Condensed Matter Physics

Part 0. Introduction

Introduction

■ What is Condensed Matter Physics?

■ Definition of Condensed Matter

Wikipedia:

Condensed matter physics is the field of physics that deals with the macroscopic and microscopic physical properties of matter, especially the solid and liquid phases which arise from electromagnetic forces between atoms. More generally, the subject deals with "**condensed**" **phases** of matter: systems of *many constituents* with *strong interactions* between them.

- Condensed matter ⇔ strongly-interacting many-body system.
  - **Condensed** ⇔ **strongly interacting** → ordering → collective behaviors.

cond.		interaction	ordering	collective behavior	
				shape	volume
×	gas	weak	none	×	×
✓	liquid	intermediate	short–ranged	×	✓
✓	solid	strong	long–ranged	✓	✓

  - **Matter** ⇔ **many-body** system
    - many **atoms**: liquid, liquid crystal, solid, superfluid, ...
    - many **electrons**: metal, semiconductor, insulator, ...
    - many **spins**: paramagnet, ferromagnet, anti-ferromagnet, ...

■ Hard v.s. Soft

Condensed matter physics (CMP) is further divided into two sub-fields

CMP	classical	quantum	statistical	topics
Hard CMP		✓	✓	crystals, glass, magnets, ...
Soft CMP	✓		✓	polymers, foams, gels, ...

This course will be focusing on **hard** condensed matter (closer to solid state physics).

- **Prerequisites**

- **Quantum Physics**: 130A, 130B*
- **Statistical Physics**: 140A, 140B*

Why do we Study Condensed Matter Physics?

Because it is the world around us.

Almost all of the physical world we see in our everyday life is condensed matter.

- Why are metals shiny and why do they feel cool? - Band theory
- Why is glass transparent? - Anderson localization
- Why is water a fluid and why does fluid feel wet? - Hydrogen bond
- Why is rubber soft and stretchy? - Entropic force
- ...

Because it is useful.

Condensed matter physics lays the foundation for

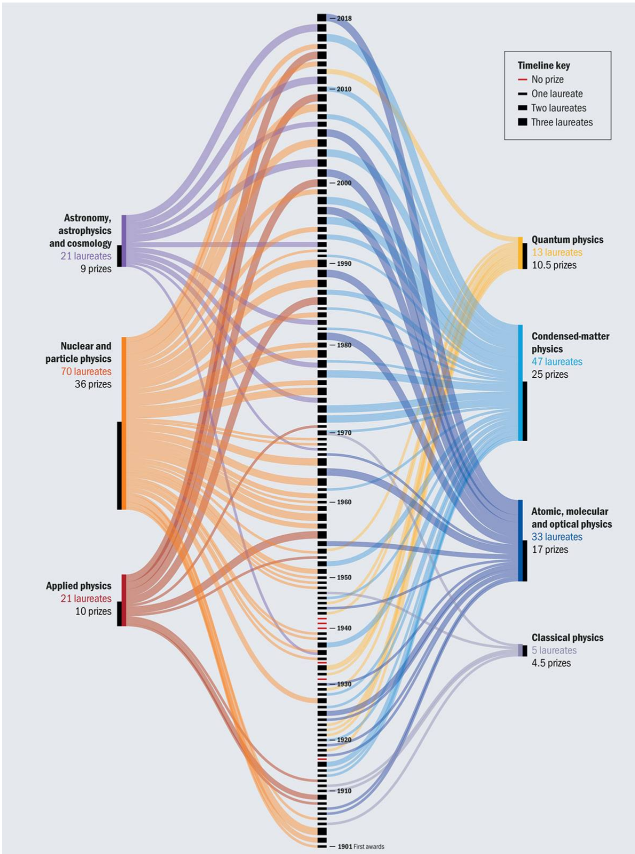
- Material science
- Semiconductor technology
- Quantum information technology (hardware)

Because it is deep.

Many profound ideas in condensed matter physics impact other fields of physics

- *Anderson-Higgs mechanism*. The mechanism of superconductivity also gives mass to elementary particles. (2013 Nobel Prize)
- *Renormalization group*. The idea was developed simultaneously in both high-energy and condensed matter physics. (1982 Nobel Prize)
- *Emergent particles*. Dirac, Weyl, Majorana fermions are found in materials (topological semimetals).
- *Emergent gauge force*. Interacting spins can give rise to gauge bosons as low-energy collective excitation (string-net condensation, U(1) spin liquid).
- *Emergent gravity*. Black-hole physics emerges in interacting fermion systems (Sachdev-Ye-Kitaev model).

Nobel physics prize by field. (credit Physics Word) (click to enlarge)



■ Because reductionism doesn't always work.

- *Reductionism*: we will learn about a system by studying its constituents.

The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact the more elementary particle physicists tell us about the fundamental laws of the universe, the less relevance they seems to have ...

— Philip W. Anderson (1977 Nobel laureate)

- *Emergentism*: interacting constituents can give rise to emergent collective behavior that can not be explained by each individual.

  Example: fractional quantum Hall effect (1998 Nobel prize). A collection of interaction electrons (charge $-e$) can give rise to emergent particles of fractional charge $-e/3$.

■ Central Themes of Condensed Matter Physics

■ Classify Phases of Matter

A central theme of condensed matter physics is to classify (quantum) phases of matter. Two concepts are essential:

- **Order**: the universal *pattern* / *rule* that microscopic constituents are *organized* to form the phase of matter. Each distinct order correspond to a different phase of matter.
- **Excitation**: the emergent low-energy *collective modes* that can be *excited* in the material (which determine the macroscopic property).

Examples of condensed matter systems:

consituents	**phase (order)**	**emergent excitations**
atoms	solid (crystal order)	phonons (2 transverse + 1 longitudinal)
	liquid	phonons (longitudinal)
	superfluid (SSB* order)	2nd–sound phonons
electrons	metal (Fermi liquid)	quasi–electrons (fermions)
	semi–metal	Dirac / Weyl fermions
	superconductor (topological order)	Bogoliubov quasiparticles, Cooper pairs
	topological insulator (SPT† order)	topological edge mode (chiral fermions)
spins	magnet (SSB* order)	magnons
	spin liquid (topological order)	spinons
strings	string liquid (topological order)	gauge bosons (photons / gluons)

* SSB: spontaneous symmetry breaking
† SPT: symmetry protected topological

"**Zeroth law**" of condensed matter physics:

Order determines the emergent **excitations**, **excitations** reflect the underlying **order**.

Understand Phase Transitions

Another theme of condensed matter physics is to understand the phase transitions between different phases of matter.

- **Landau-Ginzburg-Wilson** (LGW) paradigm

  liquid-solid transition, insulator-superfluid transition, metal-superconductor transition, magnetic transition ...

- **Beyond LGW** (frontier of CMP)

trivial-topological insulator transition, spin liquid transition, confinement-deconfinement transition, ...