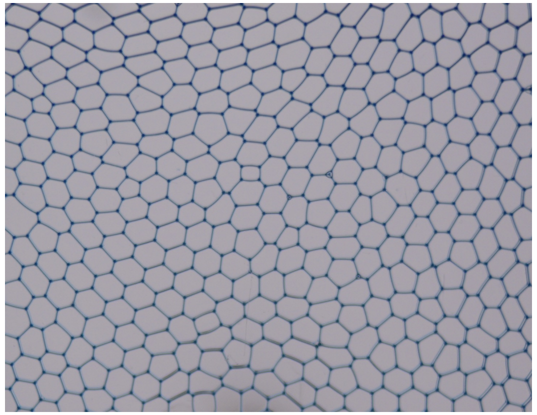
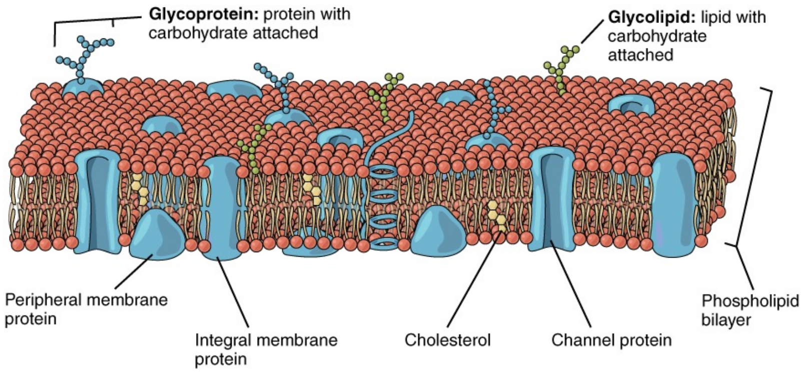
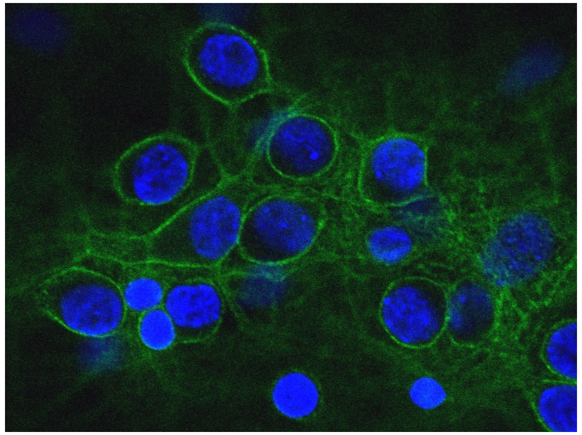
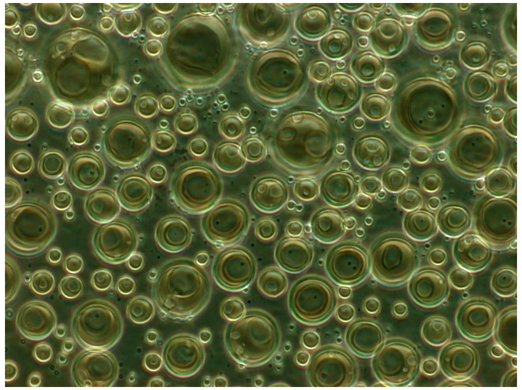
ME470: Mechanics of Soft and Biological Matter
Lecture1: Introduction & Continuum Mechanics









Red Blood Cells

Sangwoo Kim

MESOBIO – IGM – STI – EPFL

School of Engineering

ME470: Mechanics of Soft and Biological Matter
Lecture1-1: Introduction

School of
Engineering

EPFL

MESOBIO

Mechanics of Soft and Biological Matter Laboratory:

Biomechanics and Soft Condensed Matter Physics
@ EPFL since 2023

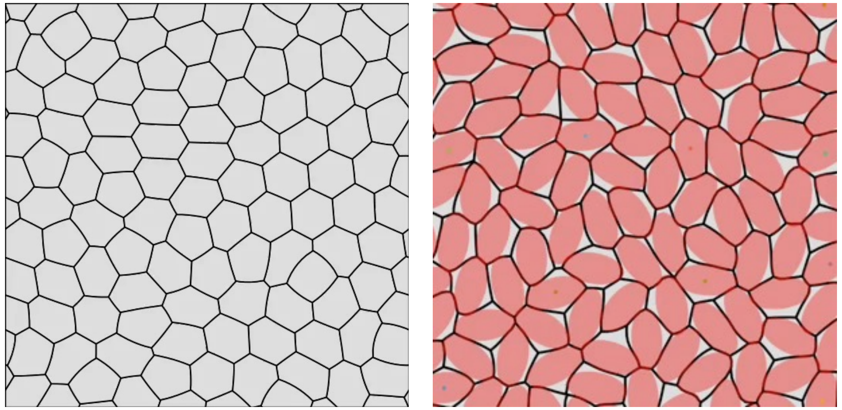
Theoretical modeling based on mechanics and physics principles

Biological & Living Systems

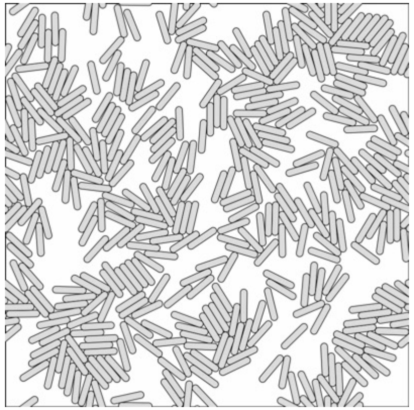
Soft & Active Matter

Prof. Sangwoo Kim

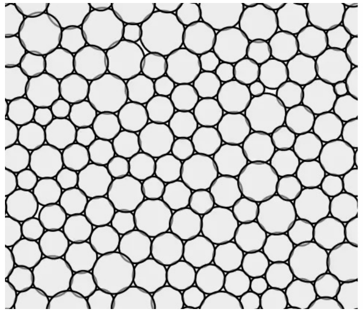
- Originally from South Korea
- B.Sc (Maths and MechE) POSTECH, South Korea [2004-12]
- M.S (Theoretical and Applied Mechanics) UIUC, USA [2012-13]
- Ph.D (Theoretical and Applied Mechanics) UIUC, USA [2013-18]
- Postdoc (MechE) UCSB, USA [2018-23]
- Assistant Professor, IGM, EPFL [2023-present]



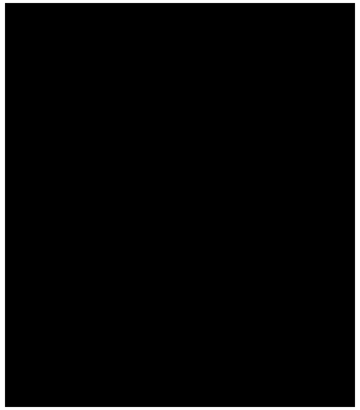
Biological tissues



Bacteria aggregates



Soft particle packings

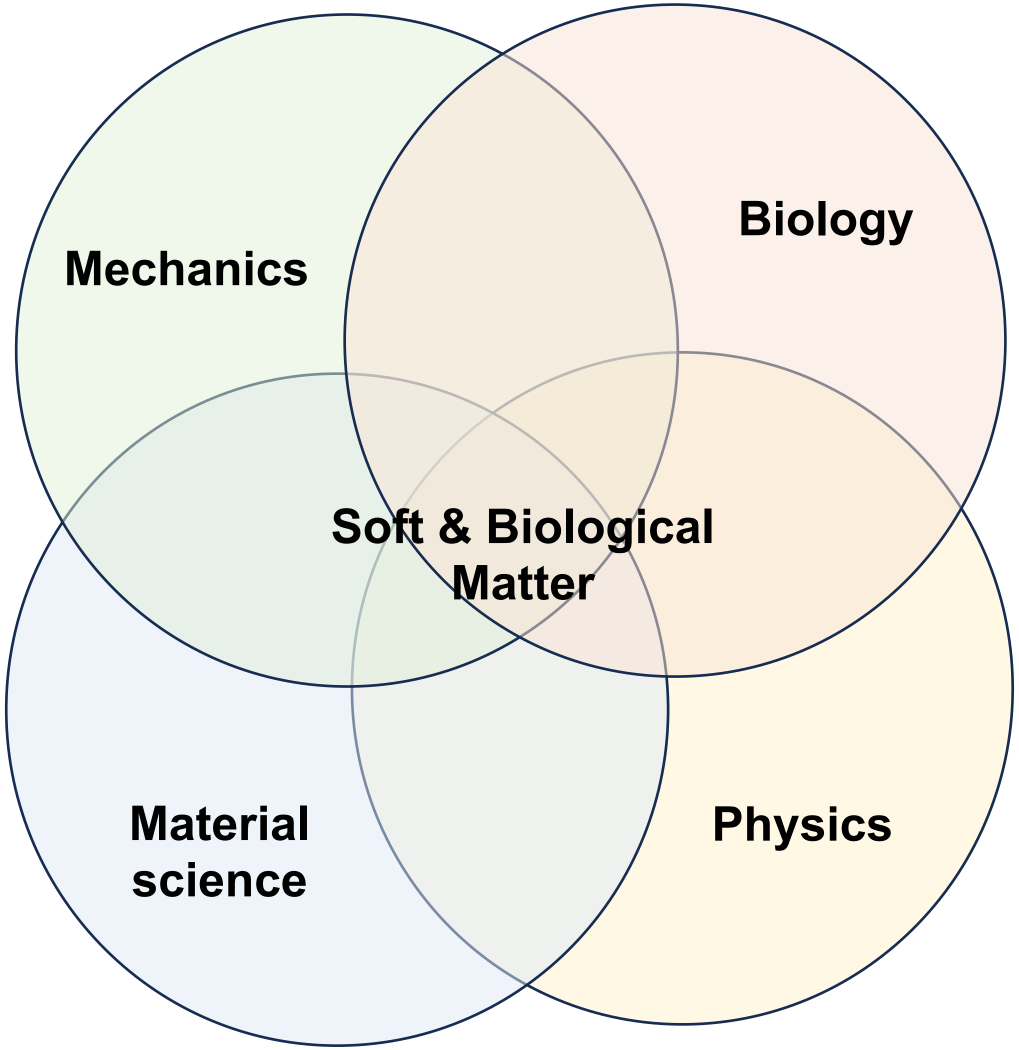


Network system

Motivation

Soft and Biological Matter

- Polymer melts/solutions
- Foams, emulsions, suspensions
- Granular materials
- Rubber
- Cells
- Tissues, Organs
- Membrane, vesicles



Many, but not all, soft and biological matter

- Are viscoelastic/viscoplastic
- Are self-organized
- Show “slow” relaxation of strain
- Show entropic effects (thermal fluctuations)

What are Soft Materials?

Soft materials: materials that will not hurt your hand if you hit them

- T.C. Lubensky -

Hard material

Soft material

Shape changes in soft materials can be easily induced with minimal efforts

⇩

Large strain can be induced by small stress

⇩ Linear elasticity

Small elastic modulus!

Estimation of Young's modulus for soft cat toy

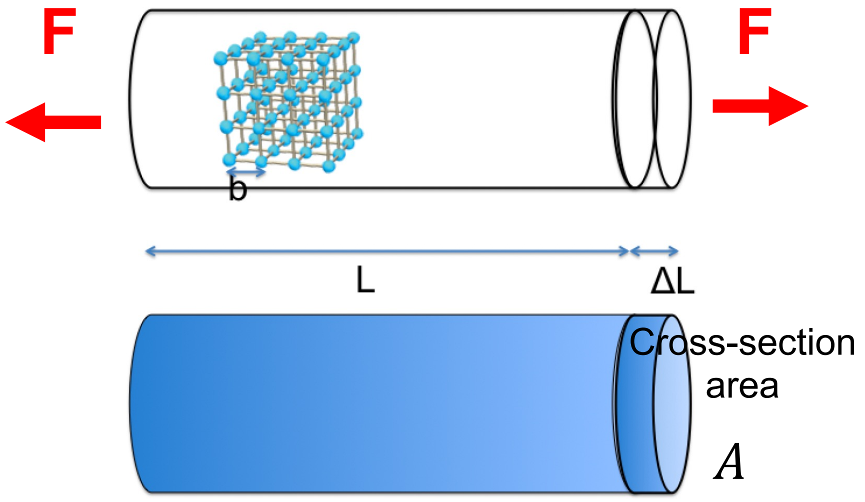
$$F = 10N$$
$$A = 10cm^2$$
$$\varepsilon = 0.1$$

$$\sigma = \frac{F}{A} \sim E\varepsilon$$

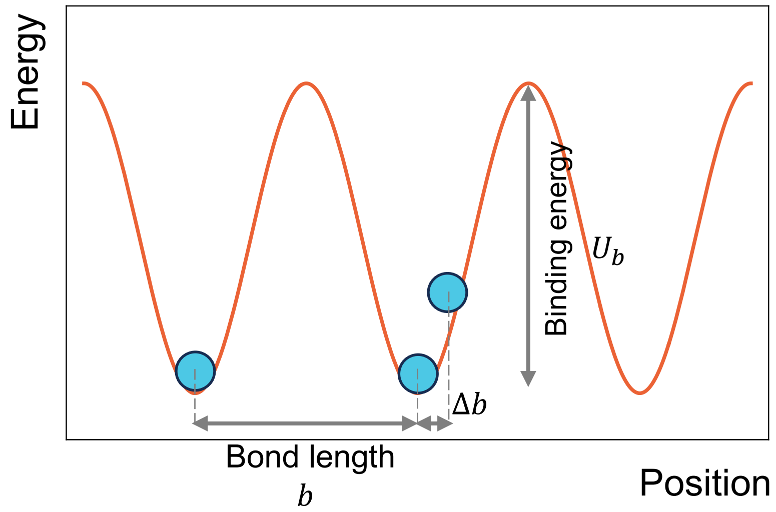
⇨ $E \sim 10^5\ Pa$

Rough rule of thumb:
Soft materials have moduli ~ 10^5 Pa

Estimation of Young's modulus for crystalline solid



Regular arrangement of constituent atoms at lattice sites



Microscopic interpretation: energy cost due to deviation of atoms from lattice sites

$$U(\Delta b) = U_b \left(\frac{\Delta b}{b}\right)^2 \Rightarrow U_{tot} = N_b U_b \left(\frac{\Delta b}{b}\right)^2 \quad (1)$$

Parabolic approximation of energy cost

N_b : total number of bonds

Macroscopic interpretation: work of force

$$U_{tot} = W = \int F ds = \sigma A \Delta L = \sigma V \frac{\Delta L}{L} = EV \left(\frac{\Delta L}{L}\right)^2 \quad (2)$$

Assume homogeneous deformation: $\varepsilon = \frac{\Delta L}{L} = \frac{\Delta b}{b}$

(1)=(2): $N_b U_b = EV$

$$E = \frac{N_b}{V} U_b = n_b U_b$$

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Estimation of Young's modulus for crystalline solid

$$E = \frac{N_b}{V} U_b = n_b U_b$$

- Atomic density in solids & liquids is almost invariant: $n \sim 10^{29} m^{-3}$.
- Covalent bonds/metal bonds have a bonding energy: $U_b \sim 1eV \approx 1.6 \times 10^{-19} J$

$$E \sim 10^{10} Pa = 10GPa$$

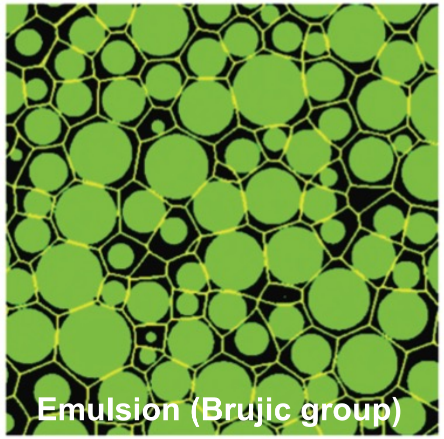
Typical values for metals

Q: How do soft materials exhibit very small elastic moduli?

Atomic density is almost constant so the bond energy should be reduced. However, U_b cannot be arbitrarily small as $U_b \leq k_B T \sim 4 \times 10^{-21} J$, the material melts!!

Soft materials must have $E \geq 2.5 \times 10^8$ Pa !! (contradiction)

Soft Materials around Us



Mayonnaise

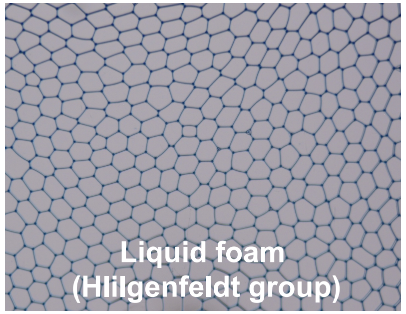
(https://www.eggs.ca/recipes/homemade-mayonnaise)

Face cream

(https://www.glamour.com/story/
got-face-cream-that-isnt-worki)

Shaving foam

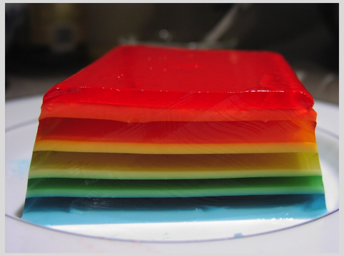
(https://www.thriftyfun.com/tf250938.tip.html)



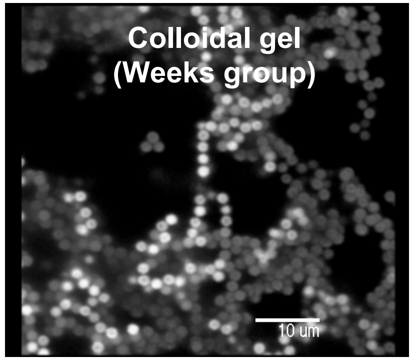
Bread

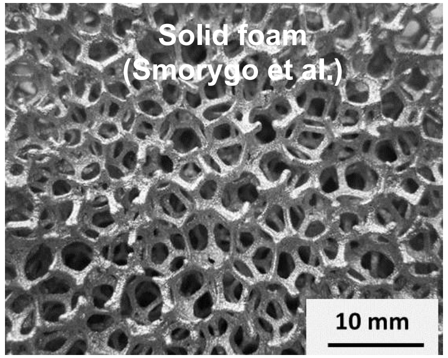
(https://apfoodonline.com/)

Gelatin



(Wikipedia: gelatin desert)





Memory foam mattress

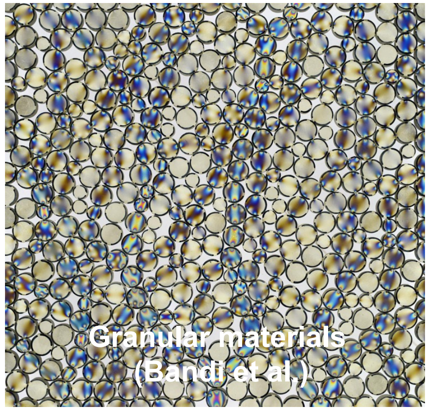
(https://www.thesleepjudge.com/)

Sand pile

(https://source.wustl.edu/

Grains

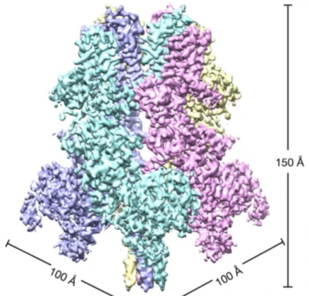
http://www.shieldhealthcare.com/



Softness arises from mesoscale structures

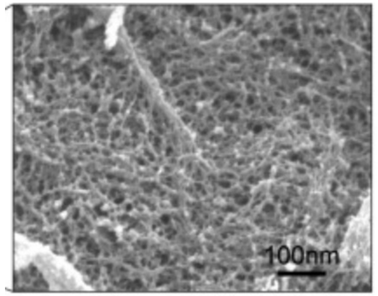
Biological Tissues: Hierarchical Materials

Protein structure



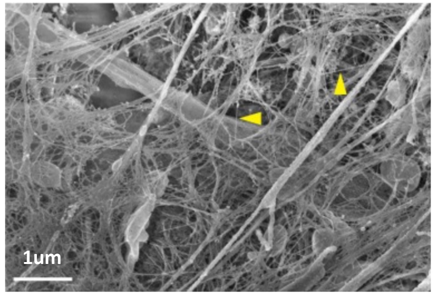
Guo et al. Nature (2017)

Cell cortex



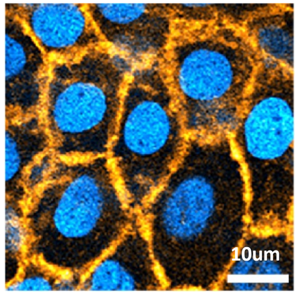
Kelkar et al. Curr. Opin. Cell Biol. (2020)

ECM



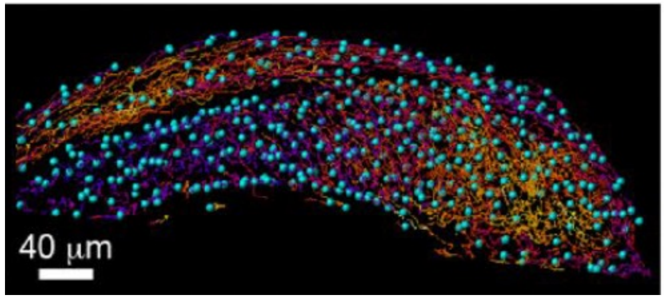
Lansky et al. J Struct. Biol. X (2019)

Zebrafish tail skin



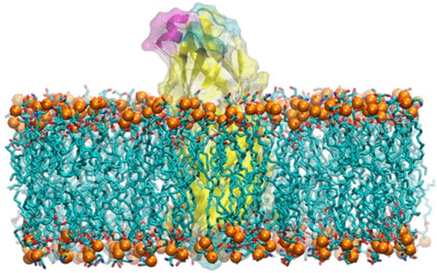
Campàs group: Rana Amini

Zebrafish tailbud



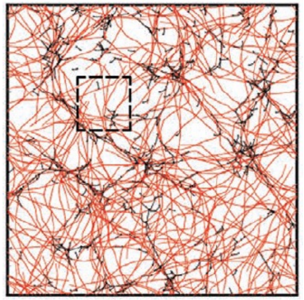
Banavar et al. Sci. Rep. (2021)

MD simulation



Goossens et al. J. Chem. Inf. Model (2018)

Active network simulation

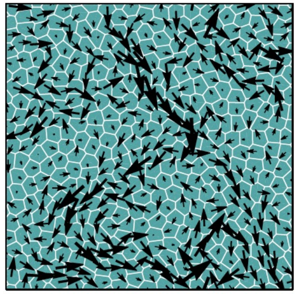


Tabatabai et al. Adv. Funct. Mater (2020)

Phase field model

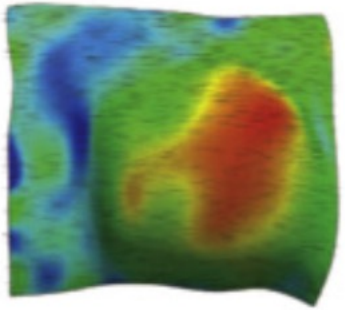
Kuang et al. arXiv (2022)

Self-Propelled Voronoi model



Bi et al. PRX (2018)

Continuum description



Lee et al. J. Mech. Behav. Biomed Mat. (2018)

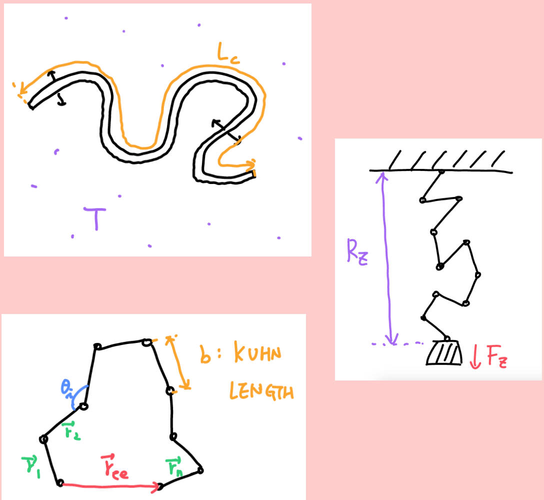
~nm ~μm ~mm **Length scale**

Interactions between characteristic structures within a length scale as well as across length scales determine emergent tissue properties!

Course Contents

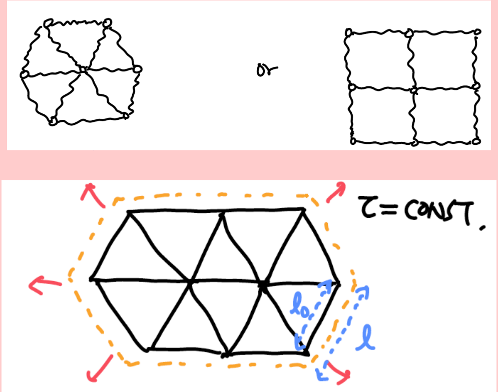
Objective: a comprehensive understanding of theoretical (and computational) modeling of soft and biological matter, emphasis on biological system

Part 1



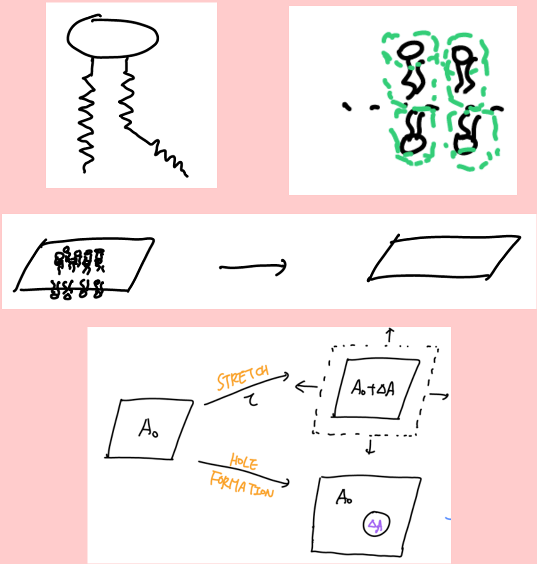
Mechanics of 1D elements

Part 2



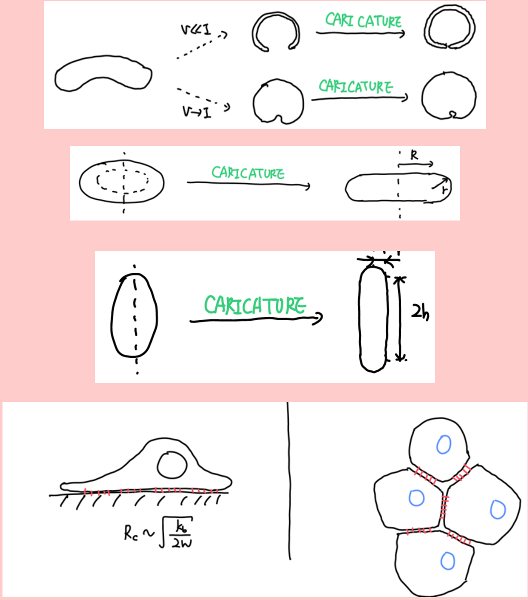
Mechanics of 2D network

Part 3



Mechanics of membranes

Part 4



Mechanics of cells and tissues

Course Contents

Date	Topic
19.9	L1.1: Introduction
19.9	L1.2: Review on continuum mechanics
19.9	L2.1: Review on thermodynamics and statistical mechanics I
26.9	L2.2: Review on thermodynamics and statistical mechanics II
26.9	L3.1, 3.2: 1D chain – motivation, stretching vs bending, persistence length
3.10	L4.1, 4.2: 1D chain – Ideal chain & freely jointed chain
3.10	E1: Exercise 1 discussion session
10.10	L5.1: 1D chain – worm-like chain, entropic materials
10.10	L5.2: 2D network – motivation, 2D elasticity
10.10	E2: Exercise 2 discussion session
17.10	L6.1, 6.2: 2D network – triangular lattice
17.10	NE1: Numerical exercise 1 introduction session
24.10	Fall break
31.10	L7.1, 7.2: 2D network – prestressed network, numerical approach
31.10	NE2: Numerical exercise 1 help session1
7.11	L8.1, 8.2: Membrane – motivation, monolayer
7.11	NE3: Numerical exercise 1 help session2
14.11	L9.1, 9.2: Membrane – bilayer, differential geometry
14.11	E3: Exercise 3 discussion session
21.11	L10.1, 10.2: Membrane – vesicle formation and rupture
21.11	NE4: Numerical exercise 2 introduction session
28.11	L11.1, 11.2: cell – vesicle shape
28.11	E4: Exercise 4 discussion session
5.12	L12.1, 12.2: cell – adhesion, tissue modeling
5.12	NE5: Numerical exercise 2 help session
12.12	L13.1: tissue – computation methods in biological tissues
12.12	L13.2: tissue – phase transitions in biological tissues
12.12	L14: review
19.12	**Final exam**

Intro & review

1D elements

2D networks

2D membranes

Cell & tissue

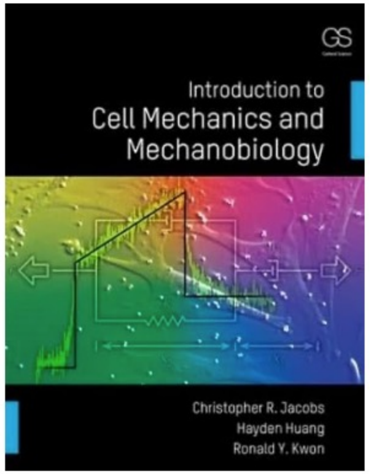
Logistics & Exercise Sessions

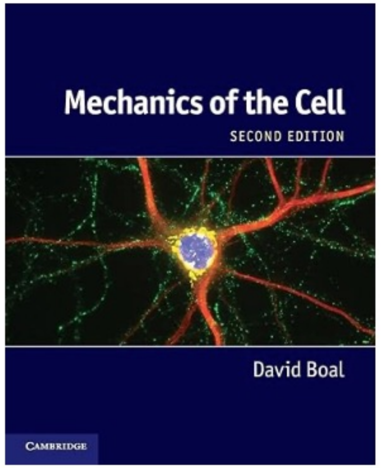
Logistics: 2 hours lecture + 1 hour exercise
- Lectures mainly with blackboard

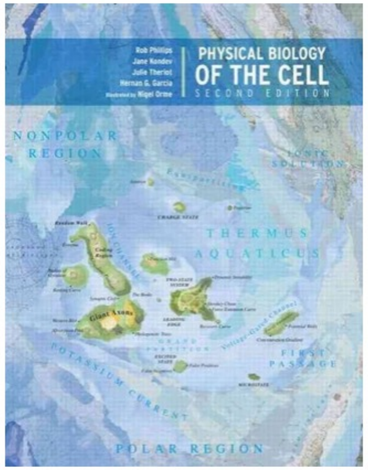
Exercise: lead by PhD TAs (Alessandro Rizzi, Roxane Ollivier)
- 4 analytic problem sheets, discussed during exercise sessions
- 2 numerical problem sheets, help sessions are organized

Evaluation: Final exam (70%) + Numerical assignment (30%)

References
- Course materials will be provided though lecture notes
- A part of course materials is adapted from following textbooks.







Exercise Sessions: Analytic Problem Sheets

- 4 analytic problem sheets
  - Problem sheet #1: Continuum mechanics and statistical mechanics (already posted on Moodle)
  - Problem sheet #2: 1D elements – Polymer chains (posted on September 26th)
  - Problem sheet #3: 2D network structure (posted on October 10th)
  - Problem sheet #4: Membrane, vesicles, and cells (posted on November 11th)
- Each problem sheet will be discussed during exercise sessions (check the schedule in syllabus). You are expected to work through the problems on your own before the exercise sessions. TAs will lead the discussions, but you may also be asked to solve part of the problems.
- The solutions to each problem sheet will be provided after the respective discussion session.
- You are encouraged to maximize the office hours for analytic problem sheets:
  - Friday between 9am — 11am, ME A2 392 (TAs)
  - During break times between the lectures and by appointment (professor)

Exercise Sessions: Numerical Problem Sheets

- 2 analytic problem sheets
  - Numerical problem sheet #1: Ideal chain & freely jointed chain (posted on September 26th)
  - Numerical Problem sheet #2: Single cell shape (posted on November 11th)
- The final answers, source codes, and description of source codes should be submitted by due dates.
  - Numerical problem sheet #1: **November 10th**
  - Numerical problem sheet #1: **December 8th**
- Help sessions are organized for each numerical problem sheets, where TAs will explain about essential numerical methods and basic coding structures.
- The submitted report will be graded, and the grades will contribute 15% each for the final grade.
- Late submission will incur 20% grade reduction per day, and submissions more than 5 days past the due date will not be graded.

Final Exam

- Final exam is scheduled on **December 19th**. Please make note of the date.
- The exam will consists of multiple-choice concept questions and three analytic problems. Further details will be provided during the review session before the final exam.
- Three analytic problems will be similar to questions covered in the problem sheets.

Questions?