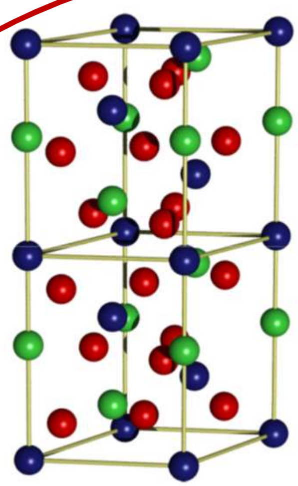
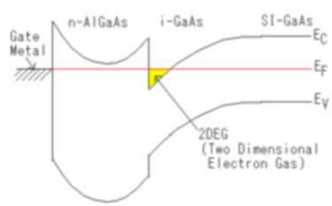
Condensed matter physics is the branch of physics that studies properties of large collections of atoms that compose natural and synthetic materials. Typical questions: phase diagrams, mechanical properties, electrical and heat transport.

In most cases CMP studies perfect crystals but other structures are investigated as well.

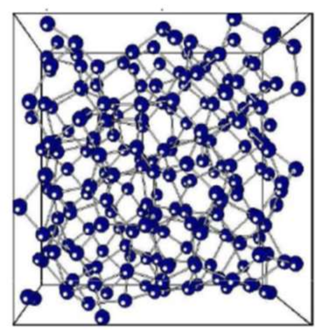
It deals with properties of matter at energy and length-scales that range from microscopic (microKelvin and nanometers) to ordinary chemical and thermal scales to thousands of Kelvin.
The roots of condensed matter lie in the discoveries of quantum mechanics. It overlaps with statistical physics, materials physics, fluid and solid mechanics. Condensed matter physics aims to explain all of the material world.



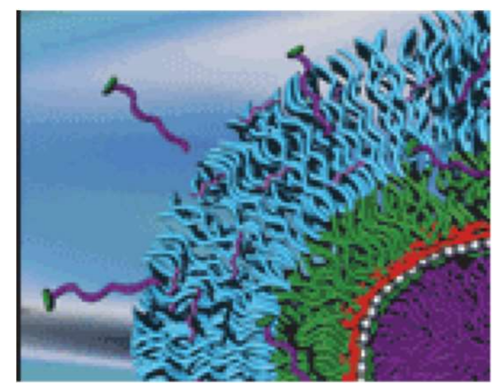
Crystals



Heterostructures



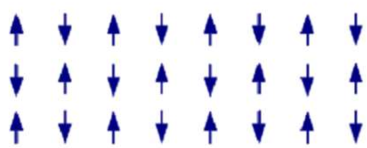
Amorphous materials



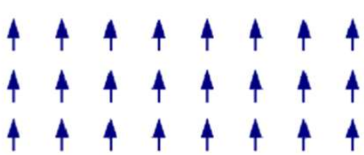
Soft Condensed Matter

Condensed Matter Physics provided intellectual advances that had major impact on science as a whole.
The idea of spontaneous symmetry breaking came first in CMP in understanding magnetism.
It was then applied for superconductivity and finally to high energy physics,
where it is now the basis of the standard model.
Fractional quantum Hall effect gave rise to understanding topological field theories.

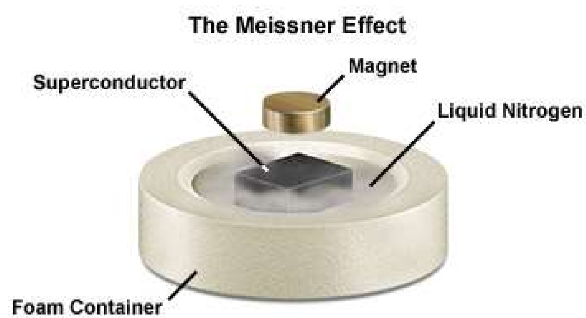
Antiferromagnetism



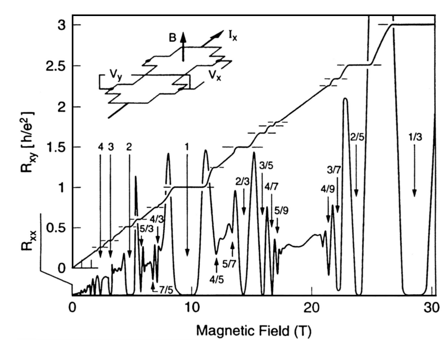
Ferromagnetism



Superconductivity

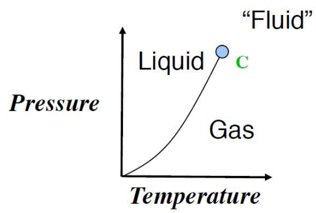


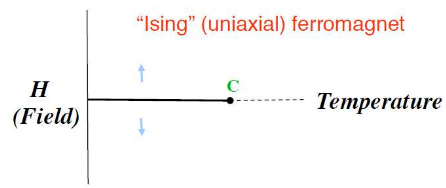
Quantum Hall Effect



Universality of physical phenomena

Universality of thermodynamic properties, phase transitions



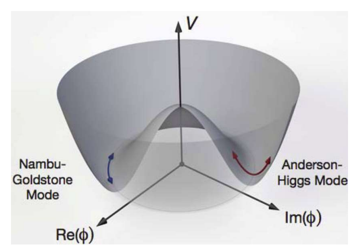


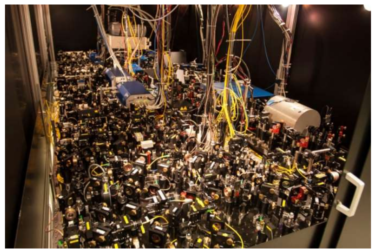
$$\rho_L - \rho_G \sim \left(\frac{T_C - T}{T_C} \right)^{\beta} \qquad M_{\uparrow} - M_{\downarrow} \sim \left(\frac{T_C - T}{T_C} \right)^{\beta}$$

Universality of collective excitations

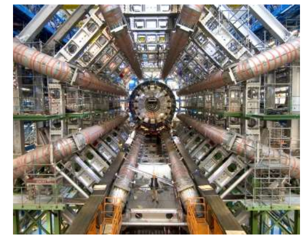
Goldstone modes:
spin waves,
Bogoliubov modes

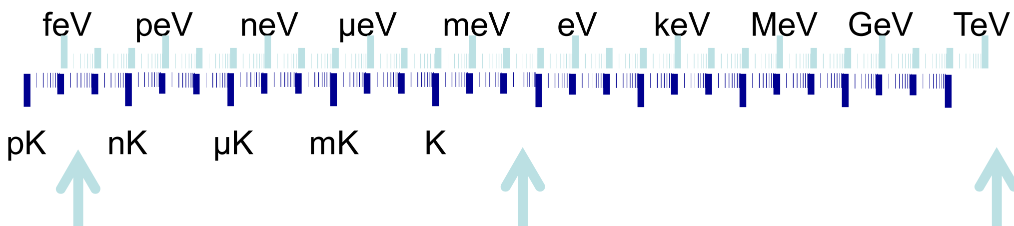
Amplitude Mode:
Anderson-Higgs excitation





Universality of physical phenomena: Higgs mode

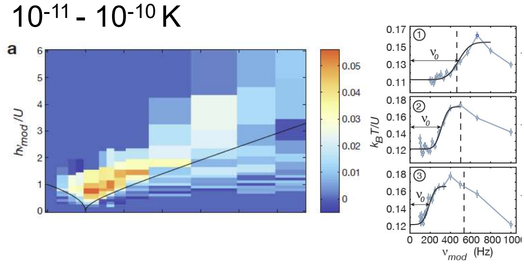




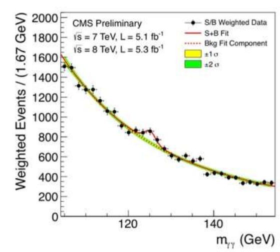
Cold atoms experiments
10^{-11} - 10^{-10} K

room temperature

LHC

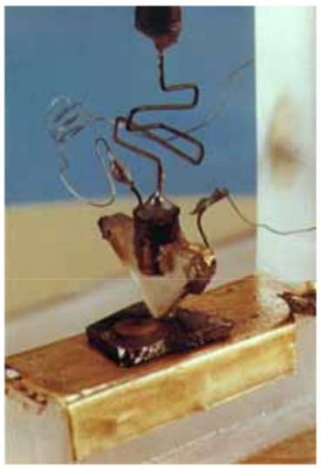


Higgs mode in ultracold atoms, 2012

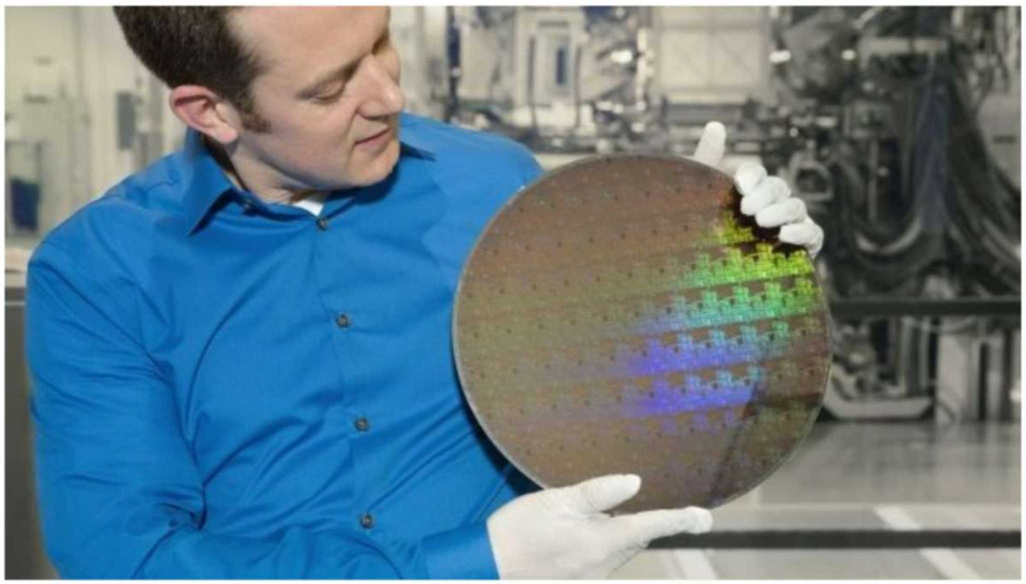


Higgs mode of the standard model, 2012

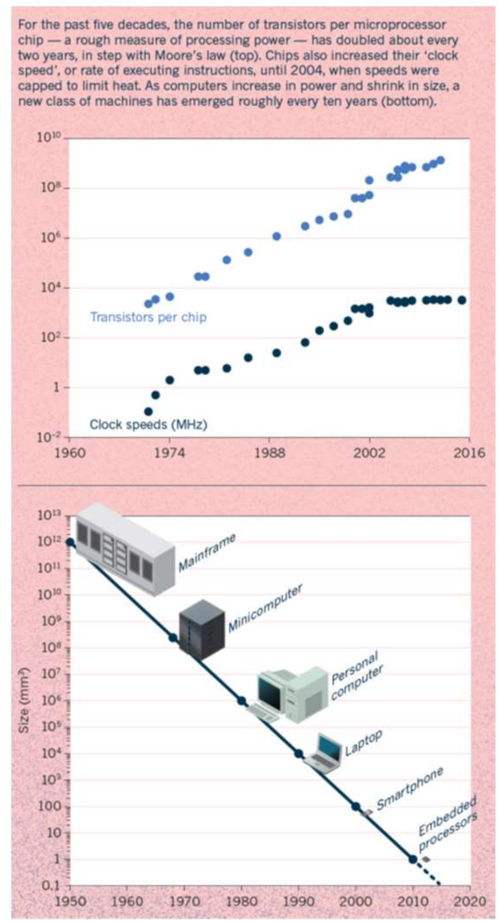
Condensed matter physics plays a central role in many technological and scientific advances of the last decades. Condensed Matter Physics gave birth to the transistor, the first integrated circuit, the laser, the low-loss optical fibers. This made it possible to create a modern computer and communication industries.



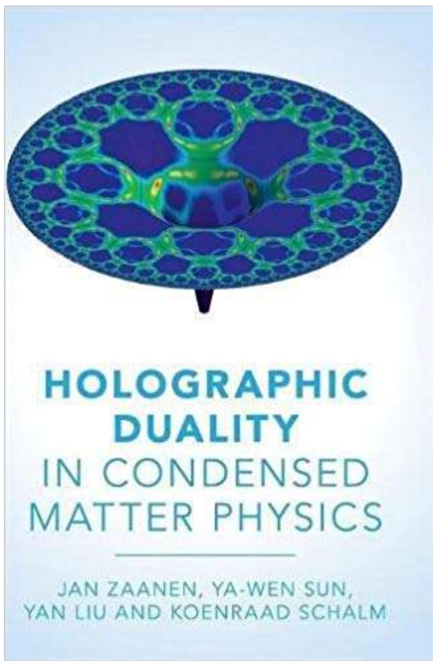
First solid state transistor created at Bell labs

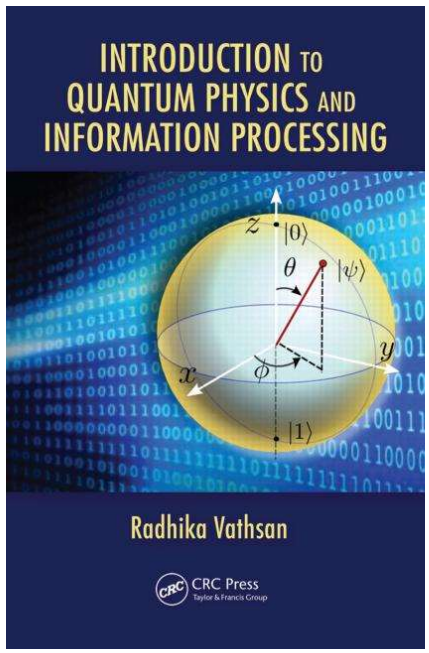


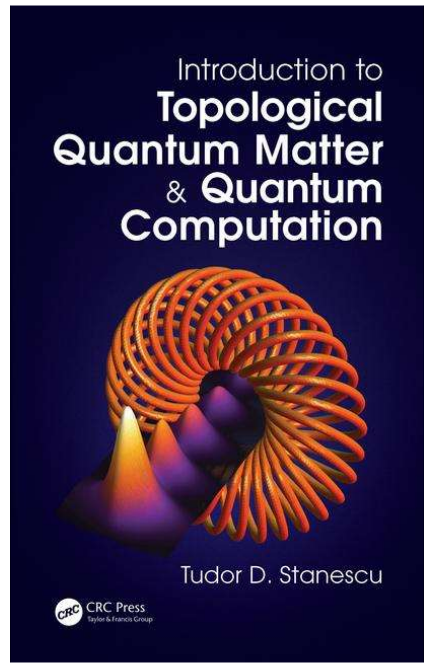
IBM Research scientist Nicolas Loubet holds a wafer of chips with 5nm silicon nanosheet transistors manufactured

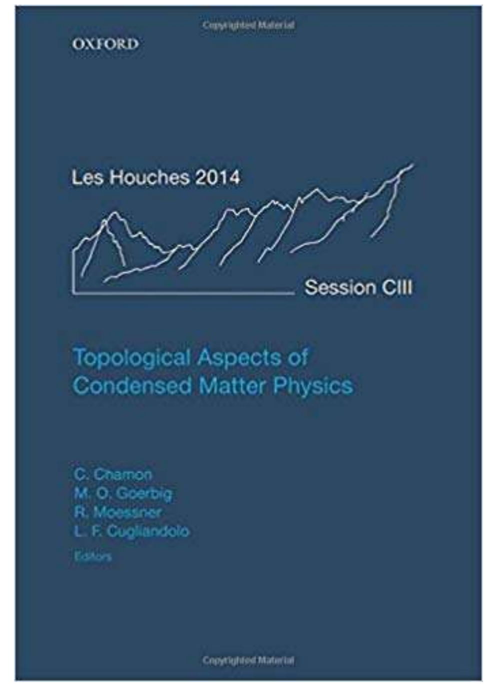


Intellectually condensed matter physics is very vital now. Recent studies find overlaps with string theory, topology, computer science (new field of quantum information), atomic physics, quantum optics, …

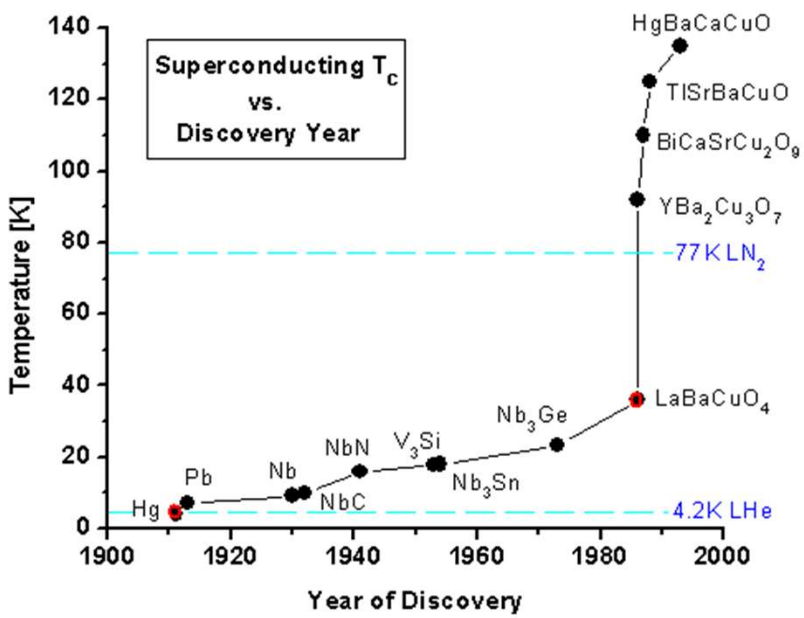




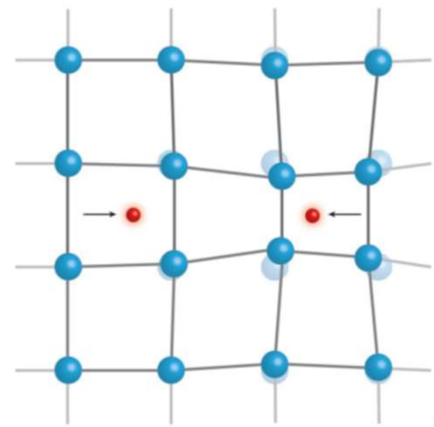




Experiments play a crucial role in Condensed Matter Physics. Nature brings surprises



Prior to discovery of high temperature superconductors, theorists suggested fundamental bounds on Tc

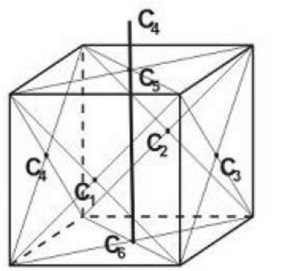


Matthias' rules for discovery of new superconductors

1. high symmetry is good, cubic symmetry is the best
2. high density of electronic states is good
3. stay away from oxygen
4. stay away from magnetism
5. stay away from insulators

We are dealing with complicated systems
and there is no hope to solve them exactly.

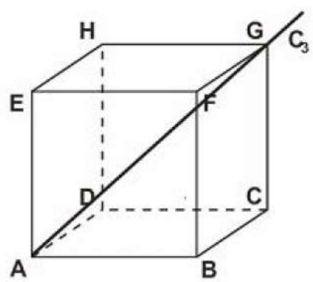
Ideas of symmetry are crucial



– three rotations by 90° ($\mathbf{C}_4$)

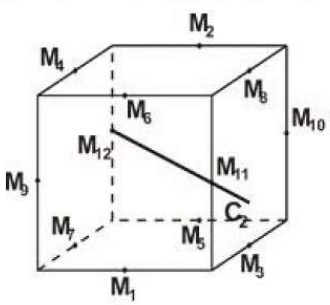
– three rotations by 180° ($\mathbf{C}_4^2$)

– three rotations by 270° ($\mathbf{C}_4^3$)



– four rotations by 120° ($\mathbf{C}_3$)

– four rotations by 240° ($\mathbf{C}_3^2$)



– the picture on the left shows only $\overline{M_{11}M_{12}}$, other possible 2-fold axes are $\overline{M_1M_2}$, $\overline{M_3M_4}$, $\overline{M_5M_6}$, $\overline{M_7M_8}$ and $\overline{M_9M_{10}}$, thus altogether six

We often use simplified models that capture the essential aspects of the phenomena

Tentative Course Outline

1. Crystal structure of solids: Bravais lattices and primitive vectors. Lattices with bases. The reciprocal lattice. Xray and neuron scattering experiments.

2. Free electrons in a periodic potential: Bloch theorem and band structure. Electrons in a weak periodic potential. The tight-binding approximation. Topological aspects of band structures.

3. Electron-electron interactions: Hartree and Hartree-Fock approximations. Density functional theorem. Thomas-Fermi theory. Kohn-Sham equations. Landau Fermi liquid theory.

4. Phonons: Lattice vibrations. The force constant model. Vibrations of a quantum mechanical lattice.

5. Electron transport: dynamics of Bloch electrons. Boltzmann equation.

6. Semiconductors and their applications.

7. Collective phenomena in electron systems: Magnetism. Superconductivity.

Emphasis of this course: models of non-interacting quasiparticles

Primary references

1. A. Abrikosov. *Fundamentals of the theory of metals.*

2. **N. Ashcroft and N. Mermin. Solid State Physics**.

3. E. Kaxiras. *Atomic and electronic structure of solids.*

4. C. Kittel. *Introduction to Solid State Physics.*

5. C. Kittel. *Quantum theory of solids.*

6. G. Mahan. *Condensed Matter in a nutshell.*

7. M. Marder. *Condensed matter physics.*

8. P. Nozieres and D. Pines *The theory of quantum liquids.*

9. J. Ziman, *Theory of solids.*

PHYSICS 295 A Fall 2018

INTRODUCTION TO QUANTUM THEORY OF SOLIDS

Instructor Eugene Demler

email: demler@physics.harvard.edu

Office: Lyman 322

Office hours: Wed 3:00 - 4:00 pm

Teaching Fellow

Jong Yeon Lee email: jlee12@g.harvard.edu

Course Meetings: Mon Wed 10:30 - 11:45 in Jefferson 356

Homework: Weekly or biweekly problem sets

Midterm: October 10

Final Take-Home exam (24-hour): starting on Dec 10 at 11am

Grading: Homework 25%, Midterm 25%, Final Exam 40%, Class participation 10%