Systems in Mechanical Engineering 202041

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Course Objectives:

1. To identify the sources of energy and their conversions
2. To explain the basic concept of engineering thermodynamics and its application
3. To understanding the specifications of vehicles
4. To get acquainted with vehicle systems
5. To introduce manufacturing processes applying proper method to produce components
6. To be able to select and compare domestic appliances

Course Outcomes

On completion of the course, learner will be able to

CO1: Describe and compare the conversion of energy from renewable and non-renewable energy sources
CO2: Explain basic laws of thermodynamics, heat transfer and their applications
CO3: List down the types of road vehicles and their specifications
CO4: Illustrate various basic parts and transmission system of a road vehicle
CO5: Discuss several manufacturing processes and identify the suitable process
CO6: Explain various types of mechanism and its application

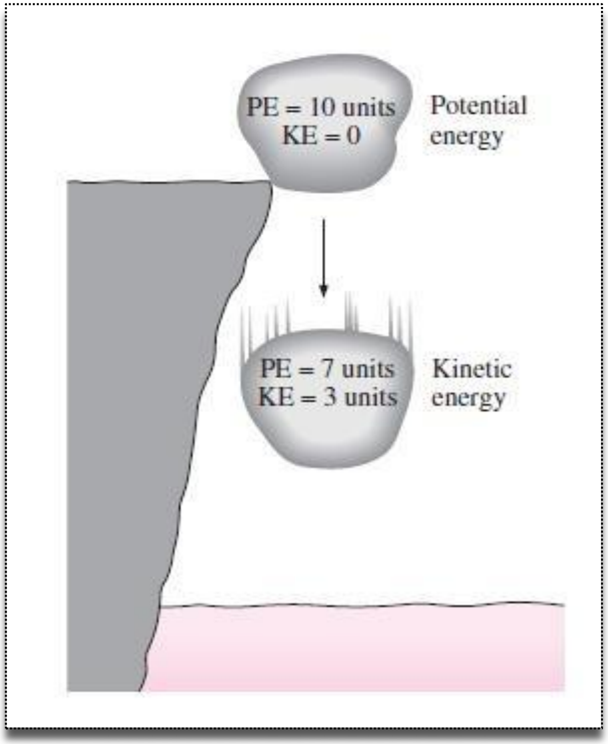
Unit II Introduction to Thermal Engineering

Laws of thermodynamics, heat engine, heat pump, refrigerator (simple numerical)

Modes of heat transfer Conduction, convection , Radiation, Fourier’s law, Newton’s law of cooling , Stefan Boltzmans law (simple Numerical)

Two stroke and Four stroke engines (Petrol, Diesel and CNG engines). Steam generators.

- Thermodynamics can be defined as the science of energy.
- The name thermodynamics stems from the Greek words **therme (heat)** and **dynamis (power)**, which is most descriptive of the early efforts to convert heat into power.
- One of the most fundamental laws of nature is the **conservation of energy principle.** It simply states that during an interaction, energy can change from one form to another but the total amount of energy remains constant.
- A rock falling off a cliff, for example, picks up speed as a result of its potential energy being converted to kinetic energy



Classical Thermodynamics (Macroscopic approach)

Statistical Thermodynamics (Microscopic approach)

Thermodynamics

Classical Thermodynamics & Statistical Thermodynamics

- Macroscopic approach to the study of thermodynamics that *does not require a knowledge of the behaviour of individual particles* is called **Classical Thermodynamics(Macroscopic approach).** It provides a direct and easy way to the solution of engineering problems. Eg. Pressure, Temperature...Etc

- The matter is composed of molecules and the *analysis is carried out by considering the position, velocity and energy of each molecules*, is called **Statistical Thermodynamics(Microscopic approach).** The effect of molecular motion is considered

Application Areas of Thermodynamics

- The heart is constantly pumping blood to all parts of the human body, various energy conversions occur in trillions of body cells, and the body heat generated is constantly rejected to the environment. The human comfort is closely tied to the rate of this metabolic heat rejection. We try to control this heat transfer rate by adjusting our clothing to the environmental conditions
- Some other applications are

❖ The heating and air-conditioning systems,

❖ The refrigerator

❖ The humidifier

❖ The pressure cooker

❖ The water heater

❖ Automotive engines, rockets,jet engines

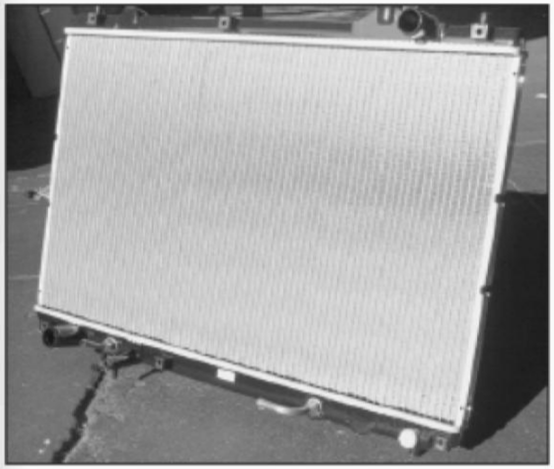
❖ Power plants, solar collectors

Some application areas of thermodynamics

The human body

Air conditioning systems

Airplanes

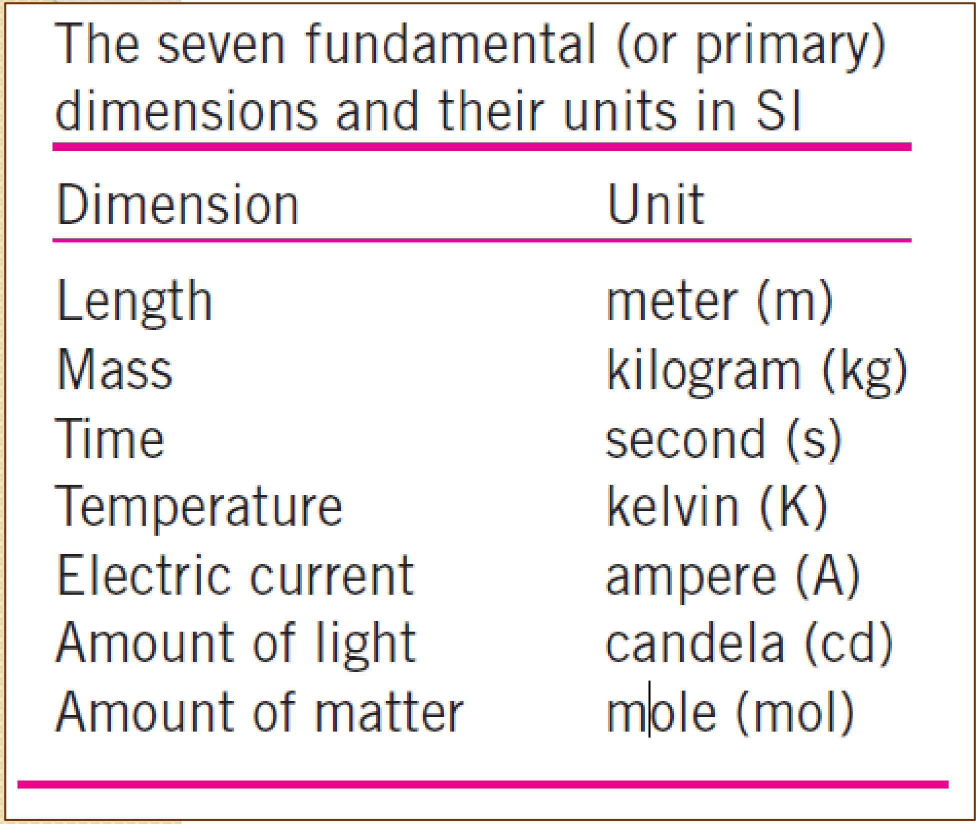


Car radiators

Power plants

Refrigeration systems

DIMENSIONS AND UNITS



The seven fundamental (or primary) dimensions and their units in SI

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Amount of light	candela (cd)
Amount of matter	mole (mol)

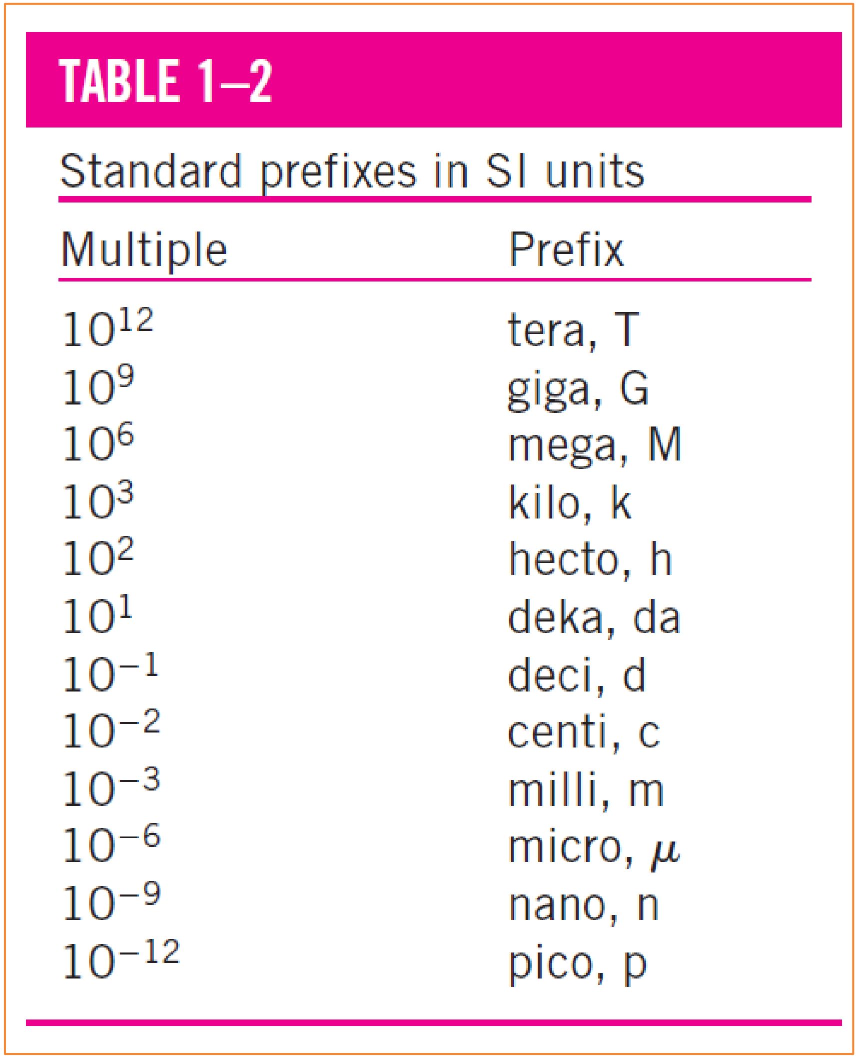
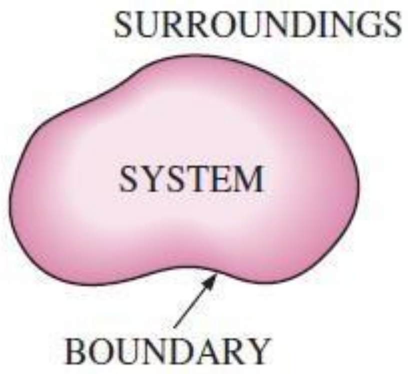


TABLE 1–2

Standard prefixes in SI units

Multiple	Prefix
10^{12}	tera, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p

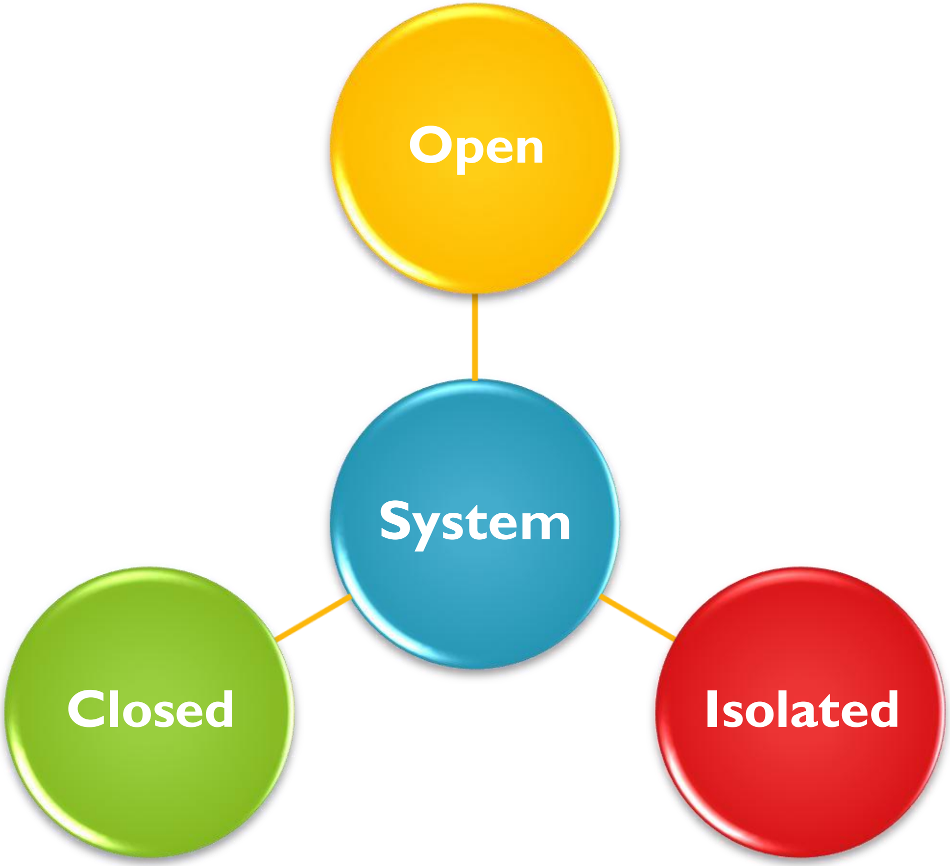
SYSTEMS



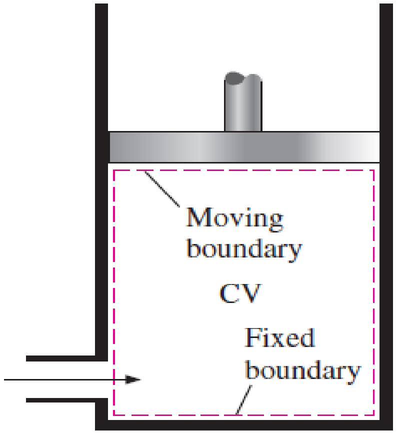
- A system is defined as *a quantity of matter or a region in space chosen for study*.

- The mass or region outside the system is called the **Surroundings**. The real or imaginary surface that separates the system from its surroundings is called the **Boundary**. The boundary of a system can be fixed or movable. Note that the boundary is the contact surface shared by both the system and the surroundings. Mathematically speaking, the boundary has zero thickness, and thus it can neither contain any mass nor occupy any volume in space.

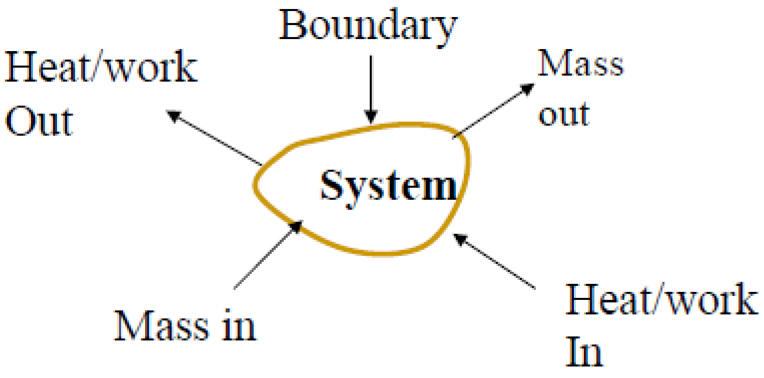
Types of systems



Open System(Control Volume)

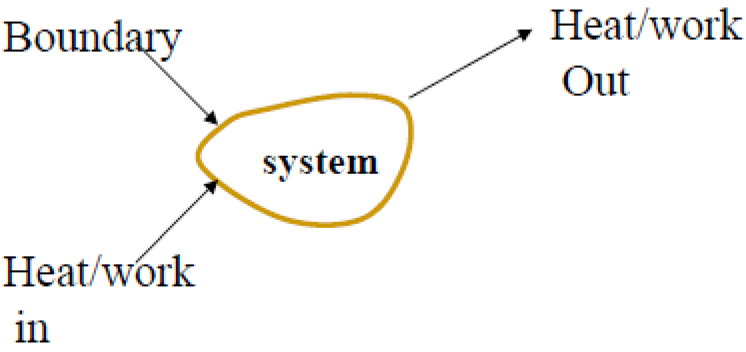


(*b*) A control volume with fixed and moving boundaries

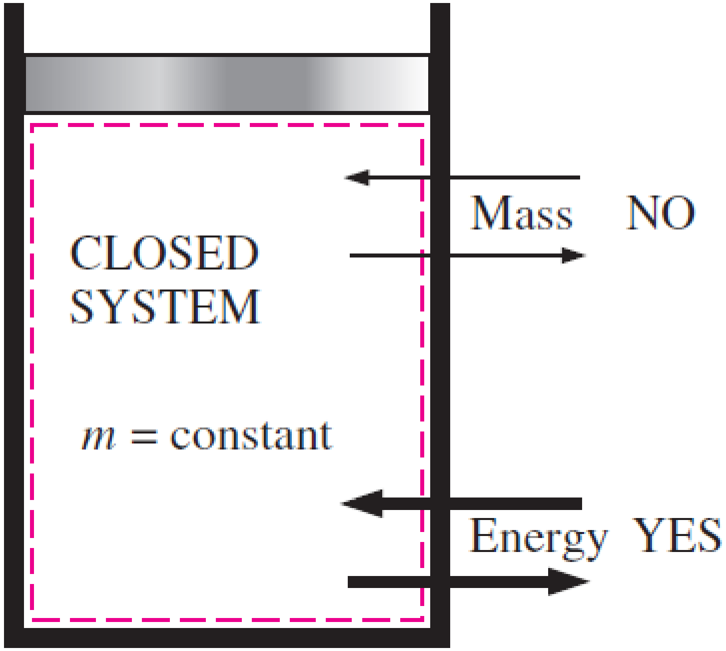


- *<u>Both mass and energy can cross the boundary</u>* of a control volume
- Eg. compressor, turbine, nozzle

Closed System

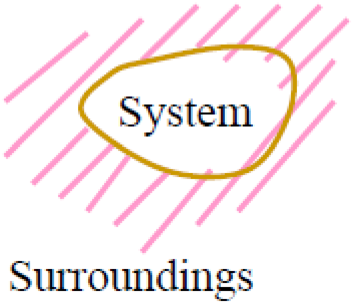


No mass entry or exit



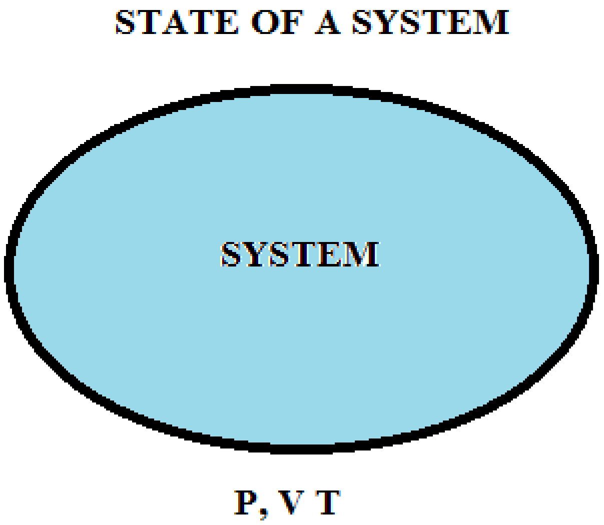
- Fixed amount of mass, and *no mass can cross its boundary*
- Energy in the form of heat or work, can cross the boundary; and the volume of a closed system does not have to be fixed

Isolated system



- There is *no interaction between system and the surroundings*. It is of fixed mass and energy, and hence there is no mass and energy transfer across the system boundary
- Eg. Universe

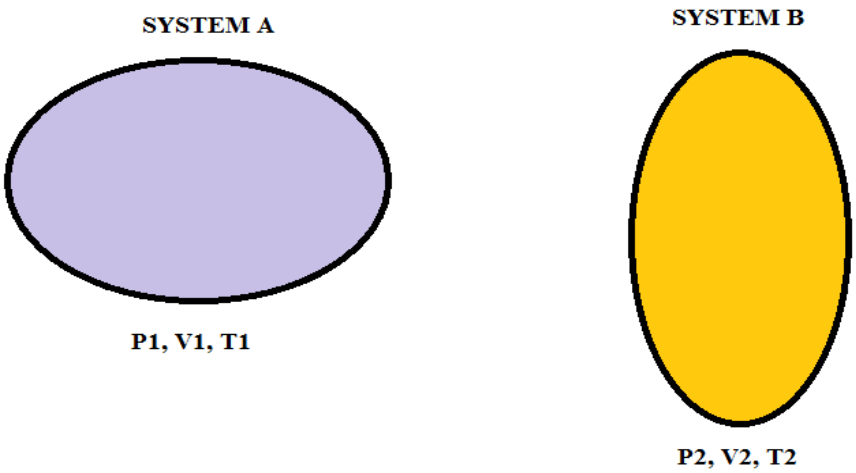
State of a System

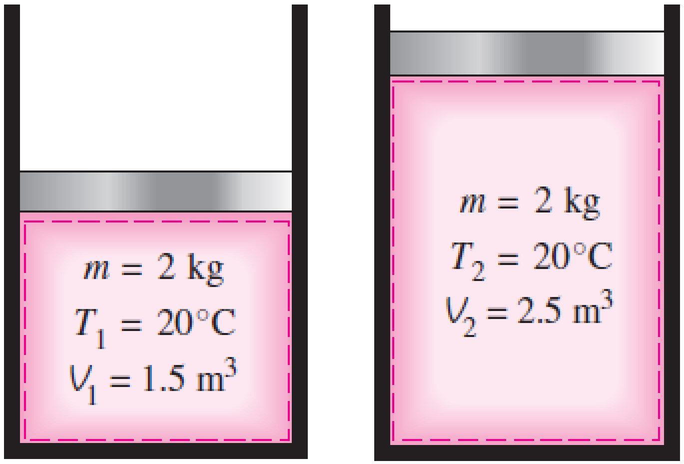


- *Condition of physical existence of a system* at any instant
- State of a thermodynamic system is described by specifying its thermodynamic co-ordinates or thermodynamic properties
- At a given state, all the properties of a system have fixed values

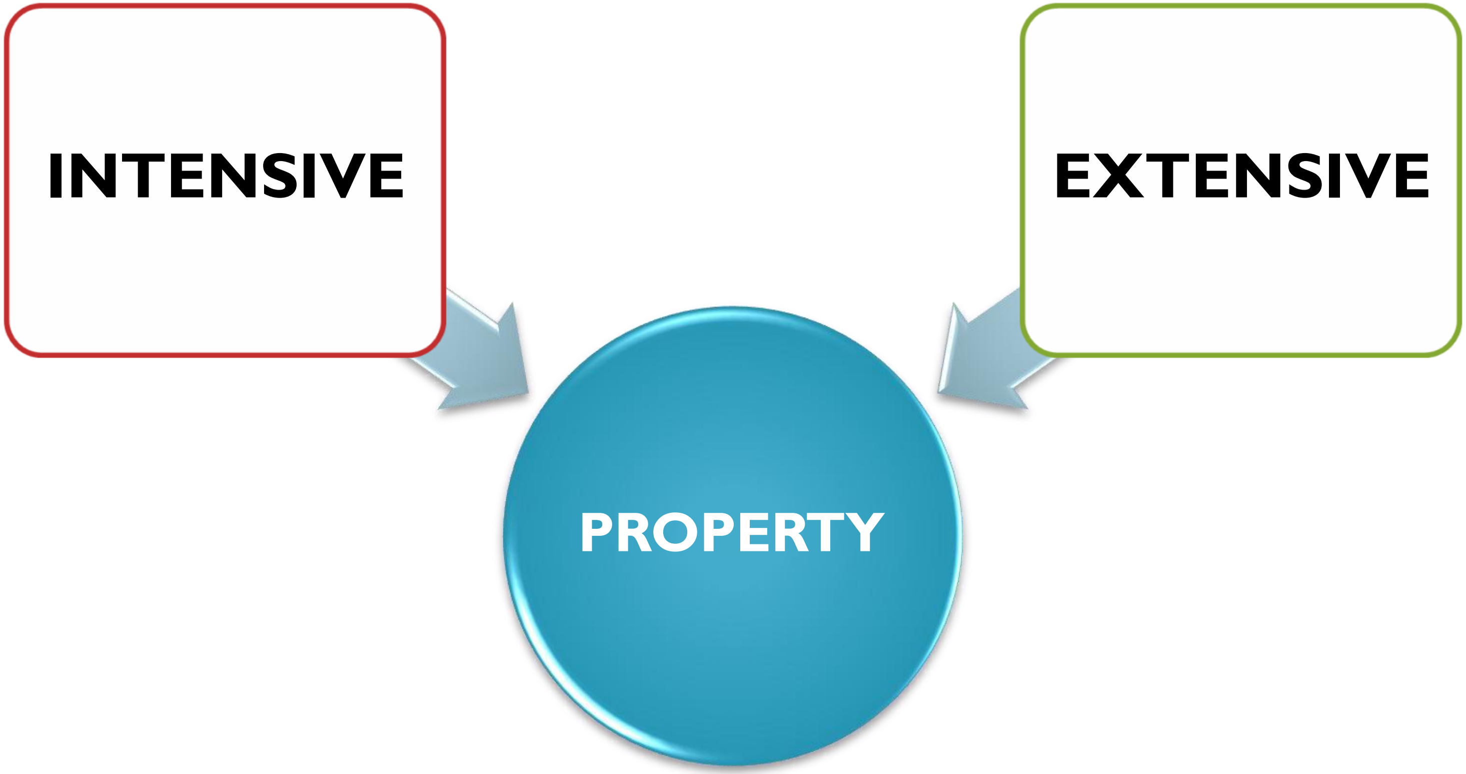
Properties of a System

- Any characteristic of a system is called a property. Some familiar properties are Pressure P, Temperature T, Volume V, and Mass m.
- *Quantities which identify the state of a system*. Property must have a definite value when the system is at a particular state.





State 1 State 2



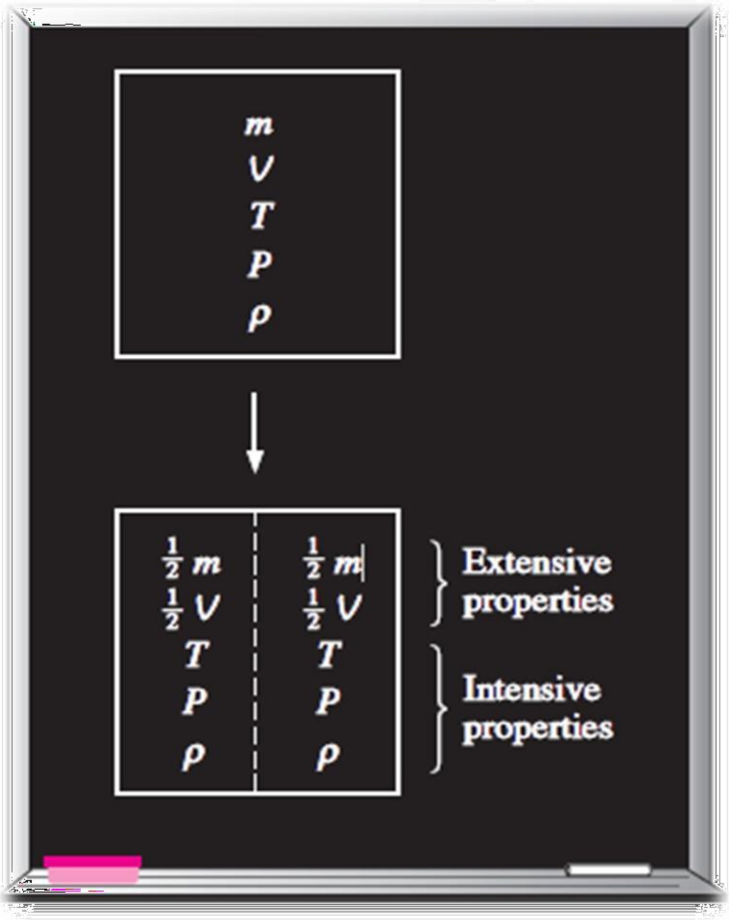
INTENSIVE

EXTENSIVE

PROPERTY

- Intensive properties are those that are **<u>independent of the mass</u>** of a system, such as temperature, pressure, and density

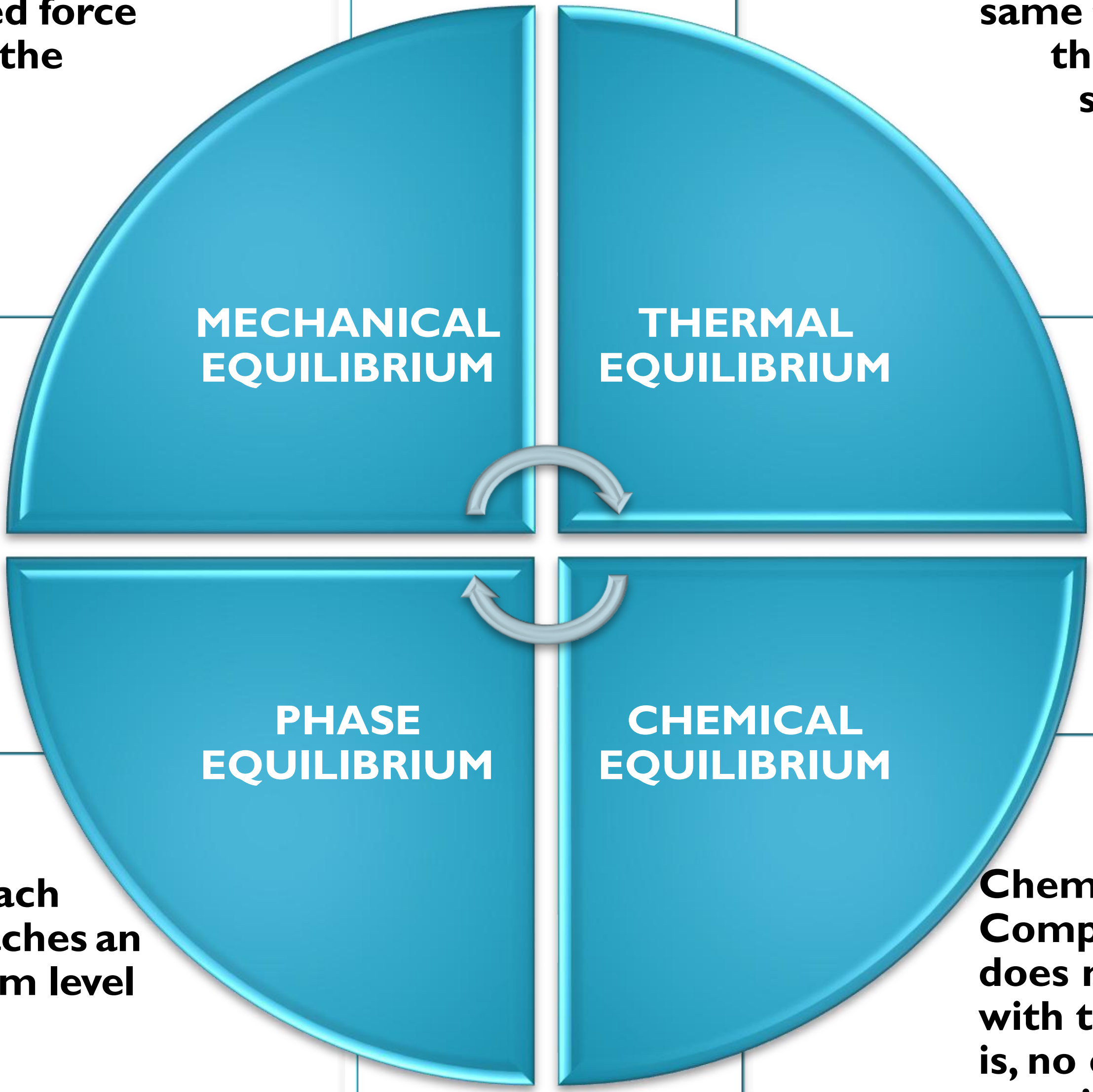
- Extensive properties are those whose values **<u>depend on the size</u>**—or extent—of the system. Total mass, total volume, and total momentum are some examples of extensive properties



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*. A system in equilibrium experiences no changes when it is isolated from its surroundings.
- A system is said to be in thermodynamic equilibrium , if it satisfies the following requirements of equilibrium

  - ❖Mechanical equilibrium
  - ❖Thermal equilibrium
  - ❖Chemical equilibrium
  - ❖Phase equilibrium



MECHANICAL EQUILIBRIUM

- There is no unbalanced force acting on the system

THERMAL EQUILIBRIUM

- Temperature is same throughout the entire system

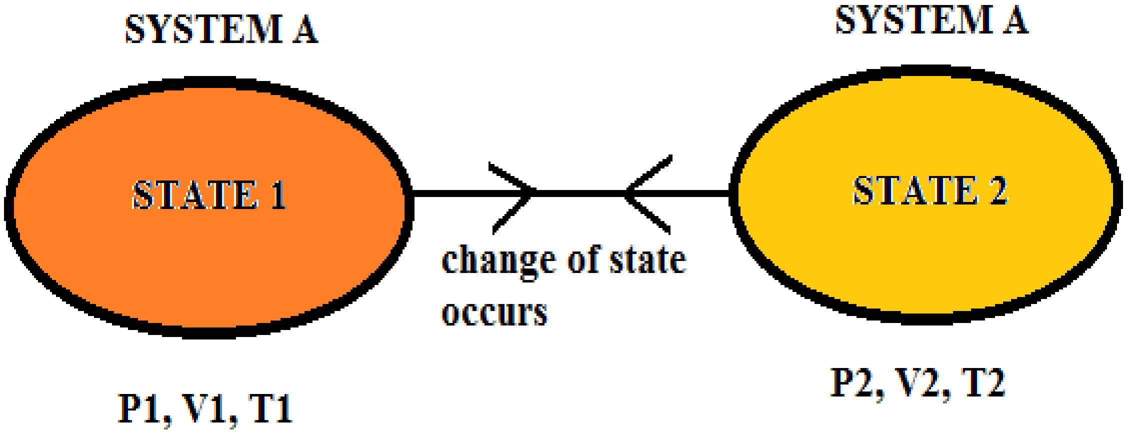
PHASE EQUILIBRIUM

- Mass of each phase reaches an equilibrium level

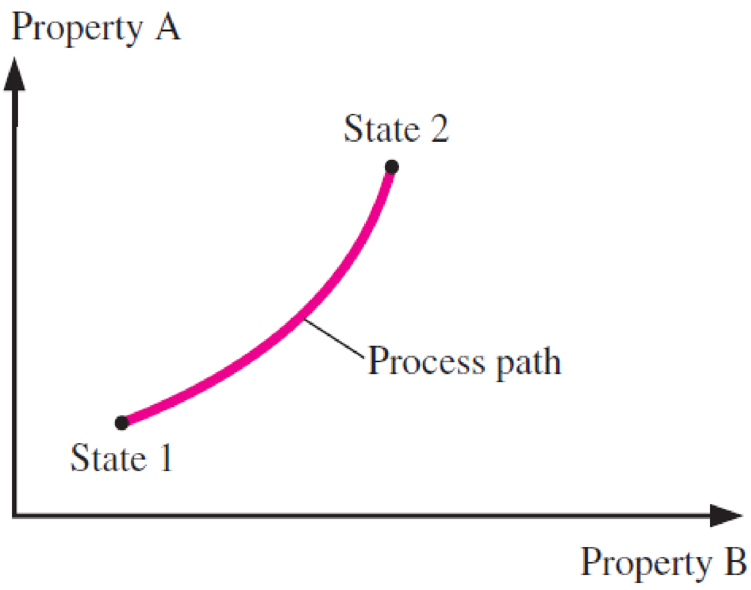
CHEMICAL EQUILIBRIUM

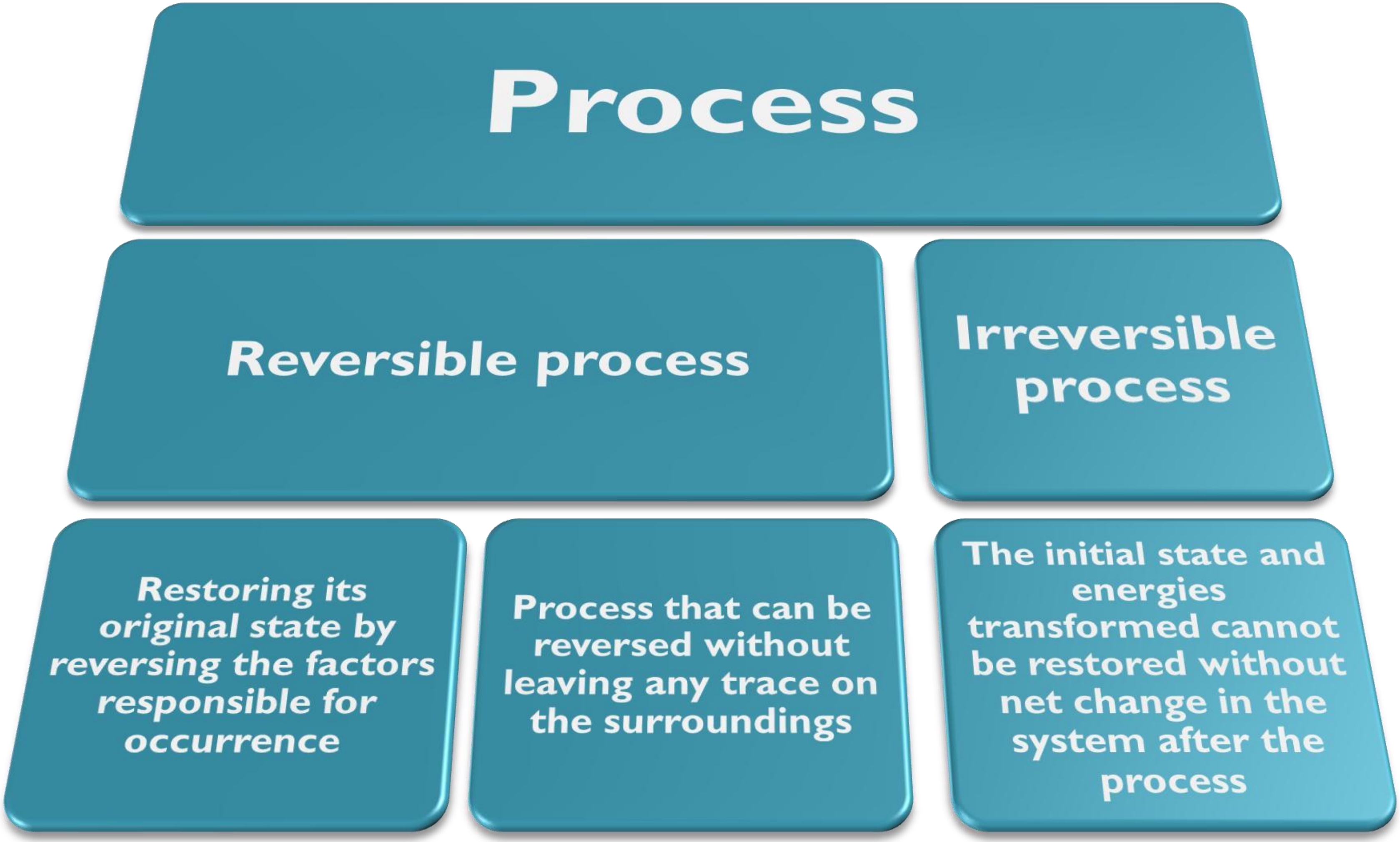
Chemical Composition does not change with time, that is, no chemical reactions occur

PROCESS



- Any change that a *system undergoes from one equilibrium state to another* is called a **process**
- Transformation from one state to another





Process

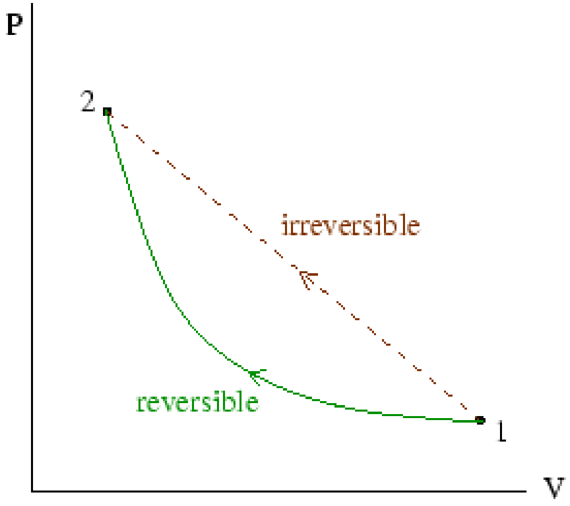
Reversible process

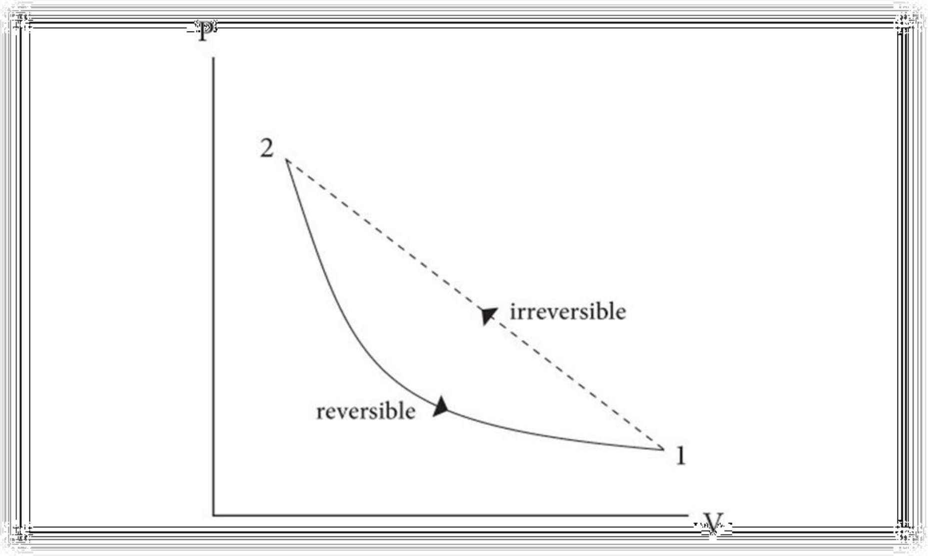
Restoring its original state by reversing the factors responsible for occurrence

Process that can be reversed without leaving any trace on the surroundings

Irreversible process

The initial state and energies transformed cannot be restored without net change in the system after the process





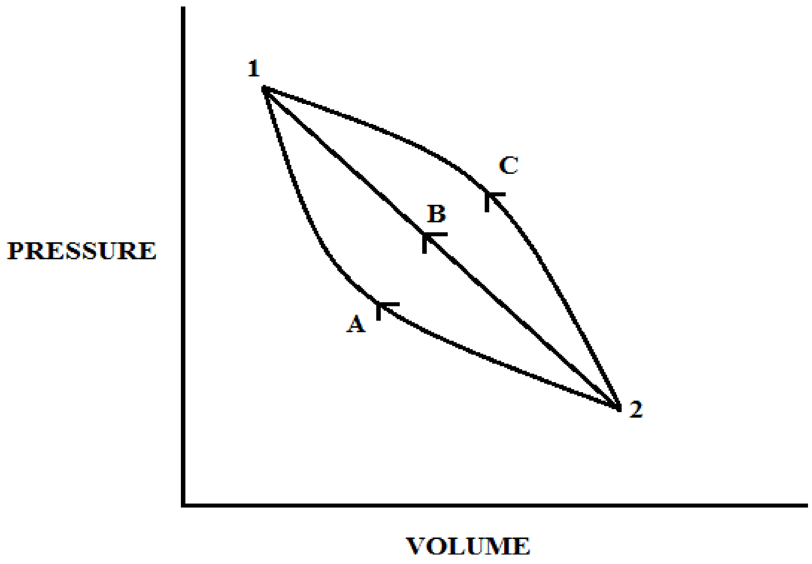
- In reversible process, *two states can be shown by a continuous line*
- Reversible process is an ideal process

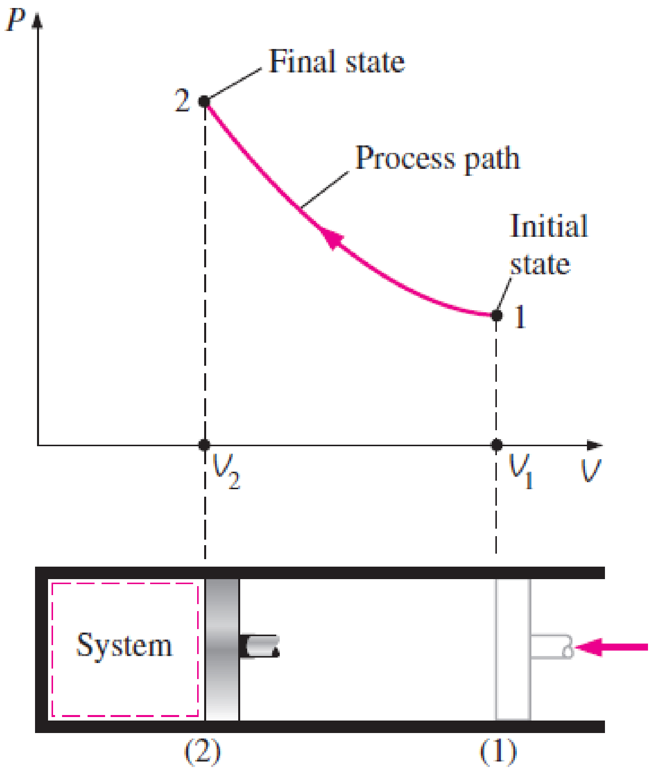
- Irreversible process is usually *represented by a dotted line joining the end states*
- In a real process, the intermediate state points cannot be located

Factors for Irreversibility

- Friction
- Chemical reactions
- Viscosity
- Inelastic deformation of solids
- Electric resistance
- Unrestrained expansion
- Mixing of two fluids
- Heat transfer across a finite temperature difference

PATH





- The *series of states through which a system passes* during a process is called the **path of the process**

- To describe a process completely, one should specify the initial and final states of the process, as well as the path it follows, and the interactions with the surroundings

Path and Point Functions

- **Path Functions**

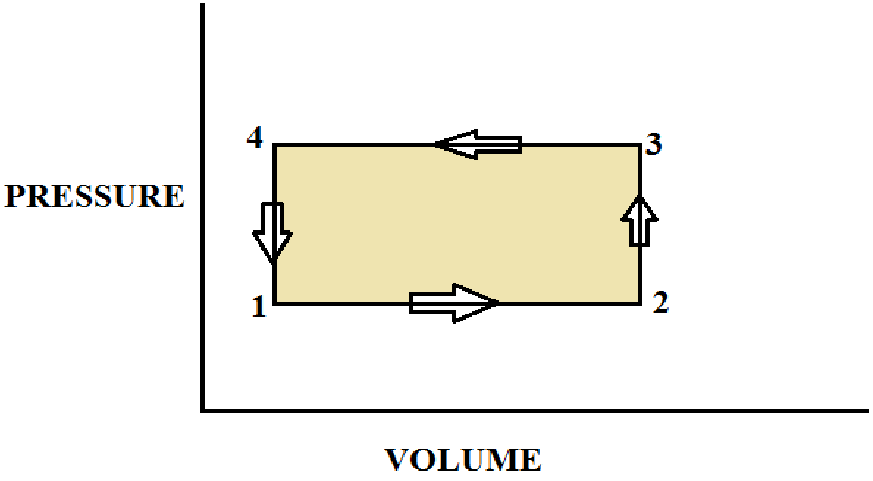
- If the value of the *thermodynamic variable depends upon the path* followed in going from one state to another
- Path functions are not properties of the system
- Path functions have inexact differentials designated by the symbol ‘δ’
- Eg. Work(W), Heat(Q)
- $\int_1^2 \delta W = W_{12}$; Not $(\mathbf{W_2 - W_1})$; Not $\mathbf{dW}$
- $\int_1^2 \delta \mathbf{Q} = \mathbf{Q}_{12}$; Not $(\mathbf{Q_2 - Q_1})$; Not $\mathbf{dQ}$

- **POINT FUNCTIONS**

- *Properties does not depend on the path followed* in reaching the state, but only on the equilibrium state itself
- Point functions are properties of the system
- Point functions have exact differentials designated by the symbol ‘d’
- Eg. Pressure, Volume, Temperature, Density, Enthalpy, Entropy

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

CYCLE



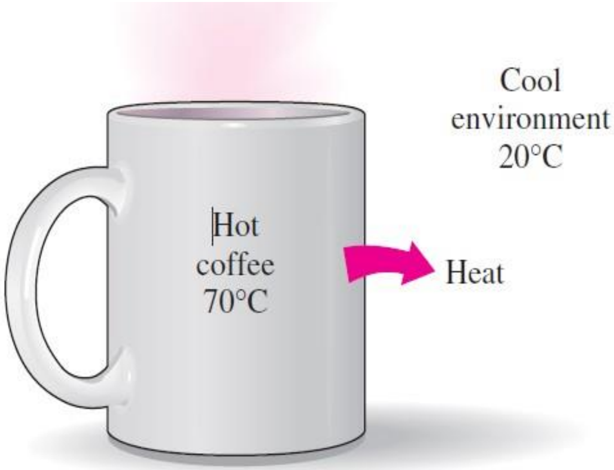
- When a *system in a given initial state experiences a series of processes and returns to the initial state*, the system undergoes a cycle. At the end of the cycle the properties of the system have the same values they had at the beginning.
- Thermodynamic path in a cycle is in closed loop form
- **Cyclic integral of any property in a cycle is zero**
- $\oint$**dp =0** ; '**p**' is any thermodynamic property

Temperature and The Zeroth Law of Thermodynamics

- *Degree of hotness or coldness of a body or environment*

- The equality of temperature is the only requirement for thermal equilibrium

- Driving potential causing the flow of energy as heat



Gas Temperature

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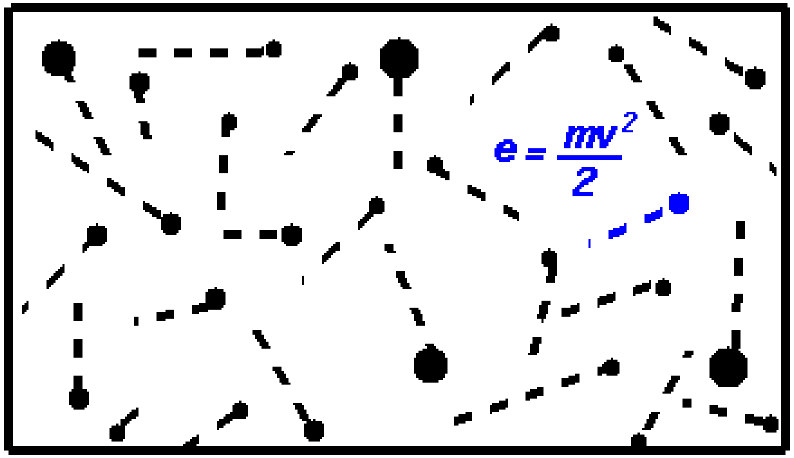
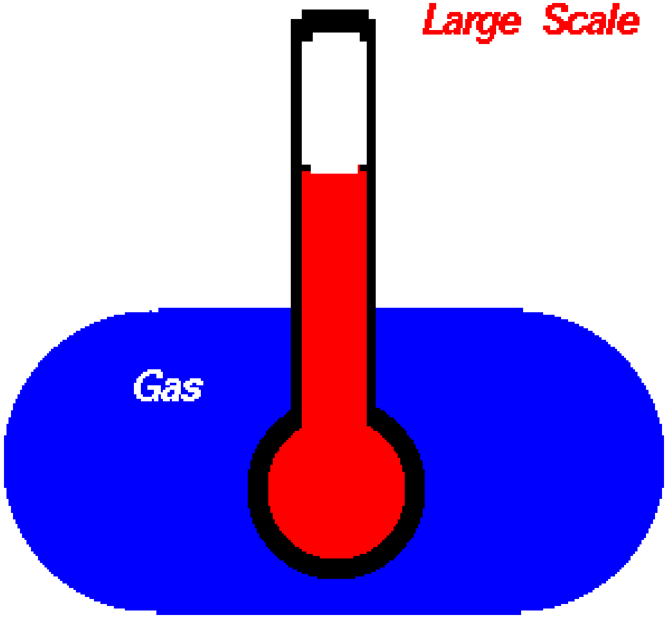
Small Scale

m = mass　*v = velocity*
e = kinetic energy



Temperature is a measure of the average kinetic energy of translation of the gas molecules.

Large Scale

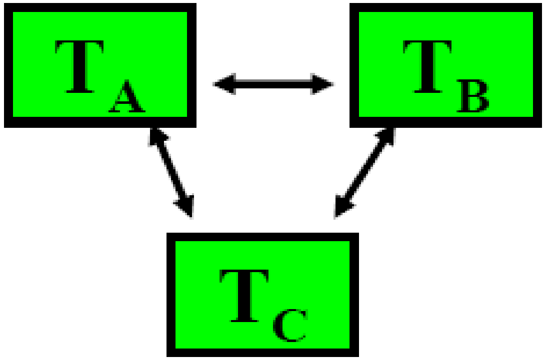


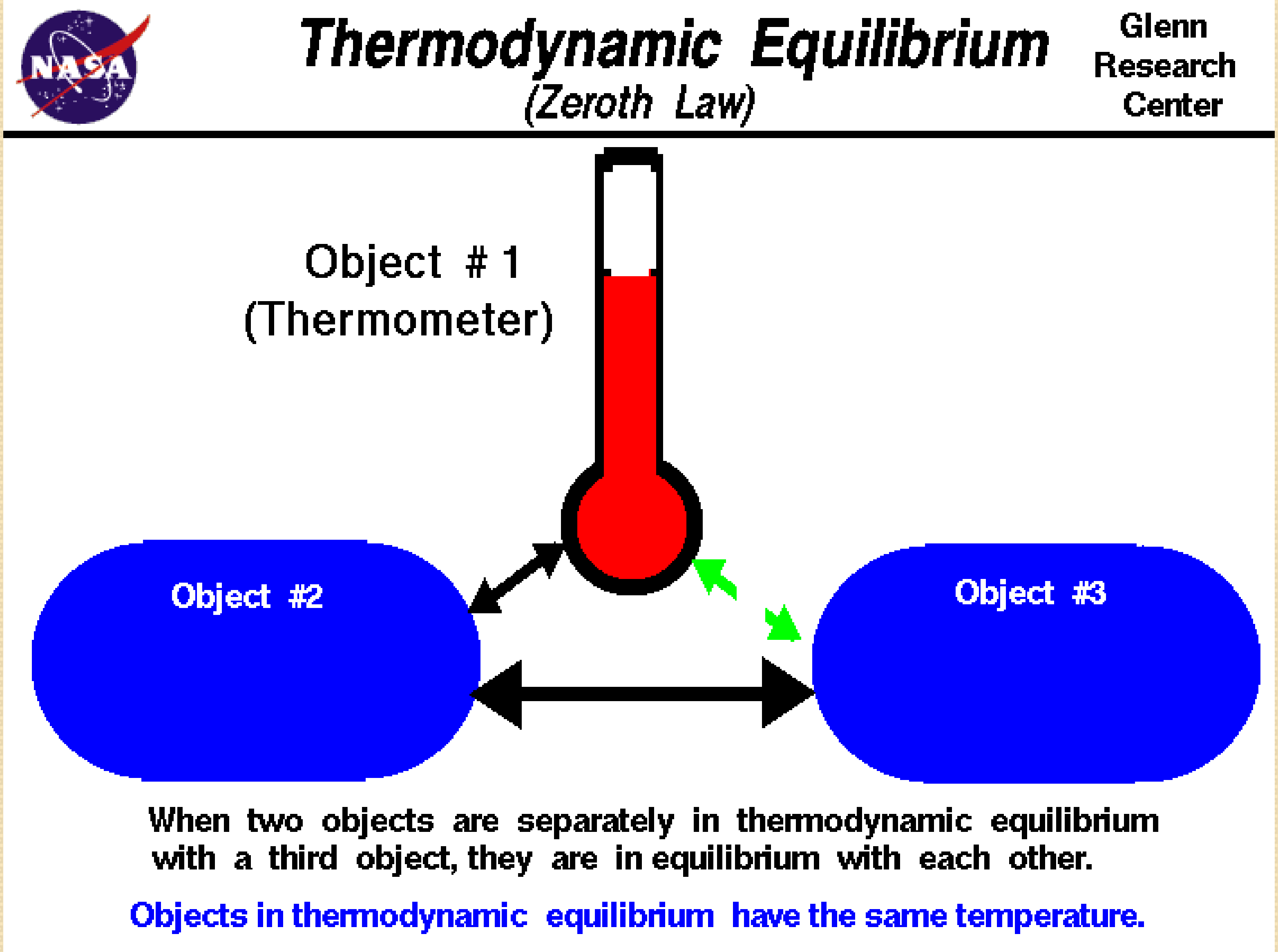
Objects in thermal equilibrium have the same temperature.

Temperature is a scalar quantity.
(magnitude, no direction)

Zeroth Law of Thermodynamics

- The zeroth law was first formulated and labelled by R. H. Fowler in1931
- ***If two systems (say A and B) are in thermal equilibrium with a third system (say C) separately (that is A and C are in thermal equilibrium; B and C are in thermal equilibrium) then they are in thermal equilibrium themselves (that is A and B will be in thermal equilibrium)***
- All temperature measurements are based on this LAW





Thermodynamic Equilibrium

(Zeroth Law)

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When two objects are separately in thermodynamic equilibrium with a third object, they are in equilibrium with each other.

Objects in thermodynamic equilibrium have the same temperature.

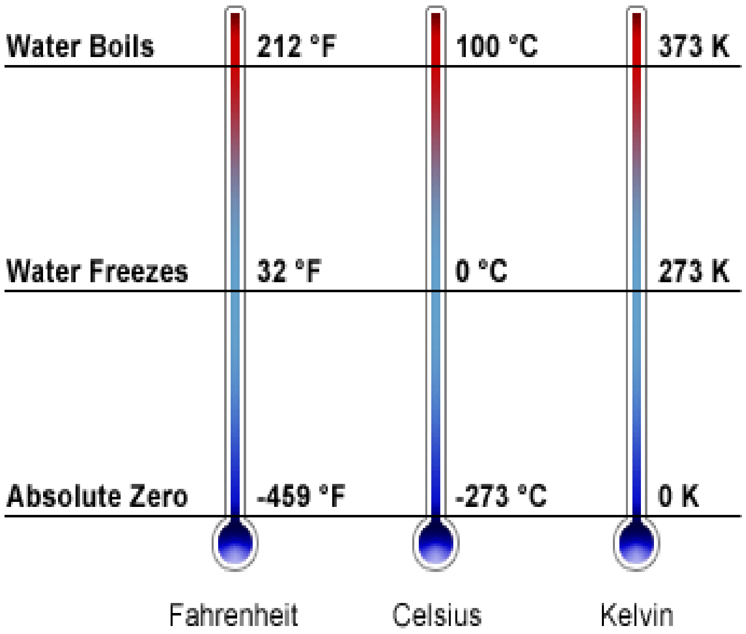
Temperature Scales

- Temperature scales enable us to use a common basis for temperature measurements

- **Celsius scale** (A. Celsius, 1702–1744); 0^{0}C - 100^{0}C

- **Fahrenheit scale** (G. Fahrenheit, 1686–1736) ; 32^{0}F – 212^{0}F; $T(^{0}F) = 1.8\,T(^{0}C) + 32$

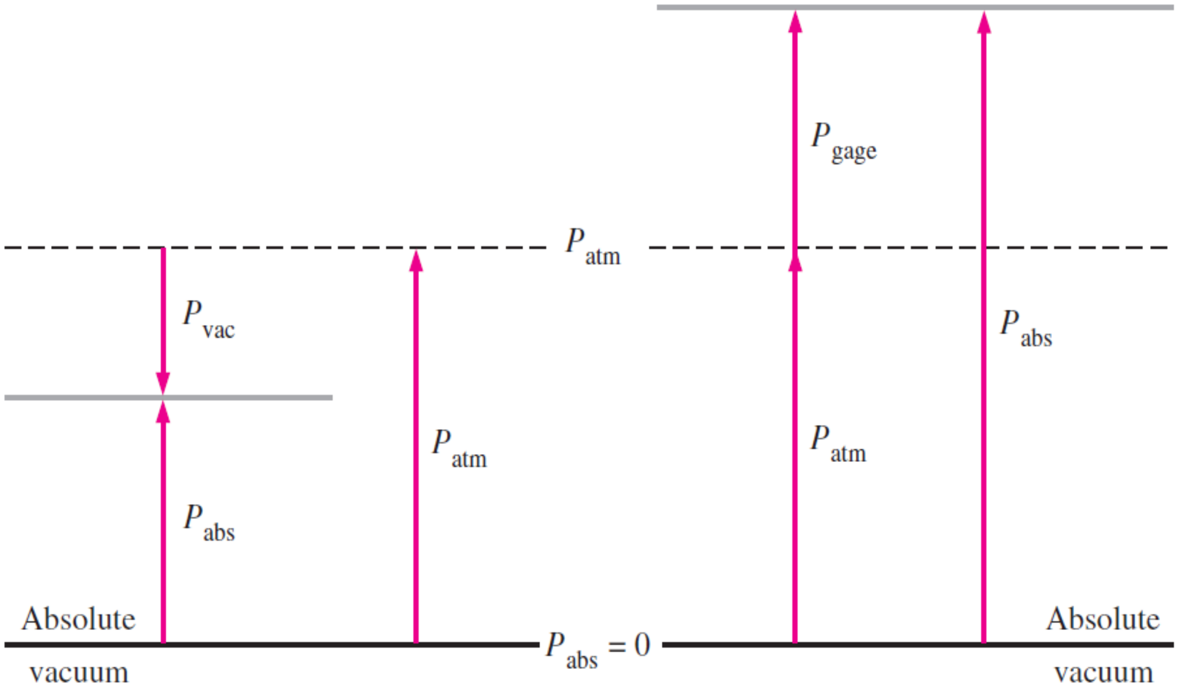
- **Kelvin scale** (Lord Kelvin,1824–1907);   273.15K - 373.15K ; $T(K) = T(^{0}C) + 273.15$



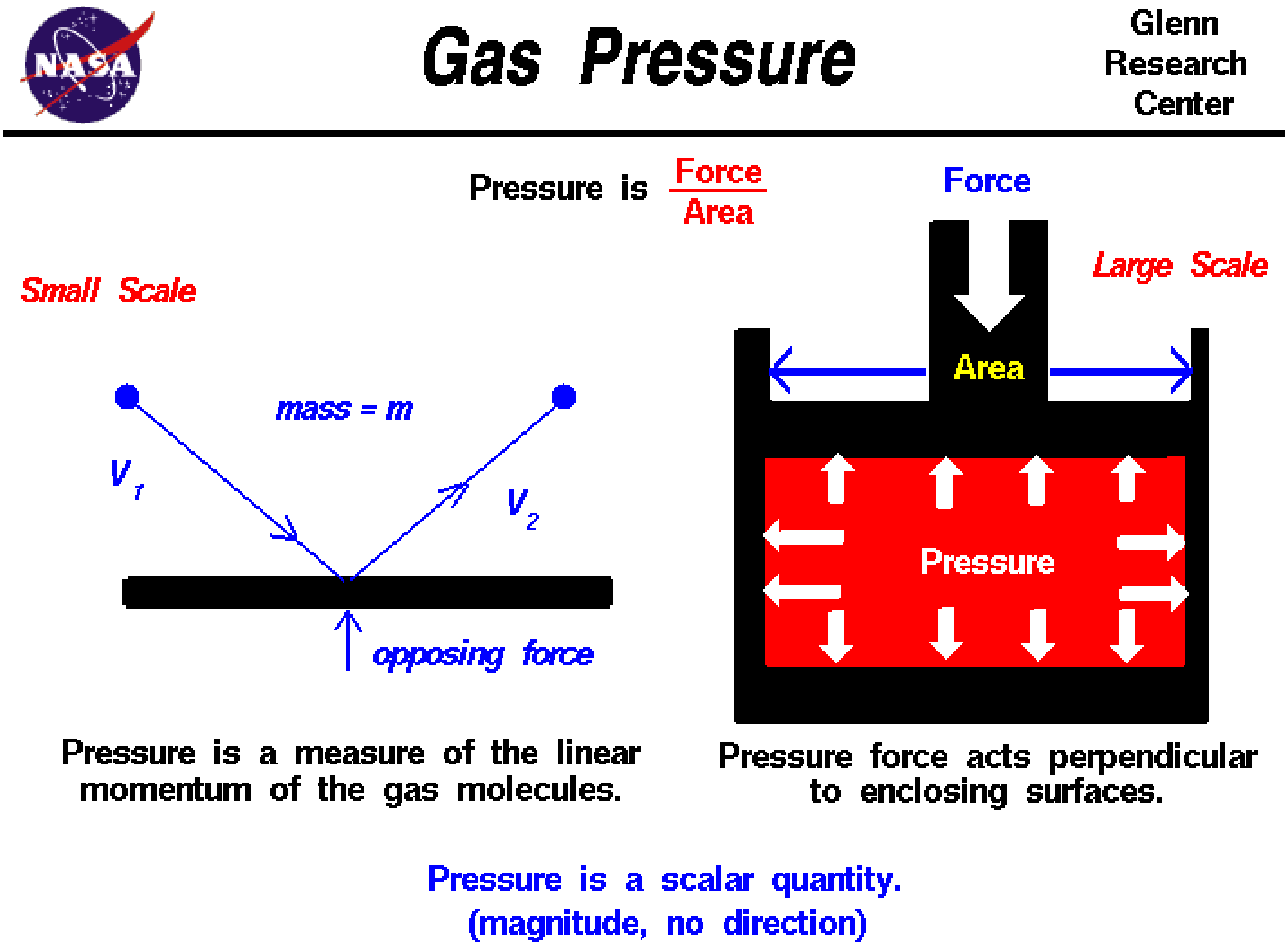
Absolute Zero

Thermometers compare Fahrenheit, Celsius, and Kelvin scales

Pressure



- Pressure is defined as a normal force exerted by a fluid per unit area
- 1Pa = 1N/m^2 ; 1 bar = 10^5 N/m^2 ; 1atm = 1.01325 x 10^5 N/m^2
- $\mathbf{P_{gage} = P_{abs} - P_{atm}}$; P_{gage} - gauge pressure, P_{abs} - absolute pressure
- $\mathbf{P_{vac} = P_{atm} - P_{abs}}$; P_{atm} - atmospheric pressure, P_{vac} - vacuum pressure



Gas Pressure

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

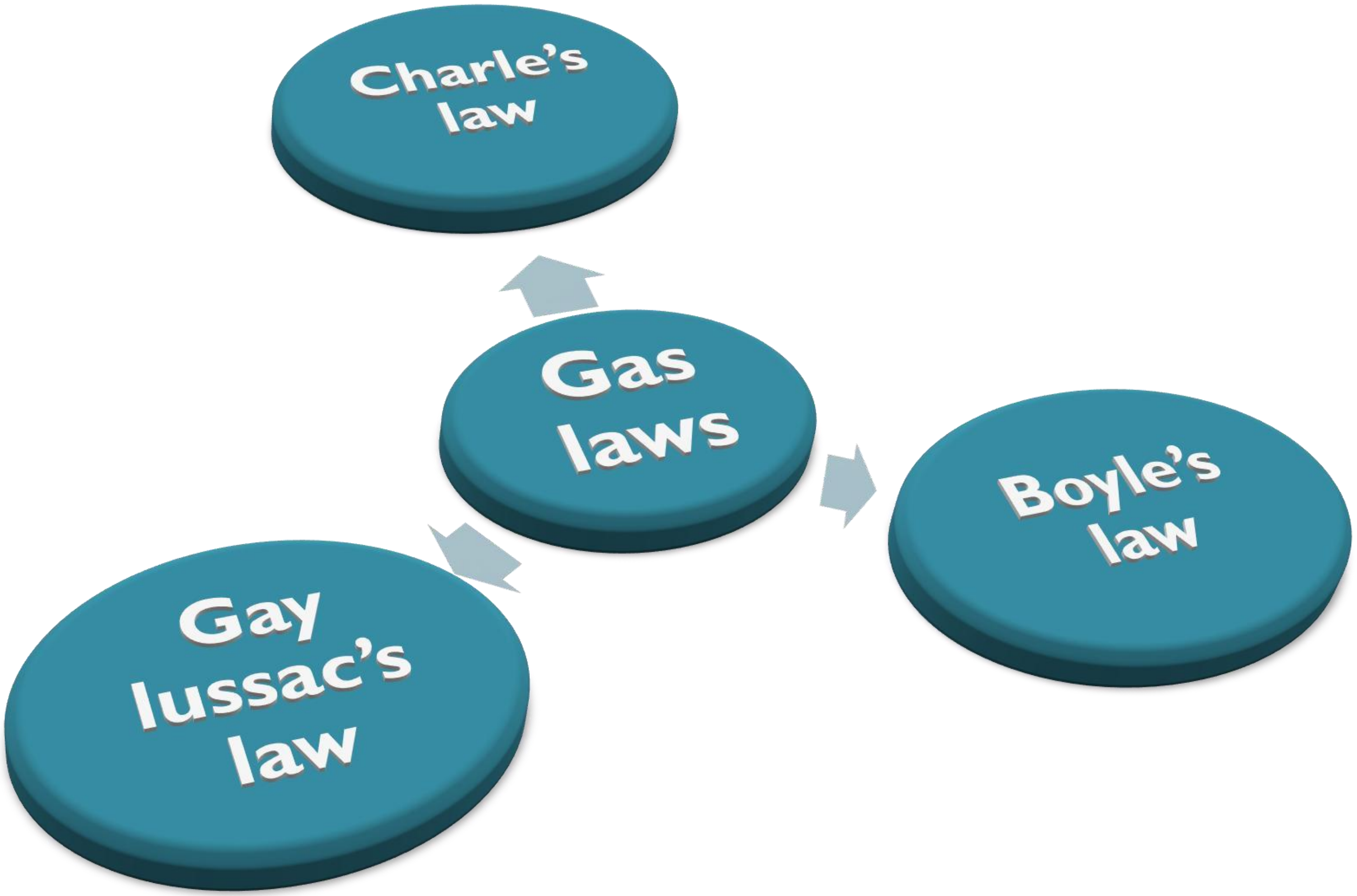
Small Scale

Pressure is a measure of the linear momentum of the gas molecules.

Large Scale

Pressure force acts perpendicular to enclosing surfaces.

Pressure is a scalar quantity.
(magnitude, no direction)



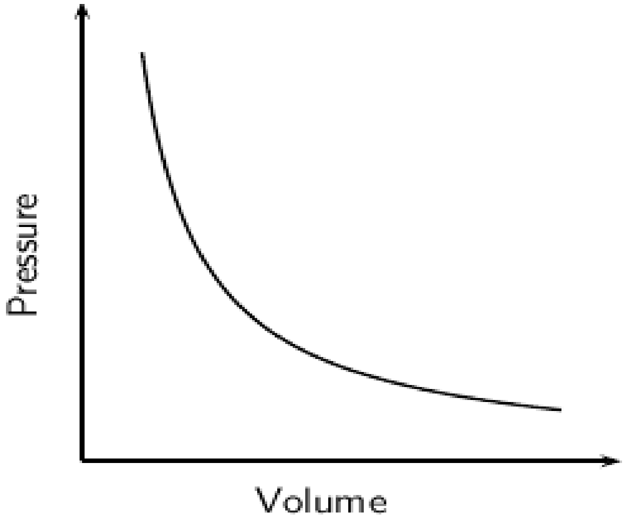
Charle's law

Gas laws

Boyle's law

Gay lussac's law

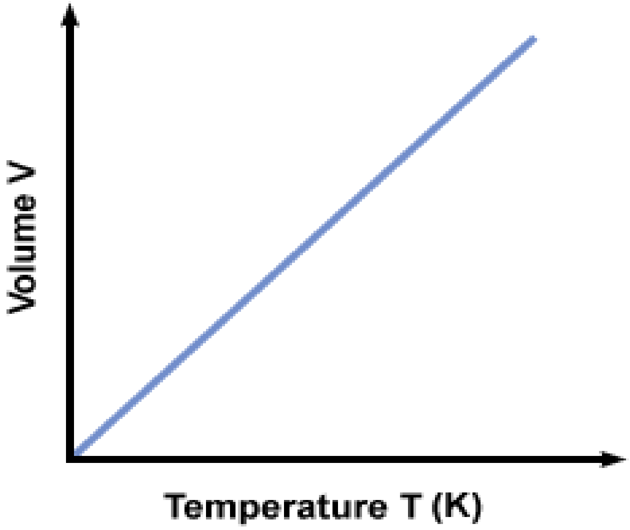
Boyle’s Law



- Formulated by Robert Boyle in 1662
- *It states that absolute pressure of a given mass of a perfect gas varies inversely as its volume, when the temperature remains constant*

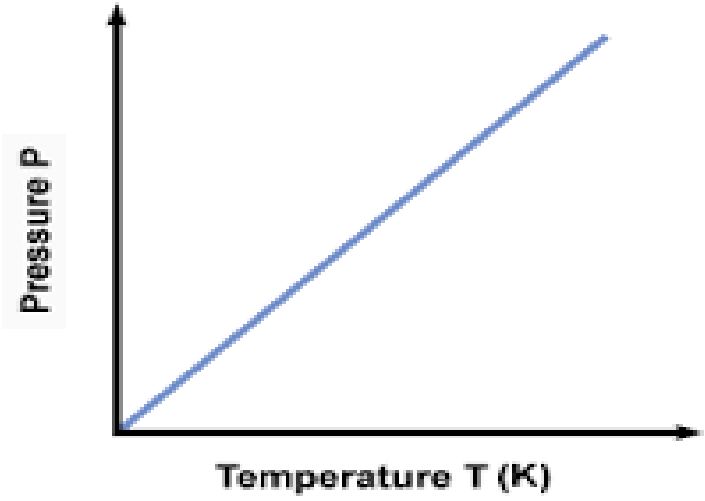
- **$V \alpha 1/P$, T = constant**
- **PV = constant, T = constant**
- **$P_1V_1 = P_2V_2 = P_3V_3 = PV$ = constant, T = constant**

Charle’s Law

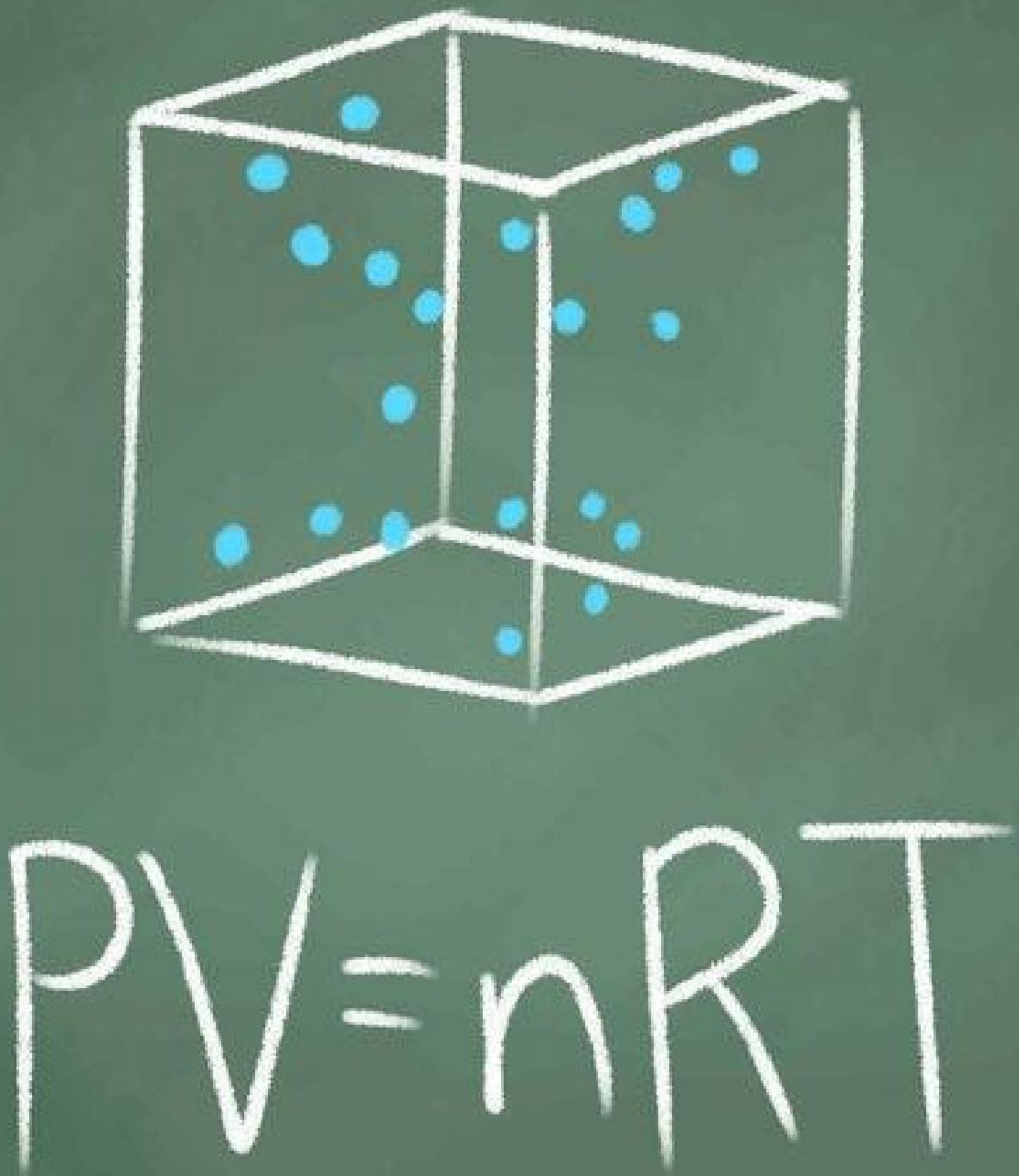


- Formulated by A.C Charles in 1787
- *It states that, the volume of a given mass of a perfect gas varies directly as its absolute temperature, if the pressure remains constant*
- **$V \alpha T$, P = constant**
- **V/T = constant, P = constant**
- **$V_1/T_1 = V_2/T_2 = V_3/T_3 = V/T$ = constant, P = constant**

Gay Lussac's Law



- Formulated by Joseph Louis Gay-Lussac(1778–1850)
- *It states that, the absolute pressure of a given mass of a perfect gas varies directly as its absolute temperature, if the volume remains constant*
- **P α T, V = constant**
- **P/T = constant, V = constant**
- **$P_1/T_1 = P_2/T_2 = P_3/T_3 = P/T$ = constant, V = constant**


PV=nRT

Characteristic Gas Equation

- *Combining the 3 gas laws obtain a relationship between Pressure, Volume & Temperature*
- A perfect or ideal gas is the gas which strictly obeys all the gas laws under all conditions of pressure and temperature. Also, a theoretical gas composed of a set of randomly moving non- interacting point particles
- **$PV/T = \text{constant}$**
- **$P_1V_1/T_1 = P_2V_2/T_2 = P_3V_3/T_3 = PV/T = \text{constant}$**
- **$PV = mRT$ (**Characteristic gas equation)

; m-mass, R-characteristic gas constant

For air R = 287 J/KgK

Universal Gas Constant

- Product of molecular weight and characteristic gas constant of any gas is constant
- **$R_u = R \times M$**
- **R_u = 8314 J/Kg mol K**

Substance	Atomic mass	Molecular mass
Hydrogen	1	2
Oxygen	16	32
Carbon	12	-
Steam or water	-	18

Real Gas And Real Gas Equations

- Real gas behaves more like an ideal gas when it is under **high temperature and low pressure**
- The deviation from ideal-gas behavior at certain ranges of temperature and pressure can accurately be accounted for by the introduction of a correction factor called the **compressibility factor, Z**
- **Z = PV/mRT**

- Mathematical equations of state for analyzing the real gas behavior are
  - Van der-Waals Equation
  - Berthelot Equation
  - Dieterici Equation
  - Redlich-Kwong Equation
  - Beattie-Bridgeman Equation
  - Martin-Hou Equation

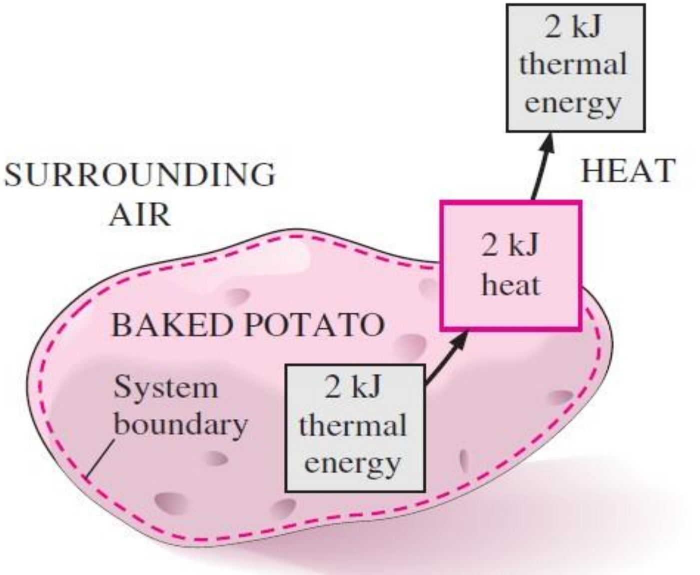
Van der-Waals Equation

- Improving the ideal-gas equation of state by including two of the effects not considered in the ideal-gas model; the **intermolecular attraction forces and the volume occupied by the molecules themselves**

- **$(P + a/v^2)(v-b) = RT$** ; **v**-specific volume, **a**- mutual attraction of molecules, **a/v^2**- accounts for cohesion forces, **b**- accounts for the volume of molecules

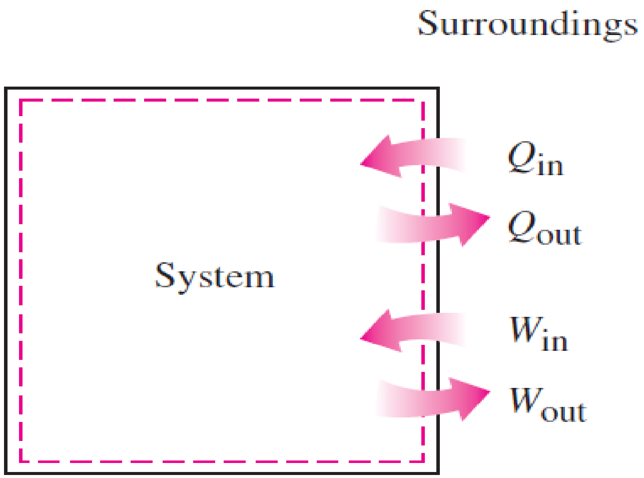
- Real gas conform more closely with the van der Waals equation of state than the ideal gas equation of state, particularly at higher pressures

HEAT



- *Heat is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a* ***temperature difference***
- The transfer of heat into a system is frequently referred to as heat addition and the transfer of heat out of a system as heat rejection
- Heat is transferred by three mechanisms: Conduction, Convection, and Radiation
- A process during which there is no heat transfer is called an adiabatic process

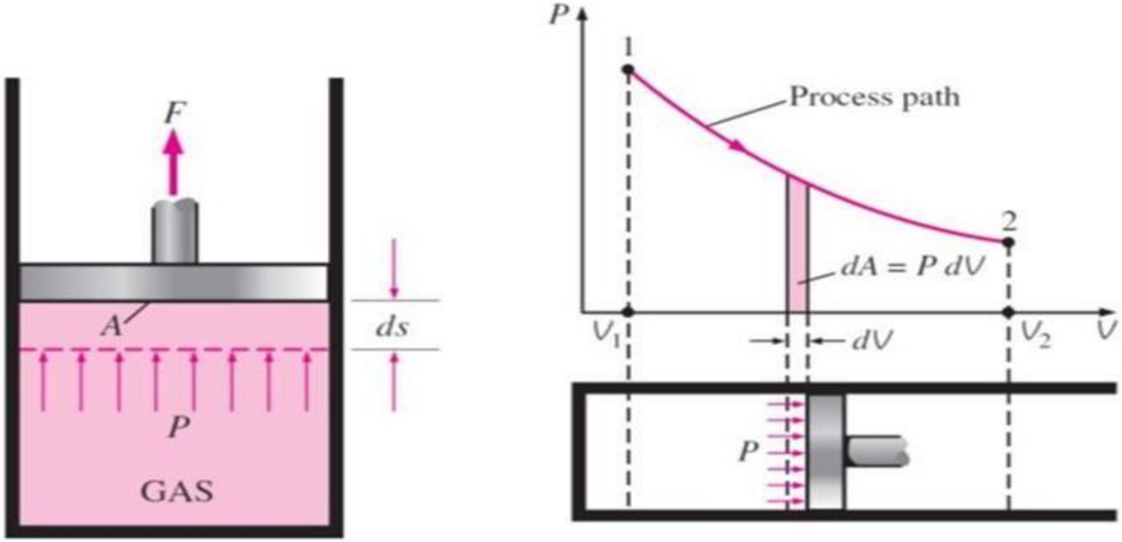
WORK



- Work, like heat, is an energy interaction between a system and its surroundings

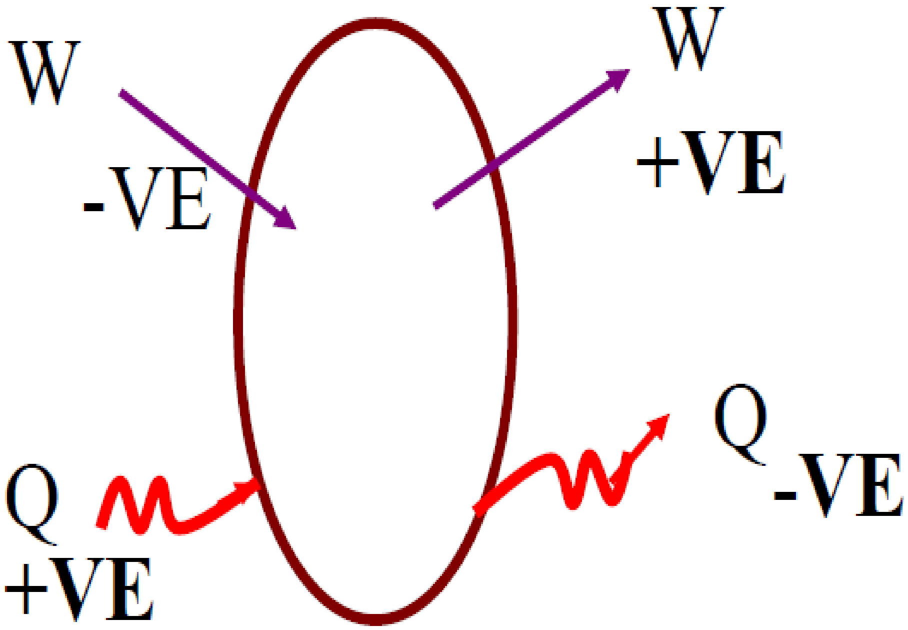
- **Positive work is done by a system when the sole effect external to the system could be reduced to the rise of a weight**

- *Work is the energy transfer associated with a force acting through a distance*. A rising piston, a rotating shaft, and an electric wire crossing the system boundaries are all associated with work interactions



- For a closed system, Work, δW or $\mathbf{W_{1\text{-}2} = \int_1^2 PdV}$, area under the curve 1-2
- Unit , N-m or Joules(J)

Sign Conventions



- Heat transfer to a system and work done by a system are **positive**; heat transfer from a system and work done on a system are **negative**

Similarities Between Heat and Work

- Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are boundary phenomena

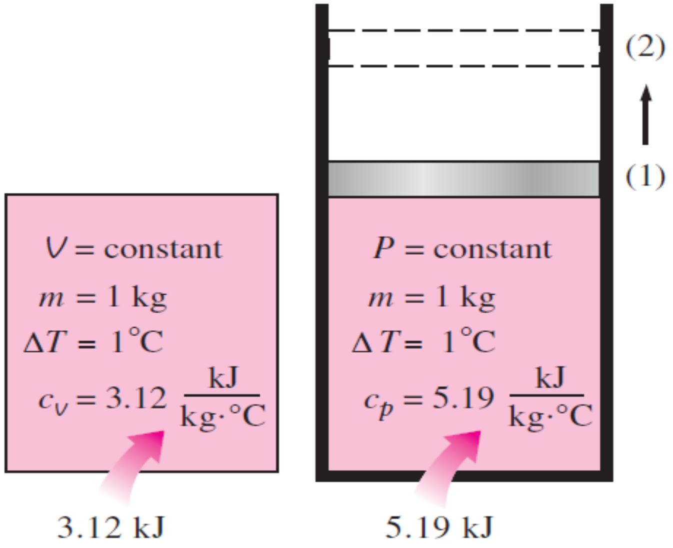
- Systems possess energy, but not heat or work

- Both are associated with a process, not a state. Unlike properties, heat or work has no meaning at a state

- Both are path functions (i.e., their magnitudes depend on the path followed during a process as well as the end states)

- Heat is low grade energy and work is high grade energy

SPECIFIC HEATS

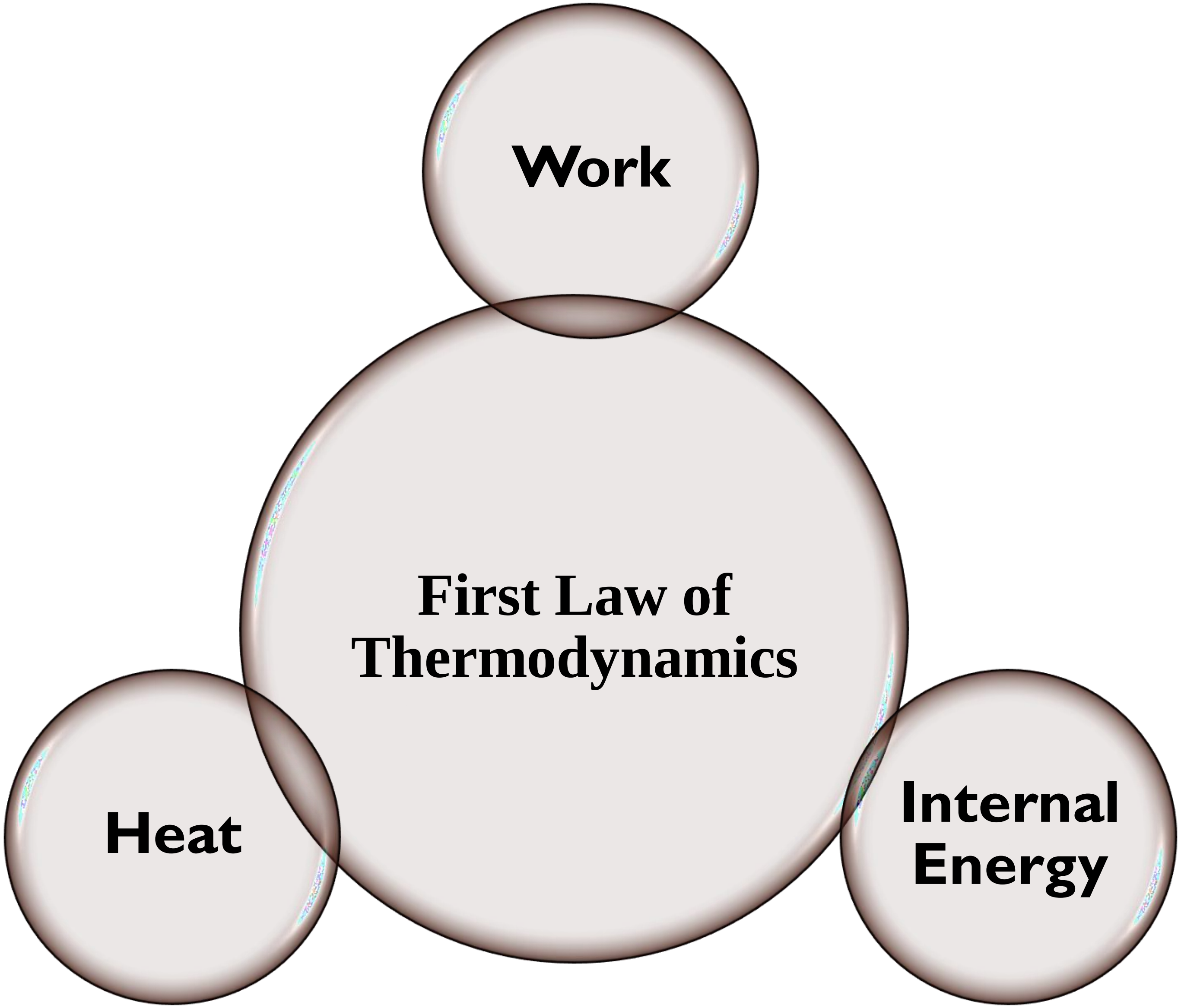


- ***The specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree***
- The specific heat at constant volume, **Cv** can be viewed as the energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant
- The specific heat at constant pressure, **Cp** can be viewed as the energy required to raise the temperature of the unit mass of a substance by one degree as the pressure is maintained constant

- **Heat Capacity, $C = Q/dT$**
- **Specific heat capacity, $c = Q/(mdT)$,** J/Kg K
- **$c_p = Q/[m(T_2-T_1)]$**
- **$c_v = Q/[m(T_2-T_1)]$**
- **$c_p/c_v = \gamma$;** **γ-** ratio of specific heats
- *For air, c_p= 1.005 KJ/Kg K, c_v= 0.718 KJ/Kg K, γ= 1.4*

- The specific heat at constant pressure **Cp is always greater than Cv** because at constant pressure the system is allowed to expand and the energy for this expansion work must also be supplied to the system

Material	**J/kg°C**	**cal/g°C**
Water	4186	1
Ice	2090	0.50
Steam	2010	0.48
Silver	234	0.056
Aluminum	900	0.215
Copper	387	0.0924
Gold	129	0.0308
Iron	448	0.107
Lead	128	0.0305
Brass	380	0.092
Glass	837	0.200
Wood	1700	0.41
Ethyl Alcohol	2400	0.58
Beryllium	1830	0.436



First Law of Thermodynamics

Work

Heat

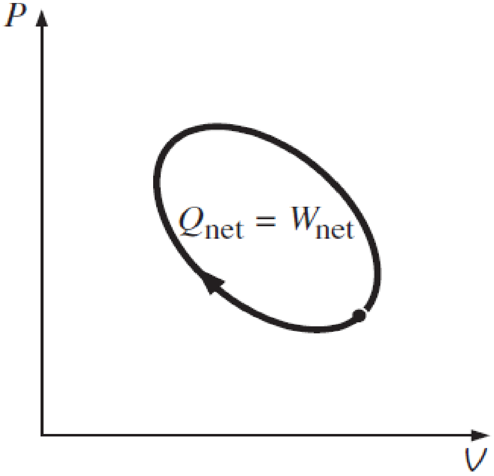
Internal Energy

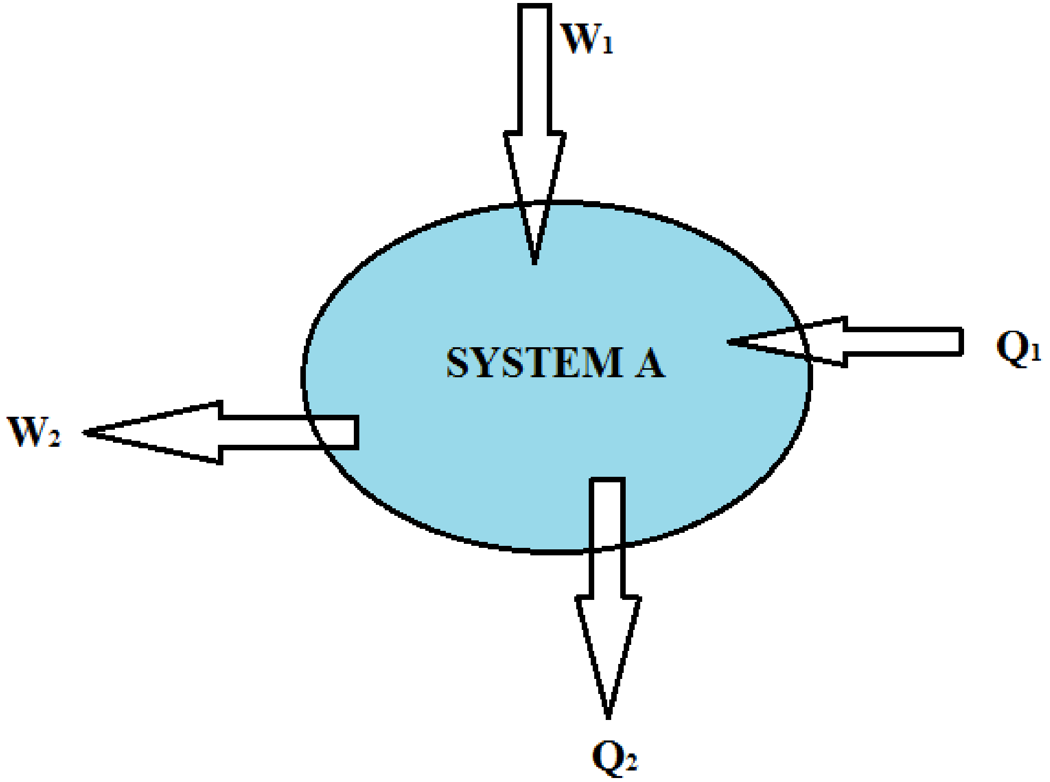
The First Law of Thermodynamics

- The first law of thermodynamics, also known as the conservation of energy principle, provides a sound basis for studying the relationships among the various forms of energy and energy interactions

- *First law states that, When a closed system executes a complete cycle* ***the sum of heat interactions is equal to the sum of work*** *interactions*

- $\sum Q = \sum W$; $Q_{net} = W_{net}$; $\oint \delta Q = \oint \delta W$

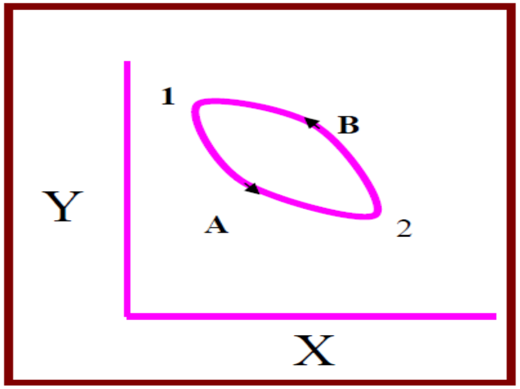




Net heat transfer = Net work transfer

$$\sum Q = \sum W \; ; \quad Q_1 - Q_2 = W_2 - W_1$$

First Law Applied to a Process



$$Q_{A1-2} = \underset{\text{Along path A}}{\int_{1}^{2}} \delta Q$$

$$\underset{\text{Along path A}}{\int_{1}^{2}} (\delta Q - \delta W) + \underset{\text{Along path B}}{\int_{2}^{1}} (\delta Q - \delta W) = 0$$

$$\underset{\text{Along path A}}{\int_{1}^{2}} (\delta Q - \delta W) - \underset{\text{Along path B}}{\int_{1}^{2}} (\delta Q - \delta W) = 0$$

$$\underset{\text{Along path A}}{\int_{1}^{2}} (\delta Q - \delta W) = \underset{\text{Along path B}}{\int_{1}^{2}} (\delta Q - \delta W)$$

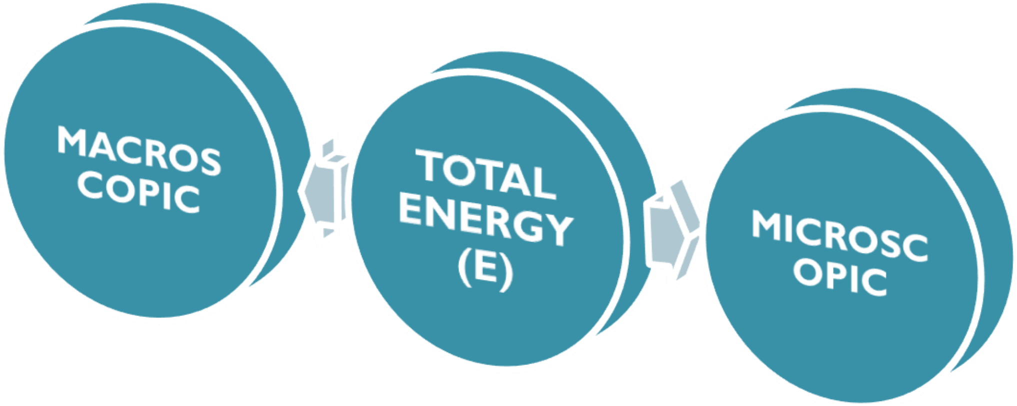
- Since A and B are arbitrarily chosen, the conclusion is, as far as a process is concerned (A or B) the **difference (δQ – δW) remains a constant as long as the initial and the final states are the same**. The difference depends only on the end points of the process. Note that Q and W themselves depend on the path followed. But their difference does not.

- This implies that the difference between the heat and work interactions during a process is a property of the system

- This property is called the **total energy of the system**. It is designated as **E** and is equal to some of all the energies at a given state

- **$\delta Q - \delta W = dE$; E-** total energy of a system

Forms of Energy



- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **total energy E of a system**
- **Total energy, E = Macroscopic Energy + Microscopic Energy**
- Thermodynamics provides no information about the absolute value of the total energy. It deals only with the change of the total energy

- The macroscopic forms of energy are those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies
- The microscopic forms of energy are those related to the molecular structure of a system and the degree of the molecular activity, and they are independent of outside reference frames. The sum of all the microscopic forms of energy is called the **Internal energy** of a system and is denoted by **U**

$$E = U + \mathrm{KE} + \mathrm{PE} = U + m\frac{V^2}{2} + mgz \qquad (\mathrm{kJ})$$

- Energy change = Energy at final state - Energy at initial state

$$\Delta E_{\mathrm{system}} = E_{\mathrm{final}} - E_{\mathrm{initial}} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta \mathrm{KE} + \Delta \mathrm{PE}$$

$$\Delta U = m(u_2 - u_1)$$

$$\Delta \mathrm{KE} = \tfrac{1}{2} m(V_2^2 - V_1^2)$$

$$\Delta \mathrm{PE} = mg(z_2 - z_1)$$

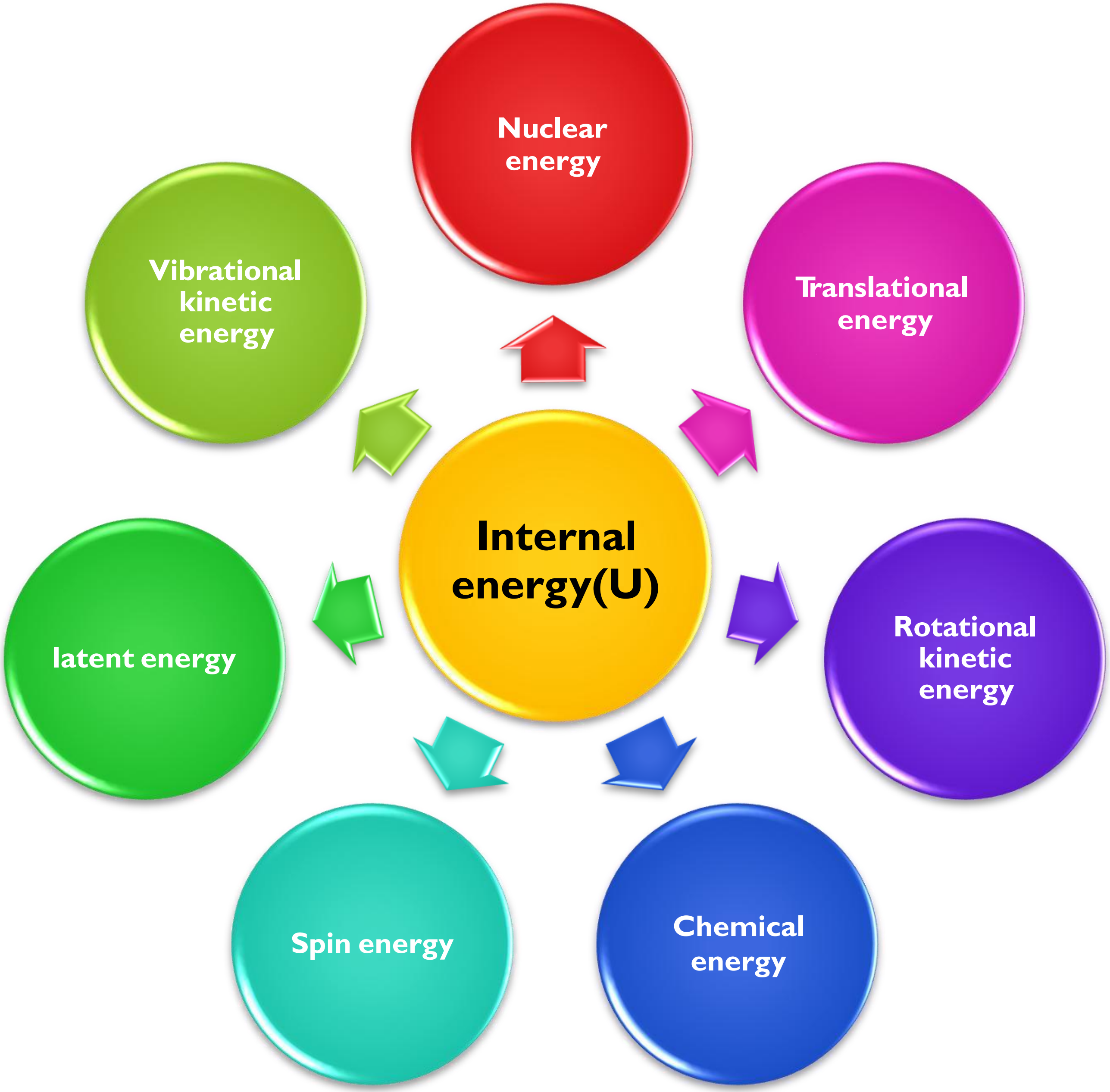
Stationary Systems

$$z_1 = z_2 \rightarrow \Delta \mathrm{PE} = 0$$

$$V_1 = V_2 \rightarrow \Delta \mathrm{KE} = 0$$

$$\Delta E = \Delta U$$

Hence, **$\delta Q - \delta W = dU/\Delta U$**



Internal energy(U)

Nuclear energy

Translational energy

Rotational kinetic energy

Chemical energy

Spin energy

latent energy

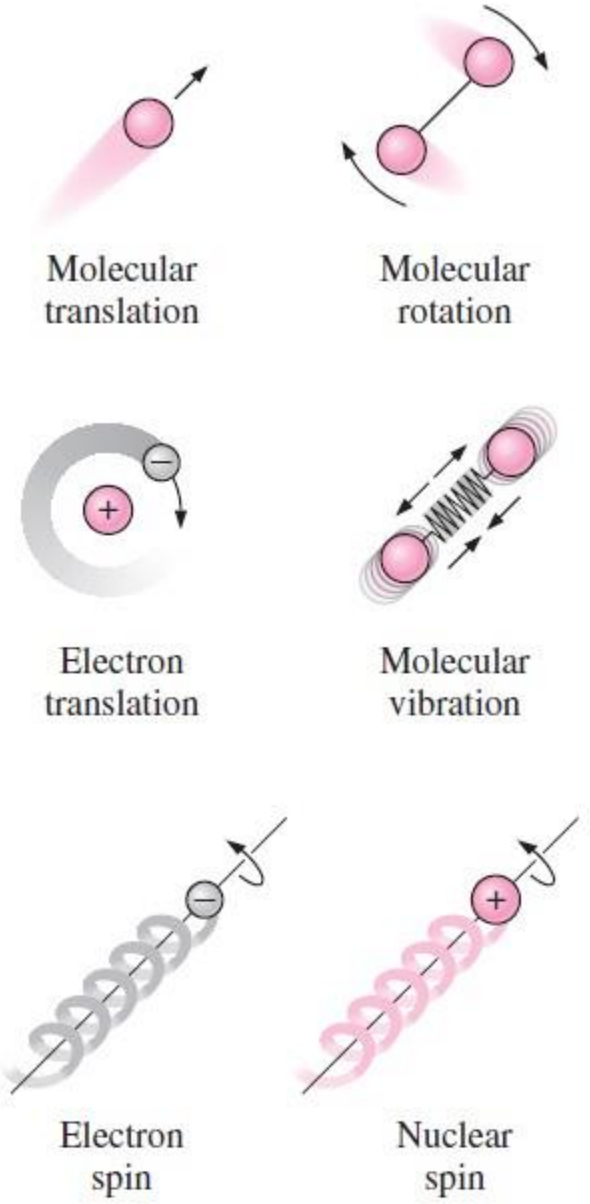
Vibrational kinetic energy

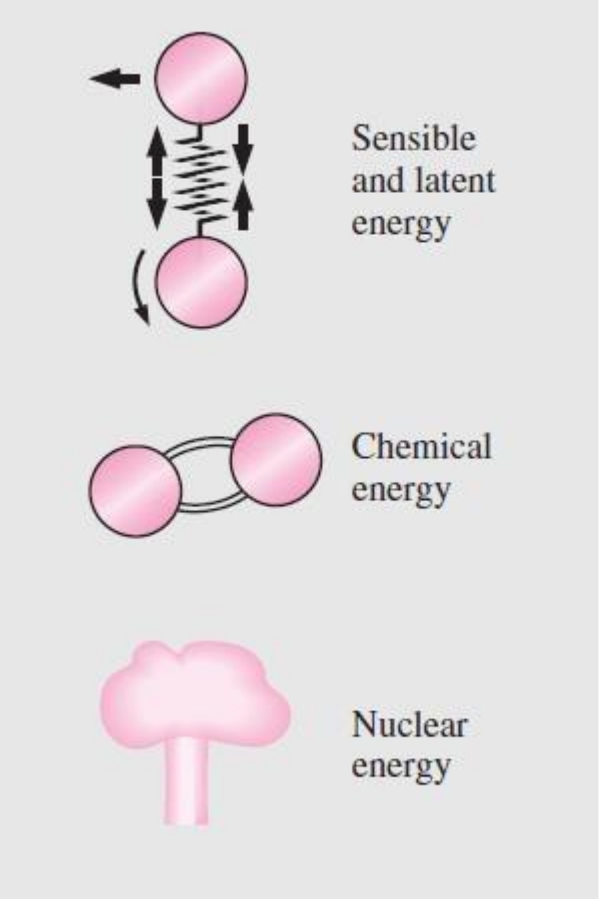
- **$\delta Q - \delta W = dU$** or **$Q_{1-2} = W_{1-2} + dU$**

- For a constant volume process from 1 to 2, $W_{1-2} = 0$
- **$Q_{1-2} = dU$; $Q_{1-2} = mc_v(T_2 - T_1)$**
- So, **$dU = mc_v(T_2 - T_1)$**

- Change of internal energy is directly proportional to change of temperature. For an ideal gas the internal energy is a function of the temperature only

- Internal energy is a point function. Increase of internal energy of the gas is considered as positive and decrease of internal energy of the gas is considered as negative

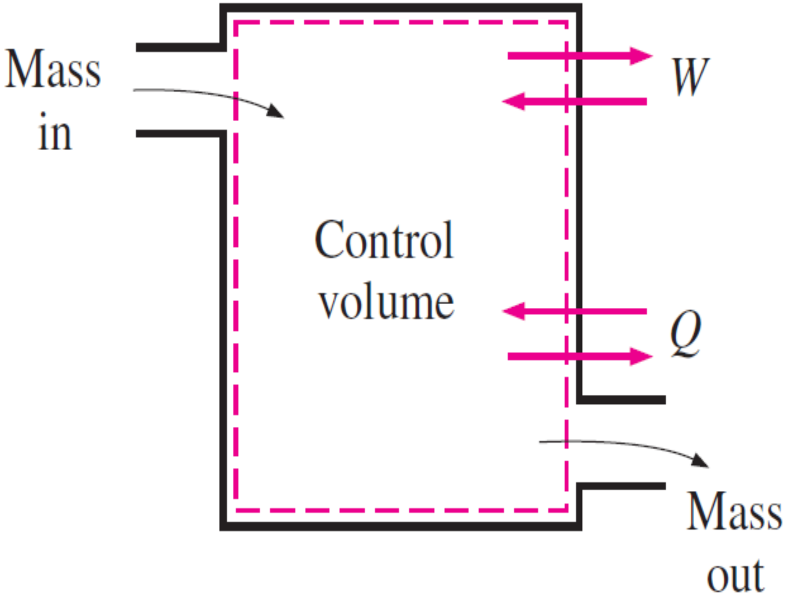

Molecular translation
Molecular rotation
Electron translation
Molecular vibration
Electron spin
Nuclear spin


Sensible and latent energy
Chemical energy
Nuclear energy

Mechanisms of Energy Transfer

- Energy can be transferred to or from a system in three forms: **heat, work and mass flow**

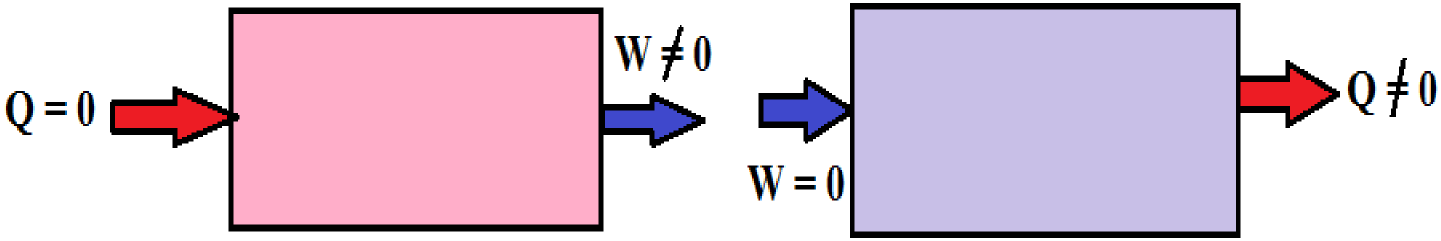
- **Heat Transfer, (Q)** Heat transfer to a system (heat gain) increases the energy of the molecules and thus the internal energy of the system, and heat transfer from a system (heat loss) decreases it since the energy transferred out as heat comes from the energy of the molecules of the system



- **Work Transfer, (W)** An energy interaction that is not caused by a temperature difference between a system and its surroundings is work. A rising piston, a rotating shaft, and an electrical wire crossing the system boundaries are all associated with work interactions. Work transfer to a system (i.e., work done on a system) increases the energy of the system, and work transfer from a system (i.e., work done by the system) decreases it since the energy transferred out as work comes from the energy contained in the system.

- **Mass Flow, (m)** Mass flow in and out of the system serves as an additional mechanism of energy transfer. When mass enters a system, the energy of the system increases because mass carries energy with it (in fact, mass is energy). Likewise, when some mass leaves the system, the energy contained within the system decreases because the leaving mass takes out some energy with it.

Perpetual Motion Machine of First Kind (PMM-1)



- *Violates first law of thermodynamics*
- Produce work without consuming an equivalent amount of heat energy
- Device continuously emitting heat without consuming any work

ENTHALPY

- Measure of the total energy of a thermodynamic system
- Sum of the internal energy and pressure volume product
- **$H = U + PV$**
- Enthalpy is also a property of the system

- $dH = dU + PdV + VdP$; $\delta Q = dU + PdV$
- Also, $dH = \delta Q + VdP$
- For a constant pressure process, $dP = 0$
- **$dH = \delta Q = Q_{1\text{-}2} = mc_p(T_2 - T_1)$**

- The enthalpy of an ideal gas is also a function of temperature

Ratio of Specific Heats

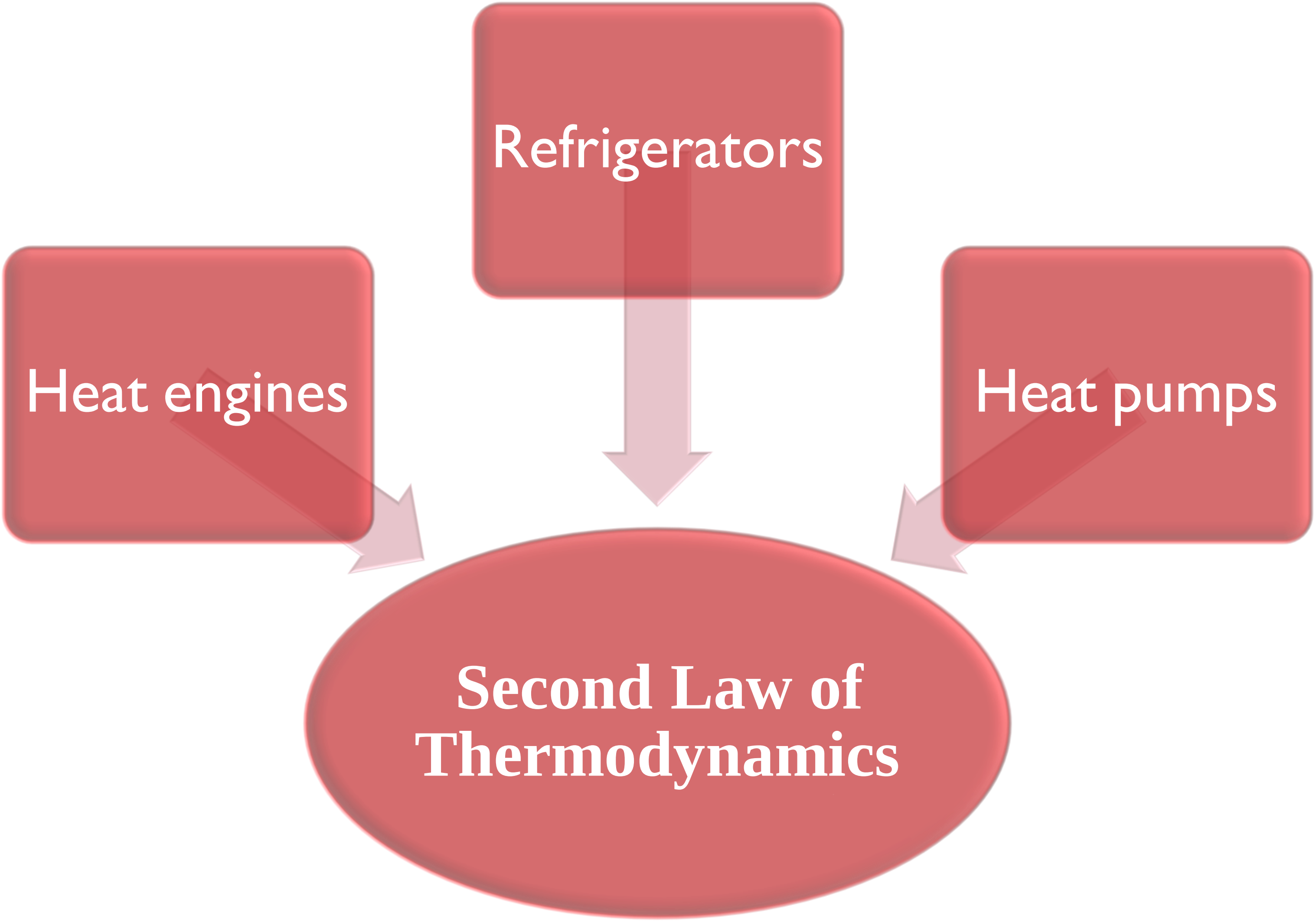
- **$c_p / c_v = \gamma$**

- $H = U + PV\ ;\ PV = mRT$
- $H = U + mRT$

- $dH = dU + mRdT$
- $dH/dT = dU/dT + mR$
- $m\,c_p = m\,c_v + mR$

- **$c_p - c_v = R$**

- **$c_p = \gamma R/(\gamma-1) \quad ; \quad c_v = R/(\gamma-1)$**



Refrigerators

Heat engines

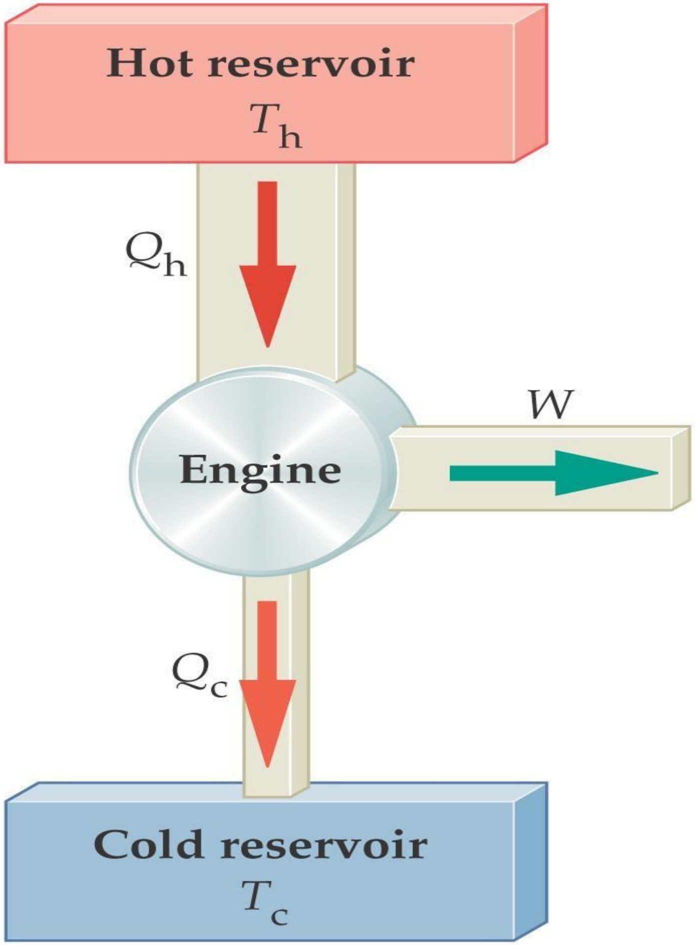
Heat pumps

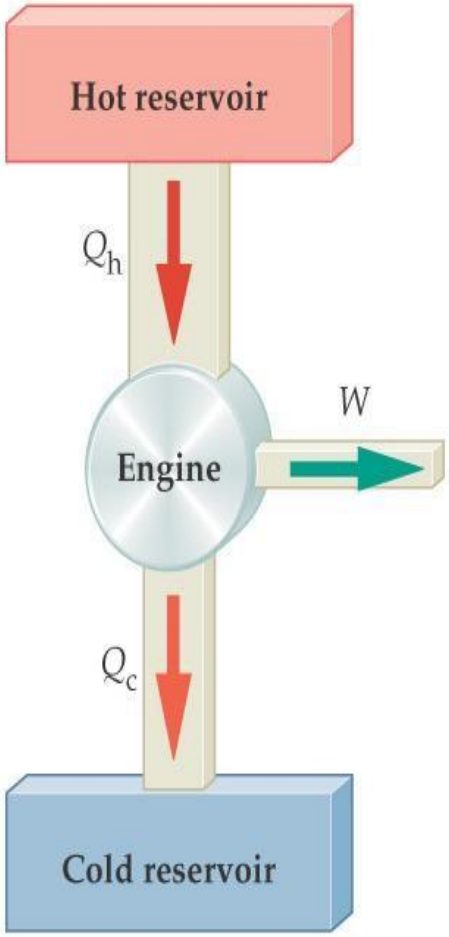
Second Law of Thermodynamics

Introduction to the Second Law of Thermodynamics

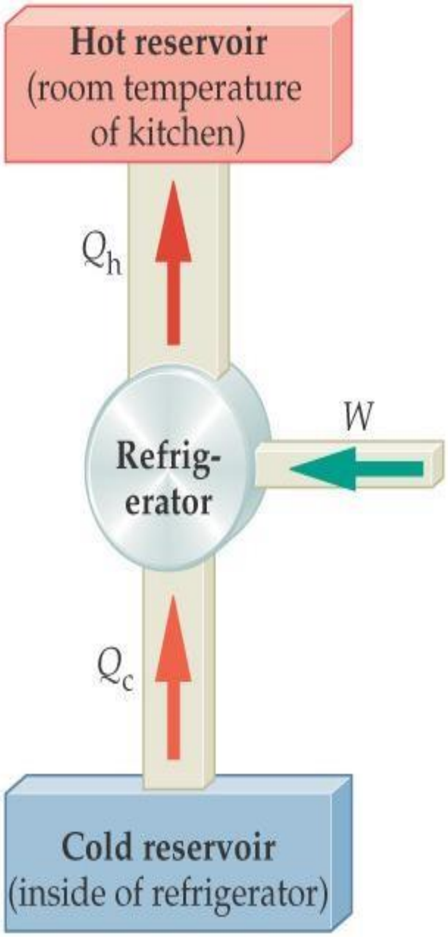
- A process cannot occur unless it satisfies both the first and the second laws of thermodynamics

- The second law also asserts that energy has **quality** as well as **quantity**

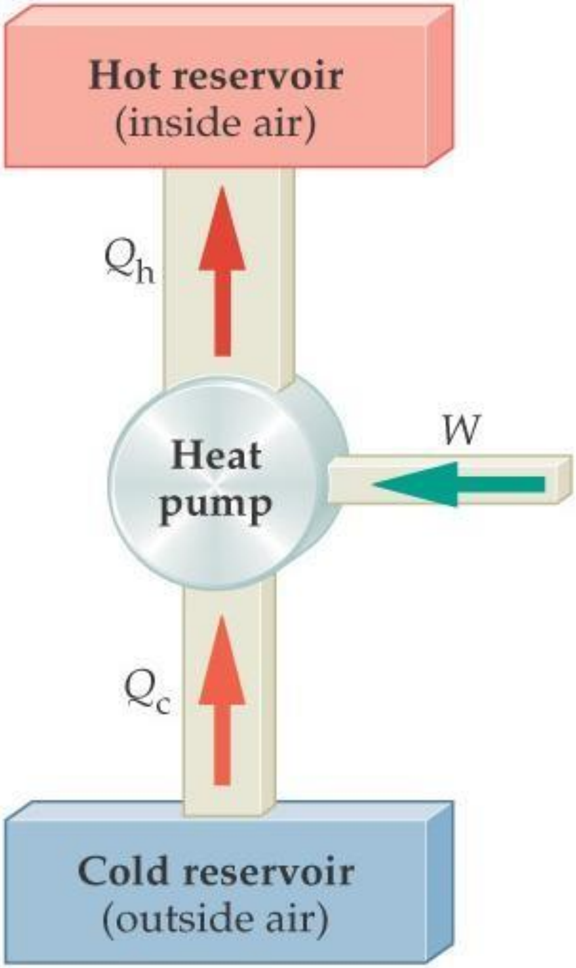




Heat engine



Refrigerator

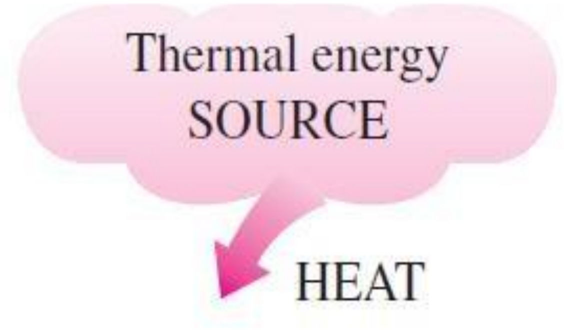


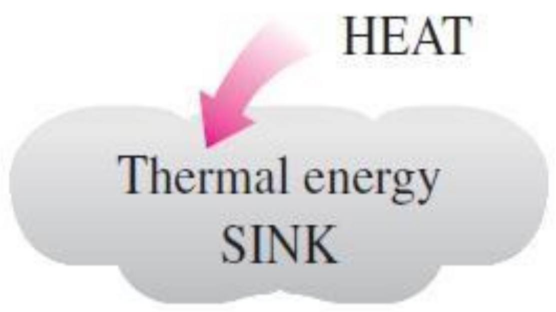
Heat pump

Thermal Reservoirs

- In the development of the second law of thermodynamics, it is very convenient to have a *hypothetical body with a relatively* ***large thermal energy capacity****(mass x specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature*. Such a body is called a **thermal energy reservoir**, or just a reservoir. Eg. Atmosphere, furnace…etc

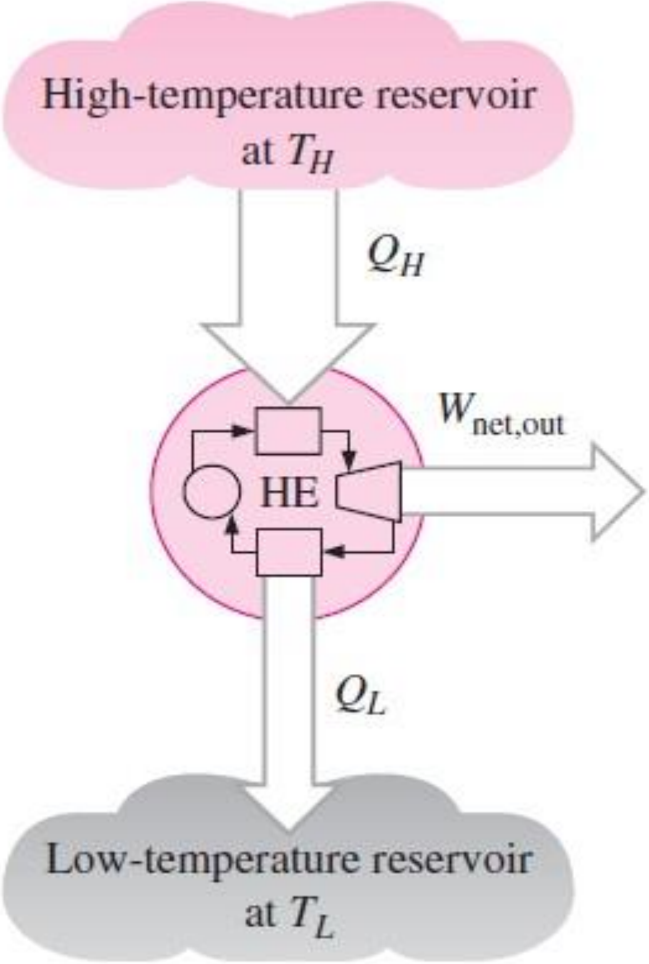
- A reservoir that supplies energy in the form of heat is called a **source**, and one that absorbs energy in the form of heat is called a **sink**





Heat Engines

- They receive heat from a high-temperature source
- They convert part of this heat to work
- They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).
- They operate on a cycle.
- Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the **working fluid**
- Eg. Internal combustion engine, gas turbine



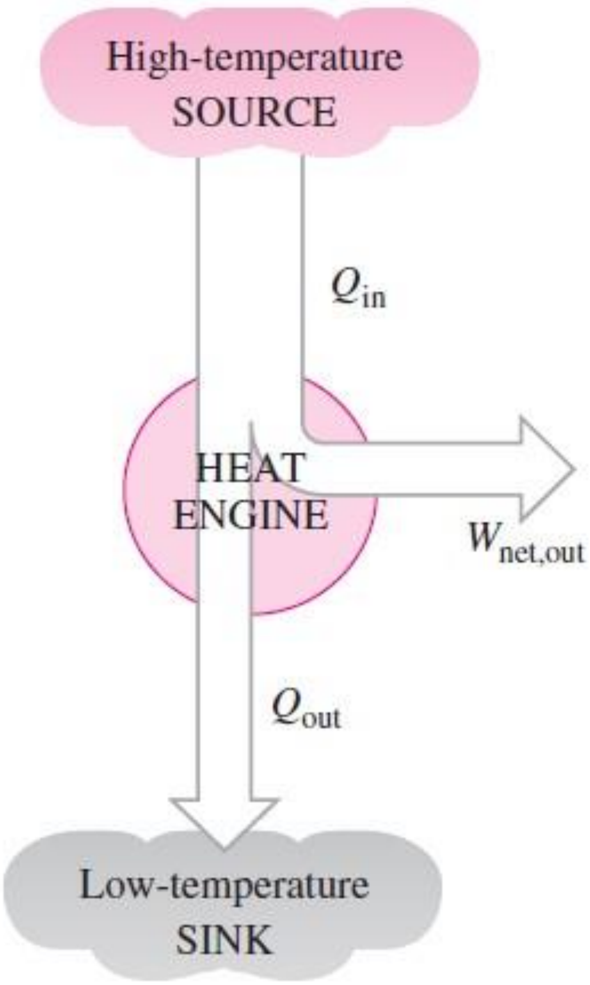
Thermal Efficiency

- The fraction of the heat input that is converted to net work output is a measure of the performance of a heat engine and is called the **thermal efficiency(η_{th})**

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_{\text{in}}}$$

$$\eta_{\text{th}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}}$$

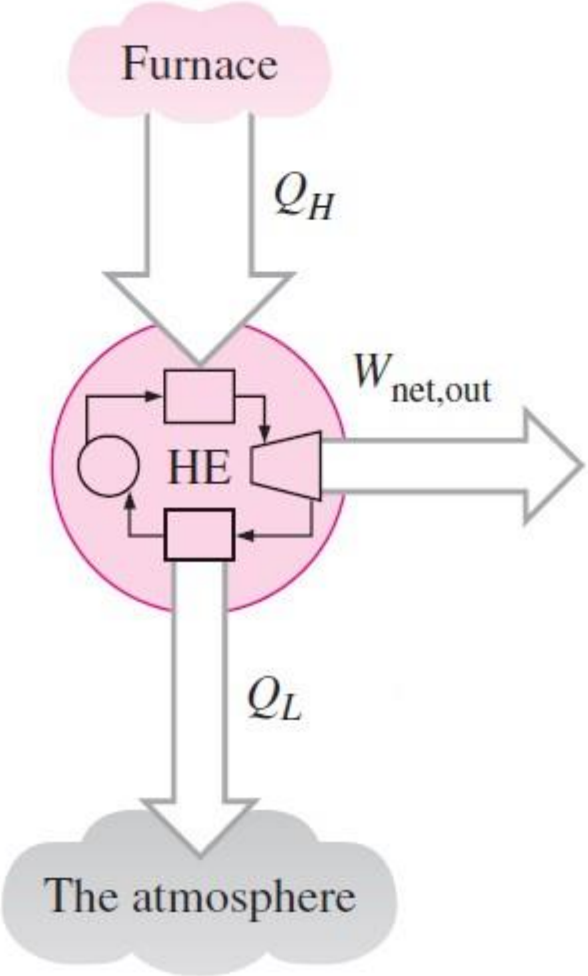


The Second Law of Thermodynamics

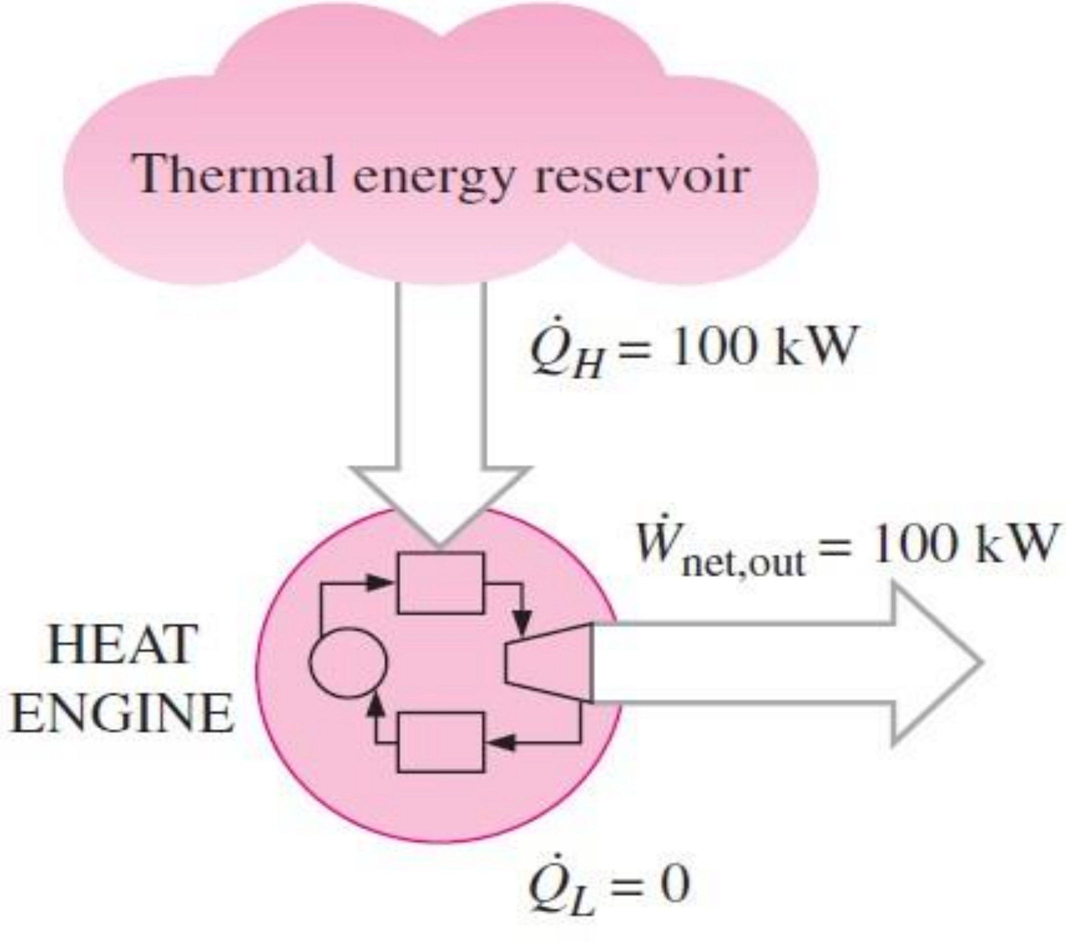
1.Kelvin–Planck Statement

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work

- That is, a heat engine must exchange heat with a low-temperature sink as well as a high-temperature source to keep operating. The Kelvin–Planck statement can also be expressed as **no heat engine can have a thermal efficiency of 100 percent**



Violation of Kelvin - Planck statement

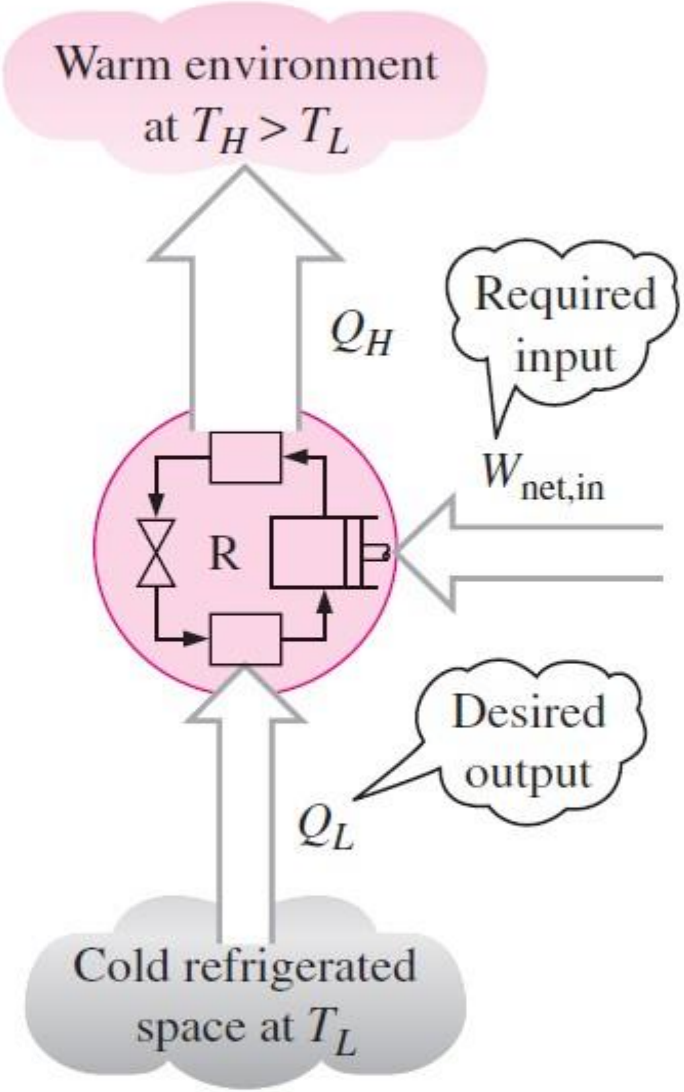


Refrigerators

- The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called **refrigerators**

- The objective of a refrigerator is to maintain the refrigerated space at a low temperature by removing heat from it

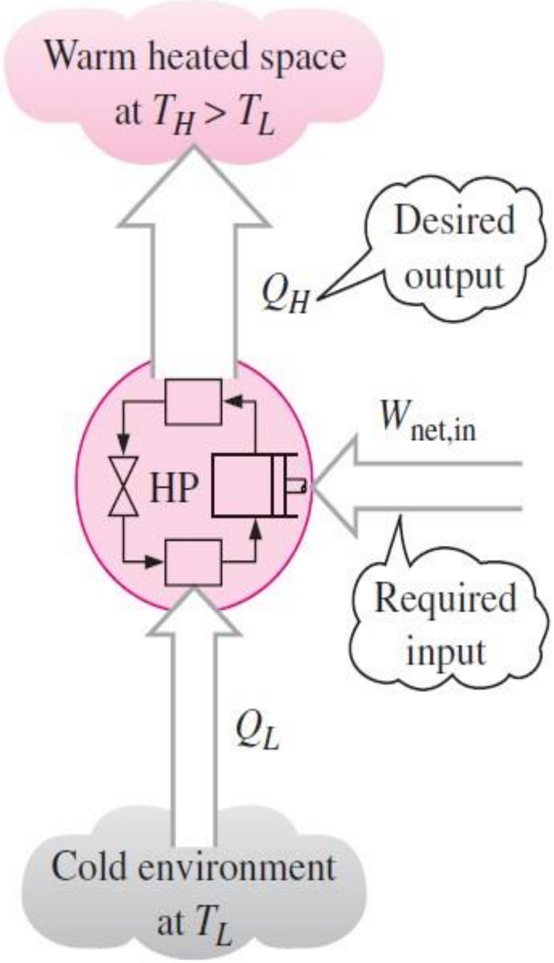
- Refrigerators, like heat engines, are cyclic devices. The working fluid used in the refrigeration cycle is called a **refrigerant**



Heat Pumps

- Another device that transfers heat from a low-temperature medium to a high-temperature one is the **heat pump**

- The objective of a heat pump, however, is to maintain a heated space at a high temperature. This is accomplished by absorbing heat from a low-temperature source, such as well water or cold outside air in winter, and supplying this heat to the high-temperature medium such as a house

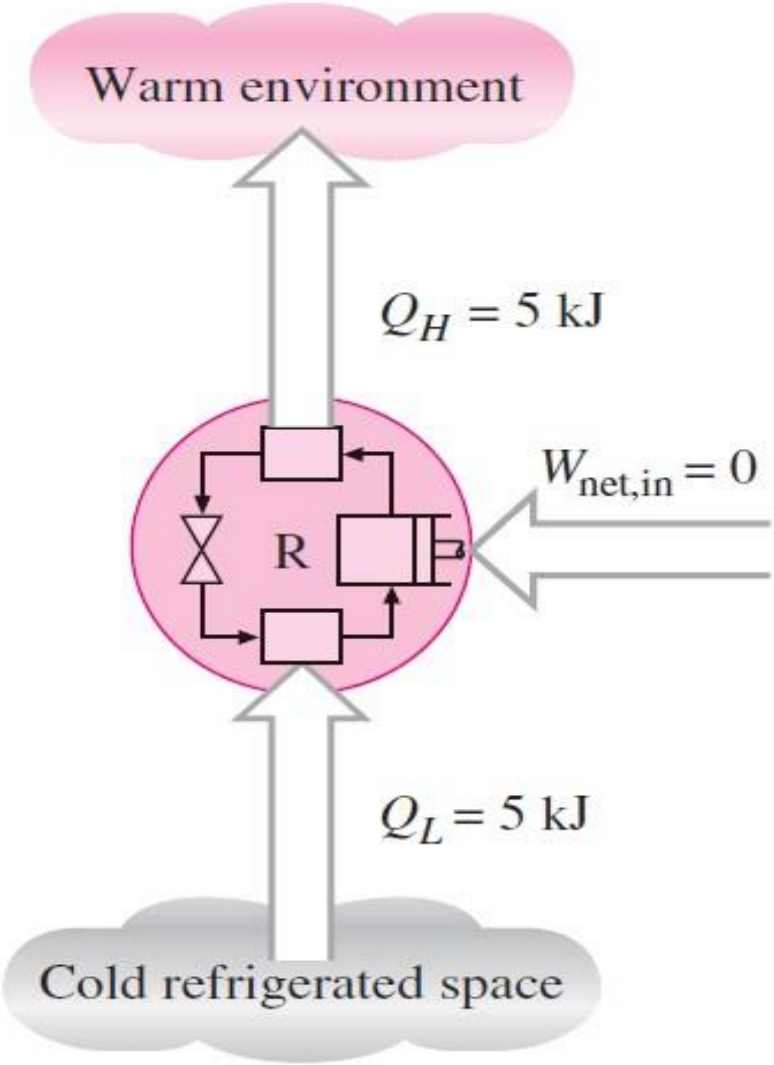


2.Clausius Statement

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body

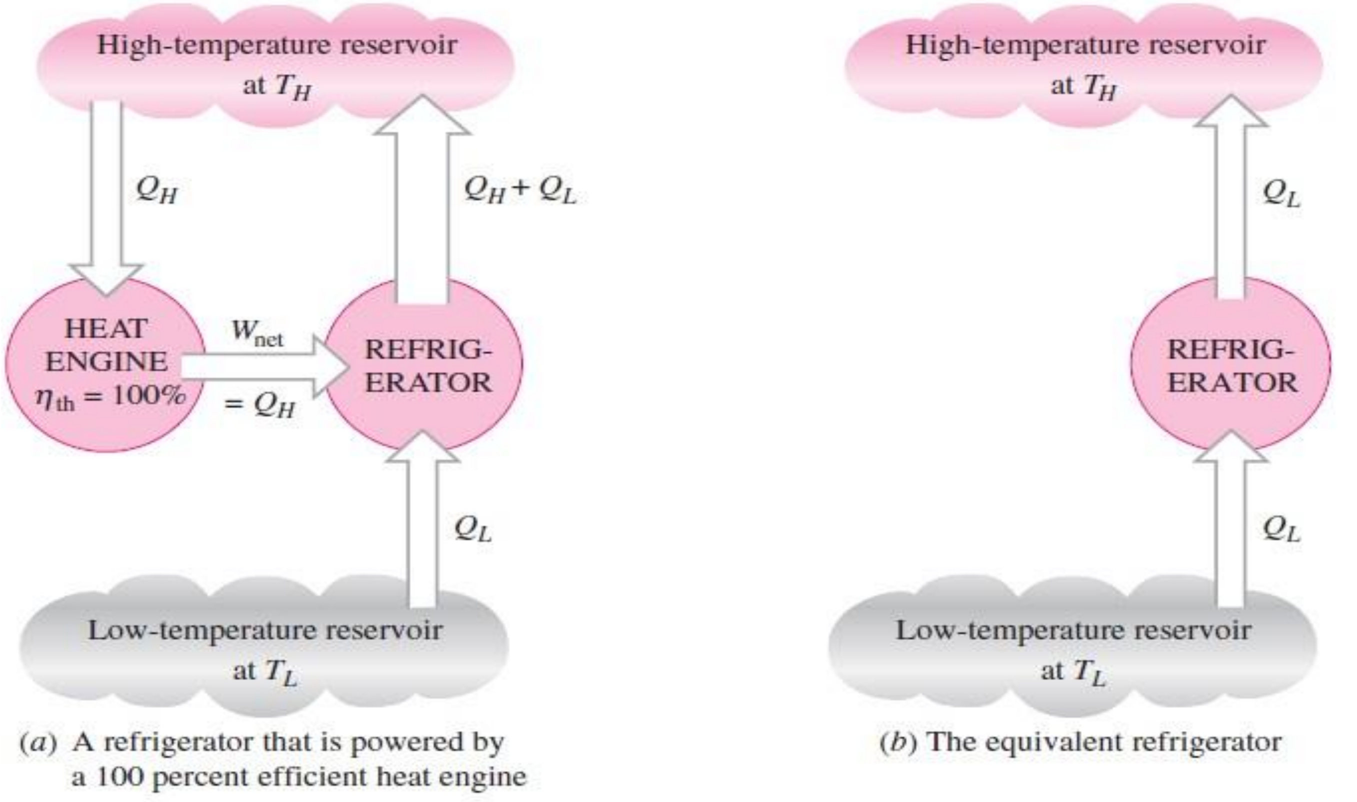
- Both the Kelvin–Planck and the Clausius statements of the second law are negative statements, and a negative statement cannot be proved. Like any other physical law, the second law of thermodynamics is based on experimental observations

Violation of Clausius statement



Equivalence of Kelvin-Planck and Clausius Statements

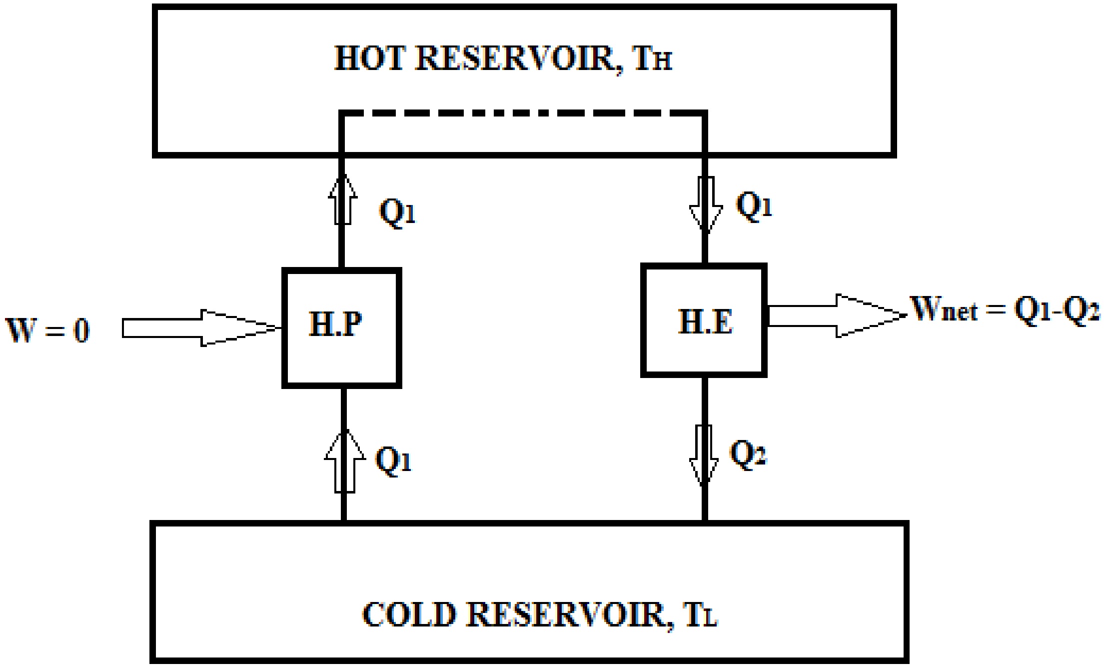
Violation of the Kelvin–Planck statement leads to the violation of the Clausius statement



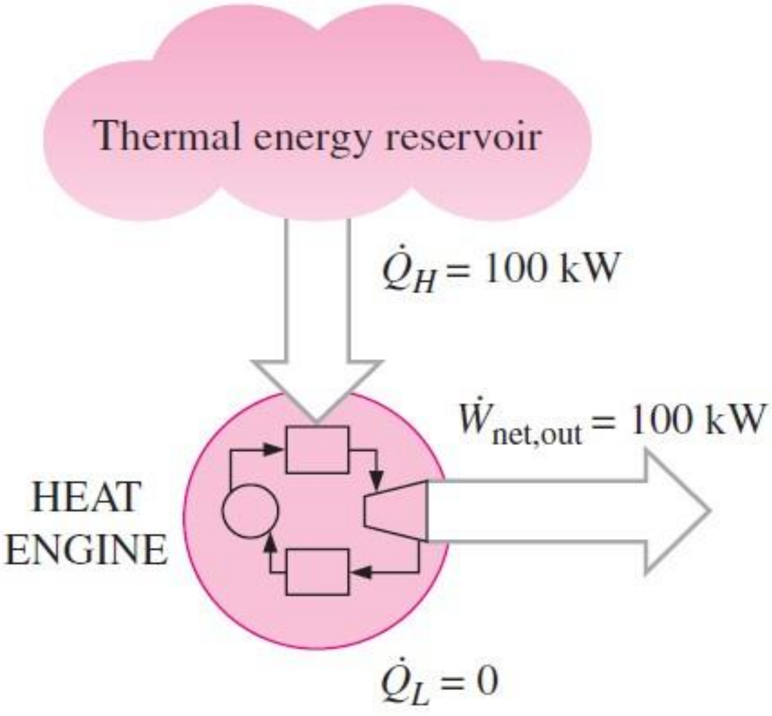
(*a*) A refrigerator that is powered by a 100 percent efficient heat engine

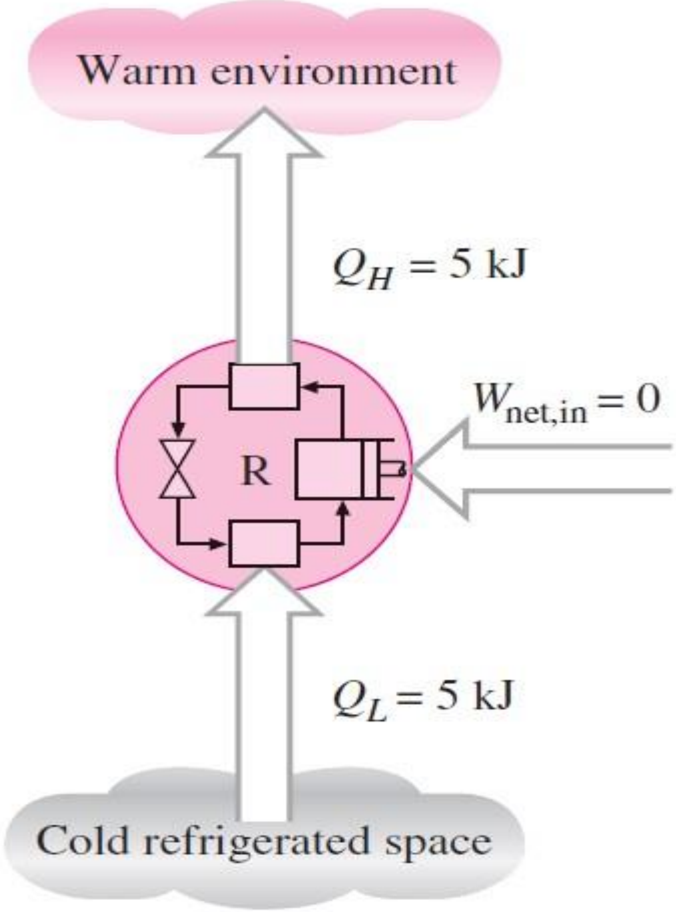
(*b*) The equivalent refrigerator

Violation of the Clausius statement leads to the violation of the Kelvin–Planck statement



Perpetual-Motion Machine of The Second Kind (PMM2)





- Device that violates the second law of thermodynamics

The efficiency of a reversible heat engine in which heat is received solely at T_1 is found to be

$$\eta_{rev.} = \eta_{max} = 1 - \left(\frac{Q_2}{Q_1}\right)_{rev.} = 1 - \frac{T_2}{T_1}$$

or
$$\eta_{rev.} = \frac{T_1 - T_2}{T_1}$$

From the above expression, it may be noted that as T_2 decreases and T_1 increases, the efficiency of the reversible cycle increases.

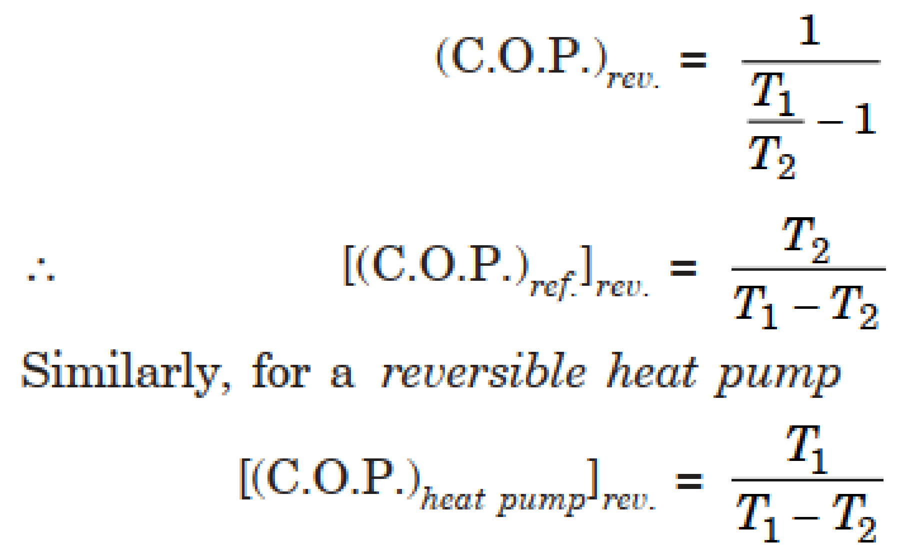
Since η is always less than unity, T_2 is always greater than zero and + ve.

The C.O.P. of a refrigerator is given by

$$(\text{C.O.P.})_{ref.} = \frac{Q_2}{Q_1 - Q_2} = \frac{1}{\frac{Q_1}{Q_2} - 1}$$

For a *reversible refrigerator*, using

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$$



$$(\text{C.O.P.})_{rev.} = \frac{1}{\dfrac{T_1}{T_2} - 1}$$

$$\therefore \qquad [(\text{C.O.P.})_{ref.}]_{rev.} = \frac{T_2}{T_1 - T_2}$$

Similarly, for a *reversible heat pump*

$$[(\text{C.O.P.})_{heat\ pump}]_{rev.} = \frac{T_1}{T_1 - T_2}$$

Example 5.1. *A heat engine receives heat at the rate of 1500 kJ/min and gives an output of 8.2 kW. Determine :*

(i) The thermal efficiency ; *(ii) The rate of heat rejection.*

Solution. Heat received by the heat engine,

$$Q_1 = 1500 \text{ kJ/min}$$

$$= \frac{1500}{60} = 25 \text{ kJ/s}$$

Work output, $W = 8.2 \text{ kW} = 8.2 \text{ kJ/s}$.

(*i*) Thermal efficiency, $\eta_{th} = \frac{W}{Q_1}$

$$= \frac{8.2}{25} = 0.328 = 32.8\%$$

Hence, **thermal efficiency = 32.8%. (Ans.)**

(*ii*) Rate of heat rejection,

$$Q_2 = Q_1 - W = 25 - 8.2$$

$$= 16.8 \text{ kJ/s}$$

Hence, **the rate of heat rejection = 16.8 kJ/s. (Ans.)**

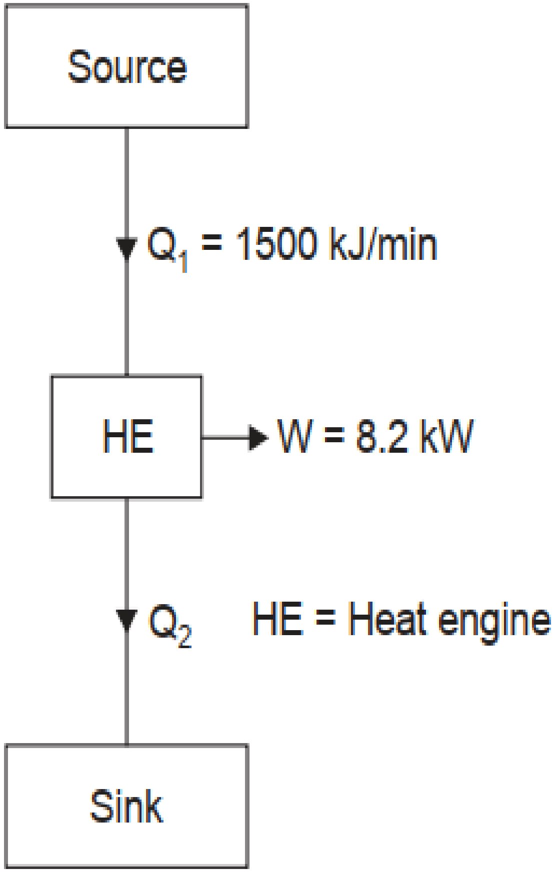


Fig. 5.9

Example 5.3. *Find the co-efficient of performance and heat transfer rate in the condense of a refrigerator in kJ/h which has a refrigeration capacity of 12000 kJ/h when power input is 0.75 kW.*

Solution. Refer Fig. 5.11.

Refrigeration capacity, Q_2 = 12000 kJ/h

Power input, W = 0.75 kW (= 0.75 × 60 × 60 kJ/h)

Co-efficient of performance, C.O.P. :

Heat transfer rate :

$$(\text{C.O.P.})_{refrigerator} = \frac{\text{Heat absorbed at lower temperature}}{\text{Work input}}$$

$$\therefore \qquad \text{C.O.P.} = \frac{Q_2}{W} = \frac{12000}{0.75 \times 60 \times 60} = 4.44$$

Hence **C.O.P. = 4.44. (Ans.)**

Hence transfer rate in condenser = Q_1

According to the first law

$Q_1 = Q_2 + W = 12000 + 0.75 \times 60 \times 60 = 14700$ kJ/h

Hence, **heat transfer rate = 14700 kJ/h. (Ans.)**

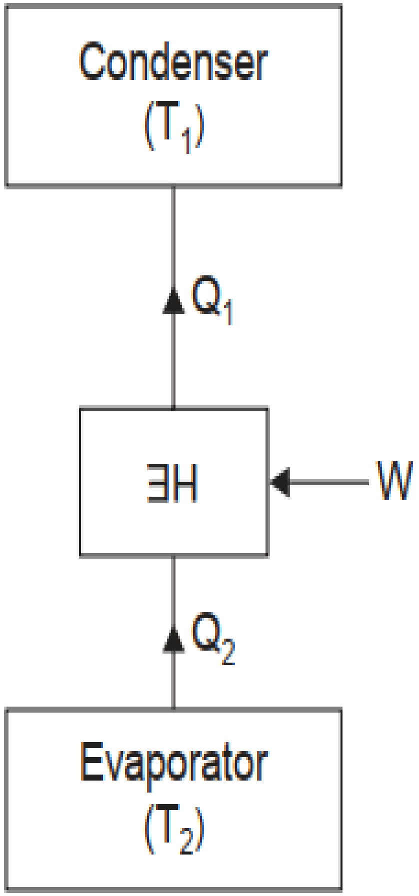


Fig. 5.11

Example 5.4. *A domestic food refrigerator maintains a temperature of – 12°C. The ambient air temperature is 35°C. If heat leaks into the freezer at the continuous rate of 2 kJ/s determine the least power necessary to pump this heat out continuously.*

Solution. Freezer temperature,

$$T_2 = -12 + 273 = 261 \text{ K}$$

Ambient air temperature,

$$T_1 = 35 + 273 = 308 \text{ K}$$

Rate of heat leakage into the freezer = 2 kJ/s

Least power required to pump the heat :

The refrigerator cycle removes heat from the freezer at the same rate at which heat leaks into it (Fig. 5.12).

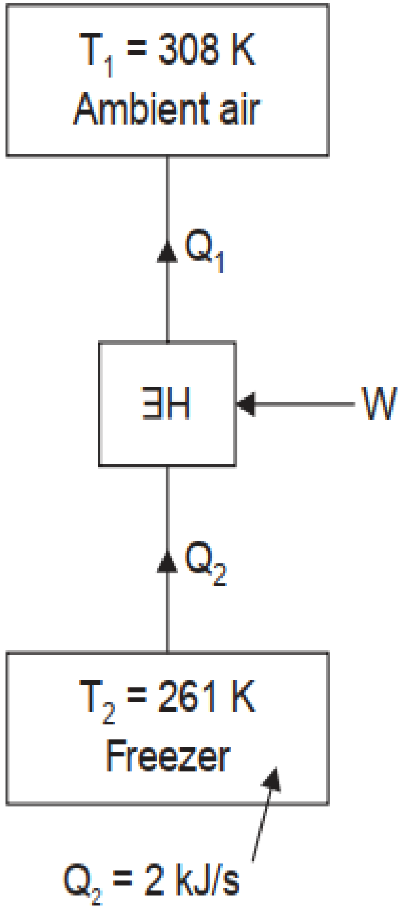


Fig. 5.12

For minimum power requirement

$$\frac{Q_2}{T_2} = \frac{Q_1}{T_1}$$

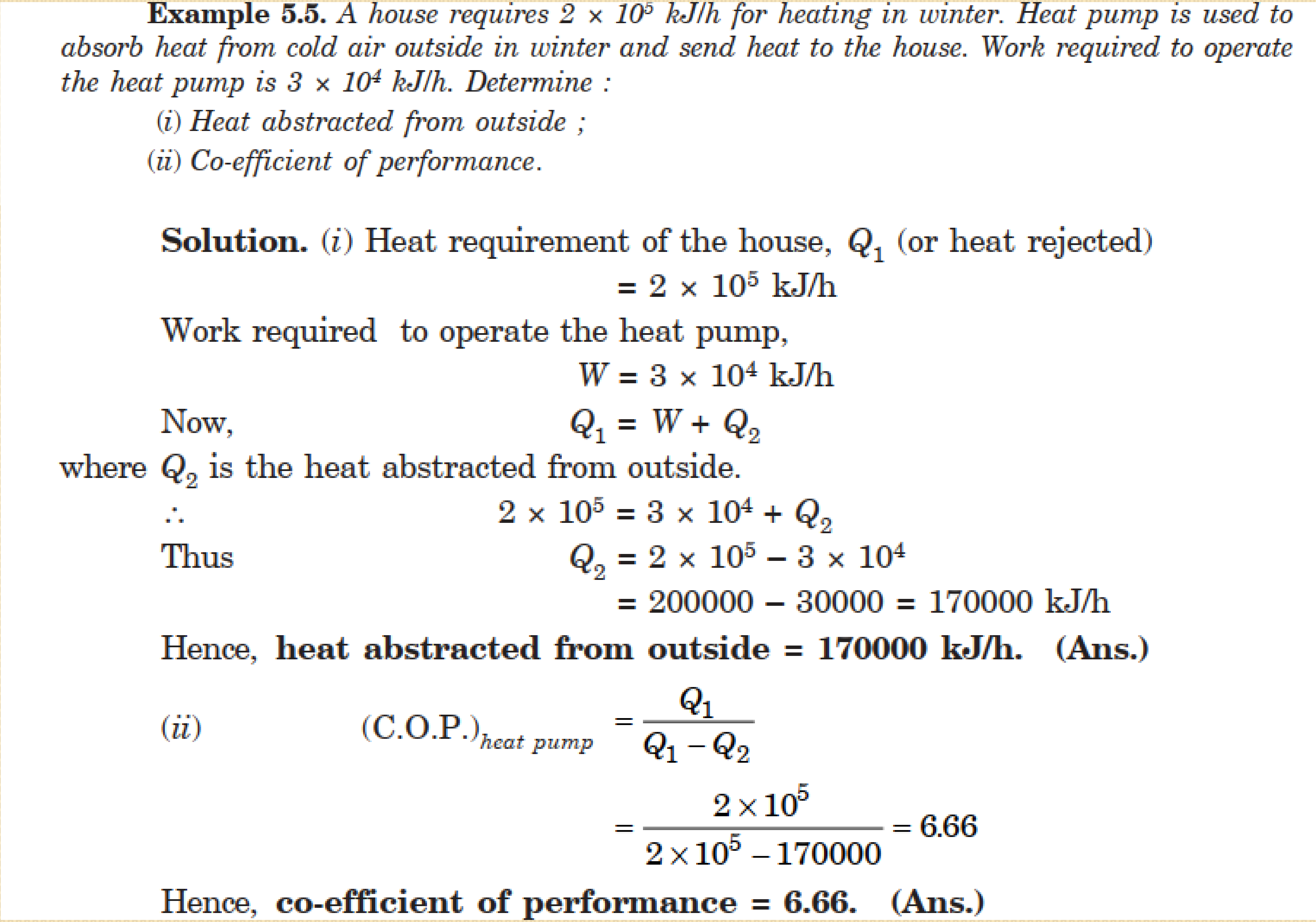
$$\therefore \qquad Q_1 = \frac{Q_2}{T_2} \times T_1 = \frac{2}{261} \times 308 = 2.36 \text{ kJ/s}$$

$$\therefore \qquad W = Q_1 - Q_2$$

$$= 2.36 - 2 = 0.36 \text{ kJ/s} = 0.36 \text{ kW}$$

Hence, *least power required to pump the heat continuously*

$$= \mathbf{0.36\ kW.} \quad \textbf{(Ans.)}$$



Example 5.5. *A house requires 2 × 10^5 kJ/h for heating in winter. Heat pump is used to absorb heat from cold air outside in winter and send heat to the house. Work required to operate the heat pump is 3 × 10^4 kJ/h. Determine :*

(*i*) *Heat abstracted from outside ;*

(*ii*) *Co-efficient of performance.*

Solution. (*i*) Heat requirement of the house, Q_1 (or heat rejected)

$$= 2 \times 10^5 \text{ kJ/h}$$

Work required to operate the heat pump,

$$W = 3 \times 10^4 \text{ kJ/h}$$

Now, $$Q_1 = W + Q_2$$

where Q_2 is the heat abstracted from outside.

$\therefore$ $$2 \times 10^5 = 3 \times 10^4 + Q_2$$

Thus $$Q_2 = 2 \times 10^5 - 3 \times 10^4$$

$$= 200000 - 30000 = 170000 \text{ kJ/h}$$

Hence, **heat abstracted from outside = 170000 kJ/h. (Ans.)**

(*ii*) $$(\text{C.O.P.})_{heat\ pump} = \frac{Q_1}{Q_1 - Q_2}$$

$$= \frac{2 \times 10^5}{2 \times 10^5 - 170000} = 6.66$$

Hence, **co-efficient of performance = 6.66. (Ans.)**

Example 5.9. *A cyclic heat engine operates between a source temperature of 1000°C and a sink temperature of 40°C. Find the least rate of heat rejection per kW net output of the engine ?*

Solution. Temperature of source,

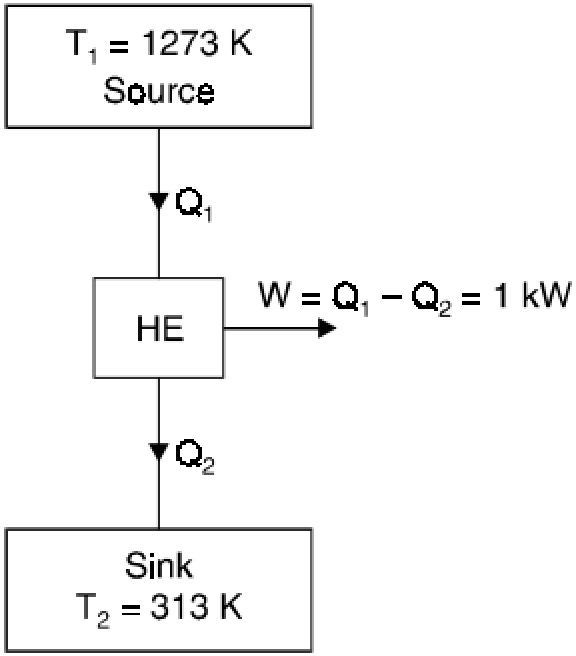
$$T_1 = 1000 + 273 = 1273 \text{ K}$$

Temperature of sink,

$$T_2 = 40 + 273 = 313 \text{ K}$$

Least rate of heat rejection per kW net output :

For a reversible heat engine, the rate of heat rejection will be minimum (Fig. 5.13)



$$\eta_{max} = \eta_{rev.} = 1 - \frac{T_2}{T_1}$$

$$= 1 - \frac{313}{1273} = 0.754$$

Now $$\frac{W_{net}}{Q_1} = \eta_{max} = 0.754$$

$\therefore$ $$Q_1 = \frac{W_{net}}{0.754} = \frac{1}{0.754} = 1.326 \text{ kW}$$

Now $$Q_2 = Q_1 - W_{net} = 1.326 - 1 = 0.326 \text{ kW}$$

Hence, **the least rate of heat rejection = 0.326 kW. (Ans.)**

Example 5.10. *A fish freezing plant requires 40 tons of refrigeration. The freezing temperature is – 35°C while the ambient temperature is 30°C. If the performance of the plant is 20% of the theoretical reversed Carnot cycle working within the same temperature limits, calculate the power required.*

Given : 1 ton of refrigeration = 210 kJ/min.

Solution. Cooling required = 40 tons = 40 × 210

= 8400 kJ/min

Ambient temperature, $T_1 = 30 + 273 = 303$ K

Freezing temperature, $T_2 = -35 + 273 = 238$ K

Performance of plant = 20% of the theoretical reversed Carnot cycle

$$(\text{C.O.P.})_{refrigerator} = \frac{T_2}{T_1 - T_2} = \frac{238}{303 - 238} = 3.66$$

∴ Actual C.O.P = 0.20 × 3.66 = 0.732

Now work needed to produce cooling of 40 tons is calculated as follows :

$$(\text{C.O.P.})_{actual} = \frac{\text{Cooling reqd.}}{\text{Work needed}}$$

$$0.732 = \frac{8400}{W} \quad \text{or} \quad W = \frac{8400}{0.732} \text{ kJ/min} = 191.25 \text{ kJ/s} = 191.25 \text{ kW}$$

Hence, **power required = 191.25 kW. (Ans.)**

Example 5.11. *Source 1 can supply energy at the rate of 12000 kJ/min at 320°C. A second source 2 can supply energy at the rate of 120000 kJ/min at 70°C. Which source (1 or 2) would you choose to supply energy to an ideal reversible heat engine that is to produce large amount of power if the temperature of the surroundings is 35°C ?*

Solution. Source 1 :

Rate of supply of energy = 12000 kJ/min

Temperature, $T_1 = 320 + 273 = 593$ K.

Source 2 :

Rate of supply of energy = 120000 kJ/min

Temperature, $T_1 = 70 + 273 = 343$ K

Temperature of the surroundings, $T_2 = 35°\text{C} + 273 = 308$ K

Let the Carnot engine be working in the two cases with the two source temperatures and the single sink temperature. The efficiency of the cycle will be given by :

$$\eta_1 = 1 - \frac{T_2}{T_1} = 1 - \frac{308}{593} = 0.4806 \quad \text{or} \quad 48.06\%$$

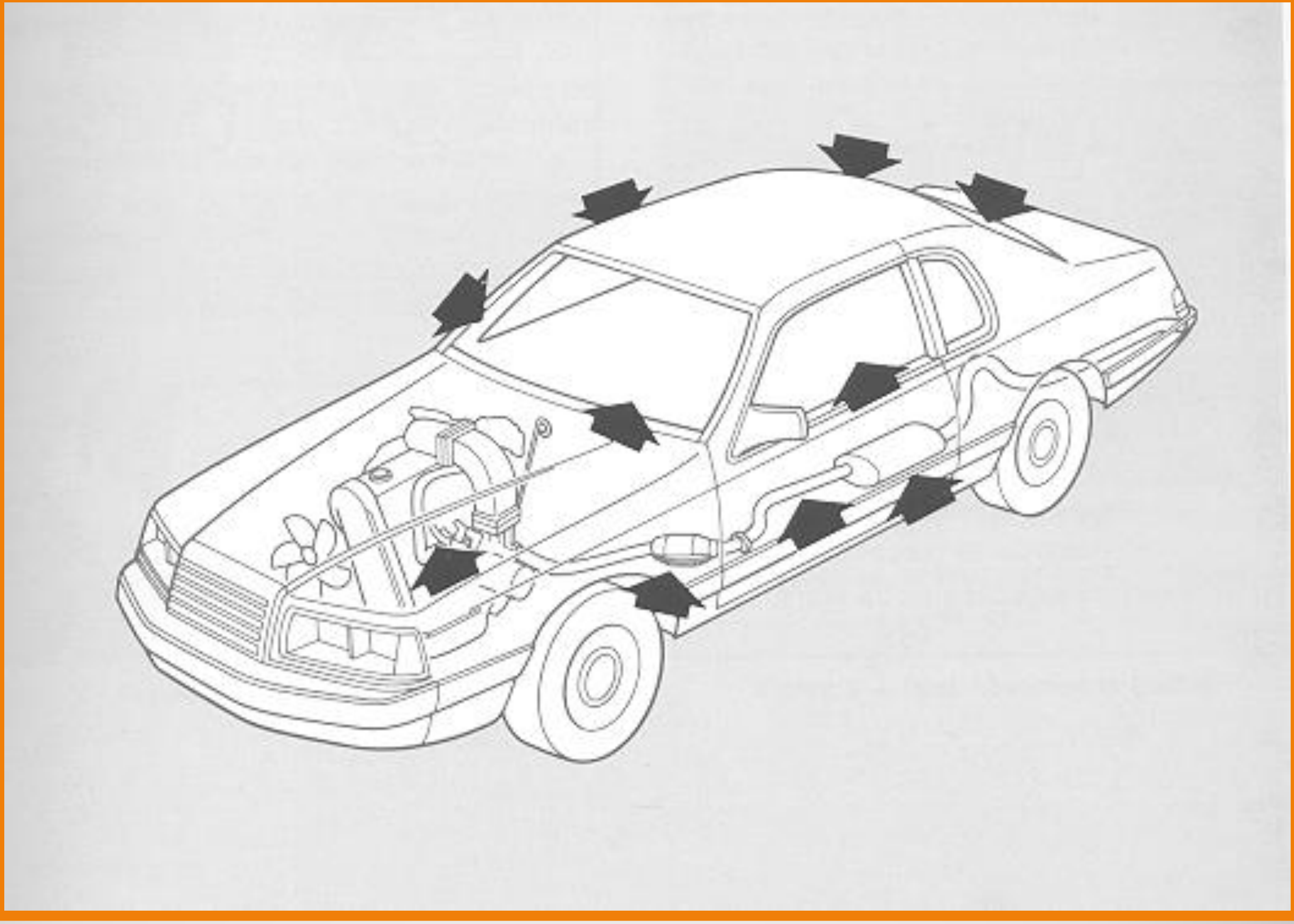
$$\eta_2 = 1 - \frac{T_2}{T_1} = 1 - \frac{308}{343} = 0.102 \quad \text{or} \quad 10.2\%$$

∴ The work delivered in the two cases is given by

$$W_1 = 12000 \times 0.4806 = 5767.2 \text{ kJ/min}$$

and $$W_2 = 120000 \times 0.102 = 12240 \text{ kJ/min.}$$

Thus, choose **source 2.** **(Ans.)**



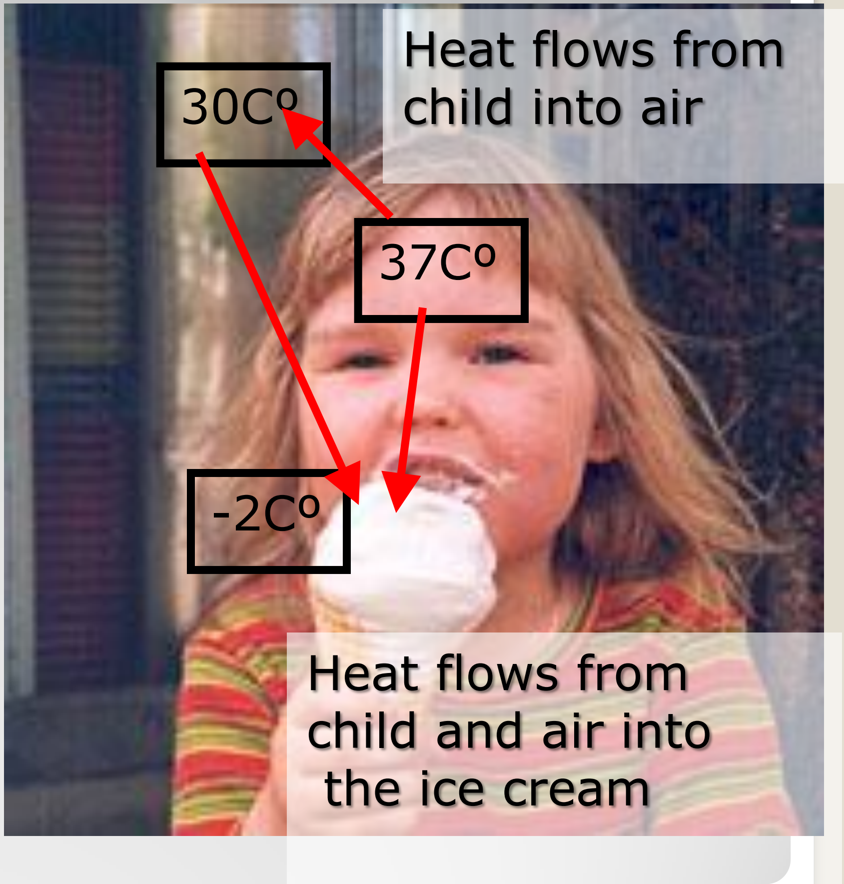
SOURCES OF HEAT

Heat Transfer

Heat *always* flows from high temperature objects to low temperature objects.

Heat flow stops when temperatures equal.

Various ways by which heat may flow.



Heat flows from child into air

Heat flows from child and air into the ice cream

Modes of Heat Transfer

1. Conduction
2. Convection
3. Radiation

Modes of Heat Transfer

- **Conduction:** Flow of heat energy by direct contact & through free electrons e.g. heat flow through solids
- **Convection:** Transfer of heat energy by fluid flowing over a surface e.g. heat transfer from engine surface to surrounding atmospheric air
- **Radiation:** Flow of heat energy without any intervening medium e.g. energy of sun reaching the earth

Fourier's Law of Heat Conduction

Rate of heat transfer by conduction (through a solid) in a given direction is proportional to the area normal to the direction of heat flow and the temp gradient in that direction. Mathematically ;

$$Q \propto A \frac{\Delta T}{\Delta x} Watt$$ OR $$Q = -kA \frac{dT}{dx} Watt(J/s)$$

where Q = heat flow rate, Watt (J/s)

A = area normal to heat flow direction,m^2

k = conductivity of material (property), W/mK

dT/dx = temp gradient in x direction

ΔT = temp difference across Δx

Δx = thickness of material in heat flow direction

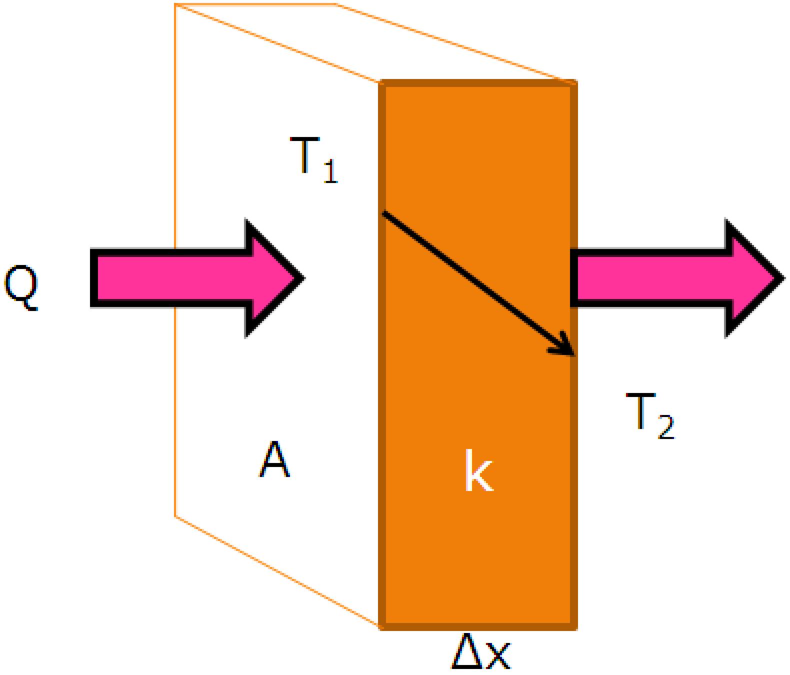
Conduction

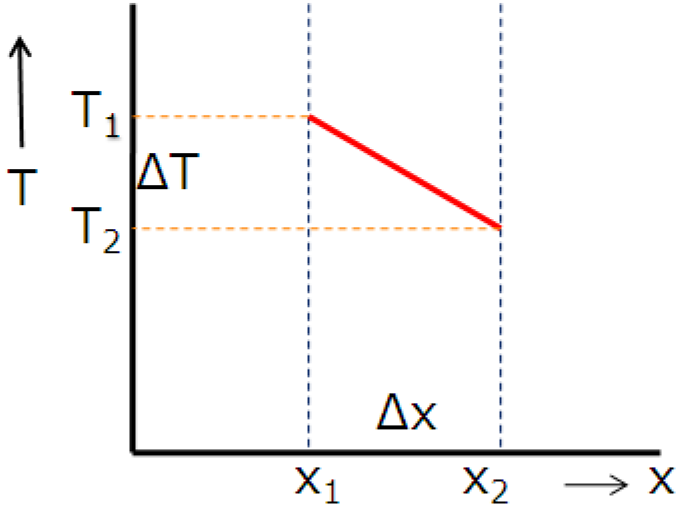
$$Q = -kA\frac{dT}{dx}$$

$$Q = kA\frac{(T_1 - T_2)}{(x_1 - x_2)}$$

$$Q = -kA\frac{(T_1 - T_2)}{(x_2 - x_1)}$$

$$Q = kA\frac{\Delta T}{\Delta x}$$





Heat Flux q=Q/A, W/m^2

Assumptions of Fourier's Law

1. Unidirectional heat flow
   (only one direction)
2. Steady state heat flow
3. Constant temp gradient
4. Constant conductivity, k
5. Both faces isothermal

Thermal Conductivities

Metals
have
high
thermal
conductivity

Substance	Thermal Conductivity: k (W/mK)
Copper	390
Aluminum	240
Brass	110
Iron	75

Thermal Conductivities

Insulators have low conductivity.

Air is a good insulator, except that large air spaces allow heat flow by convection

Substance	Thermal Conductivity: k (W/mK)
Glass	0.84
Water	0.60
Wood	0.10
Air	0.023

Variation of Thermal Conductivity

1. It is the property of material; defined as ability of material to conduct heat through it.
2. Thermal conductivity in decreasing order :
   Metals » Non-metallic Solids » Liquids » Gases
3. Higher conductivity in metals due to free electrons in their outer orbits
4. k depends on grain structure. When k is different in different directions (k_x , k_y , k_z), material is known as anisotropic. When k is constant in all directions, it is called Isotropic.
5. k is strongly dependent on temp; $k=k_o(1+\alpha T)$

Isotropic & Anisotropic Materials

- Some materials exhibit same conductivity in all directions. These are called ISOTROPIC materials ($kx = ky = kz = k$)

- While some materials have different conductivity in different directions(k_x , k_y , k_z), such materials are known as anisotropic.

- Wood exhibits directional conductivity; different along grains

HEAT CONVECTION

Heat Convection

When a fluid flows over a solid body or surface and temp of the fluid and solid surface are different, heat transfer between the solid surface and fluid takes place due to motion of fluid relative to the surface.

If the fluid motion is artificially induced, then heat transfer is said to be by FORCED convection.

If the fluid motion is set up by buoyancy effects resulting from density difference caused due to temp difference in the fluid, heat transfer is said to be by FREE or NATURAL convection

Newton’s Law of Cooling

Rate of heat transfer by convection from a surface to a fluid or vice versa , flowing along it is equal to the product of temp difference between surface and the free stream of the fluid, the area of the surface normal to the direction of heat flow and a quantity h called convective heat transfer coefficient.

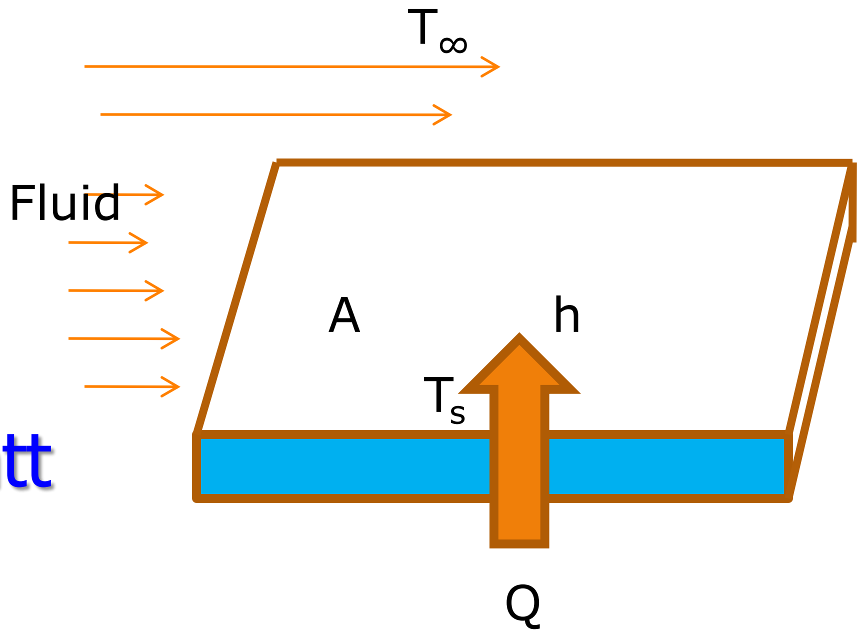
Mathematically;

$$Q = hA(T_s - T_\infty);\ \text{Watt}$$

h is not a property of fluid or surface, but it depends on properties of the fluid and vital dimensions of the surface

Convection

$T_s > T_\infty$



$$Q = hA(T_s - T_\infty);\ \text{Watt}$$

HEAT RADIATION

Heat Radiation

All bodies continuously emit energy if their temp is above zero absolute (0K) and energy thus emitted is called thermal radiation.

Thermal radiations are electromagnetic waves and do not require any medium for propagation.

Thermal radiation is a surface phenomenon.

Theories of Thermal Radiation

1. Wave/Maxwell's Classical Theory : Propagation by electromagnetic waves
2. Quantum/ Planck's Theory: Propagation by quanta possessing certain amount of energy

Stefan Boltzmann's Law of Radiation

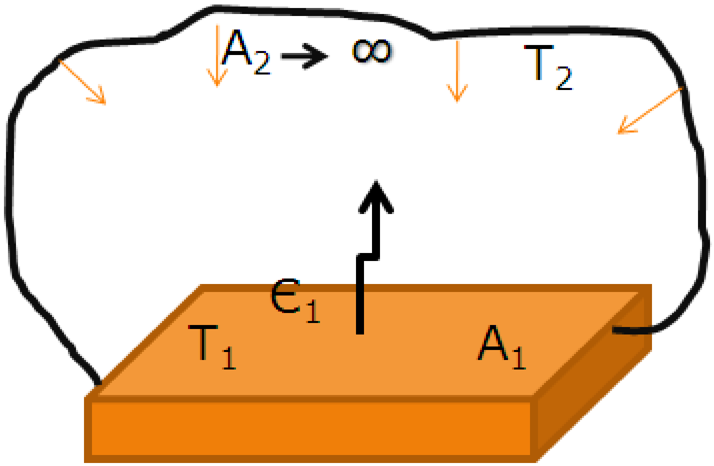
Thermal radiation emitted by a black body is proportional to the Fourth Power of its absolute temp.

Mathematically;

$q \infty T^4 \quad W/m^2;$

$Q = \sigma A T^4$ W; where σ is Stefan Boltzmann's constant ($5.67 \times 10^{-8}\ W/m^2K^4$)

$$Q = A_1 \epsilon_1 \sigma (T_1^4 - T_2^4)$$



$T_1 > T_2$

Numerical Problem

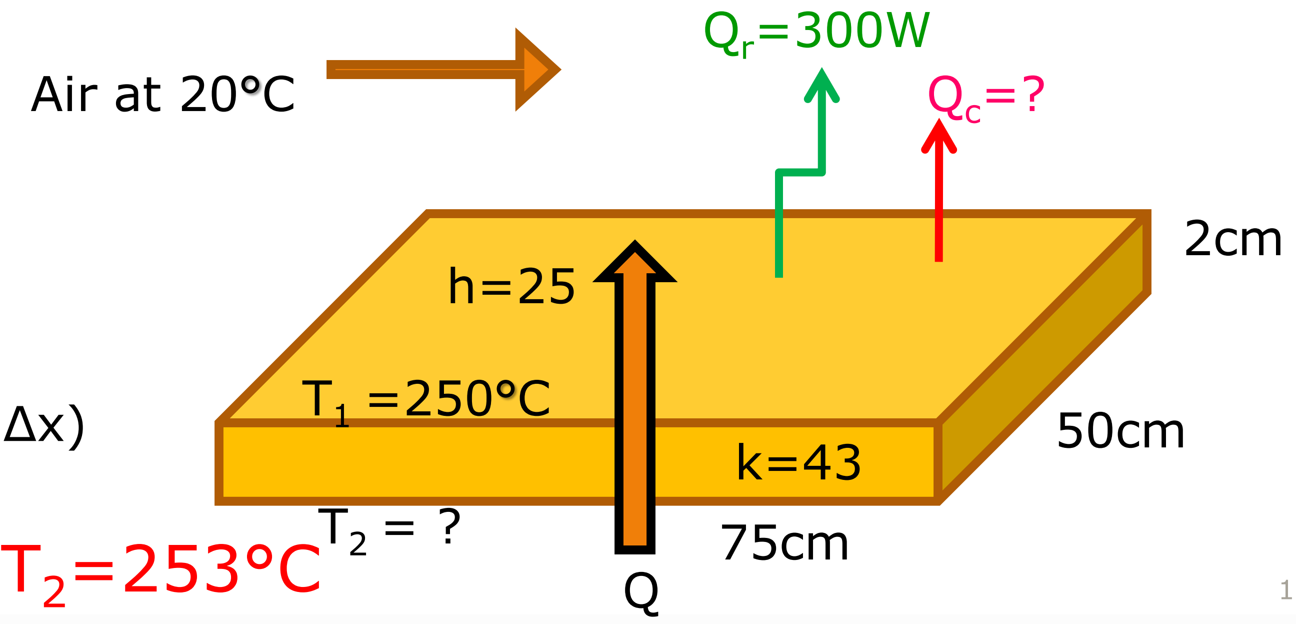
Q1: Air at 20°C blows over a 50cm x 75cm hot plate at 250°C. The film heat transfer coefficient is 25 W/m^2K. 300 W is lost from the plate surface by radiation. Calculate heat transfer rate and other side plate temp. Thermal conductivity of the plate material is 43 W/mK. The plate is 2cm thick.

$Q=?$

$Q=Q_c+Q_r$

$Q_c=hA(T_1 - T_a)$

$Q=kA(\Delta T/\Delta x)$
$=kA(T_2-T_1)/(\Delta x)$



$Q=2456W; \quad T_2=253°C$

Electrical Analogy

	Electrical Energy	**Heat Energy**
What flows?	Electrons	Heat energy through electrons
Driving Potential	Voltage Diff, ΔV	Temp Diff, ΔT
Flow	Current, I	Heat Transfer Rate, Q
Resistance to flow	ρ, A, L of conductor	R, Thermal Resistance

Example 1.1. *Calculate the rate of heat transfer per unit area through a copper plate 45 mm thick, whose one face is maintained at 350°C and the other face at 50°C. Take thermal conductivity of copper as 370 W/m°C.*

Solution. Temperature difference, $dt\ (= t_2 - t_1) = (50 - 350)$

Thickness of copper plate, $L = 45\text{ mm} = 0.045\text{ m}$

Thermal conductivity of copper, $k = 370\text{ W/m°C}$

Rate of heat-transfer per unit area, q :

From Fourier's law

$$Q = -\,kA\,\frac{dt}{dx} = -\,kA\,\frac{(t_2 - t_1)}{L} \qquad \text{...(Eqn. 1.1)}$$

or,

$$q = \frac{Q}{A} = -\,k\,\frac{dt}{dx}$$

$$= -\,370 \times \frac{(50 - 350)}{0.045}$$

$$= 2.466 \times 10^6\ \text{W/m}^2 \text{ or}$$

2.466 MW/m² (Ans.)

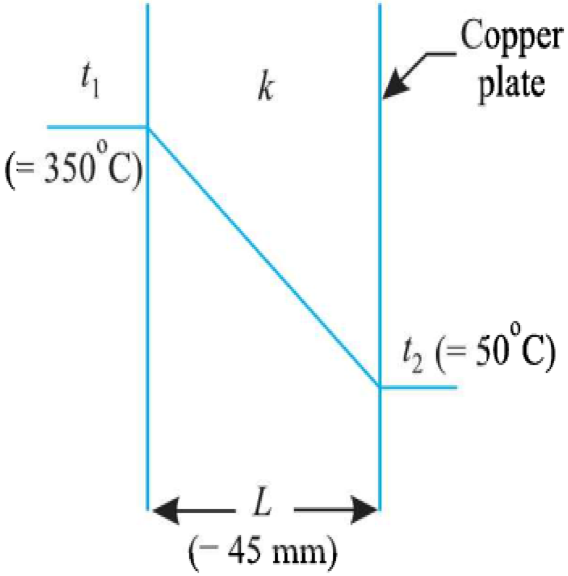


Fig. 1.8.

Example 1.2. *A plane wall is 150 mm thick and its wall area is 4.5 m^2. If its conductivity is 9.35 W/m°C and surface temperatures are steady at 150°C and 45°C, determine :*

(*i*) *Heat flow across the plane wall;*

(*ii*) *Temperature gradient in the flow direction.*

Solution. Thickness of the plane wall,

$$L = 150 \text{ mm}$$

$$= 0.15 \text{ m}$$

Area of the wall, $A = 4.5 \text{ m}^2$

Temperature difference, $dt = t_2 - t_1 = 45 - 150 = -105°\text{C}$

Thermal conductivity of wall material,

$$k = 9.35 \text{ W/m°C}$$

(*i*) **Heat flow across the plane wall, Q :**

As per Fourier's law,

(*i*) **Heat flow across the plane wall, Q :**

As per Fourier's law,

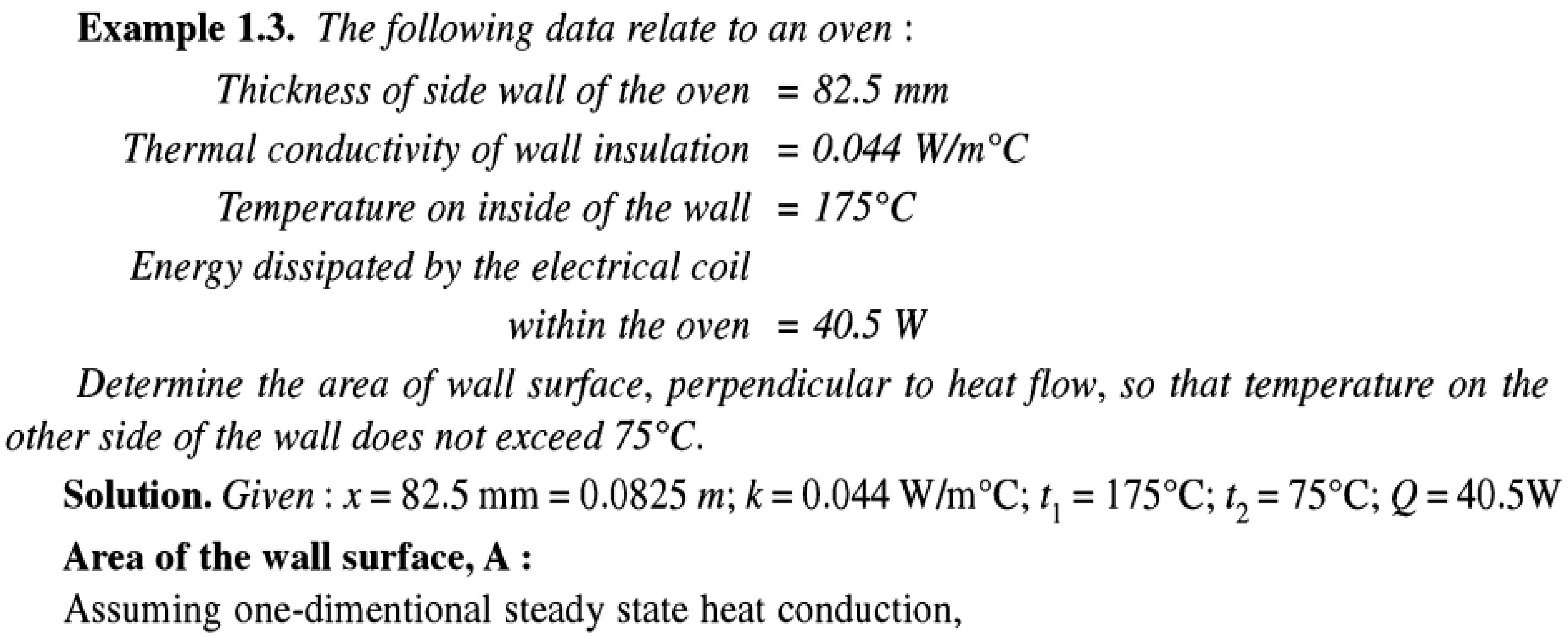
$$Q = -\,kA\,\frac{dt}{dx} = -\,kA\,\frac{(t_2 - t_1)}{L}$$

$$= -\,9.35 \times 4.5 \times \frac{(-105)}{0.15} = \mathbf{29452.5\ W}$$

(*ii*) **Temperature gradient, $\frac{dt}{dx}$:**

From Fourier's law, we have

$$\frac{dt}{dx} = -\,\frac{Q}{kA} = \frac{29452.5}{9.35 \times 4.5} = \mathbf{-\,700°C/m}$$



Example 1.3. *The following data relate to an oven :*

Thickness of side wall of the oven = *82.5 mm*
Thermal conductivity of wall insulation = *0.044 W/m°C*
Temperature on inside of the wall = *175°C*
Energy dissipated by the electrical coil within the oven = *40.5 W*

Determine the area of wall surface, perpendicular to heat flow, so that temperature on the other side of the wall does not exceed 75°C.

Solution. *Given* : $x = 82.5$ mm $= 0.0825\ m$; $k = 0.044$ W/m°C; $t_1 = 175$°C; $t_2 = 75$°C; $Q = 40.5$W

Area of the wall surface, A :

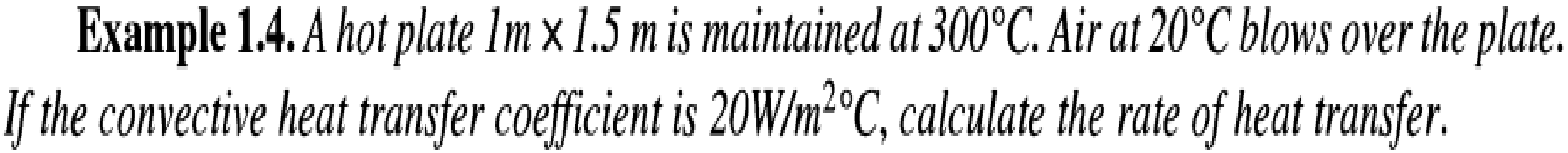
Assuming one-dimentional steady state heat conduction, Rate of electrical energy dissipation in the oven.

= Rate of heat transfer (conduction) across the wall

i.e.
$$Q = -kA\frac{dt}{dx} = -kA\frac{(t_2 - t_1)}{x} = \frac{kA\,(t_1 - t_2)}{x}$$

or,
$$40.5 = \frac{0.044\ A\,(175 - 75)}{0.0825}$$

or,
$$A = \frac{40.5 \times 0.0825}{0.044\,(175 - 75)} = \mathbf{0.759\ m^2}$$


Example 1.4. *A hot plate 1m × 1.5 m is maintained at 300°C. Air at 20°C blows over the plate. If the convective heat transfer coefficient is 20W/m²°C, calculate the rate of heat transfer.*

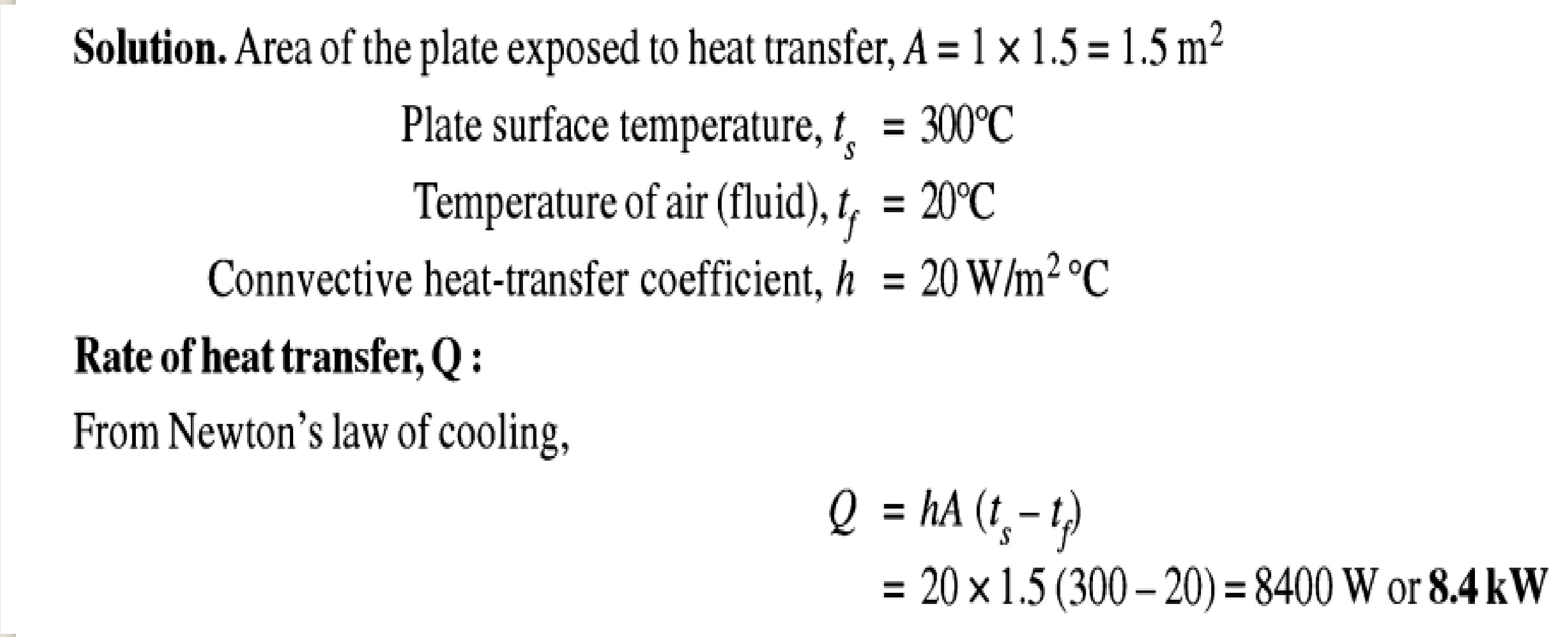

Solution. Area of the plate exposed to heat transfer, $A = 1 \times 1.5 = 1.5\ \text{m}^2$

Plate surface temperature, $t_s = 300°\text{C}$

Temperature of air (fluid), $t_f = 20°\text{C}$

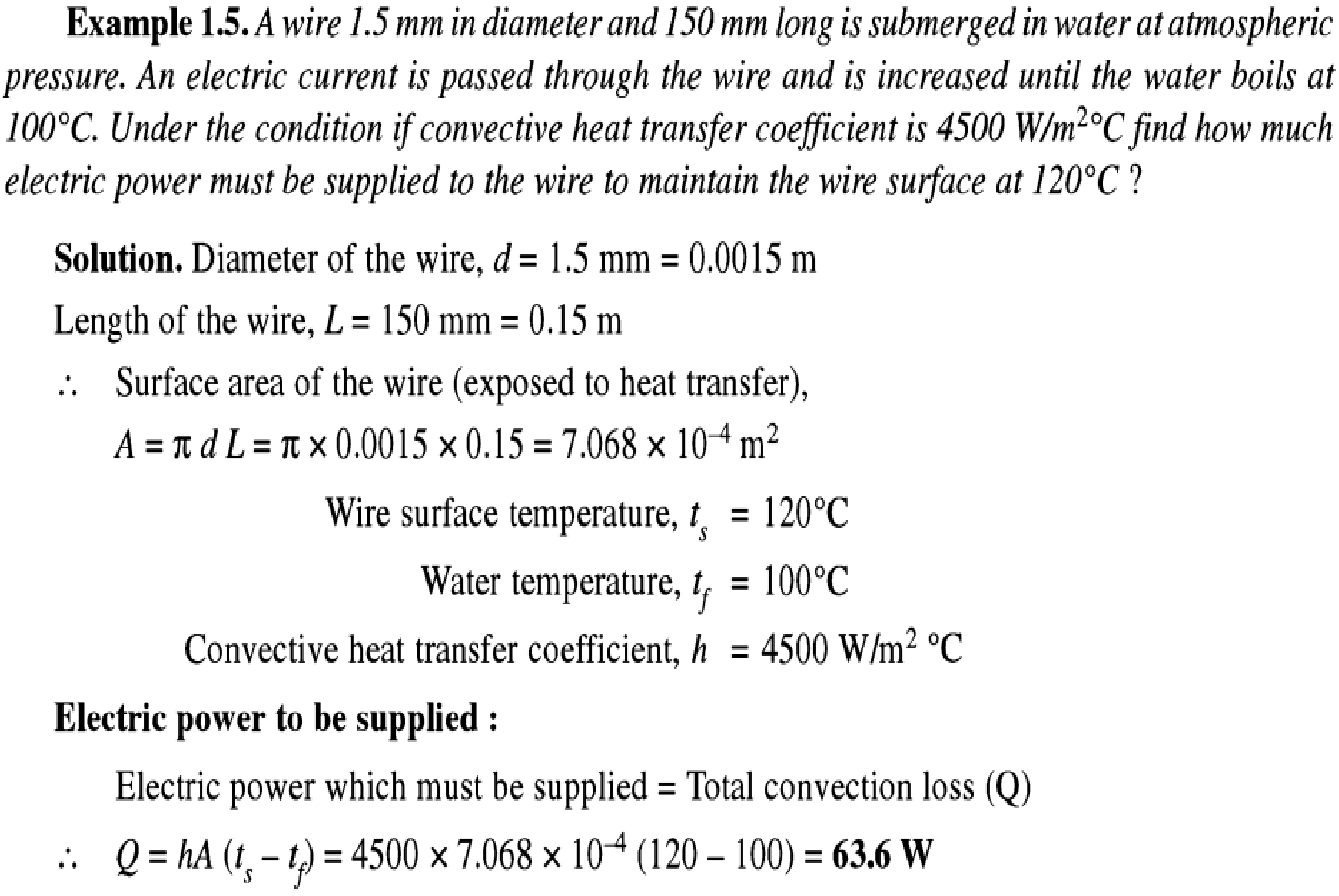
Connvective heat-transfer coefficient, $h = 20\ \text{W/m}^2\ °\text{C}$

Rate of heat transfer, Q :

From Newton's law of cooling,

$$Q = hA\,(t_s - t_f)$$

$$= 20 \times 1.5\,(300 - 20) = 8400\ \text{W or } \mathbf{8.4\ kW}$$



Example 1.5. *A wire 1.5 mm in diameter and 150 mm long is submerged in water at atmospheric pressure. An electric current is passed through the wire and is increased until the water boils at 100°C. Under the condition if convective heat transfer coefficient is 4500 W/m*^{2}*°C find how much electric power must be supplied to the wire to maintain the wire surface at 120°C ?*

Solution. Diameter of the wire, $d = 1.5\text{ mm} = 0.0015\text{ m}$

Length of the wire, $L = 150\text{ mm} = 0.15\text{ m}$

∴ Surface area of the wire (exposed to heat transfer),

$$A = \pi\, d\, L = \pi \times 0.0015 \times 0.15 = 7.068 \times 10^{-4}\text{ m}^2$$

Wire surface temperature, $t_s = 120°\text{C}$

Water temperature, $t_f = 100°\text{C}$

Convective heat transfer coefficient, $h = 4500\text{ W/m}^2\,°\text{C}$

Electric power to be supplied :

Electric power which must be supplied = Total convection loss (Q)

$$\therefore \quad Q = hA\,(t_s - t_f) = 4500 \times 7.068 \times 10^{-4}\,(120 - 100) = \mathbf{63.6\ W}$$

Example 1.6. *A surface having an area of 1.5 m^2 and maintained at 300°C exchanges heat by radiation with another surface at 40°C. The value of factor due to the geometric location and emissivity is 0.52. Determine :*

(*i*) *Heat lost by radiation,*

(*ii*) *The value of thermal resistance, and*

(*iii*) *The value of equivalent convection coefficient.*

Solution. *Given* : $A = 1.5\ \text{m}^2$; $T_1 = t_1 + 273 = 300 + 273 = 573\text{K}$; $T_2 = t_2 + 273 = 40 + 273 = 313\text{K}$; $F = 0.52$.

(*i*) Heat lost by radiation, Q :

$$Q = F\sigma A(T_1^4 - T_2^4) \qquad \text{...[Eqn. (1.9)]}$$

(where $\sigma = 5.67 \times 10^{-8}\ \text{W/m}^2\ \text{K}^4$)

or,

$$Q = 0.52 \times 5.67 \times 10^{-8} \times 1.5\ [(573)^4 - (313)^4]$$

$$= 0.52 \times 5.67 \times 1.5 \left[\left(\frac{573}{100}\right)^4 - \left(\frac{313}{100}\right)^4\right]$$

(Please note this step)

or,

$$Q = \mathbf{4343\ W}$$

(*ii*) The value of thermal resistance, (Rth)rad :

We know that, $$Q = \frac{(T_1 - T_2)}{(R_{th})_{rad}}$$ ...[Eqn. (1.10)]

$$\therefore \qquad (R_{\text{th}})_{\text{rad.}} = \frac{(T_1 - T_2)}{Q} = \frac{(573 - 313)}{4343} = \mathbf{0.0598\ °C/W}$$

(*iii*) The value of equivalent convection coefficient, hr :

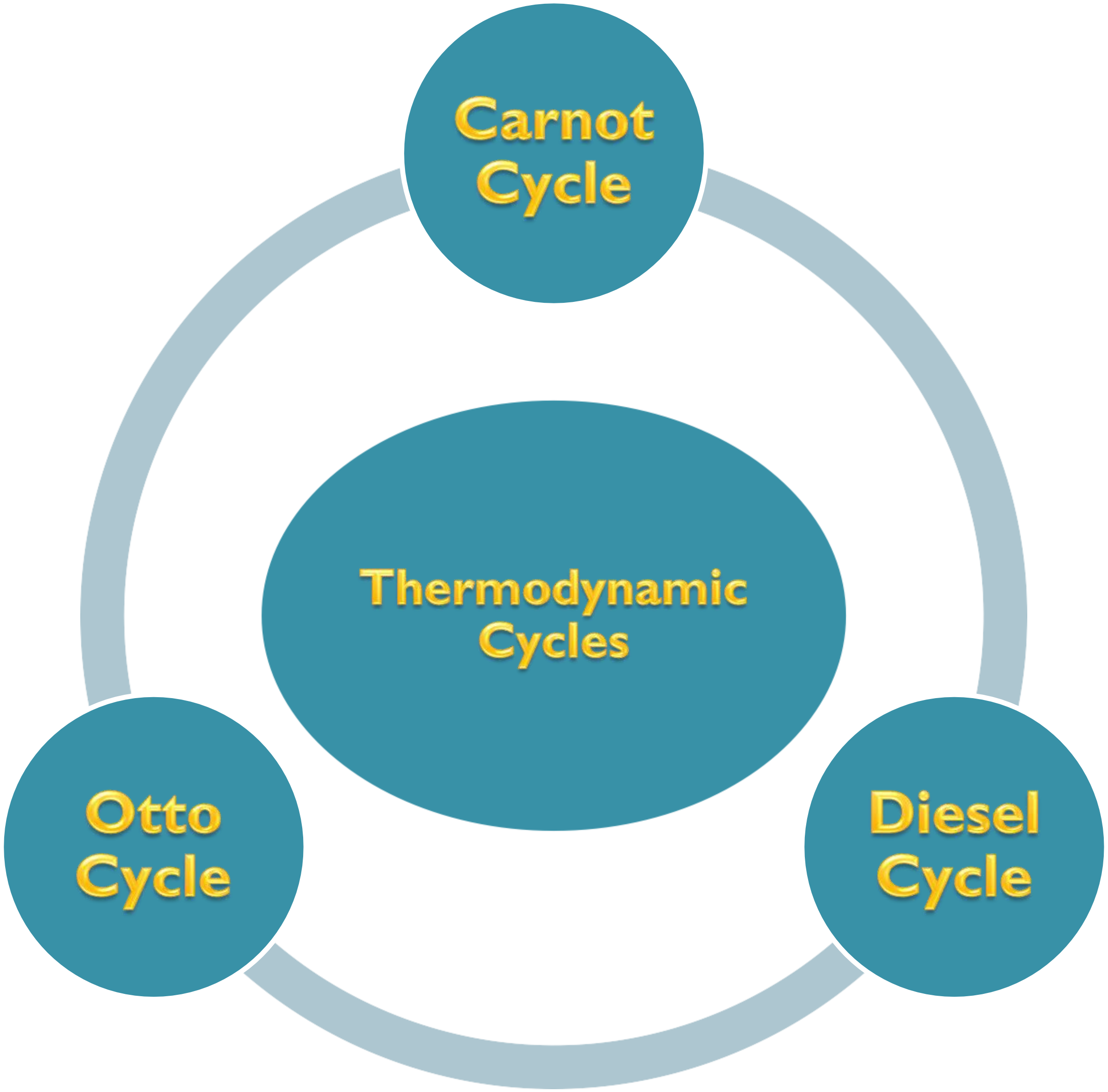
$$Q = h_r A\,(t_1 - t_2)$$

or, $$h_r = \frac{Q}{A\,(t_1 - t_2)} = \frac{4343}{1.5\,(300 - 40)} = \mathbf{11.13\ W/m^2\ °C}$$

Alternatively, $$h_r = F\,\sigma\,(T_1 + T_2)\,(T_1^{\,2} + \mathrm{T}_2^{\,2})$$ ...From eqn. (1.10)

$$= 0.52 \times 5.67 \times 10^{-8}\,(573 + 313)\,(573^2 + 313^2)$$

$$= \mathbf{11.13\ W/m^2\ °C}$$



Carnot Cycle

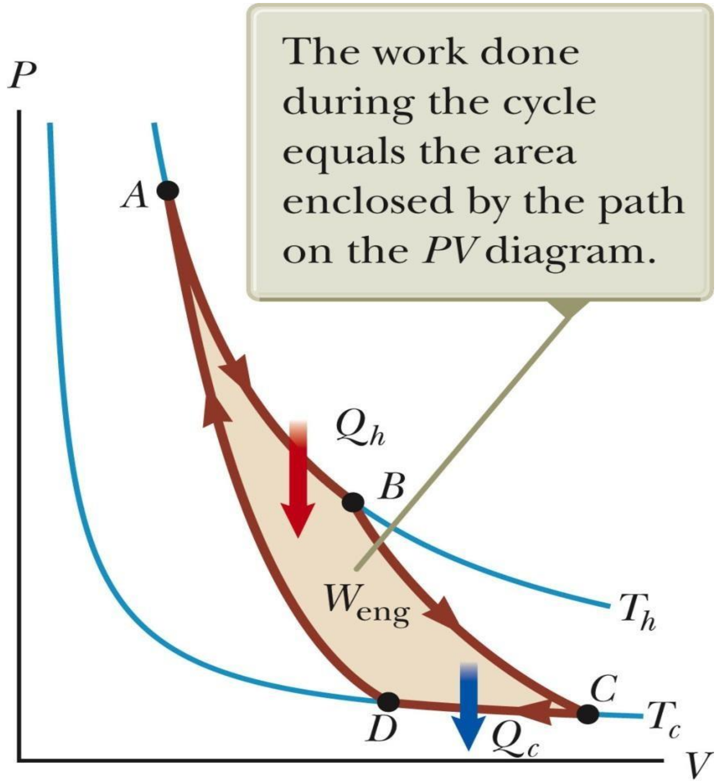
Thermodynamic Cycles

Otto Cycle

Diesel Cycle

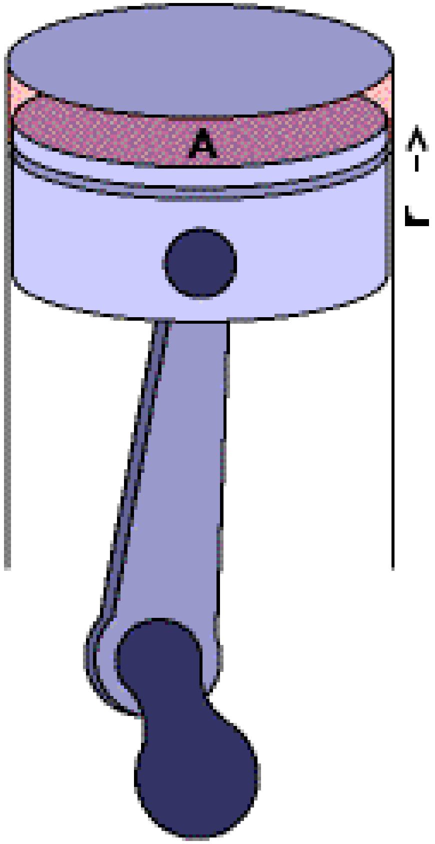
Carnot Cycle

Sadi Carnot 1796-1832



The work done during the cycle equals the area enclosed by the path on the *PV* diagram.

- Probably the best known reversible cycle is the Carnot cycle, first proposed in 1824 by French engineer **Sadi Carnot**. The theoretical heat engine that operates on the Carnot cycle is called the **Carnot heat engine**. The Carnot cycle is composed of four reversible processes—**<u>two isothermal and two adiabatic</u>**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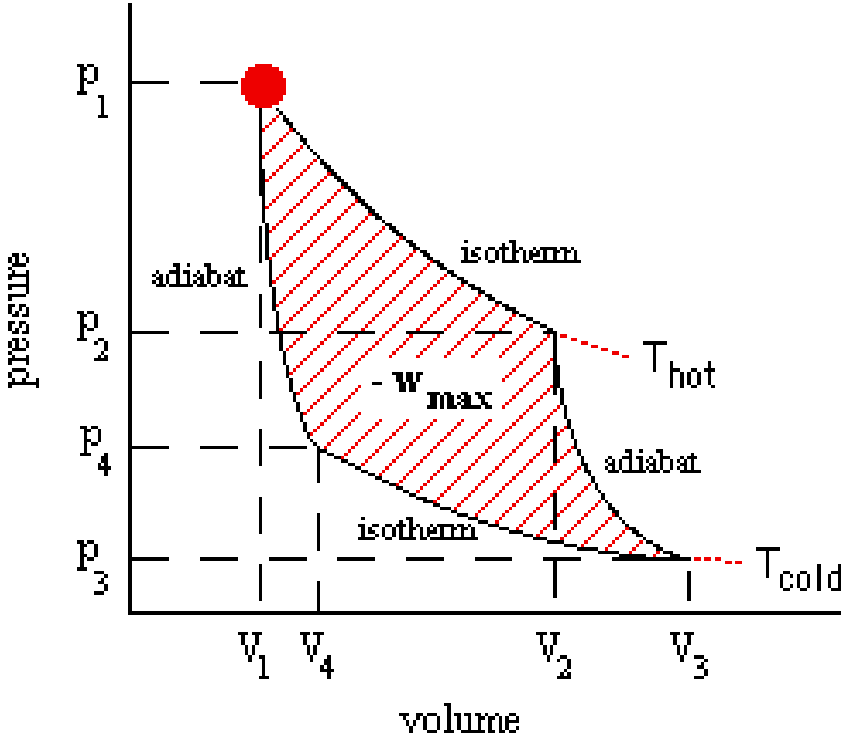
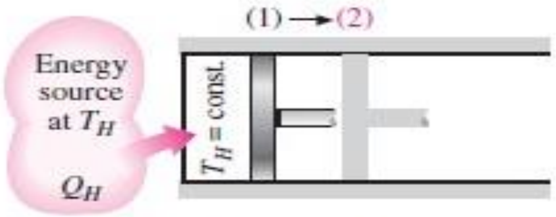
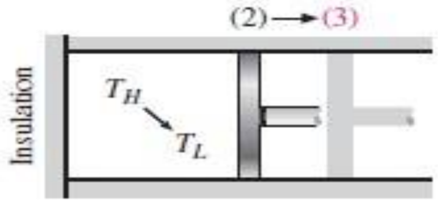
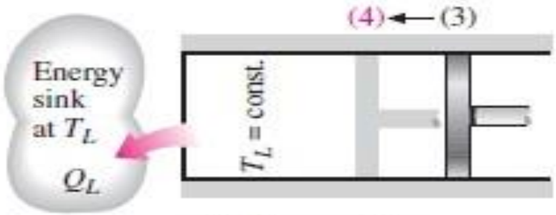

pressure
p_1
p_2
p_4
p_3
adiabat
isotherm
$- w_{max}$
T_{hot}
adiabat
isotherm
T_{cold}
V_1
V_4
V_2
V_3
volume



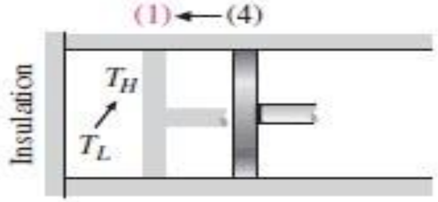
(*a*) Process 1-2



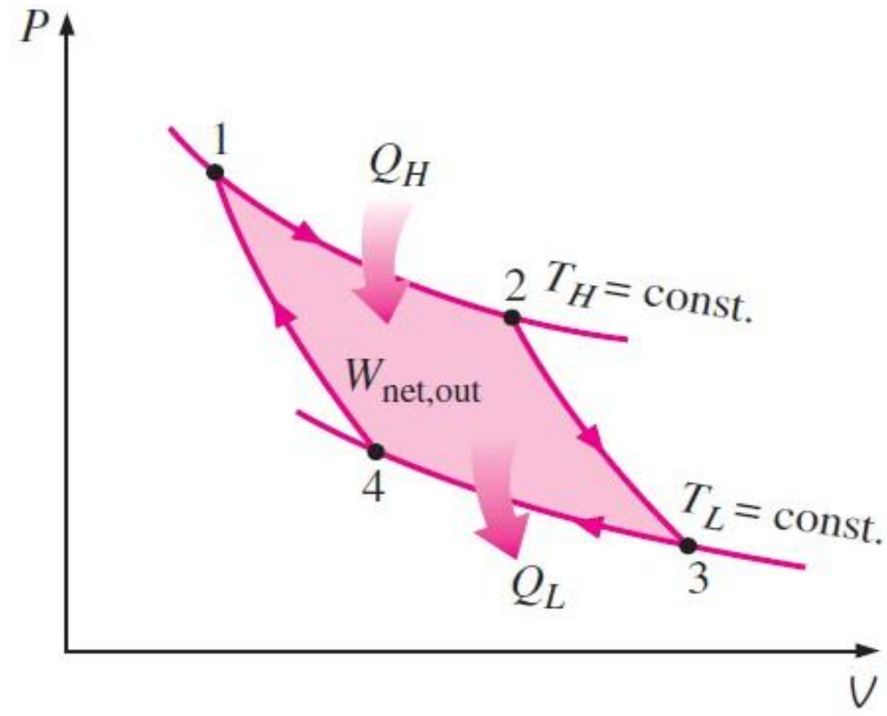
(*b*) Process 2-3



(*c*) Process 3-4



(*d*) Process 4-1



- Process 1-2, Isothermal expansion process
- Process 2-3, Isentropic expansion process
- Process 3-4, Isothermal compression process
- Process 4-1, Isentropic compression process

- Area under curve 1-2-3 is the work done by the gas during the expansion part of the cycle, and the area under curve 3-4-1 is the work done on the gas during the compression part of the cycle.
- The area enclosed by the path of the cycle (area 1-2-3-4-1) is the difference between these two and represents the net work done during the cycle

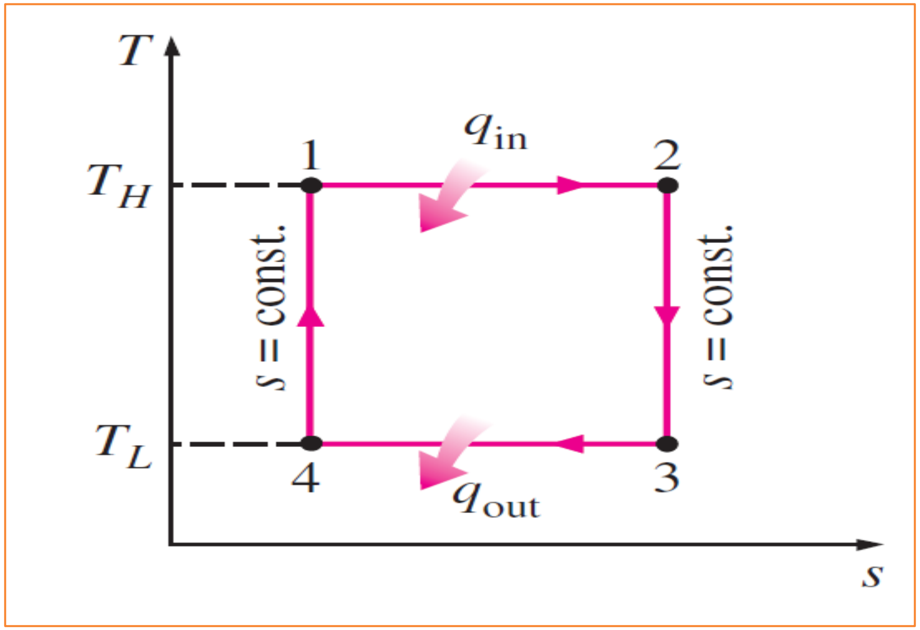
- **$V_3/V_2 = V_4/V_1$ or $V_3/V_4 = V_2/V_1$**
- **Heat Supplied, $Q_H = P_1V_1\log_e(V_2/V_1)$**
- **Heat Rejected, $Q_L = P_3V_3\log_e(V_3/V_4)$**
- **Work Done, $W_{net} = Q_{in} – Q_{out}$**

- **Thermal efficiency, $\eta = 1- (Q_{out}/Q_{in})$**

$= 1- (Q_L / Q_H)$

$= 1- (T_L/T_H)$

= 1- (Low Temperature/High temperature)

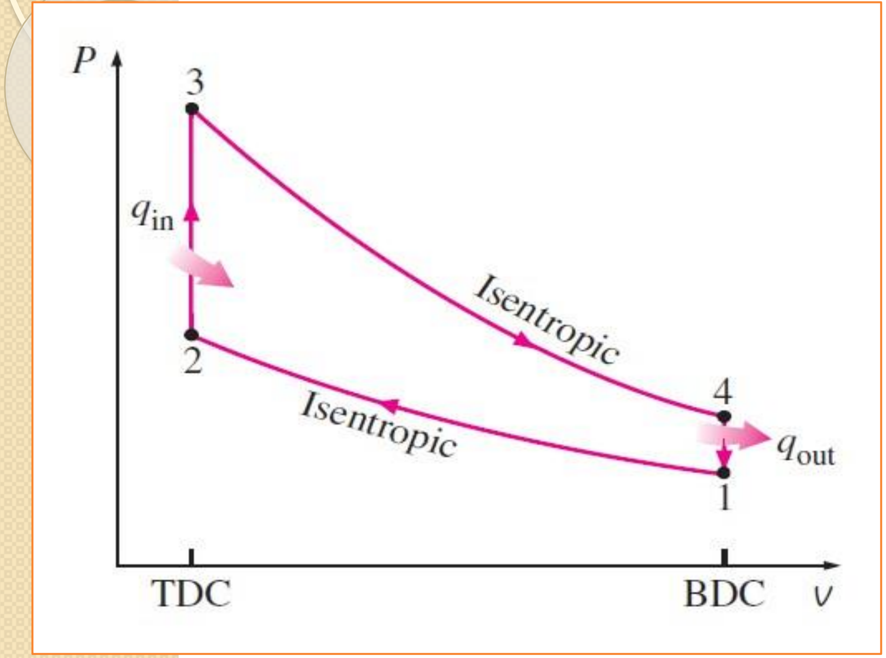


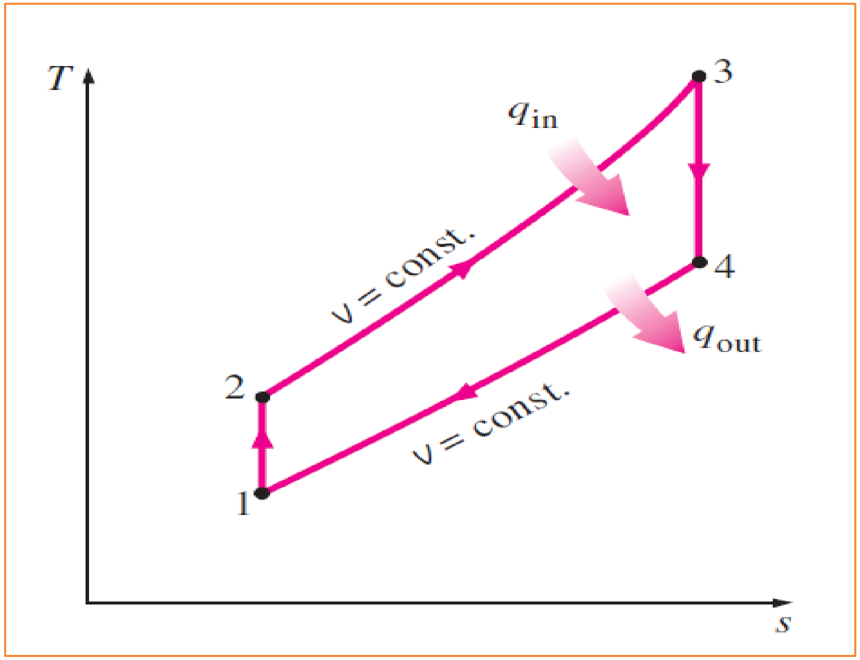
- **$Q_L/T_L = Q_H/T_H$ or Q/T-** Independent of path, called entropy
- **$Q/T = dS$**
- The area enclosed by the path of the cycle (area 1-2-3-4-1) represents the net work done during the cycle

- Carnot cycle is not a practical cycle

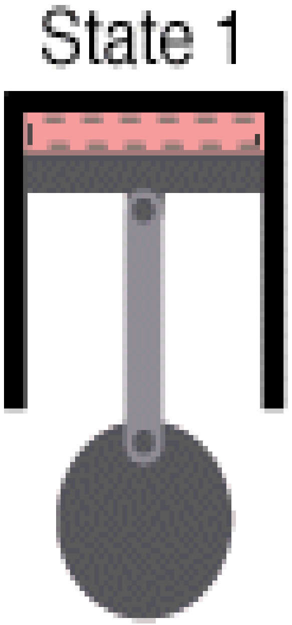
In order to achieve isothermal process, the piston has to move very slowly, so that the temperature remains constant during heat exchange. But, in order to achieve adiabatic process, the piston has to move very fast, so that there is no heat exchange with the surroundings. Since isothermal and adiabatic processes are to take place simultaneously, the cycle is not practically possible

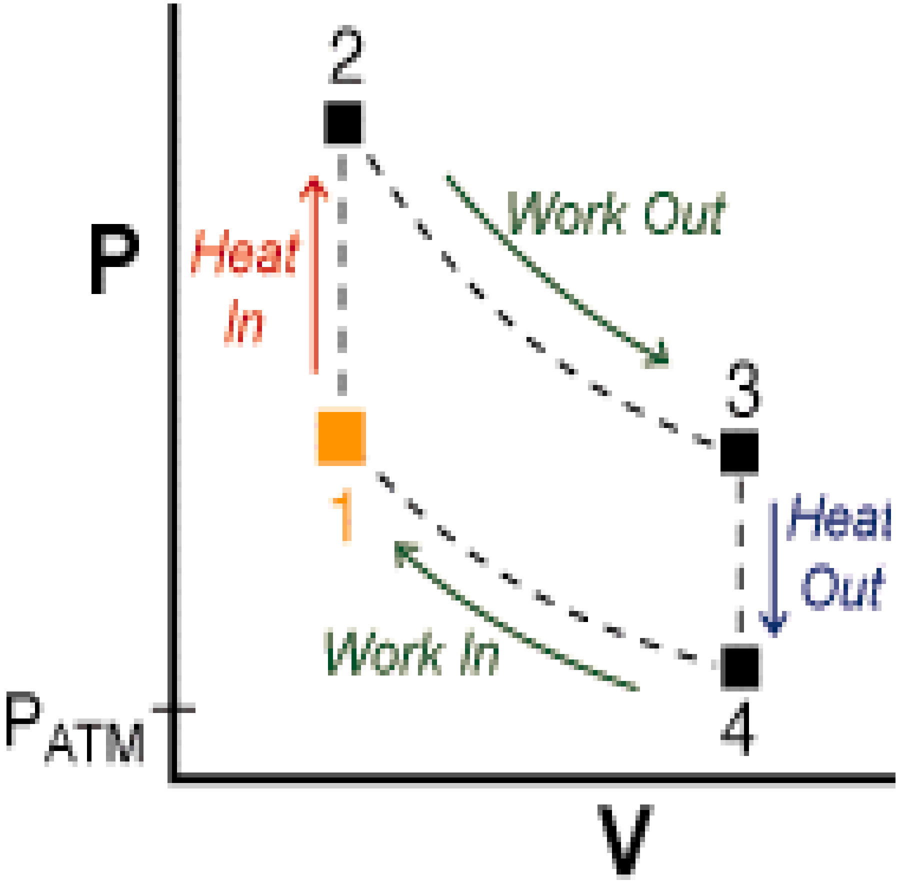
Otto Cycle





- The Otto cycle is the ideal cycle for spark-ignition reciprocating(Petrol) engines. It is named after **Nikolaus A. Otto**, who built a successful four-stroke engine in 1876 in Germany using the cycle proposed by Frenchman Beau de Rochas in 1862


State 1


P
P_ATM
V
1
2
3
4
Heat In
Work Out
Heat Out
Work In

- Process 1-2, Isentropic compression
- Process 2-3, Constant volume heat addition
- Process 3-4, Isentropic expansion(Power Stroke)
- Process 4-1, Constant volume heat rejection

- Compression Ratio, **$r = V_1/V_2$; also** Expansion Ratio, **$r = V_4/V_3$**
- **Heat Supplied, $Q_{in} = mc_v(T_3-T_2)$**
- **Heat Rejected, $Q_{out} = mc_v(T_4-T_1)$**
- **Work Done, $W_{net} = Q_{in} – Q_{out}$**
- **Thermal Efficiency, $\eta = 1- (Q_{out}/Q_{in})$**

$$= 1 – [mc_v(T_4-T_1)/ mc_v(T_3-T_2)]$$

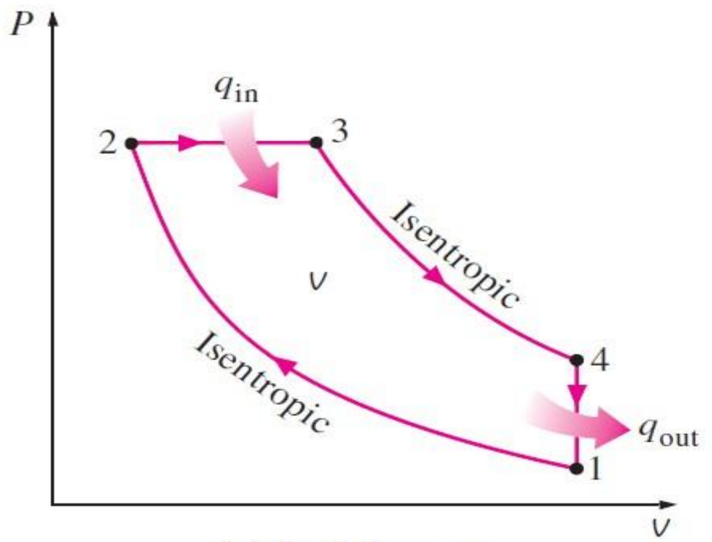
$$= 1- [1/r^{(\gamma-1)}]$$

- Thermal efficiency is a function of the compression ratio ‘**r**’ and the ratio of specific heats ‘**γ**’

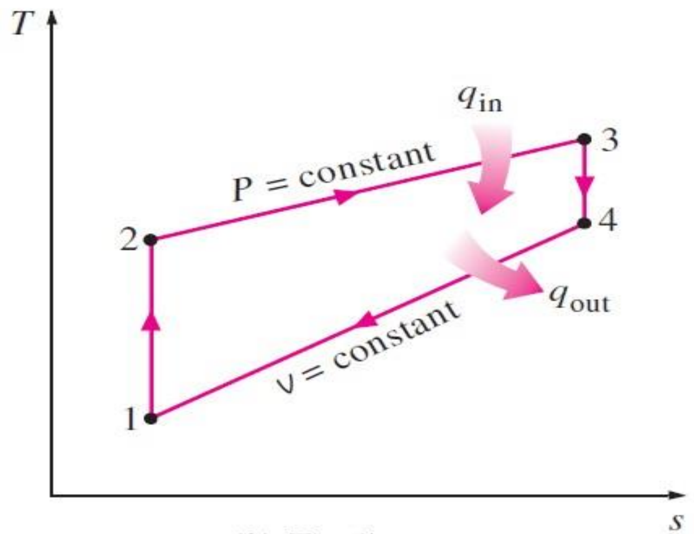
- Efficiency will be more for gases having higher value of ‘**γ**’

- Compression ratio increases cause increase in thermal efficiency

Diesel Cycle



(*a*) *P*- v diagram



(*b*) *T*-*s* diagram

- The Diesel cycle is the ideal cycle for Compression Ignition(CI) reciprocating engines. The CI engine, first proposed by Rudolph Diesel in the 1890s

- Process 1-2, Isentropic compression
- Process 2-3, Constant pressure heat addition
- Process 3-4, Isentropic expansion(Power Stroke)
- Process 4-1, Constant volume heat rejection

- **Compression Ratio, $r = V_1/V_2$**
- **Expansion Ratio, $r_1 = V_4/V_3$**
- **Cutoff Ratio, $\rho = V_3/V_2$**
- **$r_1 = r/\rho$**

- **Heat Supplied, $Q_{in} = mc_p(T_3-T_2)$**
- **Heat Rejected, $Q_{out} = mc_v(T_4-T_1)$**
- **Work Done, $W_{net} = Q_{in} – Q_{out}$**

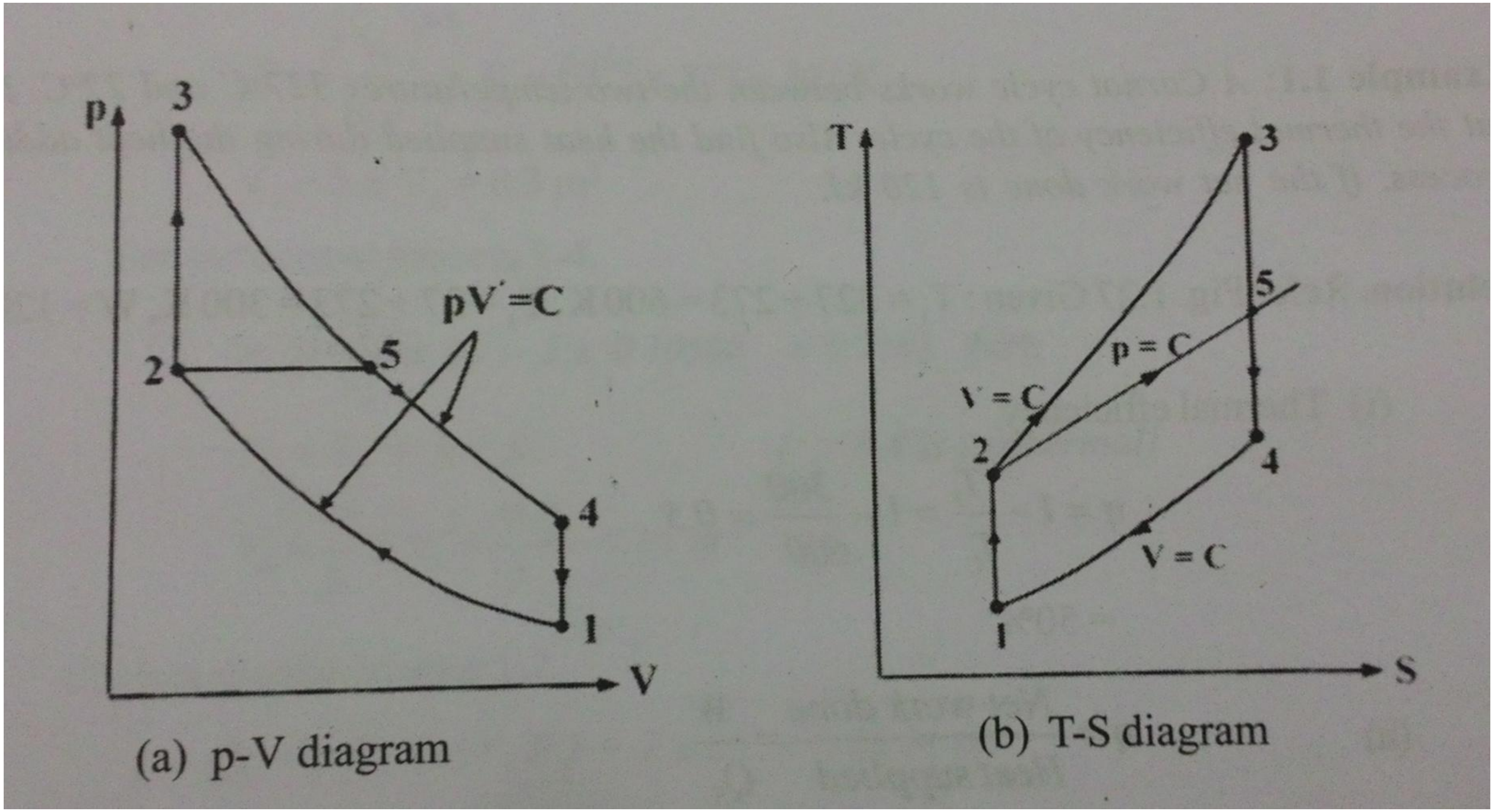
- **Thermal Efficiency, $\eta = 1- (Q_{out}/Q_{in})$**

  $= 1 – [mc_v(T_4-T_1)/ mc_p(T_3-T_2)]$

$$\eta = 1 - \frac{1}{r^{\gamma-1}} \left(\frac{1}{\gamma}\right) \left[\frac{\rho^{\gamma}-1}{\rho-1}\right]$$

Comparison of Otto and Diesel Cycle

1. On the basis of same Compression Ratio



(a) p-V diagram

(b) T-S diagram

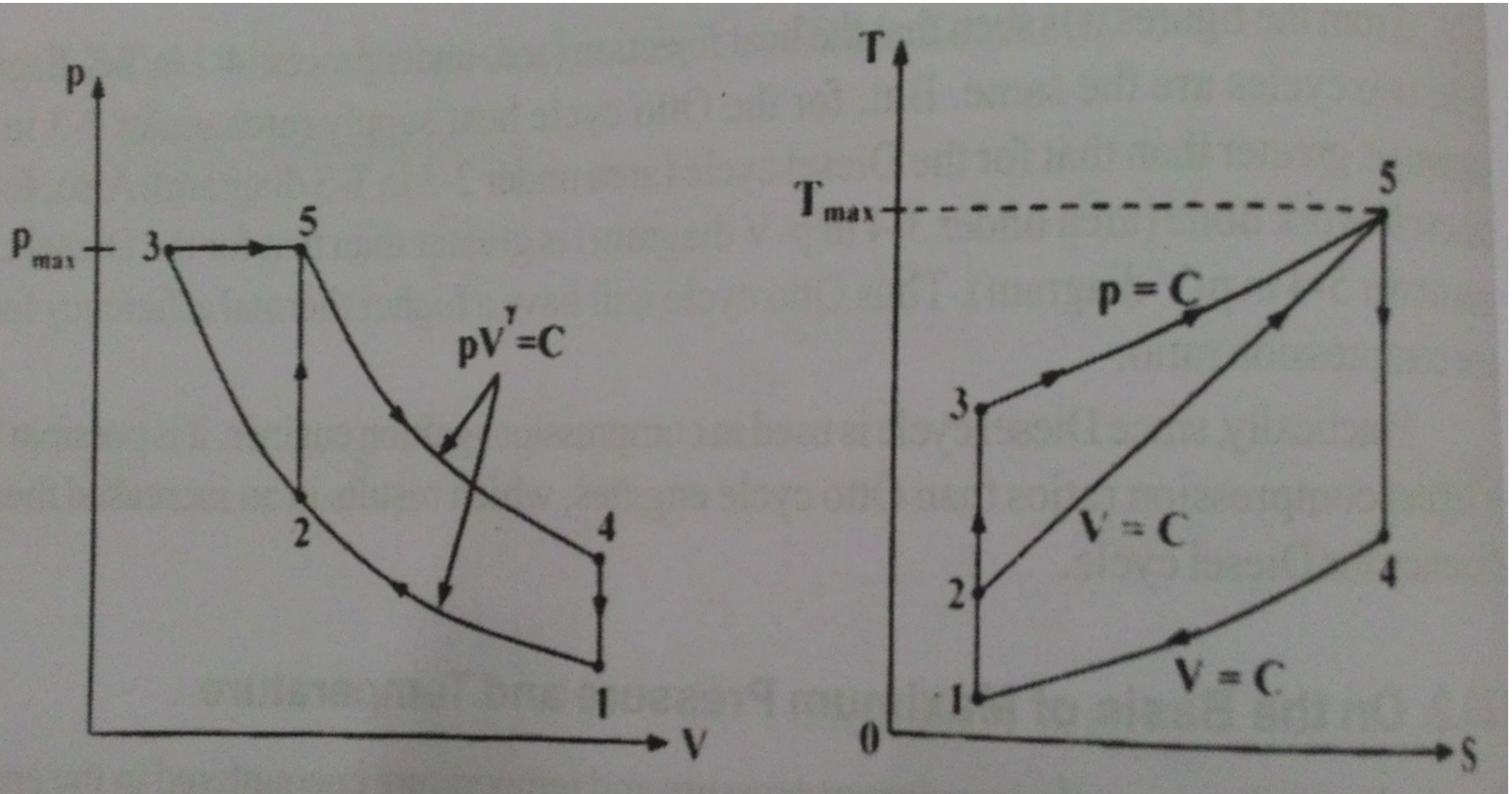
- Cycle 1-2-3-4-1 shows Otto cycle
- Cycle 1-2-5-4-1 shows Diesel cycle

- For the Otto cycle heat supply(area under 2-3 in T-S diagram) is greater than that for the Diesel cycle(area under 2-5 in T-S diagram)

- For the Otto cycle work done(area under 3-4 in P-V diagram) is greater than that for the Diesel cycle(area under 5-4 in P-V diagram)

- **Otto cycle will have a higher thermal efficiency for the same Compression Ratio**

2. On the basis of maximum Pressure and Temperature



(a) p-V diagram

(b) T-S diagram

- Cycle 1-2-5-4-1 shows Otto cycle
- Cycle 1-2-3-5-4-1 shows Diesel cycle

- Heat supply for the Diesel cycle(area under 3-5 in T-S diagram) is greater than that for Otto cycle(area under 2-5 in T-S diagram). Since Otto cycle receives less heat for the same heat rejection, its efficiency will be lower than that of diesel

THANK YOU