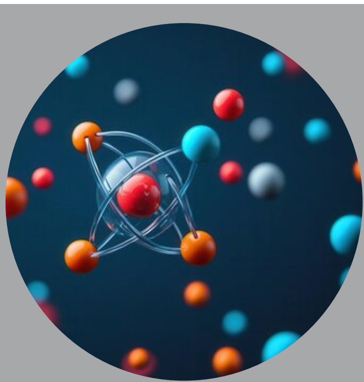

Thermodynamics and Statistical Mechanics

PHYS 301

Instructor Info

Prof. Francis-Yan Cyr-Racine

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Course Info

Prereq: PHYS 330 Modern Physics; Good knowledge of classical and quantum mechanics, including knowing what an Hamiltonian is.

Tues & Thurs

12:30-1:45pm

PAIS 1160

Course Website

Office Hours

Wed

2-3pm

PAIS 3214

TA Info

Fernando Garcia-Cortez

Thurs 11-12noon

PAIS 3414

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Why Thermodynamics and Statistical Mechanics?

The world is a messy place. A single glass of water contains more molecules ($\sim 10^{23}$) than the number of stars in the observable Universe. How do we describe the collective behavior of so many molecules? One approach that will not work is to write the Schrödinger equation for all these molecules and solve it. This is very difficult to do for 23 particles, let alone 10^{23}. But even if you could do it, is that even an interesting question to ask? Instead, we are typically interested in much simpler questions: Is the water hot? Cold? Is it liquid? Is it frozen? How can we use our knowledge of fundamental physics at the atomic and molecular scales to answer simple questions about the macroscopic state of physical systems around us? This is where statistical mechanics comes in. It aims at turning the microscopic laws of physics into a macroscopic description of Nature. As the name says, statistical mechanics adopts a probabilistic view of physical systems in which their observed macroscopic state is the most probable state (usually overwhelmingly so) given a set of constraints. The law of large numbers rules as king here and ensures that statistical mechanics makes absolutely definite (i.e. not random) predictions about the macroscopic state of physical systems.

Classical thermodynamics largely predates the advent of statistical mechanics and was developed in fits and starts by aristocrats and lords tinkering in their attic or basement. Importantly, thermodynamics was established before the existence of atoms was accepted as a scientific fact. Many empirical laws were discovered (usually named after whoever stumbled into them first, e.g. Curie's law, Boyle's law, the Stefan-Boltzmann law, etc.), but it wasn't always clear what the underlying physics was. This process was turbocharged by the industrial revolution and the need to develop better steam engines. The fundamental laws of thermodynamics were then established. These laws touch on some of the most important concepts in physics: energy conservation, the arrow of time, the concept of absolute zero, etc. The subsequent development of statistical mechanics finally connected these laws to the underlying microphysics.

Overview

In this course, we will first establish the modern basis of statistical mechanics, providing rigorous definitions of entropy, temperature, pressure, and heat capacity, while connecting these to the available microstates of a physical system. We will use simple examples, such as ideal gases and two-level systems, to illustrate these concepts. We will then introduce key tools such as the canonical ensemble, the partition function, and the Helmholtz free energy, that will help us compute macroscopic properties of systems with very large number of constituents. We will then consider weakly interacting systems and how they can undergo phase transitions. We will also discuss the different statistical properties of bosons and fermions. In the last part of the course, we will turn our attention to classical thermodynamics, putting it in its historical context and discussing how the study of simple heat engines led physicists to the fundamental laws of thermodynamics. We will discuss how the thermodynamic definitions of things like entropy and temperature naturally coincide with their equivalent in statistical mechanics.

About Me

I am a practicing theoretical cosmologist/particle astrophysicist with a keen interest in the physics of the early Universe. Thermodynamics and statistical mechanics play significant roles in my day-to-day research.

Material

Suggested Text

Schroeder, D. V. *An Introduction to Thermal Physics*. 1st edition, Oxford University Press (2021) (ISBN:978-0-19-289554-7). Older version published by Pearson is fine. Also available in paperback and as an e-book.

FAQs

What is the difference between Thermodynamics and Statistical Mechanics?

Thermodynamics does not care that systems are made of a very large number of atoms and molecules. Instead, it aims at describing the relationship between macroscopic observables like pressure and temperature, without ever invoking the microphysics of the system considered. Statistical mechanics on the other hand is built from the microphysical constituents (e.g. atoms) of a system and use probabilistic tools to obtain macroscopic observables.

What kind of mathematics will be use in this class?

Derivatives and integrals, a lot of Taylor expansions and series. An important tool will be able to accurately approximate expressions involving very large numbers by only keeping the leading contribution. It is important to get comfortable with this: very few calculations in this class will be exact, but they will be very, very good approximations.

Do I need to know how to code to take this class?

Being able to perform basic numerical calculations (numerical integrals, summing series, etc.) and making plots are basic skills that everyone needs to have. Such knowledge will be assumed in this class.

Grading Scheme

10%	In-class worksheets
15%	In-class quizzes (best 4 out of 6)
10%	Homework assignments
40%	Two midterm exams (20% each)
25%	Final exam

Class Format

This class is aimed at senior undergraduate physics and astronomy majors. The class format will usually (but not always) consist of a brief lecture at the beginning of class about the topic of the day, followed by active problem solving in small groups made up of 3-4 students. It is very important that you attend every class and do the worksheets. Groups will be asked often to share their solutions with the rest of the class. To ensure fairness, groups will be rotated on a regular basis.

Student Learning Outcomes

Upon successful completion of this course, students will be able to . . .

- Explain the fundamental assumption underpinning statistical mechanics.
- Provide the definition of entropy in terms of the accessible microstates of a system.
- Provide the rigorous definition of temperature and explain how it makes sense given our everyday understanding of temperature.
- Define and compute the heat capacity of simple physical systems.
- Write down the partition function for simple physical systems and use it to compute their macroscopic properties.
- Explain the difference between the microcanonical, canonical, and grand canonical ensembles.
- Define an ideal gas, use it for practical calculations, and compute simple deviations from it.
- Know the meaning of Helmholtz and Gibbs free energy and use them in practical physics calculations.
- State the difference between a first- and second-order phase transition.
- State the key assumption beyond the derivation of the Planck function and explain why it solves the ultraviolet catastrophe.
- Derive the Bose-Einstein and Fermi-Dirac distributions.
- Explain the key differences between the behavior of bosons and fermions at low temperatures.
- Determine the efficiency of a simple heat engine.
- Explain in their own words the physical content of the zeroth, first, second, and third law of thermodynamics.

In-class worksheets

In some lectures, there will be an active-learning activity centered on a worksheet. Students will be expected to solve the problems on the worksheet in class in their pre-assigned group of 3-4 students. After 20-30 minutes, I will ask one group to volunteer and present their answers in front of the class. It is understood that each student will present for their group at least once during the semester. Students will get the credits for the worksheet by actively participating in their group as they work through the worksheet. It is thus very important for all students to attend every classes. Students who are absent from class will have one week from the missed lecture to complete the missing worksheet and hand it in to me. In general, there will not be a worksheet on days when we have an in-class quiz.

PHYS 311: Problems in Thermodynamics and Statistical Mechanics

This is a very important adjunct to the main lecture class, taking place every Wednesday from 1-2pm in PAIS 1160. It will provide you additional practice with solving problems beyond the homework assignments and self study. Furthermore, the class will also give you a valuable opportunity to bring to my attention your difficulties with any concepts covered in the lecture class so I can address them in a group setting. The problem sheets would be posted on the course webpage. The corresponding solutions will be posted after the problem class. *You will receive credit for the problems class as long as you register and show up for more than 10 sessions.* Even if you don't register for the class, I encourage you to attend anyway, just to get the extra practice.

Homework Assignments and Quizzes

There will be homework assignments spread out over the course of the semester. They will be posted on the course webpage and on Canvas. Homeworks are to be submitted on UNM Canvas on the due date before the due time. Late Homework assignments will be accepted but with a 25% penalty for each day past the deadline. So a homework handed-in within 24 hrs of the deadline will carry a 25% penalty, one handed-in within 48 hrs will carry a 50% penalty, as so on. Let me know if you are planning on submitting your homework late such that I can delay the posting of the solutions. It is very important that you attempt every assignment as very similar problems will be asked in-class as part of the quizzes and exams. While I strongly encourage you to discuss the homework assignments with your classmates, the work you hand in must be entirely yours (see also the AI policy below).

Policy on Artificial Intelligence (AI) Tools

AI tools based on Large Language Models are powerful resources for coding, writing, and problem-solving. While we recognize that familiarity with these tools is a career asset, their misuse can rob you of the intellectual struggle necessary to understand physics and astronomy.

Permitted Use: You may use AI to clarify concepts, check grammar, or debug code during homework assignments, provided you critically analyze the output (as AI often makes errors). However, simply generating answers to paste into your submission is unlikely to result in learning and will result in a score of zero, even if cited.

Requirements for Use: If you utilize AI for homework, you must include an acknowledgment section providing:

- The Tool: Which specific AI model was used (e.g., ChatGPT-4, Claude, Gemini).
- The Prompt: The exact text you fed into the model.
- The Learning: A brief explanation of what you learned from the output or how you verified it.

Prohibited Use:

- Undeclared use of AI is considered academic dishonesty and carries standard disciplinary consequences.
- The use of AI tools during midterm and final exams is strictly prohibited.

Course Material Access

Your digital course materials are directly available now on the My Shelf link in Canvas. To simplify your course materials access, you are automatically enrolled in a Complete option at a flat rate of $279 per semester. This will show up on your bursar bill. The Complete option covers all your required course materials for all your Albuquerque campus courses, including any graduate courses you may be taking. If you are interested in course materials access for only selected courses, or if you want to opt out entirely, you will need to select the option you want in the My Shelf link in Canvas. You can change your selected option in the My Shelf link in Canvas until the registrar's "Last Day to Drop Without a 'W' Grade and 100% Tuition Refund." Make sure that you review the video and information here to understand cost and the options for Complete (automatic enrollment), Select (take action), and Opt-out (take action).

Academic Integrity

Each student is expected to maintain the highest standards of honesty and integrity in academic and professional matters. The University reserves the right to take disciplinary action, up to and including dismissal, against any student who is found guilty of academic dishonesty or otherwise fails to meet the standards. Any student judged to have engaged in academic dishonesty in course work may receive a reduced or failing grade for the work in question and/or for the course. Academic dishonesty includes, but is not limited to, dishonesty in quizzes, tests, or assignments; claiming credit for work not done or done by others (including AI; see AI policy above); hindering the academic work of other students; misrepresenting academic or professional qualifications within or without the University; and nondisclosure or misrepresentation in filling out applications or other University records.

Credit-hour statement

This is a three credit-hour course. Class meets for two 75-minute sessions of direct instruction for fifteen weeks during the Spring 2026 semester. Please plan for a minimum of six hours of out-of-class work (or homework, study, assignment completion, and class preparation) each week.

Respectful behavior and absences

I am committed to building with you a positive classroom environment in which everyone can learn. I reserve the right to intervene and enforce standards of respectful behavior when classroom conduct is inconsistent with University expectations. Interventions and enforcement may include but are not limited to required meetings to discuss classroom expectations, written notification of expectations, and/or removal from a class meeting. Removal from a class meeting will result in an unexcused absence. Three or more unexcused absences may result in permanent removal and a drop from the course. The University of New Mexico ensures freedom of academic inquiry, free expression and open debate, and a respectful campus through adherence to the following policies.

Accommodations

UNM is committed to providing equitable access to learning opportunities for students with documented disabilities. As your instructor, it is my objective to facilitate an inclusive classroom setting, in which students have full access and opportunity to participate. To engage in a confidential conversation about the process for requesting reasonable accommodations for this class and/or program, please contact the Accessibility Resource Center at arcsrvs@unm.edu or by phone at 505-277-3506.

UAP 2720 and 2740

Our classroom and our university should foster mutual respect, kindness, and support. If you have concerns about discrimination, harassment, or violence, please seek support and reports incidents. Find confidential services at the LoboRESPECT Advocacy Center, the Women's Ressource Center, and the LGBTQ Ressource Center. UNM prohibits discrimination on the basis of sex (including gender, sex stereotyping, gender expression, and gender identity). All instructors are "responsible employees" who must communicate reports of sexual harassment, sexual misconduct and sexual violence to Compliance, Ethics, and Equal Opportunity. For more information, please see UAP 2720 and UAP 2740.

Grade Distribution Scale

- 98-100: A+
- 87-97.99: A
- 80-86.99: A-
- 77-79.99: B+
- 73-76.99: B
- 70-72.99: B-
- 67-69.99: C+
- 63-66.99: C
- 60-62.99: C-
- 57-59.99: D+
- 53-56.99: D
- 50-52.99: D-
- Below 50: F

Tentative Class Schedule

MODULE 1: Foundation of Statistical Mechanics: Ensembles, Entropy, and Temperature

Week 1	Statistical Mechanics versus Thermodynamics, microstates versus macrostates, microcanonical ensemble, fundamental assumption of statistical mechanics, entropy and the 2nd law	Schroeder 2.1-2.3,2.6
Week 2	Entropy, large numbers, Stirling's Formula, temperature, and heat capacity	Schroeder 1.6,2.4,2.6,3.1

Week 3	Ideal gas: multiplicity, entropy, pressure, volume; 1st law of thermodynamics	Schroeder 1.2, 2.5, 3.4
Week 4	Canonical ensembles, Boltzmann distribution, partition function, mean energy and fluctuations, Gibbs entropy	Schroeder 6.1-6.2
Week 5	Partition function of ideal gas, equipartition of energy, Helmholtz free energy and its connection to the partition function.	Schroeder 6.3,6.5-6.7
Week 6	Midterm #1; Chemical potential, chemical equilibrium	Schroeder 3.5
Week 7	Grand canonical ensemble and potential, Gibbs free energy, extensive and intensive quantities	Schroeder 5.2, 7.1
MODULE 2: Weakly interacting systems, phase transitions, bosons, and fermions		
Week 8	Weakly interacting gases, virial expansion, van der Waals interactions and equation of states, Mayer f-function, gas-liquid coexistence	Schroeder Ch. 5.3, 8.1
Week 9	Spring Break (No class)	
Week 10	Landau theory of phase transitions, first- and second-order transition, latent heat, density of states, Planck function, Stefan-Boltzmann law	Schroeder 7.4
Week 11	Phonons and the Debye model of solids, Bose-Einstein (BE) distribution, high-temperature limit, BE condensation	Schroeder 7.2, 7.6
Week 12	Fermi-Dirac distribution, degenerate Fermi gas, Fermi surface; Midterm # 2	Schroeder 7.2,7.3
MODULE 3: Classical Thermodynamics		
Week 13	Intro to thermodynamics, equilibrium, zeroth law, first law, heat, reversible processes, second law, carnot cycle, thermal efficiency	Schroeder 4.1
Week 14	Carnot's theorem, Equivalence of thermodynamics and statistical mechanics temperature, real engines and refrigerators	Schroeder 4.2,4.3
Week 15	Entropy and irreversibility, second law and the arrow of time, thermodynamics potentials, Maxwell's relations	Schroeder 2.6
Week 16	Third law of thermodynamics and review of material	Schroeder 3.2