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**Nottingham**  
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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](https://phys3009.github.io)

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



# The AI tutor (optional)

The screenshot shows the AI tutor interface for the topic "Intermolecular and Surface Forces". The interface is divided into three main panels: Sources, Chat, and Studio.

- Sources Panel:** Includes a search bar with the text "Search the web for new sources", a "Web" dropdown, a "Fast research" dropdown, and a list of sources. One source, "Phys3009\_ForceAndFunction.pdf", is selected and checked.
- Chat Panel:** Contains a chat history with four questions and answers from the AI tutor. The questions are:
  - Question 1: The Nature of Nanoscale Motion** - Asks for the fundamental difference between sub-micron particles and macroscopic objects.
  - Question 2: Mean Square Displacement** - Asks for the mathematical relationship between mean square displacement ( $\langle x^2 \rangle$ ) and time ( $t$ ), including the diffusion coefficient ( $D$ ).
  - Question 3: The Environment and Force** - Asks why Newtonian concepts like inertia and momentum are deemed "no longer important" at the nanoscale.
  - Question 4: The Diffusion Coefficient ( $D$ )** - Asks for the equation relating  $D$  to thermal energy scale ( $k_B T$ ) and liquid viscosity ( $\eta$ ), known as the Stokes-Einstein equation.At the bottom of the chat panel is a "Start typing..." input field and a "Save to note" button.
- Studio Panel:** Features a grid of interactive tools: Audio Overview, Video Overview, Mind Map, Reports, Flashcards, Quiz, Infographic, and Slide deck. Below this grid is a list of generated content items:
  - "Nanoscale Physics Thermal Chaos a..." (1 source - 55d ago)
  - "Nanoscale Quiz" (1 source - 55d ago)
  - "Nanoscale Forces, Interactions, and Self-..." (1 source - 55d ago)At the bottom right of the Studio panel is an "Add note" button.

Simple instructions [https://phys3009.github.io/content/info\\_course/aitutor.html](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

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*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	$c$	$3.00 \times 10^8 \text{ m s}^{-1}$
Gravitational constant	$G$	$6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$
Planck's constant	$h$	$6.63 \times 10^{-34} \text{ J s}$
	$\hbar$	$1.055 \times 10^{-34} \text{ J s}$
Elementary charge	$e$	$1.60 \times 10^{-19} \text{ C}$
Mass of electron	$m_e$	$9.11 \times 10^{-31} \text{ kg}$
Mass of proton	$m_p$	$1.6726 \times 10^{-27} \text{ kg}$
Mass of neutron	$m_n$	$1.6749 \times 10^{-27} \text{ kg}$
Boltzmann's constant	$k_B$	$1.38 \times 10^{-23} \text{ J K}^{-1}$
Gas constant	$R$	$8.31 \text{ J K}^{-1} \text{ mol}^{-1}$
Permittivity of free space	$\epsilon_0$	$8.85 \times 10^{-12} \text{ F m}^{-1}$
Permeability of free space	$\mu_0$	$4\pi \times 10^{-7} \text{ H m}^{-1}$
Bohr magneton	$\mu_B$	$9.27 \times 10^{-24} \text{ J T}^{-1}$
Stefan-Boltzmann constant	$\sigma$	$5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
Avogadro's number	$N_A$	$6.02 \times 10^{23} \text{ mol}^{-1}$

Turn Over

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## Questions

# Questions?!





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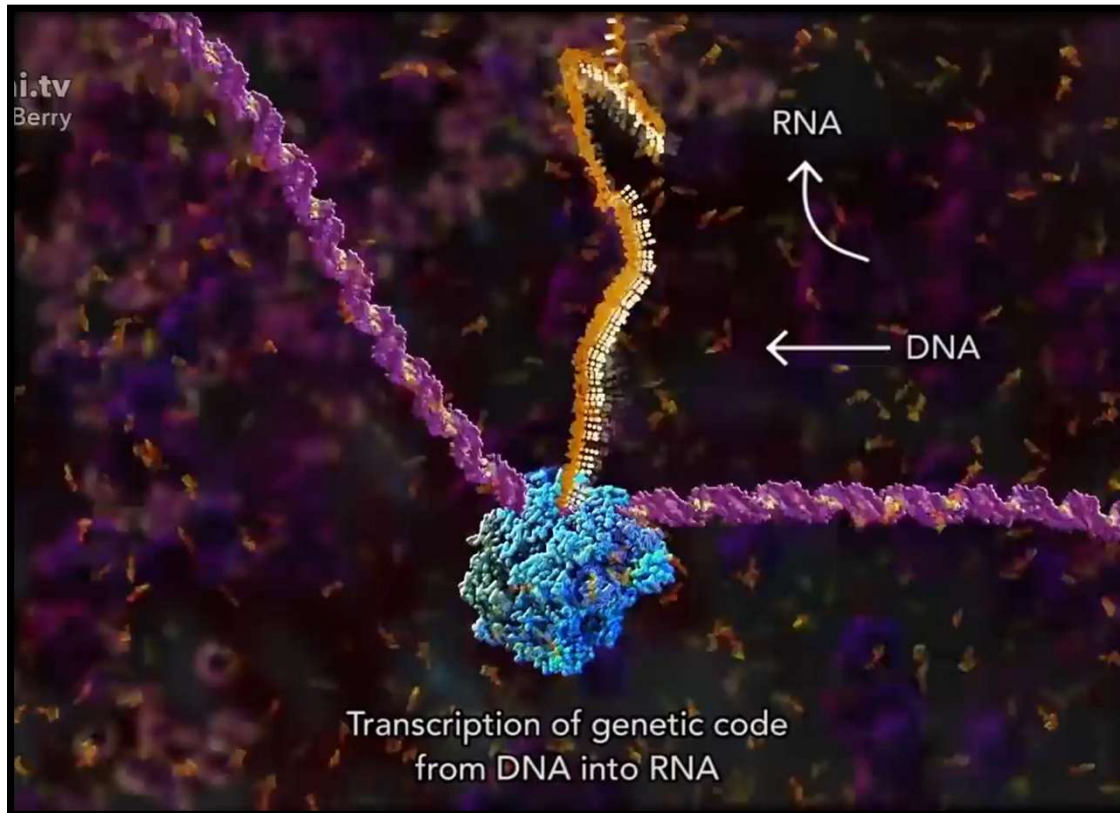
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# Macro vs nanoscale

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





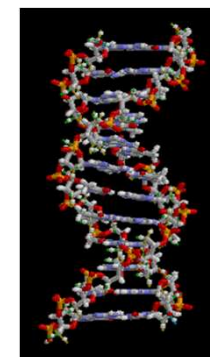
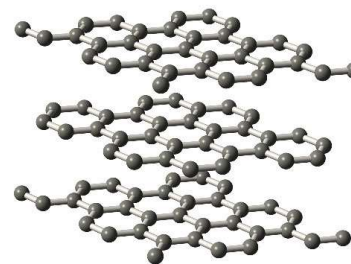
## The thermal energy scale

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  $kT$

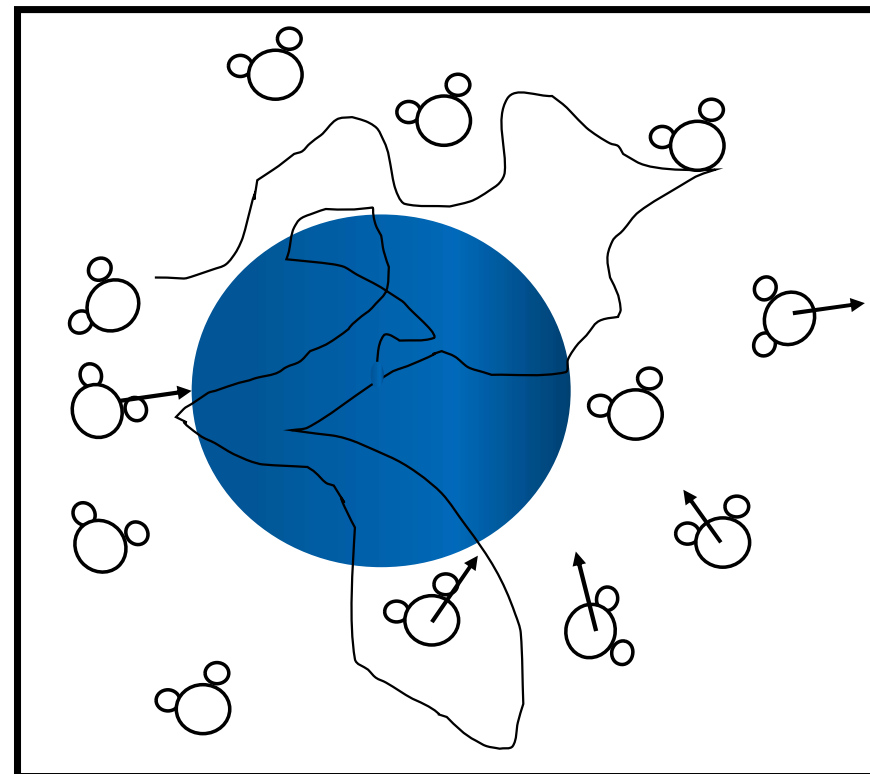
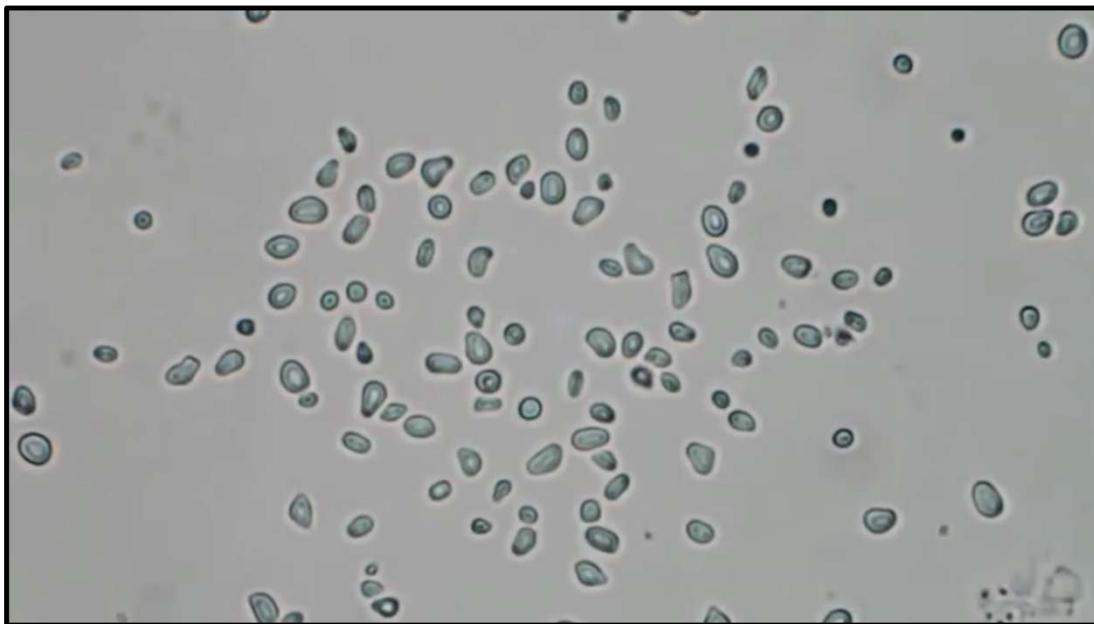
$$U_{thermal} \approx kT$$

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





# 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 ( $\text{m}^2\text{s}^{-1}$ ) given by the Stokes equation,

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

$a$  is the radius of the particle (m)

$\eta$  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

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

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

What is different between the particles in the two bottles?

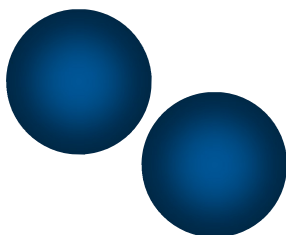
Can you come up with an explanation as to why they behave differently?





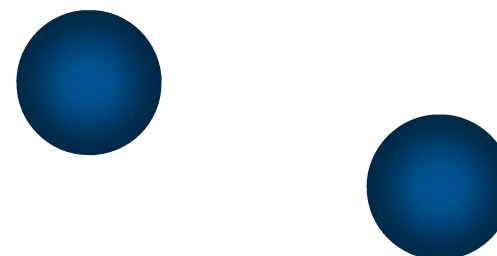
## The range of an interaction

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.

$$|U(x)| = kT$$

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...

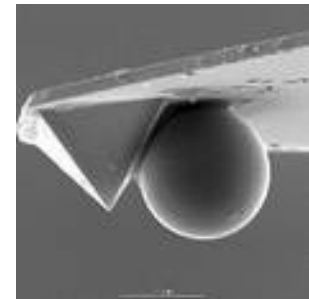


## Summary of key concepts

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



$$U_{thermal} \approx kT$$