Statistical Physics of Soft/Biological Matter

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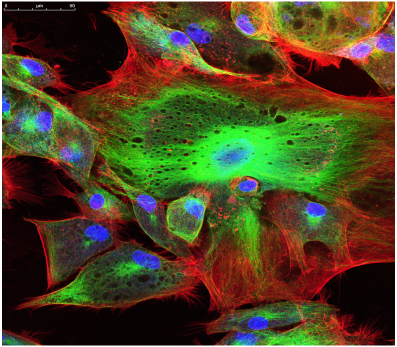


(Fluorescent micrograph of skin cells: DNA stained in blue, microtubules stained in green, F-actin stained in red.)

Condensed Matter: Hard *vs* Soft Matter

Condensed matter physics is the study of complex phenomena in the collective behaviour of systems consisting of many ($\sim 10^{23}$) interacting particles.

Hard Matter

- The constituent particles and their interactions should be described quantum mechanically (spin, Pauli principle, etc)
- Energy dominated (Fermi energy, energy bands)
- Conventional solids are "hard". Typical scale of shear modulus:

$$G = \frac{E}{V} \sim \frac{1\mathrm{eV}}{(0.15nm)^3} \sim 50GPa$$

Soft Matter

- The constituent particles are much larger in size and well-described by classical mechanics (quantum effects are negligible)
- Entropy dominated (entropic elasticity, entropic forces, constituent particles doing Brownian motion)
- Most soft materials are "soft." Typical scale of shear modulus:

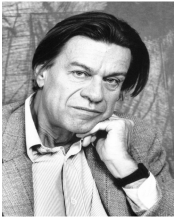
$$G = \frac{E}{V} \sim \frac{k_{\mathrm{B}} T}{(1\mu m)^3} \sim 4mPa$$

Soft Matter

- Examples of soft materials: polymers, membranes, liquid crystals, colloids, surfactants, granular systems. Structural glasses (e.g., window glass) are hard, but share many features with soft systems.
- Biological matter at various degrees of organisation is also soft matter: biopolymers (e.g., DNA, F-actin, microtubules, intermediate filaments, collagen), biomembranes, cells, the extracellular matrix, tissues.
- Main characteristics:
  - Entropy dominated (large thermal fluctuations)
  - Large length and time scales
  - Very sensitive to external perturbations
  - Very often out of equilibrium (active, driven)

- Soft matter is a relatively young field of physics.

  Soft materials have been studied by chemists, chemical engineers and biologists for many years. But it was not until the 1960s that they became of interest to physicists, thanks to the pioneering work of three prominent theoretical physicists:



Pierre-Gilles de Gennes (1991 Nobel)

Sam Edwards

Ilya Lifshitz

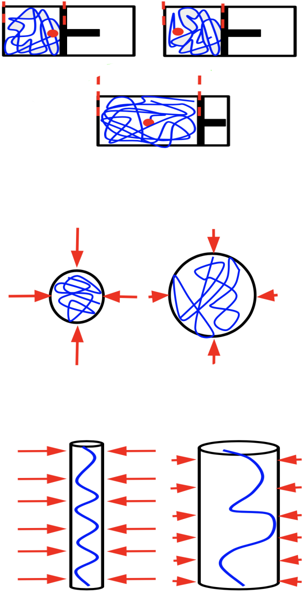
- Now it has become clear that many interesting properties of soft materials are independent of the chemical details of the constituent molecules and can be understood using the methods of statistical physics. Moreover, the study of soft materials gives fresh insight into some fundamental questions of condensed matter and statistical physics (e.g., the nature of disordered systems or the limits of thermodynamics at small scale).

- (The current holder of the Lucasian Chair of Mathematics at the University of Cambridge is a **soft-matter theorist**, Michael Cates. Previous occupants include Isaac Newton, Paul Dirac, and Stephen Hawking.)

Recent publication

Statistical ensemble inequivalence for flexible polymers under confinement in various geometries, Soft Matter 16, 2114, (2020)

(with S. Dutta, IBS, Ulsan)



- Systems with a well-defined thermodynamic limit (e.g., the ideal gas) exhibit ensemble equivalence:

  $P\langle V\rangle = Nk_{\mathrm{B}}T$, $\langle P\rangle V = Nk_{\mathrm{B}}T$

  Fixed pressure: Gibbs ensembe

  Fixed volume: Helmholtz ensemble

- Confinement, in general, causes ensemble inequivalence. We obtain a different equation of state in each ensemble.

- For a squashing compression, irrespective of geometry, we asymptotically recover equivalence.

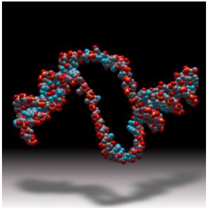
- Ensemble inequivalence is traced to the persistence of strong fluctuations.

Current project

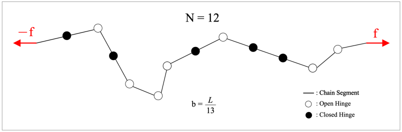
(with graduate student Geunho Noh)

Tensile elasticity of a freely-jointed chain with reversible hinges

- Some important semiflexible biopolymers consist of reversible blocks of different bending stiffness (e.g., DNA has double-stranded parts (stiff) and reversibly opening and closing single-stranded “bubbles” (flexible)).
- We analytically investigate the response to tension of a freely-jointed chain with reversible hinges.
- We calculate the force-extension relation and the dependence of the closing probability on the tension.
- We find that, under strong tension, the hinges close and the whole chain stiffens very fast.

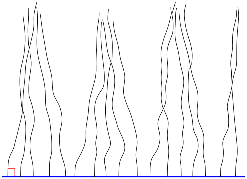


(Univ. of Glasgow)



Proposed project

Order in permanently cross-linked semiflexible brushes



In *Phys. Rev. E* 88, 042601 (2013), we have shown that a short-range attraction between semiflexible polymers perpendicularly grafted at random points on a planar substrate leads to a periodic array of bundles (bundling). This is an example of microphase separation resulting when a long(er)-range repulsion competes with a short(er)-range attraction. (*Adv. Colloid Interface Sci.* 232, 144 (2016))

- What if, instead of an explicit attractive potential, we introduce random permanent cross-links between the polymers?
- Random cross-links act as quenched disorder, but they also give rise to an effective short-range attraction.
- Can we get order (bundling) out of disorder (random cross-linking)?

??? Questions ???

I will be happy to receive your questions at

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