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Introduction to Force & Function

Force & function at the nanoscale

How the course will work

Each week will consist of:

- 2 Lectures (Monday at 5pm; Friday at 4pm, Physics C04)
    - All core content
    - Worked Problems

- 2-3 Activities / Problems for you to work on at home

Resources for the course

We will be using a class Onenote book during the sessions. **Please check you can access.**

- A copy of the slides
- All my written working
- Space for you to make your own notes

The online course pages: via Moodle or directly at phys3009.github.io

- Info about the course
- Notes that follow lectures
- Weekly activities
- Download slides

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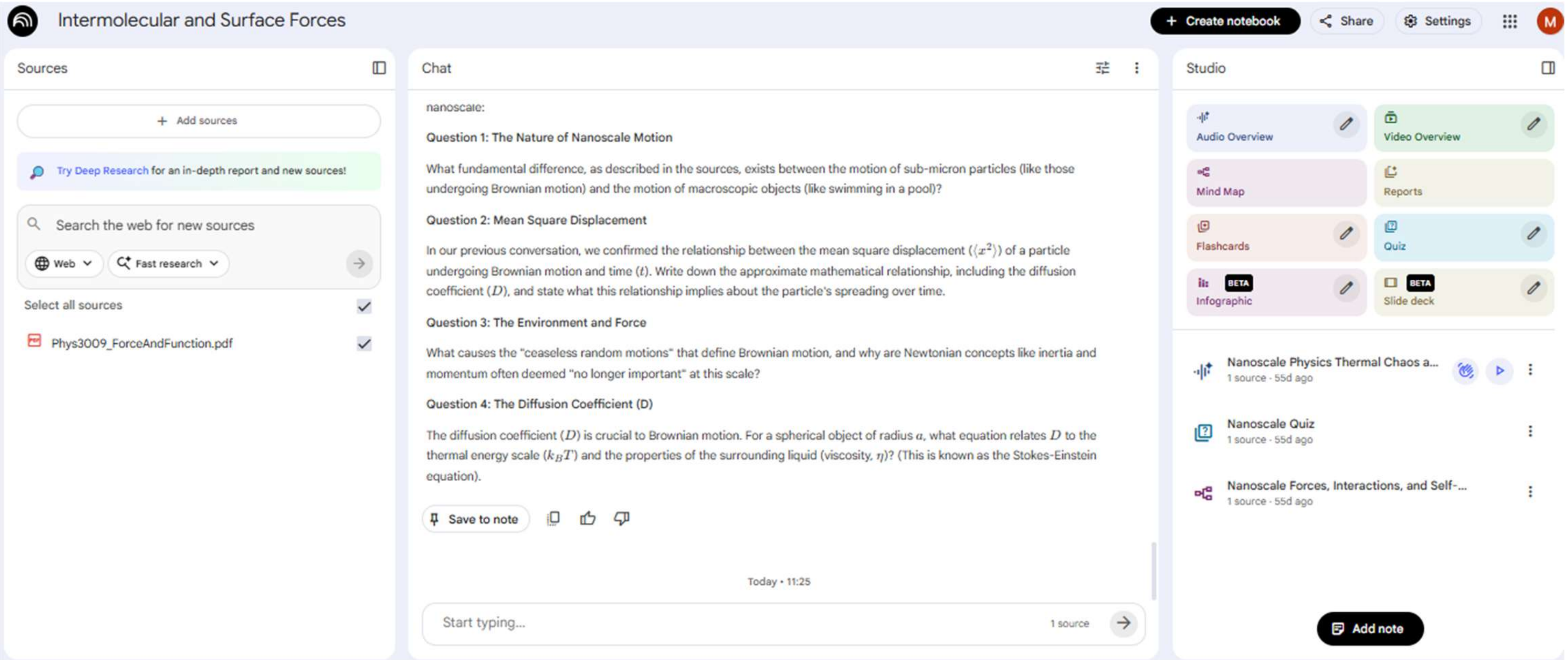
The AI tutor (optional)

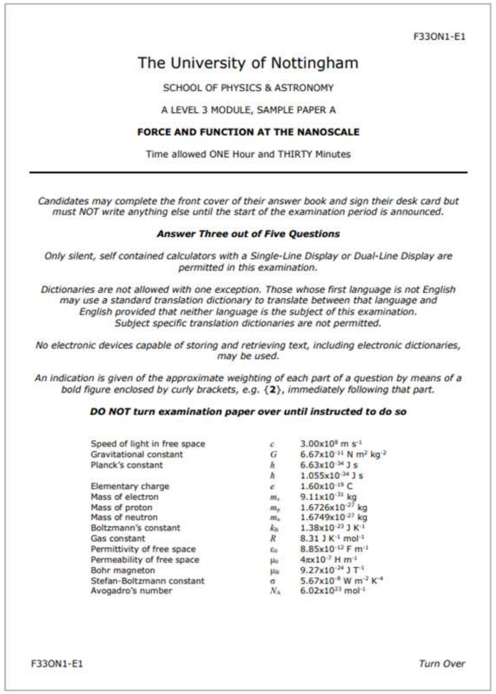


Simple instructions https://phys3009.github.io/content/info_course/aitutor.html

Assessment of the course

- Examination (100%)
- In person, closed book
- 2 hours to complete the paper
- Answer all 3 questions
- Access to key equations sheet, provided in advance.

The equation sheet, example exam papers + answers, are at the bottom of the Moodle page and on the course pages



F33ON1-E1

The University of Nottingham

SCHOOL OF PHYSICS & ASTRONOMY

A LEVEL 3 MODULE, SAMPLE PAPER A

FORCE AND FUNCTION AT THE NANOSCALE

Time allowed ONE Hour and THIRTY Minutes

Candidates may complete the front cover of their answer book and sign their desk card but must NOT write anything else until the start of the examination period is announced.

Answer Three out of Five Questions

Only silent, self contained calculators with a Single-Line Display or Dual-Line Display are permitted in this examination.

Dictionaries are not allowed with one exception. Those whose first language is not English may use a standard translation dictionary to translate between that language and English provided that neither language is the subject of this examination. Subject specific translation dictionaries are not permitted.

No electronic devices capable of storing and retrieving text, including electronic dictionaries, may be used.

*An indication is given of the approximate weighting of each part of a question by means of a bold figure enclosed by curly brackets, e.g. {**2**}, immediately following that part.*

DO NOT turn examination paper over until instructed to do so

Speed of light in free space	c	3.00×10^{8} m s^{-1}
Gravitational constant	G	6.67×10^{-11} N m^{2} kg^{-2}
Planck's constant	h	6.63×10^{-34} J s
	$\hbar$	1.055×10^{-34} J s
Elementary charge	e	1.60×10^{-19} C
Mass of electron	m_e	9.11×10^{-31} kg
Mass of proton	m_p	1.6726×10^{-27} kg
Mass of neutron	m_n	1.6749×10^{-27} kg
Boltzmann's constant	k_B	1.38×10^{-23} J K^{-1}
Gas constant	R	8.31 J K^{-1} mol^{-1}
Permittivity of free space	ε_0	8.85×10^{-12} F m^{-1}
Permeability of free space	μ_0	$4\pi\times10^{-7}$ H m^{-1}
Bohr magneton	μ_B	9.27×10^{-24} J T^{-1}
Stefan-Boltzmann constant	σ	5.67×10^{-8} W m^{-2} K^{-4}
Avogadro's number	N_A	6.02×10^{23} mol^{-1}

F33ON1-E1 *Turn Over*

Questions

Questions?!

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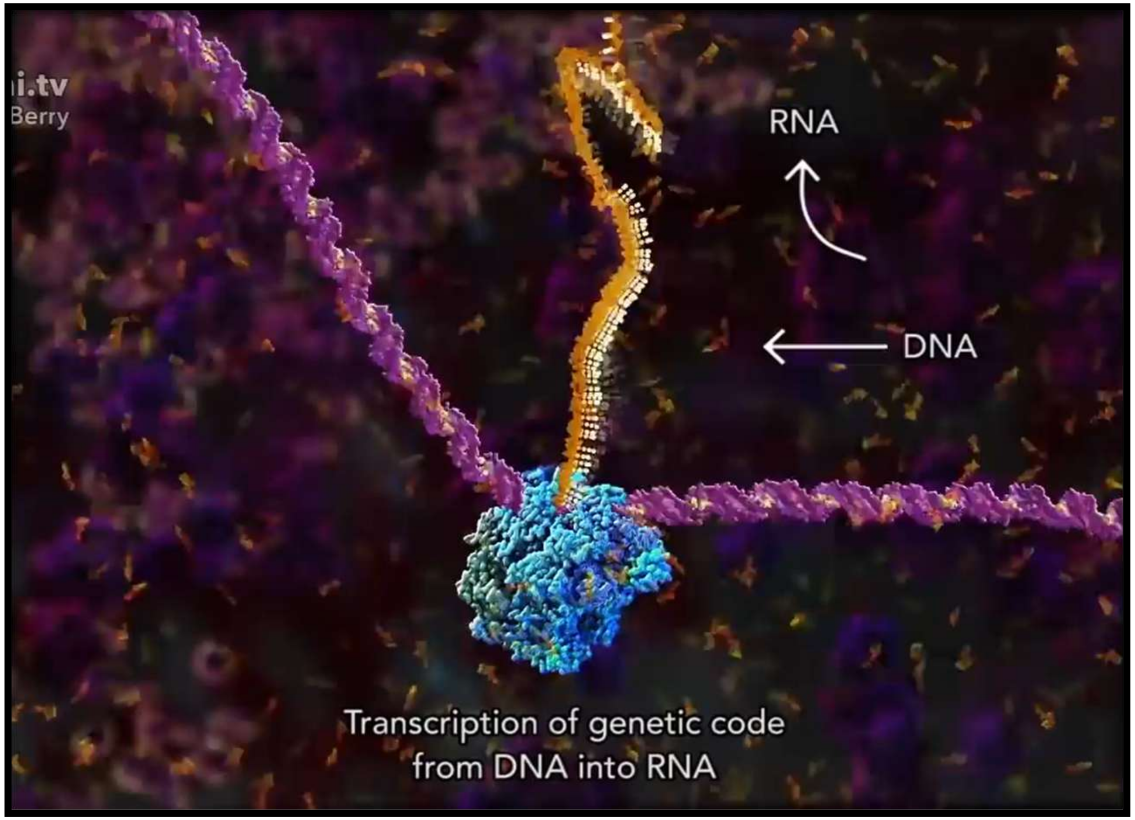
Macro vs nanoscale

Force & function at the nanoscale

The nanoscale world

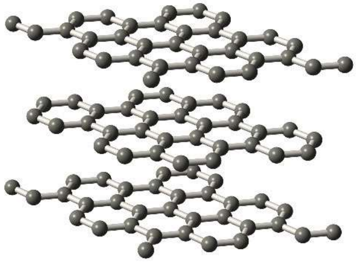


The nanoscale world is dominated by ceaseless thermal motion

Every bit of “nanoscale machinery” inside each one of our cells relies on an intricate balance of chemical reactions and forces

Strong & weak interactions

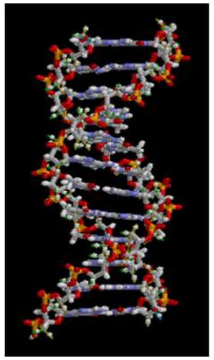
The thermal energy scale



At the nanoscale thermal energy is extremely important. Molecules are in constant random motion.

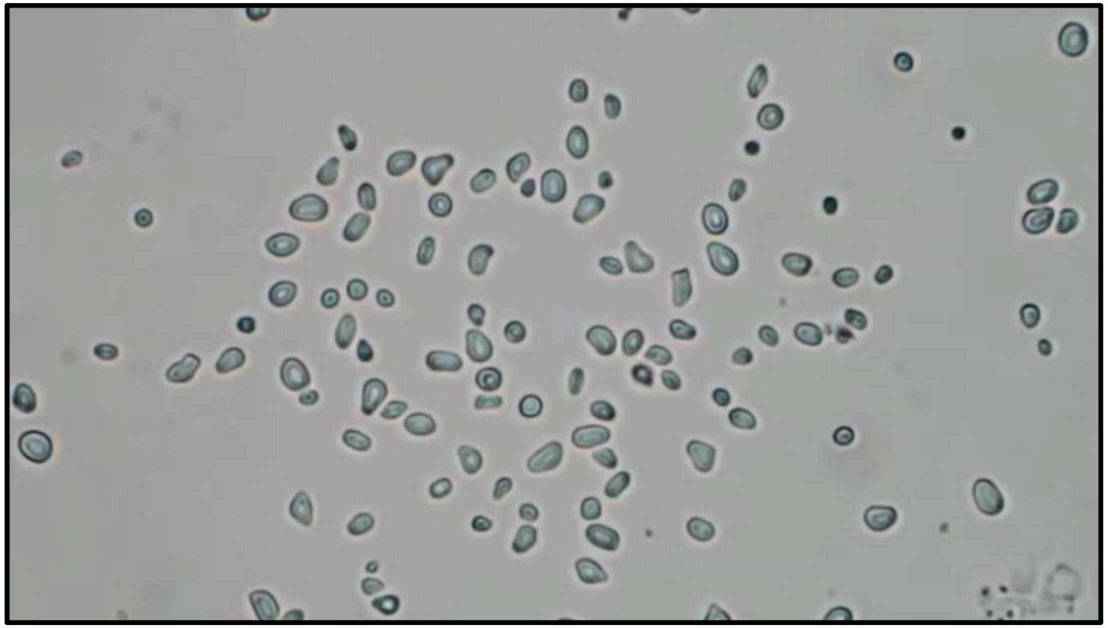
Whether an interaction is significant depends on its size relative to kT

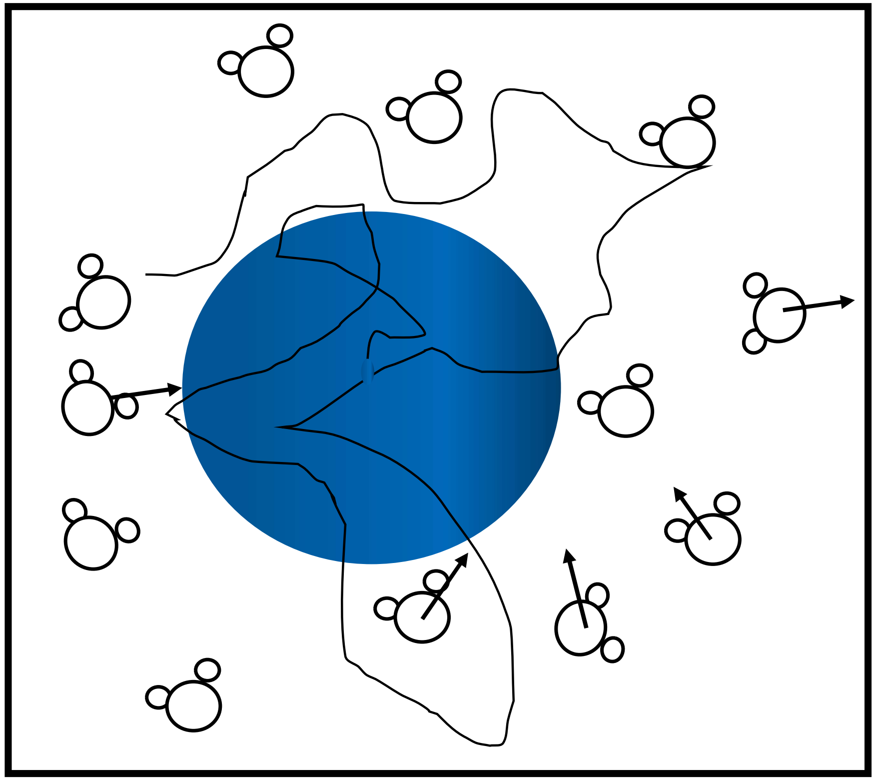
$$\boxed{U_{thermal} \approx kT}$$



$kT = 4.14 \times 10^{-21}$ J = 0.026 eV (or 26 meV)

Brownian Motion and what it tells us about the micro / nanoworld





Microscopic particles move randomly due to the thermal motion of the neighbouring molecules.

Motion on the microscopic scale

The motion of molecules on the micron and nanometre length scale is highly random, determined by the thermal motion of neighbouring atoms and molecules. Atoms, molecules and small particles execute a random walk.

In a time t, a small particle in a liquid, will diffuse an average mean squared distance given by

$$\langle x^2 \rangle \sim 6Dt$$

where D is the diffusion coefficient (m^2s^{-1}) given by the Stokes equation,

$$D = \frac{kT}{6\pi\eta a}$$

a is the radius of the particle (m)
η is the viscosity of the surrounding medium (Pa.s)

Boltzmann equation and gravity

Can compare statistical fluctuations to the potential energy of an interaction

Boltzmann equation:

$$P(x) \propto exp^{-U/k_B T}$$

Thermal fluctuations

Proportional

Potential of interaction

Problem 1.1 - Sedimentation of small particles

$$\Phi(z) = \Phi_0 exp^{-mgz/k_BT} = \Phi_0 exp^{-4\pi R^3 \rho g z/3k_BT}$$

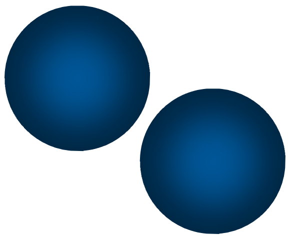
Consider the potential energy change for a sphere of radius R, density 1100kgm^{-3} in a fluid of density 1000kgm^{-3}. Thermal fluctuations “disrupt” the effect of the gravitational potential affecting the particle sedimentation.

What is different between the particles in the two bottles?

Can you come up with an explanation as to why they behave differently?

The range of an interaction

Thermal motion of atoms and molecules tends to disrupt the interactions between them.



At ‘small’ distances, interactions between atoms and molecules are strong enough to overcome the effects of thermal motion.

At ‘large’ distances, interactions between atoms and molecules become too weak to overcome the effects of thermal motion.

When are interactions significant?

"Weak" and "strong" are relative terms and depend upon the nature and strength of the interaction between two atoms/molecules.

We can consider the strength of an interaction by comparing the thermal energy to the magnitude of the potential energy of two molecules.

$$\boxed{|U(x)| = kT}$$

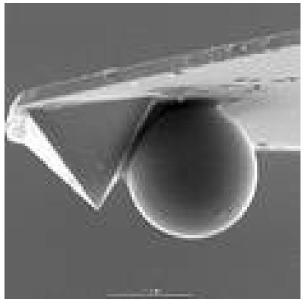
When $|U(x)| \leq kT$ thermal motion tends to disrupt the interactions.

When $|U(x)| > kT$ the atoms/molecules still feel the interactions between them.

We'll define more precisely what we mean by "strong" in the next lecture…

Summary of key concepts

The nanoscale world is very different from our macroscopic world and dominated by thermal fluctuations



Different forces start to become important on the nanometre length scale.

Comparing interaction potentials with the thermal energy gives an indication of their relative importance

$$\boxed{U_{thermal} \approx kT}$$