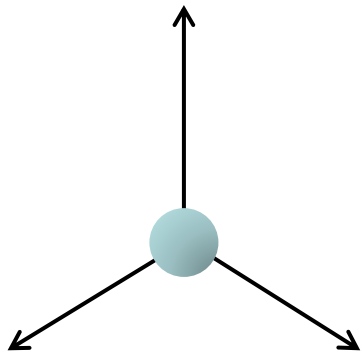


Internal Energy

- Internal energy is due to the molecular motion at the **microscopic** level (read chapter 21).

monatomic



Degrees of freedom

Monatomic: 3

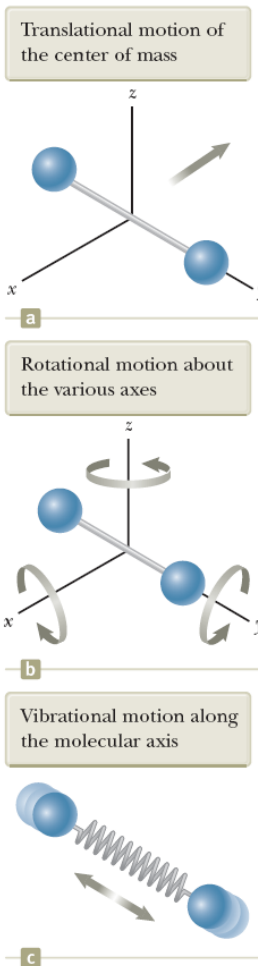
Diatomic: 5

Each degree of freedom:

$$KE = \frac{1}{2} nRT$$

Equipartition of Energy

diatomic



$$U = \frac{3}{2} nRT \quad \text{monatomic gas}$$

$$\Delta U = nC_V \Delta T$$

$$\Delta U = \frac{3}{2} nR \Delta T \quad \text{monatomic gases}$$

$$\Delta U = \frac{5}{2} nR \Delta T \quad \text{diatomic gases}$$

$$C_V = \frac{3}{2} R \quad \text{For monatomic gases}$$

$$C_V = \frac{5}{2} R \quad \text{For diatomic gases}$$

Internal Energy

- Internal energy is due to the molecular motion at the **microscopic** level (read chapter 21).
- For any ideal gas, *the internal energy (U) depends only on its temperature*, not on its pressure or volume.

$$\Delta U = \frac{3}{2} nR\Delta T \quad \text{monatomic gases}$$

$$\Delta U = \frac{5}{2} nR\Delta T \quad \text{diatomic gases}$$

- The change in internal energy (ΔU) is the same for all ideal-gas processes that have the same ΔT .

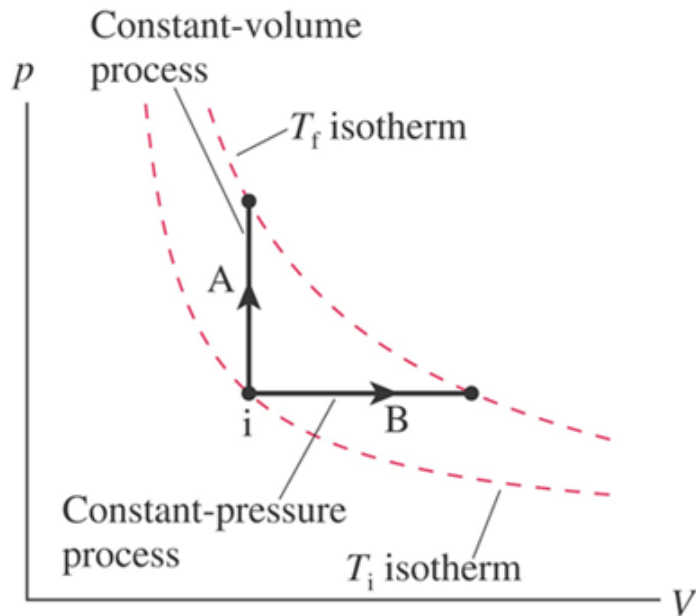
$$\Delta U = nC_V\Delta T$$

$$C_V = \frac{3}{2} R \quad \text{For monatomic gases}$$

$$C_V = \frac{5}{2} R \quad \text{For diatomic gases}$$

A monatomic gas of volume 100 cm^3 is initially at 100°C and a pressure of 1 atm , it follows the processes shown.

- During process A, how much heat is needed to double its pressure at a constant volume?
- During process B, how much heat is needed to double its volume at a constant pressure?



Process A and B involve the same change in temperature, but why Q is different?

$$\text{A: } \Delta U = Q + W = Q_A = nC_V\Delta T$$

$$\begin{aligned} \text{B: } \Delta U &= Q + W = Q_B - P\Delta V = nC_V\Delta T \\ Q_B &= nC_V\Delta T + P\Delta V \end{aligned}$$

A monatomic gas of volume 100 cm^3 is initially at 100°C and a pressure of 1 atm , it follows the processes shown.

- During process A, how much heat is needed to double its pressure at a constant volume?
- During process B, how much heat is needed to double its volume at a constant pressure?

$$\text{A:} \quad \Delta U = Q + W = Q_A = nC_V\Delta T = \frac{3}{2}nR\Delta T$$

For monatomic gases

$$C_V = \frac{3}{2}R$$

$$\text{B:} \quad \Delta U = Q + W = Q_B - P\Delta V = nC_V\Delta T$$

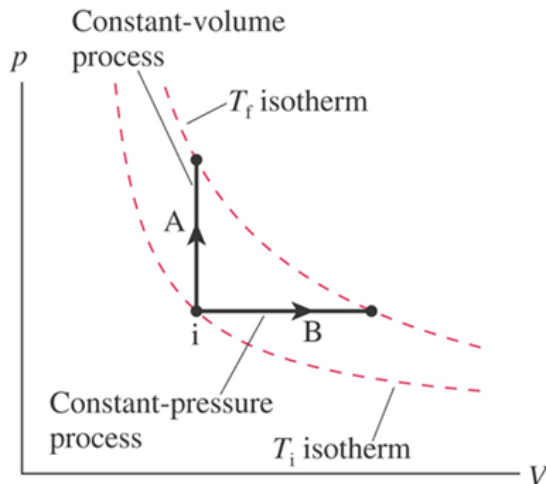
$$Q_B = \Delta U + P\Delta V = nC_V\Delta T + P\Delta V$$

$$PV = nRT \Rightarrow P\Delta V = nR\Delta T$$

$$Q_B = nC_V\Delta T + P\Delta V = n\frac{3}{2}R\Delta T + nR\Delta T$$

$$Q_B = n\frac{5}{2}R\Delta T = nC_P\Delta T \quad C_P = \frac{5}{2}R$$

For monatomic gases



Specific Heats for Ideal-Gases

- The *heat* required to cause a specified temperature change **depends on the process by which the gas changes states.**

Temperature change at constant volume

$$Q = nC_V\Delta T$$

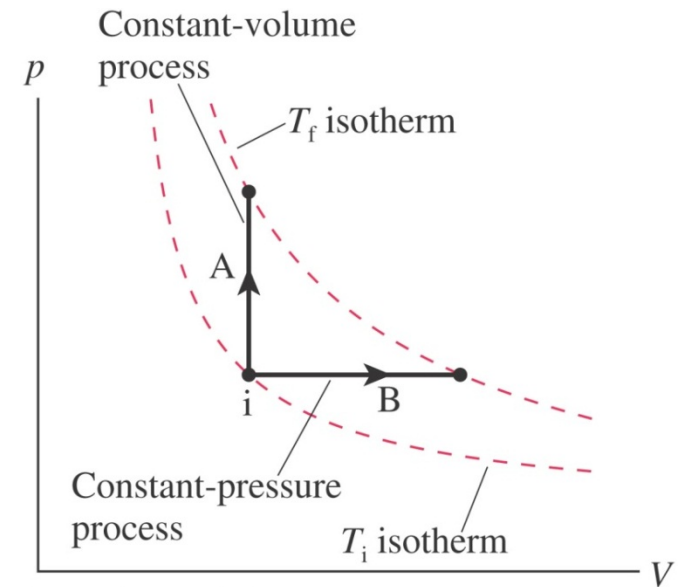
C_V Molar specific heat at constant *volume*

Temperature change at constant pressure

$$Q = nC_P\Delta T$$

C_P Molar specific heat at constant *Pressure*

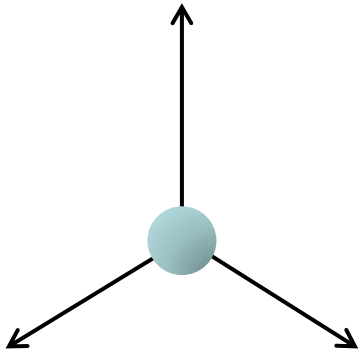
$$C_P = C_V + R$$



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Molar Specific Heats of Gases

monatomic



Degrees of freedom

Monatomic: 3

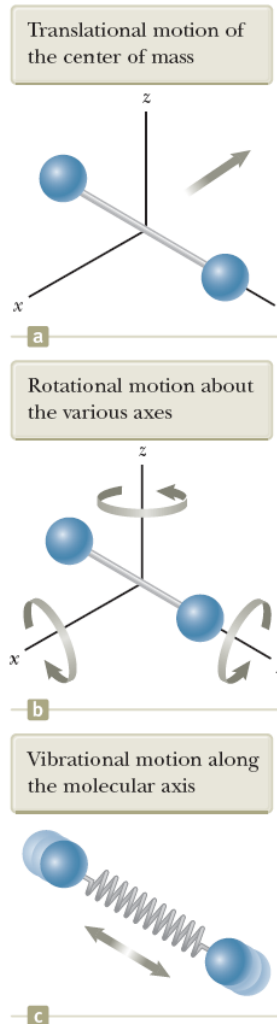
Diatomic: 5

Each degree of freedom:

$$KE = \frac{1}{2} nRT$$

Equipartition of Energy

diatomic



$$C_P = C_V + R$$

$$C_V = \frac{3}{2} R$$

monatomic
ideal-gases

$$C_V = \frac{5}{2} R$$

diatomic
ideal-gases

$$\gamma = \frac{C_P}{C_V}$$

specific
heat ratio

Molar Specific Heats of Gases

TABLE 17.4 Molar specific heats of gases (J/mol K)

Gas	C_P	C_V	$C_P - C_V$
Monatomic Gases			
He	20.8	12.5	8.3
Ne	20.8	12.5	8.3
Ar	20.8	12.5	8.3
Diatomic Gases			
H ₂	28.7	20.4	8.3
N ₂	29.1	20.8	8.3
O ₂	29.2	20.9	8.3

$$C_P = C_V + R$$

$$C_V = \frac{3}{2} R$$

monatomic
ideal-gases

$$C_V = \frac{5}{2} R$$

diatomic
ideal-gases

$$\gamma = \frac{C_P}{C_V}$$

specific
heat ratio

Summary – Heat and Internal Energy

Temperature change at constant volume

$$Q = nC_V\Delta T \quad C_V \text{ Molar specific heat at constant } \textit{volume}$$

Temperature change at constant pressure

$$Q = nC_P\Delta T \quad C_P \text{ Molar specific heat at constant } \textit{Pressure}$$

$$C_P = C_V + R \quad C_V = \frac{3}{2}R \quad \textit{monatomic gases}$$

$$PV = nRT \quad C_V = \frac{5}{2}R \quad \textit{diatomic gases}$$

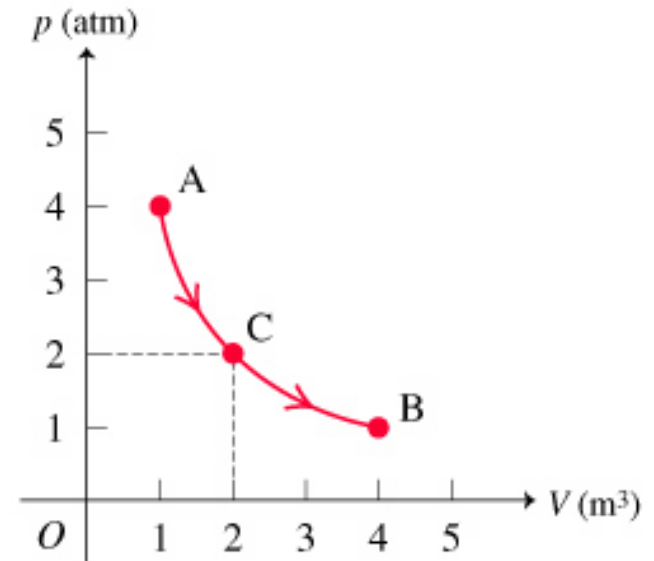
$$\Delta U = nC_V\Delta T \quad \Delta U = Q + W$$

You need to raise the temperature of a gas by 10°C . To use the least amount of heat energy, should you heat the gas at constant pressure or at constant volume?

1. Constant pressure.
2. Constant volume.
3. The same.
4. Can not tell from the given information.

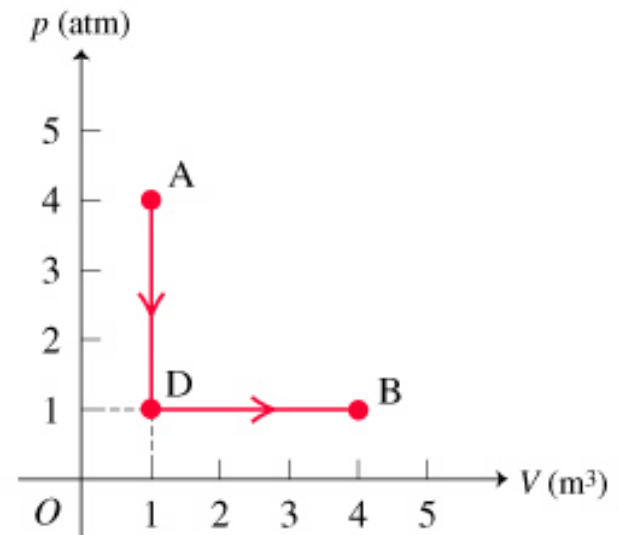
Which of the following statement is true about the ideal-gas isothermal process from A to B?

1. $\Delta U > 0$, $W_{\text{on gas}} = 0$, $Q > 0$
2. $\Delta U > 0$, $W_{\text{on gas}} > 0$, $Q = 0$
3. $\Delta U = 0$, $W_{\text{on gas}} > 0$, $Q < 0$
4. $\Delta U = 0$, $W_{\text{on gas}} < 0$, $Q > 0$
5. $\Delta U < 0$, $W_{\text{on gas}} = 0$, $Q < 0$
6. $\Delta U < 0$, $W_{\text{on gas}} < 0$, $Q = 0$
7. None of the above



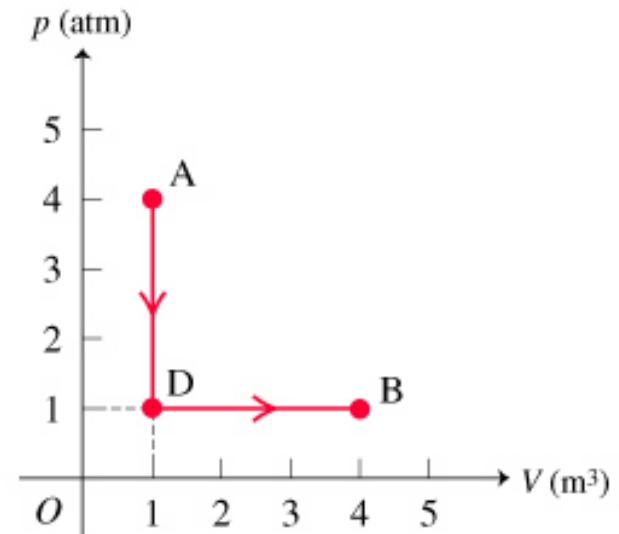
Which of the following statement is true about the ideal gas process A to D?

1. $\Delta U > 0$, $W_{\text{on gas}} = 0$, $Q > 0$
2. $\Delta U > 0$, $W_{\text{on gas}} > 0$, $Q = 0$
3. $\Delta U = 0$, $W_{\text{on gas}} > 0$, $Q < 0$
4. $\Delta U = 0$, $W_{\text{on gas}} < 0$, $Q > 0$
5. $\Delta U < 0$, $W_{\text{on gas}} = 0$, $Q < 0$
6. $\Delta U < 0$, $W_{\text{on gas}} < 0$, $Q = 0$
7. None of the above



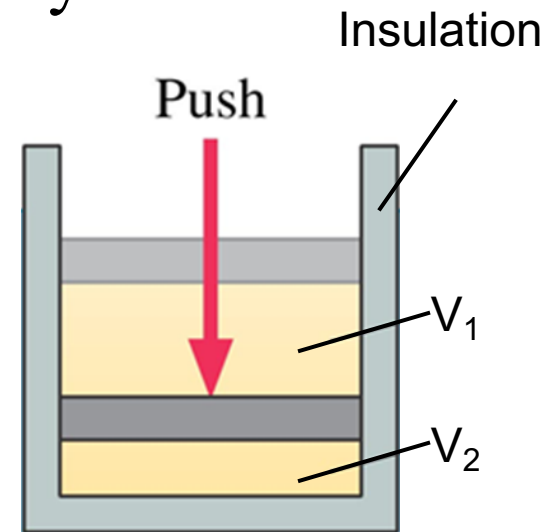
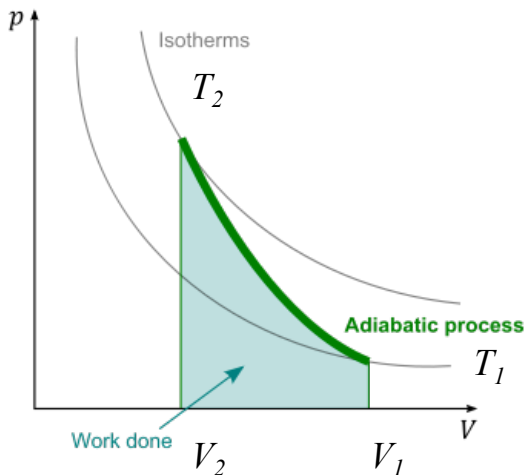
Which of the following statement is true about the ideal gas process D to B?

1. $\Delta U > 0$, $W_{\text{on gas}} = 0$, $Q > 0$
2. $\Delta U > 0$, $W_{\text{on gas}} > 0$, $Q = 0$
3. $\Delta U = 0$, $W_{\text{on gas}} > 0$, $Q < 0$
4. $\Delta U = 0$, $W_{\text{on gas}} < 0$, $Q > 0$
5. $\Delta U < 0$, $W_{\text{on gas}} = 0$, $Q < 0$
6. $\Delta U > 0$, $W_{\text{on gas}} < 0$, $Q > 0$
7. None of the above



Adiabatic Process

- An adiabatic process
 - A process in which no heat energy is transferred between the system and environment.
 - $Q=0 \rightarrow \Delta U=W$
 - Warning: This does not mean $\Delta T=0$.
 - Well insulated or happens very quickly



Adiabatic Process

$$\Delta U = nC_V \Delta T$$

$$\Delta U = W + Q = W \quad \Rightarrow \quad W = nC_V \Delta T$$

$$dU = dW = -PdV = nC_V dT$$

$$PV = nRT \Rightarrow PdV + VdP = nRdT$$

$$PdV + VdP = nR\left(-\frac{PdV}{nC_V}\right) = \left(\frac{C_V - C_P}{C_V}\right)PdV$$

$$\frac{dV}{V} + \frac{dP}{P} = (1 - \gamma) \frac{dV}{V} \quad \gamma \frac{dV}{V} + \frac{dP}{P} = 0$$

$$\ln V^\gamma + \ln P = \ln PV^\gamma = \text{const.}$$

$$PV^\gamma = \text{const.} \quad TV^{\gamma-1} = \text{const.}$$

$$T_f V_f^{\gamma-1} = T_i V_i^{\gamma-1}$$

$$P_f V_f^\gamma = P_i V_i^\gamma$$

Four Ideal-Gas Processes Summary

Process	Definition	Stays constant	Work	Heat
Isochoric	$\Delta V = 0$	V and p/T	$W = 0$	$Q = nC_V\Delta T$
Isobaric	$\Delta p = 0$	p and V/T	$W = -p\Delta V$	$Q = nC_P\Delta T$
Isothermal	$\Delta T = 0$	T and pV	$W = -nRT \ln(V_f/V_i)$	$\Delta E_{th} = 0$
Adiabatic	$Q = 0$	pV^γ	$W = \Delta E_{th}$	$Q = 0$
All gas processes	First law $\Delta E_{th} = W + Q = nC_V\Delta T$		Ideal-gas law $pV = nRT$	

Quantitative example. 0.005 mol of a diatomic ideal gas is brought from state (1) $V_1 = 100 \text{ cm}^3$ and $P_1 = 1.0 \text{ atm}$ to state (2) $V_2 = 300 \text{ cm}^3$ and $P_2 = 3.0 \text{ atm}$.

a) Draw a PV diagram for this process (assume it follows a straight line)

Find Q for this process 1-2.

*Use $1 \text{ atm} = 1 \times 10^5 \text{ Pa}$
to simplify calculation.*

The gas is then brought to state (3) $V_3 = 300 \text{ cm}^3$ and $P_3 = 1.0 \text{ atm}$ and then back to state (1).

b) Complete the PV diagram for this whole cycle.

c) Find W, Q and ΔU for processes 2-3 and 3-1, and for the whole cycle.

Quantitative example. 0.005 mol of a diatomic ideal gas is brought from state (1) $V_1 = 100 \text{ cm}^3$ and $P_1 = 1.0 \text{ atm}$ to state (2) $V_2 = 300 \text{ cm}^3$ and $P_2 = 3.0 \text{ atm}$.

a) Draw a PV diagram for this process (assume it follows a straight line). Find Q for this process 1-2.

The gas is then brought to state (3) $V_3 = 300 \text{ cm}^3$ and $P_3 = 1.0 \text{ atm}$ and then back to state (1).

b) Complete the PV diagram for this whole cycle.

c) Find W, Q and ΔU for processes 2-3 and 3-1, and for the whole cycle.

*Use $1 \text{ atm} = 1 \times 10^5 \text{ Pa}$
to simplify calculation.*

$$R = 8.31 \text{ J/mol} \cdot \text{K} \quad R = 0.082 \frac{\text{L} \cdot \text{atm}}{\text{mol} \cdot \text{K}}$$

$$\Delta U = nC_V \Delta T \quad \Delta U = Q + W$$