Lecture 39

(Chapter 12: 1-2)

Topic 12: The Laws of Thermodynamics

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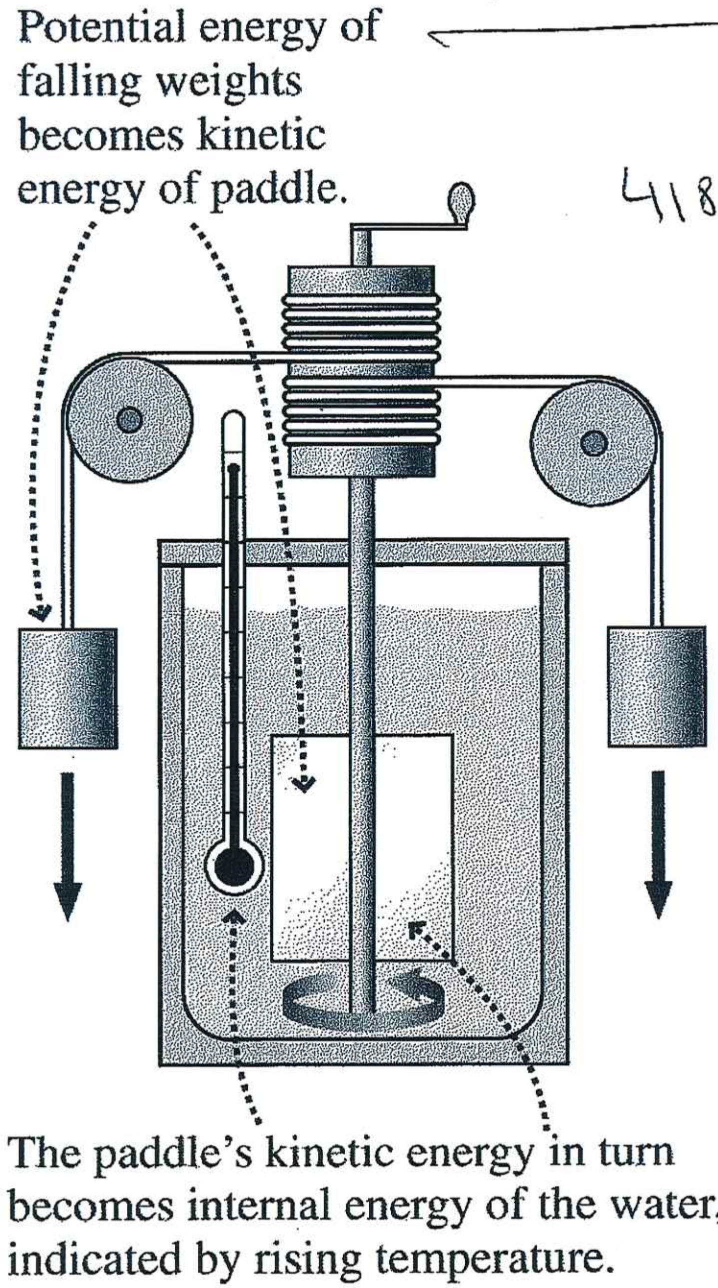
- **Units of heat (Q):**
  - *calorie* (cal): heat 1 gram of water from 14.5° C to 15.5° C
  - *British thermal unit* (Btu): heat 1 lb of water from 63° F to 64° F
  - *Joule* (J): SI unit ; 1 cal = 4.186 J

$$1 \text{ cal} = 3.969 \times 10^{-3} \text{ Btu} = 4.186 \text{ J}$$

1 Food Calorie = 1,000 cal = 4186 J

Mechanical equivalent of heat

Figure 13.1



4186 J raise 1kg H_2O by 1°C

Chapter 12: Thermodynamics

Internal Energy

- We defined ***thermal energy*** before as the kinetic and potential energy associated with individual molecules.

- Here we expand the concept, defining ***internal energy*** to include also any potential energy associated with interactions among molecules, such as the energy of bonds that get broken during phase changes.

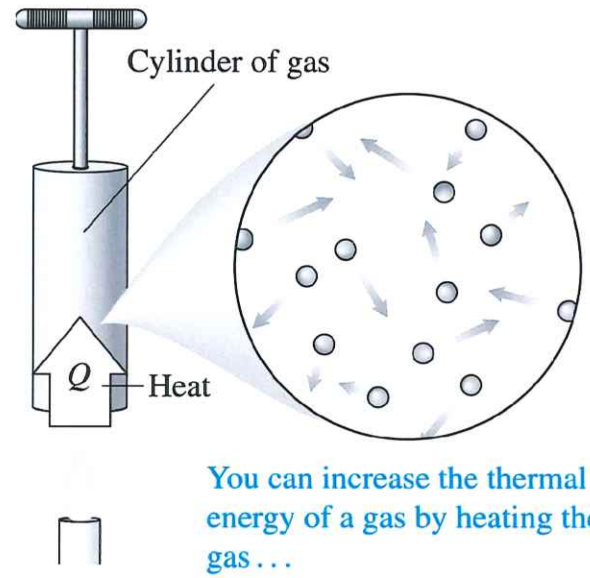
- Here, we will use $\boldsymbol{U}$ as the ***internal energy***, not potential energy.

Chapter 12: Thermodynamics

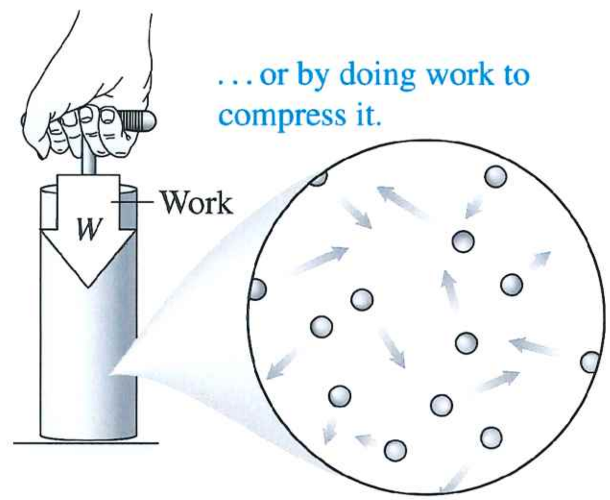
The first law of thermodynamics says that the change in internal energy of a system is equal to the heat flow into the system plus the work done on the system:

$$\Delta U = Q + W \text{, } 1^{st} \text{ law of thermodynamics}$$

This is a law of energy conservation.



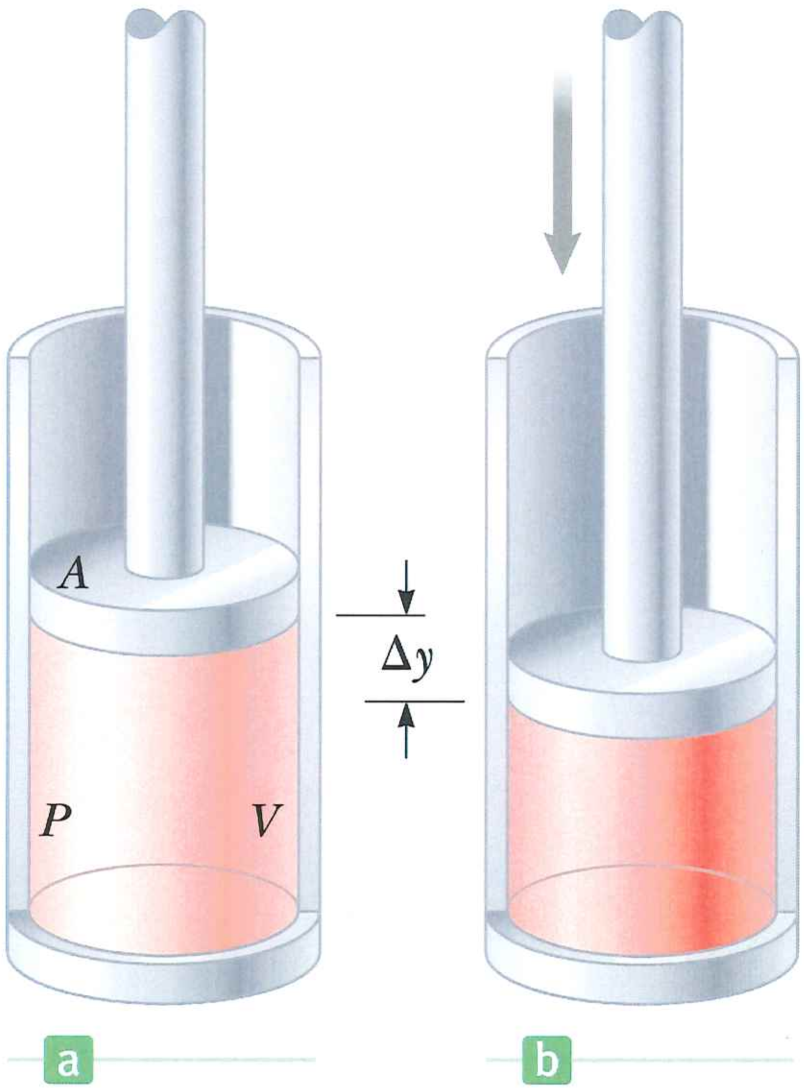
You can increase the thermal energy of a gas by heating the gas . . .



. . . or by doing work to compress it.

In addition to the potential and kinetic energies discussed in the previous chapters, the internal energy of the system is also added to the total energy of the system that needs to be conserved.

Work in Thermodynamic Processes

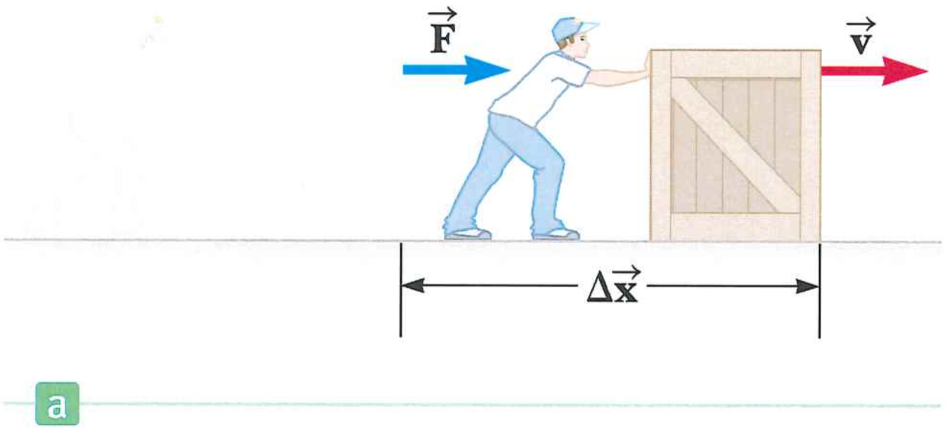


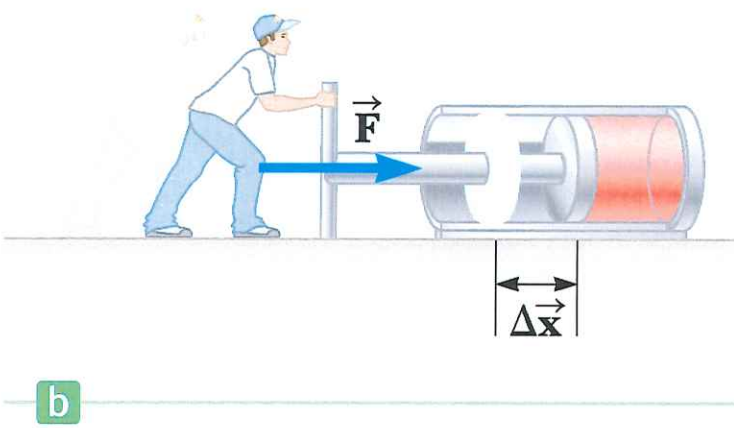
$$W = -F\Delta y = -PA\Delta y$$

$$\Delta V = A\Delta y$$

$$W = -P\Delta V$$

Work in Thermodynamic Processes





Chapter 12: Thermodynamics

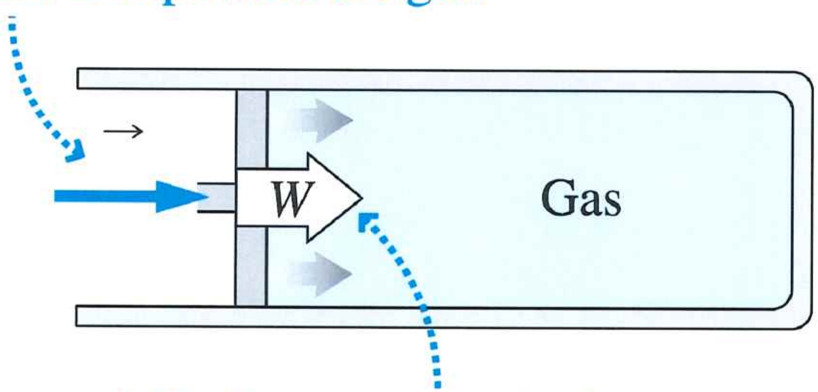
Compressing a Gas

The work done on a gas can be positive or negative, depending on whether volume decreases or increases.

Sign rule for work:

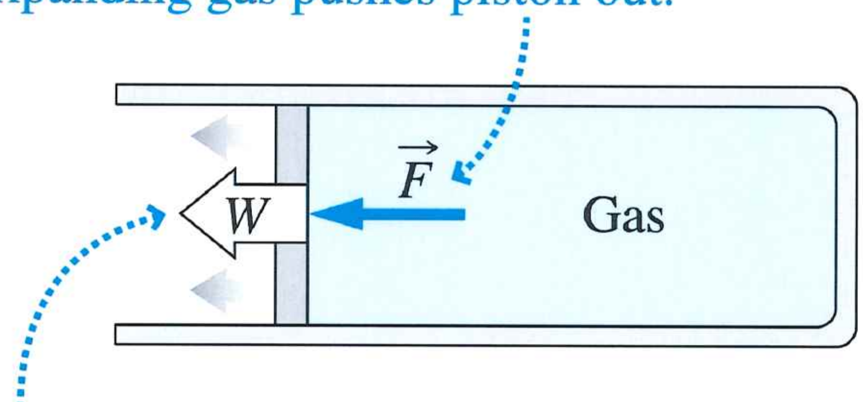
When a gas is compressed, the work W done on it is positive. When a gas expands, the work W done on it is negative.

Piston compresses the gas.



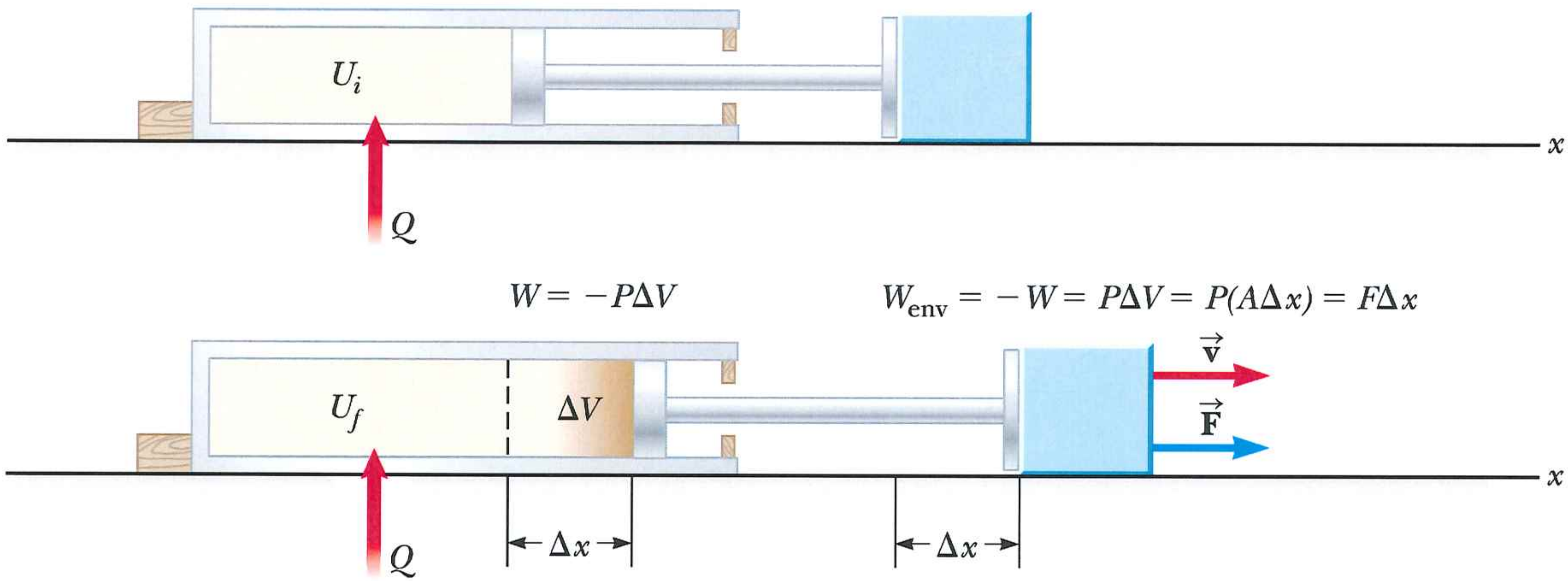
Force and displacement are in the same direction, so the piston does positive work on the gas.

Expanding gas pushes piston out.



Because the gas does positive work on the piston, the work done *on the gas* is *negative*.

The First Law of Thermodynamics



Chapter 12: Thermodynamics

Quantity	Definition	Meaning of + Sign	Meaning of − Sign
Q	Heat flow into the system	Heat flows *into* the system	Heat flows *out of* the system
W	Work done *on* the system	Surroundings do *positive* work on the system	Surroundings do *negative* work on the system (system does positive work on the surroundings)
ΔU	Internal energy change	Internal energy *increases*	Internal energy *decreases*

3. T Gas in a container is at a pressure of 1.5 atm and a volume of $4.0\ m^3$. What is the work done *on* the gas

a. if it expands at constant pressure to twice its initial volume, and

Answer

b. if it is compressed at constant pressure to one-quarter its initial volume?

12.3 The constant pressure is $P = (1.5\ \text{atm})(1.013 \times 10^5\ \text{Pa/atm})$ and the work done on the gas is $W = -P(\Delta V)$.

(a) $\Delta V = +4.0\ m^3$ and

$$W = -P(\Delta V) = -(1.5\ \text{atm})(1.013 \times 10^5\ \text{Pa/atm})(+4.0\ m^3) = \boxed{-6.1 \times 10^5\ J}$$

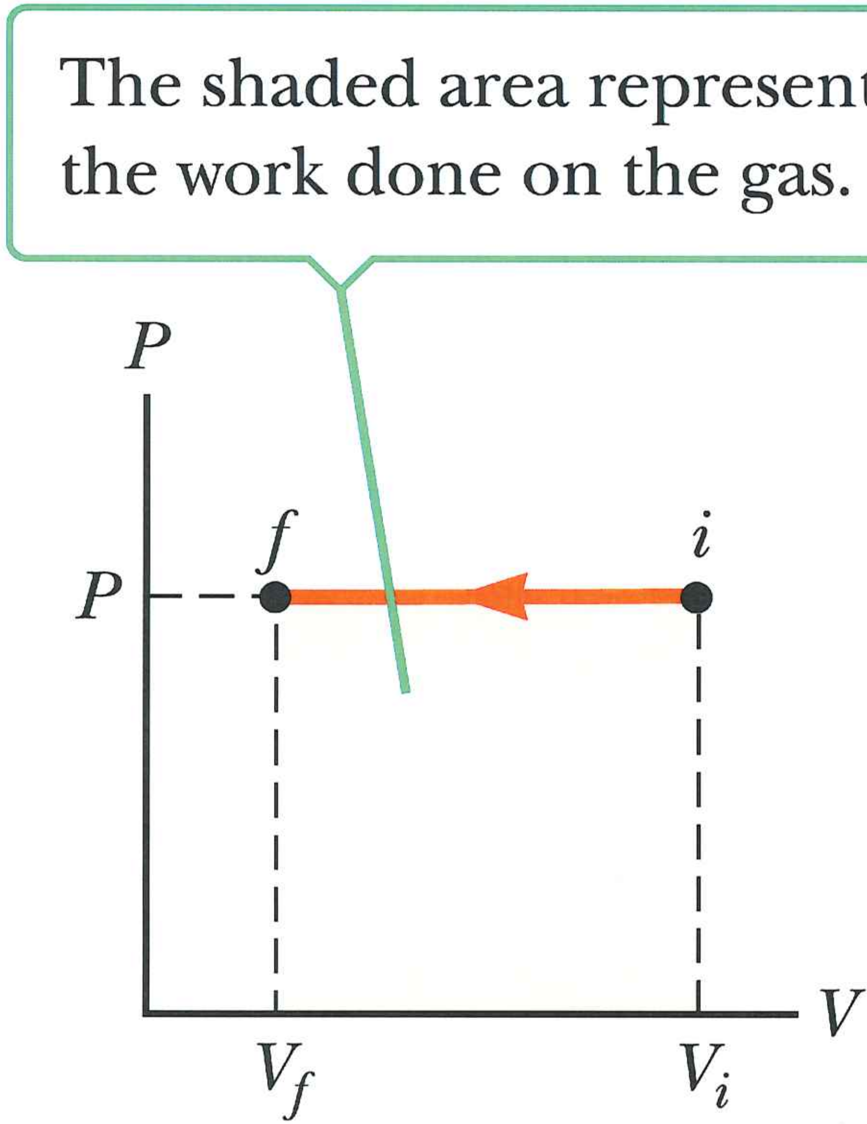
(b) $\Delta V = -3.0\ m^3$, so

$$W = -P(\Delta V) = -(1.5\ \text{atm})(1.013 \times 10^5\ \text{Pa/atm})(-3.0\ m^3) = \boxed{+4.6 \times 10^5\ J}$$

Work in Thermodynamic Processes

$$W = -P\Delta V$$

$$\text{Area} = P\left(V_f - V_i\right) = P\Delta V$$



6. A gas follows the PV diagram in Figure P12.6. Find the work done on the gas along the paths

a. AB,

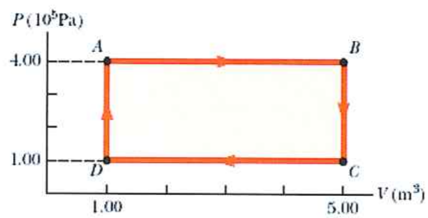
b. BC,

c. CD,

d. DA, and

e. $ABCDA$.

Figure P12.6



12.6 Calculate the area under each indicated path section. The work on the gas for each section is positive if the gas is compressed and negative if the gas expands.

(a) The area under path AB is a rectangle of height 4.00×10^5 Pa and width $4.00\ \text{m}^3$ so that

$$A_{AB} = \text{height} \times \text{width} = \left(4.00 \times 10^5\ \text{Pa}\right)\left(4.00\ \text{m}^3\right) = 16.0 \times 10^5\ \text{J}$$

The gas expands on path AB so the work is negative and

$$W_{AB} = -A_{AB} = \boxed{-16.0 \times 10^5\ \text{J}}$$

(b) Path BC is a vertical line with $\Delta V_{BC} = 0$ so that $A_{BC} = 0$ and $W_{BC} = \boxed{0}$.

(c) The area under path CD is a rectangle of height 1.00×10^5 Pa and width $4.00\ \text{m}^3$ so that

$$A_{CD} = \left(1.00 \times 10^5\ \text{Pa}\right)\left(4.00\ \text{m}^3\right) = \boxed{4.00 \times 10^5\ \text{J}}$$

The gas is compressed on path CD so the work is positive and

$$W_{CD} = +A_{CD} = \boxed{4.00 \times 10^5\ \text{J}}$$

(d) Path *DA* is a vertical line with $\Delta V_{DA} = 0$ so that $A_{DA} = 0$ and $W_{DA} = \boxed{0}$.

(e) The work $W_{ABCDA} = W_{AB} + W_{BC} + W_{CD} + W_{DA} = -16.0 \times 10^5\ \text{J} + 0 + 4.00$

$\times 10^5\ \text{J} + 0 = \boxed{-12.0 \times 10^5\ \text{J}}$.

8.

a. Find the work done *by* an ideal gas as it expands from point A to point B along the path shown in Figure P12.8.

b. How much work is done by the gas if it compressed from B to A along the same path?

Figure P12.8

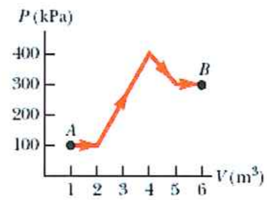


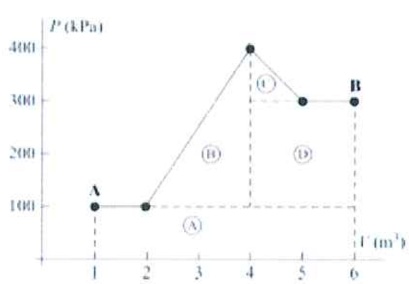
Figure P12.8

12.8 **(a)** The work done by the gas as it expands from point A to point B is given by the area under the PV diagram between these points. Consider the sketch given below and observe that this area can be broken into two rectangular areas and two triangular areas. The total area is given by

$$W_{env} = (100\text{ kPa})(5.00\text{ m}^3) + \frac{1}{2}(300\text{ kpa})(2.00\text{ m}^3) + \frac{1}{2}(100\text{ kPa})(1.00\text{ m}^3) + (200\text{ kPa})(2.00\text{ m}^3)$$

or

$$W_{env} = 1\,250\,(\text{kPa})(\text{m}^3) = 1.25\times10^3\,(\text{N/m}^2)(\text{m}^3) = \boxed{1.25\text{ MJ}}$$



(b) When the volume is decreasing, the work done by the gas is the negative of the area under the PV diagram. Thus, if the gas is compressed from point B to point A along the same path,

$$W_{env} = \boxed{-1.25\text{ MJ}}$$

15. T A gas expands from I to F in Figure P12.5. The energy added to the gas by heat is 418 J when the gas goes from I to F along the diagonal path.

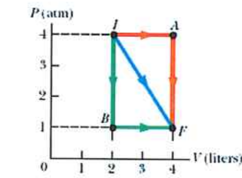
a. What is the change in internal energy of the gas?

Answer

b. How much energy must be added to the gas by heat for the indirect path IAF to give the same change in internal energy?

Figure P12.5

Problems 5 and 15.



12.15 (a) Along the direct path IF, the work done on the gas is

$$W = -(-\textit{area under curve})$$
$$= -\left[(1.00\text{ atm})(4.00\text{ L} - 2.00\text{ L}) + \frac{1}{2}(4.00\text{ atm} - 1.00\text{ atm})(4.00\text{ L} - 2.00\text{ L})\right]$$
$$W = -5.00\text{ atm}\cdot\text{L}$$

Thus,

$$\Delta U = Q + W = 418\text{ J} - 5.00\text{ atm}\cdot\text{L}$$
$$= 418\text{ J} - (5.00\text{ atm}\cdot\text{L})\left(\frac{1.013\times10^{5}\text{ Pa}}{1\text{ atm}}\right)\left(\frac{10^{-3}\text{ m}^{3}}{1\text{ L}}\right) = \boxed{-88.5\text{ J}}$$

(b) Along path IAF, the work done on the gas is

$$W = -(4.00\text{ atm})(4.00\text{ L} - 2.00\text{ L})\left(\frac{1.013\times10^{5}\text{ Pa}}{1\text{ atm}}\right)\left(\frac{10^{-3}\text{ m}^{3}}{1\text{ L}}\right) = -810\text{ J}$$

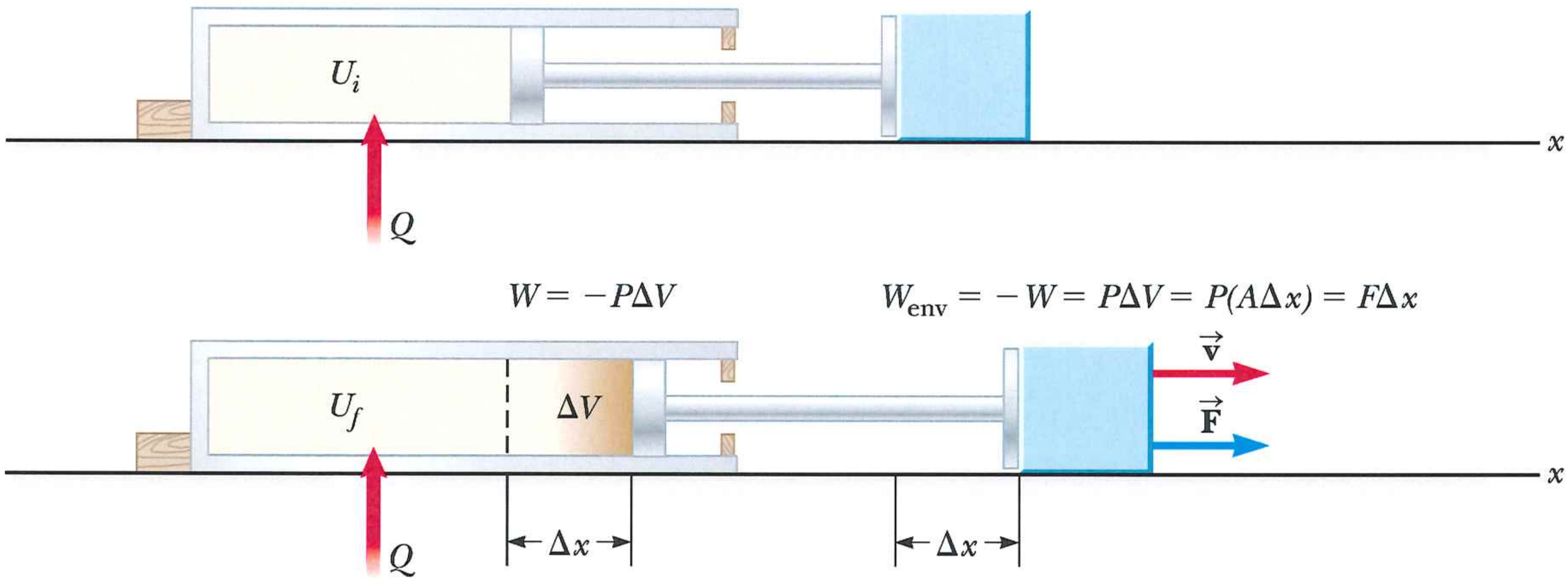
From the first law, $Q = \Delta U - W = -88.5\text{ J} - (-810\text{ J}) = \boxed{722\text{ J}}$

The First Law of Thermodynamics

First Law of Thermodynamics:

$$\Delta U = U_f - U_i = Q + W$$

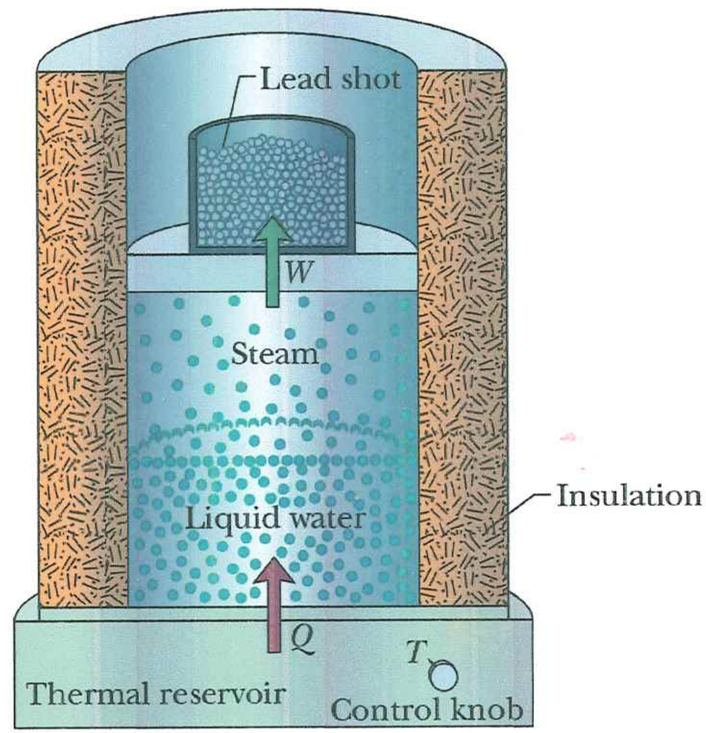
The First Law of Thermodynamics



$$\Delta U = U_f - U_i = Q + W$$

Sample Problem 18-5

Let 1.0 kg of liquid water at 100°C be converted to steam at 100°C by boiling at standard atmospheric pressure (which is 1.0 atm or 1.01×10^5 Pa) in the arrangement of the figure, The volume of the water changes from an initial value of 1.0×10^{-3} m^3 as a liquid to 1.672 m^3 as steam.



(a) How much work is done by the system?

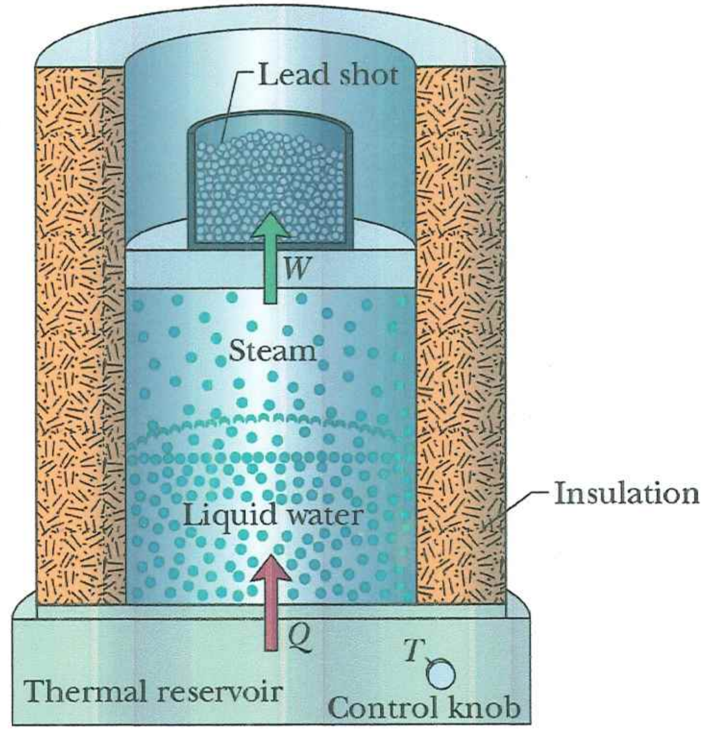
$$W = -p_0(V_f - V_i)$$

ΔV

$$= -(1.01 \times 10^5\ Pa)(1.67\ m^3 - 1.0 \times 10^{-3}\ m^3)$$

$$= -1.69 \times 10^5\ J = -169\ kJ$$

Sample Problem 18-5 (cont)



(b) How much energy is transferred as heat during the process? to the system

$$Q = L_V m = (2256 \text{ kJ/kg})(1.0 \text{ kg})$$

$$= 2{,}256 \text{ kJ}$$

(c) What is the change in the system's internal energy?

$\Delta U = Q + W$, but $W = -169$ kJ

$$\Delta U = Q + W = 2256 \text{ kJ} - 169 \text{ kJ}$$

$$= 2{,}087 \text{ kJ}$$

p = const; isobaric

$\Delta U = W + Q$

16. QIC In a running event, a sprinter does 4.8×10^5 J of work and her internal energy decreases by 7.5×10^5 J.

a. Determine the heat transferred between her body and surroundings during this event.

b. What does the sign of your answer to part (a) indicate?

12.16 **(a)** We treat the sprinter's body as a thermodynamic system and apply the first law of thermodynamics, $\Delta U = Q + W$. Then, with $\Delta U = -7.5 \times 10^5$ J and $W = -4.8 \times 10^5$ J (negative because the sprinter does work on the environment), the energy absorbed as heat is

$$Q = \Delta U - W = -7.5 \times 10^5 \text{ J} - (-4.8 \times 10^5 \text{ J}) = \boxed{-2.7 \times 10^5 \text{ J}}$$

(b) The negative sign in the answer to part (a) means that energy is transferred from the sprinter to the environment by heat.

12. A chemical reaction transfers 1 250 J of thermal energy into an ideal gas while the system expands by 2.00×10^{-2} m^3 at a constant pressure of 1.50×10^5 Pa. Find the change in the internal energy.

12.12 **(a)** From the problem statement, $Q = 1.25 \times 10^3$ J and $W = -P\Delta V =$

$-(1.50 \times 10^5 \text{ Pa})(2.00 \times 10^{-2} \text{ m}^3) = -3.00 \times 10^3$ J. Substitute values into

the first law of thermodynamics to find

$$\Delta U = Q + W = 1.25 \times 10^3 \text{ J} - 3.00 \times 10^3 \text{ J}$$
$$\Delta U = \boxed{-1.75 \times 10^3 \text{ J}}$$

(b) From the ideal gas law, $P\Delta V = nR\Delta T$. Solve for ΔT and substitute

values to find

$$\Delta T = \frac{P\Delta V}{nR} = \frac{(1.50 \times 10^5 \text{ Pa})(2.00 \times 10^{-2} \text{ m}^3)}{(10.0 \text{ mol})(8.31 \text{ J/mol} \cdot \text{K})}$$
$$= \boxed{36.1 \text{ K}}$$