Thermal & Statistical Physics

PHYS 343

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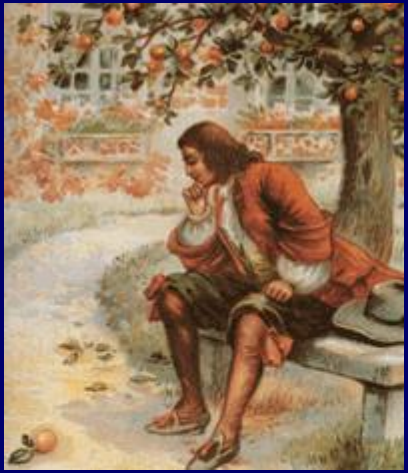
LECTURE 3



Work and Heat

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Changes in Thermal Systems

Change where system is always in thermal equilibrium:

reversible process

Change where system is not always in thermal equilibrium:

irreversible process

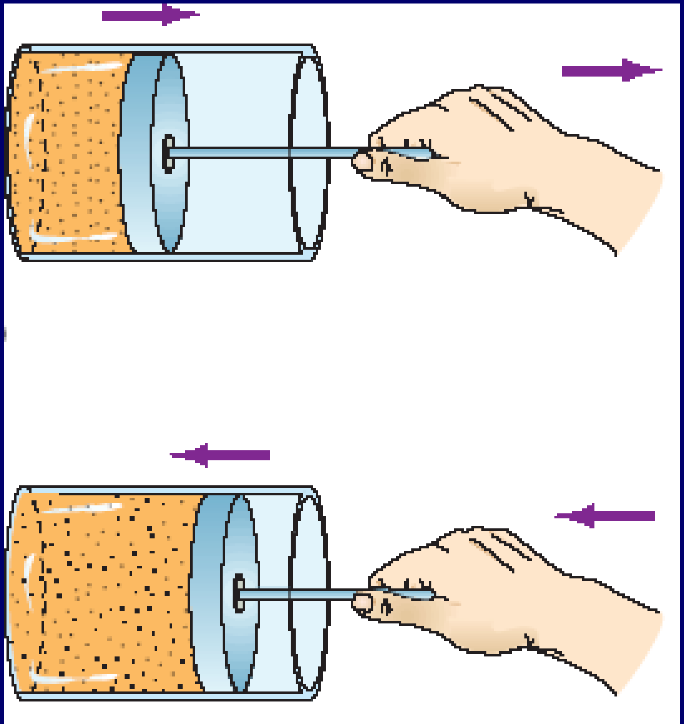
Examples of irreversible processes:

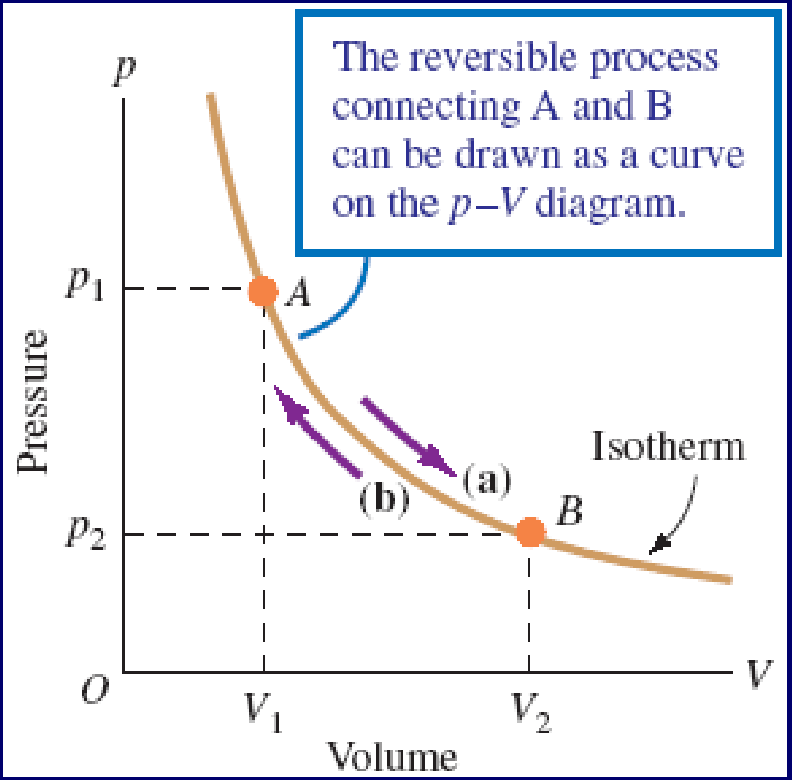
- **Free expansion**
- **melting of ice in warmer liquid**
- **frictional heating**

Changes in Thermal Systems

Example of a Reversible Process:

Cylinder must be pulled or pushed slowly enough that the system remains in thermal equilibrium





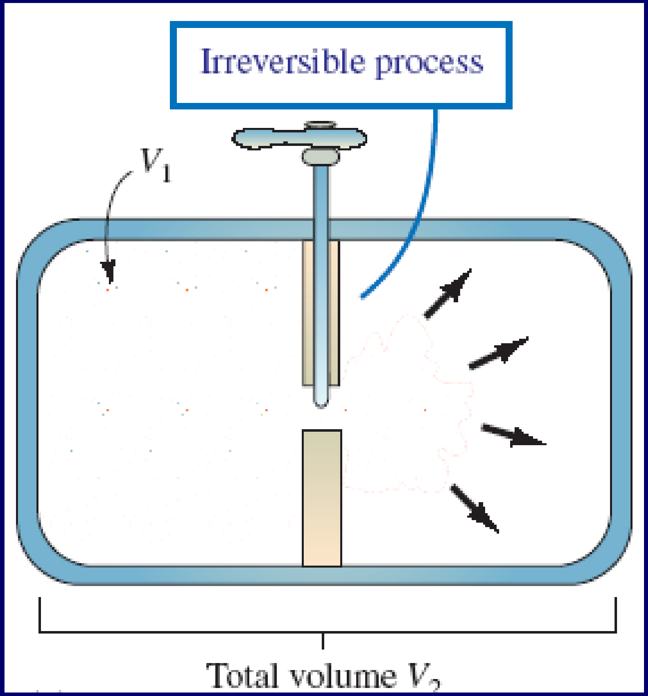
The reversible process connecting A and B can be drawn as a curve on the p–V diagram.

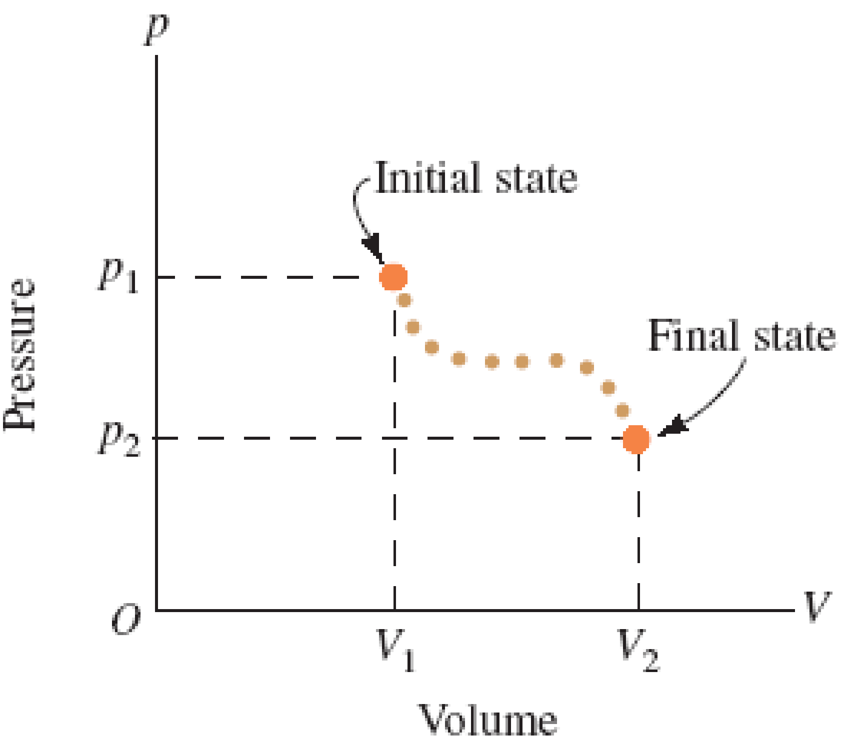
Changes in Thermal Systems

Example of an Irreversible Process:

The gas expands freely when

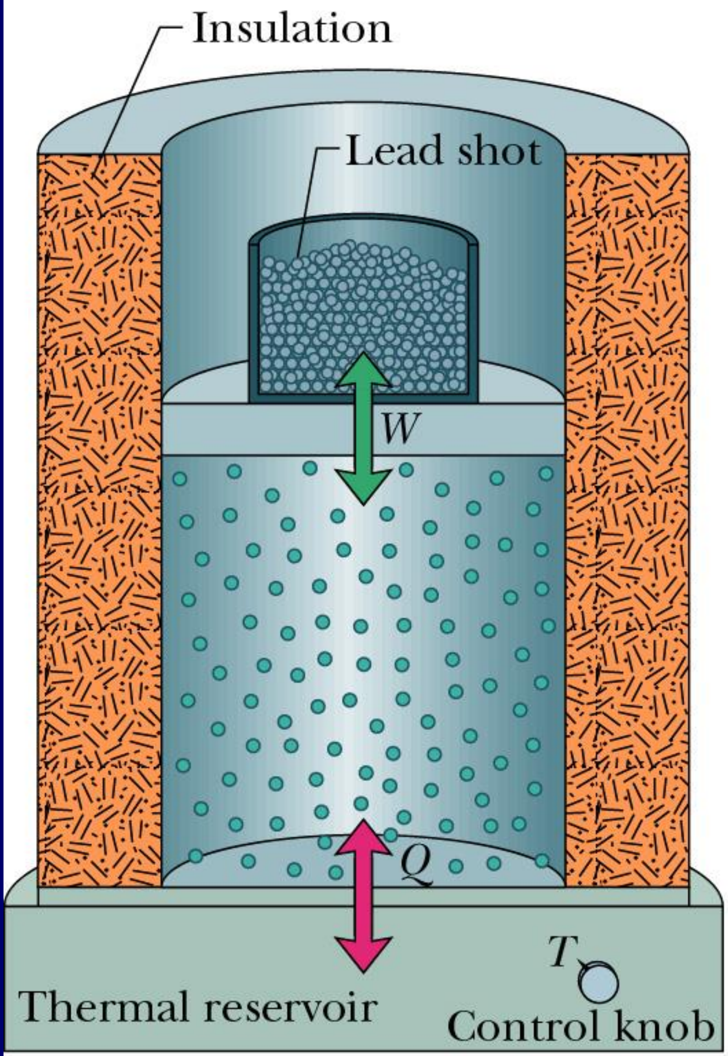
the valve is opened.





Work and Heat

$$dW = F.ds = pA.ds = pdV$$



- Consider a system consisting of a gas and a piston in the figure.
- Lead shot rest on the piston and is part of the environment.
- The bottom of the cylinder rest on a thermal reservoir that we can use to control the temperature with a knob.
- The system is insulated from everything else.

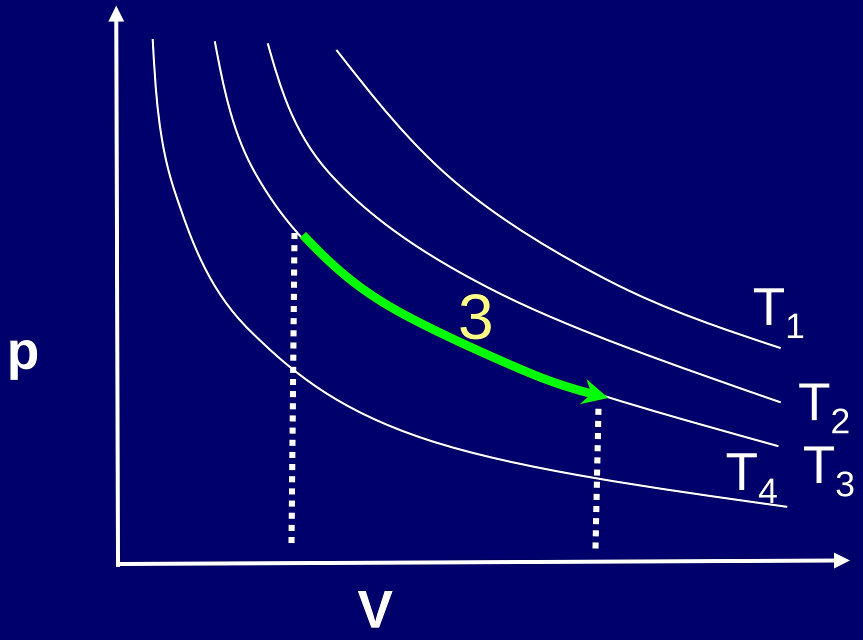
Isothermal processes

- Work done when PV = nRT = constant → P = nRT / V

$$W = -\int_{\text{initial}}^{\text{final}} p\,dV = -(\text{area under curve})$$

$$W = -\int_{V_i}^{V_f} nRT\,dV/V = -nRT\int_{V_i}^{V_f} dV/V$$

$$W = -nRT\ \ell n(V_f/V_i)$$

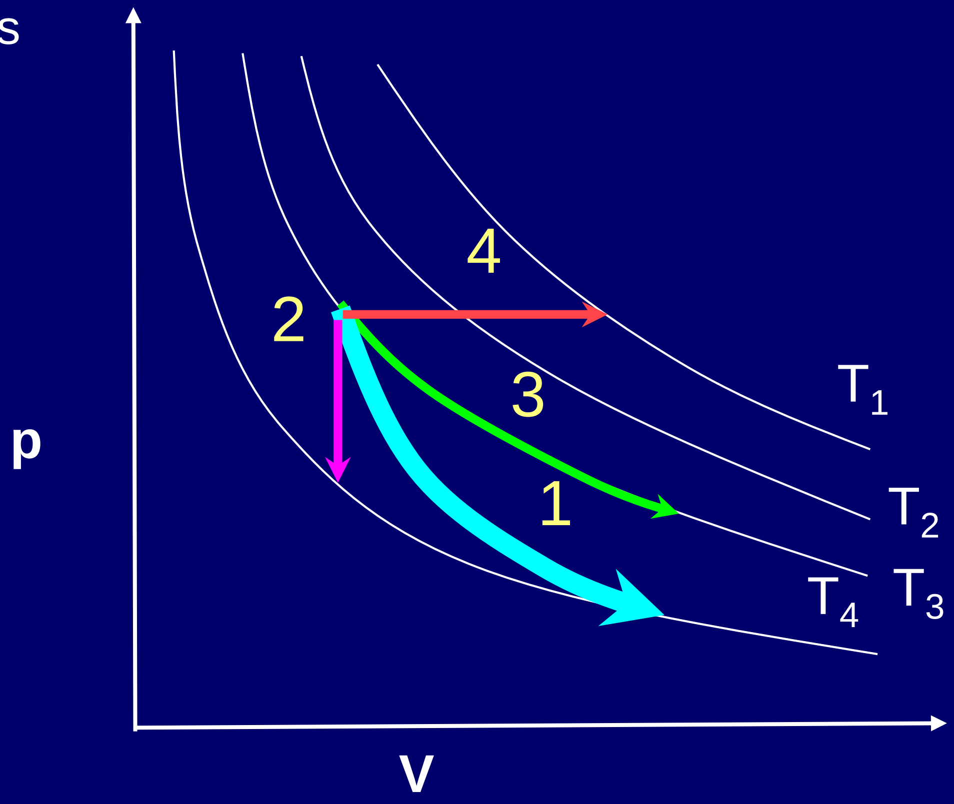


Adiabatic Processes

- ***Remember…*** An adiabatic process is process in which there is **no** thermal energy transfer to or from a system (Q = 0)

- A **reversible** adiabatic process involves a “worked” expansion in which we can return all of the energy transferred.
- In this case

  PV^{γ} = const.
- All **real** processes are not.



Work and Ideal Gas Processes (on system)

- Isothermal

$$W = -\mathrm{nRT}\ \ell n(\mathrm{V_f}/\mathrm{V_i})$$

- Isobaric

$$W = -\mathrm{p}\ (\mathrm{V_f} - \mathrm{V_i})$$

- Isochoric

$$W = 0$$

- FYI: Adiabatic (and reversible)

$$W = -\int_{V_1}^{V_2} P dV = -\int_{V_1}^{V_2} \frac{\text{const}}{V^{\gamma}} \frac{dV}{V} = \frac{\text{const}}{\gamma}\left(V_2^{-\gamma} - V_1^{-\gamma}\right)$$

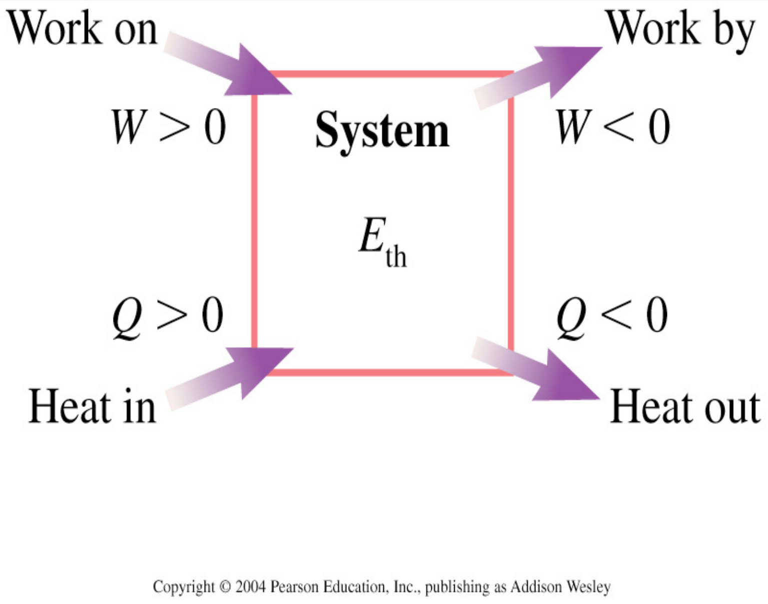
Combinations of Isothermal & Adiabatic Processes

All engines employ a thermodynamic cycle

$W = \pm$ (area under each pV curve)

W_{cycle} = area shaded in turquoise

Watch sign of the work!



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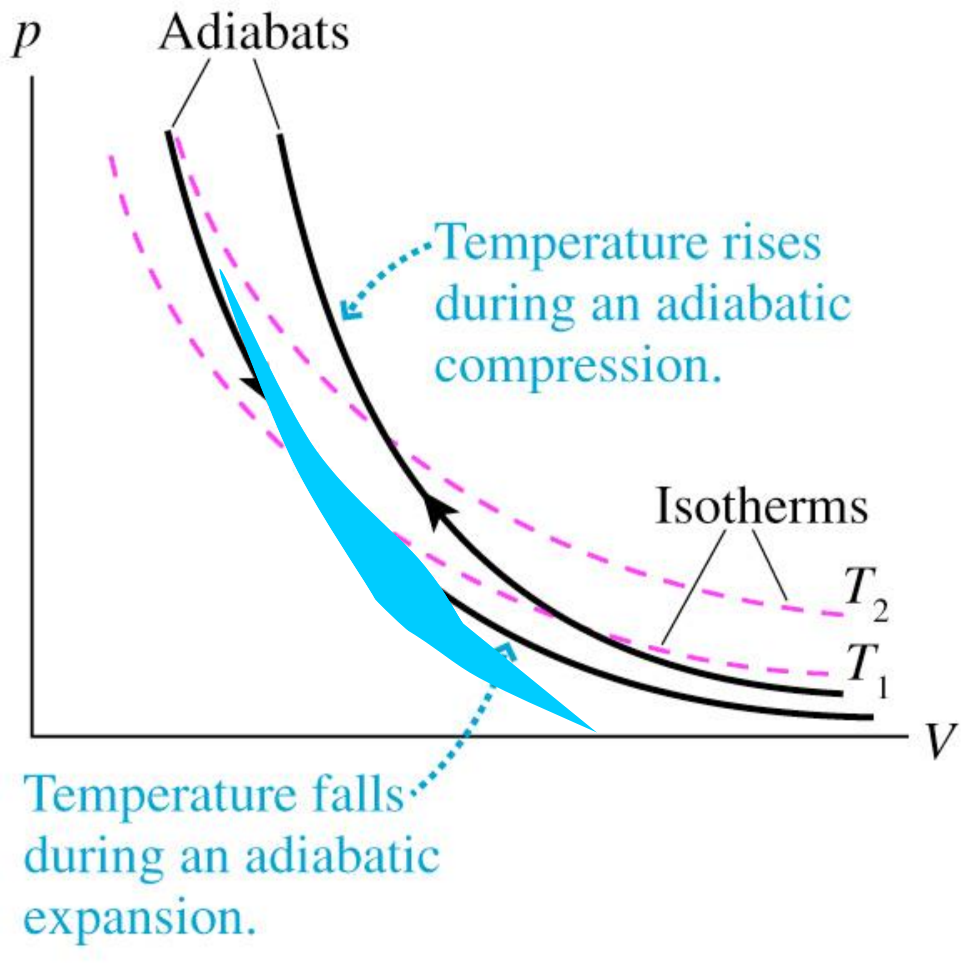


Temperature rises during an adiabatic compression.

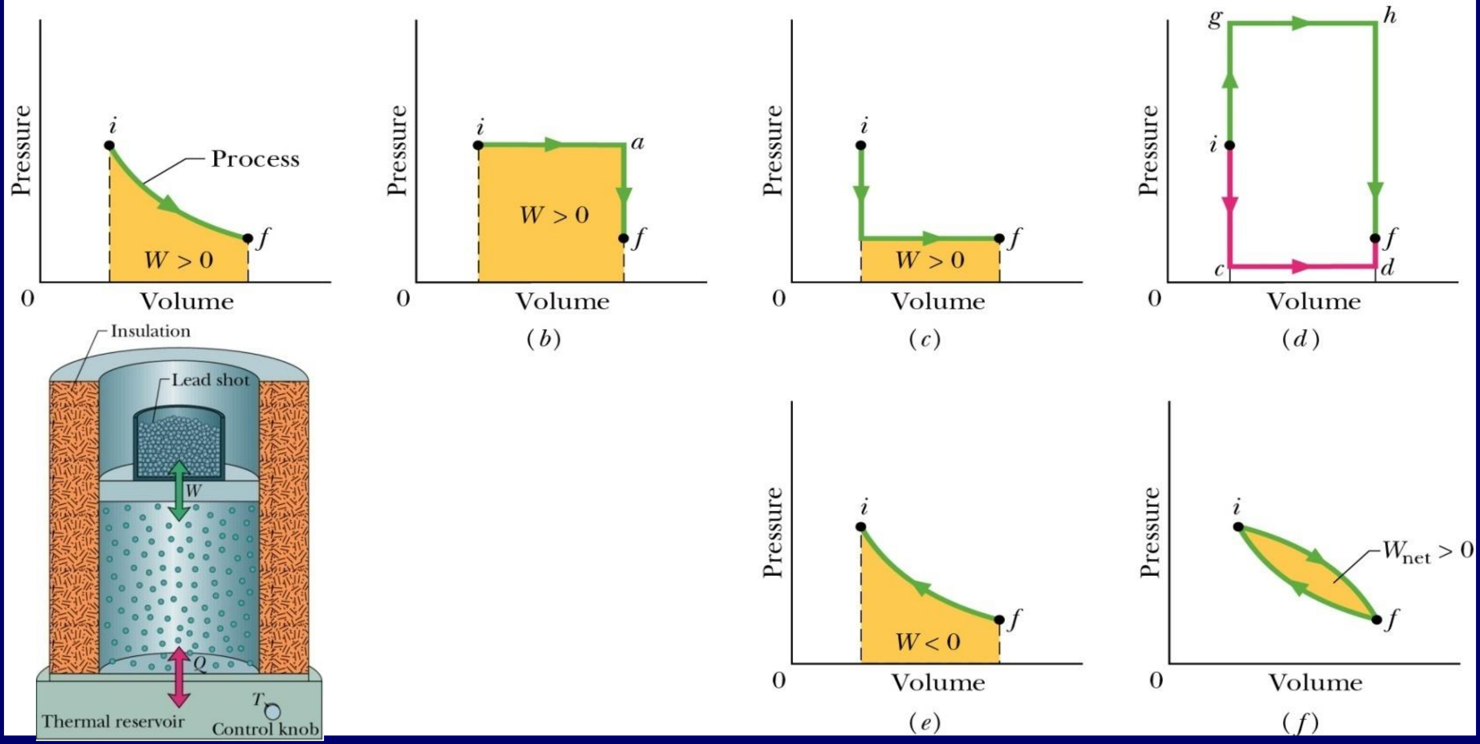
Temperature falls during an adiabatic expansion.

Shaded area is the work done by the system

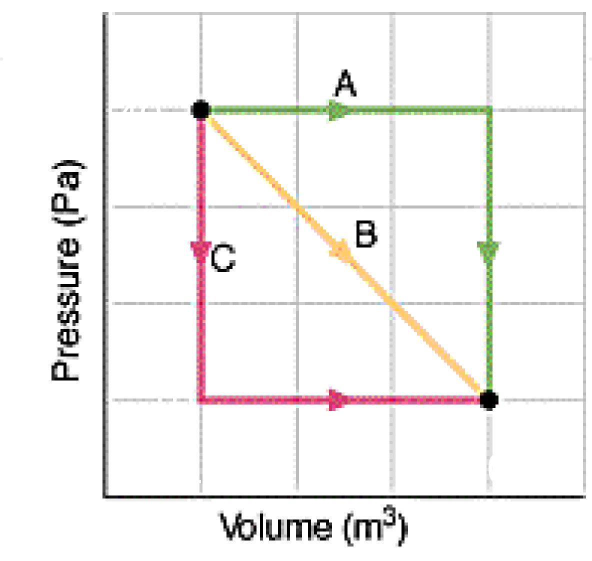
$$W = \int_{V_i}^{V_f} p\,dV$$

p depends on V in general

Below are ***many ways to take the system from i to f***.
The work W done and Q depends on the path.



A sample of gas expands from 1.0 m^3 to 4.0 m^3 while its pressure decreases from 40 Pa to 10 Pa. How much work is done by the gas if its pressure changes with volume via each of the three paths shown in the Figure below?



Path A: W = +120 J
Path B: W =+75 J
Path C: W =+30 J

Heat and Latent Heat

- Latent heat of transformation L is the energy required for 1 kg of substance to undergo a phase change. (J / kg)

$$Q = \pm ML$$

- Specific heat c of a substance is the energy required to raise the temperature of 1 kg by 1 K. (Units: J / K kg)

$$Q = M c \Delta T$$

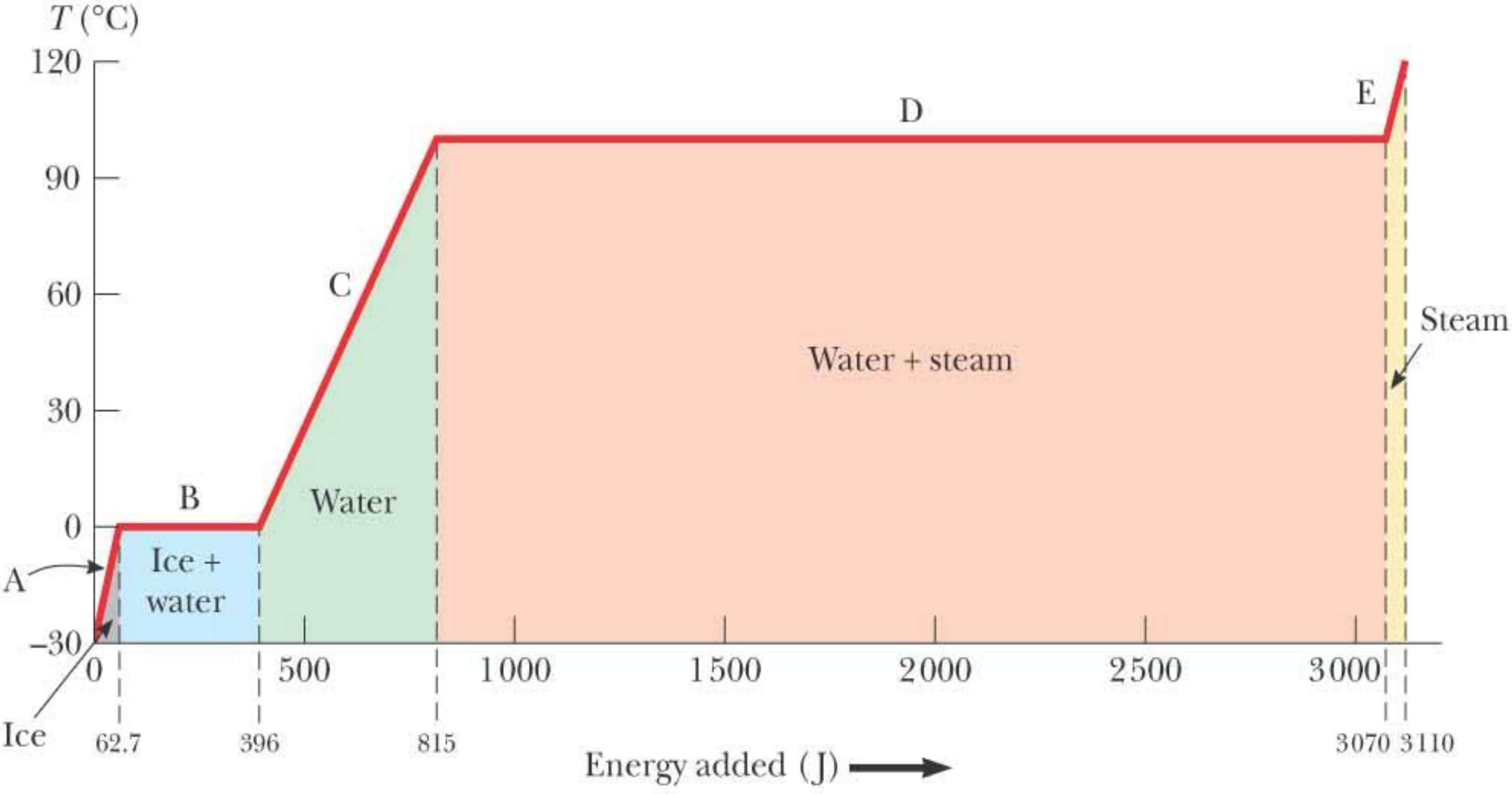
- Molar specific heat C of a gas at constant volume is the energy required to raise the temperature of 1 mol by 1 K.

$$Q = n C_V \Delta T$$

If a phase transition involved then the heat transferred is

$$Q = \pm ML + M c \Delta T$$

Relationship between energy transfer and T



Q : Latent heat and specific heat

- The molar specific heat of gasses depends on the process path
- C_V= molar specific heat at constant volume
- C_p= molar specific heat at constant pressure
- C_p= C_V+R (R is the universal gas constant)

$$\boxed{\gamma = \frac{C_p}{C_V}}$$

Exercise Latent Heat

- Most people were at least once burned by hot water or steam.
- Assume that water and steam, initially at 100°C, are cooled down to skin temperature, 37°C, when they come in contact with your skin. Assume that the steam condenses extremely fast, and that the specific heat c = 4190 J/ kg K is constant for both liquid water and steam.
- Under these conditions, which of the following statements is true?

(a) Steam burns the skin worse than hot water because the thermal conductivity of steam is much higher than that of liquid water.

(b) Steam burns the skin worse than hot water because the latent heat of vaporization is released as well.

(c) Hot water burns the skin worse than steam because the thermal conductivity of hot water is much higher than that of steam.

(d) Hot water and steam both burn skin about equally badly.

Thermodynamic Systems

Remember….

Thermodynamics: Fundamental laws that heat and work obey

System: Collection of objects on which the attention is being paid

Surrounding – Everything else around

System can be separated from surrounding by:

Diathermal Walls – Allows heat to flow through

Adiabatic Walls - Perfectly insulating walls that do not allow flow of heat

State of a system – the physical condition – can be defined using various parameters such as **volume, pressure, temperature etc**.

Before We Start

- Why is $T \propto K_{\text{trans}}$?
- Why is C larger when there are more modes?
- Why does energy partition between modes?

Thermodynamic Paths

energy transfers

§ 19.3–19.4

Energy Transfers

Between system and surroundings

- Work
- Heat

Work

From a volume change of the system

$$W = -\int_{V_1}^{V_2} p\, dV$$

Heat and Work

$$dW = F.ds \quad = (PA)\, ds$$
$$= p\,(Ads = p\, dV$$
$$W = \int dw \quad = \int p\, dV$$

Work done represented by the area under the curve on pV diagram.

Area depends upon the path taken from i to f state. Also PV= nRT

For b) from i to a process volume increase at constant pressure i.e

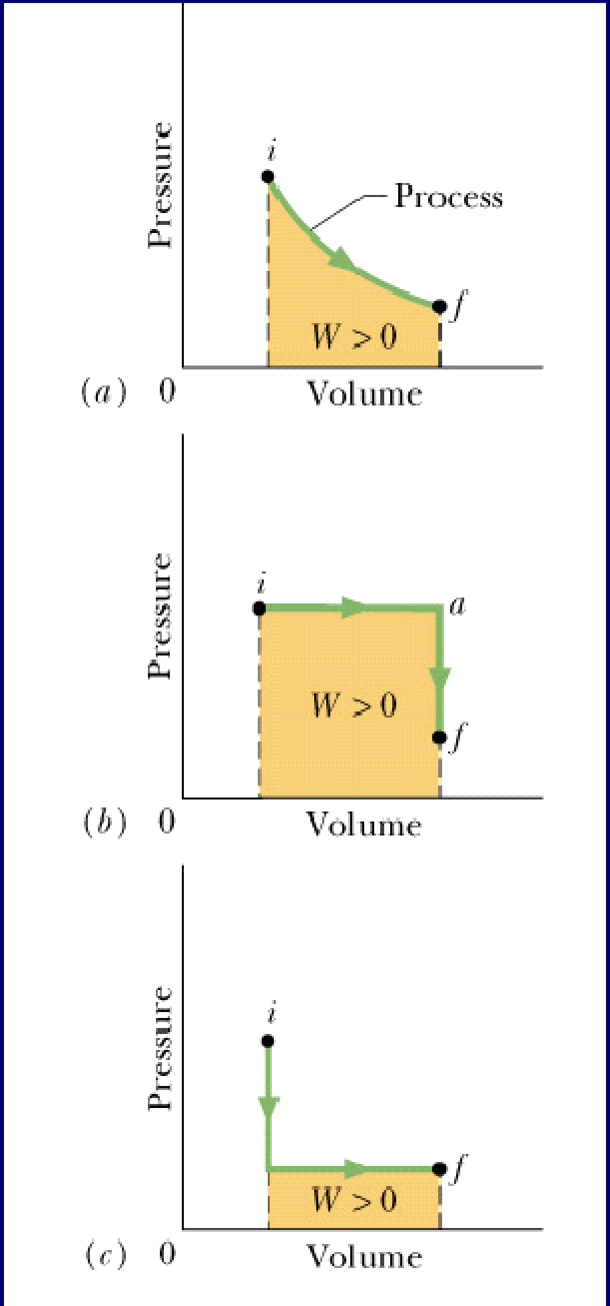
$T_a = T_i\,(V_a/V_i)$

then $T_a > T_i$. Heat Q must be absorbed by the system and work W is done

a to f process is at constant V ($P_f > P_a$) then $T_f = T_a(p_f/p_a)$

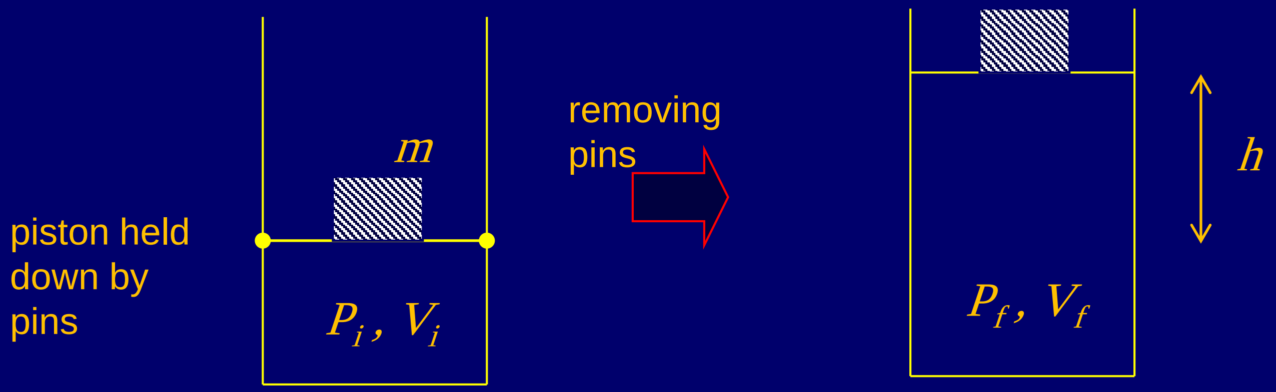
Since $T_f < T_a$, heat Q' must be lost by the system

For process iaf total work W is done and net heat absorbed is Q-Q'



Mechanical Work

Expansion of a gas



Work performed by the gas:

$$w = -P_{\text{ext}}\Delta V$$

Infinitesimal volume change

$$\delta w = -P_{\text{ext}}\delta V$$

Convention: work done on the system is taken as positive.

Mechanical work:

$$w = -\int_{V_i}^{V_f} P_{\text{ext}}(V)\,dV$$

Reversible Processes

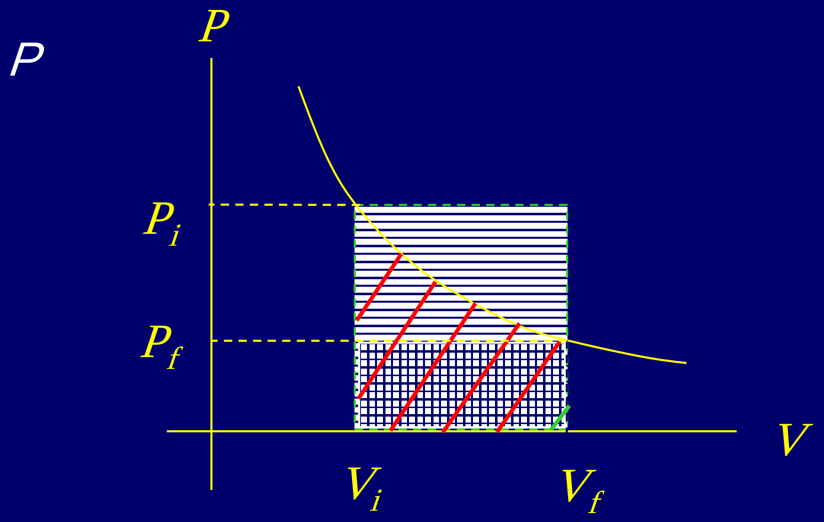
A process is called reversible if $P_{\text{system}} = P_{\text{ext}}$ at all times. The work expended to compress a gas along a reversible path can be completely recovered upon reversing the path.

When the process is reversible the path can be reversed, so expansion and compression correspond to the same amount of work.

$$w = -\int_{V_i}^{V_f} P(V)\,dV$$

- ❖ To be reversible, a process must be infinitely slow.

Reversible Isothermal Expansion/Compression of Ideal Gas



$$w = -nRT\ln\frac{V_f}{V_i}$$

Reversible isothermal compression: minimum possible work

Reversible isothermal expansion: maximum possible work

Heat

From a temperature difference

$$dQ/dT \propto T_{\mathrm{surr}} - T_{\mathrm{sys}}$$

Work and Heat

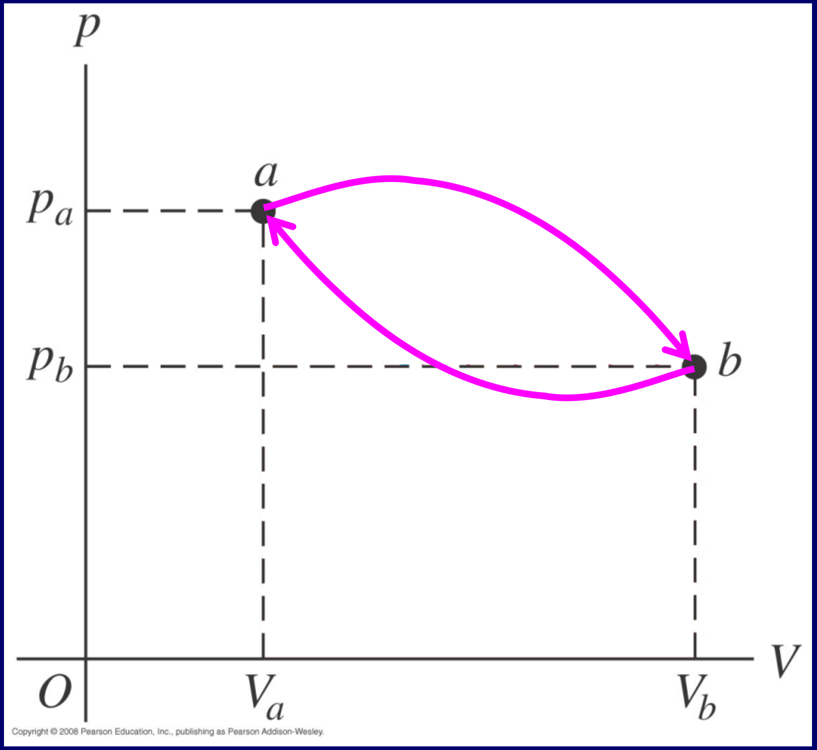
Depend on the path taken between initial and final states.

Question

Is the work done by a thermodynamic system in a cyclic process (final state is also the initial state) zero.

A. *True.*

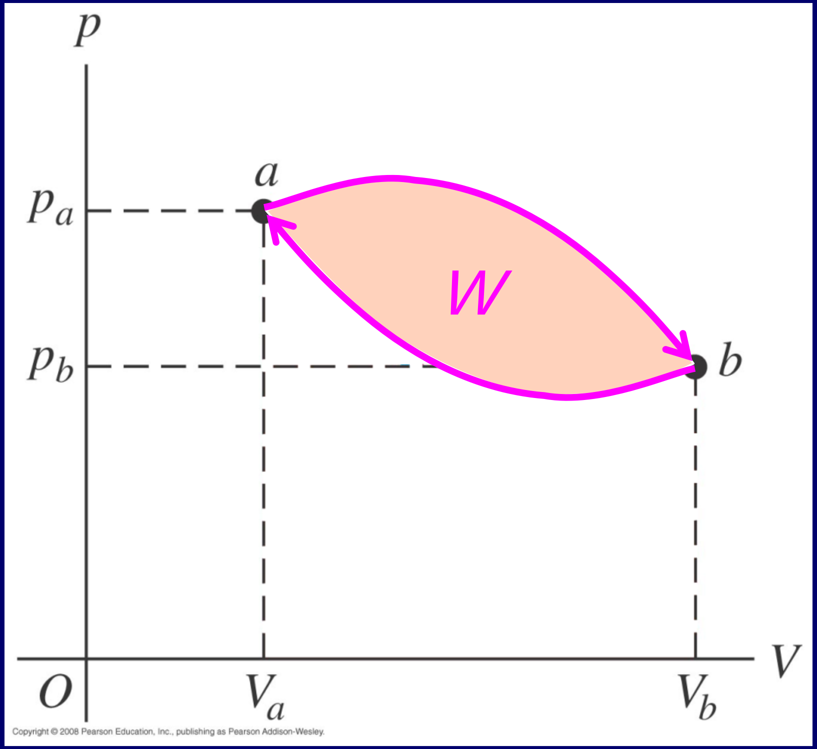
B. *False*.



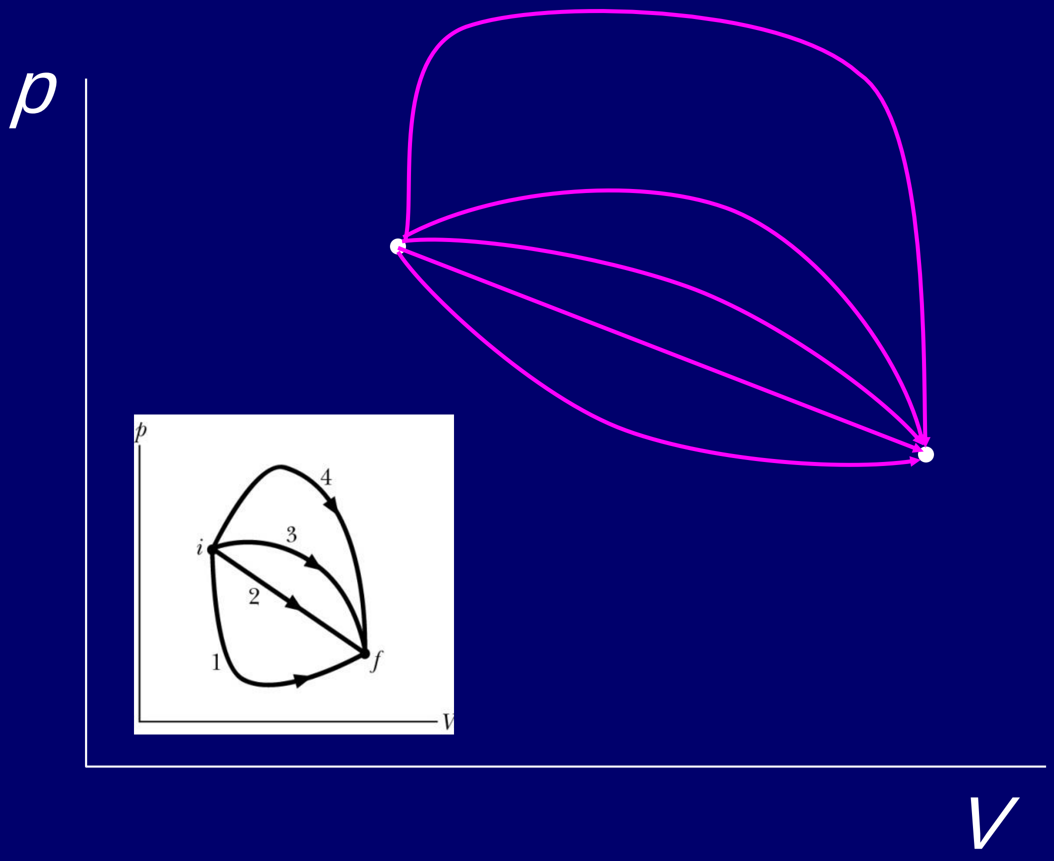
Source: Y&F, Figure 19.12

Cyclic Process

$$W \neq 0$$

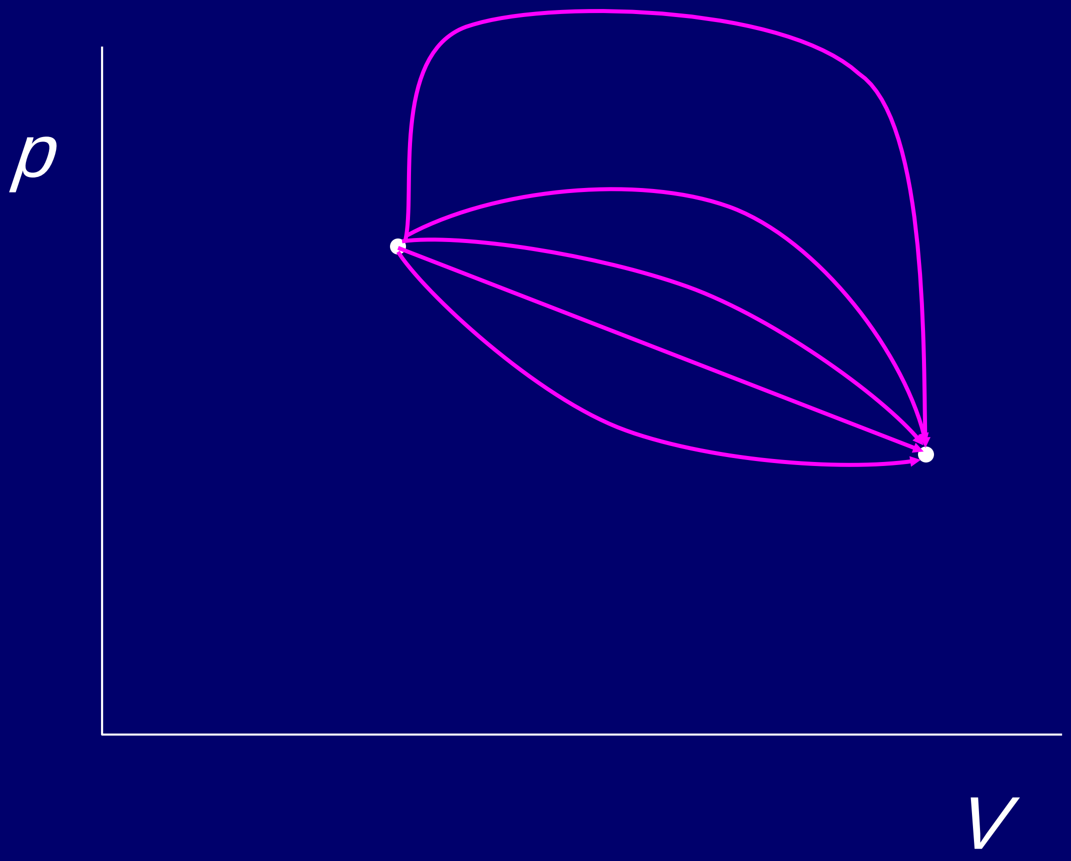


Work between States



W is not uniquely determined by initial and final states

What Are the Processes?



Group Work

Qualitatively sketch a pV plot for each described process A→B.

a) Volume is gradually doubled with no heat input, then heated at constant volume to the initial temperature.

b) System is heated at constant pressure until volume doubles, then cooled at constant volume to the initial temperature.

c) System is allowed to expand into a vacuum (free expansion) to twice its volume.

d) Volume is gradually doubled while maintaining a constant temperature.

Group Work

Conservation of Energy

ΔE of a system =

work done on the system

+

heat added to the system

Internal Energy

Question

All other things being equal, adding heat to a system increases its internal energy *E*.

A. *True.*
B. *False.*

Question

All other things being equal, lifting a system to a greater height increases its internal energy *U*.

A. True.

B. False.

Question

All other things being equal, accelerating a system to a greater speed increases its internal energy *E*.

A. True.
B. False.

Question

All other things being equal, doing work to compress a system increases its internal energy *E*.

A. *True.*

B. *False.*

Cyclic Processes

$$\Delta E = E_1 - E_1 = 0$$

so

$$Q - W = 0$$

so

$$Q = W$$

- Work output = heat input

Work out = Heat in

Does this mean cyclic processes convert heat to work with 100% efficiency?

(Of course not.)

Waste heat is not recovered.

Example Problem

A thermodynamic cycle consists of two closed loops, I and II.

d) In each of the loops, I and II, does heat flow into or out of the system?

c) Over one complete cycle, does heat flow into or out of the system?