# Introduction of Thermodynamics

Lecture Notes:

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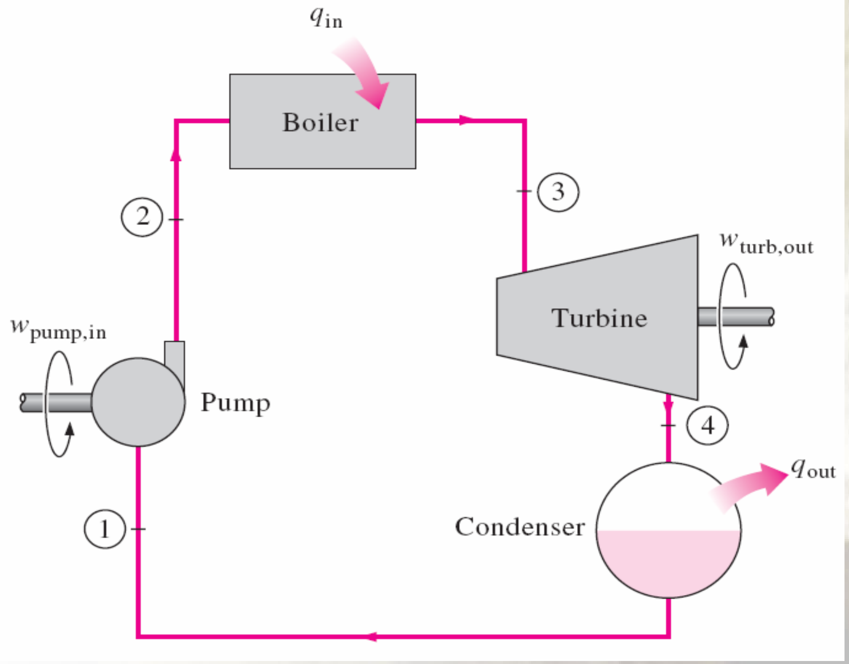
# What is Thermodynamics?

- The science of energy, that concerned with the ways in which energy is stored within a body.
- Energy transformations – mostly involve heat and work movements.
- The Fundamental law is the *conservation of energy* principle: energy cannot be created or destroyed, but can only be transformed from one form to another.



# Definition of Thermodynamics

“Thermodynamics is the branch of physical science that deals with the various phenomena of energy and related properties of matter, especially of the laws of transformations of heat into other forms of energy and vice-versa.”

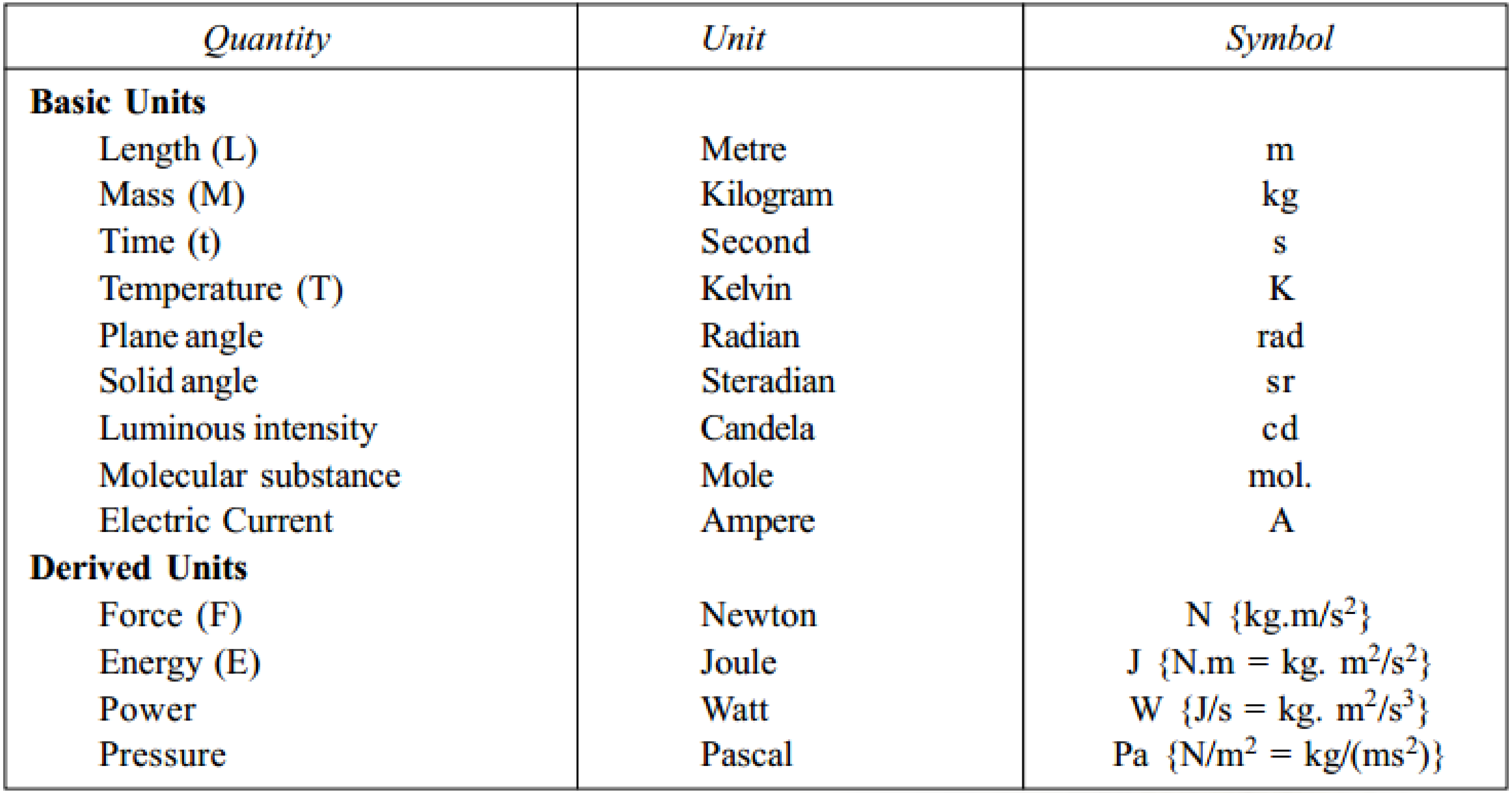
Thermodynamics can be classified as ‘**Classical thermodynamics**’ and ‘**Statistical thermodynamics**’. Here in engineering systems analysis the classical thermodynamics is employed.

# DIMENSIONS AND UNITS

“**Dimension**” refers to certain fundamental physical concepts that are involved in the process of nature and are more or less directly evident to our physical senses, thus dimension is used for characterizing any physical quantity.

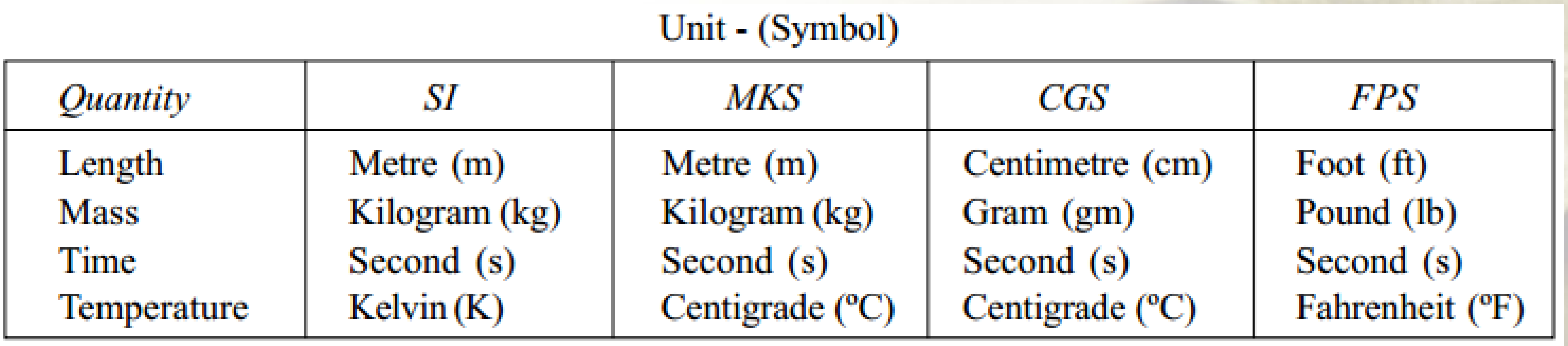
“Units” are the **magnitudes assigned to the dimensions**. Units assigned to “primary dimensions” are called “basic units” whereas units assigned to “secondary dimensions” are called “derived units”.

# *Table 1.1 SI system of units*



| *Quantity* | *Unit* | *Symbol* |
|---|---|---|
| **Basic Units** | | |
| Length (L) | Metre | m |
| Mass (M) | Kilogram | kg |
| Time (t) | Second | s |
| Temperature (T) | Kelvin | K |
| Plane angle | Radian | rad |
| Solid angle | Steradian | sr |
| Luminous intensity | Candela | cd |
| Molecular substance | Mole | mol. |
| Electric Current | Ampere | A |
| **Derived Units** | | |
| Force (F) | Newton | N $\{kg.m/s^2\}$ |
| Energy (E) | Joule | J $\{N.m = kg.\ m^2/s^2\}$ |
| Power | Watt | W $\{J/s = kg.\ m^2/s^3\}$ |
| Pressure | Pascal | Pa $\{N/m^2 = kg/(ms^2)\}$ |

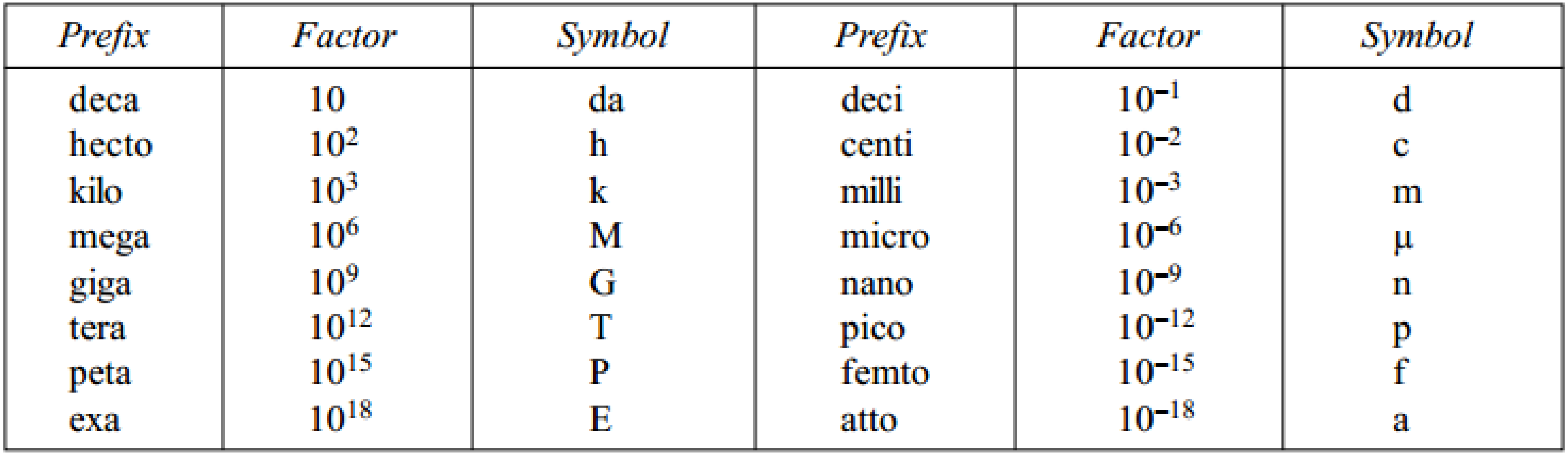
# Table 1.2 Various systems of units



Unit - (Symbol)

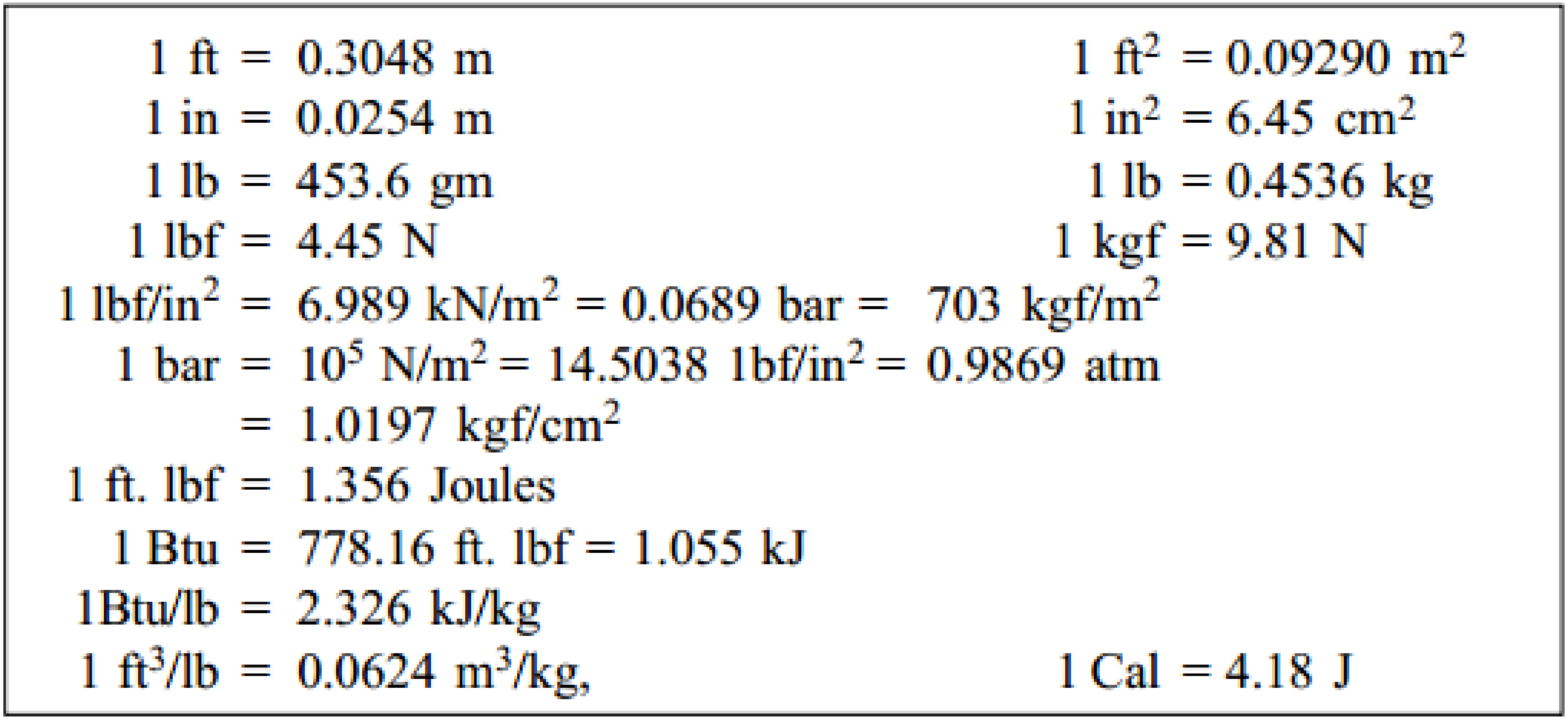
| *Quantity* | *SI* | *MKS* | *CGS* | *FPS* |
|---|---|---|---|---|
| Length | Metre (m) | Metre (m) | Centimetre (cm) | Foot (ft) |
| Mass | Kilogram (kg) | Kilogram (kg) | Gram (gm) | Pound (lb) |
| Time | Second (s) | Second (s) | Second (s) | Second (s) |
| Temperature | Kelvin (K) | Centigrade (ºC) | Centigrade (ºC) | Fahrenheit (ºF) |

# Table 1.3 Various prefixes



| *Prefix* | *Factor* | *Symbol* | *Prefix* | *Factor* | *Symbol* |
|---|---|---|---|---|---|
| deca | $10$ | da | deci | $10^{-1}$ | d |
| hecto | $10^2$ | h | centi | $10^{-2}$ | c |
| kilo | $10^3$ | k | milli | $10^{-3}$ | m |
| mega | $10^6$ | M | micro | $10^{-6}$ | µ |
| giga | $10^9$ | G | nano | $10^{-9}$ | n |
| tera | $10^{12}$ | T | pico | $10^{-12}$ | p |
| peta | $10^{15}$ | P | femto | $10^{-15}$ | f |
| exa | $10^{18}$ | E | atto | $10^{-18}$ | a |

# *Table 1.3 Unit* conversion table



1 ft = 0.3048 m

1 in = 0.0254 m

1 lb = 453.6 gm

1 lbf = 4.45 N

1 lbf/in$^2$ = 6.989 kN/m$^2$ = 0.0689 bar = 703 kgf/m$^2$

1 bar = 10$^5$ N/m$^2$ = 14.5038 1bf/in$^2$ = 0.9869 atm

= 1.0197 kgf/cm$^2$

1 ft. lbf = 1.356 Joules

1 Btu = 778.16 ft. lbf = 1.055 kJ

1Btu/lb = 2.326 kJ/kg

1 ft$^3$/lb = 0.0624 m$^3$/kg,

1 ft$^2$ = 0.09290 m$^2$

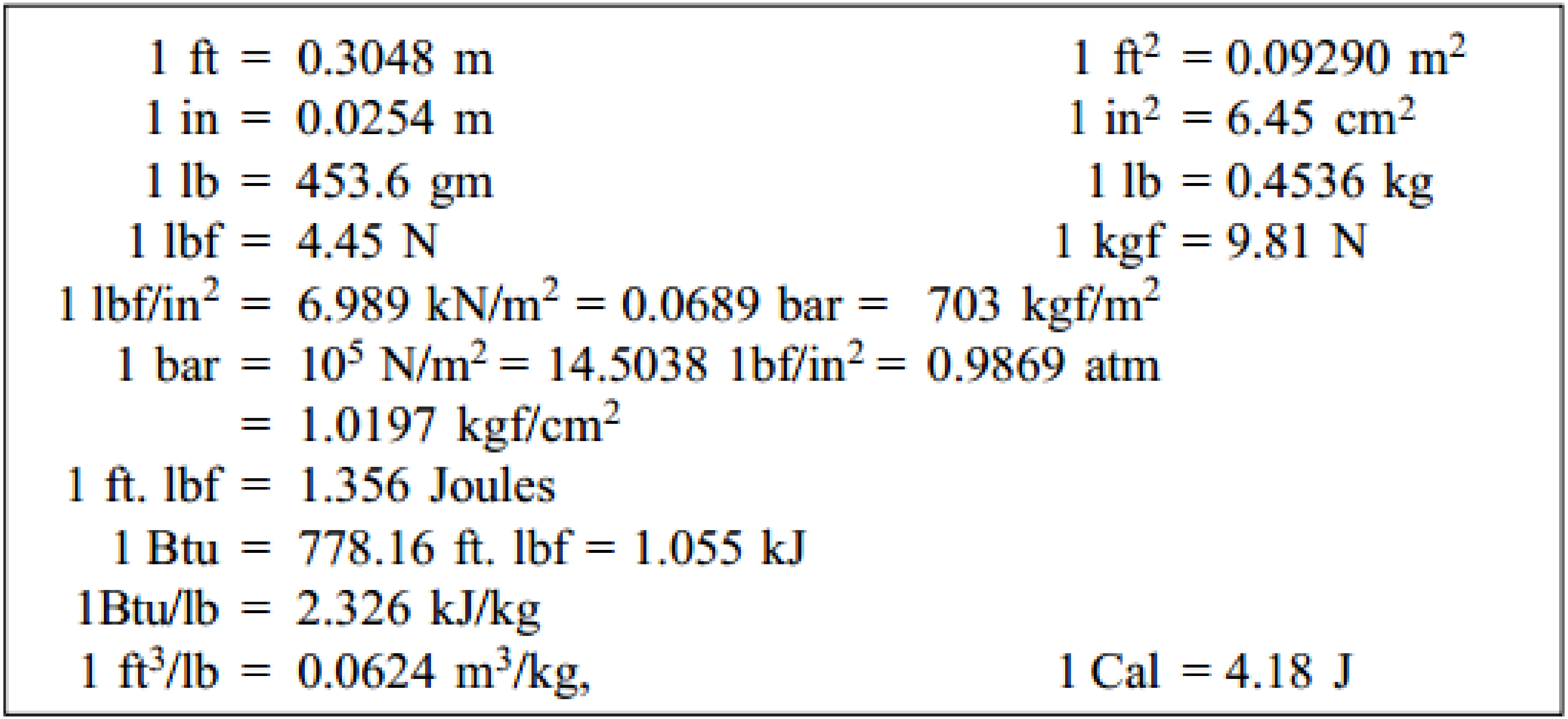
1 in$^2$ = 6.45 cm$^2$

1 lb = 0.4536 kg

1 kgf = 9.81 N

1 Cal = 4.18 J

# *Table 1.3 Unit* conversion table



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# Relation of Heat Transfer to Thermodynamics

Energy exists in various forms. In heat transfer, we are primarily interested in heat, which ***is the form of energy that can be transferred from one system to another as a result of temperature difference***. The science that deals with the determination of the rates of such energy transfers is **heat transfer**.

# Relation of Heat Transfer to Thermodynamics

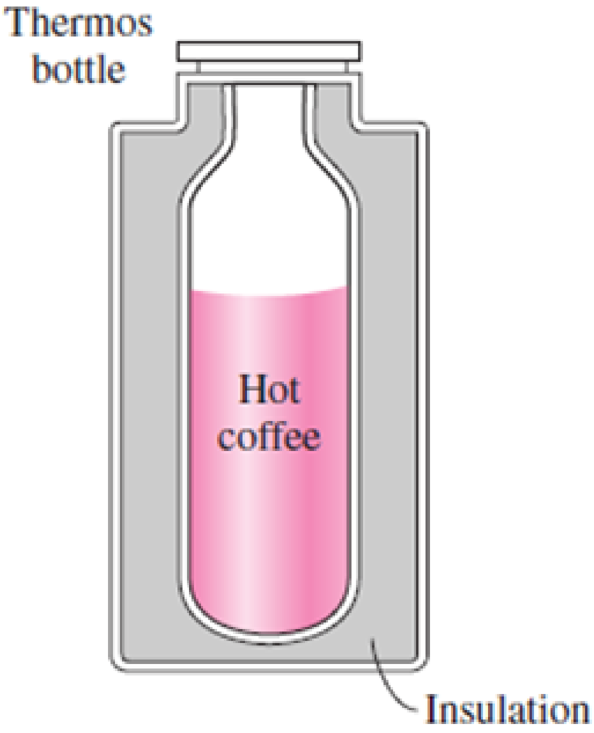


Figure 1-1

We are normally interested in how long it takes for the hot coffee in a thermos to cool to a certain temperature, which cannot be determined from a thermodynamic analysis alone.

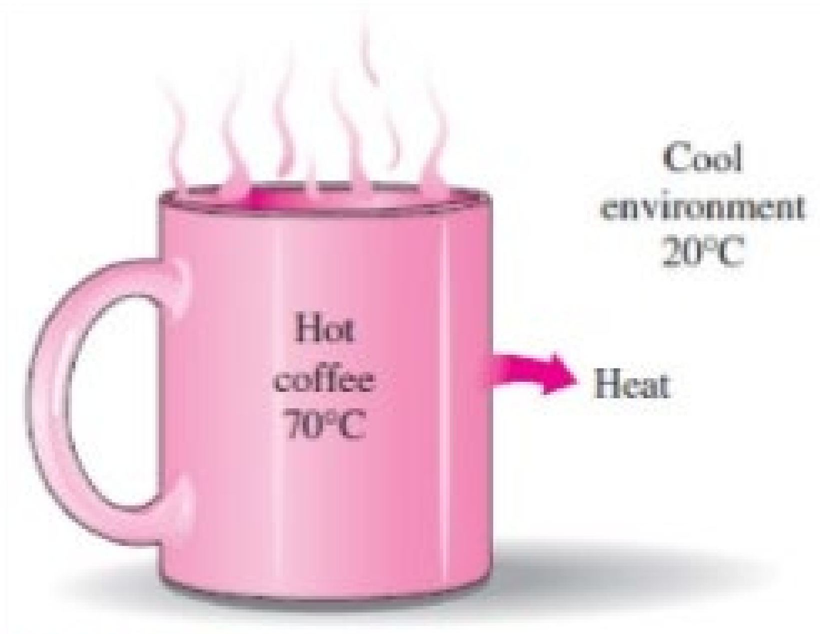
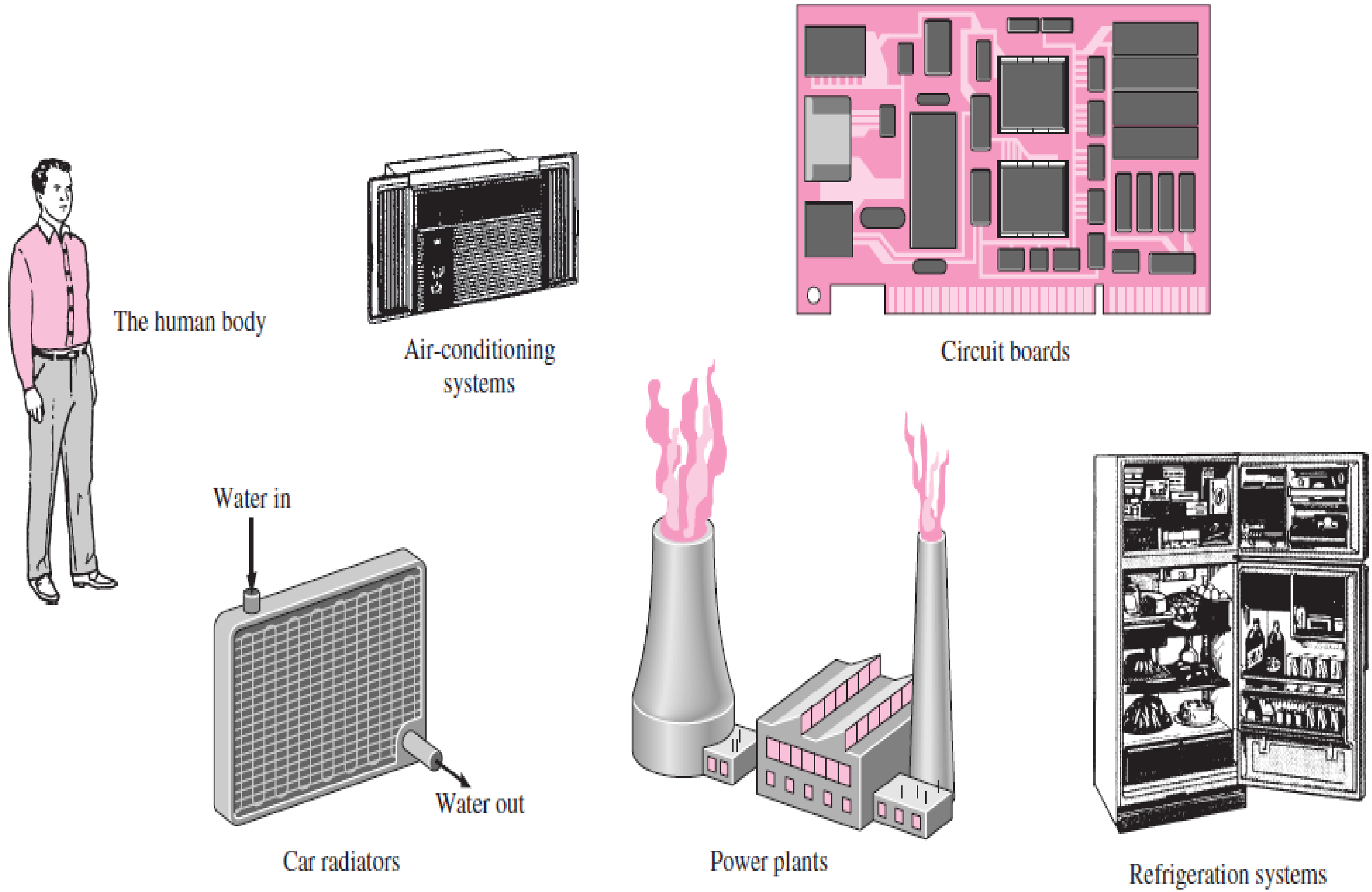
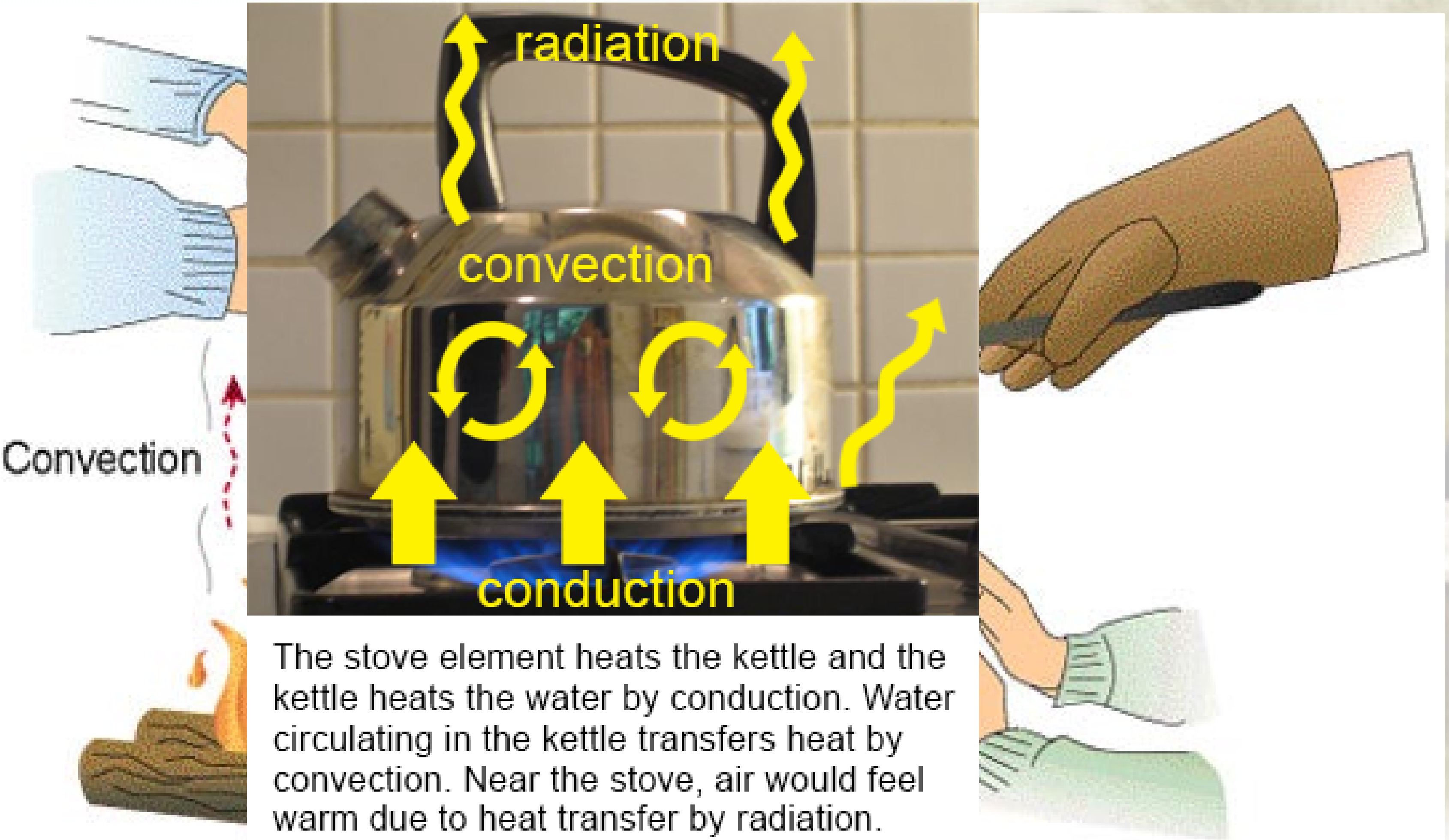


**FIGURE 1–2**
Heat flows in the direction of decreasing temperature.

# Relation of Heat Transfer to Thermodynamics



# Modes of Heat Transfer



The stove element heats the kettle and the kettle heats the water by conduction. Water circulating in the kettle transfers heat by convection. Near the stove, air would feel warm due to heat transfer by radiation.

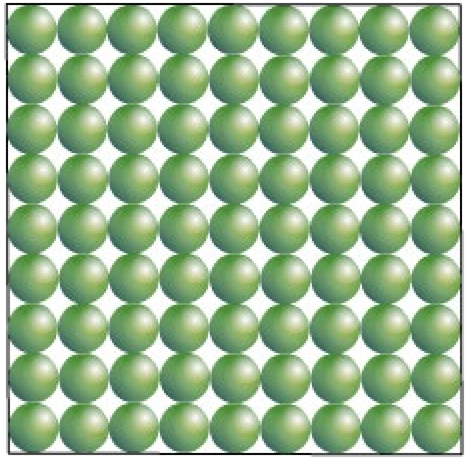
# Modes Of Heat Transfer

- Heat can travel through a medium and also through vacuum.

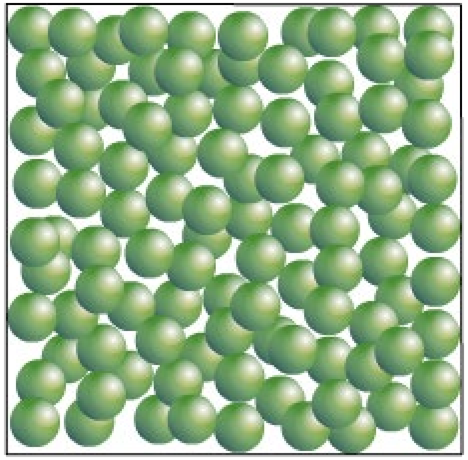
- **Types Of Modes**
    1. Conduction
    2. Convection
    3. Radiation

# What is Conduction?

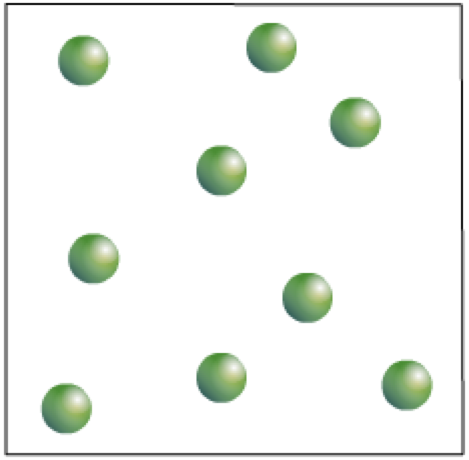
How are the particles arranged in a solid, a liquid and a gas?



solids



liquids



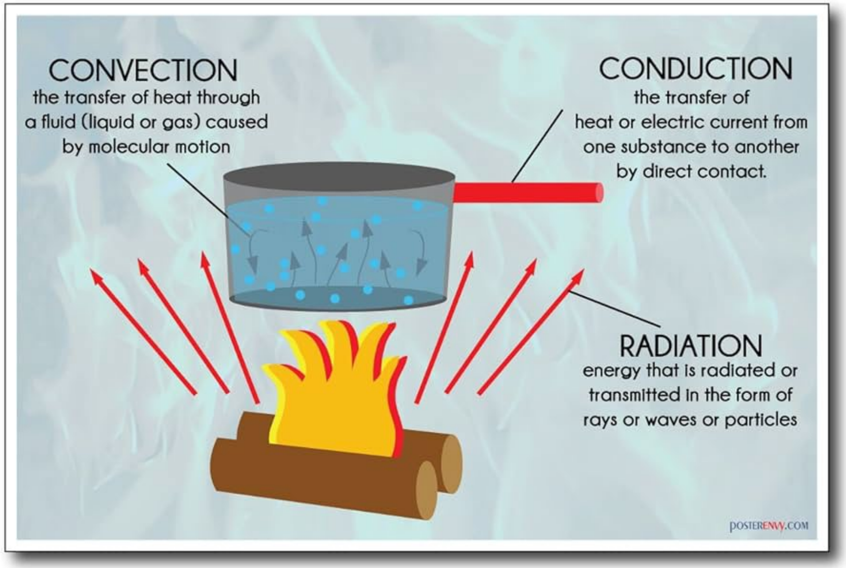
gases

Conduction is the transfer of energy from more energetic particles of a substance to adjacent less energetic ones result of interaction between particles.

It can be Understood from the Fourier law of Conduction

# HEAT TRANSFER

- Once generated, heat can be transferred through various mechanisms:
  - **Conduction:** Direct contact between objects at different temperatures.
  - **Convection:** Movement of heated fluids (liquids or gases).
  - **Radiation:** Transfer of heat through electromagnetic waves (doesn't require a medium).



# CONDUCTION

**Conduction:** The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles.

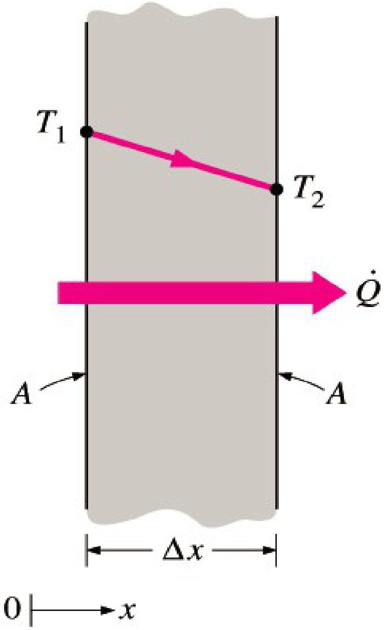
In gases and liquids, conduction is due to the *collisions* and *diffusion* of the molecules during their random motion.

In solids, it is due to the combination of *vibrations* of the molecules in a lattice and the energy transport by *free electrons.*

The rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the

$$\text{Rate of heat conduction} \propto \frac{(\text{Area})(\text{Temperature difference})}{\text{Thickness}}$$

$$\dot{Q}_{\text{cond}} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x} \qquad (\text{W})$$



# Fourier's law of heat conduction

When $x \to 0$

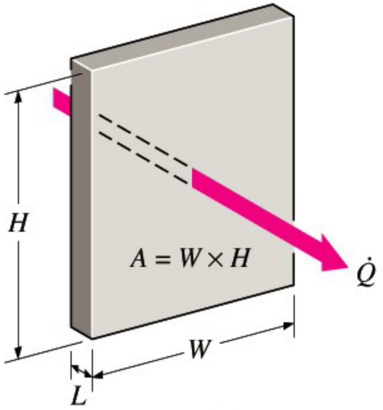
$$\dot{Q}_{\text{cond}} = -kA\frac{dT}{dx}$$

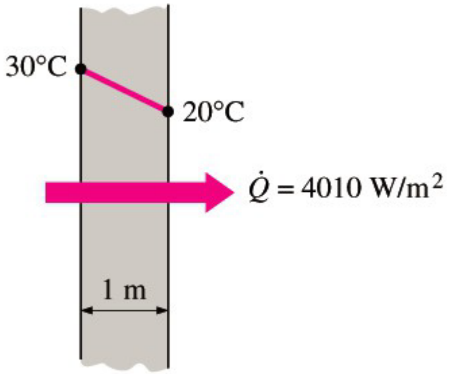
**Thermal conductivity, *k***: A measure of the ability of a material to conduct heat.

**Temperature gradient *dT/dx***: The slope of the temperature curve on a *T*-*x* diagram.

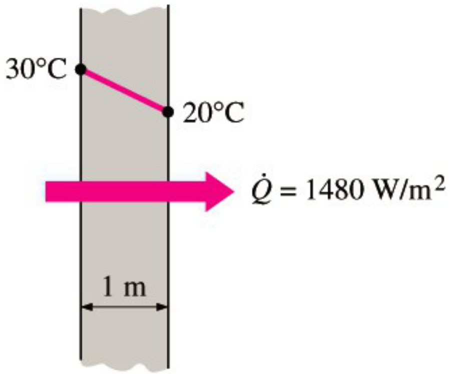
Heat is conducted in the direction of decreasing temperature, and the temperature gradient becomes negative when temperature decreases with increasing *x*. The *negative sign* in the equation ensures that heat transfer in the positive *x* direction is a positive quantity.

In heat conduction analysis, *A* represents the area *normal* to the direction of heat transfer.





(*a*) Copper ($k$ = 401 W/m·°C)



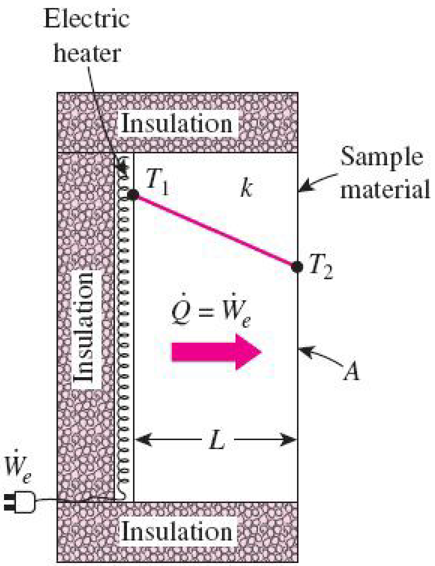
(*b*) Silicon ($k$ = 148 W/m·°C)

# Thermal Conductivity

**Thermal conductivity:** The rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference.

The thermal conductivity of a material is a measure of the ability of the material to conduct heat.

A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or *insulator*.



$$k = \frac{L}{A(T_1 - T_2)} \dot{Q}$$

A simple experimental setup to determine the thermal conductivity of a material.

The thermal conductivities of some materials at room temperature

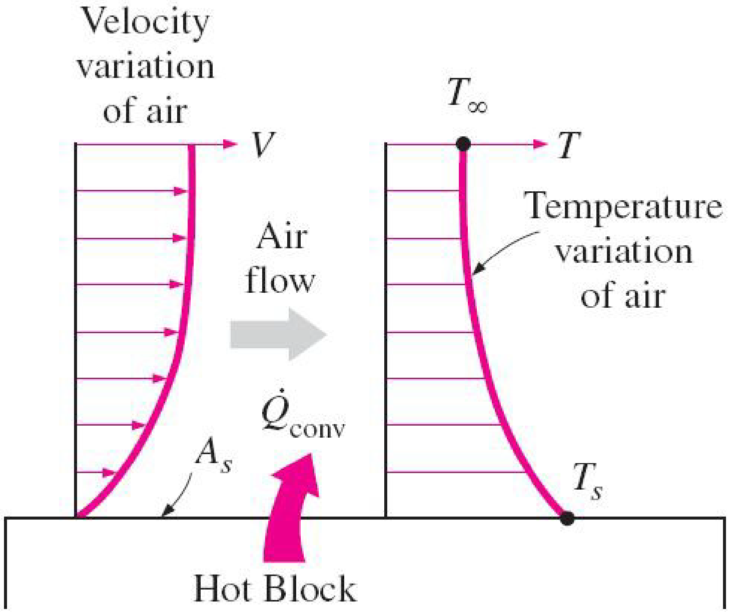
| Material | $k$, W/m · °C* |
|---|---|
| Diamond | 2300 |
| Silver | 429 |
| Copper | 401 |
| Gold | 317 |
| Aluminum | 237 |
| Iron | 80.2 |
| Mercury (l) | 8.54 |
| Glass | 0.78 |
| Brick | 0.72 |
| Water (l) | 0.607 |
| Human skin | 0.37 |
| Wood (oak) | 0.17 |
| Helium (g) | 0.152 |
| Soft rubber | 0.13 |
| Glass fiber | 0.043 |
| Air (g) | 0.026 |
| Urethane, rigid foam | 0.026 |

# CONVECTION

**Convection:** The mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of *conduction* and *fluid motion*.

The faster the fluid motion, the greater the convection heat transfer.

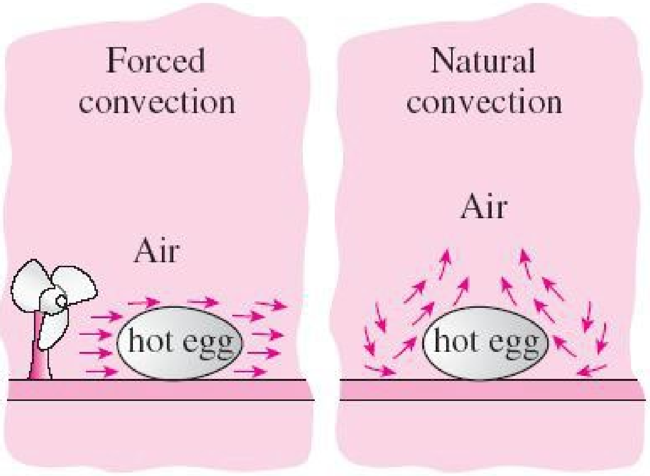
In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction.



Heat transfer from a hot surface to air by convection.

**Forced convection:** If the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind.

**Natural** (or **free**) **convection:** If the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid.



The cooling of a boiled egg by forced and natural convection.

Heat transfer processes that involve *change of phase* of a fluid are also considered to be convection because of the fluid motion induced during the process, such as the rise of the vapor bubbles during boiling or the fall of the liquid droplets during condensation.

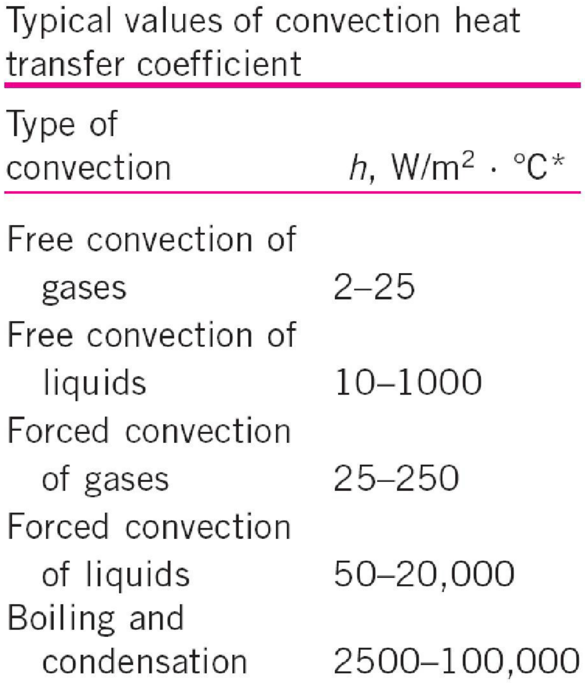
| | |
|---|---|
| **$h$** | convection heat transfer coefficient, W/m$^2$ · °C |
| **$A_s$** | the surface area through which convection heat transfer takes place |
| **$T_s$** | the surface temperature |
| **$T_\infty$** | the temperature of the fluid sufficiently far from the surface |

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty) \qquad \text{(W)}$$

The convection heat transfer coefficient *h* is not a property of the fluid.

It is an experimentally determined parameter whose value depends on all the variables influencing convection such as

- the surface geometry
- the nature of fluid motion
- the properties of the fluid
- the bulk fluid velocity



Typical values of convection heat transfer coefficient

| Type of convection | $h$, W/m$^2$ · °C* |
|---|---|
| Free convection of gases | 2–25 |
| Free convection of liquids | 10–1000 |
| Forced convection of gases | 25–250 |
| Forced convection of liquids | 50–20,000 |
| Boiling and condensation | 2500–100,000 |

# RADIATION

- **Radiation:** The energy emitted by matter in the form of *electromagnetic waves* (or *photons*) as a result of the changes in the electronic configurations of the atoms or molecules.
- In fact, heat transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.
- In heat transfer studies we are interested in *thermal radiation*, which is the form of radiation emitted by bodies because of their temperature.
- All bodies at a temperature above absolute zero emit thermal radiation.
- Radiation is a *volumetric phenomenon*, and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees.
- However, radiation is usually considered to be a *surface phenomenon* for solids.

$$\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4 \qquad \text{(W)}$$

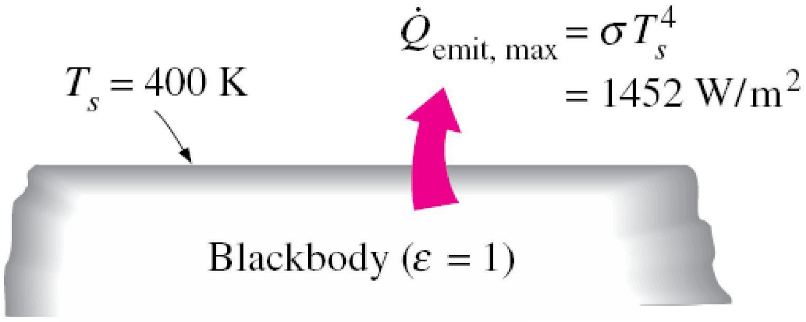
$\boldsymbol{\sigma}$ = 5.670 × $10^{-8}$ W/$m^2$ · $K^4$ *Stefan–Boltzmann constant*

**Blackbody:** The idealized surface that emits radiation at the maximum rate.

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \qquad \text{(W)}$$

Radiation emitted by real surfaces

**Emissivity ε:** A measure of how closely a surface approximates a blackbody for which ε = 1 of the surface. **$0 \leq \varepsilon \leq 1$**.



Emissivities of some materials at 300 K

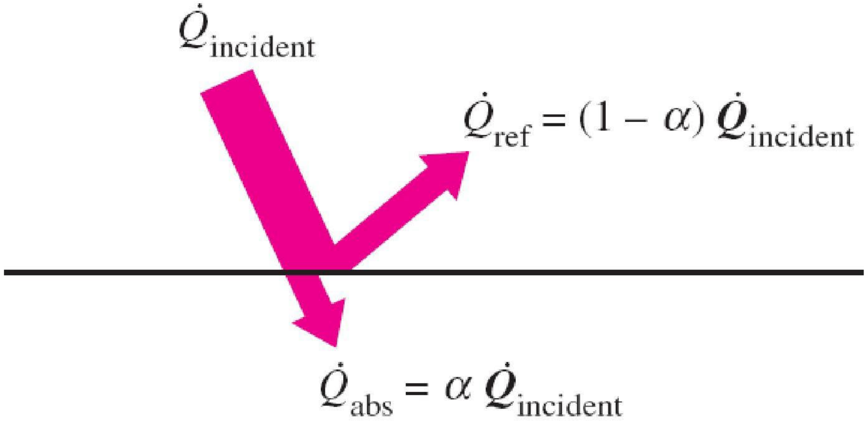
| Material | Emissivity |
|---|---|
| Aluminum foil | 0.07 |
| Anodized aluminum | 0.82 |
| Polished copper | 0.03 |
| Polished gold | 0.03 |
| Polished silver | 0.02 |
| Polished stainless steel | 0.17 |
| Black paint | 0.98 |
| White paint | 0.90 |
| White paper | 0.92–0.97 |
| Asphalt pavement | 0.85–0.93 |
| Red brick | 0.93–0.96 |
| Human skin | 0.95 |
| Wood | 0.82–0.92 |
| Soil | 0.93–0.96 |
| Water | 0.96 |
| Vegetation | 0.92–0.96 |

Absorptivity $\alpha$: The fraction of the radiation energy incident on a surface that is absorbed by the surface. $0 \leq \alpha \leq 1$

A blackbody absorbs the entire radiation incident on it (**$\alpha = 1$**).

**Kirchhoff's law:** The emissivity and the absorptivity of a surface at a given temperature and wavelength are equal.

$$\dot{Q}_{\text{absorbed}} = \alpha \dot{Q}_{\text{incident}} \qquad \text{(W)}$$



The absorption of radiation incident on an opaque surface of absorptivity.

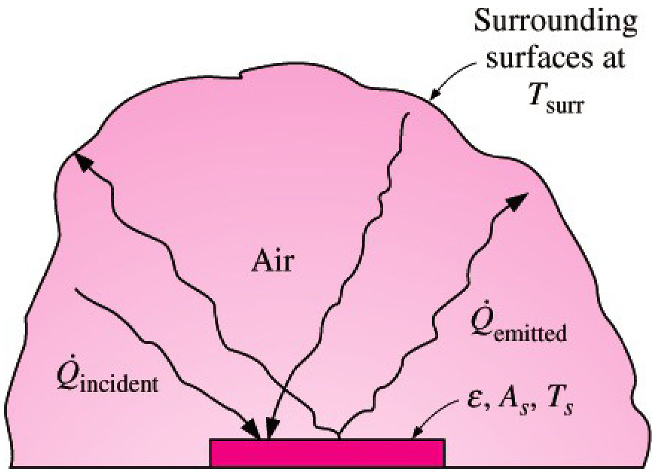
**Net radiation heat transfer:** The difference between the rates of radiation emitted by the surface and the radiation absorbed.

The determination of the net rate of heat transfer by radiation between two surfaces is a complicated matter since it depends on

- the properties of the surfaces
- their orientation relative to each other
- the interaction of the medium between
- the surfaces with radiation

Radiation heat transfer between a surface and the surfaces surrounding it

$$\dot{Q}_{\text{rad}} = \varepsilon\sigma A_s\,(T_s^4 - T_{\text{surr}}^4) \qquad \text{(W)}$$



$$\dot{Q}_{\text{rad}} = \varepsilon\sigma A_s(T_s^4 - T_{\text{surr}}^4)$$

When radiation and convection occur simultaneously between a surface and a gas:

$$\dot{Q}_{\text{total}} = h_{\text{combined}} A_s (T_s - T_\infty) \qquad \text{(W)}$$

**Combined heat transfer coefficient *h*$_{\text{combined}}$**
includes the effects of both convection and radiation.

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = h_{\text{conv}} A_s (T_s - T_{\text{surr}}) + \varepsilon\sigma A_s (T_s^4 - T_{\text{surr}}^4)$$

$$\dot{Q}_{\text{total}} = h_{\text{combined}} A_s (T_s - T_\infty) \qquad \text{(W)}$$

$$h_{\text{combined}} = h_{\text{conv}} + h_{\text{rad}} = h_{\text{conv}} + \varepsilon\sigma (T_s + T_{\text{surr}})(T_s^2 + T_{\text{surr}}^2)$$

# SIMULTANEOUS HEAT TRANSFER MECHANISMS

Heat transfer is only by conduction in *opaque solids,* but by conduction and radiation in *semitransparent solids.*

A solid may involve conduction and radiation but not convection. A solid may involve convection and/or radiation on its surfaces exposed to a fluid or other surfaces.

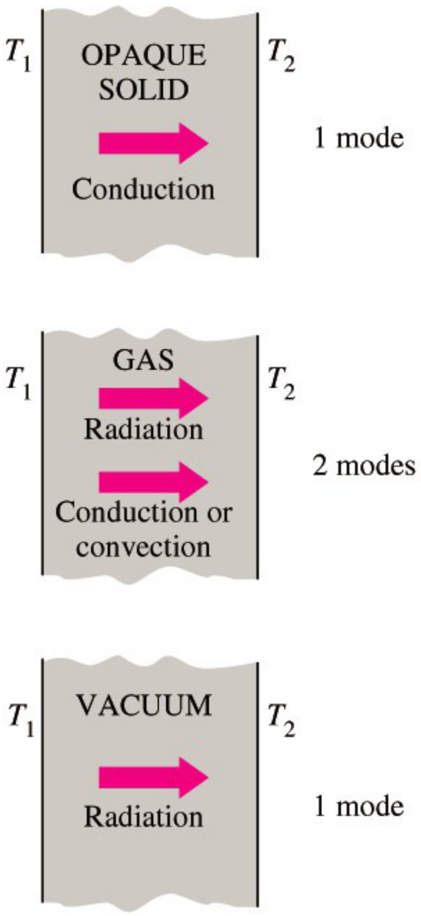
Heat transfer is by conduction and possibly by radiation in a *still fluid* (no bulk fluid motion) and by convection and radiation in a *flowing fluid.*

In the absence of radiation, heat transfer through a fluid is either by conduction or convection, depending on the presence of any bulk fluid motion.

Convection = Conduction + Fluid motion

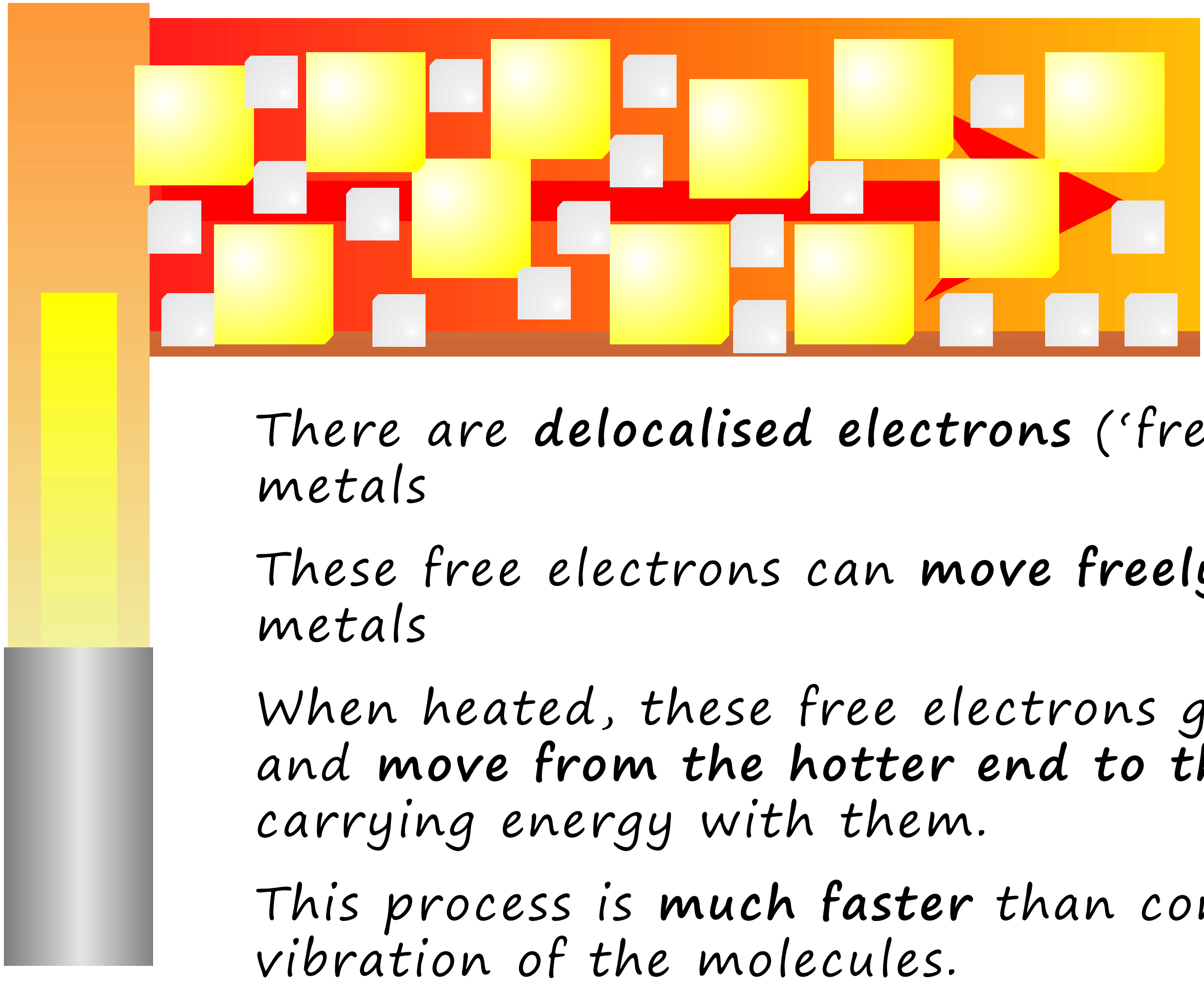
Heat transfer through a *vacuum* is by radiation. Most gases between two solid surfaces do not interfere with radiation.

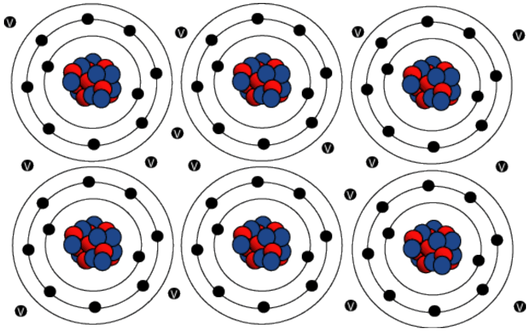
Liquids are usually strong absorbers of radiation.



Although there are three mechanisms of heat transfer, a medium may involve only two of them simultaneously.

# Why are metals good thermal conductors?





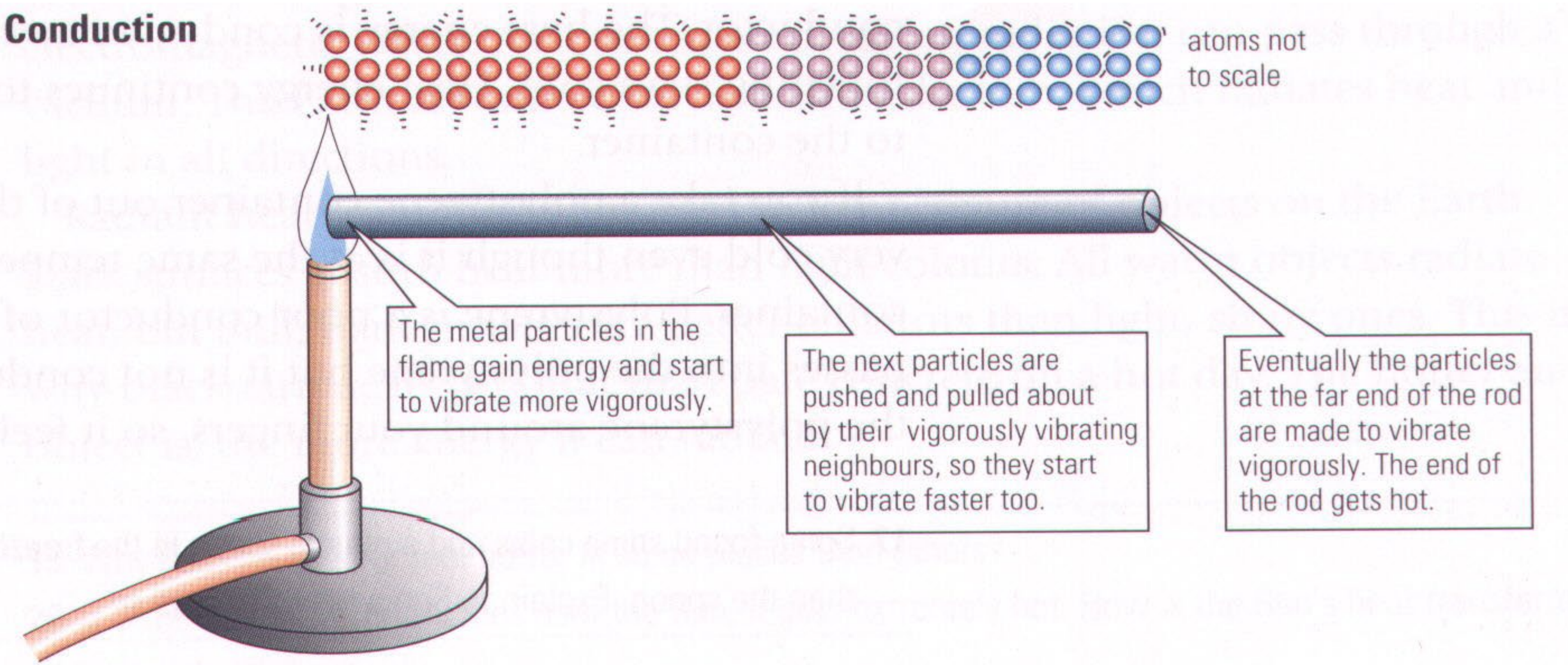
There are **delocalised electrons** (‘free’ electrons) in metals

These free electrons can **move freely** throughout the metals

When heated, these free electrons gain kinetic energy and **move from the hotter end to the colder end**, carrying energy with them.

This process is **much faster** than conduction by the vibration of the molecules.

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



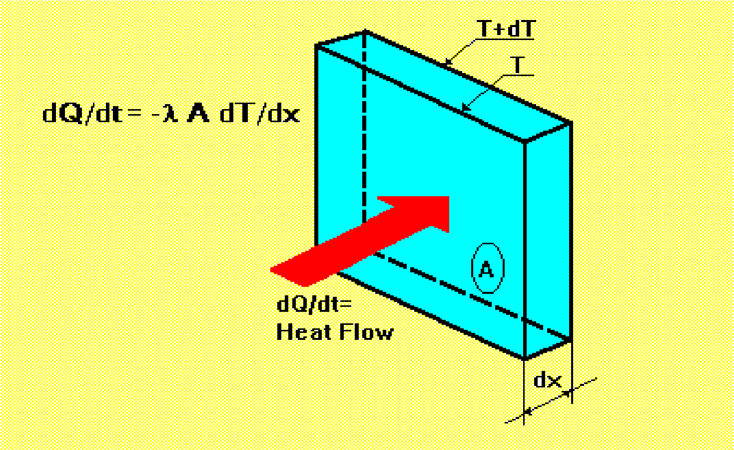
The metal particles in the flame gain energy and start to vibrate more vigorously.

The next particles are pushed and pulled about by their vigorously vibrating neighbours, so they start to vibrate faster too.

Eventually the particles at the far end of the rod are made to vibrate vigorously. The end of the rod gets hot.

# Fourier law Of Conduction

- In 1822 Fourier postulated that the rate of heat transfer is proportional to the temperature gradient present in a solid.



$$\dot{Q}_{\text{cond}} = -kA\frac{dT}{dx} \qquad (\text{W})$$

$$\text{Rate of heat flow} = \frac{\text{thermal conductivity } (k) \times \text{cross-section area } (A) \times \text{temperature difference } (\Delta\theta)}{\text{length } (l)}$$

# Factors affecting thermal conductivity

Thermal conductivity in materials depends on the following factors:

(i) The temperature difference ($a\theta$) between

The ends of the conductor.

(Ii) the length of the conductor ($l$).

(Iii) the cross-section area($a$) of the conductor.

(Iv) the nature of the material ($k$).

## Example:

The inner and outer surfaces of a 5-m x 6-m brick wall of thickness 30 cm and thermal conductivity 0.69 W/m.°C are maintained at temperatures of 20°C and 5 °C, respectively. Determine the rate of heat transfer through the wall, in W.

## Thermal conductivity in solid

If you stir hot tea using a metal spoon, you will observe that the handle of the spoon becomes warm.

Solids that are good conductors of heat (metals) use both atom vibration and free electrons to conduct heat.

## Why liquids are poor conductors of heat ?

This is because there are large inter-molecular distances between liquid molecules.There are also fewer and rare collisions between the molecules.

Electrolytes, e.g., Salt solution are better conductors of heat than pure liquids because of an increased compactness of the particles.

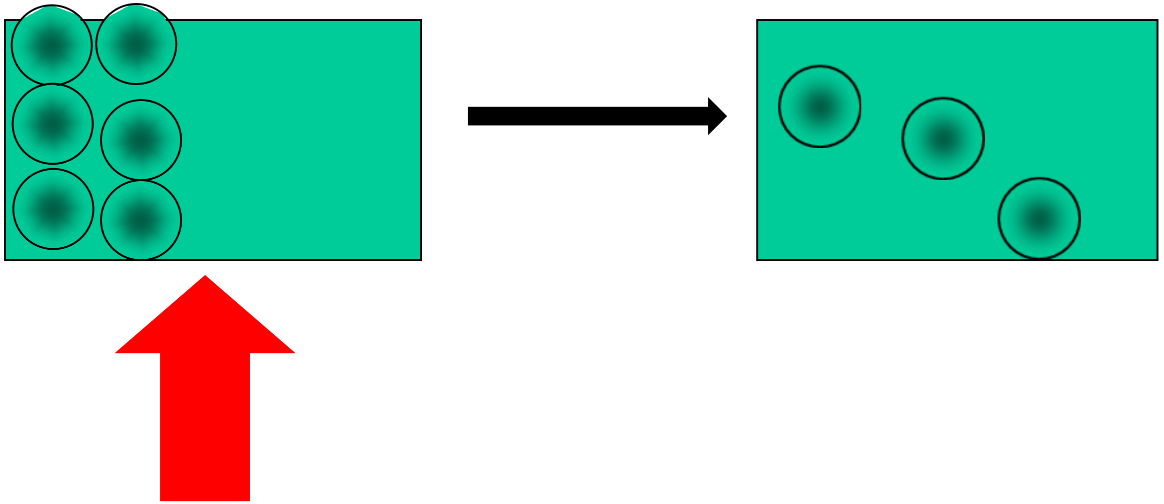
## Thermal conductivity in gases

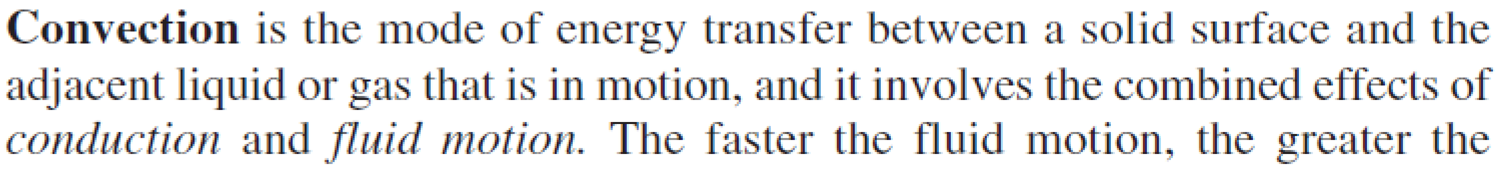
Gases are worse conductors of heat because of large inter-molecular distance.

# What is Convection ?

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

The particles spread out and
become less dense.



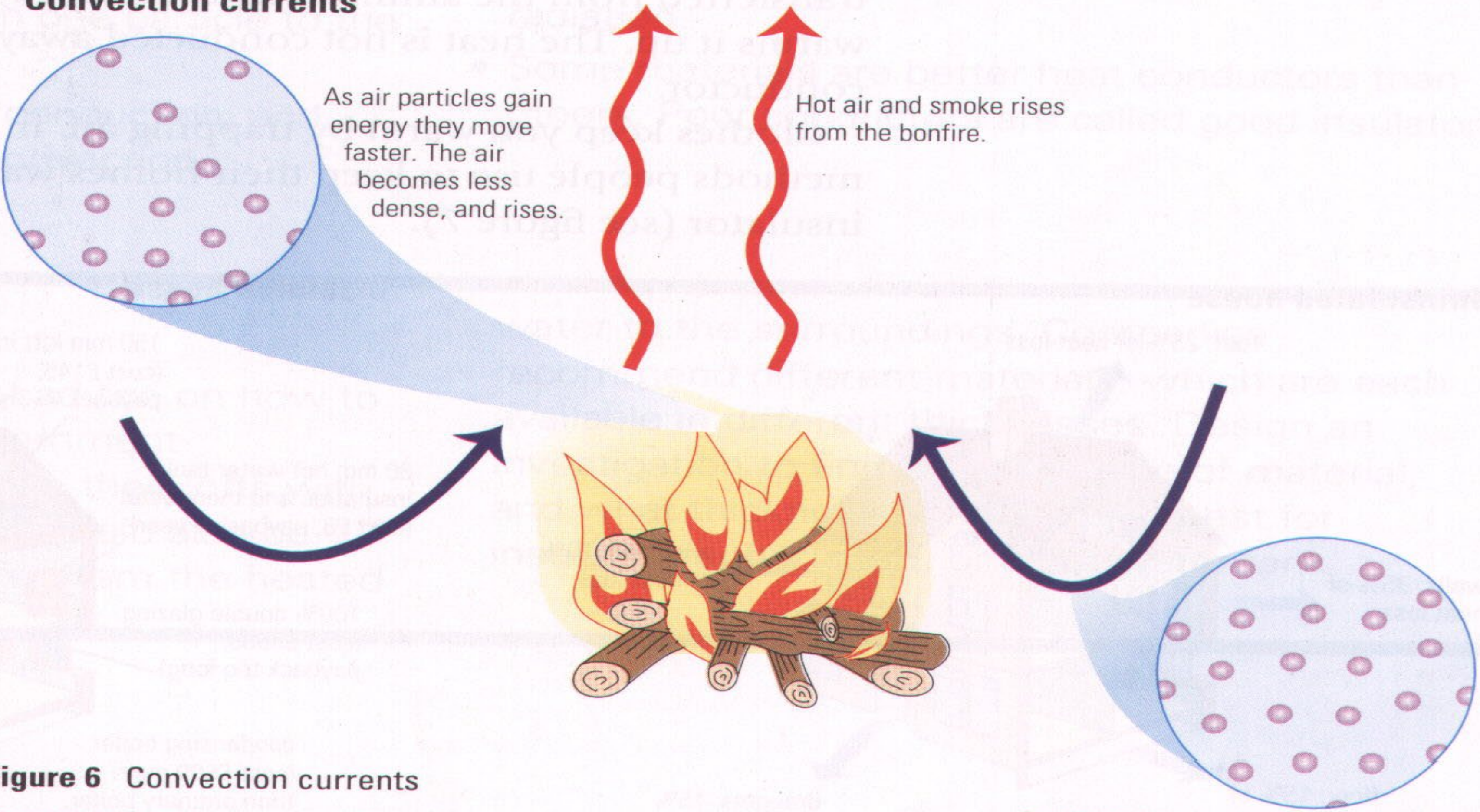


**Convection** is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of *conduction* and *fluid motion*. The faster the fluid motion, the greater the

convection heat transfer

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.

**Convection currents**



As air particles gain energy they move faster. The air becomes less dense, and rises.

Hot air and smoke rises from the bonfire.

Particles in cold air are relatively close together. This cold, dense air falls and

**Figure 6** Convection currents carry smoke particles up from the bonfire into the air

**Definition** : Convection is the process by which heat is transferred through fluids (liquids and gases).

When a liquid is heated, it expands and this lowers its density.

The less dense liquid rises and its place is taken by more dense colder liquid. This movement of liquid forms convection currents.

Molecules in fluids are further apart and have negligible cohesive force.

Convection currents are set up much faster in gases than in liquids because of the extremely low cohesive forces existing between the molecules of the gases.

# Types of Convection :

1. Natural convection: Natural convection occurs whenever heat flows between a solid and fluid, or between fluid layers.

As a result of heat exchange, Change in density of effective fluid layers taken place, which causes upward flow of heated fluid.

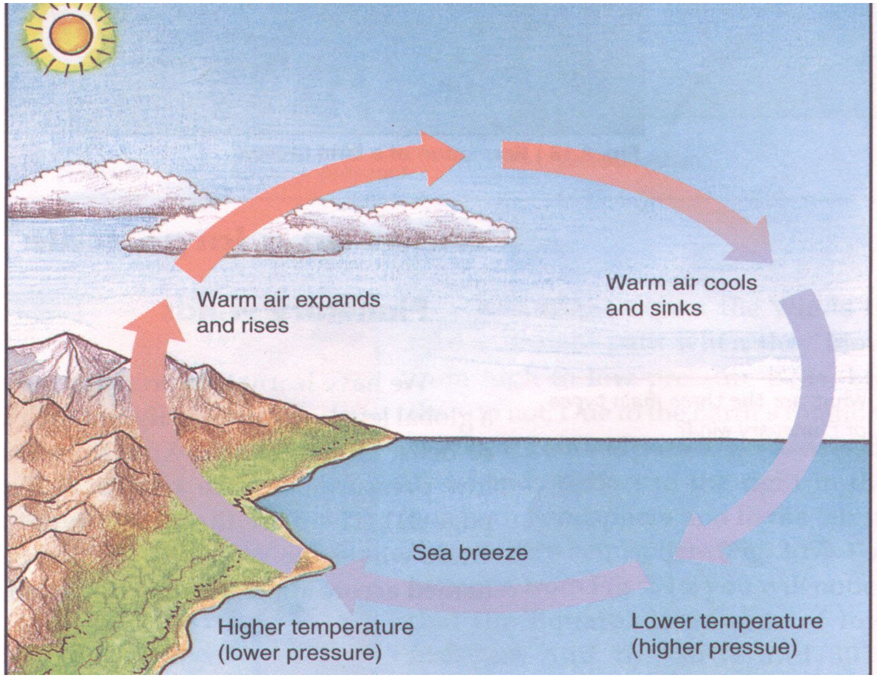
If this motion is associated with heat transfer mechanism only, then it is called Natural Convection.

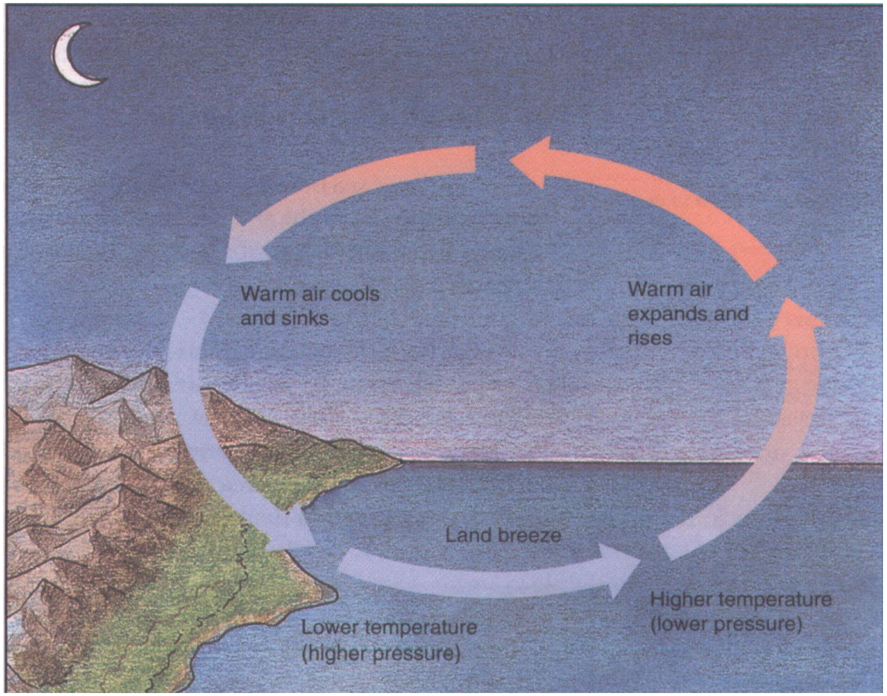
2. Forced convection: Mixing of hot and cold parts of the fluid through some external stirring, like a fan or pump.

If this motion is associated by mechanical means such as pumps, gravity or fans, the movement of the fluid is enforced.

And in this case, we then speak of Forced convection

- During the day the sun heats the land much faster than the sea.
- The air above the land is heated, expands and rises.
- Cold air from the sea moves inland to take its place.
- Hence, sea breeze is obtained.

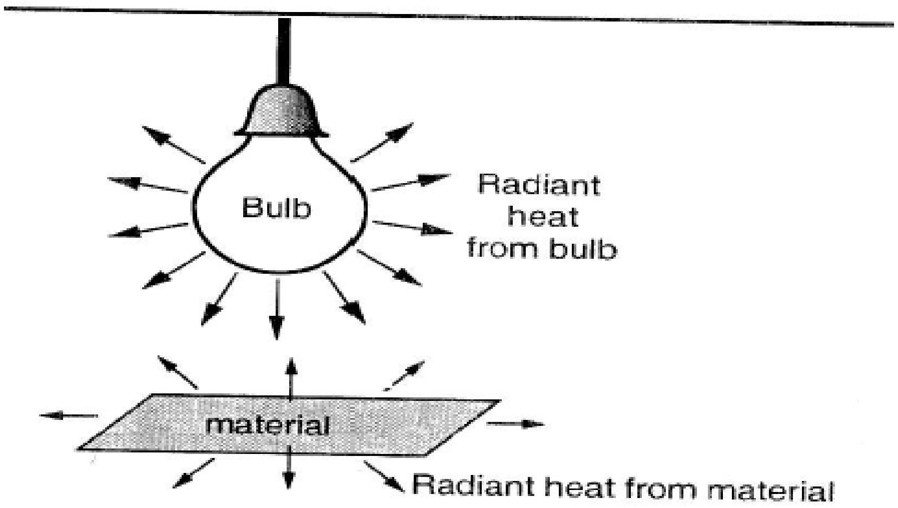




- Land loses heat faster than the sea.
- Hot air above the sea which is less dense, expands and rises.
- Cold air from the land moves towards the sea.
- Convection current is formed.
- Land Breeze is obtained.

# Radiation

- Heat transfer through vacuum is called **thermal radiation.** All bodies absorb and emit radiation.



An electric bulb in a room produces both light and radiant heat. The radiant heat is absorbed by the materials in the room, which in turn give out radiant heat of lower energy.

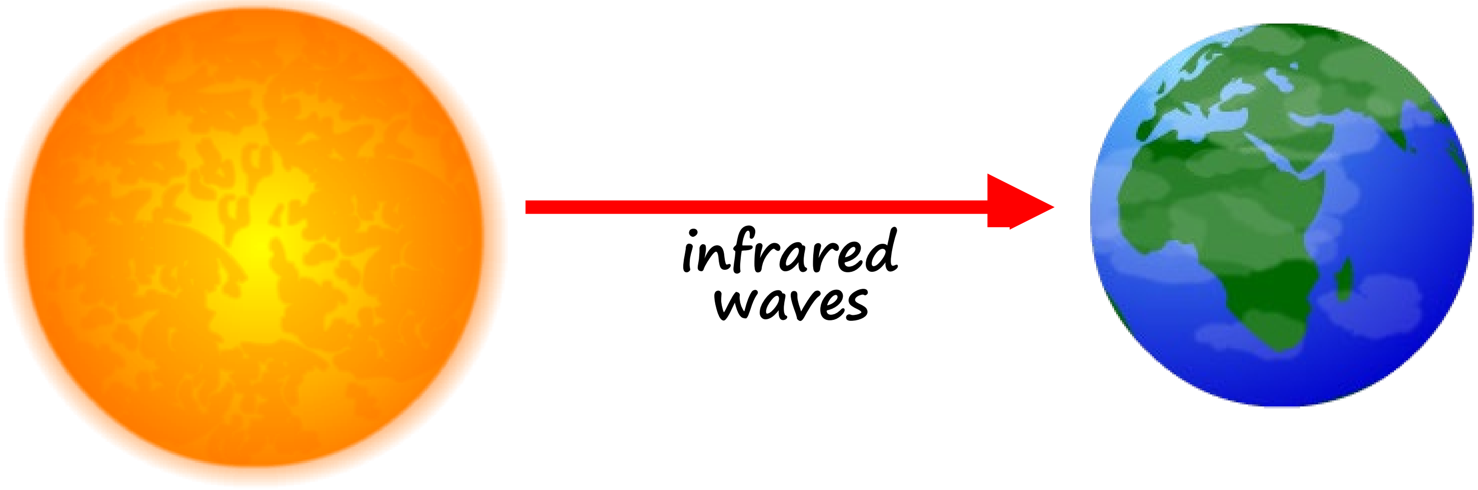
Radiation is a method of heat transfer that does not require any medium.

It can take place in a vacuum. In radiation, heat transmits energy in the form of waves.

The heat energy from the sun is radiated to us.

# How Does Heat Travel Through Space?

The Earth is warmed by heat energy from the Sun. How does this heat energy travel from the Sun to the Earth?

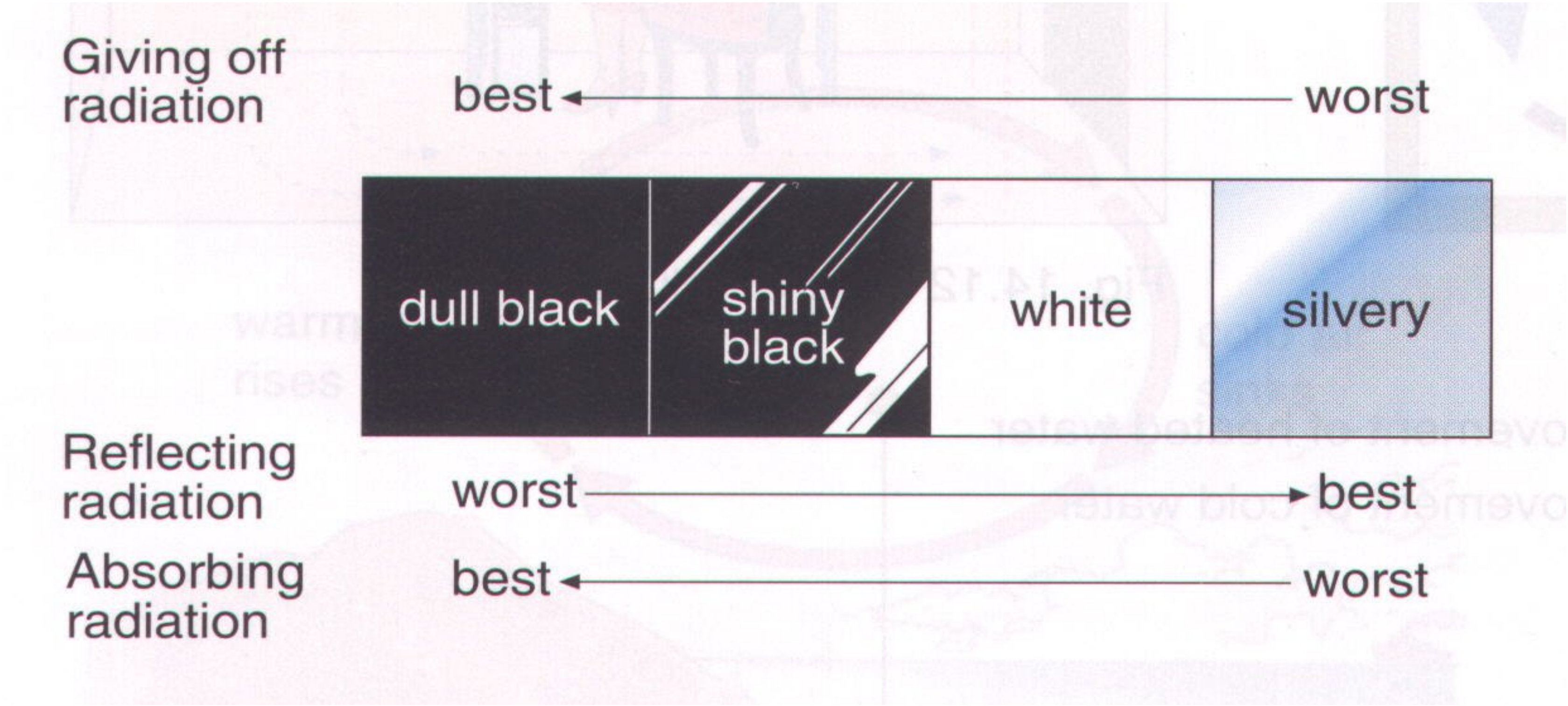


**infrared waves**

There are no particles between the Sun and the Earth, so the heat **cannot** travel by conduction or by convection.

The heat travels to Earth by **infrared waves**. These are similar to light waves and are able to travel through empty space.

# Emission Experiment



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.

# Radiation Questions ?

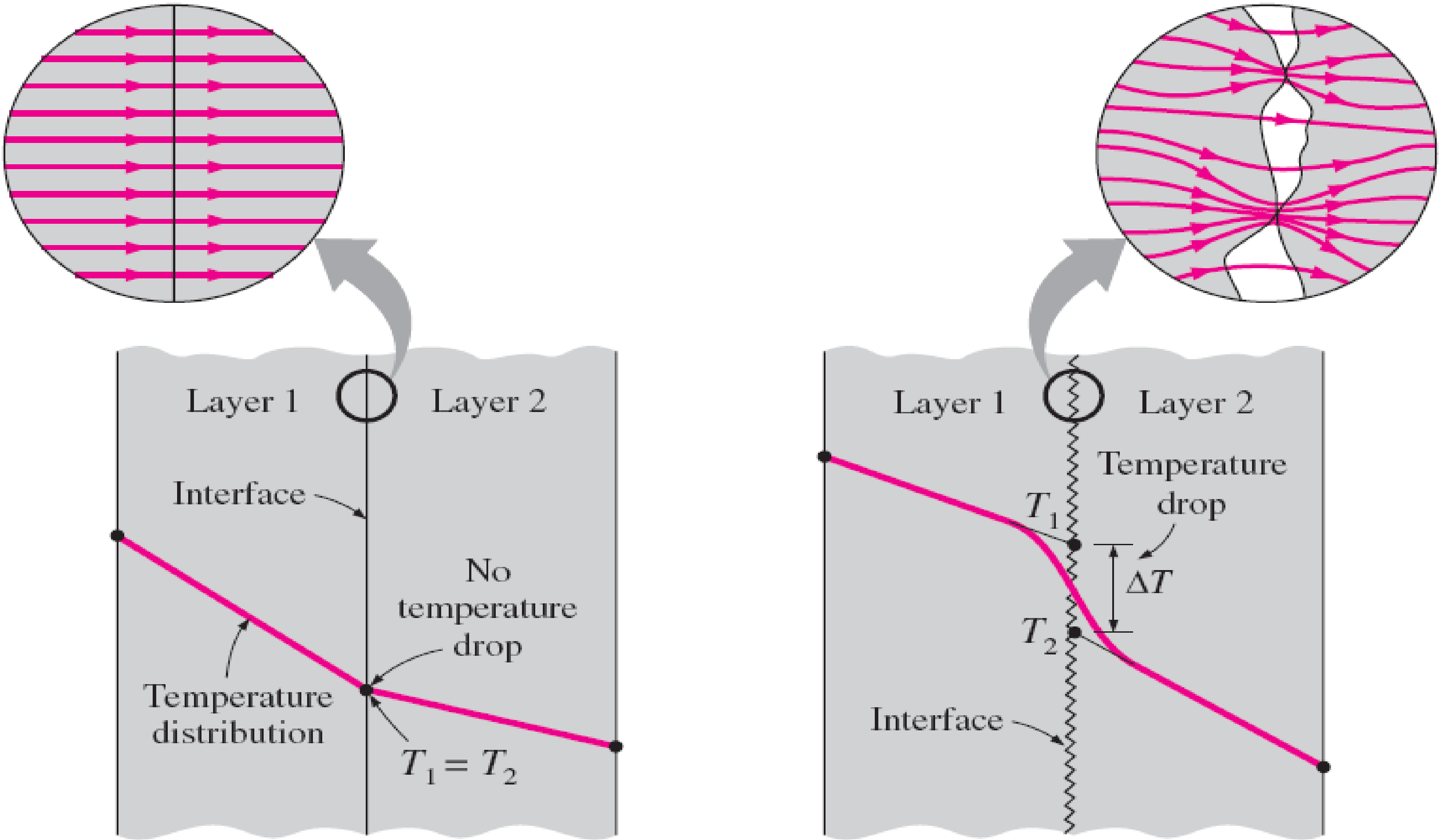
Why are houses painted white in hot countries?

White reflects heat radiation and keeps the house cooler.

Why are shiny foil blankets wrapped around marathon runners at the end of a race?

The shiny metal reflects the heat radiation from the runner back in, this stops the runner getting cold.

# Thermal Contact Resistance



(*a*) Ideal (perfect) thermal contact

(*b*) Actual (imperfect) thermal contact

Temperature distribution and heat flow lines along two solid plates pressed against each other for the case of perfect and imperfect contact.

# Summary

- ✓ Heat is a form of energy which flows as a result of temperature difference between two regions.
- ✓ There are three modes of heat transfer namely conduction,convection and radiation.
- ✓ In conduction and convection a material is required while in radiation,heat travels through a vacuum.
- ✓ Thermal conductivity depends on:

  Temperature difference-the greater the temperature difference the higher the rate of conduction.

  Cross- sectional area-thicker materials conduct heat faster than thin ones.

# Example 1: heat transfer from a person

Consider a person standing in a breezy room at 20°C. Determine the total rate of heat transfer from this person if the exposed surface area and the average outer surface temperature of the person are 1.6 $m^2$ and 29°C, respectively, and the convection of heat transfer coefficient is 6 $W/m^2.°C$

# Solution 1: heat transfer from a person

Assumption: The emissivity and heat transfer coefficient are constant and uniform. Heat conduction through the feet is negligible.

$$\dot{Q}_{conv} = hA(T_s - T_f)$$

$$\dot{Q}_{conv} = (6\ W/m^2.°C)(1.6\ m^2)(29 - 20)°C$$

$$\dot{Q}_{conv} = 86.4\ \mathrm{W}$$

# Solution 1: heat transfer from a person

The person will also lose heat by radiation to the surrounding wall

$$\dot{Q}_{rad} = \varepsilon\sigma A(T_s^4 - T_{surr}^4)$$

$$\dot{Q}_{rad} = (0.95)(5.67 \times 10^{-8} W/m^2.K^4)(1.6\,m^2)(302^4 - 293^4)$$

$$\dot{Q}_{rad} = 81.7\text{ W}$$

***Thus, the rate of total heat transfer from the body;***

$$\dot{Q}_{total} = \dot{Q}_{conv} + \dot{Q}_{rad}$$

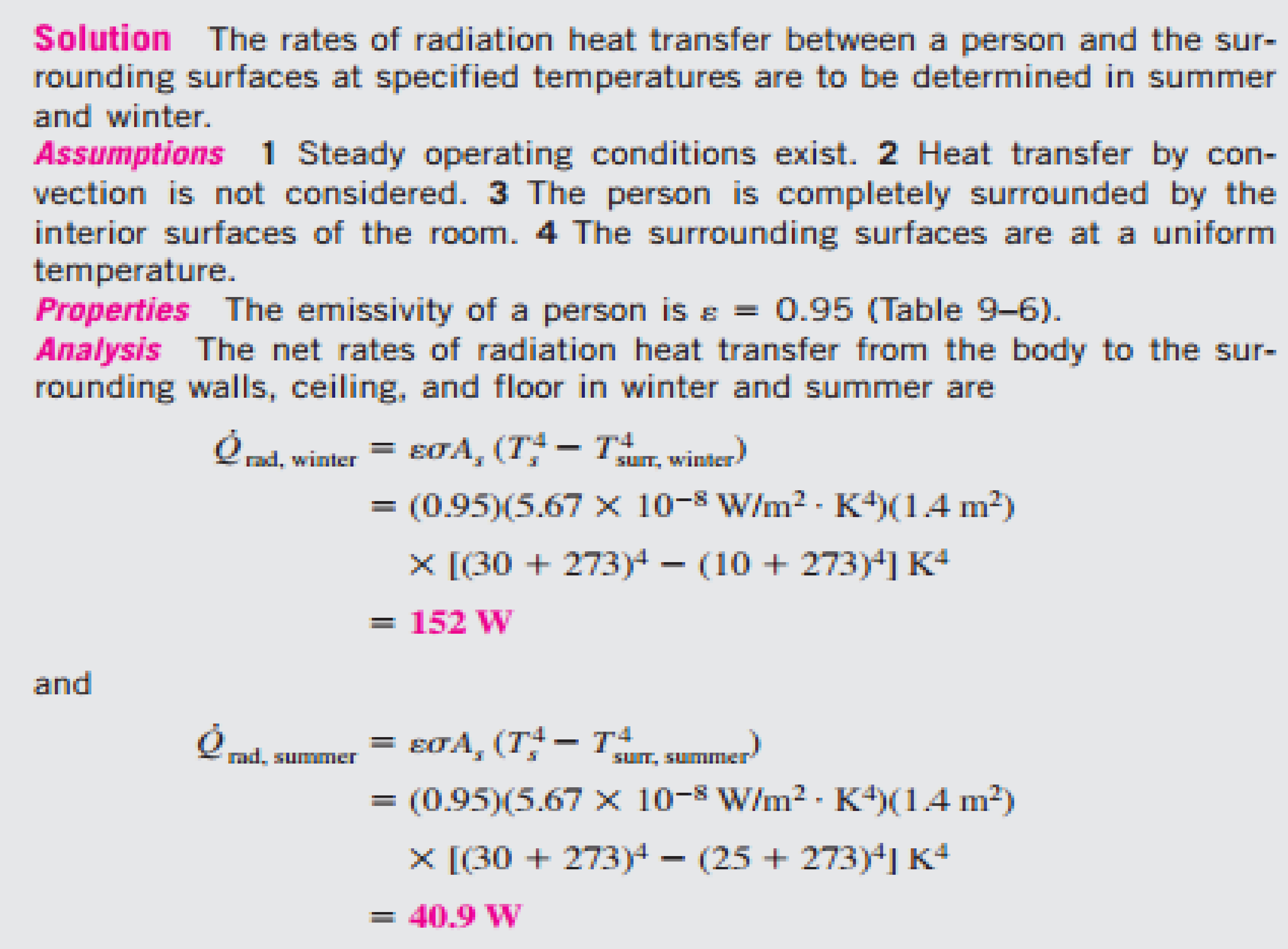
$$\dot{Q}_{total} = 86.4 + 81.7 = \mathbf{168.1\,W}$$

# Exercise 1

- Consider a person standing in a room maintained at 20°C at all times. The inner surface of the walls, floor and ceiling of the house are observed to be at average temperature of 12°C in winter and 23°C in summer. Determine the rates of radiation heat transfer between this person and the surrounding surfaces in both summer and winter if the exposed surface area, emissivity and the average outer surface temperature of the person are 1.6$m^2$, 0.95 and 32°C, respectively. (Takes Stefan-Botlzmann constant, $\sigma = 5.67x10\text{-}8$ $W/m^2.K^4$

# Exercise 1

- Consider a person standing in a room maintained at 22°C at all times. The inner surface of the walls, floor and ceiling of the house are observed to be at average temperature of 10°C in winter and 25°C in summer. Determine the rates of radiation heat transfer between this person and the surrounding surfaces in both summer and winter if the exposed surface area, emissivity and the average outer surface temperature of the person are 1.4 $m^2$, 0.95 and 30°C, respectively. (Takes Stefan-Botlzmann constant, $\sigma$ = 5.67 x 10-8 $W/m^2.K^4$).



**Solution** The rates of radiation heat transfer between a person and the surrounding surfaces at specified temperatures are to be determined in summer and winter.

***Assumptions*** **1** Steady operating conditions exist. **2** Heat transfer by convection is not considered. **3** The person is completely surrounded by the interior surfaces of the room. **4** The surrounding surfaces are at a uniform temperature.

***Properties*** The emissivity of a person is $\varepsilon = 0.95$ (Table 9–6).

***Analysis*** The net rates of radiation heat transfer from the body to the surrounding walls, ceiling, and floor in winter and summer are

$$\begin{aligned}\dot{Q}_{\text{rad, winter}} &= \varepsilon\sigma A_s\,(T_s^4 - T_{\text{surr, winter}}^4)\\ &= (0.95)(5.67 \times 10^{-8}\ \text{W/m}^2\cdot\text{K}^4)(1.4\ \text{m}^2)\\ &\quad \times [(30 + 273)^4 - (10 + 273)^4]\ \text{K}^4\\ &= \mathbf{152\ W}\end{aligned}$$

and

$$\begin{aligned}\dot{Q}_{\text{rad, summer}} &= \varepsilon\sigma A_s\,(T_s^4 - T_{\text{surr, summer}}^4)\\ &= (0.95)(5.67 \times 10^{-8}\ \text{W/m}^2\cdot\text{K}^4)(1.4\ \text{m}^2)\\ &\quad \times [(30 + 273)^4 - (25 + 273)^4]\ \text{K}^4\\ &= \mathbf{40.9\ W}\end{aligned}$$

# Exercise 1

- Consider steady heat transfer between two large parallel plates at constant temperatures of T1 = 300K and T2 = 200 K that are L = 0.01 m apart, as shown in figure. Assuming the surfaces to be black (emissivity, ε = 1), determine the total rate of heat transfer between the plates per unit surface area assuming the gap between the plates is filled with atmospheric air. Assume the thermal conductivity at the average temperature is k = 0.0219 W/m.K for air.

# Exercise 2

- An ice chest whose outer dimension are 30 cm x 40 cm and 40 cm is made of 3-cm-thick Styrofoam (k_0.033 W/m.°C). Initially, the chest is filled with 28kg of ice at 0°C, and the inner surface temperature of the ice chest can be taken to be 0°C at all times. The heat fusion of ice at 0°C is 333.7 kJ/kg, and the surrounding ambient air is at 25°C. Disregarding any heat transfer from the 40-cm x 40-cm base of ice-chest, determine how long it will take for the ice in the chest to melt completely if the outer surface of the ice chest are at 8°C.

# Basic Concepts of Thermodynamics

## JOB20103 THERMODYNAMICS

Lecture Notes:

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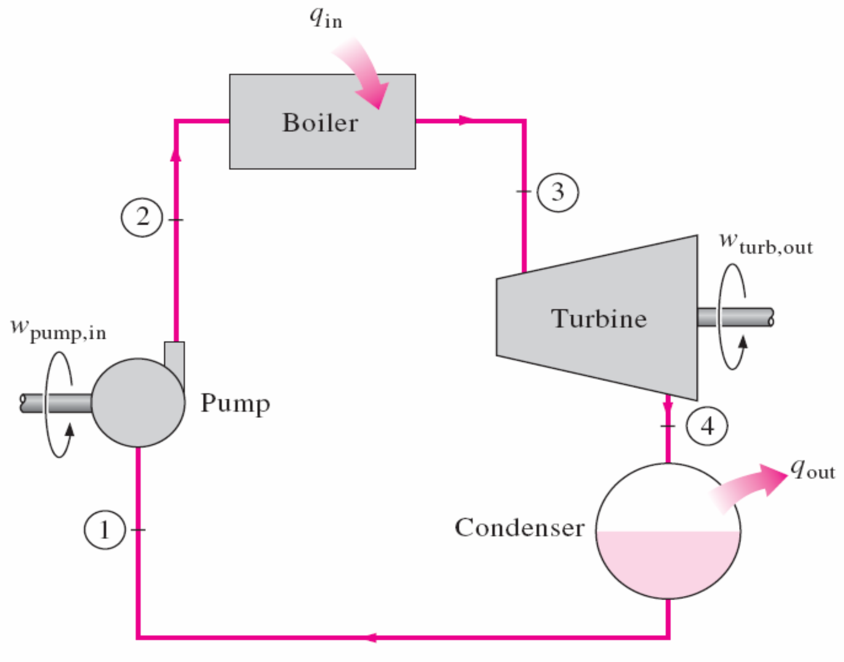
*Malaysian Institute of Industrial Technology*
*Universiti Kuala Lumpur*

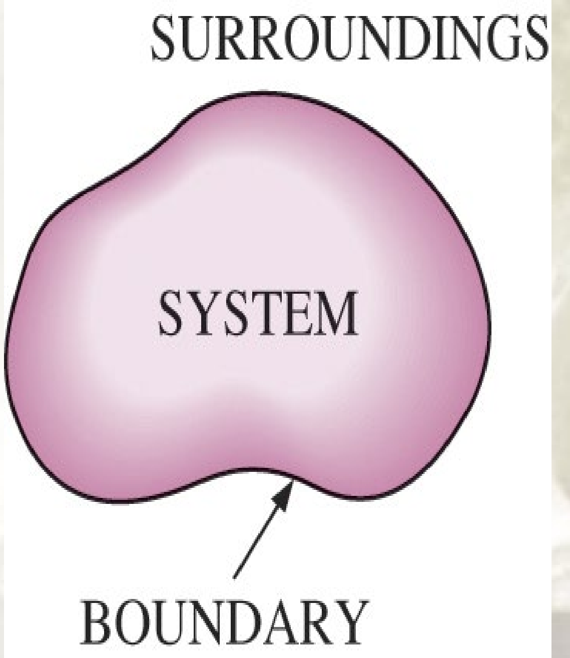
# What is Thermodynamics?

- The science of energy, that concerned with the ways in which energy is stored within a body.
- Energy transformations – mostly involve heat and work movements.
- The Fundamental law is the *conservation of energy* principle: energy cannot be created or destroyed, but can only be transformed from one form to another.

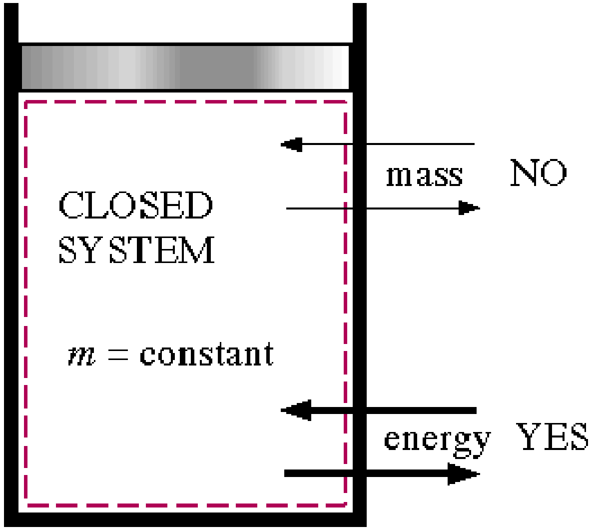


# System, surroundings and boundary

- **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.

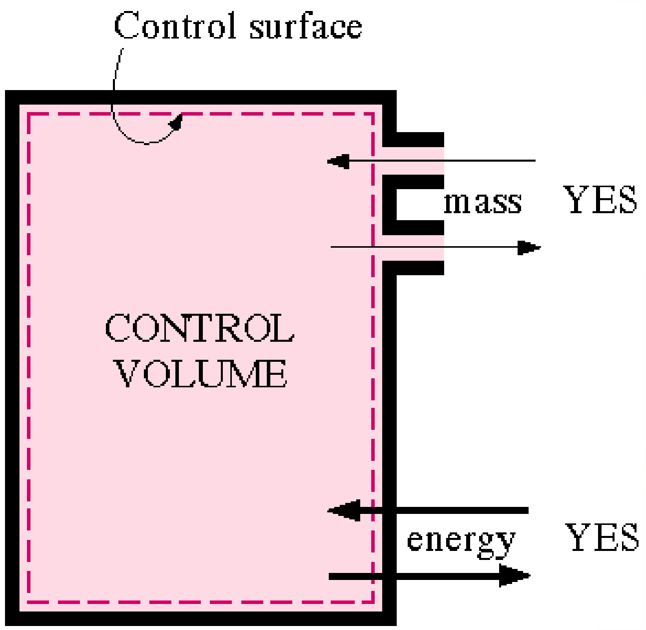


# Type of system (Closed system)



- Closed system – only energy can cross the selected boundary
- Examples: a tightly capped cup of coffee

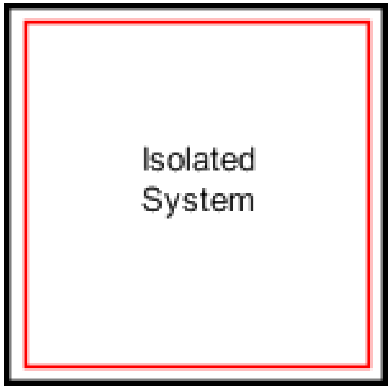
# Type of system (Open system)



- Open system – both mass and energy can cross the selected boundary
- Example: an open cup of coffee

# Type of system

## (isolated system)

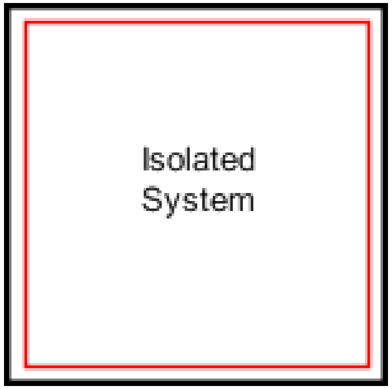


- Isolated system – neither mass nor energy can cross the selected boundary

- Example (approximate): coffee in a closed, well-insulated thermos bottle

# Type of system

## (isolated system)



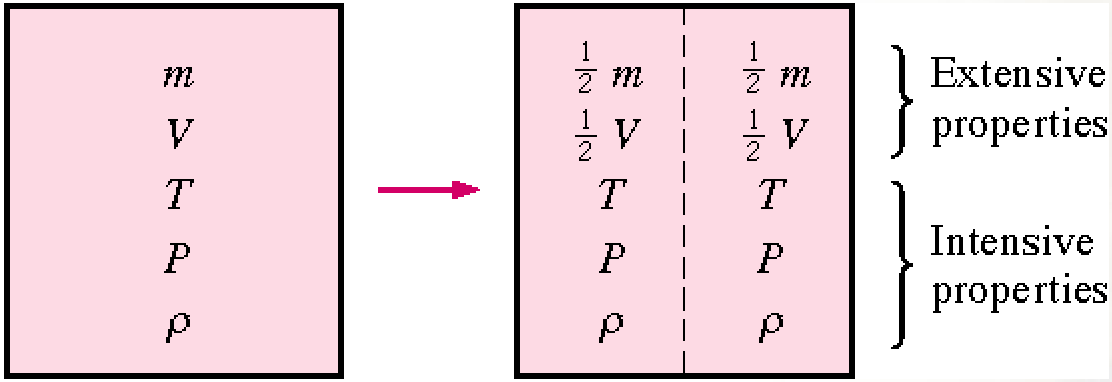
- Isolated system – neither mass nor energy can cross the selected boundary
- Example (approximate): coffee in a closed, well-insulated thermos bottle

# Properties of a system

Properties of a system is a measurable characteristic of a system that is in equilibrium.
Properties may be intensive or extensive.

- **Intensive – Are independent of the amount of mass:**
  **e.g: Temperature, Pressure, and Density,**

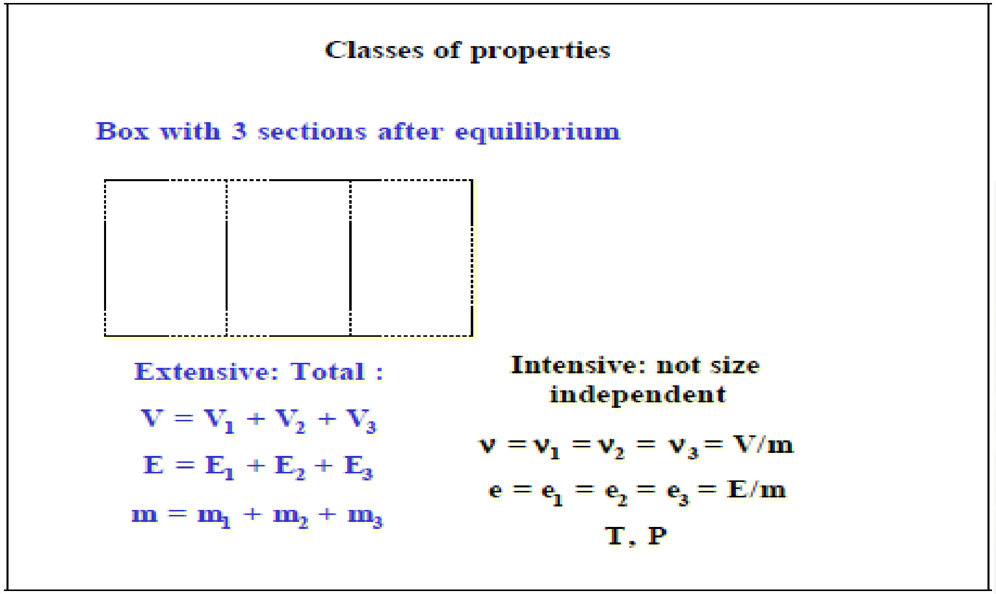
- **Extensive – varies directly with the mass**
  **e.g: mass, volume, energy, enthalpy**



# Properties of a system

**Specific properties** – The ratio of any extensive property of a system to that of the mass of the system is called an average specific value of that property (also known as intensives property)

| | | |
|---|---|---|
| Specific Volume | $V/m = v$ | $m^3/kg$ |
| Total Energy | $E/m = e$ | $J/kg$ |
| Internal Energy | $U/m = u$ | $J/kg$ |



Classes of properties

Box with 3 sections after equilibrium

**Extensive: Total :**

$V = V_1 + V_2 + V_3$

$E = E_1 + E_2 + E_3$

$m = m_1 + m_2 + m_3$

**Intensive: not size independent**

$v = v_1 = v_2 = v_3 = V/m$

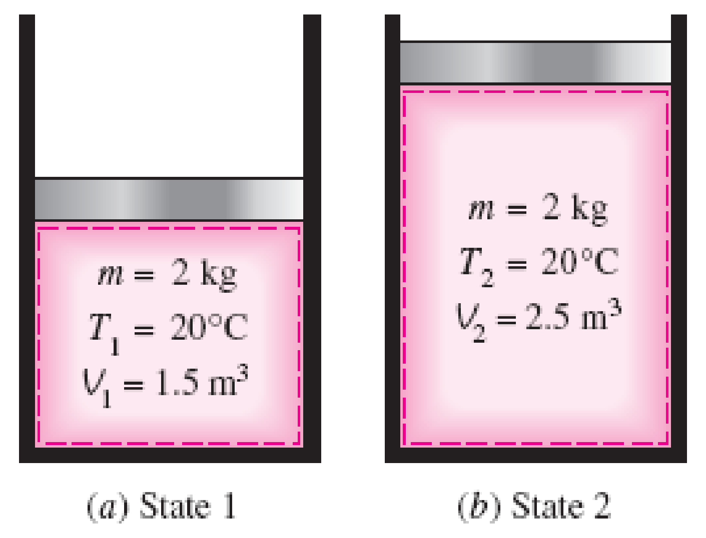
$e = e_1 = e_2 = e_3 = E/m$

T, P

# State, Equilibrium and Process

- State – a set of properties that describes the conditions of a system. Eg. Mass m, Temperature T, volume V

- Thermodynamic equilibrium - system that maintains thermal, mechanical, phase and chemical equilibriums.



(*a*) State 1 (*b*) State 2

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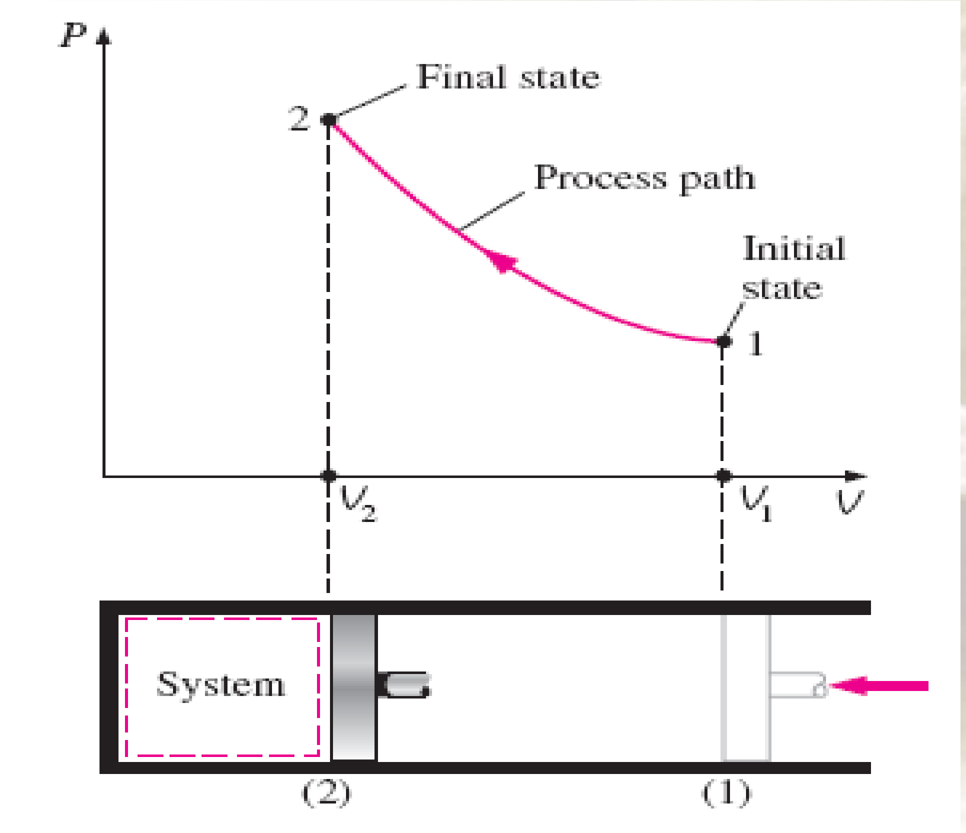
# State, Equilibrium and Process

- Process – change from one equilibrium state to another.

| Process | Property held constant |
|---|---|
| isobaric | pressure |
| isothermal | temperature |
| isochoric | volume |
| isentropic | entropy |

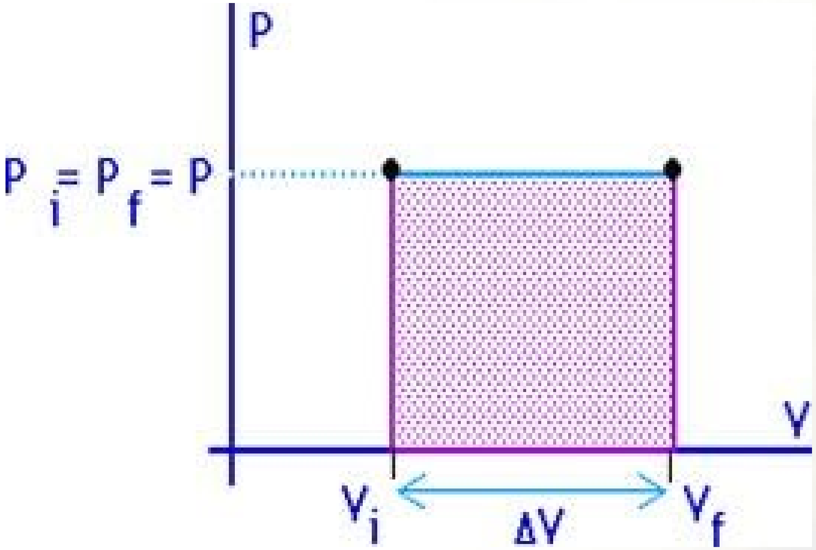


# State, Equilibrium and Process

The prefix *iso*- is often used to designate a process for which a particular property remains constant.

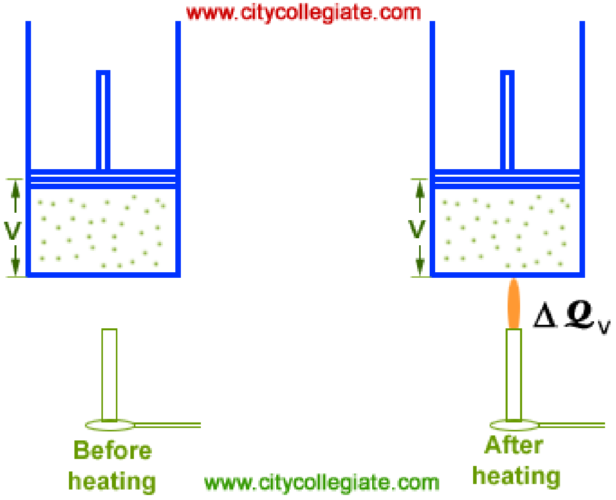
**Isobaric process**: A process during which the pressure *P* remains constant.

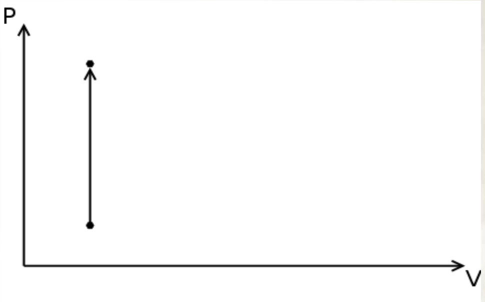
**Pressure** is Constant (**ΔP = 0**)



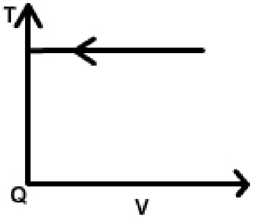
# State, Equilibrium and Process

**Isochoric (or isometric) process**: A process during which the specific volume *v* remains constant





**Isothermal process**: A process during which the temperature *T* remains constant.



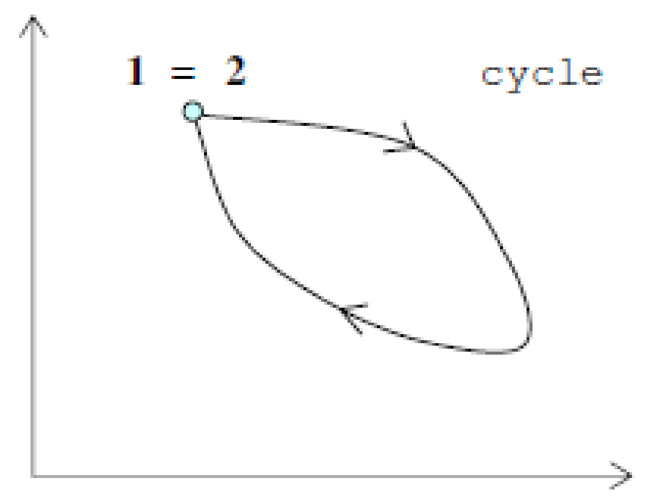
| Process | Property held constant |
|---|---|
| isobaric | pressure |
| isothermal | temperature |
| isochoric | volume |
| isentropic | entropy |

# Types of Thermodynamics Processes

- **Cyclic process** - when a system in a given initial state goes through various processes and finally return to its initial state, the system has undergone a cyclic process or cycle.

- **Reversible process** - it is defined as a process that, once having take place it can be reversed. In doing so, it leaves no change in the system or boundary.

- **Irreversible process** - a process that cannot return both the system and surrounding to their original conditions



# Types of Thermodynamics Processes

- **Adiabatic process** - a process that has no heat transfer into or out of the system. It can be considered to be perfectly insulated.

- **Isentropic process** - a process where the entropy of the fluid remains constant.

- **Polytropic process** - when a gas undergoes a reversible process in which there is heat transfer, it is represented with a straight line, $PV^n$ = constant.

- **Throttling process** - a process in which there is no change in enthalpy, no work is done and the process is adiabatic.

# SOME THERMODYNAMIC PROPERTIES

Pressure, temperature, density, volume etc. are some of the thermodynamic properties frequently used.

Pressure is defined as the force per unit area :
$p = F/A$, (N/m$^2$)

In general during analysis one comes across the following four types of pressure,
(*i*) Atmospheric pressure (*ii*) Absolute pressure
(*iii*) Gauge pressure (*iv*) Vacuum pressure

# SOME THERMODYNAMIC PROPERTIES

The bar chart shown in Fig.  further clarifies the interrelationship amongst the different pressures.

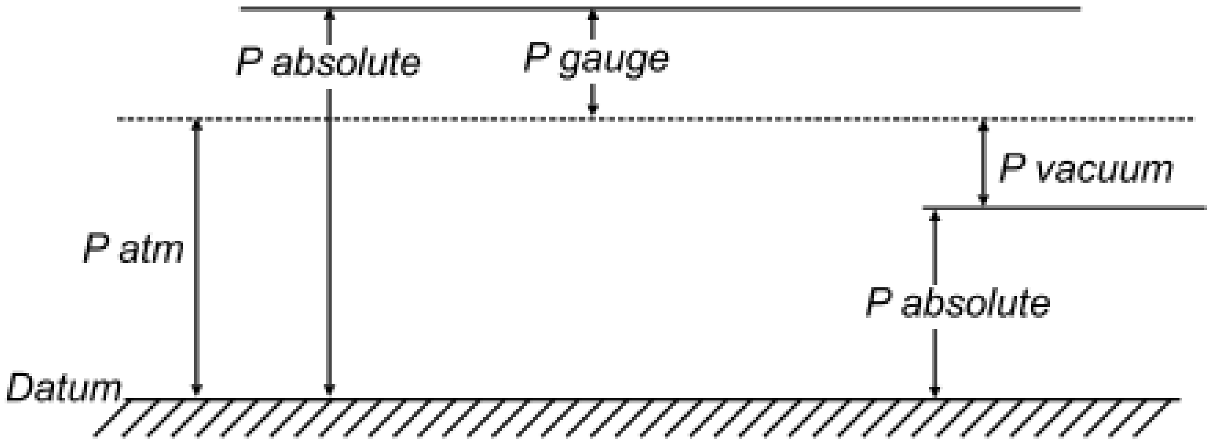


***Fig. 1*** *Different pressures*

# ENERGY AND ITS FORMS

Energy can be classified in the following general categories;

(*a*) ***Energy in transition***: It refers to the energy that is in process of transition between substances or regions because of some driving potential, such as difference or gradient of force, or of temperature, or of electrical potential etc.

(*b*) ***Energy stored in particular mass***: It refers to the potential and kinetic energy associated with masses that are elevated or moving with respect to the earth.

(*i*) *Macroscopic energy*: (*ii*) *Microscopic energy*:

# ENERGY AND ITS FORMS

Some of the popular forms of energy are described below:

***Potential energy***: This type of energy is based on relative position of bodies in a system, i.e. elevation in a gravitational field.

***Kinetic energy***: It is based on the relative movement of bodies. For a mass *m* moving with certain velocity it could be mathematically expressed as;

***Internal energy***: Internal energy of a system is the energy associated with the molecular structure at molecular level.

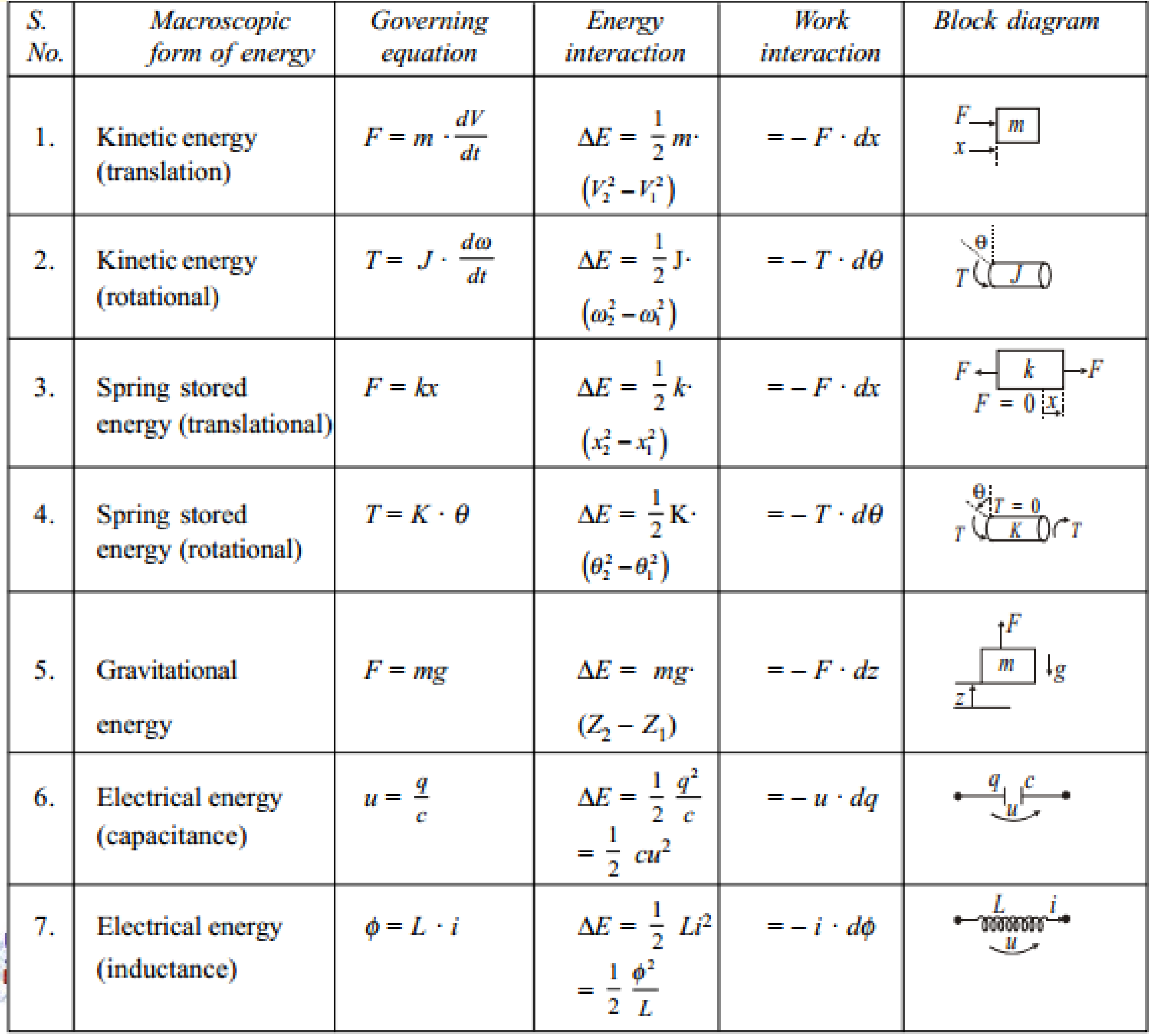
# ENERGY AND ITS FORMS

Total energy of a system may be given as summation of different forms of energy at a moment. Mathematically;

T.E (Total energy) = K.E + P.E + I.E

where K.E = Kinetic energy, P.E = Potential energy, I.E = Internal energy

# Some forms of energy and the associated work interactions



| S. No. | Macroscopic form of energy | Governing equation | Energy interaction | Work interaction | Block diagram |
|---|---|---|---|---|---|
| 1. | Kinetic energy (translation) | $F = m \cdot \frac{dV}{dt}$ | $\Delta E = \frac{1}{2} m \cdot \left(V_2^2 - V_1^2\right)$ | $= - F \cdot dx$ | |
| 2. | Kinetic energy (rotational) | $T = J \cdot \frac{d\omega}{dt}$ | $\Delta E = \frac{1}{2} J \cdot \left(\omega_2^2 - \omega_1^2\right)$ | $= - T \cdot d\theta$ | |
| 3. | Spring stored energy (translational) | $F = kx$ | $\Delta E = \frac{1}{2} k \cdot \left(x_2^2 - x_1^2\right)$ | $= - F \cdot dx$ | |
| 4. | Spring stored energy (rotational) | $T = K \cdot \theta$ | $\Delta E = \frac{1}{2} K \cdot \left(\theta_2^2 - \theta_1^2\right)$ | $= - T \cdot d\theta$ | |
| 5. | Gravitational energy | $F = mg$ | $\Delta E = mg \cdot (Z_2 - Z_1)$ | $= - F \cdot dz$ | |
| 6. | Electrical energy (capacitance) | $u = \frac{q}{c}$ | $\Delta E = \frac{1}{2} \frac{q^2}{c} = \frac{1}{2} cu^2$ | $= - u \cdot dq$ | |
| 7. | Electrical energy (inductance) | $\phi = L \cdot i$ | $\Delta E = \frac{1}{2} Li^2 = \frac{1}{2} \frac{\phi^2}{L}$ | $= - i \cdot d\phi$ | |

# HEAT AND WORK

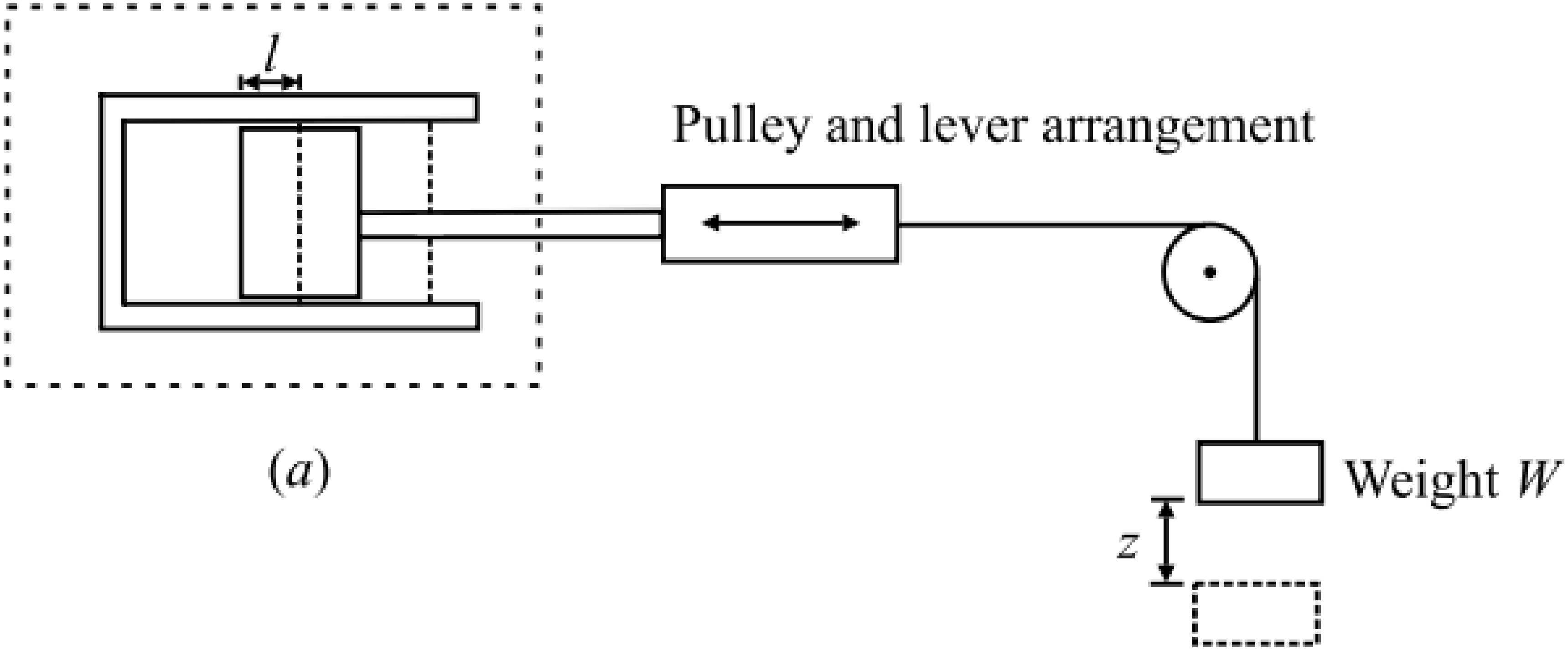
*‘**Heat**’ may be termed as the energy interaction at the system boundary which occurs due to temperature difference only.*

*Heat is observable in transit at the interface i.e. boundary, it can not be contained in a system. In general the heat transfer to the system is assigned with **positive (+)** sign while the heat transfer from the system is assigned with **negative (–)** sign. Its units are Calories.*

# HEAT AND WORK

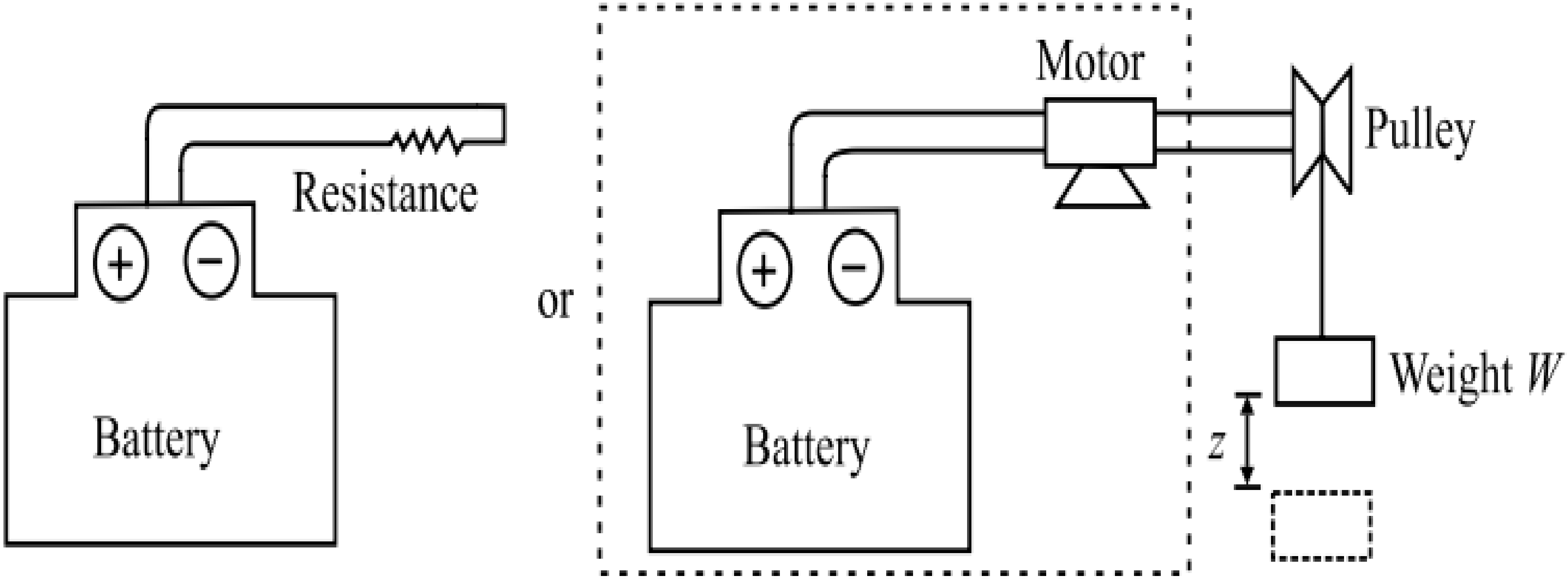
*“**Work**” shall be done by the system if the total effect outside the system is equivalent to the raising of weight and this work shall be positive work”.*

# HEAT AND WORK



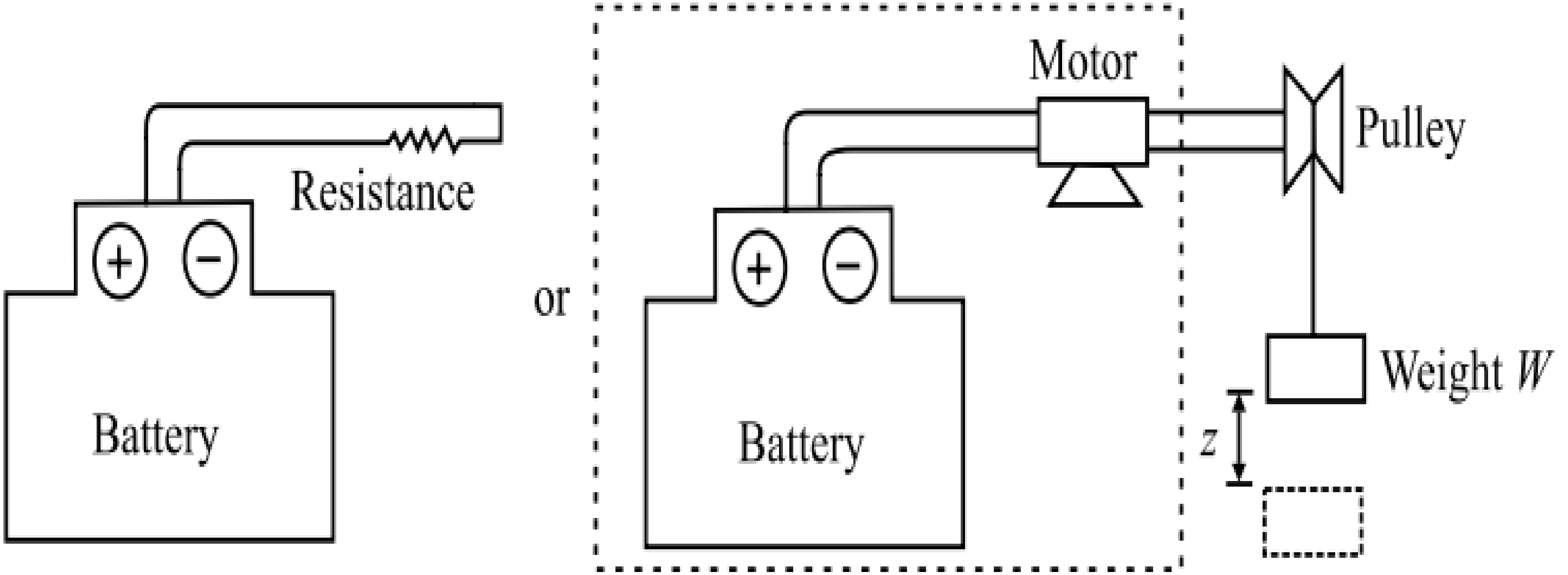
(a)

# HEAT AND WORK



*Thermodynamic work*

# HEAT AND WORK



*Thermodynamic work*

# Law of Thermodynamics

## JOB20103 THERMODYNAMICS

Lecture Notes:

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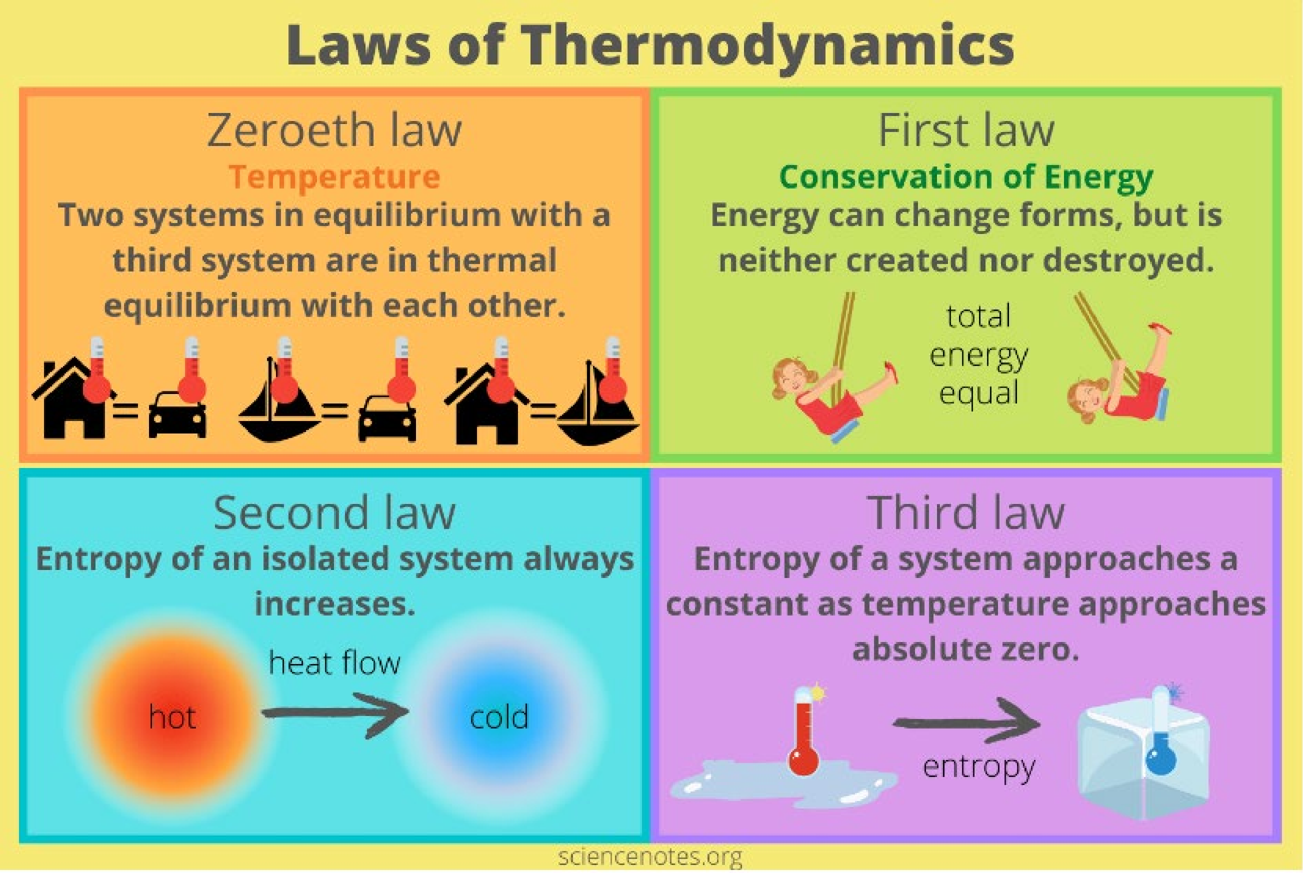
*Universiti Kuala Lumpur*



# Laws of Thermodynamics

## Zeroeth law

**Temperature**

**Two systems in equilibrium with a third system are in thermal equilibrium with each other.**

## First law

**Conservation of Energy**

**Energy can change forms, but is neither created nor destroyed.**

## Second law

**Entropy of an isolated system always increases.**

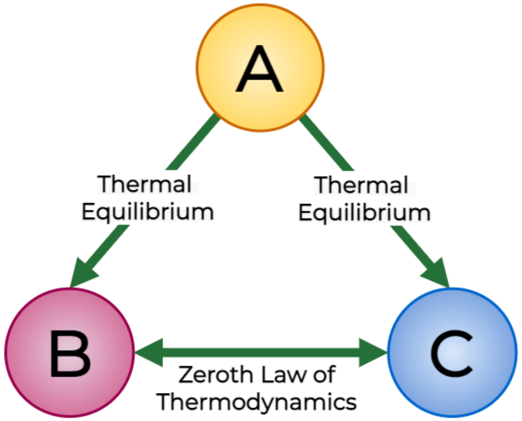
## Third law

**Entropy of a system approaches a constant as temperature approaches absolute zero.**

sciencenotes.org

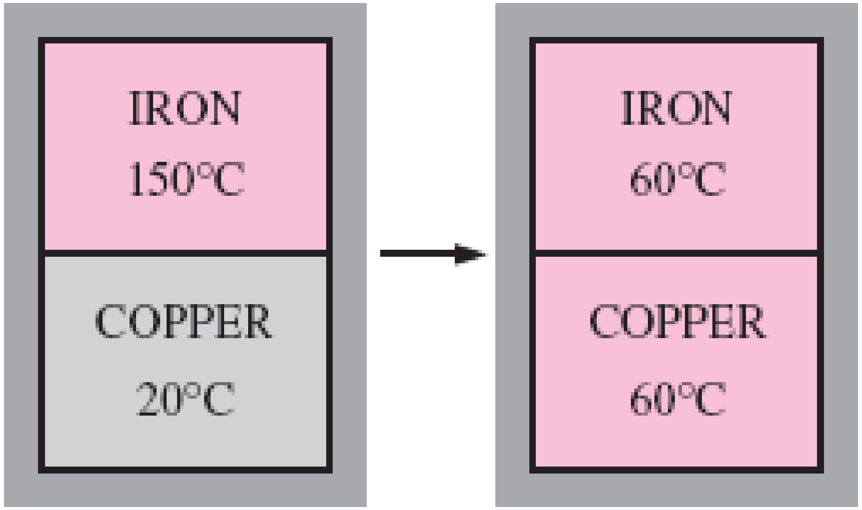
# THE $0^{TH}$ LAW OF THERMODYNAMICS

- Two systems are in ***thermal equilibrium*** if there is no net transfer of heat between them when placed in contact.
- They are at the ***same*** temperature.
- The Zeroth Law establishes a ***transitive property*** for thermal equilibrium.
    - If system A is in thermal equilibrium with system B (A ⟷ B)
    - AND system B is in thermal equilibrium with system C (B ⟷ C)
    - Then, system A must also be in thermal equilibrium with system C (A ⟷ C).



# Zeroth Law of Thermodynamics

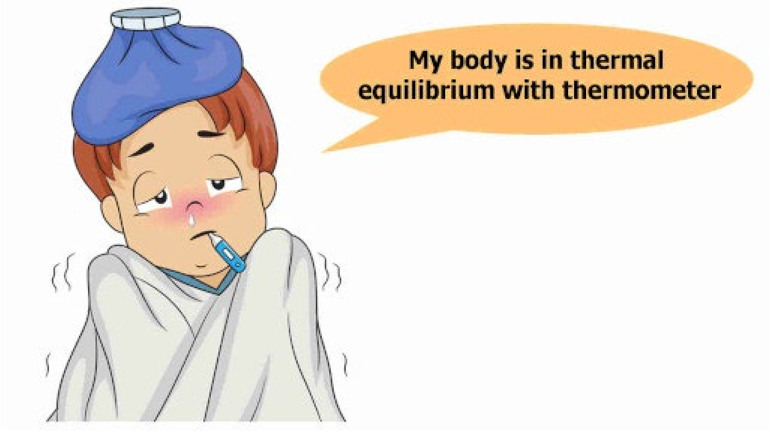
*“ If two bodies are in thermal equilibrium with a third body, there are also in thermal equilibrium with each other.”*



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

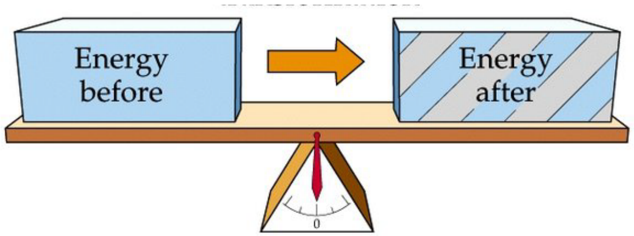
# THE $0^{TH}$ LAW OF THERMODYNAMICS

- Foundation of Temperature Measurement allows us to define temperature based on thermal equilibrium.
- We can create a temperature scale using a reference system and establish the concept of "hotter" and "colder".
- ***Thermometers*** work by achieving <u>thermal equilibrium</u> with the object's temperature being measured.



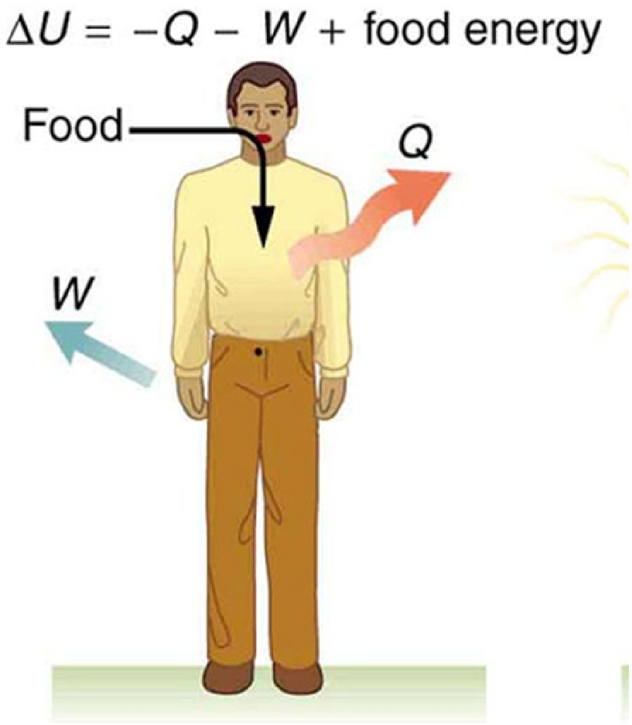
# THE 1st LAW OF THERMODYNAMICS

- The First Law of Thermodynamics states that energy ***cannot be created or destroyed*** in a closed system (no matter transfer).
- The total energy remains ***constant***.
- Energy transfer can occur through two main mechanisms:
  - Heat (Q): Transfer of thermal energy due to a temperature difference (system absorbs or releases heat).
  - Work (W): Transfer of energy when a force acts on an object over a distance (work done on or by the system).



# THE 1st LAW OF THERMODYNAMICS

- The ***internal energy (U)*** of a system represents the total random microscopic kinetic and potential energy of its particles.
- The First Law expresses the relationship between these: ΔU = Q + W
  - ΔU: Change in internal energy of the system (positive for increase, negative for decrease)
  - Q: Net heat transfer into the system (positive for heat entering, negative for heat leaving)
  - W: Net work done by the system (positive for work done by the system, negative for work done on the system)



# THE $1^{st}$ LAW OF THERMODYNAMICS

- The change **in internal energy** of a closed system is **equal** to the **net heat transferred** into the system **plus** the **net work done** by the system.
- If Q is ***positive*** and W is ***positive***, both heat enters the system and work is done by the system, resulting in an ***increase*** in internal energy.
- If Q is ***negative*** and W is ***positive***, heat leaves the system while work is done by the system, and the internal energy might ***increase or decrease*** depending on the relative magnitudes.

# THE $2^{nd}$ LAW OF THERMODYNAMICS

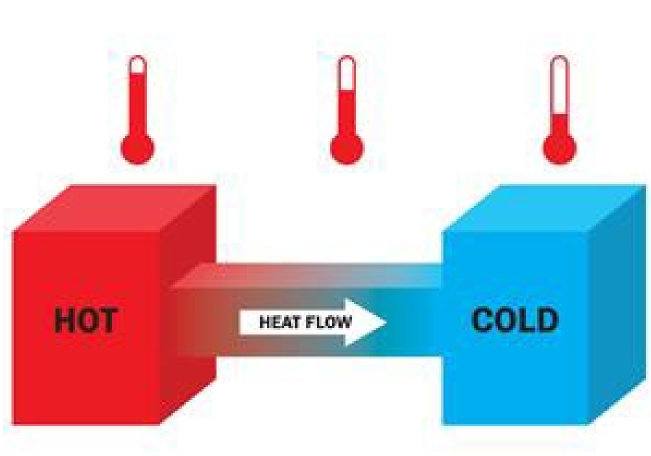
- The Second Law introduces the concept of ***entropy***, a measure of disorder or randomness within a system.
- It's generally considered a measure of how spread out the system's energy is.

# THE 2nd LAW OF THERMODYNAMICS

- The Second Law states that in a closed isolated system, ***the total entropy always tends to increase*** over time.
- This means systems naturally progress towards a state of higher disorder.
- Most natural processes are ***irreversible***, meaning they cannot be perfectly reversed to their original state.
- This is because some usable energy is inevitably ***degraded into unusable heat*** during the process, increasing the overall entropy.

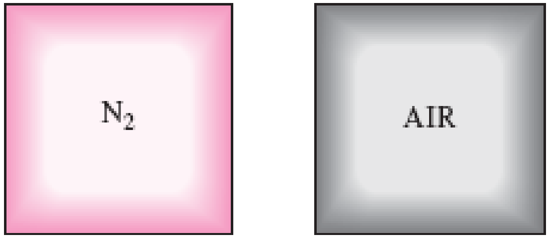
# THE 2nd LAW OF THERMODYNAMICS

- Heat naturally flows from a region of ***higher temperature to a region of lower temperature*** (spontaneous process).
- The reverse process (heat flowing from cold to hot) ***requires external work*** input (non-spontaneous).
- The Second Law explains why no heat engine can be 100% efficient in converting thermal energy into work.
- Some energy is always lost as unusable heat, reflecting the increase in entropy.



# What is Pure Substances ?

❖A substance that has a fixed chemical composition throughout is called a **pure substance.**



❖A pure substance does not have to be of a single chemical element or compound, however. A mixture of various chemical elements or compounds also qualifies as a pure substance as long as the mixture is *homogeneous*.

(*a*) $H_2O$

(*b*) AIR

# Pure Substances

❖A mixture of liquid and water vapor is a pure substance, but a mixture of liquid and gaseous air is not.

*Examples:*

- ❖ Water (solid, liquid, and vapor phases)
- ❖ Mixture of liquid water and water vapor
- ❖ Carbon dioxide, $CO_2$
- ❖ Nitrogen, $N_2$
- ❖ Mixtures of gases, such as air, as long as there is no change of phase.

# Phases of A Pure Substance

❖The substances exist in different phases, e.g. at room temperature and pressure, copper is solid and mercury is a liquid.

❖It can exist in different phases under variations of condition.

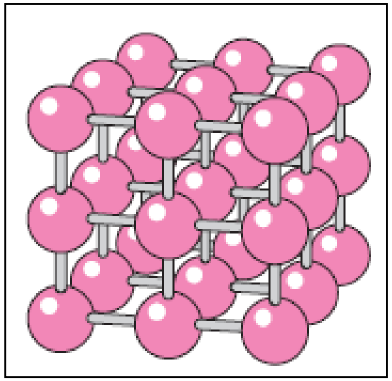
❖There are 3 Principal phases

- *Solid*
- *Liquid*
- *Gas*

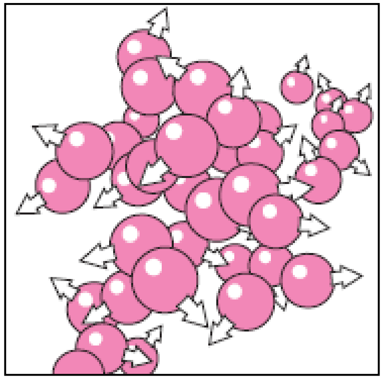
Each with different molecular structures.

# Phase-change Processes of Pure Substances

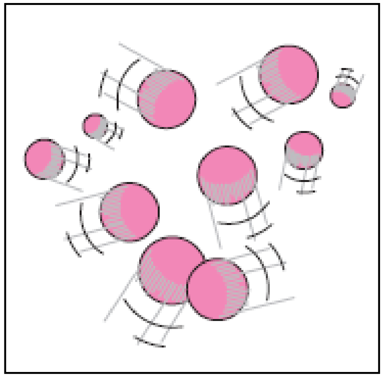
- There are many practical situations where two phases of a pure substances coexist in equilibrium.
- E.g. water exists as a mixture of liquid and vapor in the boiler and etc.



*Solid*

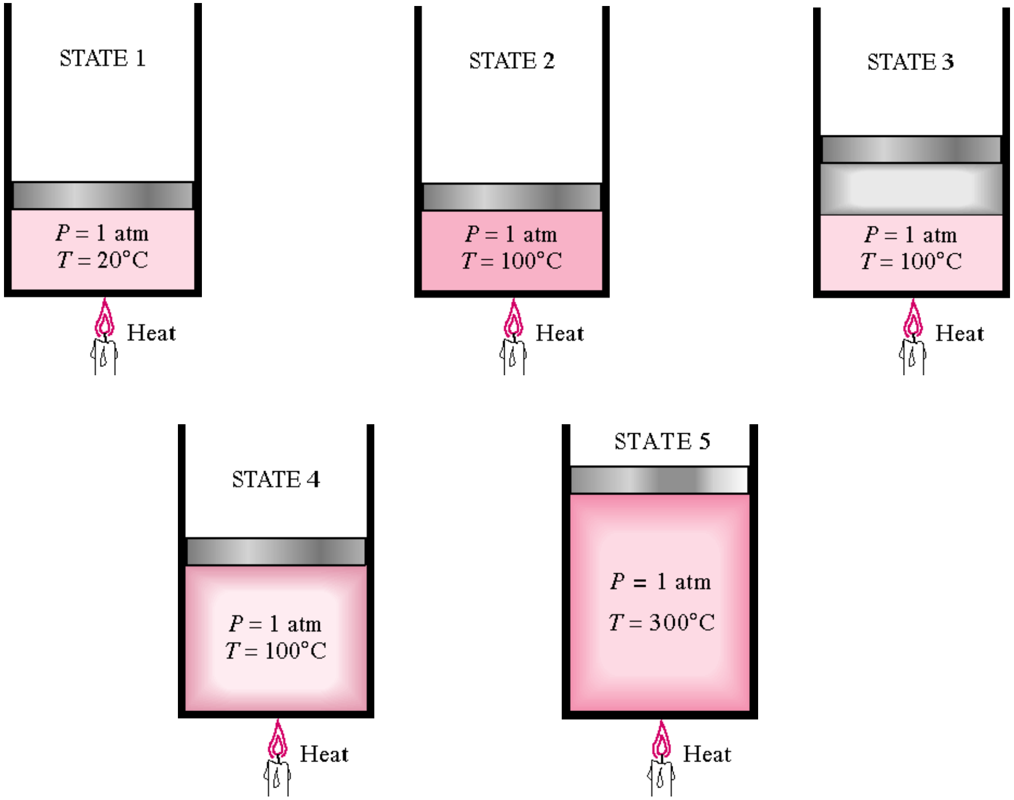


*Liquid*



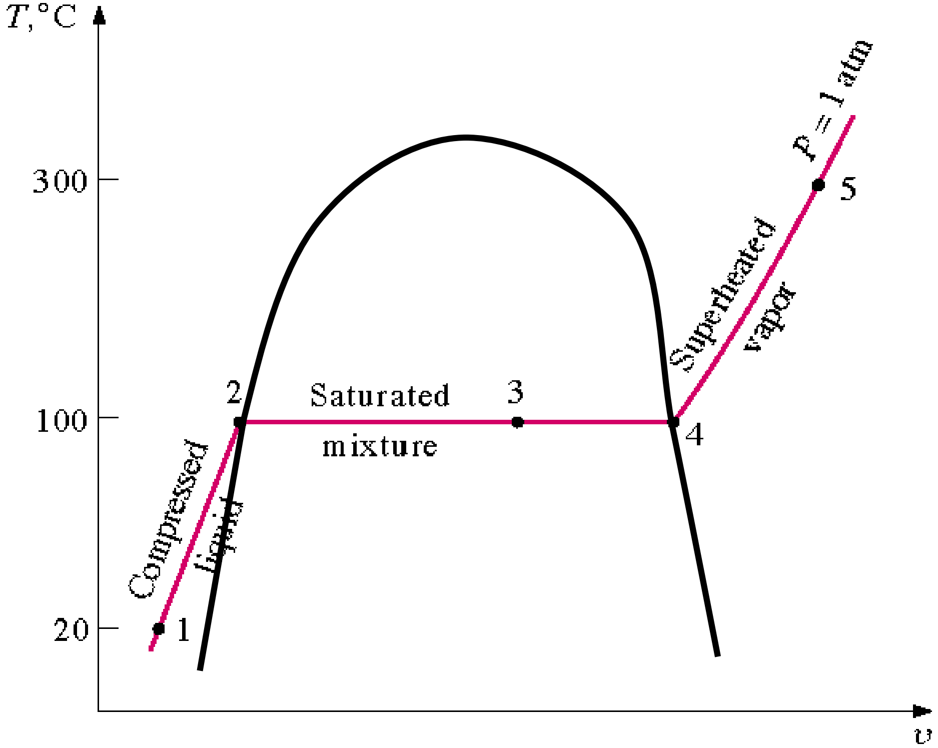
*Gas*

# Phase-change Processes of Pure Substances

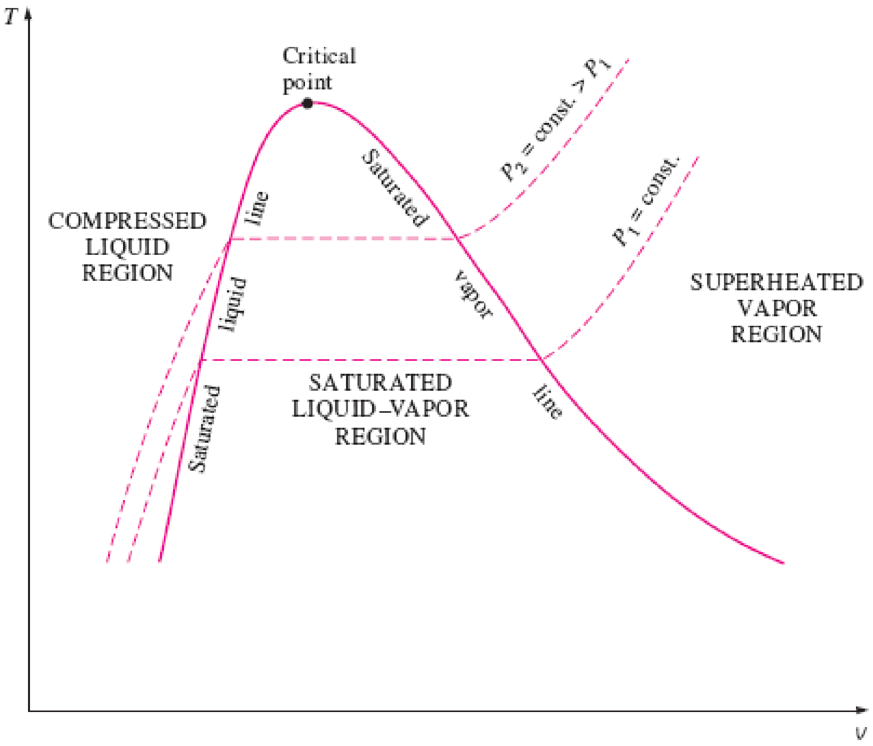


# Phase-change Processes of Pure Substances

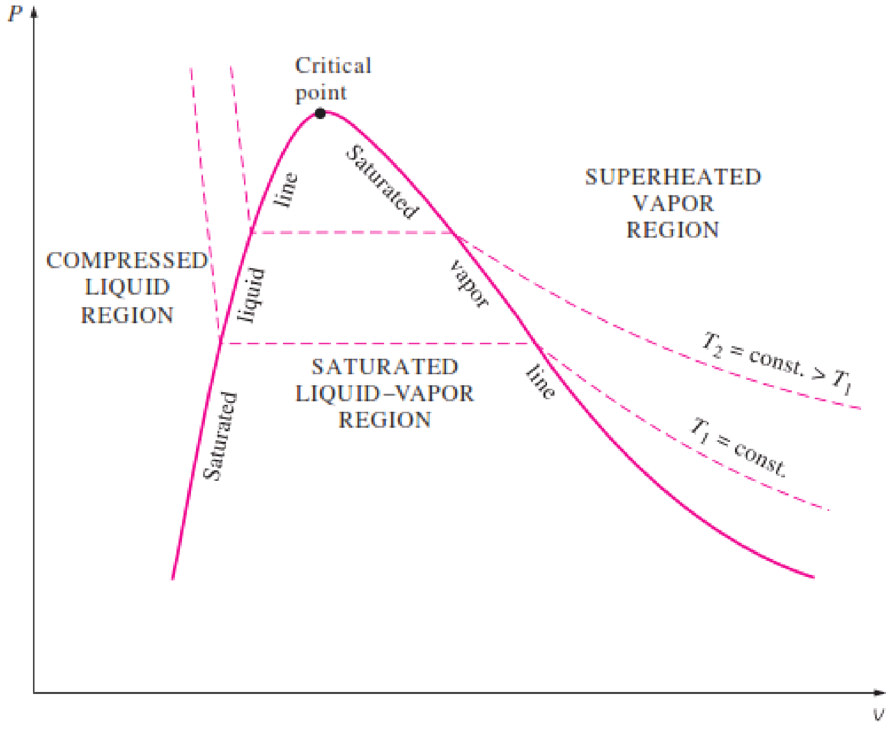
This constant pressure heating process can be illustrated as:



# Property Diagram
# T-v diagram



# Property Diagram
# P-v diagram



# Saturation

- *Saturation* is defined as a condition in which a mixture of vapor and liquid can exist together at a given temperature and pressure.

- *Saturation pressure* is the pressure at which the liquid and vapor phases are in equilibrium at a given temperature

- For a **pure substance** there is a definite relationship between saturation pressure and saturation temperature. The **higher** the pressure, the **higher** the saturation temperature

# Saturation

The graphical representation of this relationship between temperature and pressure at saturated conditions is called the *vapor pressure curve*

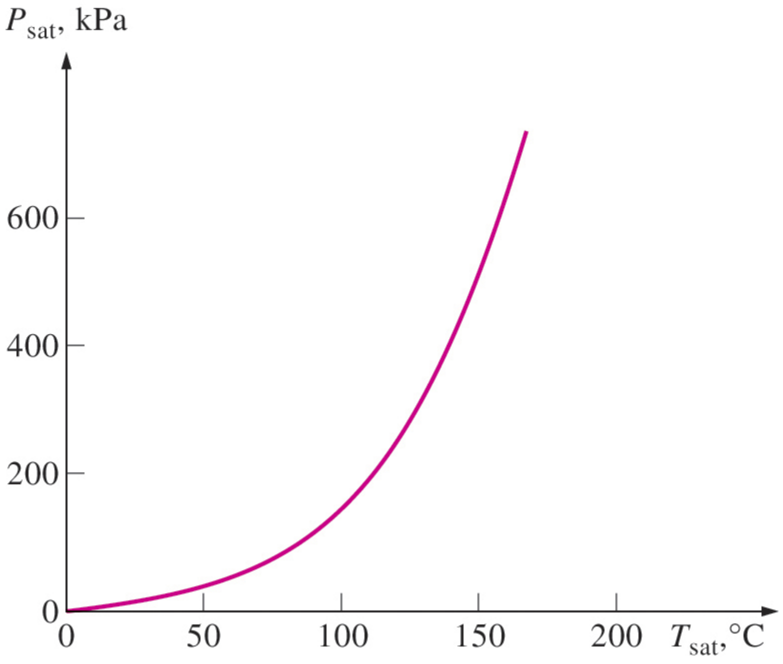


**TABLE 3–1**

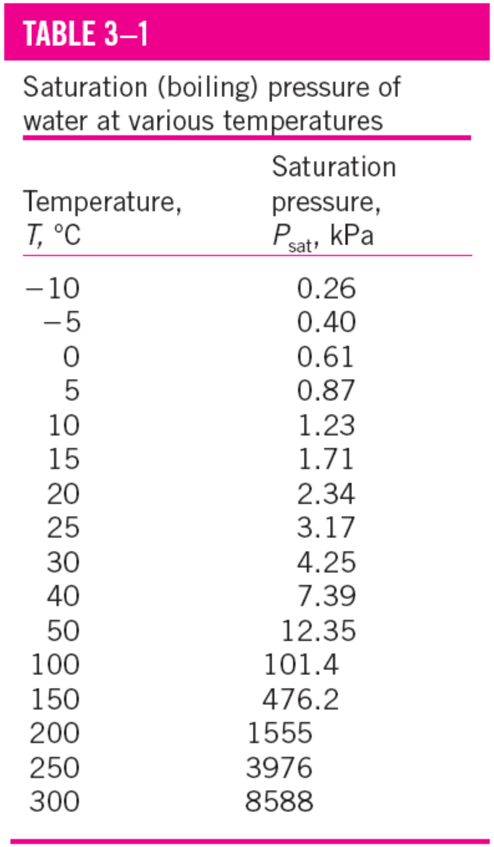
Saturation (boiling) pressure of water at various temperatures

| Temperature, $T$, °C | Saturation pressure, $P_{sat}$, kPa |
|---|---|
| −10 | 0.26 |
| −5 | 0.40 |
| 0 | 0.61 |
| 5 | 0.87 |
| 10 | 1.23 |
| 15 | 1.71 |
| 20 | 2.34 |
| 25 | 3.17 |
| 30 | 4.25 |
| 40 | 7.39 |
| 50 | 12.35 |
| 100 | 101.4 |
| 150 | 476.2 |
| 200 | 1555 |
| 250 | 3976 |
| 300 | 8588 |

# Saturated and Sub-cooled Liquids

❖If a substance exists as a liquid at the saturation temperature and pressure, it is called a *saturated liquid*

❖If the temperature of the liquid is lower than the saturation temperature for the existing pressure, it is called either a *subcooled liquid* or a ***compressed liquid***



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# Saturated and Superheated Vapors

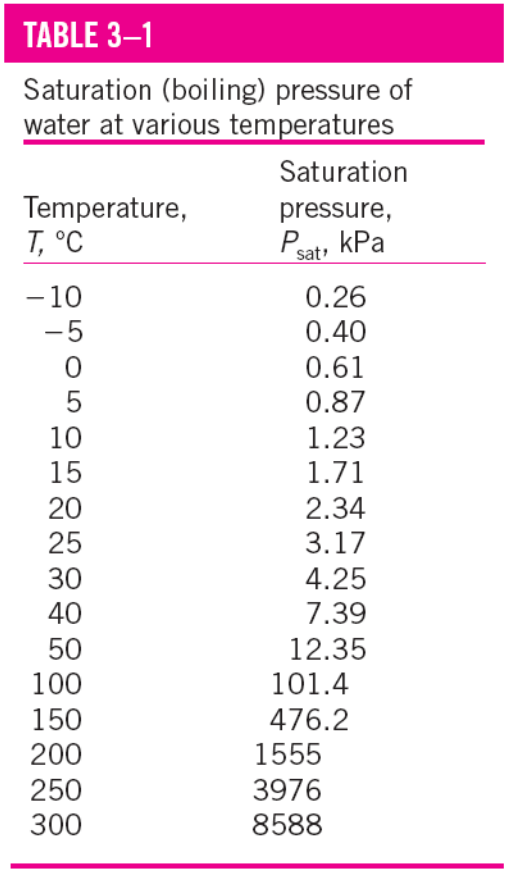

**TABLE 3–1**

Saturation (boiling) pressure of water at various temperatures

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| 20 | 2.34 |
| 25 | 3.17 |
| 30 | 4.25 |
| 40 | 7.39 |
| 50 | 12.35 |
| 100 | 101.4 |
| 150 | 476.2 |
| 200 | 1555 |
| 250 | 3976 |
| 300 | 8588 |

- If a substance exists entirely as vapor at saturation temperature, it is called ***saturated vapor***.
- When the vapor is at a temperature greater than the saturation temperature, it is said to exist as ***superheated vapor***.
- The pressure and temperature of superheated vapor are independent properties, since the temperature may increase while the pressure remains constant

# Latent Heat

❖**Latent heat**: The amount of energy absorbed or released during a phase-change process.

❖**Latent heat of fusion**: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.

❖**Latent heat of vaporization:** The amount of energy absorbed during vaporization and it is equivalent to the energy released during condensation.

❑*At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg.*

# Quality

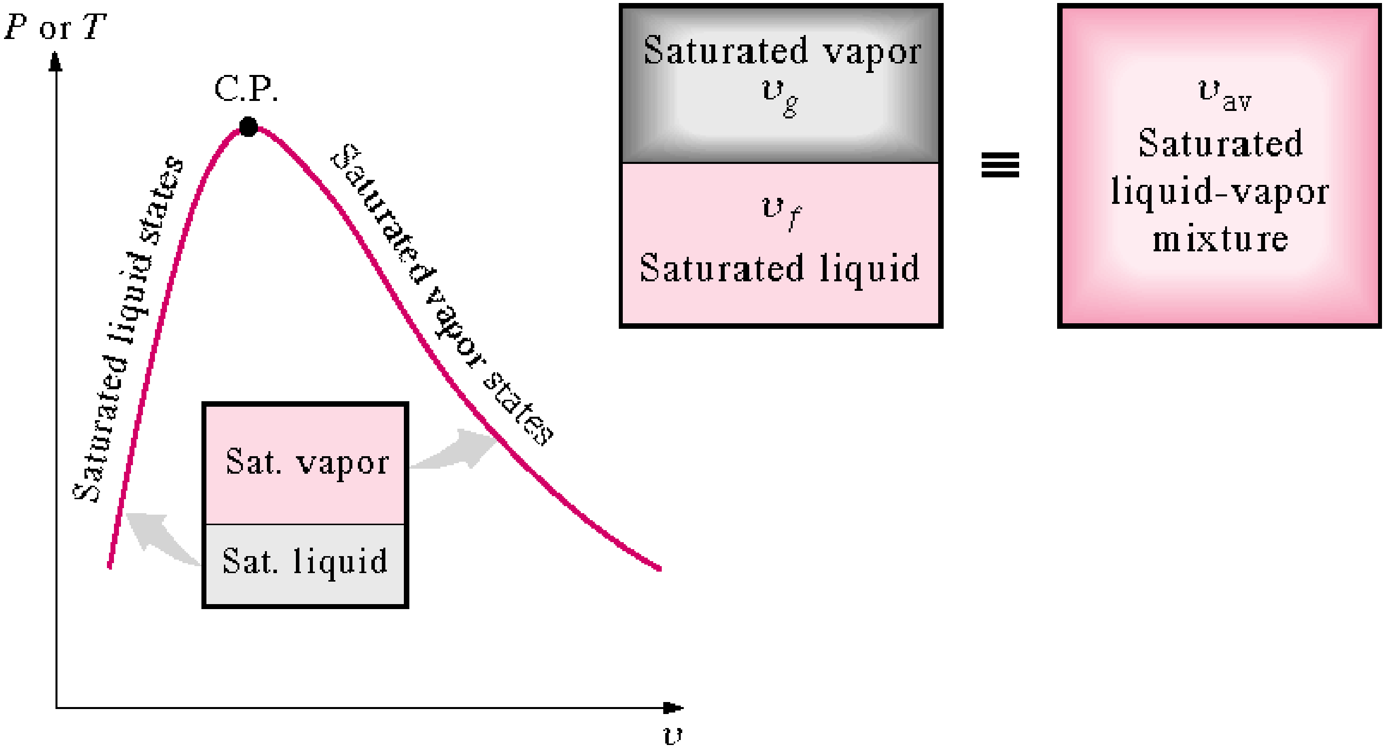
- When a substance exists as part liquid and part vapor at saturation conditions, its *quality* (x) is **defined** as the ratio of the mass of the vapor to the total mass of both vapor and liquid.

- The quality is zero for the saturated liquid and one for the saturated vapor ($0 \leq x \leq 1$)

- For example, if the mass of vapor is 0.2 g and the mass of the liquid is 0.8 g, then the quality is 0.2 or 20%.

$$x = \frac{mass_{saturated\ vapor}}{mass_{total}} = \frac{m_g}{m_f + m_g}$$

# Quality



**Mixture of liquid and vapor**

# Moisture Content

- The ***moisture content*** of a substance is the opposite of its quality. Moisture is defined as the ratio of the mass of the liquid to the total mass of both liquid and vapor

- Recall the definition of quality $x$

$$x = \frac{m_g}{m} = \frac{m_g}{m_f + m_g}$$

- Then

$$\frac{m_f}{m} = \frac{m - m_g}{m} = 1 - x$$

## Moisture Content

- Take specific volume as an example. The specific volume of the saturated mixture becomes

$$v = (1 - x)v_f + xv_g$$

- The form that is most often used

$$v = v_f + x(v_g - v_f)$$

- Let *Y* be any extensive property and let *y* be the corresponding intensive property, *Y/m*, then

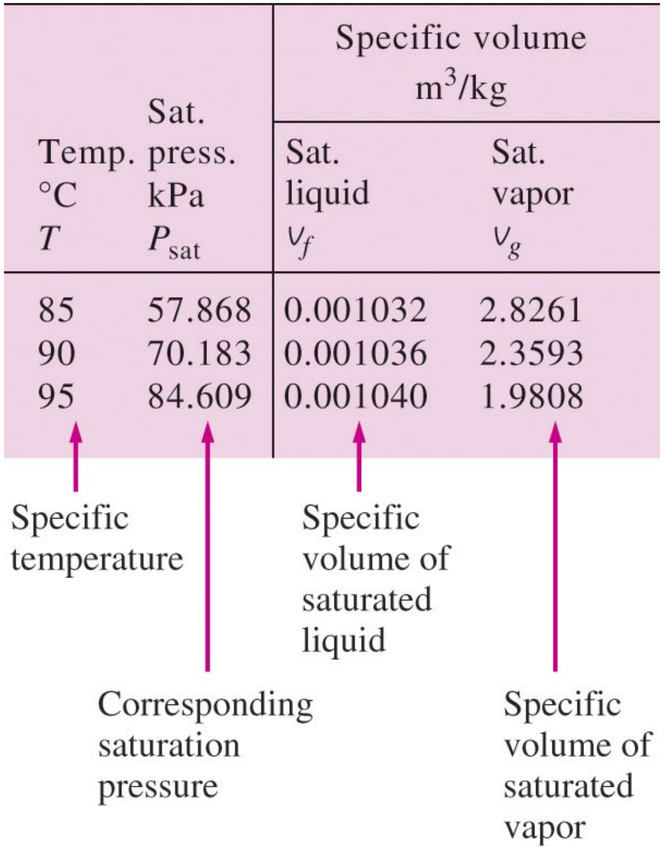
$$y = \frac{Y}{m} = y_f + x(y_g - y_f)$$

$$= y_f + x\, y_{fg}$$

$$where \quad y_{fg} = y_g - y_f$$

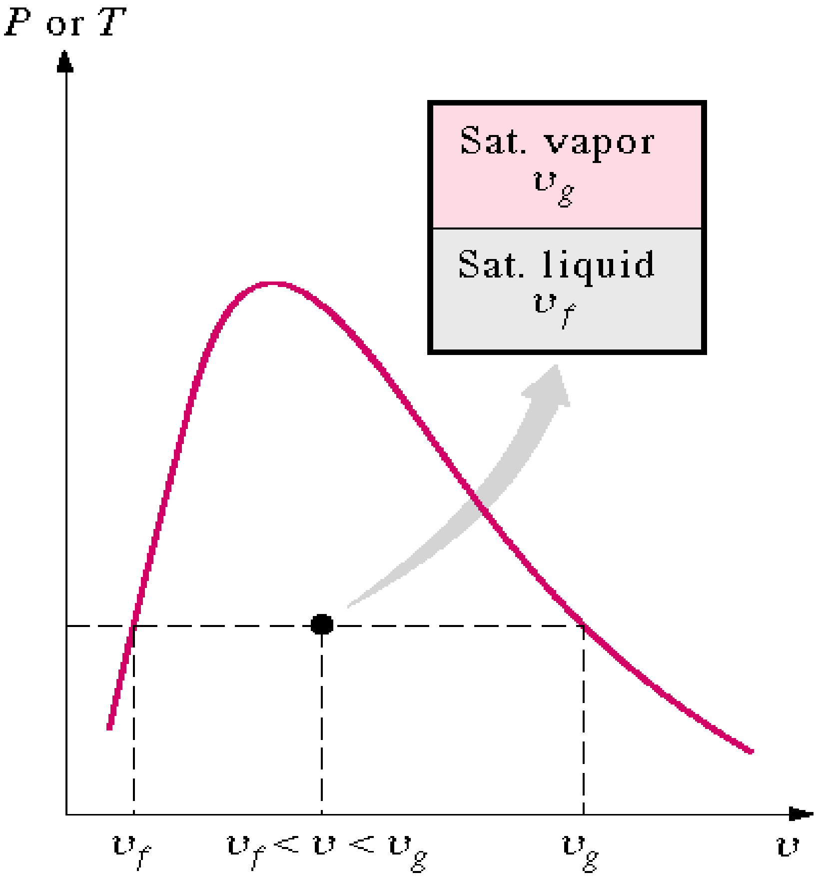
# Property Table

❖For example if the **pressure** and **specific volume** are specified, three questions are asked: For the given pressure,



| Temp. °C $T$ | Sat. press. kPa $P_{\text{sat}}$ | Specific volume m$^3$/kg<br>Sat. liquid $v_f$ | <br>Sat. vapor $v_g$ |
|---|---|---|---|
| 85 | 57.868 | 0.001032 | 2.8261 |
| 90 | 70.183 | 0.001036 | 2.3593 |
| 95 | 84.609 | 0.001040 | 1.9808 |

# Property Table



# Property Table

- If the answer to the first question is yes, the state is in the compressed liquid region, and the compressed liquid table is used to find the properties. (or using *saturation temperature table*)

$$v < v_f$$

- If the answer to the second question is yes, the state is in the saturation region, and either the saturation temperature table or the saturation pressure table is used.

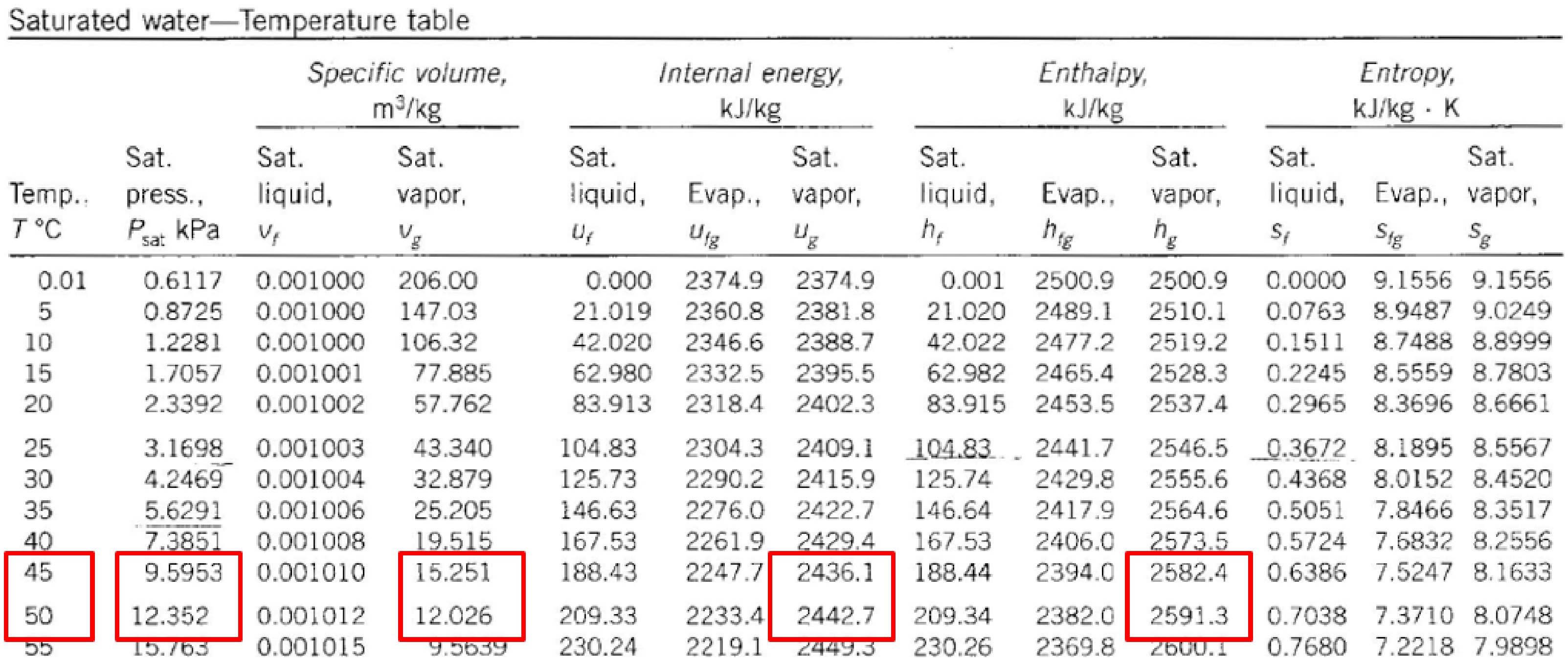
$$v_f < v < v_g$$

- If the answer to the third question is yes, the state is in the superheated region and the superheated table is used.

$$v_g < v$$

# Example 1.1

Determine the saturated pressure, specific volume, internal energy and enthalpy for saturated water vapor at 45°C and 50°C.

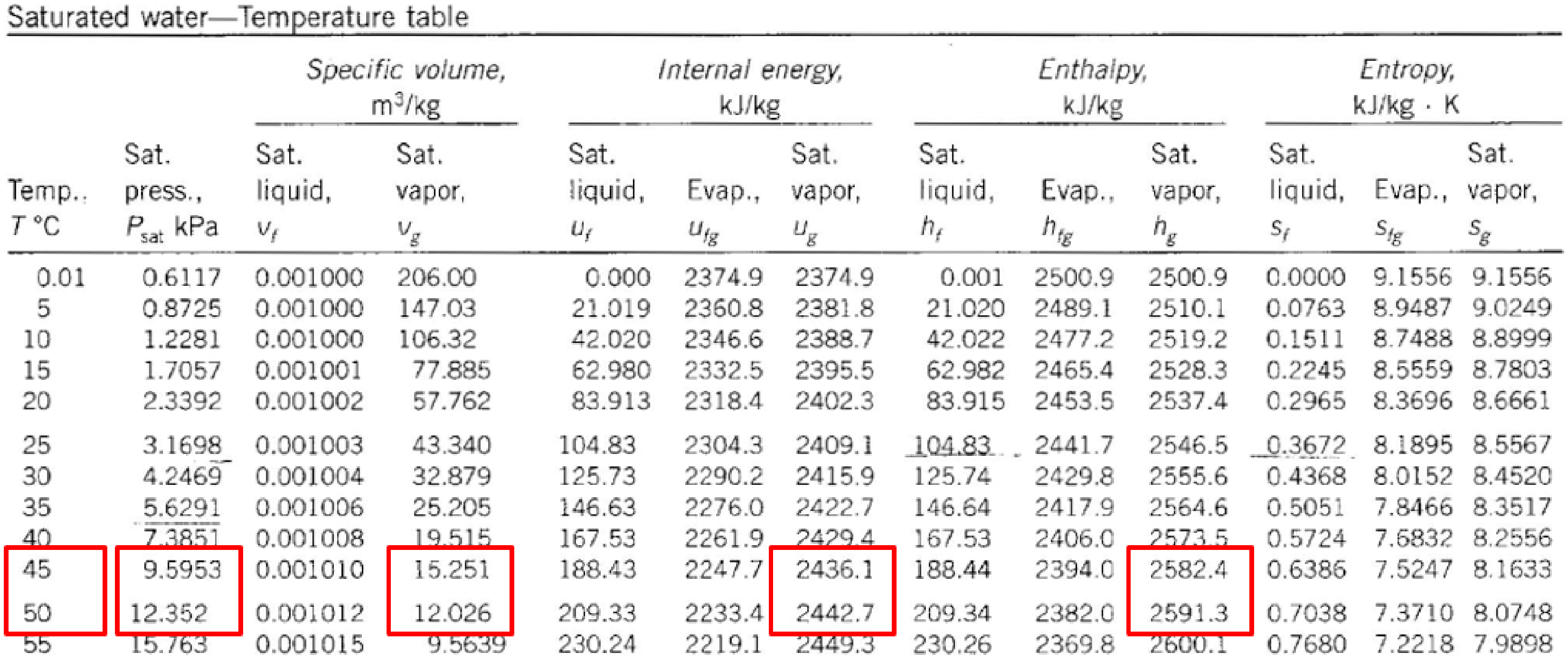


Saturated water—Temperature table

| | | Specific volume, m$^3$/kg | | Internal energy, kJ/kg | | | Enthalpy, kJ/kg | | | Entropy, kJ/kg · K | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temp., $T$ °C | Sat. press., $P_{sat}$ kPa | Sat. liquid, $v_f$ | Sat. vapor, $v_g$ | Sat. liquid, $u_f$ | Evap., $u_{fg}$ | Sat. vapor, $u_g$ | Sat. liquid, $h_f$ | Evap., $h_{fg}$ | Sat. vapor, $h_g$ | Sat. liquid, $s_f$ | Evap., $s_{fg}$ | Sat. vapor, $s_g$ |
| 0.01 | 0.6117 | 0.001000 | 206.00 | 0.000 | 2374.9 | 2374.9 | 0.001 | 2500.9 | 2500.9 | 0.0000 | 9.1556 | 9.1556 |
| 5 | 0.8725 | 0.001000 | 147.03 | 21.019 | 2360.8 | 2381.8 | 21.020 | 2489.1 | 2510.1 | 0.0763 | 8.9487 | 9.0249 |
| 10 | 1.2281 | 0.001000 | 106.32 | 42.020 | 2346.6 | 2388.7 | 42.022 | 2477.2 | 2519.2 | 0.1511 | 8.7488 | 8.8999 |
| 15 | 1.7057 | 0.001001 | 77.885 | 62.980 | 2332.5 | 2395.5 | 62.982 | 2465.4 | 2528.3 | 0.2245 | 8.5559 | 8.7803 |
| 20 | 2.3392 | 0.001002 | 57.762 | 83.913 | 2318.4 | 2402.3 | 83.915 | 2453.5 | 2537.4 | 0.2965 | 8.3696 | 8.6661 |
| 25 | 3.1698 | 0.001003 | 43.340 | 104.83 | 2304.3 | 2409.1 | 104.83 | 2441.7 | 2546.5 | 0.3672 | 8.1895 | 8.5567 |
| 30 | 4.2469 | 0.001004 | 32.879 | 125.73 | 2290.2 | 2415.9 | 125.74 | 2429.8 | 2555.6 | 0.4368 | 8.0152 | 8.4520 |
| 35 | 5.6291 | 0.001006 | 25.205 | 146.63 | 2276.0 | 2422.7 | 146.64 | 2417.9 | 2564.6 | 0.5051 | 7.8466 | 8.3517 |
| 40 | 7.3851 | 0.001008 | 19.515 | 167.53 | 2261.9 | 2429.4 | 167.53 | 2406.0 | 2573.5 | 0.5724 | 7.6832 | 8.2556 |
| 45 | 9.5953 | 0.001010 | 15.251 | 188.43 | 2247.7 | 2436.1 | 188.44 | 2394.0 | 2582.4 | 0.6386 | 7.5247 | 8.1633 |
| 50 | 12.352 | 0.001012 | 12.026 | 209.33 | 2233.4 | 2442.7 | 209.34 | 2382.0 | 2591.3 | 0.7038 | 7.3710 | 8.0748 |
| 55 | 15.763 | 0.001015 | 9.5639 | 230.24 | 2219.1 | 2449.3 | 230.26 | 2369.8 | 2600.1 | 0.7680 | 7.2218 | 7.9898 |

# Example 1.2

Determine the saturated pressure, specific volume, internal energy and enthalpy for saturated water vapor at 47º C .



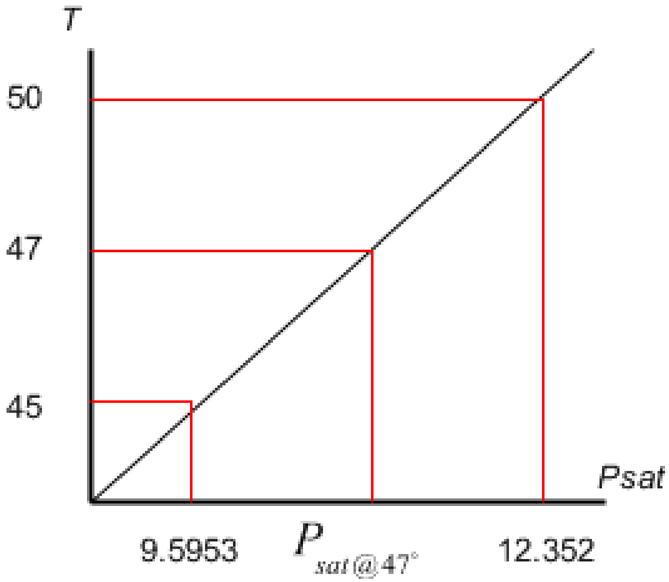
Saturated water—Temperature table

| | | Specific volume, $m^3/kg$ | | Internal energy, kJ/kg | | | Enthalpy, kJ/kg | | | Entropy, kJ/kg · K | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temp., $T$ °C | Sat. press., $P_{sat}$ kPa | Sat. liquid, $v_f$ | Sat. vapor, $v_g$ | Sat. liquid, $u_f$ | Evap., $u_{fg}$ | Sat. vapor, $u_g$ | Sat. liquid, $h_f$ | Evap., $h_{fg}$ | Sat. vapor, $h_g$ | Sat. liquid, $s_f$ | Evap., $s_{fg}$ | Sat. vapor, $s_g$ |
| 0.01 | 0.6117 | 0.001000 | 206.00 | 0.000 | 2374.9 | 2374.9 | 0.001 | 2500.9 | 2500.9 | 0.0000 | 9.1556 | 9.1556 |
| 5 | 0.8725 | 0.001000 | 147.03 | 21.019 | 2360.8 | 2381.8 | 21.020 | 2489.1 | 2510.1 | 0.0763 | 8.9487 | 9.0249 |
| 10 | 1.2281 | 0.001000 | 106.32 | 42.020 | 2346.6 | 2388.7 | 42.022 | 2477.2 | 2519.2 | 0.1511 | 8.7488 | 8.8999 |
| 15 | 1.7057 | 0.001001 | 77.885 | 62.980 | 2332.5 | 2395.5 | 62.982 | 2465.4 | 2528.3 | 0.2245 | 8.5559 | 8.7803 |
| 20 | 2.3392 | 0.001002 | 57.762 | 83.913 | 2318.4 | 2402.3 | 83.915 | 2453.5 | 2537.4 | 0.2965 | 8.3696 | 8.6661 |
| 25 | 3.1698 | 0.001003 | 43.340 | 104.83 | 2304.3 | 2409.1 | 104.83 | 2441.7 | 2546.5 | 0.3672 | 8.1895 | 8.5567 |
| 30 | 4.2469 | 0.001004 | 32.879 | 125.73 | 2290.2 | 2415.9 | 125.74 | 2429.8 | 2555.6 | 0.4368 | 8.0152 | 8.4520 |
| 35 | 5.6291 | 0.001006 | 25.205 | 146.63 | 2276.0 | 2422.7 | 146.64 | 2417.9 | 2564.6 | 0.5051 | 7.8466 | 8.3517 |
| 40 | 7.3851 | 0.001008 | 19.515 | 167.53 | 2261.9 | 2429.4 | 167.53 | 2406.0 | 2573.5 | 0.5724 | 7.6832 | 8.2556 |
| 45 | 9.5953 | 0.001010 | 15.251 | 188.43 | 2247.7 | 2436.1 | 188.44 | 2394.0 | 2582.4 | 0.6386 | 7.5247 | 8.1633 |
| 50 | 12.352 | 0.001012 | 12.026 | 209.33 | 2233.4 | 2442.7 | 209.34 | 2382.0 | 2591.3 | 0.7038 | 7.3710 | 8.0748 |
| 55 | 15.763 | 0.001015 | 9.5639 | 230.24 | 2219.1 | 2449.3 | 230.26 | 2369.8 | 2600.1 | 0.7680 | 7.2218 | 7.9898 |

# Solution:

❑Extract data from steam table

| $T$ | $P_{sat}$ | $v$ | $u$ | $h$ |
|---|---|---|---|---|
| 45 | 9.5953 | 15.251 | 2436.1 | 2582.4 |
| 47 | $P_{sat}$ | $v$ | $u$ | $h$ |
| 50 | 12.352 | 12.026 | 2442.7 | 2591.3 |



❑Interpolation for $P_{sat}$

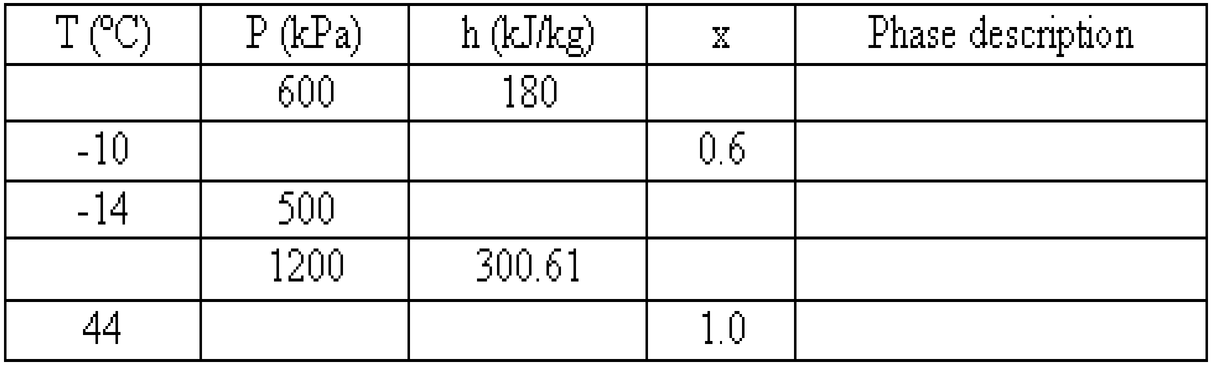
$$\frac{P_{sat}-9.5953}{12.352-9.5953}=\frac{47-45}{50-45}$$

$$P_{sat@47^\circ}=\underline{\underline{10.698\,kPa}}$$

❑Do the same principal to others!!!!

# Exercises

1. Fill in the blank using R-134a



| T (°C) | P (kPa) | h (kJ/kg) | x | Phase description |
|---|---|---|---|---|
| | 600 | 180 | | |
| -10 | | | 0.6 | |
| -14 | 500 | | | |
| | 1200 | 300.61 | | |
| 44 | | | 1.0 | |

2. Determine the saturated temperature, saturated pressure and enthalpy for water at specific volume of saturated vapor at 10.02 $m^3/kg$ .

# Example 1.3

Determine the enthalpy of 1.5 kg of water contained in a volume of 1.2 m$^3$ at 200 kPa.

***Solution:***

- Specific volume for water

$$v = \frac{Volume}{mass} = \frac{1.2\,m^3}{1.5\,kg} = 0.8\frac{m^3}{kg}$$

- From table A-5:

$$v_f = 0.001061\, {m^3}/{kg}$$

$$v_g = 0.8858\ {m^3}/{kg}$$

Is $v < v_f$ ? No

Is $v_f < v < v_g$ ? Yes

Is $v_g < v$ ? No

- Find the quality

$$v = v_f + x(v_g - v_f)$$

$$x = \frac{v - v_f}{v_g - v_f}$$

$$= \frac{0.8 - 0.001061}{0.8858 - 0.001061}$$

$$= 0.903 \quad \text{(What does this mean?)}$$

- The enthalpy

$$h = h_f + x\,h_{fg}$$

$$= 504.7 + (0.903)(2201.6)$$

$$= 2492.7\frac{kJ}{kg}$$

# Example 1.4

Determine the internal energy of refrigerant-134a at a temperature of 0°C and a quality of 60%.

***Solution:***

- From table A-11:

$$u_f = 51.63 \frac{kJ}{kg}$$

$$u_g = 230.16 \frac{kJ}{kg}$$

- The internal energy of R-134a at given condition:

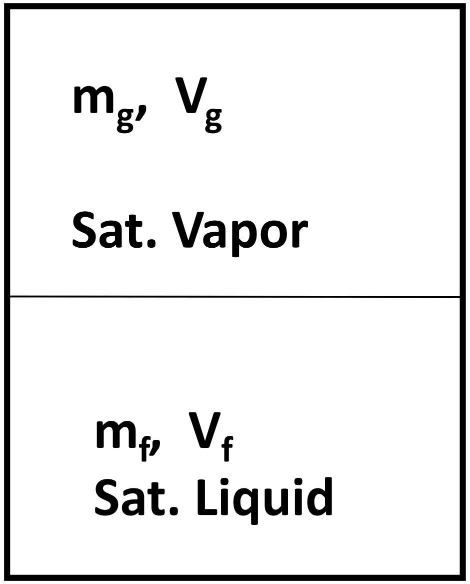
$$u = u_f + x(u_g - u_f)$$

$$= 51.63 + (0.6)(230.16 - 51.63)$$

$$= 158.75 \frac{kJ}{kg}$$

# Example 1.5

Consider the closed, rigid container of water as shown. The pressure is 700 kPa, the mass of the saturated liquid is 1.78 kg, and the mass of the saturated vapor is 0.22 kg. Heat is added to the water until the pressure increases to 8 MPa. Find the final temperature, enthalpy, and internal energy of the water.



**$m_g$, $V_g$**

**Sat. Vapor**

**$m_f$, $V_f$**

**Sat. Liquid**

**_Solution:_**

- Theoretically:

$$v_2 = v_1$$

- The quality before pressure increased (***state 1***).

$$x_1 = \frac{m_{g1}}{m_{f1} + m_{g1}}$$

$$= \frac{0.22\,kg}{(1.78 + 0.22)\,kg} = 0.11$$

- Specific volume at ***state 1***

$$v_1 = v_{f1} + x_1(v_{g1} - v_{f1})$$

$$= 0.001108 + (0.11)(0.2728 - 0.001108)$$

$$= 0.031\frac{m^3}{kg}$$

## ***State 2:***

- Information :

$$P_2 = 8\,MPa \quad v_2 = 0.031\tfrac{m^3}{kg}$$

- From table A-5:

$$v_{f,2} = 0.001384\frac{m^3}{kg}$$

$$v_{g,2} = 0.02352\frac{m^3}{kg}$$

$$v_{g2} < v_2$$

- Since that it is in superheated region, use table A-6:

$$T_2 = 361.8^o\,C$$

$$h_2 = 3024\tfrac{kJ}{kg}$$

$$u_2 = 2776\tfrac{kJ}{kg}$$

# Exercises

1. Four kg of water is placed in an enclosed volume of 1m$^3$. Heat is added until the temperature is 150°C. Find ( a ) the pressure, ( b ) the mass of vapor, and ( c ) the volume of the vapor.

2. A piston-cylinder device contains 0.1 m$^3$ of liquid water and 0.9 m$^3$ of water vapor in equilibrium at 800 kPa. Heat is transferred at constant pressure until the temperature reaches 350°C.
   (a) what is the initial temperature of the water,
   (b) determine the total mass of the water,
   (c) calculate the final volume, and
   (d) show the process on a P-v diagram with respect to saturation lines.

# Exercises

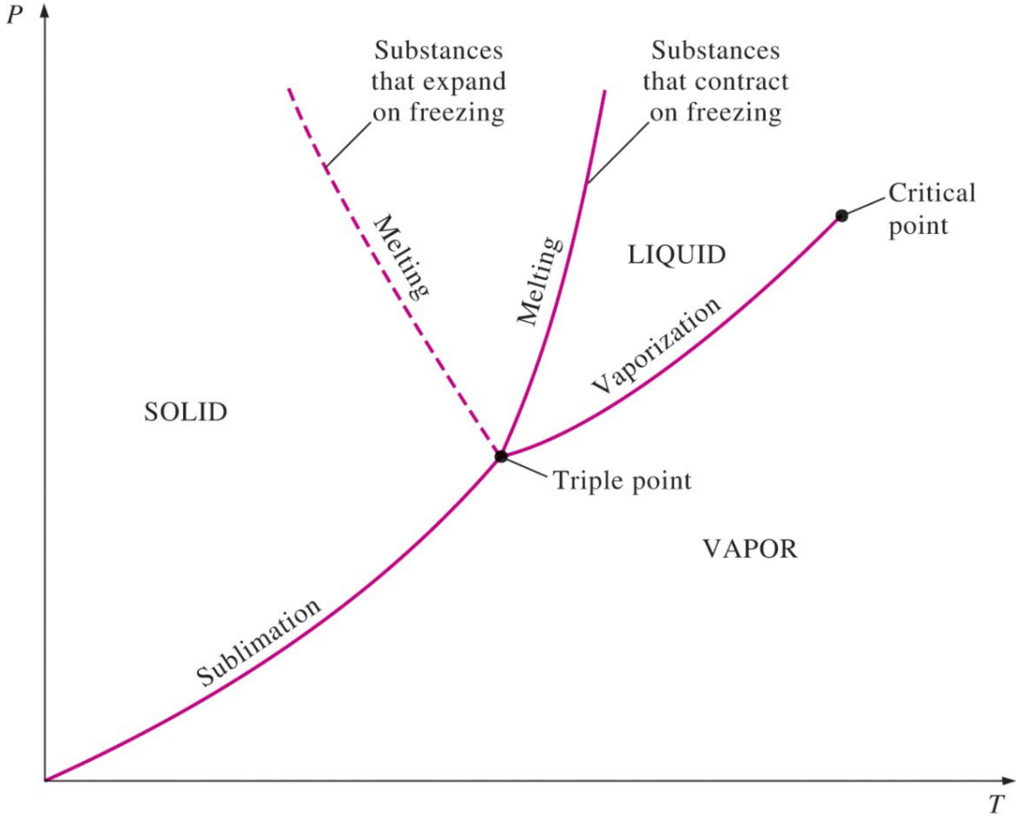
3. For a specific volume of 0.2 m$^3$/kg, find the quality of steam if the absolute pressure is (a) 40 kPa and (b) 630 kPa. What is the temperature of each case?

4. Water is contained in a rigid vessel of 5 m$^3$ at a quality of 0.8 and a pressure of 2 MPa. If the a pressure is reduced to 400 kPa by cooling the vessel, find the final mass of vapor $m_g$ and mass of liquid $m_f$.

# Important Definition

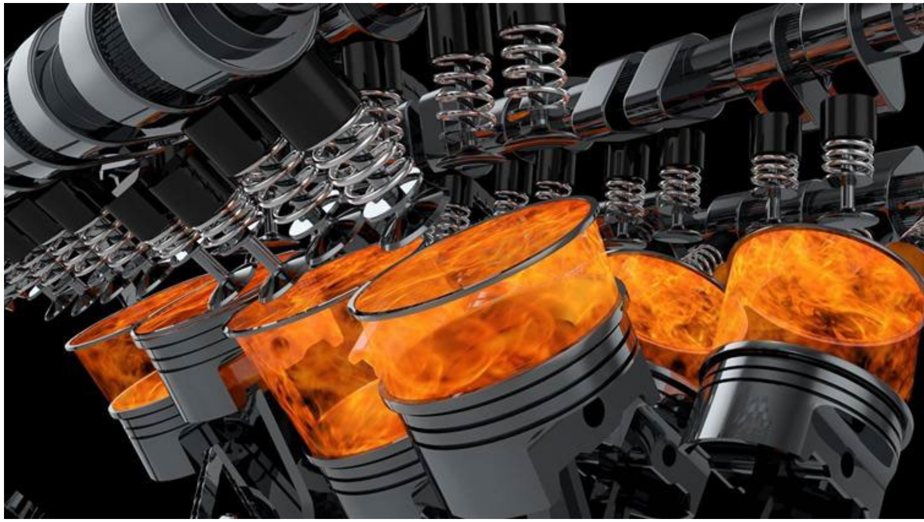
- **Critical point** - the temperature and pressure above which there is no distinction between the liquid and vapor phases.
- **Triple point** - the temperature and pressure at which all three phases can exist in equilibrium.
- **Sublimation** - change of phase from solid to vapor.
- **Vaporization** - change of phase from liquid to vapor.
- **Condensation** - change of phase from vapor to liquid.
- **Fusion or melting** - change of phase from solid to liquid.

# Important Definition



# GAS POWER CYCLE

- The gas power cycle describes the theoretical operating principles of internal combustion engines like spark-ignition engines (e.g., gasoline cars) and compression ignition engines (e.g., diesel engines).
- It analyzes the thermodynamic processes involved in converting chemical energy from fuel combustion into usable work.



# Ideal Gas Law

- *Robert Boyle* formulates a well-known law that states the pressure of a gas expanding at constant temperature varies inversely to the volume, or

$$P_1V_1 = P_2V_2 = \text{constant}$$

- As the result of experimentation, *Charles* concluded that the pressure of a gas varies directly with temperature when the volume is held constant, and the volume varies directly with temperature when the pressure is held constant, or

$$\frac{V_1}{V_2} = \frac{T_1}{T_2} \quad or \quad \frac{P_1}{P_2} = \frac{T_1}{T_2}$$

- By combining the results of Charles' and Boyle's experiments, the following relationship can be obtained

$$\frac{Pv}{T} = \text{constant}$$

- The constant in the above equation is called *the ideal gas constant* and is designated by *R*; thus the ideal gas equation becomes

$$Pv = RT \quad or \quad PV = mRT$$

- In order to make the equation applicable to all ideal gas, a universal gas constant $R_U$ is introduced

$$R = \frac{R_U}{M}$$

# Ideal Gas Law

- ☐ For example the ideal gas constant for air, $R_{\text{air}}$

$$R_{air} = \frac{(R_U)_{air}}{(M)_{air}} = \frac{8.3144}{28.96} = 0.2871 kJ/kg.K$$

- ☐ The amount of energy needed to raise the temperature of a unit of mass of a substance by one degree is called the *specific heat at constant volume* $C_v$ for a constant-volume process and the *specific heat at constant pressure* $C_p$ for a constant pressure process. They are defined as

$$C_v = \left(\frac{\partial u}{\partial T}\right)_v \quad and \quad C_P = \left(\frac{\partial h}{\partial T}\right)_P$$

# Ideal Gas Law

- ☐ Using the definition of enthalpy ($h = u + Pv$) and writing the differential of enthalpy, the relationship between the specific heats for ideal gases is

$$\boxed{h = u + Pv}$$

$$dh = du + RT$$

$$C_P dt = C_V dt + RdT$$

$$C_P = C_V + R$$

- ☐ The *specific heat ratio, k* is defined as

$$\boxed{k = \frac{C_P}{C_v}}$$

# Ideal Gas Law

- For ideal gases $u$, $h$, $C_v$, and $C_p$ are functions of temperature alone. The $\Delta u$ and $\Delta h$ of ideal gases can be expressed as

$$\Delta u = u_2 - u_1 = C_v (T_2 - T_1)$$

$$\Delta h = h_2 - h_1 = C_P (T_2 - T_1)$$

# Example 1.6

An ideal gas is contained in a closed assembly with an initial pressure and temperature of 220 kPa and 70$^0$C respectively. If the volume of the system is increased 1.5 times and the temperature drops to 15$^0$C, determine the final pressure of the gas.

***Solution:***

*given*

$\boxed{state\,1}$

$P_1 = 220\,kPa$

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

$\boxed{state\,2}$

$T_2 = 15 + 273 = 288\,K$

$V_2 = 1.5V_1$

❖ From ideal-gas law:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$P_2 = \frac{V_1}{1.5V_1}\left(\frac{288}{343}\right)\left(220\times10^3\right)$$

$$= 123.15\,kPa$$

# Example 1.7

A closed assembly contains 2 kg of air at an initial pressure and temperature of 140 kPa and 210$^0$C respectively. If the volume of the system is doubled and temperature drops to 37$^0$C, determine the final pressure of the air. Air can be modeled as an ideal gas.

***Solution:***

*given*

$$\boxed{state\,1}$$

$$P_1 = 140\,kPa$$

$$T_1 = 210 + 273K = 483\,K$$

$$\boxed{state\,2}$$

$$T_2 = 37 + 273 = 310\,K$$

$$V_2 = 2V_1$$

❖ From ideal-gas law:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$P_2 = \frac{V_1}{2V_1}\left(\frac{310}{483}\right)\left(140\times10^3\right)$$

$$= 44.93\,kPa$$

# Example 1.8

An automobile tire with a volume of 0.6 m$^3$ is inflated to a gage pressure of 200 kPa. Calculate the mass of air in the tire if the temperature is 20°C.

***Solution:***

***given***

$\boxed{state1}$

$$P = 200 + 100\ kPa$$

$$T = 20 + 273K = 293\,K$$

- From ideal-gas law:

$$m = \frac{PV}{RT}$$

$$= \frac{300 \times 10^3 \frac{N}{m^3}\left(0.6m^2\right)}{287 \frac{Nm}{kg.K}\left(293K\right)}$$

$$= 2.14\,kg$$

## Exercises

1. The pressure in an automobile tire depends on the temperature of the air in the tire. When the air temperature is 25°C, the pressure gage reads 210 kPa. If the volume of the tire is 0.025 m3, determine the pressure rise in the tire when the air temperature in the tire rises to 50°C. Also, determine the amount of air that must be bled off to restore pressure to its original value at this temperature. Assume the atmospheric pressure is 100 kPa.

   [ *26 kPa, 0.007 kg*]

2. A 1-m$^3$ tank containing air at 25°C and 500 kPa is connected through a valve to another tank containing 5 kg of air at 35°C and 200 kPa. Now the valve is opened, and the entire system is allowed to reach thermal equilibrium with the surroundings, which are at 20°C. Determine the volume of the second tank and the final equilibrium pressure of air.

   [ *2.21 m$^3$, 284.1 kPa*]

## Exercises

3. A 1 $m^3$ rigid tank has propane at 100 kPa, 300 K and connected by a valve to another tank of 0.5 $m^3$ with propane at 250 kPa, 400 K. The valve is opened and the two tanks come to a uniform state at 325 K. What is the final pressure?

   [ *139.9 kPa*]

4. A cylindrical gas tank 1 m long, inside diameter of 20 cm, is evacuated and then filled with carbon dioxide gas at 25°C. To what pressure should it be charged if there should be 1.2 kg of carbon dioxide?

   [ *2152 kPa*]

# GAS POWER CYCLE

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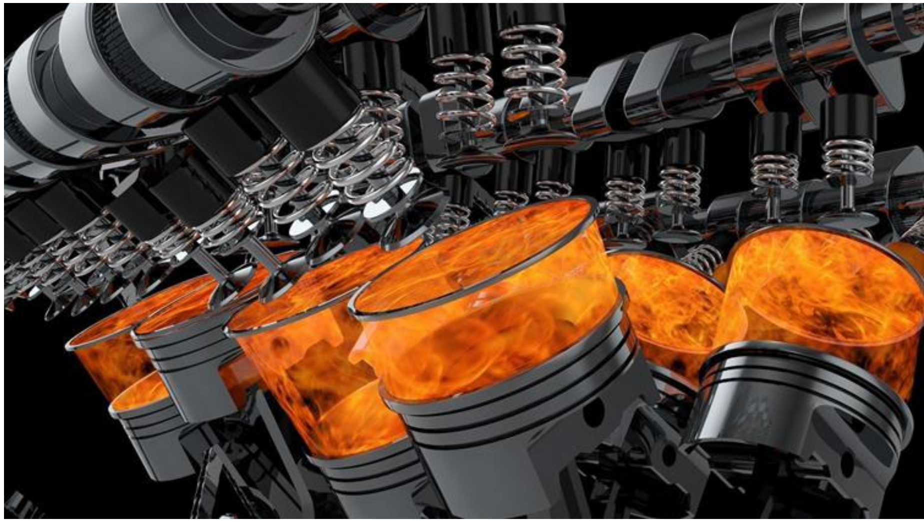
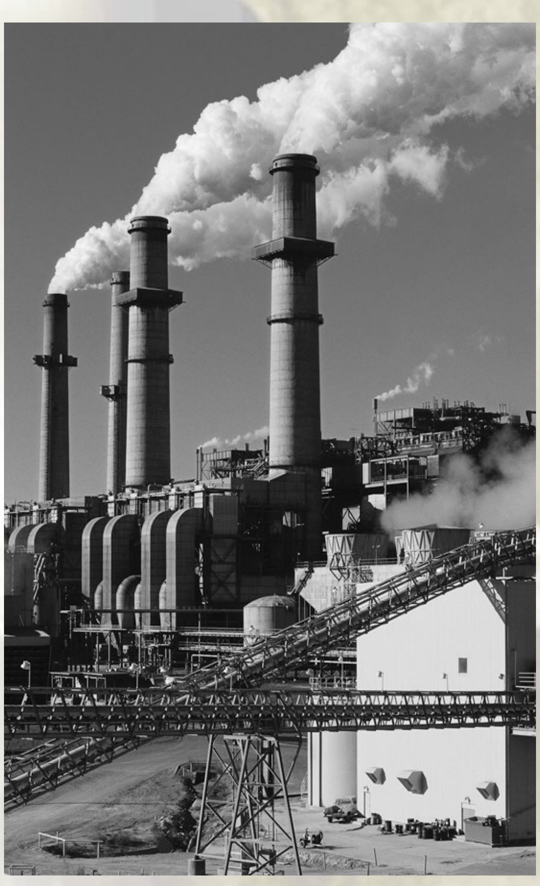


# Application Areas of Thermodynamics



# THANK YOU