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Introduction to Force & Function

Force & function at the nanoscale

Introduction of Force and Function at the Nanoscale

Force and function at the nanoscale is about understanding the ways in which atoms and molecules interact on their own and as part of larger liquids and solid materials.

This is a really interesting area of physics that connects with our curiosity in understanding the everyday world around us.

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Topics

1. The Nanoscale world
2. Forces and potentials
3. Polar interactions
4. Dispersion interactions
5. Special interactions
6. Measurement of nanoscale forces
7. Surface energy, surface tension and adhesion energy
8. Capillary pressure
9. Colloidal interactions
10. Steric interactions and entropic repulsion
11. Depletion Interactions
12. Aggregation
13. Self assembly
14. Biological Membranes

Why can a Gecko walk across a smooth glass ceiling?
Why is Ice less dense than water?
How can we “see” atoms?
How do Startrek tractor beams work?
Why is there rising damp in my student house?!
Why do oil and water separate out?
What is going on when I scramble an egg?
How do cells stick together?

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How the course will work

Each week will consist of:

•2 Lectures (Tuesday at 10am, Physics C12; Friday at 9am, Chemistry C15)

- All core content
- Worked Problems
- Links to interesting phenomena related to the lecture

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

We will be using a class onenote book during the sessions.

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How to study this course

The Moodle page has comprehensive information to guide you through what to do each week.

Important info / links for whole course

How to study this course

1. The Nanoscale World (Week 20, 29/01 - 5/02)
2. Polar & Dispersion Interactions (Week 21, 6/02-12/02)
3. Adding up Interactions (Week 22, 13/02- 19/02)
4. The importance of Interfaces (Week 23, 20/02-26/02)
5. Measuring Forces at the Nanoscale (Week 24, 27/02 - 5/03)
6. Colloidal Stability & Osmotic Pressure (Week 25, 6/03 -12/03)
7. Entropic Forces (Week 26, 13/03 -20/03)
8. Aggregation and Self-assembly (Week 27, 21/03-28/03)
9. Membranes (Week 28, 29/03-2/04)
10. Revision

Each week is self-contained and has the expected completion date indicated.

Important Info

Please read the "Important Info" and the "How to study this course" sections.

- Lectures
- Lectures via Teams - (This is a backup)
- Join the Team
- Class OneNote Book
- Textbook

The Course OneNote Book

When I derive something or discuss solutions to problems in the lectures I will make use of the OneNote Class Notebook. The hope is it will mean you can refer back to it later.

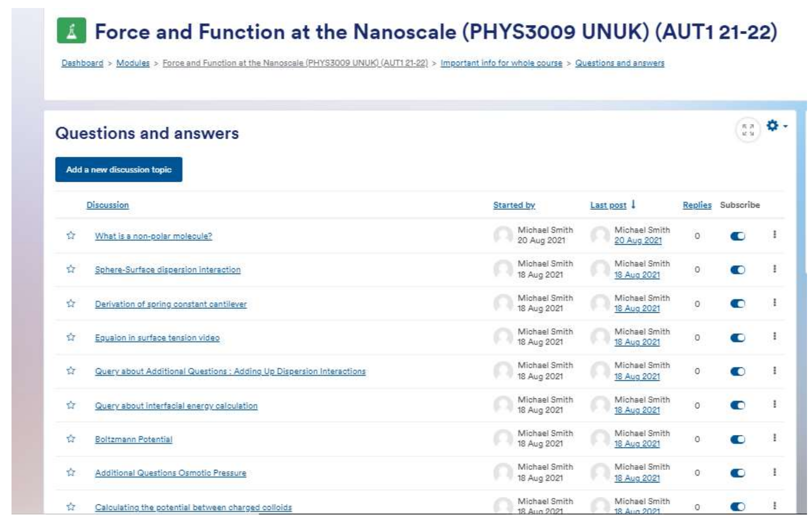
Can access:
a) via the Office365 Interface in a web browser
b) directly from the Teams window
c) from Microsoft OneNote if you link your University account.

Select "_Content Library" and look for the appropriate session

How to get help?!

If you have reviewed the core material and are struggling to understand something here are your options:

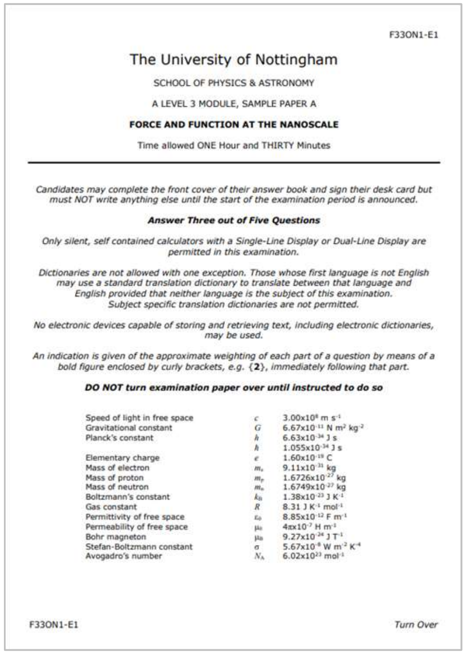
- Raise a question during or following a lecture
- Read the accompanying section in the course handbook.
- Look at the Q & A forum to see if someone else has had the same query.
- Send me an email with your question – mike.i.smith@nottingham.ac.uk
- Subscribe (optional) to see others questions and answers, maybe they are stuck on the same thing.



It really is true that no question is stupid and although I post questions to the forum I remove all names etc. What's the worst that could happen!

Assessment of the course

- Examination (100%)
- In person, closed book
- 2 hours to complete the paper
- Choose 3 questions from 5
- Access to key equations sheet, provided in advance.



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*

The equation sheet, example exam papers + answers, are at the bottom of the Moodle page under revision.

Questions

Questions?!

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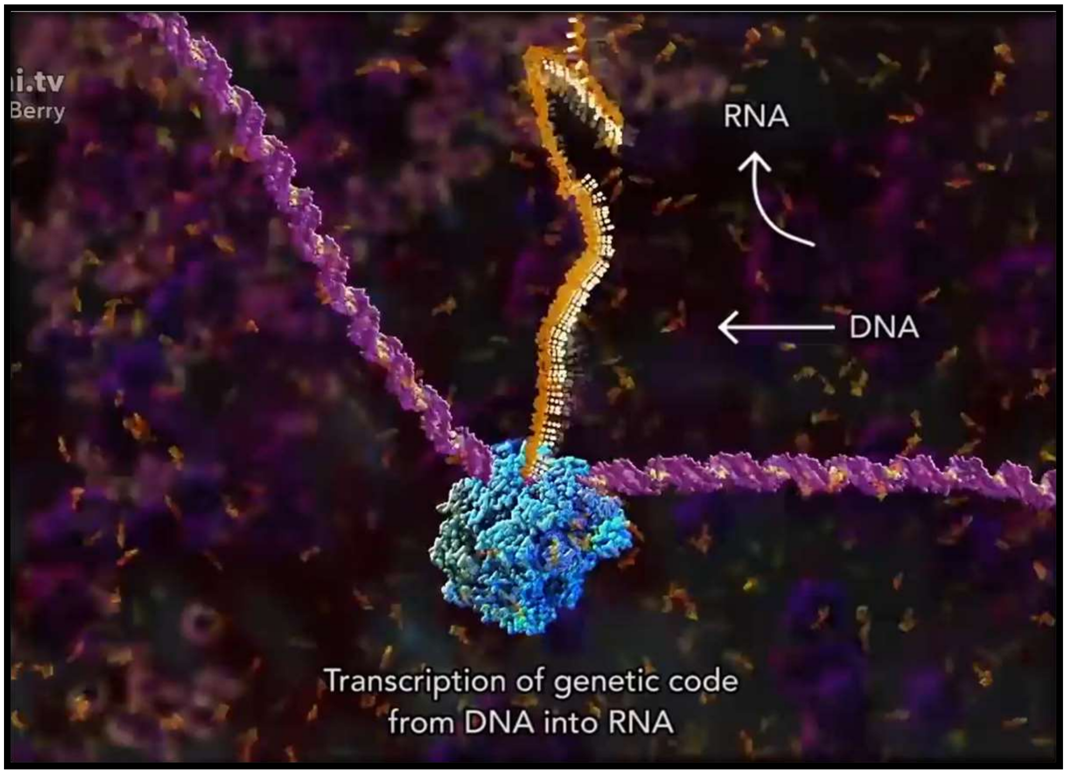
Macro vs nanoscale

Force & function at the nanoscale

The nanoscale world



The nanoscale world is dominated by ceaseless thermal motion

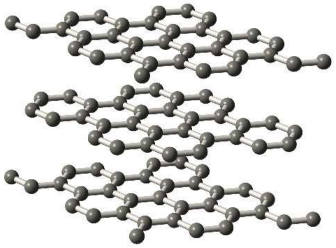
Every bit of “nanoscale machinery” inside each one of our cells relies on an intricate balance of chemical reactions and forces

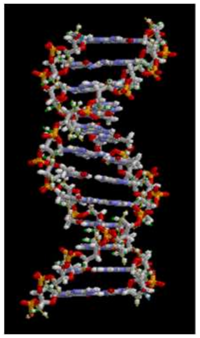
Strong & weak interactions

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

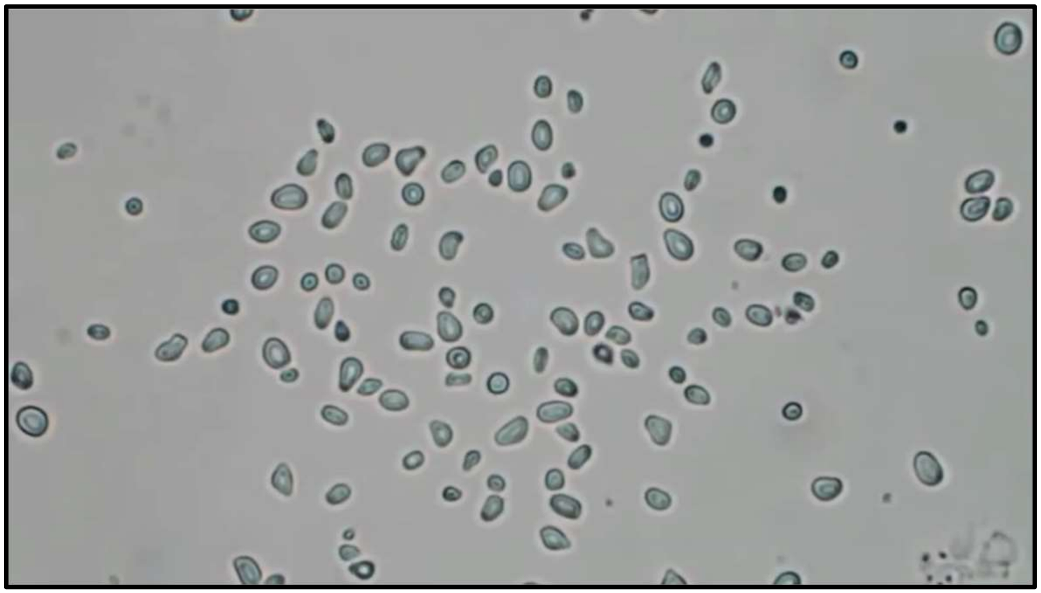


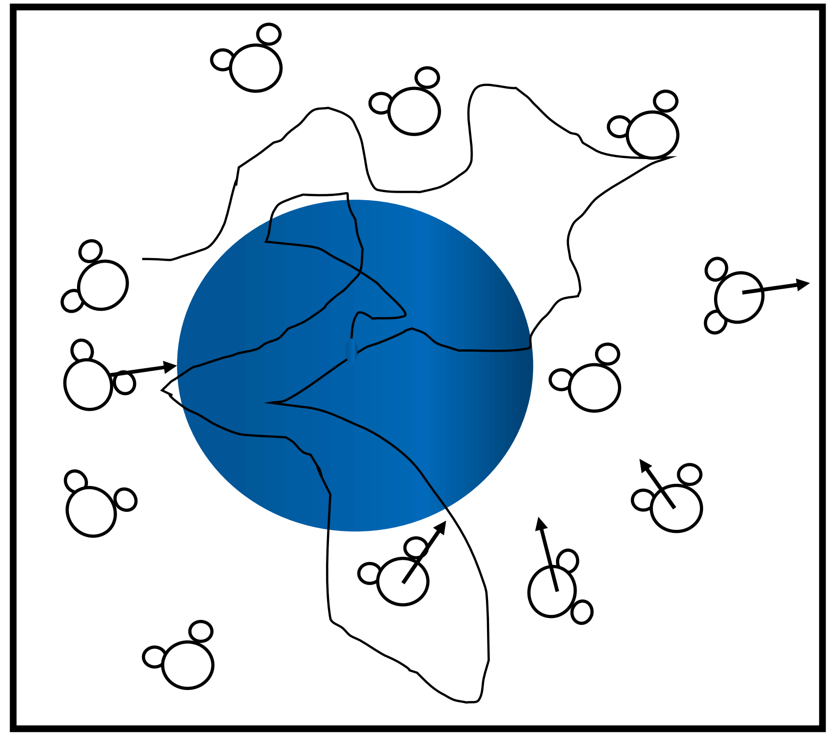


$$\boxed{U_{thermal} \approx kT}$$

kT = 4.14 x 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

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Problem 1.1 - Sedimentation of small particles

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

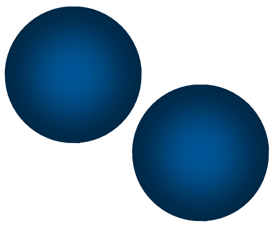
Consider the potential energy change for a sphere of radius R, density 1100kgm^{-3} in a fluid of density 1kgm^{-3}. Thermal fluctuations “disrupt” the effect of the gravitational potential affecting the particle sedimentation.

What is different between the particles in the two bottles?

Can you come up with an explanation as to why?

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.

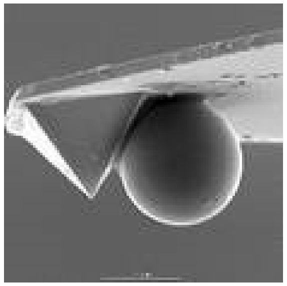
$$\boxed{|U(x)| = kT}$$

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

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