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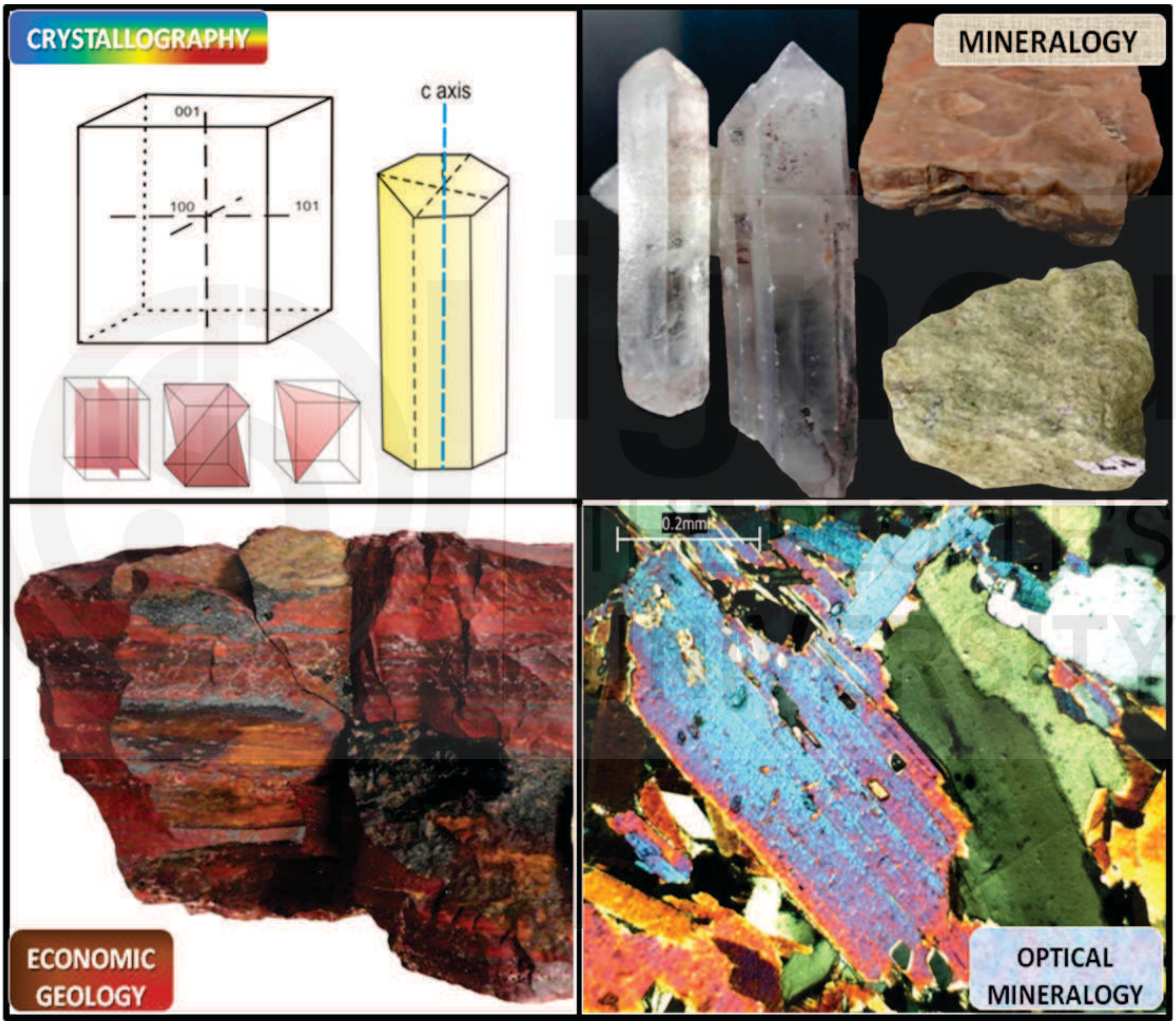
School of Sciences

BGYCT – 133
CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY



Crystallography and Mineralogy

Vol. 1

Indira Gandhi National Open University
School of Sciences

BGYCT – 133
CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY

Volume

1

CRYSTALLOGRAPHY AND MINERALOGY

Course Design Committee

Volume Preparation Team

Course Contributors

Dr. S.D. Shukla (Retd.) (Units 1 & 2)
Department of Geology
SGRR (PG) College, Dehradun

Prof. Meenal Mishra (Units 3, 6 & 7)
School of Sciences
IGNOU, New Delhi

Prof. Benidhar Deshmukh (Units 4 & 5)
School of Sciences
IGNOU, New Delhi

Content and Language Editors

Prof. Pankaj Srivastava (Units 1 to 3)
Department of Geology
Jammu University, Jammu

Prof. J. P. Shrivastava (Units 4 to 7)
Centre of Advanced Study in Geology
University of Delhi, Delhi

Transformation: Prof. Benidhar Deshmukh

Course Coordinators: Prof. Meenal Mishra and Prof. Benidhar Deshmukh

Audio Visual Materials

Dr. Amitosh Dubey
Producer, EMPC, IGNOU

Prof. Meenal Mishra and Prof. Benidhar Deshmukh
Content Coordinators

Production

Mr. Rajiv Girdhar
A.R. (P), MPDD, IGNOU

Mr. Sunil Kumar
A.R. (P), SOS, IGNOU

Mr. Hemant Kumar
S.O. (P), MPDD, IGNOU

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BGYCT-133: CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY

List of audio / video materials related to this course

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   Link: http://egyankosh.ac.in//handle/123456789/63948

3. **Minerals and Their Uses**

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4. **Microscopic Study of Basaltic Rocks**

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    Link: https://www.youtube.com/watch?v=Wrbw0MQzSQU

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BGYCT-133: CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY

Man has always been fascinated by the beauty and forms of colourful minerals. Archaeological finds of unusual shaped rocks and minerals suggest that minerals have been an important part of our society since prehistoric times. Man has been using minerals for carving out tools and making pots/utensils, ornaments, for medicinal purposes, and also as paints and pigments making use of their characteristics such as hardness, colour, luster, chemistry, etc. We are all familiar with the importance of the mineral halite (i.e. sodium chloride, commonly known as table salt) for its taste and utility in food preservation. However, not all of us are familiar that almost all the objects we see all around us and use at home or outside are derived from minerals. Right from metals, jewellery, building and road construction materials, cosmetics, fuel, components in electic and electronic items, automobiles, etc. are all derived from one or other minerals. Man has learnt early that minerals are formed in nature by some natural processes and has been interested to know the processes and locations of potential mineral deposits from where these minerals could be extracted.

This course introduces you to three core branches of geology, viz. crystallography, mineralogy, and economic geology. The course consists of four blocks. First block i.e. **Block 1: Basic Concepts of Crystallography** would introduce you to the crystallography, a branch of dealing with geometry of crystals, their properties and crystal systems. Second and third blocks are devoted to the megascopic and microscopic studies of minerals, respectively. In **Block 2: Mineralogy**, you will learn about physical properties of minerals useful in their identification, classification of minerals, and physical properties of common rock-forming minerals. **Block 3: Optical Mineralogy** would introduce you to the polarising microscope used to study optical properties of minerals in their identification. You will also study optical properties of common rock-forming minerals. And, the fourth block deals with minerals of economic significance which are a subject matter of the branch known as economic geology. In the **Block 4: Economic Geology**, you would learn about metallic and non-metallic minerals deposits, processes of their formation, properties and their Indian distribution.

Expected Learning Outcomes

After studying this course, you should be able to:

- define crystal and discuss crystal properties, elements of symmetry and crystal systems;
- list physical properties of minerals and describe mineral classification schemes, and physical properties of common rock-forming minerals;
- elaborate optical properties of common rock-forming minerals, and
- discuss properties of metallic and non-metallic mineral deposits including coal and petroleum, processes of their formation, and their distribution in India.

This course would equip you with the basic understanding of crystallography, mineralogy and economic geology which would help you to learn about rocks that you would study in the next core course, their identification and the process of their formation.

We wish you all success in this endeavour!

VOLUME 1: CRYSTALLOGRAPHY AND MINERALOGY

The course **BGYCT-133 Crystallography, Mineralogy and Economic Geology** consists of four blocks, which have been packaged in two volumes.

The **Volume 1** consists of two blocks namely, crystallography and mineralogy. The first block, **Block 1: Basic Concepts of Crystallography** will introduce you to the crystallography, which deals with crystals, their properties, laws of crystallography, crystal symmetry and crystal systems. Minerals crystallise in regular geometric forms under favourable conditions. Crystals have distinct internal atomic structure and hence their characteristics are important to identify different types of minerals. Crystallography, the branch of mineralogy dealing with the study of crystals, plays an important role nearly in all branches of science and technology.

After studying about crystals, their symmetry and crystal systems in Block-1, you shall learn about minerals in the next block. Minerals are the building blocks of rocks, which are studied to unravel Earth's geological history. Also, study of minerals occurring in a particular geological environment is of significance as it helps geologists to locate potential mineral deposits. **Block 2: Mineralogy** introduces you to the mineralogy, the science of minerals. In this block, you will learn about minerals, physical properties useful in their identification, their chemical and structural classification schemes, major rock-forming mineral groups, and physical properties of common rock-forming mineral groups.

Expected Learning Outcomes

After studying this volume, you should be able to:

- define crystal and discuss crystal properties,;
- discuss elements of symmetry and crystal systems;
- describe mineral classification schemes;
- list and elaborate on the physical properties of minerals used in their identification, and physical properties of common rock-forming minerals.

After studying this volume, you will be equipped with the basic knowledge of crystallography, mineralogy and megascopic study of common rock-forming minerals. In the next volume, you would learn about the microscopic properties of common rock-forming minerals and also about the basics of economic mineralogy, process of formation of ore deposits, minerals of economic significance, and their distribution in India.

We wish you success in this endeavour!

Indira Gandhi National Open University
School of Sciences

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CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY

Block

1

BASIC CONCEPTS OF CRYSTALLOGRAPHY

Block Preparation Team

Course Contributors

Dr. S. D. Shukla (Retd.) (Units 1 & 2)
Department of Geology
SGRR (PG) College, Dehradun

Prof. Meenal Mishra (Unit 3)
School of Sciences
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Prof. Pankaj Srivastava
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BGYCT-133: CRYSTALLOGRAPHY, MINERALOGY AND ECONOMIC GEOLOGY

BLOCK 1: BASIC CONCEPTS OF CRYSTALLOGRAPHY

Crystallography plays an important role nearly in all branches of science and technology. Man has been inquisitive to explore the beautiful morphological features of natural crystals which has helped in understanding the internal symmetry of crystals. Under favourable conditions, minerals crystallise in regular geometric forms assuming well defined plane surfaces that are known as **crystals**. The branch of mineralogy dealing with the study of crystals is called **crystallography**. The crystals have distinct internal atomic structure and hence their characteristics are important to identify different types of minerals.

This block consists of three units that will introduce you to the crystallography, as a branch of mineralogy dealing with crystals, their properties, laws of crystallography, crystal symmetry and crystal systems.

Unit 1 Crystal Properties introduces you to crystals and the crystallography. It largely focuses on the basic concepts pertaining to crystals. It discusses the definition of a crystal, its parts, characteristics and forms, crystallographic axes, parameters and crystallographic notation.

Crystals exhibit observable regularity in their faces, edges and solid angles, which is referred to as crystal symmetry. In **Unit 2 Crystal Symmetry**, you would get introduced to the basics related to crystallographic laws and the elements of crystal symmetry.

As its title suggests, **Unit 3 Crystal Systems** deals with different crystal systems. It begins with the basic concepts of crystal systems, their nomenclature and classification of crystals into seven crystal systems. It also familiarises you with seven crystal systems namely, cubic, tetragonal, hexagonal, trigonal, orthorhombic, monoclinic and triclinic systems, and their characteristics.

Expected Learning Outcomes

After studying this block, you should be able to:

- get acquainted with crystals, its parts, forms and representation of crystal face;
- describe laws of crystallography and elements of symmetry, and
- discuss nomenclature of seven crystal systems and their characteristics.

The knowledge of the basic concepts of crystallography you would attain through this block would help you to identify crystals, their properties, symmetry elements and crystal systems. In the next block, you would be introduced to the branch of geology called mineralogy in which you would learn about physical properties of the minerals.

We wish you all success!

UNIT 1

CRYSTAL PROPERTIES

Structure

1.1 INTRODUCTION

The delicately faceted surfaces of crystals that occur in nature have always been a source of fascination and delight to human beings. The ancient Greeks in about 400 B.C. observed that in the Alps Mountain, quartz (rock crystal) occurred in a characteristic shape bounded by flat surfaces. They mistook that quartz had resulted from freezing of water under intense cold and named it as *krustallos* meaning ‘clear ice’. Gradually, other minerals which showed flat surfaces (faces), including those with metallic luster were also designated as crystals. As the studies advanced, scientists started accepting that crystals consisted of set arrangement of atoms and the internal structure.

Therefore, their characteristics are important criteria for the identification of thousands of minerals present on the Earth. **Crystallography** is the branch of Mineralogy that involves the study of crystals. The term crystallography is derived from Greek words *crystallon* meaning 'frozen drop' and *graphein* means 'to write'.

In this unit, we will study about the basic concepts pertaining to crystals.

Expected Learning Outcomes

After reading this unit, you should be able to:

- ❖ define crystal;
- ❖ identify parts of a crystal;
- ❖ list the forms present in the crystal;
- ❖ differentiate between crystallographic axes and axial ratio; and
- ❖ discuss the crystal parameters and crystallographic notation.

1.2 ELEMENTARY IDEA OF CRYSTAL

Let us understand the terms 'crystal', 'habit' and 'form' before reading about the crystal. These terms are used to describe the occurrence of crystals.

Crystal habit can be defined as the general aspect or shape that a crystal possesses which is produced by relative development of different forms. Habit is used to denote the general shapes of crystal such as cubic, octahedral or prismatic. These shapes are controlled by the environment of crystallisation, which may vary. At one place habit may be equant and at other it may be tabular or fibrous. Therefore, it is possible that a mineral may occur in more than one habit.

Crystal form is the assemblage of crystal faces related to each other by the symmetry that the crystal possesses. We use Miller Index or Miller-Bravais Index to denote crystal form. In this unit we will use Miller Index.

Crystals may be formed either by solidification from gaseous or liquid state or by precipitation from solutions by the process of crystallisation. Crystals are solid geometric figures bounded by well developed more or less plane surfaces called 'faces' (Fig. 1.1).

Fig. 1.1: Crystallised quartz crystal with well developed faces.

Let us now learn the definition of crystal.

1.2.1 Definition

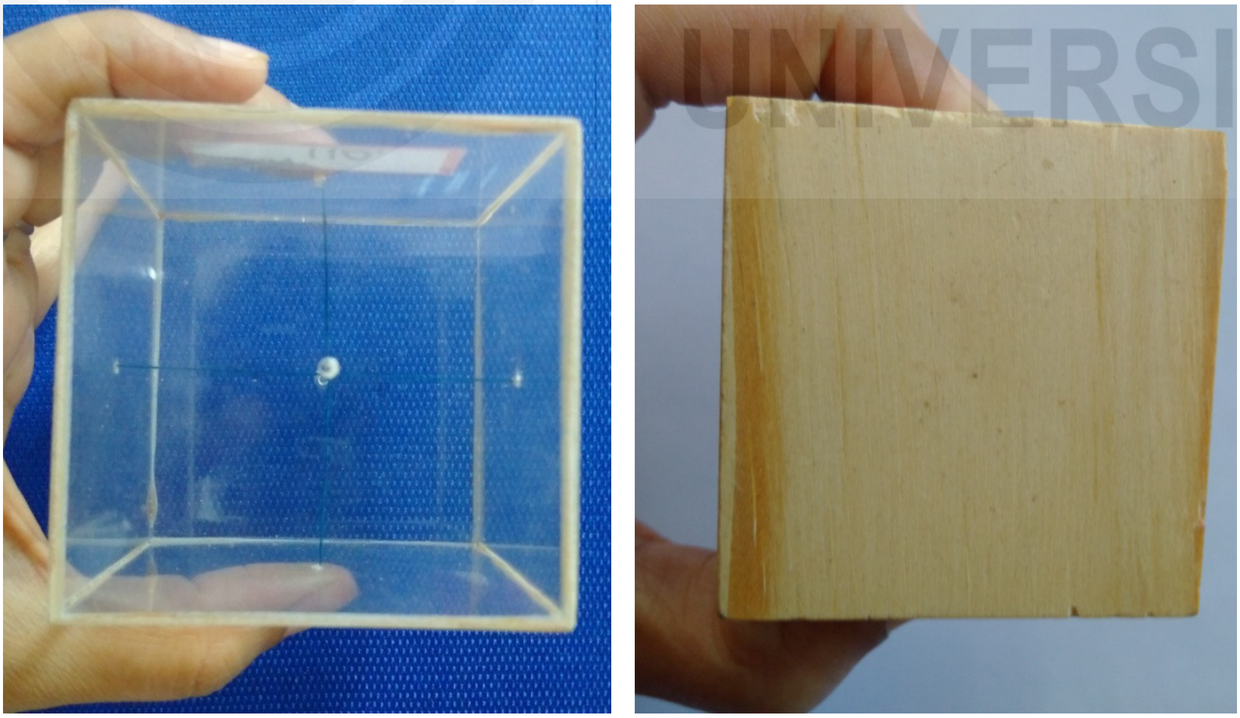
We have learnt that regular internal arrangement of atoms defines whether or not a substance is crystalline. When conditions are favorable these solid bodies become bounded by smooth surfaces. In this way, they assume regular geometric forms known as **crystals.**

"Crystals can be defined as a homogenous solid bounded by naturally formed plane surfaces termed faces which can be related to a regular arrangement of atoms" (Gribble, 1991).

Crystals exhibit following characteristics:

- Crystal is regular polyhedral form characterised by flat surfaces known as **faces.**
- They possess a typical internal atomic structure.
- Their regular geometry is developed only under suitable physicochemical conditions. Well developed crystals result due to slow cooling.
- A crystal which possesses both external form as well as internal atomic structure is said to be **perfect crystal**. But if only the internal atomic structure is present without development of corresponding external form, it is said to be **crystalline**. If neither internal atomic structure nor external form is present it is referred as an **amorphous substance**.

Thus, a naturally occurring crystal must include a regular geometric form and a characteristic internal atomic structure. If a model of a crystal is constructed out of glass, plastic or wood (Fig. 1.2), it cannot be considered as a crystal as the required atomic structure will not be present there. It is only a crystal model displaying outer faces.



(a) **(b)**

Fig. 1.2: a) Plastic; and b) wooden models of galena crystal.

Let us take example of a diamond.

You might have seen imitations of diamond, which despite their complete resemblance to the original, lack optical and physical properties, and internal atomic structure unique to diamonds. Therefore, imitation diamonds cannot be considered as naturally occurring crystals.

1.2.2 How Do We Study Crystallography?

The external shape, internal structure and the laws which govern crystal growth form the subject matter of **Crystallography**. It includes the description of crystals, their classification into different systems and classes. In addition, the mathematical relationships that exist between different faces of a crystal are also studied. The domain of crystallography also includes the imperfections of crystal growth and crystalline aggregates. Crystallography helps in qualitative and quantitative identification of minerals. Crystallography is the study of crystals and the person studying crystallography is known as **Crystallographer**.

As you know that rocks (i.e. the aggregates of minerals) represent the basic unit of the Earth's crust. The minerals whether amorphous or crystalline are natural compounds of elements. Diffraction of X-rays by crystals helps in studying their internal characteristics. In 1913 the first structural analysis of crystals of sodium chloride was done by Sir W.H. Bragg and Sir W.L. Bragg, two English physicists. The Braggs were awarded the Nobel Prize in Physics in 1915 for their work in determining crystal structures of NaCl, ZnS and diamond. X-rays have very short wavelengths, which are comparable with the actual distance between atoms in the crystal lattice. A lattice in crystallography is an abstract representation of a crystal structure. In other words, this is an imaginary three-dimensional framework that can be referenced to a network of regularly spaced points, each of which represents the position of a motif. When a beam of X-ray falls on the crystal, it 'scatters' by the phenomenon of diffraction in certain directions. The individual scattered wavelets may recombine in phase to produce a diffracted beam. They indicate the crystals appear to reflect X-ray beams at certain angles of incidence (theta, θ).

This phenomenon may be expressed as:

$$\mathbf{n\,\lambda = 2d\sin\theta} \qquad (1)$$

where,

n is an integer

λ (lambda) wavelength of the incident X-ray beam

d is the distance between atomic layers in a crystal

This is known as **Bragg's Law.**

Now portable X- ray diffractometers along with user friendly software for mineral identification are available. This helps in easy and accurate identification of the peaks shown by different minerals (Fig. 1.3).

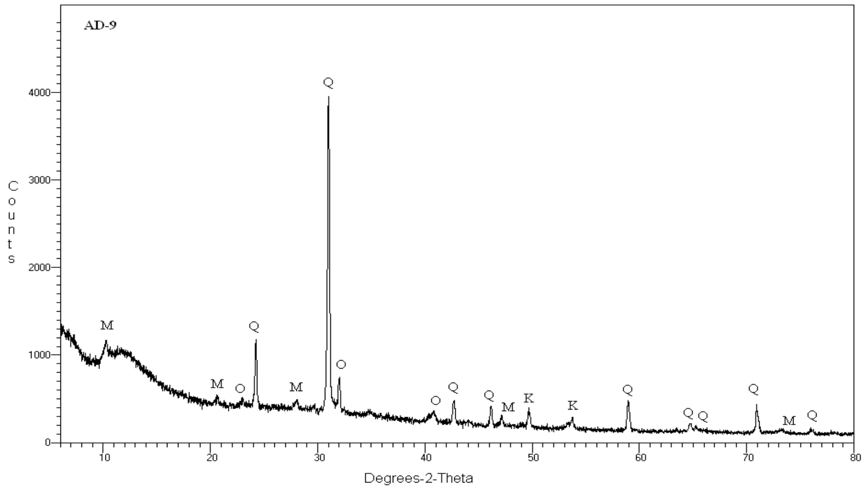


Fig. 1.3: Diffractogram showing peaks of different minerals. For example in a sandstone Q-denotes peak for quartz, M-is the peak for muscovite and K-represents peak of K-feldspar.

You have read about the definition of crystal and why and how do we study crystals. Now let us discuss about the parts of a crystal.

1.3 PARTS OF A CRYSTAL

Now let us recapitulate some terms, we referred above and learn some additional terminology to appreciate parts of a crystal.

1.3.1 Faces

The flat surfaces by which the crystals are bounded are called **faces**. The faces are parallel to the net planes in the crystal structure. In most of the cases, the faces are flat but sometimes they are curved, e.g. siderite, dolomite, diamond, etc. If all the faces of a crystal are similar, the crystal is said to have '**like faces**,' e.g. galena. On the other hand, if the crystal has faces of different types, then it is said to have '**unlike faces**,' e.g. zircon (Fig. 1.4). This difference is merely a difference of their physical properties. You should remember that variation in the size of like faces-commonly seen in natural crystals does not mean that the crystal faces are unlike. All the six faces of a cube for example galena are like faces and all the faces possess similar properties. If only like faces are present in the crystal it is known as **single form.** When both like and unlike faces are present it is called **combination form** (Fig. 1.4).

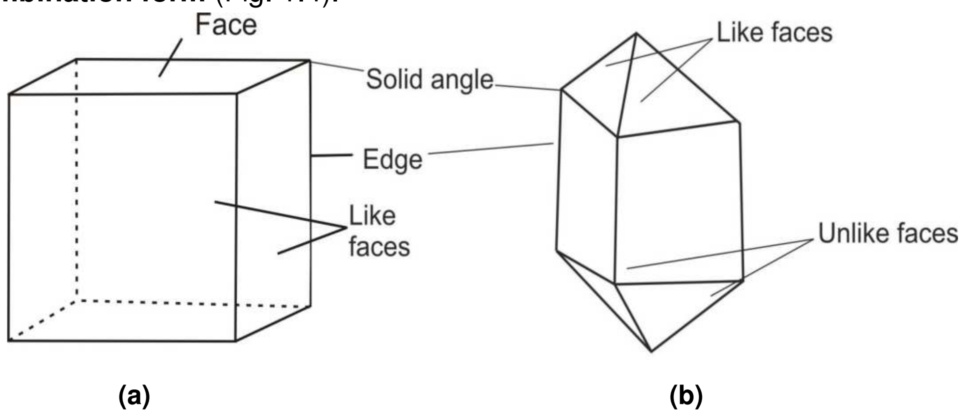


Fig. 1.4: Faces, Forms, Edges and Solid angles in: a) Cube showing single form; and b) Zircon showing combination form.

1.3.2 Edges

The edges are formed by intersection of two adjacent faces. The edge is naturally straight and its position on a crystal is exclusively a matter of the position of the adjacent faces (Fig. 1.4).

1.3.3 Solid Angle

Solid angles are formed at the intersection of three or more than three faces as shown in Fig. 1.4. Solid angle is also known as vertex. The relationship between these elements in a crystal can be expressed by the formula,

$$\mathbf{f + c = e + 2} \qquad (2)$$

where,

f number of faces
c number of solid angles
e number of edges

Let us apply this formula on a cube (Fig. 1.4a) to appreciate how these crystal characteristics are mutually related.
Number of faces in cube = 6
Number of solid angles in cube = 8
Number of edges in cube = 12
Putting these values in the formula (2) we find 6 + 8 = 12 + 2

1.3.4 Zone and Zone Axis

The study of crystals shows that in many crystals, faces are arranged in a manner that the edges formed by intersection of such faces are parallel to one another. Each such set of edges belongs to a group of faces. Set of faces whose mutual intersection gives rise to parallel edges defines a **zone**. One imaginary line is chosen within a crystal to which the set of parallel edges of a zone are all parallel. The line or axis to which these edges are parallel is called as '**zone axis**'. In Fig. 1.5 of a quartz crystal shows a set of faces and edges parallel to c-axis. These faces and edges form a zone and they are parallel to c-axis which is the zone axis in the present case. There may be many zones and zone axis in a crystal.

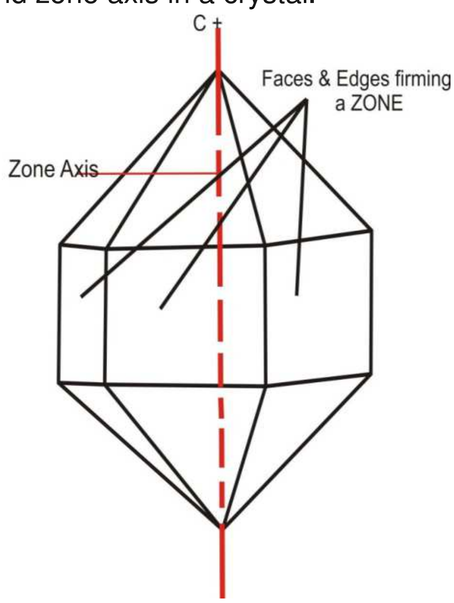


Fig. 1.5: Quartz crystal showing zone and zone axis.

1.4 INTERFACIAL ANGLES AND THEIR MEASUREMENTS

You have read about the parts of crystal in the previous section. Let us now learn about the interfacial angles and their measurements.

It has been observed that two crystals in nature rarely look similar with regard to their size and shape of crystal faces. Nicolas Steno, a Danish scientist gave the first precise observations on a type of crystal in his 1669 book *"De solido intra solidum naturaliter contento"*. The principle in crystallography, known as *Steno's* **law of constant angles,** is also called the **first law of crystallography**. This law states that the angles between the corresponding faces on crystals are same for different crystals of same mineral.

Steno examined the interfacial angles in a variety of quartz crystals from perfect examples to some which were highly distorted. The prismatic crystals of quartz were sliced at right angles to their length. He measured the angles between adjoining faces and their shape was accurately traced on to a sheet of paper. He found that whatever be the shape of the quartz crystal, the angle between adjoining faces was always 120°. A similar results were obtained for other interfacial angles between corresponding faces on quartz crystals with different habits.

Interfacial angle may be defined as the angle between any two adjacent faces of a crystal. In crystallography, the interfacial angle of a crystal is the angle subtended between the normal drawn on the two adjacent faces. As shown in Fig. 1.6, the interfacial angle is the angle between two faces a and b has been denoted by 'A'. It is complimentary to the angle 'B'. The accurate measurement of the interfacial angle is important in crystallographic studies of minerals.

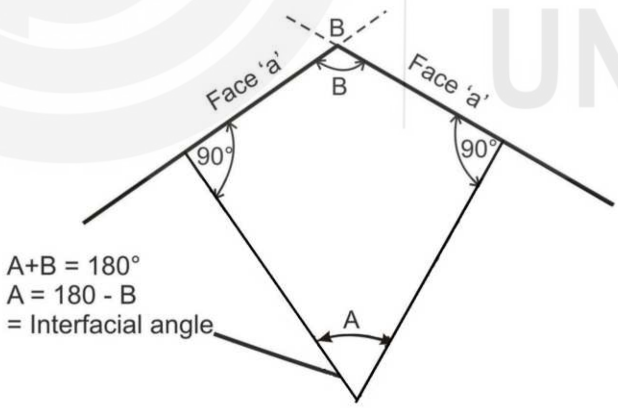


Fig. 1.6: Interfacial angle, i.e. A = 180 – B.

Interfacial angles are measured using goniometer. There are two types of goniometers, you will learn about them in the next subsection.

1.4.1 Contact Goniometer

Contact Goniometer was invented in by Carangeot in 1780. It has a graduated arc like protractor and one movable arm as shown in Fig. 1.7. The arm and base of the arc are kept in close contact of the crystal face and the reading is directly taken. As shown in Fig. 1.7, 'A' is the vertically opposite angle known as interfacial angle. As the interfacial angle is complimentary to the angle ‘B’, it can be directly read on the arc of the goniometer.

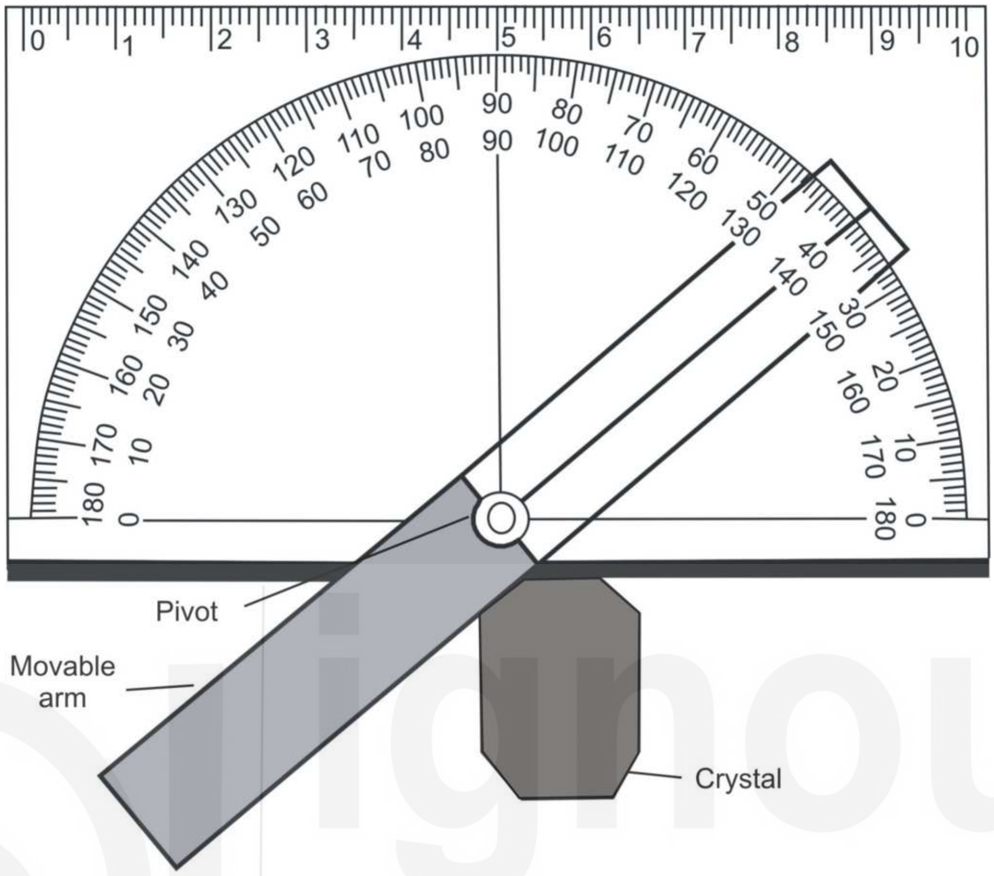


Fig. 1.7: Contact goniometer used for measuring interfacial angle. It can be directly measured as ‘B’ (as in fig. 1.6) which is complimentary to interfacial angle.

1.4.2 Reflecting Goniometer

Reflecting Goniometer is also known as optical goniometer. It is useful for measuring interfacial angles of smaller crystals. This type of instrument was devised by Wollaston in 1809. It has undergone extensive modifications and improvements since that time. Reflecting Goniometer is used for more accurate work. The working principle is shown in Fig. 1.8. A crystal mounted on this instrument can be rotated about a zone axis and will reflect light from its faces into the telescope to the eye. The angle through which a crystal must be turned in order to throw successive beams of light from two adjacent faces into the telescope. This will determine the angle between the faces. It has a rotating disc which is graduated. Source of light is present on one side and telescope on other side. The crystal is kept on the rotating disc and the source of light is present one side and telescope on other side. Signal is sent through light source and the image is seen by the telescope. It is being reflected by the face ‘PQ’. Reading ‘A´’ is taken. Rotation is given and image disappears. When the face ‘PS’ comes in the same plane in which ‘PQ’ was present, the image again appears. Now reading ‘B’ is taken. The actual rotation (B-C) is complimentary to the angle ‘B’. Hence, it is the actual interfacial angle.

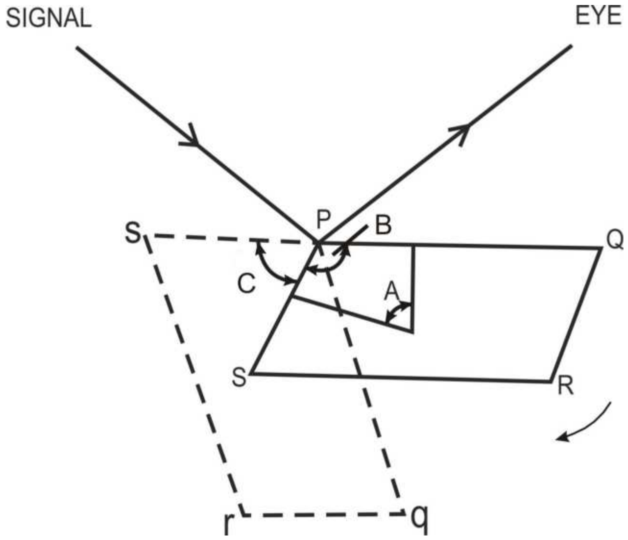


Fig.1.8: a) Reflecting goniometer; and b) Working principle of reflecting goniometer (A + B = 180^0, C + B = 180^0, Hence A = C = rotation given = Interfacial angle).

Let us spend five minutes here to check our progress.

SAQ **1**

a) Define crystal.

b) What is a solid angle?

c) Define interfacial angle. How do we measure the interfacial angle?

d) Differentiate between like face and unlike face.

1.5 REPRESENTATION OF CRYSTAL FACE

We will learn about the crystallographic axes and axial ratio in Unit 2 of this Block. Let us now read about the crystal parameter and indices.

1.5.1 Crystal Parameter

Crystal parameter is the relative distance that a face cuts on the crystallographic axes of that face. In order words, crystal parameters are the ratios of the intercepts, i.e. ratios of the distances on the faces from the centre of the crystal.

Let us try to understand the parameters as shown in Fig. 1.9. Oa, Ob and Oc are the crystallographic axes and O is the origin. The standard face ABC is the crystal face making intercepts OA, OB and OC on the crystallographic axes. The ratio of OA, OB and OC will be the parameters of the face ABC.

If intercepts of face ABC are taken as unit, it is convenient to represent any other face. For example, let us take face DEF, where OD is same as OA meaning (1/1), OE is twice of OB (2/1) and OF is half of OC (1/2). Hence the parameters for face DEF will be 1/1, 2/1, 1/2 with reference to face ABC which has been taken as standard in the present case.

Parameters of the face ABC are: OD/OA, OE/OB and OF/OC on a, b and c axes, respectively.

This is expressed as 1a, 2/1b and 1/2c [since OD=OA, OE=2OB and OF=1/2OC]

This type of representation of parameters is said to be in accordance with parameter system of Weiss, about which we will discuss later.

The symbols 1a, 2b and 1/2c DEF indicate that the face under consideration which intersects the a-axis at unit distance, b-axis at twice of the unit distance and c-axis at half of the unit distance. Gypsum is an example of a face which cuts all three axes and has parameters of 0.374 (a):1 (b): 0.444. The relationship between parameters and indices is simple; the reciprocals of parameters are known as **indices.**

In another example, let us take any face which cuts a-axis at 2 units, b-axis at unit and is parallel to c-axis with reference to unit form. It's Weiss symbol would be: 2a b ∞ c

Unit form is the face whose intercepts on the axes a, b, c determine their assumed unit lengths. The intercepts that any face makes on the crystallographic axes are either infinite or small rational multiples of intercepts made by unit form.

Crystal faces are defined by indicating their intercepts on the crystallographic axes. If we have to describe a face or position of a face in space, it is necessary to determine the relation a given face has with respect to the three crystal axes; whether it is intersecting all the three axes; or parallel to two axes and cuts the third; or parallel to one axis and intersects the other two. We must also determine the relative distance at which the face intersects the different axes. Since a crystal is a three-dimensional polyhedral form its crystal face can be expressed by parameters of Weiss and Miller indices. It is the brief method of expressing the relationship of any crystal face to the crystallographic axes. Now let us learn about the following two methods are commonly used:

- Parameter system of Weiss
- Index system of Miller

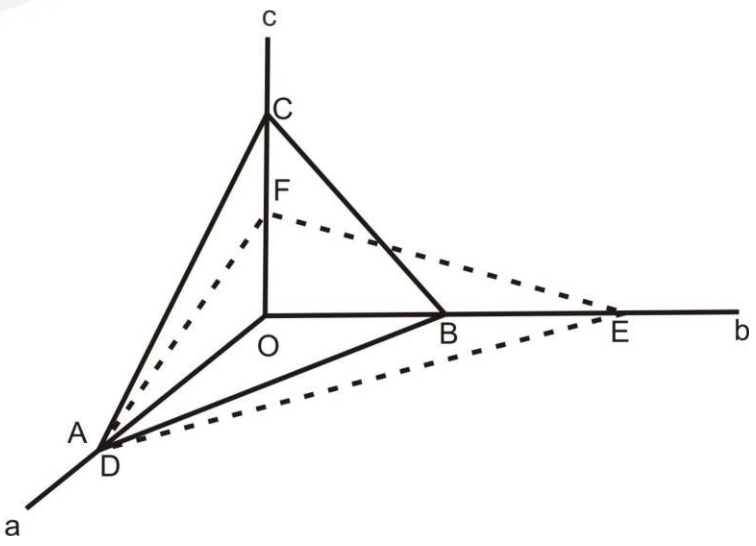


Fig. 1.9: Notice the parameters of the face DEF with reference to standard face ABC are 1/1, 2/1, 1/2. a, b and c are crystallographic axes and O is the origin.

1.5.2 Parameter System of Weiss

Weiss parameter was introduced by Christian Samuel Weiss in 1818. It provides an approximate indication of a face orientation with respect to the crystallographic axes, and was used as a symbol for the face.

We use notation parameters in this method. The axes are written in the order of crystallographic axes. You have learnt in the previous section that parameters are the ratios of the intercepts, i.e. the intercepts of the face in consideration are compared with those of unit form. Intercepts are the distance between the centre of the crystal (point of intersection of crystallographic axes) and the points of intersection of the faces and axes. **Parametral plane** is any plane, which cuts all three crystallographic axes. Parametral plane consists of a series of numbers that express the relative intercepts of that plane upon the crystallographic axes. The length of each axis is defined for a specific mineral by selecting a face on the crystal which cuts all three axes, such face is called as **parametral face**.

These are the ratios of the intercepts (lengths cut off) made by the crystal face on the crystallographic axes (Fig. 1.9). The intercept, which a crystal face makes on a-axis is written before 'a'. The intercept on b-axis is written before 'b' and the intercept on c-axis is written before 'c'. Recall that these intercepts are measured with reference to the intercepts made by the unit form on these axes.

Let us consider three simple faces (Fig. 1.10) separately in relationship to the three axes. In Fig. 1.10a, the face is parallel to a-axis, parallel to b-axis and cutting the c-axis. While in the Fig. 1.10b face is parallel to a-axis and c-axis but cutting the b-axis. While in Fig. 1.10c, face is parallel to b-axis and c-axis but cutting the a-axis. When a face is parallel to a particular axis it can be considered as cutting that axis at infinity (∞). Thus, Weiss symbol for the faces will be ∞∞c, ∞b∞ and a∞∞.

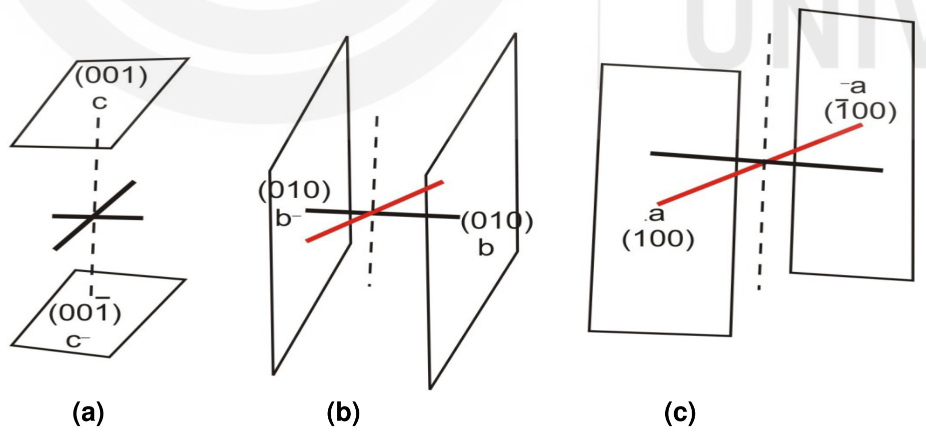


Fig. 1.10: Weiss symbol and Miller symbol (in bracket).

1.5.3 Index System of Miller

The Miller indices were introduced by W. Whewell in 1829 and later developed by W.H. Miller. In this system of notation indices are used. **Indices are the reciprocals of parameters**. The indices are written in their most simple form (integer) in the order 'a', 'b', 'c' after clearing all the fractions. The letters a, b and c are not written.

Again let us take an example of a face represented with respect to Weiss symbol as:

2a b ∞c

The reciprocals of the parameters will be:

1/2 1/1 0

Now if we clear the fraction by multiplying with 2, the Miller symbol will be indicated as follows:

1 2 0

Similarly a face, with Weiss symbol a ∞b ∞c, will have Miller symbol:

1 0 0

With reference to Fig. 1.10a, the symbols of two faces will be as given in (Table 1.1).

Table 1.1: Weiss and Miller symbol.

Face	Weiss Symbol	Reciprocals	Miller Symbol
ABC (Unit)	a b c	1/1 1/1 1/1	1 1 1
DEF	a 2b 1/2 c	1/1 1/2 2/1	2 1 4

The **law of Rational Indices** states that the indices of any crystal face are always rational numbers and are determined by dividing the intercepts of the parametral plane and clearing fractions.

The Miller symbol of notation puts forth a few important considerations:

- The face parallel to any axis is expressed by a zero corresponding to the place of that axis.
- As reciprocals are used in it, the larger the figure in the symbol, the nearer will the face that cut the axis and vice-versa the smaller the figure the farther will the face that cuts the axis. Ultimately, when it is 0 (zero) the face is parallel to that axis and it is presumed to cut the related axis at infinity.

1.5.4 Conventions in Notation

- The symbol is used to denote any crystal face, and it is written without using any bracket, e.g. I00 means the front face of the cube.
- If it is used to denote the form, it is enclosed within the bracket, e.g. (I00) denotes the form ‘cube’.
- In the symbol to represent the negative end of the axis, ‘bar’ (-) is placed over the figure representing that axis, e.g. IŌI.
- To show the general relationship the letters h,k,l are used for three axes and h,i,k,l are used for four axes.

1.5.5 How to Index a Face?

You must be wondering what do symbols like 00I, I0I and III mean? The crystal faces have symbols just as each chemical element has its own symbol. These symbols are called index. You might have read about the names like cube (4 faces), octahedron (8 faces), dodecahedron (2+10 faces), trapezohedron (it refers to the shape trapezium), prism, pyramid and dome. Before knowing about indexing a face let us read about crystallographic axes.

Crystallographic axes are imaginary reference lines and are generally taken parallel to the intersection edges of major crystal faces. The crystal axes originate from the centre of a crystal and emerge both in vertical and horizontal directions. The crystals mostly have three axes namely a, b and c or a_1, a_2 and a_3. We will discuss in detail about the crystallographic axes in Unit 2 Crystal Symmetry. The crystals are oriented by placing the positive (+) end of a-axis at the front and negative (-) end at the back (Fig. 1.11). The positive (+) side of b-axis is to the right and negative (-) to left. The positive (+) side of c axis is at the top and negative (-) at the bottom.

Let us discuss how the symbols of different faces of cube get their names?

The face of the cuboid, which is parallel to a and b but intercepts positive side of c-axis has 00I symbol (Fig. 1.11).

00Ī symbol is given to the exactly opposite face which intercepts negative side of c-axis. The symbols for other four faces are 0Ī0, 0I0, I00 and Ī00. These actually describe the relationship of a particular shape to the three axes. The negative sign (-) is called bar which means that we are talking of the negative ends of the axis. For example symbol 00Ī is known as 'zero zero bar one' which indicates that the face cuts b-axis at negative end but is parallel to a and c-axes.

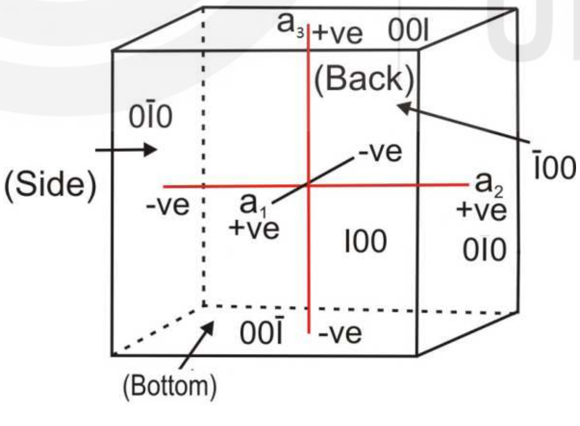


Fig. 1.11: Crystallographic axes of cuboid and their face symbols.

1.6 CRYSTAL FORMS

You have learnt about the parts of a crystal and the measurement of interfacial angles in previous sections. In crystallography, a form is a collection of similar faces which partially or completely constitute of the exterior of crystals. A form is made up of all those faces, which are required by the symmetry elements. Each face of the form has not only the same size and shape but also similar orientation with respect to the crystallographic axes, a, b and c. In a zircon crystal, there are two sets of faces labeled A and B (Fig. 1.12). Each such set is called a form in crystallographic terms. Each of the four faces labeled A are parallel to the c-axis and they are of the same size and shape. The distribution around c-axis of the four faces makes it as a **tetrad symmetry** axis characteristic of tetragonal system. Another form made of four pyramidal faces labelled as 'B' is distributed around the c-axis. All these faces are of the same size and shape and intersect the c-axis at both its positive and negative ends.

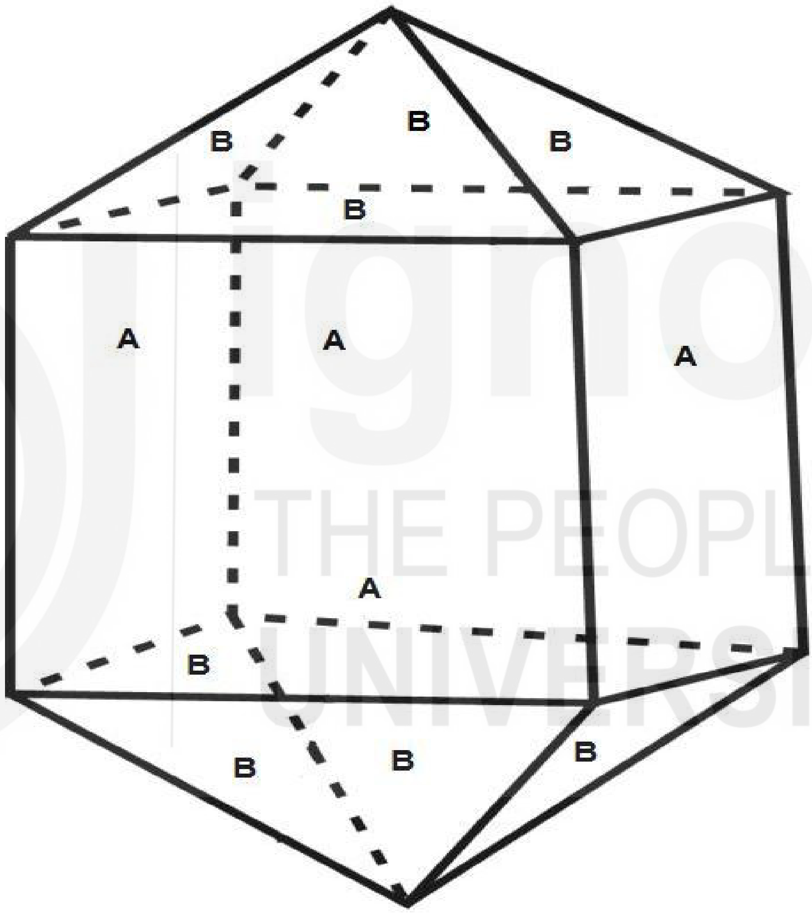


Fig. 1.12: Zircon showing Prism A (100) and Pyramid, B (111) forms.

1.6.1 Closed and Open Forms

- **Closed form:** It is an assemblage of faces, which can enclose a volume of space, e.g. cube (001) has 6 faces or rhombdodecahedron (110) to form a solid.
- **Open form:** A crystal form is called open if its faces are two few to enclose its space completely. In these forms, the faces cannot enclose space all by themselves, as they do not have adequate number of faces to do so and as a result they occur only in combination such as in zircon there are pyramid and prism forms.

In **combination form,** a crystal is made up of two or more simple forms, such as zircon has 8 triangular faces and 4 square faces. The open forms obviously cannot exist by itself on a real crystal, because it does not enclose space.

1.6.2 Naming of Crystal Forms

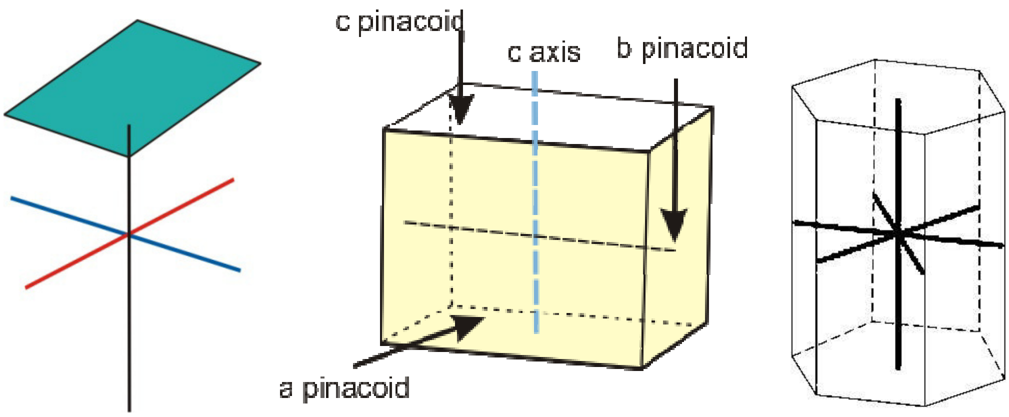
There are 48 different forms found in crystals. Some of these forms are unique to one particular system, while others are found in several systems. We will be discussing some of the crystal forms in Unit 3 Crystal Systems but let us get acquainted with some basic forms. Crystallographic forms are given common names according to the following:

- Number of faces, e.g. tetrahedron (4 faces)
- Shape of faces, e.g. pentagon (geometric form)
- Arrangement of faces, e.g. pyramid
- Specific names indicating systems in which they occur, e.g. ditetragonal prism. This form consists of an eight faced prism in some classes of the tetragonal system.

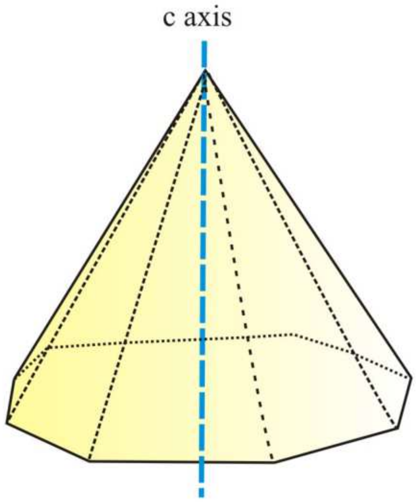
1.6.3 Common Forms

Let us study some common forms present in the crystals.

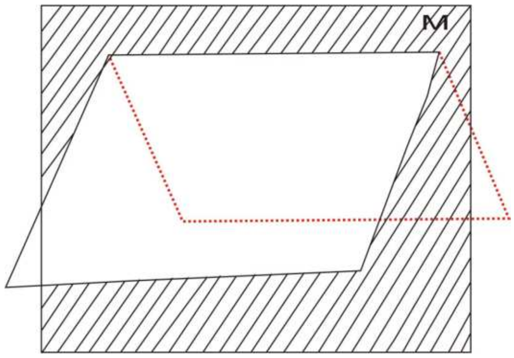
- **Pedion** (Monohedran) consists of single form represented by one face. It is a form situated on a crystal that it is not repeated by any of the elements of symmetry as shown in Fig. 1.13a.
- **Pinacoid** (two parallel faces; *pina* in Greek meaning board face) is a face cutting one crystallographic axis and remaining parallel to the other two axes as shown in Fig. 1.13b. It cuts one of the axes 'a' or 'b' or 'c' and is known as front pinacoid, side pinacoid and basal pinacoid, respectively.
- **Prism** is a face cutting horizontal axes but remaining parallel to the vertical axis (c-axis) as shown in Fig. 1.13c. It is an open form consisting of four faces; each face is parallel to vertical axes and cuts one or more horizontal axes. Prisms may be composed of 3, 4, 6, 8 or 12 faces.
- **Pyramid** is a face cutting all the three crystallographic axes as shown in Fig. 1.13d.



(a) (b) (c)



(d)



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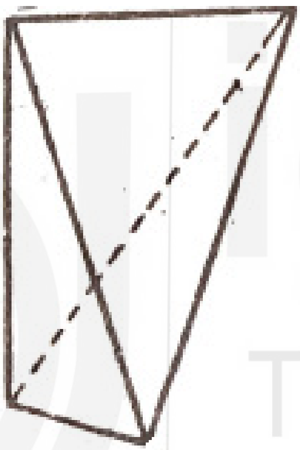

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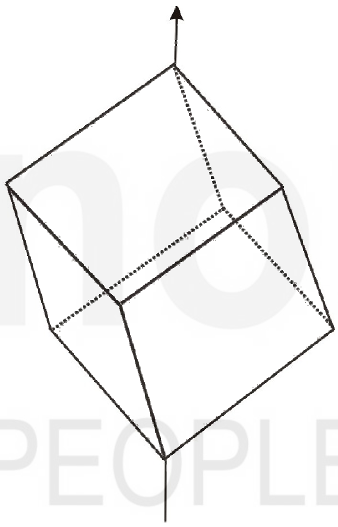

(g)

Fig. 1.13: Common forms in crystals: a) Pedion; b) Pinacoid; c) Hexagonal Prism; d) Hexagonal Pyramid; e) Dome; f) Sphenoid; and g) Rhombohedron.

- **Dome** is a face cutting one of the horizontal axes and the vertical axis and remaining parallel to the other horizontal axis/axes. It is an open form, which is intermediate between the prism and pyramid. The faces are parallel to a- or b- crystallographic axis as shown in Fig. 1.13e. It resembles gabled roof of a house.

- **Sphenoid** is a wedge like form which is obtained by repetition of a face around a **diad axis** as shown in Fig. 1.13f. Diad axis is the axis of two fold (times) symmetry where same face occupies the same position once in every 180° on rotation axes. Thus, in one complete rotation through 360° the same position of the face occurs twice.

- **Rhombohedron** is a closed form of 6 rhomb-shaped faces as shown in fig. 1.13g.

Let us spend five minutes to check your progress.

SAQ 2

a) Define prism.

b) What is crystal parameter?

c) Differentiate between open form and closed form.

d) Define unit form.

1.7 SUMMARY

In this unit, you have learnt about basic concepts of crystallography. Now let us summarise what you have learnt:

- Crystals can be defined as a homogenous solid bounded by naturally formed plane surfaces termed faces which can be related to a regular arrangement of atom.
- Crystallography includes the description of crystals, their external shape, internal structure, classification into different systems, in addition to the laws which govern their growth and the mathematical relationships that exist between different faces.
- The flat surfaces by which the crystals are bounded are called as faces. The edges are formed by intersection of two adjacent faces. Solid Angles are formed at the intersection of three or more than three faces.
- Interfacial angle may be defined as the angle between any two adjacent faces of a crystal. It is measured with the help of goniometer.
- Crystallographic axes are imaginary reference lines and are generally taken parallel to the intersection edges of major crystal faces. Axial angle is the angle between the positive ends of the axes and are conventionally designated by Greek letters α, β, γ. Axial ratio can be defined as the ratio of the length of the crystallographic axes of a crystal which is expressed in terms of one of horizontal axes.
- The crystals are oriented by placing the a-axis (+) to back (-), the b-axis right (+) to left (-) and c-axis up (+) and down (-).
- Crystal parameter is the relative distance that a face cuts on the crystallographic axes. Indices are reciprocals of parameters. They are used in crystallographic notation. Crystal face can be expressed by parameters of Weiss and Miller indices.
- Closed form is assemblage of faces, which can enclose a volume of space, whereas in open forms the faces cannot enclose space all by themselves. Some common forms present in crystals are pedion, pinacoid, prism, pyramid, rhombohedron, sphenoid and dome.

1.8 ACTIVITY

1. Visit a shop in your town. Find out natural 'Rock Salt' and buy some of it. It may be white or pink in colour. Break and observe fresh surface of large crystals. What is the shape of the crystals? Rock salt is mineral

'Halite'. Cube crystals of cubic system are clearly visible. Try to make out faces, edges and solid angles. Sketch, label and write your observations.

1.9 TERMINAL QUESTIONS

1. Mention the characteristics of a crystal.
2. What is crystal parameter and its representative?
3. Explain five common forms present in the crystal. Give neat well labeled diagrams.
4. Discuss the Index system of Miller and Parameter system of Weiss giving examples.

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1.11 FURTHER/ SUGGESTED READINGS

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1.12 ANSWERS

Self Assessment Questions

1 a) Crystals can be defined 'as a homogenous solid bounded by naturally formed plane surfaces termed faces which can be related to a regular arrangement of atom.

b) The intersection of two faces is an edge and the intersection of three or more faces constitutes the solid angle. They depend on internal atomic structure.

c) Interfacial angle may be defined as the angle between any two adjacent faces of a crystal. Interfacial angle of a crystal is the angle subtended between the normal drawn on the two concerned faces. Goniometer are used for measuring interfacial angles.

d) The faces of a crystal are similar, the crystal is said to have 'like faces,' e.g. cube. If the crystal has faces of different types, then it is said to have 'unlike faces,' e.g. zircon.

2 a) Prism is a face cutting horizontal axes but remaining parallel to the vertical axis (c-axis) whereas pyramid is a face cutting all the there crystallographic axes.

b) Crystal parameter is the relative distance that a face cuts on the crystallographic axes of that face. The parameters are the ratios of the intercepts, i.e. ratios of the distances on the faces from the centre of the crystal.

c) Open form means that it cannot form solid on its own. It can occur only in combination. 'Closed form' indicates that complete solid can be formed out of it only, although it can be found in combination.

d) The unit form is the face from whose intercepts on the axes x ,y ,z determine their assumed unit lengths.

Terminal Questions

1. Your response should include following points: (1) regular polyhedral form characterised by flat surfaces known as faces, (2) possess a typical internal atomic structure, (3) Regular geometry is developed only under suitable physicochemical conditions, (4) possess both external form as well as internal atomic structure is said to be perfect crystal.
2. Your response should include definition of crystal parameter as given in subsection 1.5.1, and discuss its representation.
3. You can discuss any 5 common forms present in crystals as mentioned in subsection 1.6.3 such as Pedion as shown in Fig. 1.13a, Pinacoid as shown in Fig. 1.13b, Prism as shown in Fig. 1.13c, Pyramid as shown in Fig. 1.13d and Dome as shown in Fig. 1.13e.
4. Your response should include Index system of Miller and Parameter system of Weiss is given in sections 1.5.3 and 1.5.4. Discuss this giving example of a cube.

UNIT 2

CRYSTAL SYMMETRY

Structure

2.1 INTRODUCTION

We have learnt about crystals and their properties in the previous unit. Let us recall that the crystals are a homogenous solid bounded by naturally formed plane surfaces termed faces which are related to a regular arrangement of atoms. The development of a crystal cannot be haphazard as there appears to be a good degree of regularity in a crystal. This observable regularity in their faces, edges and solid angles is referred as symmetry. Mineralogists have observed from the earlier times that the minerals displayed flat surfaces which at times looked very beautiful and called them as “flowers of the mineral kingdom”.

In this unit, we will learn about the basics pertaining to crystallographic laws, crystallographic axes and angles, elements of symmetry, crystallographic and geometric symmetry.

Expected Learning Outcomes

After reading this unit, you would be able to:

- ❖ differentiate between crystallographic and geometric symmetry;
- ❖ describe the basic laws of crystallography;
- ❖ identify crystallographic axes, axial ratios and axial angles; and
- ❖ discuss the elements of crystal symmetry.

2.2 LAWS OF CRYSTALLOGRAPHY

Crystallographers were initially attracted by the beautiful shapes and sizes of the naturally occurring crystals. Thus, the crystals were investigated mostly from geometrical point of view, i.e. with respect to their shape, size, and regularity of bounding surfaces. These studies gave rise to three basic laws of crystallography which laid the foundation of crystallography. These concepts essentially remained a subject of geometrical crystallography until beginning of 19th century.

Let us get acquainted with the fundamental laws of crystallography in this section.

2.2.1 Law of Constancy of Interfacial Angles

In nature, rarely we find two similar looking crystals with regard to their size and crystal faces. The law of constancy of interfacial angles was enunciated by Nicholas Steno, a Danish physician and natural scientist in 1669. Steno showed that the bounding surfaces of crystals are not by chance; rather the similar faces on different crystals of the same mineral species have constant angles. He discovered by cutting the sections of differently looking quartz crystals and examining them that when measured at the same temperature, the angles between similar crystal faces remain constant, regardless of the size or the shape of the crystal. So whether the crystal grew under ideal conditions or not and if you compare the angles between corresponding faces on various crystals of the same mineral, the angles remain the same. Most often crystals grow more easily in one direction as compared to the other because of supply of solution from one side or space availability and so called distorted or malformed crystals may develop. **Distortion** may be produced because of either more supply of material from one direction or crystallisation under pressure from one direction in limited space. But in all these cases the corresponding interfacial angles will remain the same (Fig. 2.1a and 2.1b). The term **symmetry** refers to the property of being balanced or well-proportioned in common English usage.

Steno's law is called the **Constancy of interfacial angles**. However, he could not put forth any explanation.

The advent of X-rays proved that the atomic structure of any mineral remains within a close set of given geometric relationships. It was observed that the interfacial angles of crystals of a particular mineral always remain constant, since the atomic structure of the crystal of particular mineral is fixed. **Law of constancy of interfacial angle states that measured at same temperature, similar angles on crystals of the particular mineral remain constant, regardless the size and shape of crystals**. The angles between corresponding faces of the crystal are not only constant but also characteristics of the particular mineral. Therefore, the angles between faces may serve for identification of crystals.

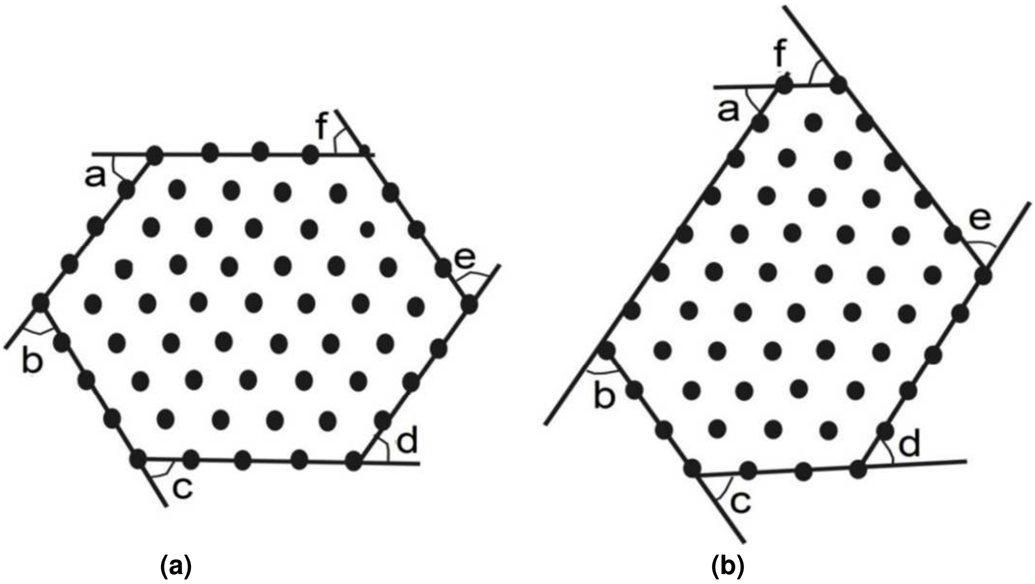


Fig. 2.1: a) Interfacial angles of a regular hexagon. The angles a, b, c, d, e and f are all of 60°; and b) Interfacial angles of a distorted hexagon. Here the angles remain constant and are all of 60°.

2.2.2 Law of Rational Indices

The law of rational indices was proposed by Abbe Rene Just Hüvy. Prior to understanding the law, let us first get acquainted with the terms that would be used. **Intercepts** are the distance between the centre of the crystal (point of intersection of crystallographic axes) and the points of intersection of the faces and axes. **Parametral plane** is any plane, which cuts all three crystallographic axes. **Unit form** is the face from whose intercepts on the axes x, y, z determine their assumed unit lengths. The intercepts that any face makes on the crystallographic axes are either infinite or small rational multiples of intercepts made by unit form. **Lattice** is a regular repeated three-dimensional arrangement of ions, atoms or molecules in a metal or other crystalline solid. Crystals are constituted of three dimensional patterns consisting of atoms or groups of atoms in symmetrical and ordered arrangements which are repeated at regular intervals. Crystal lattice is obtained by replacing each group of atoms by a representative point.

The Hüvy's law of rational indices states that the indices of any crystal face are always rational numbers and are determined by dividing the intercepts of the parametral plane and clearing fractions. The intercept made by every crystal face on the crystallographic axes is either infinite or small rational multiples of the intercepts made by the unit form. This is logical because the position of one face on a crystal can always be referred to that of another face on the same crystal by ratios which may be expressed in small whole numbers. The positions of the points in the lattice determine the position of the crystal faces. The points in a lattice represent an orderly periodic arrangement. Crystal faces correspond to lattice planes, edges correspond to rows of nodes and solid angles to nodes. Only those planes will be manifested outwardly into crystal faces that are thickly covered with nodes. The position of any crystal face in space can be designated by three whole numbers if the directions of three rows are used as reference axes, i.e. OX, OY and OZ (Fig. 2.2).

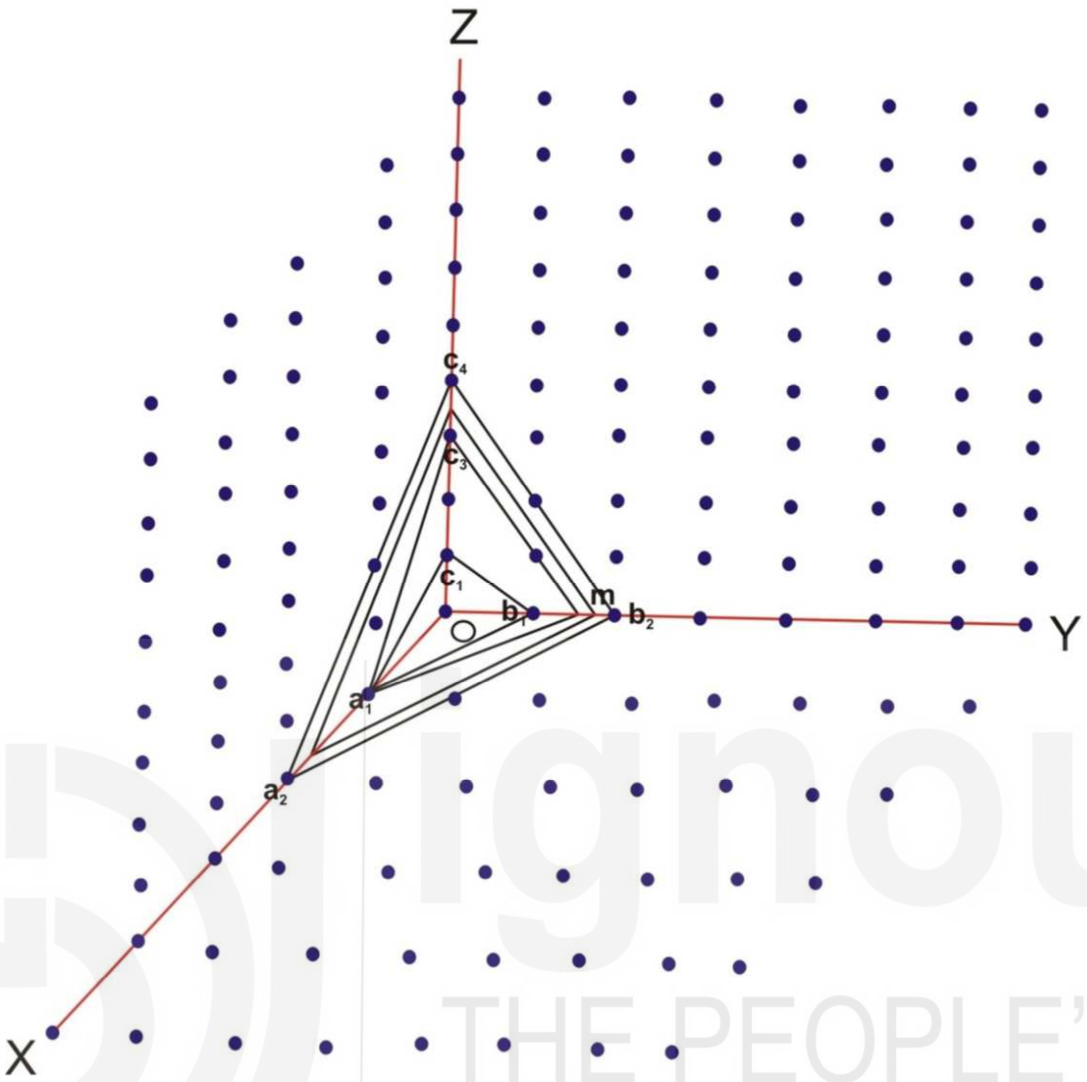


Fig. 2.2: Intercepts and Miller indices of some faces on the crystallographic axes OX, OY, OZ.

Let us consider two faces, i.e. a_1, b_1, c_1 and a_1, m, c_3. Their intercepts contain segments on the reference axes (i.e. OX, OY and OZ). The first face, i.e. a_1, b_1, c_1 intercepts segments on Oa_1, Ob_1 and Oc_1, whereas the second face, i.e. a_1, m, c_3 intercepts segments on Oa_1, Om, Oc_3. These segments are the linear parameters of the two faces. The length of the unit segments is not necessarily equal in all crystals.

If we assume that the first face (a_1, b_1, c_1) intercepts one-spacing in each row, i.e. one-spacing on X, Y and Z axes, respectively (Fig. 2.2). We call the first face a **unit face** because it makes one intercepts on each axis. It gives three values related to each other as 1a:1b:1c. The second face (a_1, m, c_3) will intercept one-spacing on X axes, one and a half spacing on Y axes and three spacing on Z axes, respectively. The second face gives 1a:3/2b:3c. These numbers 2, 3, 6 are numerical parameters of a face by clearing fractions must always be whole numbers.

We find that indices of all crystal faces will be small integers or zero. This is known as the law of rational indices. It is of fundamental importance to crystallography.

2.2.3 Law of Axial Ratio

Now let us discuss about the third fundamental law of crystallography.
The length of each axis is distinct for a specific mineral. This can be determined by selecting a parametral face on the crystal. You have read that the face which cuts all three axes is called **parametral face** whereas the plane which cuts all three axes is called as **parametral plane**.
Axial ratio can be defined as the ratio of the length of the crystallographic axes expressed in terms of one of horizontal axes, usually 'b' axes as unity. **Law of axial ratio states that the ratio between the lengths of axes of the crystal of mineral is constant**.
In cubic system where all the three axes are identical 1:1:1.
We will discuss in detail about axial ratio in Section 2.4.
Now you are well equipped to learn and appreciate the crystallographic and geometric symmetry.

2.3 CRYSTALLOGRAPHIC AND GEOMETRIC SYMMETRY

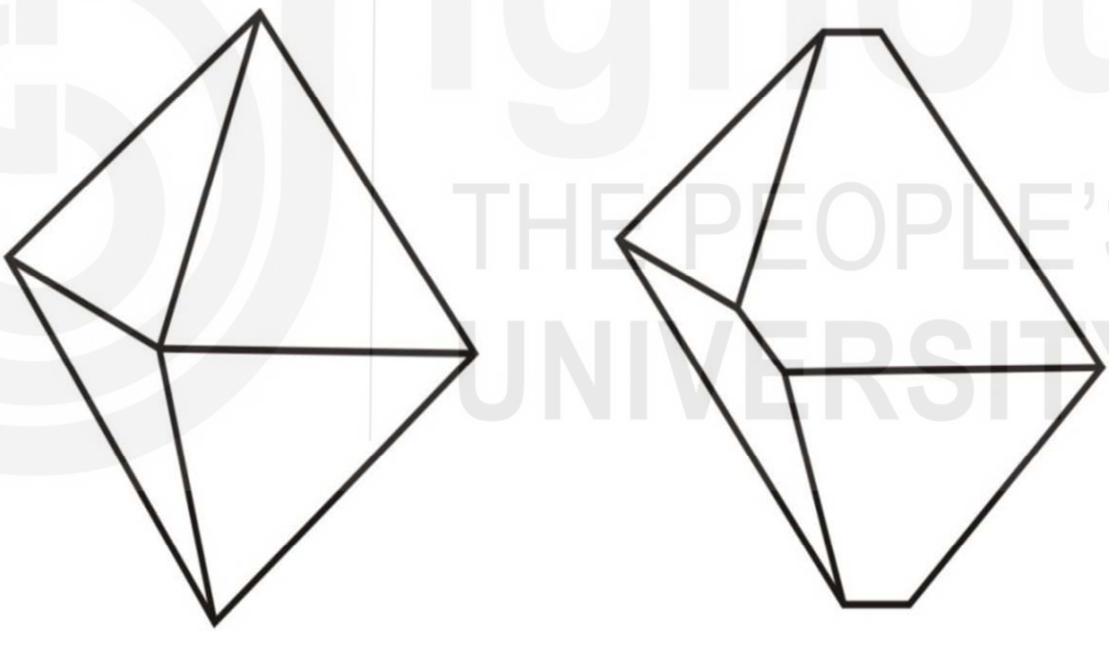
We have discussed about the distorted crystals in previous section. In nature, rarely do we find ideal crystals with well developed similar faces showing same size. We find that in nature majority of the crystals occur in distorted forms in which like faces are not of the same size and some faces may be entirely missing (Fig. 2.3). The fluctuating physicochemical conditions provide hindrance in the growth of the crystal. Real crystals are very much different from ideal crystals. Ideal crystals serve only as museum specimens or as decorative pieces.

Fig. 2.3: Beautiful congregation of pyrite (Iron sulphide-FeS_2) mineral, yellow to bronze in color, showing perfect crystals as pyritohedron (extreme right, shown by white arrow) and striated cube (top and left center). Pyritohedron is a common from in mineral pyrite and is an irregular dodecahedron comprised of identical irregular pentagons.
(Photo courtesy: Nishit Shukla)

Now with this background let us get acquainted with the difference between the crystallographic symmetry and geometric symmetry. The definition of crystal states that it a homogenous solid bounded by naturally formed plane surfaces termed faces which can be related to internal arrangement of atom. Crystallographic symmetry depends on the internal atomic structure and the interfacial angles are most important in this regard. Try to recollect in the previous section we have read about the Law of constancy of interfacial angle which states that regardless of the size and shape of crystals, the interfacial angles are constant. The interfacial angles in the distorted forms are exactly same as in the regular form (Fig. 2.1).

Crystallographic symmetry is quite different from the **geometric symmetry**. You have read that most of the crystals occurring in distorted forms are devoid of geometrical symmetry. The regular crystal possess all the symmetry elements (plane, axes and centre of symmetry) which are absent in a distorted crystal. Thus, regular crystals possess both geometric and crystallographic symmetry whereas, distorted octahedron exhibit crystallographic symmetry but no geometric symmetry.

Let us study this with the help of an example of a regular and distorted octahedron (Fig. 2.4a and b).



(a) (b)

Fig.2.4: a) Regular Octahedron shows both geometrical and crystallographic symmetry; and b) Distorted Octahedron possess only crystallographic and is devoid of geometrical symmetry.

In case of a regular octahedron, we will find all the symmetry elements (plane of symmetry, axes of symmetry and centre of symmetry); we will discuss it in next section, which are absent in a distorted octahedron. However, the distorted octahedron will have a regular arrangement of atomic structure, i.e. crystallographic symmetry. You can see real crystal of regular and distorted garnet in Figs. 2.5a and b.

(a) (b)

Fig. 2.5: a) Regular crystal and b) distorted crystal of garnet.

In the **distorted crystals,** the like faces can exhibit similar properties such as **etch marks**, physical, thermal and electrical properties. For example, if we closely observe distorted quartz crystal shown in Fig. 2.5c, we find similar etch marks on like faces. Etch marks are developed when crystal faces are attacked by certain reagents and they develop regular shaped pits.

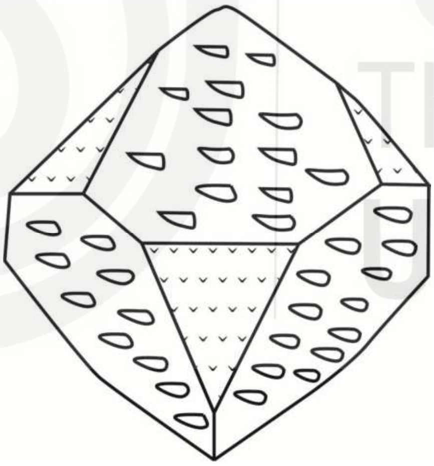


Fig. 2.5c: Quartz crystal showing similar etch marks on like faces. (source: Gribble, 1991)

We have read about the crystallographic and geometric symmetry in this section. Before discussing about crystallographic axes and axial ratio let us spend 5 minutes to check our progress.

SAQ 1

a) State the law of constancy of interfacial angles.

b) What is law of rational ratio?

c) Define axial ratio.

d) Distinguish between a regular and distorted octahedron.

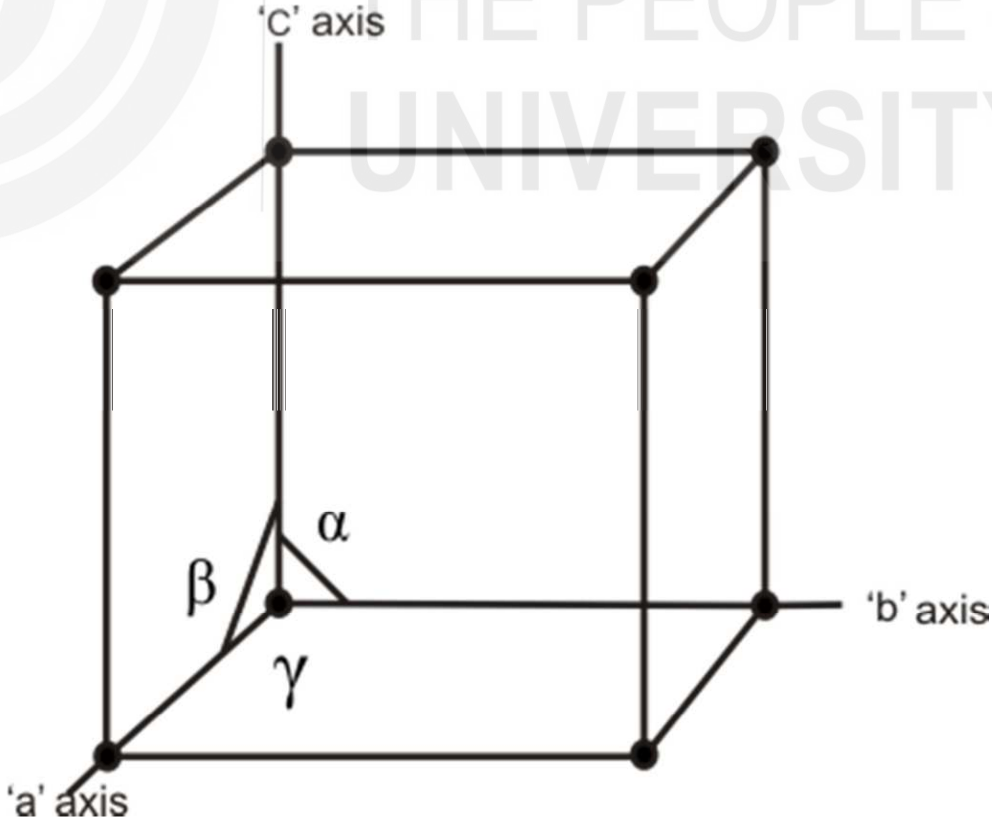
2.4 CRYSTALLOGRAPHIC AXES AND AXIAL RATIOS

You have learnt about the fundamental laws of crystallography in previous section. Let us read about the crystallographic axes in a crystal.

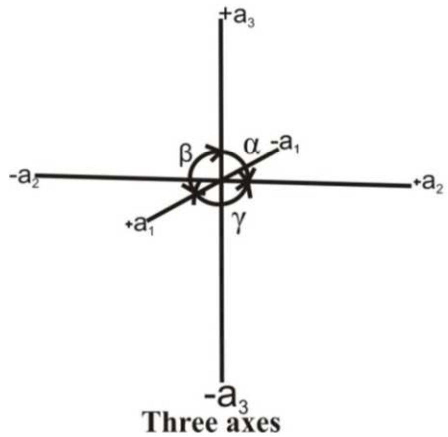
2.4.1 Crystallographic Axes

You have read in Section 2.2.2 about the reference axes, i.e. OX, OY and OZ as shown in Fig. 2.2. **Crystallographic axes** are imaginary reference lines and are generally taken parallel to the intersection edges of major crystal faces. They are fundamental in examining the morphology of the crystal. The position of a plane in space is given by the intercepts that the plane makes on three given lines called crystallographic axes as shown in Fig. 2.6a. The crystal axes originate from centre of the crystal and emerge both in vertical and horizontal directions. The crystals mostly have three axes namely, a, b and c, corresponding to front-back (a-axis), right-left (b-axis), top-bottom (c-axis), with the exception to those belonging to the hexagonal and trigonal system (Fig. 2.6c). The three axes intersect at the origin. The axial lengths depend on the crystal system to which the crystal belongs. The crystallographic axes can be of different lengths in different crystal systems as shown in Fig. 2.6. They are named and indicated as follows:

- a_1, a_2 and a_3 = three equal axes
- a_1, a_2 and c = two equal and third ‘c’ is unequal axis
- a, b and c = three unequal axes
- a_1, a_2, a_3 and c = three equal and fourth unequal axis

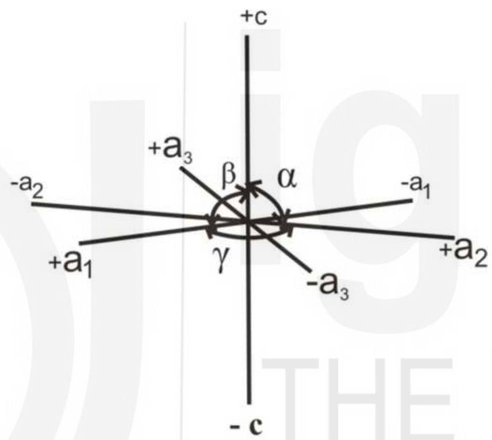


(a)



Three axes

(b)



Four axes

(c)

Fig. 2.6: Crystallographic axes originating from the center of a crystal. Each axis is divided into two parts, positive and negative side, as illustrated. Notice the angles α, β and γ: a) crystallographic axes corresponding to geometric axes; b) three axes can be named a_1, a_2 and a_3 or a_1, a_2 and c or a, b and c; and c) four axes namely a_1, a_2, a_3 and c.

The end of each axes are designated plus (+) or minus (-); the front end of 'a-axis', right end of 'b-axis' and top end of 'c-axis' are positive and opposite ends are negative. Crystals are oriented by placing the a-axis front (+) to back (-); the b-axis right (+) to left (-); and c-axis up (+) and down (-). Positive and negative ends are marked in Fig. 2.6b.

The crystals of hexagonal and trigonal systems (Fig. 2.6c) have four crystallographic axes where a_1, a_2 and a_3 are horizontal with a_3 running from back to front and c is vertical. In such crystals, the vertical axis (3 or 6 fold) is always chosen as c-axis. The a_2 runs from left (-) to right (+) end. The positive end a_1 is at 120^o toward left from $+a_2$ and the a_3 axis is located between a_1 and a_2. The positive and negative ends alternate and hence a_3 has negative end at 60^o towards right of the $+a_1$. We will discuss in detail about crystallographic axes of different crystal systems in Unit 3 Crystal Systems.

2.4.2 Axial Length and Axial Ratios

We have discussed about the crystallographic axes. Now let us read about axial length and axial ratios. We have been introduced to axial ratios while reading about the law of axial ratio.

Axial ratio can be defined as the ratio of the length of the crystallographic axes of a crystal which is expressed in terms of one of horizontal axes. It is the ratio of the intercepts of the parametral plane on the crystallographic axes, conventionally expressed in terms of b axis as unity. Each mineral possess a unique axial ratio.

Axial plane is the plane that divides the crystal into two equal halves along the crystallographic axes or in other words, a**xial plane** is a plane which contains two crystallographic axes. **Diagonal plane** is the plane that divides the crystal into two equal halves along the diagonal surface.

Let us consider some examples of axial ratios.

In cubic system, you find that all the crystallographic three axes (a_1, a_2 and a_3) are identical the axial ratio is 1:1:1. However, this is not the case in other systems.

In orthorhombic system, for example, all the three axes (a, b, c) are unequal. The crystallographic axes-b will be considered as unit and the lengths of a-axes and c-axes will be with reference to b. For example, sulphur belonging to orthorhombic system, has following axial ratio:

a:b:c= 0.8131:1:1.9034

Olivine also belongs to orthorhombic system, which has all three unequal axes, has following axial ratio:

a:b:c= 0.4648:1:0.5857

Augite belongs to monoclinic system, which has all three unequal axes, has following axial ratio:

a:b:c=1.0921:1:0.5885

Beryl is a mineral of hexagonal system with axial ratios of a:c 1:0.99751. All the horizontal axes (a_1, a_2, a_3) in hexagonal system are of same length.

Modern crystallographers can accurately measure axial ratios with the application of x-rays in angstrom units (Å).

You will read in detail about the axial length in different crystal systems in Unit 3 Crystal Systems.

2.4.3 Axial Angles

You have learnt about axial ratio, now let us read about axial angle.

Axial angle is the angle between the positive ends of the axes and are conventionally designated by Greek letters α, β, γ (Fig. 2.6b and c). The angles between the axes are denoted as follows:

- α (alpha) angle - positive b axis and positive c axis
- β (beta) angle - positive c axis and positive a axis
- γ (gamma) angle - positive a axis and positive b axis

Similarly, in the cube, α, β and γ are between the a_2 axis and a_3 axis, a_1 axis and a_3 axis, and a_1 axis and a_2 axis, respectively.

You will read in detail about the axial angles in different crystal systems in Unit 3 Crystal Systems.

2.5 ELEMENTS OF SYMMETRY

You have read about the crystallographic and geometric symmetry, crystallographic axes, axial length, ratios and angles.

Now let us discuss and define the three elements of symmetry.

While reading about crystallographic and geometric symmetry you have learnt that symmetry depends on the internal atomic structure and space lattice. Now you know that the internal atomic symmetry in crystal manifest in the external crystal form, which may consist of a set of naturally, formed plane faces. A crystal also shows certain regularity of position of faces, edges, corners, solid-angles, etc. The geometric locus about which a group of repeating operations act is known as **symmetry elements**. Crystals belonging to different crystal systems exhibit different symmetry elements. We can differentiate one crystal from the other with the help of symmetry elements. The symmetry of the crystals is explained with the help of following three elements:

- **Plane of Symmetry**
- **Axis of Symmetry**
- **Centre of Symmetry**

If the repetition is with respect to a line, it is called as “axis of symmetry” and if the repetition is with respect to plane, it is said to have a “plane of symmetry”. If the repetition is with respect to a point, in which case it is referred as “centre of symmetry”. The act of reflection along a plane by a mirror (plane of symmetry), act of rotation about an axis (axis of symmetry), and act of inversion about a central point (centre of symmetry) are collectively referred to as symmetry elements.

Crystals belonging to cubic or isometric system exhibit the highest symmetry elements. On the other hand, crystals of the triclinic system have lowest symmetry elements. Let us consider another example.

Galena type belonging to the normal class of cubic system exhibits highest symmetry elements whereas tetrahedrite type of the same system exhibits the lowest symmetry elements.

Thus, the symmetry elements of a crystal within a system may also differ. The crystals of minerals of the same system have been further divided into classes. Now let us understand the three elements of symmetry.

2.5.1 Plane of Symmetry

Plane of Symmetry is the imaginary plane which divides the crystal into two similar halves or similarly placed halves such that one half is the mirror image of the other half (Fig. 2.7). Cube has 9 planes of symmetry. You can identify them as indicated on the faces of the cube as shown in Fig. 2.8. Their dissected planes clearly specify the position of the other part with respect to the first one as shown in Fig. 2.9. Cubic system has 9 planes of symmetry, of which 3 are axial and 6 are diagonal planes. The diagonal planes of symmetry may be horizontal as well as vertical.

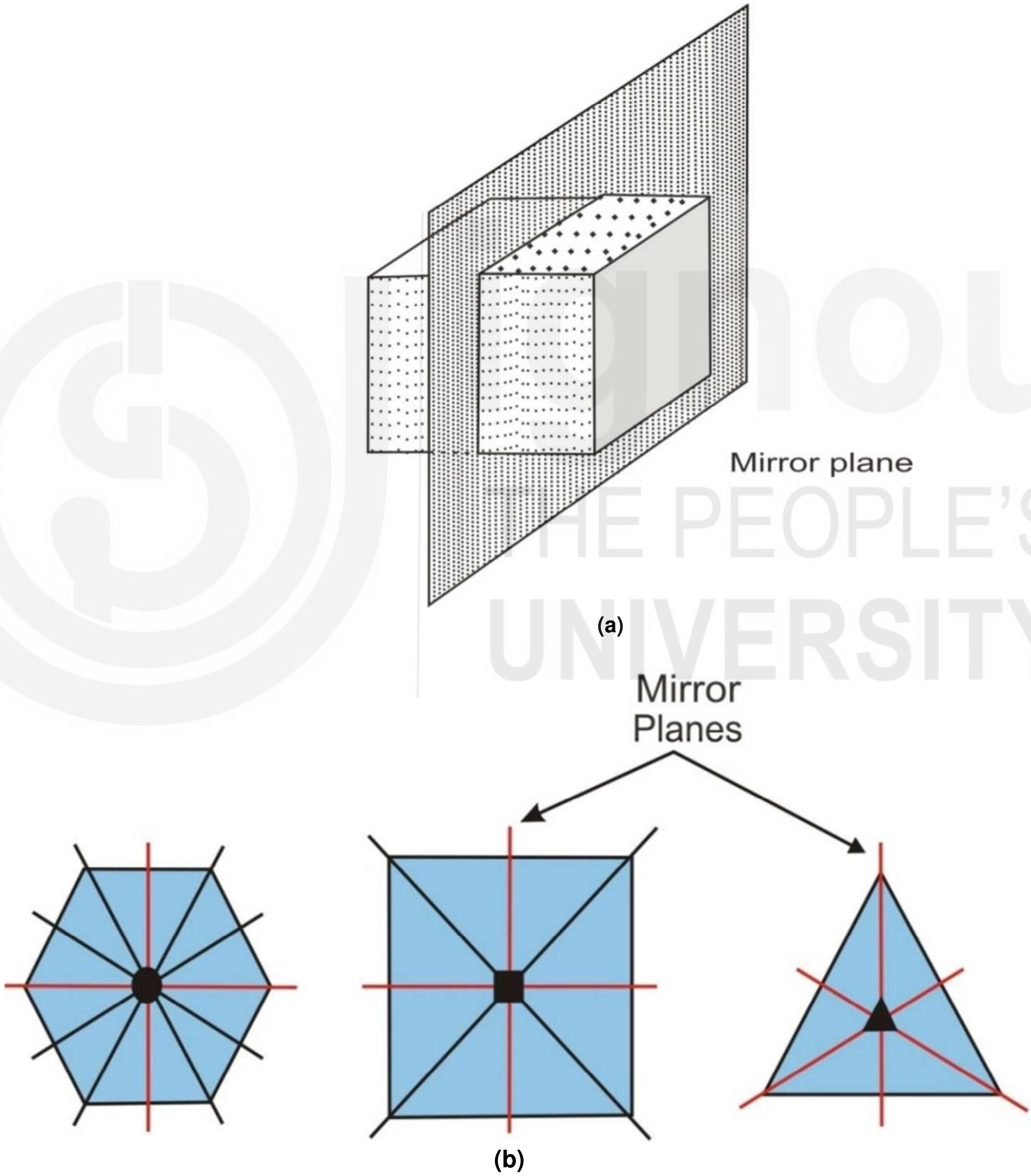


Fig. 2.7: a) Mirror plane; and b) Mirror images indicating planes of symmetry.

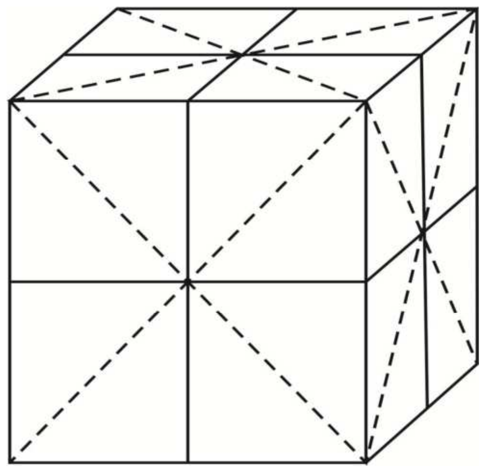


Fig. 2.8: Planes of symmetry in a cube are marked with dashed lines which are elaborately shown in Fig. 2.9.

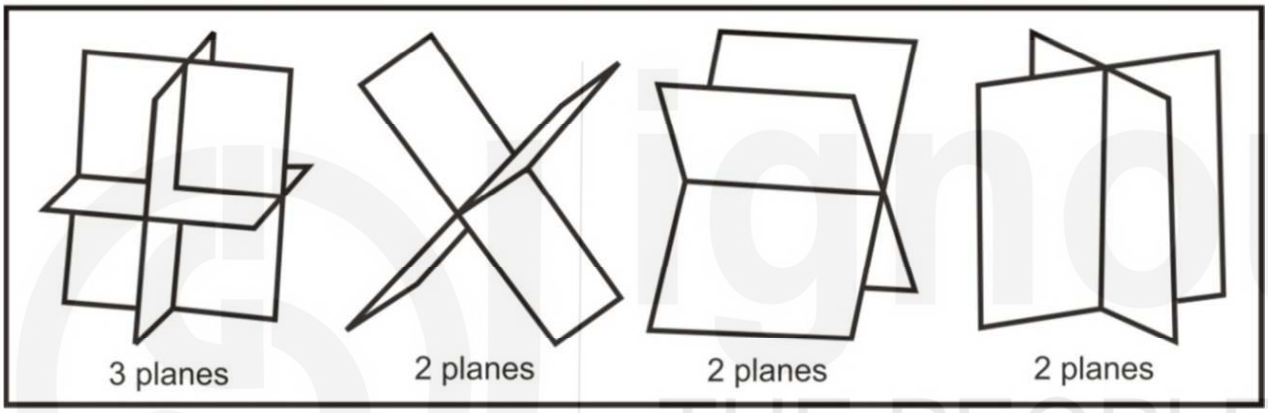


Fig. 2.9: Dissected planes of symmetry in the cube showing 9 planes of symmetry (3 planes are axial which follow crystallographic axis and 6 (2+2+2) are diagonal).

2.5.2 Axis of Symmetry

We have discussed and can recognise the plane of symmetry now let us know about the axis of symmetry.

If a crystal on being rotated occupies the same position more than once in one complete rotation through 360°(n#1) then the axis along which rotation is being given is known as **Axis of Symmetry**. There are four kinds of axis of symmetry:

- **Diad axis** of two fold symmetry where n=2: i.e. same view occupies the same position once in every 180° on rotation axes. Thus, in one complete rotation through 360° the same position occurs twice.
- **Triad axis** of three fold symmetry where n=3: i.e. same view occupies the same position once in every 120° on rotation axes. Thus, in one complete rotation through 360° the same position occurs thrice.
- **Tetrad axis** of four fold symmetry where n=4: i.e. same view occupies the same position once in every 90° on rotation axes. Thus, in one complete rotation through 360° the same position occurs four times.

- **Hexad axis** of six fold symmetry where n=6: i.e. same view occupies the same position once in every 60° on rotation axes. Thus, in one complete rotation through 360° the same position occurs six times.

Five fold of symmetry does not exist in nature.

You have read that symmetry elements have a particular relationship with the internal atomic structure of the crystals. Accordingly, they form the basis for the classification of crystal systems into thirty two classes of symmetry. You will study that the normal classes of the system which exhibits a maximum number of symmetry elements in Unit 3 Crystal Systems.

You had read the example of cube while recognising the planes of symmetry. Now to be acquainted with the axes of symmetry, let us again consider the example of a cube.

Cube has 13 axes of symmetry as shown in Fig. 2.10, out of which 3 are four fold (tetrad), 4 are three fold (triad) and 6 are two fold (diad) axes of symmetry.

They are written in the following manner:

Cube

Axes 13 $\begin{cases} 3^{iv} \text{ (also written as } 3A_4\text{) crystallographic axes} \\ 4^{iii} \text{ (also written as } 4A_3\text{) joining opposite} \\ 6^{ii} \text{ (also written as } 6A_2\text{) joining mid points of opposite edges} \end{cases}$

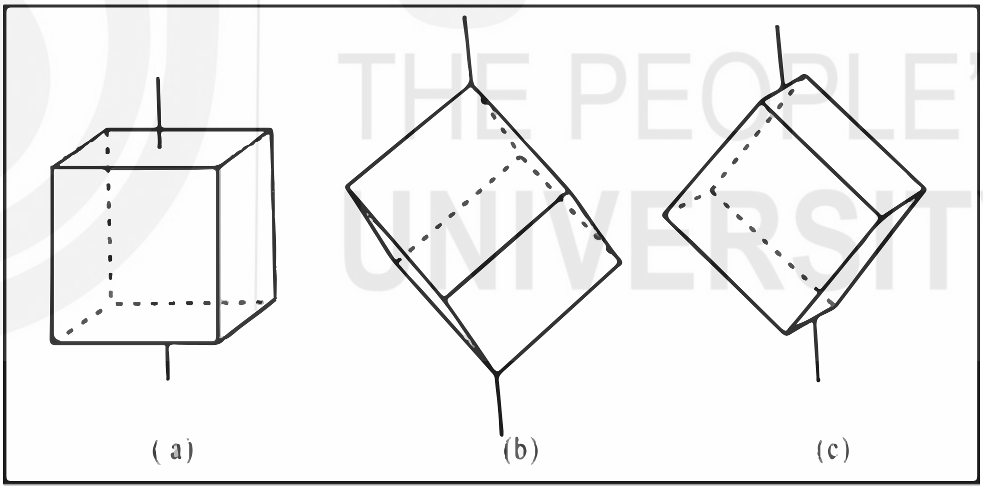


Fig. 2.10: Thirteen axes of symmetry in a cube: a) Four fold; b) Three fold; and c) Two fold.

2.5.3 Centre of Symmetry

You have read about plane and axis of symmetry. Now let us familiarise ourselves with the third element of symmetry, i.e. centre of symmetry. Centre of symmetry is in fact the symmetry with respect to a point. A crystal is said to have a centre of symmetry when like faces, edges are arranged in corresponding positions on opposite sides of a central point. If through this central point a line is drawn, the points of similar character are equidistantly present on the both sides of this point as shown in Fig. 2.11. When similar faces occur in parallel pairs, on opposite sides of a crystal then the crystal is said to possess a **Centre of symmetry**. All faces of crystal must occur in parallel pairs for a crystal to possess a centre. For an example, a regular cube possesses a centre of symmetry. If we remove one corner of a cube then no centre of symmetry exists. Similarly, centre of symmetry is not present in tetrahedron (Fig. 2.12).

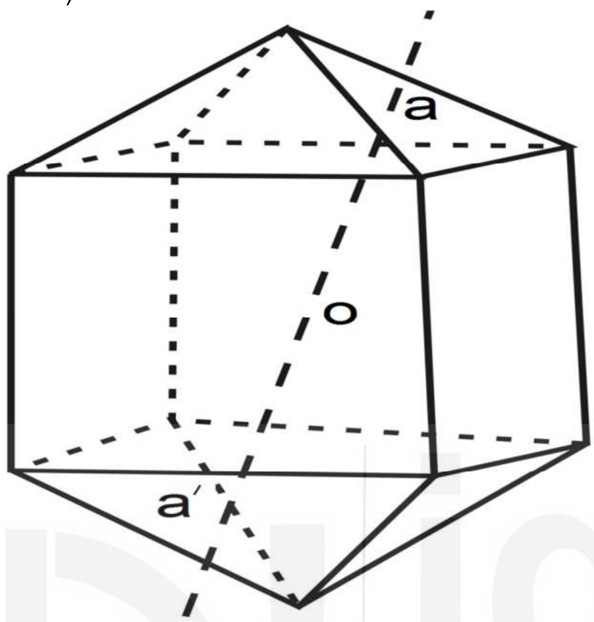


Fig. 2.11: Centre of symmetry present in zircon. Line a-b passes through the centre of the crystal, '0'. Points a and a' are equidistant from o and are in equivalent positions.

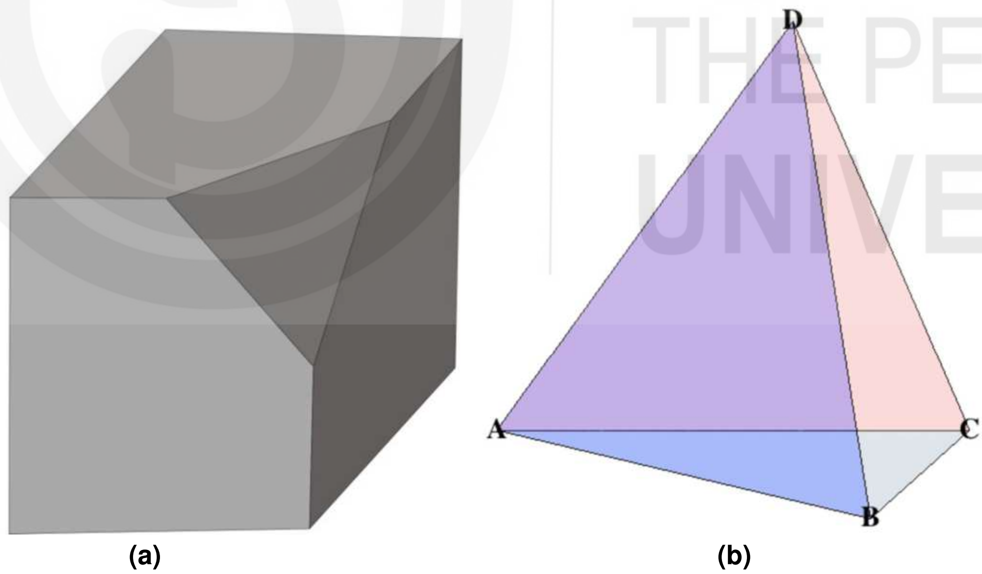


Fig. 2.12: Centre of symmetry absent in: a) defaced cube; and b) tetrahedron.

SAQ 2

a) What is axial angle?

b) Explain the crystallographic axis of hexagonal and trigonal systems.

c) What is axial ratio?

d) What is crystallographic axis?

2.6 SUMMARY

In this unit, you have learnt about laws of crystallography, crystallographic axes, axial length, ratio and angles and elements of symmetry. Now let us summarise what you have learnt:

- Law of constancy of interfacial angle states that regardless of size and shape, similar angles on crystals of particular mineral remains constant. The law of rational indices states that the indices of any crystal face are always rational numbers and are determined by dividing the intercepts of the parametral plane and clearing fractions. Law of axial ratio states that ratio between the lengths of axes of the crystal of mineral is constant.
- The regular crystal possess all the symmetry elements (plane, axes and centre of symmetry) which are absent in a distorted crystal. Thus, regular crystals possess both geometric and crystallographic symmetry. Whereas, distorted octahedron exhibit crystallographic symmetry but no geometric symmetry.
- Crystallographic axes are imaginary reference lines and are generally taken parallel to the intersection edges of major crystal faces. These axes are three or four intersecting on their origin. The axial lengths depend on the crystal system to which the crystal belongs.
- The crystals mostly have three axes namely a, b and c, corresponding to front-back (a-axis), right-left (b-axis), top-bottom (c-axis), with the exception to those belonging to the hexagonal and trigonal system.
- The crystals of hexagonal and trigonal systems have four crystallographic axes where a_1, a_2 and a_3 are horizontal with a_3 running from back to front and c is vertical.
- Axial ratio can be defined as the ratio of the length of the crystallographic axes of a crystal which is expressed in terms of one of horizontal axes which is normally ‘b’ axis.
- Axial angle is the angle between the positive ends of the axes and is conventionally designated by Greek letters α, β, γ.
- Symmetry of the crystals refers to regularity present in it with respect to Plane, Axes and Centre of Symmetry. Crystals belonging to different crystal systems exhibit different symmetry elements.
- Plane of Symmetry is the plane which divides the crystal into two similar halves. If a crystal on being rotated occupies the same position more than once in one complete rotation through 360°(n#1) and the axis along which rotation is being given is known as Axis of Symmetry. When similar faces occur in parallel pairs, on opposite sides of a crystal then the crystal is said to possess a Centre of symmetry.

2.7 ACTIVITY

1. It would be interesting to construct few crystals from modelling or simple clay. Construct and hold it with proper orientation. Observe the symmetry elements and write your observations.

2.8 TERMINAL QUESTIONS

1. Discuss crystallographic axes and axial ratio.
2. Explain elaborately the elements of symmetry.
3. What is meant by three fold symmetry? Give example of a cube.
4. Describe briefly the three laws of crystallography.

2.9 REFERENCES

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2. 11 ANSWERS

Self Assessment Questions

1 a) Law of constancy of interfacial angle states that 'measured at same temperature, similar angles on crystals of the particular mineral remain constant, regardless the size and shape of crystals'.

b) Law of rational indices states that the indices of any crystal face are always rational numbers and are determined by dividing the intercepts of the parametral plane and clearing fractions.

c) Axial ratio can be defined as the ratio of the length of the crystallographic axes expressed in terms of one of horizontal axes, usually 'b' –axes as unity.

d) The regular crystal possess all the symmetry elements (plane, axes and centre of symmetry) which are absent in a distorted crystal. Thus regular crystals possess both geometric and crystallographic symmetry. Whereas, distorted octahedron exhibit crystallographic symmetry but no geometric symmetry. Please refer to Fig. 2.4. In case of a regular octahedron we will find all the symmetry elements which are absent in a distorted octahedron. The distorted octahedron possesses crystallographic symmetry, i.e. it has regular arrangement of atomic structure.

2 a) Crystallographic axes are imaginary reference lines and are generally taken parallel to the intersection edges of major crystal faces.

b) In hexagonal and trigonal systems there are four crystallographic axes where a1, a2 and a3 are horizontal with a3 running from back to front and c is vertical. In such crystals the vertical axis (3 or 6 fold) is always chosen as c axis. The a2 runs left (-) to right (+) end. The positive end a1 is at 60o toward left from +a2 and the a3 axis locate between a1 and a2. The positive and negative ends alternate and hence a3 has negative end at 60o towards right of the +a2.

c) Axial ratio can be defined as the ratio of the length of the crystallographic axes of a crystal which is expressed in terms of one of horizontal axes.

d) Axial angle is the angle between the positive ends of the axes and are conventionally designated by Greek letters α, β, γ. Please refer Fig. 2.6b and c. The angles between the axes are denoted as follows: α (alpha) angle -positive b and positive c; β (beta) angle -positive c and positive a; γ (gamma) angle -positive a and positive b.

Terminal Questions

1. Your response should include their definitions. While discussing crystallographic axes negative and positive ends of crystals with three and four axes as given in subsection 2.4.1. Give examples of axial ratio as mentioned in subsection 2.4.2.

2. Symmetry elements in a crystal are the regularity shown by the crystal. They are measured with the help of three elements. They are: Plane, Axes and Centre of symmetry. Elaborate the three elements. Please refer to section 2.5.

3. Three fold symmetry is axis of symmetry which means that on being rotated along that axis the crystal occupies same position three times in one rotation of 360^o. Please refer to section 2.5.2 and Fig. 2.9.

4. Please refer to section 2.2. Three laws have been discussed. Law of constancy of interfacial angle states that measured at same temperature, similar angles on crystals of the particular mineral remain constant, regardless the size and shape of crystal. The law of rational indices states that the indices of any crystal face are always rational numbers and are determined by dividing the intercepts of the parametral plane and clearing fractions. Law of axial ratio states that ratio between the lengths of axes of the crystal of mineral are constant.

UNIT 3

CRYSTAL SYSTEMS

Structure

3.1 INTRODUCTION

In Unit 1 Crystal Properties of this course, you have been introduced to the parts of crystal, crystal forms and representation of crystal face. Further in Unit 2 Crystal Symmetry, you have learnt about laws of crystallography, elements of symmetry and crystallographic axes and axial ratios. We have discussed the basic concepts of crystallography which form the basis of classification of crystals into seven crystal systems. In this unit, we will discuss about the basic concepts of nomenclature of crystal systems and characteristics of seven crystal systems.

Expected Learning Outcomes

After reading this unit, you would be able to:

- ❖ discuss the basic concepts of crystal systems;
- ❖ classify crystal systems;
- ❖ elaborate the normal class of cubic system;
- ❖ describe the normal class of tetragonal system;
- ❖ explain with the normal class of hexagonal system;
- ❖ discuss the normal class of trigonal system;
- ❖ explain the normal class of orthorhombic system;
- ❖ examine the normal class of monoclinic system; and
- ❖ discuss the normal class of triclinic system.

3.2 BASICS CONCEPTS OF CRYSTAL SYSTEMS

Let us first discuss the basics concepts of nomenclature of crystals into seven systems.

The formation of minerals takes place by precipitation from a solution, solidification of a magma or sublimation from vapour which may or may not involve the process of crystallisation. During this process the atoms assume a definite orderly three dimensional (3d) arrangement. Bravais in 1848 had put forth that there are only 14 three dimensional patterns in which these units might be arranged. These 14 patterns are called as **Space lattice** or **Bravais lattice**. A space lattice is a regular repetition of points in space (3D network) at constant intervals in a given direction. The unit cell is the smallest complete unit of the pattern. This three dimensional pattern is repeated many times and the unit of the pattern is called as **Unit cell**. The whole crystal is made up of the same units joined together.

Let us comprehend this with an example.

This is like the repeating patterns on a tiled floor (Fig. 3.1) or on a fabric or wallpaper which extends indefinitely to fill the entire area.

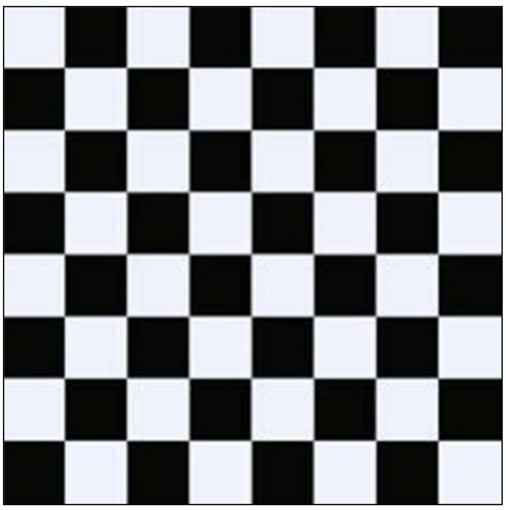


Fig. 3.1: Repeating patterns on a tiled floor.

The seven types of unit cells are:

1. Cubic
2. Tetragonal
3. Orthorhombic
4. Monoclinic
5. Hexagonal
6. Trigonal
7. Triclinic

The lengths of crystallographic axes and axial ratios, and angles of the above mentioned unit cells are different from one another (Fig. 3.2). On the basis of seven types of shapes of unit cells, **seven crystal systems** and **32 classes** have been recognised in crystallography. Hessel in 1930 predicted the number of crystal classes to 32. Since then mathematically and graphically it has been proved that his predictions are valid and all the crystalline substances can be divided into 32 types of symmetry. The commonly occurring minerals are from 15 classes out of the above mentioned 32 classes which are confined to 7 crystal systems. The seven crystal systems have been established on the basis of number, position, relative axial length, axial ratios, axial angles and elements of symmetry.

Now let us discuss the seven crystallographic systems with special reference to the elements of symmetry of their **normal class**. The normal class is also known as **holosymmetric** or **holohedral** in every crystal system. This class exhibits the highest degree of symmetry or symmetry elements. Among the seven crystal systems, highest degree of symmetry is shown by cubic or isometric system and lowest degree of symmetry by triclinic system. It has been observed that more than 50% minerals crystallise in monoclinic and orthorhombic system.

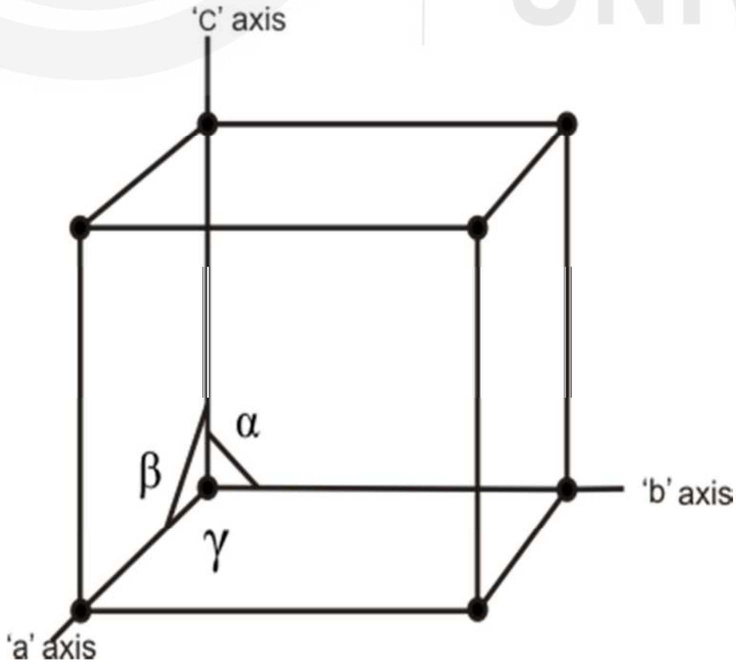


Fig. 3.2: A unit cell. Notice the crystallographic axes a, b and c. α, β and γ represent angles between the axes.

3.2.1 Classification of Crystal Systems

Let us elaborate the basis of classification of the crystals into seven systems (as shown Fig. 3.3). The basis of the classification are:

- number of crystallographic axes
- relative length or axial ratios of crystallographic axes
- linear and angular relationships of crystallographic axes
- elements of symmetry, i.e. plane, axis and centre

Now we will study that on the basis of above mentioned parameters, the crystals can be grouped into following **seven crystal systems**:

- **Cubic or Isometric system**: The crystals belonging to this system have three equal and mutually perpendicular axes which have been designated as a_1, a_2 and a_3 of equal length (Fig. 3.3a). Crystals possess four triad axes of symmetry (4^{iii}) or $4A_3$. For example: galena, octahedron, fluorite, rock salt, garnet, crystals.
- **Tetragonal system**: Crystals of tetragonal system have three mutually perpendicular axes, two horizontal axes of equal length and one vertical which can be either longer or shorter (Fig. 3.3b). The axes are designated as a_1, a_2 and c. Tetragonal system possess one tetrad axis of symmetry (1^{iv}). For example: zircon, rutile, scapolite, anatase, vesuvianite.
- **Orthorhombic system**: Crystals with three unequal and mutually perpendicular axes designated as a, b and c belong to this system (Fig. 3.3c). Crystals of orthorhombic system have three diad axes of symmetry (3^{ii}). For example: baryte, sulphur, olivine, topaz, staurolite.
- **Monoclinic system**: This system has crystals of three unequal axes; one is at right angles to the other two. Whereas the other two axes are not at right angles to each other (Fig. 3.3d). The axes are designated as a, b, c with a- and c-axes inclined to each other and b-axes at right angles to the plane containing a- and c-axes. The obtuse angle between positive ends of a- and c-axes is identified as β (beta). The crystals of monoclinic system have 1 diad axis (1^{ii}) and possess no higher degree of axis of symmetry. For example: gypsum, orthoclase, augite, hornblende, muscovite.
- **Hexagonal system**: Crystals belonging to this system have four axes; three of these lie in a horizontal plane, intersect at 60^o and 120^o angles, and are equal in length. Fourth axis is perpendicular to the plane containing the other three and is either longer or shorter than the other three axes. These four axes have been designated as a_1, a_2, a_3 and c (Fig. 3.3e). Hexagonal system has one hexad axis of symmetry (1^{vi}). For example: beryl, kalsilite.
- **Trigonal system**: This system also has four axes are designated as a_1, a_2, a_3 and c, quite similar to Hexagonal system. Three of these axes lie in a horizontal plane. They intersect at 60^o and 120^o angles and are equal in length; fourth axis is perpendicular to the plane containing the other three and is either longer or shorter than the other axes (Fig. 3.3f). Crystals belonging to trigonal system exhibit one triad axis of symmetry (1^{iii}). For example: calcite, hematite, corundum.
- **Triclinic system:** Crystals belonging to this system have three unequal axes. However, none of the axes are at right angles to each other. The axes are designated as a, b, c (Fig. 3.3g). The angle between the positive ends of b- and c-

axes is called α (alpha); angle between positive ends of c- and a-axes is designated as β (beta) and angle between positive ends of c- and b-axes is called γ (gamma). Triclinic system has no axis of symmetry. For example: axinite, plagioclase, kyanite, albite, rhodonite.

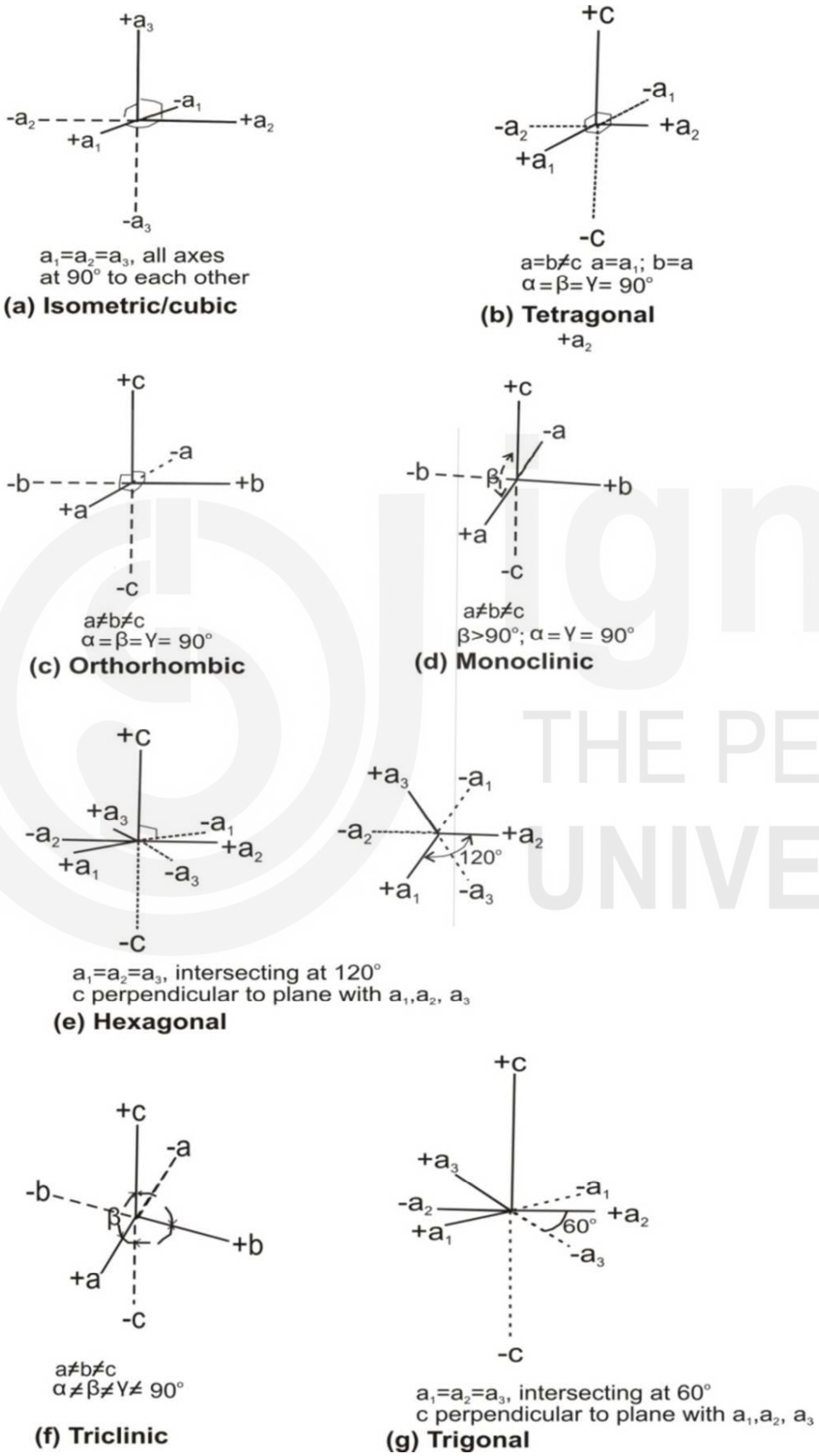


Fig. 3.3: Crystallographic axes with different linear and angular relationship in the seven crystal systems.

The summary of the crystallographic axes and axial angles of seven crystal systems are given in Table 3.1.

Table 3.1: Crystallographic axes and axial angles of the seven crystal systems.

S.N.	Crystallographic system	General appearance of crystal	Crystallographic axes	Axial angles	Classes
1.	Cubic or Isometric System (Fig. 3.3a)	Equidimensional, rounded	a=b=c	$\alpha=\beta=\gamma=90^0$	5
2.	Tetragonal System (Fig. 3.3b)	Long crystals, squarish cross section	a=b≠c	$\alpha=\beta=\gamma=90^0$	7
3.	Orthorhombic System (Fig. 3.3c)	Matchbox or brick like appearance, stubby to short prismatic	a≠b≠c	$\alpha=\beta=\gamma=90^0$	3
4.	Monoclinic System (Fig. 3.3d)	Stubby and blocky crystals, short or long prismatic	a≠b≠c	$\alpha=\gamma=90^0$, $\beta\neq90^0$	3
5.	Hexagonal System (Fig. 3.3e)	Columnar: short or long prismatic	$a_1=a_2=a_3\neq c$	$\alpha=\beta=90^0$, $\gamma=120^0$	7
6.	Trigonal System (Fig. 3.3f)	Columnar: short or long prismatic	$a_1=a_2=a_3\neq c$	$\alpha=\beta=90^0$, $\gamma=120^0$	5
7.	Triclinic System (Fig. 3.3g)	Absence of right edges on faces and edges	a≠b≠c	$\alpha\neq\beta\neq\gamma\neq90^0$	2

You can distinguish the seven crystal systems on the basis of axes of symmetry as following:

- **Triclinic system** has no axis of symmetry.
- **Monoclinic system** has diad axis (1^{ii}) and no higher degree axis of symmetry.
- **Orthorhombic system** has three diad axes of symmetry (3^{ii}) or $3A_2$.
- **Tetragonal system** has one tetrad axis of symmetry (1^{iv}) or $1A_4$.
- **Cubic** or **isometric system** has four triad axes of symmetry (4^{iii}) or $4A_3$.
- **Hexagonal system** has one hexad axis of symmetry (1^{vi}) or $1A_6$.
- **Trigonal system** has one triad axis of symmetry (1^{iii}) or $1A_3$.

We will discuss the **normal class** of the seven crystal systems briefly in the following sections.

3.3 CUBIC / ISOMETRIC SYSTEM

Cubic system is also known as **isometric system**. Crystals belonging to isometric (**iso** means equal and **metric** means measuring) system possess three crystallographic axes, which are equal in length and are at right angles to each other as shown in Fig. 3.3a and Table 3.1.

There are five symmetry classes under this system. Normal class of cubic system is known as **galena type** because galena is the common mineral of this type. Some of the common minerals belonging to normal class are garnet octahedron, fluorite, halite and magnetite.

3.3.1 Crystallographic Axes

We have discussed in the earlier section that there are three crystallographic axes designated by letter 'a' which are mutually perpendicular and interchangeable. However, we therefore rename the axes a_1, a_2, and a_3 because they are of the same length (**a** becomes a_1, **b** becomes a_2, and **c** becomes a_3). All are equal and are at right angles to each other.

$a_1=a_2=a_3$ a_1^a_2^a_3=90°; $\alpha=\beta=\gamma=90°$

a_1 – axis runs front to back

a_2 – axis runs right to left

a_3 – axis runs top to bottom

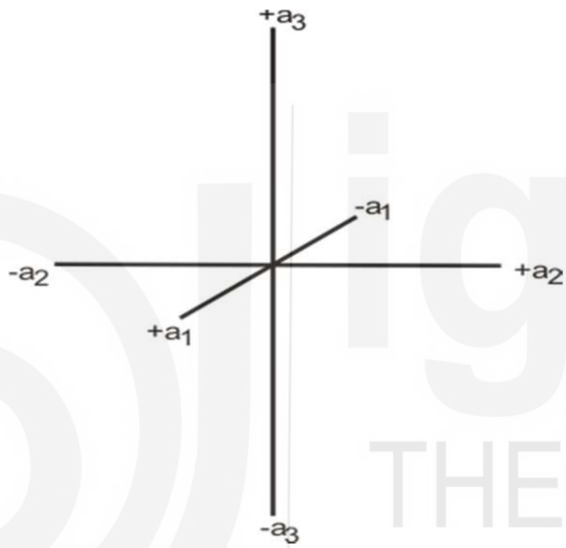
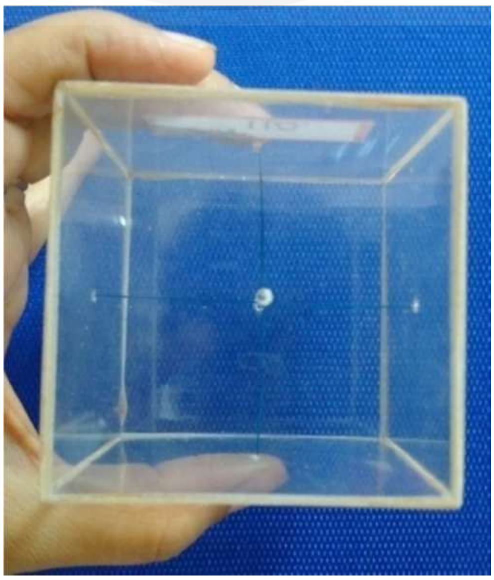


Fig. 3.4: Crystallographic axes of galena type of cubic system.

Axial ratio: a_1:a_2:a_3 = 1:1:1

Type: Normal class or galena type



(a)

(b)

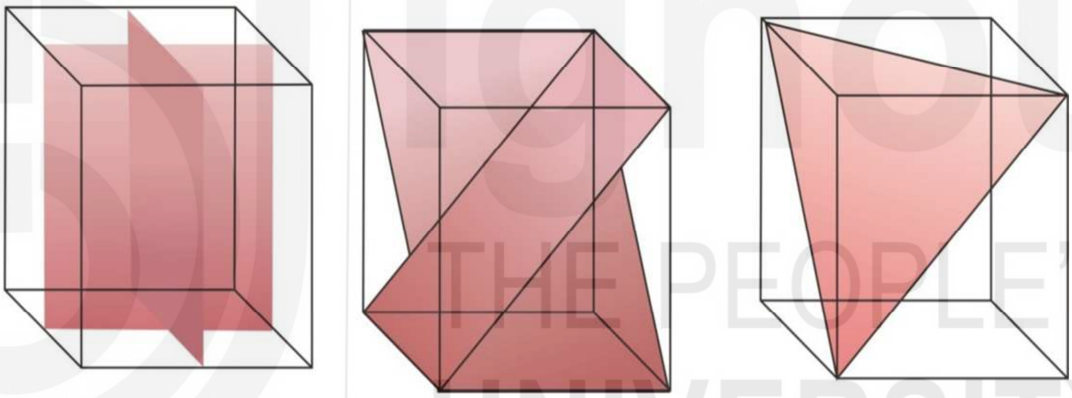
Fig. 3.5: a) Plastic; and b) wooden models of galena crystal.

3.3.2 Symmetry Elements

Cubic system exhibits highest degree of symmetry. Let us read about the symmetry elements of normal class of cubic system.

- Planes 9
  - 3 axial planes
  - 6 diagonal planes
- Axes 13
  - 3^{iv} crystallographic axes
  - 4^{iii} opposite solid angles
  - 6^{ii} mid points- opposite edges
- Centre of Symmetry is present

The normal class of cubic system exhibits 9 planes of symmetry; 3 are axial planes and 6 are diagonal planes (Fig. 3.6). There are 13 axes of symmetry; 3 axes show four- fold symmetry, 4 axes exhibit three fold symmetry and 6 axes demonstrate two fold symmetry. The centre of symmetry is present.



(a) (b) (c)

Fig. 3.6: Planes of symmetry of cubic system: a) 3 planes are parallel to the axial planes; b) and c) shows diagonal planes.

You have read that a cube has 9 planes (3-axial and 6-diagonal planes) of symmetry.
Let us perform a small exercise to find out the planes of symmetry in a cube. Hold the cube along the axial planes to find out three planes parallel to the three major axes of the crystal. Then hold the cube from the opposite edges and find out six planes passing diagonally through the edges (Fig. 3.6).

Now let us do another exercise to find out the 13 axes of symmetry in a cube namely six axes of two fold symmetry ($6A_2$), four axis of three fold symmetry ($4A_3$) and three axes of four fold symmetry ($3A_4$).

For example, you can rotate a cube 90° around an axis perpendicular to any pair of its six faces at mid points of opposite edge. These are six axes of two fold symmetry shown as C_2 in Fig. 3.7. The two-fold (C_2) axes that pass diagonally through the centers of the six pairs of opposite edges. Now hold diagonally placed solid angles and find out three mutually perpendicular four axes of three fold symmetry, abbreviated C_3 axes in Fig. 3.7. For finding out the three axes of four fold symmetry, hold the cube with the opposite faces hold the cube along the three crystallographic axes (C_4).

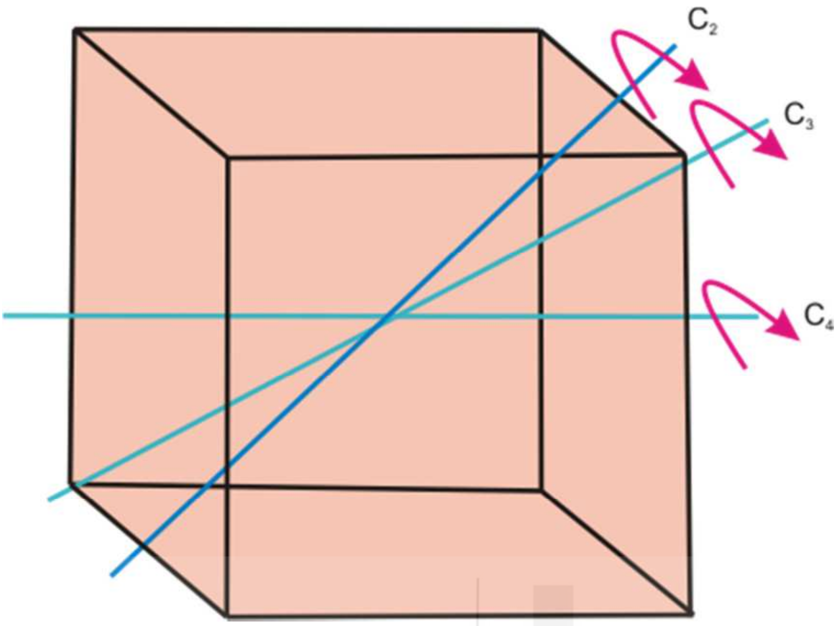


Fig. 3.7: Axes of symmetry of the cubic system.

3.3.3 Forms

We have discussed the crystallographic axes and symmetry elements of cubic system. Let us now discuss about some of the forms of present in cubic system.

(a) Cube: It is a solid bounded by six faces. Each face is a square. Each face cuts one crystallographic axis and remains parallel to the other two axes (Fig. 3.8).

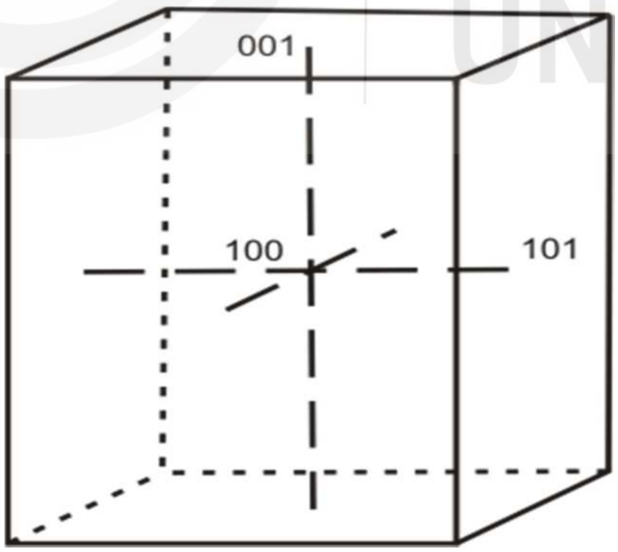


Fig. 3.8: Cube with symbols of faces cutting the crystallographic axes.

(b) Rhombdodecahedron: It is a solid bounded by 12 faces. Each face is a rhomb shaped and cuts two crystallographic axes at equal distance and remains parallel to the third axis (Fig.3.9).

(c) **Octahedron**: It is a solid bounded by eight faces. Each face is an equilateral triangle. Each face cuts all the three axes at equal distance. It is unit form of galena type (Fig. 3.10).

(d) **Trapezohedron**: It is a solid with 24 like faces. Each face is a trapezoid in shape. It cuts two axes at equal distance and third at shorter distance (Fig. 3.11).

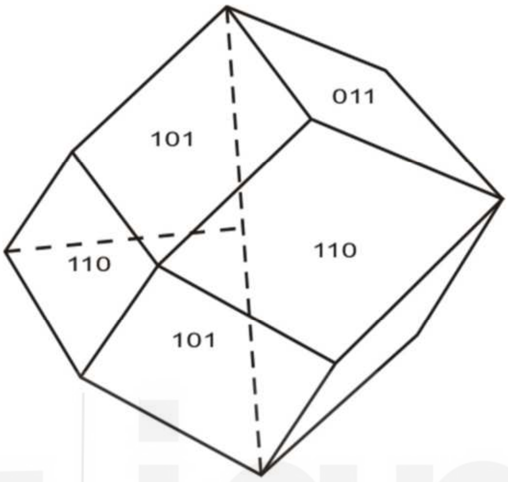


Fig. 3.9: Rhombdodecahedron with symbols of faces cutting the crystallographic axes.

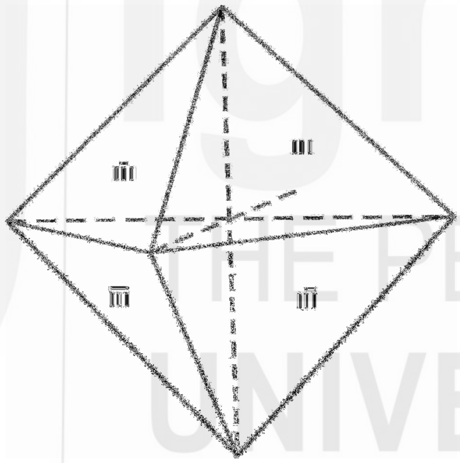


Fig. 3.10: Octahedron with symbols of faces cutting the crystallographic axes.

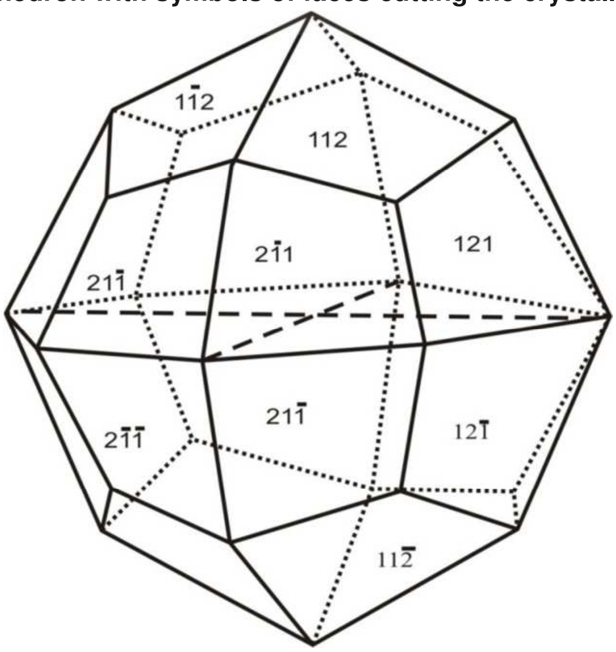


Fig. 3.11: Trapezohedron with face symbols.

Unique features of cubic or isometric system are as follows:

- The highest degree of symmetry is shown by isometric system. The axial ratios are 1:1:1
- Each of its classes has 4 axis of III fold symmetry, i.e. 4^{iii} or four fold of triad symmetry.
- Every form occurring in the system is a closed form and can exist as a real crystal.
- The forms occurring in this system are unique, as the forms like pedion and pinocoid which occur in all other system do not occur in this cubic system.

SAQ **1**

a) List the seven crystal systems.

b) Elaborate the basis of classification of seven crystal systems.

c) Tetragonal system has _______tetrad axis of symmetry.

d) Hexagonal system has ______ hexad axis of symmetry.

e) Normal class of cubic system has __________planes of symmetry.

3.4 TETRAGONAL SYSTEM

We have discussed about cubic system now let us be familiar with the tetragonal system. Please refer Fig. 3.3b and Table 3.1 to learn briefly about the crystallographic axes and axial angles of tetragonal system. Minerals of the tetragonal crystal system are referred to three mutually perpendicular axes. The two horizontal axes are of equal length, while the vertical axis is of different length and may be either sorter or longer than the other two. The normal class of tetragonal system is known as **zircon type**. As the name suggests zircon mineral is common mineral of this type. Other common minerals of tetragonal system are cassiterite, vesuvianite, anatase and rutile.

3.4.1 Crystallographic Axes

There are three crystallographic axes at right angle or perpendicular to one another. Two horizontal axes are equal and the third axis is vertical and unequal, which may be shorter or longer. The axis a_1 runs from front to back, a_2 from right to left and c is vertical (Fig. 3.12).

$a_1=a_2 \neq c$ a_1a_2^$c=90°$ $a_1=a_2$ $b=a_2$ $\alpha=\beta=\gamma=90°$

There are seven symmetry classes under this system. We will discuss the symmetry elements of the normal class of tetragonal system.

Axial Ratio: Here it is being given in general and for zircon which forms the normal class.

In general, it is: $a_1:a_2:c$ = 1: 1:? (c axis can be shorter or longer)

For **zircon,** it is: $a_1:a_2:c$ = 1:1:0.9054

Type: Normal class or zircon type

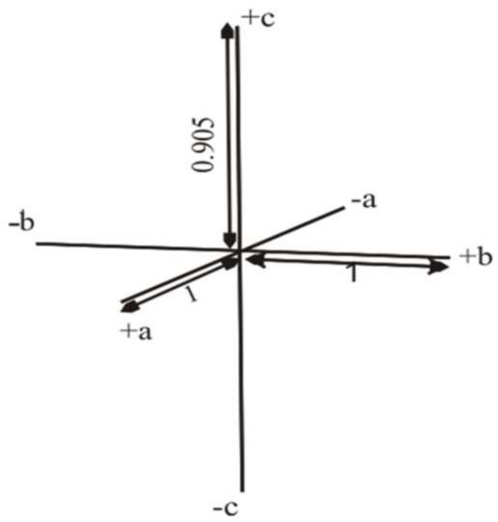


Fig. 3.12: Crystallographic axes of zircon type of tetragonal system.

3.4.2 Symmetry Elements

- Planes 5 — 3 axial plane; 2 diagonal (1 horizontal, 2 vertical) and vertical plane
- Axes 5 — 3^{iv} crystallographic axes; 4^{ii} on vertical face and edge
- Centre of Symmetry is present.

Now you will find out the planes of symmetry. They possess five mirror planes. Let us hold the crystal along c-axis. You will find that along this axis the crystal can be divisible into two equal halves which are mirror images of each other. Try this exercise holding the crystal a_1 and a_2 axes. So these are 3 axial planes of symmetry. The two diagonal planes can be found by holding the crystal diagonally.

Let us find the axes of symmetry in zircon crystal (Fig. 3.13). If we hold the crystal along three axes simultaneously and rotate the crystal by 360°, you will find 3 axes of four fold symmetry. Now on holding the crystal along the vertical faces and edges you will find 4 axes of two-fold symmetry. This is the important feature of this system.

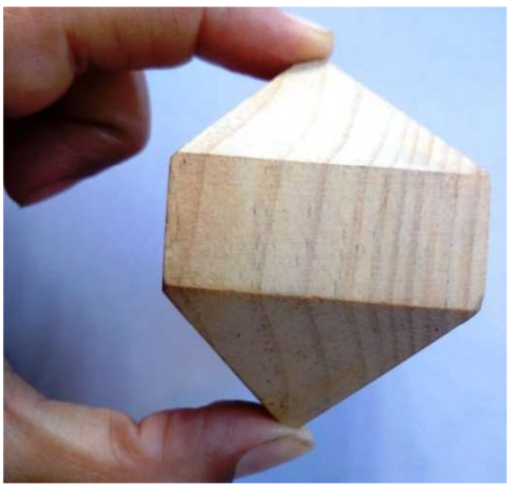


Fig. 3.13: A wooden zircon crystal in its holding position.

3.4.3 Forms

Let us discuss some of the forms of tetragonal system.

a) **Basal Pinacoid:** It is an open form of two rectangular faces. Each face cuts vertical axis and remains parallel to the two horizontal crystallographic axes. As it is open form, it occurs in combination with other forms (Fig. 3.14).

b) **Tetragonal Prism of second order:** It is an open form of four rectangular faces. Each face cuts one horizontal axis and remains parallel to the other horizontal axis and also to vertical crystallographic axis (Fig. 3.14).

There are two types of prisms in the tetragonal system: a) Prism of First order, which is bounded by four similar faces parallel to vertical axis, meeting the horizontal axes at equal distances, with general symbol (110); and b) Prism of Second order, which includes four faces parallel to vertical axis and a horizontal axis, with general symbol (100). Similarly, these names are also used in the hexagonal system.

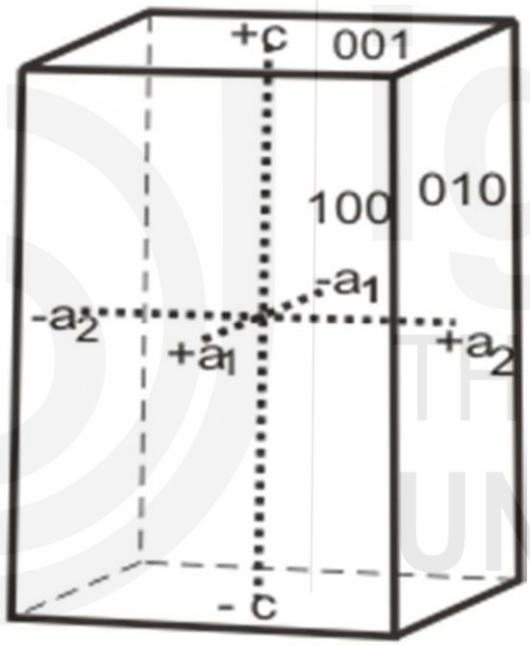


Fig. 3.14: Tetragonal prism of second order (100) and basal pinacoid (001).

3.5 HEXAGONAL SYSTEM

Now let us discuss about the hexagonal system. Please see Table 3.1 and Fig. 3.3e to learn about the axes and axial angles of hexagonal system. This system consists of the highest number of symmetry classes, i.e. 12 classes. We will talk about normal class of the hexagonal system. Beryl is an example of normal class. So the normal class is also known as beryl type. Other common minerals are kalsilite, pyrrhotite and apatite.

3.5.1 Crystallographic Axes

You have read in the earlier section that in hexagonal system there are four crystallographic axes. Minerals of the hexagonal crystal system possess three crystallographic axes which intersect at 120° with one another. The fourth 'c' axis is vertical and unequal and perpendicular to the other three. It is at right angles to the plane containing the horizontal axes. Positive and negative ends are marked in Fig. 3.15. In case of a_2 front end is negative.

As a result of four axes, the symbols of hexagonal system will have four digits.

$a_1=a_2=a_3 \neq c$ $\alpha=\beta=90^0$, $\gamma=120^0$

Axial Ratio: $a_1:a_2:a_3:c$ = 1:1:1:?

For Beryl: $a_1:a_2:a_3:c$ = 1:1:1: 0.4989

Type: Normal class or beryl type (Fig. 3.16).

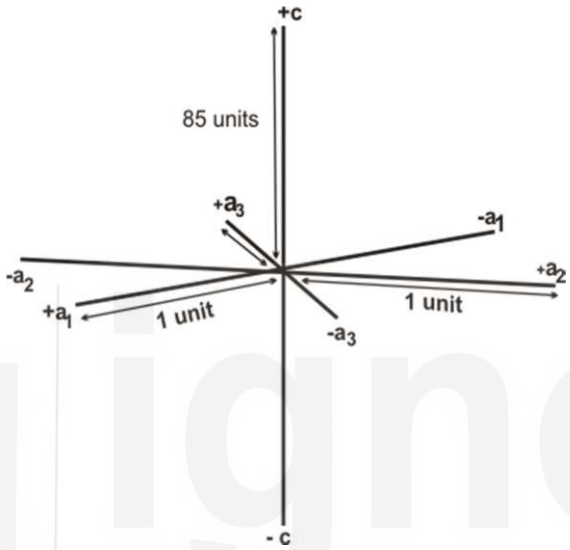


Fig. 3.15: Crystallographic axes of Hexagonal system.

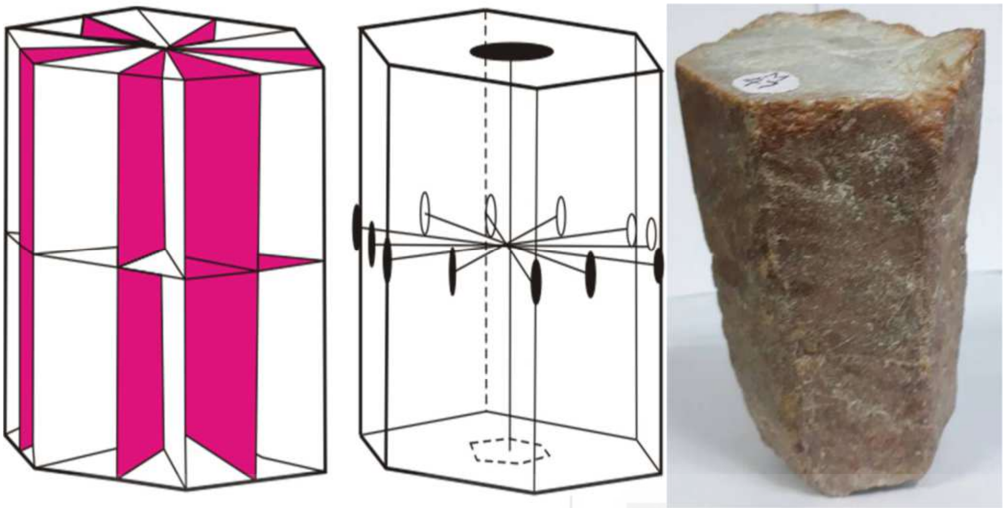
Fig. 3.16: A wooden model of beryl crystal in its holding position.

3.5.2 Symmetry Elements

You will find 7 planes of symmetry and 7 axes of symmetry as shown in Fig. 3.17.

- Planes 7 { 1 Horizontal; 6 Vertical { 3 Axial; 3 Diagonal }}
- Axes 7 { $6A_2$ crystallographic axes; $1A_6$ on vertical face and edge }
- Centre of Symmetry is present.

When you hold and rotate the crystal along 'C' axis you will find that the rectangular face is repeated six times. So this is known as one axis of six fold symmetry. All crystals of hexagonal system possess a single 6-fold axis of rotation.



(a) (b) (c)

Fig. 3.17: Normal class of Beryl showing: a) 7 planes; b) 7 axes of symmetry; and c) Beryl crystal as found in nature.

3.5.3 Forms

a) **Basal Pinacoid**: It is an open form of two faces. Its symbol is 0001. Each face cuts vertical axis and remains parallel to three horizontal crystallographic axes (Fig. 3.18). As it is open form it occurs in combination with other forms.

b) **Hexagonal Prism**: It is open form of six faces. Each face is parallel to vertical axis and cuts all the three horizontal axes, one at unit and other two at twice the distance. The horizontal axes emerge at the centre of vertical faces (Fig. 3.18).

Beryl is combination of hexagonal prism ($10\bar{1}0$) and basal pinacoid (0001).

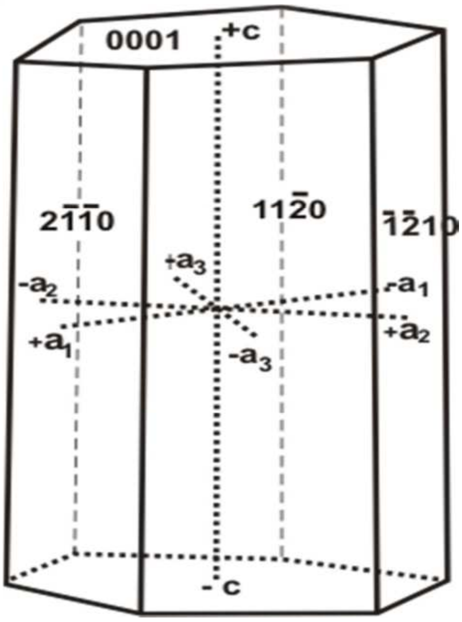


Fig. 3.18: Hexagonal prism ($l\bar{l}20$) and basal pinacoid (0001).

3.6 TRIGONAL SYSTEM

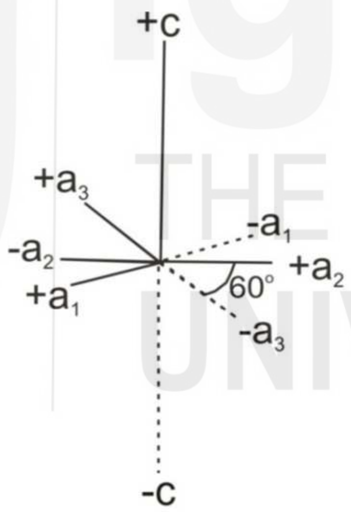
We have discussed three crystal systems and their normal classes. Now you read the trigonal system. Please see Table 3.1and Fig. 3.3g to learn about the crystallographic axes, axial angles and symmetry elements of trigonal system. It is important to note that the axes of trigonal system are similar to hexagonal system. Calcite is an example of the normal class of trigonal system. Normal class is known as **calcite type.** Other common minerals belonging to this system are quartz, rhodochrosite, corundum and dolomite.

3.6.1 Crystallographic Axes

You have read in the earlier section that in trigonal system there are four crystallographic axes like those in hexagonal system. Three are equal horizontal, and make an angle of 120°to one another. The fourth, 'c' axis is vertical unequal. It is at right angles to the plane containing the horizontal axes. Positive and negative ends are marked in Fig. 3.19. In case of a_2 front end is negative. As a result of four axes, the symbols of trigonal system will have four digits.

$a_1=a_2=a_3 \neq c$ $\alpha=\beta=90°$, $\gamma=120°$

Type: Normal class / rhombohedral class / calcite type



$a_1=a_2=a_3$, intersecting at 60°
c perpendicular to plane with a_1,a_2, a_3

Fig. 3.19: Crystallographic axes of Trigonal system.

3.6.2 Symmetry Elements

All the crystals of the trigonal system are characterised by a vertical axis of 3 fold symmetry. This system includes five classes.

- Planes 3 vertical, diagonal plane
- Axes 4 $\left\{\begin{array}{l} 1A_3 \\ 3A_2 \end{array}\right.$
- Centre of Symmetry is present

3.6.3 Forms

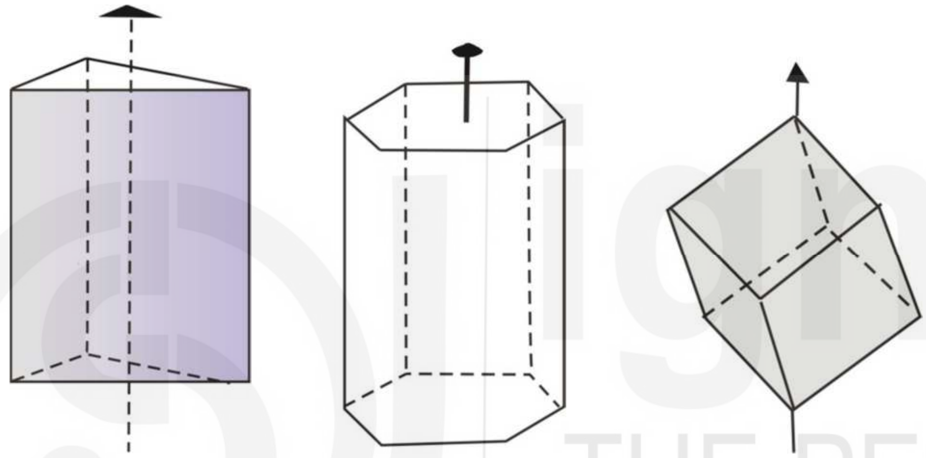
The forms present in trigonal system are:

a) **Pedion:** A pedion is an open, one faced form

b) **Trigonal prism**: It is a three faced pyramid form with all three faces parallel to a 3-fold rotation axis (Fig. 3.20a).

c) **Hexagonal prism:** It is 6-faced form with all faces parallel to a 6-fold rotation axis. The 6 vertical faces in the drawing make up the hexagonal prism (Fig. 3.20b).

d) **Rhombohedron:** This form consists of six rhomb-shaped faces wherein 3 faces on top are offset by the three identical upside down faces towards the bottom. Rhombohedron can also result from a 3-fold axis with perpendicular 2-fold axes (Fig. 3.20c).



(a) (b) (c)

Fig. 3.20: a) Trigonal prism; b) Hexagonal prism; and c) Rhombohedron.

3.7 ORTHORHOMBIC SYSTEM

We have become familiar with the cubic system and tetragonal system. Now we will discuss orthorhombic system. Please refer Fig. 3.3c and Table 3.1 to learn briefly about the crystallographic axes and axial angles of orthorhombic system. You have learnt earlier that the orthorhombic crystal system has three mutually perpendicular axes, each of which is of a different length than the others. The normal class of orthorhombic system is known as **baryte type**. As the name suggests baryte mineral is common mineral of this type. Other common minerals of orthorhombic system are olivine, sillimanite, sulphur, aragonite and bronzite.

3.7.1 Crystallographic Axes

We have already discussed about the crystallographic axes of orthorhombic system earlier. There are three crystallographic axes. All are unequal and are at right angles to one another. The a-axis is horizontal running from front to back, 'b' runs from right to left and 'c' is vertical as shown in Fig. 3.3c.

It consists of mutually perpendicular three axes of unequal length.

$a \neq b \neq c \quad \alpha = \beta = \gamma = 90°$

It is customary to orient a crystal of this system in such a way that b-axis is greater than a-axis. There is divergence of opinion regarding the relative length of the c-axis, some crystallographers follow the convention c>a>b. whereas other prefer c>b>a. But we choose the length of the 'b' axis as unity (Fig. 3.21 and 3.22).

There are 3 symmetry classes in this system.

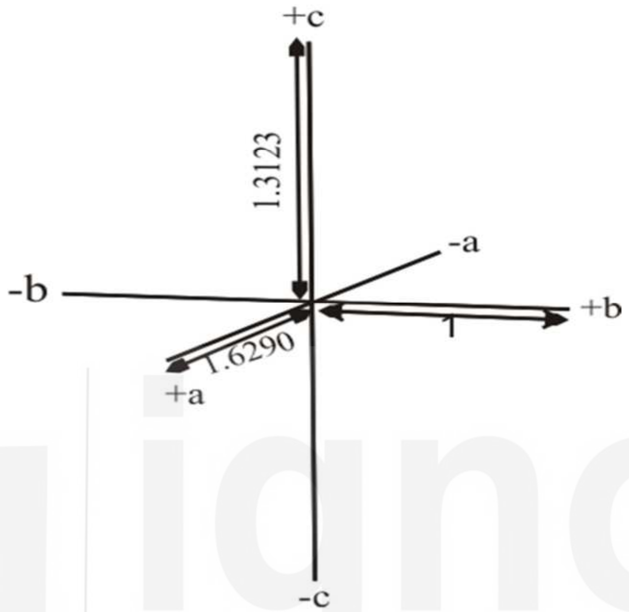


Fig. 3.21: Crystallographic axes of baryte type of orthorhombic system.

Axial Ratio: For Baryte - a:b:c = 1.63:1:1.31

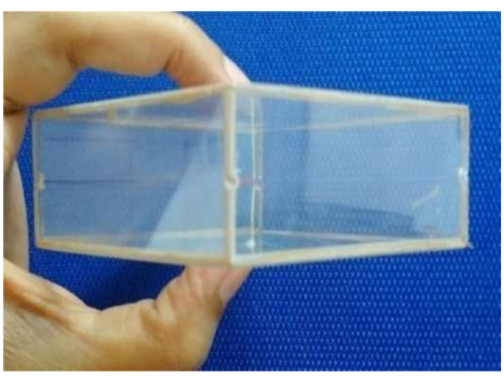
Type: Normal class or baryte type

3.7.2 Symmetry Elements

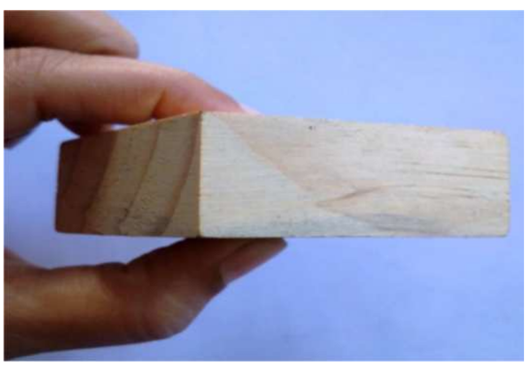
It has geometrical symmetry of a matchbox

- Planes 3 axial
- Axes $3A_2$ crystallographic axes
- Centre of symmetry is present

Crystals of this system uniformly possess three 2-fold axes of symmetry and three mirror planes. This is unique characteristic of orthorhombic system.



(a)



(b)

Fig. 3.22: Baryte in its holding position: a) Plastic model and b) Wooden model.

3.7.3 Forms

Some common forms of orthorhombic system are basal pinacoid; (a) pinacoid, (b) pinacoid and rhombic prism (Fig. 3.23).

There are 3 types of forms in this class. The special forms are:

a) **Pinacoid**: It consists of two parallel faces that occur in three different orientation such as:

- front or a-pinacoid (intersecting only a-axis)
- side or b-pinacoid (intersecting only b-axis)
- basal or c-pinacoid (parallel to a- and b-axes but intersecting c-axis).

b) **Rhombic Prism**: It consists of four faces that are parallel to one axis and intersect the other two. As the face (0II) cuts the b and c axes and parallel to a-axis, the symmetry requires three additional faces ($0\bar{I}I$), ($0\bar{I}\bar{I}$) and ($0I\bar{I}$). This four-faced open form is called a first-order prism.

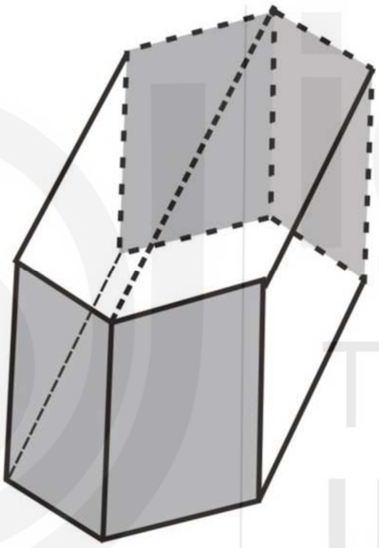


Fig. 3.23: Rhombic prism and pinacoid. The 4 shaded faces are rhombic prism and unshaded faces are pinacoid. Notice side pinacoid and top and bottom pinacoid.

3.8 MONOCLINIC SYSTEM

You have learnt about the cubic system, tetragonal and orthorhombic system. Now we will discuss monoclinic system. Please refer Fig. 3.3d and Table 3.1 to learn briefly about the crystallographic axes and axial angles of the monoclinic system. You have learnt in the earlier that this crystal system is referred to three unequal axes. Two of these axes are inclined towards each other at an oblique angle; these are depicted vertically. The third axis is perpendicular to the other two. The two vertical axes therefore do not intersect one another at right angles, although both are perpendicular to the horizontal axis. The normal class of monoclinic system is known as **gypsum type**. Other common minerals are orthoclase, augite, hornblende, azurite, malachite and mica.

Now let us discuss about normal class of monoclinic system.

3.8.1 Crystallographic Axes

You have read earlier that in the crystals of monoclinic all the three crystallographic axes are unequal. Out of these ‘b’ and ‘c’ are at right angles to one another. The first axis is not at right angle. The axis ‘a’ runs from front to back and is inclined to the plane containing other two axes. Axis ‘a’ is also called as **clino axis**, ‘b’ running from right to left is also known as **ortho axis** and ‘c’ is the vertical crystallographic axis (Fig. 3.24 and 3.25). The ‘a’-axis runs up and away from the observer is known as the ‘clino-axis’. The obtuse angle ‘β’ between ‘+c’ and ‘+a’ is important and is fixed for every mineral.

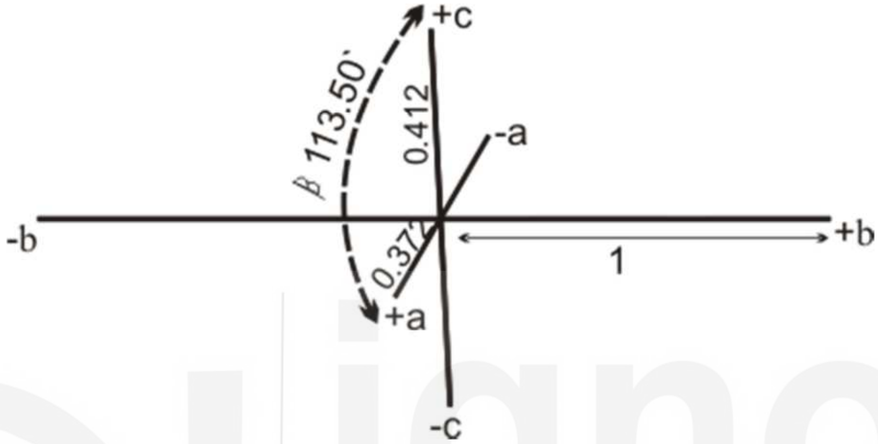


Fig. 3.24: Crystallographic axes of gypsum type of monoclinic system.

Axial Ratio: a≠b≠c, α=γ=90°, β≠90°

For Gypsum- a:b:c = 0.372:1:0.412 β=113° 50’

Type: Normal class or gypsum type

Fig. 3.25: A wooden model showing gypsum crystal.

3.8.2 Symmetry Elements

- Plane- 1 contain clino and vertical axes
- Axis- $1A_2$ ortho axis
- Centre of symmetry is present.

3.8.3 Forms

There are only two types of forms in this class: pinacoids and prisms and both are open forms.

a) **Pinacoids**: They are in pairs because of centre of symmetry. Therefore, we have front or a-pinacoid, side or b-pinacoid and basal or c-pinacoid. There are positive and negative second order pinacoids.

b) **Prism**: The four faced prism is the general form.

SAQ 2

a) Mention the crystallographic axes of tetragonal system.

b) What are the elements of symmetry of zircon?

c) Write the plane and axes of symmetry of barite type.

d) Write about the crystallographic axes of monoclinic system.

3.9 TRICLINIC SYSTEM

We have discussed about the normal class of cubic, tetragonal, orthorhombic, monoclinic and hexagonal systems. Now let us learn about triclinic system. Please refer to the Table 3.1 and Fig. 3.3f to learn and understand the axes, axial angles, symmetry elements and other characteristics of triclinic system. The normal class of triclinic system is also known as **axinite type**. Other common minerals are plagioclase feldspar, microcline.

3.9.1 Crystallographic Axes

You have read in the earlier sections that all three crystallographic axes are unequal and none is at right angle to the other.

The axis ‘a’ generally smaller, running up and away from the observer, is also known as **brachy** axis. The axis ‘b’ running from right to left, is also called as **macro** axis. Axis ‘c’ is vertical.

Angle between ‘+c’ and ‘+b ‘is α, between ‘+ a’ and ‘+c ‘ is β and between ‘+a’ and ‘+b’ is γ (Figs. 3.25 and 3.26)

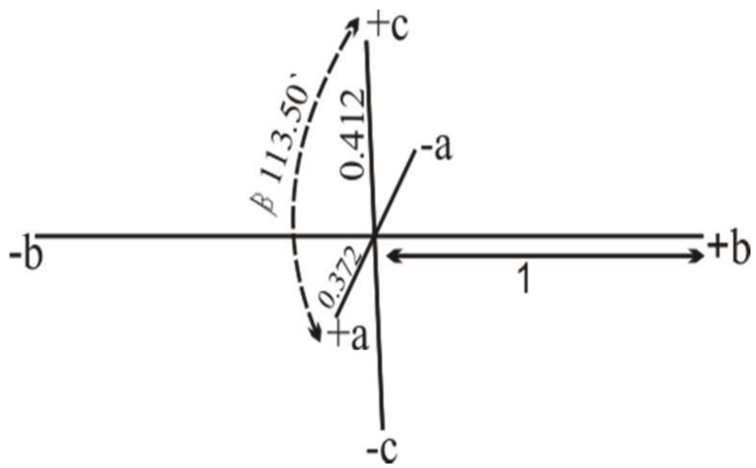


Fig. 3.25: Crystallographic axes of axinite belonging to Triclinic system.

(a) (b)

Fig. 3.26: Axinite crystal: a) wooden; and b) plastic model.

Axial Ratio: $a \neq b \neq c$ $\alpha \neq \beta \neq \gamma \neq 90^o$

For Axinite- a:b:c = 0.49:1:0.48

$\alpha = 82^o 54'$, $\beta = 91^o 52'$, $\gamma = 131^o 32'$.

Type: Normal class or axinite type

3.9.2 Symmetry Elements

- Planes - None
- Axes - None
- Centre of Symmetry is present.

Crystals of the triclinic system may be said to possess only a 1-fold symmetry axis, which is equivalent to possessing no symmetry at all. Crystals of this system possess no mirror planes and demonstrates a centre of symmetry.

3.9.3 Forms

Common forms present are basal pinacoid, front pinacoid, side pinacoid and hemi-prisms.

3.10 SUMMARY

In this unit, we have discussed seven crystal systems. Now let us summarise what we have learnt in this unit. It is tabulated in Table 3.2.

Table 3.2: Seven crystal systems and their characteristics.

Crystal system and normal class	Common minerals	Crystallographic axes	Plane of symmetry	Axes of symmetry	Centre of symmetry	Common forms Present
Cubic System Normal class or Galena Type	Galena, garnet, fluorite, halite, magnetite.	Three equal and mutually perpendicular axes	Planes -9 (3 axial 6 diagonal)	Axes-13 (3^{iv}, 4^{iii},6^{ii})	Present	Cube Rhombdodeca-hedron Octahedron Trapezohedron
Tetragonal System Normal Class or Zircon Type	Zircon, sulphur, cassiterite, vesuvianite, anastase, rutile	Two equal horizontal, third vertical shorter or larger. All at right angles. 3 axes at right angles	Planes- 5 (3 axial, 2 diagonal)	Axes -5 (4^{ii}, 1^{iv})	Present	Basal Pinacoid Tetragonal second order Prism
Hexagonal System Normal Class or Beryl Type	Beryl, kalisite, pyrrhotite, apatite	4 Axes. 3 horizontal, a_1:a_2:a_3 at 120^0 Fourth vertical at 90^0	Planes-7 (4 axial 1 horizontal 3 diagonal 3 vertical)	Axes 7 (6^{ii} ,1^{vi})	Present	Basal Pinacoid Hexagonal Prism
Trigonal System Normal Class or Calcite Type	Calcite, quartz, rhodochrosit, corundum, dolomite	4 Axes, 3 equal Horizontal at 120^0 Fourth vertical at 90^0	Planes-3 (vertical diagonal)	Axes-4 (1^{iii} ,3^{ii})	Present	Pedion, Hexagonal prism, Rhombohedron
Ortho-rhombic System Normal Class or Baryte Type	Baryte, sulphur, olivine, sillimanite, aragonite	Three unequal Axes a, b, c mutually perpendicular. All unequal.	Planes-3 axial	Axes 3^{II}	Present	Basal Pinacoid Front Pinacoid Side Pinacoid Rhombic p,rism
Monoclinic System Normal Class or Gypsum Type	Gypsum, orthoclase, hornblende, augite, hornblende, malachite, mica.	Three unequal axes, a, b, c. B is at right angles to c. a is inclined.	Plane1 (containing a and c axes)	Axes 1^{II} (the b axis)	Present	Basal Pinacoid Clino Pinacoid Ortho Pinacoid Prism
Triclinic System Normal Class or Axinite Type	Axinite, plagioclase feldspar, kyanite, microcline	3 unequal axes, a, b, c not at right angles.	Plane – None	Axes - None	Present	Basal Pinacoid Front Pinacoid Side Pinacoid

3.11 ACTIVITY

1. It would be interesting to construct few crystals belonging to the normal class of seven crystal systems from modeling or simple clay. Hold it with proper orientation. Observe and write your observations.

3.12 TERMINAL QUESTIONS

1. Discuss briefly about the crystallographic axes, symmetry elements and forms of cubic system.
2. Explain how you will distinguish between seven crystal systems on the basis of axis of symmetry.
3. Discuss briefly about the crystallographic axes, symmetry elements and forms of tetragonal system.
4. Describe the crystallographic axes, symmetry elements and forms of monoclinic system.
5. Distinguish the seven crystal systems on the basis of their crystallographic axes and symmetry elements.

3.13 REFERENCES

- Gribble, C.D. (1991) Rutley's Elements of Mineralogy, 27th Edition. CBS Publishers and Distributors, Delhi.
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3.14 FURTHER/SUGGESTED READINGS

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- Gribble, C.D. (1991) Rutley's Elements of Mineralogy, 27th Edition. CBS Publishers and Distributors, Delhi.
- Singh, P. (2013) Engineering and General Geology, S.K. Kataria & Sons, Delhi.
- Sharma Ram S. and Sharma, A. (2013) Crystallography and Mineralogy - Concepts and Methods, Editors: A.K. Jain and Sandeep Singh, Geological Society of India, Banglore.

3.15 ANSWERS

Self Assessment Questions

1 a) Cubic or Isometric system, tetragonal system, orthorhombic system, monoclinic system, hexagonal system, trigonal system, triclinic system.

b) Number of crystallographic axes, relative length or axial ratios of crystallographic axes, linear and angular relationships of crystallographic axes, elements of symmetry, i.e. plane, axis and centre.

c) One.

d) One.

e) Nine

2 a) There are three crystallographic axes at right angle or perpendicular to one another. Two horizontal axes are equal and the third axis is vertical and unequal, which may be shorter or longer. The axis a_1 runs from front to back, a_2 from right to left and c is vertical.

b) Five planes of symmetry, 5 axes of symmetry and a centre of symmetry.

c) Three planes and three axes of symmetry.

d) In monoclinic system there are three crystallographic axes. All are unequal. Axes 'b' and 'c' are at right angles but 'a' is inclined. It runs up and away from the observer. Angle between +a and +c is β which in this case is obtuse angle.

Terminal Questions

1. Please refer to section 3.3.
2. Triclinic system has no axis of symmetry. Monoclinic system has diad axis (1^{ii}) and no higher degree axis of symmetry. Orthorhombic system has three diad axes of symmetry (3^{ii}). Tetragonal system has one tetrad axis of symmetry (1^{iv}). Cubic or isometric system has four triad axes of symmetry (4^{iii}). Hexagonal system has one hexad axis of symmetry (1^{vi}). Trigonal system has one triad axis of symmetry (1^{iii}).
3. Please refer to section 3.4.
4. Please refer to section 3.6.
5. Please refer to Table 3.2.

GLOSSARY

Amorphous : This term is used for those rocks, minerals and materials which have no form and definite crystal structure.

Axial angle : Axial angleis the angle between the positive ends of the axes and are conventionally designated by Greek letters α, β, γ.

Axial plane : Axial plane is a plane which contains two crystallographic axes.

Axial ratio : Axial ratio can be defined as the ratio of the length of the crystallographic axes expressed in terms of one of horizontal axes, usually 'b' –axes as unity.

Axis of symmetry : This is the axis along which on rotation at 360^o the crystal comes in the same position more than once.

Basal plane : This refers to plane parallel to lateral or horizontal axis of a crystal.

Centre of symmetry : When similar faces occur in parallel pairs, on opposite sides of a crystal, the crystal is said to possess a Centre of symmetry.

Crystal symmetry : Crystal symmetry refers to regularity present in it with respect to Plane, Axes and Centre of Symmetry. Crystals belonging to different crystal systems exhibit different symmetry elements.

Crystallographic axes : Crystallographic axes are imaginary reference lines and are generally taken parallel to the intersection edges of major crystal faces.

Crystallography : Crystallography is the study of crystals and the laws which govern their growth, external shape and internal structure and form.

Diad axis : Diad axis is the axis showing of two times symmetry- n=2 (at 180^o) on every 360° on rotation.

Distortion : Distortion may be produced because of more supply of material from one direction or crystallization under pressure from one direction in limited space.

Diagonal plane	:	Diagonal plane is tha plane along which the crystal can be divided into two equal halves.
Face	:	It is the flat and plane surface which demarcates the boundary of a crystal.
Hexad axis	:	Hexad axis is the axis showing of five times symmetry- n=2 (at 60^o) on every 360° on rotation.
Micro-axis	:	b-axis of orthorhombic or triclinic system.
Normal class	:	Normal class is the class or type of maximum symmetry of that system.
Octahedral	:	Comprising faces with eight plane, concerned with eight faces or made with eight faces.
Pedion	:	Pedion consists of single form represented by one face.
Plane of symmetry	:	Plane of Symmetry is the plane which divides the crystal into two similar halves.
Prism	:	Prism is a face cutting horizontal axes but remaining parallel to the vertical axis (c-axis). It is an open form consisting of four faces; each face is parallel to vertical axes and cuts one or more horizontal axes.
Pyramid	:	Pyramid is a face cutting all the three crystallographic axes.
Subhedral	:	It is concerned with a form which is partially comprises of its own crystal faces in crystallography.
Symmetry	:	The term symmetry refers to the property of being balanced or well-proportioned in common English usage.
Tetrahedral	:	Concerned with those crystals having four faces in crystallography.
Tetrad axis	:	Tetrad axis is the axis showing of three times symmetry- n=2 (at 90o) on every 360° on rotation.
Triad axis	:	Triad axis is the axis showing of three times symmetry- n=2 (at 120^o) on every 360° on rotation.

Twinning	:	Formation of twinned crystals.
Twinning law	:	It is the law governing the relation between different parts of a plane. It is based on following factors: Axis of twinning or plane of twinning Internal change of twinned plane Nature of twinned plane Few laws of twinning are: Albite law, Baveno law, Carlsbad law etc.
Unit form	:	Unit form is the face from whose intercepts on the axes a ,b ,c determine their assumed unit lengths. The intercepts that any face makes on the crystallographic axes are either infinite or small rational multiples of intercepts made by unit form.