Lecture 8

Atomic structure of matter

Announcements:

- review session Fri 4-5:30pm
- lecture 8 is posted
- homework 3 solutions are posted
- homework 4 due Fri, Feb 11
- reading for this week is:
  - Ch 3 in TZD

Last Time

recall lecture 7:

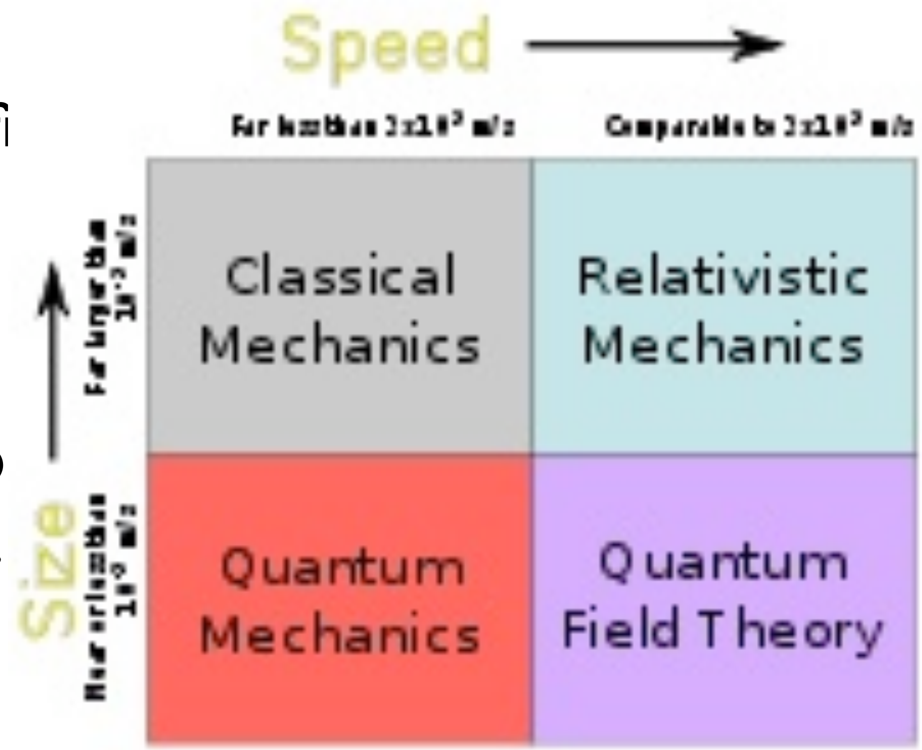
Relativity:

- time dilation $\longrightarrow$ $t = \dfrac{t'}{\sqrt{1 - v^2/c^2}} > t'$
- length contration $\longrightarrow$ $\ell = \ell' \sqrt{1 - v^2/c^2} < \ell'$
- Lorentz transformation $$\begin{aligned} x' &= \gamma(x - vt) \\ t' &= \gamma(t - \frac{v}{c^2}x) \end{aligned}$$
- relativistic mechanics:
  - energy $\Longrightarrow$ $E = \dfrac{m_0 c^2}{\sqrt{1 - v^2/c^2}}$
  - momentum $\Longrightarrow$ $p = \dfrac{m_0 v}{\sqrt{1 - v^2/c^2}}$ $\quad m_0 = m(u=0)$

Course overview

Modern Physics: (relativistic quantum fi

- established during 1900-1920
- exotic and counter-intuitive
- now common place in all modern
  GPS, electronics (cell phones, iPo
  throughout science, e.g., physics,



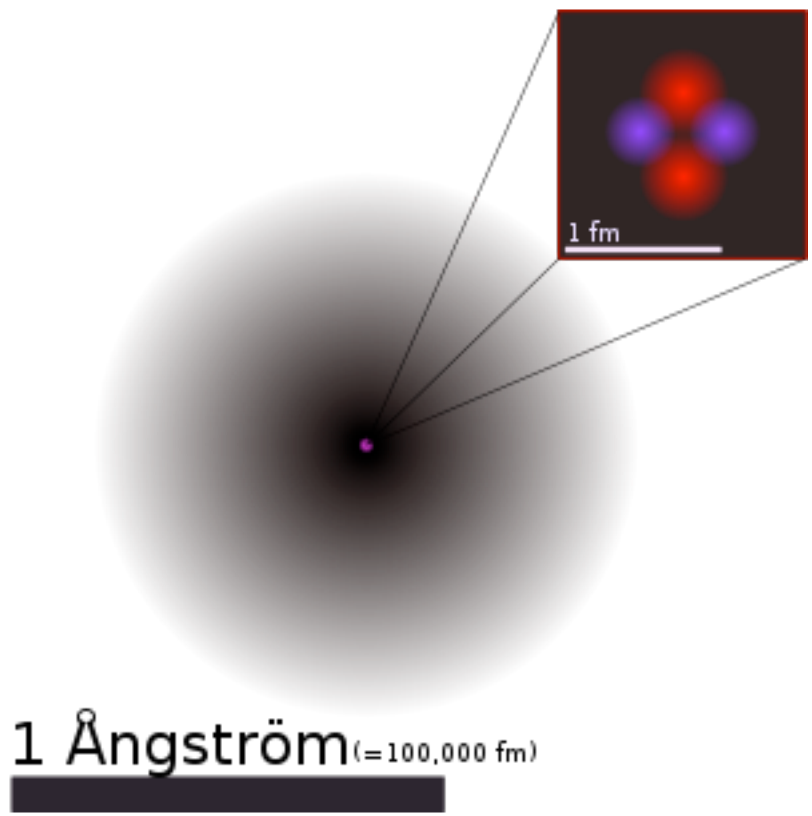
- (special) theory of relativity (mostly Einstein, 1905)
  - how does the world look when you are moving...fast?

- quantum physics (Bohr, Heiseberg, Einstein, Schrodinger, ...)
  - what are the laws of nature for very small things, like electron, proton, photon,...a tiny electrical circuits in you i-Pod?

Today

Fundamentals of matter:

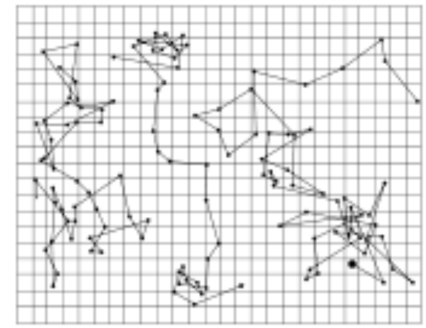
- structure of matter: atoms
- structure of atoms: electrons, protons, neutrons
- experimental evidence



Atoms

- basic unit of matter *– "invisible" in Greek, postulated more than 2000 years ago*
- early evidence for existence:

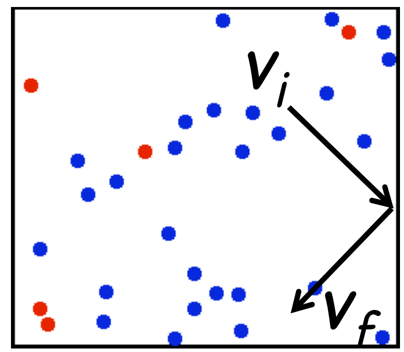
  - *chemical reactions* (Dalton 1800): $C + O \rightarrow CO$, $2H + O \rightarrow H_2O$



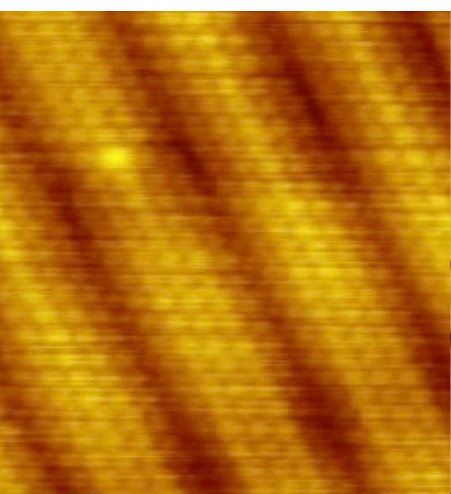
  - *Brownian motion* (Brown 1827, Einstein 1905, Perrin 1909)
  - *kinetic theory of gases:* $PV = N\,k_BT$

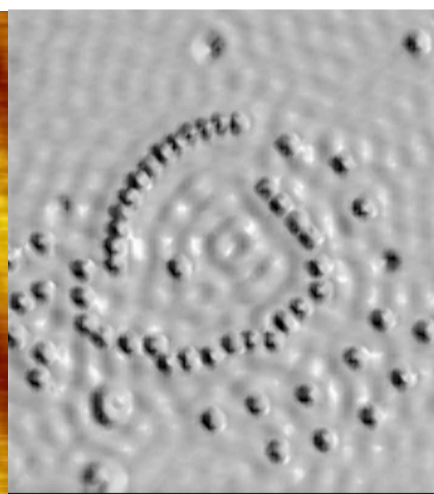
    (Avagadro number $N_A = 6\times10^{23}$ = 1 mole)

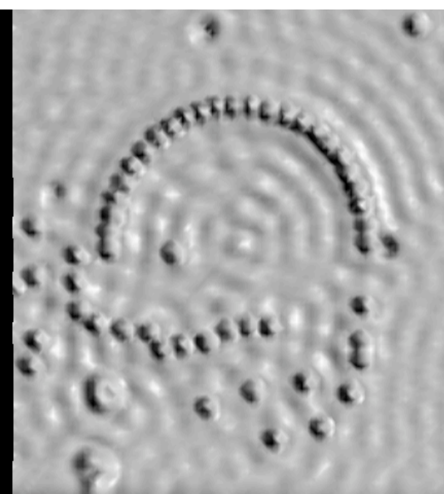
    $dp/dt = 2mv_x/(2L/v_x) = F = A\,P$, $\quad 3/2\,k_BT = \frac{1}{2}mv^2$

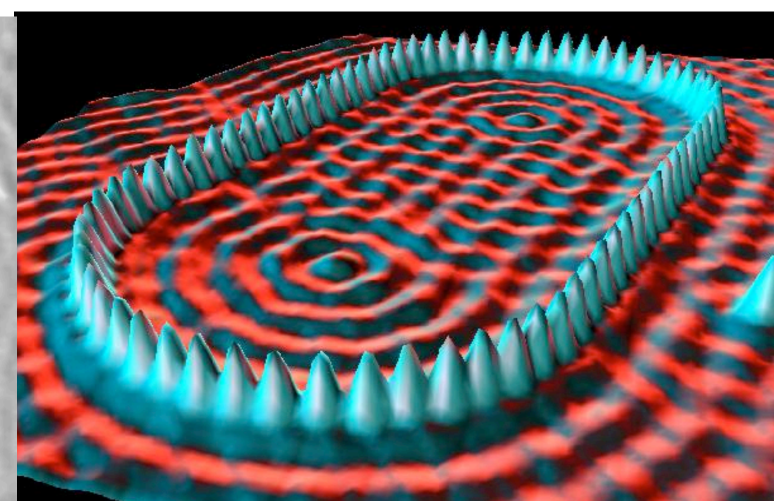


  - *first "seen" via STM 1950's,* now regularly manipulated and made useful



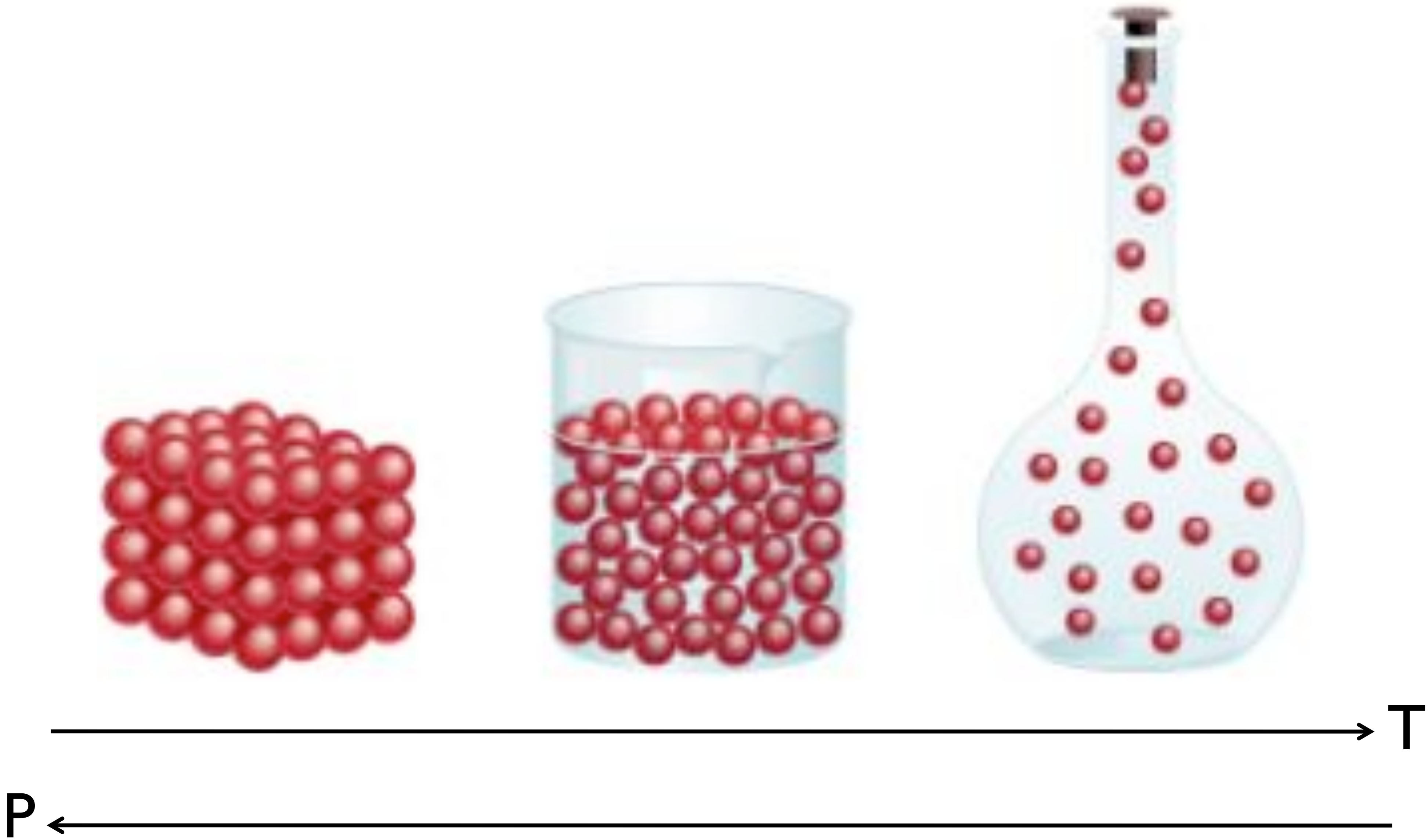






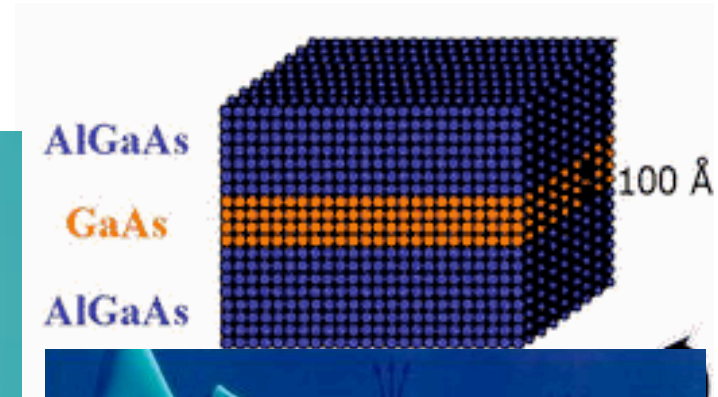
Molecules, macroscopic materials

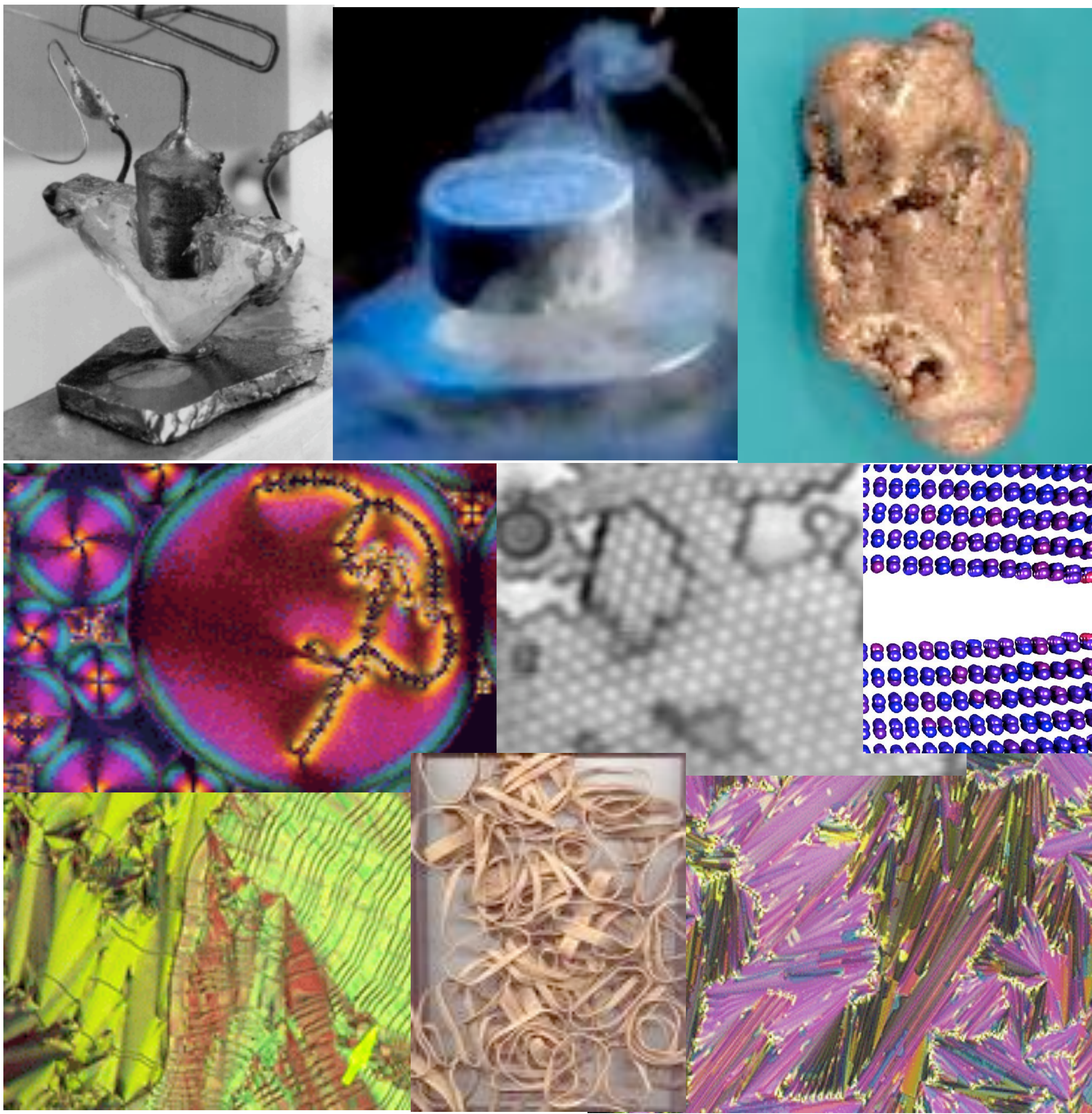
- form molecules: H_2O, O_2, H_2, $C_6H_{12}O_6$, DNA, ...
- solids, liquids, gases:



…and much, much more

- magnets, superconductors, superfluids, liquid crystals, rubber, colloids, glasses, conductors, insulators,…

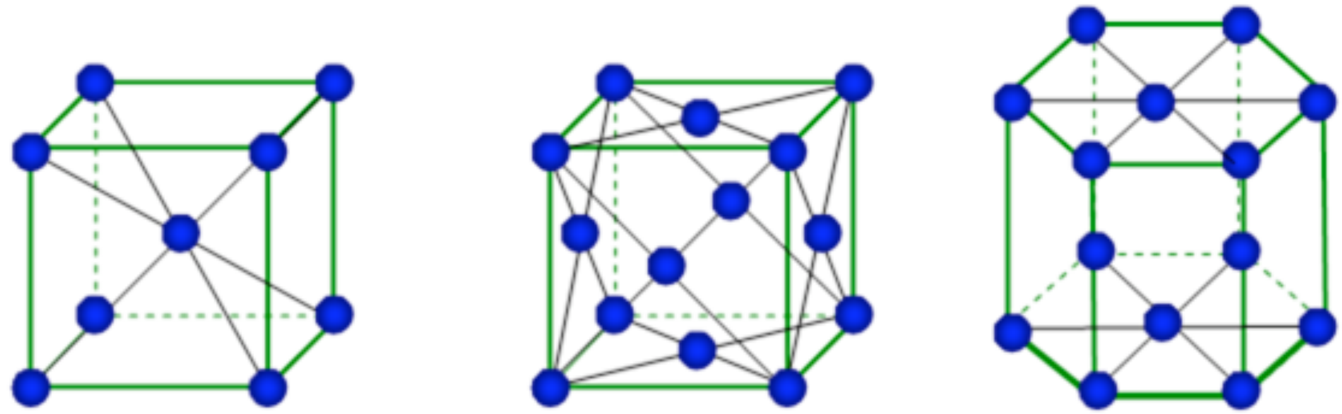




Crystals

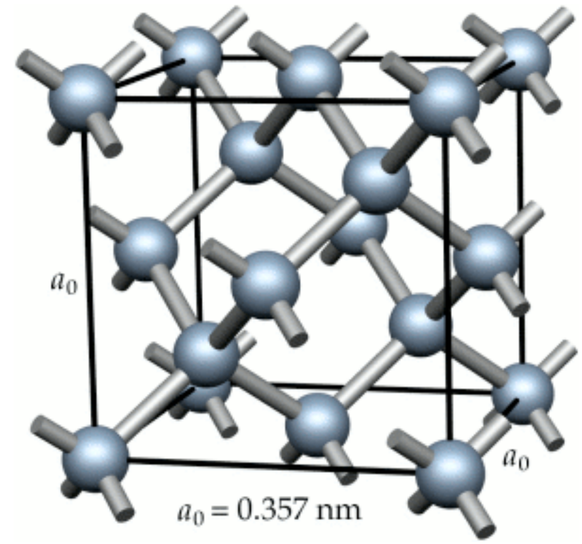
- very large number (230) of periodic atomic structures

Crystal lattice examples

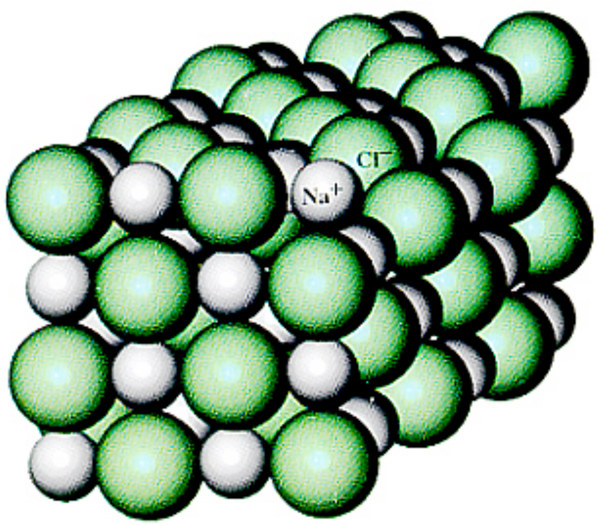


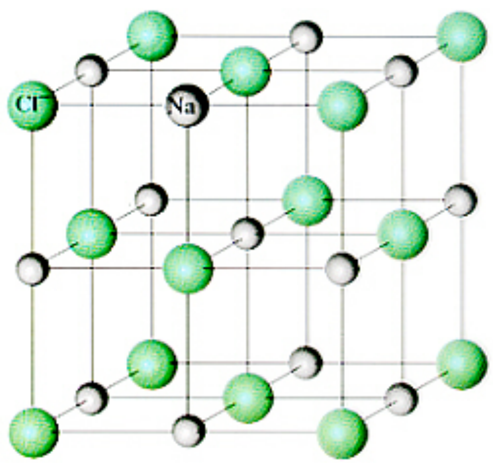
Cubic body centered (bcc) | Cubic face centered (fcc) | Hexagonal

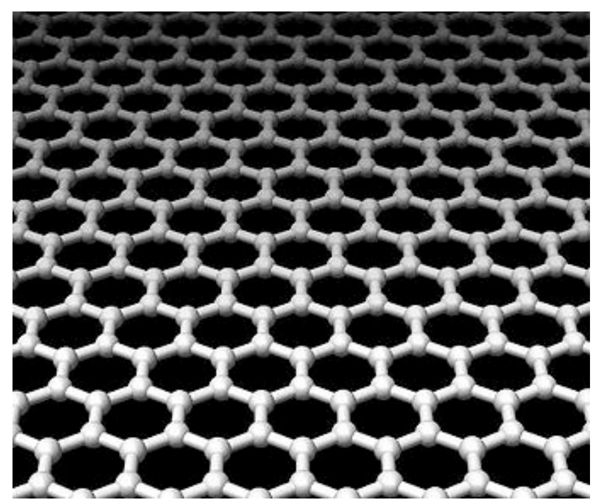
Fe, V, Nb, Cr | Al, Ni, Ag, Cu, Au | Ti, Zn, Mg, Cd



diamond

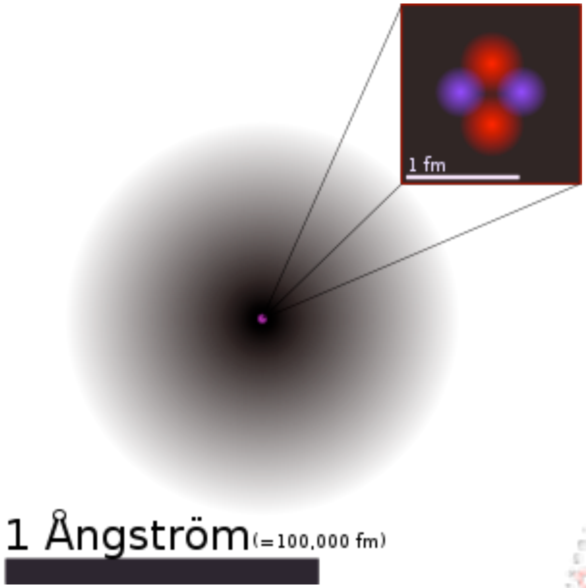


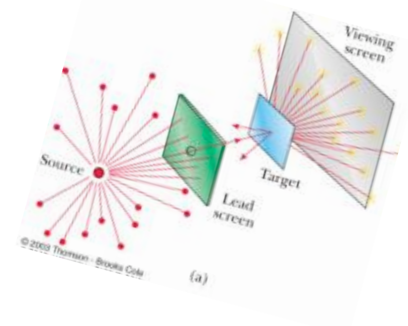


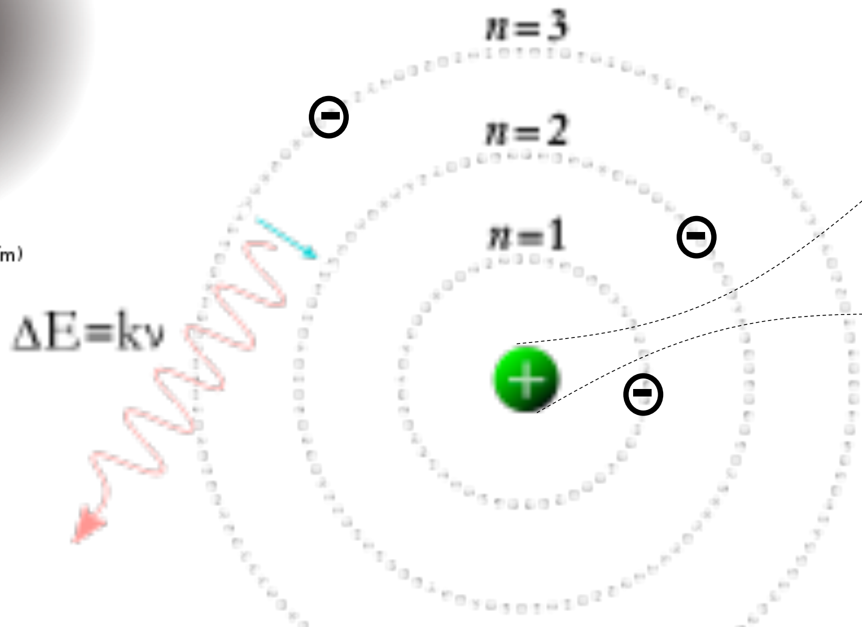


graphene

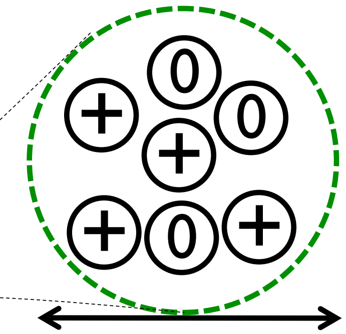
Subatomic structure







atom (10^{-10}m = 1 Angstrom)



nucleus (10^{-15}m)
(E. Rutherford, 1911)

most of the atom is empty space

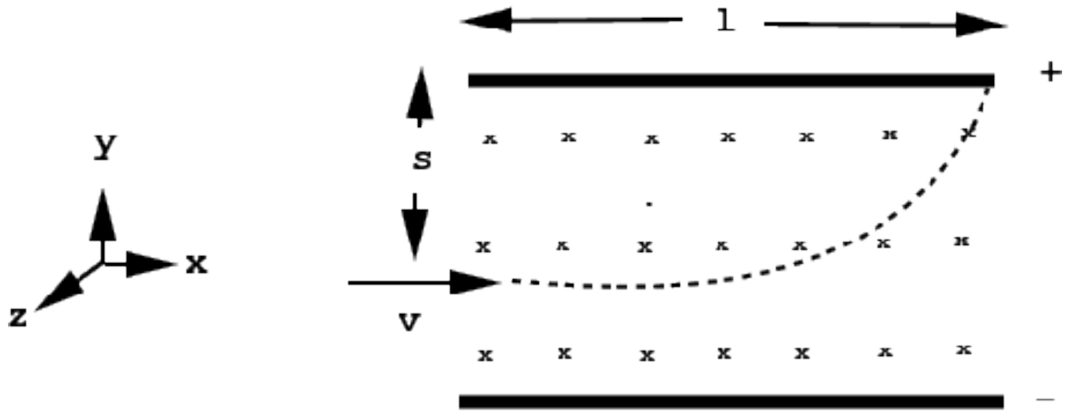
Particle	Mass	Size	Charge	discovered
Electron (e)	9.1×10^{-31} kg = 0.5 MeV	point-like no known substructure	$-e = 1.6 \times 10^{-19}$ C	J.J.Thomson* (CRT) 1897 R. Millikan* (oil drop) 1909
Proton (p)	1.673×10^{-27} kg = 935 MeV ≈ 1GeV	10^{-15} m = Fermi	+e	Rutherford 1919
Neutron (n)	1.675×10^{-27} kg = 939 MeV ≈ 1GeV	10^{-15} m = Fermi	0	Chadwick 1932

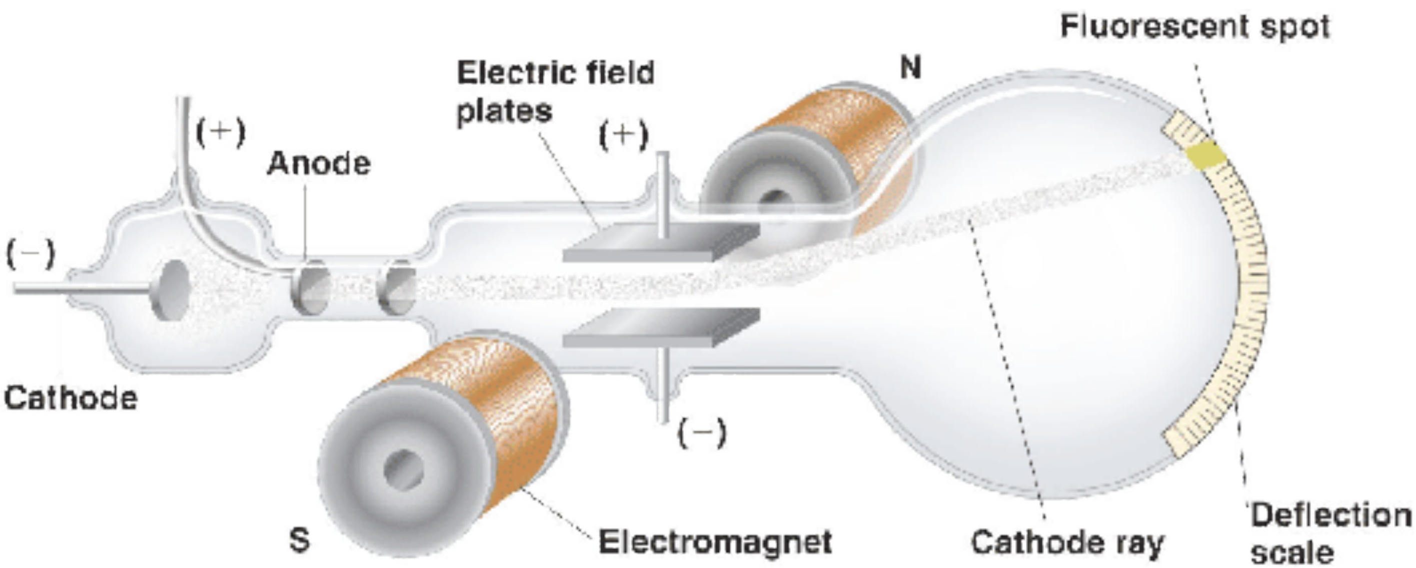
charge is quantized in units of e, exactly

J. J. Thomson experiment

1856-1940

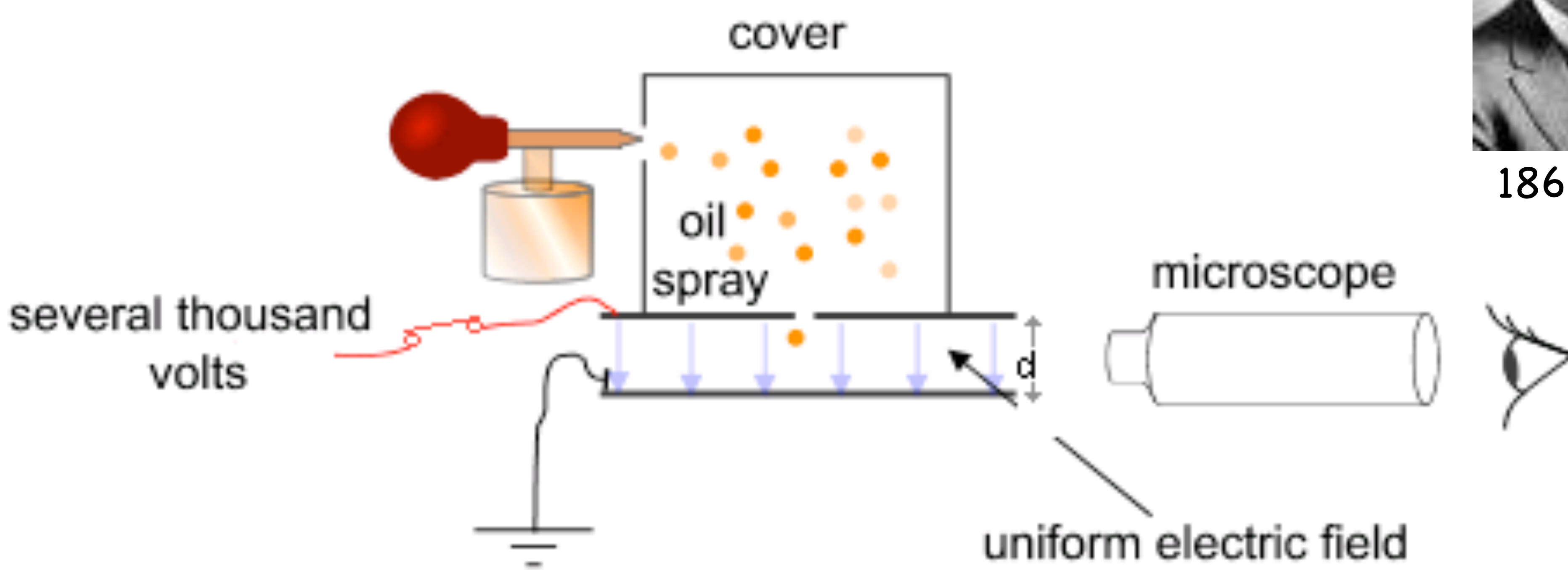
- discovery of the electron (1897)
- measured e/m ratio:
  - $mv^2/r = evB \rightarrow e/m = v/rB$
  - $v=E/B$ from balance of electric and magnetic forces ($eE = evB$)





Robert Millikan experiment


1868–1953

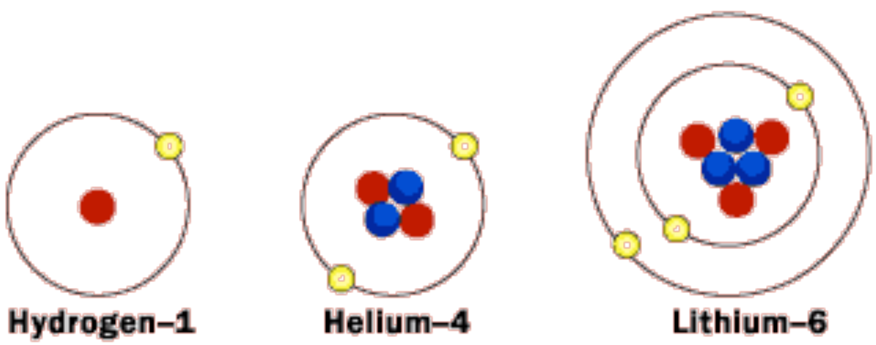


- measured electron's charge → charge quantization (1909)
  - $q_{drop}E - m_{drop}g = F_{drag}$
    $= (6\pi r\eta)v$
  - → $q_{drop} = m_{drop}g/E$ *(find m_{drop} by measuring v in air)*
- all charges in the universe are multiples (simple fractions) of e

Atomic and mass numbers

- atomic number Z = *number of p's (= e's in neutral atom)*
- mass number A = #p + #n: $m_A \approx A m_H$ *(#n -> isotopes)*

Atom	#e	#p	#n	Z	A	mass (u)
Hydrogen (^{1}H)	1	1	0	1	1	1
Helium (^{4}He)	2	2	2	2	4	4
Helium (^{3}He)	2	2	1	2	3	3
Carbon (^{12}C)	6	6	6	6	12	12



- atomic mass unit: *u = 1/12 of a mass of ^{12}C atom*

$$1\ u = 1\ \text{gram}/N_A \approx m_{proton} \quad (N_A = 6 \times 10^{23} = 1\ \text{mole})$$

- isotopes: *same #p but different #n, e.g.* ^1_1H Protium ^2_1H Deuterium ^3_1H Tritium

Periodic table of elements

- atomic number Z = *number of p's (= e's in neutral atom)*
- mass number A = #p + #n: $m_A \approx A m_H$ *(#n -> isotopes)*

- Mendeleev's table of elements (1869): http://www.ptable.com/

Periodic Table of the Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.01																	2 He 4.00
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.30											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 30.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (97.91)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (208.98)	85 At (209.99)	86 Rn (222.02)
87 Fr (223.02)	88 Ra (226.03)	89 Ac (227.03)	104 Rf (261.11)	105 Ha (262.11)	106 Sg (263.12)												
				58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (144.91)	62 Sm 150.36	63 Eu 151.97	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
				90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237.05)	94 Pu (244.06)	95 Am (243.06)	96 Cm (247.07)	97 Bk (247.07)	98 Cf (251.08)	99 Es (252.08)	100 Fm (257.10)	101 Md (258.10)	102 No (259.10)	103 Lr (262.11)

clicker question

Number of atoms inside you

Q: *Estimate (within a factor of 100) the number of atoms inside your body*

a) 100 trillion (10^{14})
b) No idea, as there is too many to count
c) 1000 x Avagadro number → approximately 10^{26}
d) None of the above

A: 12 gram chunk of carbon has N_A of C atoms in it, so you (≈ 50kg ≈ 50,000g) have 5000 times more