PHYS 425: Statistical and Thermal Physics, Fall 2016

Logistical details

Meets: 1:00pm – 2:15pm, T-Th, BRK 103
Instructor: Prof. Douglas Natelson (BRK 301, x3214, natelson@rice.edu)
Grader: TBD
Office hours: 1:00pm – 3:00pm, Mon. For additional time, my door is open, but you should email ahead to make sure that I'm around.
Webpage: https://canvas.rice.edu/courses/2195

About the course

As the name implies, statistical and thermal physics deals with the use of statistical methods to understand the behavior of complex, many-particle systems; in particular, this machinery was originally developed to understand quantitatively the ideas of temperature, heat flow, and irreversibility. Why do we need a statistical approach? You already know that general interacting problems involving more than two particles seldom have exact solutions. On the other hand, the air in this room (on the order of 10^{24} particles) seems to be in a well-defined "equilibrium state" that we're accustomed to characterizing by a small number of parameters (temperature, pressure, volume). Despite the fact that we can't keep track of the movements of each particle individually, we can still make predictions about some sort of average behavior of the whole set of particles. Further observations tell us that fluctuations away from the equilibrium state seem to be unnoticeably small, despite the fact that there's nothing in the microscopic laws obeyed by each particle to prevent all the gas molecules from ending up in the upper half of the room at the same time. Similarly, you know from experience that "heat energy" flows from hot objects to cold objects spontaneously, and never the reverse. Statistical and thermal physics aims to examine the properties of "large" systems, and explain observations like those described above.

The machinery of statistical physics is extremely powerful because of its generality. The same formalism used to understand the classical ideal gas can be applied to understanding such highly quantum mechanical problems as electrons in metals, black body radiation, Bose-Einstein condensation, and the behavior of ferromagnets.

Statistical physics and the phenomena it explains are the prime example of *emergent properties*, rich and complex properties that occur in systems with many degrees of freedom, even when those microscopic degrees of freedom obey simple rules (*i.e.* Newton's laws). The phrase that best describes this is "More is different", the title of an article by P.W. Anderson (Nobel 1977) (*Science* **177**, 393 (1972)). The fact that the collective properties of matter are so amazing and so difficult to deduce *a priori* from the underlying simple rules is the reason statistical (and condensed matter) physics continues to be a hot topic of current research.

By the end of this course, you should be able to answer questions like:

- What is temperature, and why does energy flow from high temperature to low temperature bodies?

- What is the difference between heat and work?
- Why can't I cool my house by leaving the refrigerator door open?
- Why is the air thinner on top of Mt. Everest?
- Why do you asphyxiate if you breath too much carbon monoxide?
- Why are metals stable? Why don't white dwarf stars collapse? Why do gases of lithium-6 and lithium-7 behave very differently at low temperatures? (These three share a common answer.)
- Why does outer space glow like it has a temperature of 2.7 K?
- What is the Ising model? What do planar ferromagnets, superfluids, and liquid crystals have in common?

Course objectives and learning outcomes

By the end of this course, students will be able to:

- Formulate the basic principles of statistical mechanics, including the definitions of entropy and the partition function, the importance of distinguishability, the thermodynamic ensembles, and thermodynamic potentials.
- Define intensive and extensive thermodynamic parameters, and manipulate thermodynamic potentials and their derivatives (e.g. the Maxwell relations) to find the relationship between thermodynamic variables, including equations of state.
- Use the laws of thermodynamics as they pertain to heat engines, heat pumps, and related systems.
- Derive the ideal gas law and the van der Waals equation of state.
- Understand and use the Maxwell distribution, as well as the Fermi-Dirac and Bose-Einstein distributions.
- Explain degenerate gases, including the Fermi gas and the Bose-Einstein condensation.
- Demonstrate knowledge of the properties of phonons and photon gases (black body radiation).

Required text and materials

Textbook: *Fundamentals of Statistical and Thermal Physics*, by F. Reif. Note that I will supplement this book substantially with additional material from a variety of sources – see below. Feel free to purchase a used copy of this book. I chose it because it has nice explanations of some key concepts, even though it lacks newer material.

Exams, papers, and grading

The course will consist of two 80-minute lectures per week. There will be weekly problem sets, given out on **Thursday** and due the following **Thursday** at the beginning of class. Late work will only be accepted if due to illness or emergency - I want a legitimate excuse.

Understanding the material is at least as important as getting a numerically or formulaically correct answer to the problem. If your reasoning isn't obvious, please write little explanations of what you're doing and why, so partial credit can be assigned in a reasonable way.

Every week I will also hand out additional problems in addition to those that make up the problem set. These problems will collectively be known as the **question bank**, and will provide additional practice for you as the semester progresses. You don't have to do these, and solutions to them will not be handed out. However, I will tell you that approximately 1/3 of the final exam will be problems from the question bank. You probably don't want to leave all these for the end of the semester....

The problem sets are not pledged. **I encourage you to discuss the problem sets and question bank material with each other.** You may give each other guidance and advice on problem solving approaches, and you may compare solutions to check your work. However, you may not copy solutions from another student, and the problem sets you submit must be entirely your own work and your own words. If you used a book, you must cite the relevant material. If you collaborated strongly with other students, cite them as well - this is intellectual honesty.

There will be two exams in the course – these will be take-home, pledged, open-notes (yours only!), open-*Reif-only* tests. The overall grading will be:

40% homework
30% first exam (takehome, handed out Thu. September 28, due back Thu. October 5)
30% final exam (also takehome, scheduling TBA.)

Course Outline

A detailed breakdown as well as a schedule of classes will be available on canvas, and will be updated as the semester progresses. We may not get to everything, but I intend to try.

I. Overview and introduction

II. A bit of probability and necessary mathematics
 Probability, distributions, counting, continuous vs discrete variables, partial derivatives

III. Basics of classical thermodynamics
 States, macroscopic vs. microscopic, "heat" and "work",
 energy, entropy, equilibrium, laws of thermodynamics

IV. More classical thermodynamics
 Equations of state, thermodynamic potentials, temperature, pressure,
 chemical potential, thermodynamic processes (engines, refrigerators),
 Maxwell relations, phase equilibria.

V. Statistical mechanics - the formalism.
 Counting states, ensembles (microcanonical, canonical, grand canonical),
 the partition function and its applications, fluctuations from equilibrium,
 equipartition.

VI. Magnetic systems
 Paramagnetism, ferromagnetism, adiabatic cooling, susceptibility & correlations,
 mean field theory, Ising model.

VII. Gases

Classical ideal gas (Maxwell distribution), Bose gas (mode-counting, photons, phonons, BEC), Fermi gas (degeneracy pressure, heat capacity), van der Waals and "real" gases.

VIII. Phase transitions

Landau theory, scaling, renormalization, solution to 1D Ising

Rice Honor Code

In this course, all students will be held to the standards of the Rice Honor Code, a code that you pledged to honor when you matriculated at this institution. If you are unfamiliar with the details of this code and how it is administered, you should consult the Honor System Handbook at http://honor.rice.edu/honor-system-handbook/. This handbook outlines the University's expectations for the integrity of your academic work, the procedures for resolving alleged violations of those expectations, and the rights and responsibilities of students and faculty members throughout the process. I take the Honor Code seriously, and I expect you to do the same. If you have any questions about this, raise them with me at the beginning of the course.

Disability support services

If you have a documented disability or other condition that may affect academic performance you should: 1) make sure this documentation is on file with Disability Support Services (Allen Center, Room 111 / adarice@rice.edu / x5841) to determine the accommodations you need; and 2) talk with me to discuss your accommodation needs.

References texts: (* = on reserve in Fondren)

- S. J. Blundell and K. M. Blundell. *Concepts in Thermal Physics*, Oxford University. I just found this one over the summer, and it's very good - I might actually switch the course to this next year.
- D.V. Schroeder. *Introduction to Thermal Physics*, Addison Wesley. This was my runner-up for the course textbook. More modern, but not as in depth in some places.*
- H.C. Callen. *Thermodynamics and an Introduction to Thermostatistics*, 2nd ed., Wiley. The gold standard treatment of classical thermodynamics, though the statistical mechanics portion is tacked on.*
- C. Kittel and H. Kroemer. *Thermal Physics*, 2nd ed., Freeman. Another standard, this one more on the statistical physics side. It uses rather nonstandard notation in places, but has great problems.*
- H. Gould and J. Tobochnik. *Statistical and Thermal Physics with Computer Applications*. Online version here. Lots of exercises, developed w/ physics pedagogy in mind.
- R. Baierlein. *Thermal Physics*, Cambridge University. Haven't used it; supposed to be a decent undergrad book.
- D.L. Goodstein. *States of Matter*, Dover. Excellent, but somewhere between a stat mech and a solid state text. It's very readable, and a very good deal since it's a Dover book.
- L.D. Landau and E.M. Lifshitz. *Statistical Physics Part 1*, 3rd ed., Pergamon. A classic. Very dense, borderline graduate level.

- R.P. Feynman. *Statistical Mechanics: a set of lectures*, Addison Wesley. Another classic. Graduate level, good for understanding the density matrix.
- P.M. Chaikin and T.C. Lubensky. *Principles of Condensed Matter Physics*. Cambridge University. Has very good chapters on phase transitions. Avail. in paperback, so it's not absurdly expensive.

Updated: July 15, 2017