Atoms and Atomic Structure

A remarkable fact, which is important to science and technology:

Nature is simple.

What is matter?

Physics is a reductionist science.
Beneath the surface, nature is simple!

All matter is composed of elements.

There are 91 stable elements, and about 20 other unstable elements which decay by radioactive processes.

Ancient ideas about matter –
from the philosophers of ancient Greece

Elements. They had the idea that all matter is composed of a few basic forms of matter – air, earth, fire and water.

Atoms. They had the idea that matter has smallest particles; matter is not infinitely divisible.

Democritus (460 — 370 BC)

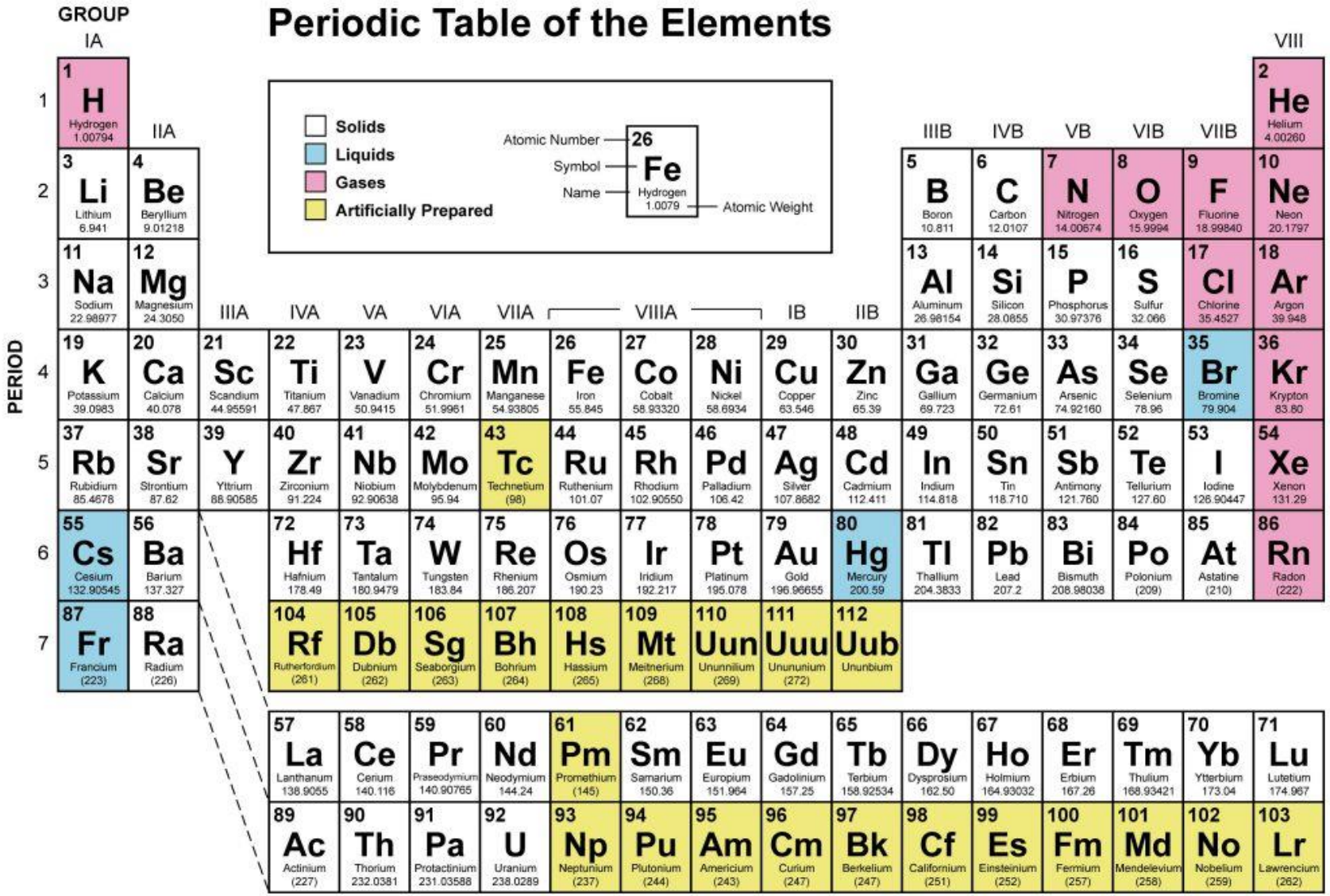
The word "Atom" comes from Greek,
meaning "cannot be cut."

Democritus of Abdera (460 – 370 BC)

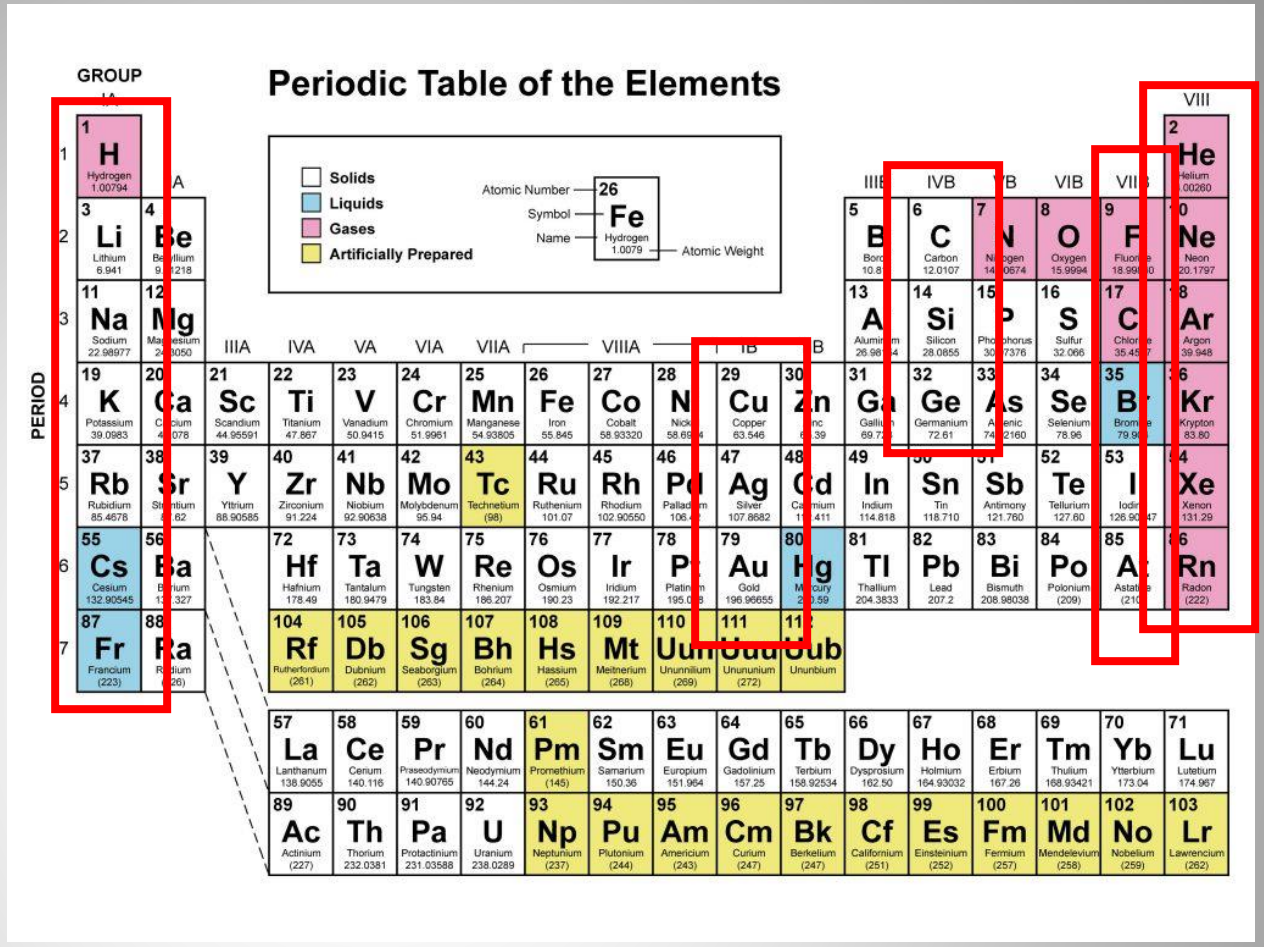
“A + tome” …
…cannot be cut

… the laughing philosopher

The Elements


Periodic Table of the Elements
GROUP
PERIOD
Solids
Liquids
Gases
Artificially Prepared
Atomic Number
Symbol
Name
Atomic Weight
26
Fe
Hydrogen
1.0079
IA
IIA
IIIA
IVA
VA
VIA
VIIA
VIIIA
IB
IIB
IIIB
IVB
VB
VIB
VIIB
VIII
1 H Hydrogen 1.00794
2 He Helium 4.00260
3 Li Lithium 6.941
4 Be Beryllium 9.01218
5 B Boron 10.811
6 C Carbon 12.0107
7 N Nitrogen 14.00674
8 O Oxygen 15.9994
9 F Fluorine 18.99840
10 Ne Neon 20.1797
11 Na Sodium 22.98977
12 Mg Magnesium 24.3050
13 Al Aluminum 26.98154
14 Si Silicon 28.0855
15 P Phosphorus 30.97376
16 S Sulfur 32.066
17 Cl Chlorine 35.4527
18 Ar Argon 39.948
19 K Potassium 39.0983
20 Ca Calcium 40.078
21 Sc Scandium 44.95591
22 Ti Titanium 47.867
23 V Vanadium 50.9415
24 Cr Chromium 51.9961
25 Mn Manganese 54.93805
26 Fe Iron 55.845
27 Co Cobalt 58.93320
28 Ni Nickel 58.6934
29 Cu Copper 63.546
30 Zn Zinc 65.39
31 Ga Gallium 69.723
32 Ge Germanium 72.61
33 As Arsenic 74.92160
34 Se Selenium 78.96
35 Br Bromine 79.904
36 Kr Krypton 83.80
37 Rb Rubidium 85.4678
38 Sr Strontium 87.62
39 Y Yttrium 88.90585
40 Zr Zirconium 91.224
41 Nb Niobium 92.90638
42 Mo Molybdenum 95.94
43 Tc Technetium (98)
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.90550
46 Pd Palladium 106.42
47 Ag Silver 107.8682
48 Cd Cadmium 112.411
49 In Indium 114.818
50 Sn Tin 118.710
51 Sb Antimony 121.760
52 Te Tellurium 127.60
53 I Iodine 126.90447
54 Xe Xenon 131.29
55 Cs Cesium 132.90545
56 Ba Barium 137.327
72 Hf Hafnium 178.49
73 Ta Tantalum 180.9479
74 W Tungsten 183.84
75 Re Rhenium 186.207
76 Os Osmium 190.23
77 Ir Iridium 192.217
78 Pt Platinum 195.078
79 Au Gold 196.96655
80 Hg Mercury 200.59
81 Tl Thallium 204.3833
82 Pb Lead 207.2
83 Bi Bismuth 208.98038
84 Po Polonium (209)
85 At Astatine (210)
86 Rn Radon (222)
87 Fr Francium (223)
88 Ra Radium (226)
104 Rf Rutherfordium (261)
105 Db Dubnium (262)
106 Sg Seaborgium (263)
107 Bh Bohrium (264)
108 Hs Hassium (265)
109 Mt Meitnerium (268)
110 Uun Ununnilium (269)
111 Uuu Unununium (272)
112 Uub Ununbium
57 La Lanthanum 138.9055
58 Ce Cerium 140.116
59 Pr Praseodymium 140.90765
60 Nd Neodymium 144.24
61 Pm Promethium (145)
62 Sm Samarium 150.36
63 Eu Europium 151.964
64 Gd Gadolinium 157.25
65 Tb Terbium 158.92534
66 Dy Dysprosium 162.50
67 Ho Holmium 164.93032
68 Er Erbium 167.26
69 Tm Thulium 168.93421
70 Yb Ytterbium 173.04
71 Lu Lutetium 174.967
89 Ac Actinium (227)
90 Th Thorium 232.0381
91 Pa Protactinium 231.03588
92 U Uranium 238.0289
93 Np Neptunium (237)
94 Pu Plutonium (244)
95 Am Americium (243)
96 Cm Curium (247)
97 Bk Berkelium (247)
98 Cf Californium (251)
99 Es Einsteinium (252)
100 Fm Fermium (257)
101 Md Mendelevium (258)
102 No Nobelium (259)
103 Lr Lawrencium (262)

Periodic properties of the elements: Elements in the same column have similar chemical and physical properties.



Noble gases

Alkali metals

Halogen gases

Precious metals

Semiconductors

What is an element?

These are not the elements of ancient Greece (air, earth, fire, water). There are 91 stable elements, plus some unstable ones.

Each element has a unique atom.

Atomic number of an element = the number of electrons in an atom of the element

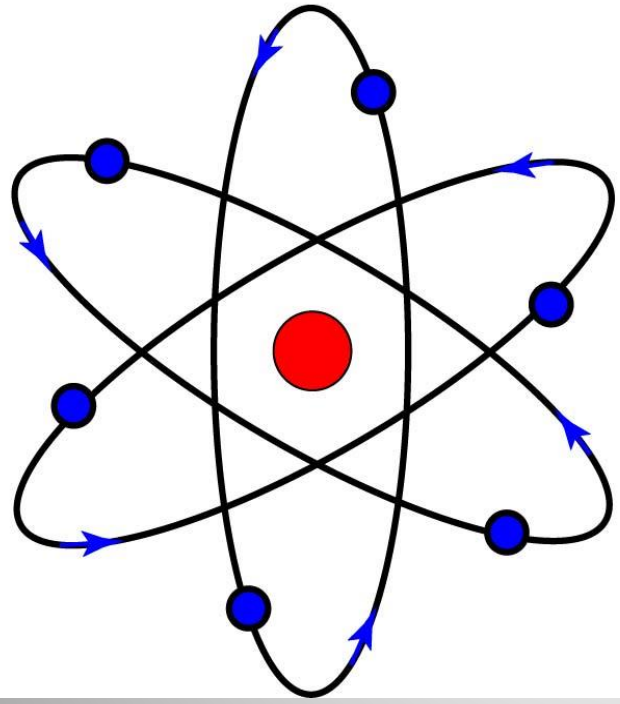
Examples of materials that are not elements: compounds and mixtures. A *chemical compound* has a complex molecule (a bound state of different atoms) as its basic particle.

The Atomic Theory

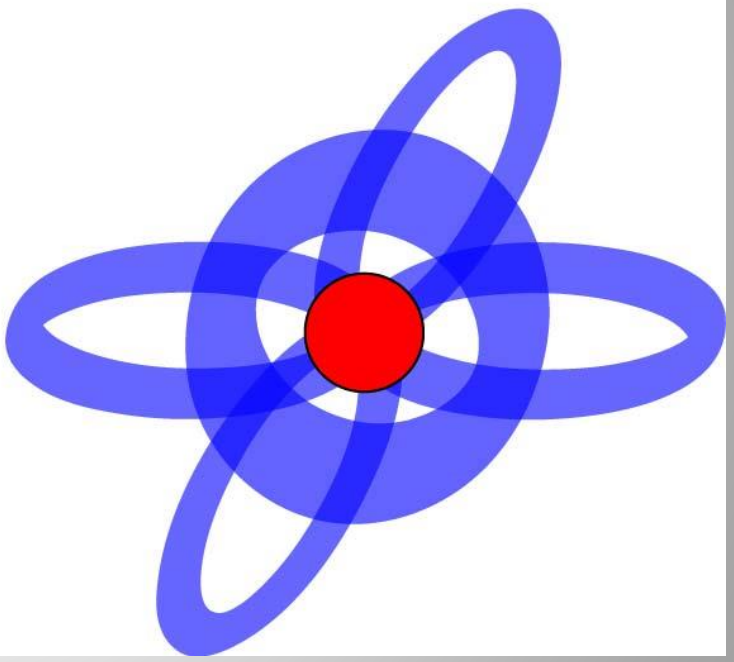
Link

Atomic Structure

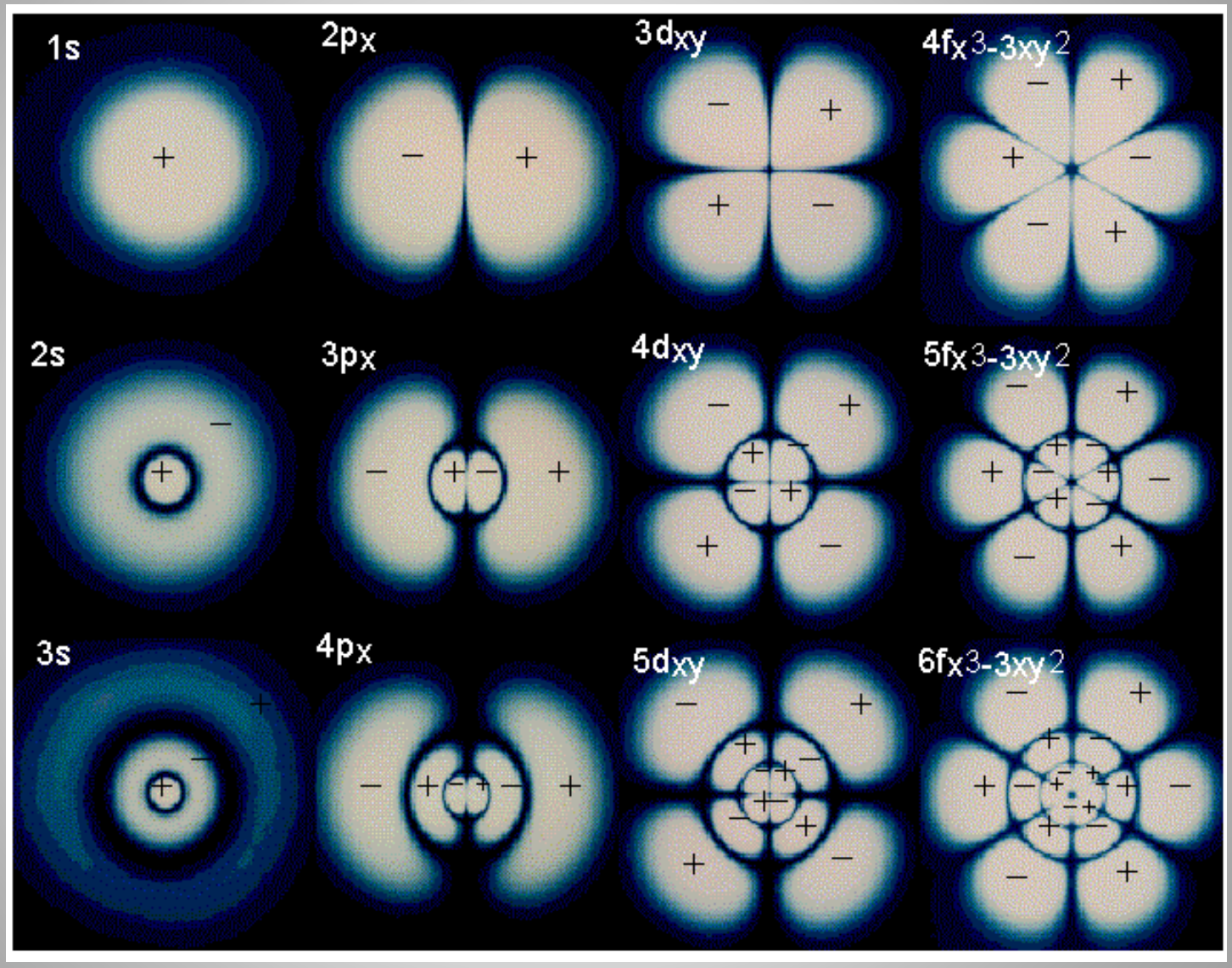
The incorrect classical picture of an atom



In an atomic state, an electron is a wave.

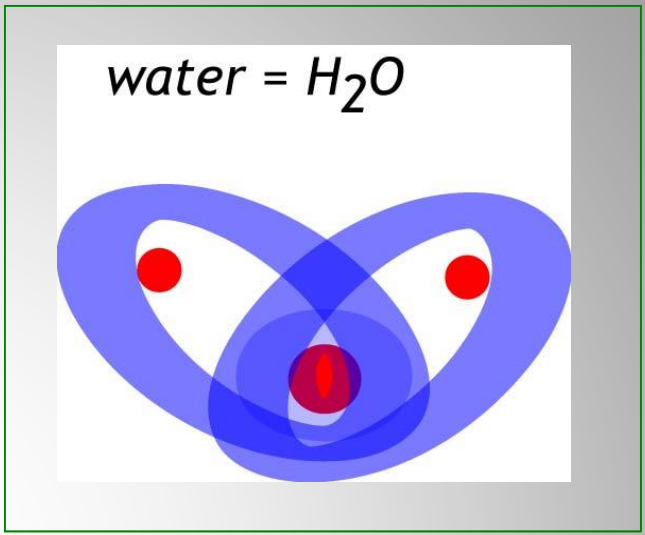


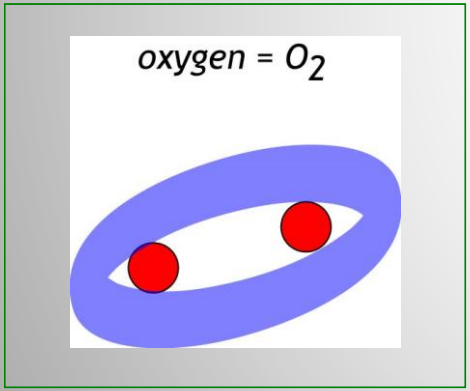
Atomic Orbitals

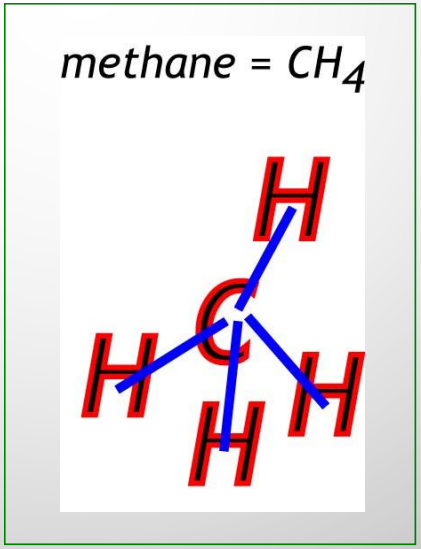


Chemistry

Atoms combine in molecules, by sharing electrons







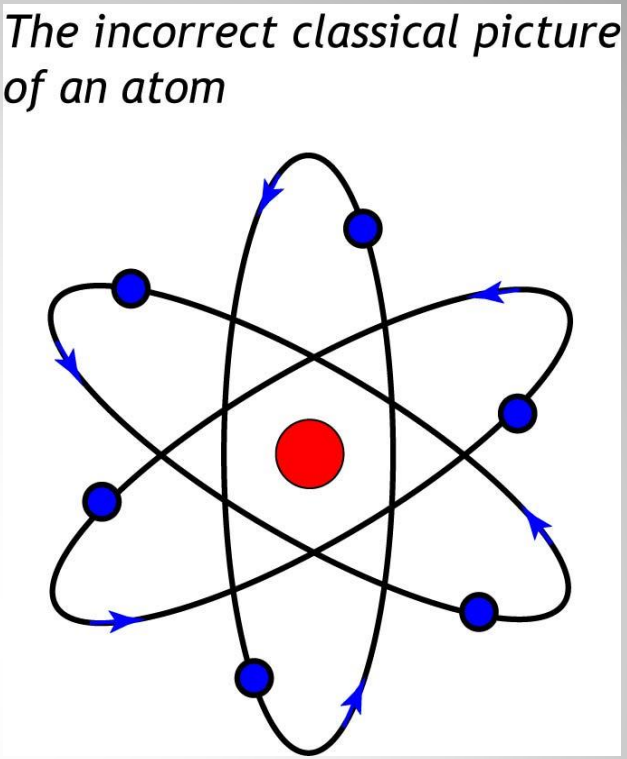
How big is an atom?

The Atom

How large is an atom?

How can we measure the size of an atom?

The incorrect classical picture of an atom



What fundamental factors determine the size of an atom?

Amedeo Avogadro
1776 - 1856

… define a *standard number* of atoms or molecules, to use in the interpretation of chemical reactions by the atomic theory.

N

But how do we know that atoms and molecules even exist?

When does a theory become accepted as true?

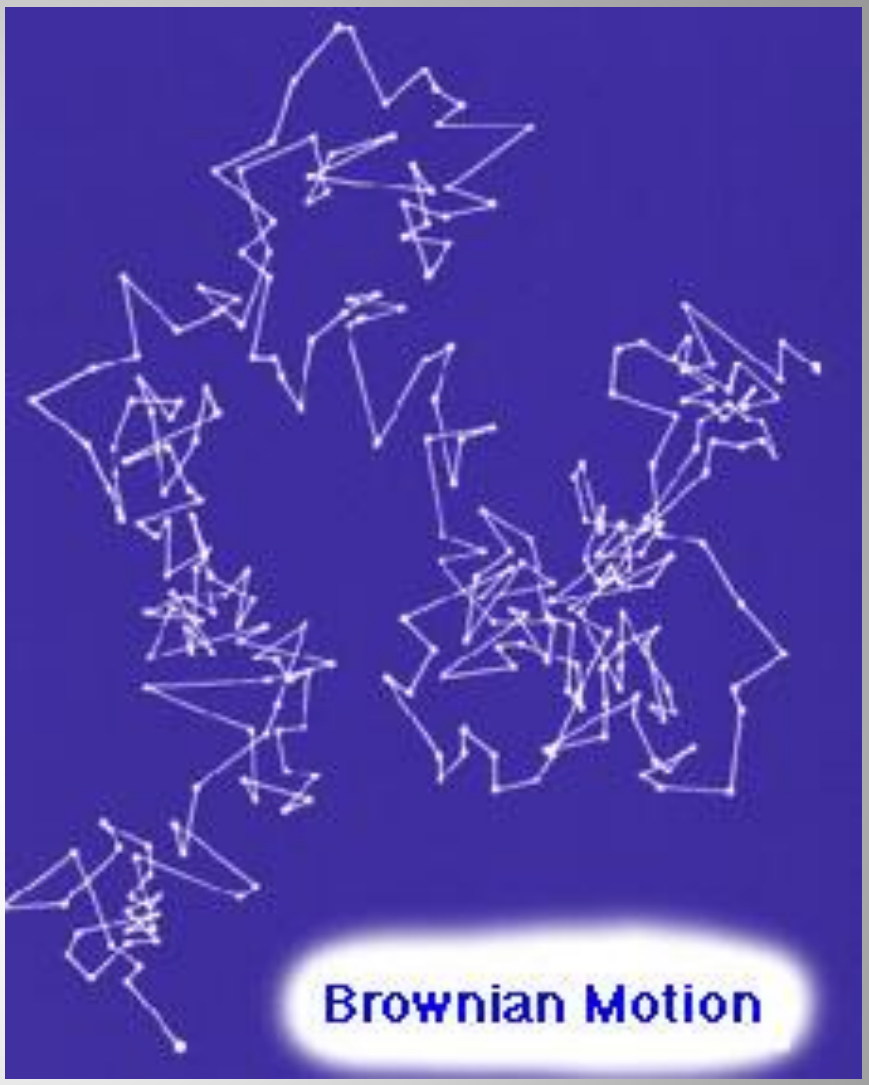
Atoms and molecules are much too small to be seen. An atom is only ***1 / 5000 times as large*** as one wavelength of visible light.

If we cannot see an atom, can the atomic theory be accepted as true?

The truth of atoms was not generally accepted until the 20th century. But how?

Brownian motion

Brownian motion is the random jittery motion of a small particle suspended in a fluid, due to collisions with the molecules of the fluid.



Picture from *Atoms* by Jean Baptiste Perrin

Brownian motion is direct evidence of atoms.

First Solvay Congress, 1911; Brussels; L-R seated at table: Nernst; Brillouin; Solvay; Lorentz; Warburg; Perrin; Wien; Curie; Poincare. L-R Standing: Goldschmidt; Planck; Rubens; Sommerfeld; Lindemann; De Broglie; Knudsen; Hasenohrl; Hostelet; Herzen; Jeans; Rutherford; Kamerlingh-Onnes; Einstein; Langevin

Jean Baptiste Perrin and Avogadro's number N

Perrin used Brownian motion to measure Avogadro's number, in 1909. The theory had been worked out in 1905 by Einstein.

The properties of the motion depend on temperature, molecular weight, and number density. From the observations Perrin could deduce the value of *N*. He got the Nobel prize in 1926.

Today *N* is determined most accurately by X-ray scattering.

$N = 6.02 \times 10^{23}$ atoms

How large is an atom?

(1) The mass density of solid carbon (diamond) is 3.52 g/cm³; so the volume of 12 grams of carbon is

$$V_{12} = \frac{12\ \mathrm{g}}{3.52\ \mathrm{g/cm^3}} = 3.5\ \mathrm{cm^3}$$

(2) Therefore the volume of a *single* carbon atom (from N) is

$$\frac{V_{12}}{N} = 0.6 \times 10^{-23}\ \mathrm{cm^3}$$

(3) Convert V_a to an atomic radius ($V_a = 4/3\ p\ r^3$)

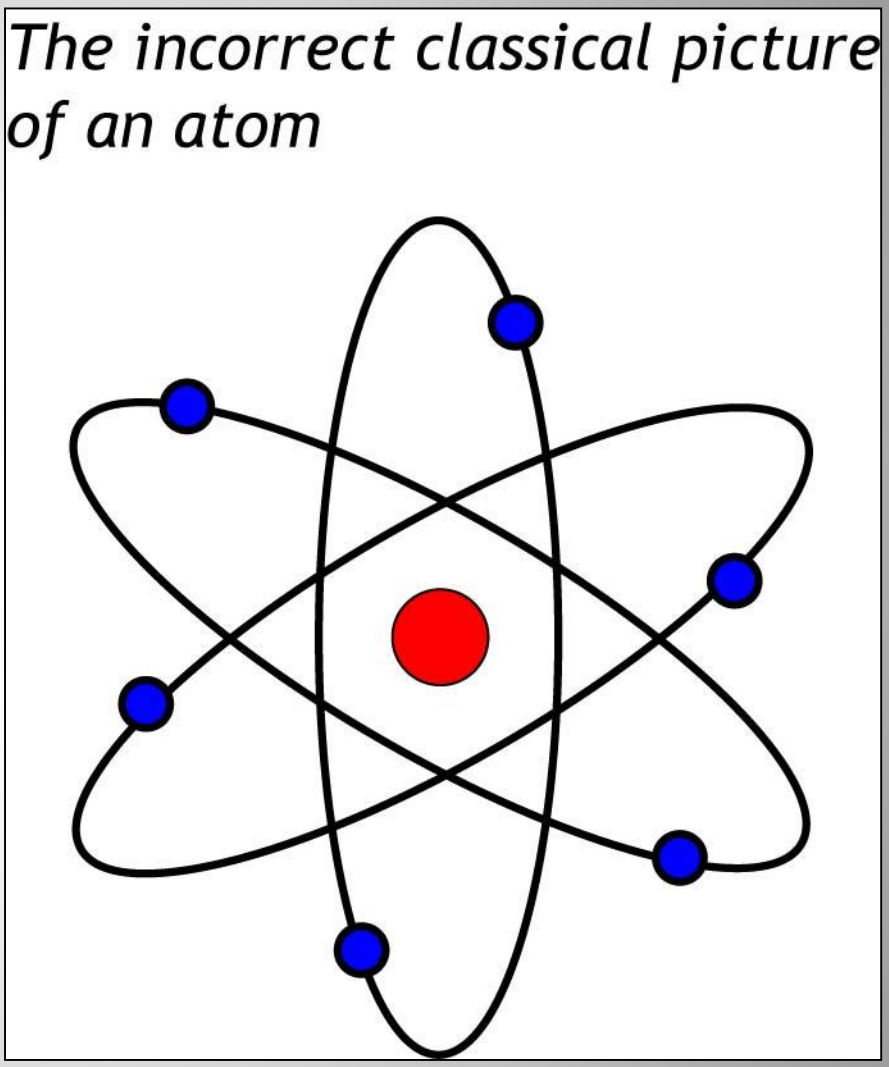
$$r = \left(\frac{3}{4\pi} V_a \right)^{1/3} = 1 \times 10^{-8}\ \mathrm{cm}$$

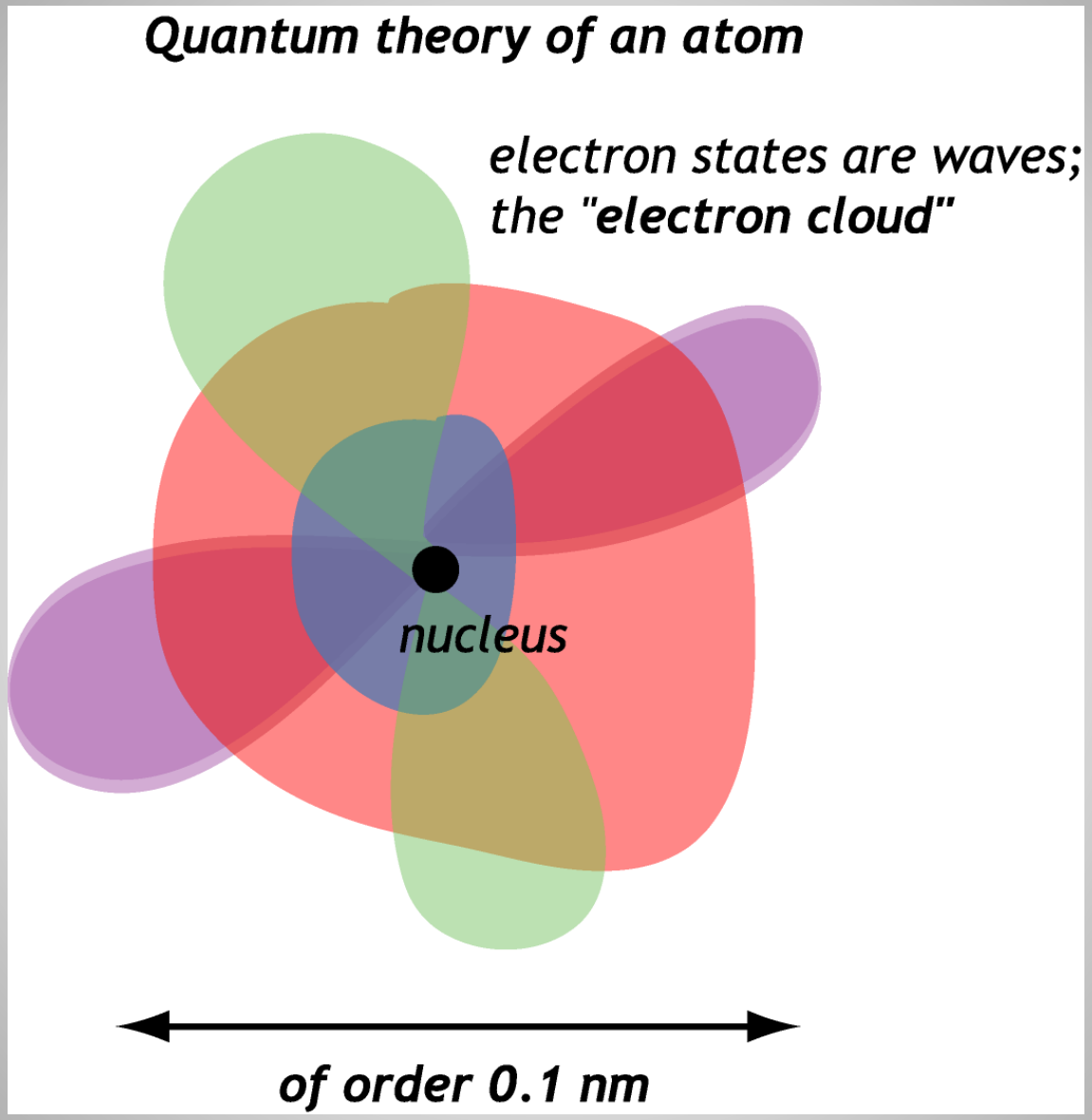
Result:
The typical order of magnitude of an atomic radius is 10^{-10} m = 0.1 nm.

What determines this size?

Atomic structure

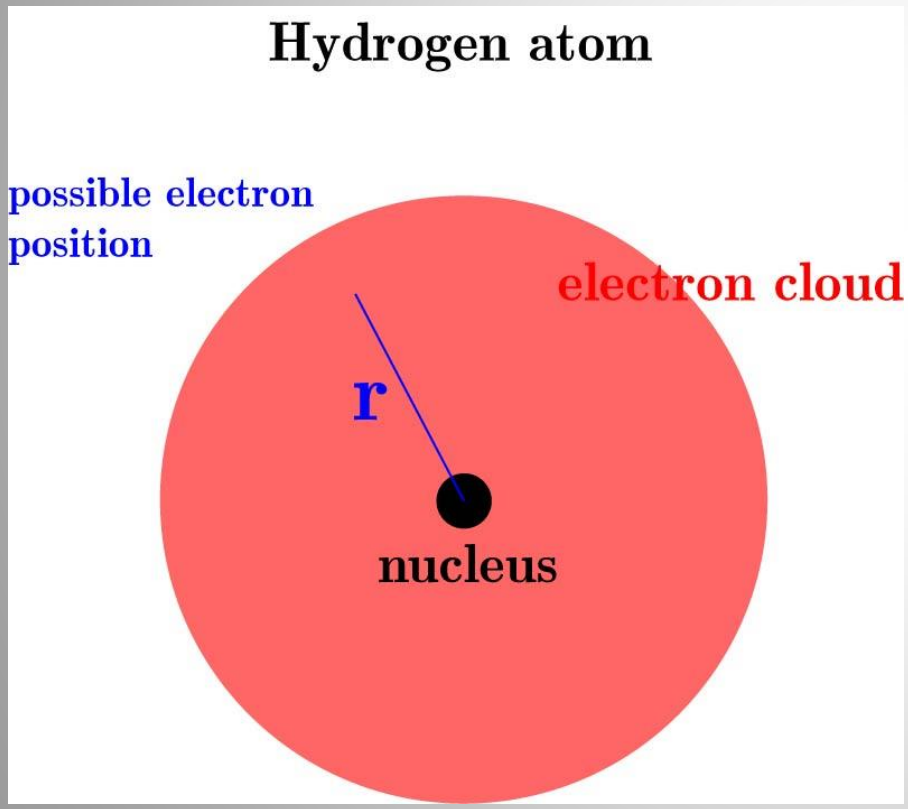
How do we know that an atom has this structure?




Quantum theory of an atom
electron states are waves;
the "electron cloud"
nucleus
of order 0.1 nm

The typical order of magnitude of an atomic radius is 10^{-10} m = 0.1 nm. Why?

What determines this size? …quantum dynamics of the electron



potential energy $V(r) = \dfrac{-e^2}{4\pi\varepsilon_0 r}$

kinetic energy $K = \dfrac{p^2}{2m} = \dfrac{1}{2m}\left(\dfrac{h}{2\pi r}\right)^2$

Heisenberg uncertainty principle

The state with lowest energy has mean radius =

$$\frac{h^2}{me^2}\frac{4\pi\varepsilon_0}{(2\pi)^2} = 0.53\times10^{-10}\ \text{m}$$

"Bohr radius"

Democritus of Abdera (460 – 370 BC)