Syllabus for PHY531, *Thermodynamics & Statistical Physics*, Fall 2007

Instructor

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Prerequisites

This course requires PHY361, Modern Physics, or an equivalent course. We will be relying on using the quantum mechanical solution of a "particle in a box", the quantum harmonic oscillator, and mechanical ideas of work and collisions.

The better prepared that you are in math, the easier this course will be. You certainly should have had MAT397 (multivariable calculus and vectors) to take this course. I will hand out a review summary of much of the mathematical tools that we will be using: partial derivatives (multivariable calculus), Taylor series, binomial coefficients, Stirling's formula (you might not have seen this yet), Gaussian integrals (which you may not have used much), probability distribution functions, hyperbolic functions, and practice in keeping dominant terms. Some of this is reviewed in Appendix B of Schroeder's book.

Course goals and content

Goals

My primary goal is to work with you through the concepts and mathematical tools of thermal physics, so that you are able to understand and explain many of the thermal properties of matter, including quantum gases. We will also work on using a computer algebra system to help us solve problems in physics. If you do well in this class, you should be able to

- Define temperature, precisely.
- Easily solve almost all GRE questions on thermodynamics and statistical physics.
- Use the phrases "canonical distribution", "degenerate Fermi gases" (in the same sentence as "white dwarf"), "chemical potential", -"Clausius-Clapeyron", and "negative temperature" in an appropriate context.
- Explain why perpetual motion machines of the second kind are doomed to fail.
- Explain why microwaves don't heat food.
- Compute the maximum efficiency of a steam engine or refrigerator.
- Explain everything about the ideal gas.
- Tell someone two facts about Ludwig Boltzmann's death.

Perspective

Thermodynamics is the treatment of the macroscopic properties of physical systems. Macroscopic properties are described by quantities such as temperature, pressure, volume, etc. Statistical mechanics relates these macroscopic quantities to the microscopic composition of the physical system (such as atoms or electrons). While thermodynamics has its own separate beauty and mathematical apparatus that makes connections between macroscopic properties, it is now usually derived as a consequence of statistical mechanics. We will study both of these treatments in an integrated approach.

Thermodynamics ("heat" and "motion") first arose in the study of steam engines, which were revolutionizing the world (especially Britain) in the early 19th Century. The results of thermodynamics and the improved understanding provided by statistical mechanics are central not just to building better engines, but to the whole of physics. Without thermal physics, one cannot understand the transistor, recent experiments on large nuclei, energy production and climate change, stars, or any other large chunk of matter.

Thermal physics is the most general and best understood treatment of "collective" phenomena. It is directly applied to understand the properties of gases, chemical reactions, black holes, the early universe (big bang), and homogeneous materials like solids. The tools developed in this subject have been extended to the study of flocks of birds, economic markets, information systems, star clusters, evolution, and many other systems that have many interacting elements.

Fundamental questions about systems with many interacting elements include "What can be measured? How are conserved quantities, like energy, shared among the elements? What can be known about the elements? What can be predicted about their behavior, individually and collectively?" It is well enough to be able to predict the motion of a single planet about a star, but what can we possibly do when faced with 10^{23} atoms in a box, each crying for attention, or even 10^5 stars in a globular cluster? What type of understanding and description is possible?

In answering such questions, we will run into many others, including "Why can one remember the past, but not the future?" and "Why won't my perpetual motion machine work?".

Thermodynamics and statistical mechanics involve new, subtle concepts and a sophisticated use of mathematics. Also, a large number of terms are used. This makes the subject initially more difficult than studying, say, introductory mechanics. It is important to use concepts precisely in order to avoid confusion.

Topics

We will closely follow the treatment in Schroeder's book and will therefore address the following physics topics:

- What is temperature? What is the zeroth law of thermodynamics?
- What is the behavior of the simplest collection of moving particles, the ideal gas? [First important model system]
- What are work and heat? What is the first law of thermodynamics?
- What are reversible, adiabatic, isothermal, isobaric, isochoric processes?
- Introduction of two other important model systems: the paramagnet and Einstein solid
- Multiplicity and entropy, especially in the model systems. What is the second law of thermodynamics? How is the arrow of time related to the Big Bang?
- Interactions between systems: exchange of energy (both heat and work) and particles
- Heat engines and the Carnot cycle
- Chemical potentials (free energies) and phase transitions in a pure substance
- Boltzmann factor and the partition function; canonical distribution
- Quantum statistics: gases of fermions and bosons

To address these topics, you will become more proficient with using Maple (or your favorite computer math system, such as Mathematica or Matlab). We will use Maple to solve equations, to estimate integrals numerically, and to plot curves.

Resources

Required Book

The text that will be used for the guide for this course is *An Introduction to Thermal Physics*, by Daniel V. Schroeder (Addison Wesley Longman, Publishers, 2000). You should acquire this book. I chose to use this book as it is complete for an introductory course, clearly written, and includes many useful problems, both for homework and for self-study. Some people may find the author's liberal use of the first person rather jarring - try to just ignore the use of "I" if it bothers you. Homework assignments will generally be adapted from this book. I may occassionally hand out excerpts or direct you to other sources for supporting material.

Reserve Books

It is often useful to read another author's explanation of concepts in order to understand them better. I list here books that I use as resources for this course and which are on reserve in the Physics Library:

Thermal Physics, by Ralph Baierlein (1999, Cambridge). This book is written in a similar fashion to Schroeder's.

Introductory Statistical Mechanics, by Roger Bowley and Mariana Sanchez (1996, Oxford). This is the text used in last year's version of this course. It is a very good book and takes a slightly more advanced approach.

Thermal Physics, by Kittel and Kroemer. This is a text that continues to be used as a standard introduction.

The book *Entropy, Order Parameters, and Complexity*, by J. Sethna, is available for online review at the author's website. This book is well off-topic for our approach, but if you are interested in a broad range of contemporary applications of the ideas from this course, you might want to dip into this book.

Assessment of your work

The grading scheme and assessment schedule is also designed to encourage you to learn the most, by encouraging you to keep up with the material and testing you on what you learn. I use the course grade to indicate my evaluation of how well you have learned the course material. If your submitted work and participation indicate that you can remember and apply the ideas developed in the course, you will receive a grade of "A". If you can mostly apply the ideas properly, you will receive a grade of "B". My estimate of how well you understand and apply the ideas will be based on the following assessments, with their weight indicated in brackets:

- Midterm [20%] and final [25%] exam: The midterm exam and final exam will test your ability to apply the concepts developed in this course. They will include some simple exercises as warm-up and a few analytic problems to work out. You will also need to discuss the meaning of your results. The midterm will be designed to be completed in one hour. Everything discussed in the course, including physical demonstrations, homework problems, and on-line reading assignments, will be eligible for inclusion on an exam.

- [15%] Quizzes: There will be four (4) Friday quizzes; I will use the top three scores, at 5% of your total grade each, in computing your course percentage. The quizzes will include short answer conceptual questions and a short problem to work out. The quizzes will be designed to be completed in 20 minutes and will be given promptly at the beginning of class.

- [40%] There will be 12 homework assignments, mostly due on Wednesdays (the first assignment is due on Friday!).

  - I will use the top 10 scores in computing your course percentage. Your submitted work should be neat and clear to receive full credit.
  - Your answer must not just be a set of equations. Explain your work by using a mix of words and equations and summarize your results in a clear sentence (or two).
  - Some of your work will require the use of Maple, a computer tool for aid in solving mathematical problems, or its equivalent (such as Mathematica).

Tips

- Read ahead: skim the sections first, then read more carefully. Take notes on your reading.

- Bring questions to class.

- Read the homework as soon as you receive it and start thinking it through: don't try to do it all at the last minute.

- Come to office hours, with questions.

Collaboration, sources, and academic honesty

I encourage you to share ideas with your peers both in and out of class by active discussion. Discussion and use of written materials are necessary both to advance science and to learn it well. So you may discuss homework problems with others, as long as you are an active participant in such discussions.

For homework solutions, I require only that you do not directly seek out solutions to the homework problems. You may not (1) look up solutions in printed or on-line materials or (2) share the written work of a classmate. Exams and quizzes are of course to be completed without any aid from others.

A key principle is that you should properly **acknowledge all of your sources** in your submitted work. Sources include web pages, books, articles, television shows, and people. For example, if you learn something from someone, you should credit them in your homework. Examples:

- "A graduate student, Jes Katt, suggested that I try adding zero to both sides of the following equation. My classmate Aang then suggested using the ideal gas law to replace zero with $pV - nkT$."
- "The ideas for solving this problem came out of an extended discussion with Ilya and Jocelyn".
- "The web page `http://klnw.entropy.gov/inexact.htm` has a useful discussion of entropy. I used the information on this page to help apply this next equation."

The principle of acknowledging your sources is central to scientific work. This principle avoids plagiarism and makes your work more useful. You will not be penalized for using generally available sources (except for copying solutions to problems).

Except for properly acknowledged quotations, all work that you submit should be in your own words and equations. After discussing a homework problem with another student, you must write the solution up on your own.

Improperly aiding another student is academically dishonest. Please do not share your written work in any manner, even by e-mailing your work to another student, as you will be held responsible for contributing to academic dishonesty if someone else turns in your work. Please also be aware of the details of University and College policies on academic dishonesty.

Quotations

The study of thermodynamics and statistical mechanics traditionally includes many quotations. Here are a few to get us started:

> A theory is the more impressive the greater the simplicity of its premises, the more different kinds of things it relates, and the more extended its area of applicability. Therefore the deep impression that classical thermodynamics made upon me. It is the only physical theory of universal content which I am convinced will never be overthrown, within the framework of applicability of its basic concepts.
> - A. Einstein (1949)

> It is perhaps because thermodyanmics is not concerned with fundamentals in the microscopic sense that it sometimes does not appeal readily to hte physicist; but he will disregard it at his peril. It is precisely because it avoids microscopic theories that it is so valuable.
> - C. J. Adkins, Equilibrium Thermodynamics (1968)

> The law that entropy always increases, holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations — then so much the worse for Maxwell's equations. If it is found to be contradicted by observation — well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.
> - Sir Arthur Stanley Eddington, The Nature of the Physical World (1927)

> Nothing in life is certain except death, taxes and the second law of thermodynamics. All three are processes in which useful or accessible forms of some quantity, such as energy or money, are transformed into useless, inaccessible forms of the same quantity. That is not to say that these three processes don't have fringe benefits: taxes pay for roads and schools; the second law of thermodynamics drives cars, computers and metabolism; and death, at the very least, opens up tenured faculty positions.
> - Seth Lloyd, writing in Nature (2004).

> A good many times I have been present at gatherings of people who, by the standards of the traditional culture, are thought highly educated and who have with considerable gusto been expressing their incredulity at the illiteracy of scientists. Once or twice I have been provoked and have asked the company how many of them could describe the Second Law of Thermodynamics. The

response was cold; it was also negative. Yet I was asking something which is about the scientific equivalent of: “Have you read a work of Shakespeare’s”
C.P. Snow, The Two Cultures (1959)

Ludwig Boltzmann, who spent much of his life studying statistical mechanics, died in 1906, by his own hand. Paul Ehrenfest, carrying on the same work, died similarly in 1933. Now it is our turn to study statistical mechanics.
Perhaps it will be wise to approach the subject cautiously.
- David Goodstein, States of Matter (2002)

It all works because Avogadro’s number is closer to infinity than to 10.
- Ralph Baierlein, American Journal of Physics (1978)