

Lecture 3: 09.14.05 The first law of thermodynamics

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Reading:

Engel and Reid: 2.5, 2.6, 2.7, 2.9, 3.1

Work and heat change the internal energy of a system

The first law: conservation of energy in thermodynamic calculations

- Internal energy, like kinetic and potential energy that you first encounter in physics, is conserved. Energy lost from a system is not destroyed; it is passed to its surroundings. The first law of thermodynamics is simply a statement of this conservation. The first law, mathematically, is:
 - Stated in simple language, the first law says that a change in internal energy is exactly accounted for by summing the contribution due to heat transferred (into or out of the system) and the work performed (on or by the system).
- The first law introduces the two ways of changing the energy of a system: via **heat transfer or work**.

Sign conventions in the first law

- A source of confusion to new students of thermodynamics is the sign on dq and dw - particularly because different textbooks define different sign conventions for work. We will adopt the following conventions:

Defining work and heat

Definition of work

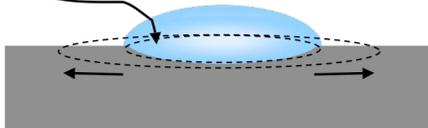
- The meaning of mechanical work is somewhat intuitive; it is energy spent in applying a mechanical force to produce a displacement- a change in size of a system. You are familiar with mechanical work where F is a mechanical force and dx is a change in the length of a (one-dimensional) system, such as a spring.
 - Where dw is the rate work is performed in creating some infinitesimal change in the extent of the system dx against the force F which resists that change.

- Work can take on many forms other than mechanical work. Some examples of interest for materials science & engineering include:

Examples of work in materials

| Type of work | Thermodynamic Force, " F " | Change in system's extent " dx " in response to this force (displacement): |
|------------------------------|------------------------------|--|
| Work of hydrostatic pressure | • | • |
| Work of polarization | • | •□ |
| Chemical work | • | •□ |
| Work of surface energy | • | •□ |

A = area of interface



Spreading droplet gives rise to area change dA

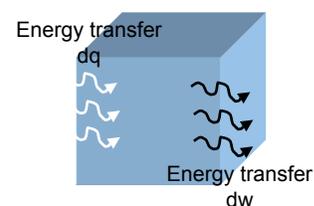
- Applying pressure changes the extent of the system's volume V . Applying an electric field changes the extent of the system's charge- each of these different kinds of work has a general form Fdx . We will discuss some of the important forms of work in more detail a few lectures from now.

Definition of heat

- We can use the first law and the definition of work given above to define heat:

▪ Heat is thus energy transferred during a process, **not** a property of the system.

Heat and work only refer to processes of energy transfer (!!!)



No guarantee heat in = heat out or work in = work out

Equivalence of work and heat

- The first law can be thought of as a statement of energy conservation, but it is also a statement of the equivalence of work and heat. (Eqn 1) says that I could change the internal energy of a system by some amount (suppose the internal energy is increased 5 Joules, for concreteness) in two entirely different ways:
 - Perform 5 J of work on the system with no heat transfer at the boundaries of the system.
 - Transfer 5 J of heat into the system while performing no mechanical work (or any other form of work).
 - Combining knowledge of the type of process occurring with the first law allows one to calculate changes in internal energy directly from measurable quantities like heat and work.
- You may be intuitively comfortable with the idea that mechanical work can convert to heat through processes such as friction- Joule was the first to rigorously test this theory. Others following Joule confirmed that *all* forms of work- not just mechanical work- can be converted to heat.

Limitations on the conversion of heat into work

Conversion of heat \rightarrow work:

Conversion of work \rightarrow heat:

- When we formally introduce the second law, we will show that it prohibits the opposite process: heat from converting 100% converted into work with no loss of energy to the surroundings. (more on this in lecture 4...)

Heat and work in reversible processes**P-V work in reversible processes**

- Pressure on a system performs work at a rate that is well defined only if the work is done extremely slowly, such that the system is in equilibrium at all times and none of the mechanical work being done is converted to heat.
 - This is referred to as a **quasi-static process**- it is **reversible**.
 - In such a process, the increment of work performed for an infinitesimal change in volume is given by:
 - The total work for a quasi-static process is readily calculated by integrating:
 - We can only integrate $-P_{ext}dV$ when the process is reversible!

Heat transfer is linked to an entropy change in reversible processes: first encounter with the second law

- Our first real encounter with entropy comes in examining heat transfer in a reversible process, which provides one definition of entropy. We have mentioned that the second law dictates that entropy increases in spontaneous processes- **but the second law first confirms the existence of a state function- entropy**, which is defined as:

- For practical calculations, we see that the units of entropy are the units of heat (energy) divided by temperature. We will discuss the definition of *temperature* next time; for now, let's just state that the temperature in all thermodynamic equations refers to absolute temperature on the Kelvin scale (*K*). Thus the units of entropy are *Joules/K*.
- The reversible process definition of entropy provides a means to measure entropy changes during reversible processes. It is the heat change in a system divided by the system's temperature.
- The definition also allows us to show the link between entropy and internal energy. Combining the first law with the reversible process definition of entropy gives us:
 - In a reversible process where no mechanical work is performed, $dU = TdS$.

Path dependence vs. path independence of work, heat, and other thermodynamic functions

Path independent variables: State functions

- We have introduced several thermodynamic functions:
 - Internal energy $U = U(S, V, N)$
 - Entropy $S = S(U, V, N)$
 - Pressure $P = P(V, N, T)$
 - Etc.
 - We've just seen how the internal energy depends on S and V for the case of reversible processes. We will show in a few lectures how U also depends on N .
- We have also introduced heat and work:
 - Heat q increment of heat transferred; dq
 - Work w increment of work: dw
- The thermodynamic functions above are distinct from work and heat: U, S , and P are examples of *state functions*, while q and w are **not** state functions

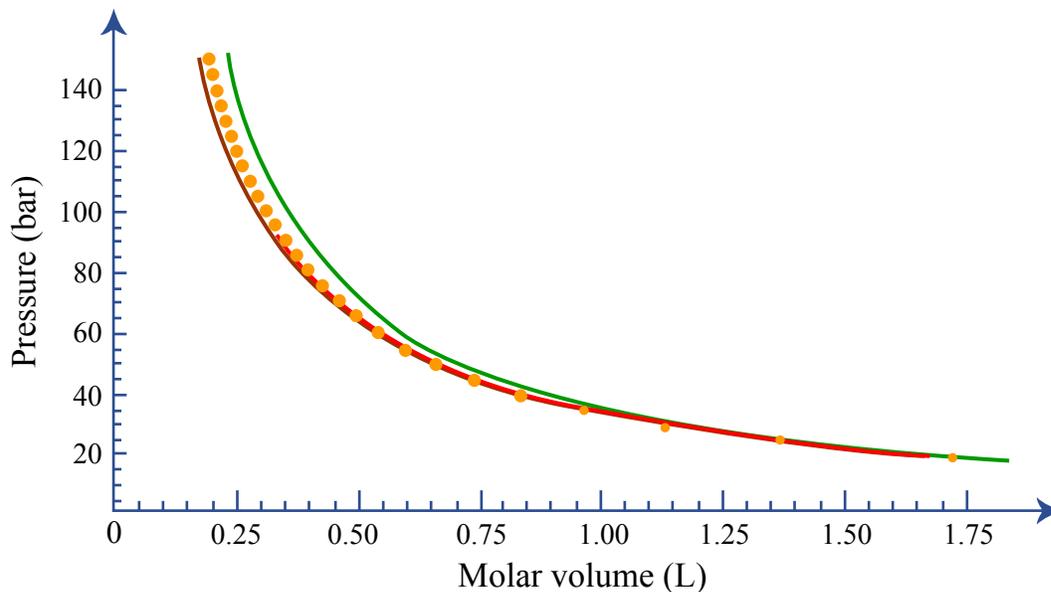
3 Characteristics of state functions using the ideal gas law as an example

□ 1: State functions are models for materials

- A special type of state function relates P , V , and T for a material: such a state function is called an **equation of state**. An example we will return to later: the P - V state function of an **ideal gas**:
 - The ideal gas equation of state can be derived by making two assumptions:
 - **The molecules do not interact**
 - **Each atom/molecule acts as a point mass**

- $R = \text{gas constant} = 8.3144 \text{ J/mole K}$

Example comparison of ideal gas law behavior with real (experimentally determined) gas behavior:



Isotherms for CO_2 are shown at (a) 426 K and (b) 310 K using the van der Waals equation of state (red curve), the Redlich-Kwong equation of state (brown curve), and the ideal gas equation of state (green curve). The orange dots are accurate values taken from the NIST *Chemistry Webbook*.

Figure by MIT OCW.

2: If I know 3 variables, the fourth is determined by a state function

3: State functions are path independent:

- A state function can be integrated to calculate changes in the value of the function:

- Integration of a state function over a cyclic process gives a change of zero in the value of the state function.

- **□ Path-dependent functions like heat and work, on the other hand, can only be integrated in reversible processes.**

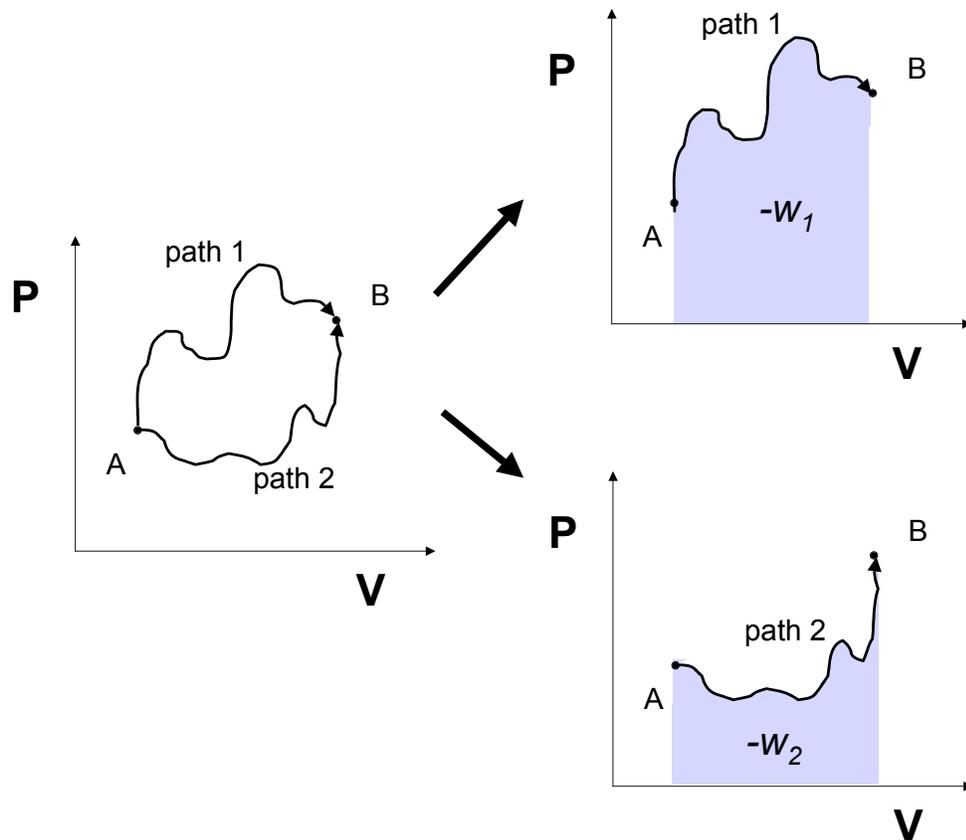
Path dependent variables: heat and work

- Work and heat are not state functions; they are path dependent- what does this mean? In most physical situations, we are concerned with a quantity of heat or work transferred into or out of a material, which causes a change from one state of the material to another. Path dependence implies that the amount of work or heat needed to make the change depends on *how* the process was performed, not just what state the material started in and ended in.

A simple example: path dependence of P-V work²

- If mechanical work is performed on a material by placing it under pressure extremely slowly- such that none of the work is converted to heat (e.g. due to friction) and the system is in equilibrium at each moment, then the work performed is given by:

- Suppose I have a block of material that I put under various conditions, varying the pressure the material is under and its volume. I do this to change from a state A (P_1, V_1) to state B (P_2, V_2) by two different paths, as illustrated below:



- Since I performed this work extremely slowly (without waste of any of the work as heat), we can calculate the total work for each path by integrating:

$$w_1 = \int_{\text{path 1}} -PdV$$

- We can clearly see from the graphical representation that the work done along path 1 will be significantly different from that along path 2: *the total work is path dependent.*

References

1. Engel, T. & Reid, P. *Physical Chemistry* (Benjamin Cummings, San Francisco, 2006).
2. Denbigh, K. *The Principles of Chemical Equilibrium* (Cambridge University Press, New York, 1997).