Lecture 41 – The laws of thermodynamics

Purdue ME 200, Thermodynamics I

Kevin J. Kircher, kircher@purdue.edu


IN THIS HOUSE, WE OBEY
THE LAWS OF
THERMODYNAMICS!

Outline

The 0th law

The 1st law for closed systems

The 2nd law for closed systems

The 1st and 2nd laws for open systems

What's next?

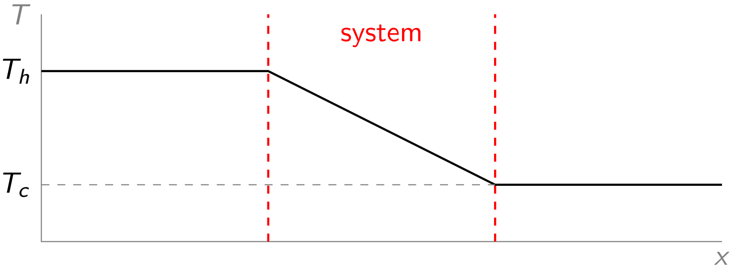
The 0th law

Any **system** in **internal equilibrium** has an **intensive property** called **temperature**, T. Two systems, each in internal equilibrium, are in **thermal equilibrium** with each other if and only if their temperatures are equal.

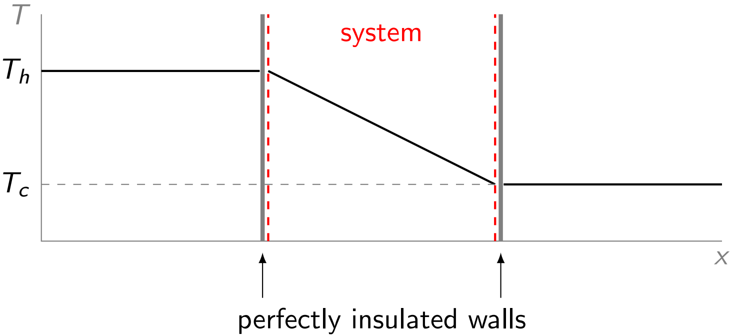
Systems, properties and internal equilibrium

- a **system** is a region of space or collection of matter
- everything but the system is the **surroundings**
- an **isolated** system does not interact with the surroundings
- **properties** are
  - ◇ characteristics of a system
  - ◇ that can be quantified with no knowledge of system history
- a system is in **internal equilibrium** if
  - ◇ when isolated, its properties stay the same forever

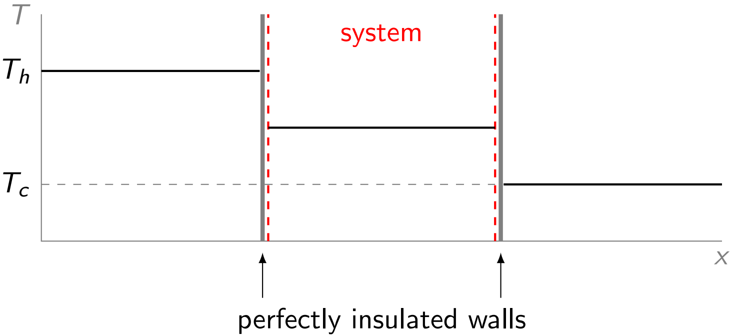
Testing for internal equilibrium



Testing for internal equilibrium

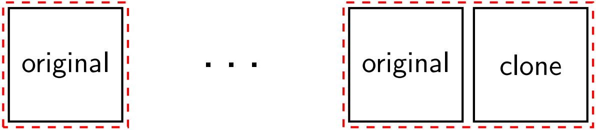


Testing for internal equilibrium



Intensive and extensive properties

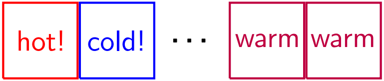
- create an identical clone of any system
- draw a new boundary around the original plus the clone



- for the new system (original + clone), the numerical values of
  - **intensive** properties equal those of the original system
  - **extensive** properties are double those of the original system

Thermal equilibrium

- imagine a block that feels hot and another that feels cold
- bring them together and periodically touch them
- the hot block will start to feel cooler; the cold block, warmer
- eventually, their feelings of warmth will stop changing
- and both blocks will feel equally warm



- at that point, the blocks are in **thermal equilibrium**

Plain English paraphrase of the 0th law

Thermometers are possible.

What is temperature?

- the property that uniquely characterizes thermal equilibrium
- (the $-$integral of) a pointer in the direction of heat transfer
- (proportional to) the average KE of microscopic stuff

Outline

- The 0th law
- The 1st law for closed systems
- The 2nd law for closed systems
- The 1st and 2nd laws for open systems
- What's next?

The 1st law for closed systems

Any system has an extensive property called **internal energy**, U.
A system's total energy E is the sum of its internal energy and the kinetic and potential energies of its center of mass:

$$E = U + \frac{1}{2}m\dot{r}^2 + mgz.$$

During a **process**, the rate of change of a **closed** system's total energy is

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \dot{Q} - \dot{W},$$

where $\dot{Q}$ is the rate of net **heat transfer** input and $\dot{W}$ is the rate of net **work** output.

Processes and equilibrium states

- a **state** is a list of properties that fully characterizes a system
  - ◇ for systems in internal equilibrium, states are *short* lists
  - ◇ out of equilibrium, states can be long, complicated lists
- a **process** is a transition between two equilibrium states

Closed systems

- the **boundary** separates the system from the surroundings
- matter never crosses the boundary of a **closed** system

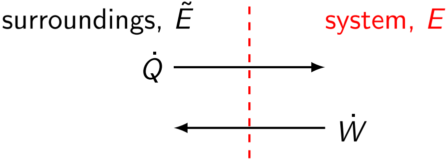
Heat transfer and work

- **transfer** means exchange between system and surroundings
- **heat** transfer is energy transfer due only to T differences
- **work** is energy transfer that's not heat transfer

Plain English paraphrase of the 1st law

The universe's total energy never changes.

Conservation of energy and the 1st law



- consider a closed system during a process
- the system's rate of total energy change is $\mathrm{d}E/\mathrm{d}t = \dot{Q} - \dot{W}$
- for the (closed) surroundings, $\mathrm{d}\tilde{E}/\mathrm{d}t = -\dot{Q} + \dot{W}$
- so the rate of change of the universe's total energy is

$$\frac{\mathrm{d}E}{\mathrm{d}t} + \frac{\mathrm{d}\tilde{E}}{\mathrm{d}t} = 0$$

What is internal energy?

- the property whose rate of change for any closed system is

$$\dot{Q} - \dot{W} - \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}m\dot{r}^2 + mgz\right)$$

- the total KE and PE of all the system's microscopic stuff

	macroscopic	microscopic
due to motion	KE	U
due to force	PE	U

Outline

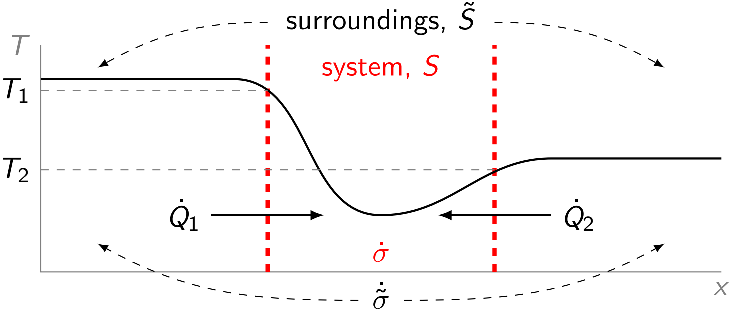
The 2nd law for closed systems

Any system has an extensive property called **entropy**, S. During a process, the rate of change of a closed system's entropy is

$$\frac{dS}{dt} = \sum_{i=1}^{N} \frac{\dot{Q}_i}{T_i} + \dot{\sigma},$$

where $\dot{Q}_i$ is the rate of input heat transfer across a section of the boundary at temperature T_i. The rate of internal entropy generation $\dot{\sigma}$ is always nonnegative, and is positive during any real process.

2nd law illustration



$$\text{system:}\quad \frac{dS}{dt} = \frac{\dot{Q}_1}{T_1} + \frac{\dot{Q}_2}{T_2} + \dot{\sigma}$$

$$\text{surroungings:}\quad \frac{d\tilde{S}}{dt} = -\frac{\dot{Q}_1}{T_1} - \frac{\dot{Q}_2}{T_2} + \dot{\tilde{\sigma}}$$

Plain English paraphrase of the 2nd law

The universe's entropy never decreases.

Increase of entropy and the 2nd law

- a closed system's rate of entropy change during a process is

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \sum_{i=1}^{N} \frac{\dot{Q}_i}{T_i} + \dot{\sigma}$$

- for the (closed) surroundings,

$$\frac{\mathrm{d}\tilde{S}}{\mathrm{d}t} = -\sum_{i=1}^{N} \frac{\dot{Q}_i}{T_i} + \dot{\tilde{\sigma}}$$

- so the rate of change of the universe's entropy is

$$\frac{\mathrm{d}S}{\mathrm{d}t} + \frac{\mathrm{d}\tilde{S}}{\mathrm{d}t} = \dot{\sigma} + \dot{\tilde{\sigma}} \geq 0$$

What is entropy?

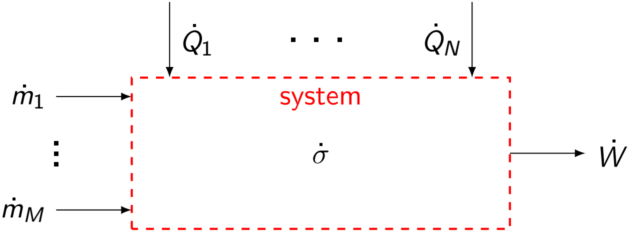
- the property whose rate of change for any closed system is

$$\sum_{i=1}^{N} \frac{\dot{Q}_i}{T_i} + \dot{\sigma}$$

- (proportional to) the maximum work that a Q could've output
- in internal equilibrium, $S = k \ln(\Omega)$
  - ◇ k is the Boltzmann constant
  - ◇ Ω is the number of possible microscopic configurations

Outline

A generic open system



- $\dot{Q}_1, \dots, \dot{Q}_N$ are rates of heat transfer input
- $\dot{Q} = \dot{Q}_1 + \cdots + \dot{Q}_N$ is the rate of net heat transfer input
- $\dot{m}_1, \dots, \dot{m}_M$ are rates of mass input
- $\dot{W}$ is the rate of net work output

⋆ a negative input is an output

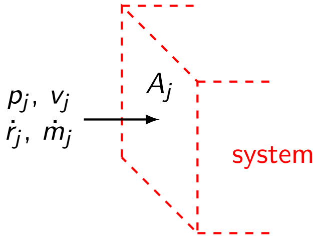
Moving matter carries energy and entropy

- consider moving matter with
  - mass flow rate $\dot{m}_j$
  - **specific** internal energy u_j
  - specific volume v_j
  - speed $\dot{r}_j$
  - height z_j
  - specific entropy s_j
- associated with the moving matter is a total energy flow

$$\dot{m}_j \left(u_j + \frac{1}{2} \dot{r}_j^2 + g z_j \right)$$

and an entropy flow $\dot{m}_j s_j$

Moving matter does work



- moving matter exerts force $F_j = p_j A_j$ on matter in the system
- the associated rate of work is $\dot{W}_j = F_j \dot{r}_j = p_j A_j \dot{r}_j$
- but $\dot{m}_j = \rho_j \dot{V}_j = \dot{V}_j / v_j$ and $\dot{V}_j = A_j \dot{r}_j$
- so $A_j \dot{r}_j = \dot{m}_j v_j$, and the rate of work is $\dot{W}_j = p_j A_j \dot{r}_j = \dot{m}_j p_j v_j$

⋆ these equations are valid if
  - ⋄ moving matter's properties are uniform over boundary
  - ⋄ flow is one-dimensional (and $\dot{r}$ is component $\perp$ to boundary)

Extending 1st law to open systems (with uniform 1D flow)

During a process, the rate of change of a system's total energy is

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \dot{Q} - \dot{W} + \sum_{j=1}^{M} \dot{m}_j \left(u_j + \frac{1}{2}\dot{r}_j^2 + g z_j + p_j v_j \right)$$

$$= \dot{Q} - \dot{W} + \sum_{j=1}^{M} \dot{m}_j \left(h_j + \frac{1}{2}\dot{r}_j^2 + g z_j \right),$$

where $h_j = u_j + p_j v_j$ is the specific **enthalpy** of the matter crossing the boundary at surface j.

Enthalpy and specific enthalpy

- **enthalpy**, $H = U + pV$, is an extensive property
- a **specific** property is an extensive property per unit mass
- specific enthalpy is

$$
\begin{aligned}
h &= \frac{H}{m} \\
&= \frac{U}{m} + p\frac{V}{m} \\
&= u + pv
\end{aligned}
$$

Extending 2nd law to open systems (with uniform 1D flow)

During a process, the rate of change of a system's entropy is

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \sum_{i=1}^{N} \frac{\dot{Q}_i}{T_i} + \sum_{j=1}^{M} \dot{m}_j s_j + \dot{\sigma},$$

where s_j is the specific entropy of the matter crossing the boundary at surface j.

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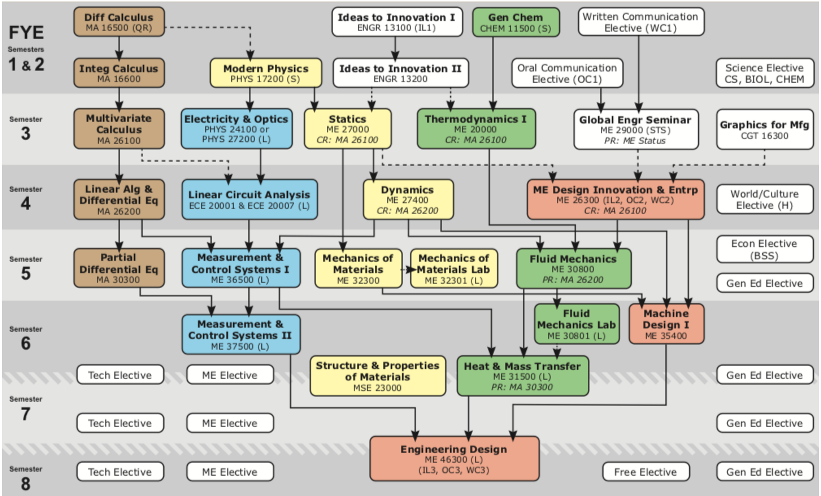
What's next?

Alongside the laws of thermo, we've learned how to...

- find property data for solids, liquids and gases
- visualize processes on property diagrams (p-v, T-s, ...)
- understand substances through simple models
  - ◇ incompressible substance model for solids and liquids
  - ◇ ideal gas model for gases
- model a small set of components
  - ◇ nozzles and diffusers (backward nozzles)
  - ◇ turbines and compressors/pumps (backward turbines)
  - ◇ throttles
  - ◇ heat exchangers
- hook components together to build useful machines
  - ◇ vapor power plants and engines (Rankine cycle)
  - ◇ heat pumps, ACs and refrigerators (vapor compression cycle)
  - ◇ automobile engines (Otto, Diesel and dual cycles)
  - ◇ gas power plants and engines (Brayton cycle)

If you liked thermo, where to go from here?



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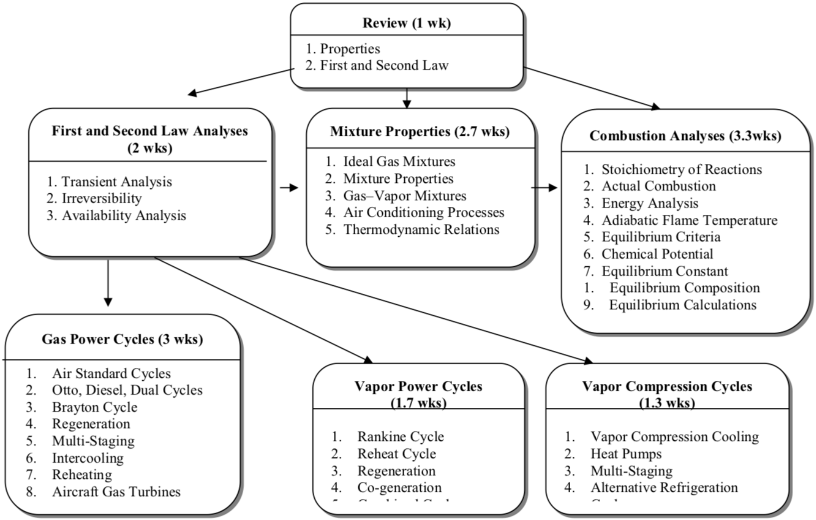

Other thermo-flavored electives

- ECE 31032, Power Systems Engineering
- AAE 33900, Aerospace Propulsion
- CE 41300, Building Envelope Design and Thermal Loads
- ME 43000, Power Engineering
- ME 43400, Gas Turbines for Power and Propulsion
- ME 50000, Advanced Thermodynamics
- ME 50100, Statistical Thermodynamics
- ME 51400, Fundamentals of Wind Energy
- ME 52900, Sustainable Energy Options and Analysis
- . . . and many more! (link)