PHYS 10352

Part I: Classical Thermodynamics

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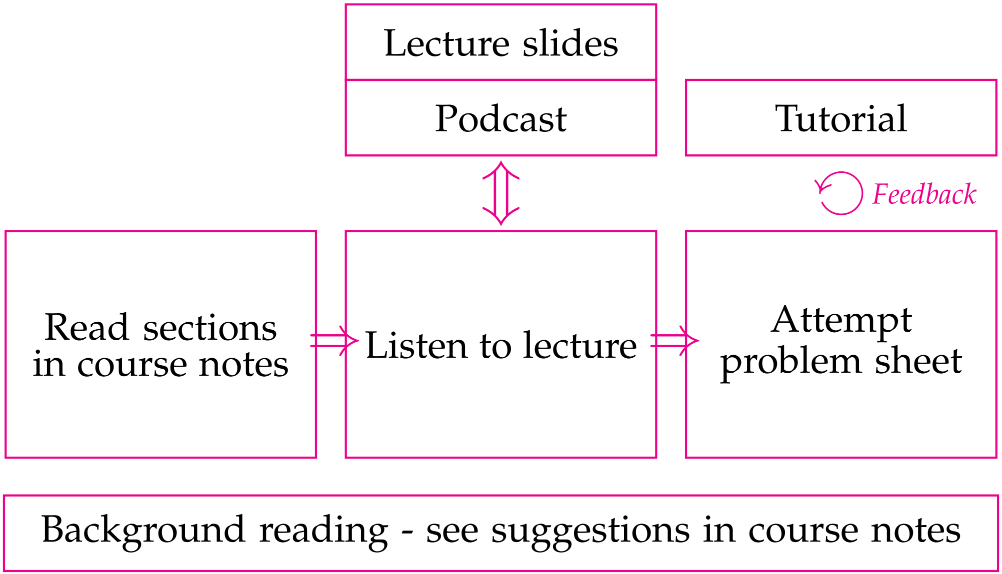
February 6, 2023

Course Overview

- Classical thermodynamics (11 lectures) + Properties of liquids, solids and gases (11 lectures).
- Lectures: Wednesday @ 09:00 (Simon Theatre E) & Friday @ 10:00 (University Place Lecture Theatre B).
- Weekly Problem/Example Sheet $\Leftarrow$ *Feedback*.
- Revision lectures on both parts in SEM2WK12 (last teaching week of the semester).
- Written notes available on Blackboard.
- Weekly material (lecture slides) will be available on Blackboard at the start of each week.
- Weekly breakdown/schedule of topics available on Blackboard.
- A Piazza discussion board is available on Blackboard.
- Past papers are available on Blackboard (UG Virtual Common Room).

How to Structure your Learning for this Course



Week 1: The 1st Law of Thermodynamics

$$\theta\epsilon\rho\mu\omega\sigma \quad \delta\upsilon\nu\alpha\mu\iota\sigma$$

(thermos) (dunamis)

"the power of heat"

Introduction

θϵρμωσ δυναμισ

industrial revolution

- 1712 Newcomen Steam Engine
- 1776 Watt Steam Engine
- 1824 Carnot publishes *Réflexions sur la Puissance Motrice du Feu*
- 1834 The term *Scientist* is coined
- 1849 Thomson reads Carnot's paper to the Royal Society of Edinburgh
  – "Thermodynamics" is born...

Introduction
Energy and Empire

- James Watt's father made his money through the slave trade - and it was his father's wealth that paid for the education resulting in his design for a steam engine.
- Steam engines not only powered manufacturing production for the British Empire, but also powered its expansion: HMS *Devastation* (1871) was the first steam powered ship in the British Navy.
- Steam power = coal power during the industrial revolution (and for long after), leading to modern climate change.

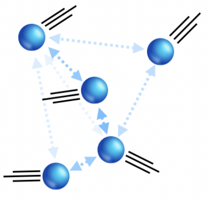
One legacy of the origins of classical thermodynamics is the way in which it is typically taught - with much emphasis on engine cycles.

In these lectures, I will attempt to use more examples of natural thermodynamic systems and cycles to demonstrate the principles of classical thermodynamics and to move away from this legacy.

Ideal Gases

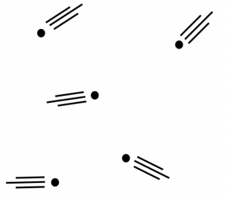
Real Gas

- particles have volume
- energy lost in collisions
- intermolecular forces



Ideal Gas

- particles have no volume
- collisions are elastic
- no interactions between particles



Real gases behave like ideal gases at:

- high temperatures
- low pressures

$$PV = nRT$$

P:	pressure	Pascals ($\equiv \mathrm{N\,m^{-2}}$)
V:	volume	$\mathrm{m^3}$
n:	number of moles	
R:	molar gas constant	$8.31\,\mathrm{m^2\,kg\,s^{-2}\,K^{-1}\,mol^{-1}}$
T:	temperature	K

THOUGHT EXPERIMENT - 1

How many moles of nitrogen are there in this lecture theatre?

THOUGHT EXPERIMENT - 1

How many moles of nitrogen are there in this lecture theatre?

Follow-up: What is the *mass* of all that nitrogen?

Hint: nitrogen gas is *molecular* nitrogen, i.e. N_2, and the mass number of nitrogen is ^{14}N.

How many moles of nitrogen are there in this lecture theatre?

- We assume that the air can be treated as an ideal gas.
- The pressure in the lecture theatre is atmospheric, therefore $P = 1\,\text{atm} = 101{,}000\,\text{Pa}$.
- The temperature in the lecture theatre is room temperature, therefore $T \simeq 20°\text{C} = 293\,\text{K}$.
- The volume of the lecture theatre[1] is $15 \times 30 \times 5 = 2250\,\text{m}^3$ and air is 78% nitrogen, so $V = 0.78 \times 2250 = 1755\,\text{m}^3$

$$PV = nRT \quad \Rightarrow \quad n = \frac{PV}{RT} = \frac{101000 \cdot 1755}{8.31 \cdot 293} \approx 73000\,\text{moles.}$$

What is the mass of all that nitrogen?

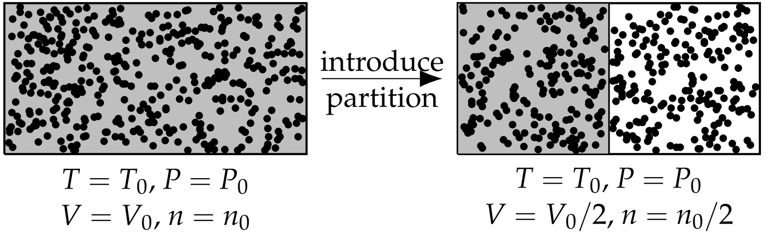
- The molar mass of nitrogen gas (N_2) is $2 \times 14 = 28\,\text{g}$.

$$M = m \cdot n = 28 \times 73000 = 2044000\,\text{g} \simeq 2000\,\text{kg.}$$

[1] This is a very rough guess...

Ideal Gases

Intensive & Extensive variables

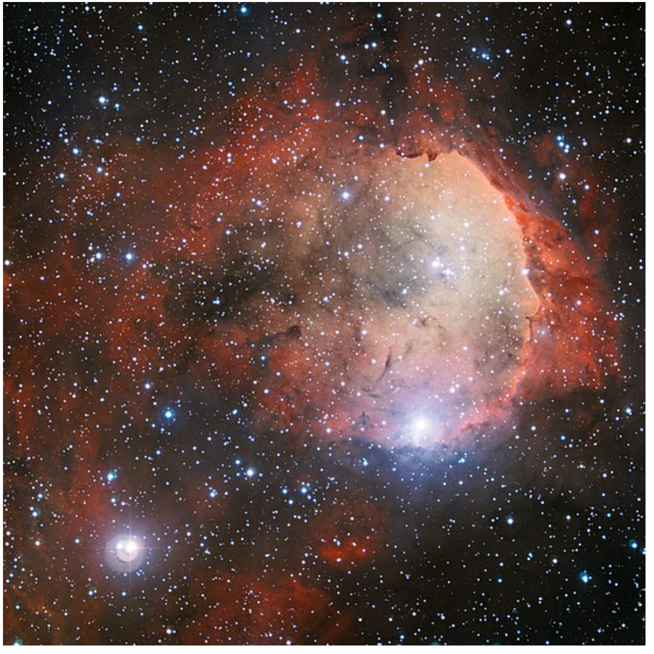


- **Intensive variables** are non-additive; their value is not proportional to the amount of substance,
- **Extensive variables** are additive; their value is linearly proportional to the amount of substance.

If a quantity is non-linearly proportional to the amount of substance, then it is neither extensive nor intensive.

Ideal Gases

Worked Example - Gabriela Mistral Nebula



https://en.wikipedia.org/wiki/NGC_3324;https://en.wikipedia.org/wiki/Gabriela_Mistral

Ideal Gases

Worked Example - Gabriela Mistral Nebula

The emission nebula IC 2599 (also known as Gum 31) is a roughly spherical region of ionized hydrogen gas with a radius of 4.5 pc and a temperature of 10^4 K. The density of ionised hydrogen in the nebula is 100 atoms cm^{-3}.

Use the ideal gas law to calculate the pressure inside the Gabriela Mistral nebula.

Ideal Gases

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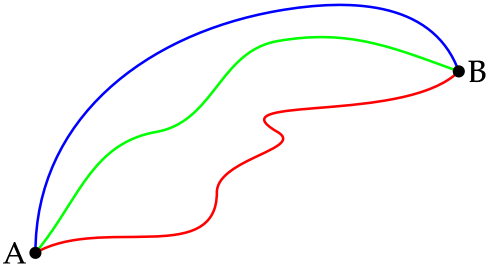
- $r = 4.5\,\mathrm{pc} = 4.5 \times 3.086 \times 10^{16} = 1.389 \times 10^{17}\,\mathrm{m} \quad \therefore \quad V = (4/3)\pi r^3 = 1.123 \times 10^{52}\,\mathrm{m}^3$.
- $\rho = 100\,\mathrm{cm}^{-3} = 10^8\,\mathrm{m}^{-3} \quad \Rightarrow \quad M = \rho V = 10^8 \cdot 1.67 \times 10^{-27} \cdot 1.123 \times 10^{52} = 1.875 \times 10^{33}\,\mathrm{kg}$
- $n = M/m = 1.875 \times 10^{36}$, where $m = 1\,\mathrm{g\,mol}^{-1}$ (for ^{1}H).

$$PV = nRT \quad \Rightarrow \quad P = \frac{nRT}{V} = \frac{1.875 \times 10^{38} \cdot 8.31 \cdot 10^4}{1.123 \times 10^{52}} = 1.387 \times 10^{-11}\,\mathrm{Pa}.$$

Note: 1 parsec = 3.086×10^{16} m; mass of hydrogen atom = 1.67×10^{-27} kg.

The 1st law of thermodynamics

Overview

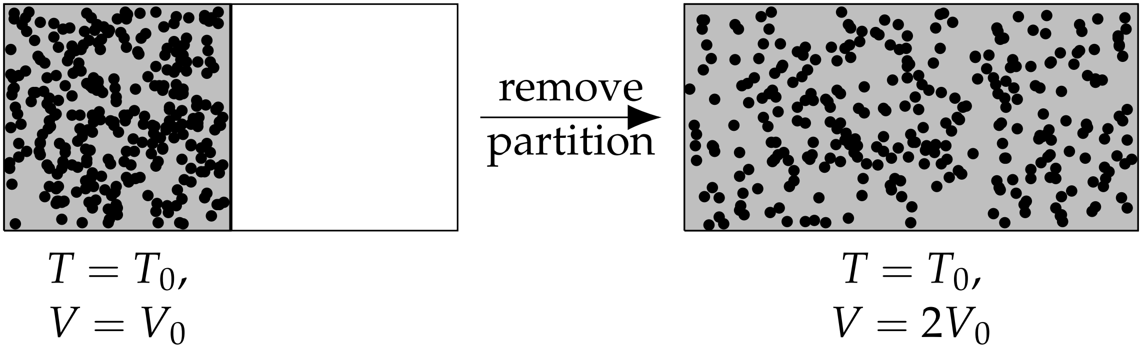


$$\underbrace{\Delta E}_{\text{Change in internal energy.}} = \underbrace{W}_{\text{Work done \underline{on} system.}} + \underbrace{Q.}_{\text{Heat supplied \underline{to} system.}}$$

- E is a **function of state**. This means that ΔE depends only on the initial and final values of E for a process.
- W and Q are <u>not</u> functions of state. Their values depend on the path taken between their initial and final states during a process.

The 1st law of thermodynamics

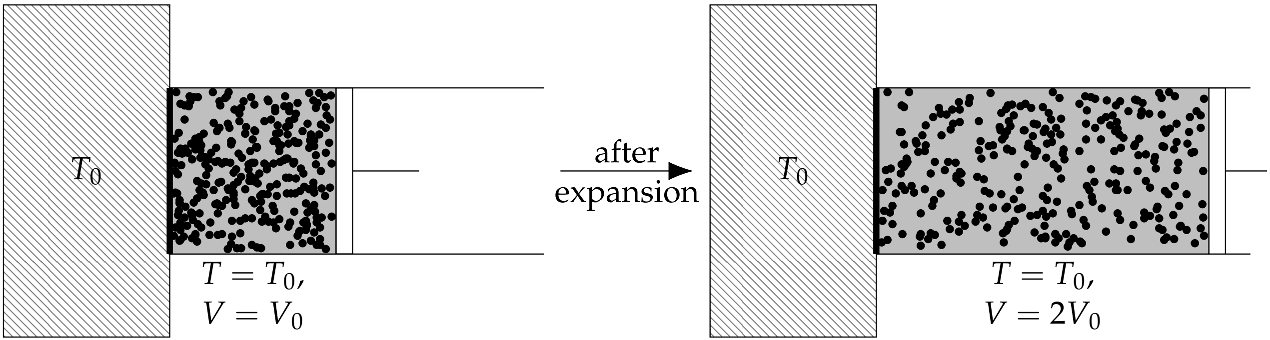
Free expansion of an ideal gas



$$W = 0; \quad Q = 0 \quad \therefore \quad \Delta E = 0$$

The 1st law of thermodynamics

Isothermal expansion of an ideal gas



$$W < 0; \quad Q > 0 \quad \Rightarrow \quad (Q + W) = 0 \quad \therefore \quad \Delta E = 0$$

The 1st law of thermodynamics
Reversible Processes

$$dE = đQ + đW,$$

For a process to be **reversible**:

1. it must be quasistatic;
2. there must be no external friction;
3. it must not cause any permanent change to the system; e.g. stretching a wire beyond its elastic limit such that it becomes permanently stretched.

- $đ$ denotes an infinitesimal change in a path-dependent variable.
- A quasistatic process is one that proceeds very slowly, such that the system is always instantaneously in thermal equilibrium.

The 1st law of thermodynamics

Worked Example - Joule's Honeymoon

In 1847, James Joule (who famously first performed the paddle wheel experiment described in Example Sheet 1) spent part of his honeymoon trying[2] to measure the temperature difference between the top and bottom of the Cascade de Sallanches waterfall in Chamonix, France.

Given that it takes 4.19 kJ of energy to raise the temperature of 1 kg of water by 1 °C, and that the height of the Cascade de Sallanches is 450 m, what difference in temperature would you expect to find?

[2] Unsuccessfully.

The 1st law of thermodynamics

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The change in potential energy experienced by water falling from the top to the bottom of the Cascade de Sallanches will be

$$\Delta E = mg\Delta h,$$

and the equivalent temperature change will be:

$$\Delta T = \frac{\Delta E}{m \cdot 4.19 \times 10^3} = \frac{m \cdot g \cdot \Delta h}{m \cdot 4.19 \times 10^3} = \frac{9.81 \cdot 450}{4.19 \times 10^3} = 1.05\,\mathrm{K}.$$

[3] Unsuccessfully.

Summary

- Ideal gases: point-like particles; elastic collisions; no interactions;
- Real gases behave like ideal gases at high temperatures and low pressures;
- The ideal gas law:

$$PV = nRT$$

- Reversible processes: quasistatic; no external friction; no permanent change to the system;
- The 1st Law of Thermodynamics:

$$dE = đQ + đW$$

FINAL SLIDE

James Prescott Joule was born on New Bailey Street in Salford on 24 December 1818.
He is buried in Brooklands Cemetery in Sale.

On his gravestone there is a number inscribed:

772.55

What does this number mean?