

A close-up photograph of a granite surface, showing a complex pattern of light beige, tan, and dark brown/black mineral grains. The texture is granular and crystalline.

Mineralogy

Rocks and Minerals

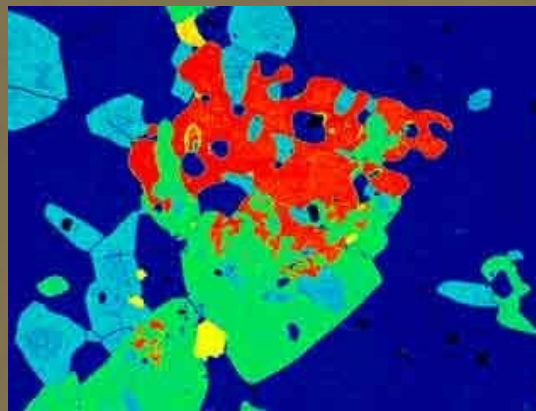
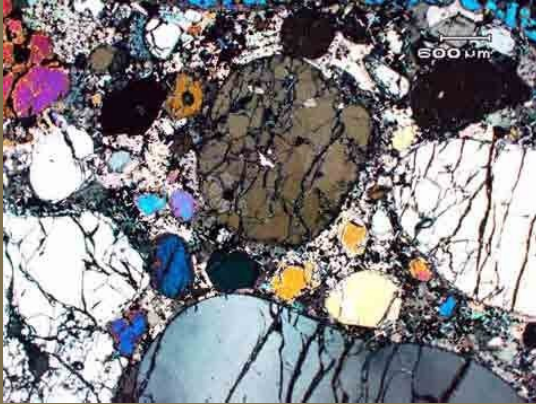
Mineralogy is fundamental to an understanding of Geology

- Petrology – the origin of rocks, evaluating the structure, texture, and chemistry of their minerals.
- Geochemistry – study of the chemistry of minerals at the surface and at high P-T
- Structural Geology– Deformation of a rock and the orientation and crystal structure of its minerals
- Weathering – the study of how the biosphere, hydrosphere, and atmosphere interact with minerals
- Economic Geology – study of the origin and concentration of ore deposits

What is the difference between a rock and a mineral?

- Mineral: a naturally occurring crystalline, inorganic, homogenous solid with a chemical composition that is either fixed or varies within certain fixed limits, and a characteristic internal structure manifested in its exterior form and physical properties
- Rock: A consolidated or unconsolidated aggregate of mineral grains consisting of one or more mineral species and having some degree of chemical and mineralogic constancy

Minerals and Rocks...



Many minerals are essential to life, however others can be very harmful..

Silicosis: a form of lung disease caused by the inhalation of crystalline silica dust (first recognized in 1705!!!) When silica is cut, broken, crushed, drilled or ground the fine silica dust is airborne. Possibly a problem for miners at Hemlo.

Chrysotile: the most common form of asbestos, a fibrous silicate mineral in the serpentine group. It causes lung disease at high concentrations.

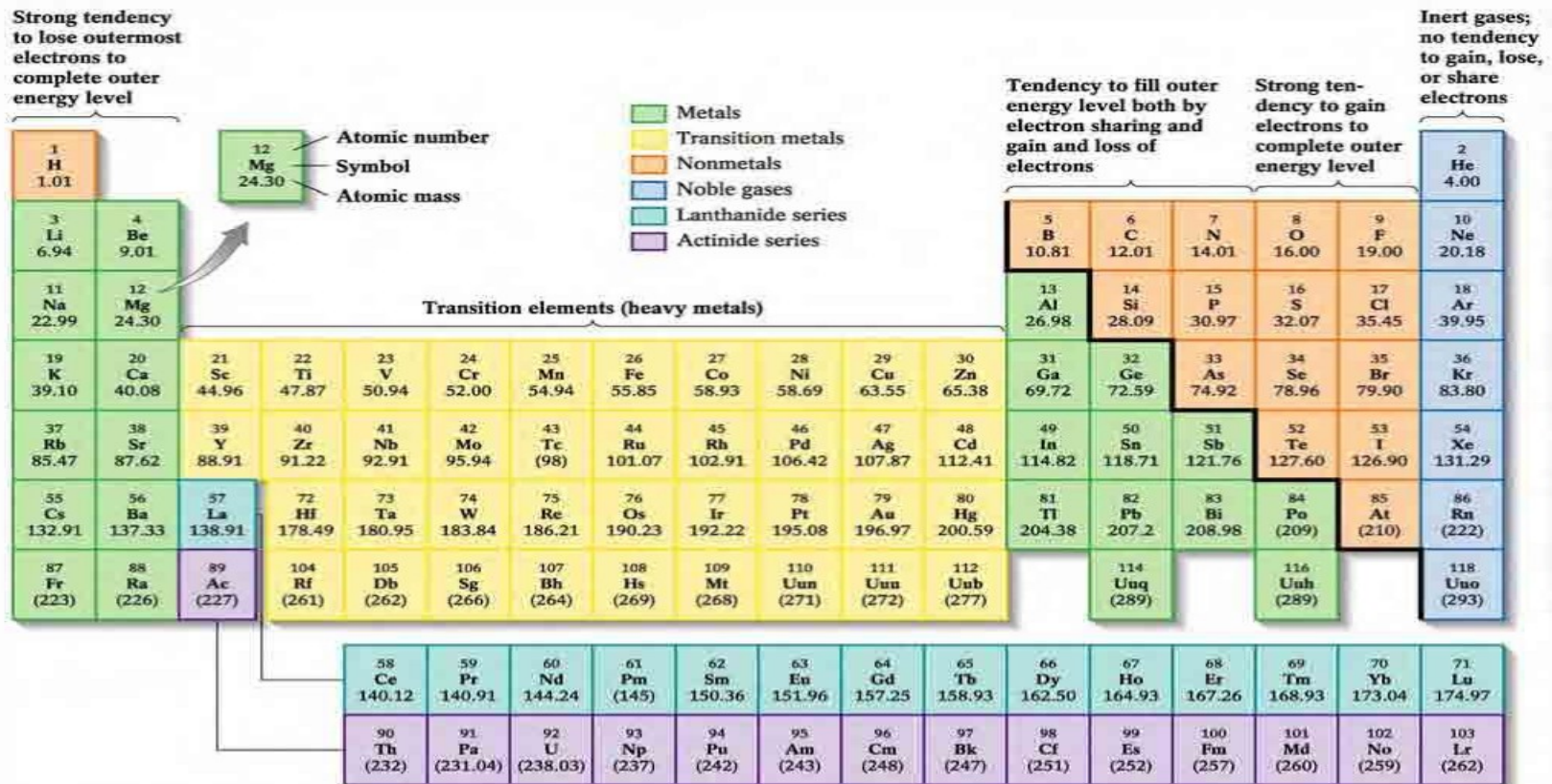


William Sacco

Murck and Skinner (1999)

What makes up minerals?

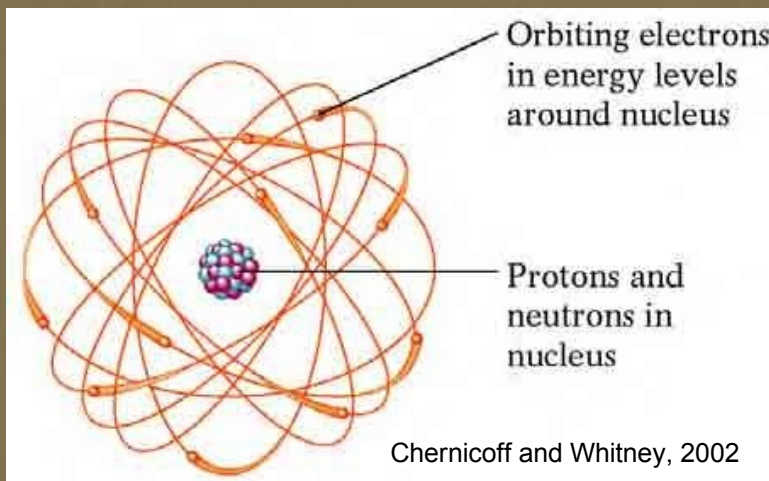
- Combinations of the 90 naturally occurring elements



Chernicoff and Whitney, 2001

The internal structure of minerals

- Minerals have a regular internal structure
- Minerals form a regular arrangement of particles within a solid
- Atom: the smallest amount of the element that retains its characteristic properties
- Elements are composed of atoms



*The nucleus is positively charged, and the electrons are negatively charged.

Isotopes

- While all atoms of an element have the same number of protons the number of neutrons can vary
- This means that the mass of the atoms of a particular element can vary
 - For example- Uranium-238 (^{238}U) - most commonly occurring form of U- weighs 238 atomic mass units comprised of 92 protons and 146 neutrons
 - ^{235}U - rare isotope (0.7%) with 92 protons but 143 neutrons
 - Similarly Carbon exists as C^{12} , C^{13} & C^{14}
- Many important geological uses such as geochronology

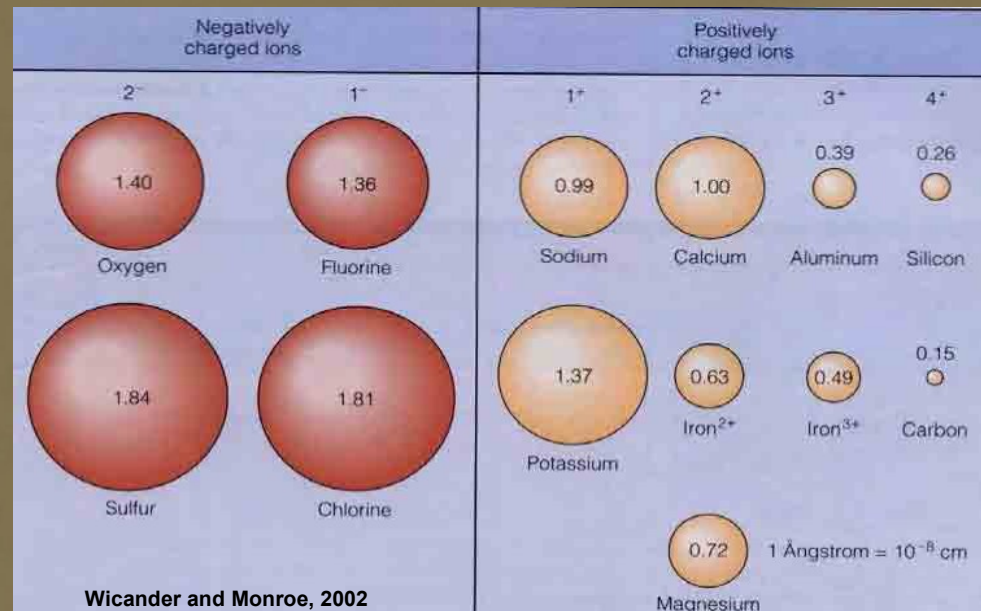
Ions

- Ideally an atom has an equal number of protons and electrons (neutral charge)
- Chemical reactions involve the sharing or transfer of electrons
- The loss or addition of electrons results in +ve or -ve charged atoms called ions

+ve = cation

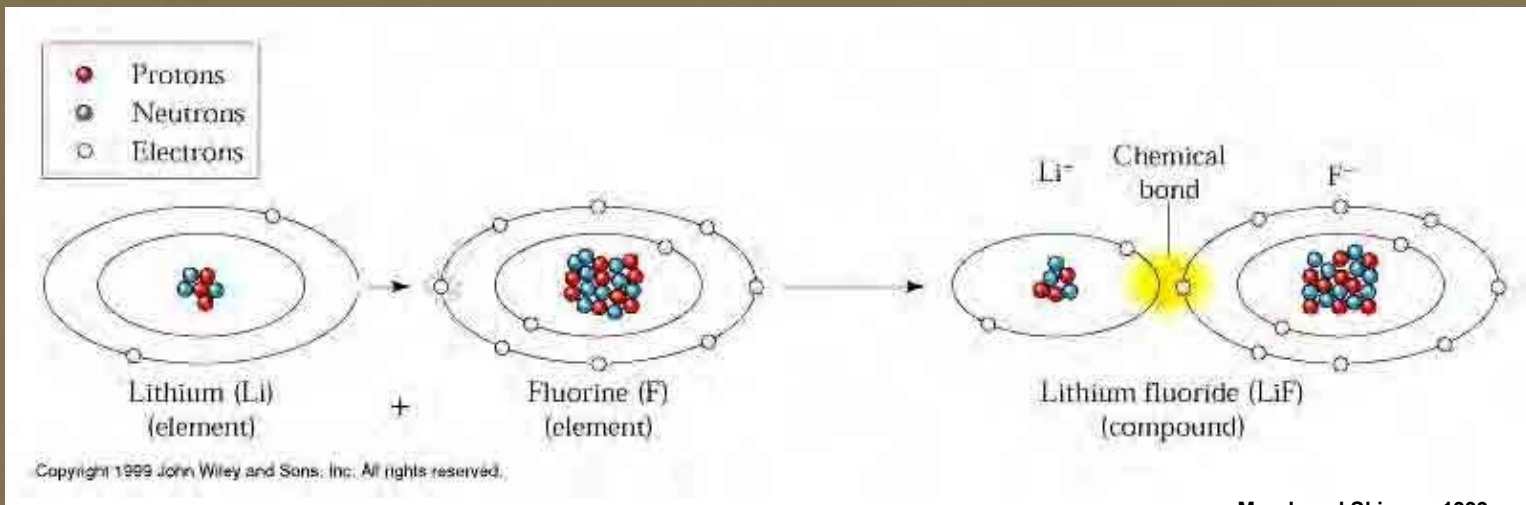
-ve = anion

Chart showing relative sizes of cations and anions of the more abundant elements



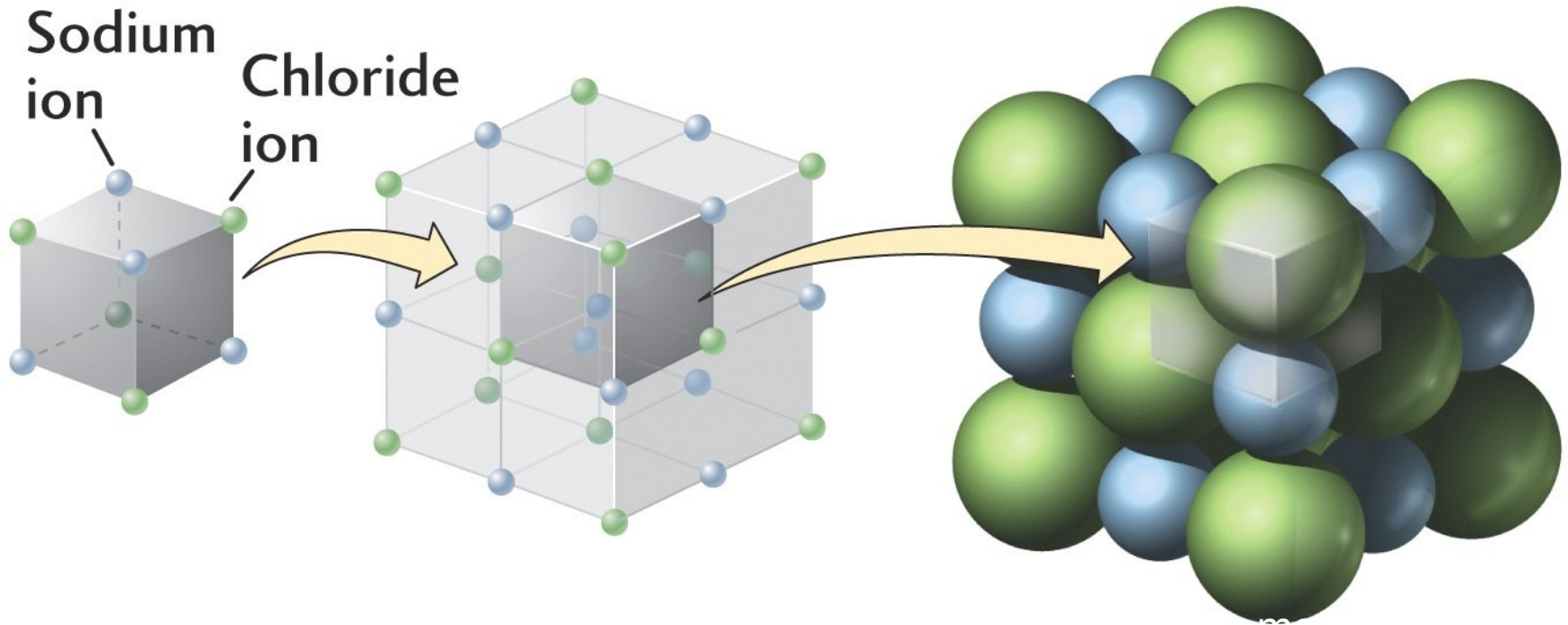
How does this apply to minerals?

- Crystal structures may be thought of as a periodic arrangement of anions, with small cations filling the interstitial spaces
- Lithium loses an electron to become +ve, while Fluorine takes an electron and becomes -ve



Murck and Skinner, 1999

Unit Cells as building blocks



Halite (salt, NaCl)

Compounds

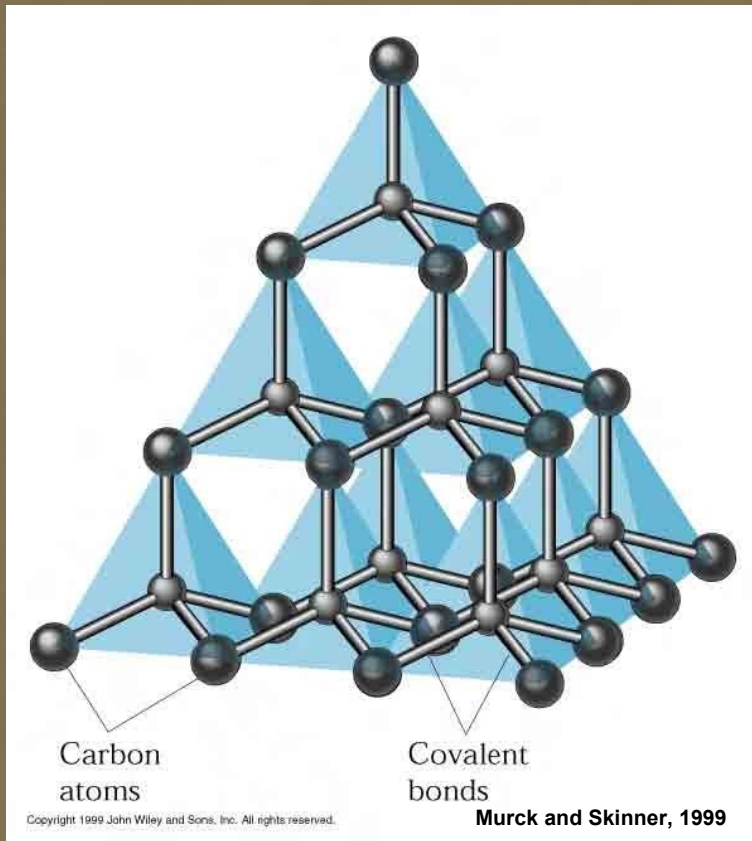
- Compounds generally have quite different properties to their constituent elements.
 - Na & Cl are toxic - NaCl is not
- **Molecule** - smallest component that has the properties of a compound (comparable to an atom)
- **Bonding** - the force that holds the atoms of a compound together

Bonding for stability

- In order to fill shells and reach a stable state atoms share and transfer electrons
- They bond in four different ways to do this
 - Ionic bonding
 - Covalent bonding
 - Metallic bonding
 - Van der Waals bonding

Ionic Bonding: (a.k.a “electron transfer”) One atom donates one or more electrons to an atom of another element. Ex: NaCl on the previous slide

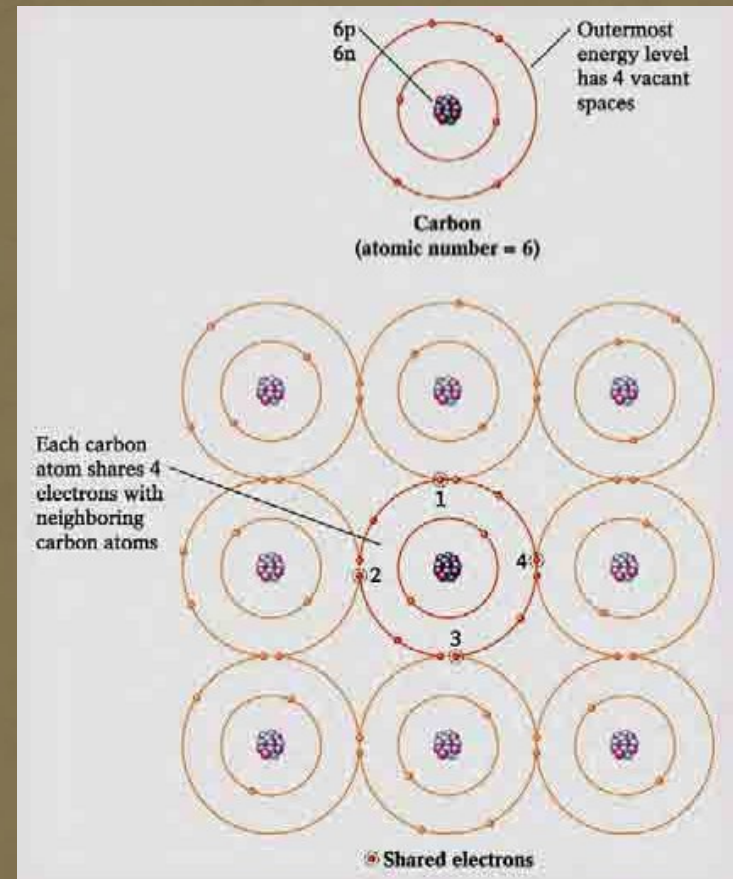
Covalent Bonding



- Rather than swapping electrons some elements share electrons through a covalent bond
- A good example is diamond (pure carbon)
- There is a very good reason why diamond is the hardest mineral on earth!

Covalent Bonding cont.

- Highest energy level shell has 4 electrons but needs 8 for stability
- Each C atom shares two electrons with four other C atoms



Chernicoff and Whitney, 2002

Metallic Bonding

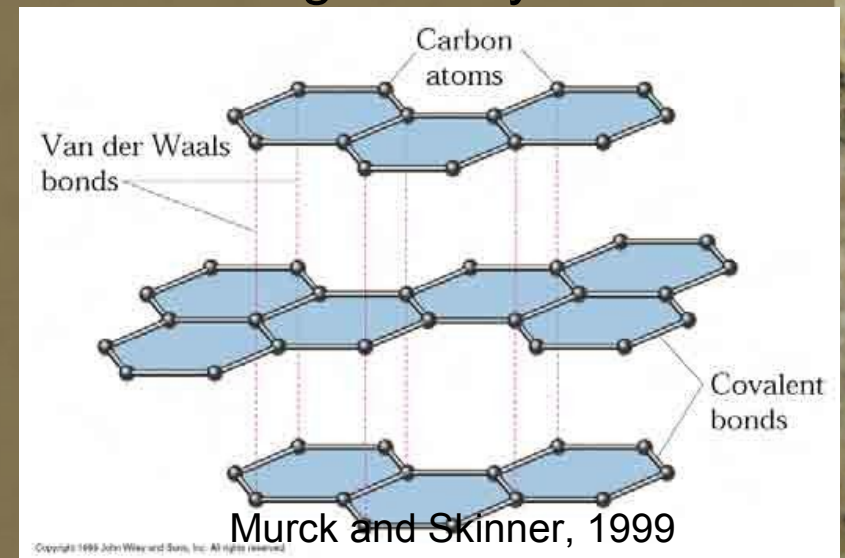
- This form of bonding is unique to metals
- Atoms are closely packed
- Electrons in the outer shells are shared between several atoms
- They drift between atoms
- Makes them good conductors of heat and electricity

Native copper Cornelai Mine, Arizona,
<http://www.johnbetts-fineminerals.com/>



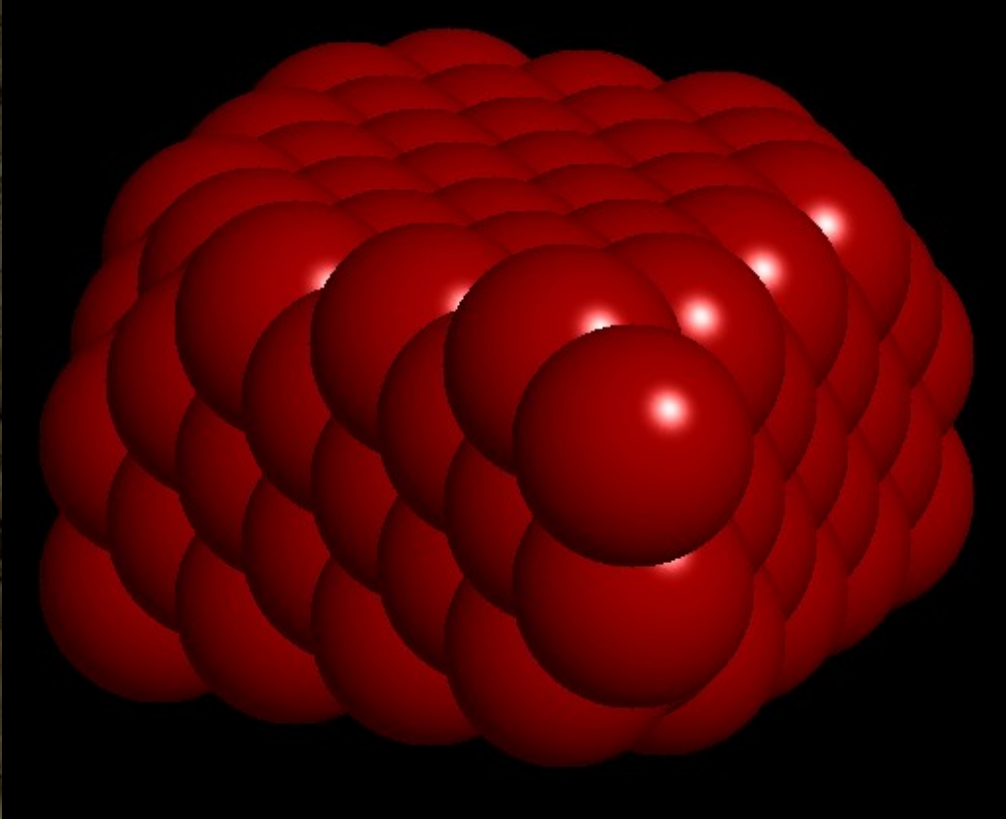
Van der Waals Bonding

- This is a weak bond formed from the secondary attraction of molecules as a result of the transfer or sharing of electrons
- Graphite is a good example
- Strong covalently bonded sheets held together by weak Van der Waals bonds



External form reflects internal form

- Minerals' atoms are regularly arranged
- Arrangement controls external crystal form



Mineral photos courtesy J. H. Betts
Used with permission

Crystal Systems

We classify crystal external form in 6 systems based on the shape of the crystal. Unit cells repeat to make external crystal form.

http://webphysics.davidson.edu/alumni/milee/JLab/Crystallography_WWW/Grown_Crystals.htm

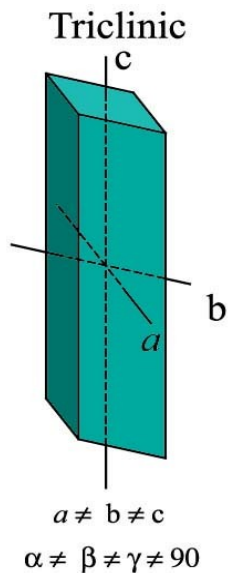


Diamond

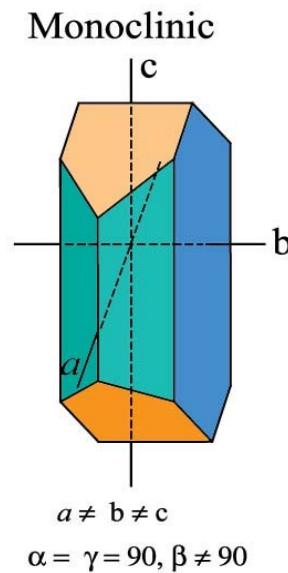
Triclinic and Monoclinic

- Triclinic crystals have unequal axis lengths and angles, none are 90° .
- Monoclinic crystals are more symmetrical: they have unequal axis lengths and two 90° angles

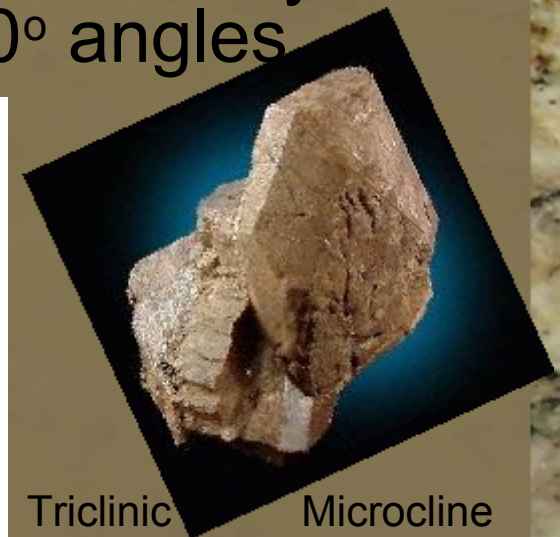
Crystal Axes



The axes are chosen as parallel to the principal face intersections. There are no symmetric restrictions to the choice of **a**, **b**, and **c**, but, by convention, the most pronounced zone is oriented vertically and the zone axis is **c**.



The axes are chosen as parallel to the principal face intersections. **b** is selected as \parallel to the 2-fold axis or \perp to the mirror. The most pronounced zone is oriented vertically and the zone axis is **c**. **a** slopes down and forward so that β is typically > 90 .



Triclinic
KAlSi3O8

Microcline



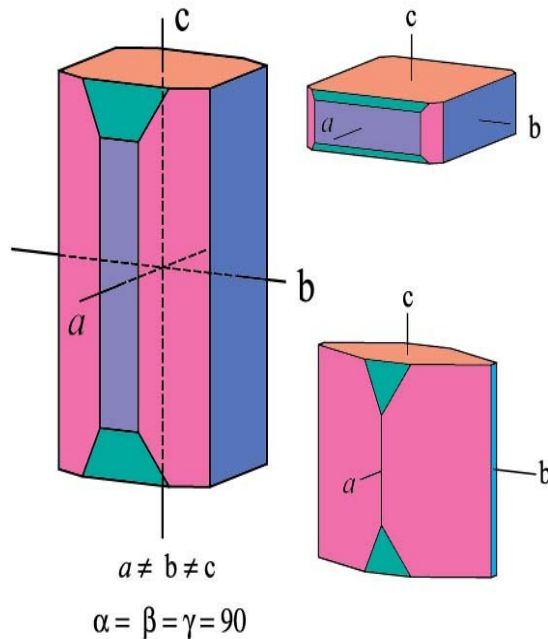
Monoclinic
CaSO4

Gypsum
fppt.com

Orthorhombic and Tetragonal crystals are more symmetrical

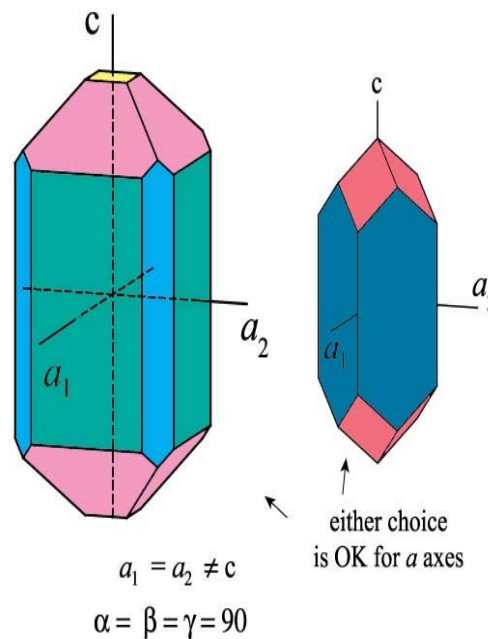
Crystal Axes

Orthorhombic



The axes are mutually perpendicular and \parallel to 2-fold axes (conventionally $c < a < b$). When crystals are elongated (as above left) c is chosen as the direction of elongation. When crystals are flattened (top insert), c is chosen as normal to the predominant plane.

Tetragonal



The axes are mutually perpendicular and c is chosen \parallel to the 4-fold axis. Due to the 4-fold symmetry, the other two axes are equal. a_1 is oriented toward the front and a_2 to the right.

Orthorhombic



Barite BaSO_4

Tetragonal

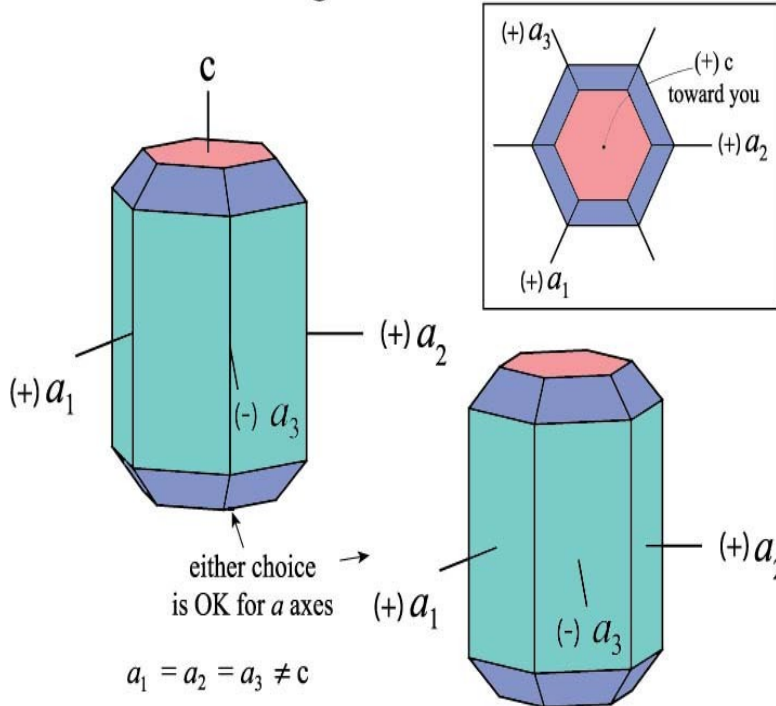


Anatase TiO_2

Hexagonal and Trigonal are still more symmetrical

Crystal Axes

Hexagonal



$$a_1 = a_2 = a_3 \neq c$$

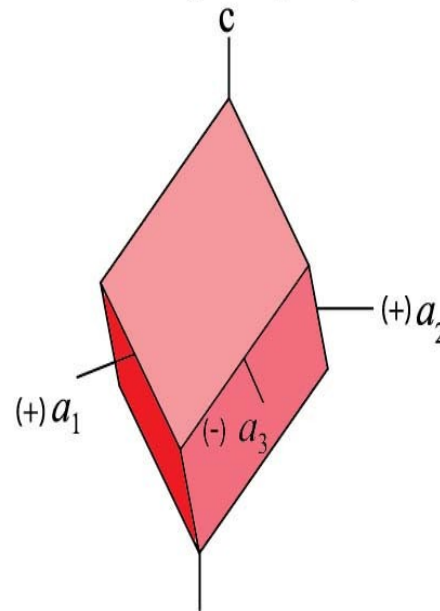
$$a \angle a = 120; a \angle c = 90$$

The Hexagonal system (and Trigonal sub-system) typically has four axes, three are of equal length at 120 degrees to one another, and all \perp to c , which is \parallel to either the 3-fold or 6-fold rotation.

The conventional choice of the three a axes is shown in the inset.

Trigonal

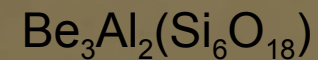
(also considered as the rhombohedral division of the Hexagonal system)



Hexagonal



Beryl



Trigonal

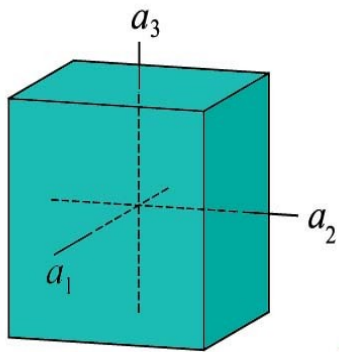


Tourmaline

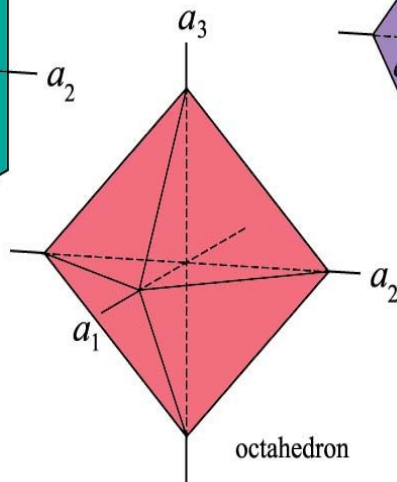
The Isometric system has the most symmetry

Crystal Axes

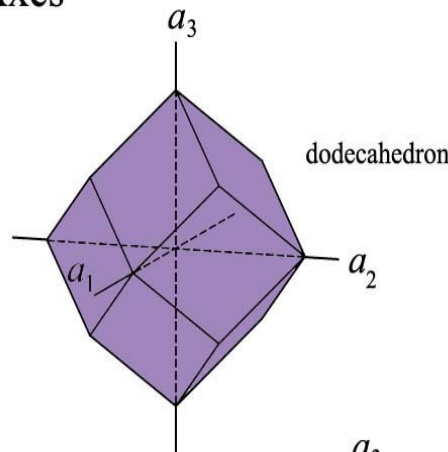
Isometric



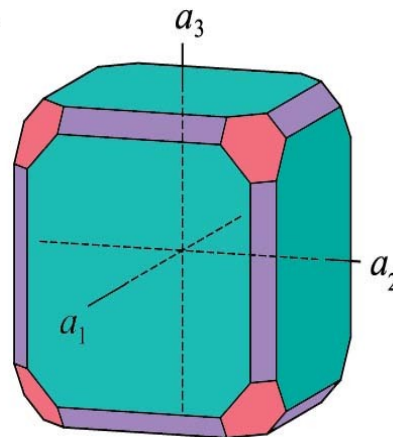
cube



octahedron



dodecahedron



all three forms combined

$$a_1 = a_2 = a_3$$
$$\alpha = \beta = \gamma = 90$$

All three axes are mutually perpendicular and of equal length. They are set \parallel to the 4-fold axes (if present), otherwise \parallel to the 2-fold axes.



Grossular $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$

dodecahedron



Grossular $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$

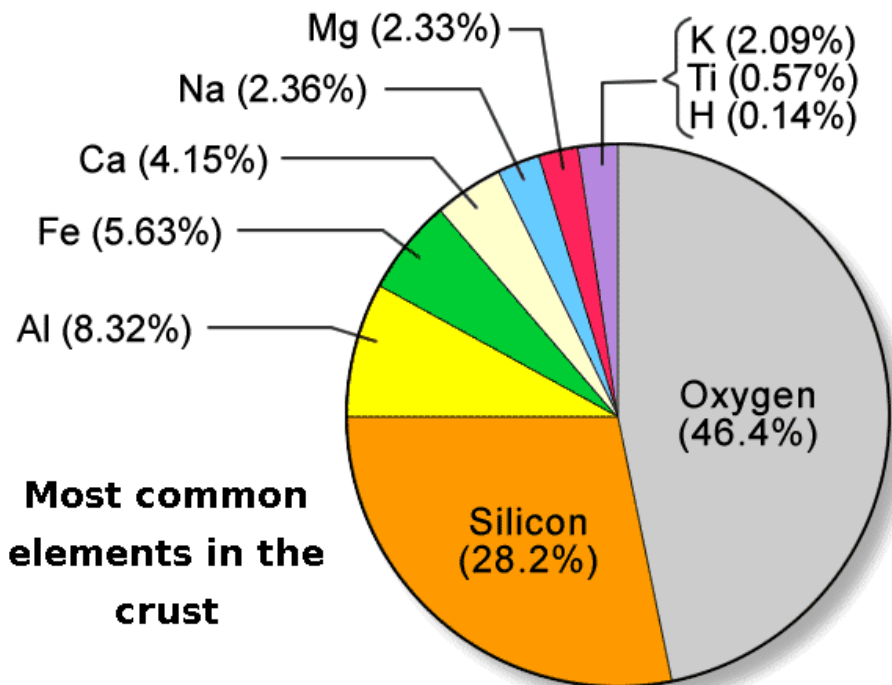
cube

The 5 characteristics of a mineral

- Naturally formed
- Solid
- Formed by inorganic processes
- Specific chemical composition
- Characteristic crystal structure

Mineral Groups

- Thousands of mineral species have been identified
- Only ~20 make up the earth's crust....



Only 12 elements occur at >0.1%....meaning that those 12 elements make up 99% of the earth's crust.

Elemental Abundance

- Given that oxygen is so abundant it is hardly surprising that it is present in many minerals
- It occurs as oxides (compounds that contain the O^{2-} anion) and as silicate anions (SiO_4^{4-}) in silicate minerals
 - Less commonly it occurs as carbonates (CO_3^{2-}), sulfates (SO_4^{2-}) and phosphates (PO_4^{3-})

Rock forming Minerals

- A few silicates and oxides in conjunction with calcium sulphate and calcium carbonate comprise the majority of the Earth's crust
- These are the **rock forming minerals**
- Found in rocks, soils, sediments and construction materials
- Quartz and feldspar = ~75% of the Earth's crust

Accessory Minerals

- These are present in common rocks but at low abundances
- They do not determine the property of the rock but may be important sources of metals
- **Trace minerals** occur at even lower abundances but are also important. Examples include zircon or diamond



Zircon, North Cheyenne County, Colorado, <http://www.johnbetts-fineminerals.com/>

Mineral Groups

MINERAL GROUP	REQUIRED ION	EXAMPLES	COMPOSITION
Carbonate	$(\text{CO}_3)^{-2}$	Calcite	CaCO_3
Halide	Cl^{-2} ,	Halite	NaCl
Native Elements	Fe^{-1}	Gold	Au
Oxide	not appl.	Hematite	Fe_2O_3
Silicate	O^{-2}	Quartz	SiO_2
Sulfate	$(\text{SiO}_4)^{-4}$	Anhydrite	CaSO_4
Sulfide	$(\text{SO}_4)^{-2}$ S^{-}	Pyrite	FeS_2

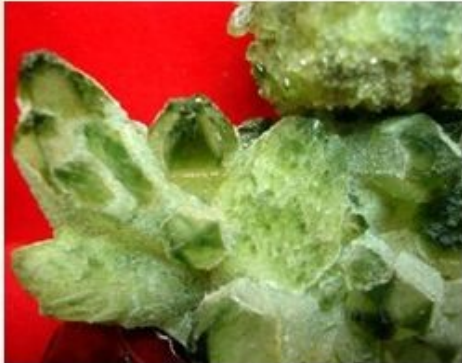
Physical Properties of Minerals

Colour

- on a fresh surface in reflected light
- The colour or lack of colour may be diagnostic
- Be careful- it can vary due to small differences in chemical composition!
- Small impurities may also change the color

Color

- Impurities and other factors can give minerals their color



These minerals are ALL forms of quartz! Color is not a reliable way to describe minerals.











Hardness

- The resistance to abrasion (scratchability)
- Determined by either trying to scratch a mineral of unknown hardness with a substance of known hardness or by using the unknown mineral to scratch a substance of known hardness.
- Mohs Scale of hardness: 10 minerals arranged by hardness

Mohs Hardness Scale



Increasing Hardness

Mineral Name	Scale Number	Common Object
 Diamond	10	
 Corundum	9	 Masonry Drill Bit (8.5)
Topaz	8	
 Quartz	7	 Steel Nail (6.5)
Orthoclase	6	
Apatite	5	 Knife/Glass Plate (5.5)
 Fluorite	4	 Copper Penny (3.5)
Calcite	3	
Gypsum	2	 Fingernail (2.5)
 Talc	1	

Cleavage

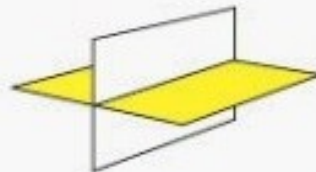
- Defined as the tendency of a mineral to break along definite planes of weakness that exist in the internal structure
- It is almost impossible to break some minerals in such a way that cleavage planes do not develop. Calcite and pyrite are great examples
- A well defined cleavage plane will reflect light off of it's very smooth surface
- Look for repetitions in the breaks of the crystal
- Do not be confused with mineral growth faces, such as quartz!
- If there is no cleavage, there is fracture. ex: conchoidal fracture patterns in obsidian, or the fibrous fracture of asbestos

Cleavage

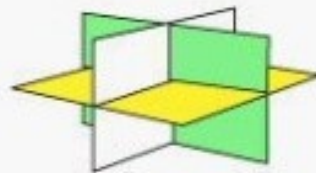
Cleavage is when a mineral breaks into flat surfaces along planes of weak bonding in the crystal structure.



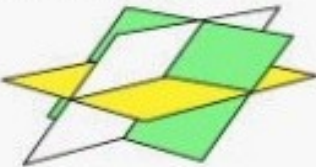
Cleavage in one direction. Example: MUSCOVITE



Cleavage in two directions. Example: FELDSPAR



Cleavage in three directions. Example: HALITE



Cleavage in 3 directions (but not at 90 degrees). Example: Calcite



Fluorite (CaF_2), an octahedral crystal, breaks along four cleavage planes.

Streak

- The colour of a mineral powder, produced from rubbing the mineral against a porcelain streak plate, either black or white
- Some minerals have a very unique colour ex: hematite
- In general, metallic minerals have a unique streak colour
- Limitation: the streak plate hardness is ~7



Tenacity

- An index of a mineral's resistance to be broken...or bent..
- Many terms are used to describe tenacity, some examples in your lab manual are brittle, elastic, flexible

Diaphaneity

- The ability of a mineral to transmit light
- Transparent, translucent, opaque
- Limitation: some minerals change properties with differing thicknesses..

Crystal Form

- The assemblage of crystal faces that constitute the exterior surface of the crystal
- Crystal Symmetry is the geometric relationship between the crystal faces
- Opposite: Amorphous
- 6 main crystal systems: Cubic (or isometric), tetragonal, hexagonal, orthorhombic, monoclinic, triclinic

“Others”

- Magnetism

Lodestone compasses

- Double refraction (very cool, Calcite)

- Taste (Rock Salt, NaCl)

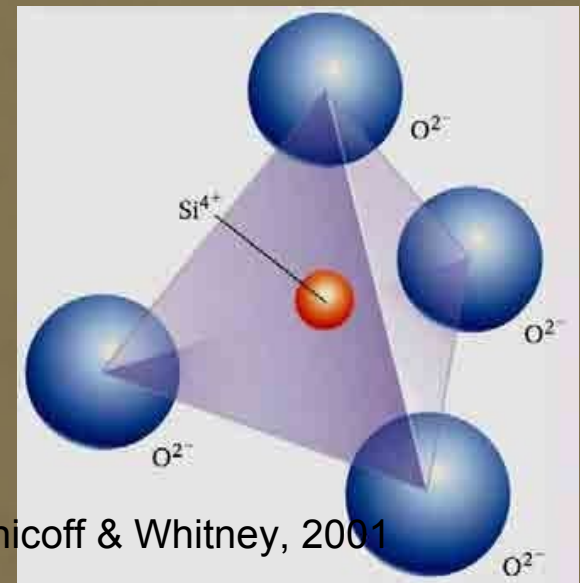
- Odor (Sulfur, Sphalerite ZnS)

- Feel (talc is greasy, hornblende is rough)

- Chemical reaction with HCL

The Silicates

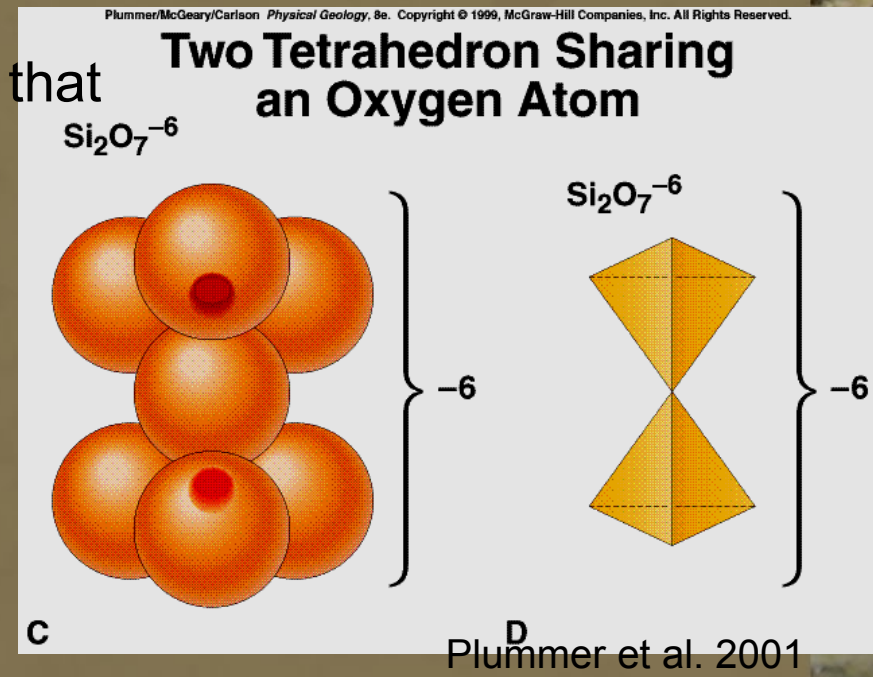
- Given that O and Si are the most abundant elements it is not surprising that they form an important compound - **the silicate anion**
- The basic building block is the tetrahedra
- This is an unbalanced anion

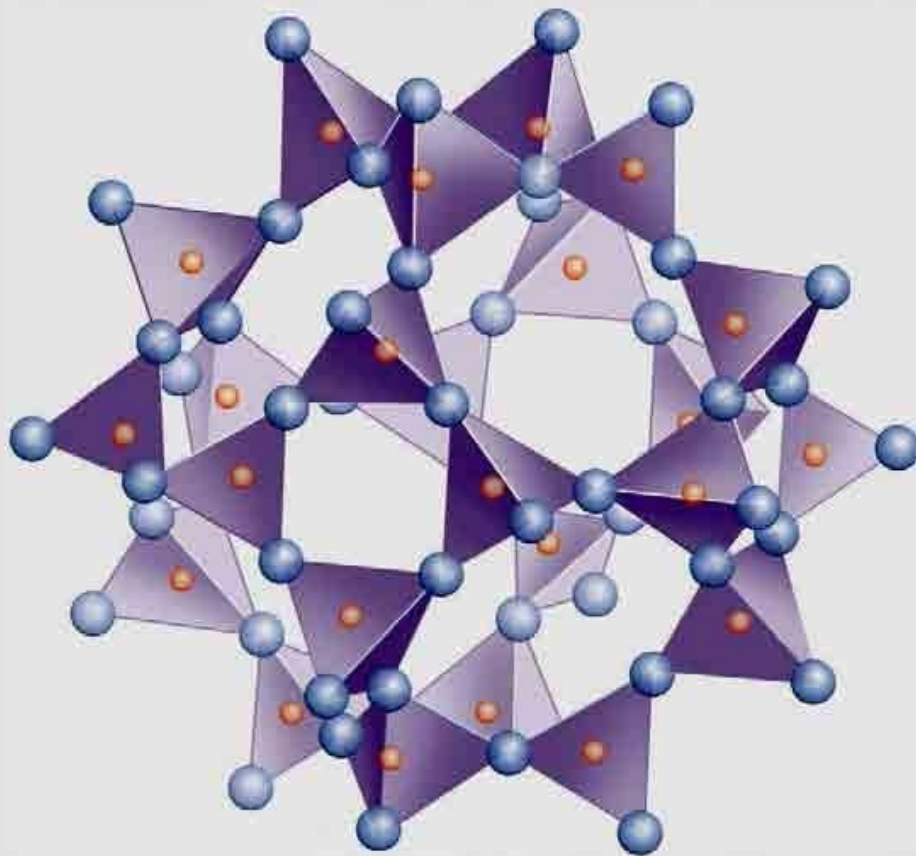


Chernicoff & Whitney, 2001

The Silicates

- The tetrahedra bond in many ways
- Polymerisation: the sharing of the O between the tetrahedra
- It is how they bond that define each of the members of the silicate group
- They are also defined by the cations that occupy the site, as well as how the cations are distributed



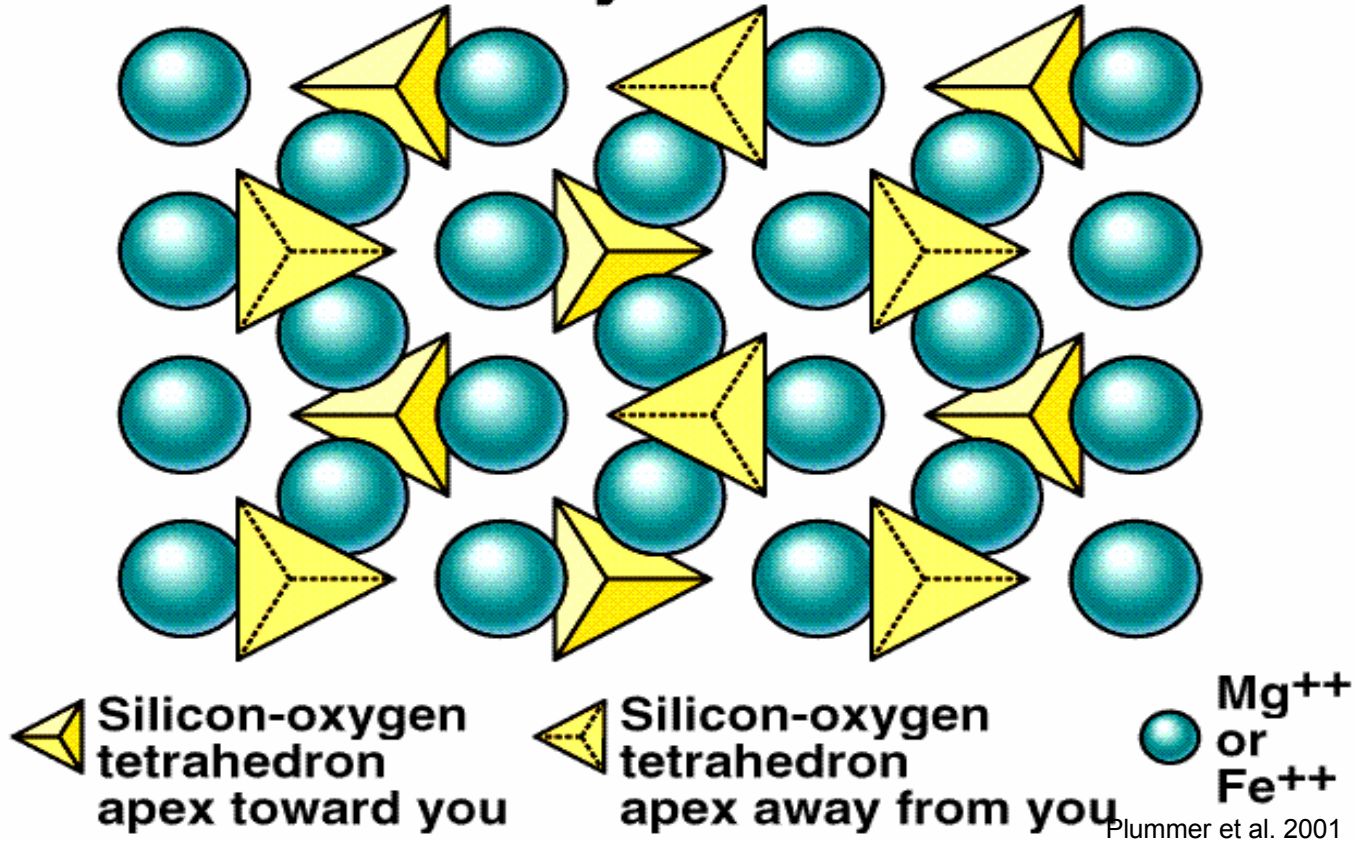


(e) Framework silicates

- Quartz
- Feldspar
- Si:O = 1:2

Chernicoff and Whitney, 2002

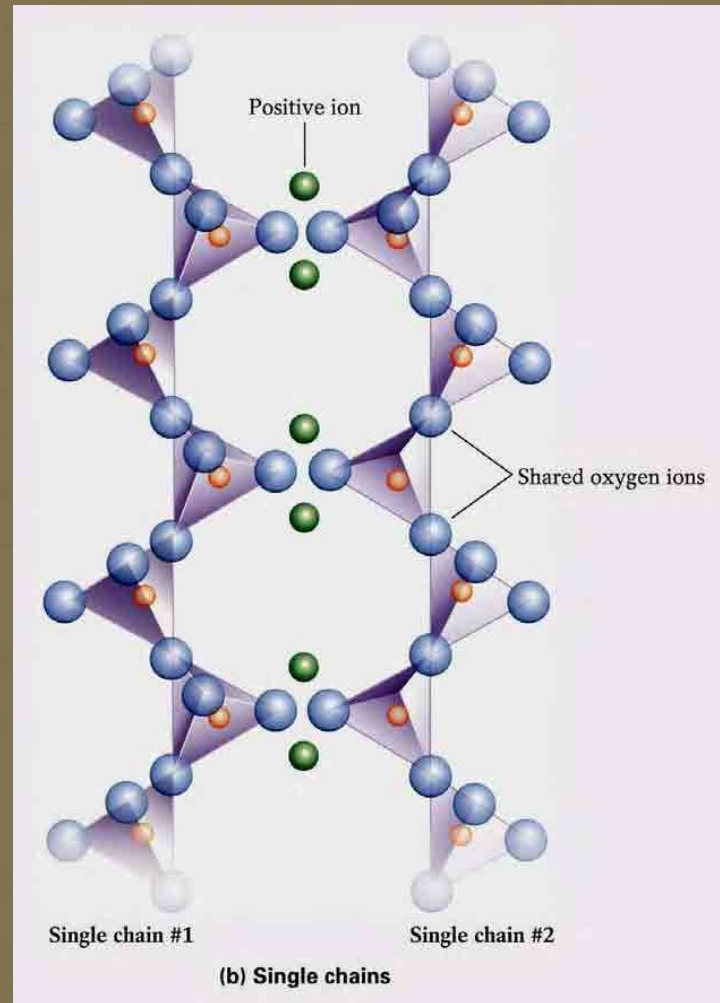
Olivine Crystal Structure



Another way: Individual tetrahedra bond together by positive ions

Chain Silicates

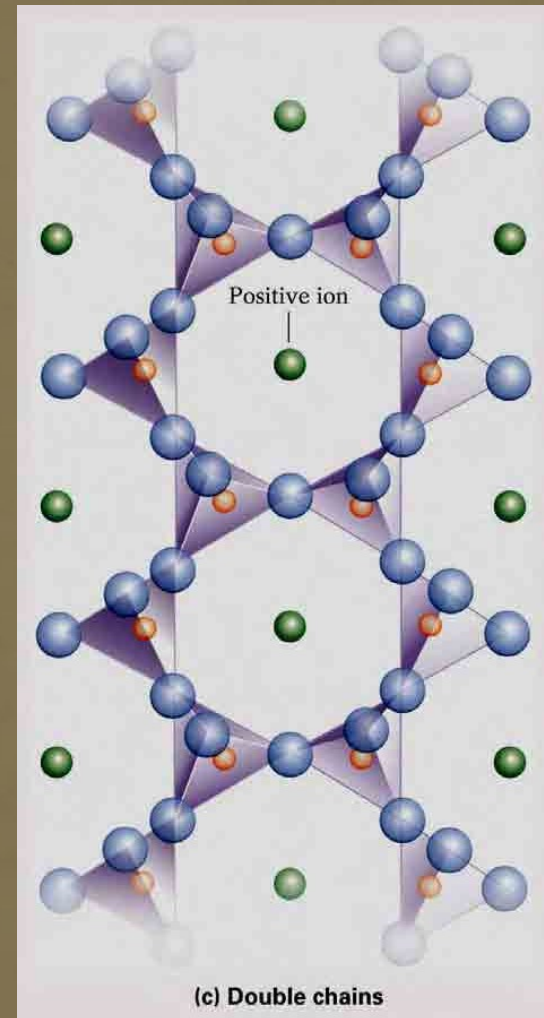
- Two O atoms of each tetrahedra are joined
- Chains bound by +ve ions
- Gives minerals a columnar, needle or fibre shape
- Si:O = 1:3
- example : Pyroxene



Chernicoff and Whitney, 2002

Double Chain Silicates

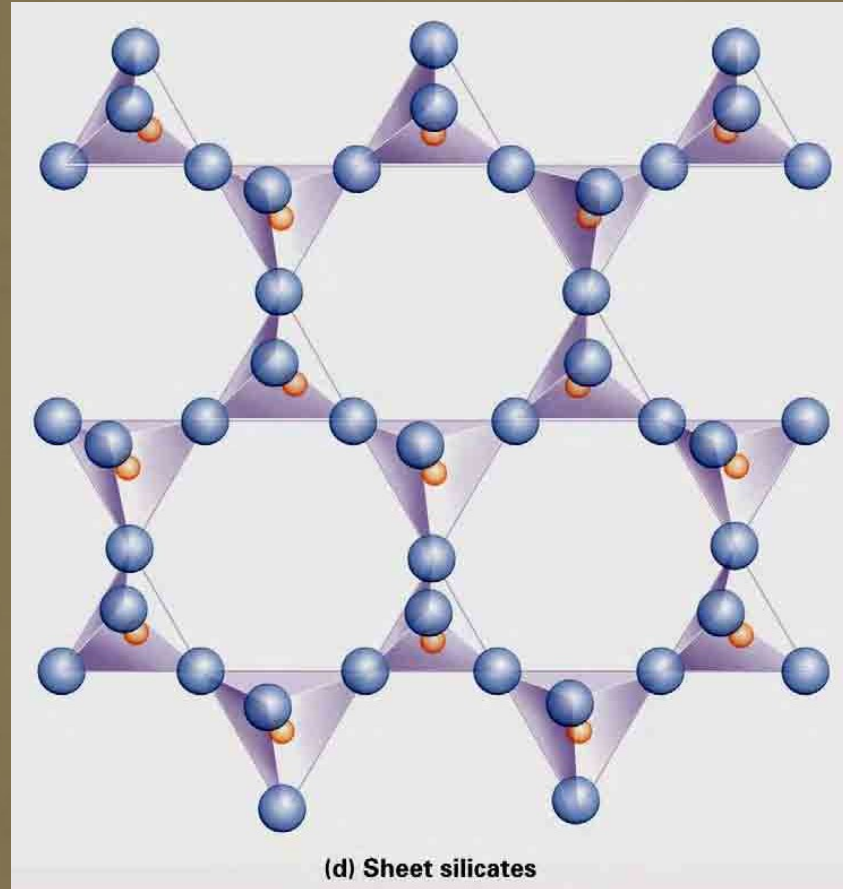
- Alternate tetrahedra share a third O atom
- Chains bound by +ve ions
- Minerals tend to be elongate
- Amphibole



Chernicoff and Whitney, 2002

Sheet Silicates

- Tetrahedra share three O atom
- Sheets bound by +ve ions
- Minerals tend to be platy or flakey
- pg 89, Fig. 3.18 and 3.19



Chernicoff and Whitney, 2002

Other mineral groups

- Oxides - the second most abundant mineral group
- The O^{2-} anion is bonded to common cations in a variety of ways
- Two of the more common are magnetite (Fe_3O_4) and hematite (Fe_2O_3)

Oxides



Hematite
 Fe_2O_3



Magnetite
 Fe_3O_4

<http://www.johnbelts-fineminerals.com/>

Other important oxides:

- Uraninite (UO_2)
- Cassiterite (SnO_2)
- Rutile (TiO_2)



Cassiterite, Schlaggenwald, Czech Republic <http://www.johnbetts-fineminerals.com/>

Sulphides



Sphalerite, Pyrite and Galena, Eagle Mine,
Colorado

<http://www.johnbetts-fine-minerals.com/>



Pyrrhotite, Calcite & Quartz, El Potosi Mine,
Mexico

<http://www.johnbetts-fine-minerals.com/>

Carbonates



Calcite , San Giovanni Mine, Italy
<http://www.johnbetts-fineminerals.com/>



Calcite and Dolomite, Tsumeb Mine, Namibia
<http://www.johnbetts-fineminerals.com/>

Calcite CaCO_3



Carbonates



Cerussite, Tsumeb Mine, Namibia
<http://www.johnbetts-fineminerals.com/>



Azurite, Tsumeb Mine, Namibia
<http://www.johnbetts-fineminerals.com/>

Lead and Copper
carbonates

Phosphates



Fluorapatite, Emmons Quarry, Maine
<http://www.johnbetts-fineminerals.com/>



Vanadinite, Mibladen, Morocco
<http://www.johnbetts-fineminerals.com/>

Sulfates



Gypsum, Paris Basin, France
<http://www.johnbetts-fineminerals.com/>

Native elements: Copper



Greenawald
Peninsula, Lake
Superior, Michigan
[http://www.johnbetts-
fineminerals.com/](http://www.johnbetts-fineminerals.com/)



Native Copper, White Pine
Mine, Michigan
[http://www.johnbetts-
fineminerals.com/](http://www.johnbetts-
fineminerals.com/)

Native elements: Silver



Silver, La Nevada Mine, Mexico
<http://www.johnbetts-fineminerals.com/>

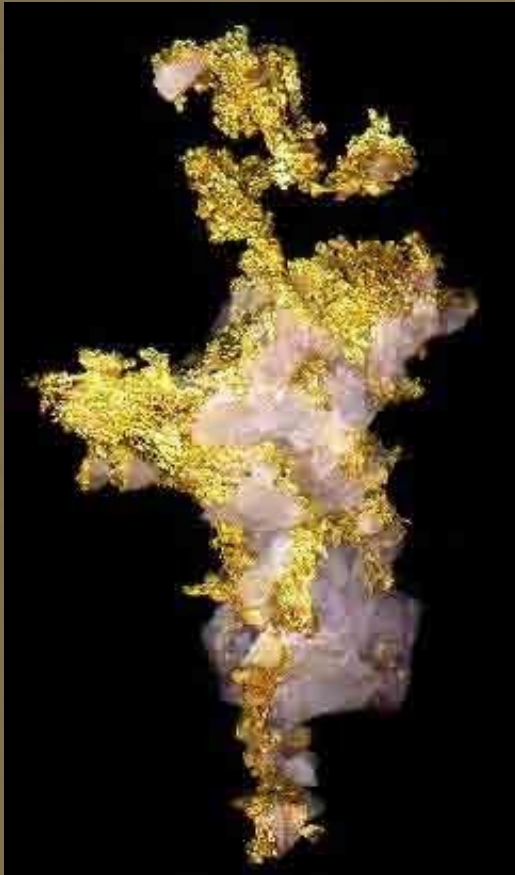


Silver, Kongsberg, Norway
<http://www.johnbetts-fineminerals.com/>



*Silver 'cobra',
Uchucchacua Mine,
Peru*
<http://www.exceptionalminerals.com/>

Native elements: Gold



Gold in quartz, Jamestown district, California
<http://www.exceptionalminerals.com/>

Gold, Sierra County, California
<http://www.johnbetts-fineminerals.com/>

Common uses of minerals in industry

- Abrasives: Industrial diamond
- Aggregates: Limestone, dolomite
- Cements: Asbestos, gypsum
- Ceramics: Feldspar, barite, REMs
- Drilling Fluids: Barite
- Electronics: Beryllium, graphite, REMs
- Fertilizers: Limestone, nitrates, phosphates
- Absorbants: Kaolinite, talc
- Glass: Felspar, silica, borates
- Insulation: Asbestos, mica group
- Lubricants: Graphite

Metals

- 35 metallic elements in total
- 6 are abundant: Si, Al, Fe, Mg, Ti, Mn
- Expensive to mine, must have high tonnage
- The Al example: bauxite ore (form by weathering processes in tropical climates)

BIFs: Banded Iron Formations



A banded-iron formation (BIF) rock recovered from the Temagami greenstone belt in Ontario, Can., and dated to 2.7 billion years ago. Dark layers of iron oxide are intercalated with red chert.

BIFs

- Date back from Early Proterozoic time (2.8 to 1.6 Ga)
- Lack of O₂ in the atmosphere during this period
- With O₂, Fe will precipitate in ferric (+3) form, however, low O₂ conditions Fe is mobile (by weathering processes) and dissolves in rivers and streams, eventually precipitating out in the layers

The scarce metals:

- 4 groups: ferro-alloy, base metals, precious and special metals
- Ferro-alloy metals: Cr, Co, Mo, Ni, W, V are added to Fe to make industrial minerals
- Base Metals: Cd, Cu, Zn, Pb, Sn, useful for electronics and coins (brass, bronze)
- Au, Ag, and PGEs are the precious metals
- Specials are from the rare metals

MVTs: Mississippi Valley Type Pb-Zn deposits

- Carbonate hosted Pb and Zn ore deposits
- Former marine basins
- Dissolution and transportation of the ore fluid
- Precipitation out of solution
- Large cavities and voids in the carbonate
- Sphalerite (ZnS) and Galena (PbS)

Literature

1. Tank R.W. 1973, Focus on Environmental Geology
2. Mclean A.C. and Gribble C.D. Geology for Civil Engineers