PHYS 504
Collective and Emergent Phenomena I

Spring 2024

Professor:	Daniel Sussman
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Class time and location:	
(Tuesday & Thursday: 1:00pm – 2:15pm)	Emerson Chemistry Bldg. E363
Office hours:	
Monday: 1:00pm – 2:30pm	MSC N212

Course description:
How is it that the same collection of atoms, evolving according to the same Hamiltonian, can collectively organize into completely different phases of matter? How do rich and interesting equilibrium (or dynamical) steady states emergent when large numbers of agents interact according to simple rules, and what constrains the possible range of such emergent behavior? What even is the right physical and mathematical language to ask and then answer these questions?

In this course we will learn how to link microscopic with macroscopic descriptions of matter, we will learn how to understand collective phenomena and emergent properties of matter, and we will do so through the lenses of symmetry, of scale, and of statistical physics. Over the semester we will study thermodynamical descriptions of both bulk phases and the transitions between them, and we will then understand how this essentially phenomenological approach can be understood via statistical physics (a subject grew out of concerns about steam engines and billiard-ball models of the air around us, led to beautiful and abstract ideas like entropy and information, and today gives us a systematic framework to study complex systems from across disciplines!). We will close with a first look at critical points, universality, and the renormalization group, one of the most beautiful ideas to come out of 20th century physics.

The material we will cover was, by far, my favorite subject when I was in graduate school, and I feel privileged to be your instructor for this course. Let's go!

Prerequisites: Physics 504 is a fairly self-contained graduate course. I will assume familiarity with multivariable calculus, linear algebra, and with undergraduate thermal and statistical physics at the level of, e.g., Kittel and Kroemer's *Thermal Physics* or Schroeder's *An Introduction to Thermal Physics*.

Homework: As in any physics class, the homework assignments are a vital part of this course; I simply do not believe you can learn physics just from sitting through lectures. So, problem sets will be distributed at regular intervals (typically on Tuesdays), and will usually be due a week after they are assigned. Each assignment will have a due date, *and late work will not get full credit.* If you have a conflict with the due date (pre-planned conference travel, time on an external experimental facility, etc.), let me know in advance and we will make arrangements.

Grading Policy: In addition to problem sets, there will be exams (a midterm and a final), and possibly a project-based component to your final grade. We will discuss this possibility both on the first day of class and later in the semester.

These various forms of assessment will combine to give your course grade as follows: Homework (50%), Midterm (20%), Project (10%), Final (20%). (With, possibly, the Project and Final components being combined).

As you can see: I value the time you spend on problem sets, and it's where I think a lot of the learning in this class happens!

References: This is a subject with a large number of available textbooks and wide disagreements about which one(s) to use. I will lean heavily on notes I have been writing over the last three years, Goldenfeld's *Lectures of Phase Transitions and the Renormalization Group*, and Sethna's *Entropy, Order Parameters, and Complexity.* I will post my lecture notes to Canvas at the start of the semester (and major revisions to them, if any, as the semester progresses) – you may find these a useful reference, but they will for obvious reasons closely track what we cover during lectures. Other texts that helped me when I was learning this subject include:

- Landau and Lifshitz, *Statistical Mechanics (Part 1)*
- Kardar, *Statistical Physics of Particles*
- Pathria *Statistical Mechanics*
- Huang, *Statistical Mechanics*
- Ma, *Statistical Mechanics*
- Chandler, *Introduction to Modern Statistical Mechanics*
- Zwanzig, *Nonequilibrium Statistical Mechanics*

I *strongly* encourage you to seek out one of these (or some other) text to see alternate views of the subject that may resonate with how you learn the material and will provide more context and background than my notes. Reading broadly, and discovering the difference between a good book to learn from and a good reference text, is a valuable skill for your research career, and I encourage you to start practicing!

Feedback: I will be actively seeking feedback from you during the semester, but please let me know if you have any suggestions or comments about the class. If you prefer to send anonymous feedback, feel free to email me from a temporary, disposable email address; just include "PHYS504" in the subject line and it won't get caught in my spam filter.

Communication: Most of our class will be organized through Canvas. For short communications *I prefer that you contact me via email with "PHYS 504" at the beginning of the subject line so that I see it.* I commit to responding to emails within 48 hours of receipt, and my intention is to respond faster than that most of the time. I will likely be slower on weekends.

Forms of address: I tend to be a fairly informal (and non-hierarchical) person when I communicate, both over email and in person. My preference is that you simply address me as "Daniel." If you are uncomfortable with this informal form of address, "Professor," "Prof. Sussman," or "Dr. Sussman" are all fine. "Dr. Daniel" is hilarious.

Similarly, I will by default address you by your full first name. If you have any other preference, or if I'm mispronouncing your name, just let me know! I believe people have the right to be called and addressed as they'd like; it seems like a pretty basic and straightforward way to show respect to each other. Oh, speaking of: if you're wondering, my pronouns are he/him/his.

Academic Honesty: I expect you to exhibit the level of integrity and honesty that being a productive member of the physics research community requires. During the course of my own work I draw inspiration, evidence, and ideas from the work of others, I argue and counter-argue with them, and I believe the scientific product that results is the better for this type of engagement.

I expect you to mirror this level of engagement with the material in this class. In practical terms, I encourage you to **collaborate, form study groups, and discuss** homework with each other, but **you must** write up solutions yourself, and those solutions must reflect your own understanding of the problem and not that of one of your peers. Just like I would never dream of using or discussing someone else's work in a paper without citing them, *if discussions with your classmates helped you with a problem set you should acknowledge that fact.*

You also **must not** simply seek out and use solutions to textbook problems (if they are assigned) from the internet, which would be a serious honor code violation. If you, as a student did in my first year here, submit one of my carefully constructed non-textbook problems to Chegg (or equivalent site) I will be very sad, and then I will refer you to the honor council.

Disability statement: As the instructor of this course I endeavor to provide an inclusive learning environment. I want every student to succeed. The Department of Accessibility Services (DAS) works with students who have disabilities to provide reasonable accommodations. It is your responsibility to request accommodations. In order to receive consideration for reasonable accommodations, you must register with the DAS. Accommodations cannot be retroactively applied so you need to contact DAS as early as possible and contact me as early as possible in the semester to discuss the plan for implementation of your accommodations.

For additional information about accessibility and accommodations, please contact the Department of Accessibility Services at (404) 727-9877 or accessibility@emory.edu.

Equal opportunity/non-discrimination statement: As the instructor of this class, I am committed to upholding Emory's principles and policies regarding equal opportunity and nondiscrimination. Emory University is dedicated to providing equal opportunities to all individuals regardless of race, color, religion, ethnic or national origin, gender, genetic information, age, disability, sexual orientation, gender identity, gender expression, and veteran's status. Please contact me with any questions or concerns related to these policies, which can be found here: http://policies.emory.edu/1.3

Course Outline: This timetable provides an overview of the material we'll cover, and when:

(lecture dates)	(Content)
	Part 1: *Introduction, thermodynamic descriptions, and emergent states of matter*
Jan 18	**Introduction:** microscopic and macroscopic descriptions of matter
Jan 23 & 25	**Thermodynamics** of bulk phases of matter: thermal equilibrium, functions of state, Maxwell Relations, etc
Jan 39, Feb 1 & 6	**Phase transitions, part 1:** Mean field condensation, corresponding states, critical points, and Landau's phenomenological theory.
Feb 8, 13, 15	**Phase transitions, part 2:** Correlation functions, critical exponents, and scaling
	Part 2: *Statistical descriptions of bulk phases of matter*
Feb 20, 22, & 27	**Probability:** Essentials of probability theory, and an information-centric view of entropy
Feb 29	**Kinetic theory:** Elements of ensemble theory
Mar 5	**Midterm Exam!**
Mar 7	**Classical statistical mechanics** Statistical basis of thermodynamics; various ensembles
Mar 12 & 14	[No Class: Spring break!]
Mar 19	**Classical statistical mechanics** continued
Mar 26	**Quantum statistical mechanics, part 1:** Quantum microstates, density matrices, quantum ensembles, and indistinguishability
	Part 3: *Statistical descriptions of phase transitions*
Mar 28 & Apr 2	**Quantum statistical mechanics, part 2:** Ideal quantum gases and Bose-Einstein condensation
Apr 9, 11, & 16	**Statistical mechanics of interacting systems:** Cumulant and cluster expansions, the van der Waals equation, classical statistical phase transitions.
Apr 18, 23, & 25	**Introduction to critical phenomena:** The Ising model and a simple view of the renormalization group approach
Week of May 6	Final Exam

While detailed, the above should be viewed as an extremely rough approximation. I fully expect us to drop, swap, or rearrange topics as the semester goes along, and the precise pace of the course will be tuned as required ("better to uncover a little, than to cover a lot," as Weisskopf is said to have said). In particular, I may want to expand the amount of time we have at the end of the semester to discuss the renormalization group, and may trim a few lectures early in the semester to accommodate that goal.