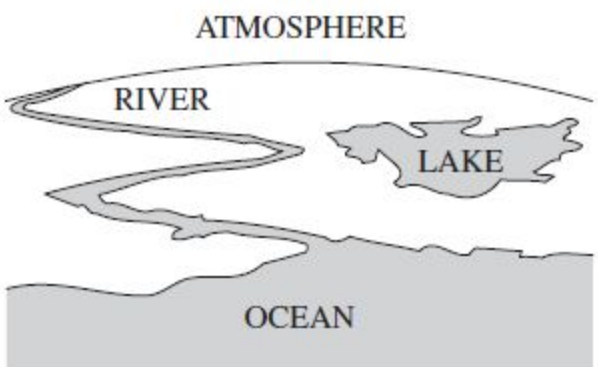
**Not Possible**



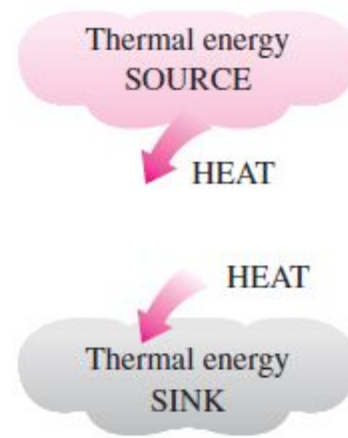
# Thermal Energy Reservoirs (TER)

- **Thermal Energy Reservoir**: It is a large body with infinite heat capacity which can supply or absorbs unlimited quantity of heat without appreciable change in its temperature

  Example: Atmosphere, Ocean, River, Industrial Furnace, Two phase mixture of liquid and vapor.
- Thermal energy reservoir serves as source or sink of thermal energy at constant temperature



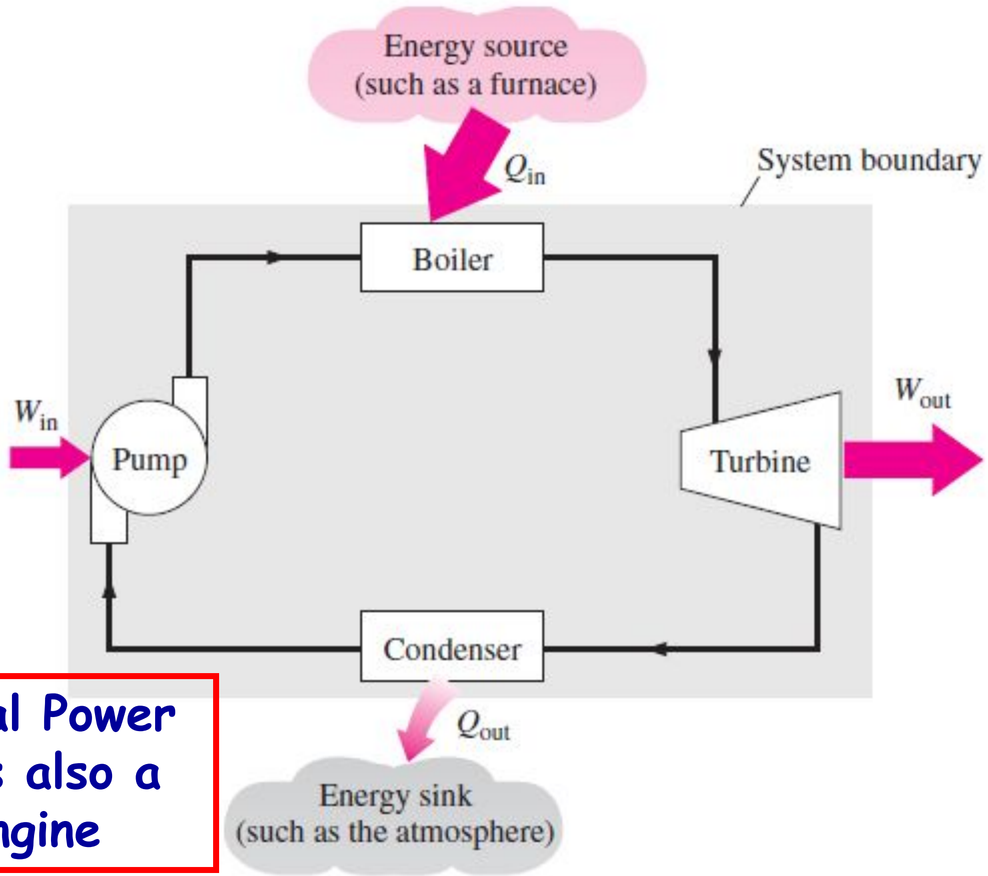
Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs.

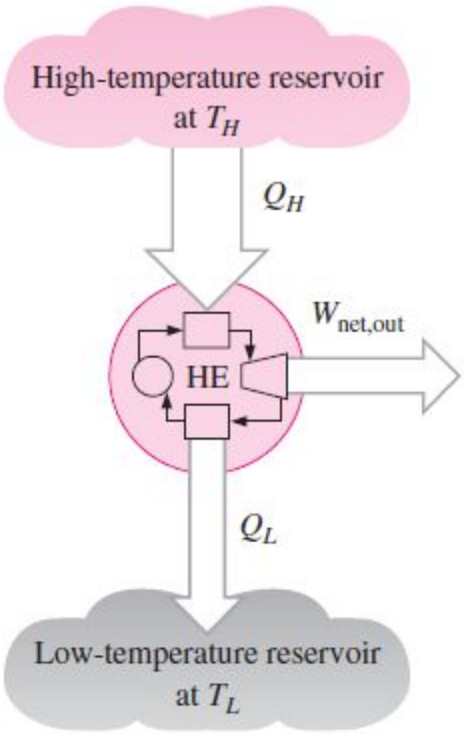


A source supplies energy in the form of heat, and a sink absorbs it.

# Heat Engine

- **Heat Engine**: It is a mechanical device which works on Carnot cycle and which converts thermal energy into mechanical work
  Example: Petrol engine, Gas turbine, Steam engine




**Thermal Power Plant is also a heat engine**

# Heat Engine

- Heat engines may differ considerably from each other but all them have following things in common

1. All heat engine operate on thermodynamic cycle
2. They receive heat from high temperature source (TER)
3. They convert only a part of the heat into useful mechanical work
4. They reject remaining part of the heat to low temperature sink (an another TER)

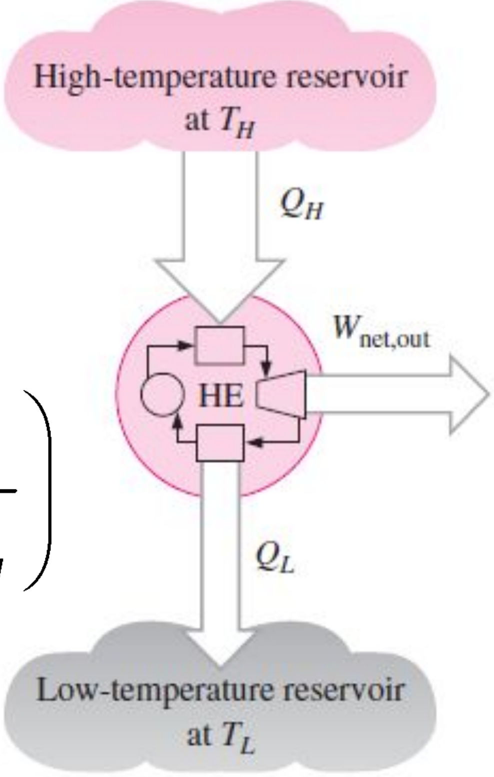
# Efficiency of Heat Engine


$$\eta = \frac{W}{Q_H}$$

$$= \frac{Q_H - Q_L}{Q_H}$$

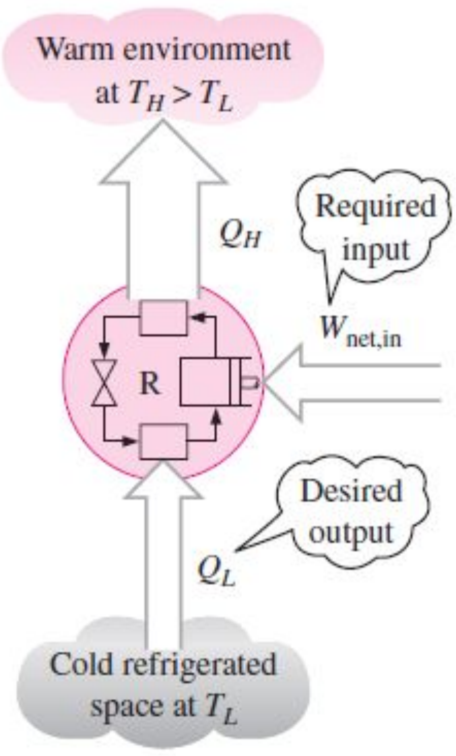
$$= 1 - \frac{Q_L}{Q_H}$$

$$= 1 - \frac{T_L}{T_H} \quad \left( \because \quad \frac{Q_L}{Q_H} = \frac{T_L}{T_H} \right)$$



# Refrigerator

- **Refrigerator**: It is a device which maintains temperature of an object below ambient temperature by transferring heat from lower temperature to higher temperature
  - Refrigerators need to have some input otherwise heat will not flow from low temperature to high temperature



# COP of Refrigerator

Coefficient of performance of a refrigerator is defined as

$$\text{COP} = \frac{\text{Desired Output}}{\text{Required Input}}$$

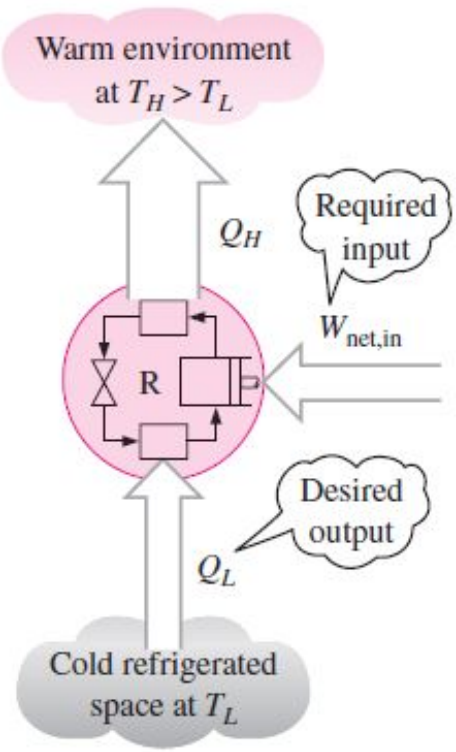
$$= \frac{Q_L}{W}$$

$$= \frac{Q_L}{Q_H - Q_L}$$

$$= \frac{1}{Q_H / Q_L - 1}$$

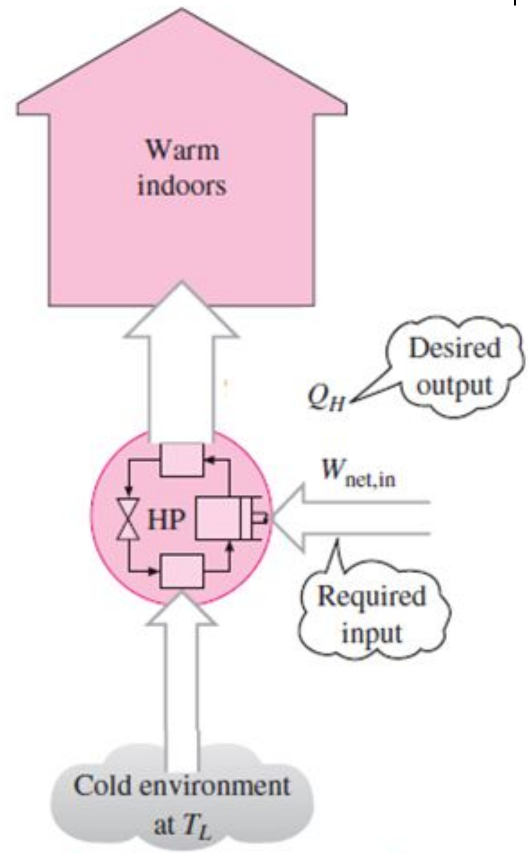
$$= \frac{1}{T_H / T_L - 1} \quad \left( \because \; \frac{Q_L}{Q_H} = \frac{T_L}{T_H} \right)$$

$$\text{COP} = \frac{T_L}{T_H - T_L}$$



# Heat Pump

- **Heat Pump**: It is a device which maintains temperature of an object above ambient temperature by transferring heat from lower temperature to higher temperature
  - Heat pumps are used in cold countries to keep home warm in winters.




$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{net,in}}$$

# COP of Heat Pump

Coefficient of performance of a heat pump is defined as

$$\text{COP} = \frac{\text{Desired Output}}{\text{Required Input}}$$

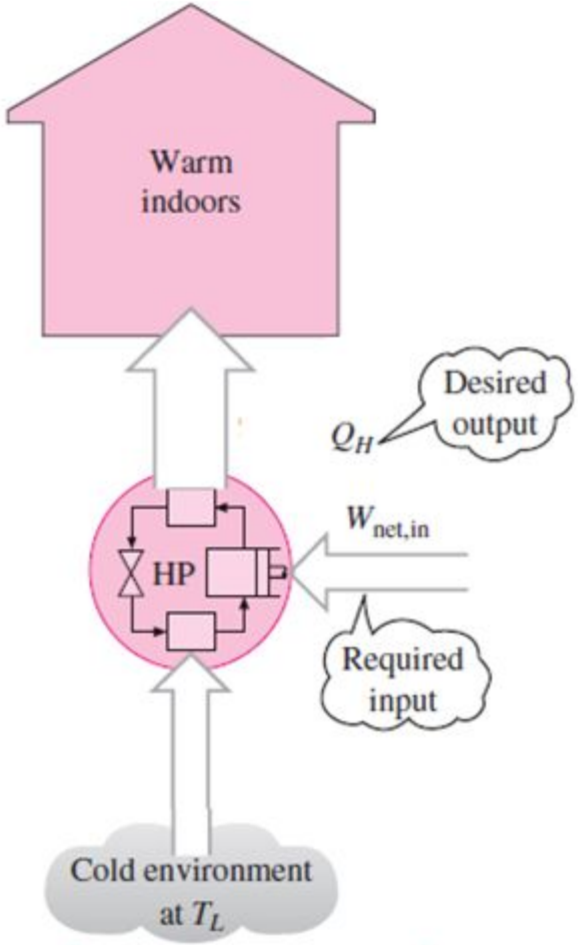
$$= \frac{Q_H}{W}$$

$$= \frac{Q_H}{Q_H - Q_L}$$

$$= \frac{1}{1 - Q_L / Q_H}$$

$$= \frac{1}{1 - T_L / T_H} \quad \left( \because \quad \frac{Q_L}{Q_H} = \frac{T_L}{T_H} \right)$$

$$\text{COP} = \frac{T_H}{T_H - T_L}$$




$$\text{COP}_{\text{HP}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{\text{net,in}}}$$

# Numerical on

## Heat Engine, Heat Pump and Refrigerator

1) A system undergoes a cycle composed of four processes. The heat transfers in each process are: 400 kJ, -365 kJ, -200 KJ and 250 kJ. The respective work transfers are 140 kJ, 0, -55 KJ and 0. Is the data consistent with the first law of thermodynamics?

**Solution:**

From First law of thermodynamics we know that for a system undergoing a cyclic process, the net heat transfer is equal to net work transfer. $\int \delta W = \int \delta Q$

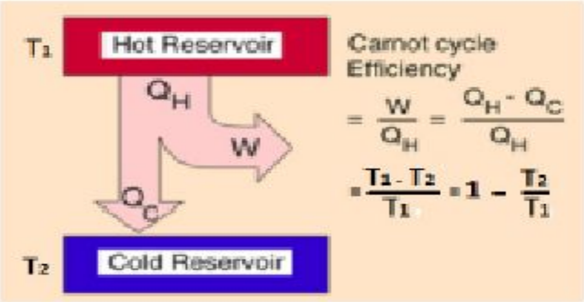
Net Heat input to the system = 400 – 365 – 200 + 250 = 85 kJ. (heat input is +ve)

Net work output from the system = 140 – 55 + 0 = 85 kJ (work done by system is +ve)

So in this cyclic process, $\int \delta W = \int \delta Q$ . Hence the data is consistent with the first law of thermodynamics

3) A reversible heat engine operates on Carnot cycle between source and sink temperatures of 225°C and 25°C respectively. If the heat engine receives 40 kW from the source, find the net work done, heat rejected to sink and efficiency of the engine.

**Solution:**




Carnot heat engine efficiency, $\eta_{carnot}$ $= W/Q_H = [Q_H - Q_L]/Q_H = [Q_H - Q_L]/Q_H$

$= (Th - Tc)/Th = 1 - Tc/Th = 1 - T2/T1$

Given:

T1 = 225°C = 225 + 273 = 498 K

T2 = 25°C = 25 + 273 = 298 K

Heat received from source, $Q_H = 40$ kW

**Carnot heat engine efficiency = = 1 - T2/T1 = 1 – 298/498 = 0.4 or 40% ..... Ans**

Carnot heat engine efficiency, $\eta_{carnot}$ $= W/Q_H$

∴ 0.4 = W/40.

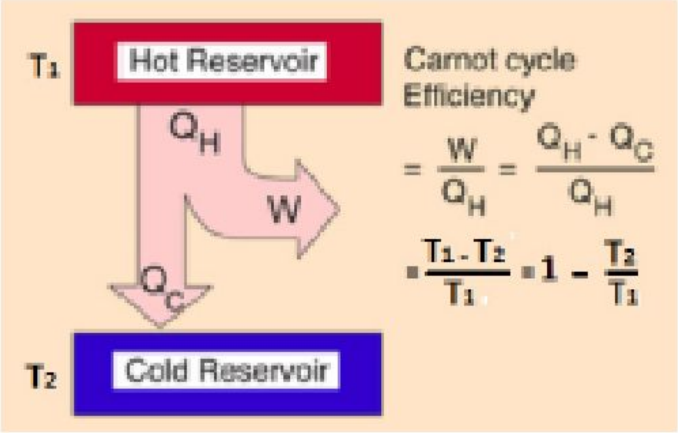
**∴ Net work done, W = 0.4 x 40 = 16 kW ..... Ans**

Now, $W = Q_H - Q_L$

**∴ Heat rejected to sink, $Q_L = Q_H - W = 40 - 16 = 24$kW**

4) The power input required for a grinding mill is 30 MJ/min. A heat engine is used as a prime mover for the grinding machine. A heat source at 420°C is available for supplying energy and the surrounding is at 30°C. If the actual heat engine is 25% as efficient as a Carnot engine working between the same temperature limits, calculate the energy supplied by the source per sec.

**Solution:**



Given:

$T1 = 420°C = 420 + 273 = 693$ K

$T2 = 30°C = 30 + 273 = 303$ K

Required work output, $W = 30$ MJ/min $= (30x10^3)/60$ kJ/sec $= 500$ kW

$\eta_{act} = 0.25 \times \eta_{carnot}$

Carnot heat engine efficiency, $\eta_{carnot} = 1 - T2/T1 = 1 - 303/693 = 0.563$ or 56.3%

$\therefore \eta_{act} = 0.25 \times \eta_{carnot} = 0.563 \times 0.25 = 0.141$ or 14.1%

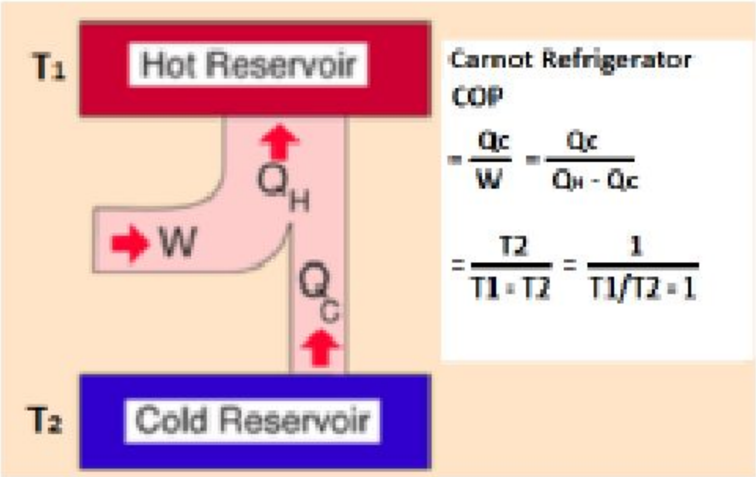
Efficiency, $\eta_{act} = W/Q_H$ $\quad \therefore 0.141 = 500/Q_H$

$\therefore$ **Heat supplied by the source, $Q_H$** $= 500/0.141$

$= 3546.1$ kW $=$ **3546.1 kJ/sec** ...

5) A heat pump is used to maintain an auditorium hall at 25°C, when the ambient temperature is 10°C. The heat leakage from the hall is 1500 kJ/min. Calculate the power required to run the actual heat pump, if the COP of the actual heat pump is 30% of the COP of the Carnot heat pump working between the same temperature limits.

**Solution:**




**Carnot Refrigerator** COP, $COP_{carnot-ref} = Qc/W = Qc / [Q_H - Qc]$

$$= T2/ (T1 - T2)$$

**Carnot Heat Pump** COP, $COP_{carnot-HP} = Q_H/W = Q_H / [Q_H - Qc]$

$$= T1/ (T1 - T2)$$

Given:

$T1 = 25°C = 25 + 273 = 298$ K

$T2 = 10°C = 10 + 273 = 283$ K

Required heat rejection to Auditorium hall, $Q_H$ = 1500 kJ/min = 25 kJ/sec = 25 kW

$COP_{act} = 0.30 \times COP_{carnot-HP}$

Carnot heat pump COP, $COP_{carnot-HP} = T1 / [T2 - T1] = 298 / [298 - 283] = 19.867$

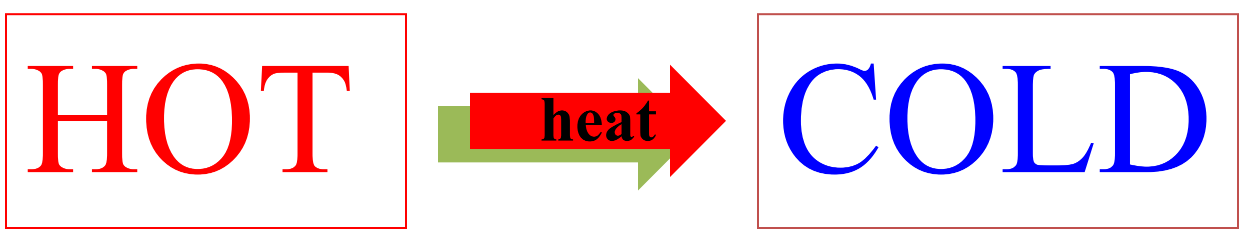
$\therefore COP_{act} = 0.30 \times COP_{carnot-HP} = 0.3 \times 19.867 = 5.96$

Now, $COP_{heat-pump} = Q_H/W = Q_H / [Q_H - Q_C]$ $\quad \therefore 5.96 = 25/W$

$\therefore$ **Power required to run Heat Pump, $W = 25/5.96 = 4.195$ kW** ..... /

# Introduction to Heat Transfer

- Heat is a **form of energy**.
- Heat **travels** from **higher temperature**(hotter) region to **lower temperature**(cooler) region.
- **Heat transfer is the movement of heat energy from one substance to another.**
- **Heat always travels from a region of higher temperature to a region of lower temperature**

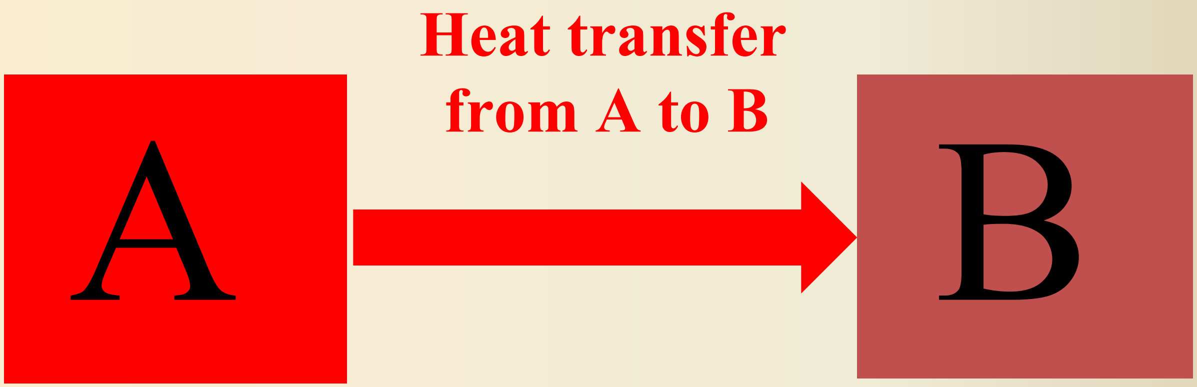


# Heat Transfer

- Heat always moves from a warmer place to a cooler place.
- Hot objects in a cooler room will cool to room temperature.
- Cold objects in a warmer room will heat up to room temperature.

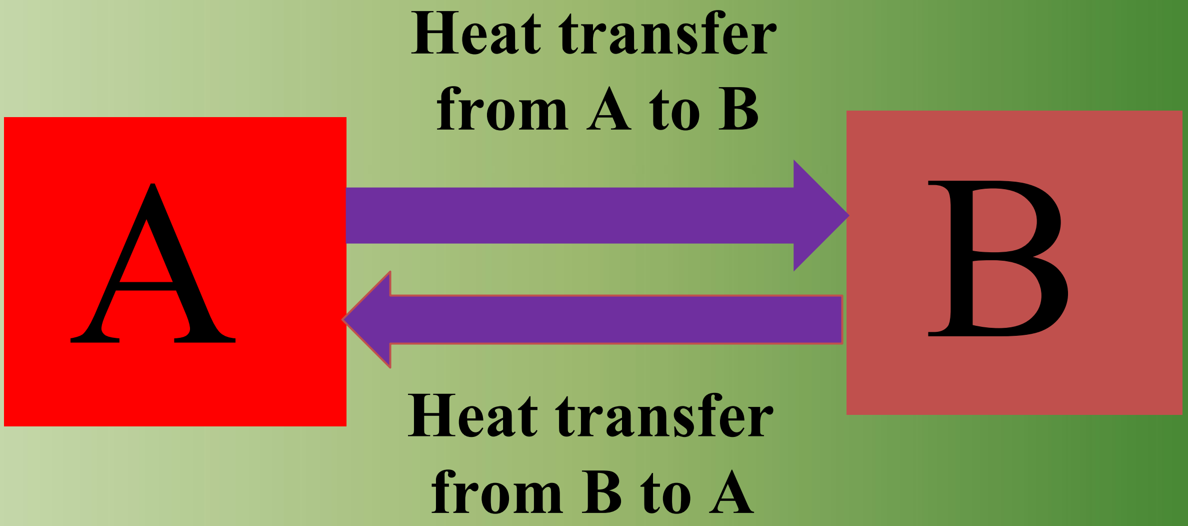
**Body A** is at a **higher temperature** than **body B**. When bodies A and B are in contact,

**A loses thermal energy** at a rate higher than the rate at which it absorbs thermal energy from B.



This causes a **temperature drop in body A** and an **increase in temperature in body B.**

Finally, the two bodies A and B have the **same temperature.**




**They are in thermal**

# Heat Transfer Modes

- The three modes of heat transfer are

1. Conduction
2. Convection
3. Radiation

# Conduction

- Conduction is the **process** by which heat is **transmitted** through **a medium** from **one particle to another.**

- **Heat transfer** by conduction is the transfer of heat through **direct contact**.

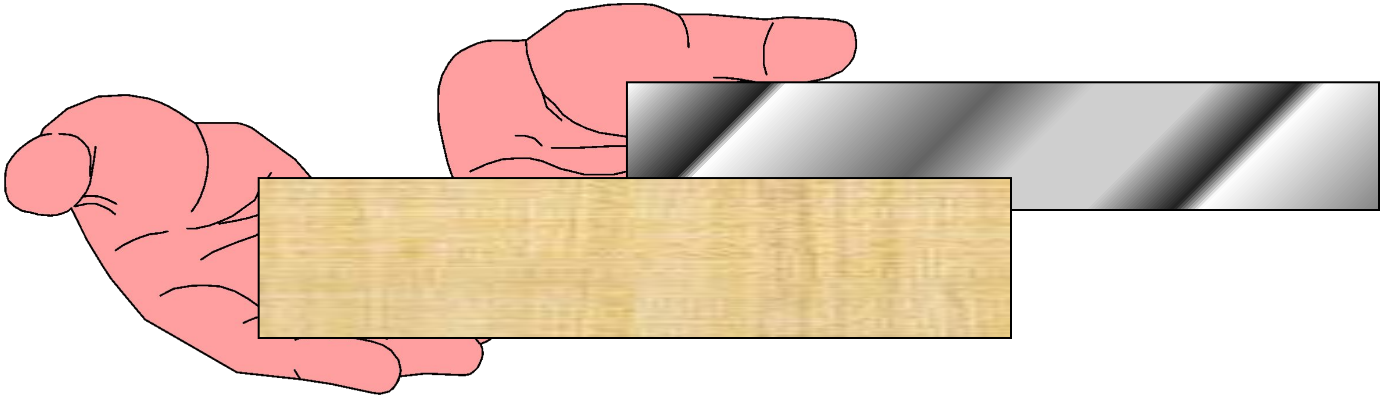
Example 1

- Warm water
- Cool water

**The metal *conducts* heat from the cup of warm water to the cup of cool water.**

# Why does metal feel colder than wood, if they are both at the same temperature?

Metal is a conductor, wood is an insulator. Metal conducts the heat away from your hands. Wood does not conduct the heat away from your hands as well as the metal, so the wood feels warmer than the metal.

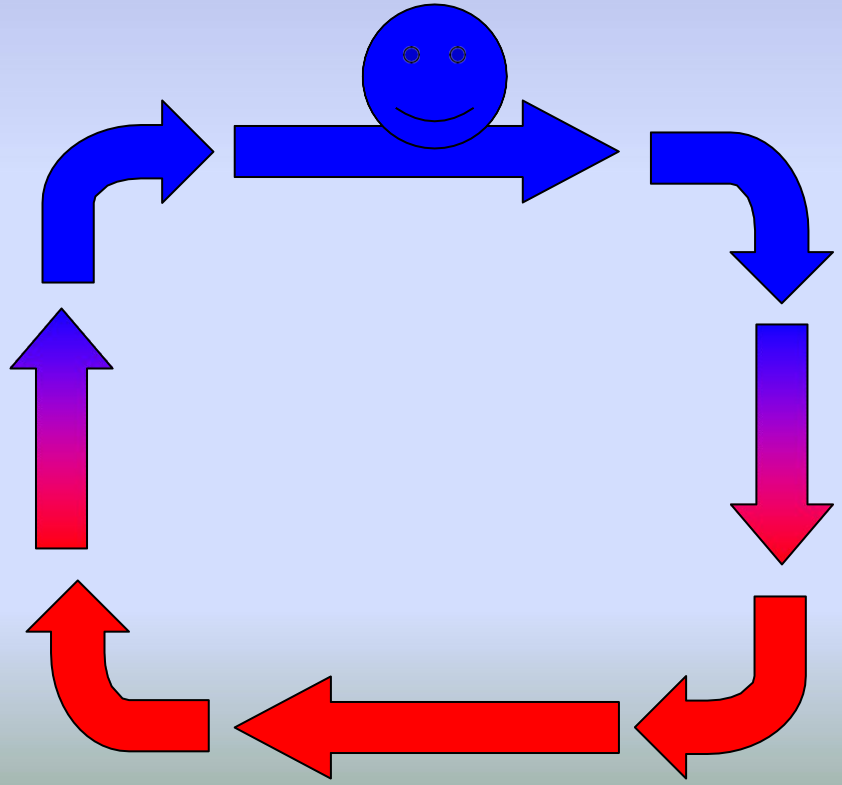


# Convection

- Convection is the **process** by which **heat** is **transmitted** from one place to another by the **movement of heated particles** of a **gas or liquid.**
- **Occurs** primarily in **liquids and gases** (fluids)

# Convection

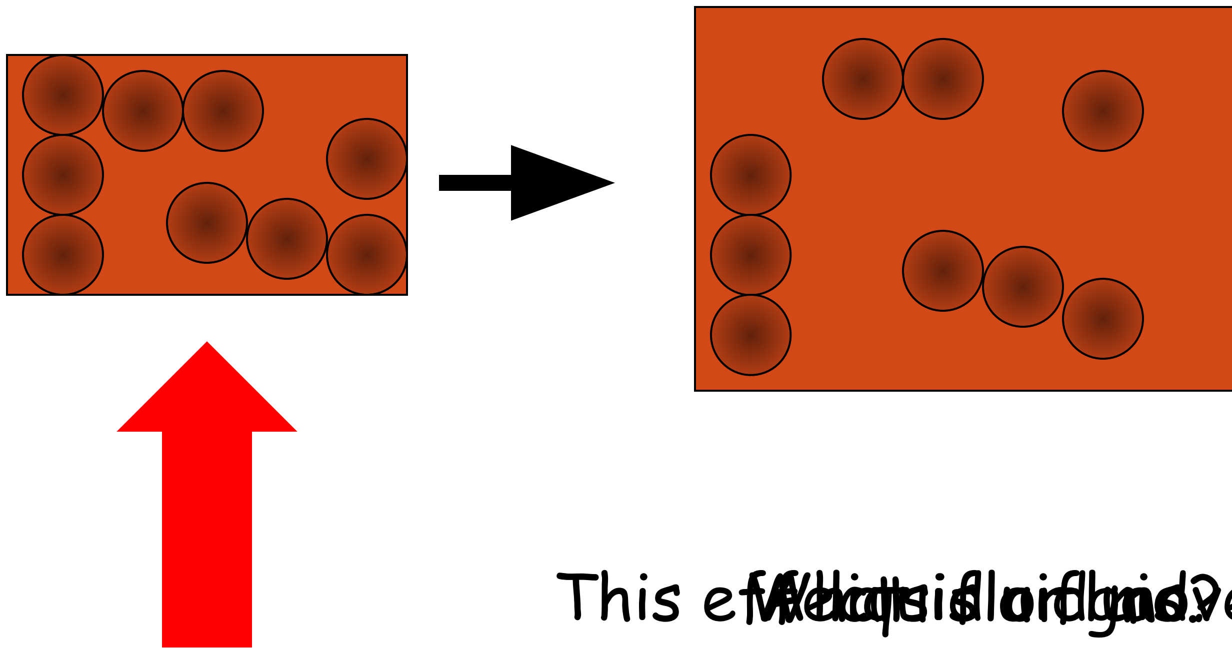
- Warm fluids rise, cool down, sink, and then  are warmed again.



# Convection

What happens to the particles in a liquid or a gas when you heat them?

The particles spread out and become less dense.

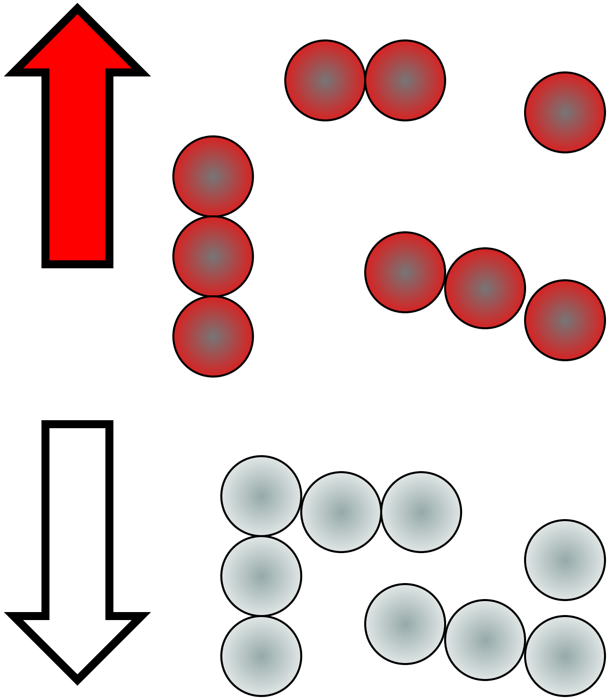


This effect is called fluid movement.

What is a fluid?

A liquid or gas.

# Fluid movement



Cooler, more d<u>ense</u>, fluids sink through w<u>armer</u>, less dense fluids.

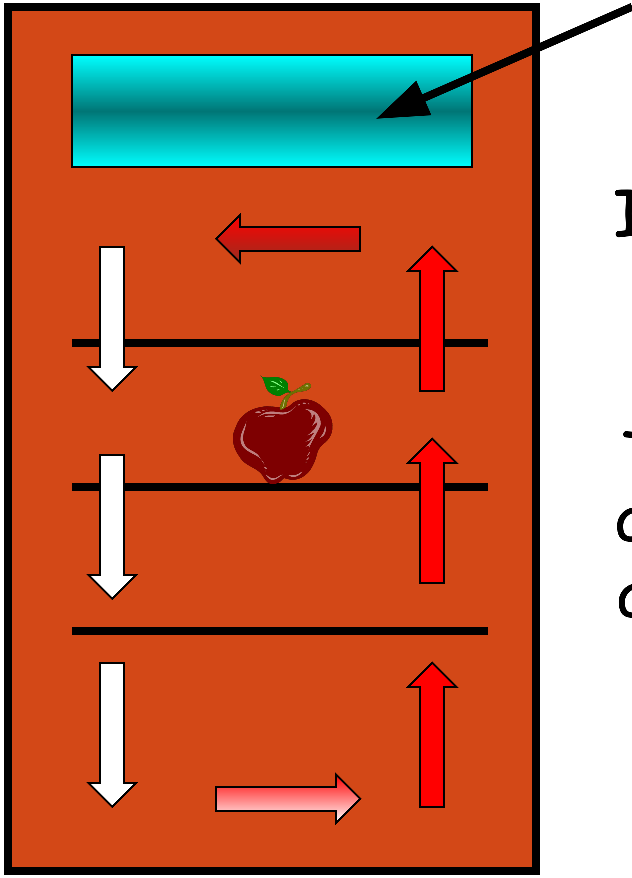
In effect, warmer liquids and gases r<u>ise</u> up.

Cooler liquids and gases s<u>ink</u>.

# Cold air sinks

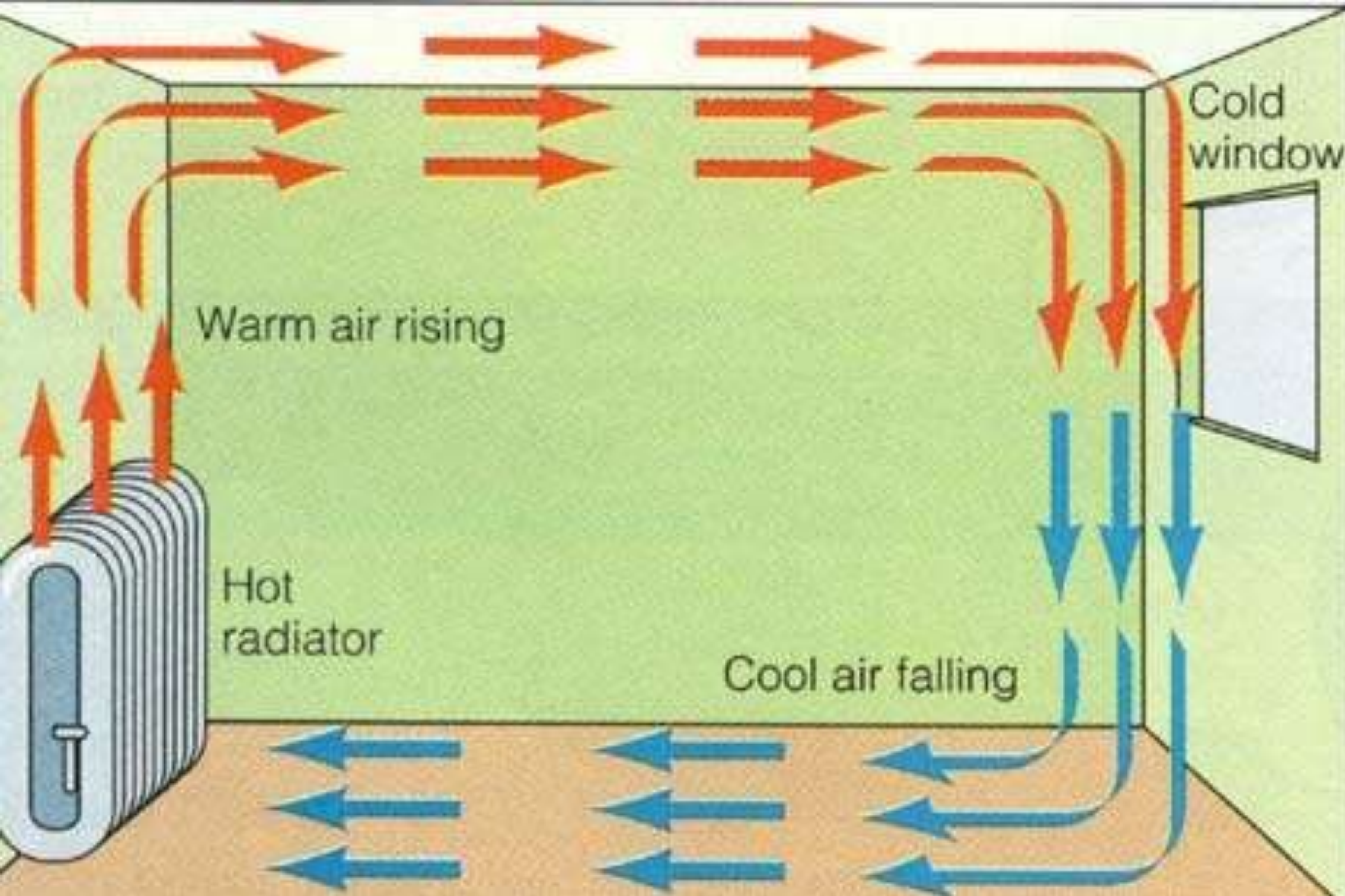
Where is the freezer compartment put in a fridge?

It is put at the top, because cool air sinks, so it cools the food on the way down.



Freezer compartment

It is warmer at the bottom, so this warmer air rises and a convection current is set up.




The radiator warms the room by warming the air around it. Then the warm air *transfers heat* to the rest of the room through convection.

http://www.eeb.ucla.edu/test/faculty/nezlin/Lecture1/Fig0803.jpg

# Radiation

- Heat is transferred by **electromagnetic waves**

- There is **no direct contact** between the substances.

- Radiation is a **method** of **heat transfer** that does

**not require** any **medium**

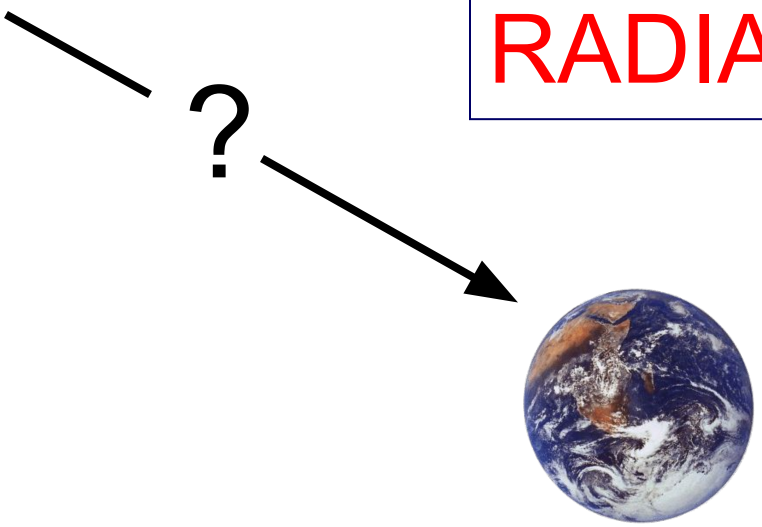
- It can take place in a vacuum.

# The third method of heat transfer

How does heat energy get from the Sun to the Earth?

There are no particles between the Sun and the Earth so it CANNOT travel by conduction or by convection.

RADIATION



# Radiation

Radiation travels in straight lines

True/~~False~~

Radiation can travel through a vacuum

True/~~False~~

Radiation requires particles to travel

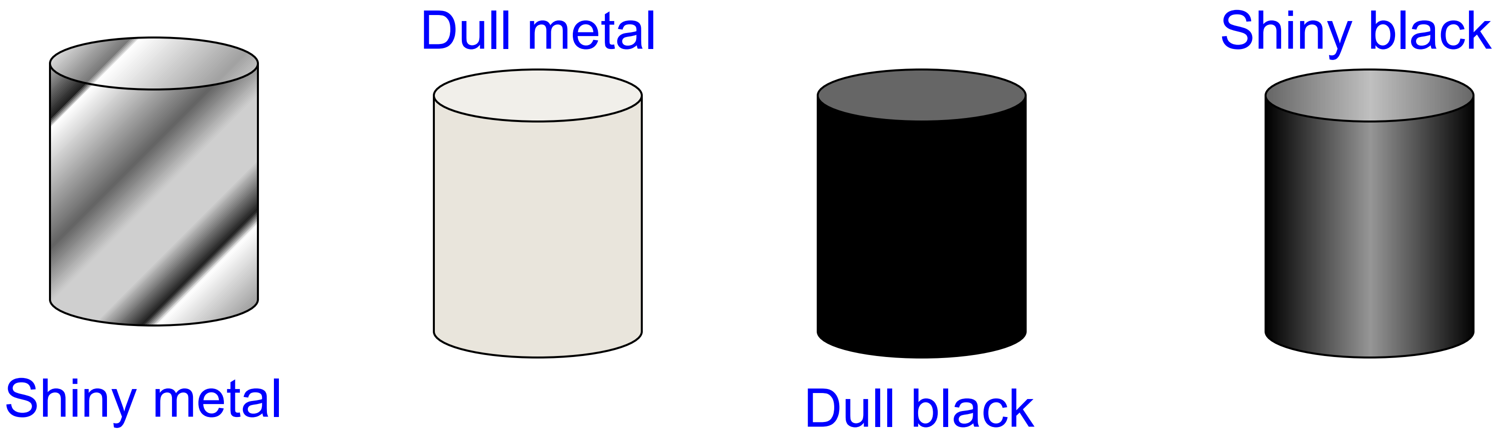
True/False

Radiation travels at the speed of light

True/False

# Emission experiment

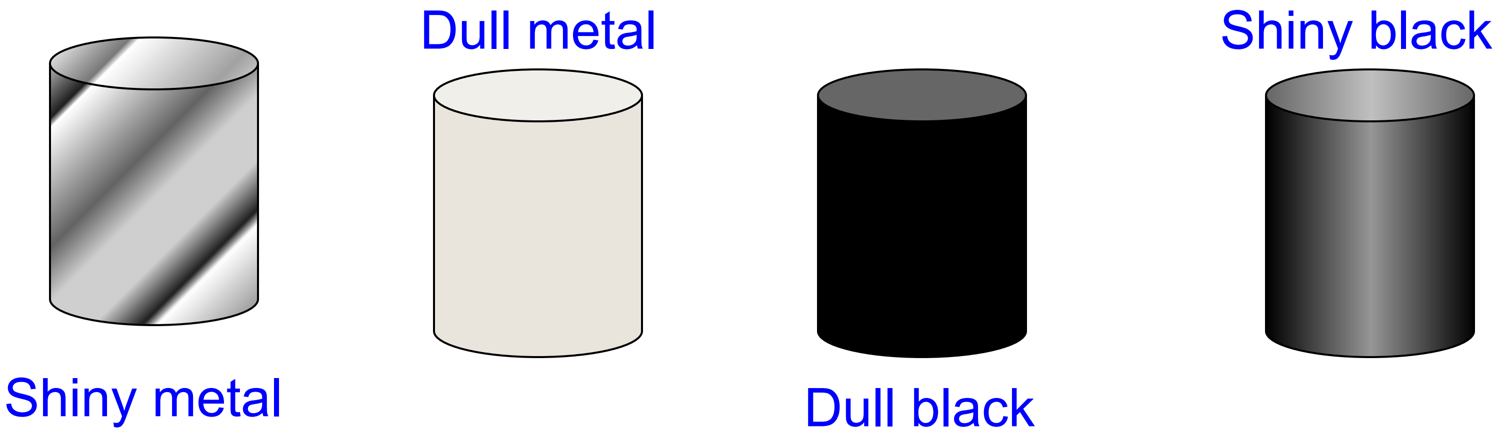
Four containers were filled with warm water. Which container would have the warmest water after ten minutes?




The shiny metal container would be the warmest after ten minutes because its shiny surface reflects heat radiation back into the container so less is lost. The dull black container would be the coolest because it is the best at emitting heat radiation.

# Absorption experiment

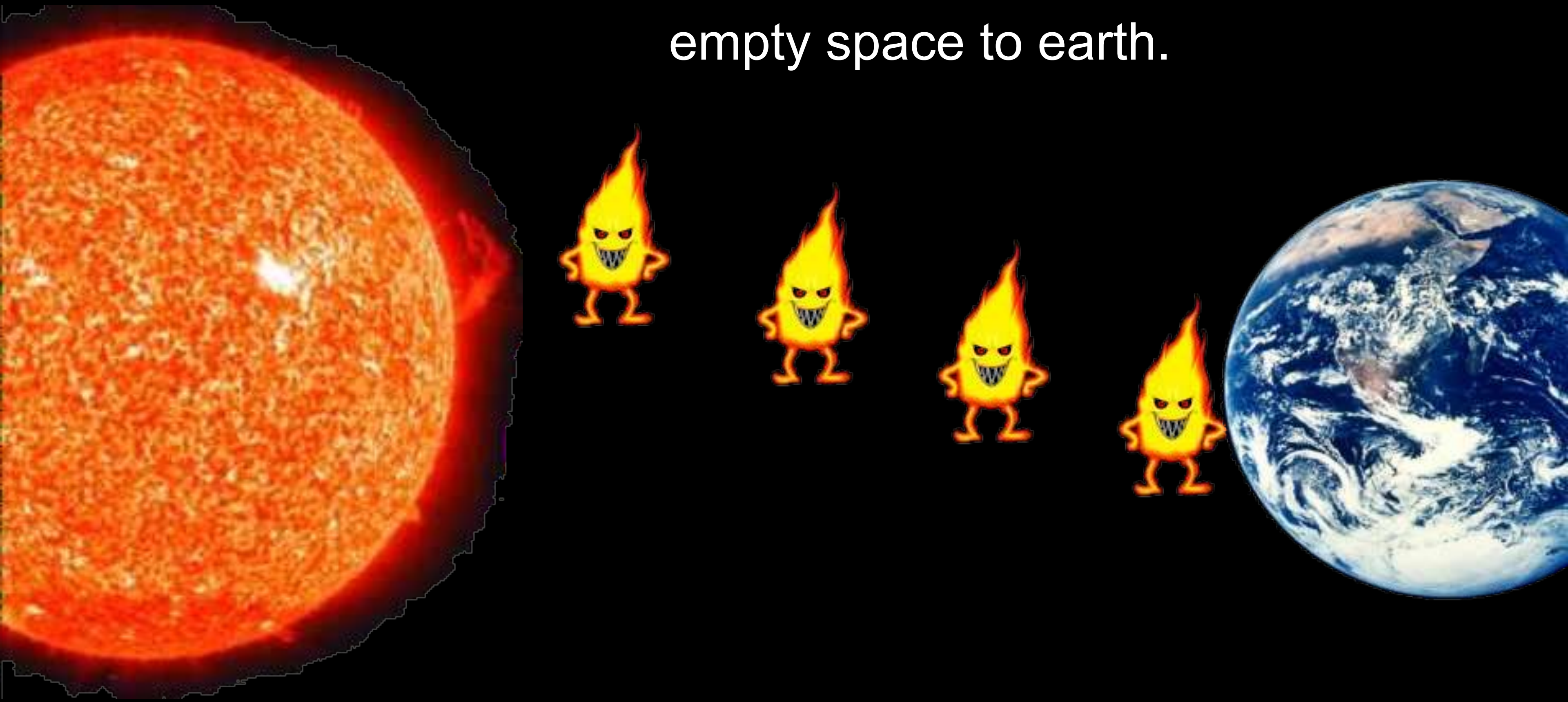
Four containers were placed equidistant from a heater. Which container would have the warmest water after ten minutes?




The __dull black__ container would be the warmest after ten minutes because its surface absorbs heat radiation the best. The shiny metal container would be the coolest because it is the poorest at __absorbing__ heat radiation.

Example 1

Heat from the sun *radiates* through empty space to earth.



# Application of Radiation

## White paint for houses

- In hot countries, houses are painted in white to reduce absorption of heat energy from the Sun

# Application of Radiation

**Tea pot :-**

- Has **smooth, shiny** and **silvery surface.**
- Smooth, shiny and silvery surface is a **bad radiator of heat.**
- This **reduces** rate of **heat loss.** Tea or coffee can be **kept warm** in the teapot.

# ARE THERE ANY QUESTIONS?

- Numericals

1. Air at 20°C blows over a 50cm x 75cm hot plate at 250°C. The film heat transfer coefficient is 25 W/m$^2$K. Calculate the rate of heat transfer from the plate.

2. In a furnace, temp of hot gases is 2100°C. Ambient temp is 40°C. Heat flow by radiation from hot gases to inner surface of the wall is $23 kW/m^2$. Find the wall surface area required if 69 KW of heat transfer is desired.

2. What will be the heat transfer rate across a temperature drop of $60^{O}$ from a 1 $m^2$ if heat transfer coefficient is 50 $W/m^2K$.