Logistics and introduction

PH3501

Claus-Dieter Ohl

Course Website and Mailing List

- Website
  - ntulearn.ntu.edu.sg
  - please check regularly for updates

Schedules

Course

- Monday 13.30-14.30 TR+7
- Wednesday 14.30-16.30 TR+7

Tutorial

- Monday 14.30-15.30 TR+7
  discussion of homework

Term tests

- Mid term after the recess week
- Final term (duration 2.5hour)

Grades, maximum of 100 points

- Homework (10% of grade)
  - 5 homework sheets will be graded
  - Online available on Wednesday, each counts 2 points
  - Must hand in latest on Friday after lecture before tutorial
  - Later hand ins are not accepted… really!
  - Mandatory
    - 0 = not completed, 1.0 = competent with some mistakes, 1.5 = basically correct, 2.0 perfect
- Midterm (30% of grade)
  - 1 hour examination
- Final Exam (60% of grade)
  - 2.5 hour examination

Getting help

- Instructor
  - In class. I encourage questions and comments during lectures. If I do not see your hand, please speak up.
  - After class. I will hold 30 minutes open for after-class questions and homework consultations (or any other issue you wish to raise)
  - Or by appointment (send email)
- Teaching Assistant (office PAP 05-13)
  - Julien Rapet (JULIEN001@e.ntu.edu.sg)
  - Milad Mohammadzadeh (MILAD001@e.ntu.edu.sg)
- E-mail
  - Send mail to cdohl@ntu.edu.sg
  - As rapid response as possible.
  - If you have involved questions it is MUCH BETTER to see me live in office (#04-01 general office)

Feedback

- Feedback on all aspects of the course are welcome at any time.

Homework Collaboration Policy

- Unless otherwise noted, you can discuss homework problems prior to submission with instructor and classmates, and you can use any reference source, computer program, etc.,
- You may not discuss homework problems prior to submission with other persons not mentioned above.
- Discussion of homeworks with others should be to the mutual benefit of all involved in the collaboration.
- The actual written submission must be completed independently and must reflect your own understanding of the material.
- You should attempt each homework problem on your own and only seek outside help and collaboration when you are truly stuck.
- 'Comparing answers' is allowable but *discouraged*. By comparing answers, I mean, for example, checking to see if an intermediate or final answer 'agrees' in order to gain confidence that your procedure is correct. A much better strategy is to double and triple check your work and develop your own confidence.

(Mid term) Exam Collaboration Policy

- **NO COLLABORATION**
- You may not consult any reference material (including online) except "your own course notes" and the text book "Fluid Mechanics" Kundu, Cohen (for mid term only)
- "Your own course notes" is defined as:
  - Notes you personally take in class. If you miss class you may Xerox another student's notes and include them as your own.
  - Instructors' prepared notes
  - Homeworks and their solutions from this class
- No calculators/computers are allowed or needed

Reading

- Required reading
  - Fluid Mechanics Kundu/Cohen
  - Fluid Dynamics: Theory, Computation and Numerical Simulation, Pozrikidis
- Suggested additional reading listed on website
- Many additional books at the library
- Reading is essential and works best if you attempt a pass through the material both before and after the corresponding lecture
- I will also use some programming for homework and tutorials. This year we'll use python, in particular the interactive version ipython.

Goal and philosophy

- The purpose of this course is to
  - Provide a serious introduction to fluid dynamics stressing first principles over comprehensive survey of applications
  - Familiarize the Mathematical tools and physical reasoning that allow the student to apply these principles to various disciplines
  - Stress the importance of dimensional analysis, order-of-magnitude analysis
  - Provide an introduction to use numerical software to analyze and model flows.
- Philosophy: the importance of Mathematical models
  - What is “physical intuition” and how is it built?
  - How do we analyze situations too complex for “physical intuition” to be of much use?

What is a fluid?

- *Panta rei. “Everything flows”. Heraclitus, 500BC*
- Liquid or gas-phase material
- Something that “takes the shape of its container”
- A material that deforms continuously and permanently under applied shearing forces, no matter how small

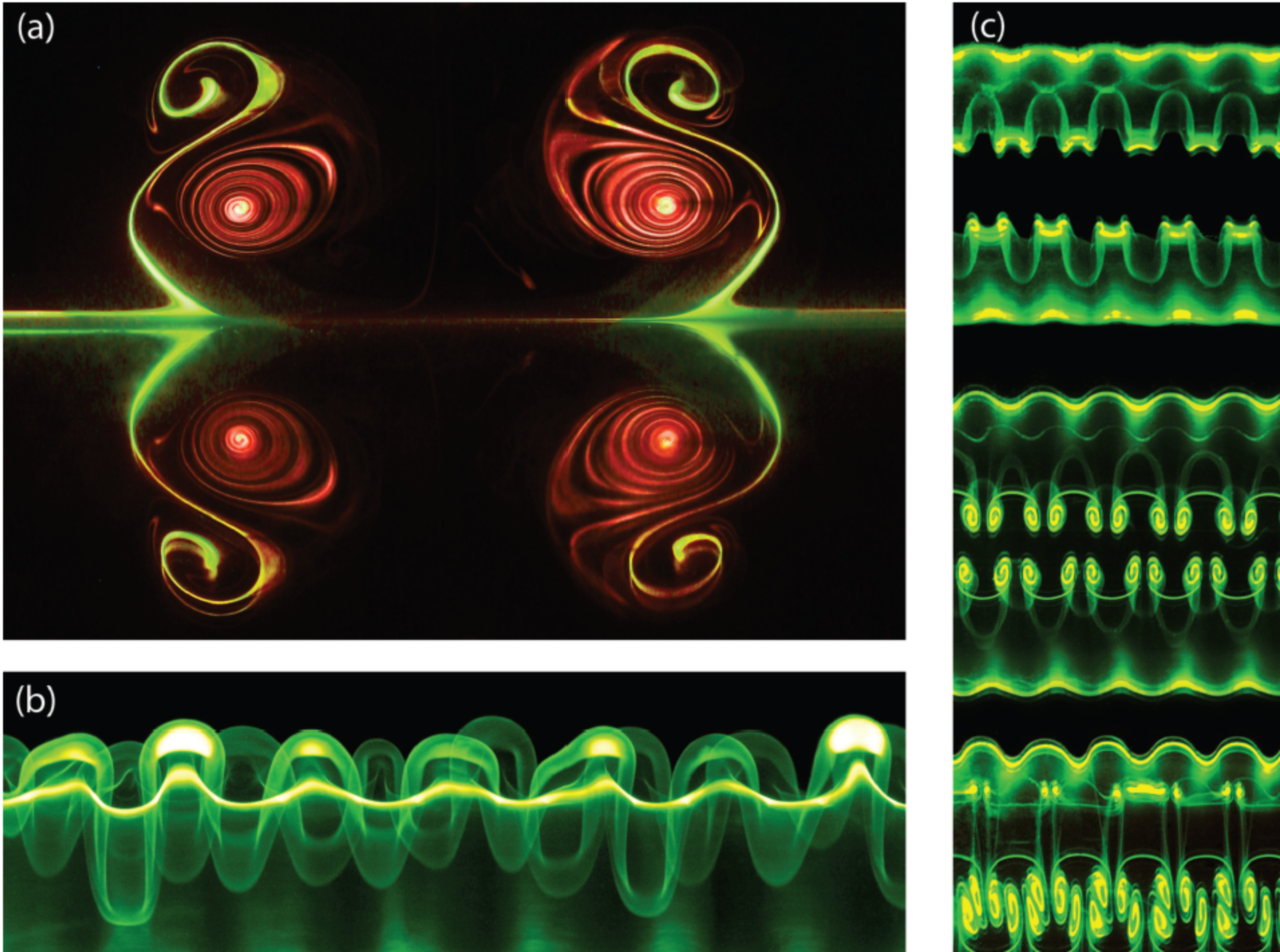
- *Newtonian Fluids*
  - *“isotropic” (no directional dependence of fluid properties)*
  - *Linear relation between (rate of) stress and deformation*
  - *Ordinary liquids and gases in engineering systems*
    - *Water, air, oil, fuels, etc.*

More complex behavior

- Behavior can depend on timescale involved (e.g. rate of shear)
- Properties can vary with orientation (polymers, liquid crystals)
- Viscosity can change as the rate of applied shear is changed
  - Shear thinning or pseuo-plastic (e.g. blood)
  - Shear thickening (e.g. suspension of corn starch in water)
- Time-dependent viscosity (duration/history of stress) (e.g. lubricants)
- Distinction of solids and fluids not always clear
  - Yield stress (Bingham fluid…solid below, fluid above)
  - Visco-elastic (silly putty, dough)

Quiz

What the heck is this?


(a)
(b)
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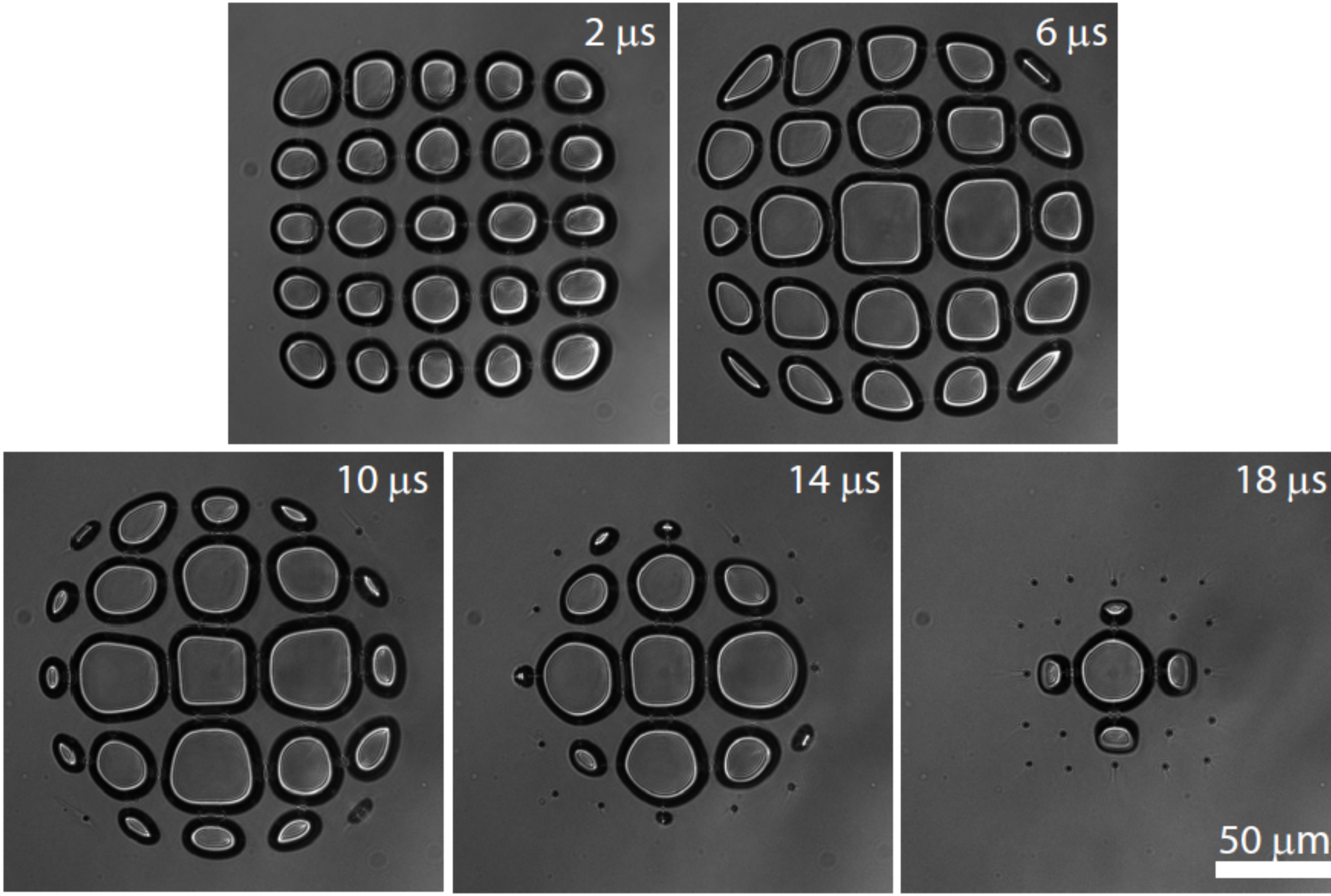
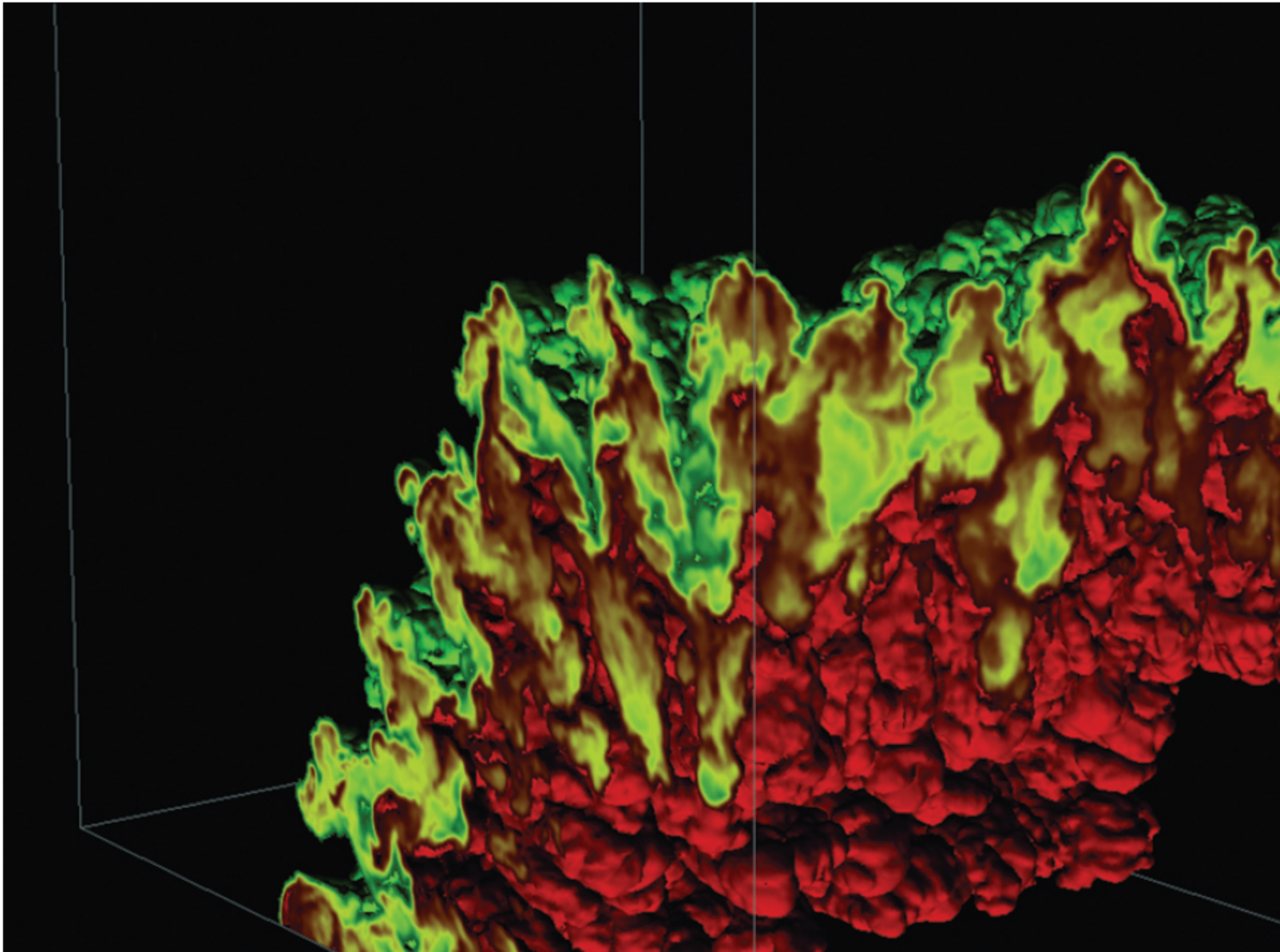
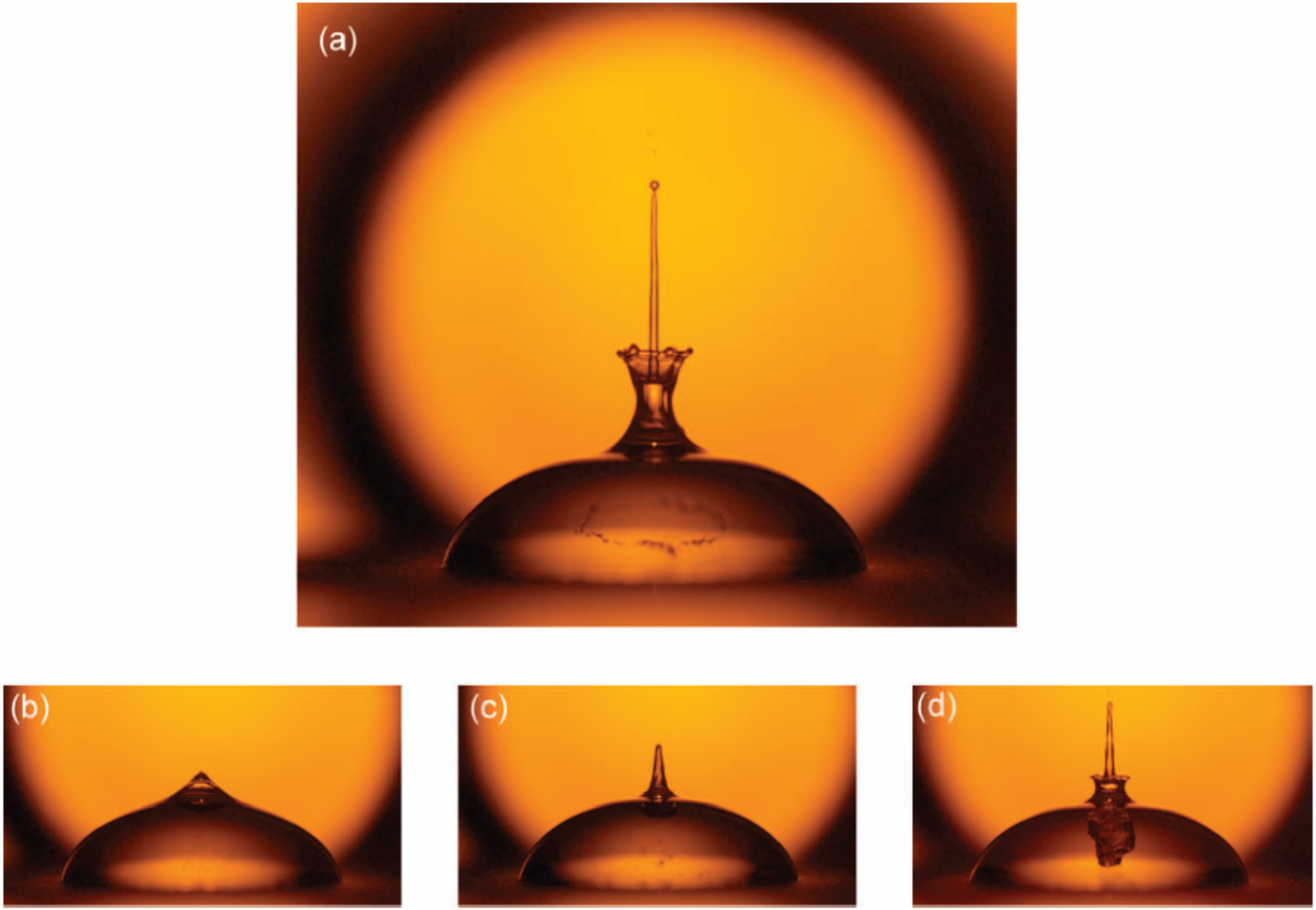

2 μs
6 μs
10 μs
14 μs
18 μs
50 μm




(a)
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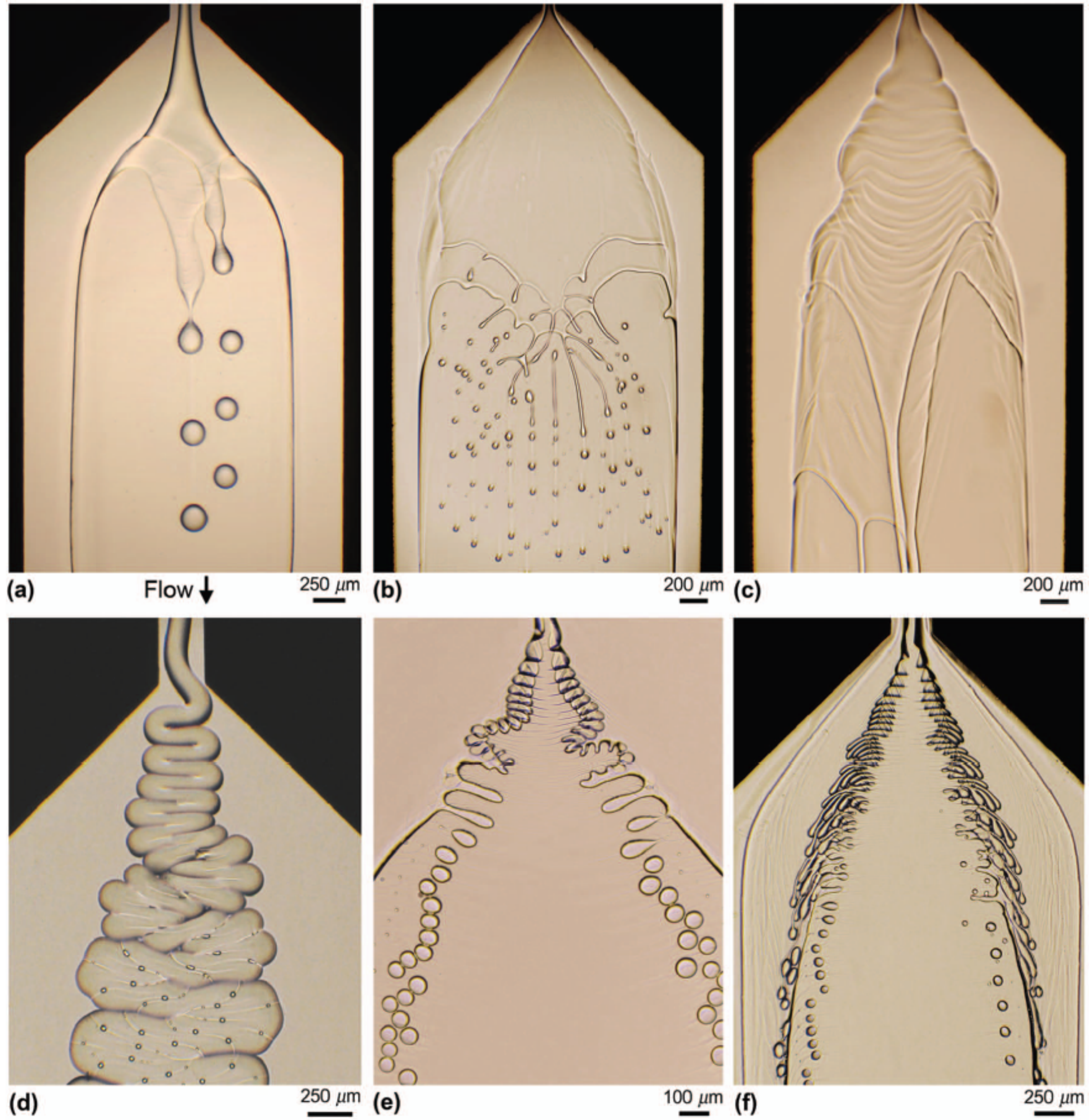
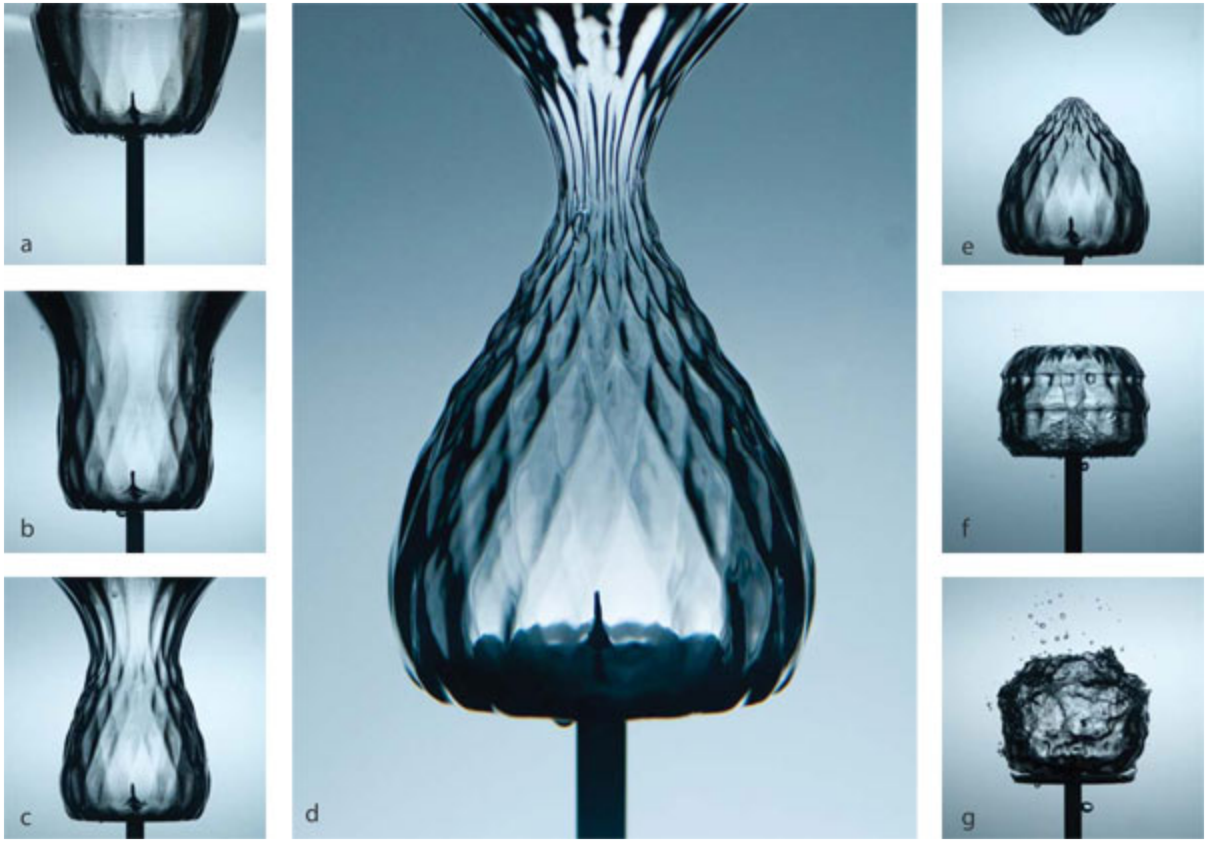
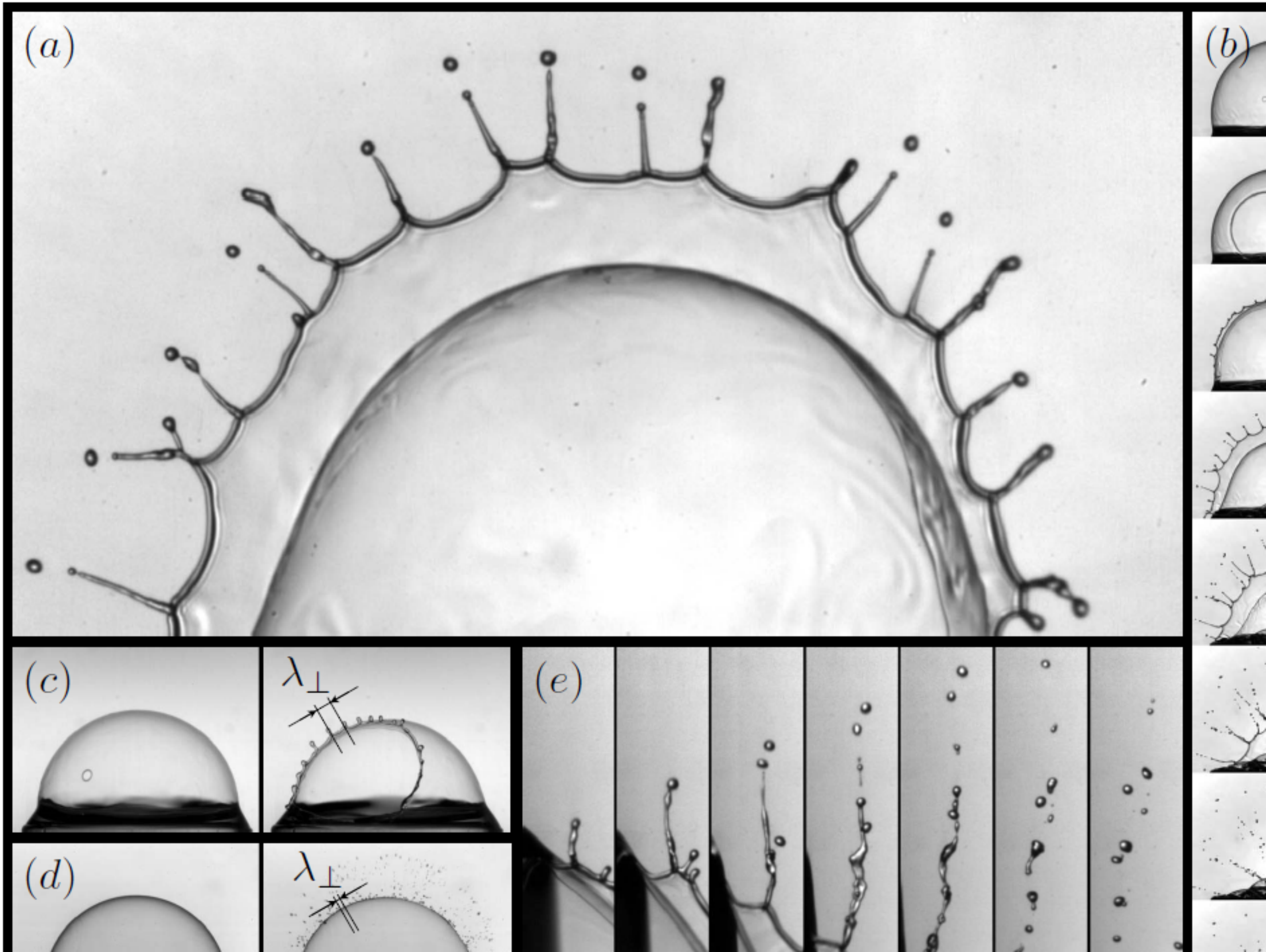
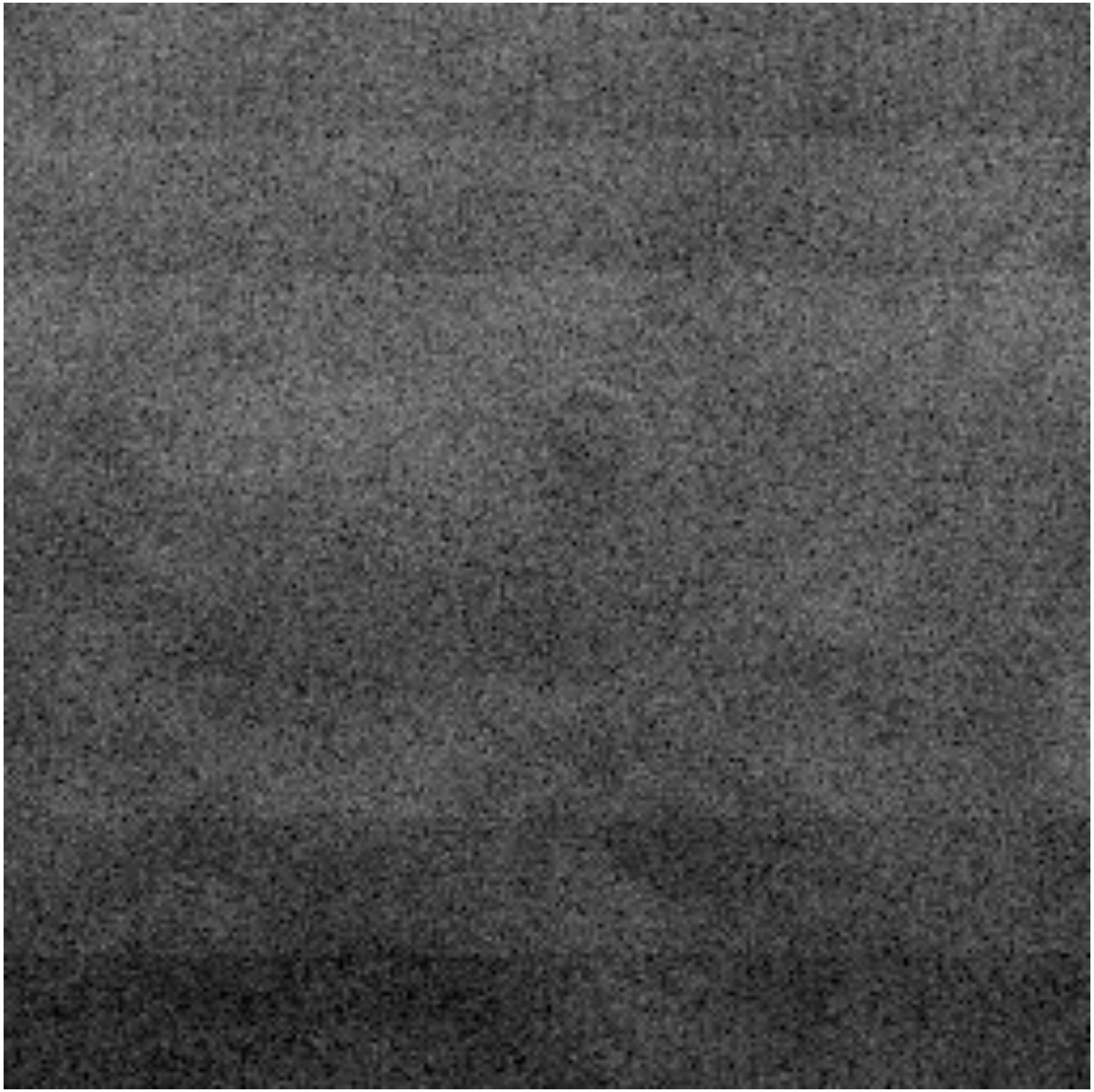


(a)
Flow
250 μm
(b)
200 μm
(c)
200 μm
(d)
250 μm
(e)
100 μm
(f)
250 μm


a
b
c
d
e
f
g


1 mm


(a)
(b)
(c)
$\lambda_\perp$
(d)
$\lambda_\perp$
(e)



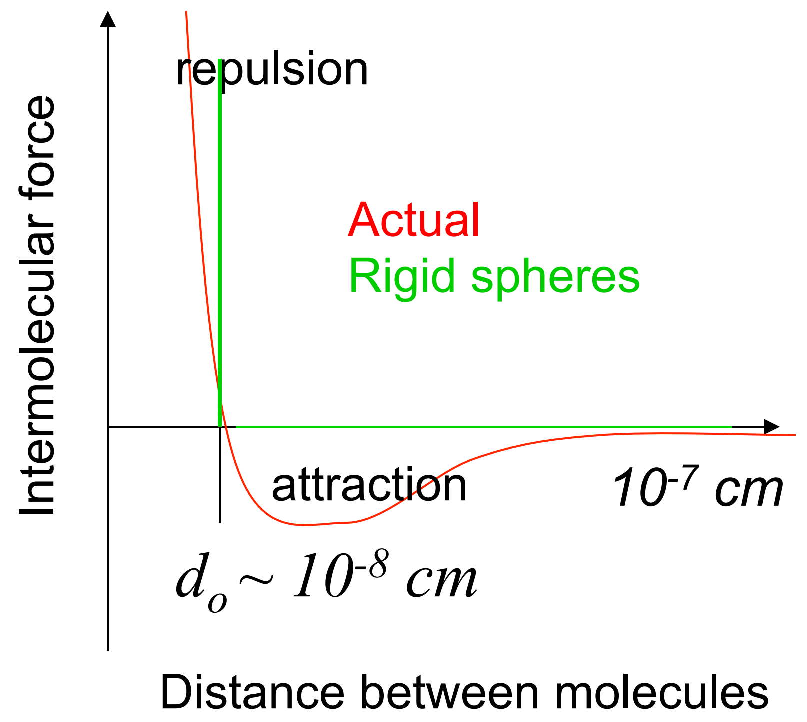
Molecular origins of fluidity

- Gases, result of large molecular spacing
- Liquids are much more complex and their fluidity is the result of the continual movement of groups of molecules (like grains) and shifting of molecules between groups

Gases d_{avg} ~ 10 d_o

Liquids & solids *davg ~ do*

Density of gas ~ 1/1000 times density of liquid/ solid



Kinetic Theory

- Random motion of molecules in equilibrium (no macroscopic variation in properties)
- Neglect intermolecular collisions (*important for driving to equilibrium*)
- Imagine force exerted on a (imaginary) wall due to specular reflection of molecules
- Simple mechanics shows that

Avg speed

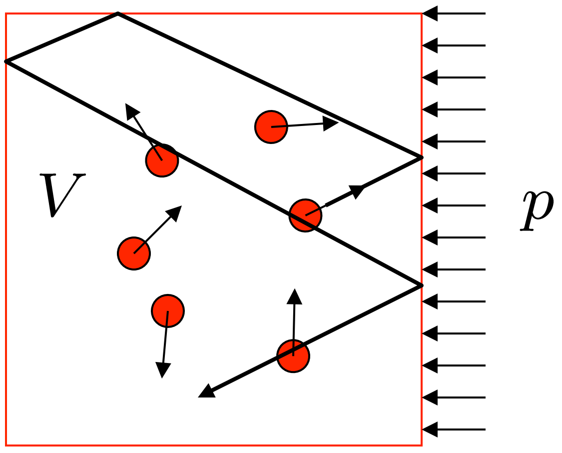
Number of molecules/
unit volume

$$p = \frac{Nm}{3}\overline{v^2}$$

Boltzman constant
1.38054 x 10^{-23} J/K

$$p = NkT$$

Temperature



Air and water at STP

quantity	air	water
N (molecules/m^3)	2.5×10^{25}	3×10^{28}
ρ (kg/m^3)	1.2	998
NkT (atm)	1	1385

Wrong! We must consider
Intermolecular interactions!

Some special properties of liquids

- Balance between large equal and opposite contributions to the pressure result in extreme sensitivity to density
  - Tiny density change → enormous pressure change
  - Highly “incompressible”
  - Temperature change at constant pressure → density change results primarily from changes in intermolecular forces. Relatively smaller density changes than gases
  - Can support tension (negative pressures) before ‘rupturing’ (cavitation)

Non-equilibrium

- Thermodynamics deals with matter under equilibrium conditions
  - No “macroscopic” variations in composition, momentum, energy
- Except under extreme conditions, thermodynamic equilibrium is achieved locally in space and time
- BUT…we must account for the effects of the macroscopic non-uniformity on the dynamics of molecules (primarily collisions)

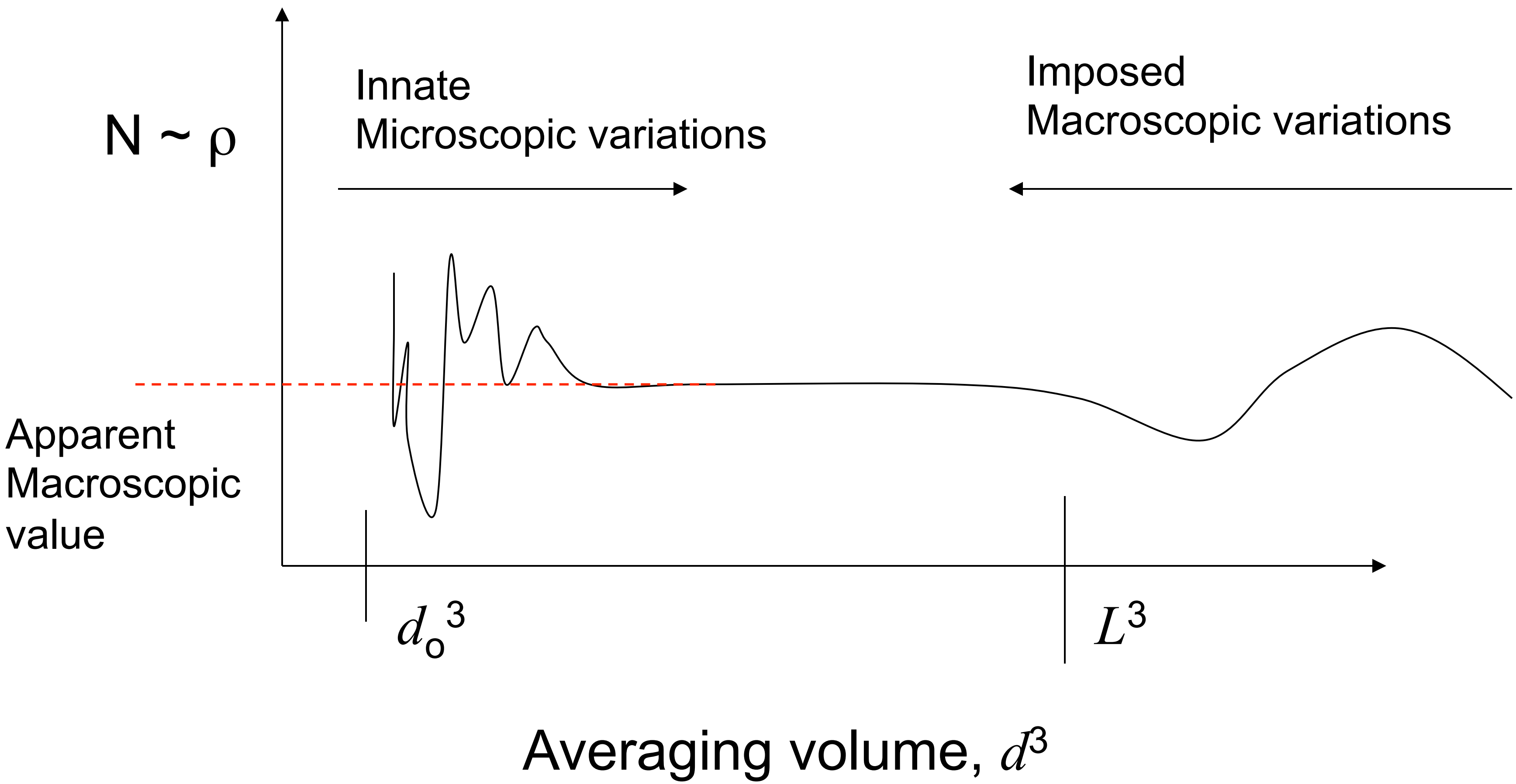
Macroscopic non-uniformity	Microscopic Exchange	Transport phenomena
Velocity	Momentum	Viscosity
Composition	Mass	(mass) diffusivity
Temperature	Energy	Conductivity

The continuum hypothesis

quantity	air	water
N (molecules/m^3)	2.5×10^{25}	3×10^{28}
N (molecules/mm^3)	2.5×10^{16}	3×10^{19}
N (molecules/μm^3)	2.5×10^{7}	3×10^{10}

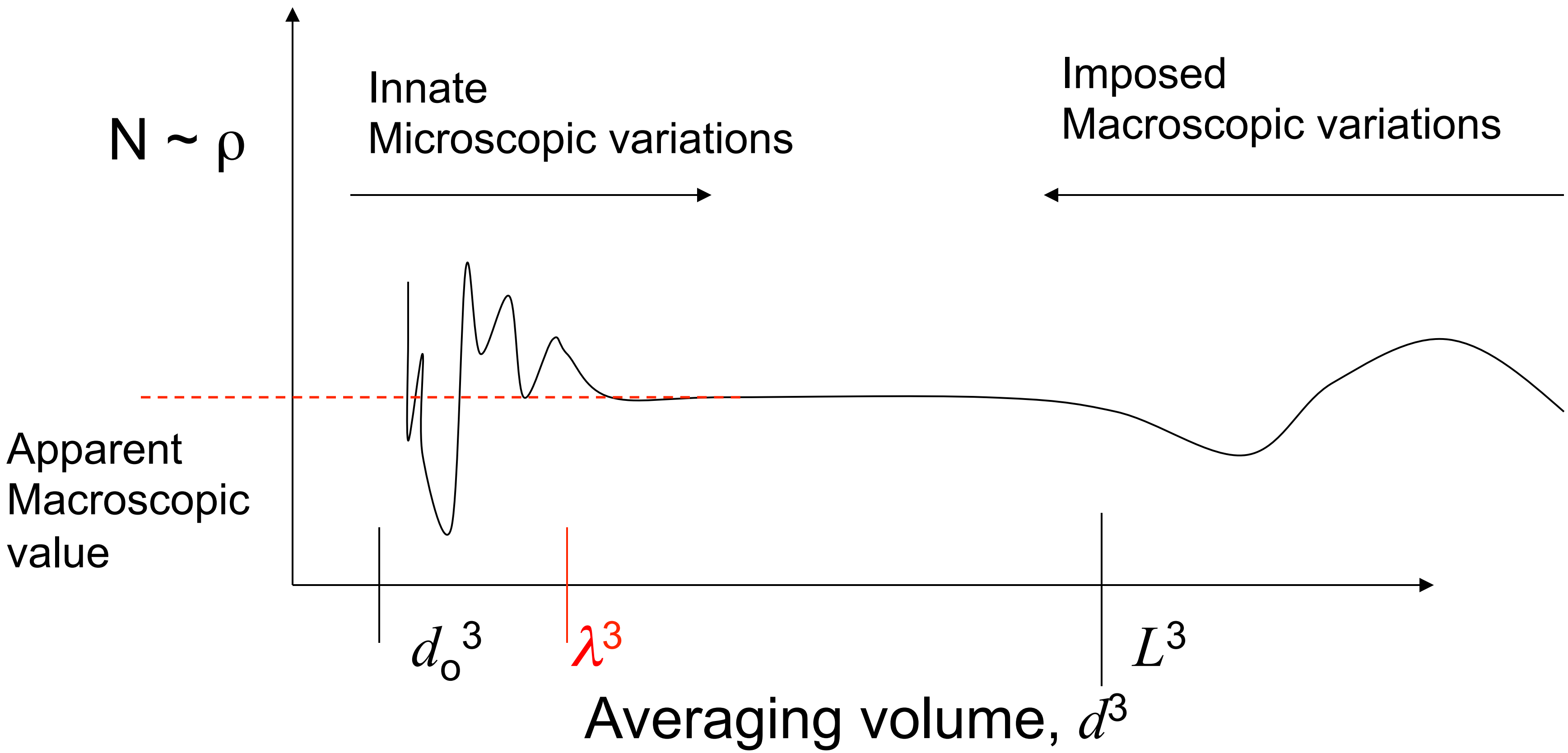
- Provided that imposed (macroscopic) variation is on a length scale greater than some tiny averaging volume (sub micron cubed!), then there are a sufficient number of molecules such to obtain reliable averages
  - i.e. there is no effect of changing numbers, velocities, etc. of molecules on the value of the averages

Qualitative situation



Continuum Hypothesis

- Require that imposed macroscopic scale, L, is much greater than innate microscopic scale
- Which scale to use for molecules? Mean-free path ≡ average distance molecules travel between collisions



Example on small scales

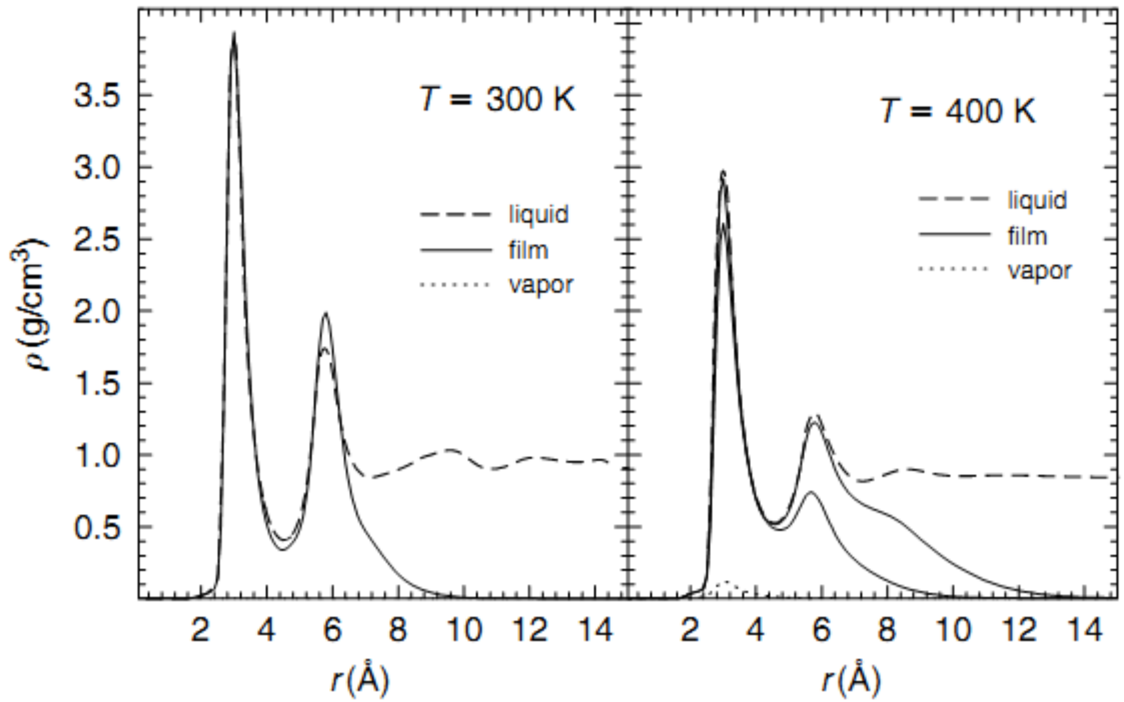


Figure 24: Density profiles of the coexisting water phases, corresponding to the prewetting transition near the hydrophilic surface of the cylindrical pore with $R_p = 25$ Å and $U_0 = -3.08$ kcal/mol.

From *Interfacial and Confined Water, Brovchenko &Oleinikova*

Knudsen number

- Form ratio of length scales:

$$\text{Kn} = \lambda / L$$

$$\begin{array}{ll} \text{Kn} \ll 1 & \text{Continuum flow} \\ \text{Kn} \approx 1 & \text{Transition/slip flow} \\ \text{Kn} \gg 1 & \text{Free molecule flow} \end{array}$$

- L is a characteristic length for the problem at hand
  - Flow past a sphere, L = diameter of sphere
  - Flow in a channel, L = width of channel
  - Etc.
- Mean free path in air at STP: $\lambda \approx 10^{-7}$ m.

Review Questions

- What is a fluid?
- What is a Newtonian fluid?
- What are examples of Newtonian fluids and more complicated (Non-Newtonian) fluids
- Give a few examples of how molecular properties of gases and liquids lead to macroscopically observed behavior?
- What is the continuum hypothesis, and how/why does the Knudsen number tell us whether we can apply it?