foam - M. Asipauskas

tissue - Blankenship et al.
Disorder, elasticity, rearrangements
e.g. in foams or biological tissues

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Outline

1. Motivations
2. 2D inert
3. 2D active
4. 3D
5. Conclusion
Motivations

Tissue morphogenesis
Multi-cellularity and neighbour changes
Fruit fly metamorphosis

Drosophila melanogaster pupae development
duration: 5 days

http://www.exploratorium.edu/
Multi-scale live imaging

1 layer ∼ 7000 cells  
12-38h after pupa formation  
∼3 decades time & space
Motivations

<table>
<thead>
<tr>
<th>2D inert</th>
<th>2D active</th>
<th>3D</th>
<th>Conclusion</th>
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</thead>
</table>

**Linking scales**

- **cell scale** → **cell group scale** → **tissue scale**

**Statistical physics:**
- Determine the material parameters: viscosity $\eta$, stiffness $G$, yield strain $\varepsilon_Y$.

**Continuum mechanics:**
- Determine the dynamical fields: velocity $V$, strain $\varepsilon$, stress $\sigma$. 
Linking scales

statistical physics:
- determine the material parameters
  - viscosity \( \eta \)
  - stiffness \( G \)
  - yield strain \( \varepsilon_Y \)
Linking scales

statistical physics: determine the material parameters
- viscosity $\eta$
- stiffness $G$
- yield strain $\varepsilon_Y$

continuum mechanics: determine the dynamical fields
- velocity $V$
- strain $\varepsilon$
- stress $\sigma$
Continuous description

It enables:
- compare experiments and/or simulations
- average them, determine their variability
- subtract them, determine effect of parameters

It requires:
- fluctuations average out
- cells in group: number $\gg 1$
- thanks to average over space, time and samples
Inert cellular materials

foam as model system
Deform a foam

local energy minimum
Deform a foam

Small deformation

- elastic solid
- reversibly comes back to its initial shape

Local energy minimum
Deform a foam

Small deformation
elastic solid
reversibly comes back
to its initial shape
Deform a foam

Small deformation
- elastic solid
  - reversibly comes back to its initial shape
Deform a foam

- **Small deformation**
  - Elastic solid
  - Reversibly comes back to its initial shape

- **Large deformation**
  - Plastic solid
  - Irreversibly sculpted, new shape

**Motivations**
- 2D inert
- 2D active
- 3D

**Conclusion**
- Marmottant

**Deformation**
- Yield
  - $\varepsilon_Y \rightarrow$
- Neighbour change
- Time
  - $\tau_R \rightarrow$
- Relaxation to other minimum

**Images**
- Local energy minimum
- Neighbour change
- Relaxation to other minimum

**Notes**
- Quick deformation rate
  - Viscous liquid
  - Irreversibly flows, stress increases with rate
  - No gap, no overlap
  - Deform through rearrangements
  - Viscous, elastic, plastic (VEP) behaviour
Deform a foam

Small deformation
- elastic solid
- reversibly comes back to its initial shape

Large deformation
- plastic solid
- irreversibly sculpted, new shape

Quick deformation rate
- viscous liquid
- irreversibly flows, stress increases with rate

local energy minimum
yield \( \varepsilon \gamma \rightarrow \)
neighbour change
\( \tau_R \rightarrow \)
relaxation to other minimum
Deform a foam

Small deformation
elastic solid
reversibly comes back to its initial shape

Large deformation
plastic solid
irreversibly sculpted, new shape

Quick deformation rate
viscous liquid
irreversibly flows, stress increases with rate

no gap, no overlap
→ deform through rearrangements
→ viscous, elastic, plastic (VEP) behaviour

yield \( \varepsilon_Y \) → neighbour change

time \( T_R \) → relaxation to other minimum

local energy minimum

Marmottant
Foam flow around obstacle

- heterogeneous: variety of shears and elastic deformations
- can discriminate between models?

control
parameters:
- 2D
- water 1.2%
- monodisperse
- \( V = 0.6 \text{ cm/s} \)
Motivations

2D inert

2D active

3D

Conclusion

Statistical measurements

Velocity

Aubouy, Marmottant
Statistical measurements

Velocity

Texture

Bubble shape and packing

**Aubouy, Marmottant**
Statistical measurements

Velocity

Texture

Bubble shape and packing

Velocity gradient

Aubouy, Marmottant
Statistical measurements

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Aubouy, Marmottant
Statistical measurements

Aubouy, Marmottant

Velocity

Texture

Bubble shape and packing

Velocity gradient

Plasticity

Neighbour change

isotropic circle

anisotropic ellipse

deformation rates: total = elastic + plastic
**Prediction?**

- Speed along the main axis $y = 0$
- Referential moving with the foam
- Visco-elasto-plastic model
- Main parameter: yield strain

**Prediction:** continuous model

Dry foam experiment: discrete measurements

**Good agreement**
- Amplitude of $v$
- Orientation of $v$
- Recirculation zones
- Up/down asymmetry
- $v = 0$ point
- Overshoot
Graphs of elastic strain tensor

Agrees on position and amplitude of local extrema
Cell monolayer around an obstacle
Migration around an obstacle

\[ t = 0\text{ min} \]

\[ t = 750\text{ min} \]

\[ 300\mu\text{m} \]
Velocity field

image correlation: "particle image velocimetry"
no need to identify ("segment") cell contours
**Averaged velocity field**

average over time and/or over experiments

$2 \mu m/min$
Deformation field

cell shape: “Fourier transform"
no need to identify (“segment”) cell contours
Comparison

Cell rearrangements & cell deformation fields

visco-elastic *liquid* behaviour

visco-elastic time 70 min
Visco-elastic time

\[ \tau \text{ independent on obstacle size & independent on division rate} \]

slowed down by myosin inhibitor, related to cell rearrangements
Cell aggregate through a constriction
Aspire a cell aggregate

- 1 movie = 3 experiments: constriction, divergence, elasto-capillarity
- heterogeneous: induced cell rearrangements, many informations
- measure and link: cell shape, neighbour changes, local viscoelastic properties
**Motivations**

2D inert

2D active

3D

Conclusion

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**All measures without segmentation**

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Shear</th>
<th>Compression</th>
<th>Shape</th>
<th>Plastic</th>
</tr>
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<tbody>
<tr>
<td><img src="image1.png" alt="Velocity Image" /></td>
<td><img src="image2.png" alt="Shear Image" /></td>
<td><img src="image3.png" alt="Compression Image" /></td>
<td><img src="image4.png" alt="Shape Image" /></td>
<td><img src="image5.png" alt="Plastic Image" /></td>
</tr>
</tbody>
</table>

- cell group scale visco-elastic relaxation time: $\tau_r \sim 10^3 \text{ s}$
- cell group scale viscosity: $\eta_r \sim 10^5 \text{ Pa.s}$
- elastic modulus: $G \sim 10^2 \text{ Pa}$
- cell scale visco-elastic relaxation time: $\tau_{\text{cell}} \sim 10^2 \text{ s}$
- cell scale viscosity: $\eta_{\text{cell}} \sim 10^4 \text{ Pa.s}$
- aggregate scale capillary modulus: $(\Gamma/R) \sim 10^2 \text{ Pa}$

$\eta_r$ from previous experiments

**Elasto-capillar number $\sim 1$**
Conclusion
Summary of approach

Objects with disorder, elasticity, rearrangements

- Very *general* applications: bubbles in foam, cells in tissue, grains in polycrystal, atoms in glass, drops in emulsion, magnetic domains, packed soft objects, etc.

- total deformation rate
  - $= \text{elastic deformation rate}$
  - $+ \text{plastic deformation rate}$

- experiments and simulations which *vary* in space

- *coarse grain* $\rightarrow$ continuous description

- *compare* experiments and/or simulations
Summary of results

How do objects with disorder, elasticity flow?

- powerful statistical tools to analyse data
- cellular structure $\rightarrow$ emergent solid behaviour
- inert case $\rightarrow$ coarse-grain & model predicts flow
- activity $\rightarrow$ emergent collective migration
- extract rheological equations and parameters
Perspectives in progress

Model

Shourick

Simulations

Beatrici

Boundaries

Durande

In vivo

Villedieu
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