



Chapter 4

Heat and Thermodynamics

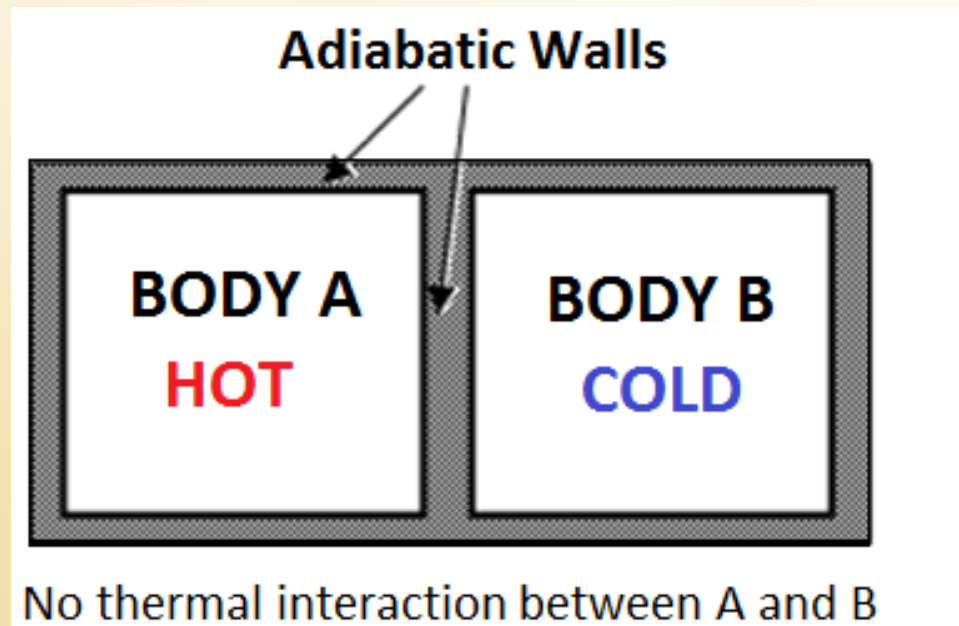
The Concept of Temperature and Heat

- What is temperature?
 - Qualitatively, based on our senses, **TEMPERATURE is a physical quantity that tells us how warm or cold an object is.**
 - This qualitative definition does not answer the question “how hot is hot?”
 - Also, our senses are misleading



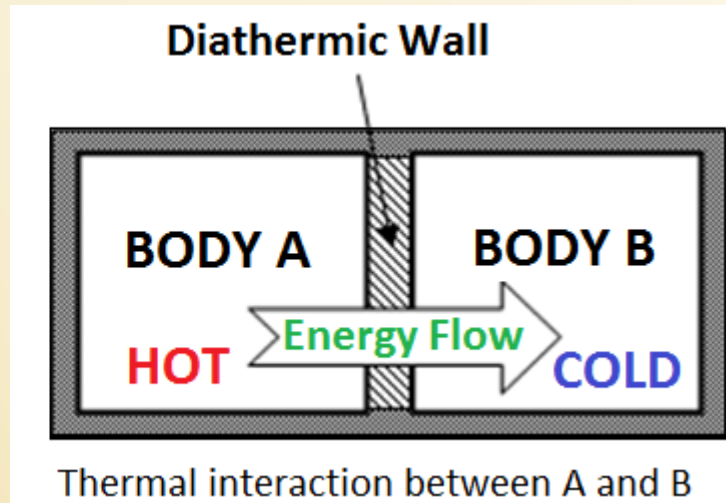
The Concept of Temperature and Heat

- What is temperature?
 - We need an *operational definition* of temperature.
 - Consider two bodies A and B, A being hotter than B, thermally isolated from each other.



- What happens when thermal contact is established between A and B?

The Concept of Temperature and Heat



- **Heat** is **energy in transfer** from a hot to a cold body.
- Objects are in **thermal contact** if heat can flow between them.

- Eventually, the energy flow stops.
- The two bodies will be in **thermal equilibrium**.
- They are said to be at the same **temperature**.

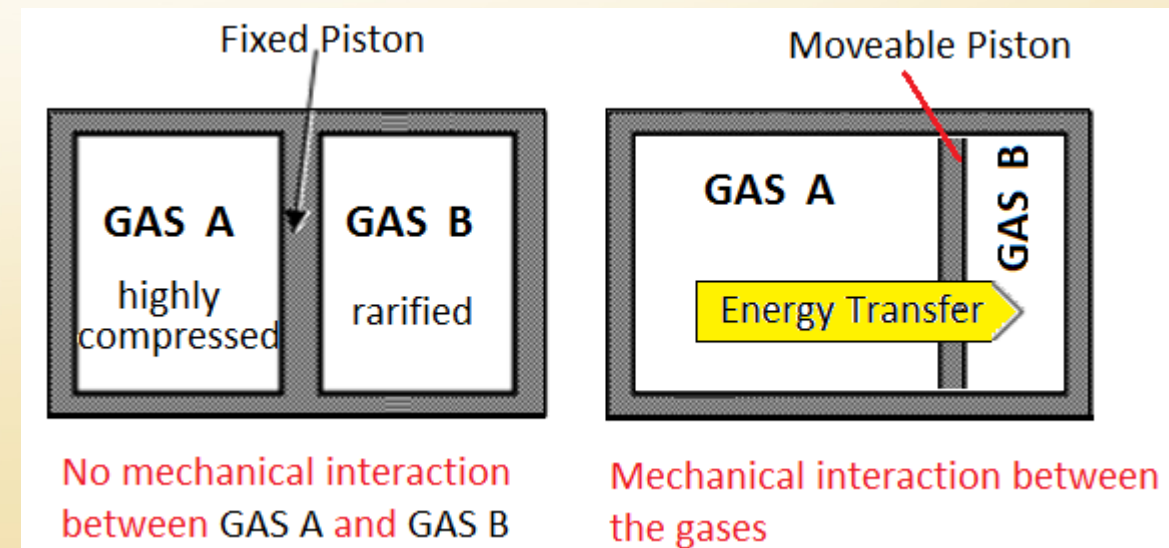
The Concept of Temperature and Heat

- Definition of temperature

*There is a scalar quantity called **temperature** that assumes the same value for bodies in thermal equilibrium.*

- Mechanical Analogy

*There is a quantity called **pressure** that assumes the same value for bodies in mechanical equilibrium.*

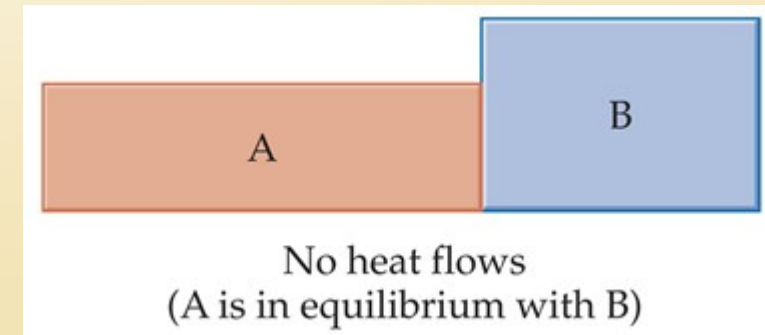
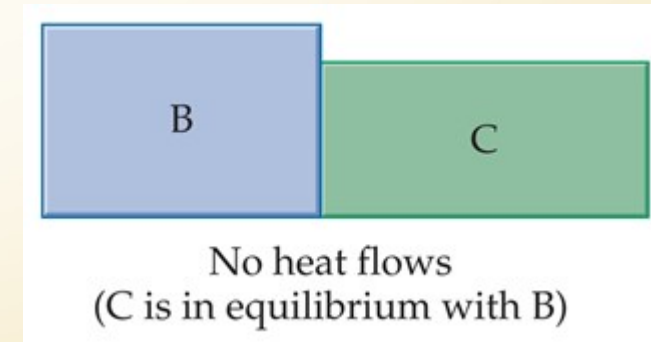
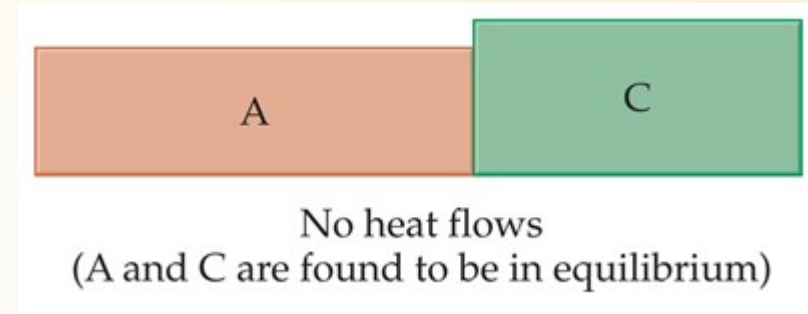


The Zeroth Law of Thermodynamics

Let's now introduce a third body C

ZEROth LAW OF THERMODYNAMICS

If bodies A and B are **separately** in thermal equilibrium with a third body C, then bodies A and B will be in thermal equilibrium if they are placed in thermal contact.



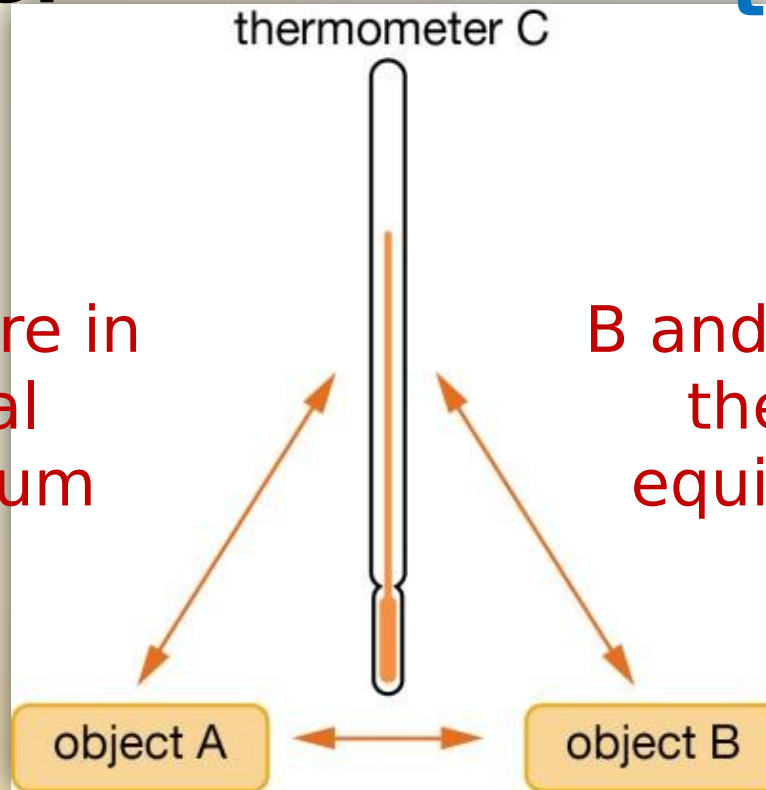
The Zeroth Law of Thermodynamics

What is the third body C?

The third body is a thermometer.

A and C are in thermal equilibrium

B and C are in thermal equilibrium



A and B are in thermal equilibrium

A thermometer is an instrument that measures the temperature of a body in a quantitative way.

Temperature is the only factor that determines whether two objects in thermal contact are in thermal equilibrium or not.

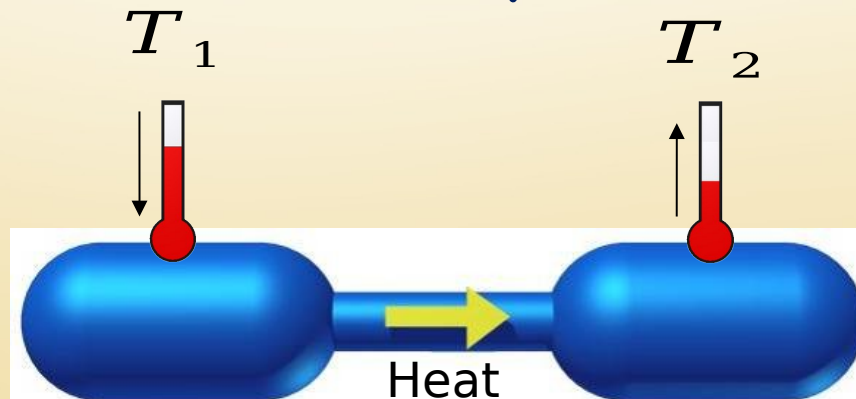
Thermal Energy (Heat) **versus** Temperature

Thermal Energy (Heat)

- is kinetic energy in transit from one object to another due to **temperature difference**.
- Measured in calories or Joules
- Any object with temperature above zero Kelvin has thermal energy

Temperature

- is the average kinetic energy of particles in an object – not the total amount of kinetic energy particles.
- Measured in °C, °F, K
- Absolute zero is zero Kelvin

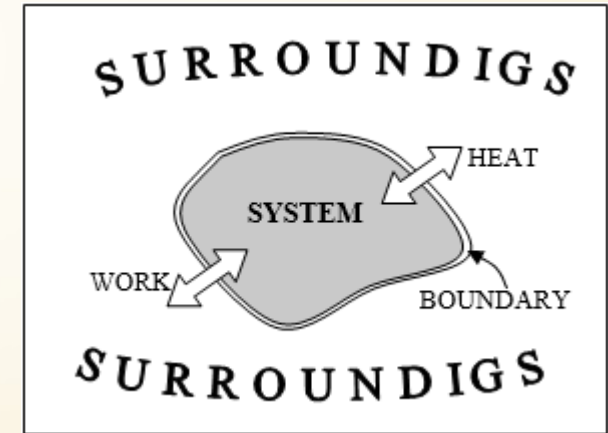


Quiz

- **The zeroth law of thermodynamics is**
 - A. A logical necessity**
 - B. An empirical fact**
 - C. A universal law**
 - D. Transitivity of thermal equilibrium**

Thermodynamics

- The study of the effects of work, heat, and energy on a **system**
- A **thermodynamic system** is a definite quantity of matter enclosed by boundaries, either real or imaginary.
- Everything outside the boundary is called the **surroundings**.
- The system may interact with the surroundings by interchanging energy through a transfer of *heat* and/or the performance of mechanical *work*.



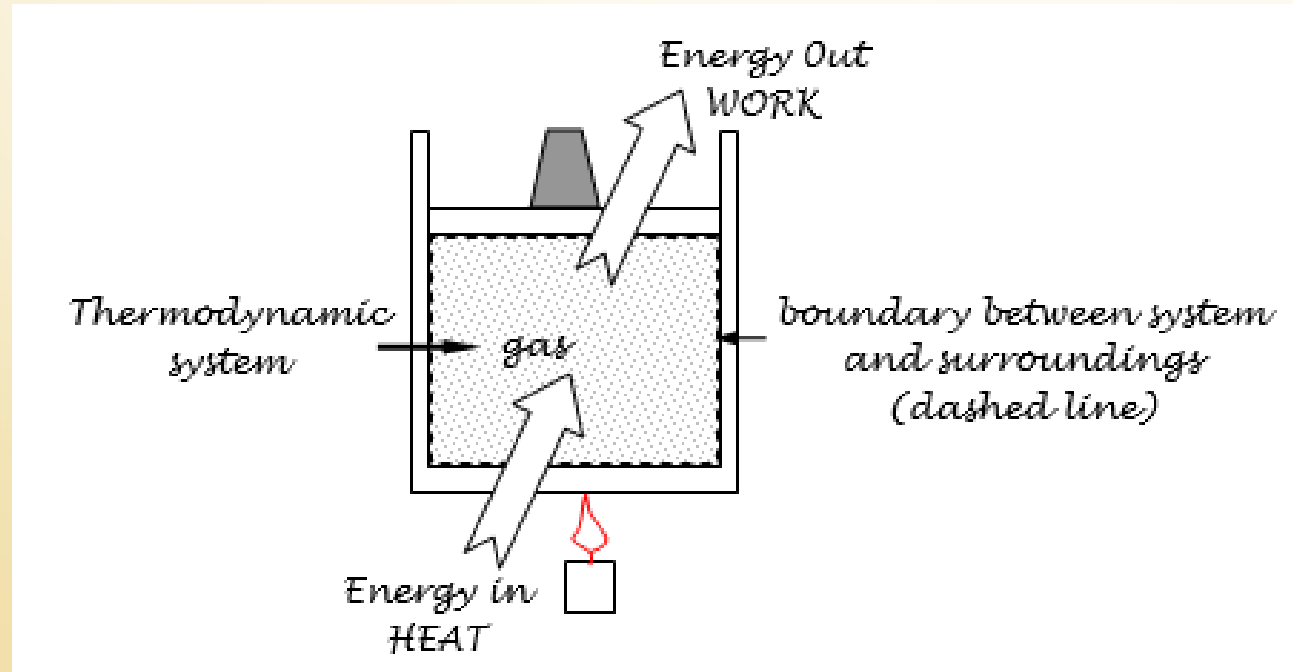
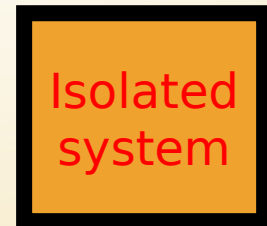
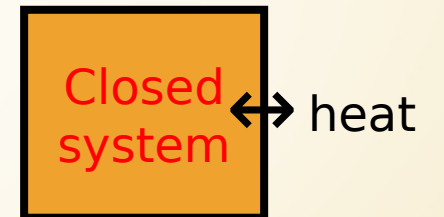
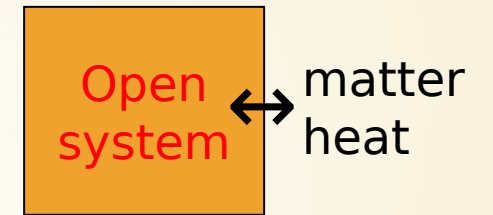
Thermal energy flows from hot to cold

- Identify the system and the surroundings
- Indicate the direction of energy flow



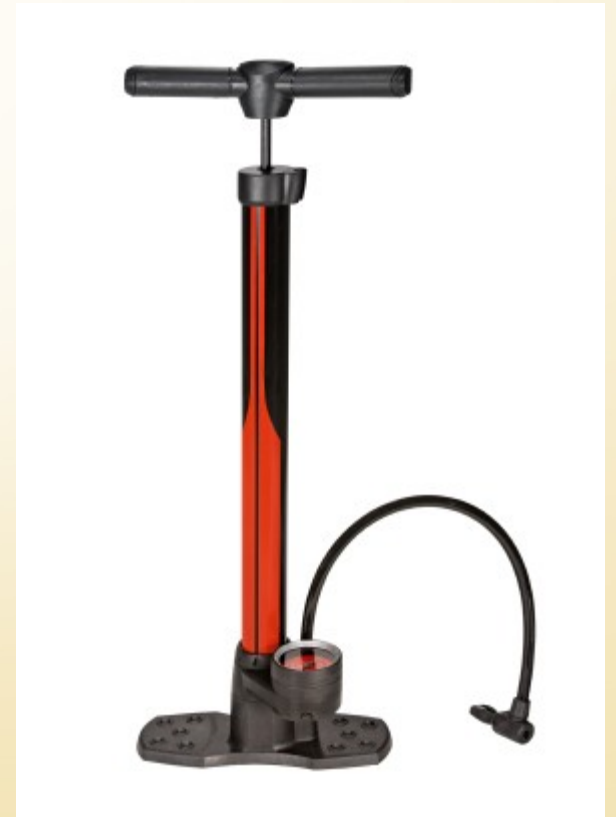
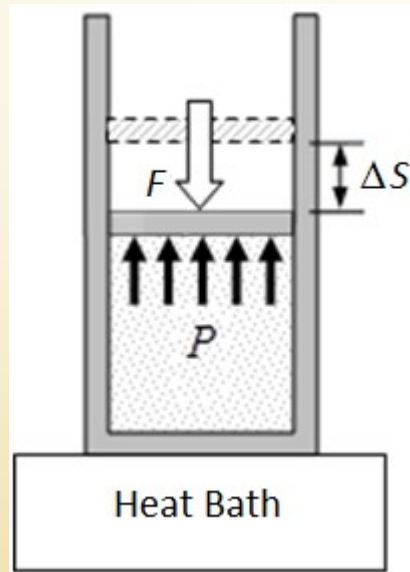
Thermodynamic Systems

- Open □ when matter CAN cross the boundary
- Closed □ when matter CANNOT cross the boundary
- Isolated □ Boundary seals matter and heat from being exchanged



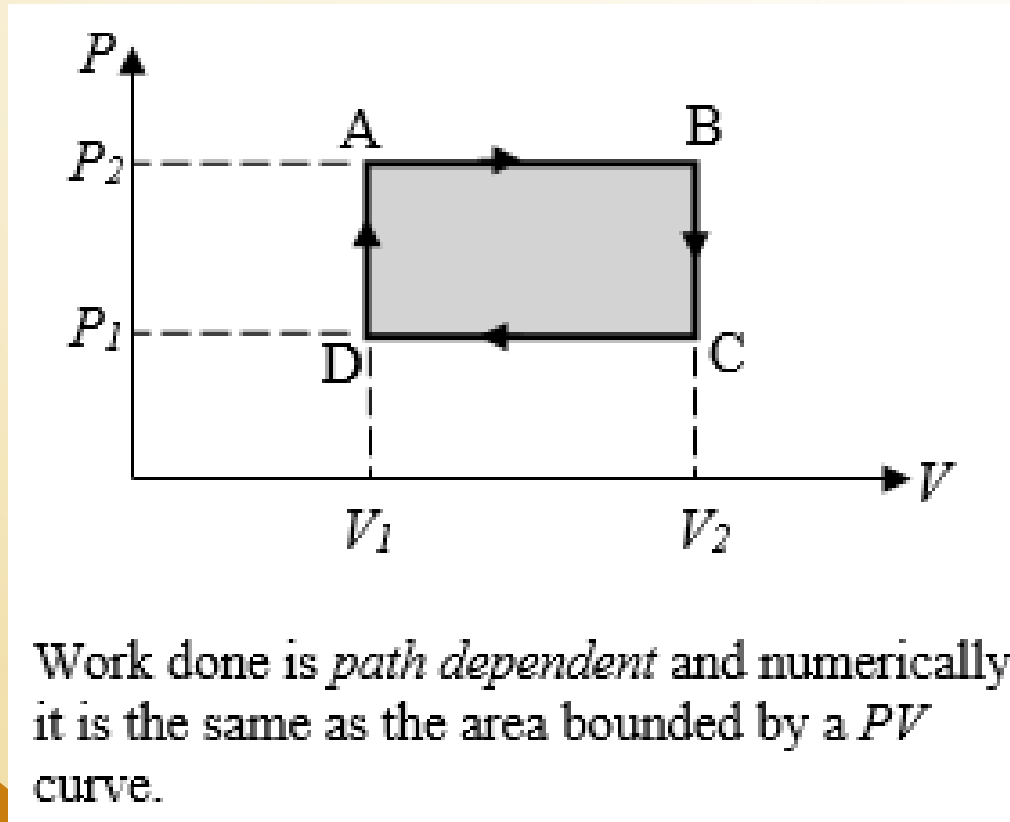
Work – Mechanical Energy Transfer

- Work done by expanding gas



Work – Mechanical Energy Transfer

- Work done depends on the thermodynamic process.



- Similarly, heat absorbed or rejected by a system depends on the thermodynamic process.

Internal Energy

Translation



Rotation



Vibration



Molecular
Interactions



The internal energy of a system is the sum of the **kinetic** and **potential** energies of the atoms and molecules making up the system.

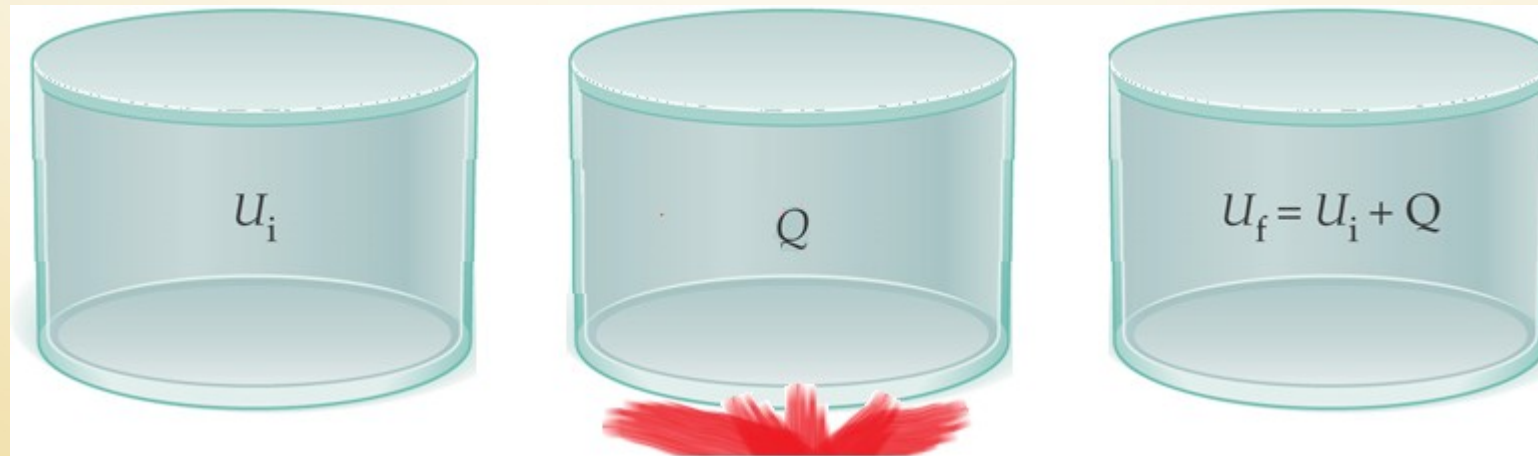


The First Law of Thermodynamics

The first law of thermodynamics is a statement of the conservation of energy.

If a system's volume is **constant**, and heat is added, its internal energy increases.

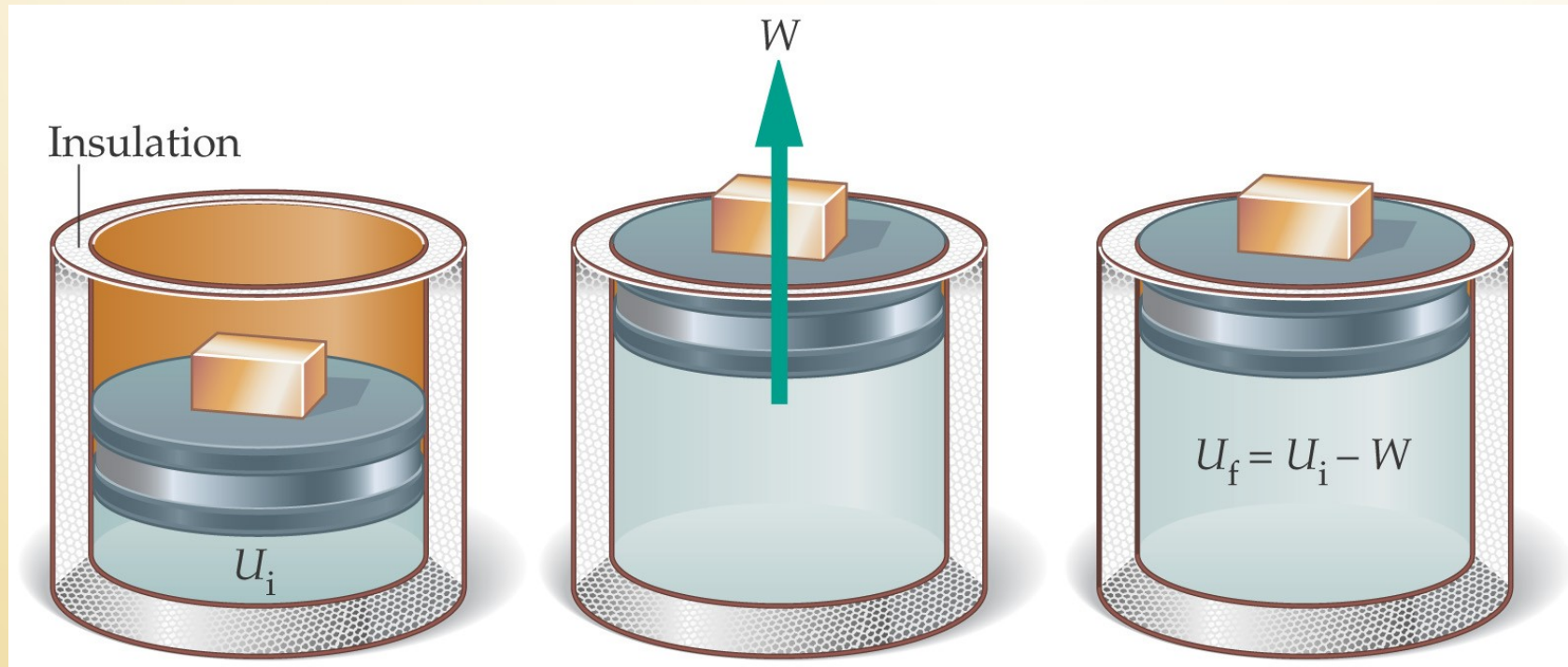
$$\Delta U = U_f - U_i = Q$$



The First Law of Thermodynamics

If a system does work on the external world, and no heat is added, its internal energy decreases.

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



The First Law of Thermodynamics

Combining these gives the first law of thermodynamics.

$$\Delta U = Q - W$$

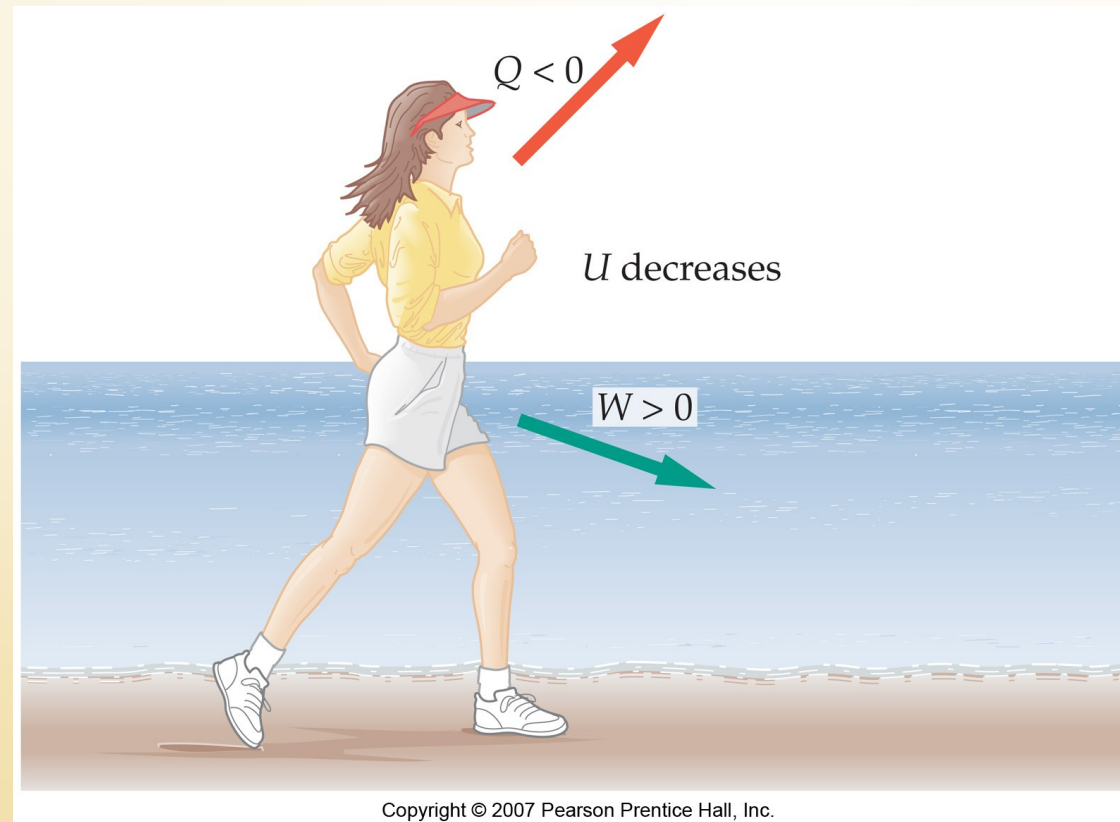
It is vital to keep track of the signs of Q and W .

TABLE 18–1 Signs of Q and W

Q positive	System <i>gains</i> heat
Q negative	System <i>loses</i> heat
W positive	Work done <i>by</i> system
W negative	Work done <i>on</i> system

The First Law of Thermodynamics

The internal energy of the system depends only on its temperature. The work done and the heat added, however, depend on the details of the process involved.



Quiz

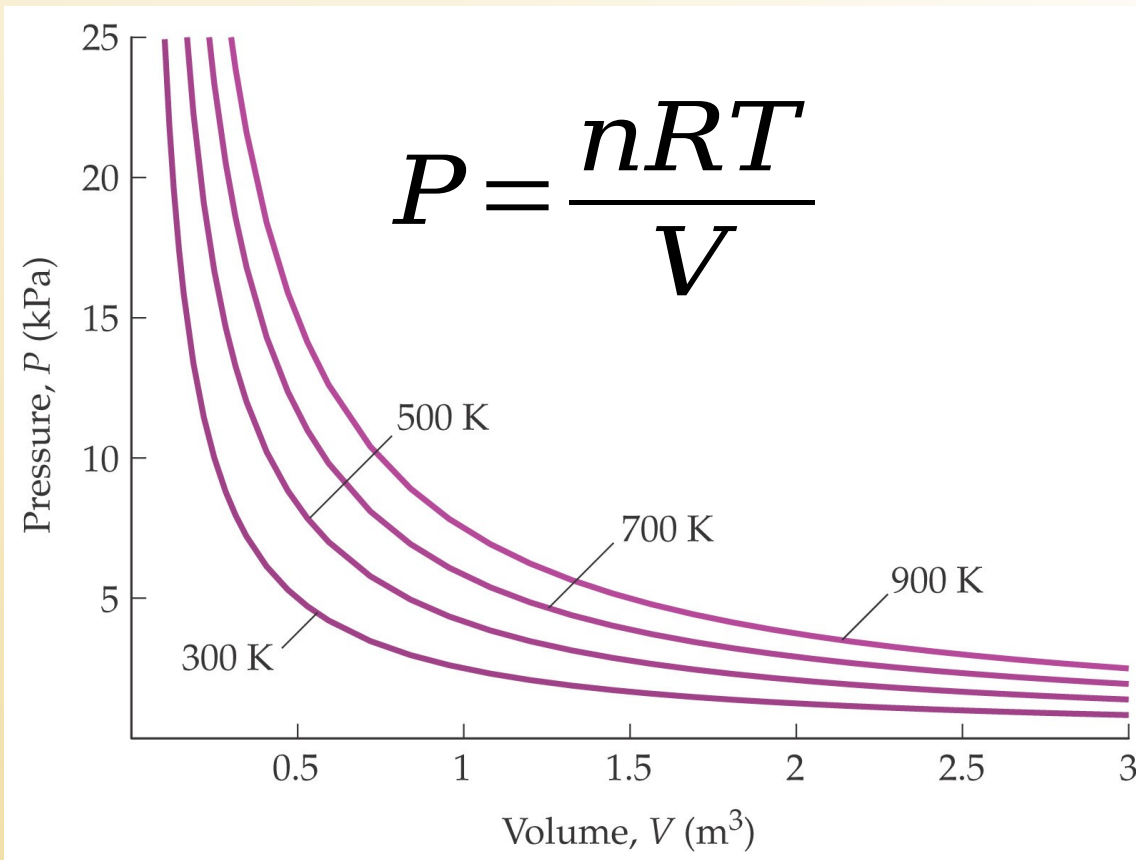
The first Law of Thermodynamics, $\Delta U = Q - W$, means:

- A. Heat cannot be added to a system without work being done.
- B. Work cannot be done without heat being added.
- C. The amount of work done always equals the amount of heat added.
- D. The total internal energy of a system is conserved.

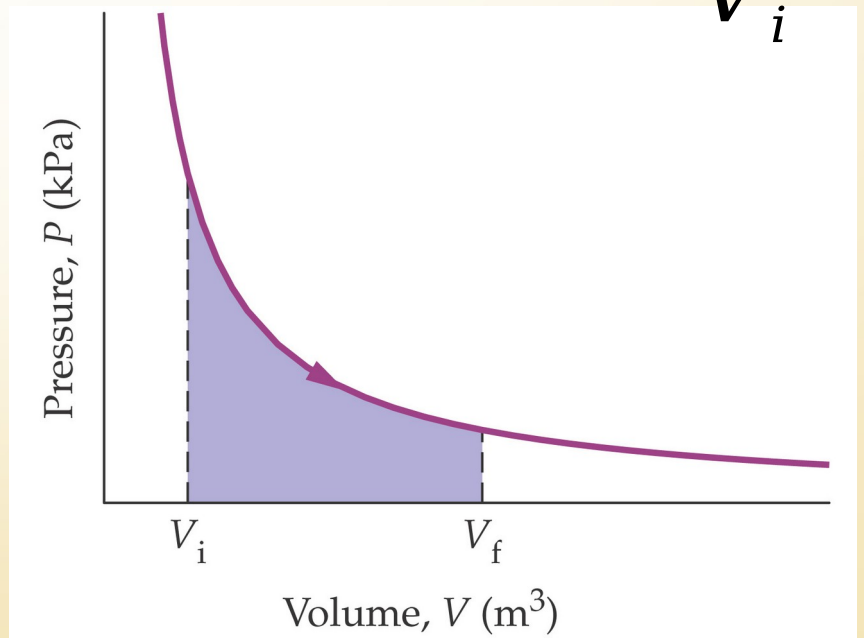
Processes in Thermodynamics

- Isothermal process → takes place at constant temperature
(*e.g. freezing of water to ice at 0°C*)
- Any heat flow into or out of the system must be slow enough to maintain thermal equilibrium
- For ideal gases, if ΔT is zero, $\Delta U = 0$
- Therefore, $Q = W$
 - Any energy entering the system (Q) must leave as work (W)

For an **ideal gas** undergoing an isothermal process, pressure varies inversely with volume.

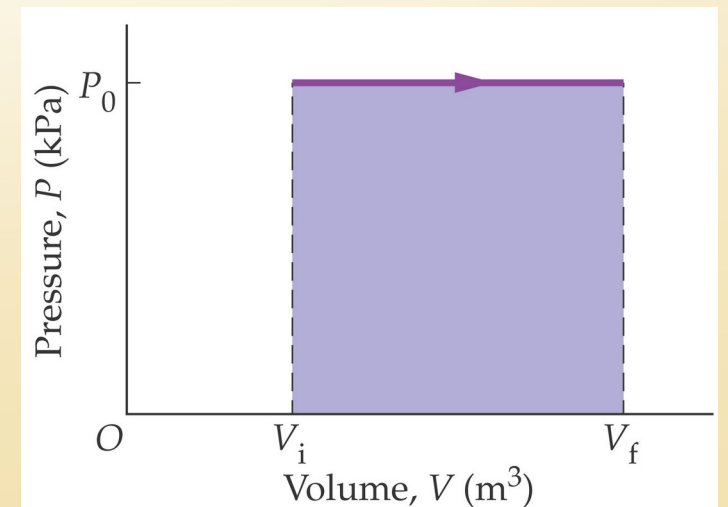
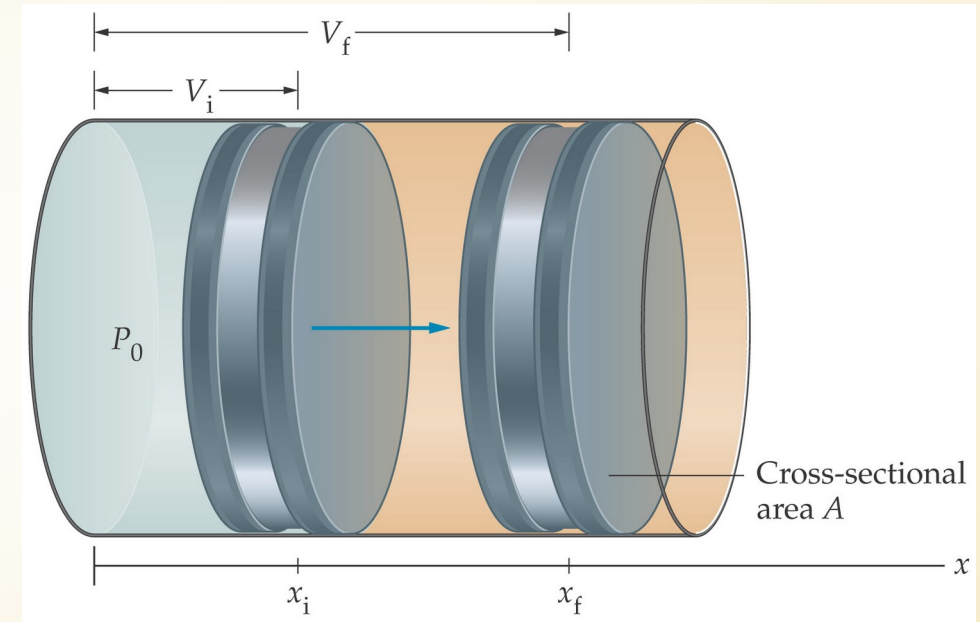


$$Q = W = nRT \ln \frac{V_f}{V_i}$$



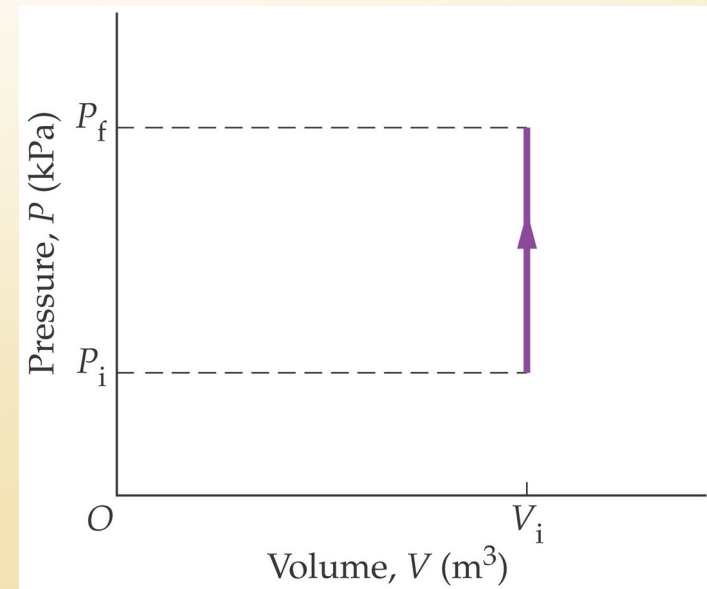
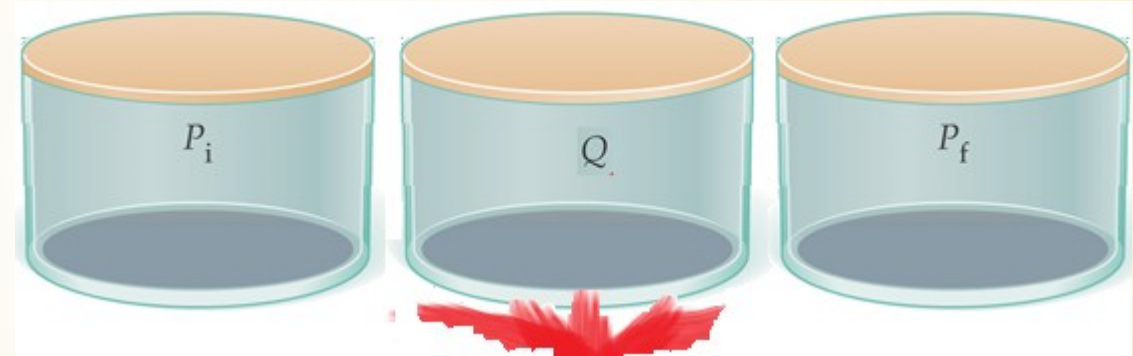
Processes in Thermodynamics

- **Isobaric process** → takes place constant pressure (*e.g. heating of water in open air* → under atmospheric pressure)
- ΔU , W , and Q are generally non-zero, but calculating the work done by an ideal gas is straightforward



Processes in Thermodynamics

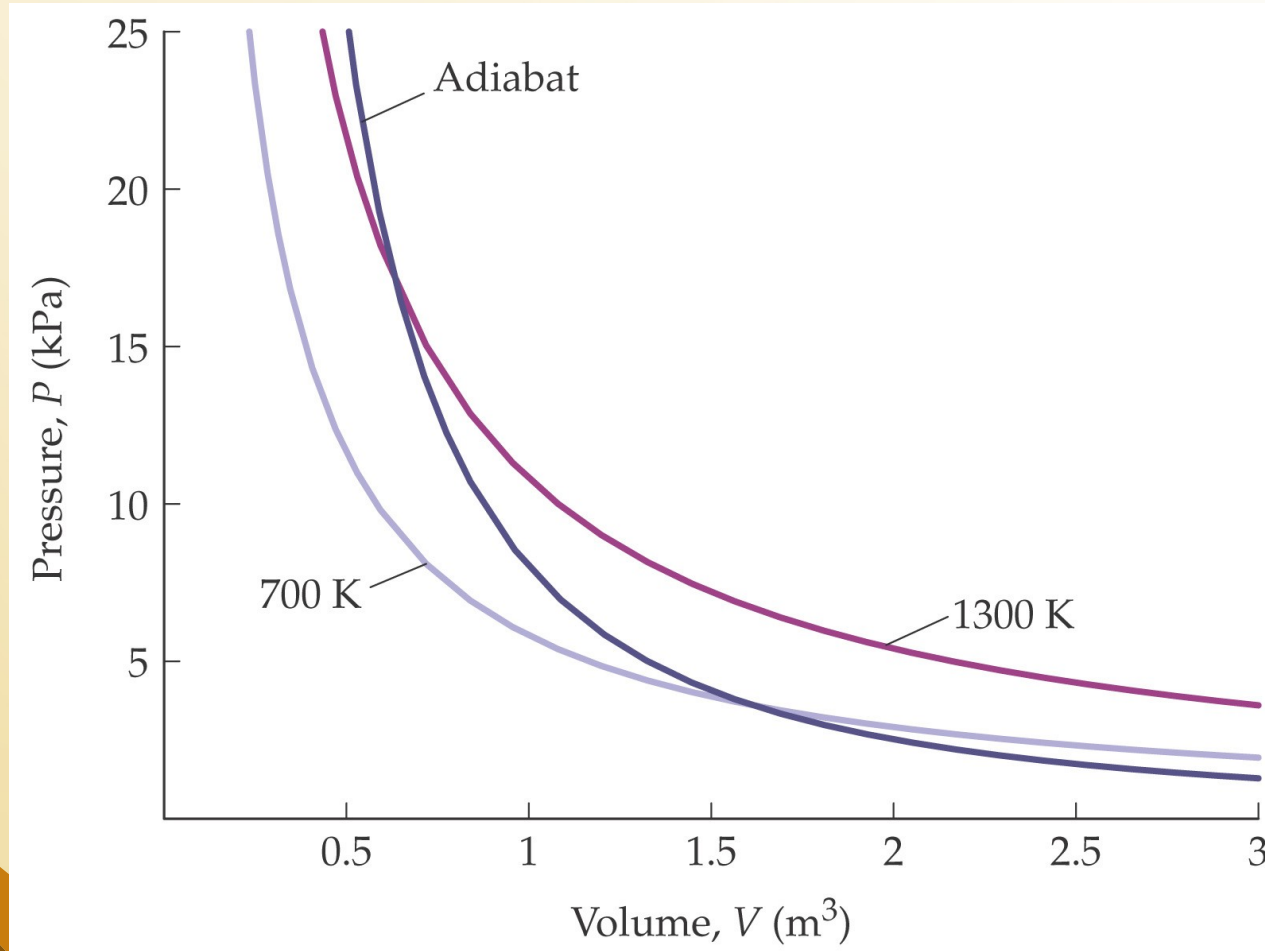
- **Isochoric process** → takes place constant volume (*e.g. heating of gas in a sealed metal container*)
- When the volume of a system doesn't change, it will do no work on its surroundings.



Processes in Thermodynamics

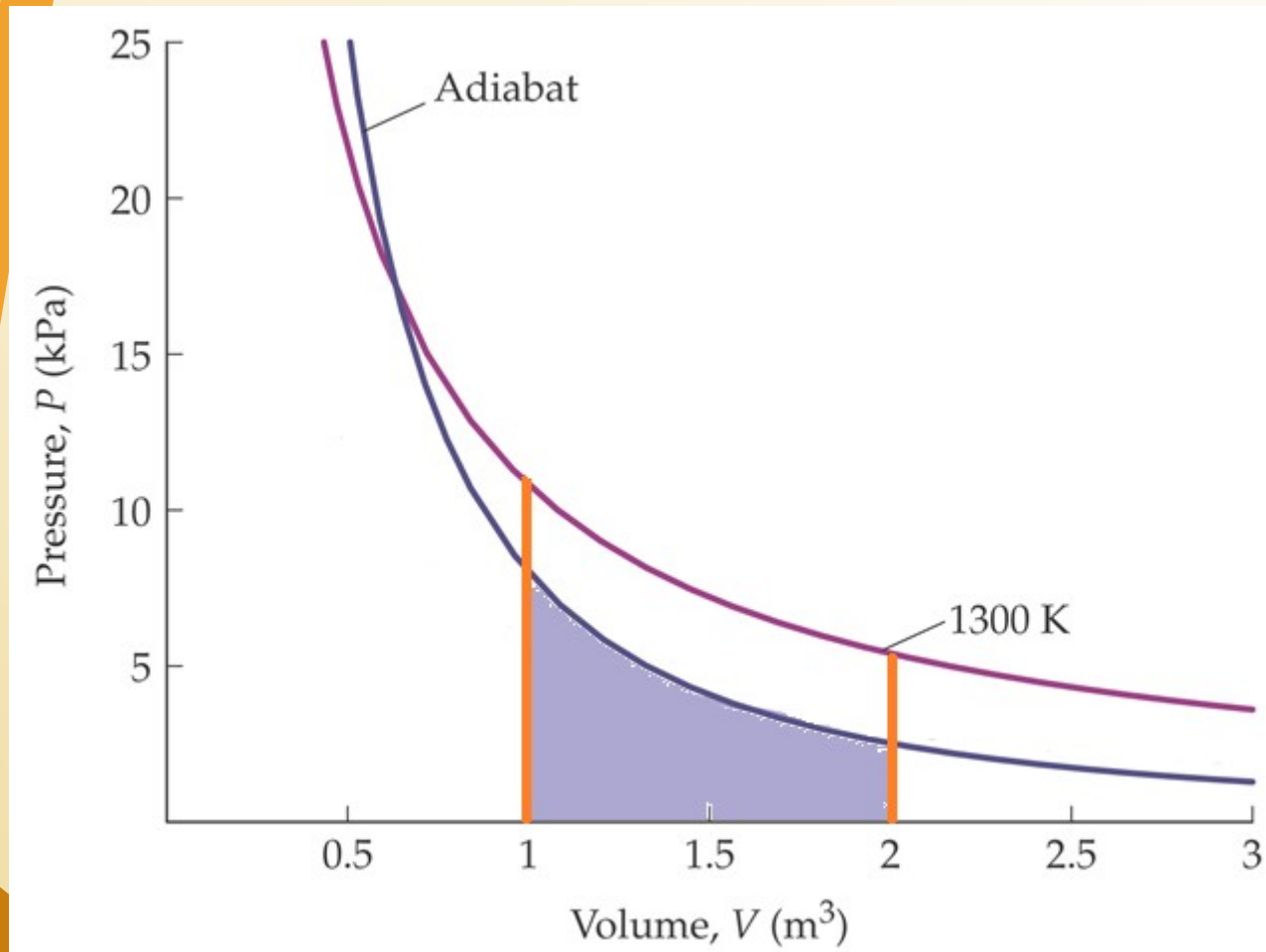
- Adiabatic process $\rightarrow$ no heat is added to/removed from the system
- Therefore and
- When a system expands adiabatically, Q is positive (the system does work) so W is negative.
- When a system compresses adiabatically, Q is negative (work is done on the system) so W is positive.

Processes in Thermodynamics



- The adiabatic P - V curve is similar to the isothermal one, but is steeper.
- The P - V curve for an adiabat is given by

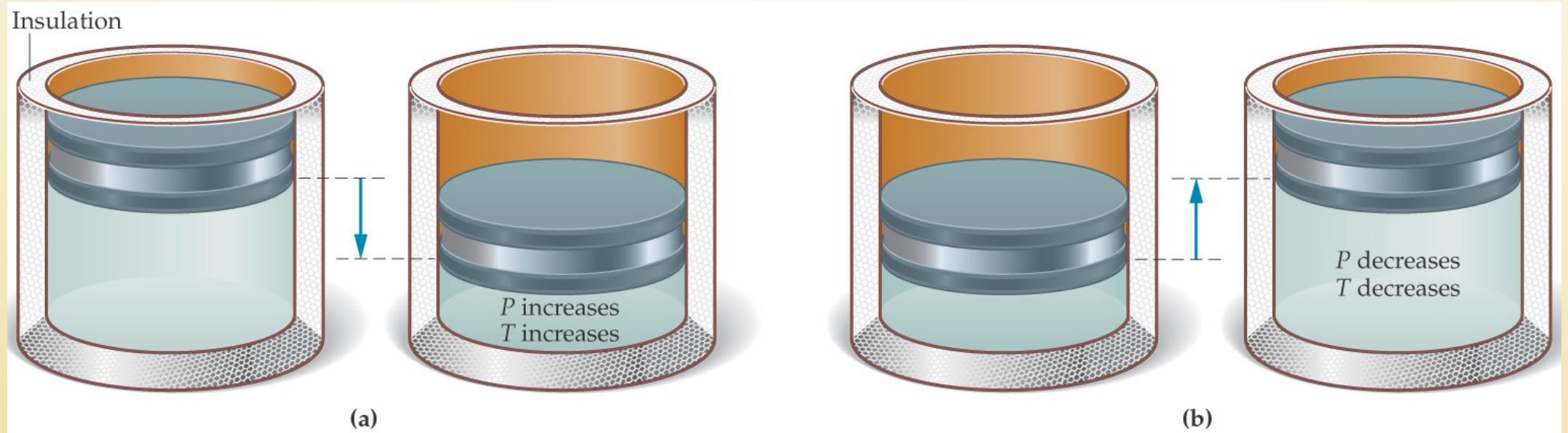
$$PV^\gamma = \text{constant}$$



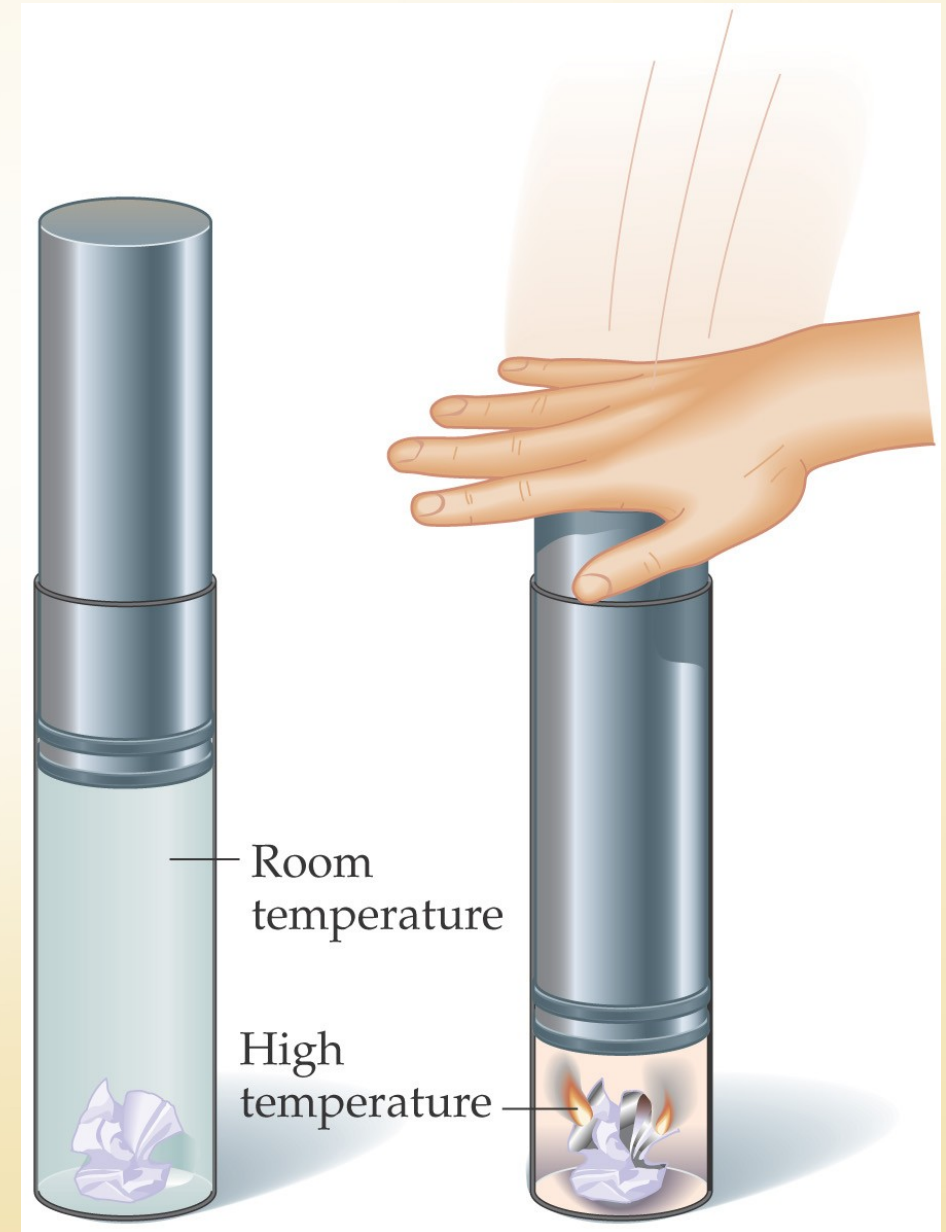
For an ideal gas:

Or

One way to ensure that a process is adiabatic is to insulate the system.



Another way to ensure that a process is effectively adiabatic is to have the volume change occur so **quickly** that heat has no time to flow in or out of the system.



In summary:

TABLE 18–2 Thermodynamic Processes and Their Characteristics

Constant pressure	$W = P\Delta V$	$Q = \Delta U + P\Delta V$
Constant volume	$W = 0$	$Q = \Delta U$
Isothermal (constant temperature)	$W = Q$	$\Delta U = 0$
Adiabatic (no heat flow)	$W = -\Delta U$	$Q = 0$

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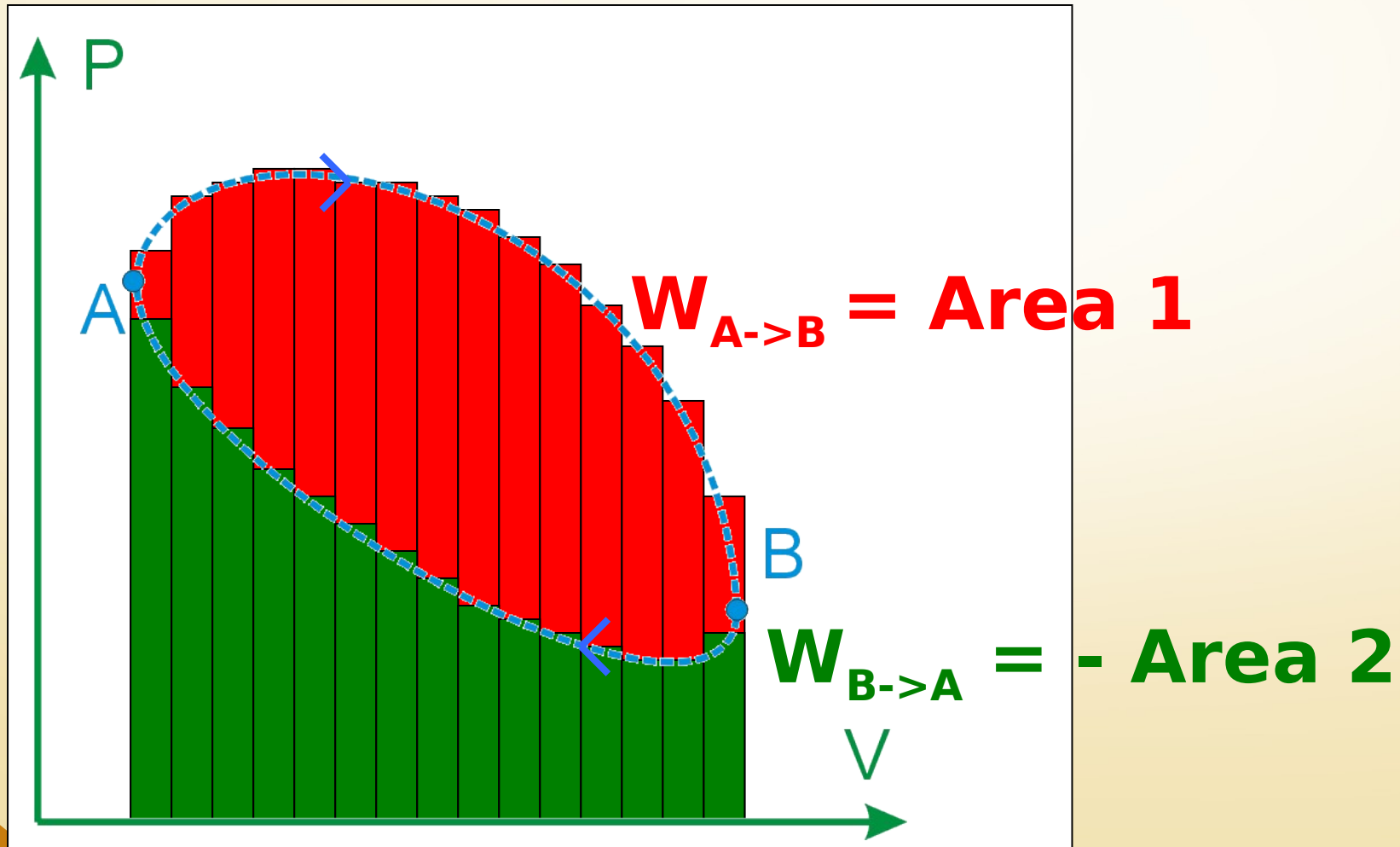
Other Processes in Thermodynamics

- Reversible process → system is close to equilibrium at all times
- Cyclic process → the final and initial state are the same.

For the ideal gas, and

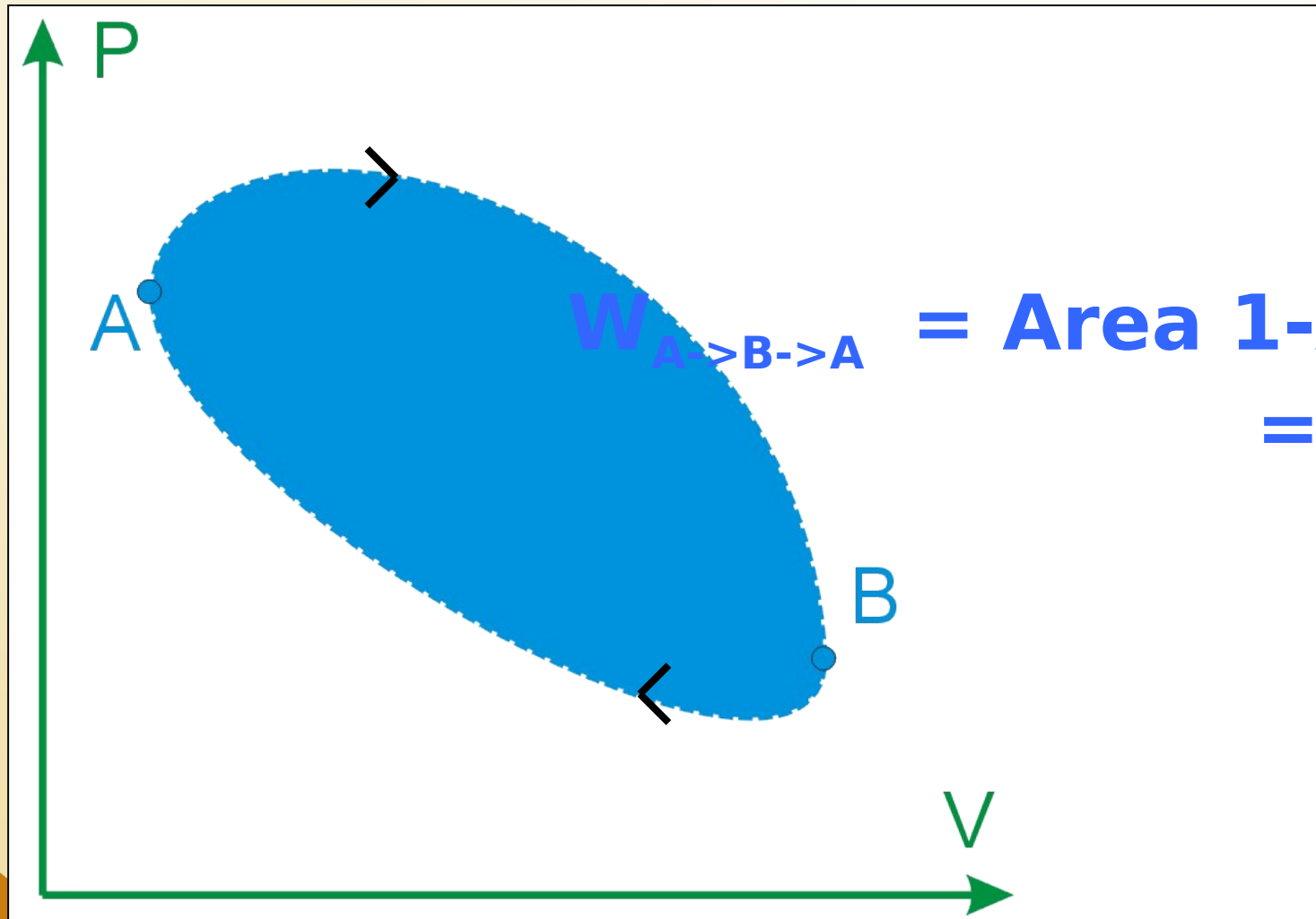
Consider cycle $A \rightarrow B \rightarrow A$

(work done by gas in a cycle)



Consider cycle $A \rightarrow B \rightarrow A$

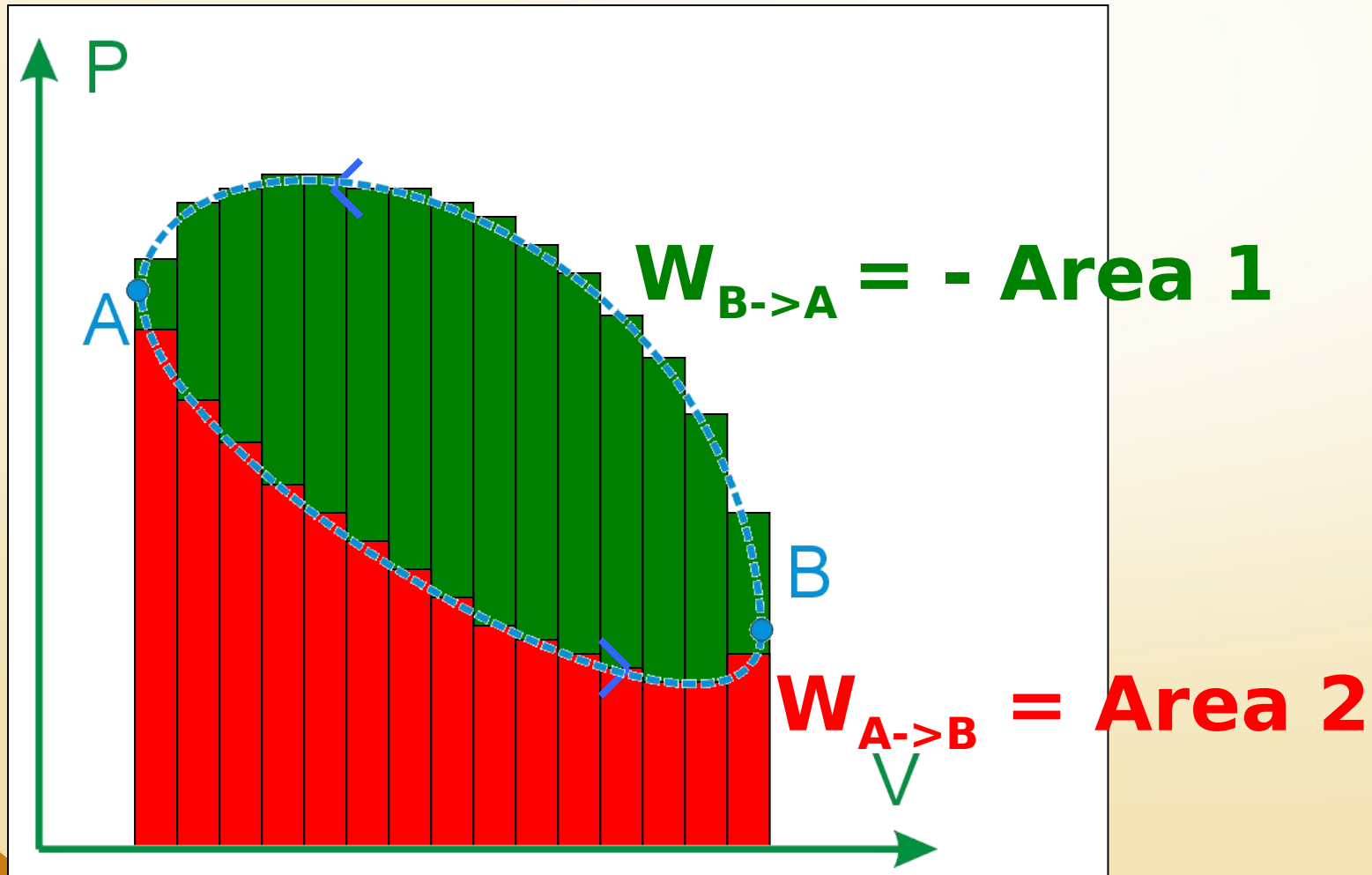
(work done by gas in a cycle)



$$W_{A \rightarrow B \rightarrow A} = \text{Area 1} - \text{Area 2} \\ = \text{Area of loop}$$

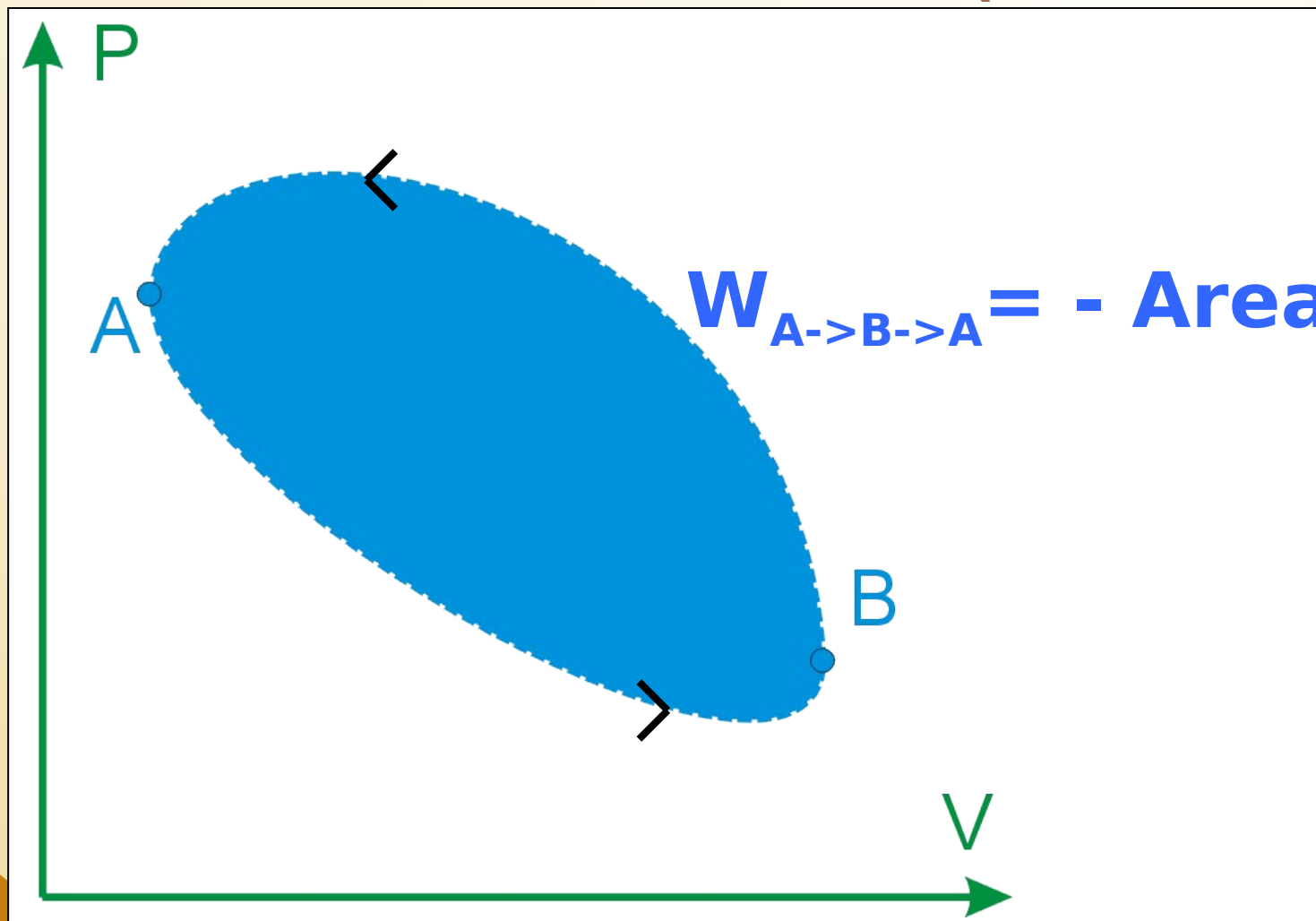
Reverse the cycle, make it counter clockwise

(work done by gas in a cycle)



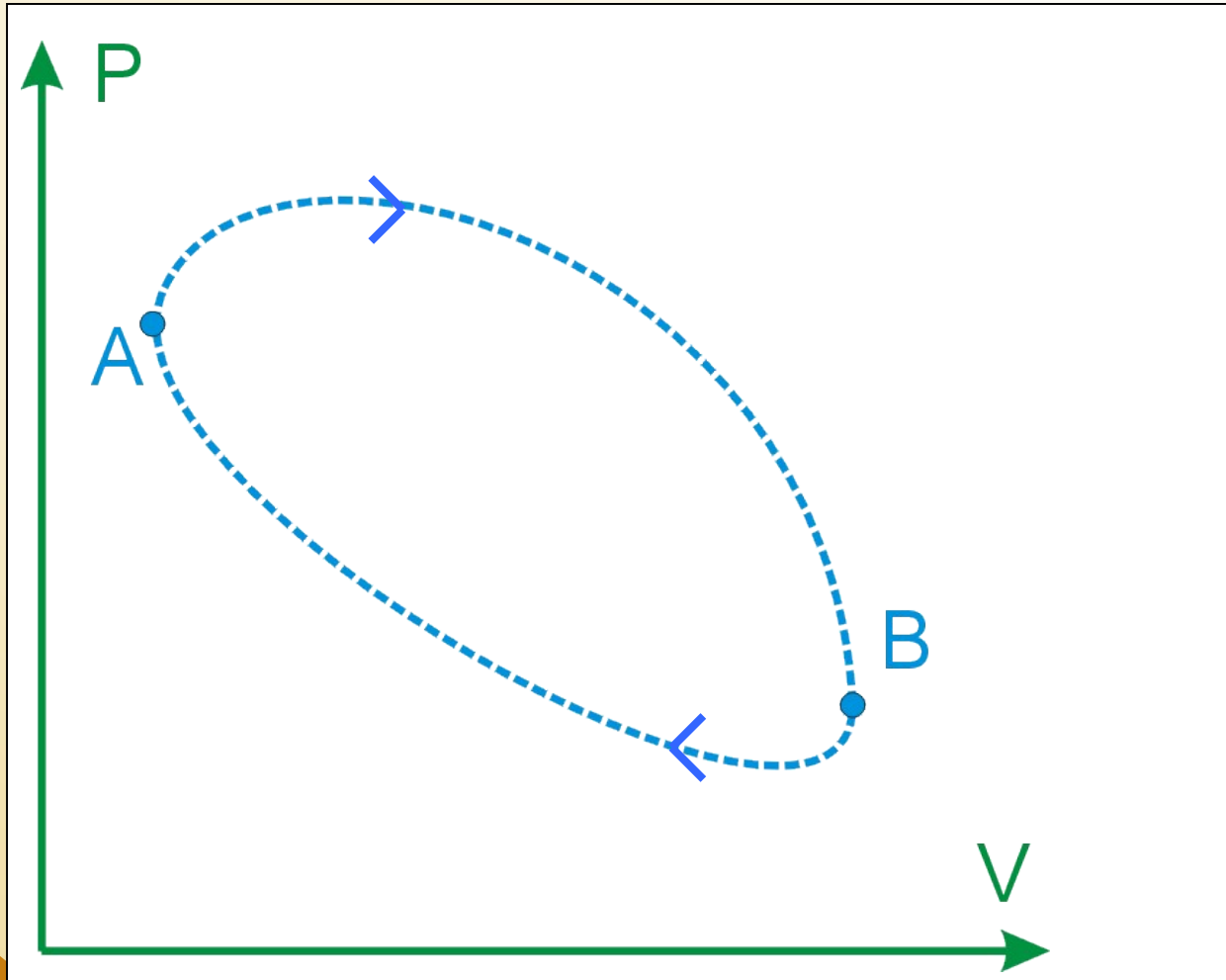
Reverse the cycle, make it counter clockwise

(work done by gas in a cycle)



$$W_{A \rightarrow B \rightarrow A} = - \text{Area of loop}$$

Internal Energy in closed cycles



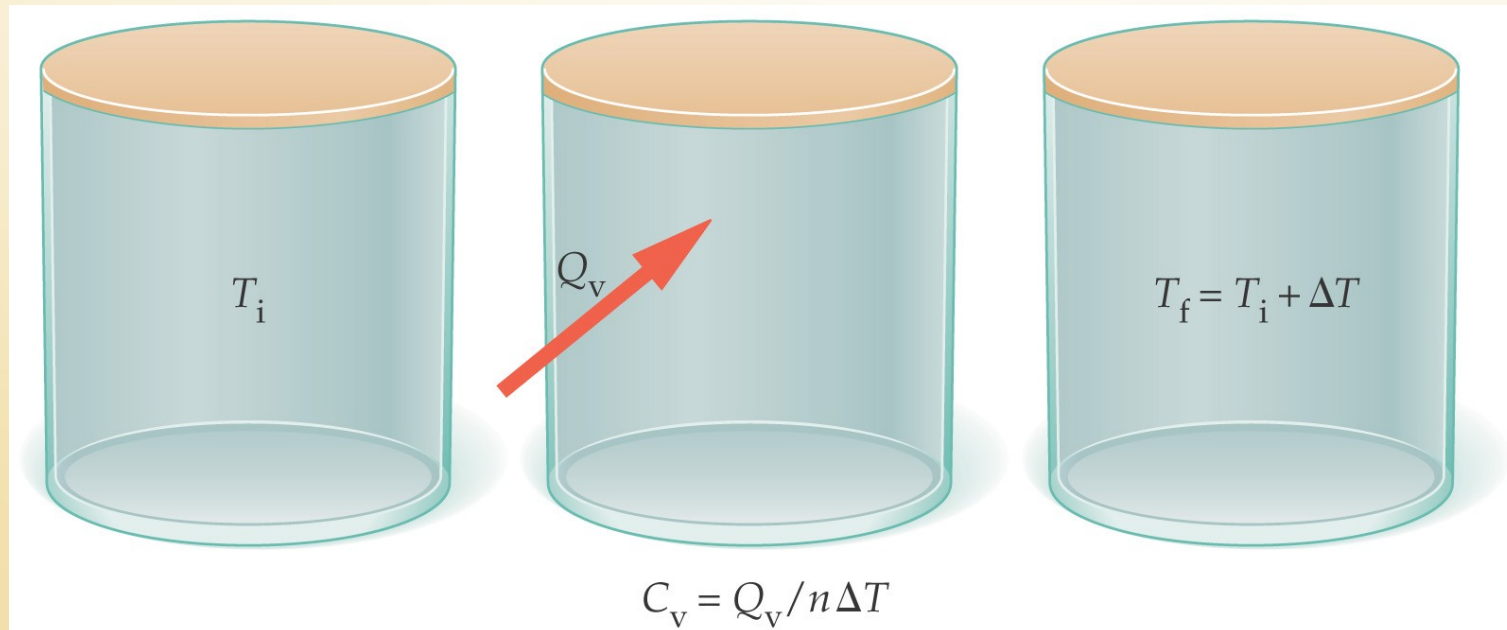
$\Delta U = 0$
in closed cycles

Specific Heats for an Ideal Gas

Specific heats for ideal gases must be quoted either at constant pressure or at constant volume.

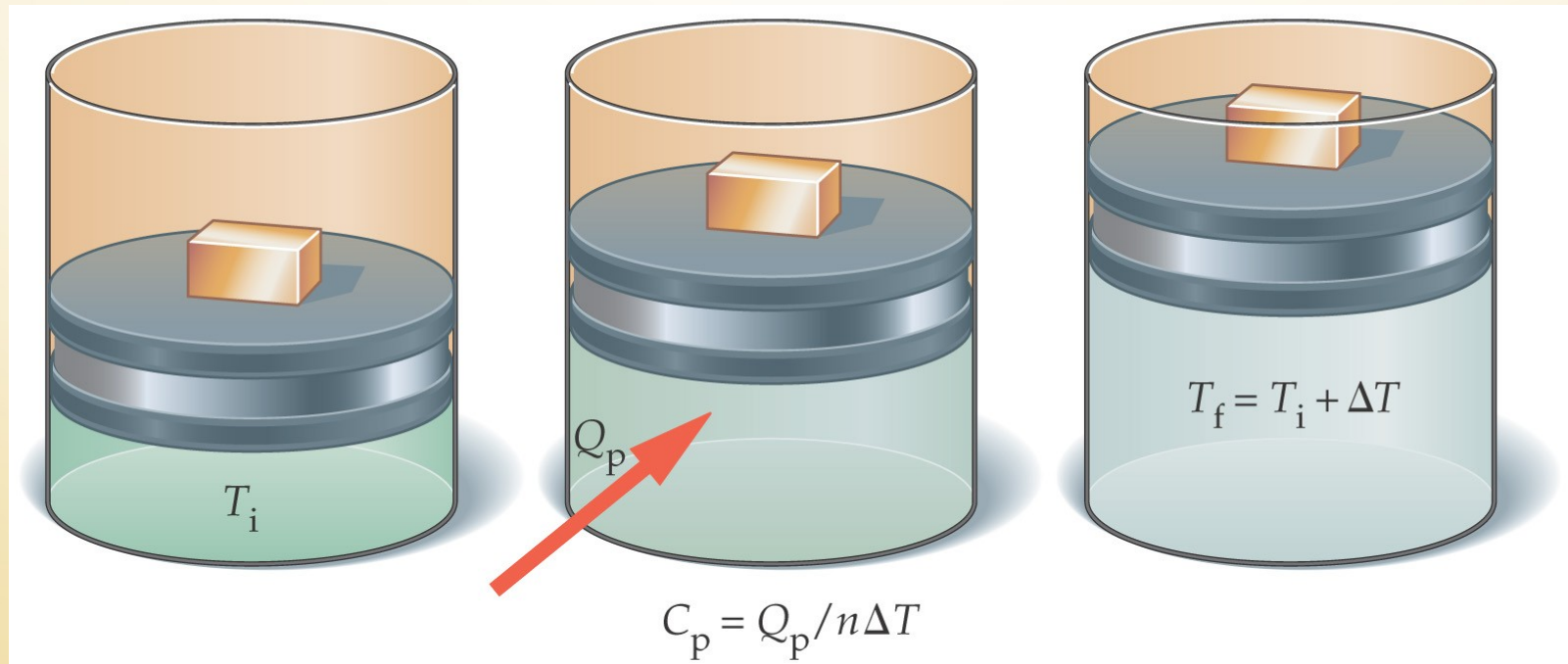
For a constant-volume process,

$$Q_v = nC_v\Delta T$$



Specific Heats for an Ideal Gas

At constant pressure, $Q_p = nC_p \Delta T$



Specific Heats for an Ideal Gas

Both C_V and C_P can be calculated for a monatomic ideal gas using the first law of thermodynamics.

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

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

$$C_P - C_V = R$$

$$\gamma = \frac{C_P}{C_V} = \frac{\frac{5}{2}R}{\frac{3}{2}R} = \frac{5}{3}$$

Specific Heats for an Ideal Gas

Although this calculation was done for an ideal, monatomic gas, it works well for real gases.

TABLE 18–3 $C_p - C_v$ for Various Gases

Helium	$0.995 R$
Nitrogen	$1.00 R$
Oxygen	$1.00 R$
Argon	$1.01 R$
Carbon dioxide	$1.01 R$
Methane	$1.01 R$

Calculating Energy Transfer

Calculate the energy transferred when a block of aluminum at 80.0°C is placed in 1.00 liter (1kg) of water at 25.0°C if the final temperature becomes 30.0°C .

Step 1. List all known values

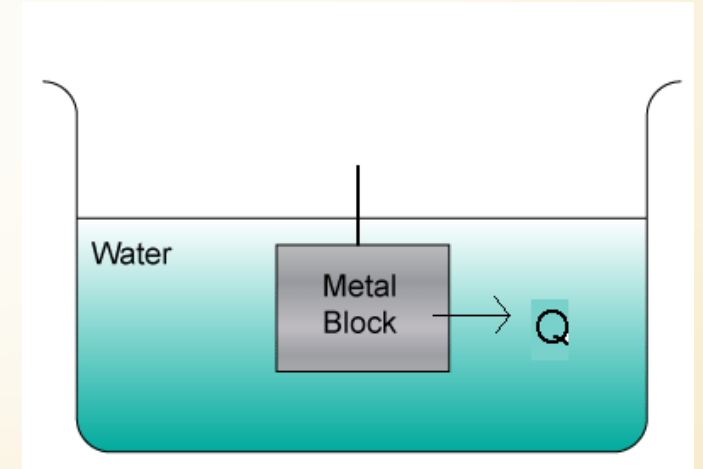
Mass of water = 1 kg

C_p of water = 4184

Difference in temperature $= \Delta T = 30.0^{\circ}\text{C} - 25.0^{\circ}\text{C} = 5.0^{\circ}\text{C}$

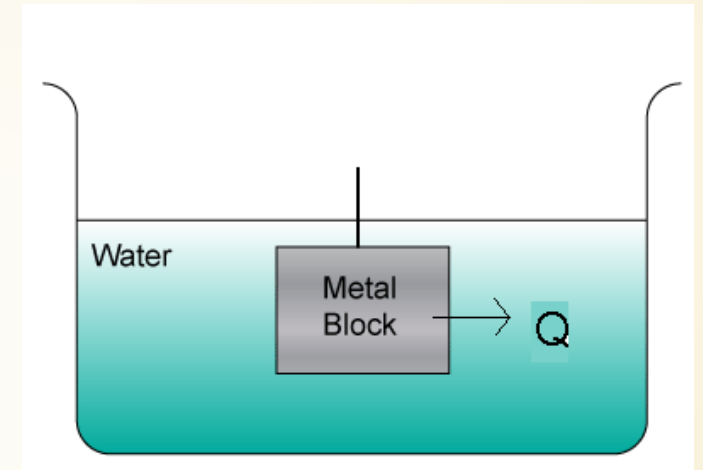
C_p of Al = 900

Difference in temperature $= \Delta T = 80.0^{\circ}\text{C} - 30.0^{\circ}\text{C} = 50.0^{\circ}\text{C}$



Calculating Energy Transfer

Step 2. List all unknown values



Step 3. Select equations to solve unknown values

$$Q = m C_p \Delta T \quad Q_{Al} = Q_{water}$$

Step 4. Solve for Q_{water}

$$Q_{water} = (1.00 \text{ kg}) \times 4184 \text{ J/kg}^\circ\text{C} \times 5.0^\circ\text{C} = 20,920 \text{ J gained}$$

Calculating Energy Transfer

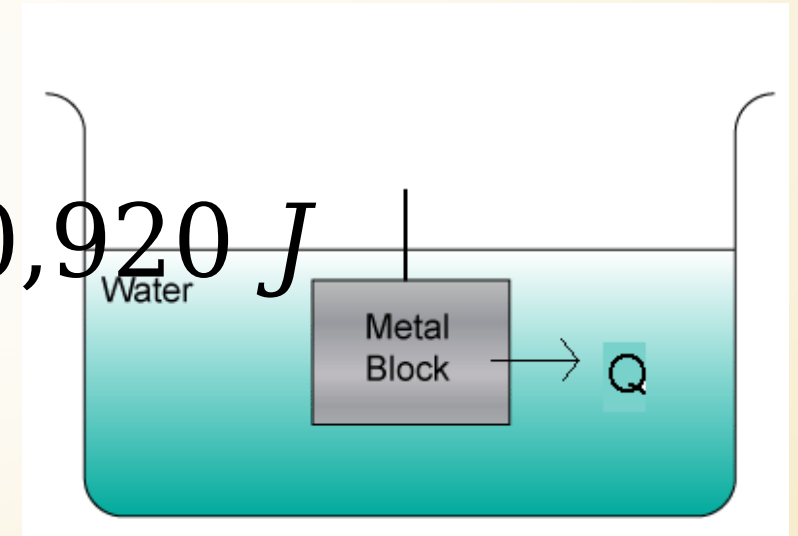
Step 5. Solve for

$$Q_{Al}(\text{lost}) = Q_{\text{water}}(\text{gained}) = 20,920 \text{ J}$$

$$Q_{Al} = m_{Al} C_p \Delta T$$

$$m_{Al} = \frac{Q_{Al}}{C_p \Delta T} = \frac{20920 \text{ J}}{900 \text{ J/kg}^\circ\text{C} \times 50.0^\circ\text{C}}$$

$$m_{Al} = 0.465 \text{ kg} = 465 \text{ g}$$





Examples and Quizzes

A cylinder of radius 5 cm is kept at a pressure with a piston of mass 75 kg.

a) What is the pressure inside the cylinder?

$1.950 \times 10^5 \text{ Pa}$

b) If the gas expands such that the cylinder rises 12.0 cm, what work was done by the gas?

183.8 J

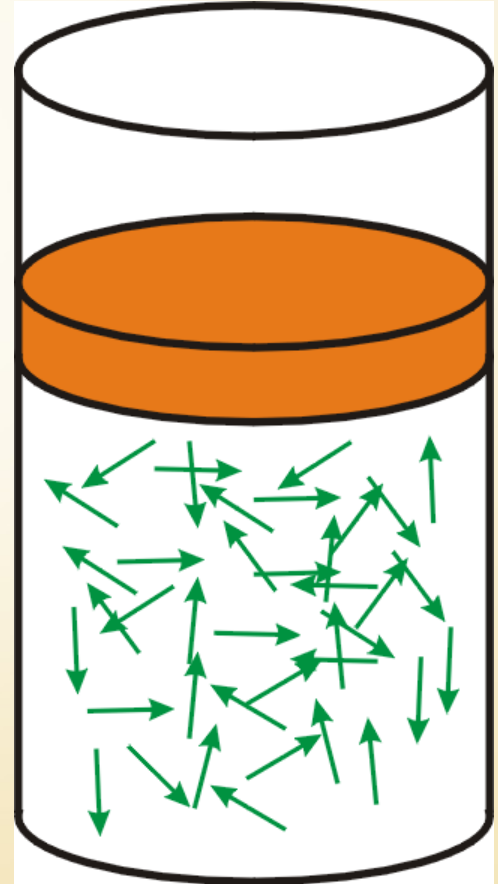
c) What amount of the work went into changing the gravitational PE of the piston?

88.3 J

d) Where did the rest of the work go?

Compressing the outside

air



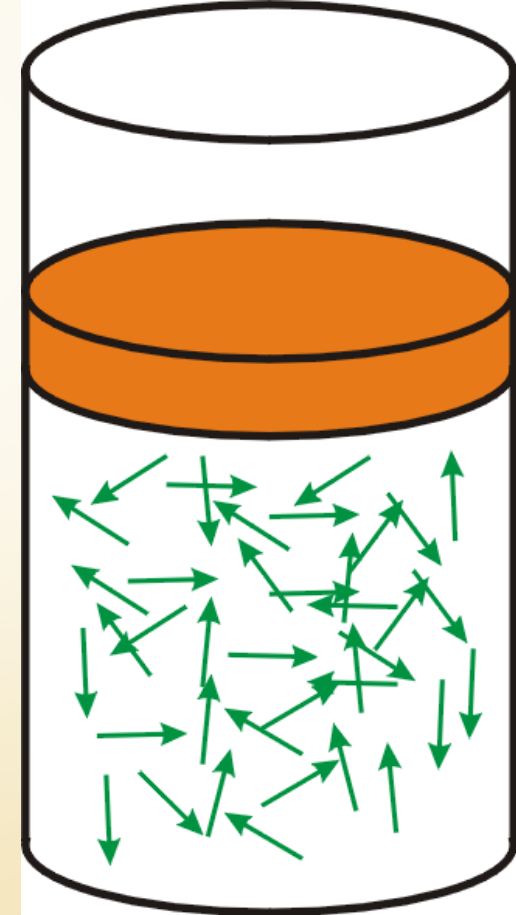
A massive copper piston traps an ideal gas as shown to the right. The piston is allowed to freely slide up and down and equilibrate with the outside air.

The pressure inside the cylinder is _____ the pressure outside.

The temperature inside the cylinder is _____ the temperature outside.

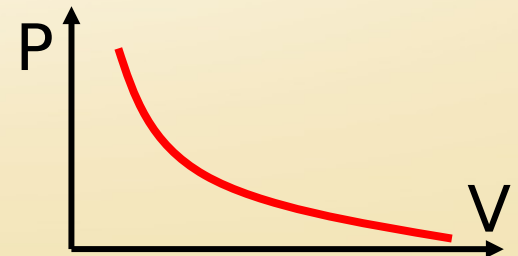
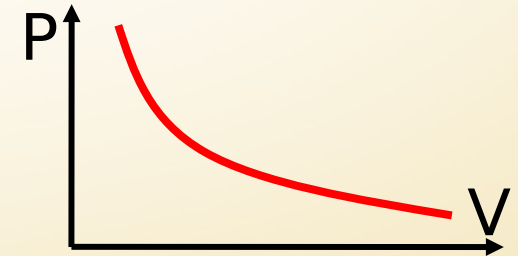
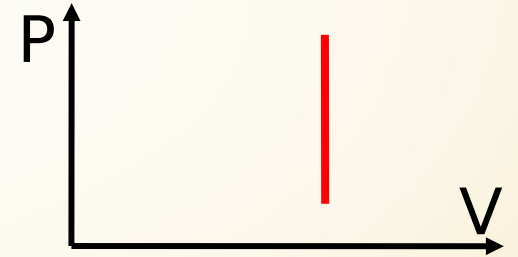
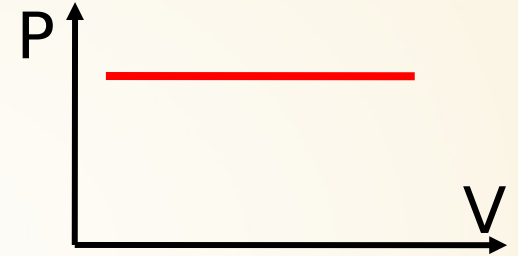
If the gas is heated by a steady flame, and the piston rises to a new equilibrium position, the new pressure will be _____ than the previous pressure.

- a) Greater than
- b) Less than
- c) Equal to



Identify the processes

- **Isobaric**
 - $P = \text{constant}$
- **Isochoric**
 - $V = \text{constant}$
 - $W = 0$
- **Isothermal**
 - $T = \text{constant}$
 - $\Delta U = 0$ (ideal gas)
- **Adiabatic**
 - $Q = 0$



A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (state a). Weight is slowly added to the piston, *isothermally* compressing the gas to half its original volume (state b).

P_b is _____ P_a

T_b is _____ T_a

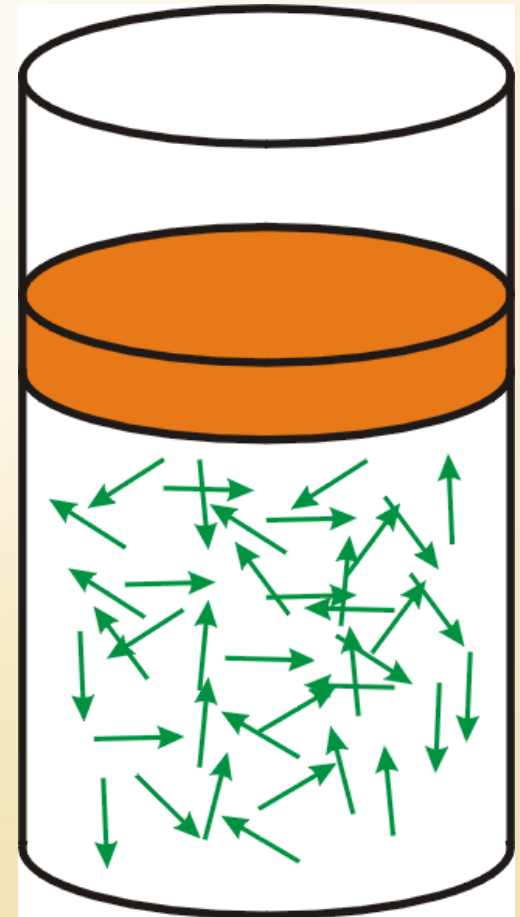
W_{ab} is _____ 0

U_b is _____ U_a

Q_{ab} is _____ 0

- a) Greater than
- b) Less than
- c) Equal to

Outside Air:
Room T, Atm. P



A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (state a). Weight is slowly added to the piston, *adiabatically* compressing the gas to half its original volume (state b).

P_b is _____ P_a

T_b is _____ T_a

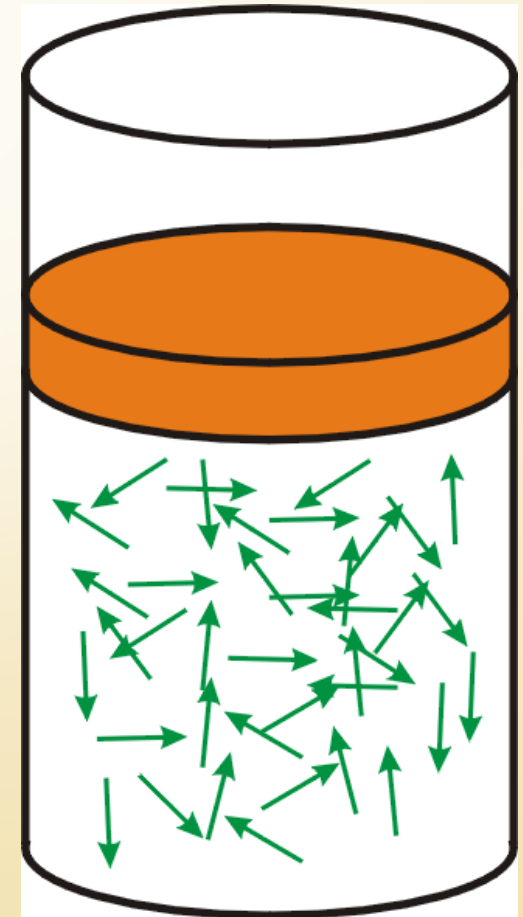
W_{ab} is _____ 0

U_b is _____ U_a

Q_{ab} is _____ 0

- a) Greater than
- b) Less than
- c) Equal to

Outside Air:
Room T, Atm. P



A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (state a). The gas is cooled, *isobarically* compressing the gas to half its original volume (state b).

P_b is _____ P_a

T_b is _____ T_a

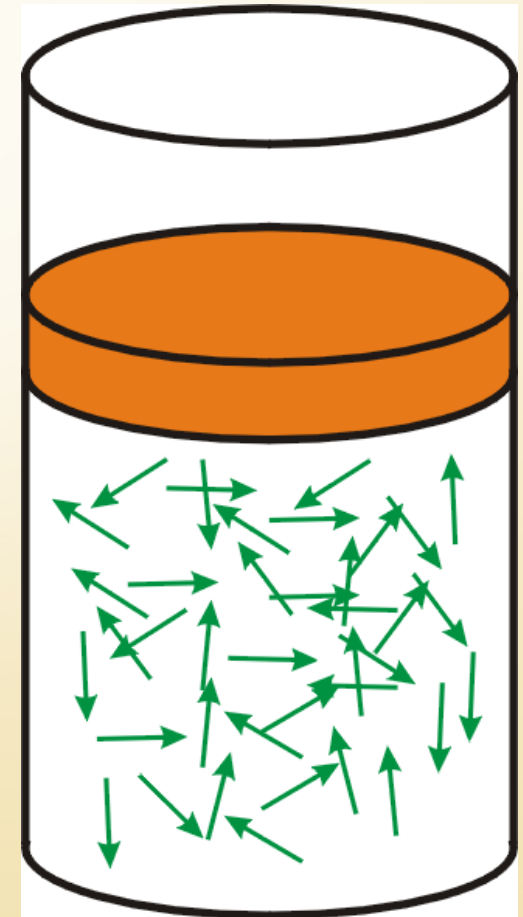
W_{ab} is _____ 0

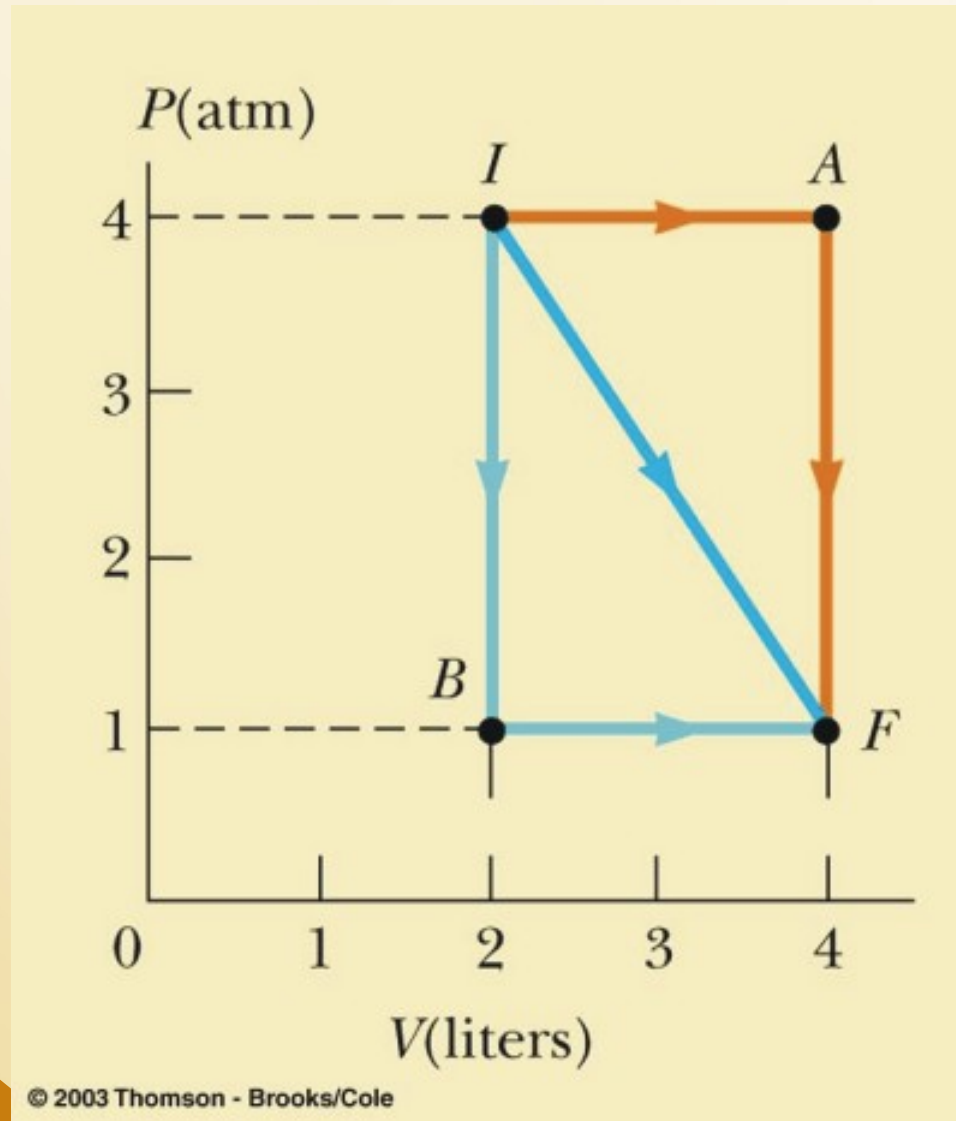
U_b is _____ U_a

Q_{ab} is _____ 0

- a) Greater than
- b) Less than
- c) Equal to

Outside Air:
Room T, Atm. P





a) What amount of work is performed by the gas in the cycle IAFI?

$$W = 304 \text{ J}$$

b) How much heat was inserted into the gas in the cycle IAFI?

$$Q = 304 \text{ J}$$

c) What amount of work is performed by the gas in the cycle IBFI?

$$W = -304 \text{ J}$$

Consider a monotonic ideal gas.

a) What work was done by the gas from A to B? **20,000 J**

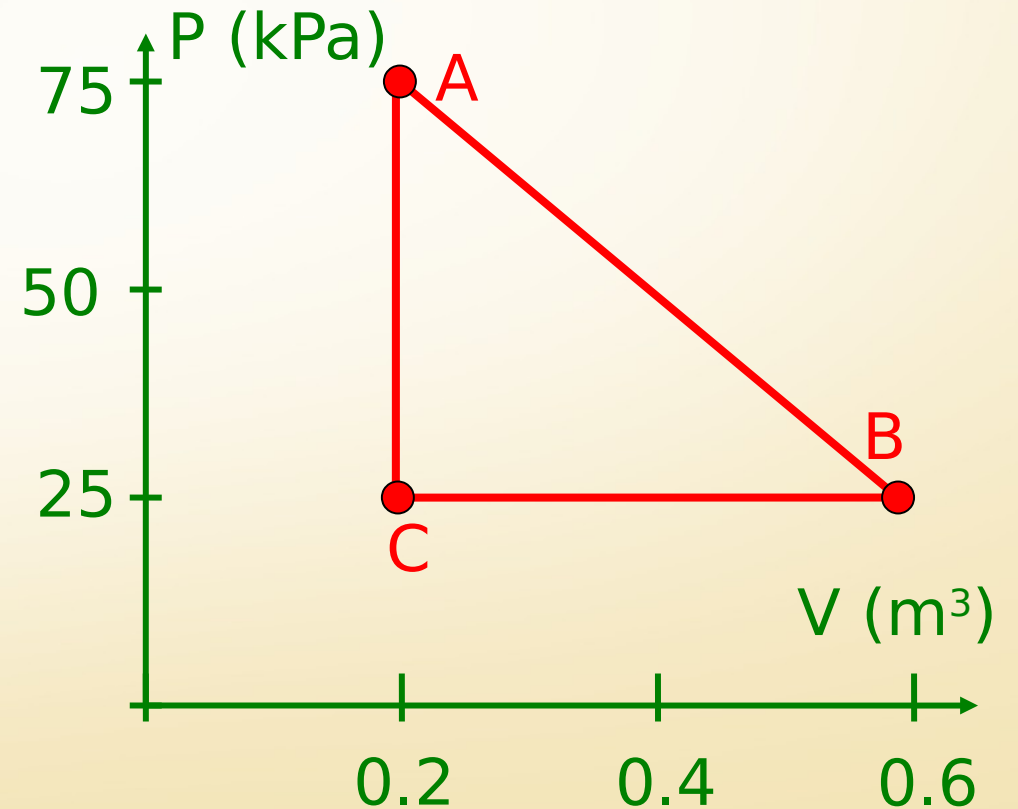
b) What heat was added to the gas between A and B? **20,000 J**

c) What work was done by the gas from B to C? **-10,000 J**

d) What heat was added to the gas between B and C? **-25,000 J**

e) What work was done by the gas from C to A? **0**

f) What heat was added to the gas from C to A? **15,000 J**



Take solutions from last problem and find:

a) Net work done by gas in the cycle

b) Amount of heat added to gas

$$W_{AB} + W_{BC} + W_{CA} = 10,000 \text{ J}$$

$$Q_{AB} + Q_{BC} + Q_{CA} = 10,000 \text{ J}$$

Consider an ideal gas undergoing the path through the PV diagram.

In going from A to B to C,

(a) the work done BY the gas is _____ 0.

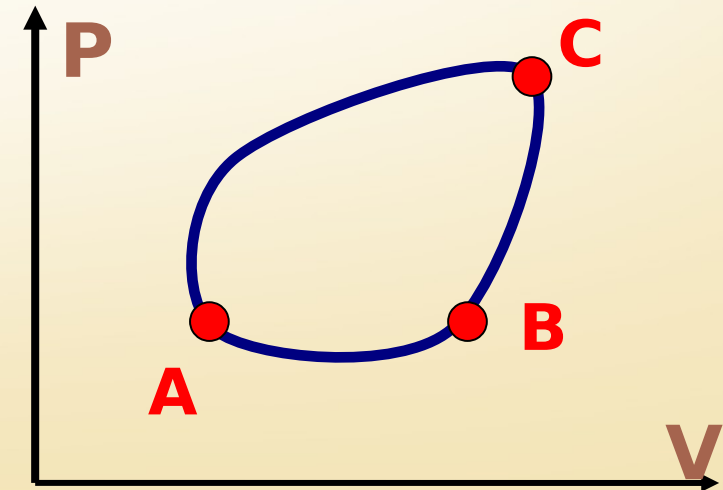
(b) the change of the internal energy of the gas is _____ 0.

(c) the amount of heat added to the gas is _____ 0.

a) >

b) <

c) =



In going from A to B to C to D to A,
(a) the work done BY the gas is _____ 0.
(b) the change of the internal energy of the gas is _____ 0.
(c) the heat added to the gas is _____ 0.

a) >

b) <

c) =

