Structure, Dynamics, and Mechanical Properties in Soft Things!

Dynamics and mechanics in attractive colloids, forces on particles, and force transduction in cytoskeleton networks
“Big Questions”

• Rigidity
  - jamming
  - glass transition, ergodicity breaking

• Self-Assembly and Pattern Formation

• Networks

• Driven Dynamics and Effective Temperature

• Interface with Biology – are there guiding principles?
  -- membranes, surfactants, emulsions, polymers, l.c.’s

→ Notions from statistical mechanics play a special role
Networks: Origin of Rigidity

Colloidal gel
Confocal image 32 x 32 µm

Cross-linked actin gel
Confocal image 32 x 32 µm
Soft Solids

Easily deformable $\rightarrow$ Low Elastic Constant: $\frac{eV}{\text{Volume}}$

Atoms: $\frac{eV}{\text{A}^3} \approx \text{GPa}$

Colloids: $\frac{k_B T}{\mu \text{m}^3} \approx \text{Pa}$

Colloidal Particles:
• Slow speed
• Large size (microns)
Colloids

1 nm - 10 \( \mu \text{m} \) solid particles in a solvent

Ubiquitous
ink, paint, milk, butter, mayonnaise, toothpaste, blood

Suspensions can act like both liquid and solid
Modify flow properties

Control: Size, uniformity, interactions
Colloidal Particles

Stability:
Short range repulsion
Sometimes a slight charge

Interactions are highly tunable
Why Hard Particles?

Most interesting things depend on repulsive part
simplest repulsion is:

\[
U(r) = \begin{cases} 
\infty, & |r| < a \\
0, & \text{otherwise}
\end{cases}
\]

The essence of the problem -- Hard Spheres
Depletion Interaction

\[ U(r) = \Pi(c) V_{\text{overlap}}(r) \]

\[ V_{\text{overlap}}(r) = \frac{4}{3} \pi a^3 (1 + \xi)^3 \left[ 1 - \frac{3r}{4a(1 + \xi)} + \frac{r^3}{16a^3(1 + \xi)^3} \right] \quad (\xi = R_g / a) \]

Asakura & Oosawa 1954; Vrij 1976
Experiments in this area can now approach the transparency of computer simulations.
Confocal Microscopy

True 3-dimensional imaging
Rejects out of plane light
What is fluorescence?

- Can attach fluorescent dye molecules to specific parts of your sample
- Can use more than one type of dye to distinguish two different parts of your sample

How does a fluorescence microscope work?
And the leap to confocal microscopy?

- Red and blue are two different sets of rays of light (not different λ’s)
- Pinhole to reject out of focus light
- Solves one of the problems with regular microscopy:
  all of sample is fluorescing → hazy images
  **Focal** point of objective lens and pinhole are “**conj**ugate points”
How a confocal microscope works:

Invented by:
Minski, 1962
Side on:

$\Delta n = 0$

decalin/tetralin 60-40

$\Delta \rho_{max} = 0.263 \text{ g/cm}^3$

$PMMA \quad \sigma = 1.26 \mu m$

$U_0 = 4.2 kT$

$\max = 0.263 \text{ g/cm}^3$

$\mu = 0.25 \mu m$
Movie of Colloidal Gel

44 µm

41 µm
Figure out how to identify particles
Refined location estimate is then

\[
\begin{pmatrix}
\varepsilon_x \\
\varepsilon_y
\end{pmatrix} = \frac{1}{m_0} \sum_{i^2+j^2 \leq w^2} \begin{pmatrix} i \\ j \end{pmatrix} A(x + i, y + j)
\]

Offset from \((x,y)\) to the brightness-weighted centroid of the pixels in a region around \((x,y)\)

- ideally, locate particle centroids to better than \(\frac{1}{2}\) pixel
- HOWEVER: suffers from poor noise rejection and includes false identifications
- reduce standard deviation of pixel measurement to better than \(1/10\) pixel
  - other information gathered can be used
- Useful for distinguishing spheres from noise and for estimating their displacements from the focal plane

Refined location estimate is then \((x_0, y_0) = (x + \varepsilon_x, y + \varepsilon_y)\)
Multiparticle tracking

Immobile bead

Relatively mobile bead

temporal resolution:
frame rate 1/30 sec or faster

→ individual tracks are minutes long!
Link particles in each frame to form trajectories

\[ \langle (r(t) - r(0))^2 \rangle \]
3D - Tracking in Depth:
Find the particles for all of your data

- distribution of data in the \((m_0, m_2)\) plane reflects the sphere’s positions along the direction normal to the imaging plane

\[ \Delta z = 0.25 \mu m \]
\[ d = 1.26 \mu m \]

- identify centroid locations that belong to the same sphere along \(z\)
- values of \(z\) for the \(i\)th frame fall in a Gaussian distribution about the centre along \(z\)

\[ z = \sum_i P(z_i \mid m_0, m_2) z_i \]

\[
\begin{bmatrix}
    x_1 & y_1 & z_1 \\
    x_2 & y_2 & z_2 \\
    \vdots & \vdots & \vdots 
\end{bmatrix}
(t)
\]
3D - Tracking in Depth:
Find the particles for all of your data
Analyze the 3D data to do your science

\[ \langle (r(t) - r(0))^2 \rangle \]

Dynamics

Spatial Correlations and Order

\[ g(r) \]

Structure
Removal of Centre-of-Mass motion of all particles
Non-equilibrium soft solids - colloids and cell mechanics

Images of colloidal gels and glasses

Network of attractive colloidal particles

Glass formed due to caging
Full 3D structure gained by confocal microscopy

System: PMMA (~1 µm) in Refractive index-matching and buoyancy-tunable suspending fluids Decalin/Tetralin/CXB

Side on: 22.6 µm
Scanning Up: 0.20 µm

150 µm

~600 particles
~9000 particles
reconstruction

~9000 particles
Highly Localized Motion in Gels

Confining effect of neighboring particles in a colloidal gel

Trajectory of particles caged by their neighbors

Not really cooperative motion

Cooperative motion

Eric R. Weeks et al., PRL vol 89, 095704 (2002)
Caged Particles in Glasses and Gels

Effect of crowding of particles plus interparticle attraction in a colloidal gel

Cage effect of neighboring particles in a colloidal glass
Direct Measurement of the Distinct Part of van Hove Correlation Function in Colloidal Gels and Glasses

Yongxiang Gao, Maria Kilfoil
Space time correlation function

Self part

\[ G_s(r, \tau) = \frac{1}{N} \left\langle \sum_{i=1}^{N} \delta \left[ r - |r_i(0) - r_i(\tau)| \right] \right\rangle \]

\[ \approx \frac{1}{\left[ \frac{4}{\pi} < \Delta r^2(\tau) > \right]^{3/2}} \exp \left[ -\frac{r^2}{\frac{4}{6} < \Delta r^2(\tau) >} \right] \]

Distinct part

\[ G_d(r, \tau) = \frac{1}{N} \left\langle \sum_{i} \sum_{j \neq i} \delta \left[ r - |r_i(0) - r_j(\tau)| \right] \right\rangle \]

\[ \tau = 28 \text{ mins} \]
Gels and glasses subject to gravitational force

\[ \Delta \rho = 0.253 \text{g/cm}^3 \]

arrested states

\[ C_p \]
Dielectrophoresis basis

Dielectrophoresis can be used to induce a force on a neutral particle with a non-uniform electric field

\[ \vec{p} = 4\pi a^3 \varepsilon_1 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \vec{E} \]

\[ \vec{F} = \vec{p} \cdot \nabla \vec{E} \]

\[ \nabla \times \vec{E} = 0 \] so the force goes as \[ \frac{1}{2} \nabla E^2 \]

\[ \vec{F}_{DEP} = 2\pi a^3 \varepsilon_0 \varepsilon_1 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \nabla E^2 \]

Clausius-Mossotti factor

So we could use this **tunable** force to replace other, less easily tunable forces.

Example: Gravity and gel collapse
A lot of work is required to change the density mismatch.

But: \[ F_{DEP} \sim \nabla E^2 \] not trivial to get \( F \) **constant** in space.

We designed a 40 electrode cell, so that the electric field gives a **uniform, unidirectional force**
Cover slip with patterned electrodes (evaporated Cr) separated by 2mm. The electrodes are on the side opposite to the solvents to avoid electrochemistry.

Cell, capillary tube 150 µm thick, 1 mm wide (glass walls are 50 µm thick)
Cover slip with patterned electrodes (evaporated Cr) separated by 2mm. The electrodes are on the side opposite to the solvents to avoid electrochemistry.

Cell, capillary tube 150µm thick, 1mm wide (glass walls are 50µm thick)
Order-disorder transitions in colloids

$\nabla E \otimes E$

$1\mu$ colloidal hard spheres

Liquid

Crystal
Heterogeneous Crystal Nucleation

Nucleation and crystallization is a typical near-equilibrium phenomenon that is not well understood. The goal of our current experiment is to understand heterogeneous nucleation which, unlike homogeneous nucleation, occurs on either “impurity” particles or walls.

We can realize this by adding bigger particles, as seed particles, into an original suspension of uniformly sized smaller particles. By changing the ratio between the native and introduced particles, we can study how the size of the seed particles affects the nucleation process. If the seed particles have the same size as the original particles, homogeneous nucleation is recovered. It is predicted by recent theory work that in such heterogeneous nucleation, the nuclei will form on the surface of the seed particles as shown in the figure above. The nucleation rate in this situation is several orders of magnitude larger than that in homogeneous nucleation. This has not been experimentally tested.
Before field is turned on

5 µm
Field turned on (3900Vpp = 1380Vrms)
Other Soft Matter Measuring Tools

TA Rheometer used to obtain viscoelastic shear moduli

Optical tweezers – coupled to confocal microscope

Two traps for manipulation
Optical Tweezers


Enable manipulation of mesoscopic objects

→ Mechanical properties
Use of probe particles in biology

• Use **thermal** fluctuations to measure properties
• Small particles \(\rightarrow\) pore size distribution
• Large particles \(\rightarrow\) rheology
• Probe structural heterogeneities at micron scale
• *In vivo* \(\rightarrow\) Must use **driven** microrheology
  • Non-linearity
  • Active components
The cytoskeleton and microtubules

• The cytoskeleton is a polymer network that can span cell volume
• It consists of actin filaments, microtubules and intermediate filaments
• It gives the cell mechanical strength and is involved in many cell activities such as cell motion and cell division

http://www.uic.edu/classes/bios/bios100/lectf03am/cytoskeleton.jpg
Motivation

- Study transduction of forces across the cell
- Examine microtubule-actin interactions
- Actin has been well studied, as networks and single filaments
- Microtubules have been studied mainly as single filaments

Schaap et. al. Eur Biophys J (2004),
Elbaum et. al. PRL (1996)
Cytoskeletal F-actin Networks

Maintain cell integrity
Generate forces in cell motility

Contractile Bundles
Protrusive Network

Dynamic, Heterogeneous

COMPLEX MATERIAL!

Cramer, JCB 1997
Hartwig, JCB 1990
Svitkina, JCB 1998
**Microtubules**

- **Structure:**
  - Diameter: 25 nm
  - Length: up to hundreds of micrometers
  - High persistence length, >1mm

- **Main functions:**
  - Intrinsic motility (motor proteins)
  - Cell division (chromosome separation)
Molecular labeling:
Microtubules
XMAP215 - microtubule associated protein
DNA


Scale bar = 10 µm
Multiparticle tracking

spatial resolution: 10 nm
temporal resolution:
frame rate 1/30 sec or faster

~ 100 particles in field of view (F.O.V.)
~ 3-15 minutes of video/ F.O.V.

2.5 mg/mL tubulin
3.5 µm CML beads
63X objective, bright field

Results depend on particle size compared to mesh size
Minimal *in vitro* model for cell mechanics

*in vitro* (in a glass chamber)

*in vivo* (in cells)

**in vivo** (in cells)
Motion of Probe Particles

Diffusion

\( a < \xi \)

Microrheology

\( a > \xi \)

Jumping motion

\( a \sim \xi \)
Motion of Probe Particles

Microrheology

\(a > \xi\)
The *in vitro* System

- Tubulin at ~2.5 mg/ml
- A fraction is labeled with cy-3
- MAPS are present
- GTP at ~1mM
- Add ~10% DMSO for nucleation
- No taxol or other drug is added
- Incubation at 36°C for 30 min

- Polystyrene beads coated with PLL-g-PEG
The analysis procedure
Results: 1 µm beads

In vivo: 100 - 1000 Pa (Fabry et al. PRL 2001)

In vitro: ~0.1 Pa and higher (Gardel et al. PNAS 2006)

Actin networks:

$G'(\omega), G''(\omega)$ (pascals)
More complex *in vitro* System: Composite networks

Final concentrations:
- Microtubules: 1.28 mg/mL
- Actin: 0.71 mg/mL
AMT3
100x lens
microtubules

10µm
AMT3
100x lens
Actin – microtubule overlay
.. Designed to mimic tissue culture cells, shown here:

actin fluorescently labeled - showing in red
microtubules labeled with another fluorophore - showing in green
Future directions: motor proteins

Myosin V and kinesin   Selvin et al, March 2007