Physics 375: Thermal & Statistical Physics; TΘ 12:40PM-4:00PM; Zoom

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Instructor: Michael Lerner, CST 213, Phone: 727-LERNERM

Office Hours: M 9-11, Θ 9:00-11:00, 2:00-4:00 and by appointment.

Where: All meetings take place on Zoom: https://us02web.zoom.us/j/88190538447

Credits: This is a four-credit course. In normal times, this is fulfilled via four hours of in-person instruction per week over a 15-week semester. During a pandemic, we'll have three hours per week of synchronous instruction, three hours per week of recorded lectures, and several hours per week of interactions via online discussion forums.

Course goals

- Students will understand the basics of thermal physics: how do macroscopic quantities such as temperature relate to each other?
- Students will understand the statistical underpinnings of thermal physics from a molecular level, including foundational topics and modern formulations of the second "law" of thermodynamics.
- Students will understand and apply the concepts of statistical and thermal physics to a topic in their area of interest.
- Students will explore the wide range of applications of statistical mechanics by developing a Monte Carlo model to simulate and evaluate March Madness brackets or Pokemon Go battles.

Required Textbook: Schroeder, **Thermal Physics** It's extremely readable, and has a good selection of real-world problems.

Required Online Forums: Moodle, and piazza.com/earlham/spring2021/phys375 real-world problems.

Prerequisite Physics 345, modern physics.

Communication: My preferred mode of communication is email. I will check my email multiple times per day during the work week. If you have sent me an email and have not heard back from me within 24 hours (excluding weekends), you should email me again or drop by my office to ask your question in person. I cannot guarantee that I will regularly check my email on evenings or on weekends.

I expect that you will check your Earlham email at least once per day. That is, 24 hours after sending an email to the class, it is my expectation that all of you will have read that email. Emailed assignments, due dates, policy changes, and other course information carry the same weight as information contained in the syllabus.

Information relevant to the course will also be posted to the Moodle page. You are responsible for checking Moodle at the same frequency and with the same conditions applied to email communication.

Assignment	Number	Drop	Weight
Attendance/preparation/participation (including Piazza)	21	3	15
Daily homework	20	2	20
Weekly homework	6	1	20
Group work	13	2	15
Independent project	1	0	20
Final exam	1	0	10

Grading Policy Your grade in this class will be determined by a weighted combination of your scores from multiple categories. Within each category, each assignment is weighted equally. It is extremely hard to catch up on late work in normal times (usually things are late because students are busy, and people don't tend to get less busy!). This is especially true in a pandemic. So, rather than accept late work, I will drop a roughly a week worth of your lowest grades from most categories. If you have to turn things in late, my strong suggestion is that you prioritize getting your schedule back under control. Feel free to simply *not do* things that will not be graded. Especially if it helps you keep the rest of your life under control.

Extra Credit Throughout the course, several homework problems are explicitly marked as extra credit. The other opportunities are listed here. Extra credit will not be included in grade updates, but will be included when I calculate your final grade in the course.

- 0.5% extra credit for visiting me in my office hours in the first two weeks of class.
- 0.5% extra credit to the whole class if the entire class completes their course evaluations.
- 0.1% extra credit for the first person to point out any significant errors on tests or any assignment, up to a maximum of 1.0%. (Spelling errors and similar mistakes do not count as significant errors unless they significantly impede your ability to do the assignment)

Attendance/preparation/participation (including Piazza): Especially in a pandemic, attendance is (1) critical (2) sometimes hard to sustain. Attendance involves attending the synchronous Zoom lectures and watching the pre-recorded videos. During class, we will work on problems together and via groups in breakout rooms. This problem solving is a critical component of the class, and it is the main reason attendance is required. We all know that circumstances sometimes make it hard or impossible to attend, so I will drop your three lowest attendance and participation grades.

It is very important that you read the appropriate text assignments before coming to class. I will repeat and re-emphasize material from the book, but you'll find that you understand and internalize the material much better if the class discussion is your second exposure to the material. In this class in particular, there are a huge variety of applied problems that we'd love to discuss. The more you've read before class, the more we can delve into the new material in class. So, **You are required to post to the Piazza site by 9 PM the day before class on Mondays, Wednesday, and Fridays.**. Your post should include what you thought was the most interesting and important from the reading. You should mention any parts of teh reading that were particularly hard to understand. You can also comment to ask a question or answer someone else's question in lieu of mentioning the most interesting/important things. This counts for 5% of your overall grade.

Daily homework: I will assign a small number of easy and medium-difficulty problems after each MWF lecture. You are responsible for completing these problems and submitting them on Moodle as a PDF by the start of the next lecture. I will check these problems only for effort and completion, and the expectation is that each assignment will take approximately one hour on average. The lowest 2 daily homework assignments will be dropped.

If it is apparent you attempted all of the problems and your work is clear, you will receive full credit, even if you got the wrong answer. If you are unable to complete a problem, you are expected to provide reflection on why you were unable to complete the problem (e.g., you know that you need to use a thermodynamic identity, but were unable to find a solution using these methods). Providing these reflective comments on unfinished problems will help you improve your problem-solving process, and will save you points.

Weekly Homework Assignments: Every week on Monday, you will be assigned a homework consisting of medium and high-difficulty problems that will take more time to work through. You are responsible for submitting these problems on Moodle as a PDF by the start of lecture on the following Monday. These assignments will be graded for correctness and are the closest we will get to quizzes and tests this term, other than the Final Exam. There are a few connected groups of problems that stretch across multiple chapters, so you will want to keep your solutions from previous weeks in case they help you in future weeks. The lowest 1 weekly homework assignment will drop from your grade. Each problem will be graded on a 5-point scale whose details are shown below.

5 Correct or close to correct, with maybe a small arithmetic error

4 Correct reasoning for the solution, with maybe an algebraic error

3 Small mistake in the reasoning for the solution, but with correct follow-through or analysis

2 Large mistake (or many small ones) in the reasoning, or significantly incomplete problems

1 Some non-trivial solution was attempted

0 No attempt was made. **You get 20% for simply writing down SOMETHING.**

Group Work: You will be broken into groups of 2 or 3 that will be chosen by the instructor. Your group is expected to find two times to meet each week, for a total of around one hour each time. In your meetings, you will work on the assigned group work problems that are posted to Moodle. These assignments are intended to give you practice with the material in an environment where you can help each other learn.

These assignments will be graded for effort and completion. If you show up to the meeting with your group, give your best effort, and are able to complete the problems, then you should receive full credit.

Each week, one group work assignment will be posted on Monday and will be due by the start of class on Friday, and the second group work assignment will be posted on Wednesday and will be due by the start of class the following Monday. Though you are expected to work together on the problems, each of you is responsible for submitting your own solution as a PDF on Moodle. Some level of similarity between submissions is allowed because these are group assignments, but you are not allowed to submit the same file for all three of you. In short, work together to determine the correct approach, then you each write your own solution

Independent project: The applications of modern statistical mechanics are so broad that we cannot hope to cover even a reasonable sampling of them in a single course. However, I don't want you to miss out on the parts that happen to be most interesting to you. Therefore, you'll each pick either an interesting problem to model or an interesting technique to learn. You'll write a short paper and present the results to the class. You'll be expected to start on this halfway through the semester, and we'll discuss it in more detail at that point. Sethna's book provides a wealth of such problems, and I'm certainly available to provide background material that you may be missing if needed.

The times of 13:00-14:00 on Tuesdays and Thursdays are reserved for project time. I will introduce the project during this time slot on Thursday of Week 1, and we'll discuss the assighment in more detail at that point. For weeks 2-6, each of you will have a 30-minute appointment with me once a week during this time slot to discuss your progress and any questions you have in a one-on-one environment. During Week 7, each of you will make a presentation about your project to the rest of the class, and attending the presentations of other students is part of your grade on the project.

Two rough drafts of your project will be due, **and the rough drafts will be worth 5% of your course grade**. Given the timing of the course, the first rough draft is allowed to be quite rough, but serves to ensure that you're making good progress, have some things written down, and know what you need to do to succeed.

Topics are largely at your discretion, but may include

- Information Theory and Statistical Mechanics
- Foundations of the Zeroth and Second "Laws" of thermodynamics
- Coarsening
- Time correlation functions
- Annealing
- Statistical Mechanics/Thermodynamics of small systems
- Further work with Monte Carlo simulations
- Thermal ratchets, theory and practice
- Order parameters and critical exponents (often an in-class topic!, see Sethna)
- Anything in Schroeder that we do not cover

Final Exam: The weekly assignments serve effectively as small-stakes quizzes/exams, and the final exam will be our only pure test in the class. We will have a clear discussion and review of topics before the exam.

Academic Integrity: http://www.earlham.edu/policies-and-handbooks/community/student-code-of-conduct/

Workload Expectations: Under the condensed schedule Earlham is currently using, workload expectations for each 4-credit class are at least 20 hours per week per class, including time spent in lecture. Each week, you will spend about 6 hours in lecture (synchronous and asynchronous), 2 hours on group work assignments, 3 hours on daily homework assignments, 3 hours on weekly homework assignments, 3 hours on your independent project, and 3 hours reading the textbok.

Please note that "at least 20 hours per week" is an average across students and across weeks. Some weeks, you'll spend more. Some weeks, you'll spend less. My aim is to keep the average workload around 20 hours per week. If, however, you find yourself needing to spend significantly more than 20 hours in a week, please let me know ASAP so that I can quickly correct things.

Books and Resources

Additional Textbooks

Gould and Tobochnik, Statistical and Thermal Physics It was a close decision between this and Schroeder. I went with Schroeder for several reasons, but this book is free and good. http://www.compadre.org/stp/

An Introduction to Statistical Mechanics and Thermodynamics An extremely well-written modern introduction. Paced a bit faster than we'll go, this would be a good intro grad text, or 475-level text.

Sethna, Entropy, Order Parameters, and Complexity This is a freely-available, modern, advanced, applied statistical mechanics textbook. Its main strengths include the broad range of problems (statistical mechanics, in its modern form, is an extremely broad, applied subject) and the extremely up-to-date content. You can download it from Sethna's website (http://www.lassp.cornell.edu/sethna/). On the other hand, it has a reputation as a book that's "fantastic if you already know the subject matter" but difficult to learn from on your own at the advanced undergraduate level. The plan is to supplement Schroeder with bits and pieces of Sethna. Please start pawing through Sethna ASAP so that you can pick out interesting topics that we may use.

Required Software

The Anaconda Python Distribution We'll do several computational exercises throughout the class. If you have a laptop, please install the Anaconda Python Distribution. If you do not have a laptop, please contact me ASAP. http://continuum.io/downloads

Recommended Textbooks

Kusse and Westwig, Mathematical Physics This text is extremely well written. It's a good reference for the math you may have forgotten.

Schey, div grad curl and all that This is an extremely conversational introduction to/refresher on vector calculus.

Bridging the Vector Calculus Gap This is a fantastic resource for vector calculus that focuses on actually using the material in practice, rather than just learning it in a mathematical context. http://www.math.oregonstate.edu/bridge/

Styer, Statistical Mechanics I just found this recently, but it looks like a nice attempt at integrating modern material into a Stat Mech course. Note that it is not yet a complete book. http://www.oberlin.edu/physics/dstyer/StatMech/book.pdf

Labs Statistical Mechanics is one of the most active areas of modern physics research. In non-pandemic times, we supplement the class with three labs. During a pandemic, we will do at least two of these as group projects.

Diffusion Statistical mechanics is also concerned with predicting diffusion constants of grains of pollen floating on water (think Einstein's famous 1905 paper) or proteins moving about in cell membranes. We will team up with Adam Hoppe at South Dakota State University to use a web-controlled TIRF (total internal reflection) microscope to measure the diffusion constant of individual lipids (actually, we'll be looking at quantum dots attached to lipids) in cell membranes. This will give us a way of calculating Boltzmann's constant. This lab is also of interest to biochemistry students, so I've invited several of them to watch and perhaps participate.

Non-equilibrium Statistical Mechanics Think for a minute about moving your hand around under water. If you move your hand infinitely slowly (called "quasistatically"), you would say that the work required to move your hand from one place (state A) to another (state B) is equal to the free energy difference between A and B. What if you move your hand quickly? Until very recently (1997), the most definite general answer we could give is that the work required would be greater than or equal to the free energy difference (you'd burn up some energy in friction), but performing several non-equilibrium processes like this would not be able to tell you exactly the free energy difference between A and B. In this lab, we will study one of the most shocking results of statistical mechanics, the Jarzynski equality, which allows us to average *nonequilibrium* processes to determine the exact energy difference between two *equilibrium* states. This lab involves computer simulations of proteins, and is normally done in two parts, separated by several weeks.

Entropy of Unknotting In this lab, we will model the unknotting of a small beaded chain via random walks, and make both quantitative and qualitative measurements of the entropy involved of unknotting.

The entropy of unkotting is a self-directed lab.

Course Outline

My plan is to move fairly quickly through the first part of the book, assuming it's mostly review. Later sections are up for discussion: should we spend more time on heat engines, or more time on statistical mechanics and applications?

In any case, we'll be doing several computational simulations throughout. In order to make things standard, we'll do them all in Python.

In addition to the focus on simulation, we'll focus more on statistical mechanics than on thermodynamics, so we will skip straight from Chapter 3 to Chapter 6, giving us time to set up Monte Carlo simulations of March Madness. The syllabus is fairly flexible, but we need to get to MD simulations *before* March, and we need to get through diffusion before the lab is scheduled. **IMPORTANT NOTE:** This year, we can replace March Madness with Pokemon Go if the class wants.

I expect this class to be a lot of work, and an enormous amount of fun.

Table 1: Course Schedule (D = daily homework, W = weekly homework, G = group work

Wk	Date	Read	Topics	In-class probs	Due	Project time
1	Feb 1	1.1-1.4	What is Statistical Physics? Equilibrium; ideal gas; equipartition; heat and work	4, 14, 18	n/a	n/a
1	Feb 3	1.5-1.7	Compressive work; Heat capacities; Rates	37, 45	D1	n/a
1	Feb 5	2.1-2.3	Two-State Systems; Einstein model of a solid; Interacting systems		D2, G1	Intro
2	Feb 8	2.4-2.5	Large Systems; Ideal Gas	16	D3, G2, W1	Proposals
2	Feb 10	2.6, 3.1	ENTROPY!; Temperature		D4	Proposals
2	Feb 12	3.2, 3.3	Entropy and Heat; Paramagnetism		D5, G3	Proposals
3	Feb 15	3.4, 3.5, 3.6	Mechanical Equilibrium and Pressure; Diffusive Equilibrium and Chemical Potential		D6, G4, W2	Check-in 1
3	Feb 17	6.1-6.2	The Boltzmann Factor, Average values		D7	Check-in 1
3	Feb 19	8.2	Ising models		D8, G5	Check-in 1
4	Feb 22	8.2, Ising.pdf	More about MC; MC Pi estimation, Monte Carlo Simulation Coding; March Madness.		D9, G6, W3	Check-in 2
4	Feb 24	4.1-4.4	Heat Engines and Refrigerators (4.1-4.2 are much more important than 4.3-4.4)		D10	Check-in 2
4	Feb 26	1.7	Diffusion, rates		D11, G7	Check-in 2
5	Mar 1	5.1-5.2	Free energy available as work; Free Energy as a force towards equilibrium	7	D12, G8, W4	Rough draft 1
5	Mar 3	5.3	Phase Transformations of Pure Substances		D13	Rough draft 1
5	Mar 5	5.4	Phase Transitions of Mixtures		D14, G9	Rough draft 1
6	Mar 8	5.5, 6.3-6.4	Dilute Solutions; Equipartition; Maxwell Speed Distribution		D15, G10, W5	Draft 2
6	Mar 10	6.5-6.7	Partition Functions, Free Energy and Composite Systems Also catch up		D16	Draft 2
6	Mar 12	PDFs	The new fluctuation theorems		D17, G11	Draft 2
7	Mar 15	7.1-7.2	The Gibbs Factor; Bosons and Fermions		D18, G12, W6	Present
7	Mar 17	7.3	Degenerate Fermi Gases, Density of States		D19	Present
7	Mar 19	7.5-7.6	Debye Theory; Bose-Einstein Condensation		D20, G13	Present
8	Mar 22	FINAL EXAM, Tuesday, March 23 8:00-10:00				n/a