What is **Condensed Matter Physics?**

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Physics of condensed phases of matter!

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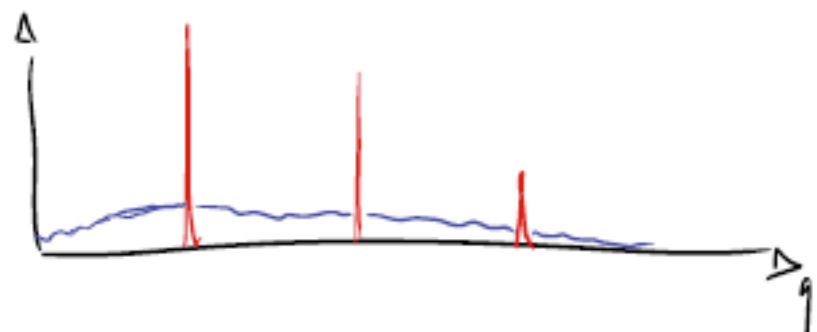
confinement in phase space

real space confinement:
a liquid has a surface
a solid has a *rigid* surface

How X-rays tell the difference between a crystal and a liquid:

$$\rho(q) \sim \sum_n \tilde{\rho}_n \, \delta\left(q - \frac{2\pi n}{a}\right) + \rho_{inc}(q)$$



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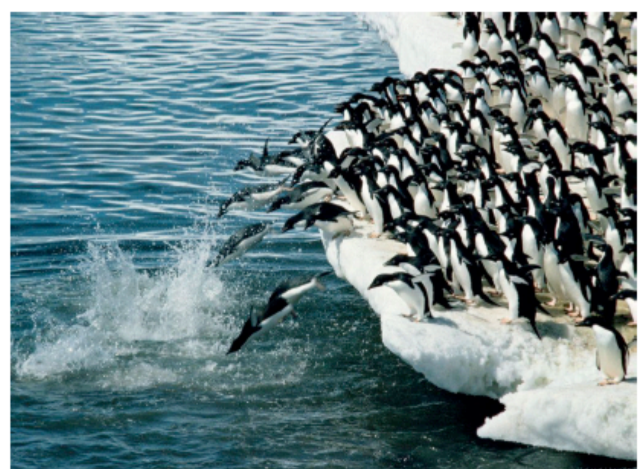
This is how penguins tell the difference between solid and liquid



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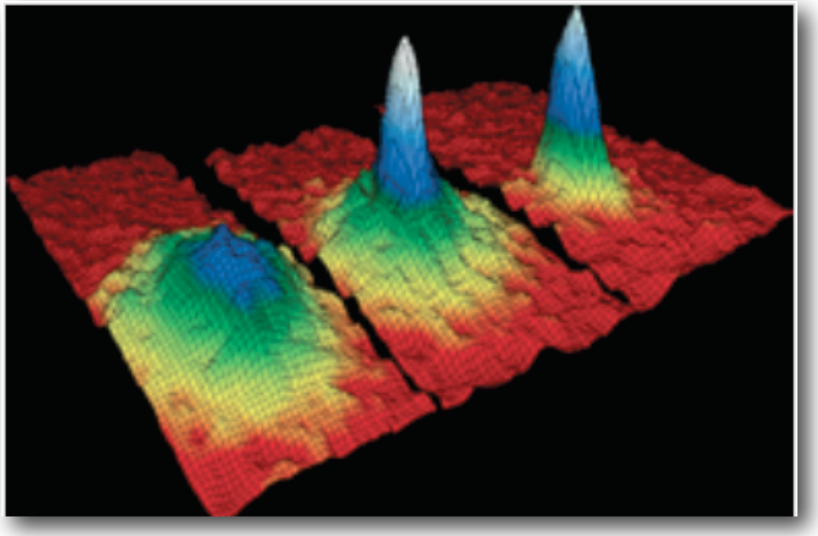
Physics of condensed phases of matter!

confinement in phase space

real space confinement:
a liquid has a surface
a solid has a *rigid* surface

momentum space confinement:
BEC
"degenerate Fermi gas"



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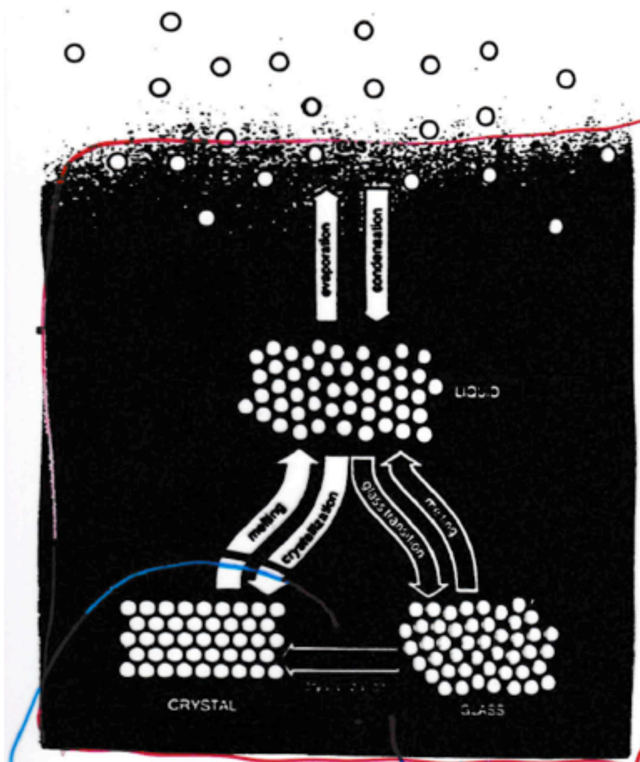
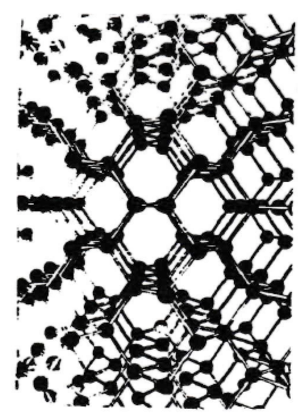


study of <u>structure</u>, <u>response</u> (thermal, electromagnetic,.....) and <u>transitions</u> of matter in liquid or solid phases

"solid state physics" (focus of the course)

properties of "ordinary" crystalline matter



hexagonal lattice
(e.g. silicon crystal)

But... lots of research today focus on other things!

"exotic" states of crystalline matter

high-T_c superconductors, heavy fermions materials,...

quantum liquids

superfluidity, quantum Hall effect, neutron stars,...

"soft matter"

polymers, liquid crystals,...

mesoscopic physics

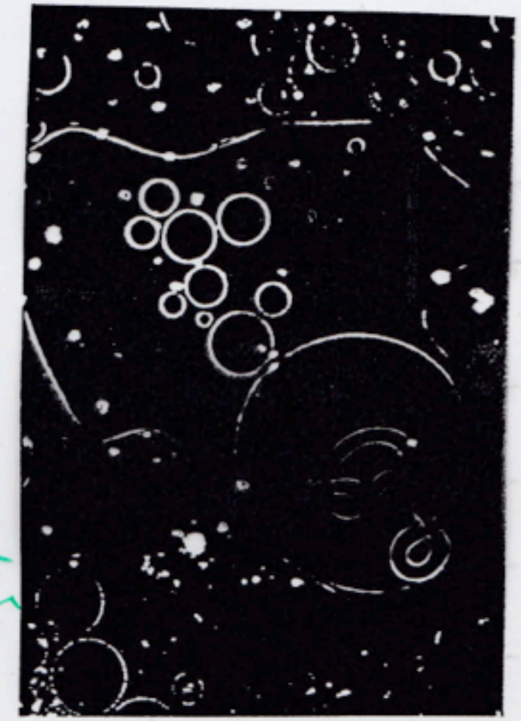
nanoscale artificial structures

surface physics

critical phenomena

"complex systems"

far-from-equilibrium phenomena, biological structures, chaos,...



One of the most important types of biological structure is the lipid bilayer membrane. It provides the enveloping layer for each cell, separating the latter's components from the exterior aqueous medium. This vital cellular 'skin' is a special example of a state of matter that lies between liquid and crystal: the liquid crystal. The molecules of liquid crystal mesogens, as they are called, invariably have elongated shapes. The bubble-like objects shown here are closed surfaces of lipid bilayer membrane, which were produced by hydration of lipids at low ionic strength. Such structures, which serve as experimental model cells devoid of their internal machinery, are known as vesicles.

But... lots of research today focus on other things!

<u>”exotic” states of crystalline matter</u>
high-T_c superconductors, heavy fermions materials,...

<u>quantum liquids</u>
superfluidity, quantum Hall effect, neutron stars,...

<u>”soft matter”</u>
polymers, liquid crystals,...

<u>mesoscopic physics</u>
nanoscale artificial structures

<u>surface physics</u>

<u>critical phenomena</u>

<u>”complex [illegible]</u>
[illegible] phenomena,
[illegible] structures, chaos,...

One of the most important types of biological structure is the lipid bilayer membrane. It provides the enveloping layer for each cell, separating the latter's com[illegible] from the exter[illegible] [illegible] special [illegible] that [illegible] between [illegible] and [illegible] li[illegible]. [illegible]olecules of li[illegible] crystal mesogens, as they are called, invariably have elongated shapes. The bubble-like objects shown here are closed surfaces of lipid bilayer membrane, which were produced by hydration of lipids at low ionic strength. Such structures, which serve as experimental model cells devoid of their internal machinery, are known as vesicles.

Slide from 2002

... since then... lots of new exciting stuff:

superfluid-insulator transition in cold atoms (exp. 2002)
graphene (exp. 2004)
topological insulators (exp. 2006)
topological superconductors (and Majoranas?) (exp. 2012)
Weyl semimetals (exp. 2015)

and much more!

How come that new things keep coming in?
Isn't the **basic theory** already known?

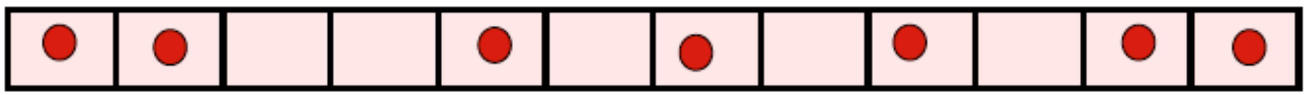
The many-body Schrodinger equation with Hamiltonian (Coulomb's law) should describe most of chemistry and solid state physics.

$$\mathcal{H} = -\sum_{j}^{N_e} \frac{\hbar^2}{2m} \nabla_j^2 - \sum_{\alpha}^{N_i} \frac{\hbar^2}{2M_\alpha} \nabla_\alpha^2 - \sum_{j}^{N_e} \sum_{\alpha}^{N_i} \frac{Z_\alpha e^2}{|\vec{r}_j - \vec{R}_\alpha|} + \sum_{j \ll k}^{N_e} \frac{e^2}{|\vec{r}_j - \vec{r}_k|} + \sum_{\alpha \ll \beta}^{N_j} \frac{Z_\alpha Z_\beta e^2}{|\vec{R}_\alpha - \vec{r}_\beta|},$$

How hard can it get? Isn't this just a messy (and boring!) exercise in quantum mechanics?

So, let's solve this messy exercise…!

Simplified Hamiltonian: n=100 particles on M=200 sites



What is the dimension of the Hilbert space?

Fermions: $dim = \frac{M!}{(M-n)!\,n!} \sim 10^{59}$

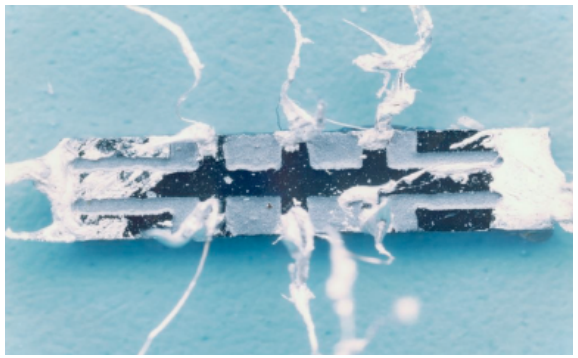
Bosons: $dim = \frac{(M+n-1)!}{(M-1)!\,n!} \sim 10^{81}$

Need to store vectors larger than particle number in the universe !

In generic cases the Hamiltonian is fundamentally unsolvable!
New and surprising things (to us) keep coming in!

Essence of Condensed Matter Physics

Take a piece of junk

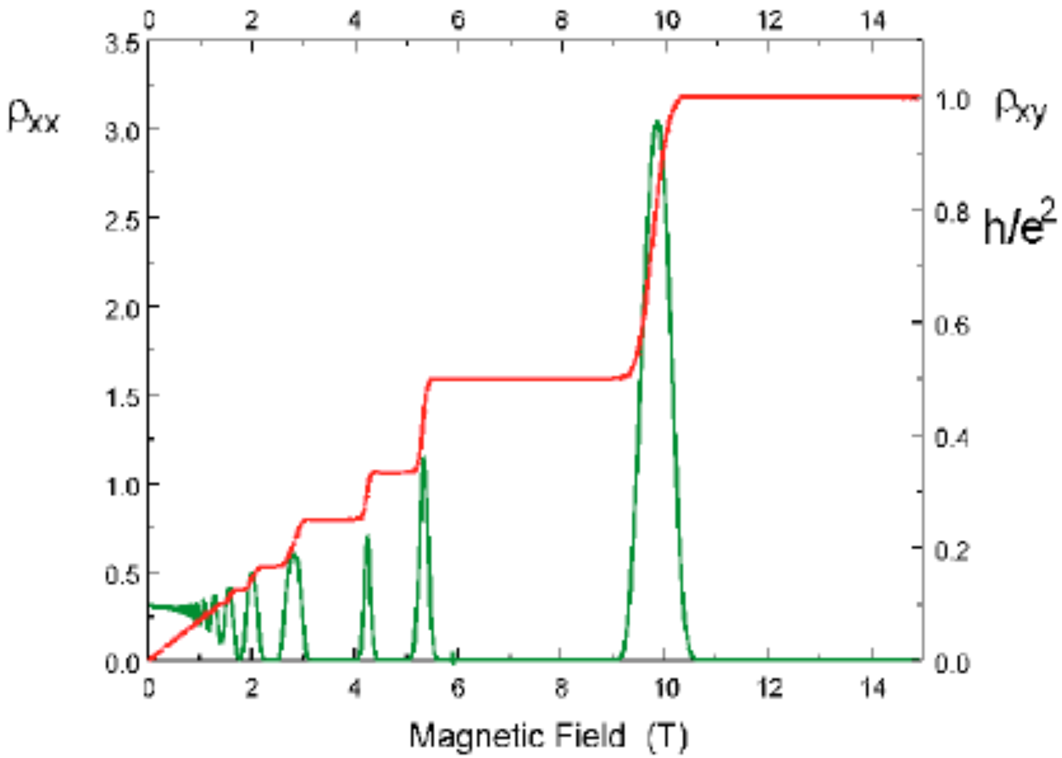


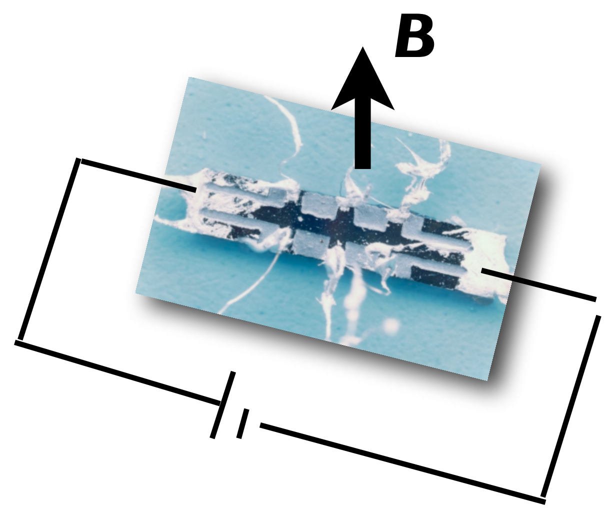
Cool it down (*quantum* condensed matter!)

Measure something

And a miracle happens!

Example: quantum Hall effect



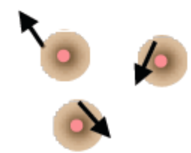


How to understand such beautiful universal data given the complicated mess that is the sample?

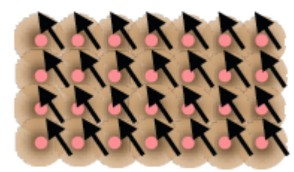
A related miracle (when you think about it!)...

Emergent phenomena of matter at large scales that cannot be directly derived from the underlying fundamental forces

A few Iron atoms are paramagnetic



A chunk of iron is a permanent magnet



Spontaneous symmetry breaking

in the thermodynamic limit, from boundary- and/or initial conditions

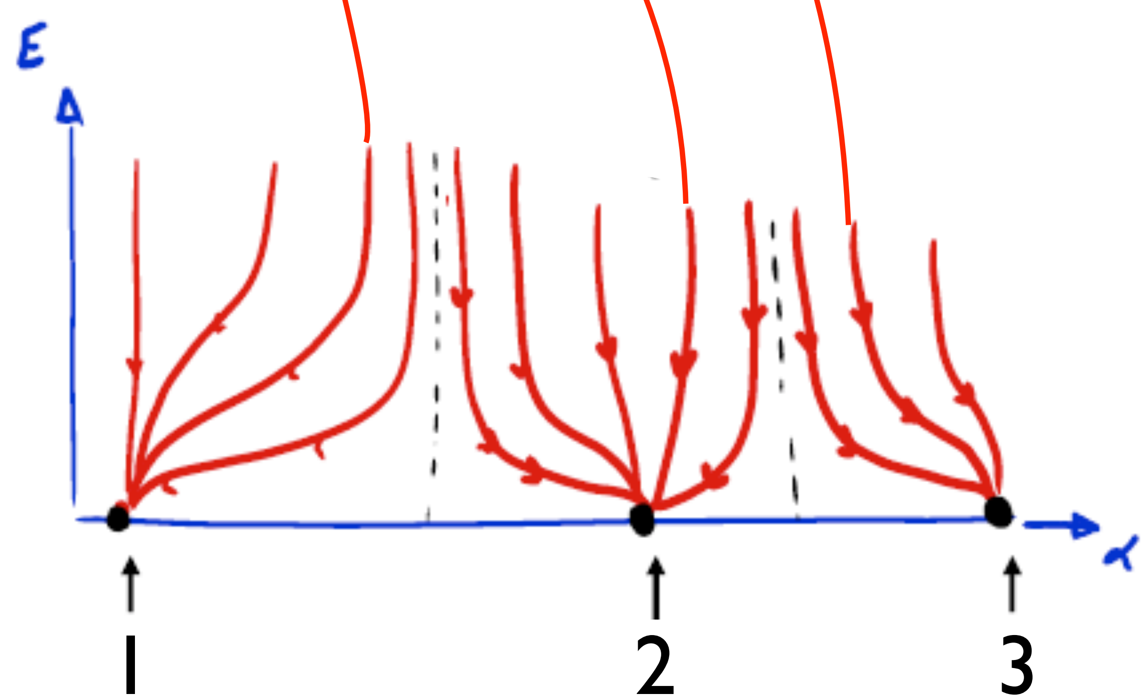
Framework for analyzing emergent phenomena

$$\mathcal{H} = -\sum_{j}^{N_e} \frac{\hbar^2}{2m} \nabla_j^2 - \sum_{\alpha}^{N_i} \frac{\hbar^2}{2M_\alpha} \nabla_\alpha^2 - \sum_{j}^{N_e} \sum_{\alpha}^{N_i} \frac{Z_\alpha e^2}{|\vec{r}_j - \vec{R}_\alpha|} + \sum_{j \ll k}^{N_e} \frac{e^2}{|\vec{r}_j - \vec{r}_k|} + \sum_{\alpha \ll \beta}^{N_j} \frac{Z_\alpha Z_\beta e^2}{|\vec{R}_\alpha - \vec{r}_\beta|}$$

"Renormalization group"

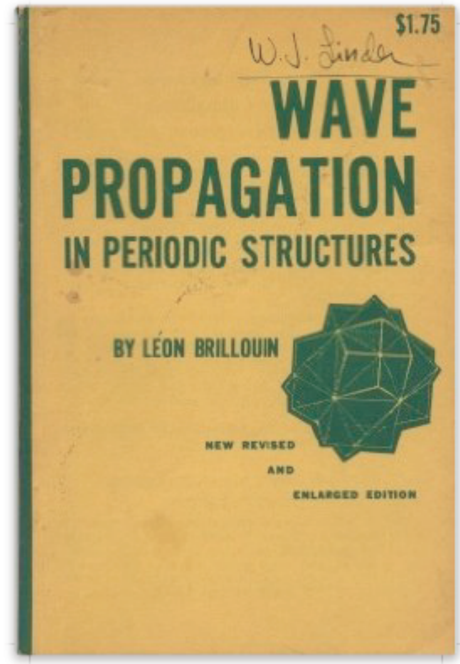
Ken Wilson, Nobel prize 1982

effective low-energy,
long-wavelength theories
1, 2, 3, ...



Example: Loosely bound electrons in a crystal

$$\mathcal{H} = -\sum_{j}^{N_e} \frac{\hbar^2}{2m} \nabla_j^2 - \sum_{\alpha}^{N_i} \frac{\hbar^2}{2M_\alpha} \nabla_\alpha^2 - \sum_{j}^{N_e} \sum_{\alpha}^{N_i} \frac{Z_\alpha e^2}{|\vec{r}_j - \vec{R}_\alpha|} + \sum_{j \ll k}^{N_e} \frac{e^2}{|\vec{r}_j - \vec{r}_k|} + \sum_{\alpha \ll \beta}^{N_j} \frac{Z_\alpha Z_\beta e^2}{|\vec{R}_\alpha - \vec{r}_\beta|}$$



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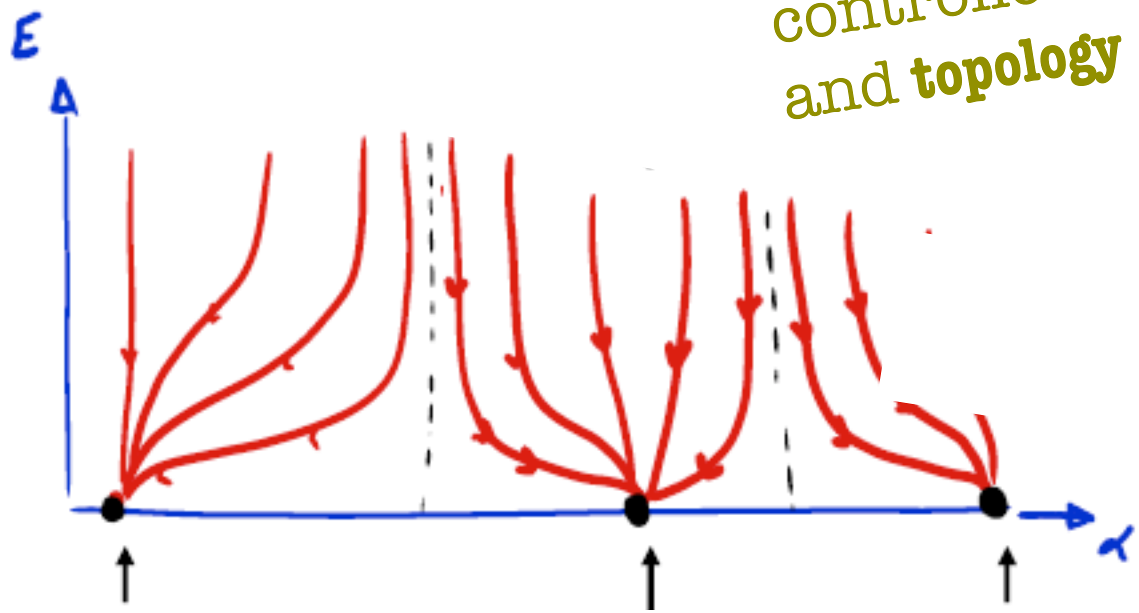
Quantum (low-temperature) condensed phases of matter controlled by **(broken) symmetries** and **topology**



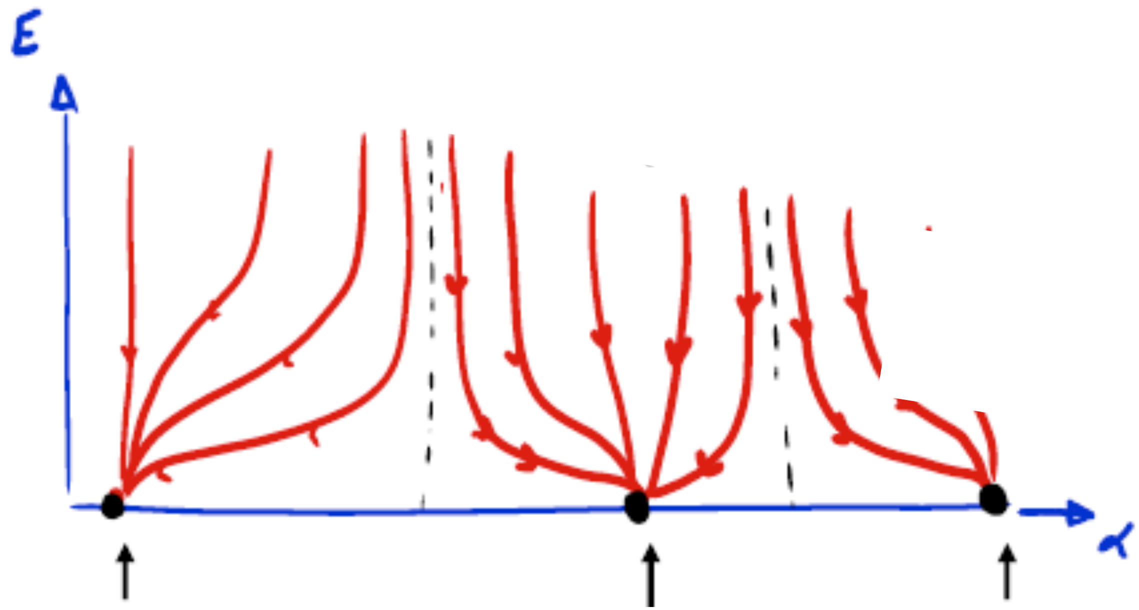
Fermi liquid: quasiparticles in a "smeared" potential; *no* broken symmetry

BCS superconductor: Cooper pairs, broken gauge symmetry

Quantum Hall system: **topologically protected** edge modes

Example: Loosely bound electrons in a crystal

$$\mathcal{H} = -\sum_{j}^{N_e} \frac{\hbar^2}{2m} \nabla_j^2 - \sum_{\alpha}^{N_i} \frac{\hbar^2}{2M_\alpha} \nabla_\alpha^2$$
$$- \sum_{j}^{N_e} \sum_{\alpha}^{N_i} \frac{Z_\alpha e^2}{|\vec{r}_j - \vec{R}_\alpha|} + \sum_{j \ll k}^{N_e} \frac{e^2}{|\vec{r}_j - \vec{r}_k|} + \sum_{\alpha \ll \beta}^{N_j} \frac{Z_\alpha Z_\beta e^2}{|\vec{R}_\alpha - \vec{r}_\beta|}$$



Fermi liquid

starting point of the course:
conduction electrons in a
"smeared" potential

Central topic: structure and response of *METALS*

fascinating properties:

metals are BEATIFUL and SHINY, have HIGH thermal and electrical CONDUCTIVITY, are DUCTILE, and easily form ALLOYS

use of metals historically/technologically important

Bronze age (3000 - 500 B.C.)
Iron age (500 B.C. -)
"Steel age" (1800 -)

"Silicon age" (1980-)
semiconductor!

"Prehistoric" theories

ARISTOTLE: "All metals (gold, silver, cupper, tin, iron, lead) are mixtures of (dry) sulphur and (wet) mercury."

↓

ultimate dream of **the alchemists**:

transform lead to gold!

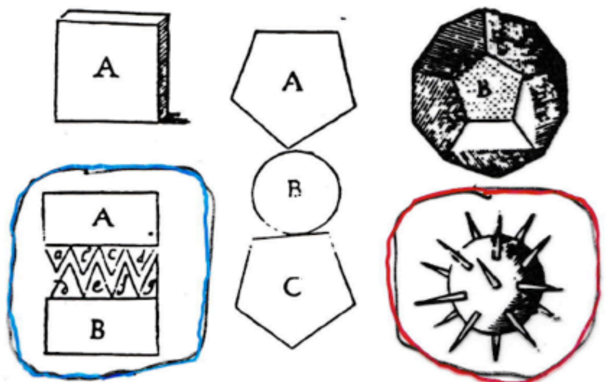
Alchemists laboratory
(Germany, c:a 1580)

"The female Mercury"

"The Male Sulphur"

In the seventeenth century:

revival of **corpuscular theory** (cf. Demokritos' atomism)
Descartes and followers



Conjectural shapes of the particles of matter according to the corpuscular physicist Nicholas Hartsoeker (1696). The spherical ball with attached spikes represents mercuric chloride; the toothed pieces are iron, which is hard when cold because the particles interlock, but is easily forged when heat particles distend the parts so that they can slide over each other.

"There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out.

Now the smallest Particles of Matter may cohere by the strongest Attractions, and compose bigger Particles of weaker Virtue and many of these may cohere and compose bigger Particles whose Virtue is still weaker, and so on for divers Successions, until the Progression end in the biggest Particles on which the Operations in Chymistry, and the Colours of natural Bodies depend, which by cohering compose Bodies of a sensible Magnitude. If the Body is compact, and bends or yields inward to Pression without any sliding of its Parts, it is hard and elastick, returning to its Figure with a Force arising from the mutual Attraction of its Parts. If the Parts slide upon one another, the Body is malleable or soft. If they slip easily, and are of a fit Size to be agitated by Heat, and the Heat is big enough to keep them in Agitation, the Body is fluid. . . ."

Isaac Newton ("Opticks", 1718)

BUT... after Newton ("Principia"!), all theories on solids disappear from Physics for almost 200 years!

Philosophical speculations replaced by **Crystallography** & **Metallurgy**
in the nineteenth century

The earliest photomicrograph of a piece of wrought iron. Made by Henry Clifton Sorby in Sheffield in August 1864. Sorby's work showed conclusively that deformation did not destroy crystallinity.

collects lots of empirical facts about
solids in general and metals in particular

⇓

increasing demand for a **theory of metals!**

c:a 1900: some physicists (Paul Drude and others) make a try...
inspired by
the new "statistical physics" of Boltzmann (1880)
&
the discovery of the electron (Thomson, 1895)

⇓

classical theory of conductivity of metals

- x-ray diffraction → crystal strcture
  (von Laue, 1912)
- theory of specific heat of metals
  (Debye, Einstein, 1913)

1925 - 28 : Quantum Mechanics
(Schrödinger, Heisenberg, Dirac, Pauli,...)

⇓

"SOLID STATE PHYSICS"

- quantum mechanical transport theory (Bloch, 1928)
- band theory, incl. theory of semiconductors
  (Bloch, Peierls, Brilluoin, Wilson,... 1928-33)
- magnetism (Pauli, Landau, Heisenberg,... 1928-33)
- detailed applications to real solids (1933-....)

"...the greatest failure of the theory is the absence of a point of view that allows one to grasp the interaction between the conduction electrons."

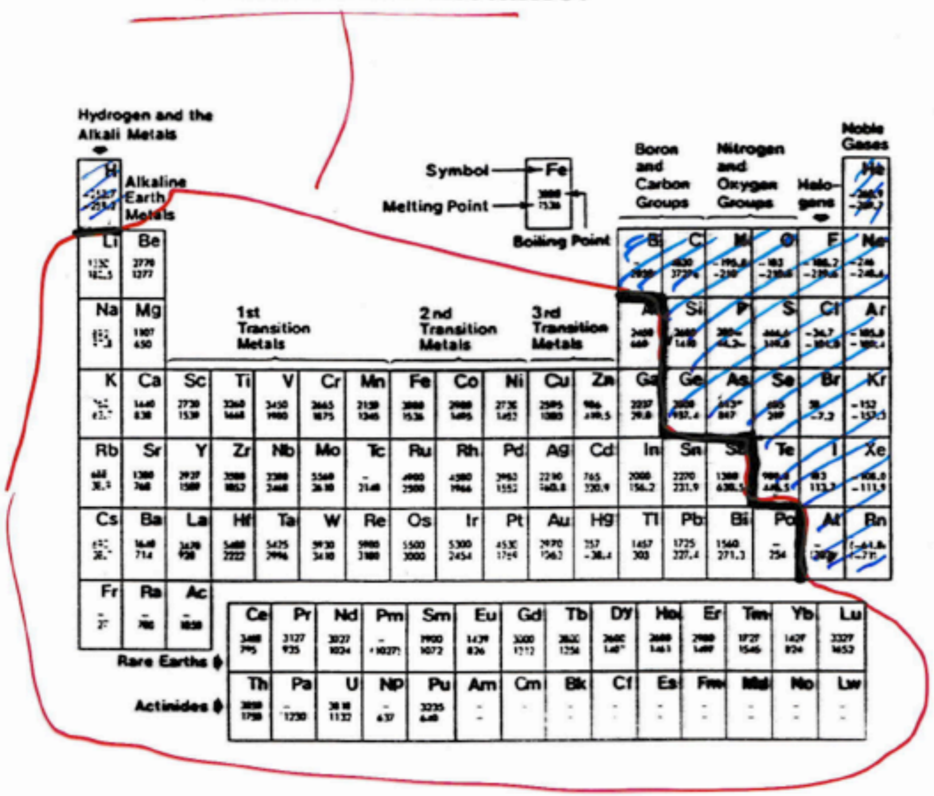
Felix Bloch
1933

- "many-body theory" (Migdal, Landau, ... late 50:s)

But why all this fuss about **metals**?

The <u>metallic state</u> is one of the fundamental states of matter!

Most of the elements are metallic!



typically low ionization energies

↓

weakly bound valence electrons

↓

formation of "electron liquid" in the metallic state

basically explains metallic properties

"Just which heavy metal did you say Edwards is researching?"

~1/3 of all physicists in the US work in CMP

Condensed matter physics is a big & important field

Gives a "fundamental" (quantum mechanical) basis for continuum mechanics, optics, hydrodynamics, metallurgy, solid state chemistry, electronics, materials science,...

Drives <u>new technology</u>

- the transistor
- superconducting magnets
- solid-state lasers
- novel materials
- NMR tomography
- fiber optics
- magnetic storage
- liquid crystal displays

and lots more!

The first transistors assembled by their inventors, John Bardeen, Walter Brattain, and William Shockley, at Bell Laboratories, were primitive by today's standards, but they revolutionized the electronics industry. This example, the original point-contact version, made its debut on 23 December 1947. It amplified electrical signals by passing them through a solid semiconductor material, basically the same operation performed by present junction transistors.

Generates models, methods, and concepts for describing systems with a large number of degrees of freedom

hard problem!
common with *biology, computer science,...*
and other fields of physics
(astrophysics, particle physics,...)