Preliminary Course: Atomic Structure

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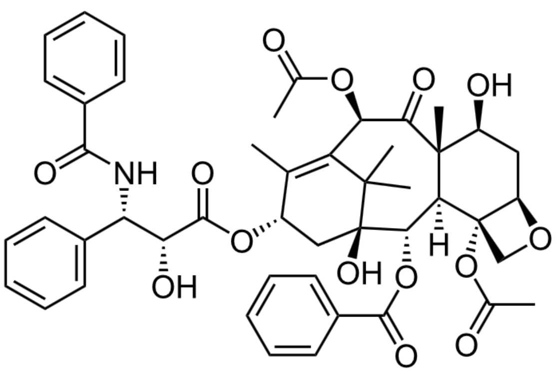
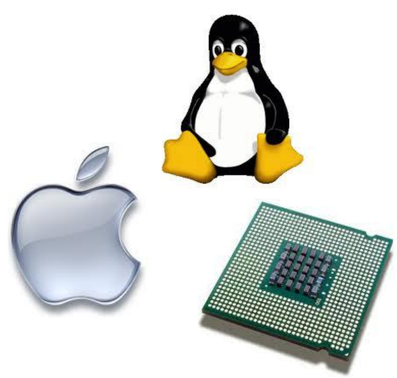
Why Learn Atomic Structure?

The material universe is made of **matter.**

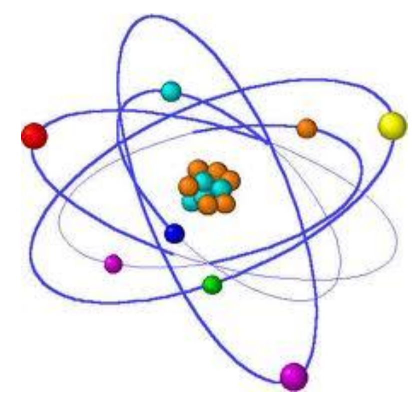
What is **matter**? What is its **structure**?
How is knowing this structure useful?



Molecular structure
Modern medicine



Electronic structure
Modern computing



Atomic structure

What is Matter?

Matter: That which has mass and occupies space.

Substance: A single form of matter. A substance can be a pure compound or a mixture of compounds.

Compound: A substance made of several different elements joined together. Eg. water is H_2O; hydrogen and oxygen.

Element: A substance with only one kind of atom. For example, hydrogen gas is H_2, just hydrogen atoms.

Atom: The smallest particle of an element that can exist.

What is Matter?

Matter:

Substance:

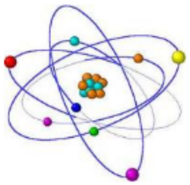
Compound:

Sodium + Chlorine
-> Sodium Chloride
= Salt

Element:

These bars contain only gold atoms

Atom:



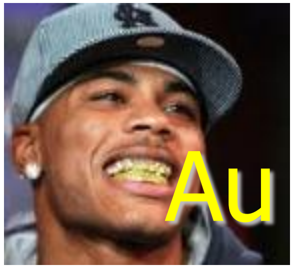
Different elements are made of different types of atoms

Different kinds of Atoms: The Elements

S = Sulfur

Pu = Plutonium

Ir = Iridium



Au = Gold

Si = Silicon

Atomic Theory of Matter

Philosophical roots: Democritus 400 BC said that matter was composed of indivisible particles (*Atomos* means indivisible).

Dalton's theory: Dalton (1803) proposed the following theory:

1. An element is made of atoms.
2. Atoms cannot be destroyed or created.
3. All atoms of a single element are identical and have the same mass.
4. Atoms of different elements have different masses.
5. Two or more elements may combine in the ratio of small whole numbers to form compounds.

Law of Multiple Proportions: When two elements combine, the ratio of each element in the compound will always be a whole number.

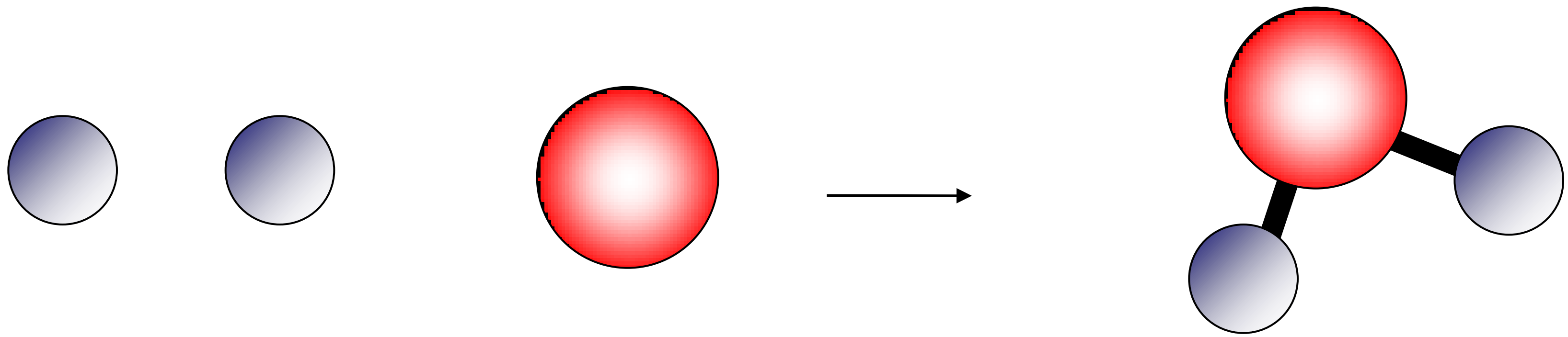
Law of Multiple Proportions

Experimental roots: Dalton observed that when elements combine to form compounds, they combine in whole number ratios.

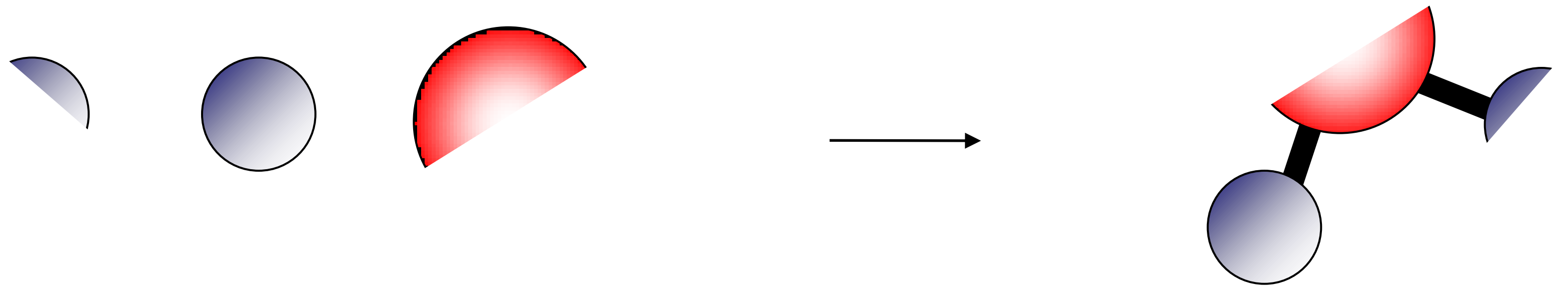
Until Dalton came along, a compound might contain any ratio of the elements it was made of. For example; any amount of hydrogen and oxygen could combine to form weird substances: For example: $H_{1.2}O_{6.1}$ $H_3O_{2.39}$ ...which we know do not exist!

The atomic theory means only whole number ratios are allowed For example: H_2O is water while H_2O_2 is hydrogen peroxide.

The atomic theory makes sense!

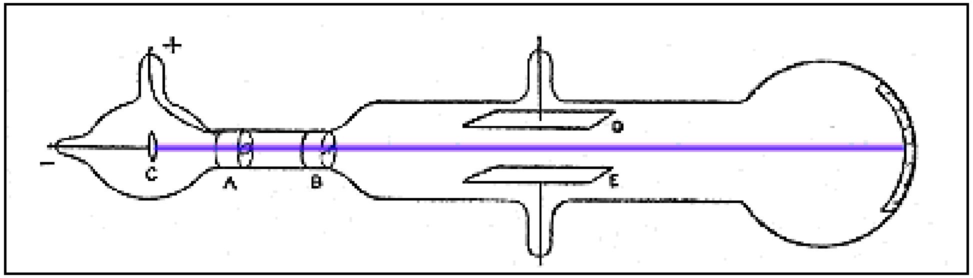


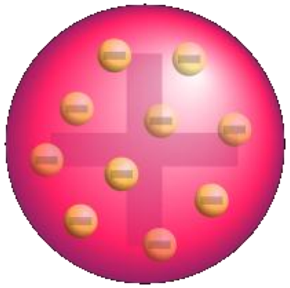
Two hydrogen atoms and one oxygen atom can combine to make Dihydrogen Monoxide (Water).



But 1.234... hydrogen atoms cannot combine with a bit of an oxygen atom to make 1.234-hydrogen Bit-oxide.

Atomic Structure: Electrons

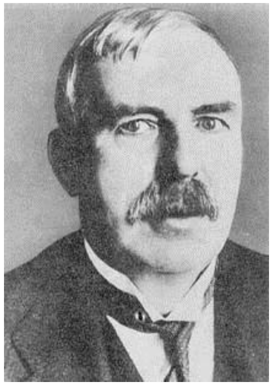




JJ Thompson (1897) applies voltage to gas in a sealed tube. The charged particles which are produced are found to be have a mass 1800 times smaller than a hydrogen atom!

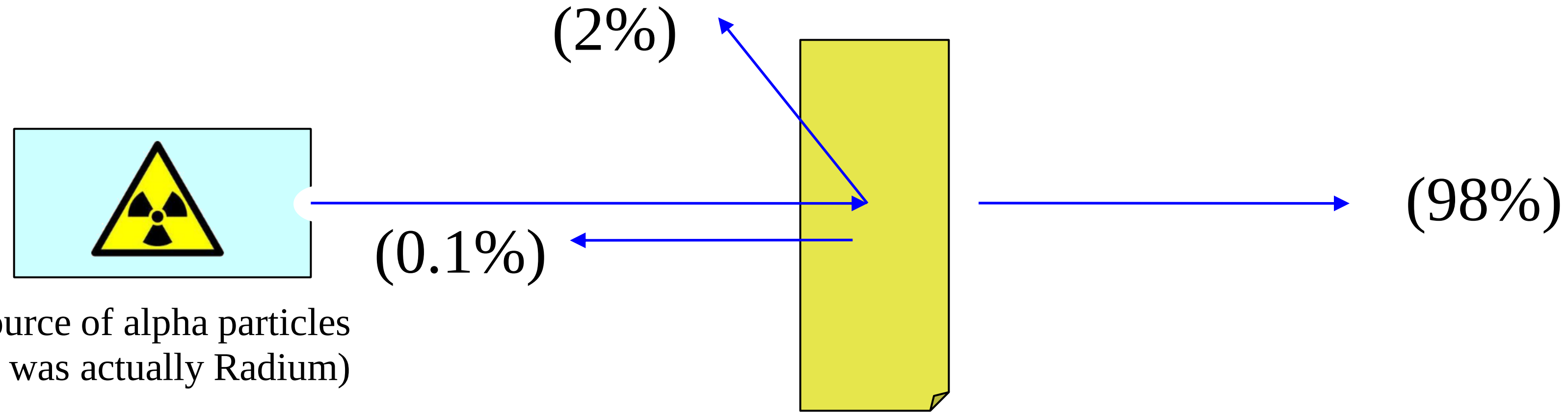
Thompson postulated that these particles reside within atoms, balanced by a 'delicious cake' of positive charge. This picture of the atom is termed the **plum pudding model**.

Beyond the Plum Pudding



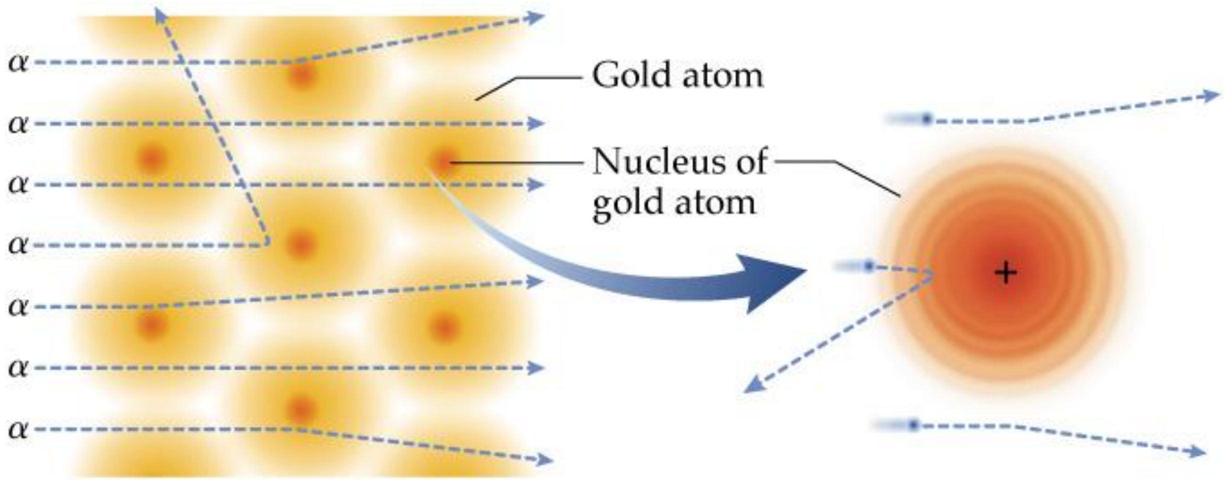
Rutherford (1911) fired charged Helium atoms (also called alpha particles) at a thin sheet of Gold foil.

Almost 98% pass through. 2% are deflected at various angles, but 0.1% bounce *straight back,* as if they had hit a brick wall.



Source of alpha particles
(It was actually Radium)

Rutherford's conclusions

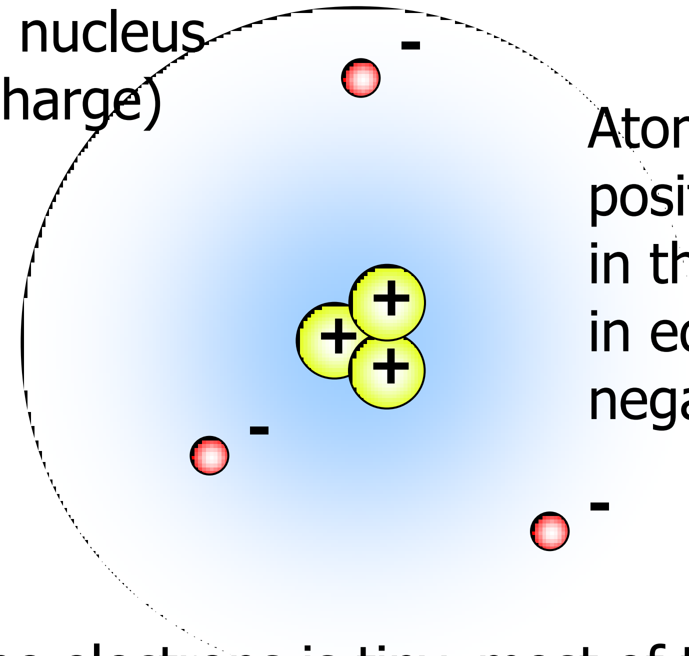


Rutherford concluded that the charged Helium atoms were deflected by a small, positively-charged core, the **Nucleus**.

Attracted by the positive core, the negative electrons orbit in the surrounding space. Because electrons are so light, most of the atom's mass must be in the Nucleus.

Rutherford's Atom

Electrons circle the nucleus due to Columbic (charge) attractive force



Atoms are neutral overall, positively charged **protons** in the nucleus are present in equal numbers to the negative electrons

The weight of the electrons is tiny, most of the atomic mass is found in the nucleus and the atomic radius is filled with predominantly empty space in which the electrons move about

The neutron is discovered

The final piece of the puzzle: Chadwick (1925) observed that alpha particles (positive helium nucleii) could knock a strange, new particle out from a sheet of Beryllium.

$$^{4}_{2}He \quad + \quad ^{9}Be \quad -> \quad ^{12}C \quad + \quad ^{1}_{0}n$$

These particles were uncharged, but had a mass very close to that of the recently discovered proton.

Chadwick postulated a new, neutral particle also existed in the nucleus and named it the **neutron**.

The Atomic Model

Atoms are made up of three, smaller particles:

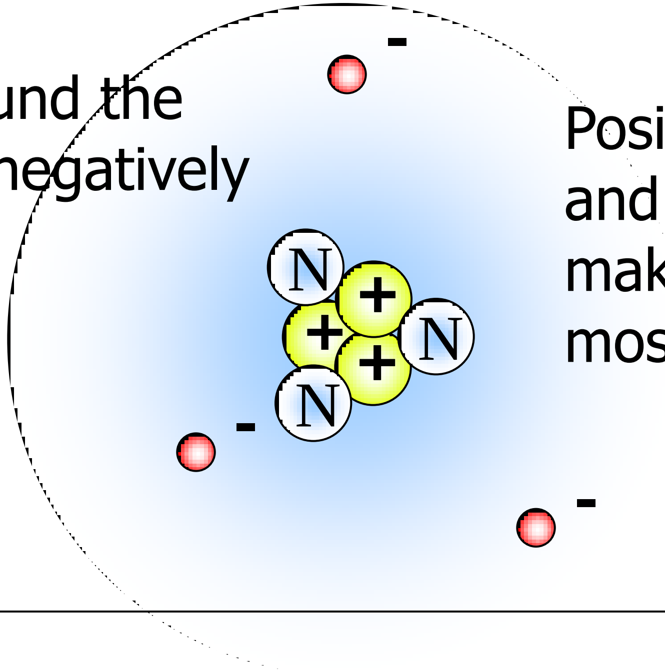
Neutrons: No charge, but have mass. Reside in the nucleus.

Protons: Positive charge, mass is nearly the same as neutrons. Found in the nucleus with the neutrons.

Electrons: Negative charge, 1/1800 times lighter than protons. Occupy the volume of space surrounding the nucleus.

The Nuclear Atom

Electrons orbit around the nucleus. They are negatively charged and have very little mass.



Positively-charged protons and uncharged neutrons make up the nucleus, and most of the atomic mass.

Particle	Symbol	Charge	Mass (g)	
electron	e^-	-1	~9 x 10^{-28}	(1/1837 AMU)
proton	p	+1	~1.7 x 10^{-24}	(1 AMU)
neutron	n	0	~1.7 x 10^{-24}	(1 AMU)

Atomic Number

The **Atomic Number (Z)** is the number of protons in the nucleus of an atom.

Since atoms are electrically neutral (number of protons = number of electrons), Z also tells us the number of electrons in that atom.

An element is defined by its atomic number.
Hydrogen atoms have only 1 proton (Z = 1), carbon has 6 protons (Z=6), uranium has 92 protons (Z=92)...

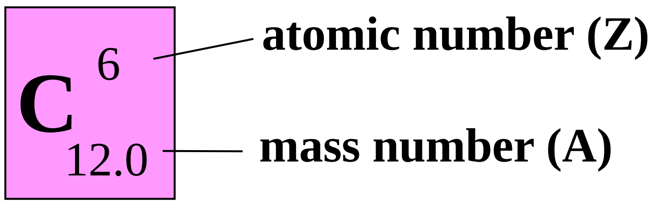
Mass Number

The **Mass Number (A)** is of the number of neutrons plus the number of protons in an atom.

By subtracting the number of protons (Z), we can find the number of neutrons in an atom using:

A – Z = # Neutrons

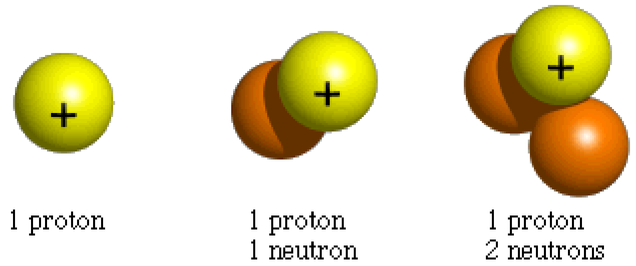
How many neutrons does this Carbon atom have?



A – Z = 6 Neutrons

Isotopes

Isotopes are atoms with the same atomic number but different mass numbers.



There are three isotopes of hydrogen:

^{1}H (protium) has no neutrons, 99.99% natural abundance.
^{2}H (deuterium) has one neutron, 0.01% abundance.
^{3}H (tritium) has two neutrons and undergoes radioactive decay.

This difference in mass is large for hydrogen (a tritium atom is 3 times heavier than protium), but for other elements the difference in mass between isotopes is small enough not to affect their chemistry.

An example: Heavy Water

H_2O

D_2O

Birth of the Periodic Table

Dmitri Mendeleev

Mendeleev (1880) arranged the elements in order of atomic weight (i.e. mass number).

Trends began to emerge; for example Lithium (A=7), Sodium (A=23) and Potassium (A=39) undergo similar chemical reactions.

Placing the elements into rows of increasing mass and columns of similar reactivity allowed Mendeleev to predict the existence of three new elements (gaps in his table).

These elements (gallium, scandium and germanium) were soon discovered.

The Modern Periodic Table

Periodic Table of the Elements

Representative (main group) elements | Transition metals | Representative (main group) elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	1 H 1.0079																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
3	11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.066	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.8
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc 98	44 Ru 101.07	45 Rh 102.906	46 Pd 106.42	47 Ag 107.868	48 Cd 112.411	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.905	54 Xe 131.29
6	55 Cs 132.905	56 Ba 137.327	57 La 138.906	72 Hf 178.49	73 Ta 180.948	74 W 183.84	75 Re 186.207	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.967	80 Hg 200.59	81 Tl 204.383	82 Pb 207.2	83 Bi 208.980	84 Po 209	85 At 210	86 Rn 222
7	87 Fr 223	88 Ra 226.025	89 Ac 227.028	104 Rf 261	105 Db 262	106 Sg 263	107 Bh 262	108 Hs 265	109 Mt 266	110 Uun 269	111 Uuu 272	112 Uub 277		114		116		118

Rare earth elements

Lanthanides	58 Ce 140.115	59 Pr 140.908	60 Nd 144.24	61 Pm 145	62 Sm 150.36	63 Eu 151.964	64 Gd 157.25	65 Tb 158.925	66 Dy 162.5	67 Ho 164.93	68 Er 167.26	69 Tm 168.934	70 Yb 173.04	71 Lu 174.967
Actinides	90 Th 232.038	91 Pa 231.036	92 U 238.029	93 Np 237.048	94 Pu 244	95 Am 243	96 Cm 247	97 Bk 247	98 Cf 251	99 Es 252	100 Fm 257	101 Md 258	102 No 259	103 Lr 262

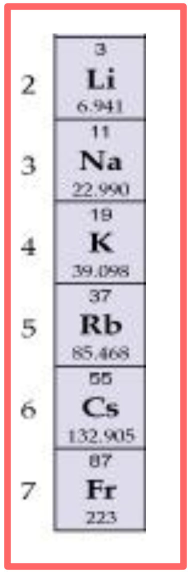
The Modern Periodic Table

The periodic table is arranged today in order of increasing **Atomic Number (Z)**, rather than by weight.

We refer to columns of elements as **Groups**, due to their shared chemical and physical properties.

Several new features are also present in the modern periodic table; these are the **transition metals** (Groups 3 – 11), the **lanthanides** and the **actinides**.

Periodic Table: Groups



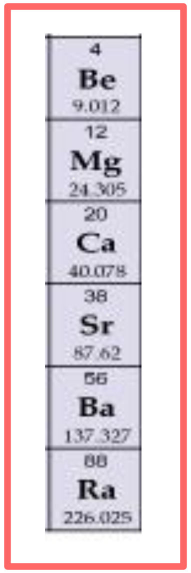
Each column of the periodic table constitutes a **group**. The elements in a group often share similar chemical and physical properties.

Group 1: The **Alkali metals**. Soft, silvery metals with low melting points. Produce H2 gas when added to water. Reactivity increases going down the group.

Examples: Lithium, Sodium, Potassium…

Note: Hydrogen is in a group all on it's own, due to its unique physical and chemical properties

Periodic Table: Groups



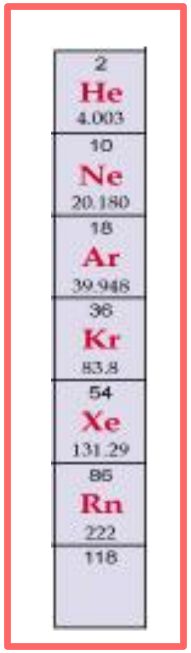
Group 2: The **Alkaline earth metals**. Also produce H2 in contact with water, but less reactive than the group 1 metals.

Examples: Beryllium, Magnesium, Calcium, Stronium, Barium, Radium…

Periodic Table: Groups

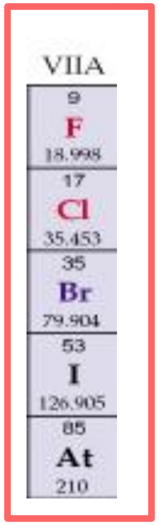
Group 18: The **Noble gases**. Colourless, odorless gases. Highly unreactive, only the heavier noble gases will be able to undergo a few chemical reactions.

Electronically stable.



Periodic Table: Groups

Group 17: The **Halogens**. Chemically reactive, often found in salts.



One more trend in periodicity is illustrated by these elements:

Flourine	GAS
Chlorine	GAS
Bromine	LIQUID
Iodine	SOLID

↓ Increasing atomic weight

Periodic Table: Transition Metals

Groups 3 – 11 are the **Transition Metals**. These elements are the shiny, hard materials we traditionally think of as metals.

Examples: Gold (Au), Platinum (Pt), Mercury (Hg)…

The **Lanthanides** and **Actinides** are two separate groups of metals with unique chemical and physical properties.

Periodic Table: Transition Metals

Periodic Table of the Elements

Transition metals

IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB
21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39
39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc 98	44 Ru 101.07	45 Rh 102.906	46 Pd 106.42	47 Ag 107.868	48 Cd 112.411
57 La 138.906	72 Hf 178.49	73 Ta 180.948	74 W 183.84	75 Re 186.207	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.967	80 Hg 200.59
89 Ac 227.028	104 Rf 261	105 Db 262	106 Sg 263	107 Bh 262	108 Hs 265	109 Mt 266	110 Uun 269	111 Uuu 272	112 Uub 277

Rare earth elements

Lanthanides	58 Ce 140.115	59 Pr 140.908	60 Nd 144.24	61 Pm 145	62 Sm 150.36	63 Eu 151.964	64 Gd 157.25	65 Tb 158.925	66 Dy 162.5	67 Ho 164.93	68 Er 167.26	69 Tm 168.934	70 Yb 173.04	71 Lu 174.967
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Chemistry is all about electrons

Halogens are highly reactive elements, and occur on the 2nd last column (Group 17) of the periodic table.

Alkali earth metals are also highly reactive, and occur as the 1st column (Group 1) of the periodic table.

Nobel gases are unreactive and are the very last column (Group 18) of the periodic table.

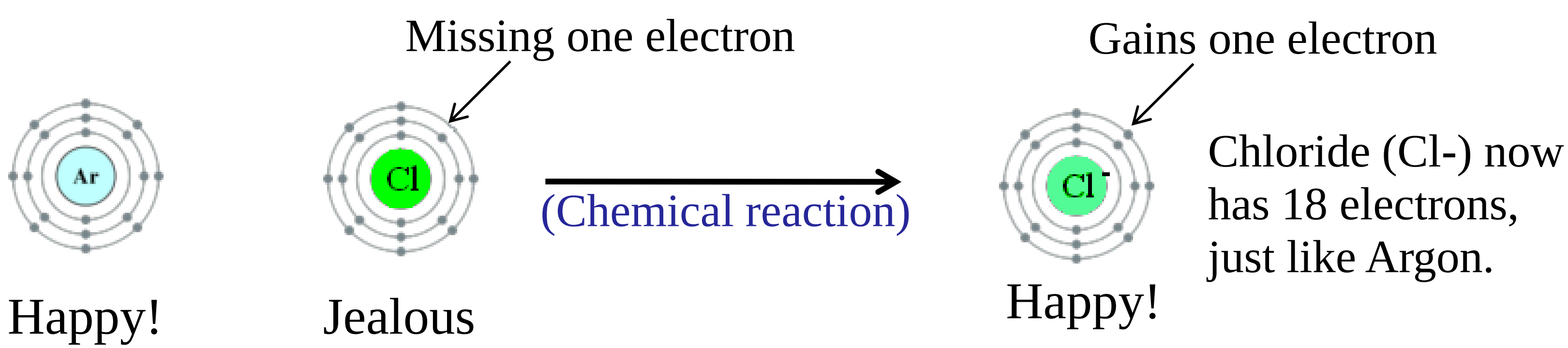
WHY? Nobel gases have the most stable **number of electrons** of all the elements. In chemical reactions, an element will try to attain the same number of electrons as the nearest noble gas.

Chlorine wants an electron!

Argon (Z=18) has 18 electrons. As a nobel gas, it doesn't react.

Chlorine (Z=17) has 17 electrons. It desperately wants to be like argon and to possess 18 electrons.

Therefore, in a chemical reaction chlorine will try to gain one electron and become a **Chloride Anion** (Cl-).

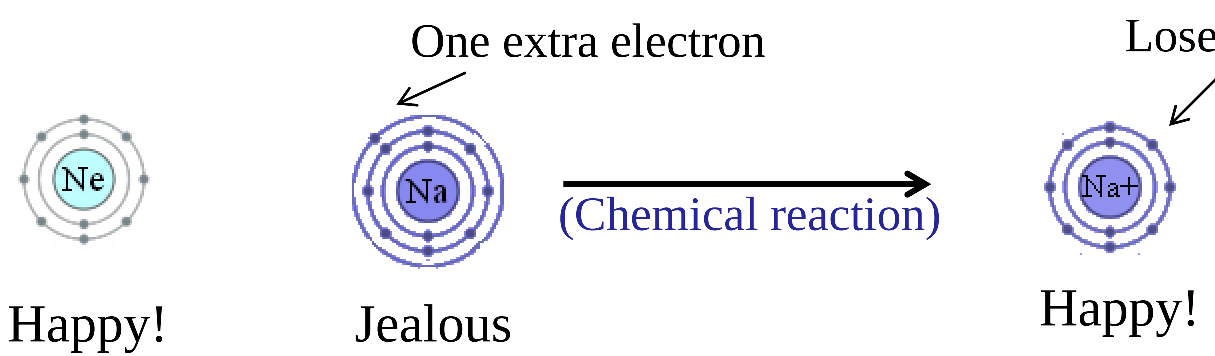


Sodium wants to lose an electron!

Neon (Z=10) has 10 electrons. As a nobel gas, it doesn't react.

Sodium (Z=11) has 11 electrons. It desperately wants to be like neon and possess to 10 electrons.

Therefore, in a chemical reaction sodium will try to lose one electron and become a **Sodium Cation** (Na+).



Sodium (Na+) now has 10 electrons, just like Neon.

Metals generally form CATIONS

Elements to the left of the periodic table will attempt to lose electrons and are **metals**.

For groups 1 and 2, the charge of the cation (number of electrons lost) will be the same as the group number.

Li and Na	(Group 1)	Li^{+}, Na^{+}
Mg and Ca	(Group 2)	Mg^{2+}, Ca^{2+}

Other metals can form cations of different charges. **Transition metals** in particular can often lose different numbers of electrons (You can find Cu+2, Cu+1 etc. in nature)

Nonmetals generally form ANIONS

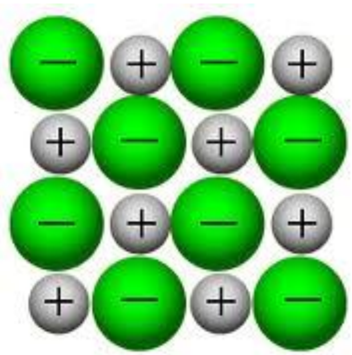
Elements to the left of the periodic table (except the nobel gases) will attempt to gain electrons and are **nonmetals**.

For groups 15, 16 and 17, the charge of the anion (number of electrons gained) will be the same as the (group number – 18).

Nitrogen	(Group 15)	15 – 18 = -3	N^{3-}
Oxygen	(Group 16)	16 – 18 = -2	O^{2-}
Chlorine	(Group 17)	17 – 18 = -1	Cl^{-}

Example: Sulfur is in group 16, so it wants to be like argon (group 18). Therefore, sulfur will become S^{2-}.

Cations and Anions stick together



Sodium chloride is made up of Na+ and Cl- ions.

The attraction between the positively charged sodium and negatively charged chlorine is what holds a grain of salt together.

What about more complex structures like DNA?

Obviously, things get much more complicated than table salt! Nonetheless, the atom remains the essential building block from which all other matter is made up.