PHYS 666: Solid State Physics I

INSTRUCTOR

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Office Hours: I am around Tuesdays and Thursdays
Web page with lecture notes: www.niu.edu/~veenendaal/666.htm

PREREQUISITES:

This course will be tough without having done quantum mechanics (560/1 or something equivalent)

Mathematical concepts:

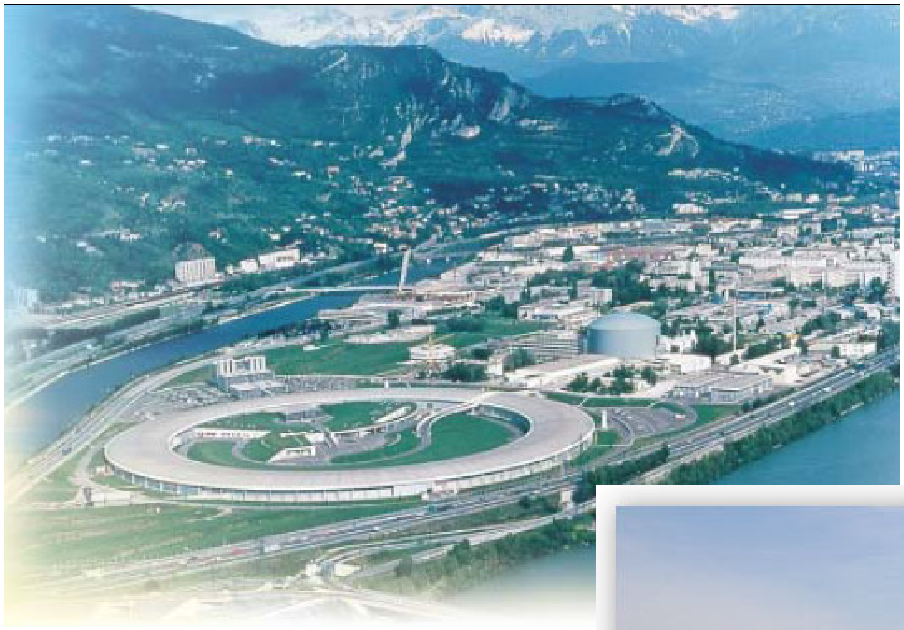
Fourier transforms
differential equations (Schrödinger equations)
linear algebra (matrices, eigenvalue problems)

- Homework: several homework sets will be given. They will be posted on the web site.
- Midterm: one midterm will be given.

- 1986-90: undergraduate Delft University of Technology (Ir.), the Netherlands
- 1990-94: Ph.D. University of Groningen (Dr.), the Netherlands
- 1994-97: European Synchrotron Radiation Facility, Grenoble, France
- 1997-98: NIU
- 1998-2002: Philips Electronics
- 2002-present: NIU
  - 2002-2008 Associate Professor
  - 2008- Professor
  - 2009-2013 Presidential Research Professor
- 2005-present: joint with Argonne National Laboratory (Physicist)

Theoretical physicist
specialty: condensed matter physics

ESRF

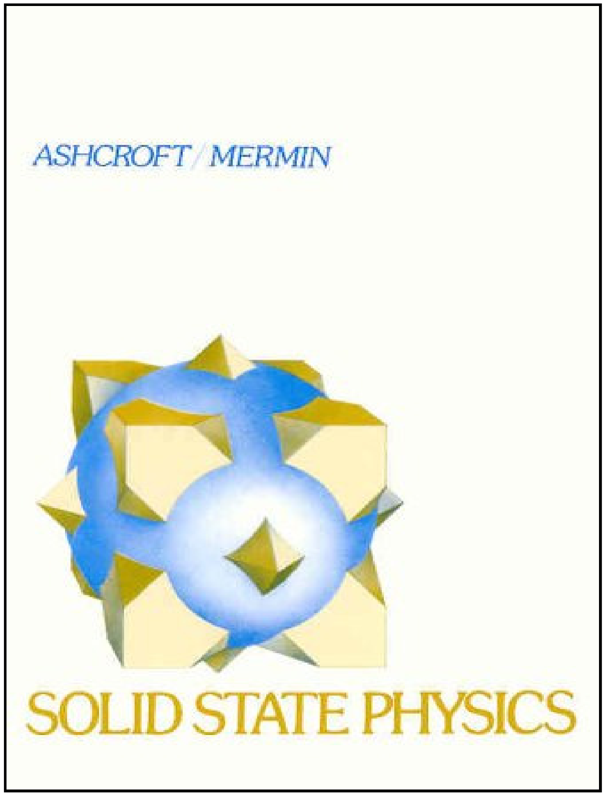


APS


Argonne Central Campus
Central Lab/Office Bldg.
APS Conference Center
Argonne Guest House
Center for
Nanoscale Materials
Booster/
Injector
Linac
Storage Ring
Experiment Hall
Lab/Office Module

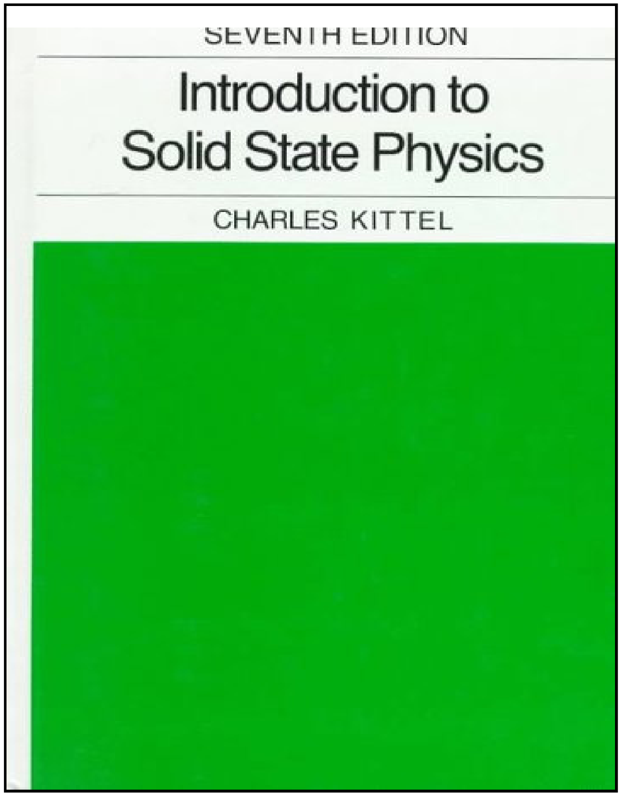
REQUIRED TEXTBOOK:

Solid State Physics
by N. W. Ashcroft and N. D. Mermin
(Harcourt, 1976).



REFERENCED TEXTBOOK

Introduction to Solid State Physics
7th Edition by C. Kittel
(John Wiley & Sons, 1996).



Solid State Physics vs. Condensed-Matter Physics

- Condensed-matter physics is the more modern term
- Condensed-matter physics is broader and applies to concepts that work in solids, but could equally applied to liquid (for example, superconductivity vs. superfluidity, soft-condensed matter)
- 1978 Division of Solid-State Physics of the American Physical Society went to the Division of Condensed-Matter Physics
- 1/3 of U.S. physicists classify themselves as Condensed-Matter Physicists
- Condensed-matter physics is closely related and overlaps with inorganic chemistry, physical chemistry, quantum chemistry, electrical and mechanical .

WHY DO WE WANT TO DO SOLID STATE PHYSICS?

http://www.er.doe.gov/bes/reports/list.html

Reports from
Basic Energy Sciences
Department of Energy

Steve Chu,
Secretary of Energy
1997 Nobel Prize in Physics

- A significant increase in the rate of discovery, innovation and technological change is needed. BES must lead a bold new initiative focused on solving the critical scientific roadblocks in next-generation, carbon-free energy technologies.

- Significant discoveries will come at the intersection of control science with advanced materials and chemical phenomena, and there is a clear first-mover advantage to those who focus their research efforts here. BES must lead U.S. energy research efforts in this direction lest the U.S. fall behind in global competition for discoveries of future energy sources and systems.

- It will take "dream teams" of highly educated talent, equipped with forefront tools, and focused on the most pressing challenges to increase the rate of discovery. BES must lead the development of these dream teams to close gaps between needs and capabilities in synthesis, characterization, theory, and computation of advanced materials.

- U.S. leadership requires BES to lead a national effort to aggressively recruit the best talent through a series of workforce development and early career programs aimed at inspiring today's students and young researchers to be the discoverers, inventors, and innovators of tomorrow's energy solutions.


Directing Matter and Energy:
Five Challenges for Science and the Imagination
Opportunities for Discovery:
Theory and Computation
in Basic Energy Sciences
Basic Research Needs
for Solar Energy Utilization
Basic Research
Needs for
Electrical
Energy Storage
Report of the Basic Energy
Sciences Workshop on
Electrical Energy Storage
April 2-4, 2007
BASIC RESEARCH NEEDS:
CATALYSIS FOR ENERGY
Report from the
U.S. Department of Energy
Basic Energy Sciences Workshop
August 6-8, 2007

Nanoscience

Catalysis, photosynthesis

Batteries

Superconductivity

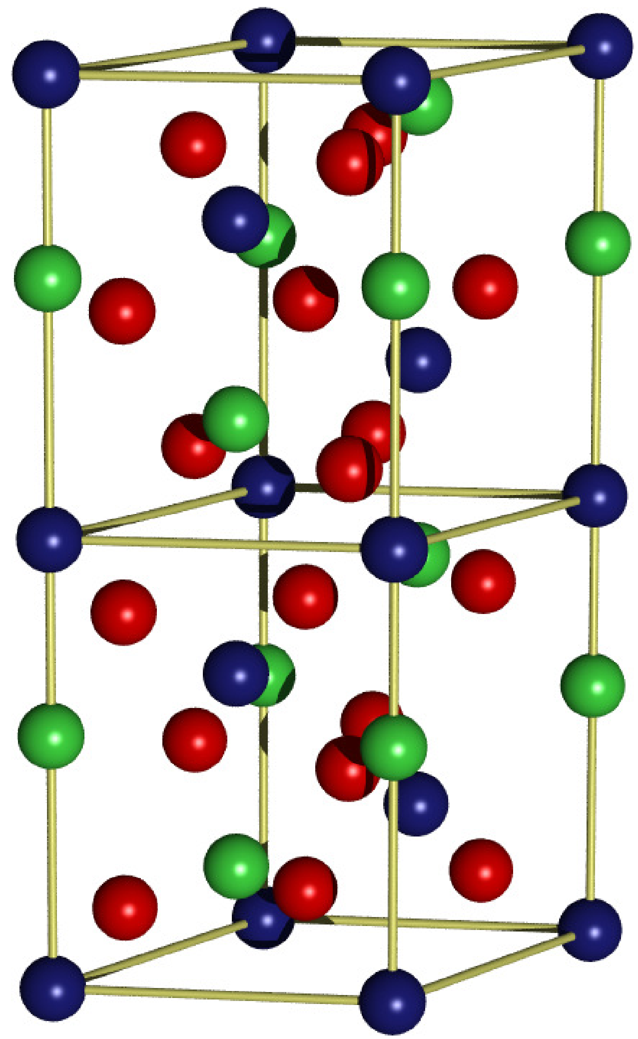
Solid-state lighting

Solar cells

New electrode materials

WHAT IS A SOLID?

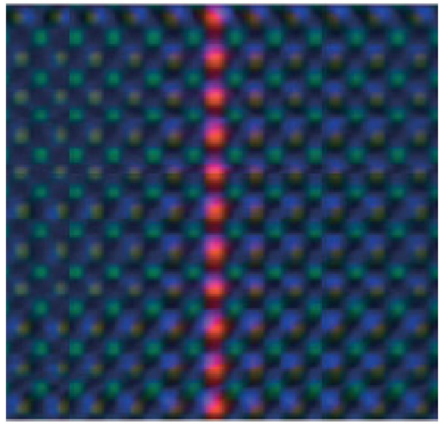
A solid is generally seen as a nice crystal made up of atom



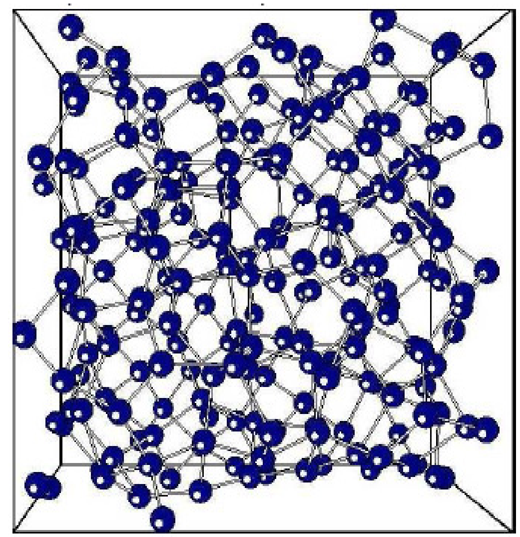
And we will generally be dealing with those

BUT ALSO

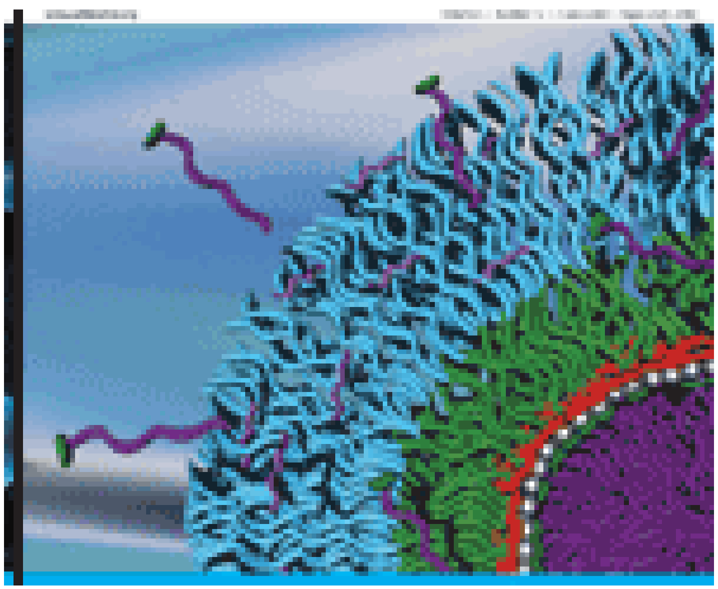
heterostuctures

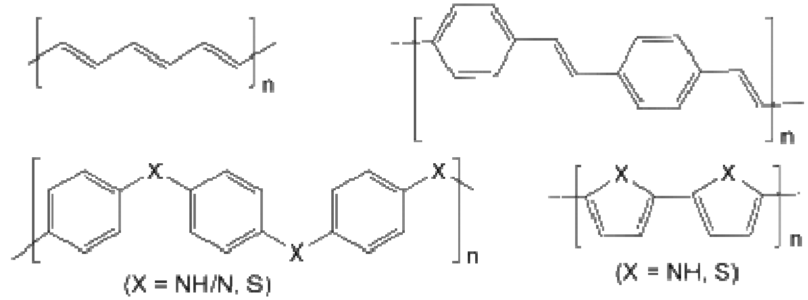


Amorphous materials



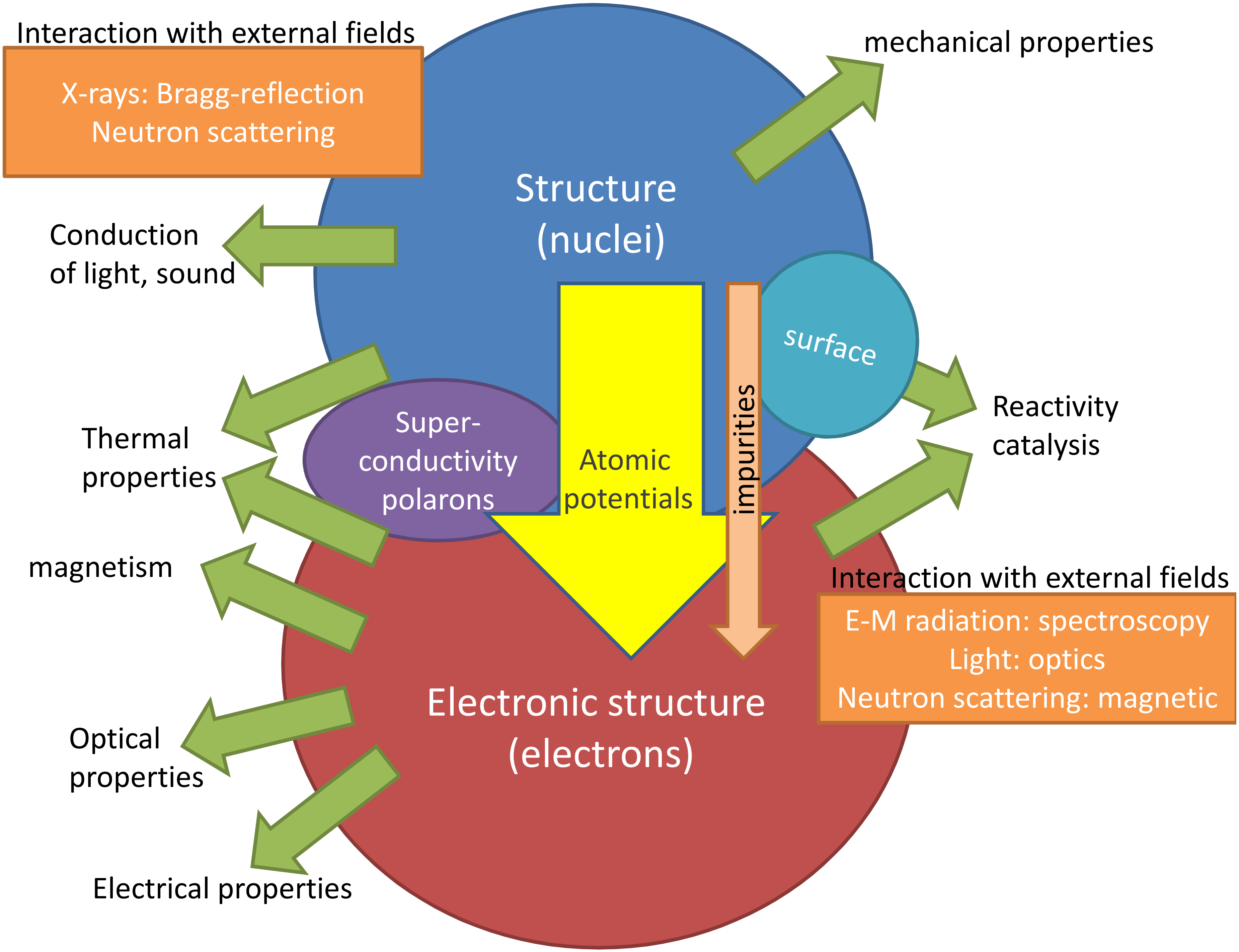
Soft condensed matter





Conducting polymers

Before you are able to deal with this, we have to get through the basics


Interaction with external fields
X-rays: Bragg-reflection
Neutron scattering
mechanical properties
Structure
(nuclei)
Conduction
of light, sound
surface
Thermal
properties
Super-
conductivity
polarons
Atomic
potentials
impurities
Reactivity
catalysis
magnetism
Interaction with external fields
E-M radiation: spectroscopy
Light: optics
Neutron scattering: magnetic
Electronic structure
(electrons)
Optical
properties
Electrical properties

HISTORY OF SOLIDS….

Whole ages are classified by our ability to control solids

17th century BC.

China (1600–1046 BC).

Stone age

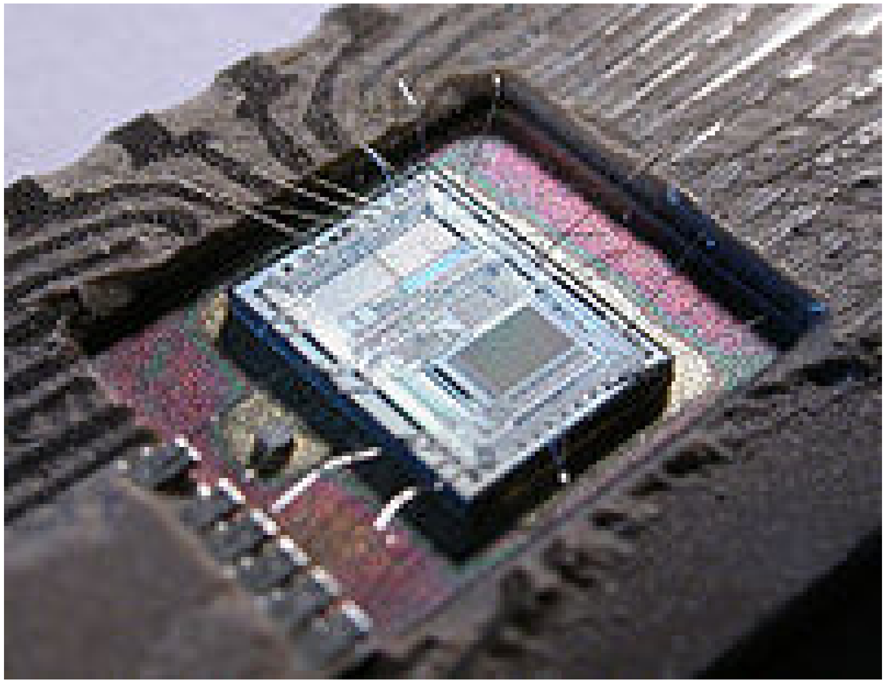
bronze age

(3300–1200 BC)

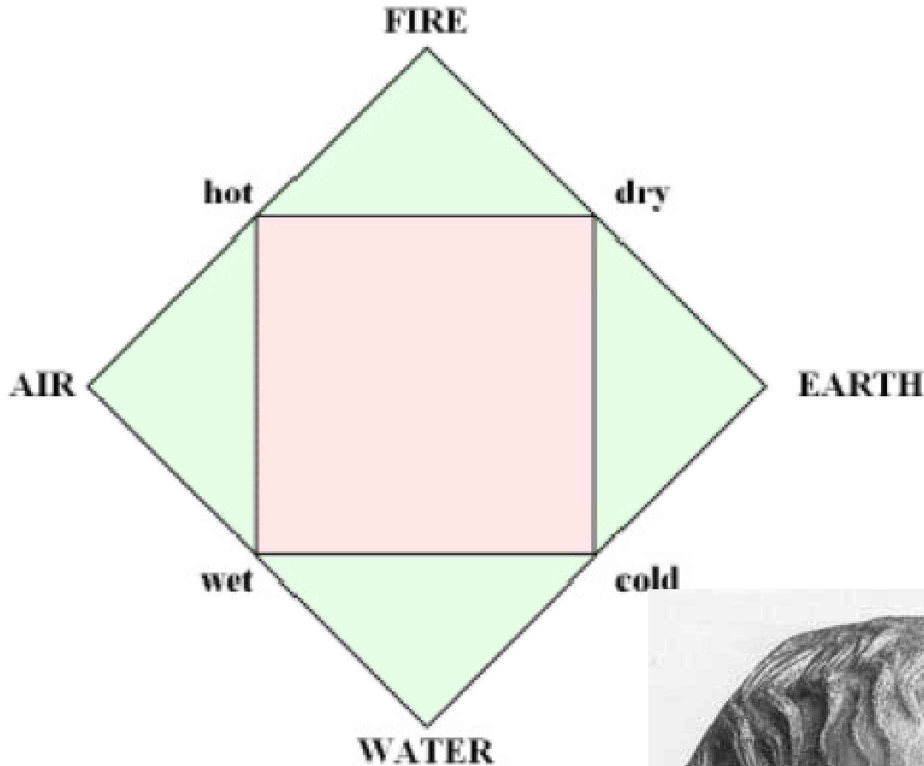
iron age

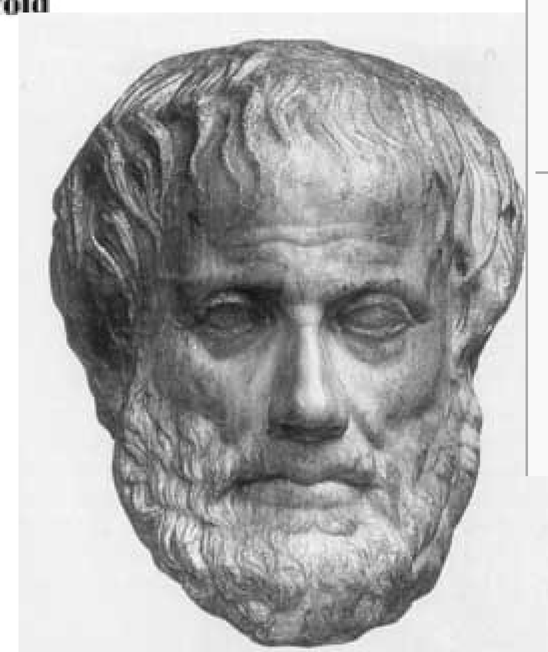
(1200 BC till present?)

Even our information age relies on our ability to manipulate materials (Si)



Ancient cultures:





Aristotle (384 BC – 322 BC)

Hinduism (Tattva) and Buddhism (Mahābhūta)

	Vayu/Pavan (Air/Wind)	
Ap/Jala (Water)	Akasha (Aether/Space)	Agni/Tejas (Fire)
	Prithvi/Bhumi (Earth)	

Japanese (Godai)

	Air/Wind (風)	
Water (水)	Void/Sky/Heaven (空)	Fire (火)
	Earth (地)	

Tibetan (Bön)

	Air	
Water	Space	Fire
	Earth	

Modern: solid, liquid, gas, combustion/chemical reactions

Alchemy workshop illustration from
Opus medico-chymicum: continens tres tractatus sive basilicas...,
Johann Mylius, Francofurtu: Hemannum a Sande, 1678

People recognized early on the difference in properties between metals

Philosopher's stone turning common metals into gold

EARLIER THEORIES TO DESCRIBE SOLIDS

Obviously, scientists tried to deal with solids before atoms and electron

- Mechanics
- Optical properties
- Thermal conductivity
- Conductive properties

Many of these questions can be addressed without understanding the underlying nature of a material

Of great importance is the strong development of calculus and differential equations starting from Newton and Leibniz, through Euler (1707 –1783) , Gauss (1777 –1855) through the French schools (Ecole polytechnique/normale/militaire):
Lagrange (1736–1813), Laplace (1749–1827), Fourier (1768–1830),
Navier (1785– 1836) , Cauchy (1789 –1857), Poisson (1781–1840), etc.

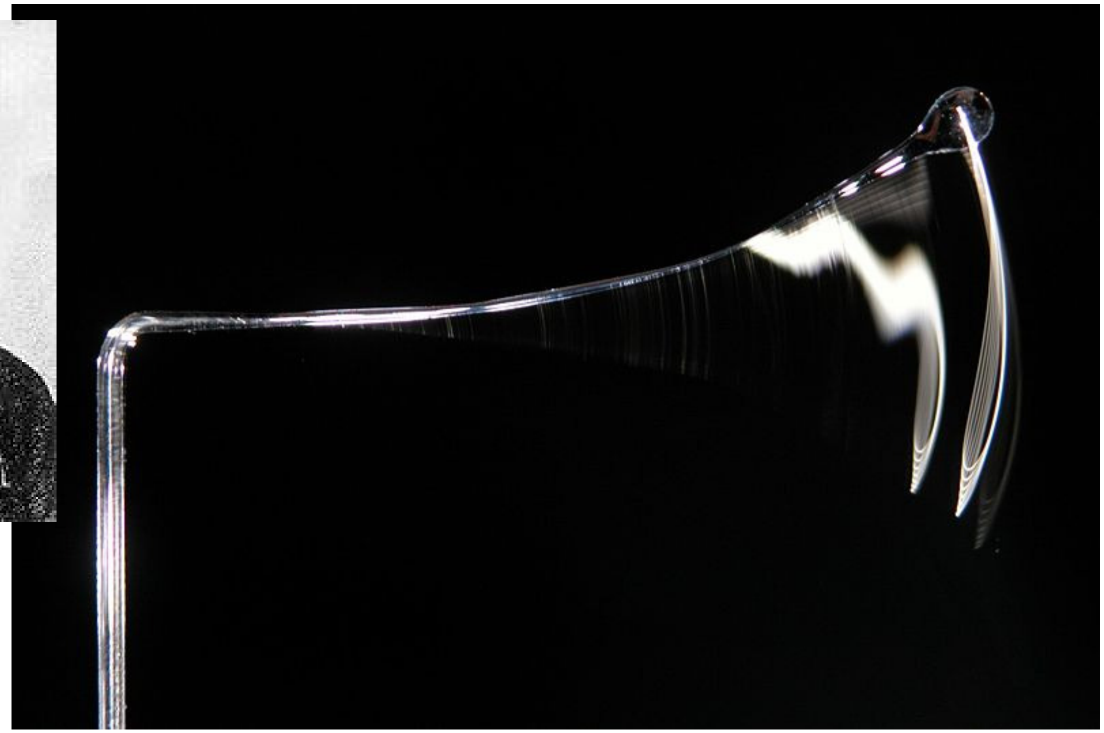
Condensed-matter physics tries to connect the properties of the nuclei and electrons to the macroscopically observed quantities

Continuum mechanics

Hooke's law $$\mathbf{F} = -k\mathbf{x}$$ (1676)

Ut tensio, sic vis As the extension, so the force.





Euler-Bernoulli equation:

(1750)

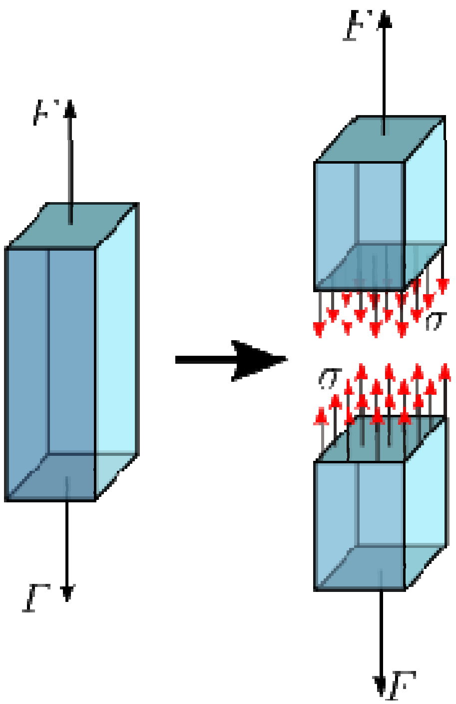
$$\frac{\partial^2}{\partial x^2}\left(EI\frac{\partial^2 u}{\partial x^2}\right) = w.$$

u deflection of the beam at some position *x*
w is a distributed load or a force per unit length
E is the elastic modulus
I is the second moment of area

Cauchy stress tensor

$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \equiv \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} \equiv \begin{bmatrix} \sigma_{x} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{y} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{z} \end{bmatrix}$$

Augustin Louis Cauchy (1789 –1857)



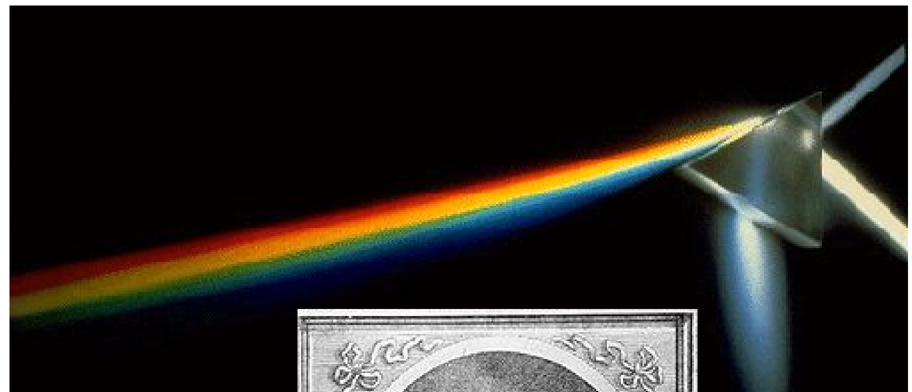
(1822)

How are the underlying atomic properties related to the elasticity?

Interactions of radiation and matter

Reflections, color, refraction, absorption are all manifestations of interactions of radiation and matter

Euclid (~300 BC) already wrote a book on Optics



Lenses: Lippershey, Janssen, Galileo

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

Snell's law is a direct consequence of the electronic properties of the material

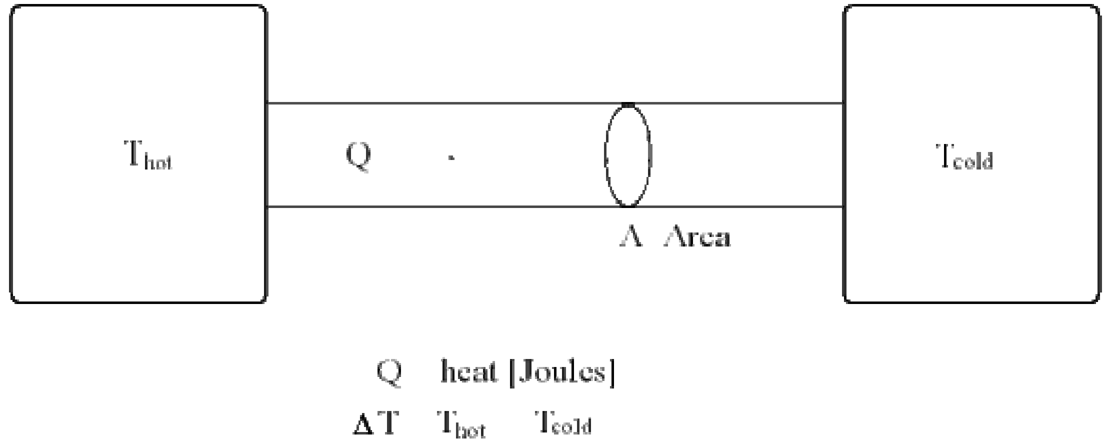
What determines the optical properties of a material: opaque, reflecting, transparent?

Late 18th and 19th century:
mechanical approach to condensed matter physics

• optical theories by Thomas Young and Jean Fresnel

• A wide variety of theories on elasticity (Navier, Cauchy)
• Theories for heat conductivity by Joseph Fourier

Thermal conductivity



Newton's law of cooling

$$\frac{dQ}{dt} = h \cdot A(T_{\text{env}} - T_0)$$

(1643-1727)

Fourier's law

$$q_x = -k\frac{dT}{dx}$$

(1822)

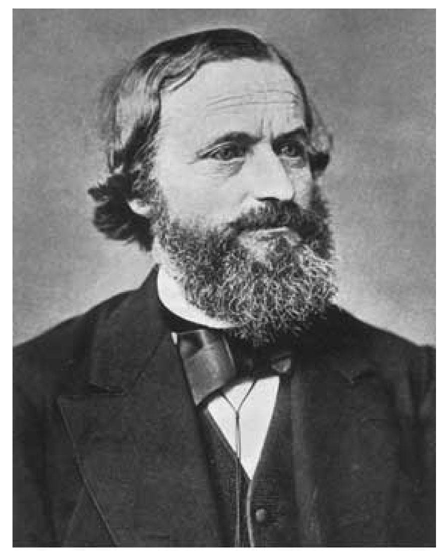
q is the local heat flux,
k is the material's thermal conductivity
dT/dx is the temperature gradient

Joseph Fourier (1768–1830)

Why do materials have different thermal properties?

• Interaction between light and matter, theory of birefringence by Franz Neumann

• Early theories of electrical conductivity by, among others, George Ohm and Gustav Kirchhoff



Library of Congress

Crystal structures

• First scientific approach René-Just Haüy (1743-1822) using an atomistic picture

• Extended by Christian Samuel Weiss, introduced crystallographic axis

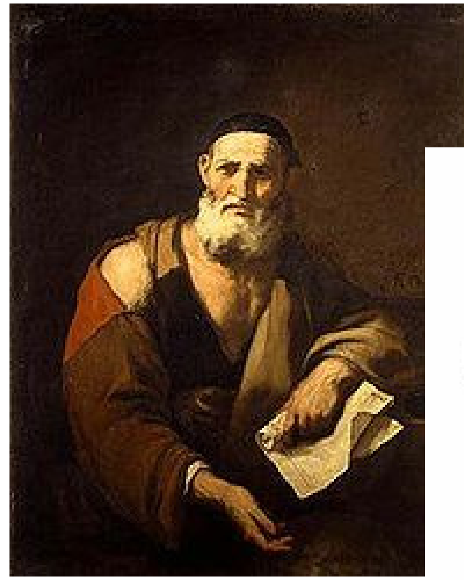
• Auguste Bravais: discovered the 14 space lattice types

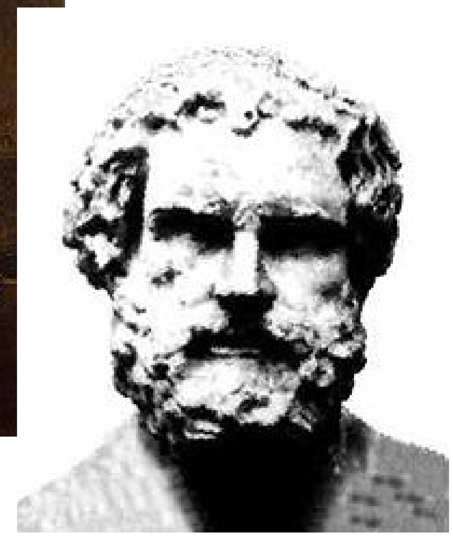
• Woldemar Voigt classified the 230 different space groups

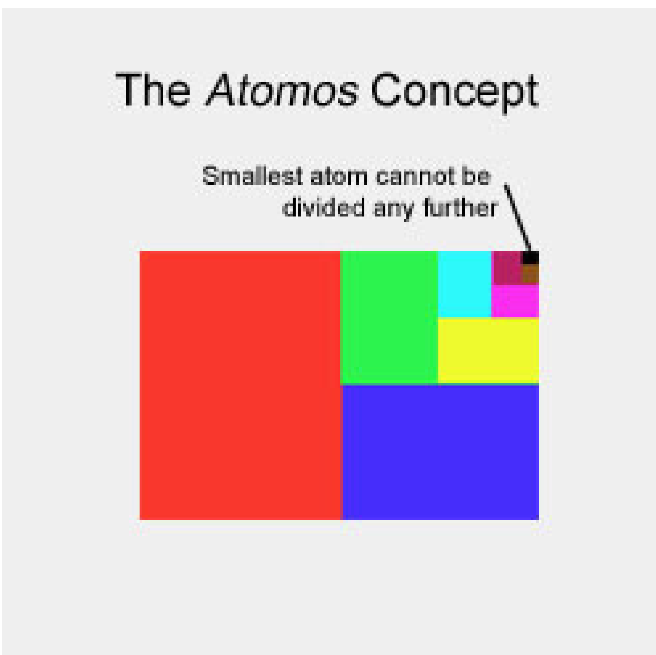
THE RISE (and fall) OF THE ATOMISTIC PICTURE

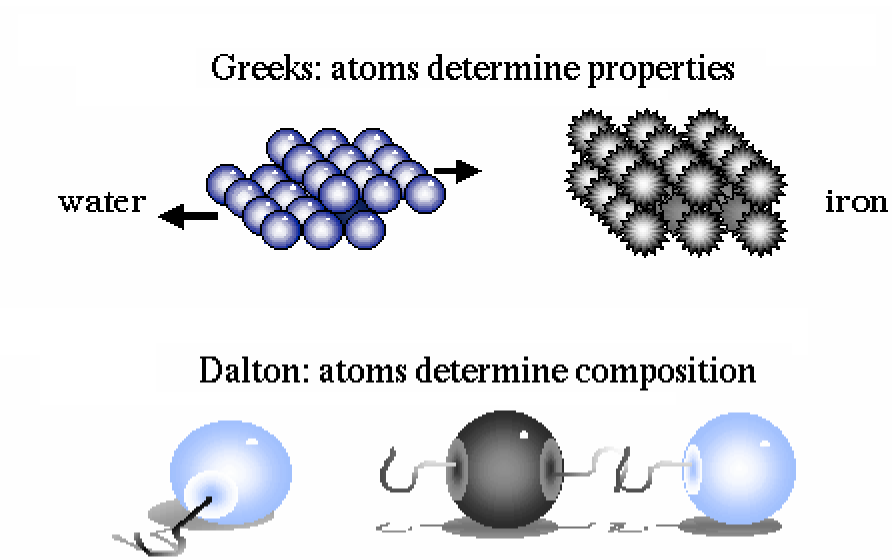
Leucippus (first half of 5th century BC)

Democritus (c. 460 BC – c. 370 BC)







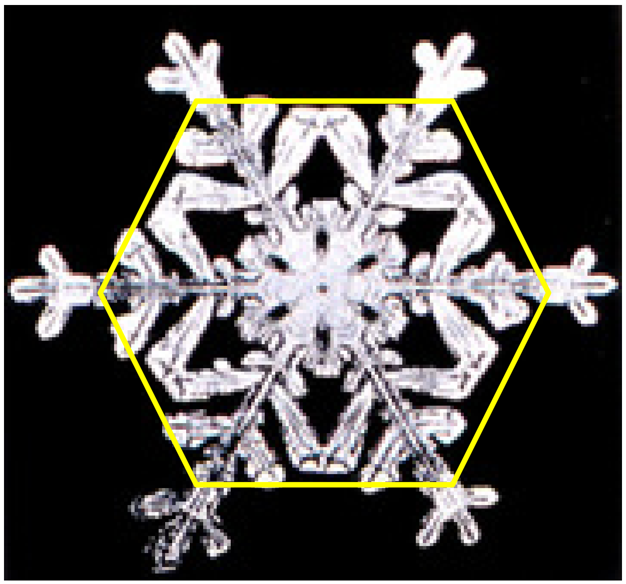


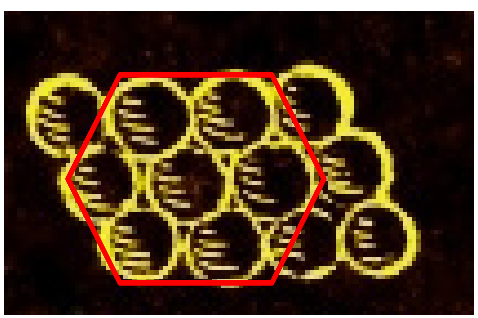
Aristotle: Horror vacui

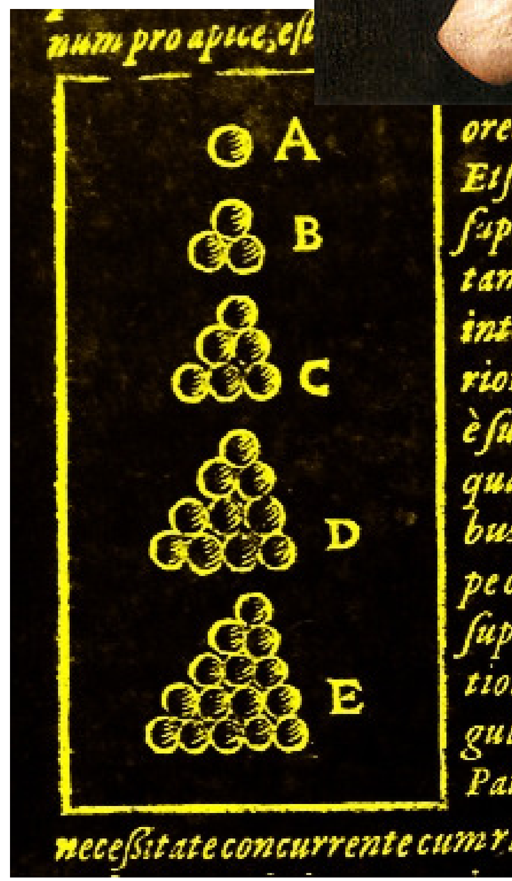
Johannes Kepler (1571 –1630)

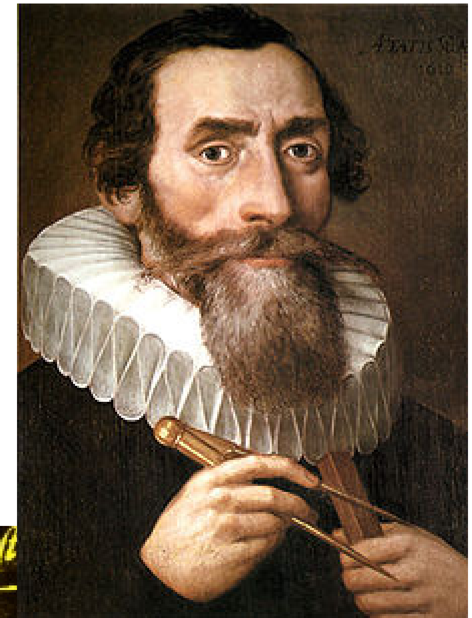
Strena Seu de Nive Sexangula (1611)
A New Year's Gift of Hexagonal Snow

The Kepler conjecture







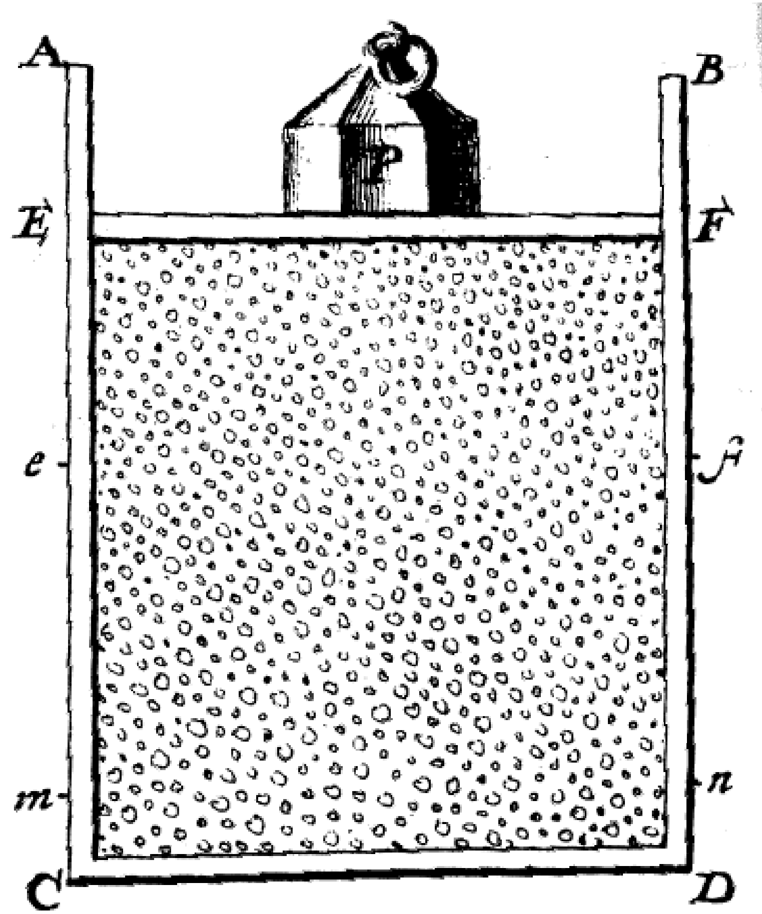


Corpuscular theory

Newton

Boyle (1627 –1691)

Daniel Bernoulli (Groningen, 1700 –1782)



Let the cavity contain very minute corpuscles, which are driven hither
and thither with a very rapid motion; so that these corpuscles, when they strike against the piston and sustain it by
their repeated impacts, form an elastic uid which will expand of itself if the weight is removed or diminished. . . ".

In physics atomistic ideas were pushed to the background in the late 18th and most of the 19th century

Unreasonable:
Not if one considers the enormous successes of continuum theories in

- Mechanics
- Thermodynamics (i.e. not statistical)
- Electricity and magnetism
- Optics

"Who needs atoms?" reigned during this period.

Not so in chemistry:

I. Law of Conservation of Mass

II. Law of Definite Proportions

Mass relationships during chemical reactions:

copper carbonate ($CuCO_3$) always gives 51.5% copper, 38.8% oxygen, and 9.7% carbon

III. Law of Multiple Proportions

1 g Carbon + 1.33 g O → CO

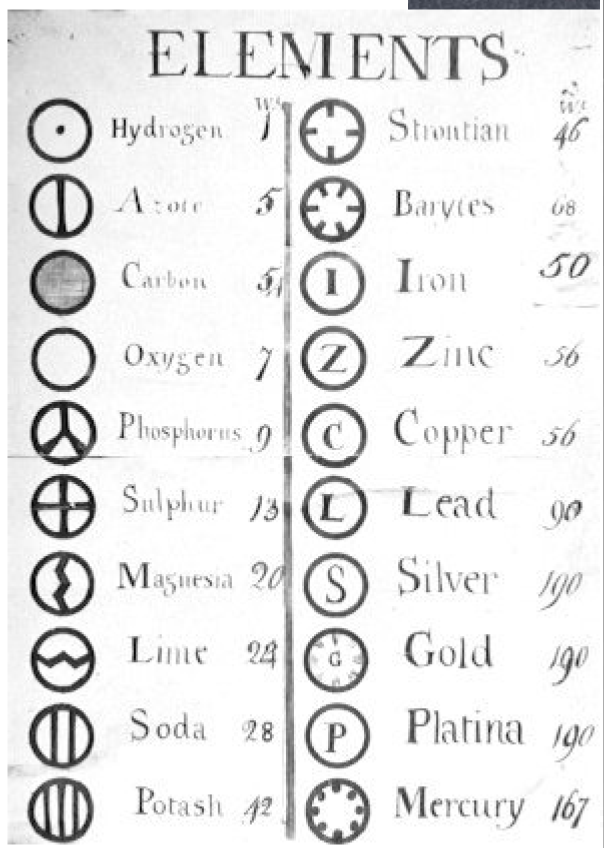
1 g Carbon + 2.66 g O → CO_2

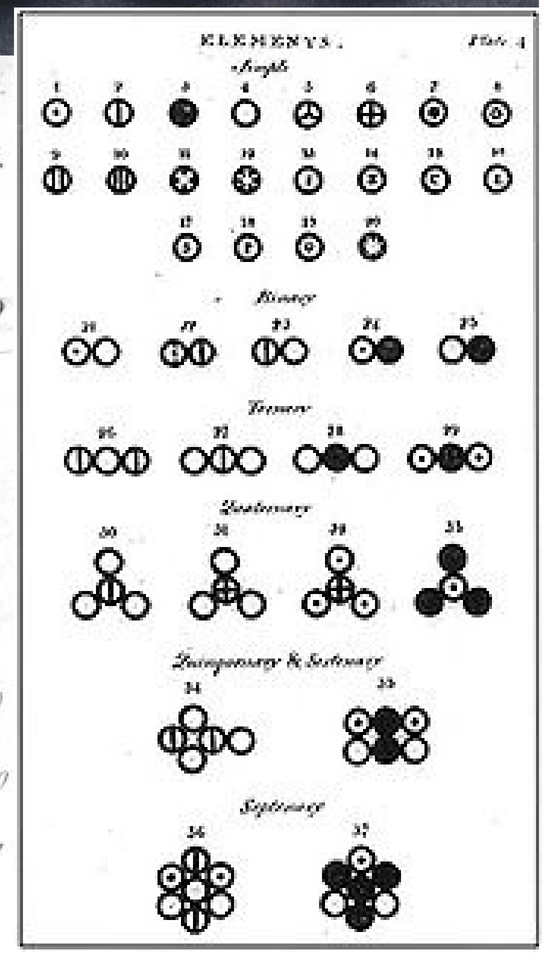
Ratio first and second oxide 1:2

Dalton's law of partial pressures

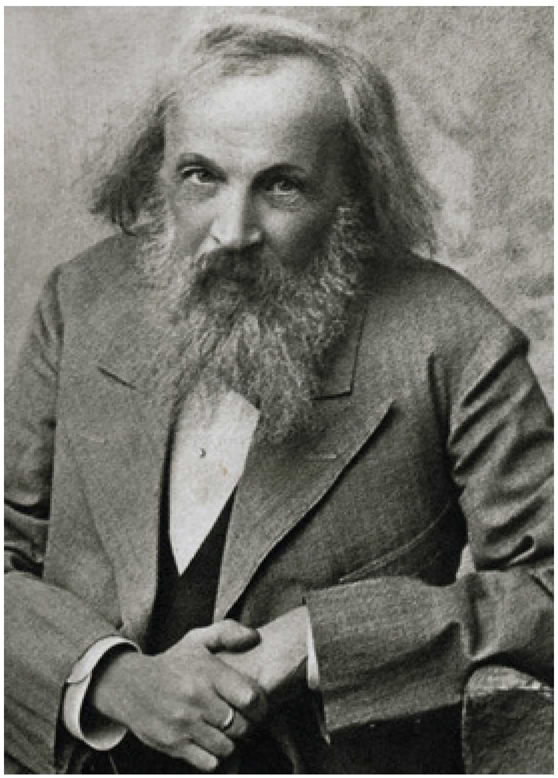
$$P_{total} = p_1 + p_2 + \cdots + p_n$$

John Dalton (1766 –1844)

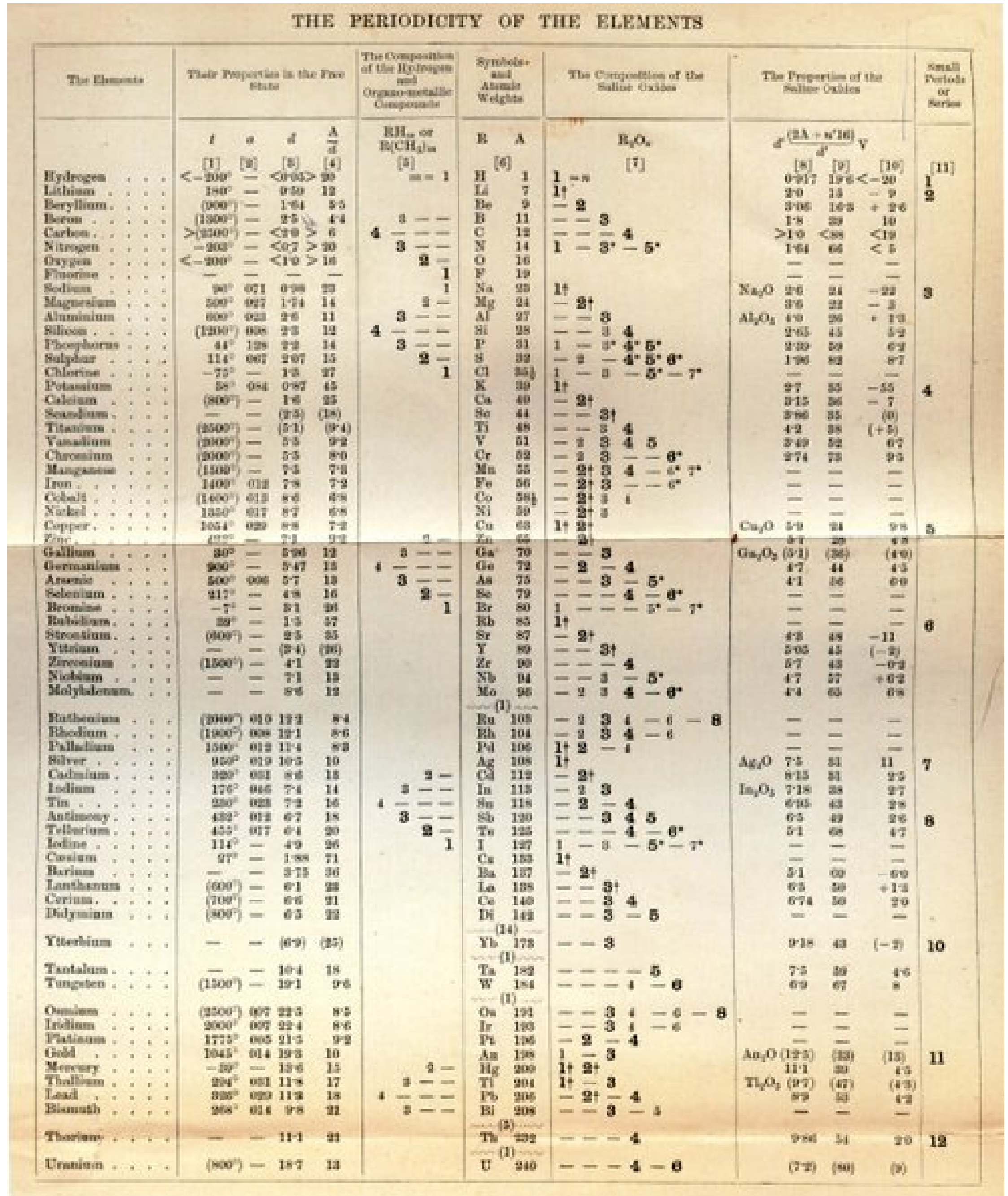




Culmination in Mendeleyev's Periodic table



Dmitri Mendeleyev (1834 –1907),



THE PERIODICITY OF THE ELEMENTS

The Elements	Symbols	Atomic Weights
Hydrogen	H	1
Lithium	Li	7
Beryllium	Be	9
Boron	B	11
Carbon	C	12
Nitrogen	N	14
Oxygen	O	16
Fluorine	F	19
Sodium	Na	23
Magnesium	Mg	24
Aluminium	Al	27
Silicon	Si	28
Phosphorus	P	31
Sulphur	S	32
Chlorine	Cl	35½
Potassium	K	39
Calcium	Ca	40
Scandium	Sc	44
Titanium	Ti	48
Vanadium	V	51
Chromium	Cr	52
Manganese	Mn	55
Iron	Fe	56
Cobalt	Co	58½
Nickel	Ni	59
Copper	Cu	63
Zinc	Zn	65
Gallium	Ga	70
Germanium	Ge	72
Arsenic	As	75
Selenium	Se	79
Bromine	Br	80
Rubidium	Rb	85
Strontium	Sr	87
Yttrium	Y	89
Zirconium	Zr	90
Niobium	Nb	94
Molybdenum	Mo	96
Ruthenium	Ru	103
Rhodium	Rh	104
Palladium	Pd	106
Silver	Ag	108
Cadmium	Cd	112
Indium	In	113
Tin	Sn	118
Antimony	Sb	120
Tellurium	Te	125
Iodine	I	127
Cæsium	Cs	133
Barium	Ba	137
Lanthanum	La	138
Cerium	Ce	140
Didymium	Di	142
Ytterbium	Yb	173
Tantalum	Ta	182
Tungsten	W	184
Osmium	Os	191
Iridium	Ir	193
Platinum	Pt	196
Gold	Au	198
Mercury	Hg	200
Thallium	Tl	204
Lead	Pb	206
Bismuth	Bi	208
Thorium	Th	232
Uranium	U	240

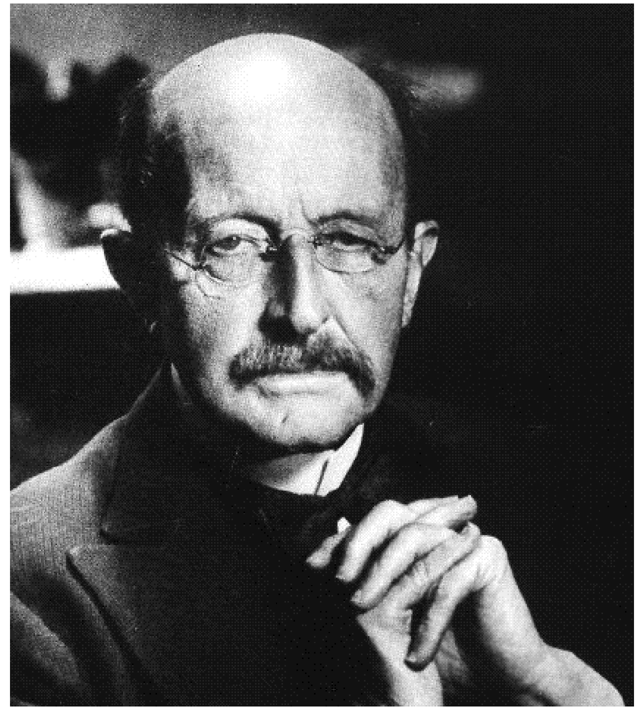
REVOLUTION IN PHYSICS

$$E = h\nu$$

frequency of radiation, sometimes written as f giving expression E = hf.

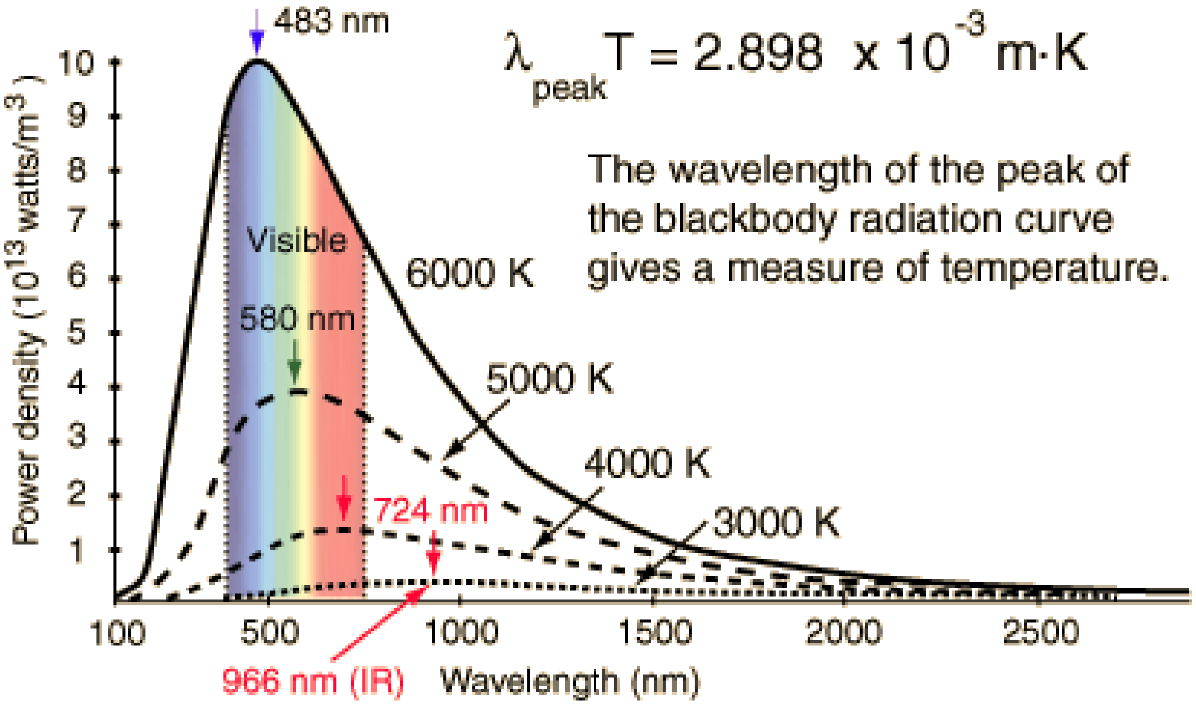
Quantum energy of a photon.

h = Planck's constant = 6.626×10^{-34} Joule·sec = 4.136×10^{-15} eV· s



$$\lambda_{peak} T = 2.898 \times 10^{-3} \text{ m·K}$$

The wavelength of the peak of the blackbody radiation curve gives a measure of temperature.



Energy per unit volume per unit frequency

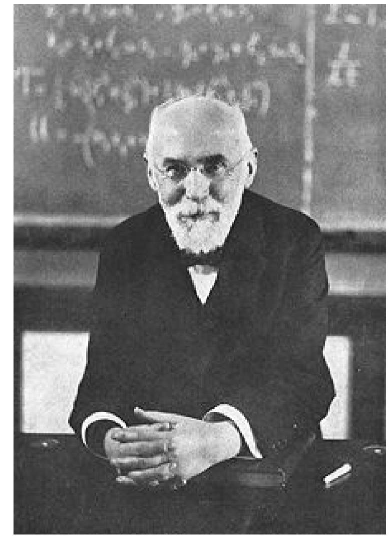
$$S_{\upsilon} = \frac{8\pi h}{c^3} \frac{\upsilon^3}{e^{h\upsilon/kT} - 1}$$

Energy per unit volume per unit wavelength

$$S_{\lambda} = \frac{8\pi hc}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

Classical electron theory

• discovery of electron J. J. Thompson, Lorentz



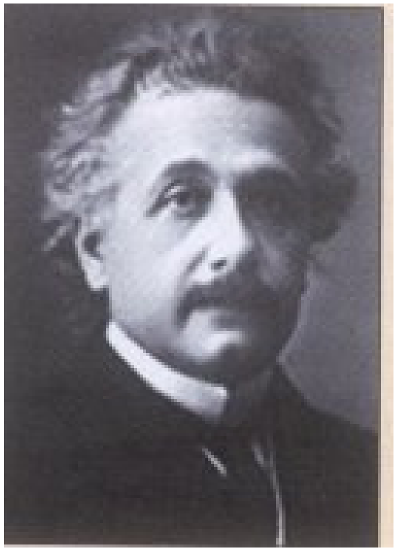
•Drude model

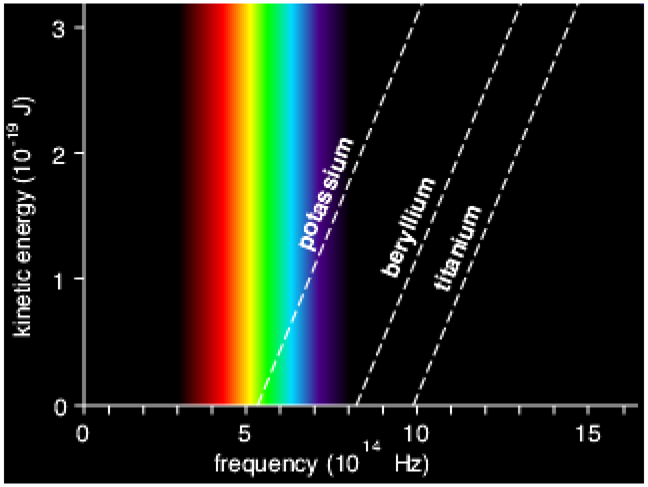
Treats electrons as a gas following Boltzmann statistics as opposed to Fermi-Dirac statistics. Quantities of by several orders of magnitude (gets a lucky break with Wiedemann-Franz law) frequency of radiation, sometimes written as f giving expression $E = hf$.

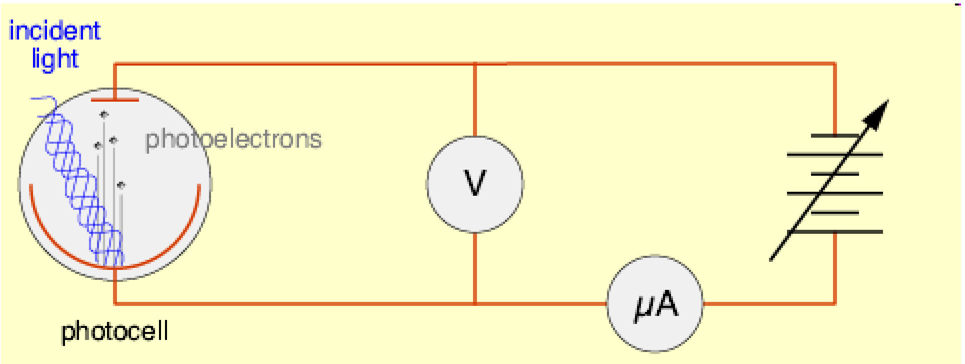
$$E = h\nu$$

Quantum energy of a photon.

h = Planck's constant = 6.626×10^{-34} Joule·sec = 4.136×10^{-15} eV·s







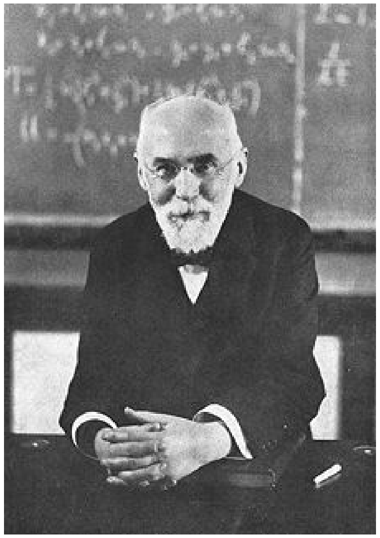
MODERN SOLID STATE PHYSICS

Solid state physics based on atoms
generally based on quantum-mechanics
(although sometimes classical mechanics)

Classical electron theory

- Drude model (1900)

Treats electrons as a gas following Boltzmann statistics as opposed to Fermi-Dirac statistics. Quantities of by several orders of magnitude (gets a lucky break with Wiedemann-Franz law)

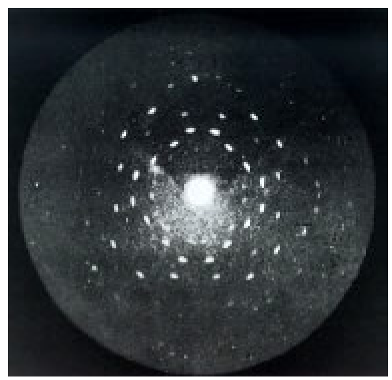


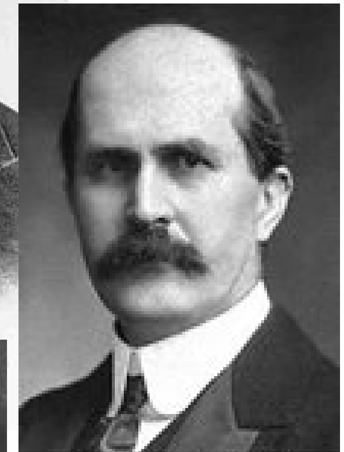
Paul Drude (1863 –1906)

X-ray diffraction

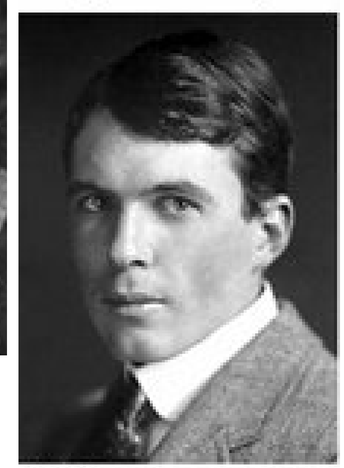
1895: discovery of X-rays by Wilhelm Röntgen (Nobel 1901)

1912: discovery of X-ray diffraction by Max von Laue, Nobel 1914 (other contributors Ewald, Sommerfeld)





Sir William Henry Bragg (1862 - 1942)



William Lawrence Bragg (1890 - 1971)

1913: interpretation by William and Lawrence Bragg, Nobel 1915

First applications of quantum mechanics

Specific heat of solids: The change in internal energy with respect to temperature

experiments by Nernst

Calculations by Einstein and Deye

Walther Nernst (1864 –1941)

Einstein

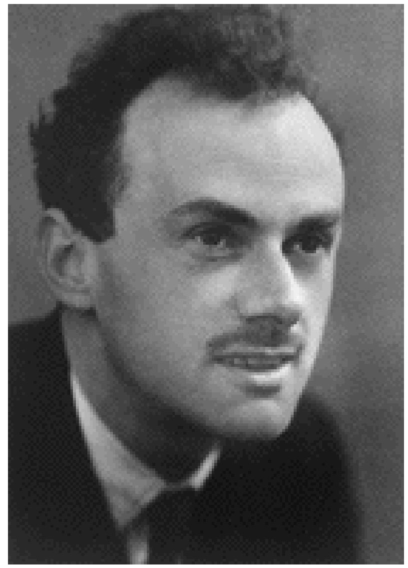
$E(k)=\omega_0$

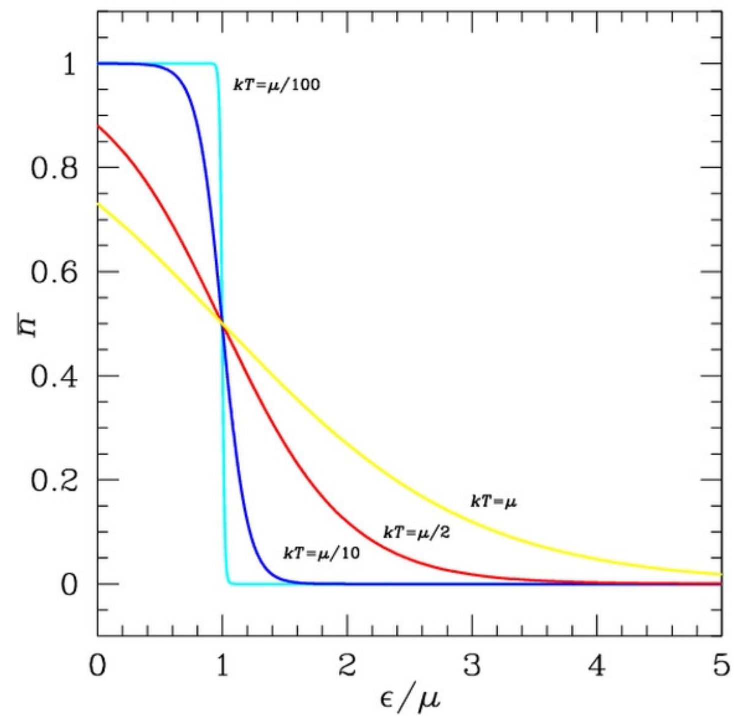
Peter Debye (1884 –1966)

Nobel Chem 1936

$E(k)\sim k$

Fermi-Dirac statistics





Sommerfeld theory including Fermi-Dirac statistics

Specific heat much smaller since very few electrons participate in the conduction

Solves dilemma of Drude-Lorentz theory

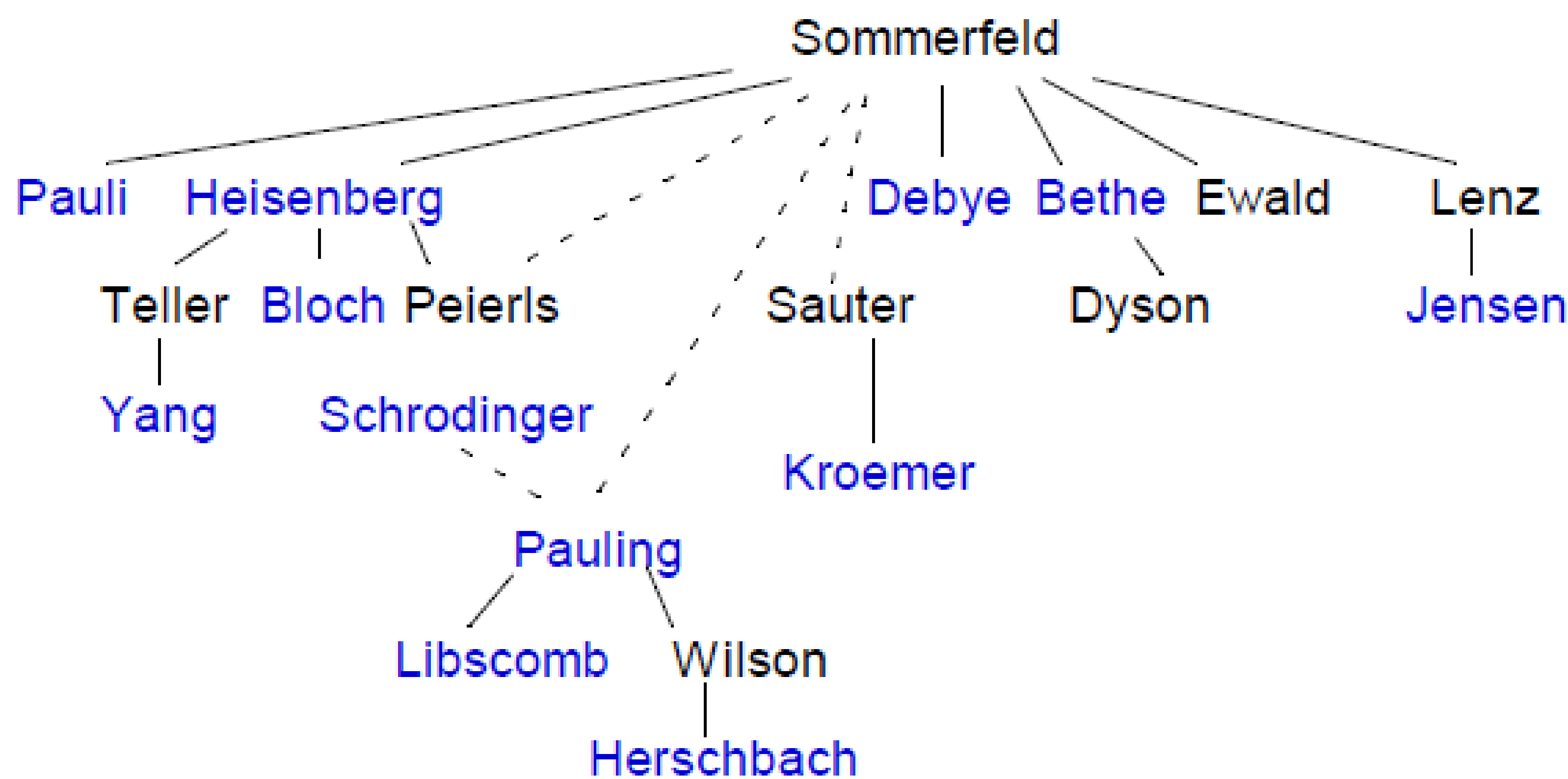
Completely ignores the presence of ions!

Still fails to describe many properties...

Fermi and Sommerfeld

Sommerfeld and Pauli

In addition, Sommerfeld was a star in producing world-class scientists (a selection)



Albert Einstein told Sommerfeld: “What I especially admire about you is that you have, as it were, pounded out of the soil such a large number of young talents.”

Bloch’s theorem

Inclusion of the ions in the theory of metals

Inclusion of translational symmetry is essential

Bloch and Heisenberg

$$\psi_{\mathbf{k}}(\mathbf{r}) = \frac{1}{\sqrt{V}} e^{i\mathbf{k}\cdot\mathbf{r}},$$

$$\boxed{\psi_{n\mathbf{k}}(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}} u_{n\mathbf{k}}(\mathbf{r}),}$$

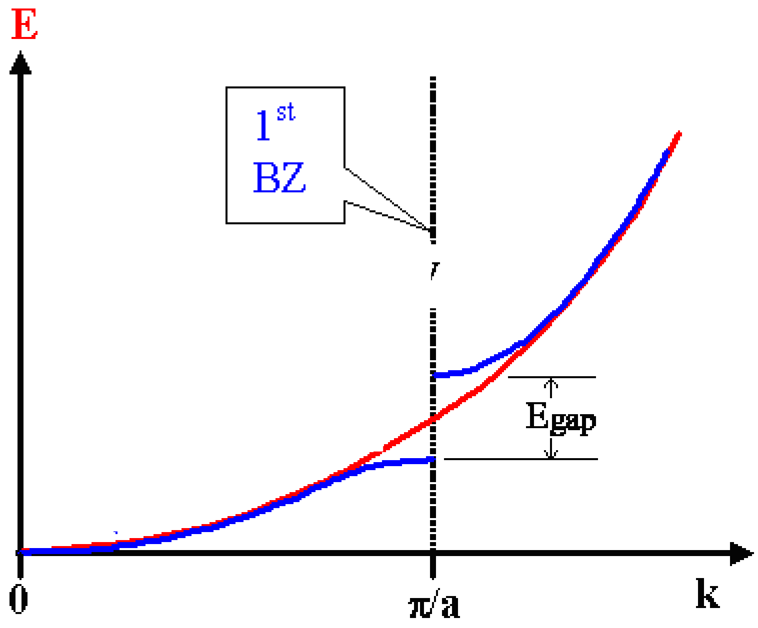
$$u_{n\mathbf{k}}(\mathbf{r} + \mathbf{R}) = u_{n\mathbf{k}}(\mathbf{r})$$

Free electrons

Bloch electrons (Bloch’s theorem)

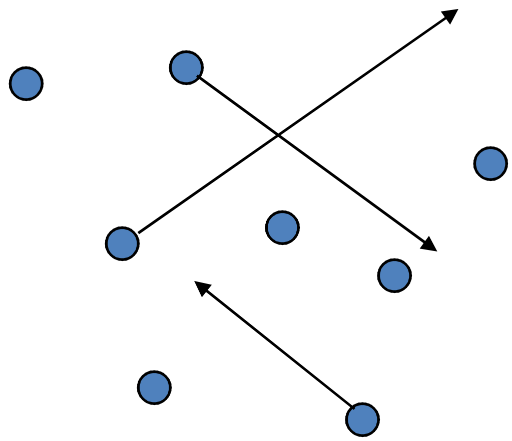
Band gaps and Brillouin zones

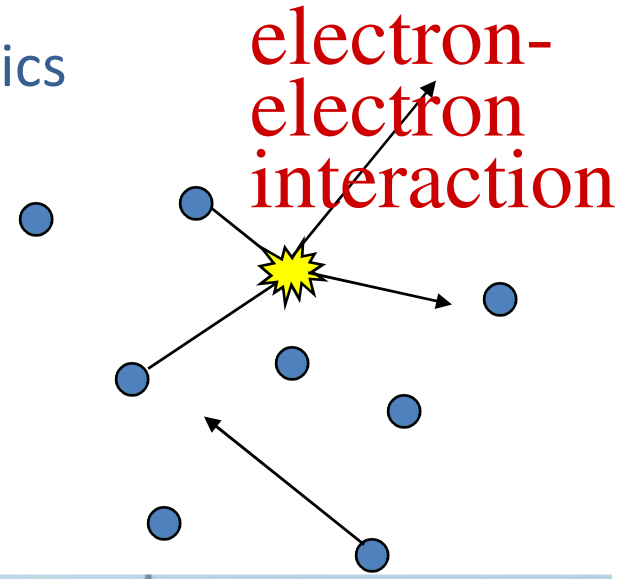
Sir Rudolf Peierls, (1907–1995),



Léon Brillouin (1889 –1969)

Independent-particle vs. many-body physics

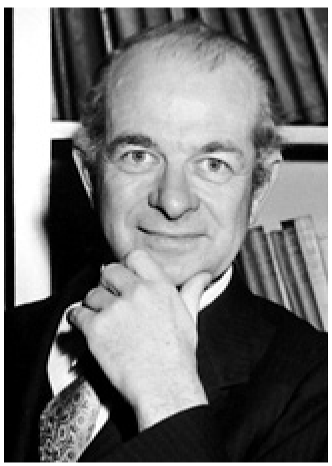




This is a fundamental problem in physics that is not well understood!

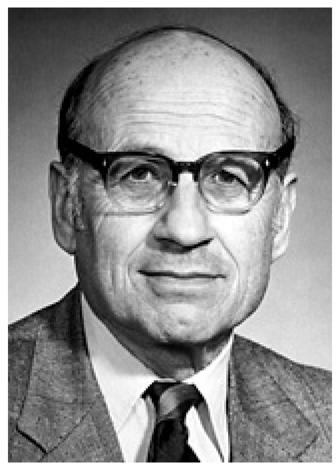
There are very extensive codes based on the independent-particle approximation

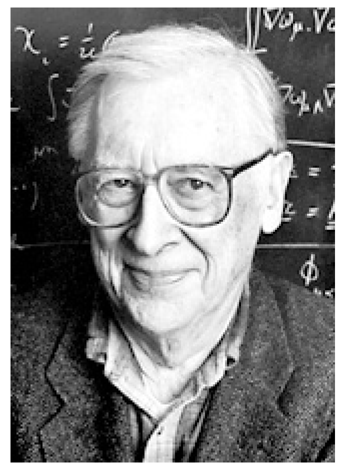
- Density functional theory
- Local Density Approximation
- Molecular orbital theory
- Quantum chemistry



Linus Pauling (1901-1994)

Nobel chem 1954



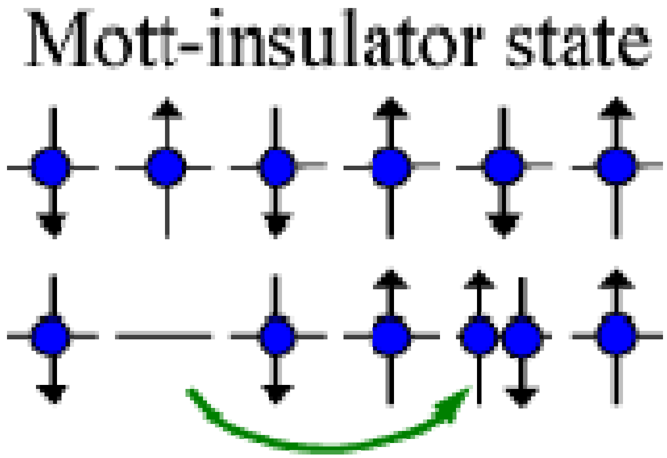


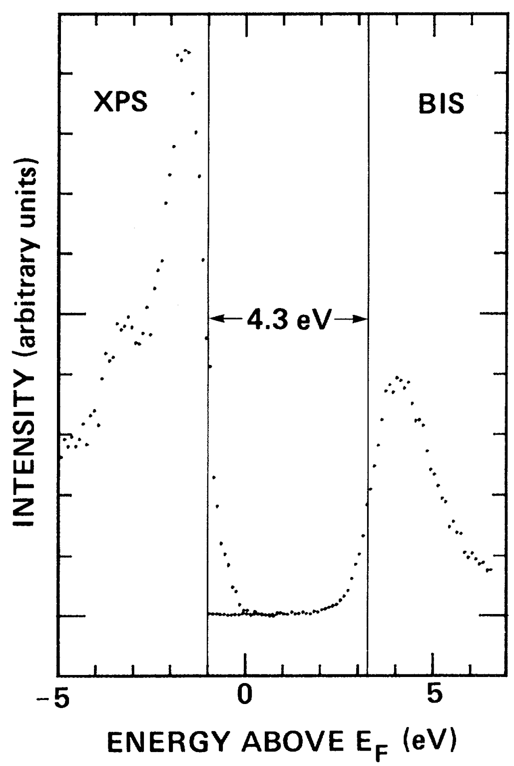
Walter Kohn (1923)   John Pople (1925-2004)

Nobel chem 1998

However, often we have to deal with many-body effects

- Effects where electron-electron interactions are important





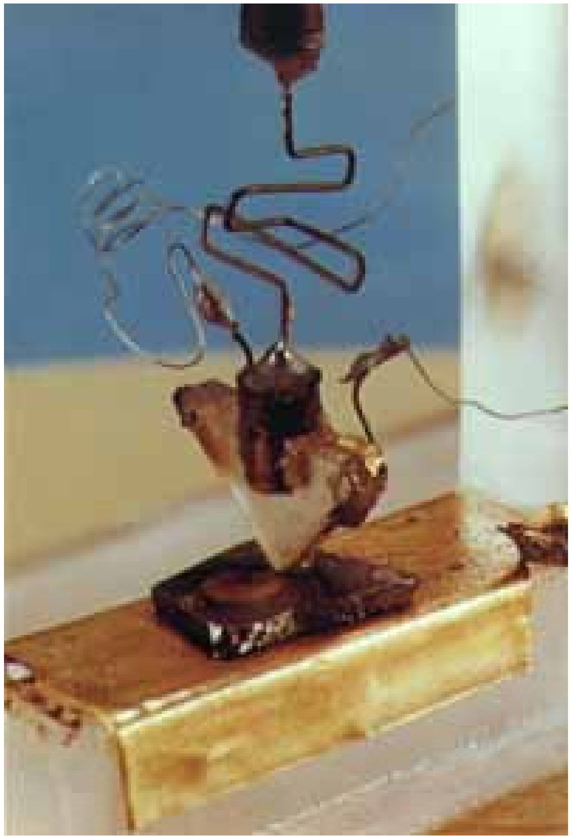
Philip W. Anderson (1923) John van Vleck (1899-1980)

Sir Nevill Mott (1905-1996)

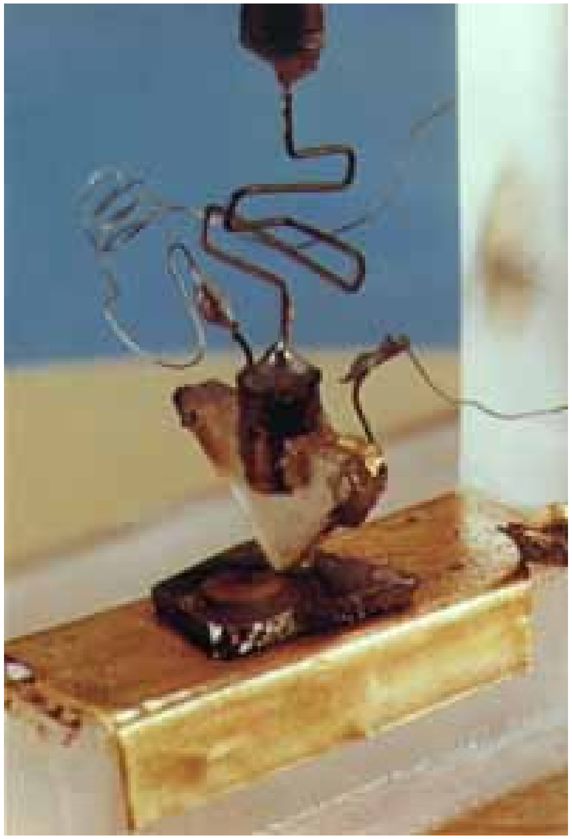
Nobel 1977

Why is NiO an insulator and not a metal?

WHAT IS THIS?



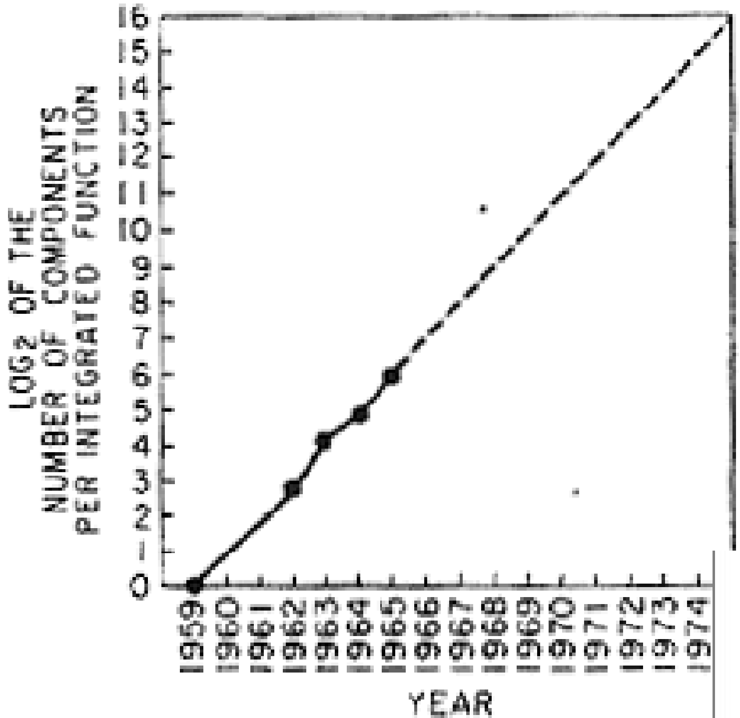
The first transistor!
Bell-Labs (1947)

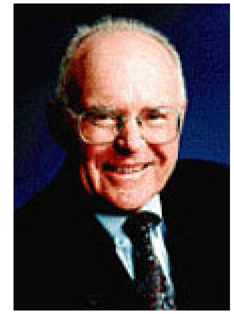


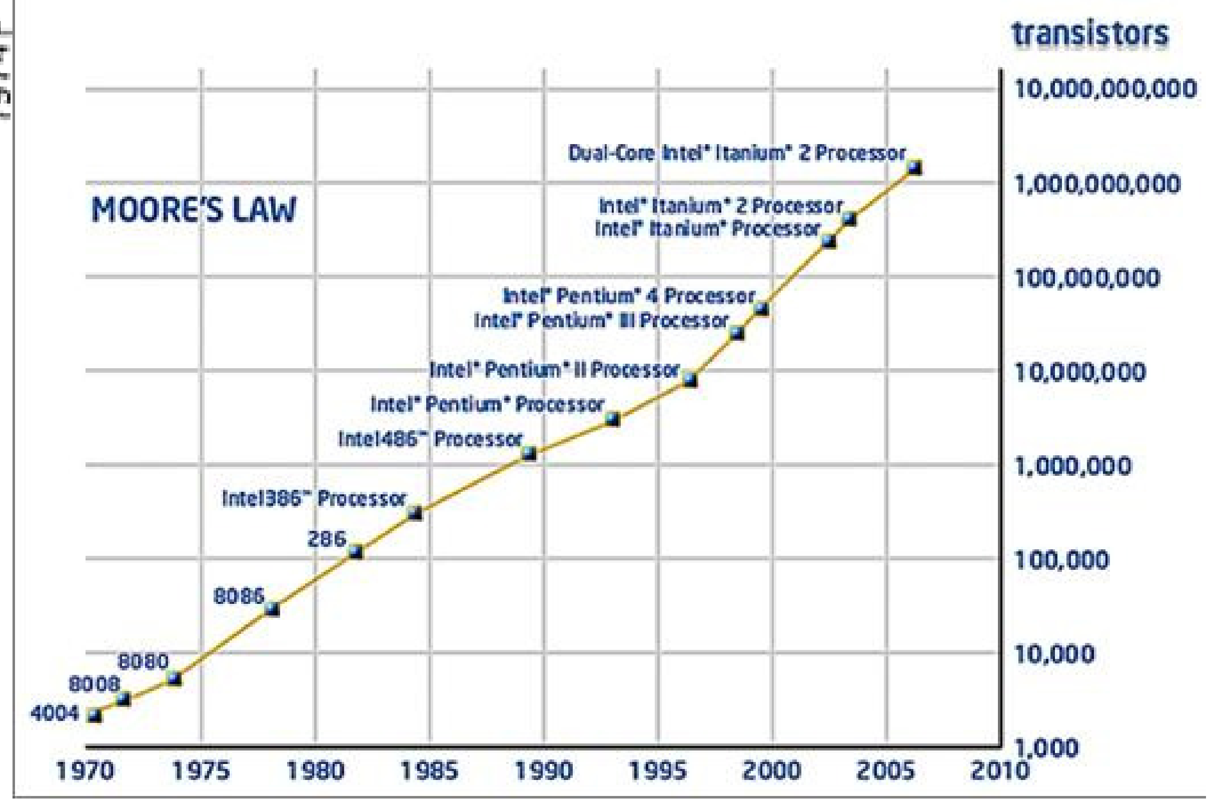
John Bardeen, Walter Brattain, and William Shockley working on the first transistor

Nobelprize 1956

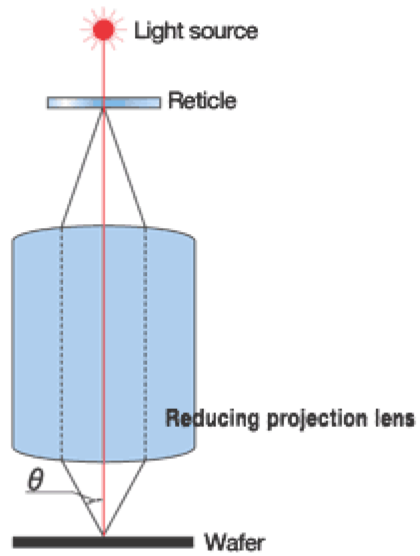
Moore's Law

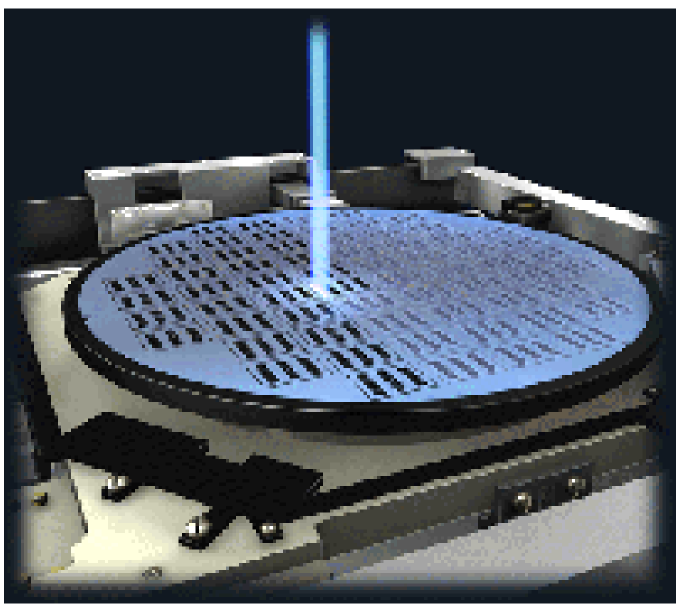

LOG_2 OF THE
NUMBER OF COMPONENTS
PER INTEGRATED FUNCTION
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
YEAR



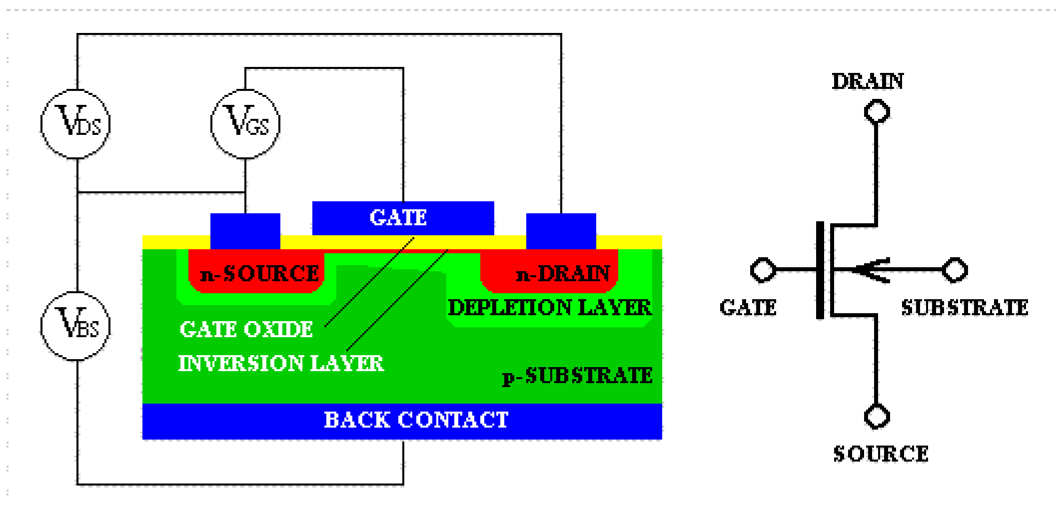

MOORE'S LAW
transistors
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
Dual-Core Intel® Itanium® 2 Processor
Intel® Itanium® 2 Processor
Intel® Itanium® Processor
Intel® Pentium® 4 Processor
Intel® Pentium® III Processor
Intel® Pentium® II Processor
Intel® Pentium® Processor
Intel486™ Processor
Intel386™ Processor
286
8086
8080
8008
4004
1970
1975
1980
1985
1990
1995
2000
2005
2010

Optical lithography

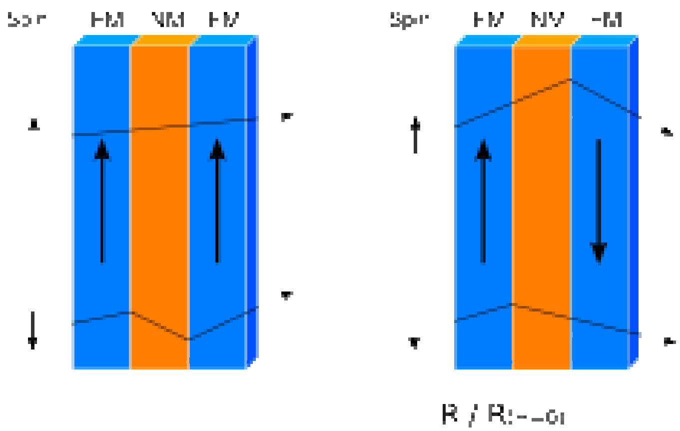


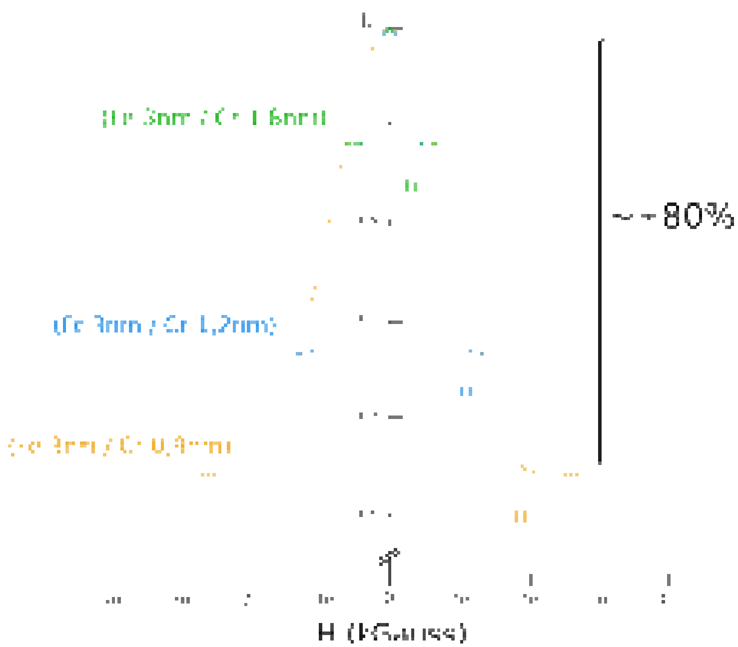


$$RES = k_1 \lambda / NA$$



Other device technology: giant magnetoresistance

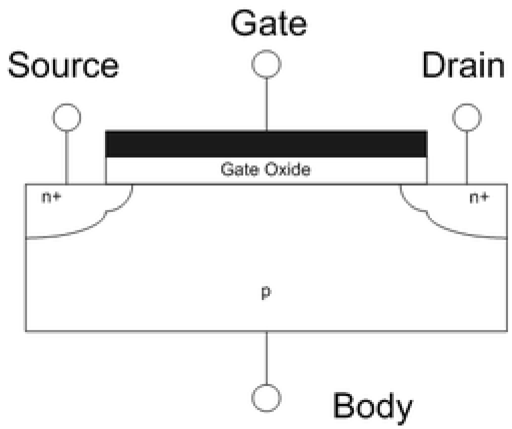




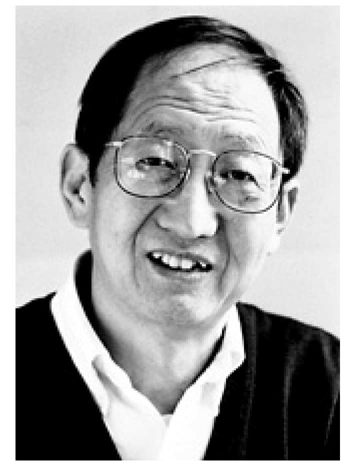
Albert Fert (1938) Peter Grünberg (1939)
Nobel 2007

Read heads of hard drives

More exotic phenomena (only at low temperatures)
Quantized resistance, quantum Hall effect, fractional quantum Hall effect





Robert B. Laughlin (1950)

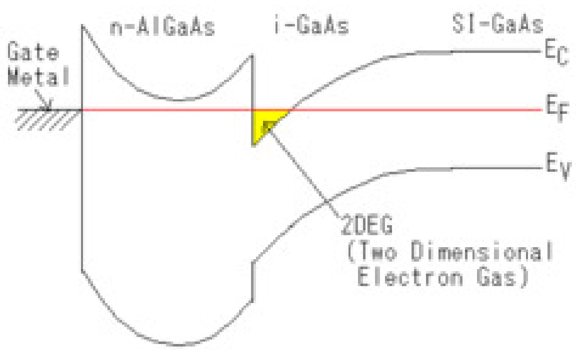
Daniel C. Tsui (1939)

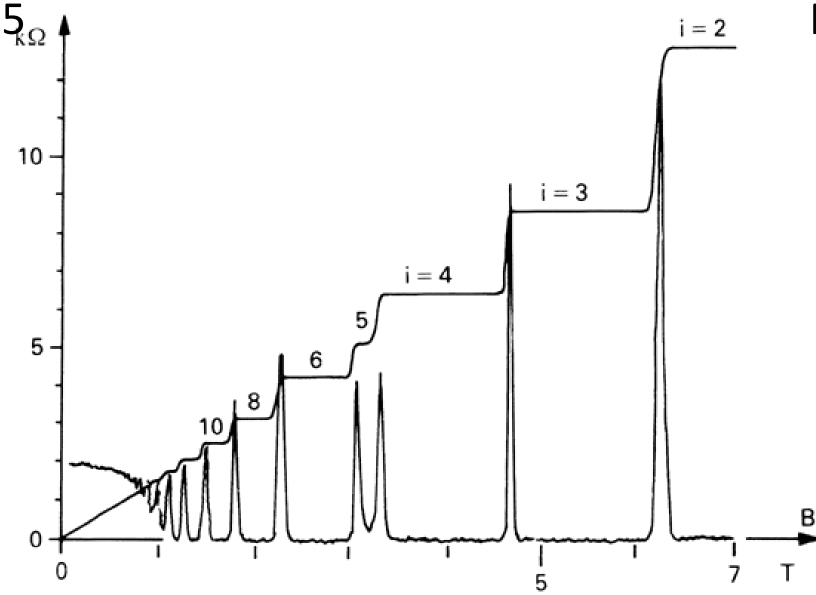
Klaus von Klitzing (1943)

Horst L. Störmer (1949)

Nobel 1985

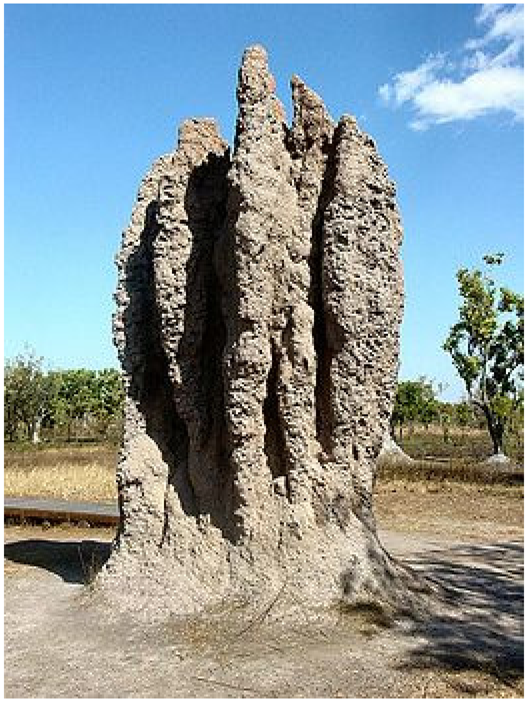
Nobel 1998





EMERGENT PHENOMENA

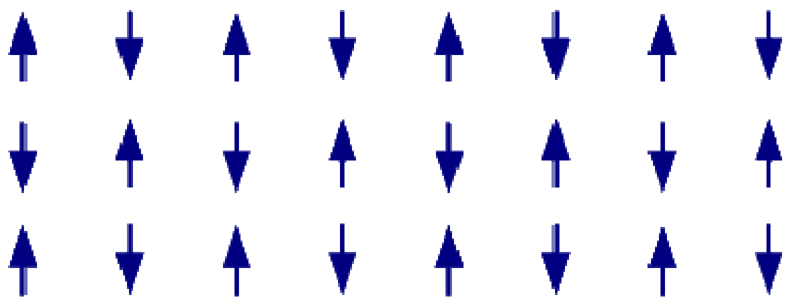
The whole is greater than the sum of its parts.



Sometimes when you put things together new order appears

- Magnetism
- Superconductivity
- Superfluidity

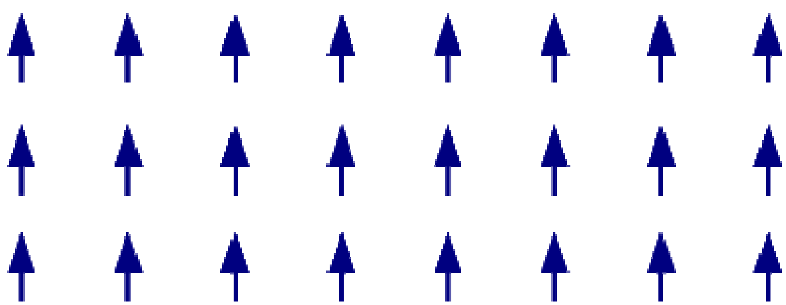
An example: Antiferromagnetism



Louis Néel (1904 –2000)

Nobel 1970

(as opposed to ferromagnetism

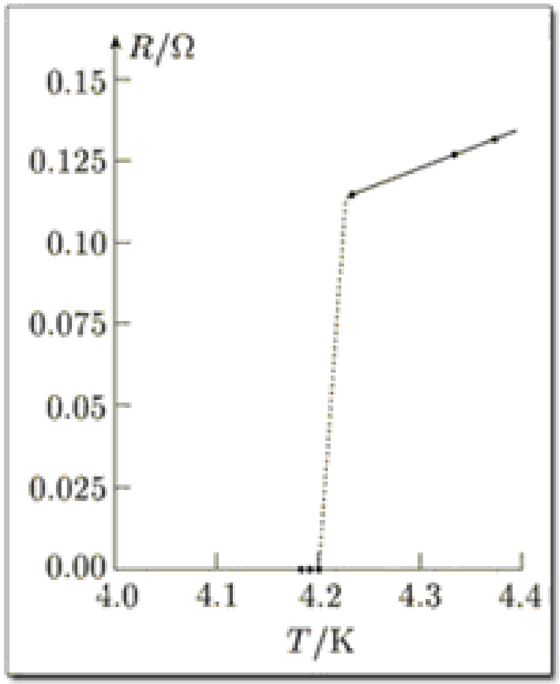


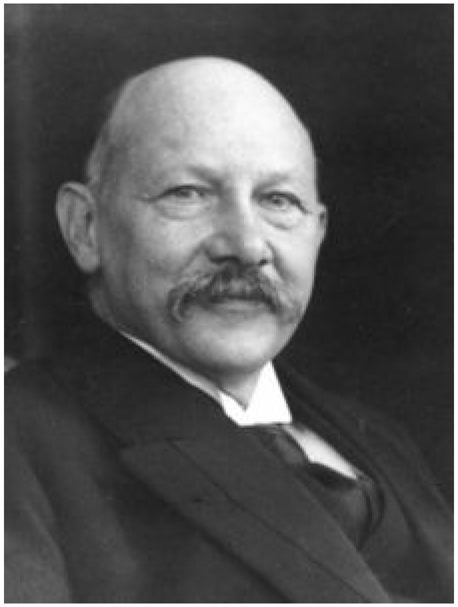
)

Experimental developments:

Low-temperature physics:

Kamerlingh-Onnes
1908: Liquefaction of Helium
1911: Discovery of superconductivity

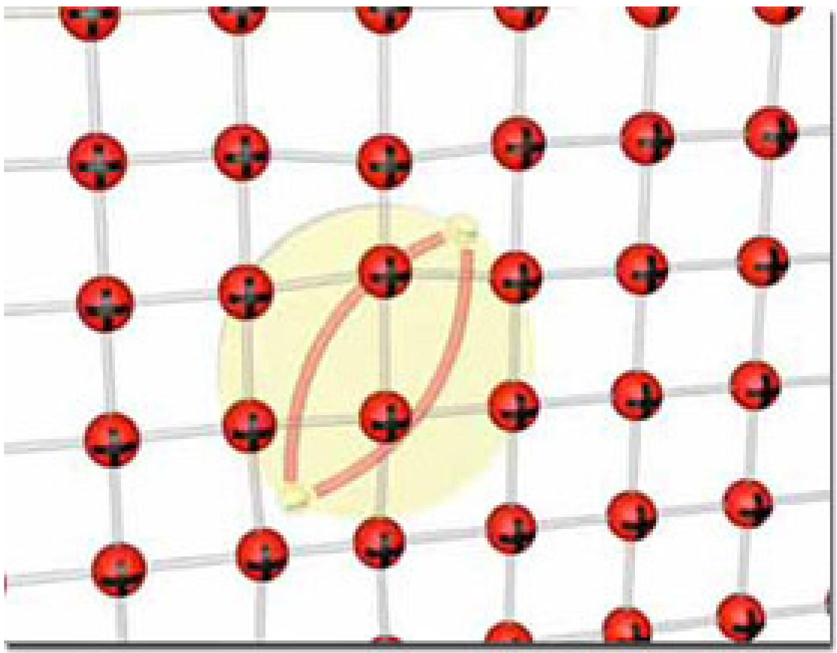




Heike Kamerlingh Onnes (1853 –1926)

Nobel 1913

Only explained in 1957:



Cooper pairs

John Bardeen (1908 –1991)

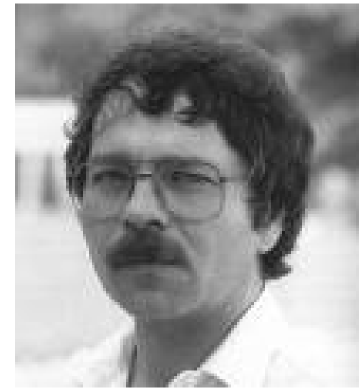
Leon Cooper (1930)

John Robert Schrieffer (1931)

Nobel 1972

High temperature superconductivity

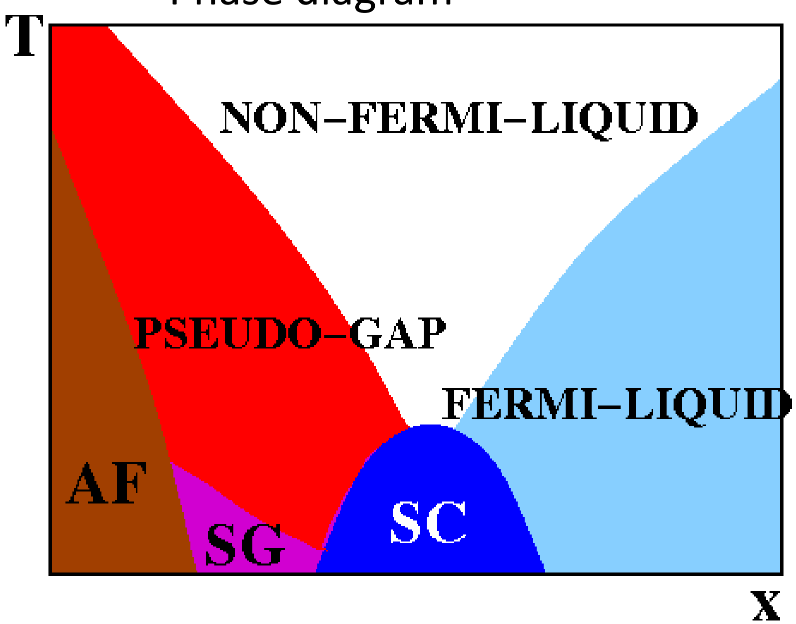
Johannes Georg Bednorz (1950)



Karl Alexander Müller (1927)

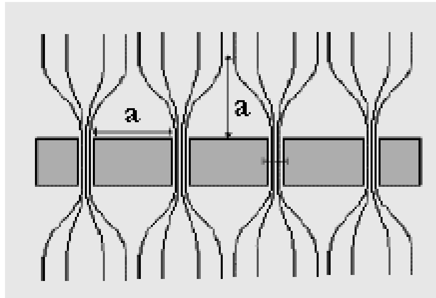
Nobel 1987

Phase diagram

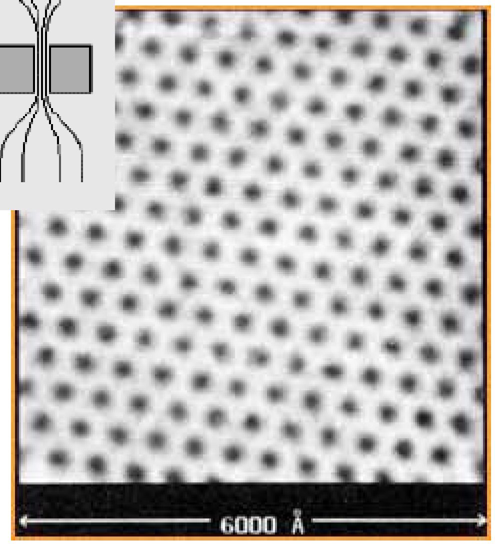


Still under debate….

Infinitely fascinating, apparently, superconductors

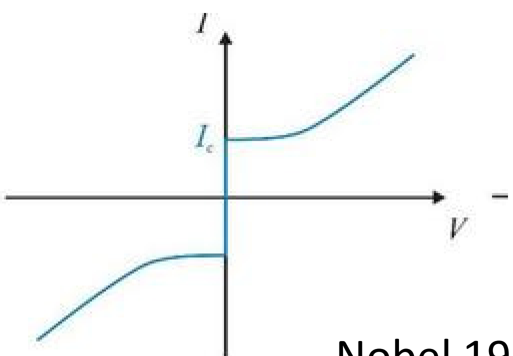


vortices



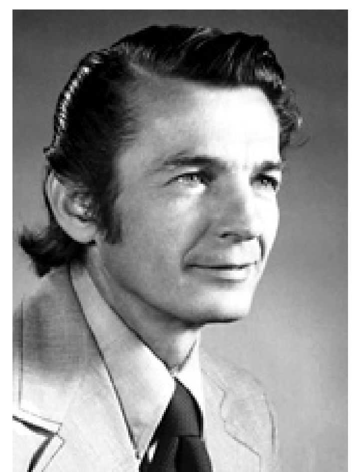
Alexei Abrikosov (1928-)
Nobel prize 2004

Plus all kinds of interesting junction effects



Nobel 1973

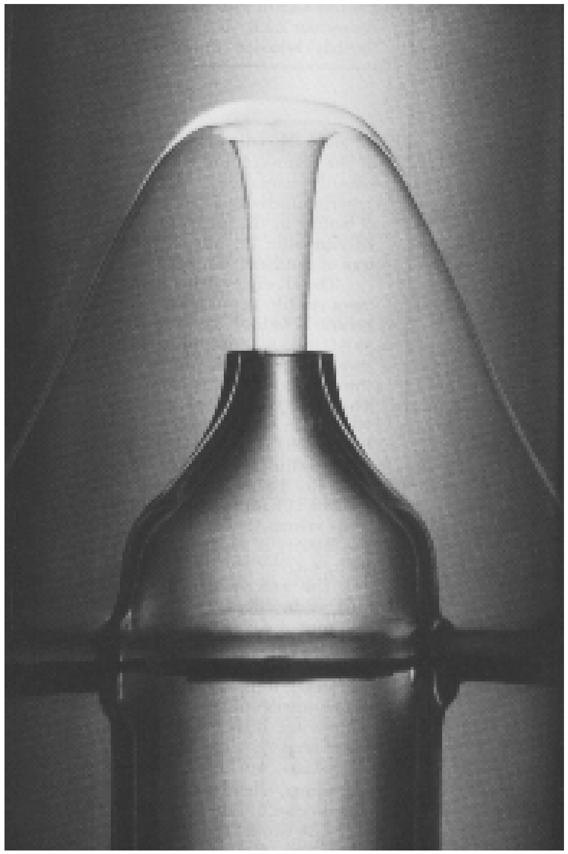
Brian Josephson (1940-)



Leona Esaki (1925)

Ivar Giaever (1929)

A strongly related phenomena (especially theoretically) is superfluidity



Helium II

Lev Landau (1908 –1968) Nobel 1962

Sir Anthony Leggett, KBE, FRS (1938-)
Nobel 2004