

Physics PHY 4523, spring semester 2009
STATISTICAL MECHANICS AND THERMODYNAMICS

Reductionist dogma asserts that once one understands the fundamental laws governing particles (*e.g.*, $\mathbf{F} = m\mathbf{a}$ or Schrödinger's equation), one can simply integrate those laws to predict the behavior of any system to which they apply. This is a big lie. Consider a gas of molecules confined to a box; to make the example even simpler, imagine that the gas molecules do not interact among themselves, so that the only force encountered is at the walls, where we can assume specular reflection. Thus the motion of any given molecule is trivial: given the initial position and velocity of a molecule, it is easy to calculate its position and velocity at any future time. The difficulty is that there are 10^{23} such molecules in the box; the logbook of initial positions and velocities (which one could never hope to measure) would not fit on all the hard drives of all the computer disks in the world. Even if one could do the calculations, the results would be another set of 6×10^{23} numbers, and it is hard to imagine how one could use them in that form.

Statistical mechanics and thermodynamics are concerned with how to extract *useful* information out of systems with large numbers of degrees of freedom. Of course, everyone is already familiar with the example of the ideal classical gas; the “solution” to the problem of how to deal with 6×10^{23} degrees of freedom reduces these to just three “state” variables: volume, pressure, and temperature. The somewhat awkward title of the course reflects two differing historical approaches. Traditional thermodynamics is a beautiful, self-contained gem based on a small number of axioms governing the state variables; its development in the nineteenth century preceded the modern atomistic understanding of matter. In contrast, statistical mechanics begins with the quantum picture of nature and derives the axioms of thermodynamics, although its application is actually broader.

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MEETING TIMES: Mondays, Wednesdays, and Fridays, 12:55–13:45, Physics Room 118.
OFFICE HOURS to be announced; I am also usually available during the day, evenings, and weekends.

PREREQUISITES

Some knowledge of quantum mechanics, at least what's covered in Modern Physics, is assumed: you need to know about the energy levels of the square well and of the hydrogen atom and to know the Schrödinger equation and the difference between Fermions and Bosons. Problem-solving experience at the level of the intermediate physics courses—any one of Quantum Mechanics, Electricity and Magnetism I, or Classical Mechanics I will suffice—is essential. This class is a prerequisite for entry to physics graduate school and for specific courses in materials science, physical chemistry, solid-state physics, plasma physics, lasers, electrical or chemical engineering, and quantum computer science, among other subjects.

REQUIRED TEXTBOOKS

Prices are estimated. “Required” means that I expect students to read these two books and will assign problems from them; of course, the books will be available on reserve at the library.

- C. Kittel and H. Kroemer, *Thermal Physics* (2nd ed. with corrections as of 1994), Freeman, ISBN 0-7167-1088-9. Retail price \$134. Kittel is a solid-state theorist, best known as the first “K” in the RKKY effect. Kroemer was awarded the Nobel Prize in Physics in 2000, in part for his work in the invention of the integrated circuit. A quick survey of other universities suggests it is the most popular book for this course.
- Enrico Fermi, *Thermodynamics*, Dover, ISBN 0-486-60361-X. Retail price \$11. One of the giants of experimental and theoretical physics, Fermi was awarded the Nobel Prize in Physics in 1938. This book presents some of the elementary results of the course from a traditional thermodynamic point of view as opposed to the statistical viewpoint of Kittel and Kroemer.

SUPPLEMENT RECOMMENDED FOR PURCHASE

A copy of this book should be available on reserve at the library.

- F. Mandl, *Statistical Physics* (second edition, 1988), Wiley, ISBN 0-471-91533-5. Retail price \$65. I recommend this book for its clear explanations and worked problems, but it doesn’t go through as many applications as Kittel and Kroemer. For magnetism, note that this text uses MKS instead of the customary Gaussian units.

TENTATIVE COURSE OUTLINE

My plan is mostly to follow the treatment in Kittel and Kroemer, using lectures to add context as well as to clarify some of the calculations.¹ The following is subject to change.

- week of 1/5 What is temperature? Review Physics I. Counting microstates.
- 1/12 Ensemble averages; statistical definitions of entropy, temperature; laws of thermodynamics; Canonical ensemble, partition function, Boltzmann factor.
 - 1/19 Birthday of the Rev. Dr. Martin Luther King, Jr. (observed); the fundamental thermodynamic identity; Helmholtz free energy; classical ideal gas.
 - 1/26 Some applications: blackbody radiation, electrical noise, Debye theory of phonons in solids.
 - 2/2 Gibbs (grand canonical) ensemble and the chemical potential.
 - 2/9 Fermi-Dirac, Bose-Einstein, and Maxwell-Boltzmann distributions; more on the ideal gas.
 - 2/16 The degenerate Fermi gas and metals; Bose-Einstein condensation.
 - 2/23 Heat and work; thermodynamic definition of entropy; heat engines; the Carnot cycle.
 - 3/2 Review and catchup; **MIDTERM EXAMINATION 6 MARCH.**
 - 3/9 Gibbs free energy and chemistry.
 - 3/16 March meeting of the American Physical Society in Pittsburgh: **no classes.**
 - 3/23 Phase transitions; the van-der-Waals gas; mean-field treatment of ferromagnetism.
 - 3/30 Binary mixtures and phase equilibrium.
 - 4/6 Cryogenics, or how to make things really impressively cold.
 - 4/13 Viscosity; transport (Boltzmann equation).
 - 4/20 The modern theory of critical phenomena and the Renormalization Group; catch-up and review.
- **FINAL EXAMINATION FRIDAY 1 MAY 12:30–2:30 P.M. (12:30–14:30)**

We are not planning to cover chapter 13 of Kittel and Kroemer on semiconductors, as this topic is treated in detail in the course on solid-state physics, nor much of chapter 15. If we run short on time, we may leave

¹ Professors often end up following the outlines of textbooks. It isn’t that we’re not clever enough to come up with our own but rather because students find it helpful to be able to read the sections of a book in order.

off the last few topics in the outline. If we have extra time, and if the class is so inclined, I have a list of more modern topics not covered in the textbooks, including density matrices, computational methods (*e.g.*, Metropolis), Onsager's solution of the two-dimensional Ising model, transfer matrices, Einstein's treatment of Brownian motion, and Shannon entropy and Fisher information.

HOMEWORK

Homework assignments will be handed out most Mondays, usually to be collected two Wednesdays following. (Think of each as really due Monday a week after it has been assigned, but I'll accept it on Wednesday.) The homework is the most important part of the course; do not skip it! Each week's assignment will also suggest relevant readings in the textbooks. Homework will count for 40% of the final grade. **You must list any sources (other than Kittel and Kroemer) you used in preparing your homework. By turning in any assignment, you certify that it represents your own effort. See policy below on cooperation, collaboration, and cheating.**

EXAMINATIONS

The midterm examination on 6 March will count for 25% of the grade, the final examination on 1 May for 35%. If you know you cannot make one of the examinations, you must tell me as soon as possible in advance. Plan to arrive on campus early on examination days.

COOPERATION, COLLABORATION, AND CHEATING

Students are encouraged to discuss problem-solving methods *after* each has attempted the problems. Research and my own experience have shown that the most common reason for a student dropping out of physics is the belief that he or she needs to do all the work alone. On the other hand, you should first try each problem. Then when you get together with your colleagues, you will find each stuck at a different place, and together you will get unstuck. While the instructor will always try to help, you will find the most valuable resource in other students.

Getting unstuck is very different from copying a solution. For example, it is reasonable for a student who has set up the problem but is having trouble evaluating an integral to ask a colleague how she evaluated the integral or for two students whose answers differ by a factor of two to compare notes to figure out where one of them might have gone wrong. It is quite another matter for Bill to copy Mary's solution (or mine from a previous year).

Please read the policy on integrity of scholarship in the general catalogue. Unfortunately, I have seen violations of this policy in my past classes. It is really very easy for me to detect cheating, and any confirmed case **will result in a grade of FF** in the course and could result in expulsion from the university.

Many of the homework exercises will come out of Kittel and Kroemer, and a note in the preface indicates that a solutions manual exists. You are not to consult this or any other solutions manual, any previous year's homework, or any other source of solutions, but you may consult other textbooks, which you should list on your homework solutions (see above). In case of any question on the policy, please e-mail me.

ADDITIONAL BOOKS (roughly in order of difficulty, some on reserve)

Most of these books aim at a level comparable to this course's, while the introductory chapters of the ones toward the end may be useful for review. Some of these books are on reserve in the library. In case you're interested in purchasing reference books, note that Dover books are inexpensive.

- Ambegaokar, *Reasoning about luck: probability and its uses in physics*, Cambridge, 1996. This intelligently and eloquently written slim book is aimed at liberal-arts majors with no mathematical or scientific background beyond high-school algebra and covers elements of statistics, mechanics, thermodynamics, and quantum mechanics.
- Feynman, *Lectures on Physics vol. I*, Addison-Wesley. Chapters 39-46 are most relevant to this course. Any time I think I understand something in elementary physics, I come back to Feynman for new insight. Feynman was awarded the 1965 Nobel Prize in Physics for his work in quantum electrodynamics; he also contributed to the statistical mechanics of superfluid helium.
- Baierlein, *Thermal Physics*, Cambridge, 1999. Slightly more modern than Kittel and Kroemer (includes an elementary development of critical phenomena). (MKS units)

- Schroeder, *An Introduction to Thermal Physics*, Addison-Wesley, 2000. This recent text begins with the thermodynamic definition of entropy, introducing the statistical interpretation a little later. (MKS units)
- Pippard, *The Elements of Classical Thermodynamics*, Cambridge, 1963. Similar to Fermi's book, somewhat more sophisticated, this book takes the completely traditional thermodynamic approach without so much as a mention of statistical mechanics. Recently reprinted.
- Reif, *Fundamentals of Statistical and Thermal Physics*, McGraw Hill, 1965. This is the second most popular undergraduate textbook, after Kittel and Kroemer's. Reif writes more elegantly, and he takes more care with subtle mathematical points, for example, in the enumeration of microstates. Finally, I think the arguments become perhaps too careful for an introductory text, as the reader encountering ideas for the first time may not see clearly which are the ideas and which the subtleties.
- Chandler, *Introduction to Modern Statistical Mechanics*, Oxford, 1987. Concise textbook with a mixture of elementary and difficult topics and problems, aimed at theoretical physical chemists. This was one of two texts in graduate Statistical Mechanics, PHY 6536, in fall 2007.
- Schrödinger, *Statistical Thermodynamics*, Dover, 1952, 1989. Notes from a set of lectures on the derivation of thermodynamics from quantum statistical mechanics. It is fascinating to see how an inventor of quantum mechanics (Nobel prize in physics, 1933) thought about these questions not long after they had first been resolved. The book assumes perhaps a little more familiarity with the ideas than at first it seems.
- Greiner, Neise, and Stoeker, *Thermodynamics and Statistical Mechanics* (transl. Rischke), Springer-Verlag, 1987, 1995. Introduces entropy thermodynamically first.
- Hecht, *Statistical Thermodynamics and Kinetic Theory*, Dover, 1990, 1998. Good text, a little formal in some places. It can be used as a textbook for graduate students in physical chemistry or for undergraduates who are already familiar with the fundamentals. I might consider this as a textbook (in conjunction with Fermi) in a future year.
- Yeomans, *Statistical Mechanics of Phase Transitions*, Oxford, 1992. This will be a useful reference when we discuss critical phenomena. Yeomans was my postdoctoral supervisor. If we had two semesters for the undergraduate course, I would use this as the primary text for part of the year.
- Goodstein, *States of Matter*, Dover, 1975, 1985. This is a graduate text, but the first chapter contains thorough discussions of thermodynamics and statistical mechanics. It will make good sense as a review once you have seen the concepts a first time.
- Thompson, *Classical Equilibrium Statistical Mechanics*, Oxford, 1988. Good advanced text. As with Goodstein, you will appreciate the first two chapters after you've spent a couple of months with the more elementary books. Includes many worked problems.
- Pathria, *Statistical Mechanics*, Pergamon, 1972. Similar to Landau and Lifshitz.
- Landau and Lifshitz, *Statistical Physics*, 3rd. ed., Part 1 (transl. Sykes and Kearsley), Pergamon, 1980. This is the classic graduate textbook. Most graduate students in theoretical physics will own the whole set by Landau and Lifshitz. Landau was awarded the Nobel Prize in Physics in 1962 for his work in solid-state physics (*e.g.*, his theory of Fermi liquids) and the physics of superfluid helium.
- Plischke and Bergersen, *Equilibrium Statistical Physics*, 3rd. ed., World Scientific, 2006. The title is misleading, as the book covers a variety of non-equilibrium topics relating to diffusion. Some sections give quite nice treatments of both standard and unusual topics; others serve as barely more than outlines of published work. Many of the problems are quite hard. This was one of two texts used in graduate statistical mechanics, PHY 6536, in fall 2007.

I could recommend numerous additional advanced textbooks and treatises on particular aspects of statistical mechanics.

OFFICIAL NOTICES IN ACCORDANCE WITH COLLEGE AND DEPARTMENT POLICY

You may give away notes for free but may not sell them or tapes. Students who will miss a class meeting due to a planned religious observance are requested to inform the instructor, in writing, by the second class meeting. Please let me know if you require any accommodation due to physical disability or injury. Any presentation as one's own work of material copied from elsewhere constitutes plagiarism and could result in expulsion from the university.