Spring Semester 2021

DYNAMICS OF COMPLEX FLUIDS

MSE 583

Instructor: Professor Ken Schweizer kschweiz@illinois.edu

Time & Place: 9:30-10:50 am (or shorter) Tuesday & Thursday
synchronous lectures via Zoom

This course is an intermediate-level introduction to the ***fundamental physical aspects (basic science)*** *of the dynamics, viscoelasticity and mechanical response of polymers and colloids in the liquid state. The formation of nonequilibrium colloidal and nanoparticle physical gels and glasses is also discussed, as is briefly the rheology of particle gels. An overarching theme is to understand the connections between molecular or colloidal particle architecture, intermolecular forces, collective fluid structure, and time-dependent phenomena. Experimental behavior and theoretical concepts are presented in an integrated manner.*

This course is NOT about continuum mechanics or hydrodynamics, detailed discussion of the equilibrium behavior of colloids or polymers, engineering applications, or biological systems (though the material is germane to biophysics and biomaterials in a soft matter general sense). There are other courses on all these subjects. The emphasis is on physical behavior which is influenced by tunable chemical structure and intermolecular interactions.

Topics covered fall into 3 main categories:

* GENERAL ASPECTS of COMPLEX FLUIDS: Fickian Diffusion, Relaxation, Mechanical Response, Flow, Colloidal Forces, Structure, Pair Correlation Functions, Scattering Structure Factors, Brownian Motion, Hydrodynamics, Langevin Equation, Time Correlation Functions, Generalized Langevin Equation

* COLLOIDAL and NANOPARTICLE SUSPENSIONS: Diversity of Tunable Forces, Liquid Structure, Phase Behavior, Fickian and non-Fickian Diffusion, Viscoelasticity, Rheology, Glass Transition, Aggregation, Percolation, Gelation, Yielding

* POLYMER LIQUIDS: Elementary Statistical Chain Models, Dense Melts, Unentangled versus Entangled Dynamics, Diffusion, Dielectric Relaxation, Viscoelasticity, Rouse Model, Reptation/Tube Model, Alternative Relaxation Mechanisms, Other Architectures (star branched, rings, rigid rods)

BOOK REFERENCES

Primary "Texts"

R.G.Larson, "Structure & Rheology of Complex Fluids" **Larson**

This book is modestly useful for both the colloid and polymer topics

M.Rubinstein & R.H.Colby, "Polymer Physics" **RC**

This book is excellent for all polymer topics

More Specialized Useful Books

(pre-pandemic these would be in Grainger library on reserve)

W.Russel, D.Saville & W.Schowalter, "Colloidal Dispersions"	**RSS**
R.J.Hunter, "Foundations of Colloid Science", volume 1	**Hunter**
M.Doi & S.F.Edwards, "Theory of Polymer Dynamics"	**DE**

Basic Statistical Mechanics Texts

D.McQuarrie, "Statistical Mechanics"	**McQ**
D.Chandler, "Introduction to Modern Statistical Mechanics"	**DC**
J.P.Hansen and I.R.MacDonald, "Theory of Simple Liquids"	**HM**

Exams and Homework

Grading: based on a mid-term exam on Part I of the course, and a "comprehensive" final exam that heavily emphasizes part II of the course. The mid-term will count *either* 33% or 45% towards your final grade; I will choose the percentage to optimize your overall exam average and course grade. ***Mid-Term date: 10-14 days after we finish the last class on Part I. This is likely the very end of March or very start of April.***

Homework: given roughly once every 2 weeks. Working hard on the problem sets is the best way to learn the material and prepare for exams. It will not be collected nor graded; there is no TA. I will send you detailed solution sets. I *strongly* suggest you (at least initially) *independently* work on the homework. After sufficient effort, discussing the problems with other students can be useful, as is then looking at the answers I give you. It is your job to carefully study the answer key and see what you did not get correct or understand. If you then have any questions, please contact me.

On Line / Pandemic Adjustments / Logistics

The lectures will be delivered using UIUC Zoom in real time starting at 9:30 am CST. Class will last (including questions) ~ 60-80 minutes.

I will create a Zoom link with password and email it to every registered student the day before each class. *Be sure to follow the latest instructions from campus about using Zoom.* You can log before 9:30 am. When you do, you will hopefully be muted; *turn off* your audio if it is not already off.

The lectures (and questions during) will be recorded. My plan is to upload it immediately after the lecture is done on UIUC Media Space (**mediaspace.illinois.edu**). Then I will send the class an email with the link to the lecture. Click on it and follow directions. This will allow you to view the lectures any time you wish. *How to access:* after clicking on the link I send you should have direct access to the lecture (after signing in with your UIUC account). All lectures should be on the same website in chronological order. I will label them as: MSE583 lecture##. *If you encounter technical problems I likely cannot help since I know none of the technical IT details. All I likely can fix is if for some reason the lecture is not uploaded correctly due to my mistake.*

The class is relatively small. *I very strongly suggest* ***(request)*** *that if you are in Illinois you attend the class in real time.* Everyone will benefit from this. I will encourage asking questions during the lectures. Given you will have the "slides" before each lecture, this should also help stimulate questions and class interactions. Of course if you are on another continent, I understand attending in real time may not be possible.

I will be using a PDF of my lecture notes to deliver the material in a style that is the same as when I teach using a blackboard or whiteboard. *This is a basic science course that is involves math derivations and critical physical thinking*. I have tried to transfer to the PDF slides my hand written notes as they would have been delivered in a step-by-step manner on the blackboard. The lecture notes are significantly supplemented with other visuals from other files that is called the vugraph file. Each subsection of the course has its own set of lecture and vugraph files. *I will toggle between the lecture slides and vugraphs files in real time during the class.* My plan is to send you the lecture notes and vugraph file corresponding to each sub-section of the course (there are 7; see course outline below) shortly before the beginning of a new section

Logistics for Questions *during* class: about every 2 slides, I will stop and ask if anyone has a question. Doing so is highly encouraged. *If I forget to stop and ask for questions, then please do interrupt me!* I will **not** use "chat" in Zoom for written questions. Please ask by "unmuting" your audio on Zoom. When our discussion of the question is done, re-mute yourself. At the very end of a lecture, I again will ask if there are any questions on any of the material of the day.

If you have a question that was not asked during class, I suggest you first try emailing me directly. Students have effectively done this in the past. If more in depth and/or many questions arise, I can arrange a 1-on-1 discussion via Zoom.

All homework sets and answers, lecture PDFs, vugraph PDFs and any other course material will be sent to you directly by email attachment. There is no "course web site".

Exams will be taken virtually in a timed manner. Details will be explained later. *For students on campus, the mid-term exam time will be the class time, and the final exam will be at the pre-arranged by campus 3 hour time slot to be announced later.* For students not on campus, I will work with you to arrange something that can work. However, the goal will *always* be that exams are taken by all students on essentially the same day, to within variations of national and global time zones differences.

There will be one mid-term covering all of part I of the course. There will be a comprehensive final that emphasizes Part II (roughly 67% of the exam on Part II). *All exams are closed book/notes except you are allowed to have 1 sheet, 1 side of any information you would like.* Putting it together is a good experience to identify what is really important.

TIMES and FORMAT:
In the pre-pandemic days, the class was taught using a huge blackboard filled up from left to right with students required to take notes. Each class ran roughly 75 minutes. Now I will be teaching by projecting a hand written multi-color version of my notes on Zoom. The amount of material presented each time will be the same as in a real class before. As I speak, I will use my computer mouse pointer to lead you through the material on each slide. The good news is you will have my notes. Slides are numbered to facilitate cross referencing. Hence, except for perhaps writing down a few things I say that are not on the slides which you feel are important, you do not need to take notes. ***I am hoping this will allow the class to ask more questions than usual. Occasionally, I will ask the class a question. Please do participate.***

OFFICE HOURS: This was explained above. There is no single specific office hour.

MSE 583 COURSE OUTLINE

Numbers in parentheses=estimated number lectures
Book refs defined above are given for each sub-topic.

PART I. GENERAL TOPICS & COLLOIDAL SUSPENSIONS (15 classes)

A. Introduction / Generic Basic Concepts (5)

* Survey of experimental phenomena
* Basics of diffusion, mechanical response, viscoelasticity
* Brownian motion / Langevin Equation / Time correlation functions
* Hydrodynamics / Stokes-Einstein relation

Larson, ch.1.1-1.4 ; DE, ch. 3
RSS, ch. 1,2.6, 3.1-3.3; Hunter ch.1,2; McQ ch. 20,21; HM, ch. 7

B. Intermolecular Forces, Structure & Phase Behavior (3)

* Atoms versus Colloids
* Tunable Forces: excluded volume, van der Waals, Coulomb, gravity
* Phase Behavior
* Liquid Structure: pair correlations, scattering profiles

Larson, ch. 2.1-2.4, 7.2
RSS, ch. 4,5, 10 ; Hunter, ch. 4,6,7 ; McQ, ch.13, 22 ; HM, ch. 1,5 ; DC, ch. 8

C. Equilibrium Dynamics of Stable Suspensions (3)

* Interactive Brownian motion; many particle hydrodynamics
* Experimental behaviors
* Intermediate concentrations; Binary collisions ideas
* Dense hard sphere suspensions ; Caging ; Viscoelasticity
  dynamic light scattering and structural relaxation

Larson, ch. 6.1-6.4, 7.2
RSS, ch. 13, 14; Hunter, ch.9; HM, ch. 9

D. NONequilibrium Processes (4)

* Glassy dynamics & Vitrification; Generalized Langevin equation; Modern experiments and theoretical concepts; Shear thinning
* Adhesive (sticky) colloid dynamics, physical bonds, percolation, gelation, yielding

Larson, ch. 7.2, 7.3 ; RSS , ch. 14

PART II. POLYMER LIQUIDS (12 classes)

A. Chain Conformation and Liquid Structure (2)

* Chemical vs. Coarse-grained statistical descriptions
* Gaussian Bead-Spring model
* Dilute solution conformations
* Conformation and structure in dense melts
* Correlations between chemical structure & coil interpenetration

RC ch. 2-5; Larson, ch. 2.2, 3.1, 3.2; DE, ch. 1,2

B. Single Chain Brownian Dynamic Theories (4)

* Langevin equations in short chain unentangled melts
* Rouse model; Segmental friction
* Self-diffusion, viscosity, stress relaxation, dielectric relaxation
* Comments on hydrodynamic effects in dilute solution

RC ch. 8 ; Larson, ch. 3.3-3.6 ; DE, ch. 3,4

C. Dense Entangled Polymer Melts (6)

* Survey of experimental phenomena for entangled chains
* Chemical crosslinks and Entropic rubber elasticity
* Melt Entanglement Plateau modulus and chemical structure
* Reptation/Tube model; predictions for diffusion, viscoelasticity, dielectrics…
* Experimental puzzles / additional motional mechanisms
* Nonlinear rheology (very brief introduction)
* Other Architectures: cyclic rings, branched stars, rigid rods….

RC 7, 9 ; Larson, ch. 3.7 ; DE, ch. 6,7