Course announcement

- The 2nd midterm score will be posted on eLearn today. I will bring the answer sheet to class for review from Friday until 12/30. You can also review it during Monday’s office hours. If you have any questions about the score, please contact me.

14	12/16(Fri.)	**Thermal Behavior of Matter:** ideal gases, and kinetic theory of ideal gas
15	12/20(Tue.)	**Thermal Behavior of Matter:** phase changes and thermal expansion
15	12/23(Fri.)	**The First Law of Thermal Dynamics:** 1^{st} law of thermal dynamics
16	12/27(Tue.)	**The First Law of Thermal Dynamics:** Thermodynamic processes (Homework5)

GENERAL PHYSICS B1
THE THERMAL BEHAVIOR OF MATTER

2022/12/20

Phase change and thermal expansion

Topic Today

Phase change:

- Heat and phase changes
- Phase diagrams

Thermal expansion

- Coefficients of thermal expansion
- Thermal expansion of water

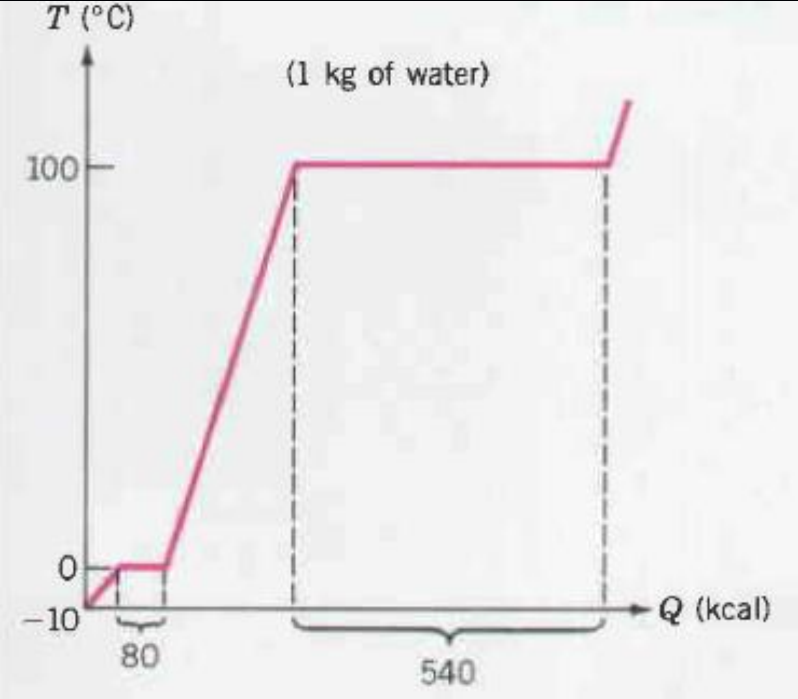
Phase Changes and Heats of Phase Transformation (Latent heat)

- Most substances occur in three phases—solid, liquid, gas.
- It takes energy, heat of transformation, L to effect phase changes from solid to liquid and liquid to gas. Example: melting and vaporization
- The amount of energy per unit mass that must be transferred as heat when a sample completely undergoes a phase change is called the heat of transformation L.

$$Q = Lm$$

Heats of Phase Transformation (Latent heat)

- The solid-liquid transition involves the heat of fusion, L_f.
- The liquid-gas transition involves the heat of vaporization, L_v.
- The direct transition from solid to gas involves the heat of sublimation, L_s.



List of Latent Heat

Table 17.1 Heats of Transformation (at Atmospheric Pressure)

Substance	Melting Point (K)	L_f (kJ/kg)	Boiling Point (K)	L_v (kJ/kg)
Alcohol, ethyl	159	109	351	879
Copper	1357	205	2840	4726
Lead	601	24.7	2013	858
Mercury	234	11.3	630	296
Oxygen	54.8	13.8	90.2	213
Sulfur	388	53.6	718	306
Water	273.15	334	373.15	2257
Uranium dioxide	3120	259	3815	1533

Example: The Heat of Fusion: Meltdown!

- A malfunctioning nuclear reactor contains $2.5 \times 10^5 kg$ of fuel in the form of uranium-dioxide that has already been heated to its melting point. How long will it take to melt the uranium-dioxide if the reactor continues to heat it at the rate of 120 MW?

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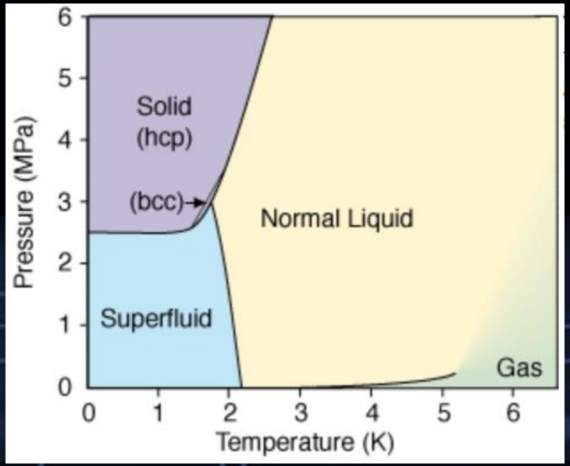
The energy required to melt an object at its melting point is determined by its heat of fusion. For uranium-dioxide, we have: Lf= 259 kJ/kg. Thus, the required energy is

Q=mLf=65GJ

The time to melt it is: Q/P=65(GJ)/0.12(GJ/s)=540s

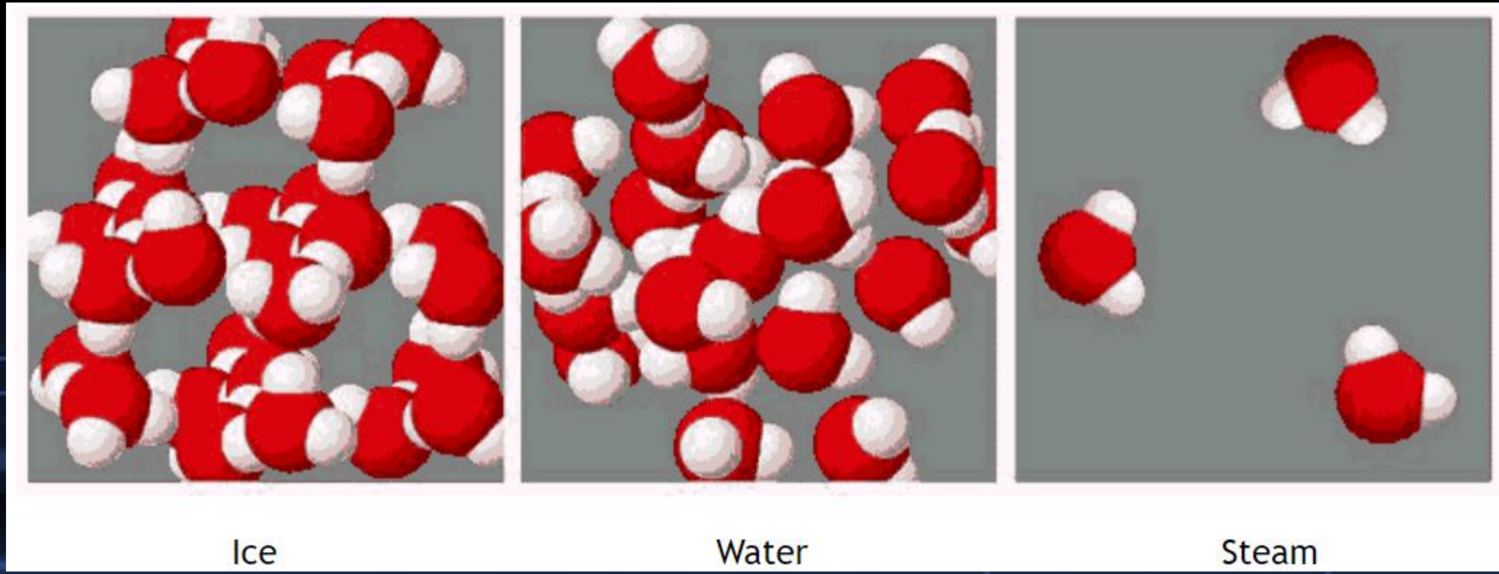
Phase Diagrams

- The phases of a substance can be displayed on a plot of pressure versus temperature:
  - Curves separate regions characterizing the different phases.
  - Different phases represent the substance has different microscopic order. For example: solid, liquid, and gas phases of water.



Phase diagram of Helium-4

http://ltl.tkk.fi/research/theory/helium.html

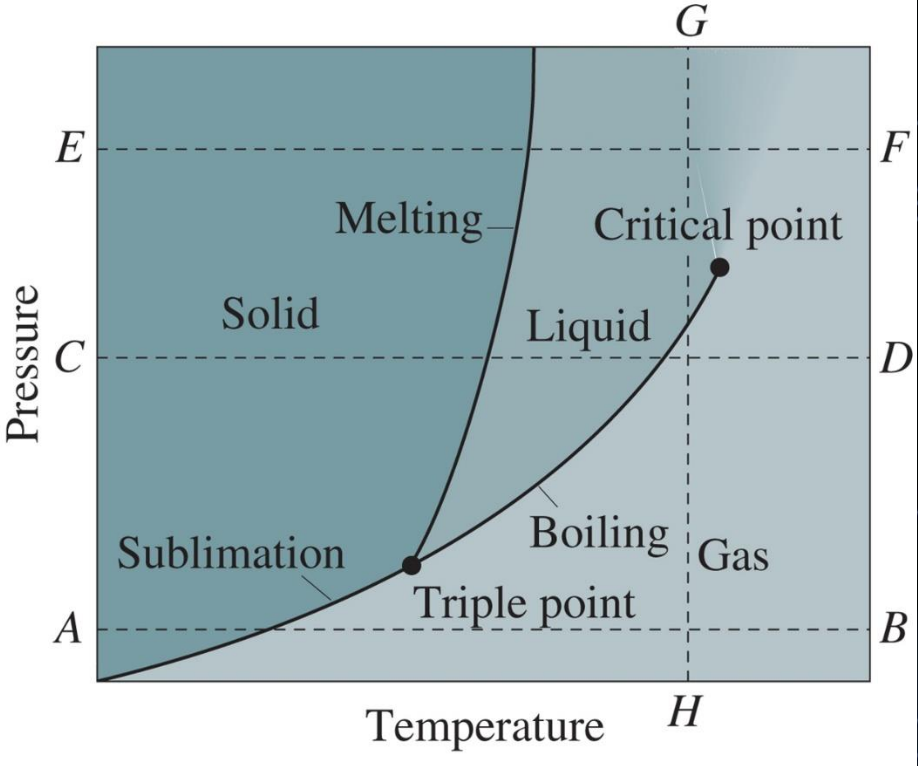


http://labman.phys.utk.edu/phys221core/modules/m9/phases_of_water.html

Phase diagram of water

Phase diagram of water:

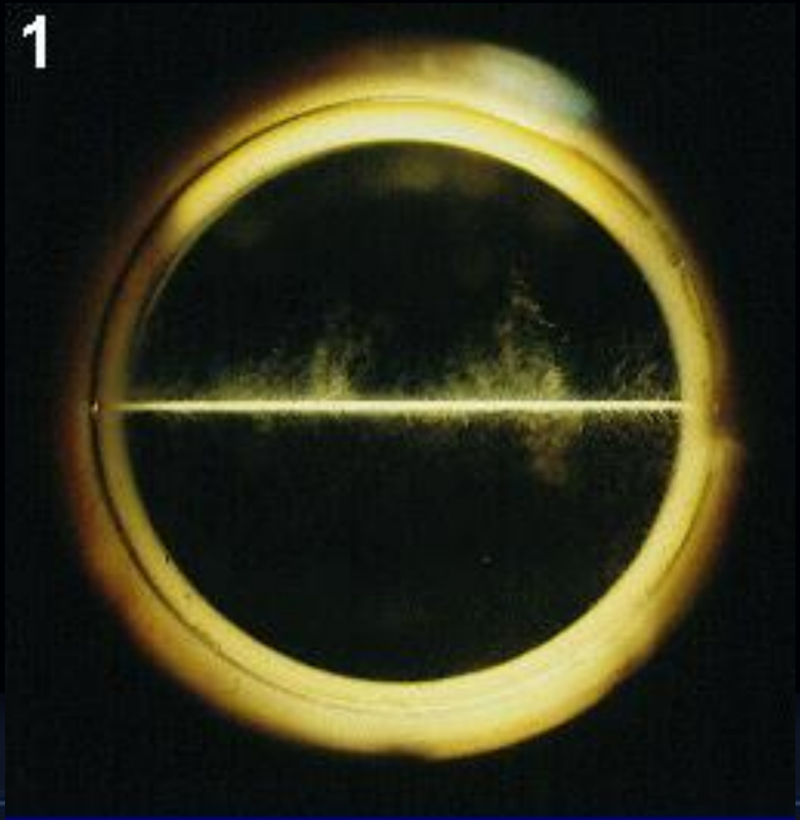
- The curves meet at the **triple point**, where all three phases coexist in equilibrium.
- The liquid-gas curve ends at the **critical point**, where the sharp distinction between liquid and gas disappears.



Triple point of water

https://commons.wikimedia.org/wiki/File:Water-triple-point-20210210.gif

Supercritical phase of water

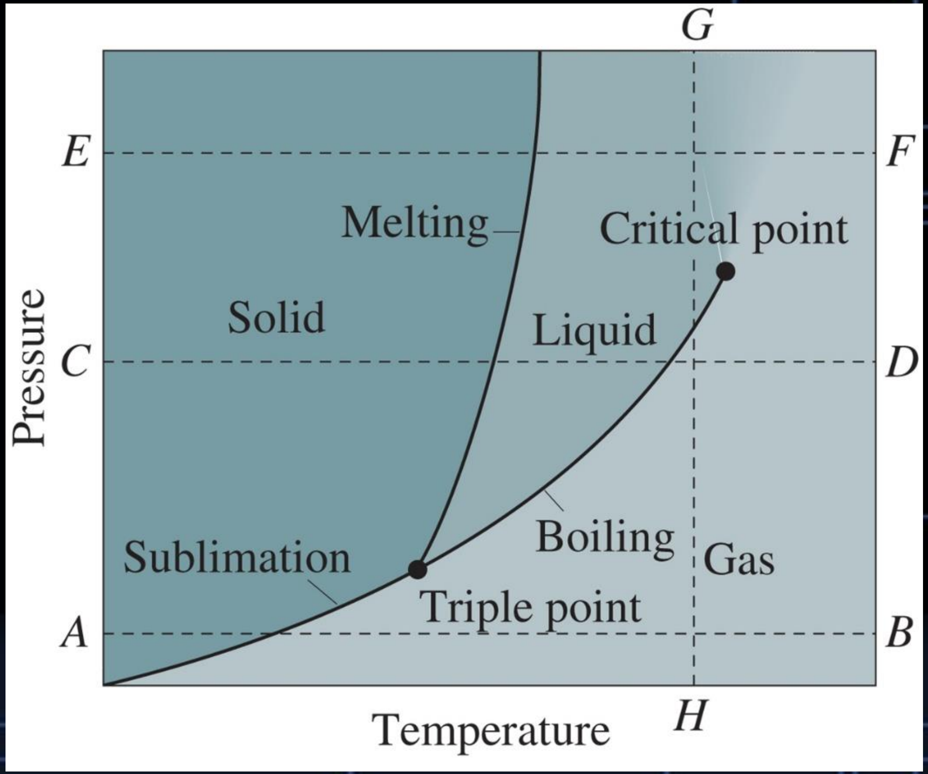


Below the critical parameters,
two distinct phases exist

Phase diagram of water

Different paths in the phase diagram take the material through different phase sequences:

- Path *CD* shows the familiar solid-liquid-gas transitions.
- Path *AB* goes directly from solid to gas (sublimation).
- Path *GH* shows that changing pressure can result in phase changes.



Thermal expansion

Most materials expand when heated.

- Liquids are best characterized by the **coefficient of volume expansion**, *β*, which is the fractional change in volume per unit temperature change:

$$\beta = \frac{\Delta V/V}{\Delta T}$$

- Solids are best characterized by the **coefficient of linear expansion**, *α*, which is the fractional change in length per unit temperature change:

$$\alpha = \frac{\Delta L/L}{\Delta T}$$

- Typical values are $\beta \approx 10^{-3}\ \mathrm{K}^{-1}; \alpha \approx 10^{-5}\ \mathrm{K}^{-1}$

Table 17.2 Expansion Coefficients*

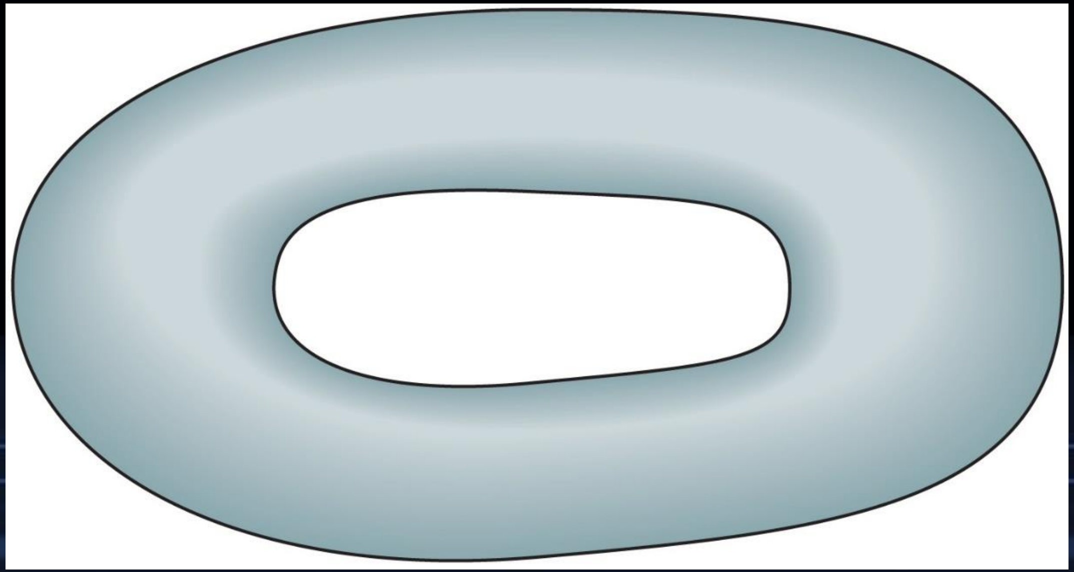
Solids	α (K^{-1})	Liquids and Gases	β (K^{-1})
Aluminum	24×10^{-6}	Air	3.7×10^{-3}
Brass	19×10^{-6}	Alcohol, ethyl	75×10^{-5}
Copper	17×10^{-6}	Gasoline	95×10^{-5}
Glass (Pyrex)	3.2×10^{-6}	Mercury	18×10^{-5}
Ice	51×10^{-6}	Water, 1°C	-4.8×10^{-5}
Invar†	0.9×10^{-6}	Water, 20°C	20×10^{-5}
Steel	12×10^{-6}	Water, 50°C	50×10^{-5}

*At approximately room temperature unless noted.

†Invar, consisting of 64% iron and 36% nickel, is an alloy designed to minimize thermal expansion.

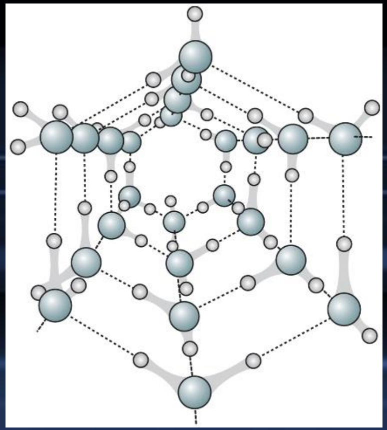
Think about it…

The figure shows a donut-shaped object. If it’s heated, will the hole get (a) larger or (b) smaller?



Thermal Expansion of Water

- Between 0°C and 4°C, water contracts on heating:
  - This is a residual effect of the hydrogen bonds that form ice crystals.
  - The open structure of the ice crystal makes ice less dense than liquid water.
  - Hence solid water—unlike most substances—floats in its liquid phase.
  - This fact has enormous consequences for aquatic life.



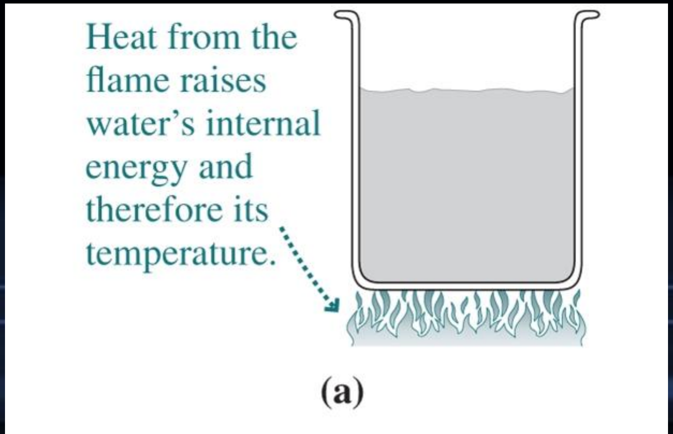
GENERAL PHYSICS B1
HEAT, WORK, AND THE FIRST LAW OF THERMODYNAMICS

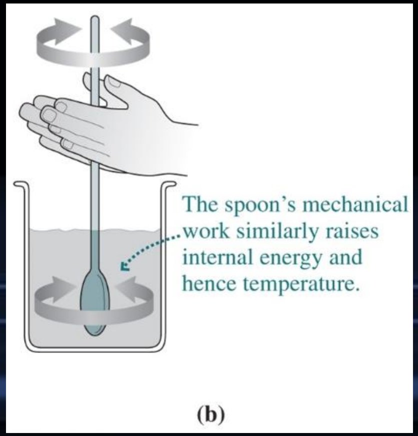
2022/12/20

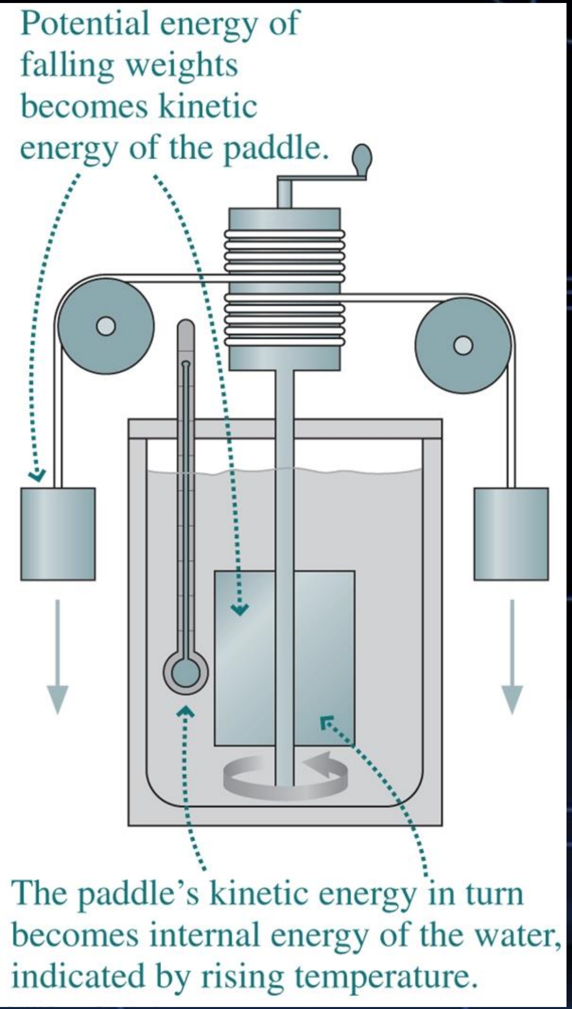
The First Law of Thermodynamics

Heat and Energy

- From previous discussion, we know that heat is a form of energy. A conversion: 1cal = 4.1868J



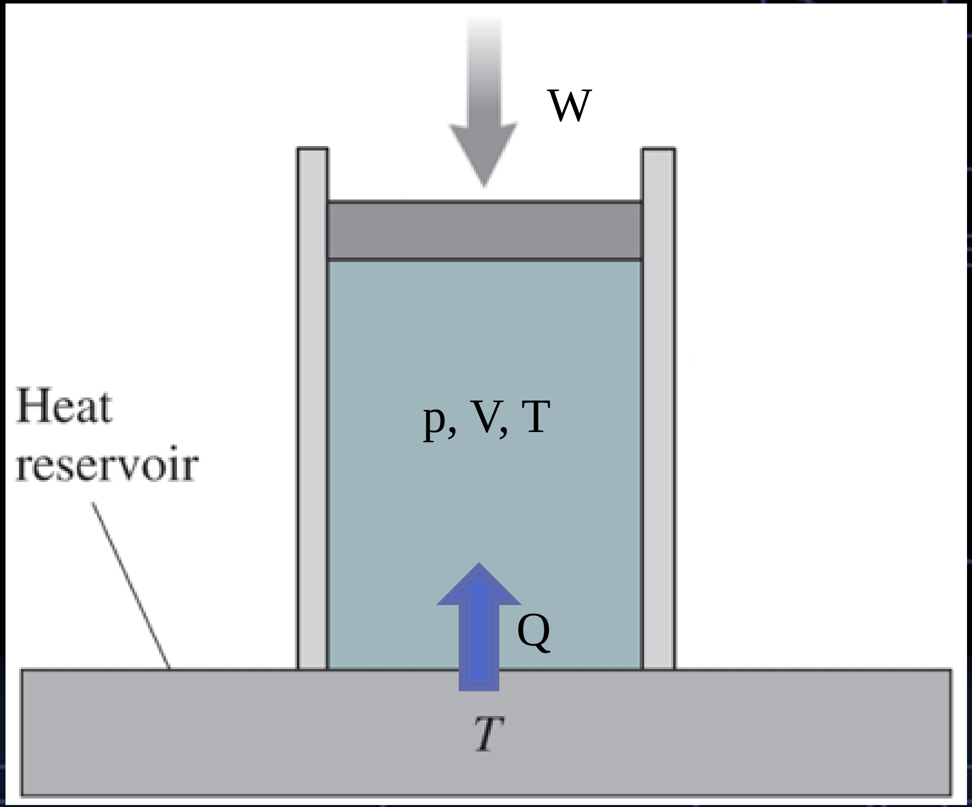




- In mechanics, we know the relationship between kinetic energy, potential energy and work. What is the relationship between heat and work?

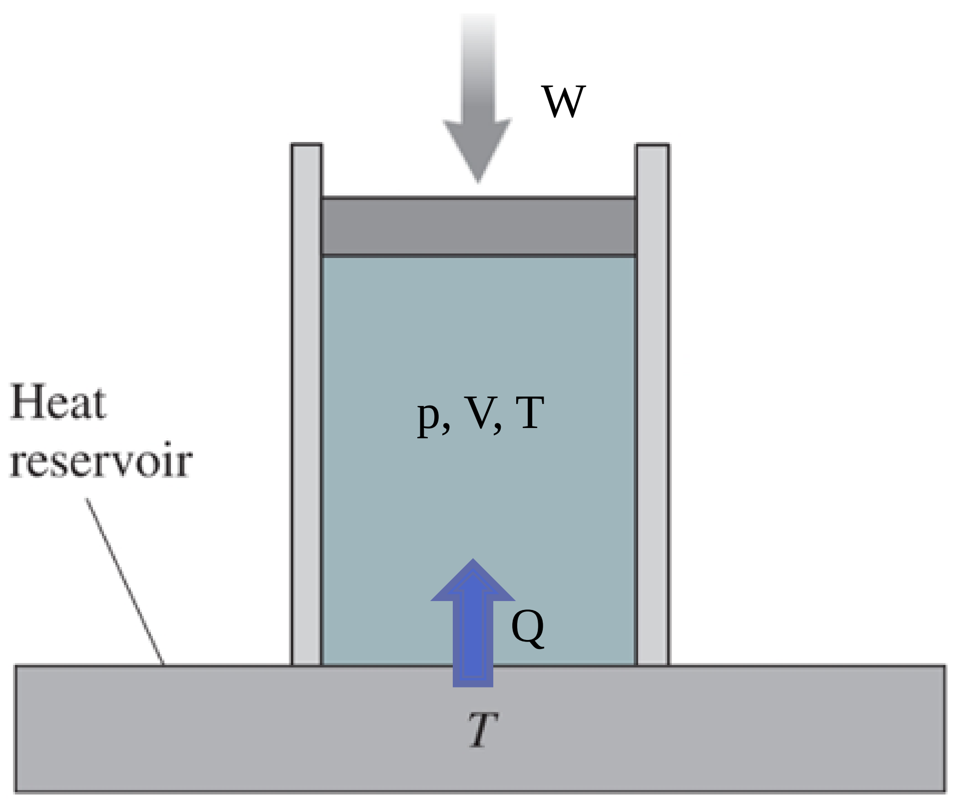
A gas system transferring heat to work

- A gas system confined to a cylinder with a movable piston.
- Thermal reservoir whose temperature T you can control.
- The upward force on the piston due to the pressure of the confined gas is equal to the weight of lead shot loaded onto the top of the piston.
- Insulation: heat can only transfer through thermal reservoir.



A gas system transferring heat to work

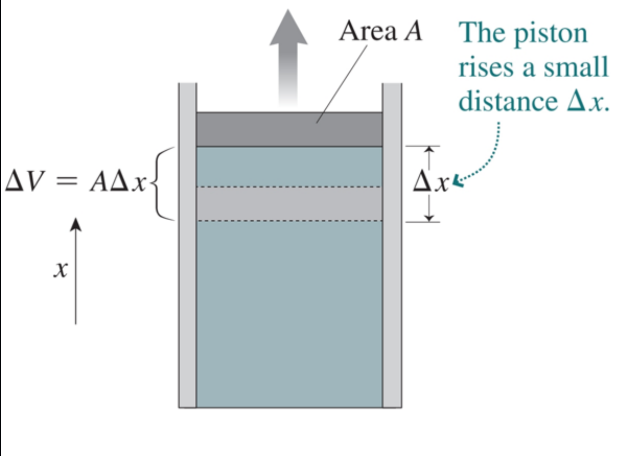
- The system (the gas) starts from an initial state i: described by a pressure p_i, a volume V_i, and a temperature T_i.
- The final state f: described by a pressure p_f, a volume V_f, and a temperature T_f.
- The procedure from its initial state to its final state is called a thermodynamic process.



Work done on the gas

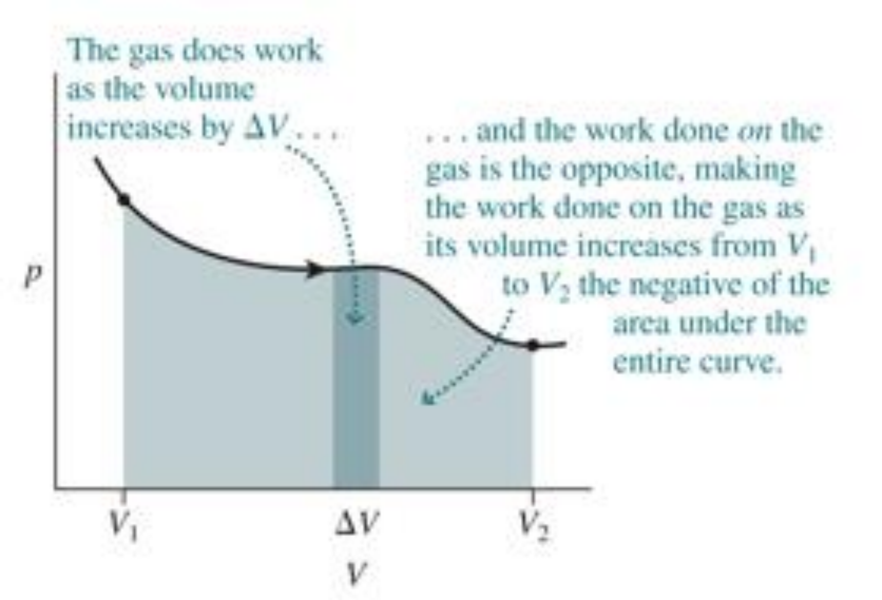
- The work done **on** the gas to the piston at a small displacement is:

$dW = -Fdx = -pAdx = -pdV$



- The work done **on** gas during change from state with volume V_1 to state with volume V_2:

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



The first law of thermodynamics

- When a system changes from a given initial state to a given final state, both the work W and the heat Q depend on the nature of the process. Experimentally, however, we find a surprising thing: The quantity Q + W is the same for all processes.
- The quantity Q + W must represent a change in some intrinsic property of the system. We call this property the internal energy E_{int} and the first law of thermodynamics is:

$$\Delta E_{int} = Q + W$$

Meaning of the first law of thermodynamics

- If the thermodynamic system undergoes only a differential change:

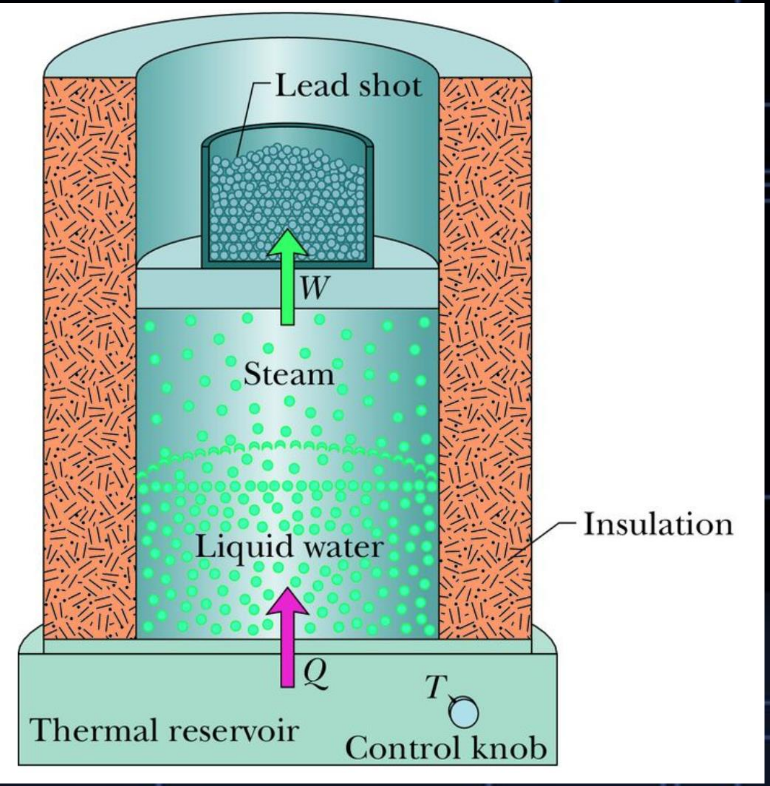
$$dE_{int} = dQ + dW$$

- The internal energy dE_{int} of a system tends to increase if energy is added as heat Q and tends to decrease if energy is lost as work W done by the system. Therefore, the first law of thermodynamics is conservation of energy.

Example

Let 1.00 kg of liquid water at 100°C be converted to steam at 100°C by boiling at standard atmospheric pressure (which is 1.00 atm or 1.01×10^5 Pa. The volume of that water changes from an initial value of 1.00×10^{-3} m^3 as a liquid to 1.671 m^3 as steam.

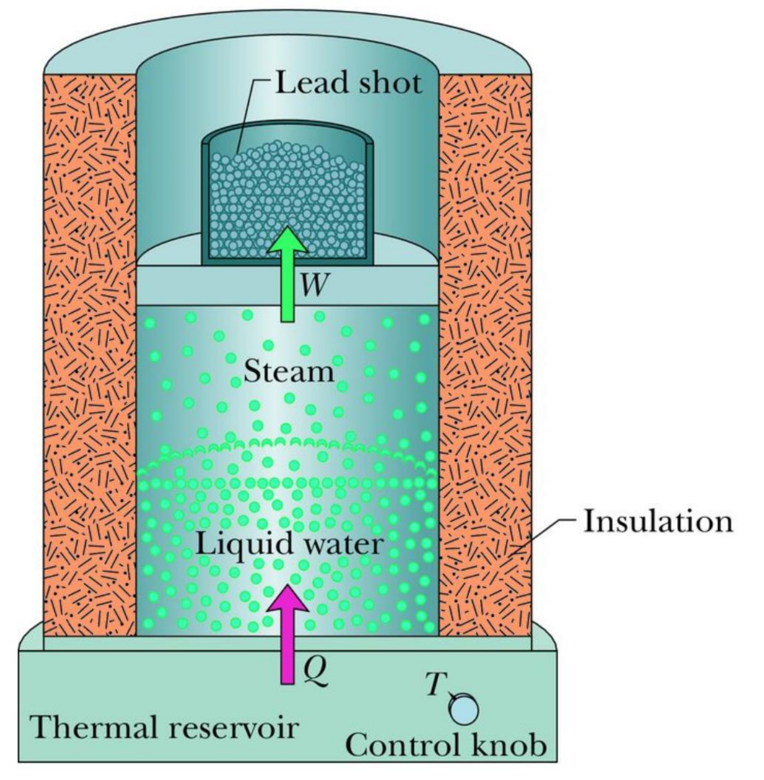
(a) How much work is done by the system during this process?



Example

(1)The system must do work to the outside world because the volume increases. (2) We calculate the work W done by integrating the pressure with respect to the volume

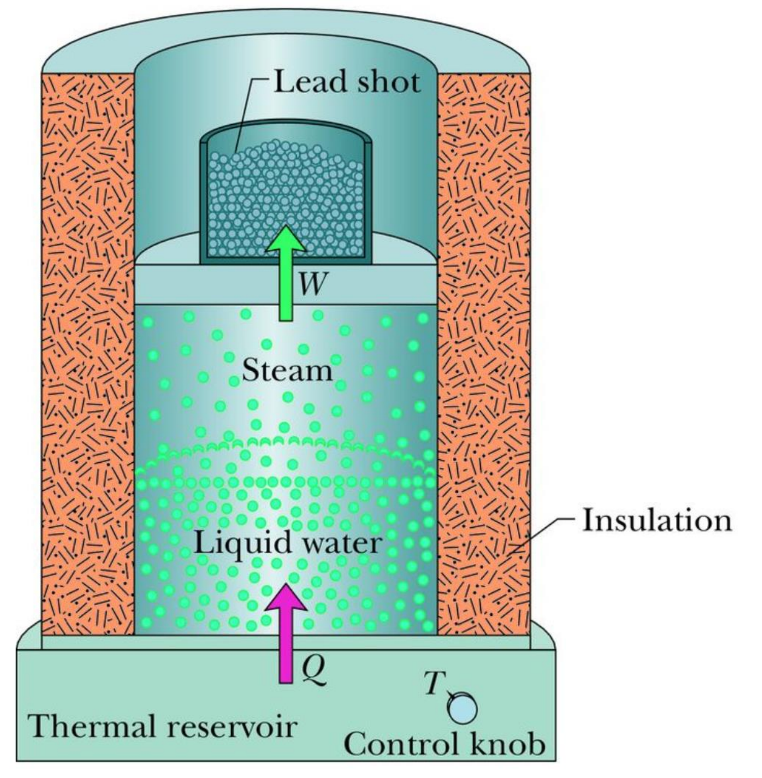
$$W = -\int_{V_i}^{V_f} p dV = -p(V_f - F_i)$$
$$= -(1.01 \times 10^5 Pa)(1.671 m^3 - 1.00 \times 10^{-3} m^3)$$
$$= -1.69 \times 10^5 J$$



Example

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

$$Q = L_V m = (2256\ \text{kJ}/\text{kg})(1.00\ \text{kg})$$
$$= 2256\ \text{kJ} \approx 2260\ \text{kJ}.$$



Example

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

$$\Delta E_{int} = Q + W$$
$$= 2256kJ - 169kJ$$
$$= 2087kJ$$