• PROGRAM OF "PHYSICS"

<u>Lecturer</u>: Dr. DO Xuan Hoi

Room A1. 503

E-mail : dxhoi@hcmiu.edu.vn

PHYSICS 2
(FLUID MECHANICS AND THERMAL PHYSICS)

02 credits (30 periods)

Chapter 1 Fluid Mechanics

Chapter 2 Heat, Temperature and the Zeroth Law of Thermodynamics

Chapter 3 Heat, Work and the First Law of Thermodynamics

Chapter 4 The Kinetic Theory of Gases

Chapter 5 Entropy and the Second Law of Thermodynamics

Chapter 3
Heat, Work and the First Law of Thermodynamics

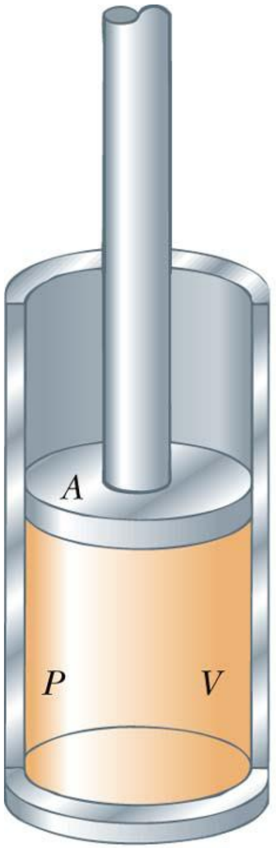
1. Work and Heat in Thermodynamic Processes
2. The First Law of Thermodynamics
3. Some Applications of The First Law of Thermodynamics
4. Energy transfer mechanisms

1. Work and Heat in Thermodynamic Processes

- **State of a system**
  - Description of the system in terms of ***state variables***
    - **Pressure**
    - **Volume**
    - **Temperature**
    - **Internal Energy**
  - A ***macroscopic state*** of an isolated system can be specified only if the system is in **internal thermal equilibrium**

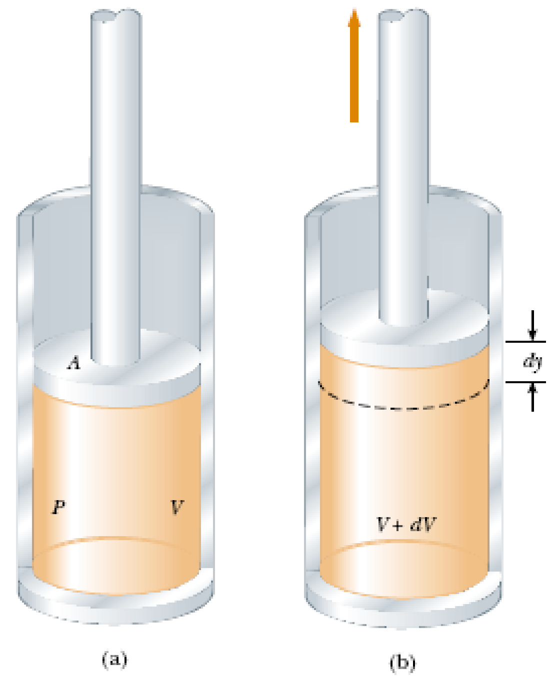
• Work

- Work is an important energy **transfer mechanism** in thermodynamic systems
- Heat is another **energy transfer mechanism**
- **Example:** gas cylinder with piston
  - The gas is contained in a cylinder with a moveable piston
  - The gas occupies a volume V and *exerts pressure* *P* on the walls of the cylinder and on the piston



• Work done by a gas

- Consider a gas contained in a cylinder fitted with a movable piston.
- At **equilibrium**, the gas occupies a volume V and exerts a uniform pressure P on the cylinder's walls and on the piston. If the piston has a cross-sectional area A, force exerted by the gas on the piston is : $F = PA$



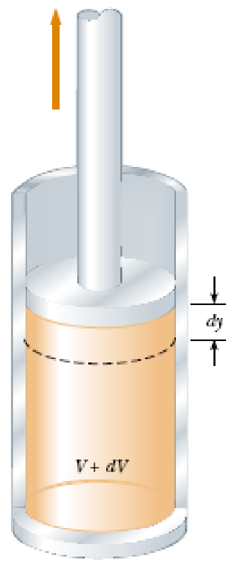
- When the gas expands quasi-statically

(slowly enough to allow the system to remain essentially in thermal equilibrium at all times)

As the piston moves up a distance dy, the work done by the gas on the piston : $dW = Fdy = PAdy = PdV$

- The work done **by the gas on the piston** :

$$dW = PdV$$



(b)

- If the gas expands : $\boldsymbol{dV > 0}$

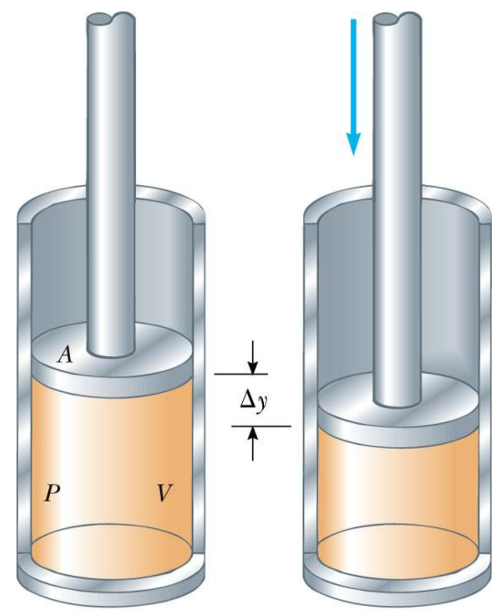
  $\rightarrow$ the work **done *by* the gas** : $\boldsymbol{dW > 0}$

If the gas were compressed : $\boldsymbol{dV < 0}$

$\rightarrow$ the work done by the gas (which can be interpreted as work **done *on* the gas**) : $\boldsymbol{dW < 0}$

When the volume remains constant

$\rightarrow$ **No work** is done on the gas



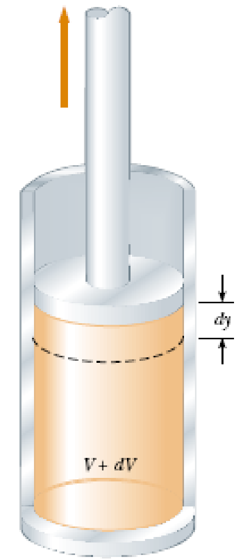
(a) (b)

- The work done **by the gas on the piston** :

$$dW = PdV$$

- If the gas expands : $\boldsymbol{dV > 0}$

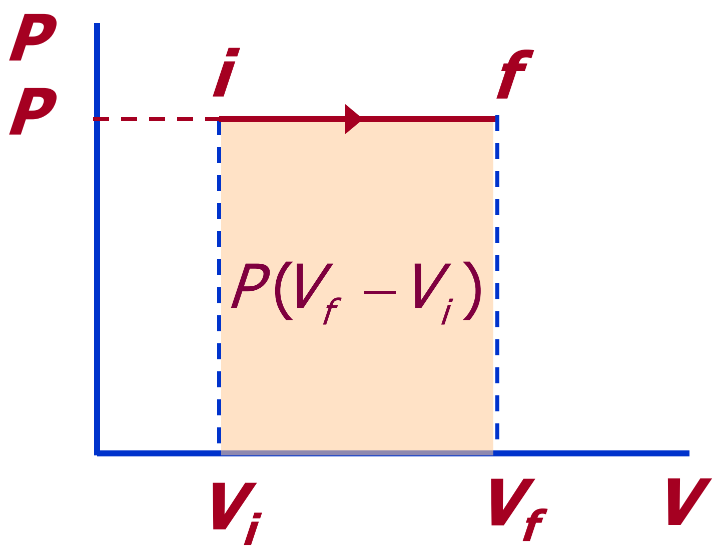
  $\rightarrow$ the work **done *by* the gas** : $\boldsymbol{dW > 0}$



(b)

- Suppose : $\boldsymbol{P}$ **= const :** ***isobaric* process**

(pronounced "eye-so-bear-ic")



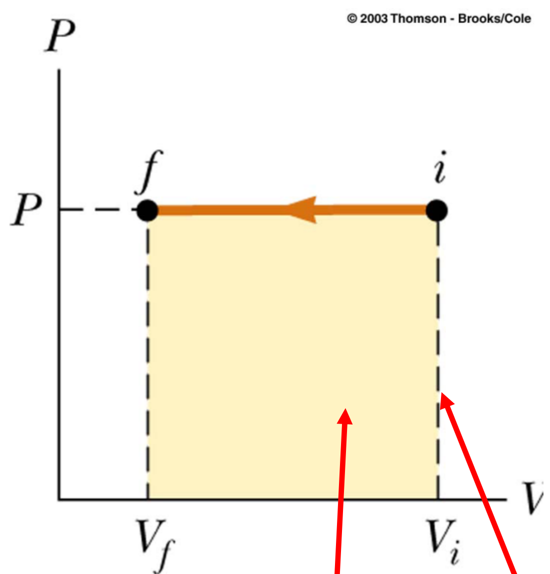
- **The work done by the gas equals the area under the *PV* curve.**

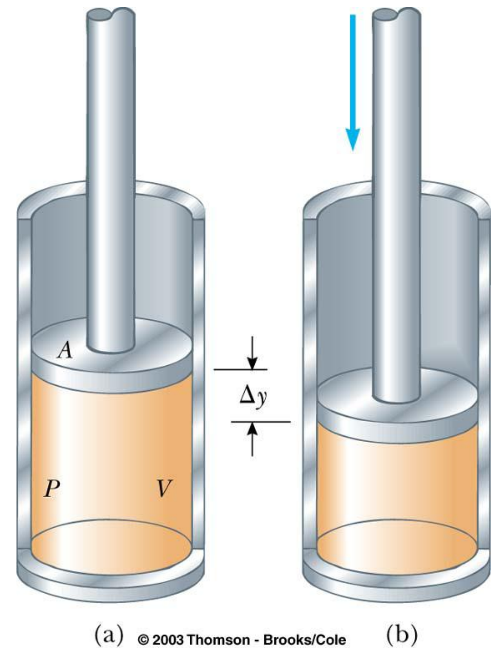
- The work done **by the gas on the piston** :

$$dW = PdV$$

If the gas were compressed : $\boldsymbol{dV < 0}$

$\rightarrow$ the work done by the gas (which can be interpreted as work **done *on* the gas**) : $\boldsymbol{dW < 0}$





W = P ΔV; W < 0

Work = Area under the curve

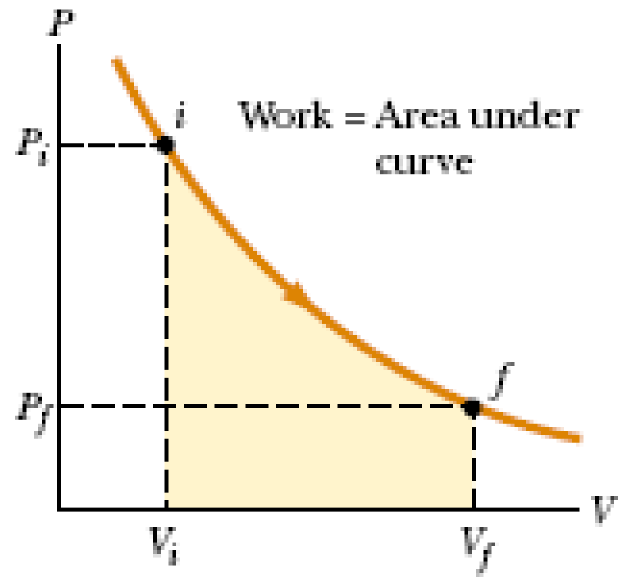
Work done on the gas

- The work done **by the gas on the piston** :

$$dW = PdV$$

- The **total work** done by the gas as its volume changes from V_i to V_f is given by the **integral**:

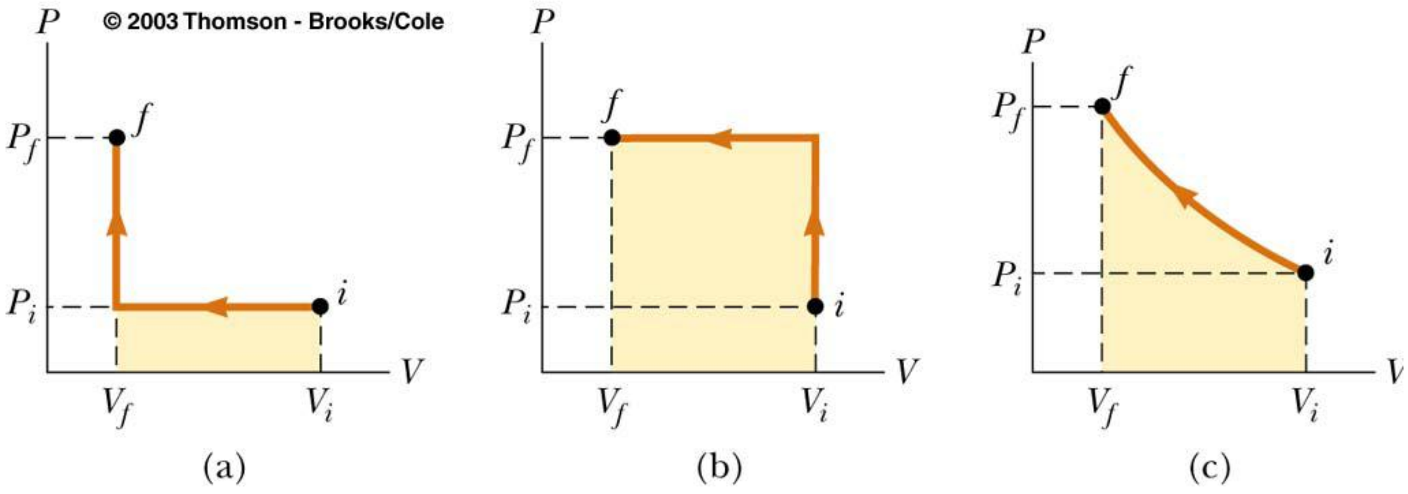
$$\boxed{W = \int_{V_i}^{V_f} PdV}$$



- The work done by a gas in the expansion from an initial state to a final state is the **area under the curve** connecting the states in a *PV* diagram

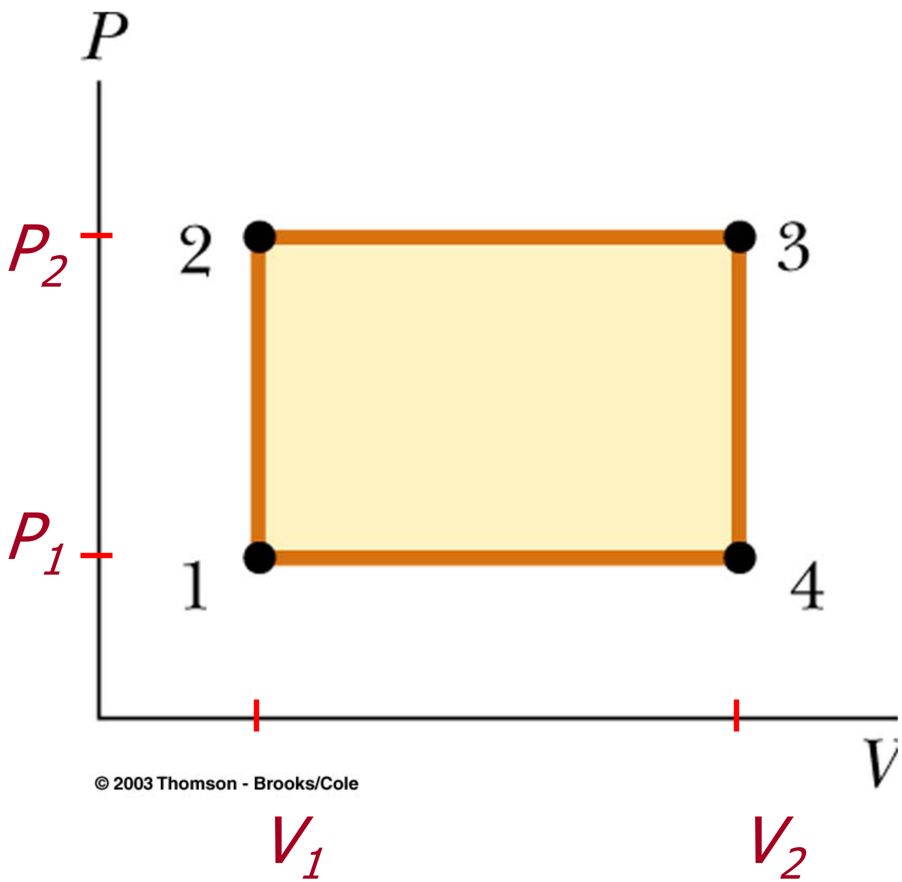
PV Diagrams

- The curve on the diagram is called the ***path*** taken between the initial and final states
- The work done depends on the particular path
  - Same initial and final states, but different amounts of work are done



Question

Find work done by the gas in this cycle.



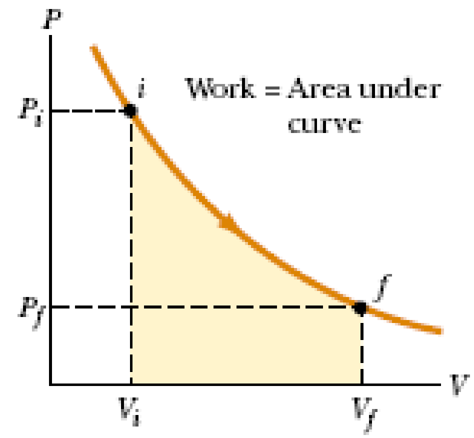
Work is equal to the area :

$$W = (p_2 - p_1)(V_2 - V_1)$$

Work done by an ideal gas at constant temperature

The **total work** done by the gas as its volume changes from

V_1 to V_f : $W = \int_{V_i}^{V_f} P dV$



Ideal gas : $PV = nRT$

$$\longrightarrow \quad W = \int_{V_i}^{V_f} \frac{nRT}{V} dV$$

Isothermal process: $T = const$

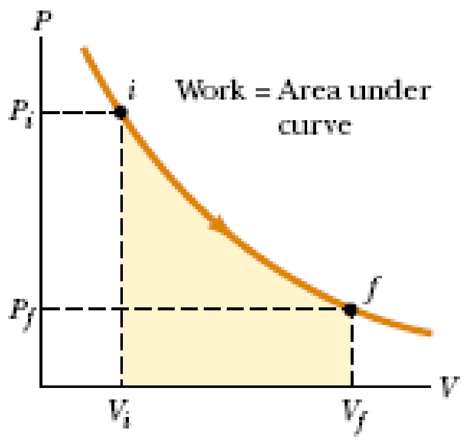
$$\longrightarrow \quad W = nRT \int_{V_i}^{V_f} \frac{dV}{V} ; \quad \boxed{W = nRT \ln \frac{V_f}{V_i}}$$

Also : $P_iV_i = P_fV_f$

$$\boxed{W = nRT \ln\frac{V_f}{V_i}}$$

$$\boxed{W = nRT \ln\frac{P_i}{P_f}}$$

$V_f > V_i$: $W > 0$



When a system expands : work is positive.

When a system is compressed, its volume decreases and it does negative work on its surroundings

Other Processes

- *Isovolumetric (or isochoric process - pronounced "eye-so-kor-ic")*
  - Volume stays constant
  - Vertical line on the PV diagram
- *Isothermal*
  - Temperature stays the same
- *Adiabatic (pronounced "ay-dee-ah-bat-ic")*
  - No heat is exchanged with the surroundings

$$Q = 0$$

Example: Calculate work done by expanding gas of 1 mole if initial pressure is 4000 Pa, initial volume is 0.2 m^3, and initial temperature is 96.2 K. Assume a process: *isobaric* expansion to 0.3 m^3, T_f = 144.3 K

Given:

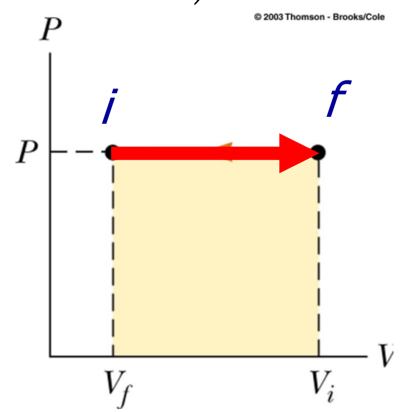
$n = 1$ mole
$T_i = 96.2\ K$
$T_f = 144.3\ K$
$V_i = 0.2\ \mathrm{m}^3$
$V_f = 0.3\ \mathrm{m}^3$
$P = const$

Find:

$W = ?$

Isobaric expansion:

$$W = P\Delta V = P\left(V_f - V_i\right) = 4000\ \mathrm{Pa}\left(0.3\mathrm{m}^3 - 0.2m^3\right)$$
$$= 400\ J$$



2. The First Law of Thermodynamics

- **What is internal energy?**

The internal energy of a system is the sum of the kinetic energies of all of *its constituent particles*, plus the sum of all the potential energies of interaction among these particles.

During a change of state of the system, the internal energy may change from an initial value U_1 to a final value U_2 . The change in internal energy : $\Delta U = U_2 - U_1$.

- Consider energy conservation in thermal processes. Must include:
  - Q
    - Heat
    - Positive if energy is transferred *to* the system
  - W
    - Work
    - Positive if done *by* the system
  - U
    - Internal energy
    - Positive if the temperature increases

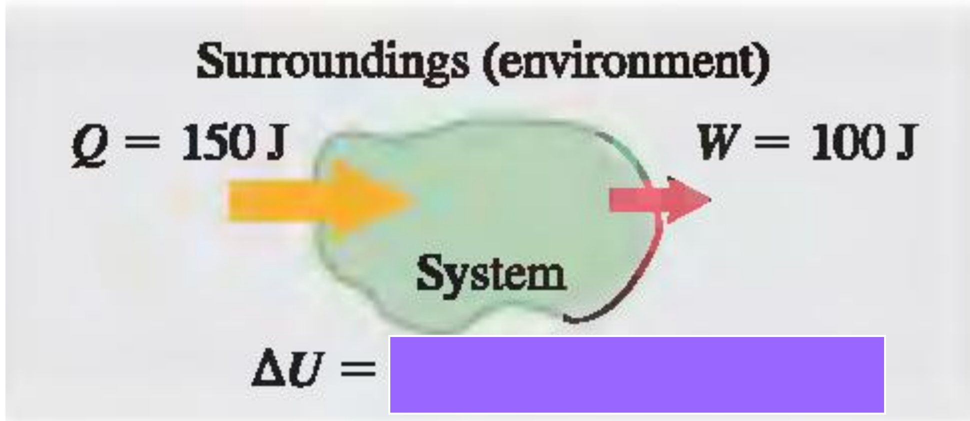
- Add a quantity of heat Q to a system and the system does no work during the process, the internal energy increases by an amount equal to Q : $\Delta U = Q$.
- When a system does work W by expanding against its surroundings and no heat is added during the process, energy leaves the system and the internal energy decreases.
- When both heat transfer and work occur, the total change in internal energy is

$$\boxed{\Delta U = Q - W}$$

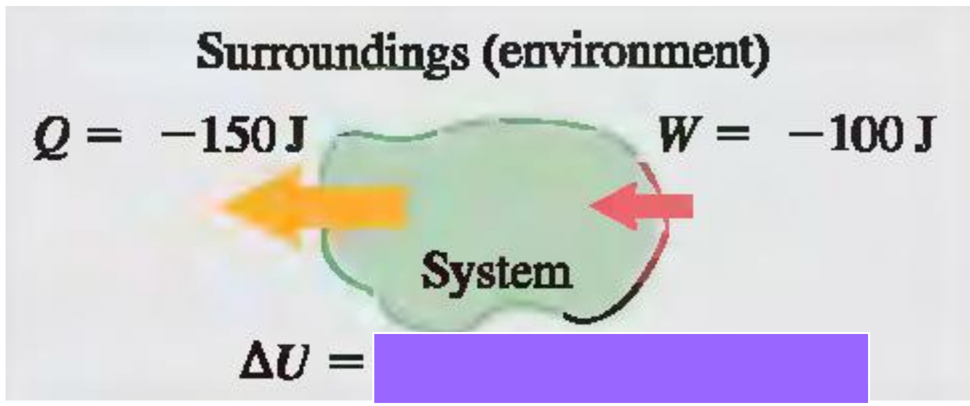
(first law of thermodynamics)

- This means that the change in internal energy of a system is equal to the sum of the energy transferred across the system boundary by heat and the energy transferred by work

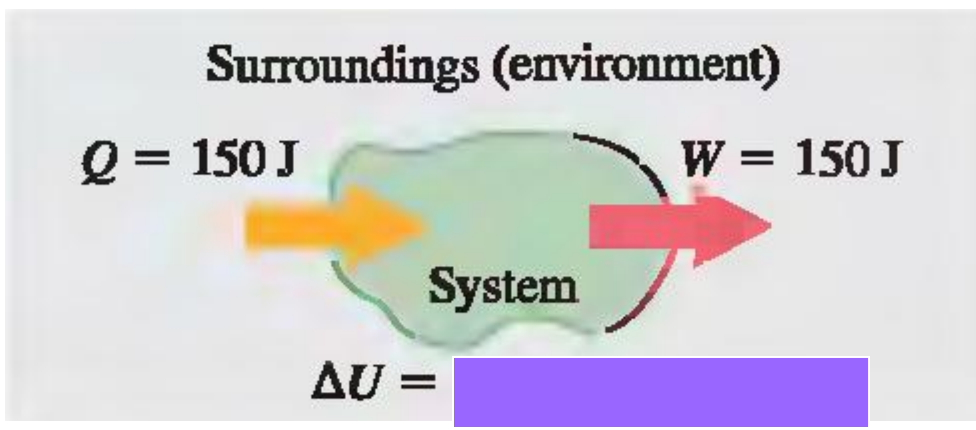
EXAMPLE :



Surroundings (environment)
$Q = 150\ \mathrm{J}$
$W = 100\ \mathrm{J}$
System
$\Delta U =$



Surroundings (environment)
$Q = -150\ \mathrm{J}$
$W = -100\ \mathrm{J}$
System
$\Delta U =$



Surroundings (environment)
$Q = 150\ \mathrm{J}$
$W = 150\ \mathrm{J}$
System
$\Delta U =$

Notes About the First Law

- The First Law is a general equation of Conservation of Energy
- There is no practical, macroscopic, distinction between the results of energy transfer by heat and by work
- Q and W are related to the properties of state for a system

Notes About the First Law

- The work W done by the system depends not only on the initial and final states, but also on the intermediate states - that is, *on the path*
- Like work, heat Q depends not only on the initial and final states but also *on the path*
- While Q and W depend on the path, $\Delta U = Q - W$ is *independent of path*. The change in internal energy of a system during any thermodynamic process depends *only on the initial and final states, not on the path* leading from one to the other.

Notes About the First Law

- When a system undergoes an *infinitesimal* change in state in which a small amount of *energy dQ* is transferred by heat and a small amount of *work dW* is done, the *internal energy* changes by a small amount :

$$\boxed{dU = dQ - dW}$$

(first law of thermodynamics for infinitesimal processes)

- Because dQ and dW are *inexact differentials*

$$\longrightarrow \quad \boxed{dU = \delta Q - \delta W}$$

$$dU = \delta Q - pdV$$

3. Some Applications of The First Law of Thermodynamics

Kinds of Thermodynamic Processes :

- **Adiabatic Process**

An adiabatic process is defined as one with **no heat transfer** into or out of a system : $Q = 0$

(We can prevent heat flow either by surrounding the system with thermally insulating material or by carrying out the process so quickly that there is not enough time for appreciable heat flow)

From the first law we find that for every adiabatic process :

$$\boxed{\Delta U = U_2 - U_1 = -W}$$

From the first law we find that for every adiabatic process :

$$\boxed{\Delta U = U_2 - U_1 = -W}$$

- When a system expands adiabatically :

$W > 0$

(the system does work on its surroundings)

$\Delta U < 0$

(the internal energy decreases)

- When a system is compressed adiabatically :

$W < 0$

(work is done on the system)

(work is done on the system by its surroundings)

$\Delta U > 0$

(the internal energy increases)

Kinds of Thermodynamic Processes :

- **Isochoric Process**

An isochoric process is a constant-volume process.

When the volume of a thermodynamic system is constant, it does no work on its surroundings : $W = 0$

From the first law :

$$\boxed{\Delta U = U_2 - U_1 = Q}$$

In an isochoric process, all the energy added as heat remains in the system as an increase in internal energy.

Example : Heating a gas in a closed constant-volume container

Kinds of Thermodynamic Processes :

- **Isobaric Process**

An isobaric process is a constant-pressure process.

In general, none of the three quantities ΔU, Q, and W is zero in an isobaric process

The work done by the gas is simply:

$$\boxed{W = P(V_2 - V_1)}$$

Kinds of Thermodynamic Processes :

- **Cyclical Processes**

A process that eventually returns a system to its initial state is called a cyclic process. For such a process, the final state is the same as the initial state

The total internal energy change must be zero :

$$\Delta U = U_2 - U_1 = 0\ ;\ U_2 = U_1$$

From the first law : $\Delta U = Q - W$

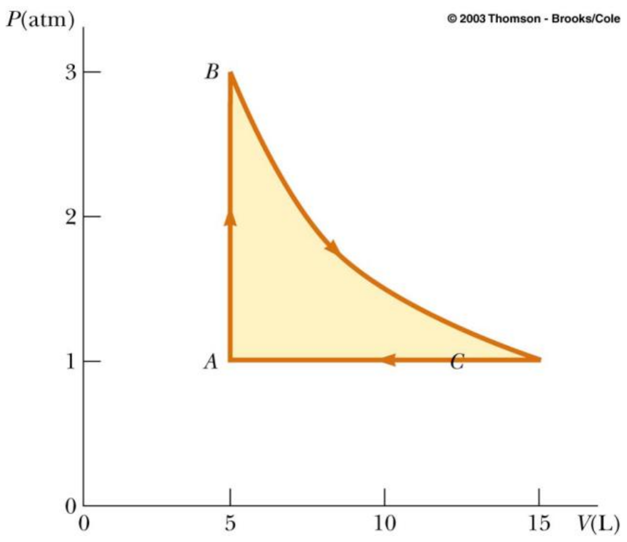
$$\longrightarrow \quad W = Q$$

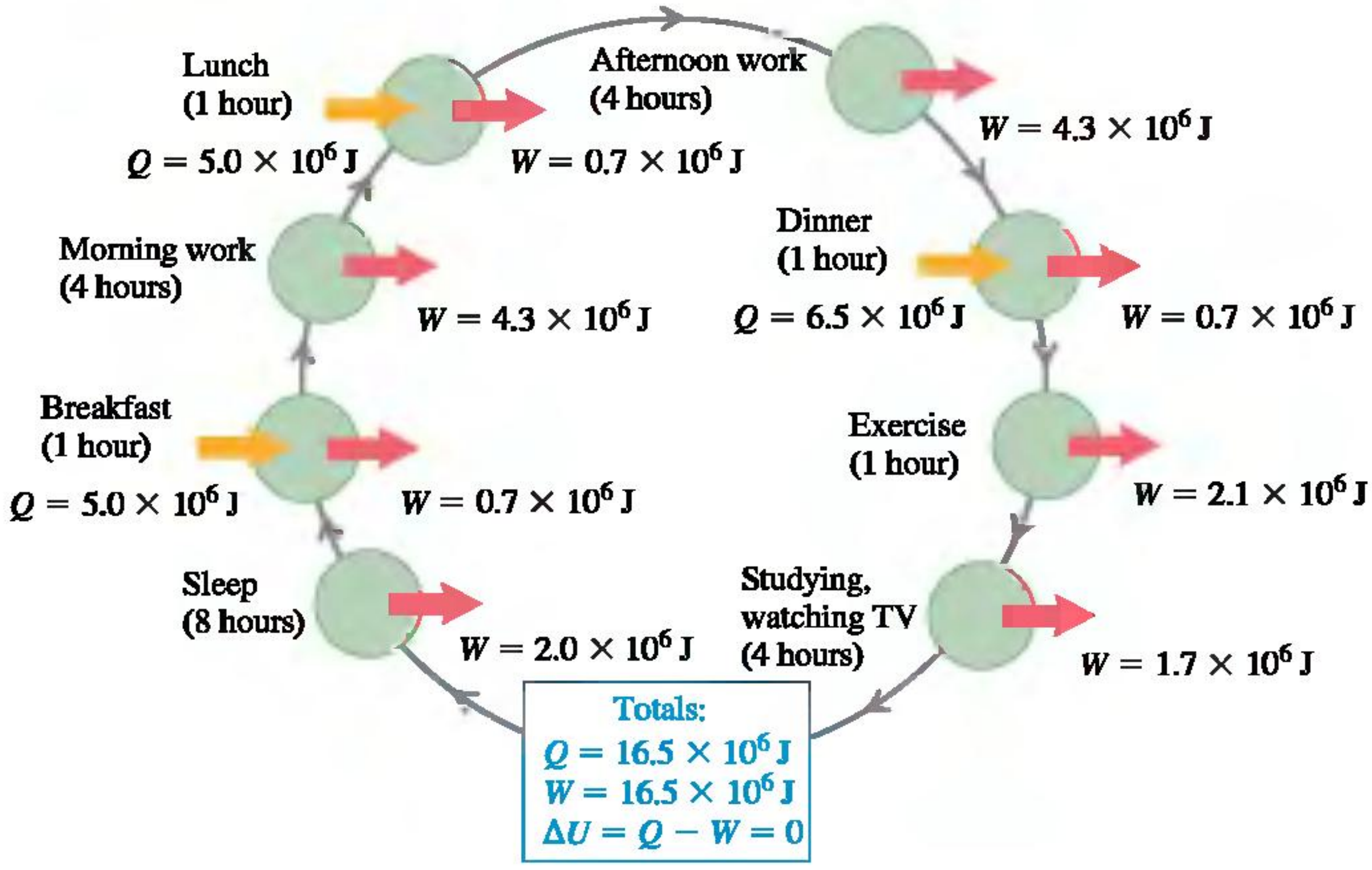
If a net quantity of work W is done by the system during this process, an equal amount of energy must have flowed into the system as heat Q

Kinds of Thermodynamic Processes :

Cyclical Process in a PV Diagram

- This is an ideal monatomic gas confined in a cylinder by a moveable piston
- A to B : isovolumetric process which increases the pressure
- B to C : isothermal expansion and lowers the pressure
- C to A : isobaric compression
- The gas returns to its original state at point A

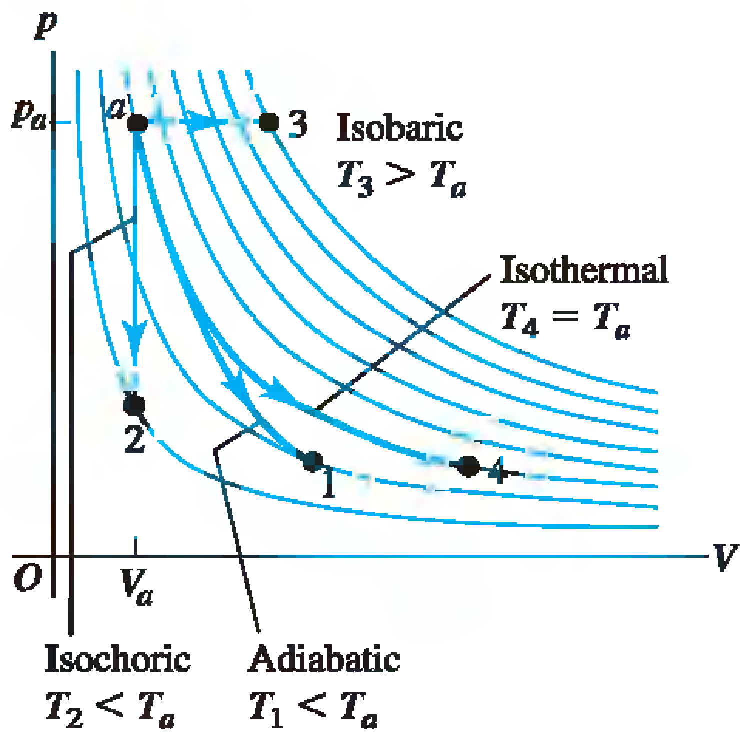




- **Cyclical Process** **Example :**

The cyclic thermodynamic process of our body (a thermodynamic system) every day

Example



Four different processes for a constant amount of an ideal gas, all starting at state *a*. For the adiabatic process, $Q = 0$; for the isochoric process, $W = 0$; and for the isothermal process, $\Delta U = 0$. The temperature increases only during the isobaric expansion.

A pV-diagram for four processes for a constant amount of an ideal gas. The path followed in an adiabatic process (a to 1) is called an adiabat. A vertical line (constant volume) is an isochor, a horizontal line (constant pressure) is an isobar, and a curve of constant temperature (shown as light blue lines) is an isotherm.

The First Law and Human Metabolism

- The First Law can be applied to living organisms
- The internal energy stored in humans goes into other forms needed by the organs and into work and heat
- The *metabolic rate* (ΔU / ΔT) is directly proportional to the rate of oxygen consumption by volume
  - Basal metabolic rate (to maintain and run organs, etc.) is about 80 W

Various Metabolic Rates

TABLE 12.1 Oxygen Consumption and Metabolic Rates for Various Activities for a 65-kg Male[a]

Activity	O_2 use rate (mL/min · kg)	Metabolic rate (kcal/h)	Metabolic rate (W)
Sleeping	3.5	70	80
Light activity (dressing, slow walking, desk work)	10	200	230
Moderate activity (walking briskly)	20	400	465
Heavy activity (basketball, (fast breast stroke)	30	600	700
Extreme activity (bicycle racing)	70	1 400	1 600

[a] Source: *A Companion to Medical Studies*, 2/e, R. Passmore, Philadelphia, F. A. Davis, 1968.

Fig. T12.1, p. 369

• **Free expansions**: These are adiabatic processes in which no transfer of heat occurs between the system and its environment and no work is done on or by the system. Thus, Q = W = 0

The first law $\rightarrow$ $\boxed{\Delta U = U_2 - U_1 = 0}$

The First Law of Thermodynamics: Four Special Cases

The Law: $\Delta E_{\text{int}} = Q - W$ (Eq. 18-26)

Process	Restriction	Consequence
Adiabatic	$Q = 0$	$\Delta E_{\text{int}} = -W$
Constant volume	$W = 0$	$\Delta E_{\text{int}} = Q$
Closed cycle	$\Delta E_{\text{int}} = 0$	$Q = W$
Free expansion	$Q = W = 0$	$\Delta E_{\text{int}} = 0$

PROBLEM 1 Suppose 1.00 g of water vaporizes isobarically at atmospheric pressure (1.013×10^5 Pa). Its volume in the liquid state is 1.00 cm^3, and its volume in the vapor state is 1671 cm^3. Find the work done in the expansion and the change in internal energy of the system.
The heat of vaporization for water 2.26×10^6 J/kg

SOLUTION

$$W = P(V_f - V_i)$$
$$= (1.013 \times 10^5\ \mathrm{Pa})(1\,671 \times 10^{-6}\ \mathrm{m^3} - 1.00 \times 10^{-6}\ \mathrm{m^3})$$
$$= \boxed{169\ \mathrm{J}}$$

$$Q = mL_v = (1.00 \times 10^{-3}\ \mathrm{kg})(2.26 \times 10^6\ \mathrm{J/kg}) = 2\,260\ \mathrm{J}$$

$$\Delta E_{\mathrm{int}} = Q - W = 2\,260\ \mathrm{J} - 169\ \mathrm{J} = \boxed{2.09\ \mathrm{kJ}}$$

PROBLEM 2 A 1.0-kg bar of copper is heated at atmospheric pressure. If its temperature increases from 20°C to 50°C, **(a)** what is the work done by the copper on the surrounding atmosphere?
The density of copper is 8.92×10^3 kg/m^3

SOLUTION

$$\Delta V = \beta V_i \Delta T$$

$$= [5.1 \times 10^{-5} (^\circ\mathrm{C})^{-1}](50^\circ\mathrm{C} - 20^\circ\mathrm{C}) V_i = 1.5 \times 10^{-3}\ V_i$$

$$\Delta V = (1.5 \times 10^{-3}) \left(\frac{1.0\ \mathrm{kg}}{8.92 \times 10^3\ \mathrm{kg/m^3}} \right) = 1.7 \times 10^{-7}\ \mathrm{m^3}$$

$$W = P\Delta V = (1.013 \times 10^5\ \mathrm{N/m^2})(1.7 \times 10^{-7}\ \mathrm{m^3})$$

$$= \boxed{1.7 \times 10^{-2}\ \mathrm{J}}$$

PROBLEM 2 A 1.0-kg bar of copper is heated at atmospheric pressure. If its temperature increases from 20°C to 50°C,

(b) What quantity of energy is transferred to the copper by heat?

The specific heat of copper is 387 J/kg^{0}C

SOLUTION

$$Q = mc\Delta T = (1.0 \text{ kg})(387 \text{ J/kg}\cdot{}^\circ\text{C})(30^\circ\text{C}) = \boxed{1.2 \times 10^4 \text{ J}}$$

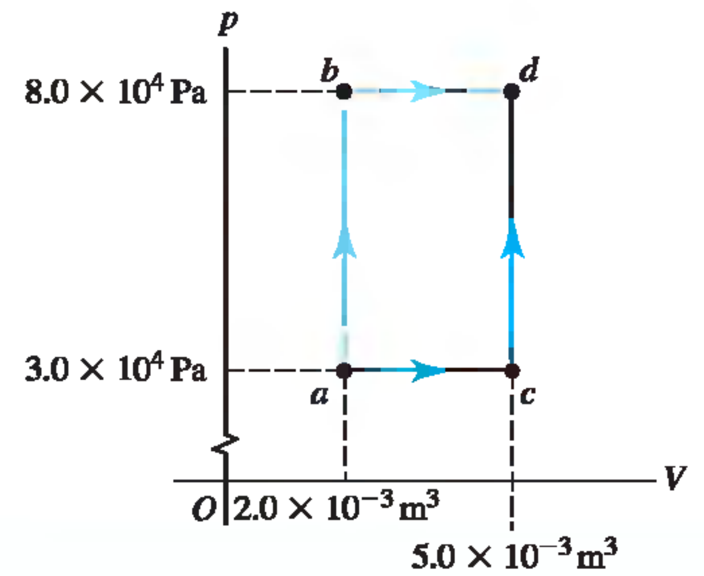
PROBLEM 2 A 1.0-kg bar of copper is heated at atmospheric pressure. If its temperature increases from 20°C to 50°C,
(c) What is the increase in internal energy of the copper?

SOLUTION

$$\Delta E_{\text{int}} = Q - W = 1.2 \times 10^{4}\,\text{J} - 1.7 \times 10^{-2}\,\text{J} = \boxed{1.2 \times 10^{4}\,\text{J}}$$

PROBLEM 3 A series of thermodynamic processes is shown in the pV-diagram of Fig. 1. In process ab, 150 J of heat is added to the system, and in process bd, 600 J of heat is added. Find **(a)** the internal energy change in process ab

SOLUTION

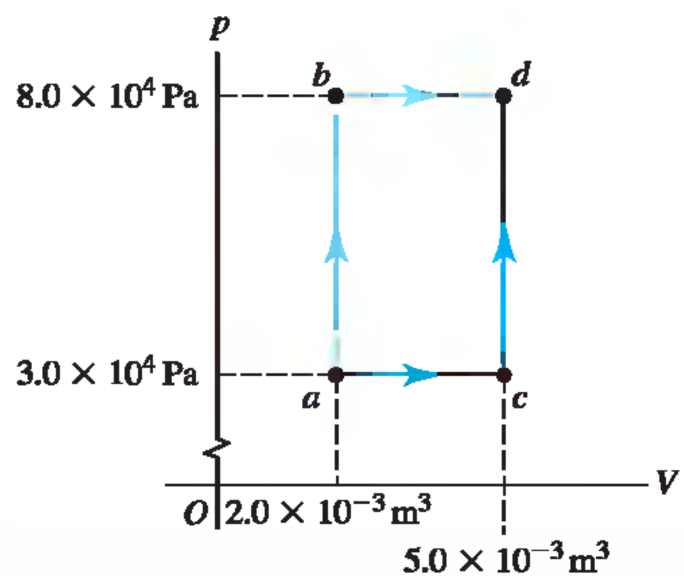


(a) No volume change occurs during process *ab*, so $W_{ab} = 0$ and $\Delta U_{ab} = Q_{ab} = 150$ J.

PROBLEM 3 A series of thermodynamic processes is shown in the pV-diagram of Fig. 1. In process ab, 150 J of heat is added to the system, and in process bd, 600 J of heat is added. Find
(a) the internal energy change in process ab;
(b) the internal energy change in process abd (shown in light blue)

SOLUTION

$$W_{bd} = p(V_2 - V_1)$$
$$= (8.0 \times 10^4\ \text{Pa})(5.0 \times 10^{-3}\ \text{m}^3 - 2.0 \times 10^{-3}\ \text{m}^3)$$
$$= 240\ \text{J}$$



The total work for process *abd* is

$$W_{abd} = W_{ab} + W_{bd} = 0 + 240\ \text{J} = 240\ \text{J}$$

and the total heat is

$$Q_{abd} = Q_{ab} + Q_{bd} = 150\ \text{J} + 600\ \text{J} = 750\ \text{J}$$

$$\Delta U_{abd} = Q_{abd} - W_{abd} = 750\ \text{J} - 240\ \text{J} = 510\ \text{J}$$

PROBLEM 3 A series of thermodynamic processes is shown in the pV-diagram of Fig. 1. In process ab, 150 J of heat is added to the system, and in process bd, 600 J of heat is added. Find
(a) the internal energy change in process ab;
(b) the internal energy change in process abd (shown in light blue); and
(c) the total heat added in process acd (shown in dark blue).

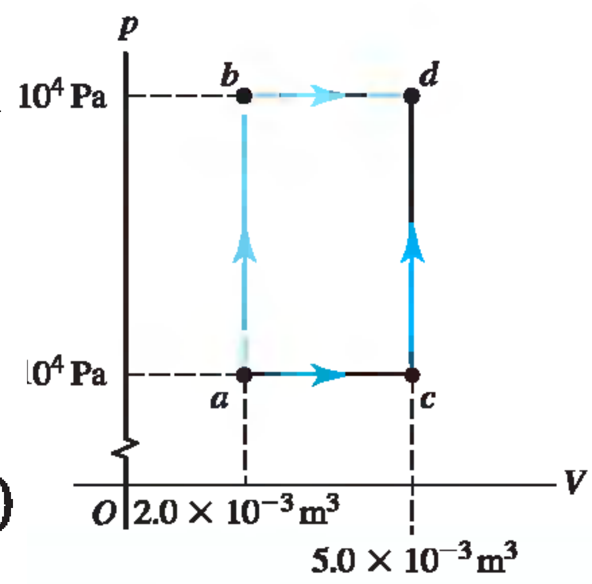
SOLUTION

(c) Because ΔU is independent of path, the internal energy change is the same for path *acd* as for path *abd*; that is,

$$\Delta U_{acd} = \Delta U_{abd} = 510\ \mathrm{J}$$

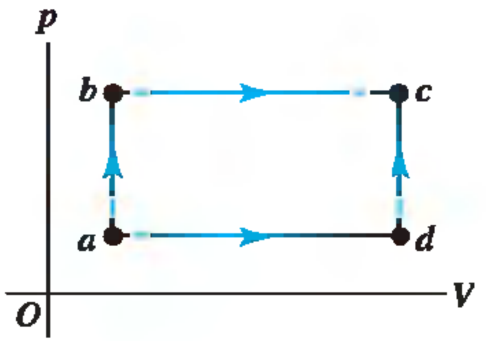
The total work for the path *acd* is

$$\begin{aligned} W_{acd} &= W_{ac} + W_{cd} = p(V_2 - V_1) + 0 \\ &= (3.0 \times 10^4\ \mathrm{Pa})(5.0 \times 10^{-3}\ \mathrm{m}^3 - 2.0 \times 10^{-3}\ \mathrm{m}^3) \\ &= 90\ \mathrm{J} \end{aligned}$$



$$Q_{acd} = \Delta U_{acd} + W_{acd} = 510\ \mathrm{J} + 90\ \mathrm{J} = 600\ \mathrm{J}$$

PROBLEM 4 A thermodynamic system is taken from state a to state c in Fig. 1 along either path abc or path adc. Along path abc, the work W done by the system is 450 J. Along path adc, W is 120 J. The internal energies of each of the four states shown in the figure are U_a = 150 J, U_b = 240 J, U_c = 680 J, and U_d = 330 J. Calculate the heat flow Q for each of the four processes ab, bc, ad, and de. In each process, does the system absorb or liberate heat?



SOLUTION

For each process, $Q = \Delta U + W$. No work is done in the processes ab and dc, and so $W_{bc} = W_{abc} = 450$ J and $W_{ad} = W_{adc} = 120$ J.

for ab, $Q = 90$ J. For bc, $Q = 440\text{ J} + 450\text{ J} = 890$ J.

ad, $Q = 180\text{ J} + 120\text{ J} = 300$ J. For dc, $Q = 350$ J.

Heat is absorbed in each process.

PROBLEM 5 A gas in a cylinder is held at a constant pressure of 2.30×10^5 Pa and is cooled and compressed from 1.70 m^3 to 1.20 m^3 . The internal energy of the gas decreases by 1.40×10^5 J.

(a) Find the work done by the gas.

(b) Find the absolute value of the heat flow into or out of the gas, and state the direction of the heat flow.

SOLUTION

$W = \int_{V_1}^{V_2} p\, dV = p(V_2 - V_1)$ for this constant pressure process.

$$W = (2.3 \times 10^5 \text{ Pa})(1.20 \text{ m}^3 - 1.70 \text{ m}^3) = -1.15 \times 10^5 \text{ J}$$

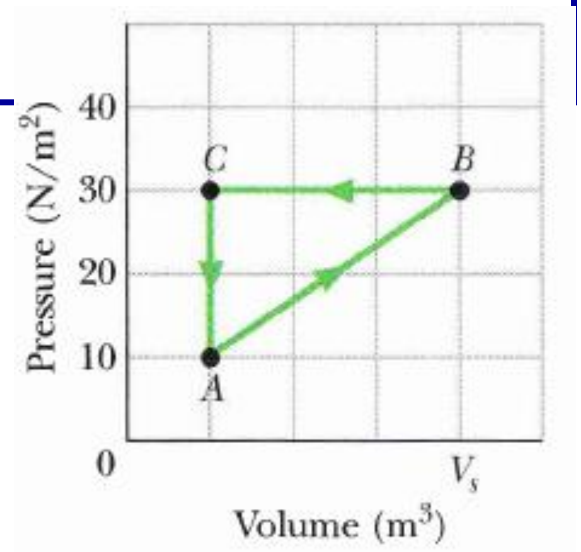
(The volume decreases in the process, so W is negative.)

(b) $\Delta U = Q - W$

$$Q = \Delta U + W = -1.40 \times 10^5 \text{ J} + (-1.15 \times 10^5 \text{ J}) = -2.55 \times 10^5 \text{ J}$$

Q negative means heat flows out of the gas.

PROBLEM 6 A gas within a closed chamber undergoes the cycle shown in the p-V diagram of Fig. 1.The horizontal scale is set by $V_S = 4.0\ m^3$. Calculate the net energy added to the system as heat during one complete cycle.



SOLUTION

Cycle: $\Delta U_{ABCA} = W - Q = 0;\ Q = W$

$$W = W_{AB} + W_{BC} + W_{CA}$$

$$W_{AB} = \int_{V_A}^{V_B} P dV$$

$$V_A = 1\ ; P_A = 10;\ \ V_B = 4\ ; P_B = 30 \longrightarrow P = \frac{20}{3}V + \frac{10}{3}$$

$$W_{AB} = \int_1^4 \left(\frac{20}{3}V + \frac{10}{3}\right) dV = 60\ J$$

$$W_{BC} = P_B(V_B - V_C) = 30(4-1) = -90\ J$$

$$W_{CA} = 0 \longrightarrow W = -30\ J; Q = -30\ J$$

4. Energy transfer mechanisms

Methods of Heat Transfer

- Need to know the rate at which energy is transferred
- Need to know the mechanisms responsible for the transfer
- Methods include
  - Conduction
  - Convection
  - Radiation

4.1 Conduction

- The transfer can be viewed on an atomic scale
  - It is an exchange of energy between microscopic particles by collisions
  - Less energetic particles gain energy during collisions with more energetic particles
- Rate of conduction depends upon the characteristics of the substance

Conduction example

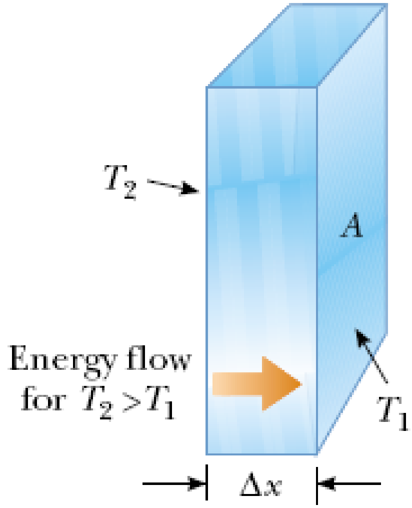
- The molecules vibrate about their equilibrium positions
- Particles near the flame vibrate with larger amplitudes
- These collide with adjacent molecules and transfer some energy
- Eventually, the energy travels entirely through the rod

Conduction can occur only if there is a difference in temperature between two parts of the conducting medium

Law of thermal conduction

Consider a slab of material of thickness Δx and cross-sectional area A. One face of the slab is at a temperature T_1, and the other face is at a temperature T_2.

- The slab allows energy to transfer from the region of higher temperature to the region of lower temperature



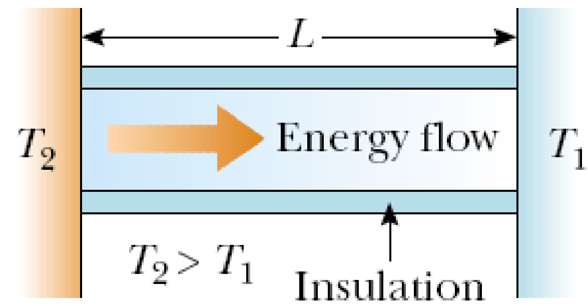
$$P = \frac{Q}{t} = kA\left|\frac{T_2 - T_1}{\Delta x}\right| = kA\left|\frac{dT}{dx}\right|$$

Heat flow

temperature gradient
(the variation of temperature with position)

- P is in Watts when Q is in Joules and t is in seconds
- k is the *thermal conductivity* of the material
  - Good conductors have high k values and good insulators have low k values

Suppose that a long, uniform rod of length L is thermally insulated so that energy cannot escape by heat from its surface except at the ends.
One end is in thermal contact with an energy reservoir at temperature T_1 , and the other end is in thermal contact with a reservoir at temperature $T_2 > T_1$



$$\left|\frac{dT}{dx}\right| = \frac{T_2 - T_1}{L}$$

The rate of energy transfer by conduction through the rod:

$$\mathcal{P} = kA\,\frac{(T_2 - T_1)}{L}$$

For a compound slab containing several materials of thicknesses L_1 , L_2, . . . and thermal conductivities k_1 , k_2, . . .

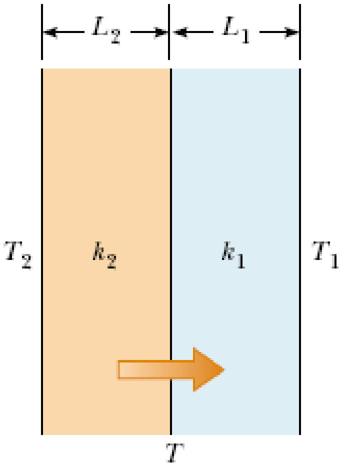
$$\mathcal{P} = \frac{A(T_2 - T_1)}{\sum_i (L_i/k_i)} \qquad \mathcal{P} = \frac{A(T_2 - T_1)}{\sum_i R_i}$$

(Home Insulation)

TABLE 20.3 Thermal Conductivities

Substance	Thermal Conductivity (W/m · °C)
Metals (at 25°C)	
Aluminum	238
Copper	397
Gold	314
Iron	79.5
Lead	34.7
Silver	427
Nonmetals (approximate values)	
Asbestos	0.08
Concrete	0.8
Diamond	2 300
Glass	0.8
Ice	2
Rubber	0.2
Water	0.6
Wood	0.08
Gases (at 20°C)	
Air	0.023 4
Helium	0.138
Hydrogen	0.172
Nitrogen	0.023 4
Oxygen	0.023 8

PROBLEM 7 Two slabs of thickness L_1 and L_2 and thermal conductivities k_1 and k_2 are in thermal contact with each other, as shown in figure. The temperatures of their outer surfaces are T_1 and T_2, respectively, and $T_2 > T_1$. Determine the temperature T at the interface and the rate of energy transfer by conduction through the slabs in the steady-state condition.



SOLUTION

The rate at which energy is transferred through slab 1:

$$(1) \qquad \mathcal{P}_1 = \frac{k_1 A(T - T_1)}{L_1}$$

The rate at which energy is transferred through slab 2:

$$(2) \qquad \mathcal{P}_2 = \frac{k_2 A(T_2 - T)}{L_2}$$

When a steady state is reached, these two rates must be equal:

$$\frac{k_1 A(T - T_1)}{L_1} = \frac{k_2 A(T_2 - T)}{L_2} \longrightarrow T = \frac{k_1 L_2 T_1 + k_2 L_1 T_2}{k_1 L_2 + k_2 L_1} \qquad \mathcal{P} = \frac{A(T_2 - T_1)}{(L_1/k_1) + (L_2/k_2)}$$

PROBLEM 8 A Styrofoam box used to keep drinks cold at a picnic has total wall area (including the lid) of 0.80 m² and wall thickness 2.0 cm. It is filled with ice and water at 0°C. What is the rate of heat flow into the box if the temperature of the outside wall is 3O°C? How much ice melts in one day?

SOLUTION

The heat current (rate of heat flow):

$$H = kA\frac{T_H - T_C}{L} = (0.010\,\mathrm{W/m\cdot K})(0.80\,\mathrm{m^2})\frac{30°\mathrm{C} - 0°\mathrm{C}}{0.020\,\mathrm{m}}$$

$$= 12\,\mathrm{W} = 12\,\mathrm{J/s}$$

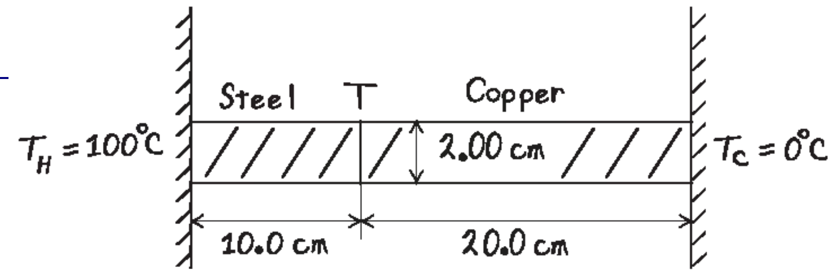
The total heat flow Q in one day (86,400 s):

$$Q = Ht = (12\,\mathrm{J/s})(86{,}400\,\mathrm{s}) = 1.04 \times 10^6\,\mathrm{J}$$

The heat of fusion of ice is 3.34×10^5 J/kg, so the quantity of ice melted by this quantity of heat:

$$m = \frac{Q}{L_f} = \frac{1.04 \times 10^6\,\mathrm{J}}{3.34 \times 10^5\,\mathrm{J/kg}} = 3.1\,\mathrm{kg}$$

PROBLEM 9 A steel bar 10.0 cm long is welded end to end to a copper bar 20.0 cm long. Both bars are insulated perfectly on their sides. Each bar has a square cross section, 2.00 cm on a side. The free end of the steel bar is maintained at 100°C and the free end of the copper bar is maintained at 0°C. Find the temperature at the junction of the two bars and the total rate of heat flow.



SOLUTION

$$H_{steel} = \frac{k_{steel} A (100°C - T)}{L_{steel}} = H_{copper} = \frac{k_{copper} A (T - 0°C)}{L_{copper}}$$

$$\frac{(50.2\ W/m \cdot K)(100°C - T)}{0.100\ m} = \frac{(385\ W/m \cdot K)\ (T - 0°C)}{0.200\ m} \longrightarrow T = 20.7°C$$

$$H_{steel} = \frac{(50.2\ W/m \cdot K)(0.0200\ m)^2(100°C - 20.7°C)}{0.100\ m}$$

$$= 15.9\ W$$

$$H_{copper} = \frac{(385\ W/m \cdot K)(0.0200\ m)^2(20.7°C)}{0.200\ m} = 15.9\ W$$

4.2 Convection

- Energy transferred by the movement of a substance
  - When the movement results from differences in density, it is called *natural conduction*
  - When the movement is forced by a fan or a pump, it is called *forced convection*

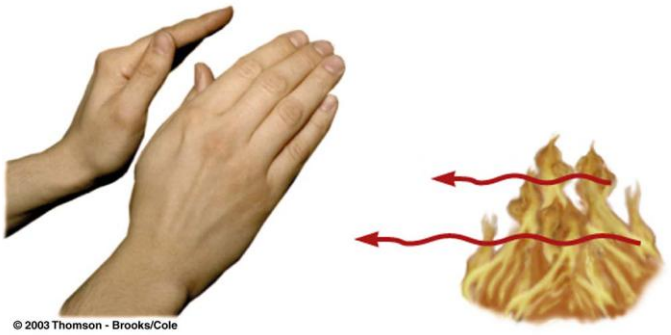
Convection example

- Air directly above the flame is warmed and expands
- The density of the air decreases, and it rises
- The mass of air warms the hand as it moves by
- Applications:
  - Radiators
  - Cooling automobile engines

4.3 Radiation

- Radiation does not require physical contact
- All objects radiate energy continuously in the form of electromagnetic waves due to thermal vibrations of the molecules
- Rate of radiation is given by *Stefan's Law*

Radiation example



- The electromagnetic waves carry the energy from the fire to the hands
- No physical contact is necessary