

Temperature, Energy and the First Law of Thermodynamics

8.01t

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Temperature

- The 'hotness' or 'coldness' of an object is a macroscopic property of that object.
- When a cold object is placed in contact with a hot object, the cold object warms up and the hot object cools down until the two objects reach a state of thermal equilibrium.
- Temperature is a quantitative description of the hotness or coldness of a system.

What is temperature?

-A measure of energy

- Random Motion of Molecules (kinetic energy)**
- Air at Mountaintop (potential energy)**
- Only some of energy can become mechanical**

Equipartition Assumption

- A system that has a temperature is in thermal equilibrium
- $\langle \text{energy in a degree of freedom} \rangle = 1/2 k_B T$

What is a Degree of Freedom?

Each coordinate of each particle

$$1/2 m \langle v_x^2 \rangle = 1/2 m \langle v_y^2 \rangle = 1/2 m \langle v_z^2 \rangle = 1/2 k_B T$$

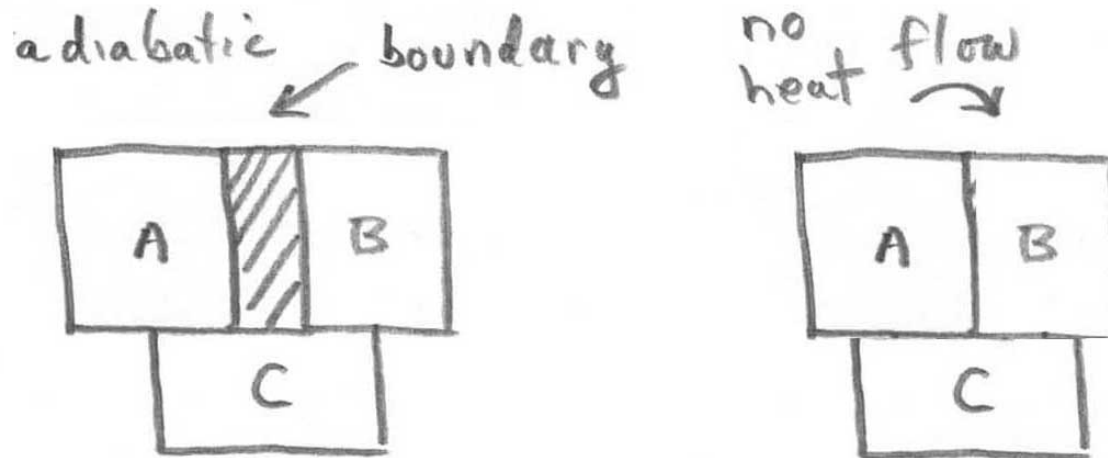
$$m g \langle z \rangle = 1/2 k_B T$$

Heat

- If two bodies are in contact but initially have different temperatures, heat will transfer or flow between them if they are brought into contact.
- heat is the energy transferred, given the symbol Q .

Thermal Equilibrium

Definition: Adiabatic boundary means no heat flow
(*a* - not + *dia* - through + *bainein* go)



If both A and B are in thermal contact with a third system C until thermal equilibrium is reached, the average energy per mode is equal to $\frac{1}{2}kT$ for all parts of the system.

Then remove adiabatic boundary, no heat will flow between A and B

Zeroth Law of Thermodynamics

- Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other.
- Temperature is that property of a system that determines whether or not a system is in thermal equilibrium with other systems.

Temperature and Equilibrium

- Temperature is Energy per Degree of Freedom
 - More on this later (Equipartition)
- Heat flows from hotter to colder object
 - Until temperatures are equal
 - Faster if better thermal contact
 - Even flows at negligible Δt (for reversible process)
- The Unit of Temperature is the Kelvin
 - Absolute zero (no energy) is at 0.0 K
 - Ice melts at 273.15 Kelvin (0.0 C)
 - Fahrenheit scale is arbitrary

Heat and Work are Processes

- Processes accompany/cause state changes
 - Work **along particular path** to state B from A
 - Heat added along path to B from A
- Processes are **not state variables**
 - Processes change the state!
 - But Eq. Of State generally obeyed

State Variables of System

- **State Variables - Definition**

Measurable Static Properties

Fully Characterize System (if constituents known)

e.g. Determine Internal Energy, compressibility

Related by Equation of State

- **State Variables: Measurable Static Properties**

- Temperature - measure with thermometer

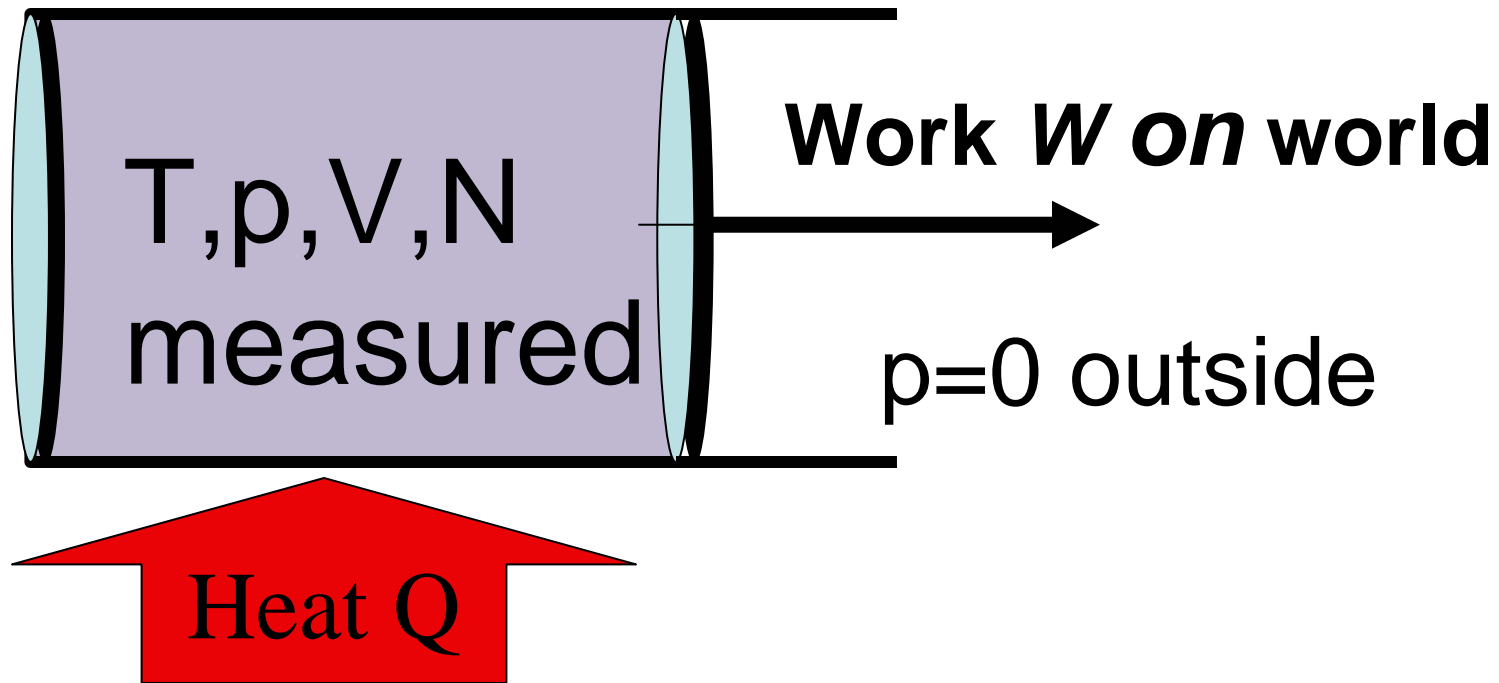
- Volume (size of container or of liquid in it)

- Pressure (use pressure gauge)

- Quantity: Mass or Moles or Number of Molecules

- Of each constituent or phase (e.g. water and ice)

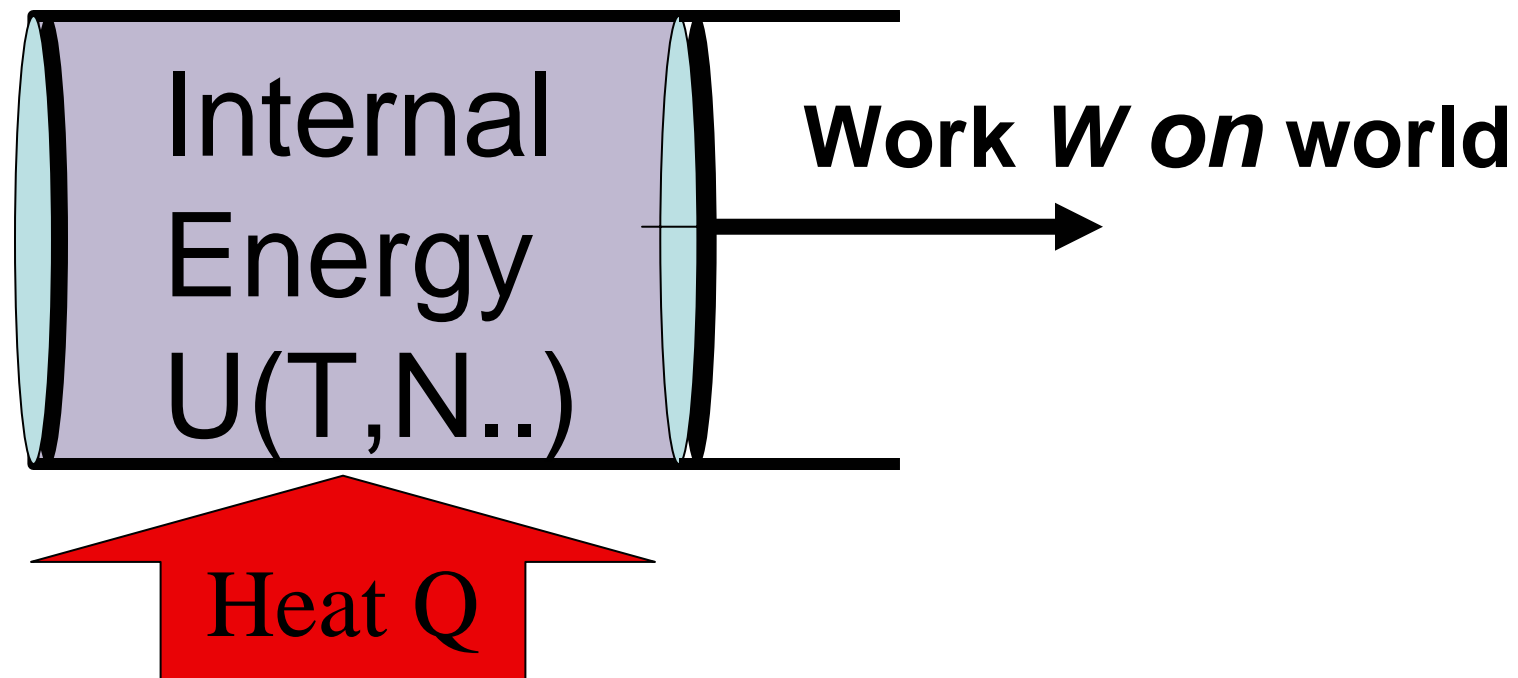
Thermodynamic Systems



The state variables are changed only in response to Q and W

No other work or heat enters

First Law - Energy Conservation



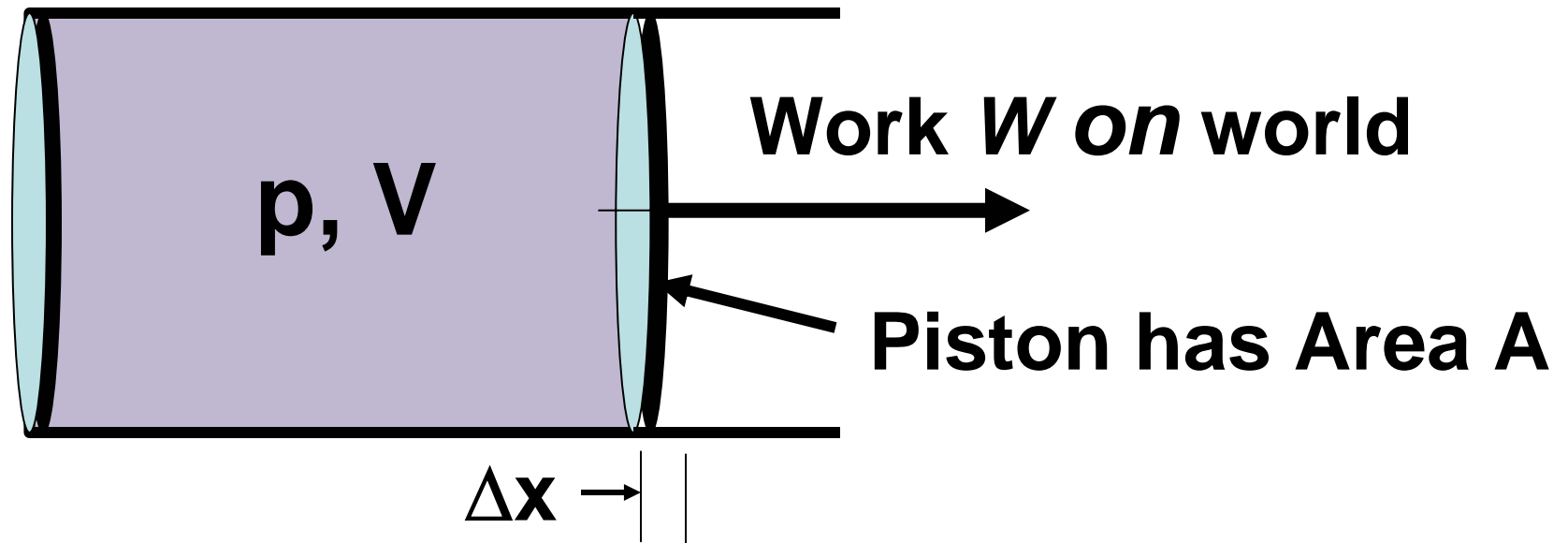
$$Q = W + \Delta U = W + U_f - U_i$$

stress: Q & W are processes,
 U is a state variable

Variables in First Law

- **Q is the Heat Added**
 - Could find from Temperature Gradient
 - But need Heat Conductivity and Area
 - Generally determine from First Law
- **W is the Work done by system**
 - Equal to $p\Delta V$
- **U is the Internal Energy of system**
 - It is determined by state variables
 - From equipartition, proportional to T

Expression for Work



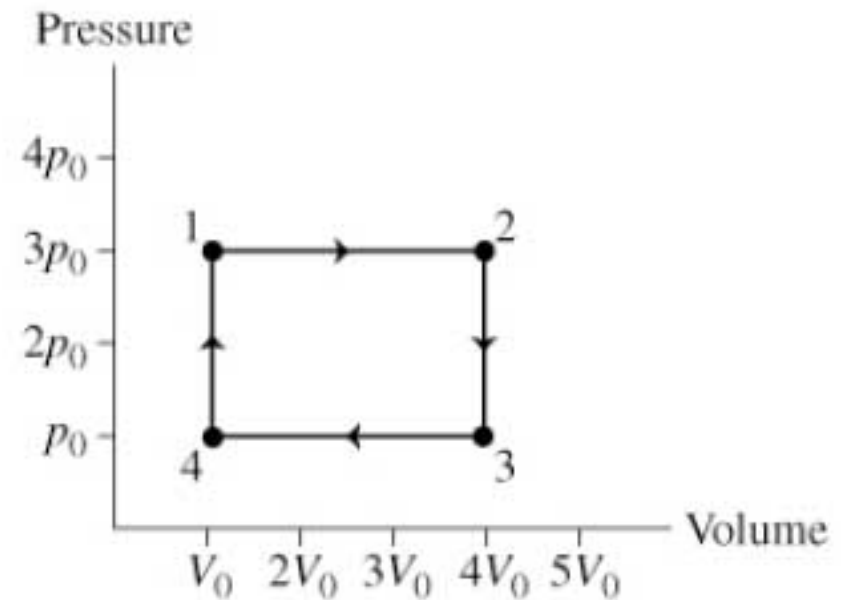
Find Work if piston moves Δx :

$$W = F \Delta x = pA \Delta x = p\Delta V$$

In General:
$$W_{fi} = \int_i^f p(V, T) dV$$

PRS: Work in p-V plane:

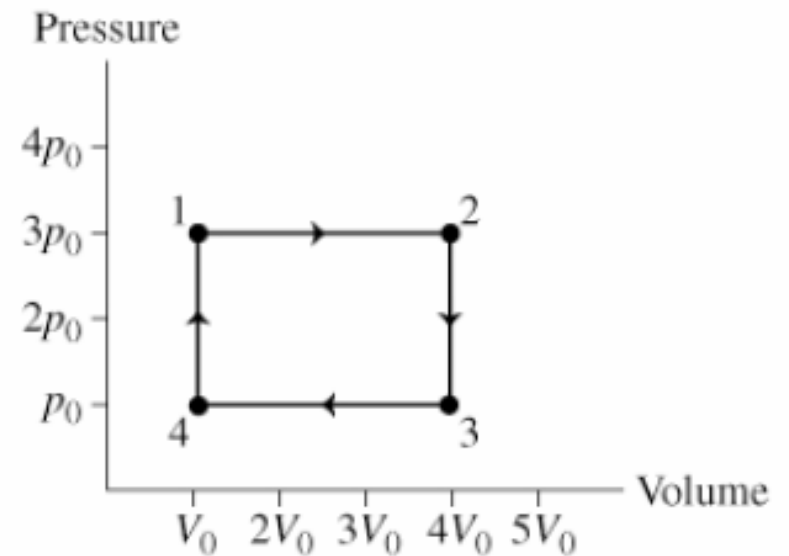
In the cycle shown what is the work done by the system going from state 1 to state 2 clockwise along the arrowed path?



1. $12 p_0 V_0$
2. $9 p_0 V_0$
3. $4 p_0 V_0$
4. $3 p_0 V_0$
5. $-12 p_0 V_0$
6. $-9 p_0 V_0$
7. $-4 p_0 V_0$
8. $-3 p_0 V_0$
9. None of above

PRS: Work in p-V plane:

In the cycle shown what is the work done by the system going from state 2 to state 4 clockwise along the arrowed path?



1. $12 p_0 V_0$
2. $9 p_0 V_0$
3. $4 p_0 V_0$
4. $3 p_0 V_0$
5. $-12 p_0 V_0$
6. $-9 p_0 V_0$
7. $-4 p_0 V_0$
8. $-3 p_0 V_0$
9. None of above

Internal Energy

Based on Equipartition:

-each coordinate of each particle

$$1/2 m \langle v_x^2 \rangle = 1/2 m \langle v_y^2 \rangle = 1/2 k_B T$$

$$1/2 \mu \langle v_{\text{rel}}^2 \rangle = 1/2 k_B T \text{ ..molecule}$$

For an ideal monatomic gas:

$$U(T) = 3/2 N k T$$

For an ideal diatomic molecular gas:

$$U(T) = 5/2 N k T \text{ (no vibration)}$$

Specific Heat - Constant Volume

Consider a **monatomic** ideal gas in a container of **fixed volume**. A small amount of heat, dQ is added with $dV = 0$ so $W = 0$. The First Law then gives:

$$dQ = dW + dU = dU$$

But $dU(T) = \frac{3}{2} N k dT$,

so $dQ/dT = \frac{3}{2} N k = \frac{3}{2} n R$

$c_V = \frac{3}{2} R$ is defined as the **specific heat**
- heats one mole one degree Kelvin

Class Problem: Heat the room

A room is 3x5x6 meters and initially at $T = 0\text{C}$.

How long will it take a 1 kW electric heater to raise the air temperature to 20C ?

1. $1/2$ min
2. $3/4$ min
3. $1 \frac{1}{4}$ min
4. None of above
5. 11 min
6. 17 min
7. 28 min

Note: In reality it will take several times this long because the walls and furnishings in the room have to be warmed up also.

Specific Heat of Aluminum

Aluminum has an atomic weight of 27 (grams per mole), and has 3 translational and 3 vibrational degrees of freedom per atom. What is its specific heat in J/kg/K ?

1. 1806
2. 903
3. 452
4. None of above

Young and Freedman gives 910 as the correct answer this shows how close the simple ideas come to reality.

Class Problem: Heat the walls

How much longer will it take a 1 kW electric heater to raise the wall temperature to 20C?

Assume the walls and ceiling are Aluminum 1 cm thick that is initially at $T = 0\text{C}$.