Chemical Composition of Rocks and Minerals

BI201 Natural History of Guam

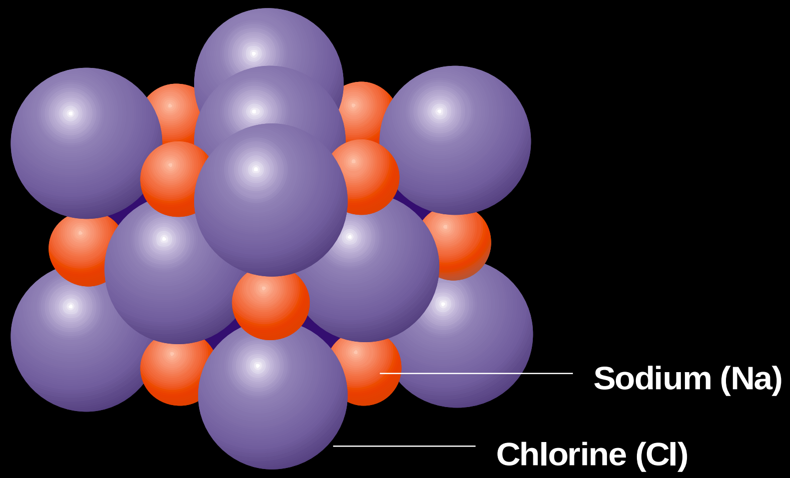
Class Presentation 08

I. Terminology

- **Rock**
  - **Rock is a** naturally formed, consolidated material composed of grains of one or more minerals or organic matter
    - e.g., **granite**
      - Granite forms from magma solidifying within Earth's lithosphere
      - It is made up mostly of the minerals *feldspar* and *quartz*

- **Mineral**
  - A mineral is a naturally occurring, usually inorganic solid, having a definite chemical composition and possessing characteristic physical properties
  - Minerals are composed of molecules arranged in very orderly, 3-D structure (i.e., they are **crystalline**)
    - e.g., **quartz** = SiO_2 [2:1 O:Si ratio]
    - e.g., **feldspar** = $KAlSi_3O_8$ [*potassium-feldspar*] or $CaAl_2Si_2O_8$ [*anorthite*]

- e.g., **rock salt**
  - Rock salt is formed when salt water is evaporated
  - Rock salt is made of only one mineral, halite, which has the chemical structure NaCl
    - Therefore, rock salt has a 1:1 Na:Cl ratio
  - In the crystalline pattern of rock salt, each Na^+ is surrounded by 6 Cl^- and each Cl^- is surrounded by 6 Na^+
  - Therefore, NaCl has a cubic crystal form



Model of the crystal structure of halite.

II. Introduction to geological chemistry

- Atoms and elements / compounds and molecules
  - Anything that has mass and occupies space is called **matter**
  - Matter is made up of tiny particles called **atoms**
  - An atom is the smallest particle of an **element** that retains all the properties of that element
  - An element is a substance that cannot be broken down into simpler substances by ordinary chemical means
    - 116 different elements have been identified so far, but only 92 of these occur naturally on Earth

Periodic Table of Elements

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1 H 1.008																	2 He 4.00
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.00	8 O 15.99	9 F 18.99	10 Ne 20.18
11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 51.99	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.71	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 7.259	33 As 74.92	34 Se 78.96	35 Br 79.91	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 (99)	44 Ru 101.97	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.30
55 Cs 132.91	56 Ba 137.34	57 *La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.98	84 Po (210)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89 *Ac (227)	104 Rf (261)	105 Db (260)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (268)	110 Ds (271)	111 Rg (272)	112* Uub (277)	113* Uut (284)	114* Uuq (289)	115* Uup (288)	116* Uuh (292)	117^{H}	118^{H}

*Lanthanide Series	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (147)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
*Actinide Series	90 Th 232.04	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lr (257)

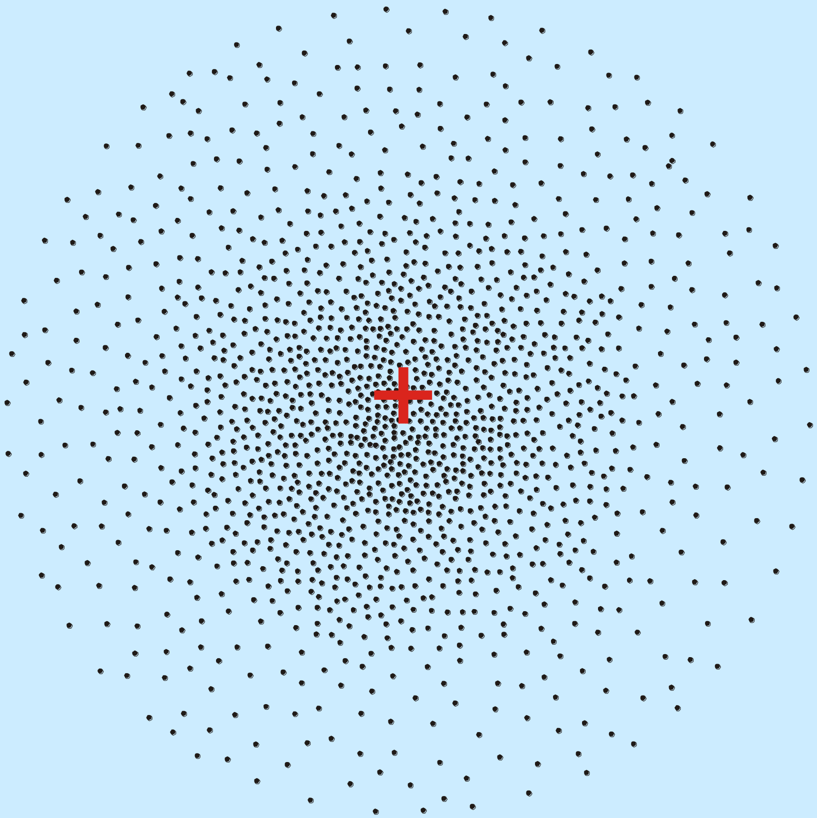
*These elements have been discovered but not yet officially confirmed and named.
^{H}These elements have yet to be discovered.

Li - Solid　**Br** - Liquid　**He** - Gas　**No** - Synthetic

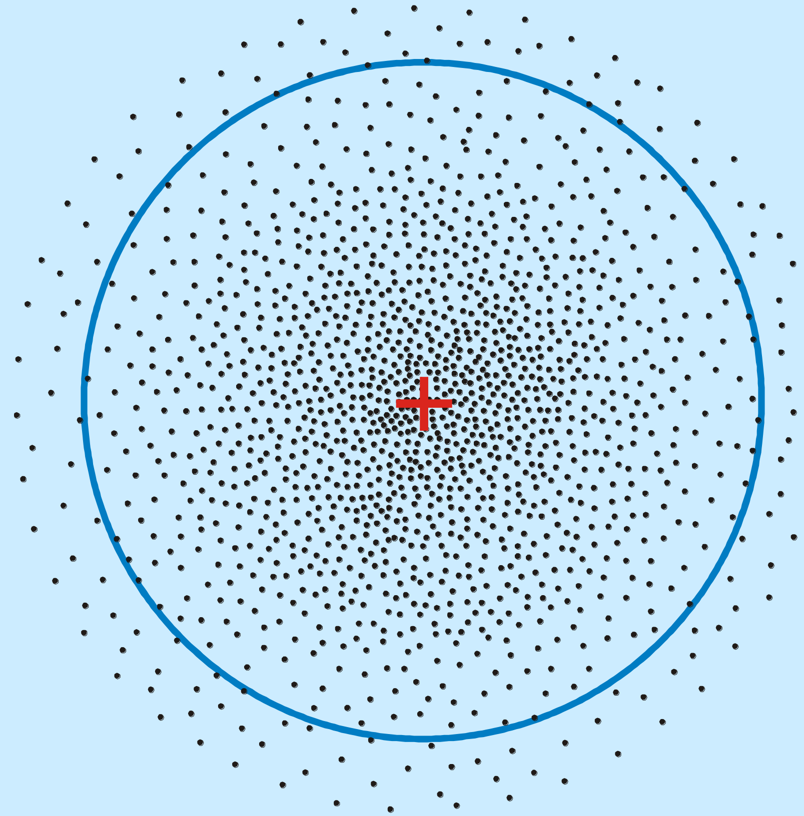
Legend:

- Non-metals
- Transition metals
- Rare Earth metals
- Halogens
- Alkali metals
- Alkali Earth metals
- Other metals
- Inert Gases

- Atoms consist of **subatomic particles**
  - **Proton**
    - particle in the nucleus of an atom
    - has mass
    - carries positive electrical charge
  - **Electron**
    - particle that travels in *orbital paths* around nucleus (actually more like 3-D shell than planar)
    - negligible mass (almost immeasurably small)
    - carries negative electrical charge



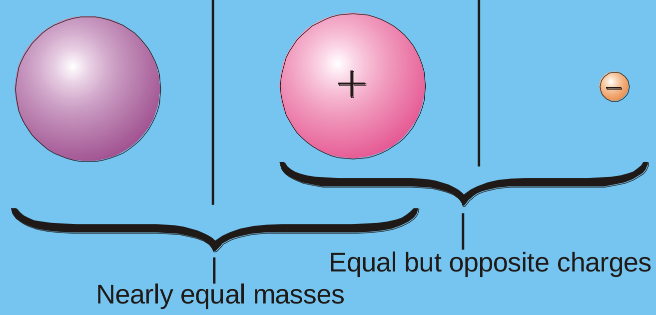
Electron density or electron cloud representation of the motion of an electron about a positive nucleus.
[After Gray and Haight, 1967].



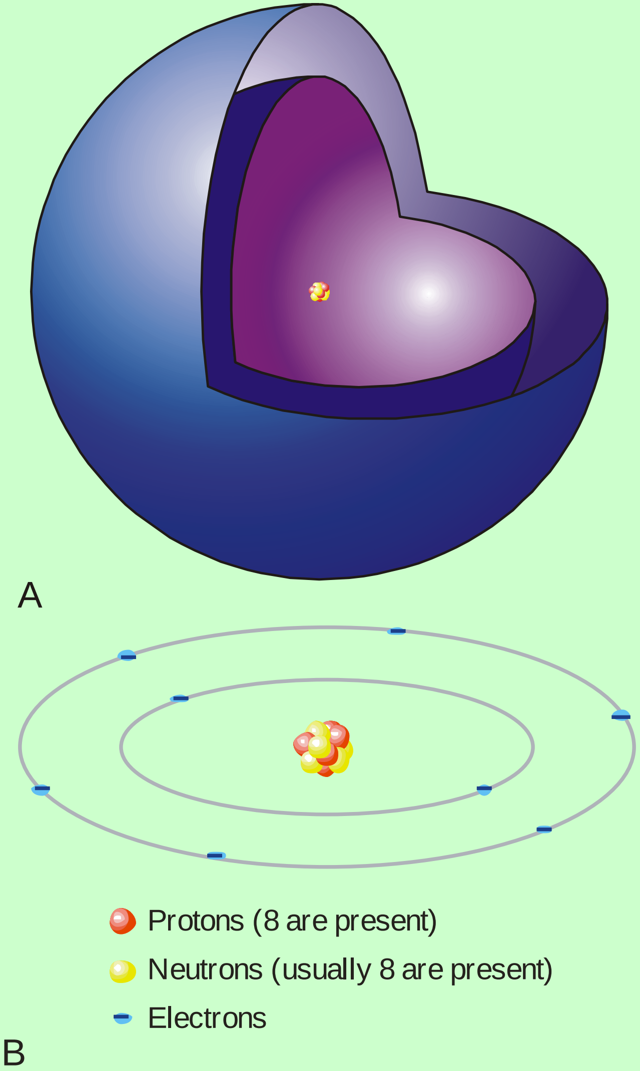
Circular cross-section of a spherical boundary surface enclosing 90-99% probability region of a 1s orbital. If you could make a large number of measurements of the position of the electron, 90-99% of the time the electron would be found within the sphere enclosed by the boundary surface. [After Gray and Haight, 1967].

- **Neutron**
  - particle in the nucleus of an atom
  - has mass equal to a proton
  - carries no electrical charge

Particle	Neutron	Proton	Electron
Charge	No charge	One positive charge or 4.80298×10^{-10} esu	One negative charge or 4.80298×10^{-10} esu
Mass	1.67×10^{-24}g	1.67×10^{-24}g	9.11×10^{-28}g



Comparison of properties of the neutron, the proton, and the electron. The mass of a proton is 1836 times as great as the mass of an electron. The electrostatic force of attraction between two particles is, however, independent of their masses and dependent only upon their charges and relative position.



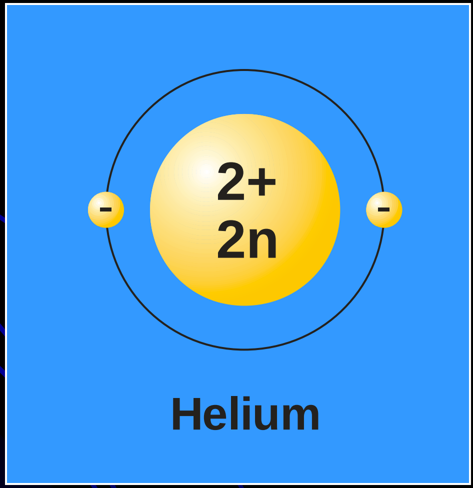
A. Model of an oxygen atom. The nucleus, composed of neutrons and protons, is actually much smaller than indicated relative to the volume of the atom. The hollow spheres represent the two electron-bearing shells.

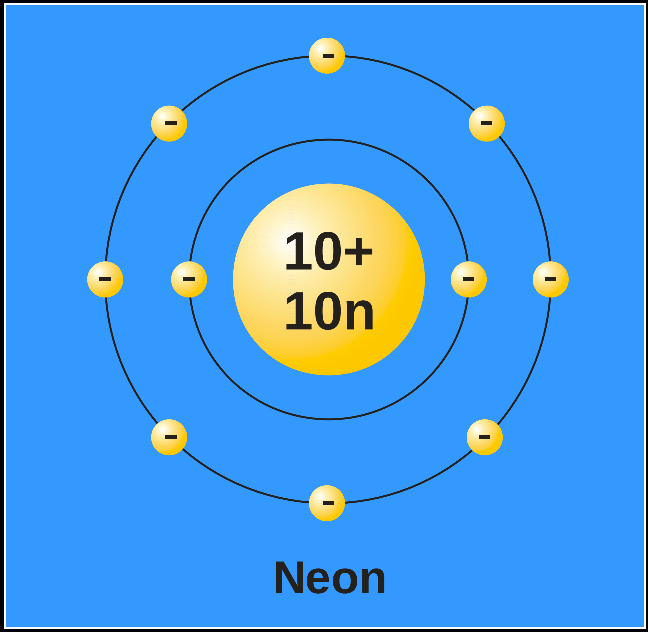
B. Schematic representation of the oxygen atom. The two circles containing electrons represent the electron-bearing shells. [Modified from Plummer et al., 2003].

- **Isotopes**
  - Isotopes are forms of an atom containing the same number of protons and electrons, but different numbers of neutrons in their nuclei
  - Therefore, isotopes differ in their atomic mass
  - Atomic mass is denoted by a superscript at the upper left of the abbreviation of the element
    - ^{12}C and ^{14}C are isotopes of carbon
    - ^{236}U and ^{238}U are isotopes of uranium

- Chemical activity
  - Many geological processes can be explained as chemical reactions
    - e.g., formation and weathering of rocks may be results of chemical reactions between substances
  - The chemical activity of an element depends upon its subatomic structure and electrical stability

- Electrically stable atoms tend to be inert, or non-reactive
  - Numbers of protons and electrons are equal
  - Electron orbitals are completely filled



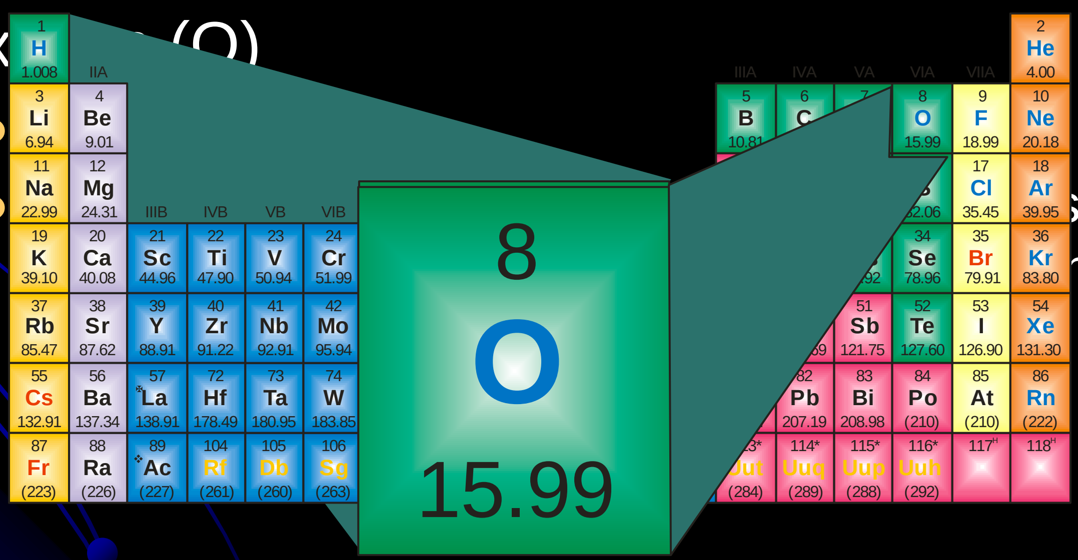


- Atoms that are not electrically neutral tend to react (or combine) with other atoms to neutralize the electrical imbalance
- Each atom not only seeks electrical neutrality, but tends to fill each of its electron shells
  - **Compound**
    - a substance composed of two or more elements chemically combined in definite proportions by weight
  - **Molecule**
    - the smallest particle of a compound that retains all the physical and chemical properties of that compound
    - consists two or more atoms (of one or more elements) chemically combined (i.e., **bonded** together)

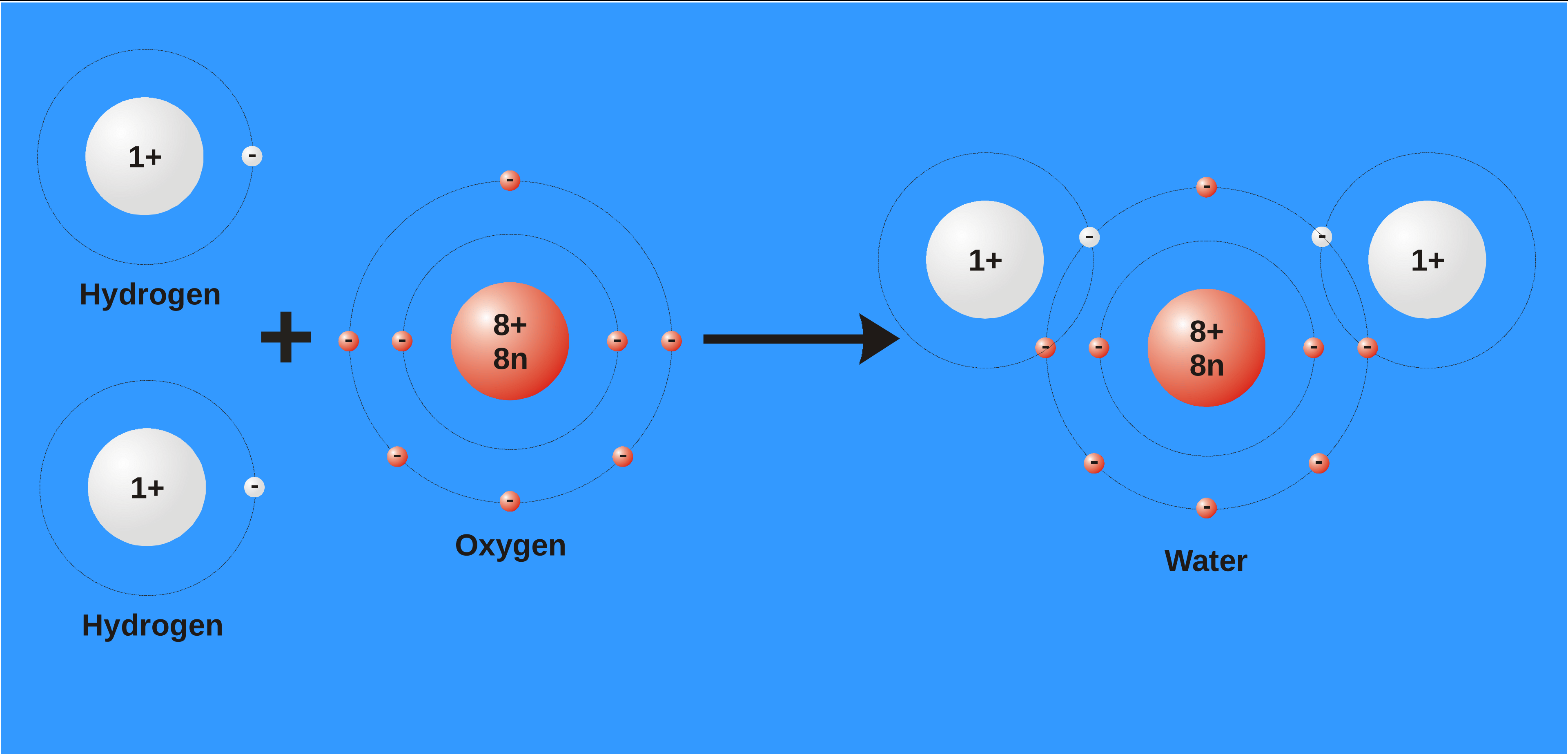
- **chemical bonds**

1. **covalent bond**
    - A covalent bond is a bond resulting when adjacent atoms share electrons
    - There is no loss or gain of electrons by atoms forming the resulting molecule
    - Therefore, a covalent bond produces a stable molecule, e.g., water
    - a.k.a. *nonpolar bond*

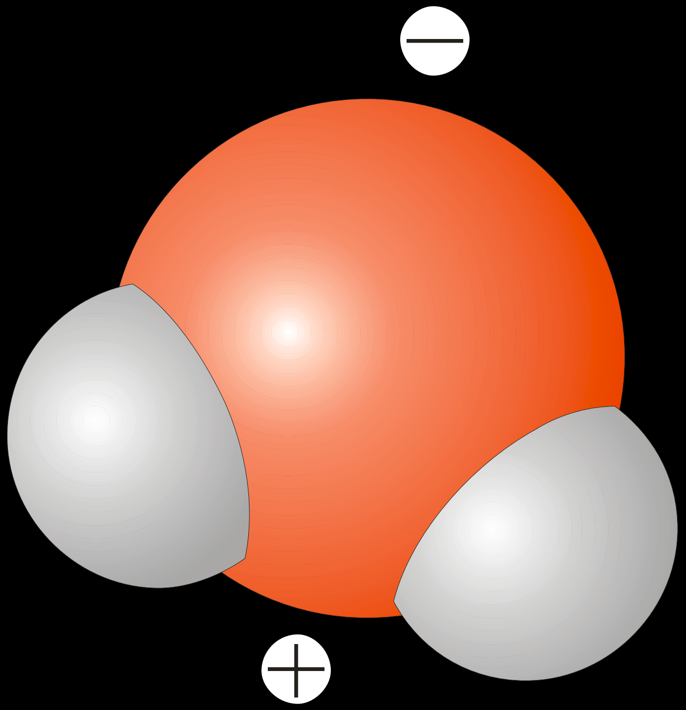
- Chemical structure of water = H_2O
  - Hydrogen (H)
    - Atomic No. = 1
    - Therefore, there is one proton in the nucleus and one electron in the orbital
  - Ox… (O)
    - …
    - …s and 8 …n the second



- In water, the two hydrogen atoms share electrons with the one oxygen atom in each water molecule



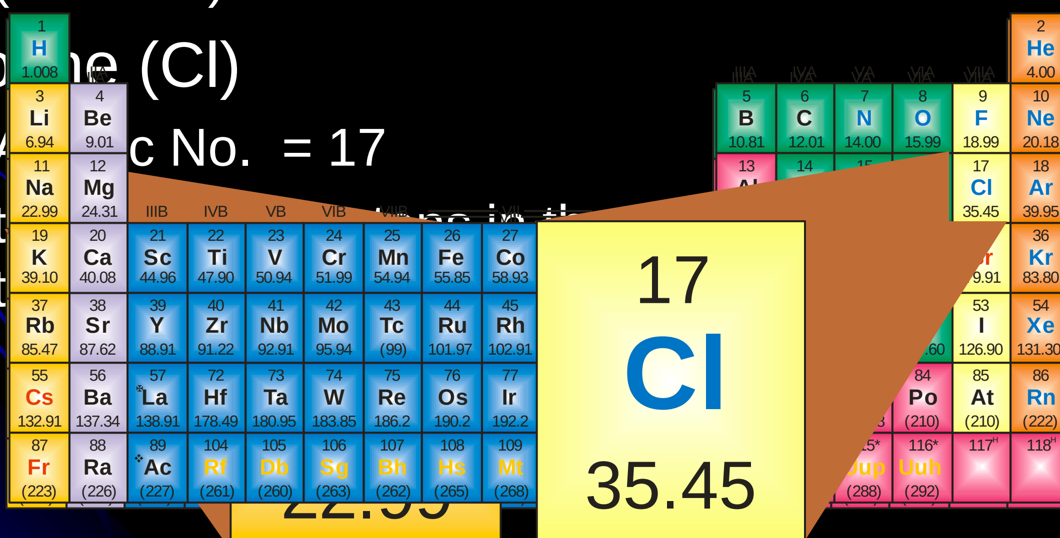
- Because the greater mass (A.M. = 16) and stronger positive charge of the oxygen nucleus (8+) produce a stronger attraction to the electrons than that of the hydrogen nuclei, the electrons spend more time with the oxygen nucleus, making the oxygen-end of the water molecule slightly negative and the hydrogen-end slightly positive



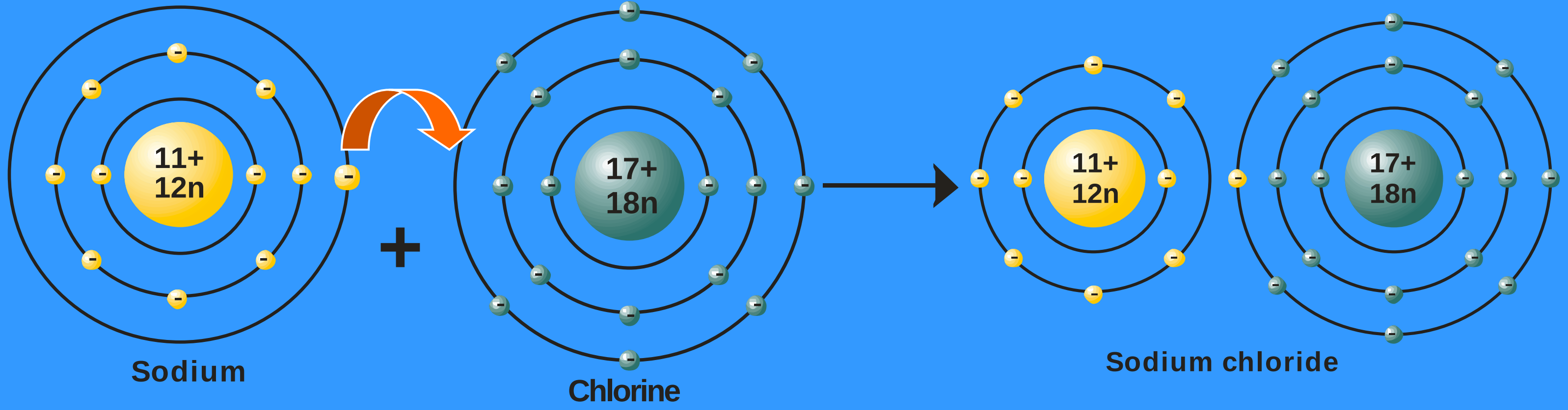
2. Ionic bond

- An ionic bond is a chemical bond formed when a molecule results from loss or gain of electrons among its constituent atoms
- a.k.a. *electrovalent bond*
- Table salt, or sodium chloride, is an example of a common substance formed by ionic bonding

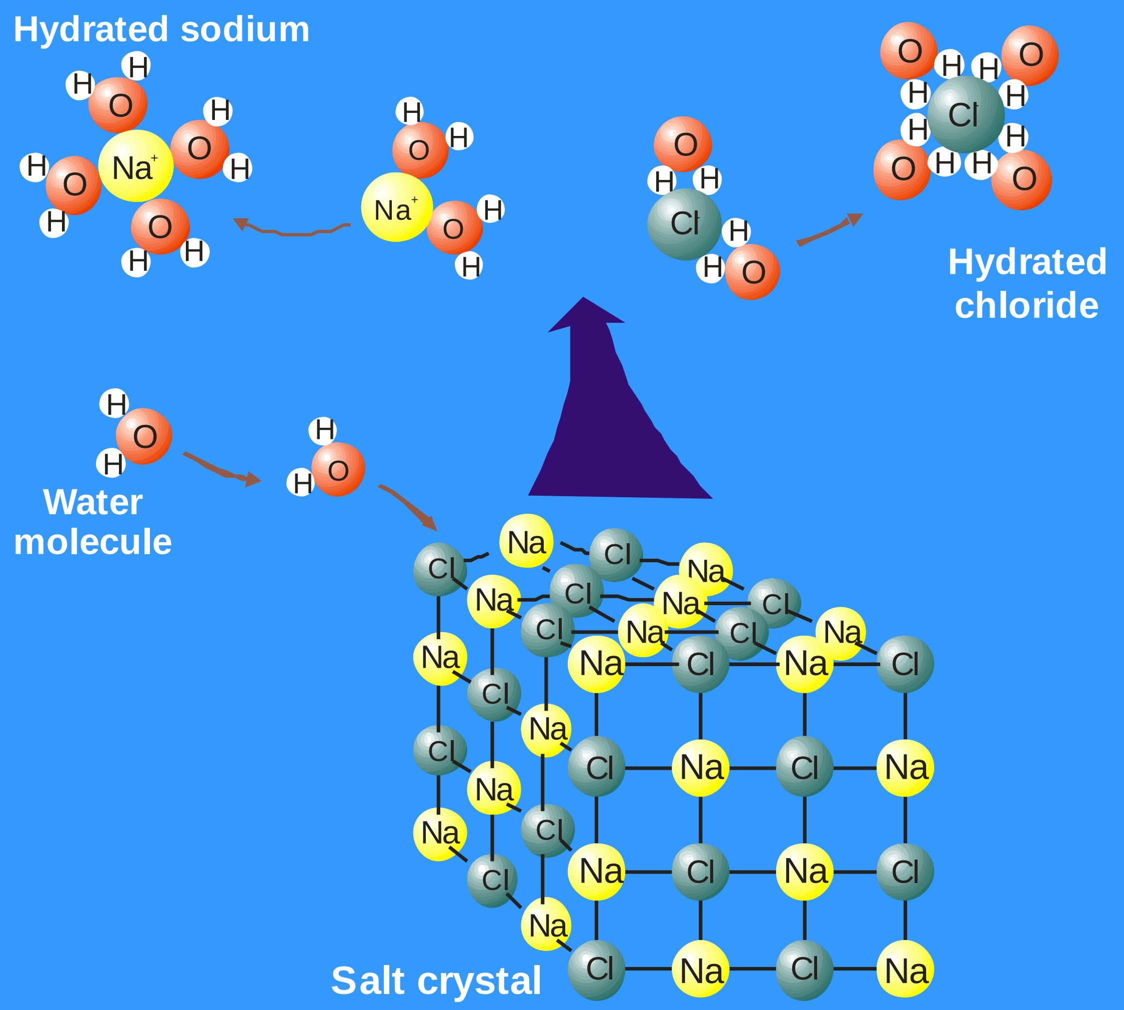
- Chemical structure of sodium chloride = NaCl
  - sodium (Na)
    - Atomic No. = 11
    - therefore, there are 11 protons in the nucleus and 11 electrons orbiting the nucleus
    - electrons are in three orbitals: 2 (filled), 8 (filled), and 1 (not filled)
  - chlo ne (Cl)
    - A c No. = 17
    - t ectrons in
      t



- When sodium and chlorine atoms are brought together, the single electron in the outer orbital of sodium is lost to the stronger nucleus of the chlorine
- This loss of an electron by sodium produces a sodium ion (Na^+), and the gain of an electron by the chlorine atom produces a chloride ion (Cl^-)
  - An **ion** is a particle carrying an electrical charge


11+
12n
Sodium
+
17+
18n
Chlorine
11+
12n
17+
18n
Sodium chloride

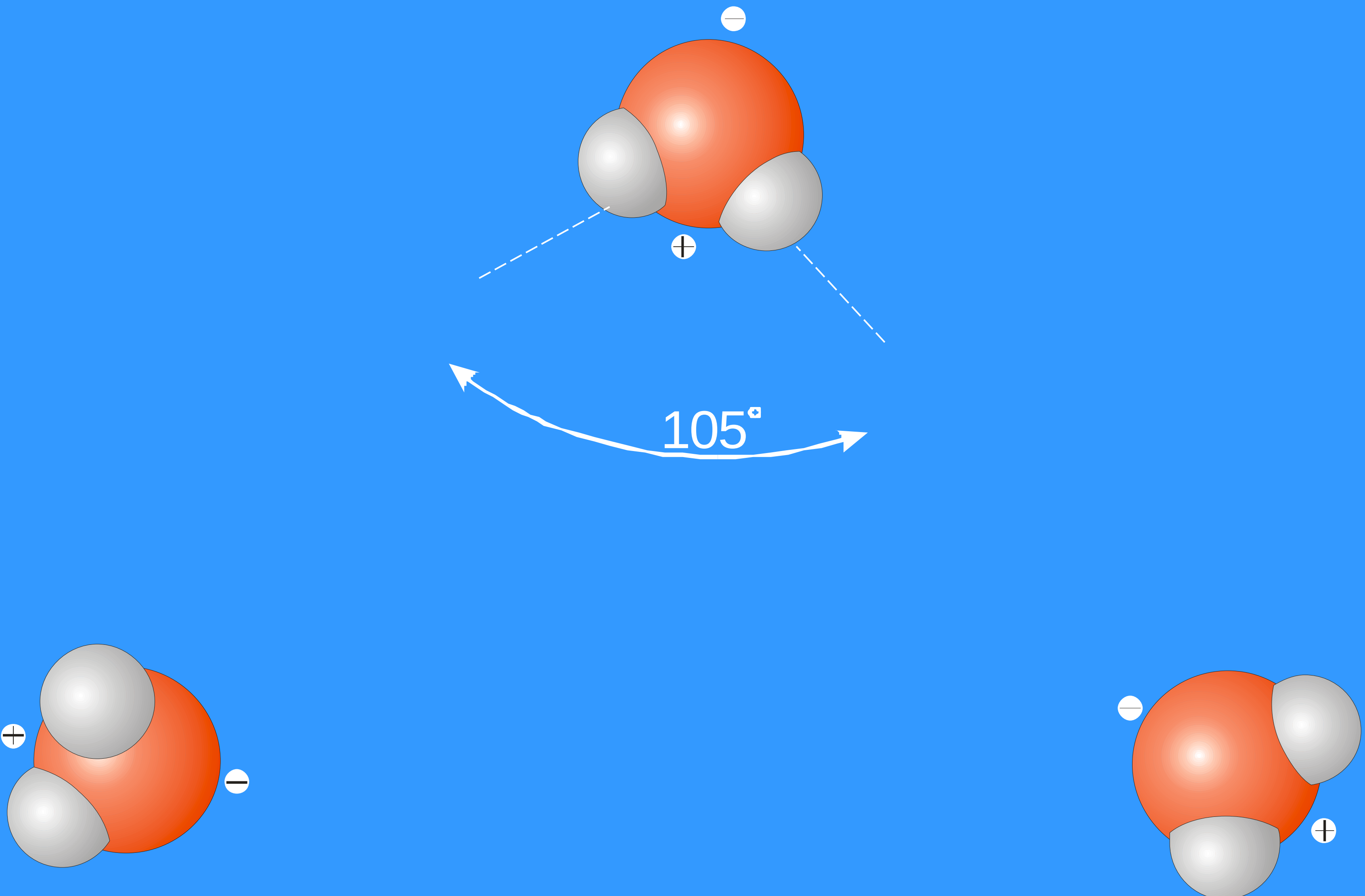
- Na^+ and Cl^- ions have opposite charges and therefore attract each other
- The resulting ionic bonds forms a molecule with the outer electron shell filled
- Therefore, the ionic bond produces a more stable compound as a solid, but the compound rapidly dissociates when dissolved in water



Salt crystal (bottom) dissolving in water. Sodium and chloride atoms are “pulled” (i.e., Dissociated) from the salt crystal surface and surrounded by water molecules (i.e., they become hydrated). [Modified from Lerman, 1986].

3. **Hydrogen bond**

- A hydrogen bond is a weak attraction between the hydrogen atoms of adjacent molecules
- Hydrogen bonds are important in the formation of water, proteins, and DNA
- As noted earlier, water is a polar molecule, because electrons spend more time with the oxygen nucleus, making the oxygen end slightly negative and the hydrogen end slightly positive
- Therefore, when water molecules come into contact, the negative end of one molecule is attracted to the positive end of the other, in chain-like fashion



The two ends of water molecules have different electrical charges. The oxygen (O) end of the molecule has a weak negative charge; the hydrogen (H) end, a slight positive charge. Opposite charges attract each other much as opposite poles of a magnet attract, so the oxygen end of one molecule is attracted to the hydrogen end of neighboring molecules. These weak attractions between water molecules are known as hydrogen bonds.

- These weak attractions form *hydrogen bonds*
- Individually, hydrogen bonds are weak, but in large numbers they are strong
- How important are hydrogen bonds?
  - Hydrogen bonds hold water molecules to form a liquid a standard temperatures
  - Hydrogen bonds also responsible for the high boiling temperature of water
  - Hydrogen bonds are responsible for the three-dimensional structure of proteins and DNA
  - The number of hydrogen bonds varies with temperature

Chemical composition of Earth (based on analysis of rocks exposed at Earth's surface)

Element	Symbol	% by wt.	% by vol.	% by # of atoms
Oxygen	O	46.6	93.8	60.5
Silicon	Si	27.7	0.9	20.5
Aluminum	Al	8.1	0.8	6.2
Iron	Fe	5.0	0.5	1.9
Calcium	Ca	3.6	1.0	1.9
Sodium	Na	2.8	1.2	2.5
Potassium	K	2.6	1.5	1.8
Magnesium	Mg	2.1	0.3	1.4
All Others		1.5	--	3.3

[N.B.: by weight Hydrogen (H) is 10th most abundant & Carbon (C) is 17th most abundant]

- Properties of minerals
  - To be a mineral in the geological sense, a substance must satisfy five conditions
    1. It must be a crystalline solid [i.e., atoms arranged in orderly, repeating regular pattern]
    2. It must occur naturally
    3. It must have a definite chemical composition
    4. Usually, it must be inorganic

5. It must possess characteristic physical properties, including color, lustre, hardness, cleavage, fracture, and relative density

- **Color**
  - Color is the most obvious characteristic, but it is not too reliable because of its variability
    - e.g., quartz may be white, pink, black, yellow or purple

Black quartz in granitic matrix

Milky quartz

Crystal quartz with amethyst tips

Rosy quartz

Smoky quartz

- **Lustre**
  - Lustre refers to the quality and intensity of light that is reflected from the surface of a mineral
    - *Metallic lustre* gives appearance of being made of metal
    - *Nonmetallic lustre* may be *glassy* (or *vitreous*) *lustre*, which is a glazed appearance like glass or porcelain
    - *Earthy lustre*, which resembles surface of unglazed pottery or clay minerals having a dull appearance

- **Hardness**
  - Hardness refers to the ability of a mineral to resist scratching in the field
  - Moh's scale of hardness [logarithmic scale 1 to 10]
    1. Talc
    2. Gypsum (scratched with a finger nail)
    3. Calcite (scratched with a copper coin)
    4. Flourite (scratched with a nail)
    5. Apatite (scratched with a knife blade or glass)
    6. Orthoclase feldspar (scratched with a file)
    7. Quartz
    8. Topaz
    9. Corundum [i.e., rubies and sapphires]
    10. Diamond [the hardest naturally occurring substance on Earth]

- The intervals between these standard minerals is roughly equal, except for that between Corundum 9 and Diamond 10
  - Diamond is the hardest natural material, and it is 140 times harder than corundum.
- A mnemonic for remembering the hardness scale is
  - The Girls Can Flirt And Other Quaint Things Can Do

- **Cleavage**
  - Cleavage refers to planes along which crystals may split because of weakness inherent in the structure of their atomic lattices
  - Therefore, cleavage has to do with how strongly the molecules bind to each other
    - To put it in layman's terms, it is much like the grain of wood. You can easily split a piece of wood along the grain, but going across the grain is much more difficult
  - Cleavage is usually rated as good, poor, etc.

- **Fracture**
  - Fracture describes any break in a material, but commonly applied to more or less clean breaks in rocks or minerals that are not due to cleavage
  - Fractures may be described as **conchoidal**, **subconchoidal**, **uneven**, **jagged**, **splintery**, or **earthy**
- **Relative density**
  - Relative density is determined calculating the mass per unit volume of the mineral

- Therefore, our definition of mineral does not apply to dietary minerals, or to the mining industry, where a mineral is anything with commercial value that is extracted from the ground