

Classification of minerals

The broadest divisions of the classification used in the present discussion are (1) native elements, (2) sulfides, (3) sulfosalts, (4) oxides and hydroxides, (5) halides, (6) carbonates, (7) nitrates, (8) borates, (9) sulfates, (10) phosphates, and (11) silicates.

1. Native elements

- Apart from the free gases in Earth's atmosphere, some 20 elements occur in nature in a pure (i.e., uncombined) or nearly pure form. Known as the native elements,
- They are partitioned into three families: metals, semimetals, and nonmetals.
- The most common native metals, which are characterized by simple crystal structures, make up **three** groups: the **gold group**, consisting of gold, silver, copper, and lead; the **platinum group**, composed of platinum, palladium, iridium, and osmium; and the **iron group**, containing iron and nickel-iron. Mercury, tantalum, tin, and zinc are other metals that have been found in the native state.
- The native semimetals are divided into two isostructural groups (those whose members share a common structure type): (1) antimony, arsenic, and bismuth, with the latter two being more common in nature, and (2) the rather uncommon selenium and tellurium.
- Carbon, in the form of diamond and graphite, and sulfur are the most important native nonmetals.

1.1 Metals

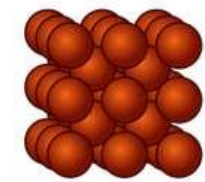
Gold, silver, and copper are members of the same group (column) in the periodic table of elements and therefore have similar chemical properties. In the uncombined state, their atoms are joined by the fairly weak metallic bond. These minerals share a common structure type, and their atoms are positioned in a **simple cubic closest-packed arrangement**. Gold and silver both have an atomic radius of **1.44 angstroms** (Å), or 1.44×10^{-7} millimetre, which enables complete solid solution to take place between them. The radius of copper is significantly smaller (1.28 Å), and as such copper substitutes only to a limited extent in gold and silver. Likewise, native copper contains only trace amounts of gold and silver in its structure.

Because of their similar crystal structure, the members of the gold group display similar physical properties. All are rather **soft, ductile (capable of being drawn into wire), malleable (capable of being shaped by a hammer or rollers), and sectile (capable of being cut smoothly by a knife or other instrument)**; gold, silver, and copper serve as excellent conductors of electricity and heat and exhibit **metallic lustre and hackly fracture (a type of fracture characterized by sharp jagged surfaces)**. These properties are attributable to their metallic bonding. The gold-group minerals crystallize in the isometric system and have high densities as a consequence of cubic closest packing.

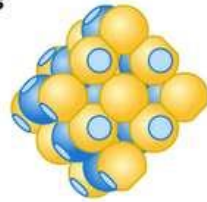
In addition to the elements listed above, the platinum group also includes rare mineral alloys such as iridosmine. The members of this group are harder than the metals of the gold group and also have higher melting points.

The iron-group metals are isometric and have a simple cubic packed structure. Its members include pure iron, which is rarely found on the surface of Earth, and two species of nickel-iron (kamacite and taenite), which have been identified as common constituents of meteorites. Native iron has been found in basalts of Disko Island, Greenland and nickel-iron in Josephine and Jackson counties, Oregon. The atomic radii of iron and nickel are both approximately 1.24 Å, and so nickel is a frequent substitute for iron. Earth's core is thought to be composed largely of such iron-nickel alloys.

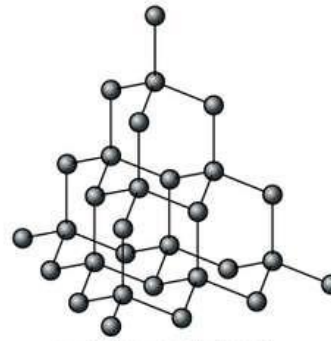
Structures of native elements



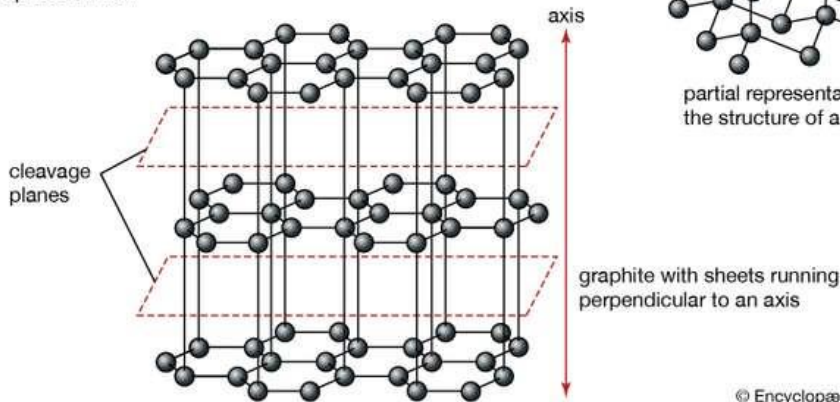
cubic packing of equal spheres in iron



close-packed model of arsenic and antimony



partial representation of the structure of a diamond



cleavage planes

graphite with sheets running perpendicular to an axis

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Figure 9: *Structures of some native elements.* (A) Close-packed model of simple cubic packing of equal spheres, as shown by iron. Each sphere is surrounded by eight closest neighbors. (B) Close-packed model of the structure of arsenic and antimony. Flat areas represent overlap between adjoining atoms. (C) Partial representation of the structure of diamond. (D) The structure of graphite with sheets perpendicular to the *c* axis.

1.2 Semimetals

The semimetals antimony, arsenic, and bismuth have a structure type distinct from the simple-packed spheres of the metals. In these semimetals, each atom is positioned closer to three of its neighbouring atoms than to the rest. The structure of antimony and arsenic is composed of spheres that intersect along flat circular areas.

The covalent character of the bonds joining the four closest atoms is linked to the electronegative nature of the semimetals, reflected by their position in the periodic table. Members of this group are fairly brittle, and they do not conduct heat and electricity nearly as well as the native metals. The bond type suggested by these properties is intermediate between metallic and covalent; it is consequently stronger and more directional than pure metallic bonding, resulting in crystals of lower symmetry.

1.3 Nonmetals

The native nonmetals diamond, fullerene, graphite, and sulfur are structurally distinct from the metals and semimetals. The structure of sulfur (atomic radius = 1.04 Å), usually orthorhombic in form, may contain limited solid solution by selenium (atomic radius = 1.16 Å).

The polymorphs of carbon—graphite, fullerene, and diamond—display dissimilar structures, resulting in their differences in hardness and specific gravity. In diamond, each carbon atom is bonded covalently in a tetrahedral arrangement, producing a strongly bonded and exceedingly close-knit but not closest-packed structure. The carbon atoms of graphite, however, are arranged in six-membered rings in which each atom is surrounded by three close-by neighbours located at the vertices of an equilateral triangle. The rings are linked to form sheets, called graphene, that are separated by a distance exceeding one atomic diameter. Van der Waals forces act perpendicular to the sheets, offering a weak bond, which, in combination with the wide spacing, leads to perfect basal cleavage and easy gliding along the sheets. Fullerenes are found in meta-

anthracite, in fulgurites, and in clays from the Cretaceous-Tertiary boundary in New Zealand, Spain, and Turkmenistan as well as in organic-rich layers near the Sudbury nickel mine of Canada.

2. Sulfides

This important class includes most of the ore minerals. The similar but rarer sulfarsenides are grouped here as well. Sulfide minerals consist of one or more metals combined with sulfur; sulfarsenides contain arsenic replacing some of the sulfur.

Sulfides are generally opaque and exhibit distinguishing colours and streaks. (Streak is the colour of a mineral's powder.) The nonopaque varieties (e.g., cinnabar, realgar, and orpiment) possess high refractive indices, transmitting light only on the thin edges of a specimen.

Arsenopyrite (FeAsS) is a common sulfarsenide that occurs in many ore deposits. It is the chief source of the element arsenic.

Sulfide minerals

name	colour	lustre	Mohs hardness	specific gravity	habit or form	fracture or cleavage	refractive indices or polished section data	crystal system
argentite	blackish lead-gray	metallic	2–2 1/2	7.2–7.4	cubic or octahedral crystals, often in groups; arborescent or hairlike massive	subconchoidal fracture	faintly anisotropic	isometric
chalcocite	blackish lead-gray	metallic	2 1/2–3	5.5–5.8	short prismatic or thick tabular crystals; massive	conchoidal fracture	weakly anisotropic	orthorhombic
chalcopyrite	brass-yellow, often tarnished and iridescent	metallic	3 1/2–4	4.1–4.3	compact massive; tetragonal crystals	uneven fracture	weakly anisotropic; often shows lamellar and polysynthetic twinning	tetragonal
cinnabar	cochineal-red to brownish or lead-gray	adamantine to metallic	2–2 1/2	8.1	rhombohedral, tabular, or prismatic crystals; massive; earthy coatings	one perfect cleavage	omega = 2.756–2.905 epsilon = 3.065–3.256	hexagonal
covellite	indigo-blue; highly iridescent; brass-yellow or deep red	submetallic to resinous (crystals); subresinous to dull (massive)	1 1/2–2	4.6–4.8	massive; rarely in hexagonal plates	one highly perfect cleavage	strongly anisotropic	hexagonal

galena	lead-gray	metallic	2 1/2–3	7.6	cubic crystals; cleavable masses	one perfect cleavage	isotropic	isometric
molybdenite	lead-gray	metallic	1–1 1/2	4.6–4.7	hexagonal tablets; foliated massive, in scales	one perfect cleavage	very strongly anisotropic and pleochroic; white	hexagonal
pyrite	pale brass-yellow	splendent to glistening metallic	6–6 1/2	5.0	cubic, pyritohedral, or octahedral crystals with striated faces; massive	conchoidal to uneven fracture	isotropic; creamy white	isometric
pyrrhotite	bronze-yellow to pinchbeck-brown, tarnishing quickly	metallic	3 1/2–4 1/2	4.6–4.7 4.8 (troilite)	granular massive; sometimes platy or tabular crystals	uneven to subconchoidal fracture	strongly anisotropic	hexagonal
realgar	aurora-red to orange-yellow	resinous to greasy	1 1/2–2	3.5–3.6	short, striated prismatic crystals; granular or compact massive; incrustations	one good cleavage, three less so	alpha = 2.486–2.538 beta = 2.602–2.684 gamma = 2.620–2.704	monoclinic
sphalerite	brown, black, yellow; also variable	resinous to adamantine	3 1/2–4	3.9–4.1	tetrahedral or dodecahedral crystals, often with curved faces; cleavable masses	one perfect cleavage	n = 2.320–2.517	isometric
stannite	steel-gray to iron-black	metallic	4	4.3–4.5	granular massive	uneven fracture	anisotropic	tetragonal
sylvanite	steel-gray to silver-white	brilliant metallic	1 1/2–2	8.1–8.2	short prismatic, thick tabular, or bladed crystals	one perfect cleavage	strongly anisotropic and pleochroic; creamy white; shows polysynthetic twinning	monoclinic

3. Sulfosalts

There are approximately 100 species constituting the rather large and very diverse sulfosalt class of minerals. The sulfosalts differ notably from the sulfides and sulfarsenides with regard to the role of semimetals, such as arsenic (As) and antimony (Sb), in their structures. In the sulfarsenides, the semimetals substitute for

some of the sulfur in the structure, while in the sulfosalts they are found instead in the metal site. For example, in the sulfarsenide arsenopyrite (FeAsS), the arsenic replaces sulfur in a marcasite- (FeS_2 -) type structure. In contrast, the sulfosalt enargite (Cu_3AsS_4) contains arsenic in the metal position, coordinated to four sulfur atoms. A sulfosalt such as Cu_3AsS_4 may also be thought of as a double sulfide, $3\text{Cu}_2\text{S} \cdot \text{As}_2\text{S}_5$.

4. Oxides and hydroxides

These classes consist of oxygen-bearing minerals; the oxides combine oxygen with one or more metals, while the hydroxides are characterized by hydroxyl (OH^-) groups.

The oxides are further divided into two main types: simple and multiple. Simple oxides contain a single metal combined with oxygen in one of several possible metal:oxygen ratios ($\text{X}:\text{O}$): XO , X_2O , X_2O_3 , etc. Ice, H_2O , is a simple oxide of the X_2O type that incorporates hydrogen as the cation. Although SiO_2 (quartz and its polymorphs) is the most commonly occurring oxide, it is discussed below in the section on silicates because its structure more closely resembles that of other silicon-oxygen compounds. Two nonequivalent metal sites (X and Y) characterize multiple oxides, which have the form XY_2O_4 .

Unlike the minerals of the sulfide class, which exhibit ionic, covalent, and metallic bonding, oxide minerals generally display strong ionic bonding. They are relatively hard, dense, and refractory.

Oxides generally occur in small amounts in igneous and metamorphic rocks and also as preexisting grains in sedimentary rocks. Several oxides have great economic value, including the principal ores of iron (hematite and magnetite), chromium (chromite), manganese (pyrolusite, as well as the hydroxides, manganite and romanechite), tin (cassiterite), and uranium (uraninite).

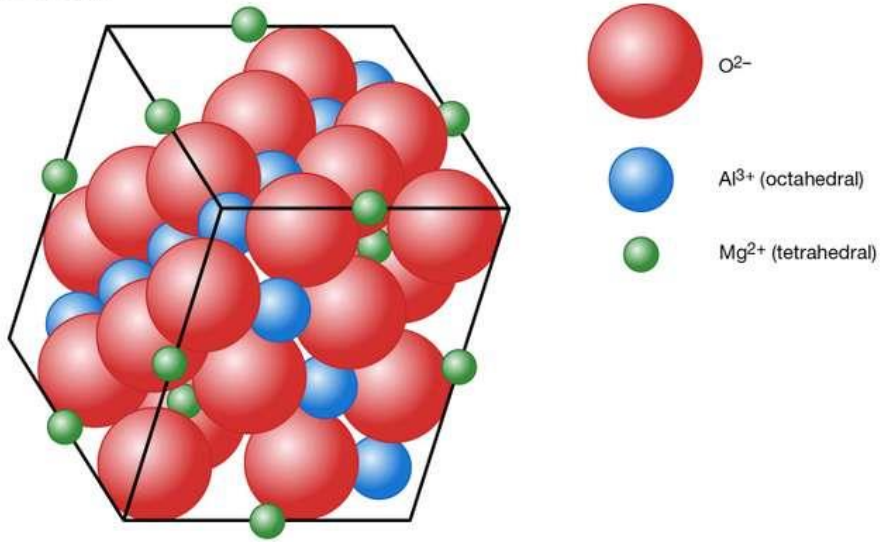
Members of the hematite group are of the X_2O_3 type and have structures based on hexagonal closest packing of the oxygen atoms with octahedrally coordinated (surrounded by and bonded to six atoms) cations between them. Corundum and hematite share a common hexagonal architecture. In the ilmenite structure, iron and titanium occupy alternate Fe-O and Ti-O layers.

The XO_2 -type oxides are divided into two groups. The first structure type, exemplified by rutile, contains cations in octahedral coordination with oxygen. The second resembles fluorite (CaF_2); each oxygen is bonded to four cations located at the corners of a fairly regular tetrahedron, and each cation lies within a cube at whose corners are eight oxygen atoms. This latter structure is exhibited by uranium, thorium, and cerium oxides, whose considerable importance arises from their roles in nuclear chemistry.

The spinel-group minerals have type XY_2O_4 and contain oxygen atoms in approximate cubic closest packing. The cations located within the oxygen framework are octahedrally (sixfold) and tetrahedrally (fourfold) coordinated with oxygen.

The (OH^-) group of the hydroxides generally results in structures with lower bond strengths than in the oxide minerals. The hydroxide minerals tend to be less dense than the oxides and also are not as hard. All hydroxides form at low temperatures and are found predominantly as weathering products, as, for example, from alteration in hydrothermal veins. Some common hydroxides are brucite [$\text{Mg}(\text{OH})_2$], manganite [$\text{MnO} \cdot \text{OH}$], diaspore [$\alpha\text{-AlO} \cdot \text{OH}$], and goethite [$\alpha\text{-FeO} \cdot \text{OH}$]. The ore of aluminum, bauxite, consists of a mixture of diaspore, boehmite ($\gamma\text{-AlO} \cdot \text{OH}$ —a polymorph of diaspore), and gibbsite [$\text{Al}(\text{OH})_3$], plus iron oxides. Goethite is a common alteration product of iron-rich occurrences and is an iron ore in some localities.

Spinel structure



Cubic packing of a spinel mineral composed of magnesium aluminum oxide (MgAl₂O₄)

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Figure: An oxygen layer in the spinel (MgAl₂O₄) structure. The large circles represent oxygen in approximate cubic closest packing; the cation layers on each side of the oxygen layer are also shown.