3te Auflage, 1886. Also founded on Weisbach's work, **Frazer's** Tables for the determination of minerals, 4th ed.. 1897.

*Microscopic Examination of Minerals.**

Cohen, E. Sammlung von Mikrophotographieen zur Veranschaulichung der mikroskopischen Structur von Mineralien und Gesteinen, 1881–82.
Doelter. Die Bestimmung der petrographisch wichtigeren Mineralien durch das Mikroskop, 1876.
Fischer. Kritische mikroskopisch-mineralogische Studien, Freiburg, 1869–1873.
Fouqué-Lévy. Minéralogie micrographique, roches éruptives Françaises, 1879.
Lévy-Lacroix. Les minéraux des roches, 1888.
Rosenbusch. Mikroskopische Physiographie der petrographisch-wichtigen Mineralien, 1873; 3d ed., 1892. Accompanied by Hülfstabellen zur mikroskopischen Mineralbestimmung, 1888. Also English translation and abridgment of the above work by Iddings, 1888. Mikroskopische Physiographie der massigen Gesteine, 1877; 3d ed., 1896.
Thoulet. Contributions à l'étude des propriétés physiques et chimiques des minéraux microscopiques.
Tschermak. Die mikroskopische Beschaffenheit der Meteoriten, 1883.
Zirkel. Die mikroskopische Beschaffenheit der Mineralien und Gesteine, 1873. Also Petrographie, 3 vols., 1893–94.

Artificial Formation of Minerals.

Gurlt. Uebersicht der pyrogeneten künstlichen Mineralien, namentlich der krystallisirten Hüttenerzeugnisse, 1857.
Fuchs. Die künstlich dargestellten Mineralien, 1872.
Daubrée. Études synthetique de Géologie expérimentale, Paris, 1879.
Fouqué and **M. Lévy.** Synthèse des Minéraux et des Roches, 1882.
Bourgeois. Réproduction artificielle des Minéraux, 1884.
Meunier. Les méthodes de synthèse en Minéralogie.

Mineralogical Journals.

The following Journals are largely devoted to original papers on Mineralogy:
Bull. Soc. Min. Bulletin de la Société Française de Minéralogie, vol. **1**, 1878; **20**, 1897.
Jb. Min. Neues Jahrbuch für Mineralogie, Geologie und Palæontologie, etc., from 1833
Min. Mag. The Mineralogical Magazine and Journal of the Mineralogical Society of Gt. Britain, vol. **1**, 1876; **11**, 1896–97.
Min. petr. Mitth. Mineralogi-che und petrographische Mittheilungen, vol. **1**, 1878; **17**, 1897. Earlier, from 1871, Mineralogische Mittheilungen gesammelt von G. Tschermak.
Zs. Kryst. Zeitschrift für Krystallographie und Mineralogie. Edited by P. Groth. vol. **1**, 1877; **28**, 1897.

ABBREVIATIONS.

Ax. pl.	Plane of the optic axes.	**H.**	Hardness.
Bx, **Bx$_a$.**	Acute bisectrix (p. 208).	**Obs.**	Observations on occurrence, etc.
Bx$_o$.	Obtuse bisectrix (p. 208).	**O.F.**	Oxidizing Flame (p. 257).
B.B.	Before the Blowpipe (p. 256).	**Pyr.**	Pyrognostics or blowpipe and allied characters.
Comp.	Composition.	**O. Ratio.**	Oxygen Ratio (p. 249).
Diff.	Differences, or distinctive characters.	**R.F.**	Reducing Flame (p. 257).
G.	Specific Gravity.	**Var.**	Varieties.

The sign $\wedge$ is used to indicate the angle between two faces of a crystal, as *am* $(100 \wedge 110) = 44° 30'$.

* See the bibliography given by Rosenbusch.

PART I. CRYSTALLOGRAPHY.

GENERAL MORPHOLOGICAL RELATIONS OF CRYSTALS.

5. Crystallography.—The subject of Crystallography includes the description of the characters of crystals in general; of the various forms of crystals and their division into groups and systems; of the methods of studying crystals, including the determination of the mathematical relations of their faces, and the measurement of the angles between them; finally, a description of compound or twin crystals, of irregularities in crystals, of crystalline aggregates, and of pseudomorphous crystals.

Allied to Crystallography is the subject of *Crystallogeny*, which describes the methods of making crystals which may be applied in the laboratory, and discusses the theories of their origin in nature. This department is only briefly touched upon in the present work.

6. Definition of a Crystal.—*A crystal** *is the regular polyhedral form, bounded by smooth surfaces, which is assumed by a chemical compound, under the action of its intermolecular forces, when passing, under suitable conditions, from the state of a liquid or gas to that of a solid.*

As expressed in the foregoing definition, a crystal is characterized, first, by its definite internal molecular structure, and, second, by its external form. A crystal is the *normal* form of a mineral species, as of all solid chemical compounds; but the conditions suitable for the formation of a crystal of ideal perfection in symmetry of form and smoothness of surface are never realized. Further, many species usually occur not in distinct crystals, but in massive form, and in some exceptional cases the definite molecular structure is absent.

7. Molecular Structure in General.—By definite molecular structure is meant the special arrangement which the physical units, called *molecules*,† assume under the action of the forces exerted between them during the formation of the solid. Some remarks are given in a later article (p. 18 *et seq.*) in regard to

* In its original signification the term *crystal* was applied only to crystals of quartz, which the ancient philosophers believed to be *water* congealed by intense cold. Hence the term, from κρύσταλλος, *ice*.

† The relation between *atoms*, *chemical molecules*, and *physical molecules* is explained under the chapter on Chemical Mineralogy. The molecules here spoken of are the physical molecules.

the kinds of molecular arrangement theoretically possible, and their relation to the symmetry of the different groups and systems of crystals.

The definite molecular structure is the essential character of a crystal, and the external form is only one of the ways, although the most important, in which this structure is manifested. Thus it is found that all similar directions in a crystal, or a fragment of a crystal, have like physical characters,* as of elasticity, cohesion, action on light, etc. This is clearly shown by the cleavage, or natural tendency to fracture in certain directions, yielding more or less smooth surfaces; as the cubic cleavage of galena, or the rhombohedral cleavage of calcite. It is evident, therefore, that a small crystal differs from a large one only in size, and that a fragment of a crystal is itself essentially a crystal in all its physical relations, though showing no crystalline faces.

Further, the external form without the corresponding molecular structure does not make a solid a crystal. A model of glass or wood, on the one hand, is not a crystal, though having its external form, because there is no relation between form and structure. Also, an octahedron of malachite, having the form of the crystal of cuprite from which it has been derived by chemical alteration, is not a crystal of malachite.

On the other hand, if the natural external faces are wanting, the solid is not called a crystal. A cleavage octahedron of fluorite and a cleavage rhombohedron of calcite are not properly crystals, because the surfaces have been yielded by fracture and not by the natural molecular growth of the crystal.

8. Crystalline and Amorphous.—When a mineral shows no external crystalline form, it is said to be *massive*. It may, however, have a definite molecular structure, and then it is said to be *crystalline*. If this structure, as shown by the cleavage, or by optical means, is the same in all parallel directions through the mass, it is described as a single individual. If it varies from grain to grain, or fiber to fiber, it is said to be a *crystalline aggregate*,† since it is in fact made up of a multitude of individuals.

Thus in a granular mass of galena or calcite, it may be possible to separate the fragments from one another, each with its characteristic cubic, or rhombohedral, cleavage. Even if the individuals are so small that they cannot be separated, yet the cleavage, and hence the crystalline structure, may be evident from the spangling of a freshly broken surface, as with fine-grained statuary marble. Or, again, this aggregate structure may be so fine that the crystalline structure can only be resolved by optical methods with the aid of the microscope. In all these cases, the structure is said to be *crystalline*.

If optical means show a more or less distinct crystalline structure, which, however, cannot be resolved into individuals, the mass is said to be *cryptocrystalline;* this is true of some massive varieties of quartz.

If the definite molecular structure is entirely wanting, and all directions in the mass are sensibly the same, the substance is said to be *amorphous*. This is true of a piece of glass, and nearly so of opal. The amorphous state is rare among minerals.

A piece of feldspar which has been fused and cooled suddenly may be in the glass-like amorphous condition as regards absence of definite molecular structure. But even in such cases there is a tendency to go over into the crystalline condition by molecular rearrangement. A transparent amorphous mass of arsenic trioxide (As_2O_3), formed by fusion, becomes opaque and crystalline after a time. Similarly the steel beams of a railroad bridge may gradually become crystalline and thus lose some of their original strength because of the molecular rearrangement made possible by the vibrations caused by the frequent jar of passing trains. The microscopic study of rocks reveals many cases in which an analogous change in molecular structure has taken place in a solid mass, as caused, for example, by great pressure.

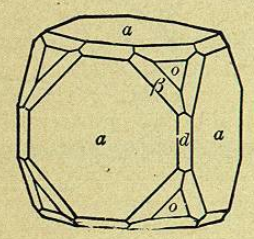
* This subject is further elucidated in the chapter devoted to Physical Mineralogy, where it is also shown that, with respect to many, but not all, of the physical characters, the converse of this proposition is true, viz., that unlike directions in a crystal have in general unlike properties.

† The consideration of the various forms of crystalline aggregates is postponed to the end of the present chapter.

9. External Form.—A crystal is bounded by smooth plane surfaces, called faces or planes,* showing in their arrangement a certain characteristic symmetry, and related to each other by definite mathematical laws.

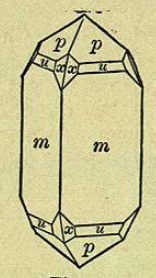
Thus, without inquiring, at the moment, into the exact meaning of the term symmetry as applied to crystals, and the kinds of symmetry possible, which will be explained in detail later, it is apparent that the accompanying figures, 1–3, show the external form spoken of. They represent, therefore, certain definite types.

1.



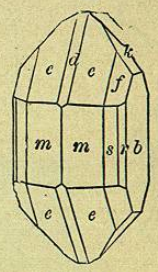
Galena.

2.



Zircon.

3.

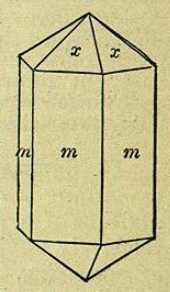


Chrysolite.

10. Variation of Form and Surface.—Actual crystals deviate, within certain limits, from the ideal forms.

First, there may be variation in the size of like faces, thus producing what are defined later as *distorted forms*. In the second place, the faces are rarely absolutely smooth and brilliant; commonly they lack perfect polish, and they may even be rough or more or less covered with fine parallel lines (called striations), or show minute elevations, depressions or other peculiarities. Both the above subjects are discussed in detail in another place.

4.



Apatite.

It may be noted in passing that the characters of natural faces, just alluded to, in general make it easy to distinguish between them and a face artificially ground, on the one hand, like the facet of a cut gem; or, on the other hand, the splintery uneven surface yielded by cleavage.

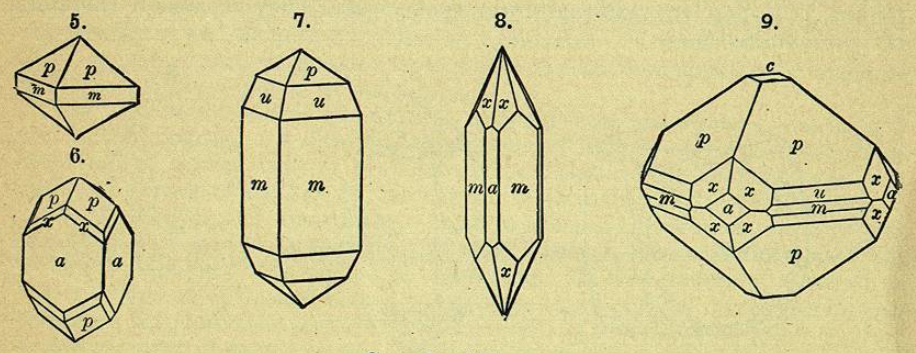
11. Constancy of Angle in the Same Species.—The crystals of any species are essentially constant in the angle of inclination between like faces, wherever they are found, and whether products of nature or of the laboratory. These angles, therefore, form one of the distinguishing characters of a species.

Thus, in Fig. 4, of apatite, the angle between the adjacent faces x and

* This latter word is usually limited to cases where the direction, rather than the definite surface itself, is designated.

m (130° 18′) is the same for any two like faces, similarly situated with reference to each other. Further, this angle is constant for the species, differing but little on crystals from different localities. Moreover, the angles between all the faces on crystals of the same species (cf. Figs. 5–9 of zircon below) are more or less closely connected together by certain definite mathematical laws.

12. Diversity of Form, or Habit.—While in the crystals of a given species there is constancy of angle between like faces, the forms of the crystals may be exceedingly diverse. The accompanying figures (5–9) are examples of a few of the forms of the species zircon. There is hardly any limit to the number of faces which may occur, and as their relative size changes, the *habit*, as it is called, may vary indefinitely. Yet for the crystals of each species, the angles between like faces are essentially constant.



Crystals of Zircon.

13. Diversity of Size.—Crystals occur of all sizes, from the merest microscopic point to a yard or more in diameter. It is important to understand, however, that in a minute crystal the development is as complete as with a large one. Indeed the highest perfection of form and transparency is found only in crystals of small size.

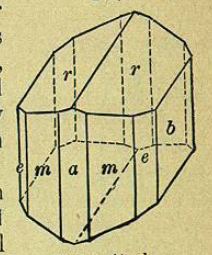
A single crystal of quartz, now at Milan, is three and a quarter feet long and five and a half in circumference, and its weight is estimated at eight hundred and seventy pounds. A single cavity in a vein of quartz near the Tiefen Glacier, in Switzerland, discovered in 1867, afforded smoky quartz crystals weighing in the aggregate about 20,000 pounds; a considerable number of the single crystals having a weight of 200 to 250 pounds, or even more. A gigantic beryl from Acworth, New Hampshire, measured four feet in length and two and a half in circumference; another, from Grafton, was over four feet long, and thirty-two inches in one of its diameters, and weighed about two and a half tons.

14. Symmetry in General.—The faces of a crystal are arranged according to certain laws of symmetry, and this symmetry is the natural basis of the division of crystals into groups and systems. The symmetry may be defined relatively to (1) *a plane of symmetry*, (2) *an axis of symmetry*, and (3) *a center of symmetry*.

These different kinds of symmetry may, or may not, be combined in the same crystal. It will be shown later that there is one group the crystals of which have neither center, axis, nor plane of symmetry; another where there is only a center of symmetry. On the other hand, some groups have all these elements of symmetry represented.

15. Planes of Symmetry.—A solid is said to be geometrically * symmetrical with reference to a plane of symmetry when for each face, edge, or solid angle there is another similar face, edge, or angle which has a like position with reference to this plane. Thus it is obvious that the crystal of amphibole, shown in Fig. 10, is symmetrical with reference to a central plane of symmetry, parallel to the face *b*, passing vertically through the edge formed by the faces *r*, *r* and through the middle of the face *a*.

10.

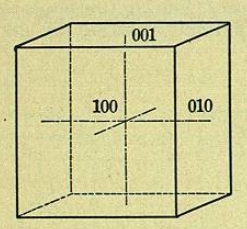


Amphibole.

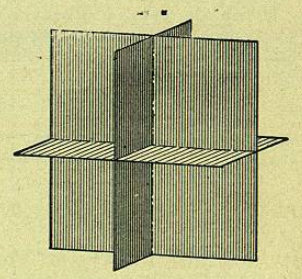
In the ideal crystal this symmetry is *right symmetry* in the geometrical sense, where every point on the one side of the plane of symmetry has a corresponding point at equal distances on the other side, measured on a line normal to it. In other words, in the ideal geometrical symmetry, one half of the crystal is the exact *mirror-image* of the other half.

A crystal may have as many as nine planes of symmetry, three of one set and six of another, as is illustrated by the cube † (Fig. 11). Here the planes of the first set pass through the crystal parallel to the cubic faces; they are shown in Fig. 12. The planes of the second set join the opposite cubic edges. On the other hand, some crystals have no plane of symmetry.

11.



12.



16. Axes of Symmetry.—If a solid can be revolved through a certain number of degrees about some line as an axis, with the result that it again occupies precisely the same position in space as at first, it is said to have an axis of symmetry. There are four different kinds of axes of symmetry among crystals; they are defined according to the angular revolution needed in each case, that is, by the number of times which the crystal repeats itself in a complete revolution of 360°.

(*a*) A crystal is said to have an axis of *binary*, or twofold, symmetry when a revolution of 180° produces the result named above; in other words, when it repeats itself twice in a complete revolution. This is true of the crystal shown in Fig. 13 with respect to the vertical axis (and indeed each of the horizontal axes also).

(*b*) A crystal has an axis of *trigonal*, or threefold, symmetry when a revolution of 120° is needed; that is, when it repeats itself three times in a complete revolution. The vertical axis of the crystal shown in Fig. 14 is an axis of trigonal symmetry.

* The relation between the ideal geometrical symmetry and the actual crystallographic symmetry is discussed in Art. **18**.

† This is the cube of the normal group of the isometric system.