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Genesis of Minerals

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Crystal Shape

A **Crystal** is a regular polyhedral form, bounded by smooth faces, which is assumed by a chemical compound, due to the action of its interatomic forces, when passing, under suitable conditions, from the state of a liquid or gas to that of a solid. A polyhedral form simply means a solid bounded by flat planes (we call these flat planes **crystal faces**).When a mineral occurs as a crystal, its shape may suffice to identify the mineral without any additional tests. Both form and habit of crystals are useful. To mineralogists, the term **form** refers specifically to a group of crystal faces, related by the crystal's symmetry, that have identical chemical and physical properties. **Habit** refers to the overall shape of a crystal or aggregate of crystals.

Natural crystals grows wherever

- Their constituent elements (atoms/ions) are free to come together in the correct proportions
- Existing conditions allows growth at a reasonably slow and steady rate
- There is free space where they can grow without physical constraint

Concepts of Atomic Bonds in Forming Mineral Crystals

Atoms in minerals and rocks are held together by forces or mechanisms called **chemical bonds**. The nature of these bonds strongly influences the properties and behavior of minerals, rocks and other Earth materials. The three most common bond types are (1) ionic, (2) covalent, and (3) metallic.

Ionic (electrostatic) bonds

When very metallic atoms bond with very non-metallic atoms, an **ionic bond**, also called an **electrostatic bond**, is formed. The very metallic atoms are electropositive while the very non-metallic atoms are electronegative.

Bonding mechanisms play an essential role in contributing to material properties. Crys-tals with ionic bonds are generally characterized by the following:

1 Variable hardness.

2 Brittle at room temperatures.

3 Quite soluble in polar substances (such as water).

4 Intermediate melting temperatures.

5 Do not absorb much light, producing translucent to transparent minerals with light colors and vitreous to sub-vitreous luster in macroscopic crystals.

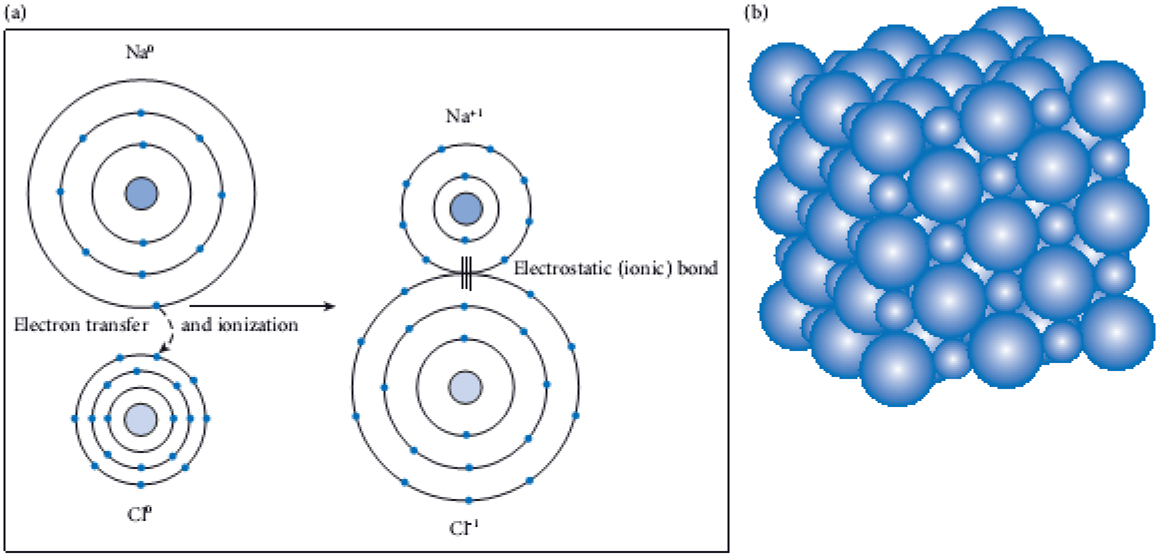


Figure 1: (a) Ionic bonding develops between highly electronegative anions and highly electropositive cations. When neutral sodium (Na) atoms release an electron to become cations (Na^{+1}) their ionic radius decreases. When neutral chlorine (Cl^0) atoms capture an electron to become anions (Cl^{-1}) their ionic radius increases. (b) Ions of opposite charge attract to form crystals such as sodium chloride (NaCl).

Covalent (electron-sharing) bonds

When non-metallic atoms bond with other non-metallic atoms they tend to form **covalent bonds**. Because the elements involved are electronegative they each tend to attract electrons; neither gives them up easily because of their high first ionization potentials and electron affinities. In simple models of covalent bonding, the atoms involved share valence (thus covalent) electrons (Figure 2). By sharing electrons, each atom gains the necessary electrons to achieve a stable electron con-figuration. The best known mineral with covalent bonding is diamond, which is composed of carbon (C).

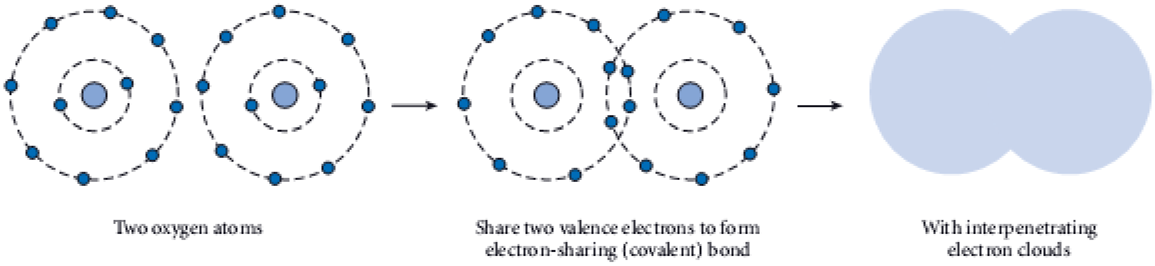


Figure 2: Covalent bonding in oxygen (O_2) by the sharing of two electrons from each atom.

Covalently bonded minerals are generally characterized by the following:

1 Hard and brittle at room temperature.

2 Insoluble in polar substances such as water.

3 Crystallize from melts.

4 Moderate to high melting temperatures.

5 Do not absorb light, producing transparent to translucent minerals with light colors and vitreous to sub-vitreous lusters in macroscopic crystals.

Metallic bonds

When metallic atoms bond with other metallic atoms, a **metallic bond** is formed. Because very metallic atoms have low first ionization they do not tend to hold their valence electrons strongly. In such situations, each atom releases valence electrons to achieve a stable electron configuration. The positions of the valence electrons fluctuate or migrate between atoms. The weak attractive forces between positive partial atoms and valence electrons bond the atoms together. Unlike the strong electron-sharing bonds of covalently bonded substances, or the sometimes strong electrostatic bonds of ionically bonded substances, metallic bonds are rather weak, less permanent and easily broken and reformed. Because the valence electrons are not strongly held by any of the partial atoms, they are easily moved in response to stress or in response to an electric field.

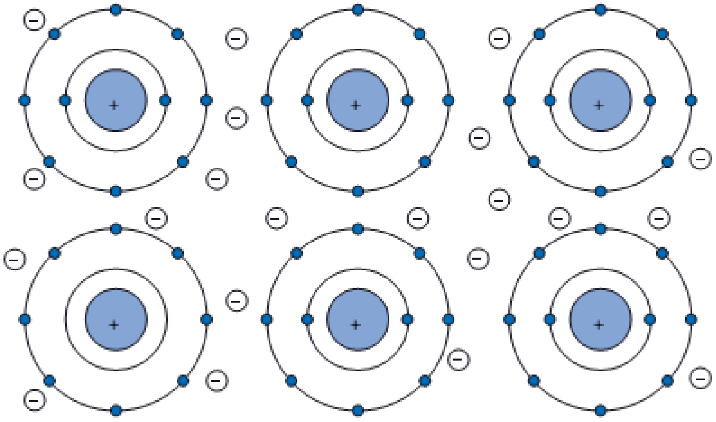


Figure 3: A model of metallic bonds with delocalized electrons surrounding positive charge centers that consist of tightly held lower energy electrons (blue dots) surrounding individual nuclei (blue).

Many good examples of metallic bonding exist in the native metals such as native gold (Au), native silver (Ag), and native copper (Cu). When subjected to an electric potential or field, delocalized electrons flow toward the positive anode, creating and maintaining a strong electric current. Similarly, when a thermal gradient exists, thermal vibrations are transferred by delocalized electrons, making such materials excellent heat conductors. When metals are stressed, the weakly held electrons tend to flow, which helps to explain the ductile behavior that characterizes copper and other metallically bonded substances.

Minerals containing metallic bonds are generally characterized by the following features:

1 Fairly soft to moderately hard minerals.

2 Plastic, malleable and ductile.

3 Excellent electrical and thermal conductors.

4 Frequently high specific gravity.

5 Excellent absorbers and reflectors of light; so are commonly opaque with a metallic luster in macroscopic crystals.

(N.B.: The **first ionization energy** is the energy required to remove the most loosely held electron from one mole of gaseous atoms to produce 1 mole of gaseous ions each with a charge of 1+).

Crystal Forms

Many crystals are enclosed by flat surfaces called crystal faces. Crystal faces are formed when mineral crystals grow, and enclose crystalline solids when they stop growing. Faces of a single crystal form have identical properties because they contain identical atoms in identical arrangements. The external symmetry expressed by crystal faces permits us to infer the geometric patterns of the atoms in mineral crystal structures as well. These patterns inferred from external symmetry have been confirmed by advanced analytical techniques such as X-ray diffraction (XRD) and atomic force microscopy (AFM). For any one mineral, the angles between particular faces are always the same even though the size of the faces may vary. Figure 1 illustrates two quartz crystals. Note the different size of faces but the constant interfacial angles.

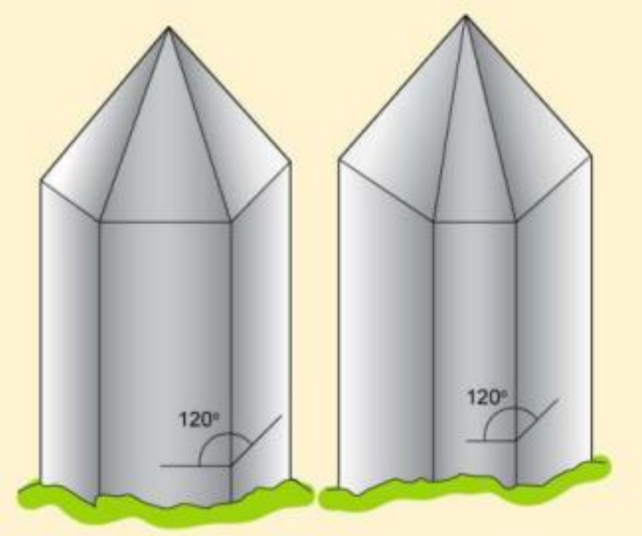


Figure 4: Interfacial angles between crystal faces

Crystal forms consist of a three-dimensional set of one or more crystal faces that possess similar relationships to the crystallographic axes. So, crystal form is a set of crystal faces that are related to each other by symmetry.

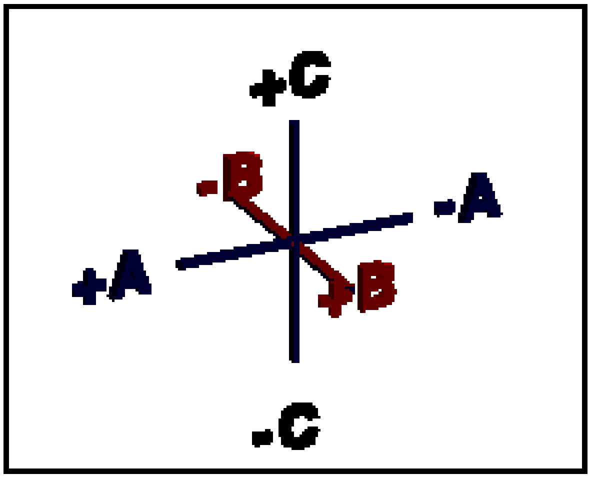


Figure 5: Crystallographic axes

To designate a crystal form (which could imply many faces) we use the Miller Index, or Miller-Bravais Index notation enclosing the indices in curly braces, i.e.

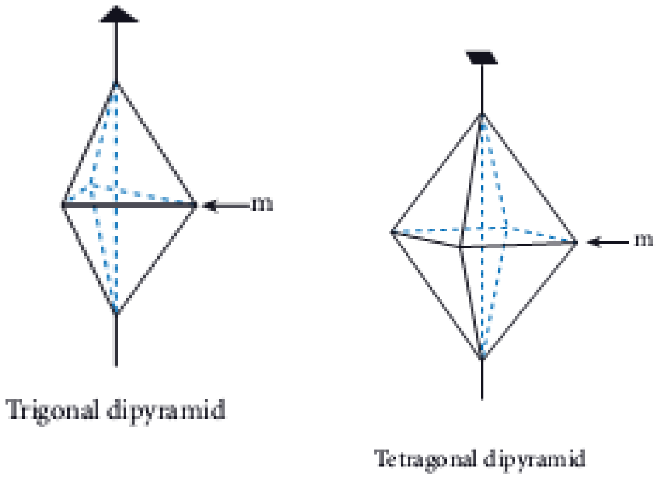
{101} or {1121}

Such notation is called a form symbol.

An important point to note is that a form refers to a face or set of faces that have the same arrangement of atoms. Thus, the number of faces in a form depends on the symmetry of the crystal.

A **general form** is a form in a particular crystal class that contains faces that intersect all crystallographic axes at different lengths. All other forms that may be present are called **special forms.**

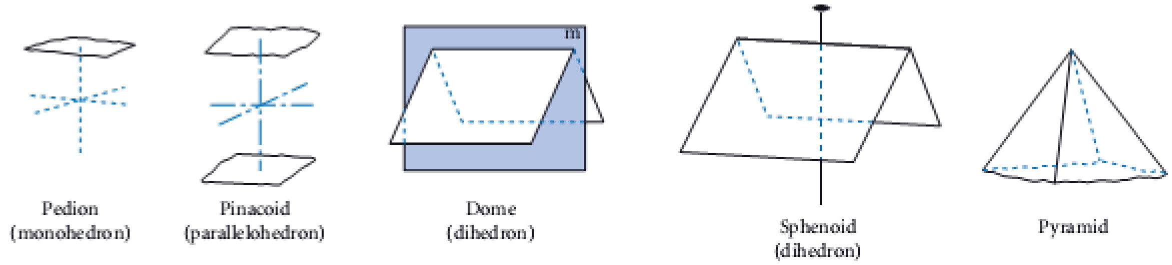
A **closed form** (Figure 3) is a set of crystal faces that completely enclose space. Thus, in crystal classes that contain closed forms, a crystal can be made up of a single form. An **open form** (Figure 4) is one or more crystal faces that do not completely enclose space and so must occur in combination with other open or closed crystal forms.



Trigonal dipyramid

Tetragonal dipyramid

Figure 6: Some closed forms.



Pedion (monohedron)

Pinacoid (parallelohedron)

Dome (dihedron)

Sphenoid (dihedron)

Pyramid

Figure 7: Some common open forms.

There are 48 possible forms that can be developed as the result of the 32 combinations of symmetry. Some important forms are:

Pedions, pinacoids, domes, sphenoids, prisms, pyramids, dipyramids, trapezohedrons, scalenohedrons, rhombohedrons, disphenoids, hexahedron, octahedron, dodecahedron, tetrahexahedron, trapezohedron, tetrahedron, gyroid, diploid, tetratoid etc.

Crystal systems

There are seven large groups or crystal systems in which all crystal forms may fall in. All of our known minerals form crystals in one of these systems. There are more than seven shapes of crystals, but they all are variations of one of these seven crystal systems. Every crystal system has a characteristic suite of forms that reflect the unique characteristics of the crystal lattice of the system, especially the relative lengths of the three crystallographic axes that directly or indirectly reflect the lengths of the unit cell edges. Therefore, we will use our crystallographic axes to subdivide all known minerals into these systems.

Each system is defined by a combination of three factors: how many axes they have, their lengths, and the angles at which they meet. An axis is a direction between the sides. The shortest one is A and the longest is C.

Isometric or cubic

The first and simplest crystal system is the isometric or cubic system. It has three axes, all of which are the same length. The three axes in the isometric system all intersect at 90 degrees to each other. Minerals that form in the isometric system include all garnets, diamond, fluorite, gold, lapis lazuli, pyrite, silver, sodalite, spinel, etc.

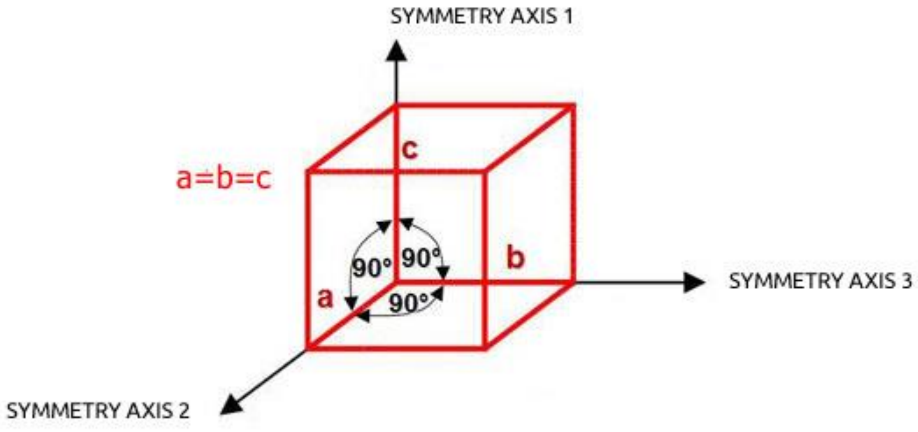


Figure 8a: The isometric crystal system has three axes of the same length that intersect at 90 degree angles.

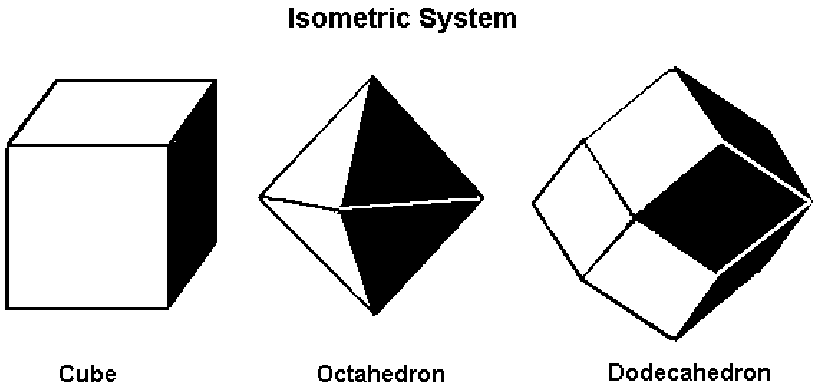


Figure 8b: Minerals that form in the isometric system form one of these three basic shapes.

Tetragonal

The tetragonal system also has three axes that all meet at 90 degrees. It differs from the isometric system in that the C axis is longer than the A and B axes, which are the same length. Minerals that form in the tetragonal system include rutile, wulfenite, zircon etc.

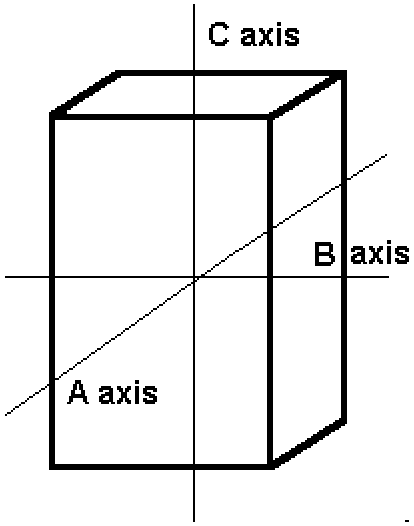


Figure 8c: The tetragonal crystal system also has three axes. Axis C is longer than Axes A and B, which are the same length.

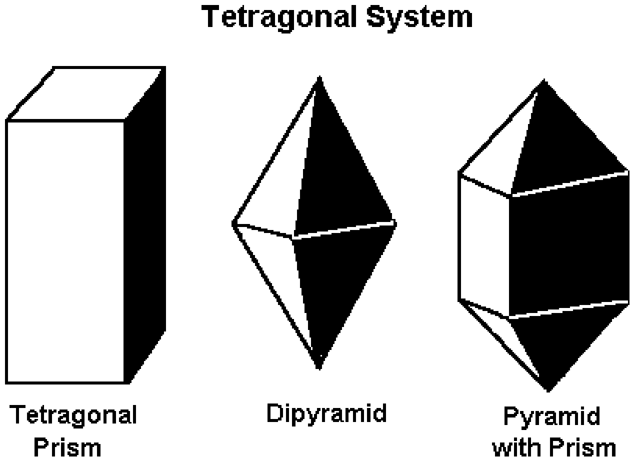


Figure 8d: Minerals that form in the tetragonal system form one of these three basic shapes.

Orthorhombic

In this system there are three axes, all of which meet at 90 degrees to each other. However, all the axes are different lengths. Minerals that form in the orthorhombic system include andalusite, celestite, chrysoberyl, cordierite, epidote, enstatite, hemimorphite, fibrolite/sillimanite, hypersthene, olivine, peridot, sulphur, topaz, zoisite, etc.

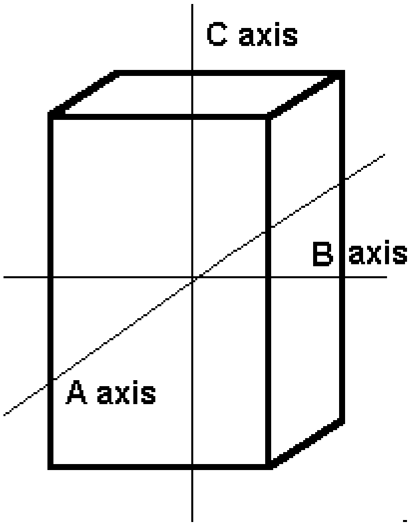


Figure 8e: The orthorhombic system has three axes, each of which is a different length. These axes intersect at 90 degree angles.

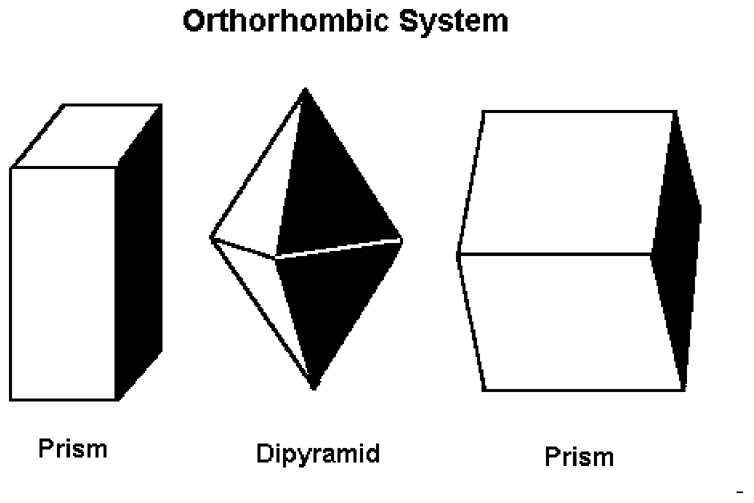


Figure 8f: Minerals that form in the orthorhombic system form one of these three basic shapes.

Monoclinic

The above crystal systems all have axes sides that meet at 90 degrees. In the monoclinic system, two of the axes, A and C, meet at 90 degrees, but Axis B does not. All axes in the monoclinic system are different lengths. Minerals that form in the monoclinic system include azurite, diopside, jadeite, lazulite, malachite, orthoclase feldspars (including albite moonstone), staurolite, sphene, etc.

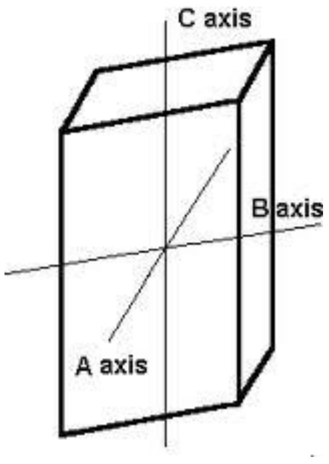


Figure 8g: The axes in the monoclinic system are all different lengths. The A and C axes intersect at 90 degrees, but Axis B does not.

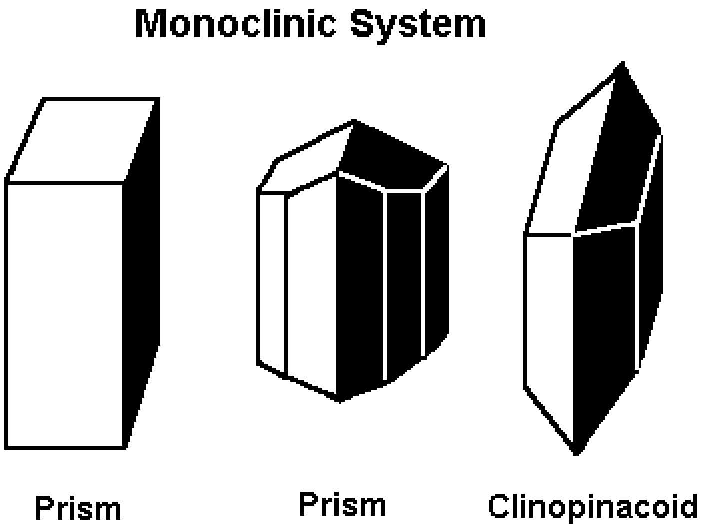


Figure 8h: Gems that form in the monoclinic system form one of these three basic shapes.

Triclinic

In the triclinic system, all the axes are different lengths and none of them meet at 90 degrees. Feldspar forms using a triclinic crystal system.

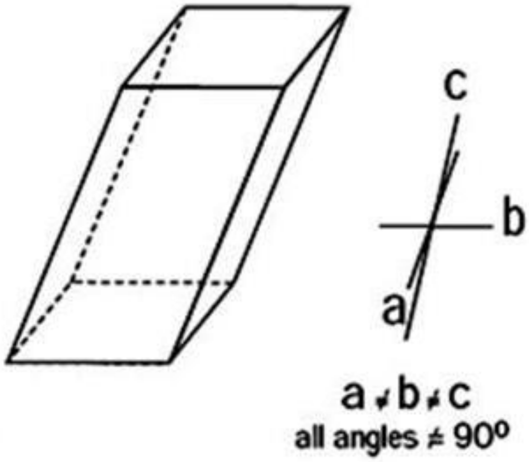


Figure 8i: None of the axes in the triclinic system intersect at 90 degrees and all are different lengths.

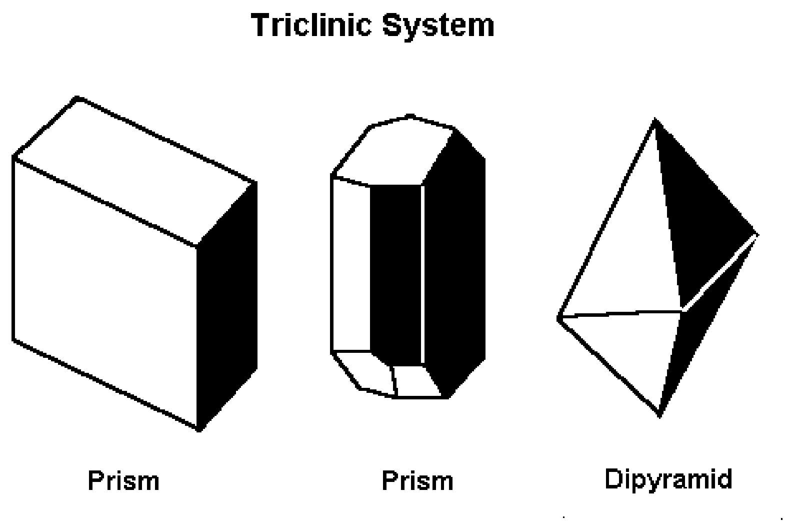


Figure 8j: Gems that form in the triclinic system form one of these three basic shapes.

Hexagonal

The crystal systems mentioned above represent every variation of four-sided figures with three axes. In the hexagonal system we have an additional axis, which gives the crystals six sides. Three of these are equal in length and meet at 60 degrees to each other. The C or vertical axis is at 90 degrees to the shorter axes. Minerals that form in the hexagonal system include apatite, beryl, zincite, etc. Mineralogists sometimes divide this into two systems, the hexagonal and the trigonal, based on their external appearance.

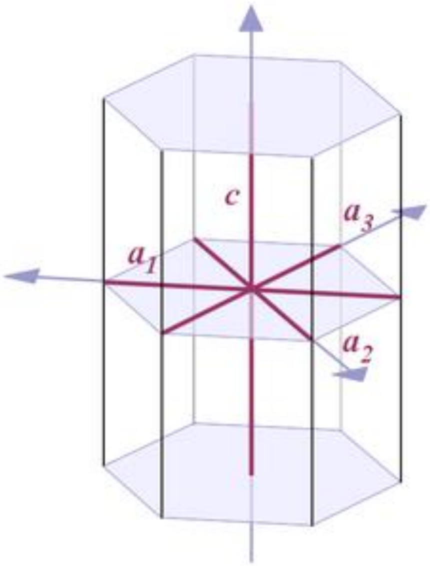


Figure 8k: Hexagonal crystal system

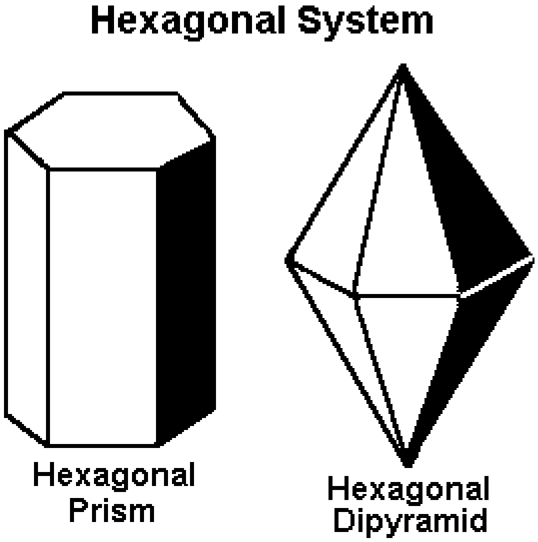


Figure 8l: Gems that form in the hexagonal system form into one of these two basic shapes.

Trigonal or rhombohedral

The three axes are equal in length and are equally inclined to each other at an angle other than 90°. Minerals those form crystals in this system are calcite, dolomite, rhodochrosite, hematite etc.

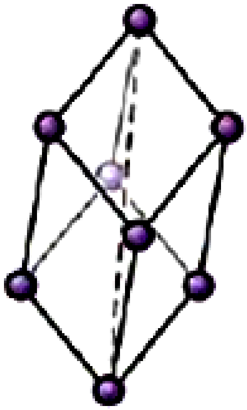


Figure 8m: Trigonal (rhombohedral) crystal system ($a=b=c$; $\alpha=\beta=\Upsilon\neq90^o$)

Amorphous materials (or solids) are not minerals; therefore, they do not form in any of these crystal systems. An **amorphous solid** is any noncrystalline solid in which the atoms and molecules are not organized in a definite lattice pattern. Examples of amorphous materials include amber, chrysocolla, glass, ivory, obsidian, opal, etc.

Vectorial Properties of Crystals

Although a crystal structure is an ordered arrangement of atoms on a lattice, as we have seen, the order may be different along different directions in the crystal. Thus, some properties of crystals depend on direction. These are called vectorial properties, and can be divided into two categories: continuous and discontinuous.

Continuous vectorial properties

Continuous vectorial properties depend on direction, but along any given the direction the property is the same. Some of the continuous vectorial properties are:

Hardness - In some minerals there is a difference in hardness in different directions in the crystal. Examples: Kyanite, Biotite, Muscovite. This can become an important identifying property and/or may lead to confusion about the hardness if one is not aware of the directional dependence.

Velocity of Light (Refractive Index) - For all minerals except those in the isometric system, the velocity of light is different as the light travels along different directions in the crystal. We will use this directional dependence of light velocity as an important tool in the second half of the course. Refractive Index is defined as the velocity of light in a vacuum divided by the velocity of light in the material. Because the velocity of light depends on direction, the refractive index will also depend on direction.

Thermal Conductivity - The ability of a material toconduct heat is called thermal conductivity. Like light, heat can be conducted at different rates along different directions in crystals.

Electrical Conductivity - The ability of a material to allow the passage of electrons is called electrical conductivity, which is also directionally dependent except in isometric crystals.

Thermal Expansion - How much the crystal lattice expands as it is heated is referred to as thermal expansion. Some crystals expand more in one direction than in others, thus thermal expansion is a vectorial property.

Compressibility - Compressibility is a measure of how the lattice is reduced as atoms are pushed closer together under pressure. Some directions in crystals may be more compressible than others.

Discontinuous vectorial properties

Discontinuous vectorial properties pertain only to certain directions or planes within a crystal. For these kinds of properties, intermediate directions may have no value of the property. Among the discontinuous vectorial properties are:

Cleavage - Cleavage is defined as a plane within the lattice along which breakage occurs more easily than along other directions. A cleavage direction develops along zones of weakness in the crystal lattice. Cleavage is discontinuous because it only occurs along certain planes.

Growth Rate - Growth rate is defined as the rate at which atoms can be added to the crystal. In some directions fewer atoms must be added to the crystal than in other directions, and thus some directions may allow for faster growth than others.

Solution Rate - Solution rate is the rate at which a solid can be dissolved in a solvent. In this case it depends on how tightly bonded the atoms are in the crystal structure, and this usually depends on direction.

Crystal Habits

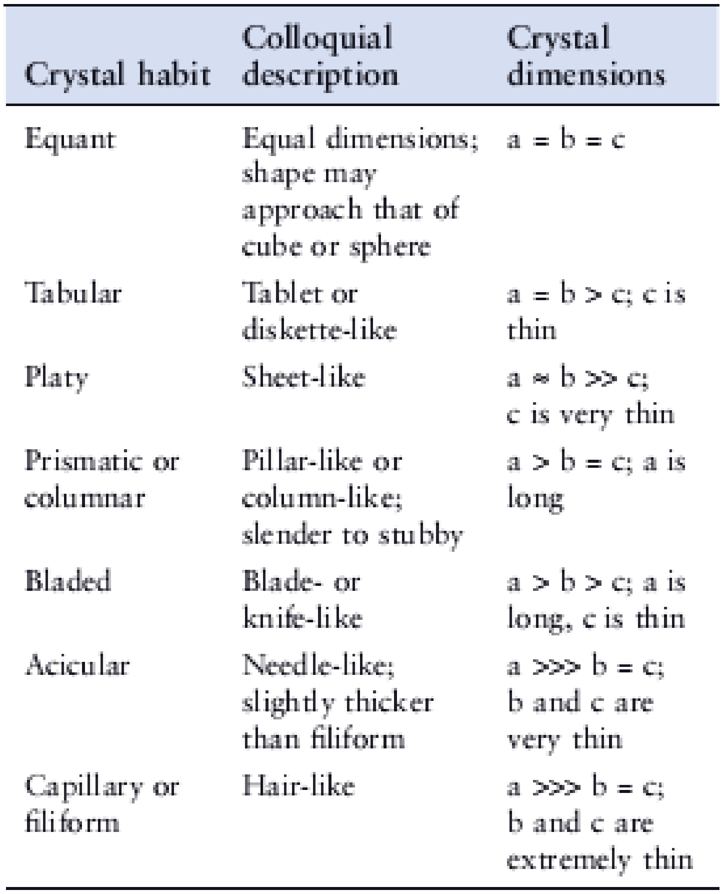
In nature perfect crystals are rare. The faces that develop on a crystal depend on the space available for the crystals to grow. If crystals grow into one another or in a restricted environment, it is possible that no well-formed crystal faces will be developed. However, crystals sometimes develop certain forms more commonly than others, although the symmetry may not be readily apparent from these common forms. The term used to describe general shape of a crystal is habit.

Habits of individual crystals

Minerals start small. Each mineral crystal begins with the bonding of a few atoms into a three-dimensional geometric pattern. Initial growth leads to the formation of small “seed crystals” called nuclei. If the appropriate atoms are available and the environmental conditions are suitable for growth, the nuclei will continue to attract appropriate atoms or ions and grow into larger mineral crystals. When it stops growing, the mineral can be bounded by crystal faces that reflect its internal crystal structure. Since minerals frequently occur as well-formed crystals and since crystal habits reflect the crystal structure of the mineral in question, being able to recognize crystal habit is very useful in mineral identification.

Single crystals can be described using a variety of terminology. The simplest terminology is based on the relative proportions of the crystals in three mutually perpendicular directions (a, b and c) where $a \geq b \geq c$. Table 1 and Figure 6a summarize the terminology used for individual crystal habits and illustrate examples of each.

Table 1: Crystal habits of individual crystals (after Hefferan and O'Brien, 2010)



Crystal habit	Colloquial description	Crystal dimensions
Equant	Equal dimensions; shape may approach that of cube or sphere	a = b = c
Tabular	Tablet or diskette-like	a = b > c; c is thin
Platy	Sheet-like	a ≈ b >> c; c is very thin
Prismatic or columnar	Pillar-like or column-like; slender to stubby	a > b = c; a is long
Bladed	Blade- or knife-like	a > b > c; a is long, c is thin
Acicular	Needle-like; slightly thicker than filiform	a >>> b = c; b and c are very thin
Capillary or filiform	Hair-like	a >>> b = c; b and c are extremely thin

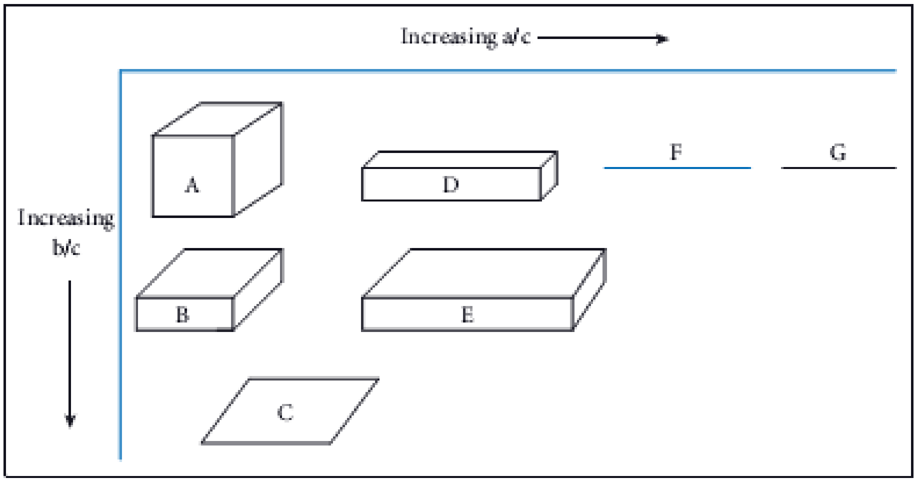


Figure 9a: Individual crystal habits: A, equant; B, tabular; C, platy; D, prismatic or columnar; E, bladed; F, acicular; G, capillary or filiform (after Hefferan and O'Brien, 2010).

Habits of crystal aggregates

When environmental conditions are suitable for the nucleation and growth of a single mineral crystal, they tend to be suitable for the formation of multiple crystals of the same mineral. The production and growth of multiple crystals closely adjacent to one another produces an assemblage of similar crystals called a crystal aggregate. In samples where crystal aggregates occur, at least two sets of crystal habits exist: one set describes the habit of individual crystals (Table 1) and the second set describes the habit of the aggregate. Examples of crystal aggregate habits are illustrated in Figure 6b and summarized in Table 2.

Table 2: Summary of the habits of crystal aggregates (after Hefferan and O'Brien, 2010).

Aggregate habit	Colloquial description
Fibrous	Parallel arrangement of acicular or filiform crystals
Radiating	Acicular–filiform crystals radiating outward from a central point
Cubic	Looks like a cube
Dendritic, arborescent	Tree-like, branching network of crystals
Lamellar/foliated	Sub-parallel layers of minerals
Massive	Aggregate of very small crystals with a fine-grained appearance
Granular	Subequant, macroscopic crystal aggregate with a granular appearance
Banded	Parallel layers of same mineral with different color; as in agate
Concentric	Spherical to sub-spherical layers about a common center
Botryoidal/colloform	Rounded, mound-like aggregates; kidney-like
Pisolitic	Spherical, concentrically layered, gravel-sized aggregates
Amygdaloidal	Spherical to ellipsoidal gas vesicles infilled with secondary minerals

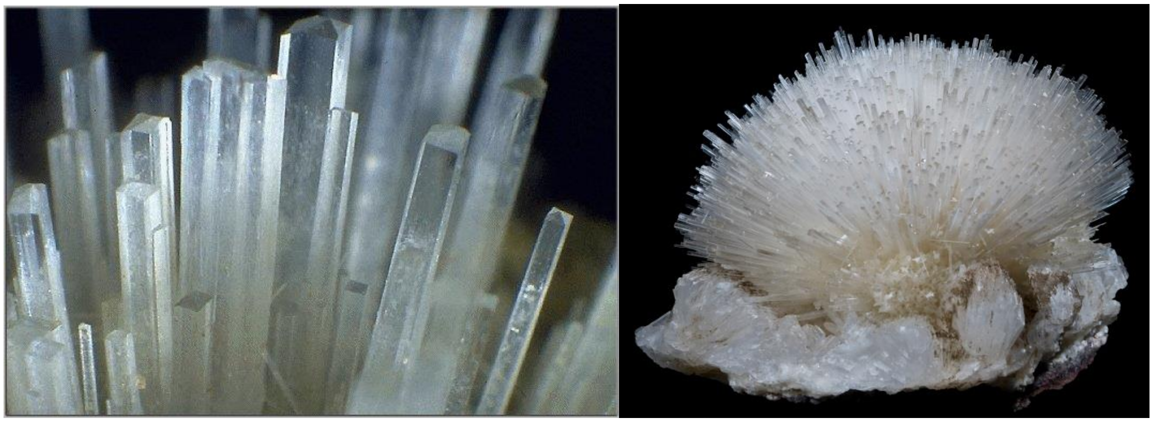


Figure 9b: Crystal habits, fibrous natrolite

Figure 9b: Crystal habits, radiating—natrolite at the left, and pyrophyllie at the right.

Figure 9b: Crystal habits, cubic halite crystal. Halite is made in the cubic crystal system. In this case, its form and its habit are also cubic.

Figure 9b: Crystal habits, dendritic—copper at the left, and gold at the right.

Figure 9b: Crystal habits, lamellar/foliated mica.

Figure 9b: Crystal habits, lamellar/foliated mica.

Figure 6b: Crystal habits, granular.

Figure 9b: Crystal habits, banded (the left most is of rhodochrosite).

Figure 9b: Crystal habits, concentric (the right most is of chrysocolla, also popularly known as torquoise—a famous gemstone).

Figure 9b: Crystal habits, botryoidal (hematite)

Figure 9b: Crystal habits, pisolitic (bauxite)

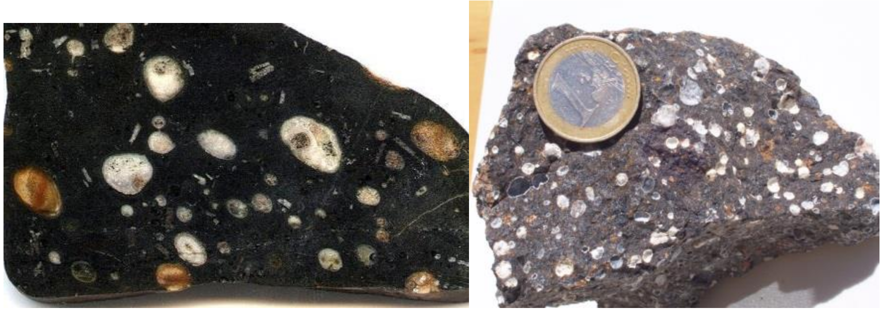


Figure 9b: Crystal habits, amygdaloidal (vesicle fills in basalt)