Physical Principles in Biology
Biology 3550
Fall 2018

Lecture 24

Thermodynamics: Expansion and Compression of a Gas

Friday, 26 October

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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 <u>will</u> 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 multiple generations of scientists in the 18th–20th centuries.
  - Periods of profound confusion.
- But it’s worth it!

Units of Energy

- Energy is the ability to do work.
- Unit of work or energy: $1\,\mathrm{J} = 1\,\mathrm{N}\cdot\mathrm{m} = 1\,\mathrm{Kg}\cdot\mathrm{m}^2/\mathrm{s}^2$
  Energy required to apply 1 N of force over a distance of 1 m.

  $1\,\mathrm{J} = 1\,\mathrm{watt}\cdot\mathrm{s}$, $1\,\mathrm{kwatt}\cdot\mathrm{hr} = 3.6\times10^6\,\mathrm{J}$
- 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 Calorie = 1,000 calories.
  - 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.

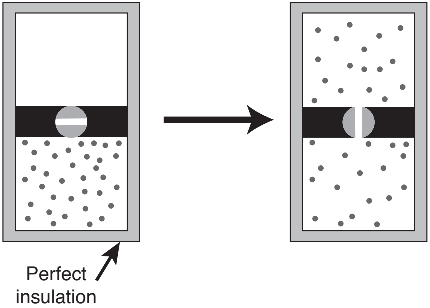
Temperature Versus Heat

- 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, $E_{\mathrm{k}} = 3kT/2$
    Three degrees of translational 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”, and it has the units of energy (joule or calorie).
  - 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

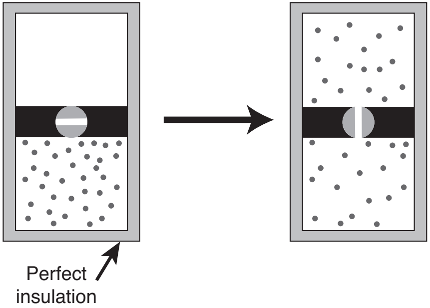
- Historical origins:
  - Development of thermodynamics was first motivated by the invention of the steam engine, and the desire to make better ones.
  - Many of the basic ideas were formulated in this context and are still easiest to visualize in it.
  - Original treatments did not consider molecular 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?

A) Temperature

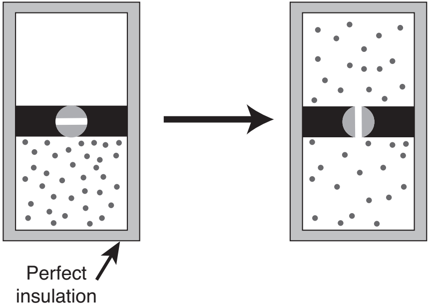
B) Pressure

C) Volume

D) Kinetic energy

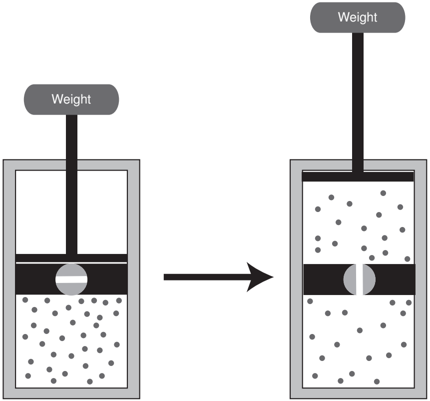
Any answers count for now!

Adiabatic (without heat flow) Expansion of a Gas



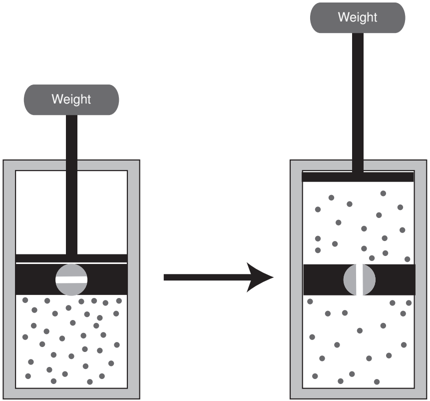
- Insulation prevents heat flow into or out of device.
  - Temperature stays constant.
- What changes?
  - Volume of gas increases.
  - Pressure of gas decreases ($PV = nRT$)
  - Does the energy stay constant? (yes)
  - Has any work been done? (no)
  - Has anything else changed?

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?

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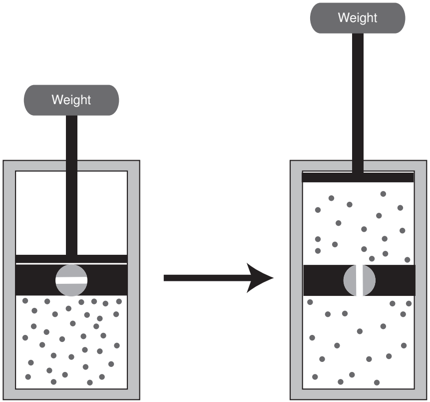
Adiabatic Gas Expansion With Work



- 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.

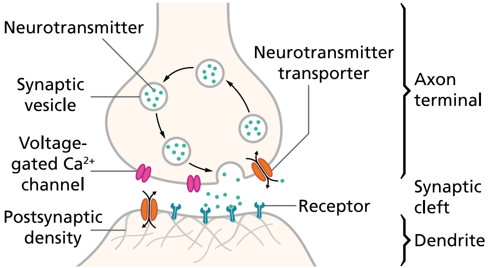
Rules for Keeping Score

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

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

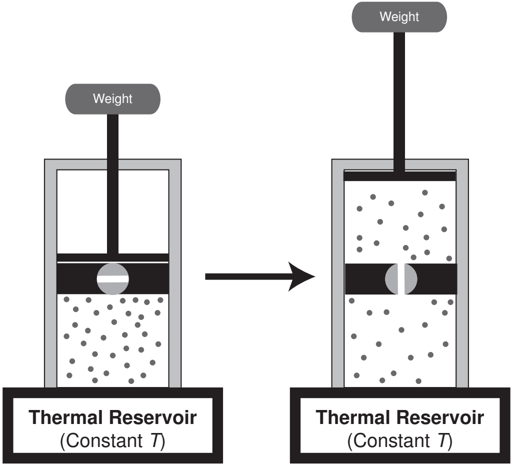
- Work, w:
  - $w > 0$, when work is done on the system.
  - $w < 0$, when the system does work on the outside world, as in the expansion of the gas.
- For the adiabatic expansion of a gas with work:
  - $E_{\text{final}} < E_{\text{start}}$, and $\Delta E < 0$
  - $w < 0$, because the system did work.
  - $\Delta E = w$: Where else could the energy come from?
  - Does ΔE always equal w?
- Some books use the opposite sign convention for w.

What Does This Have to Do with Biology?



- Dilution of molecules in solution is analogous to expansion of a gas.
- How much work (energy) is required to package neurotransmitters into vesicles?
- How much energy is lost when neurotransmitters are released into a synapse?
- Other examples of dilution and concentration in biology?

Isothermal Expansion with Work



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