**PHY560: Condensed Matter Physics  T Th 12:30 PM- 01:50 PM**
**Room:** 158 Loomis

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**Instructor:** Prof. Taylor Hughes Office: ESB 2115, Email: hughest@illinois.edu

**Office Hours:** (TLH) Tuesdays 11:00 AM on zoom and possibly via appointment.

**Textbook:** *Condensed Matter Physics* by Michael Marder.

**Prerequisites:** PHYS 427; PHYS 580. Graduate-level quantum mechanics is a required pre-requisite for a reason and will be used. If you don't have this pre-requisite make sure you are comfortable enough with the material before the drop date.

**Grade Structure:** Homework will be 50% of the total grade. There will be one exam, the final exam worth 50%of the total grade. It will be a take home exam.

**Course Objectives**: The goal of this course is to set the foundation for future coursework and research in condensed matter physics especially in the modern theory of electronic structure. A detailed, but ambitious course outline can be found on the next two pages.

**Grading**: Partial credit will be given on homework and exams *if and only if* the work is *coherent.* A random scattering of thoughts will not be awarded points. Simple numerical errors will not be strongly punished, however errors which give incorrect physical results will be. The steps to receiving partial credit are: (i) write your solution neatly and coherently using equations *and* words to describe what you are doing (ii) checking your answer for consistency *e.g.* are units correct, does the solution behave correctly in known limits. When writing solutions on homework or exams the best mindset to have is that you are explaining your method to a fellow class mate at your same level. That will require that you show your steps logically and lead the grader/reader through your solutions. This way of communicating your results will be beneficial for both yourself and the grader. Expect the exam and problem sets to be challenging but worth the effort.

**Homework**: There will be roughly one problem set every two weeks. The homework will consist of problems from the textbook and original problems. Due dates for homework will change throughout the semester. Homework which is 1-day late will receive only 75% credit. If the homework is due on Friday and turned in on Monday only 50% credit will be awarded. Homework turned in up to 5 days late will receive 25% credit. Otherwise *no* credit will be awarded. Any indications that homework solutions were derived from online internet sources will be acted upon accordingly.

**Anti-Racism and Inclusivity Statement for Inclusion in Course Syllabi:** The Grainger College of Engineering is committed to the creation of an anti-racist, inclusive community that welcomes diversity along a number of dimensions, including, but not limited to, race, ethnicity and national origins, gender and gender identity, sexuality, disability status, class, age, or religious beliefs. The College recognizes that we are learning together in the midst of the Black Lives Matter movement, that Black, Hispanic, and Indigenous voices and contributions have largely either been excluded from, or not recognized in, science and engineering, and that both overt racism and micro-aggressions threaten the well-being of our students and our university community. The effectiveness of this course is dependent upon each of us to create a safe and encouraging learning environment that allows for the open exchange of ideas while also ensuring equitable opportunities and respect for all of us. Everyone is expected to help establish and maintain an environment where students, staff, and faculty can contribute without fear of personal ridicule, or intolerant or offensive language. If you witness or experience racism, discrimination, micro-aggressions, or other offensive behavior, you are encouraged to bring this to the attention of the course director if you feel comfortable. You can also report these behaviors to the Bias Assessment and Response Team (BART) (https://bart.illinois.edu/). Based on your report, BART members will follow up and reach out to students to make sure they have the support they need to be healthy and safe. If the reported behavior also violates university policy, staff in the Office for Student Conflict Resolution may respond as well and will take appropriate action.

**Other Statements:** For statements on sexual misconduct, academic integrity, religious observances, disability-related accomodations, and FERPA please see here:
https://wiki.illinois.edu/wiki/display/ugadvise/Syllabus+Statements

# 1 Course Outline

1. Free-electron gas model for metals [Chapter 6 and Appendix C]
   - Brief introduction to solid state physics
   - Free fermi gas basics
   - Many-body quantum mechanics and second quantization [Lattice model examples, including interactions?]
   - Fermi-distribution, density of states, chemical potential, thermodynamic properties, discrete and continuous state counting.
   - Drude model for conductivity, relaxation-time approximation, Hall effect.
   - AC Conductivity, Plasma Frequency [Connect AC and DC conductivity to experiment]
2. Lattices and Symmetry [Chapters 1, 2, and 3]
   - Bravais Lattices (1D, 2D, 3D)
   - Brief introduction to point group symmetries and lattice classification
   - Proof of allowed discrete rotation symmetries
   - Miller indices and Bragg Condition
   - Atomic structure factors
3. Non-interacting electrons in a periodic potential [Chapter 7]
   - Symmetries of the Hamiltonian, Heisenberg equations of motion
   - Discrete and continuous translation symmetry
   - Properties of periodic potentials and momentum conservation
   - Consequences of discrete translation symmetry
   - Schrodinger Equation in a periodic potential
   - Bloch's Theorem, Bloch functions
   - Brillouin zones, momentum/reciprocal space, quasi-momentum
   - Bloch Hamiltonian
4. Nearly free electron model [Chapter 8 and Notes]
   - Schrodinger Equation in a weak periodic potential: Nearly-Free electron model and band theory
   - Filling fraction and Fermi-surfaces (Definition of band insulators and band metals)
5. Tight-binding Models [Chapter 8 and Notes]
   - Tight binding approximation
   - Bloch Hamiltonians
   - 1D single-orbital tight-binding model
   - Peierls distortion [CDW gap opening]
   - Su-Schrieffer-Heeger model
   - Wannier functions, projected position operator
   - Charge polarization, quantized charge pumping, adiabatic connection
6. Lattice models [Chapter 7 and Notes]
   - 2D square lattice model with s-orbitals

- Graphene/Lattice Dirac model
- Discrete symmetries (of Bloch Hamiltonians): charge-conjugation, time-reversal, point-group
- Point group symmetries and representations
- Peierls substitution

7. (Semi-classical) Dynamics of Bloch Electrons [Chapter 16]
    - Semi-classical equations of motion for electrons in periodic potentials
    - Electrons and holes in semiconductors
    - $k \cdot P$ perturbation theory
    - Lowdin perturbation theory
    - Band-projected dynamics
    - Consequences of the anomalous velocity

8. Phonons [Chapter 13]
    - Phonons: monatomic and diatomic lattices
    - Optical and acoustic modes

9. Superconductivity
    - Macroscopic Properties of Superconductors
    - Type I and Type II Superconductors
    - Vortices, Resistive State, and KT-Transition
    - Screening in Metals
    - BCS Theory and BdG Quasiparticles
    - d-Vector Formalism for Order Parameter
    - Josephson Junctions (SNS), and Tunneling in SN, SIS junctions
    - Topological Superconductors (Kitaev Chain, Chiral P+iP superconductor)
    - Majorana Modes