Physics 119a: Thermodynamics and Statistical Mechanics

Fall 2007

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Thermodynamics and Statistical Mechanics

Thermodynamics and statistical mechanics are two closely related subjects of remarkable power and beauty. We use the term "thermal physics" to encompass them both. Thermal physics deals with energy and how it is stored and transferred in macroscopic systems. *Thermodynamics* treats phenomena from a purely macroscopic point of view: it makes no reference to atoms, molecules, or their properties. In one sense, this is a limitation, but it is also a strength, because it means that the framework of thermodynamics is extremely general and powerful. *Statistical mechanics*, on the other hand, provides techniques and insights that are grounded in the microscopic properties and of matter. It provides crucial links between the microscopic and macroscopic behavior.

Thermal physics has an extraordinary degree of relevance not only to modern physics but also to key issues confronting society. Here are just a few examples of phenomena where the techniques of thermal physics are important:

- Analysis of the Big Bang and the evolution of the universe: the cosmic microwave background (CMB) radiation has a thermal origin, and its properties provide some of the most important clues to the events occuring in the early universe.
- Behavior of matter at low temperature: at low temperature, the quantum nature of matter can become manifest in amazing ways, such as in the phenomena of superconductivity and superfluidity. Thermal physics analyses are very important in these topics.
- Impact of energy usage on global climate and ecological systems (e.g., "global warming"). This is a really important application!
- Energy resources: historically, thermodynamics got much of its start when people tried to analyze and improve the performance of steam engines. Today, thermal physics is very relevant to many issues related to energy production and a large number of industrial processes.

- Analysis of chemical reactions and biological systems. This is a vast area with many applications of thermal physics.
- Astrophysics: properties of stars and black holes!
- Condensed matter physics: this is a huge area, and thermal physics plays an important role in the understanding many systems of interest. For example, the electrons in a semiconductor behave like a quantum gas.
- Noise in electronics: part of the noise in electronic devices has a thermal origin, so thermodynamics is relevant in the design of low-noise circuits.
- Information theory and computing: many of the concepts of thermal physics are relevant to information transfer and to the understanding the ultimate performance of computers.

You could almost write a history of civilization from the perspective of how people have been able to control and utilize termperature and energy!

A Note on Teaching Thermodynamics and Statistical Mechanics

Thermodynamics and Statistical Physics can be taught from several different points of view. Some people like to keep the two approaches entirely separate, which tends to emphasize the power and generality of thermodynamics. Others like the deep insights from Statistical Mechanics, and they tend to downplay the viewpoint of Thermodynamics. Still others like to mix the two subjects together without any clear distinction at all. Some people have very strong feelings on how the subject ought to be taught, and there are big arguments about how best to teach it.

The textbooks by Baierlein and Schroeder are from the "modern school," which mixes Thermodynamics and Statistical Mechanics without making much of a distinction between them. Although I like both books, I find that the authors have gone a bit too far in this respect. Apart from my first couple of lectures, here is my basic plan of Physics 119a:

- After a couple of lectures of general introduction, I will present and discuss the postulates of classical thermodynamics--this is the approach of Callen, which I find provides a very helpful framework in organizing the basics of thermodynamics so that it isn't just a lot of little bits and pieces. It is, however, a bit abstract. You will see very quickly how the big pieces fit together, even though you won't completely understand each of these big pieces! This takes several lectures.

- Statistical mechanics approach (microscopic) to entropy. Statistical mechanics really shines here, giving us a deep understanding of the concept of entropy.
- Treatment of cyclic process in thermodynamics: here we look at various types of engines, mainly from an idealized viewpoint.
- Statistical Mechanics: powerful tools to solve problems; examples from quantum systems.

- More development of thermodynamics: alternative formulations and more examples.

As we go back and forth between thermodynamics and statistical mechanics, I will make it clear which approach we developing. I will let you be the judge of whether my teaching method is successful!

Notice also that I will be discussing some quantum systems. If you have already had quantum mechanics it will help, but it shouldn't be necessary.

You might also wonder why we have two textbooks. I found each to have strong and weak points. Baierlein's book is more theoretical and in a certain way is a bit more advanced. It has some clever arguments but is short on interesting, real world examples. Schroeder's book, on the other hand, is full of great problems and examples, but seems a bit less well organized on the theoretical concepts.

I read a book review in Physics Today Online that concluded, "I stongly recommend that instructors adopt one of these two texts [Baierlein and Schroeder] for their undergraduate courses on thermal physics....They are beautifully writen and convey the feeling that physics is a discipline to be studied with devotion and love." Wow! If you can afford only one of the books, I think that I will be following Baierlein more closely. But there will certainly be problems and reading assigned from both books.

How to Succeed in This Class

Thermal physics is a difficult subject, with many abstact concepts and a fair number of mathematical tools that may be new to you.

Here are some specific suggestions on how to do well in Ph 119a:

1. As for most physics classes**, the single most important thing is to do the problem sets as well and as carefully as you can**. You have to grapple with thermal physics yourself.
2. ***Important note: copying of other people's homework solutions is strictly not allowed. It's perfectly fine to discuss and argue about homework problems with your friends, but you must write them up yourself. Our TAs are on the lookout for homeworks that are very similar.***
3. You should review your old problem sets from time to time to check that you have assimilated the material.
4. **Remember things**. Many physics students are disinclined to remember important results, thinking that these can always be derived or looked up whenever necessary. However, if you remember things, it will greatly facilitate both learning new material and solving problems: the amount of "new" material will seem less, because you will be more familiar with the old material used in the derivations.
5. Given the difficulty of the subject, it is important to work especially hard to keep up. In studying my lecture notes or the text, you will generally need to go over the

material several times. **Reading the text or lecture notes is not enough. You have to actively carry through the derivations and analyses on your own.** Some students simply try to read the same thing over and over again, and then discover that they aren't learning any more by doing so. A better approach is to read through the material once or twice and then **try to derive the results on your own**, referring to the text only if you are stuck. If you don't understand a particular aspect of the analysis, note this down and continue. Then, bring your list of questions to class, discussion section, or office hours.

6. **Be an active listener and a participant in lectures.** It is essential to make the best use of your time in lecture. This means really paying attention, taking good notes, and asking good questions. But don't just be a note-taker! Questions from students are usually incredibly helpful to everyone—professor and other students—by helping the professor to clarify confusing points and to make sure that the most important information does not get lost in the details. Often, the best students are the ones who ask questions, since others feel that they do not know enough to ask one. I strongly encourage you to ask questions even if they are not perfectly formulated!
7. **You are encouraged to find other books on thermal physics**—there is a vast number—to find alternative presentations, examples, and problems. Don't let the class set the boundary for your learning. There is no boundary!

Grades, homework, tests, and all that stuff

- Homework will be assigned on Wednesday and is due in class on the following Wednesday. A penalty will be applied to late homework.
- Lectures: Mon, Weds, Fri—9:00—9:50 PM in Phelps 3515
- Office hours: TBA
- Graduate Teaching Assistants: Kevin Chiou (kikachu@physics.ucsb.edu) and Alexey Naydenov (naydenov@physics.ucsb.edu)
- TA PLC hours: Kevin: Mon and Tues 11:00-12:30; Alexey: TBA.
- Grading policy:
  1. Homework: 35%
  2. Midterm: 15%
  3. Final exam: 50%
- Textbooks: *Thermal Physics* by R. Baierlein, Cambridge U. Press; *An Introduction to Thermal Physics* by D. Schroeder (Addison Wesley Longman).
- Midterm Exam Date: see schedule below.
- Final Exam Date: see schedule below.

Other books on thermal physics

1. *Thermal Physics*, by Ralph Baierlein. One of our textbooks.
2. *An Introduction to Thermal Physics*, Daniel V. Schroeder. Our second textbook.
3. *Thermodynamics and an Introduction to Thermostatistics*, 2^{nd} edition, Herbert B. Callen. This is the book that was used last year. It has many excellent qualities, and the discussion of the postulates of thermodynamics is the basis for my lectures on that topic.
4. *Thermodynamics and Statistical Mechanics,* Walter Greiner, Ludwig Neise, and Horst Stocker. Part of a series of books used heavily in German universities.
5. *Fundamentals of Statistical and Thermal Physics*, Frederick Reif.
6. *Thermal Physics*, 2^{nd} edition, Charles Kittel and Herbert Kroemer
7. *Statistical Mechanics, A Concise Introduction for Chemists,* by Benjamin Widom.
8. *Environmental Physics*, Egbert Boeker and Rienk van Grondelle. Shows you that Thermodynamics is relevant to saving the world!
9. *An Introduction to global warming* (article), by J.R. Barker and M.H. Ross, Am. J. Phys. 67 (12), December 1999. This issue of American Journal of Physics is devoted to thermal physics.
10. *The 2^{nd} Law: Energy, Chaos, and Form*, by P.W. Atkins. For the lay reader. This is part of the well-known series of Scientific American books. It is written by a famous Oxford, who is also an excellent writer.
11. *The Physics of Information Technology,* by Neil Gershenfeld. Not primarily about thermodynamics, but has some interesting applications.
12. *A Matter of Degrees: What Temperature Reveals about the Past and Future of our Species, Planet, and Universe*, by Gino Segre. An intruiging and well written book for the popular audience. Fun to read.
13. *Cosmology and Particle Physics*, by Lars Bergstrom and Ariel Goobar.
14. *Understanding the Properties of Matter*, Michael de Podesta. This is not strictly speaking a book on Thermodynamics, but it is full of tables and graphs with real data and shows how well predictions based on thermodynamics and statistical mechanics agree with the real world!
15. *Statistical Physics and Microscale Thermophysics*, Van P. Carey. Full of mathematical details, this useful book is written from the Stat Mech point of view.
16. *Heat and Thermodynamics*, M. W. Zemansky. A standard undergraduate text.
17. *Statistical Physics*-Berkeley Physics Course, Volume 5, F Reif.
18. *Statistical Mechanics : A Set of Lectures,* by Richard P. Feynman
19. *The Feynman Lectures on Physics*, by Richard P. Feynman, Robert B. Leighton, and Matthew Sands.
20. *Statistical Mechanics,* by Kerson Huang.
21. *Statistical Physics*, by F. Mandl.
22. Feynman Lectures on Computation, by Richard P. Feynman; edited by Tony Hey and Robin W. Allen.
23. *Thermodynamics, Kinetic Theory, and Statistical Thermodynamics,* by F.W. Sears and G.L. Salinger

Ph 119a: Approximate Schedule for Fall 2007

Class	Date	Topics	Chapters (Baierlein=B, Schroeder=S)
1	Fri, Sep 28	Introduction, origin of Avogadro's number, mole, extensive vs. intensive quantities. 1st law of thermodynamics, energy transfer via work vs. heat.	B1, S1
2	Mon, Oct 1	Equilibrium states, Postulate I of Thermodynamics, Walls and Constraints, "Basic Problem of Thermodynamics." Kinetic model for ideal gases	B1, S1
3	Weds, Oct 3	Kinetic model for ideal gases, continued.	B1, S1
4	Fri, Oct 5	Heat capacity, relation to microscopic degrees of freedom.	B1, S1
5	Mon, Oct 8	Isothermal expansion, adiabatic expansion. Comparison of heat capacity predictions with experimental data.	B1, S1
6	Weds, Oct 10	Postulates I-IV of Thermodynamics; definition of T, P, and μ. Extensive vs. intensive parameters. Additivity of entropy, scaling, fundamental relations. Examples of entropy functions.	B2, S2, S3
7	Fri, Oct 12	Equilibrium conditions for T, P, and μ. Discussion of entropy changes.	B2, S2, S3
8	Mon, Oct 15	Equilibrium conditions, continued.	B2, S2, S3
9	Weds, Oct 17	Mathematical interlude: exact and inexact differentials. Discussion of path dependence of dW and dQ.	B2, S2, S3
10	Fri, Oct 19	Comparison of energy and entropy representations of the fundamental relation. Energetic intensive parameters vs. entropic intensive parameters. Equations of state.	B2, S2, S3
11	Mon, Oct 22	Entropy and the "arrow of time," microstates and macrostates. Statistical mechanicis of particles and states, combinatorics of microstates. Occupancy numbers.	B2, S2, S3
12	Weds, Oct 24	Einstein model of solid, Stirling approximation. Multiplicity and entropy for Einstein solid.	S3
13	Fri, Oct 26	More on macrostates vs. microstates. Fundamental assumptions of Statistical Mechanics. Microcanonical ensemble.	S3, lecture notes
14	Mon, Oct 29	Multiplicity and entropy when the particles are distinguishable. Partition function. Boltzmann distribution.	S6.1, lecture notes

15	Weds, Oct 31	Statistical Mechanics and the Partition Function. Detailed calculation of the Boltzmann distribution occupancy numbers.	S6.1, lecture notes
16	Fri, Nov 2	MIDTERM EXAM	Lectures 1-12 and associated material from texts
17	Mon, Nov 5	More on Einstein solid, energy, entropy, and heat in quasi-static processes.	S3
18	Weds, Nov 7	Euler Equation and Gibbs-Duhem Equation. Entropy and multiplicity for an ideal gas (various methods).	lecture notes, S2, S3, B2
19	Fri, Nov 9	Cyclic processes, historical perspective, heat engines and entropy, entropy of an ideal gas during an adiabatic process.	B3, S4
-	Mon, Nov 12	HOLIDAY (Veterans' Day)	-
20	Weds, Nov 14	Carnot cycle.	B3, S4
21	Fri, Nov 16	Carnot cycle, continued. Refrigerators, Efficiency of reversible vs. non-reversible heat engines.	B3, S4
22	Mon Nov 19	Otto cycle and 4-stroke engine. Equivalence of Kelvin and Clausius statements of 2^{nd} Law of Thermodynamics.	B3, S4
23	Weds, Nov 21	Entropy in Quantum Theory. Spacing of energy levels and density of states for free particles in a box.	B4
X	Fri, Nov 23	Thanksgiving holiday	Therrmodynamics of turkey
24	Mon, Nov 26	Maxwell velocity distribution for ideal gas. Legendre transformations and free energies. Enthalpy, Gibbs free energy, Helmholtz free energy.	B4, S6.4, S5.1-5.2
25	Weds Nov 28	Legendre transformations and free energies. Enthalpy, Gibbs free energy, Helmholtz free energy.	S5.1-5.2, B10
26	Fri, Nov 30	More on free energies and their physical significance, extremum principles, relation to maximum entropy. Demonstration: Mystery of the drinking bird.	S5.1-5.2, B10
27	Mon, Dec 3	Enthalpy and Gibbs free energy, chemical reactions.	S5.1-5.2, B10
28	Weds, Dec 5	Latent heat, examples, Maxwell relations	S5.1, S5.2, B10
29	Fri, Dec 7	More on Maxwell relations, thermodynamic square mnemonic, Joule-Thomson process, more on enthalpy.	S5.1, S5.2, B10
FINAL	Thurs, Dec 13	*FINAL EXAM: 8:00 AM-11:00 AM*	Lectures, HW, reading