

Physical Principles in Biology
Biology 3550
Fall 2017

Lecture 23

Thermodynamics: Expansion and Compression of a Gas

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Why is Thermodynamics Important?

- Thermodynamics is the fundamental science of energy, something almost everyone cares about! (because they pay for it)
- Defines the rules for interchange of different forms of energy. (e.g., the conversion of an H^+ concentration gradient into mechanical motion in the bacterial rotary motor.)
- Places strict constraints on whether or not a physical, chemical or biological process is favorable under specified conditions.
But, it won't say whether the process will take place or how fast!
- Particularly important in the context of climate change and society's need for energy.

Why is Thermodynamics Hard?

- The ideas are abstract and subtle.
- It depends on math! (And, the quantities are subtle.)
- The language can be confusing (and varies among disciplines).
- Historical confusion.
 - Developed over several generations of scientists in the 18th and 19th centuries.
 - Periods of profound confusion.

Units of Energy

- Energy is the ability to do work.
- Unit of work or energy: $1 \text{ J} = 1 \text{ N} \cdot \text{m} = 1 \text{ Kg} \cdot \text{m}^2/\text{s}^2$
Energy required to apply 1 N of force over a distance of 1 m.
 $1 \text{ J} = 1 \text{ watt} \cdot \text{s}, 1 \text{ kwatt} \cdot \text{hr} = 3.6 \times 10^6 \text{ J}$
- Another unit of energy commonly used in thermodynamics: calorie
 - Originally defined as energy required to raise the temperature of 1 g of water by 1°C . (depends on starting temperature)
 - Now defined as exactly 4.184 J
- “Big C” Calorie, or “kg calorie”: $1 \text{ Calorie} = 1,000 \text{ calorie}$.
 - Energy required to raise the temperature of 1 kg of water by 1°C .
 - Big C Calorie is the one used for nutritional information.
- Calorie units are still commonly used in thermodynamics because they directly relate energy to temperature.

Temperature Versus Heat

■ Temperature

- A property of matter, which we measure with a thermometer.
- Directly related to the kinetic energy of the molecules making up the matter.
- For an ideal gas, $E_k = 3kT/2$
Three degrees of motional freedom, in x -, y -, and z -direction.
- Non-ideal gasses, liquids and solids have additional motional modes and generally greater kinetic energy at a given temperature.

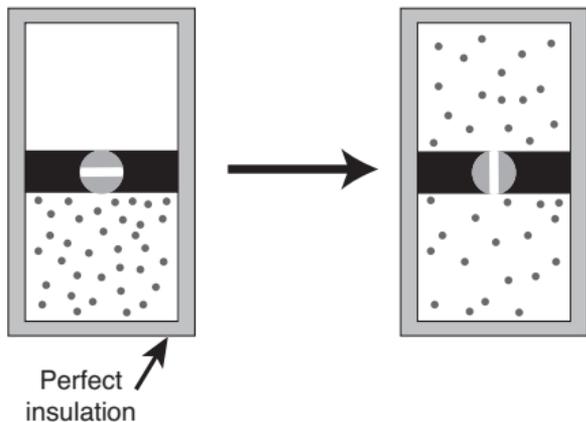
■ Heat

- Sometimes described as a “form of energy”.
- Better definition: Flow of energy from from a warmer object to a cooler one; equilibration of kinetic energy.
- At one time, heat was thought to be a massless substance, called “caloric”, that moved within or between objects.

Our Starting Point for Thermodynamics: Expansion and Compression of Gasses

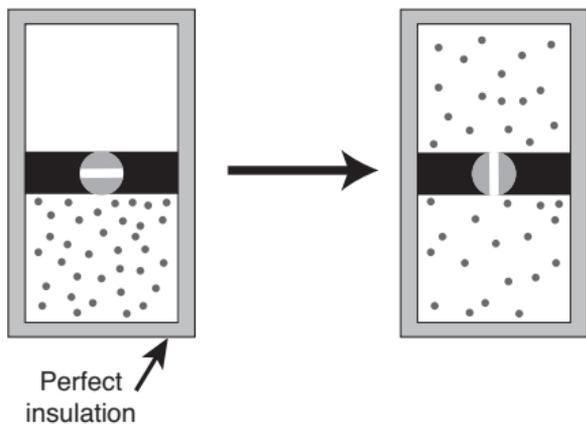
- Historical origins:
 - Development of thermodynamics was first motivated by the invention of the steam engine, and the desire to make better ones.
 - Many of the basic ideas were formulated in this context and are still easiest to visualize in it.
 - Original treatments did not consider molecular motion (because it wasn't understood) and were very abstract; “classical thermodynamics.”
 - Molecular interpretation developed later, “statistical thermodynamics”.
 - Classical and statistical thermodynamics are each self-sufficient and are consistent with one another.
- We will use both classical and statistical viewpoints, which complement each other.
- An ideal gas is the simplest system in which to formulate ideas.
- Also ties back to our discussion of molecular motion in diffusion.

Adiabatic (without heat flow) Expansion of a Gas



- Insulation prevents heat flow into or out of device.
- What changes?

Clicker Question #1

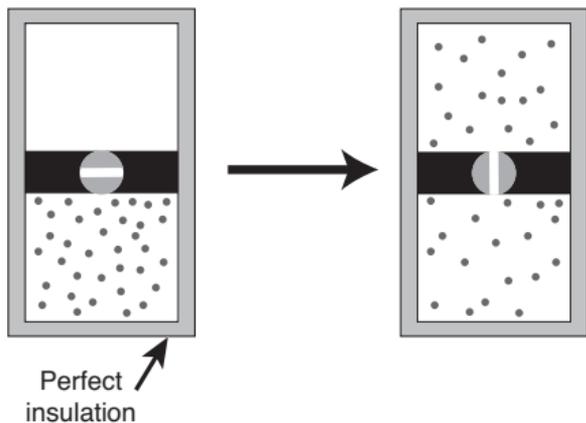


Which of the following properties of the gas change?

- 1 Temperature
- 2 Pressure
- 3 Volume
- 4 Kinetic energy

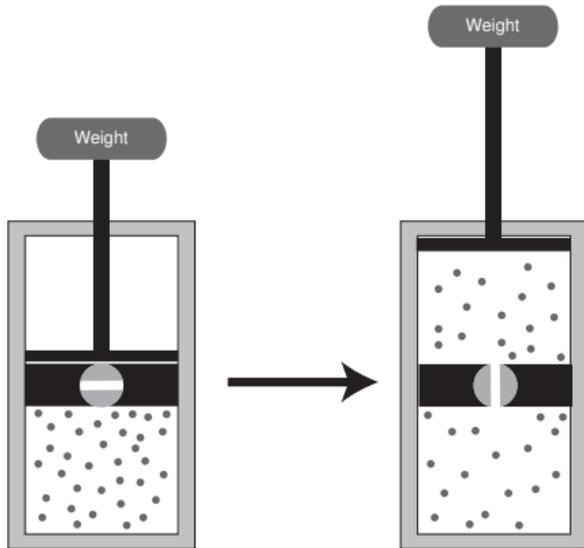
Any answers count for now!

Adiabatic (without heat flow) Expansion of a Gas



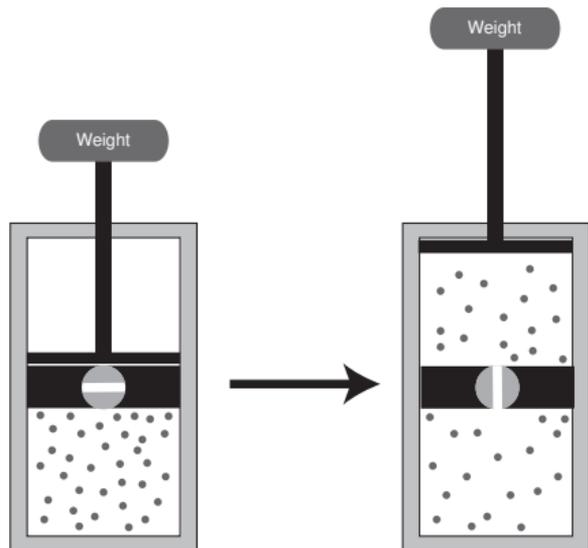
- Insulation prevents heat flow into or out of device.
- What changes?
 - Volume of gas increases.
 - Pressure of gas decreases ($PV = nRT$)
 - Temperature stays constant.
 - Energy stays constant?
 - Has any work been done? (no)
 - Anything else changed?

Adiabatic Gas Expansion With Work



- Collisions of gas molecules with piston move the weight up.
- What changes?

Clicker Question #2

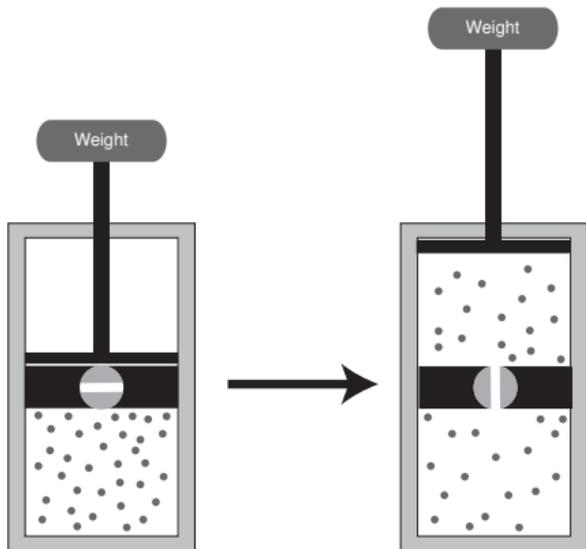


Which of the following properties of the gas change?

- 1 Temperature
- 2 Pressure
- 3 Volume
- 4 Energy

Any answers count for now!

Adiabatic Gas Expansion With Work



- Collisions of gas molecules with piston move the weight up.
- What changes?
 - Volume of gas? (increases)
 - Temperature? (decreases as energy is transferred to piston.)
 - Pressure? (decreases, more than without the weight)
 - Energy?
Has any work been done?
(yes)
 - Where did the energy to do the work come from?
Gas molecules have lost kinetic energy.

Rules for Keeping Score

- Change in energy of the gas molecules (the “system”):

$$\Delta E = E_{\text{final}} - E_{\text{start}}$$

- Work, w :

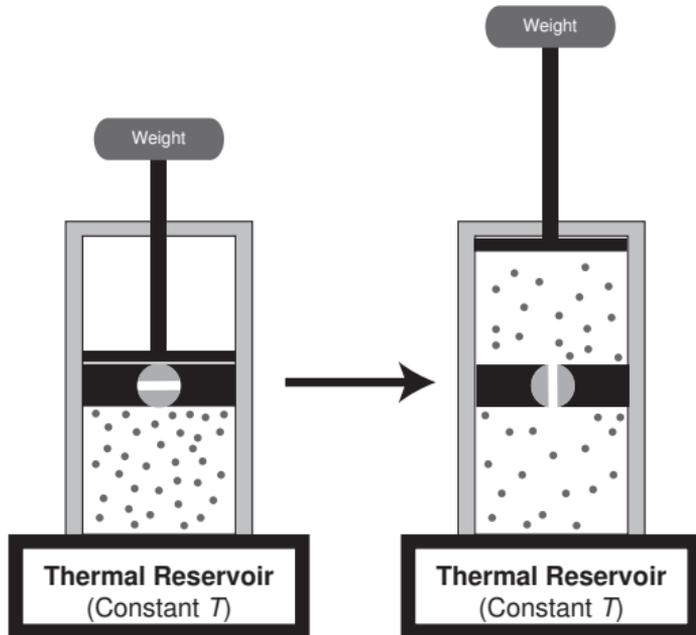
- $w > 0$, when work is done on the system.
- $w < 0$, when the system does work on the outside world, as in the expansion of the gas.

- For the adiabatic expansion of a gas with work:

- $E_{\text{final}} < E_{\text{start}}$, and $\Delta E < 0$
- $w < 0$, because the system did work.
- $\Delta E = w$: Where else could the energy come from?
- Does ΔE always equal w ?

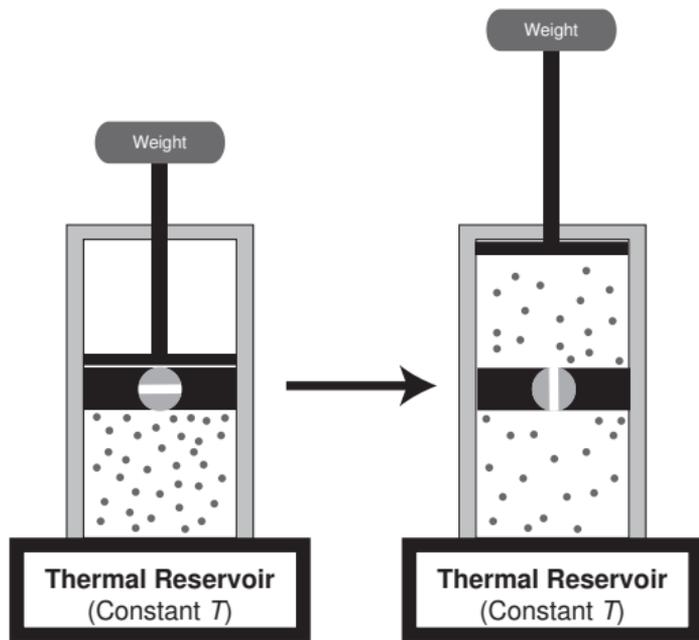
- Some books use the opposite sign convention for w .

Isothermal Expansion with Work



- Reservoir keeps the gas temperature constant. (isothermal)
- What changes?

Clicker Question #3

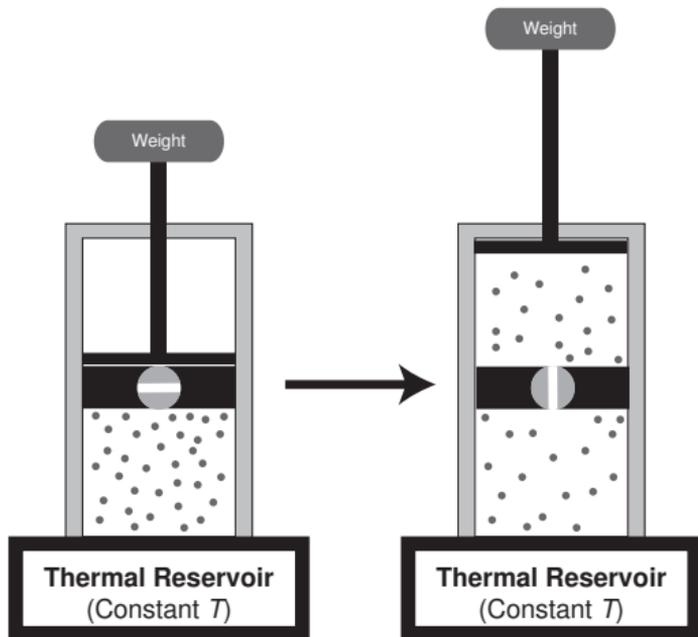


Which of the following change?

- 1 Temperature
- 2 Pressure
- 3 Volume
- 4 Energy

Any answers count for now!

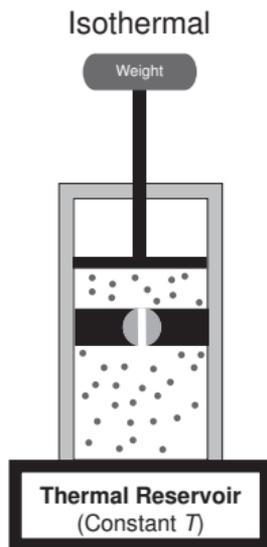
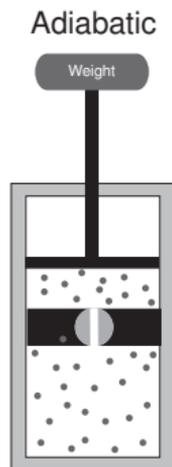
Isothermal Expansion with Work



- Reservoir keeps the gas temperature constant. (isothermal)
- What changes?
 - Heat flows to keep gas temperature the same as the reservoir (which doesn't change).
 - As piston is pushed up, gas molecules lose energy, and temperature drops.
 - Heat flows from reservoir to restore temperature.
 - At the end, temperature is the same as at the beginning, *and* work has been done!

Is More Work Done in the Adiabatic or Isothermal Expansion?

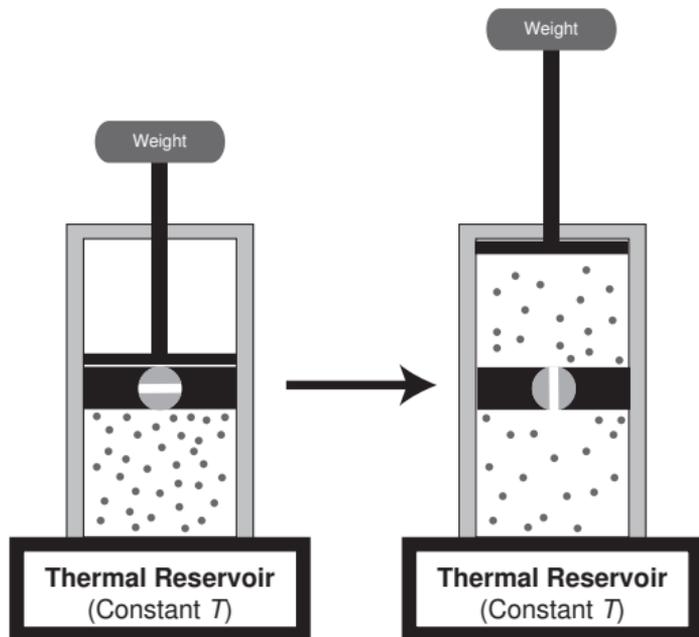
Part way through the two expansion processes:



- $V_{\text{ad}} = V_{\text{isot}}$
- $T_{\text{ad}} < T_{\text{isot}}$
- $P_{\text{ad}} < P_{\text{isot}}$
- $F_{\text{ad}} < F_{\text{isot}}$
- $P = \text{Force/area.}$
- $w_{\text{isot}} < w_{\text{ad}}$

- A more negative value of w means that the system does more work on the surroundings.

Isothermal Expansion with Work



■ The scorecard:

- $\Delta E = 0$, temperature hasn't changed.
- $w < 0$, because the system did work.
- $\Delta E \neq w$
- Where did the energy for work come from?