

LECTURE NOTES 1ST SEMESTER

UNIT- 3

Forms, Open and Closed

Any group of crystal faces related by the same symmetry is called a *form*. There are 47 or 48 crystal forms depending on the classification used.

Closed forms are those groups of faces all related by symmetry that completely enclose a volume of space. It is possible for a crystal to have faces entirely of one closed form. Open forms are those groups of faces all related by symmetry that do not completely enclose a volume of space. A crystal with open form faces requires additional faces as well. There are 17 or 18 open forms and 30 closed forms.

Triclinic, Monoclinic and Orthorhombic Forms

Pedion

A single face unrelated to any other by symmetry. Open

Pinacoid

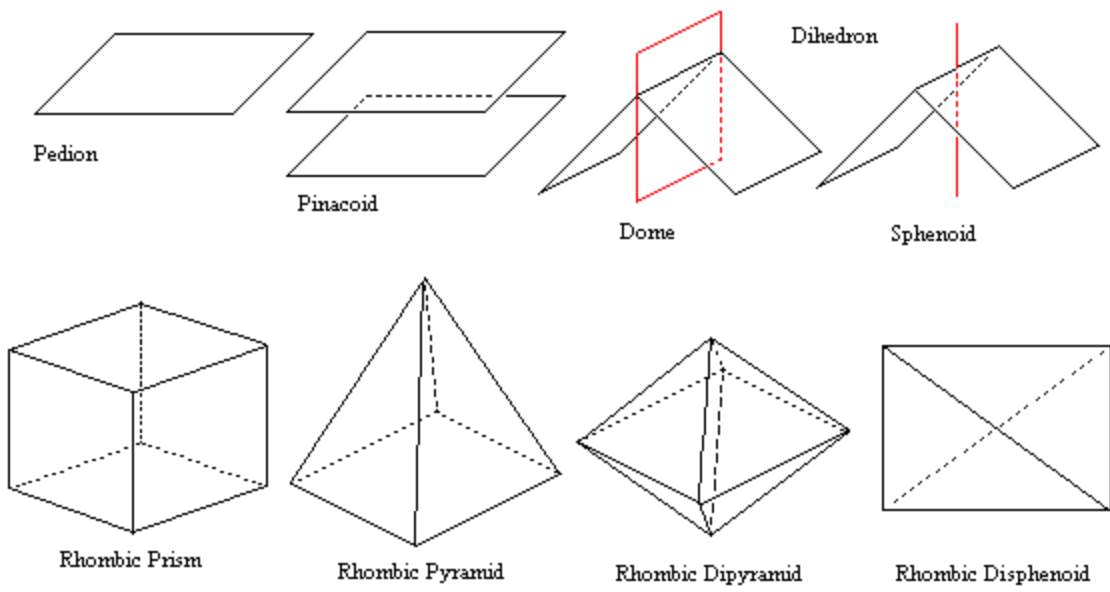
A pair of parallel faces related by mirror plane or twofold symmetry axis. Open

Dihedron

A pair of intersecting faces related by mirror plane or twofold symmetry axis. Some crystallographers distinguish between **domes** (pairs of intersecting faces related by mirror plane) and **sphenoids** (pairs of intersecting faces related by twofold symmetry axis). All are open forms

Pyramid

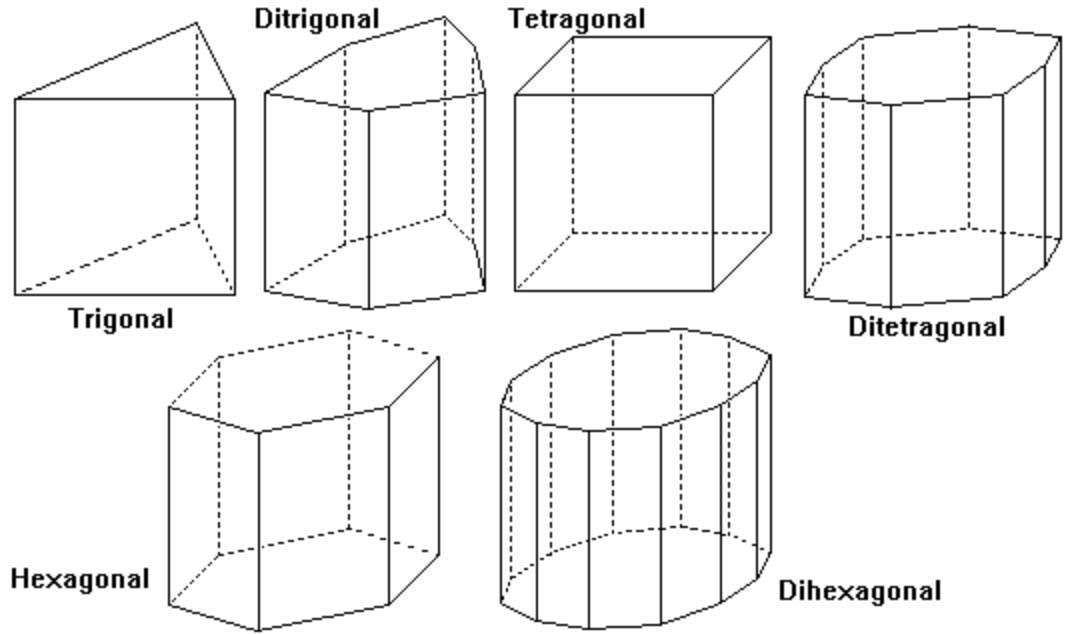
A set of faces related by symmetry and meeting at a common point. Open form.



3-, 4- and 6-Fold Prisms

Prism

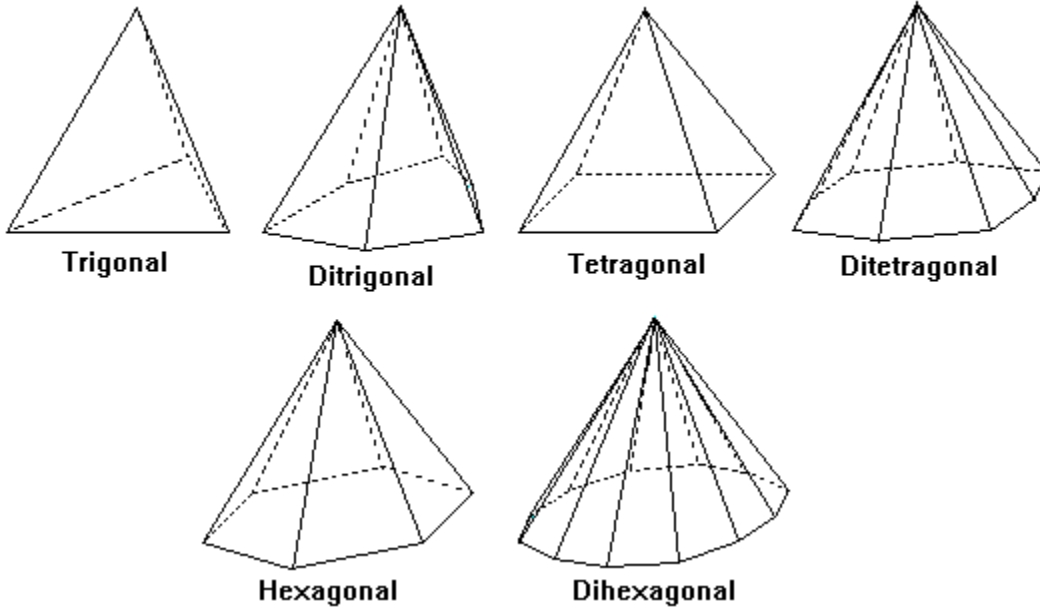
A collection of faces all parallel to a symmetry axis. All are open.



3-, 4- and 6-Fold Pyramids

Pyramid

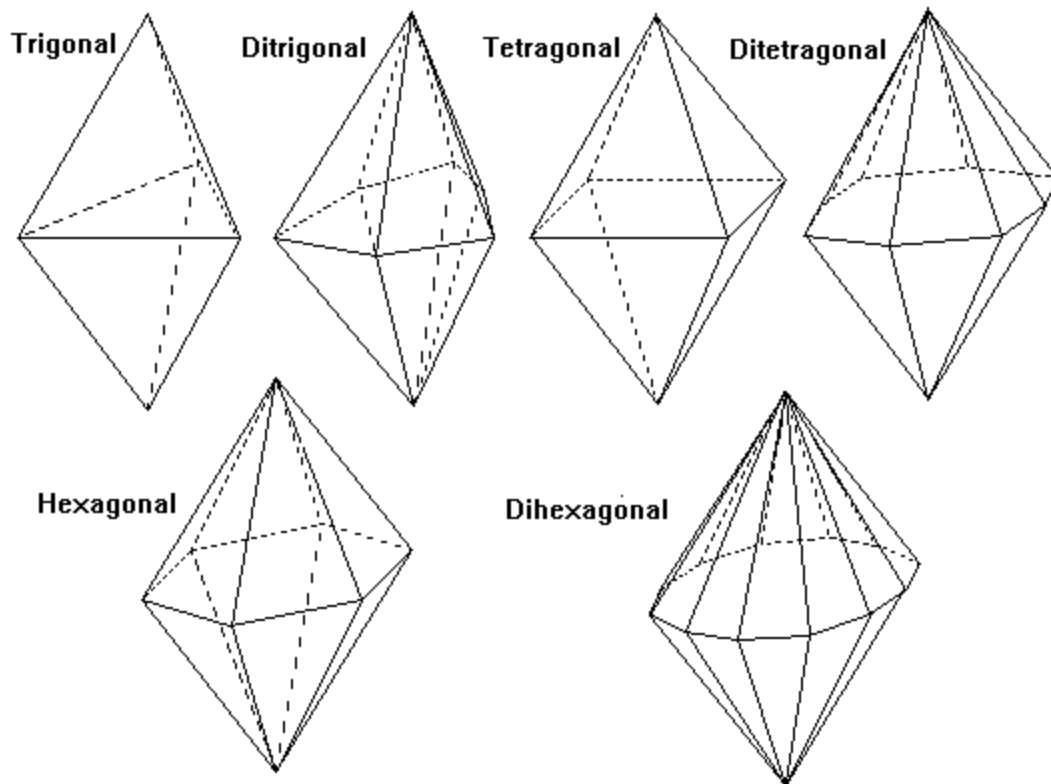
A group of faces intersecting at a symmetry axis. All are open. The base of the pyramid would be a pedion.



3-, 4- and 6-Fold Dipyramids

Dipyramid

Two pyramids joined base to base along a mirror plane. All are closed, as are all following forms.



Scalenohedra and Trapezohedra

Disphenoid

A solid with four congruent triangle faces, like a distorted tetrahedron. Midpoints of edges are twofold symmetry axes. In the tetragonal disphenoid the faces are isosceles triangles and a fourfold inversion axis joins the midpoints of the bases of the isosceles triangles.

Scalenohedron

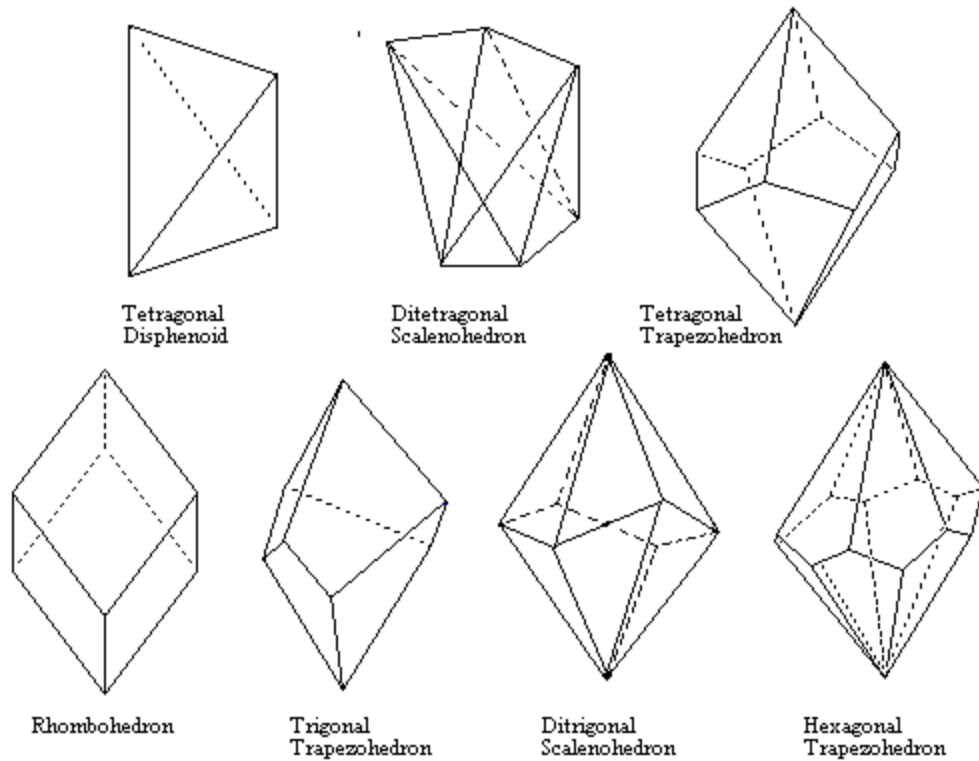
A solid made up of scalene triangle faces (all sides unequal)

Trapezohedron

A solid made of trapezia (irregular quadrilaterals)

Rhombohedron

A solid with six congruent parallelogram faces. Can be considered a cube distorted along one of its diagonal three-fold symmetry axes.



Tetartoidal, Gyroidal and Diploidal Forms

Tetartoid

The general form for symmetry class 233 . 12 congruent irregular pentagonal faces. The name comes from a Greek root for one-fourth because only a quarter of the 48 faces for full isometric symmetry are present.

Gyroid

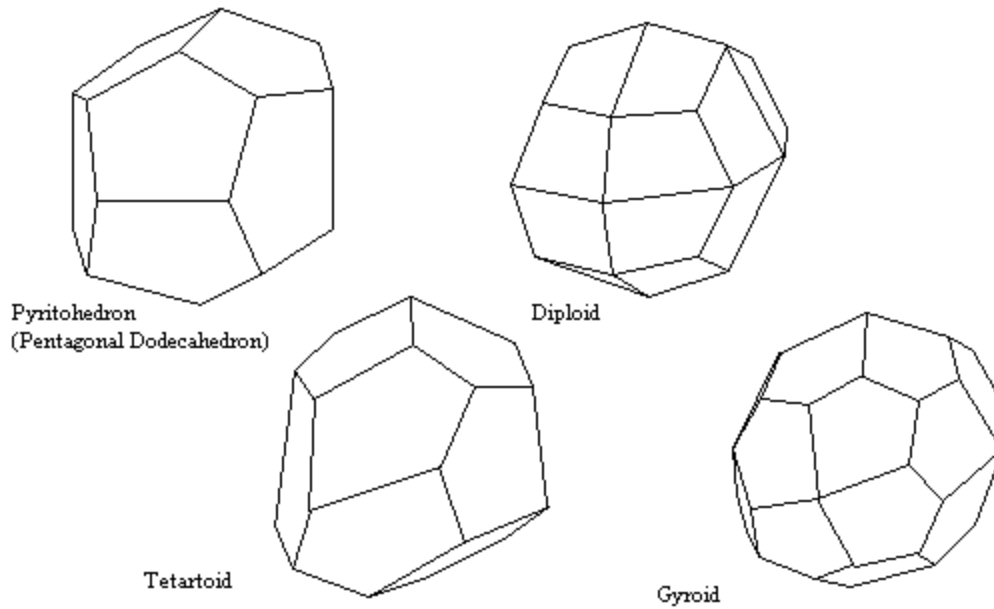
The general form for symmetry class 432 . 24 congruent irregular pentagonal faces.

Diploid

The general form for symmetry class $2/m3^*$. 24 congruent irregular quadrilateral faces. The name comes from a Latin root for half, because half of the 48 faces for full isometric symmetry are present.

Pyritohedron

Special form $(hk0)$ of symmetry class $2/m3^*$. Faces are each perpendicular to a mirror plane, reducing the number of faces to 12 pentagonal faces. Although this superficially looks like the Platonic solid with 12 regular pentagon faces, these faces are not regular.



Hextetrahedral Forms

Tetrahedron

Four equilateral triangle faces (111)

Trapezohedral Tristetrahedron

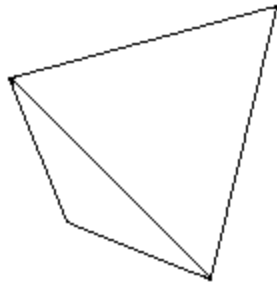
12 kite-shaped faces (hll)

Trigonal Tristetrahedron

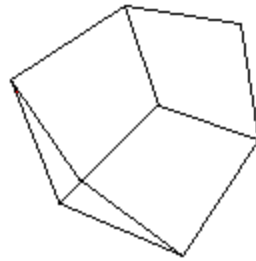
12 isosceles triangle faces (hhl). Like an tetrahedron with a low triangular pyramid built on each face.

Hextetrahedron

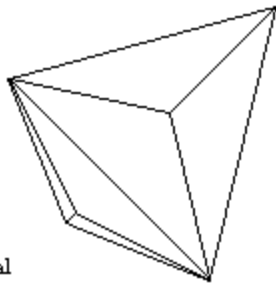
24 triangular faces (hkl) The general form.



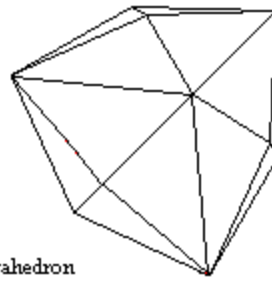
Tetrahedron



Trapezohedral
Tristetrahedron



Trigonal
Tristetrahedron



Hexetetrahedron

Hexoctahedral Forms

Cube

Six square faces (100).

Octahedron

Eight equilateral triangle faces (111)

Rhombic Dodecahedron

12 rhombic faces (110)

Trapezohedral Trisoctahedron

24 kite-shaped faces (hhl). Note that the Miller indices for the two trisoctahedra are the opposite of those for the tristetrahedra.

Trigonal Trisoctahedron

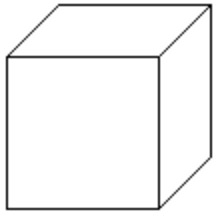
24 isosceles triangle faces (hll). Like an octahedron with a low triangular pyramid built on each face.

Tetrahexahedron

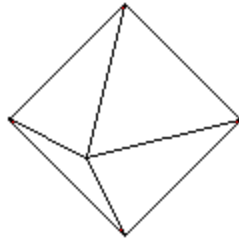
24 isosceles triangle faces (h0l). Like an cube with a low pyramid built on each face.

Hexoctahedron

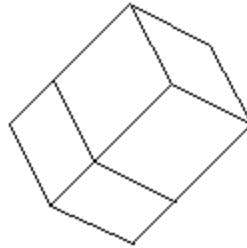
48 triangular faces (hkl) The general form



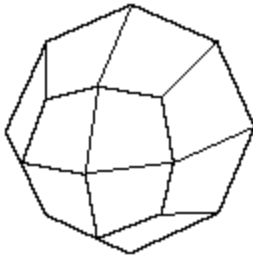
Cube



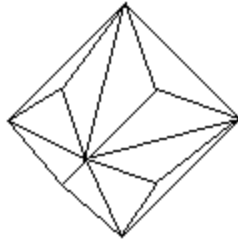
Octahedron



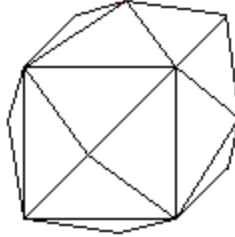
Rhombic
Dodecahedron



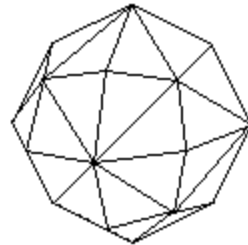
Trapezohedral
Trisoctahedron



Trigonal
Trisoctahedron



Tetrahexahedron



Hexoctahedron

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External Symmetry of Crystals, 32 Crystal Classes

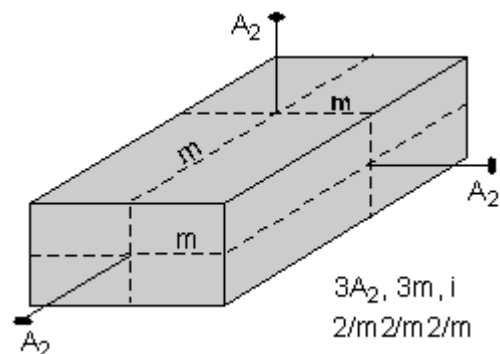
As stated in the last lecture, there are 32 possible combinations of symmetry operations that define the external symmetry of crystals. These 32 possible combinations result in the 32 crystal classes. These are often also referred to as the 32 point groups. We will go over some of these in detail in this lecture, but again I want to remind everyone that the best way to see this material is by looking at the crystal models in lab.

Hermann-Mauguin (International) Symbols

Before going into the 32 crystal classes, I first want to show you how to derive the Hermann-Mauguin symbols (also called the international symbols) used to describe the crystal classes from the symmetry content. We'll start with a simple crystal then look at some more complex examples.

The rectangular block shown here has 3 2-fold rotation axes (A_2), 3 mirror planes (m), and a center of symmetry (i). The rules for deriving the Hermann-Mauguin symbol are as follows:

1. Write a number representing each of the unique rotation axes present. A unique rotation axis is one that exists by itself and is not produced by another symmetry operation. In this case, all three 2-fold axes are



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unique, because each is perpendicular to a different shaped face, so we write a 2 (for 2-fold) for each axis

2 2 2

2. Next we write an "m" for each unique mirror plane. Again, a unique mirror plane is one that is not produced by any other symmetry operation. In this example, we can tell that each mirror is unique because each one cuts a different looking face. So, we write:

2 m 2 m 2 m

3. If any of the axes are perpendicular to a mirror plane we put a slash (/) between the symbol for the axis and the symbol for the mirror plane. In this case, each of the 2-fold axes are perpendicular to mirror planes, so our symbol becomes:

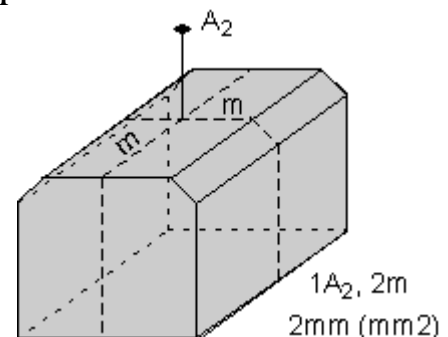
2/m2/m2/m

If you look in the table given in the lecture notes below, you will see that this crystal model belongs to the Rhombic-dipyramidal class.

Our second example involves the block shown here to the right. This model has one 2-fold axis and 2 mirror planes. For the 2-fold axis, we write:

2

Each of the mirror planes is unique. We can tell that because each one cuts a different



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looking face. So, we write 2 "m"s, one for each mirror plane:

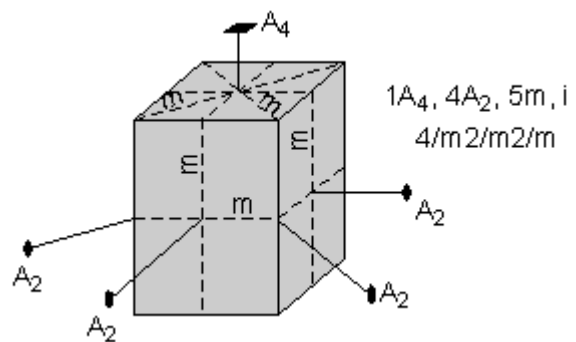
$$2\ m\ m$$

Note that the 2-fold axis is not perpendicular to a mirror plane, so we need no slashes. Our final symbol is then:

$$2mm$$

For this crystal class, the convention is to write $mm2$ rather than $2mm$ (I'm not sure why). If you consult the table below, you will see that this crystal model belongs to the Rhombic-pyramidal class.

The third example is shown here to the right. It contains 1 4-fold axis, 4 2-fold axes, 5 mirror planes, and a center of symmetry. Note that the 4-fold axis is unique. There are 2 2-fold axes that are perpendicular to identical faces, and 2 2-fold axes that run through the vertical edges of the crystal. Thus there are only 2 unique 2 fold axes, because the others are required by the 4-fold axis perpendicular to the top face. So, we write:



$$4\ 2\ 2$$

Although there are 5 mirror planes in the model, only 3 of them are unique. Two mirror planes cut the front and side faces of the crystal, and are perpendicular to the 2-fold axes that are perpendicular to these faces. Only one of these is unique, because the other is required by the 4-fold rotation axis. Another set of 2 mirror planes cuts diagonally across the top and down the edges of the model. Only one of these is

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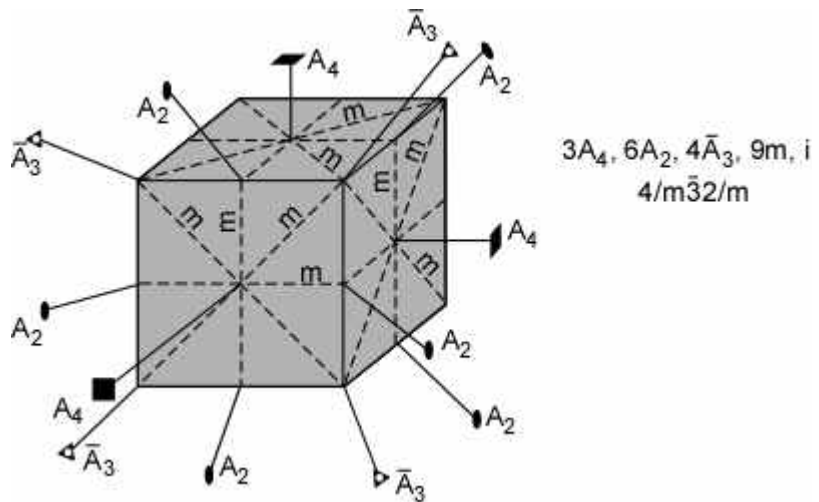
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unique, because the other is generated by the 4-fold rotation axis and the previously discussed mirror planes. The mirror plane that cuts horizontally through the crystal and is perpendicular to the 4-fold axis is unique. Since all mirror unique mirror planes are perpendicular to rotation axes, our final symbol becomes:

$$4/m2/m2/m$$

Looking in the table below, we see that this crystal belongs to the Ditetragonal-dipyramidal class.

Our last example is the most complex. Note that it has 3 4-fold rotation axes, each of which is perpendicular to a square shaped face, 4 3-fold rotoinversion axes (some of which are not shown in the diagram to reduce complexity), each sticking out of the corners of the cube, and 6 2-fold rotation axes (again, not all are shown), sticking out of the edges of the cube. In addition, the crystal has 9 mirror planes, and a center of symmetry.

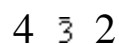


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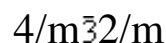
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There is only 1 unique 4 fold axis, because each is perpendicular to a similar looking face (the faces of the cube). There is only one unique 3-fold rotoinversion axes, because all of them stick out of the corners of the cube, and all are related by the 4-fold symmetry. And, there is only 1 unique 2-fold axis, because all of the others stick out of the edges of the cube and are related by the mirror planes the other set of 2-fold axes. So, we write a 4, a $\bar{3}$, and a 2 for each of the unique rotation axes.



There are 3 mirror planes that are perpendicular to the 4 fold axes, and 6 mirror planes that are perpendicular to the 2-fold axes. No mirror planes are perpendicular to the 3-fold rotoinversion axes. So, our final symbol becomes:



Consulting the table in the lecture notes below, reveals that this crystal belongs to the hexoctahedral crystal class.

The 32 Crystal Classes

The 32 crystal classes represent the 32 possible combinations of symmetry operations. Each crystal class will have crystal faces that uniquely define the symmetry of the class. These faces, or groups of faces are called crystal forms. Note that you are not expected to memorize the crystal classes, their names, or the symmetry associated with each class. You will, however, be expected to determine the symmetry content of crystal models, after which you can consult the tables in your textbook, lab handouts, or lecture notes. All testing on this material in the lab will be open book.

In this lecture we will go over some of the crystal classes and their symmetry. I will not be able to cover all of the 32 classes. You will,

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however, see many of the 32 classes during your lab work. Note that it is not easy to draw a crystal of some classes without adding more symmetry or that can be easily seen in a two dimensional drawing.

The table below shows the 32 crystal classes, their symmetry, Hermann-Mauguin symbol, and class name.

Crystal System	Crystal Class	Symmetry	Name of Class
Triclinic	1	none	Pedial
	$\bar{1}$	i	Pinacoidal
Monoclinic	2	1A ₂	Sphenoidal
	m	1m	Domatic
	2/m	i, 1A ₂ , 1m	Prismatic
Orthorhombic	222	3A ₂	Rhombic-disphenoidal
	mm2 (2mm)	1A ₂ , 2m	Rhombic-pyramidal
	2/m2/m2/m	i, 3A ₂ , 3m	Rhombic-dipyramidal
Tetragonal	4	1A ₄	Tetragonal-Pyramidal
	$\bar{4}$	\bar{A}_4	Tetragonal-disphenoidal
	4/m	i, 1A ₄ , 1m	Tetragonal-dipyramidal
	422	1A ₄ , 4A ₂	Tetragonal-trapezohedral
	4mm	1A ₄ , 4m	Ditetragonal-pyramidal

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	$\bar{4}2m$	$1\bar{A}_4, 2A_2, 2m$	Tetragonal-scalenohedral
	$4/m2/m2/m$	$i, 1A_4, 4A_2, 5m$	Ditetragonal-dipyramidal
Hexagonal	3	$1A_3$	Trigonal-pyramidal
	$\bar{3}$	$1\bar{A}_3$	Rhombohedral
	32	$1A_3, 3A_2$	Trigonal-trapezohedral
	$3m$	$1A_3, 3m$	Ditrigonal-pyramidal
	$\bar{3}2/m$	$1\bar{A}_3, 3A_2, 3m$	Hexagonal-scalenohedral
	6	$1A_6$	Hexagonal-pyramidal
	$\bar{6}$	$1\bar{A}_6$	Trigonal-dipyramidal
	$6/m$	$i, 1A_6, 1m$	Hexagonal-dipyramidal
	622	$1A_6, 6A_2$	Hexagonal-trapezohedral
	$6mm$	$1A_6, 6m$	Dihexagonal-pyramidal
	$\bar{6}m2$	$1\bar{A}_6, 3A_2, 3m$	Ditrigonal-dipyramidal
	$6/m2/m2/m$	$i, 1A_6, 6A_2, 7m$	Dihexagonal-dipyramidal
Isometric	23	$3A_2, 4A_3$	Tetaroidal
	$2/m\bar{3}$	$3A_2, 3m, 4\bar{A}_3$	Diploidal
	432	$3A_4, 4A_3, 6A_2$	Gyroidal

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	$\bar{4}3m$	$3\bar{A}_4, 4A_3, 6m$	Hextetrahedral
	$4/m\bar{3}2/m$	$3A_4, 4\bar{A}_3, 6A_2, 9m$	Hexoctahedral

Note that the 32 crystal classes are divided into 6 crystal systems.

1. The Triclinic System has only 1-fold or 1-fold rotoinversion axes.
2. The Monoclinic System has only mirror plane(s) or a single 2-fold axis.
3. The Orthorhombic System has only two fold axes or a 2-fold axis and 2 mirror planes.
4. The Tetragonal System has either a single 4-fold or 4-fold rotoinversion axis.
5. The Hexagonal System has no 4-fold axes, but has at least 1 6-fold or 3-fold axis.
6. The Isometric System has either 4 3-fold axes or 4 3-fold rotoinversion axes.

Triclinic System

Characterized by only 1-fold or 1-fold rotoinversion axis

- Pedial Class, 1, Symmetry content - none

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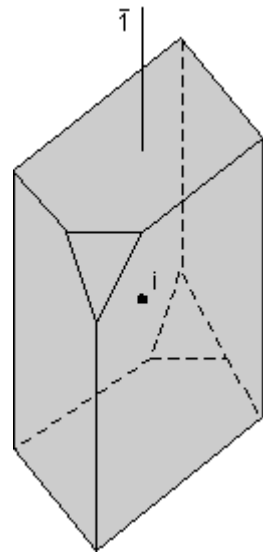
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In this class there is no symmetry, so all crystal faces are unique and are not related to each other by symmetry. Such faces are called *Pedions*, thus this is the Pedial Class. Only a few rare minerals are in this class.

- Pinacoidal Class, $\bar{1}$, Symmetry content - i

Since in this class there is only a center of symmetry, pairs of faces are related to each other through the center. Such faces are called *pinacoids*, thus this is the pinacoidal class. Among the common minerals with pinacoidal crystals are: microcline (K-feldspar), plagioclase, turquoise, and wollastonite.

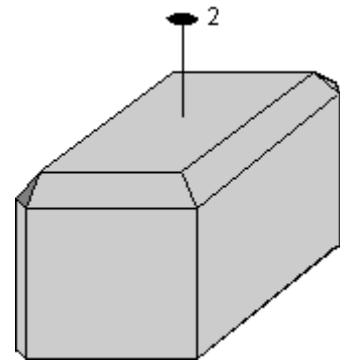


Monoclinic System

Characterized by having only mirror plane(s) or a single 2-fold axis.

- Sphenoidal Class, 2, Symmetry content - $1A_2$

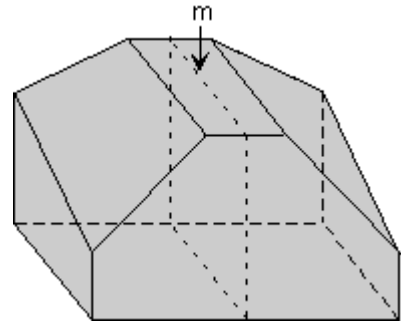
In this class there is a single 2-fold rotation axis. Faces related by a 2-fold axis are called *sphenoids*, thus this is the sphenoidal class. Only rare minerals belong to this class.



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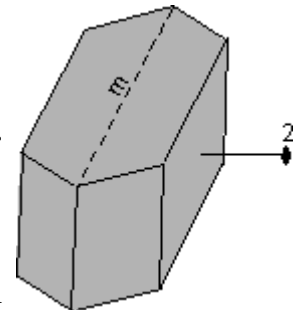
- Domatic Class, m , Symmetry content - $1m$

This class has a single mirror plane. Faces related by a mirror plane are called *domes*, thus this is the domatic class. Only 2 rare minerals crystallize in this class.



- Prismatic Class, $2/m$. Symmetry content - $1A_2$, m , i

This class has a single 2-fold axis perpendicular to a single mirror plane. This class has pinacoid faces and prism faces. A prism is defined as 3 or more identical faces that are all parallel to the same line. In the prismatic class, these prisms consist of 4 identical faces, 2 of which are shown in the diagram on the front of the crystal. The other two are on the back side of the crystal.



The most common minerals that occur in the prismatic class are the micas (biotite and muscovite), azurite, chlorite, clinopyroxenes, epidote, gypsum, malachite, kaolinite, orthoclase, and talc.

Orthorhombic System

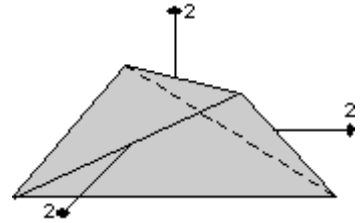
Characterized by having only two fold axes or a 2-fold axis and 2

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mirror planes.

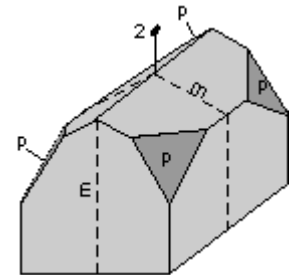
- Rhombic -disphenoidal Class, 222,
Symmetry content - $3A_2$

In this class there are 3 2-fold axis and no mirror planes. The 2-fold axes are all perpendicular to each other. The *disphenoid* faces that define this group consist of 2 faces on top of the crystal and 2 faces on the bottom of the crystal that are offset from each other by 90° . Epsomite is the most common rare mineral of this class.



- Rhombic-pyramidal Class, $2mm$ ($mm2$),
Symmetry content - $1A_2, 2m$

This class has two perpendicular mirror planes and a single 2-fold rotation axis. Because it has not center of symmetry, the faces on the top of the crystal do not occur on the bottom. A *pyramid*, is a set of 3 or more identical faces that intersect at a point. In the case of the rhombic pyramid, these would be 4 identical faces, labeled p, in the diagram.



Hemimorphite is the most common mineral with this symmetry.

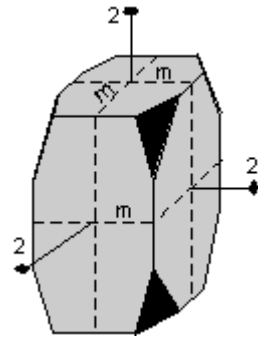
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- Rhombic-dipyramidal Class, $2/m2/m2/m$, Symmetry content - $3A_2, 3m, i$

This class has 3 perpendicular 2-fold axes that are perpendicular to 3 mirror planes. The *dipyramid* faces consist of 4 identical faces on top and 4 identical faces on the bottom that are related to each other by reflection across the horizontal mirror plane or by rotation about the horizontal 2-fold axes.



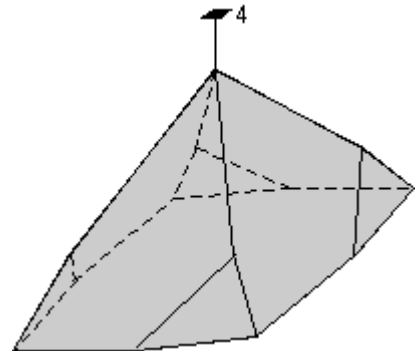
The most common minerals in this class are andalusite, anthophyllite, aragonite, barite, cordierite, olivine, sillimanite, stibnite, sulfur, and topaz.

Tetragonal System

Characterized by a single 4-fold or 4-fold rotoinversion axis.

- Tetragonal-pyramidal Class, 4, Symmetry content - $1A_4$

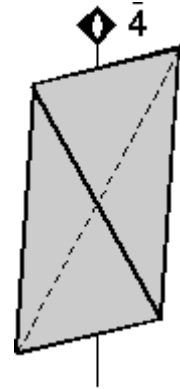
Since this class has a single 4-fold axis and no mirror planes, there are no pyramid faces on the bottom of the crystal. Wulfenite is the only mineral known to crystallize in this class.



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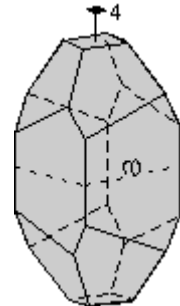
- Tetragonal-disphenoidal Class, $\bar{4}$, Symmetry content - $1\bar{A}_4$

With only a single 4-fold rotoinversion axis, the disphenoid faces consist of two identical faces on top, and two identical faces on the bottom, offset by 90° . Note that there are no mirror planes in this class. Only one rare mineral is known to form crystals of this class.



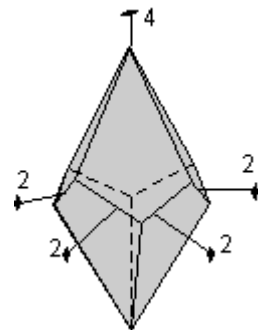
- Tetragonal-dipyramidal Class, $4/m$, Symmetry content - $1A_4, 1m, i$

This class has a single 4-fold axis perpendicular to a mirror plane. This results in 4 pyramid faces on top that are reflected across the mirror plane to form 4 identical faces on the bottom of the crystal. Scheelite and scapolite are the only common minerals in this class.



- Tetragonal-trapezohedral Class, 422 , Symmetry content - $1A_4, 4A_2$

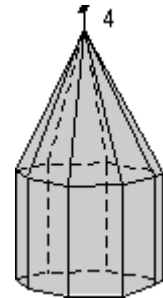
This class has a 4 fold axis perpendicular to 4 2-fold axes. There are no mirror planes. Only one rare mineral belongs to this class.



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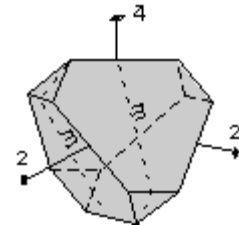
- Ditetragonal-pyramidal Class, $4mm$, Symmetry content - $1A_4, 4m$

This class has a single 4-fold axis and 4 mirror planes. The mirror planes are not shown in the diagram, but would cut through the edges and center of the faces shown. Note that the ditetragonal pyramid is a set of 8 faces that form a pyramid on the top of the crystal. Only one rare mineral forms in the crystal class.



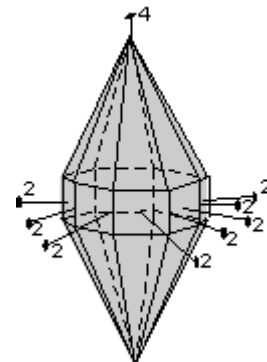
- Tetragonal-scalenohedral Class, $\bar{4}2m$, Symmetry Content - $1\bar{A}_4, 2A_2, 2m$

This class has a 4-fold rotoinversion axis that is perpendicular to 2 2-fold rotation axes. The 2 mirror planes are parallel to the $\bar{4}$ and are at 45° to the 2-fold axes. Chalcopyrite and stannite are the only common minerals with crystals in this class.



- Ditetragonal-dipyramidal Class, $4/m2/m2/m$, Symmetry content - $1A_4, 4A_2, 5m, i$

This class has the most symmetry of the tetragonal system. It has a single 4-fold axis that is perpendicular to 4 2-fold axes. All of the 2-fold axes are perpendicular to mirror planes. Another mirror plane is perpendicular to the 4-fold axis. The mirror planes are not shown in the diagram, but would cut through all of the vertical edges and through the center



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of the pyramid faces. The fifth mirror plane is the horizontal plane. Note the ditetragonal-dipyramid consists of the 8 pyramid faces on the top and the 8 pyramid faces on the bottom.

Common minerals that occur with this symmetry are anatase, cassiterite, apophyllite, zircon, and vesuvianite.

Note that I will not have time in lecture to cover the rest of the 32 crystal classes, that is those belonging to the hexagonal and isometric systems. These are difficult to draw, and are best left for the student to study using the textbook, pages 180-205, and the crystal models in lab.

Examples of questions on this material that could be asked on an exam

1. Why are there only 32 classes of crystals?
2. What criteria is involved in dividing the 32 crystal classes into 6 crystal systems?
3. Note that exams where you will be asked to recognize the different crystal classes and their symmetry, the exams will be open book, so you will have access to the tables and figures in these notes.

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Axial Ratios, Parameters, Miller Indices

Crystallographic axes can be defined for the various crystal systems. Two important points to remember are that

1. The lengths of the crystallographic axes are controlled by the dimensions of the unit cell upon which the crystal is based.
2. The angles between the crystallographic axes are controlled by the shape of the unit cell.

We also noted last time that the relative lengths of the crystallographic axes control the angular relationships between crystal faces. This is true because crystal faces can only develop along lattice points. The relative lengths of the crystallographic axes are called axial ratios, our first topic of discussion.

Axial Ratios

Axial ratios are defined as the relative lengths of the crystallographic axes. They are normally taken as relative to the length of the b crystallographic axis. Thus, an axial ratio is defined as follows:

$$\text{Axial Ratio} = a/b : b/b : c/b$$

where a is the actual length of the a crystallographic axis, b, is the actual length of the b crystallographic axis, and c is the actual length of the c crystallographic axis.

- For Triclinic, Monoclinic, and Orthorhombic crystals, where the lengths of the three axes are different, this reduces to

$$a/b : 1 : c/b \text{ (this is usually shortened to } a : 1 : c)$$

- For Tetragonal crystals where the length of the a and b axes are equal, this reduces to

$$1 : 1 : c/b \text{ (this is usually shorted to } 1 : c)$$

- For Isometric crystals where the length of the a, b, and c axes are equal this becomes

1 : 1 : 1 (this is usually shorted to 1)

- **For Hexagonal crystals where there are three equal length axes (a_1 , a_2 , and a_3) perpendicular to the c axis this becomes:**

1 : 1 : 1: c/a (usually shortened to 1 : c)

Modern crystallographers can use x-rays to determine the size of the unit cell, and thus can determine the absolute value of the crystallographic axes. For example, the mineral quartz is hexagonal, with the following unit cell dimensions as determined by x-ray crystallography:

$$a_1 = a_2 = a_3 = 4.913\text{\AA}$$

$$c = 5.405\text{\AA}$$

where \AA stands for Angstroms = 10^{-10} meter.

Thus the axial ratio for quartz is

$$1 : 1 : 1 : 5.405/4.913$$

or

$$1 : 1 : 1 : 1.1001$$

which simply says that the c axis is 1.1001 times longer than the a axes.

For orthorhombic sulfur the unit cell dimensions as measured by x-rays are:

$$a = 10.47\text{\AA}$$

$$b = 12.87\text{\AA}$$

$$c = 24.39\text{\AA}$$

Thus, the axial ratio for orthorhombic sulfur is:

$$10.47/12.87 : 12.87/12.87 : 24.39/12.87$$

or

$$0.813 : 1 : 1.903$$

Because crystal faces develop along lattice points, the angular relationship between faces must depend on the relative lengths of the axes. Long before x-rays were invented and

absolute unit cell dimensions could be obtained, crystallographers were able to determine the axial ratios of minerals by determining the angles between crystal faces. So, for example, in 1896 the axial ratios of orthorhombic sulfur were determined to be nearly exactly the same as those reported above from x-ray measurements.

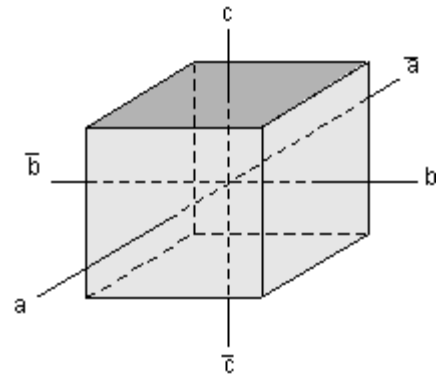
In a later lecture we will see how we can determine axial ratios from the angular relationships between faces. First, however we must determine how we can name, or index faces of crystals and define directions within crystals.

Intercepts of Crystal Faces (Weiss Parameters)

Crystal faces can be defined by their intercepts on the crystallographic axes. For non-hexagonal crystals, there are three cases.

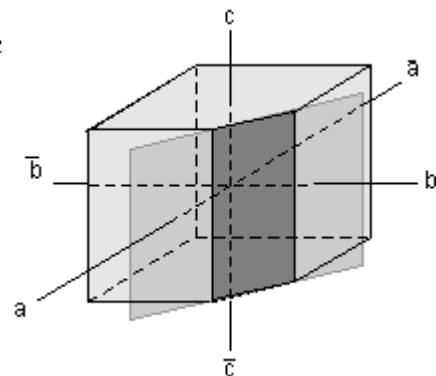
1. A crystal face intersects only one of the crystallographic axes.

As an example the top crystal face shown here intersects the c axis but does not intersect the a or b axes. If we assume that the face intercepts the c axis at a distance of 1 unit length, then the intercepts, sometimes called Weiss Parameters, are: $\infty a, \infty b, 1c$



2. A crystal face intersects two of the crystallographic axes.

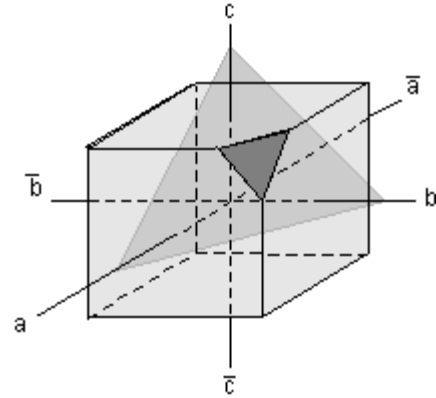
As an example, the darker crystal face shown here intersects the a and b axes, but not the c axis. Assuming the face intercepts the a and b axes at 1 unit cell length on each, the parameters for this face are: $1a, 1b, \infty c$



3. A crystal face that intersects all 3 axes.

In this example the darker face is assumed to intersect the a, b, and c crystallographic axes at one unit length on each. Thus, the parameters in this example would be:

1a, 1b, 1c

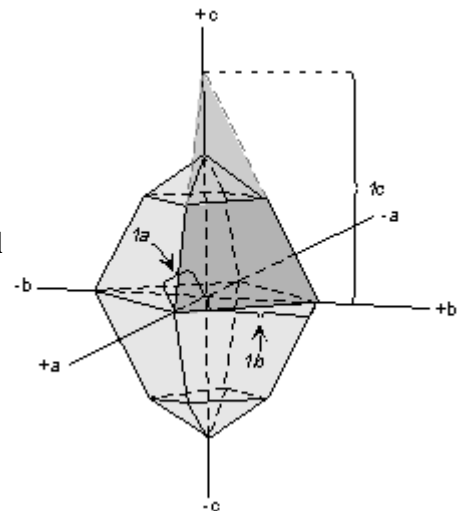


Two very important points about intercepts of faces:

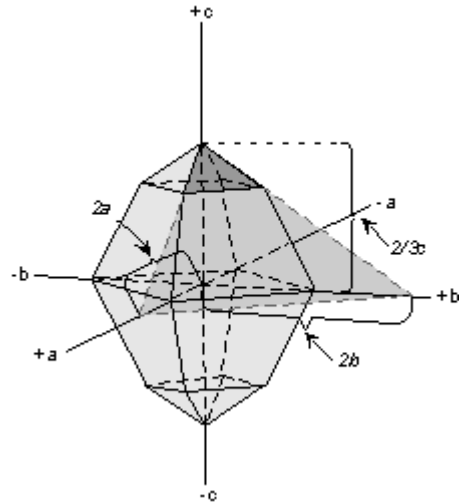
- The intercepts or parameters are relative values, and do not indicate any actual cutting lengths.
- Since they are relative, a face can be moved parallel to itself without changing its relative intercepts or parameters.

Because one does usually not know the dimensions of the unit cell, it is difficult to know what number to give the intercept of a face, unless one face is chosen arbitrarily to have intercepts of 1. Thus, the convention is to assign the largest face that intersects all 3 crystallographic axes the parameters - 1a, 1b, 1c. This face is called the *unit face*.

For example, in the orthorhombic crystal shown here, the large dark shaded face is the largest face that cuts all three axes. It is the unit face, and is therefore assigned the parameters 1a, 1b, 1c.



Once the unit face is defined, the intercepts of the smaller face can be determined. These are $2a$, $2b$, $2/3c$. Note that we can divide these parameters by the common factor 2, resulting in $1a, 1b, 1/3c$. Again, this illustrates the point that moving a face parallel to itself does not change the relative intercepts. Since intercepts or parameters are relative, they do not represent the actual cutting lengths on the axes.



By specifying the intercepts or parameters of a crystal face, we now have a way to uniquely identify each face of a crystal. But, the notation is cumbersome, so crystallographers have developed another way of identifying or indexing faces. This conventional notation called the Miller Index is our next topic of discussion.

Miller Indices

The Miller Index for a crystal face is found by

- first determining the parameters
- second inverting the parameters, and
- third clearing the fractions.

For example, if the face has the parameters $1a, 1b, \infty c$

inverting the parameters would be $1/1, 1/1, 1/\infty$

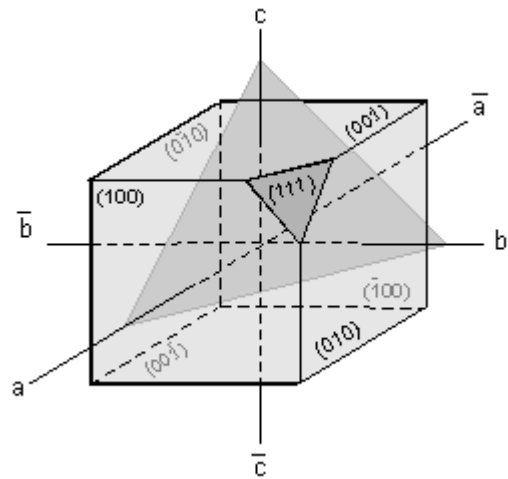
this would become $1, 1, 0$

the Miller Index is written inside parentheses with no commas - thus (110)

As further examples, let's look at the crystal shown here. All of the faces on this crystal are relatively simple. The face [labeled (111)] that cuts all three axes at 1 unit length has the parameters 1a, 1b, 1c. Inverting these, results in 1/1, 1/1, 1/1 to give the Miller Index (111).

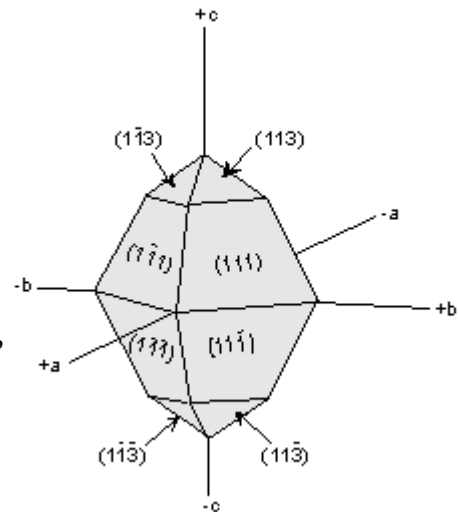
The square face that cuts the positive a axis, has the parameters 1 a, ∞ b, ∞ c. Inverting these becomes 1/1, 1/∞, 1/∞ to give the Miller Index (100).

The face on the back of the crystal that cuts the negative a axis has the parameters -1a, ∞ b, ∞ c. So its Miller Index is (1̄00). Note how the negative intercept is indicated by putting a minus sign above the index. This would be read "minus one, one, one". Thus, the other 4 faces seen on this crystal would have the Miller Indices (001), (001̄), (010), and (01̄0).



Now let's look at some more complicated examples. The drawing to the right is the same orthorhombic crystal we looked at earlier. Recall that the small triangular face near the top that cuts all three axes had the parameters 1a, 1b, 1/3c. Inverting these becomes 1/1, 1/1, 3/1 to give the Miller Index for this face as (113).

Similarly, the small triangular face the cuts the positive a axis and the negative b axis, would have the Miller Index (11̄3), the similar face on the bottom of the crystal, cutting positive a, positive b, and negative c axes would have the Miller Index (113̄).



See if you can determine the Miller Indices for the 8 faces on the back of the crystal that are not seen in this drawing.

Note once again, that moving a face parallel to itself does not change the parameters nor the Miller Index for that face.

To refer to a general face that intersects all three crystallographic axes where the parameters are not known, we use the notation (hkl). For a face that intersects the b and c axes with general or unknown intercepts the notation would be (0kl), for a face intersecting the a and c axis, but parallel to b the notation would be (h0l), and similarly for a face intersecting the a and b axes, but parallel to c we would use the notation (hk0).

This Miller Index notation applies very well to crystals in the Triclinic, Monoclinic,

Orthorhombic, Tetragonal, and Isometric systems, but requires some modification to be applied to the Hexagonal crystal system.

Miller Bravais Indices

Since the hexagonal system has three "a" axes perpendicular to the "c" axis, both the parameters of a face and the Miller Index notation must be modified. The modified parameters and Miller Indices must reflect the presence of an additional axis. This modified notation is referred to as Miller-Bravais Indices, with the general notation (hkil)

To see how this works, let's look at the dark shaded face in the hexagonal crystal shown here. This face intersects the positive a_1 axis at 1 unit length, the negative a_3 axis at 1 unit length, and does not intersect the a_2 or c axes. This face thus has the parameters:

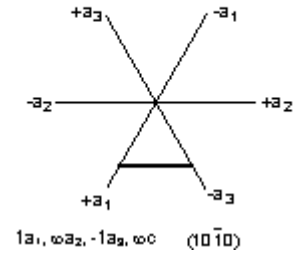
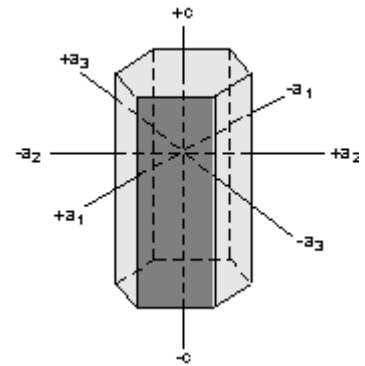
$$1 a_1, \infty a_2, -1 a_3, \infty c$$

Inverting and clearing fractions gives the Miller-Bravais Index:

$$(10\bar{1}0)$$

An important rule to remember in applying this notation in the hexagonal system, is that whatever indices are determined for $h, k,$ and $i,$

$$h + k + i = 0$$



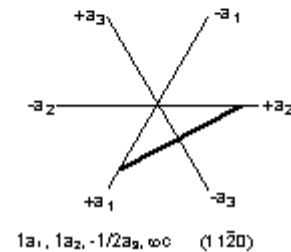
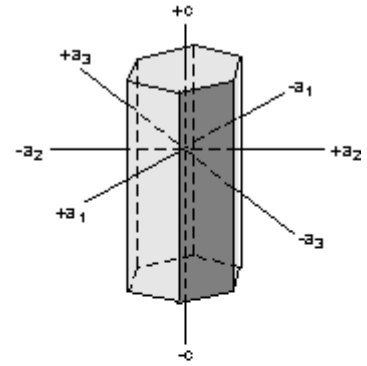
For a similar hexagonal crystal, this time with the shaded face cutting all three axes, we would find for the shaded face in the diagram that the parameters are $1 a_1, 1 a_2, -1/2 a_3, \infty c$. Inverting these intercepts gives:

$$1/1, 1/1, -2/1, 1/\infty$$

resulting in a Miller-Bravais Index of

$$(11\bar{2}0)$$

Note how the " $h + k + i = 0$ " rule applies here!



Crystal Forms

Although we will not cover this in detail in this lecture, the next step is to use the Miller Index notation to designate crystal forms. A *crystal form* is a set of crystal faces that are related to each other by symmetry. To designate a crystal form (which could imply many faces) we use the Miller Index, or Miller-Bravais Index notation enclosing the indices in curly braces, i.e.

$$\{hkl\} \text{ or } \{hkil\}$$

Such notation is called a *form symbol*.

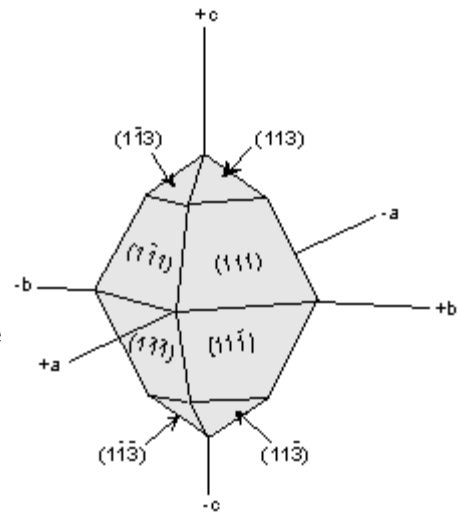
As an example, look at the crystal drawing shown here. This crystal is the same orthorhombic crystal discussed above. It has two forms. The form $\{111\}$ consists of the following symmetrically 8 related faces:

(111) , $(11\bar{1})$, $(1\bar{1}1)$, $(1\bar{1}\bar{1})$, $(\bar{1}11)$, $(\bar{1}1\bar{1})$, $(\bar{1}\bar{1}1)$, and $(\bar{1}\bar{1}\bar{1})$.

This form is called a rhombic-dipyramid.

The other form is also a rhombic-dipyramid, but consists of the triangular shaped faces similar to the face (113) . The form symbol for this form is $\{113\}$ and consists of the following 8 faces:

(113) , $(1\bar{1}3)$, $(11\bar{3})$, $(1\bar{1}\bar{3})$, $(\bar{1}13)$, $(\bar{1}1\bar{3})$, $(\bar{1}\bar{1}3)$, and $(\bar{1}\bar{1}\bar{3})$.



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LECTURE NOTES

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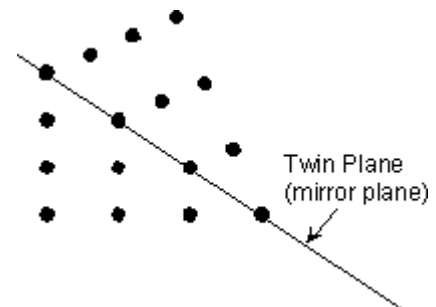
UNIT 3

Twinning, Polymorphism, Polytypism, & Pseudomorphism

Twinning in Crystals

Sometimes during the growth of a crystal, or if the crystal is subjected to stress or temperature/pressure conditions different from those under which it originally formed, two or more intergrown crystals are formed in a symmetrical fashion. These symmetrical intergrowths of crystals are called twinned crystals. Twinning is important to recognize, because when it occurs, it is often one of the most diagnostic features enabling identification of the mineral.

What happens is that lattice points in one crystal are shared as lattice points in another crystal adding apparent symmetry to the crystal pairs. Twinning, because it adds symmetry, never occurs in relation to the existing symmetry of the crystal.



Symmetry Operations that Define Twinning

Because symmetry is added to a crystal by twinning, twinning can be defined by the symmetry operations that are involved. These include:

- Reflection across a mirror plane. The added mirror plane would then be called a *twin plane*.
- Rotation about an axis or line in the crystal. The added rotation

axis would then be called a *twin axis*.

- Inversion through a point. The added center of symmetry would then be called a *twin center*.

Twin Laws

Twin laws are expressed as either form symbols to define twin planes (i.e. $\{hkl\}$) or zone symbols to define the direction of twin axes (i.e. $[hkl]$).

The surface along which the lattice points are shared in twinned crystals is called a *composition surface*.

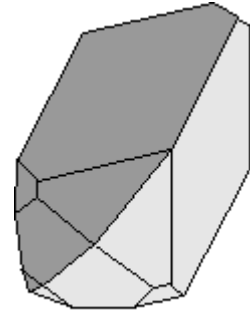
If the twin law can be defined by a simple planar composition surface, the twin plane is **always** parallel to a possible crystal face and **never** parallel to an existing plane of symmetry (remember that twinning adds symmetry).

If the twin law is a rotation axis, the composition surface will be irregular, the twin axis will be perpendicular to a lattice plane, but will never be an even-fold rotation axis of the existing symmetry. For example twinning cannot occur on a new 2 fold axis that is parallel to an existing 4-fold axis.

Types of Twinning

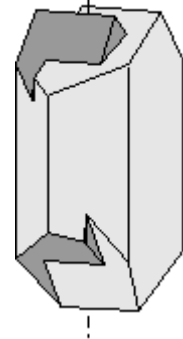
Another way of defining twinning breaks twins into two separate types.

1. **Contact Twins** - have a planar composition surface separating 2 individual crystals. These are usually defined by a twin law that expresses a twin plane (i.e. an added mirror plane). An example shown here is a crystal of orthoclase twinned on the Braveno Law, with $\{021\}$ as the twin plane.



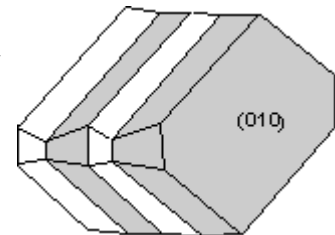
Twin Plane $\{021\}$
| $[001]$

2. **Penetration Twins** - have an irregular composition surface separating 2 individual crystals. These are defined by a twin center or twin axis. Shown here is a twinned crystal of orthoclase twinned on the Carlsbad Law with $[001]$ as the twin axis.

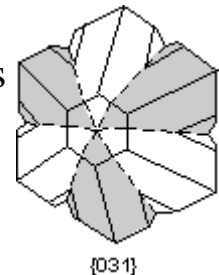


Contact twins can also occur as repeated or multiple twins.

- If the composition surfaces are parallel to one another, they are called **polysynthetic twins**. Plagioclase commonly shows this type of twinning, called the Albite Twin Law, with $\{010\}$ as the twin plane. Such twinning is one of the most diagnostic features of plagioclase.



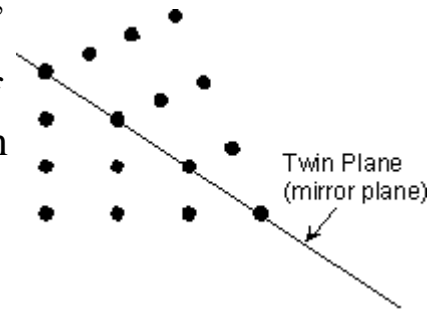
- If the composition surfaces are not parallel to one another, they are called **cyclical twins**. Shown here is the cyclical twin that occurs in chrysoberyl along a $\{031\}$ plane.



Origin of Twinning

Twinning can originate in 3 different ways, as growth twins, transformation twins, and glide or deformation twins.

1. Growth Twins - When accidents occur during crystal growth and a new crystal is added to the face of an already existing crystal, twinning can occur if the new crystal shares lattice points on the face of the existing crystal, but has an orientation different from the original crystal. Such growth twins can be contact twins, as illustrated here, or can be penetration twins. All of twins discussed so far are growth twins.



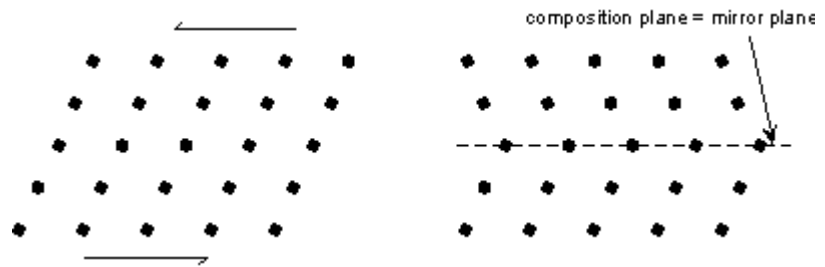
2. Transformation Twins - Transformation twinning occurs when a preexisting crystal undergoes a transformation due to a change in pressure or temperature. This commonly occurs in minerals that have different crystal structures and different symmetry at different temperatures or pressures. When the temperature or pressure is changed to that where a new crystal structure and symmetry is stable, different parts of the crystal become arranged in different symmetrical orientations, and thus form an intergrowth of one or more crystals. Dauphiné and Brazil twinning in quartz commonly forms this way during a decrease in temperature.

Similarly the combination of albite twinning and pericline twinning in alkali feldspar results when high temperature sanidine (monoclinic) transforms to low temperature microcline (triclinic). This type of twinning is only observed using the

polarizing microscope, and results in a "tartan" twinning pattern as shown in your text book on page 231, figure 10.18. When this twinning pattern is observed with the microscope it is one of the most characteristic diagnostic properties for the identification of microcline.

3. Deformation

Twins - During deformation atoms can be pushed out of place. If this happens to produce a symmetrical arrangement, it produces deformation twins. The mineral calcite can be easily twinned in this way, producing polysynthetic twins on $\{01\bar{1}2\}$.

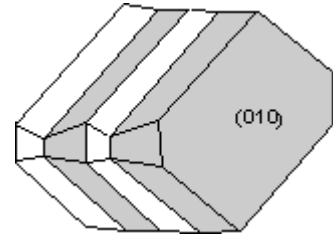


Common Twin Laws

- **Triclinic System** - The feldspar minerals plagioclase and

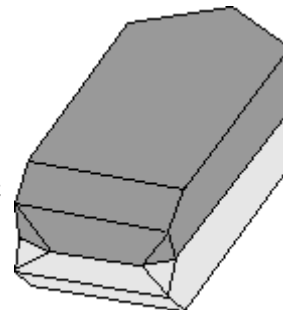
microcline are the most common triclinic minerals that show twinning. Two common twin laws are observed in these feldspars.

- Albite Law - As described above, plagioclase ($\text{NaAlSi}_3\text{O}_8$ - $\text{CaAl}_2\text{Si}_2\text{O}_8$) very commonly shows albite polysynthetic twinning. The twin law - $\{010\}$ indicates that the twinning occurs perpendicular to the **b** crystallographic axis. Albite twinning is so common in plagioclase, that its presence is a diagnostic property for identification of plagioclase.



- Pericline Law - The pericline law has $[010]$ as the twin axis. As stated above, pericline twinning occurs as the result of monoclinic orthoclase or sanidine transforming to microcline (all have the same chemical formula - KAlSi_3O_8). Pericline twinning usually occurs in combination with albite twinning in microcline, but is only observable with the polarizing microscope. The combination of pericline and albite twinning produce a cross-hatched pattern, called tartan twinning, as discussed above, that easily distinguishes microcline from the other feldspars under the microscope.
- **Monoclinic System** - The most common twins in the monoclinic system occur on the planes $\{100\}$ and $\{001\}$. The feldspars - orthoclase and sanidine - are the most commonly twinned minerals in the monoclinic system. Both contact twins and penetration twins occur, and both types result from accidents during growth.

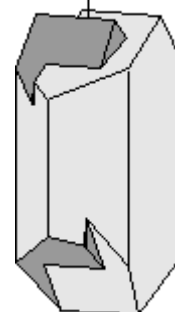
- Manebach Law - $\{001\}$ - forms a contact twin commonly observed in the mineral orthoclase. This twinning is very diagnostic of orthoclase when it occurs.



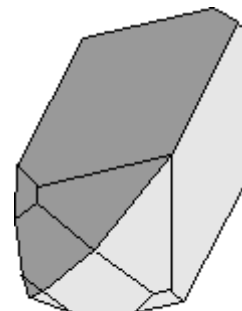
- Carlsbad Law - $[001]$ - forms a penetration twin in the mineral orthoclase. Crystals twinned under the Carlsbad Law show two intergrown crystals, one rotated 180° from the other about the $[001]$ axis. Carlsbad twinning is the most common type of twinning in orthoclase, and is thus very diagnostic of orthoclase when it occurs.

Twin Plane $\{001\}$

$[001]$

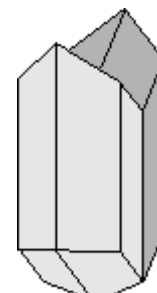


- Braveno Law - $\{021\}$ - forms a contact twin in the mineral orthoclase.



Twin Plane $\{021\}$

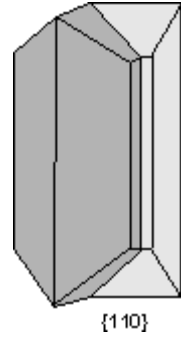
- Swallow Tail Twins - $\{100\}$ - are commonly observed in the mineral gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$).



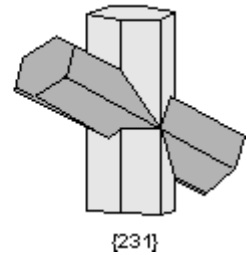
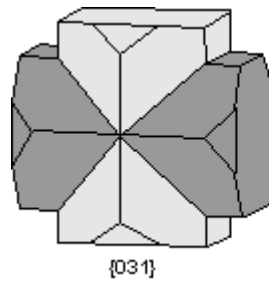
$\{100\}$

- **Orthorhombic System** - Orthorhombic crystals commonly twin on planes parallel to a prism face. The most common is a $\{110\}$ twin that results in many orthorhombic minerals having cyclical twins.

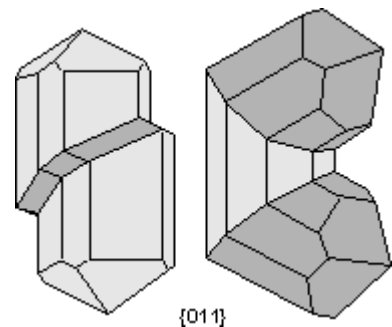
- {110} Cyclical Twins - The mineral aragonite (CaCO_3), chrysoberyl (BeAl_2O_4), and cerrusite (PbCO_3) commonly develop twinning on {110}. This results in a cyclical twin which gives these minerals a pseudo-hexagonal appearance.



- **Staurolite Law** - The mineral staurolite is really monoclinic, but it has a β angle very close to 90° so it has the appearance of an orthorhombic mineral. Two types of interpenetration twins occur in staurolite the {031} twins from a right-angled cross and the {231} twins form a cross at about 60° .

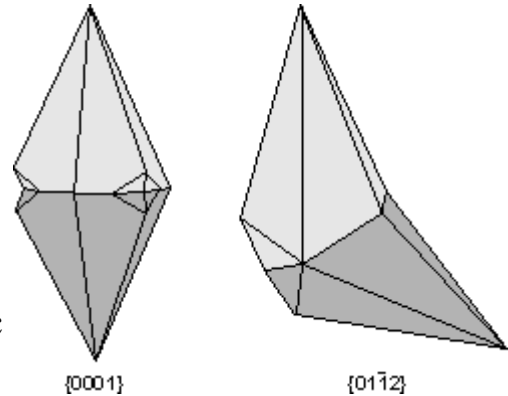


- **Tetragonal System** - Twinning in the tetragonal system usually occurs on {011} forming cyclical contact twins. The minerals rutile (TiO_2) and cassiterite (SnO_2) commonly show this type of twinning.



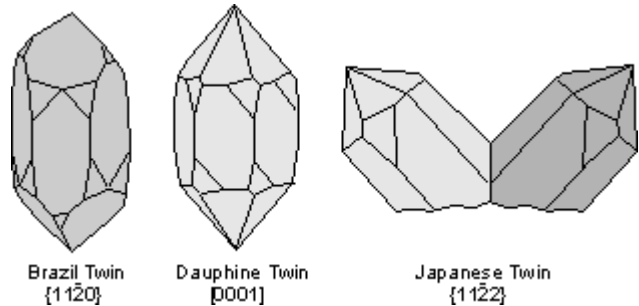
- **Hexagonal System** - The minerals calcite (CaCO_3) and quartz (SiO_2) are the most common hexagonal minerals and both show the types of twinning common in hexagonal minerals.

- Calcite Twins - The two most common twin laws that are observed in calcite crystals are $\{0001\}$ and the rhombohedron $\{01\bar{1}2\}$. Both are contact twins, but the $\{01\bar{1}2\}$ twins can also occur as polysynthetic twins that result from deformation.



Quartz shows three other hexagonal twins.

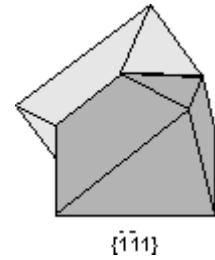
- Brazil Law - $\{11\bar{2}0\}$ - is a penetration twin that results from transformation.
- Dauphiné Law - $[0001]$ - is also a penetration twin that results from transformation.
- Japanese Law - $\{11\bar{2}2\}$ - is a contact twin that results from accidents during growth.



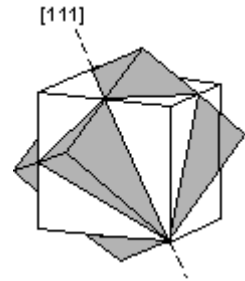
- **Isometric System** - Three types of twins are common in the

isometric system.

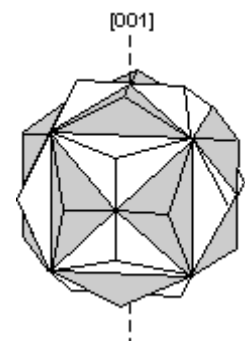
- Spinel Law - $\{\bar{1}\bar{1}1\}$ - is a twin plane, parallel to an octahedron. It occurs commonly in mineral spinel (MgAl_2O_4).



- $[111]$ - The twin axis perpendicular to an octahedral face adds three fold rotational symmetry.



- Iron Cross $[001]$ - The mineral pyrite (FeS_2) often shows the iron cross made of the interpenetration of two pyritohedrons. Since this occurs in the class $2/m\bar{3}$, with no 4-fold rotation axes, the $[001]$ twin axis gives the mineral apparent 4-fold symmetry about 3 perpendicular axes.



Polymorphism

Polymorphism means "many forms". In mineralogy it means that a single chemical composition can exist with two or more different crystal structures. As we will see when we look more closely at crystal structures, if a crystal is subjected to different pressures and temperatures, the arrangement of atoms depends on the sizes of the atoms, and the sizes change with temperature and pressure. In general, as pressure increases the volume of a crystal will decrease and a point

may be reached where a more compact crystal structure is more stable. The crystal structure will then change to that of the more stable structure, and a different mineral will be in existence. Similarly, if the temperature is increased, the atoms on the crystal structure will tend to vibrate more and increase their effective size. In this case, a point may be reached where a less compact crystal structure is more stable. When the crystal structure changes to the more stable structure a different mineral will form.

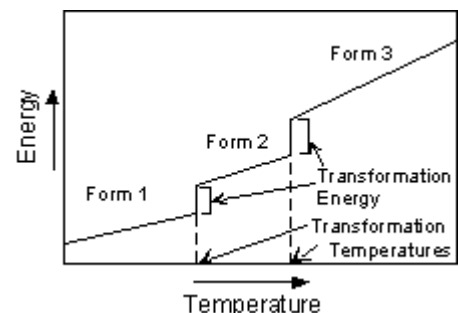
The change that takes place between crystal structures of the same chemical compound are called *polymorphic transformations*.

Types of Polymorphic Transformations

Stability of crystal structures is generally referred to in terms of the energy of the crystal structure. In general terms this can be thought of as the bond strength (enthalpy), and entropy (degree of order or randomness) of the structure. In general, the structure with the lowest energy is the most stable at any given temperature and pressure.

This results in three types of transformations.

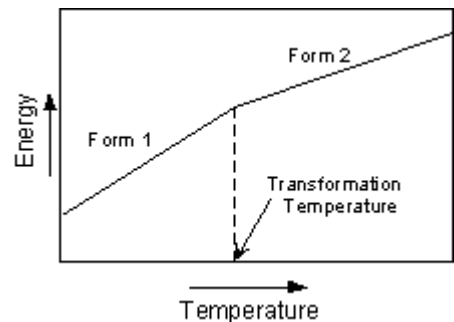
1. **Reconstructive Transformations** - these involve extensive rearrangement of the crystal structure and requires breaking of chemical bonds and reassembling the atoms into a different crystal structure. This usually involves a large change in energy of the structure which must occur at the transformation temperature or pressure. Because of the extensive rearrangement involved, the rate at which this type of transformation occurs may be very slow. If the rate of



the transformation is very slow, unstable polymorphs (*metastable*) may exist for long periods of time.

For example, diamond is a metastable polymorph of Carbon at the pressures and temperatures present at the Earth's surface, yet, as the saying goes "diamonds are forever". Not really, it's just that the rate at which diamond can rearrange its crystal structure to become graphite, the polymorph stable at low P and T, is very slow at the low temperatures found near the Earth's surface.

2. ***Displacive Transformations*** - these involve only small adjustments to the crystal structure. Generally no bonds are broken, but the angles between the atoms may change slightly. Because there is little rearrangement, displacive transformations involve no change in energy at the transformation temperature or pressure, and the transformations are instantaneous and reversible. Thus, no unstable polymorphs will occur.



For example, at 1 atmosphere pressure high quartz (Γ quartz) is the stable form of quartz above 580° C. When high quartz is brought to a temperature below 580° it immediately is transformed into low quartz (Γ quartz). Thus, high quartz is never seen in rocks at the surface of the Earth.

3. ***Order - Disorder Transformations*** - these involve the state of

order or disorder in a crystal structure. Perfect order can only occur at a temperature of absolute zero (-273°C). As temperature increases, the degree of order or randomness of a crystal structure decreases, so that the higher temperature forms of minerals are more disordered than the lower temperature forms. Because the state of order-disorder changes gradually with increasing temperature, there is no definite temperature at which a transformation occurs.

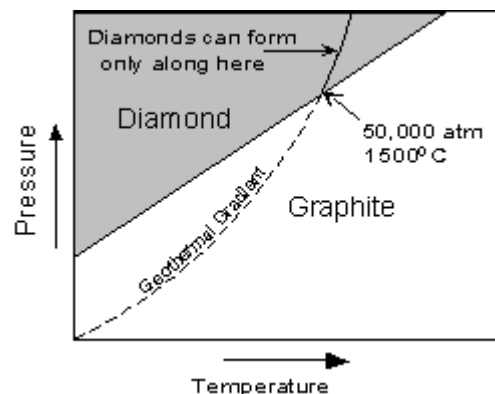
An example of polymorphic transformations that involve order-disorder is the compound KAlSi_3O_8 . At high temperature the stable form is Sanidine (Monoclinic). At lower temperature the structure changes to one of orthoclase (also Monoclinic), and at even lower temperature the structure becomes that of the more ordered structure of microcline (also Triclinic).

There is no definite temperature at which Sanidine changes to orthoclase or orthoclase changes to Microcline, since the structure changes gradually as temperature decreases. If the temperature change is rapid, then unstable polymorphs can continue to exist at a low temperature.

Important Polymorphs

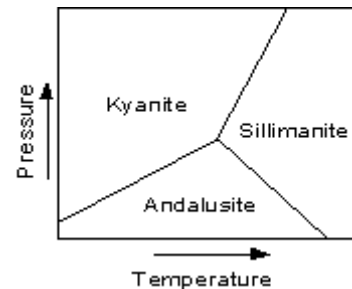
Many common minerals show polymorphism. We here look at some of the more common ones.

- **Carbon** - has two polymorphs. At high pressure carbon has an isometric crystal structure that is called diamond. As temperature and/or pressure are decreased diamond should undergo a



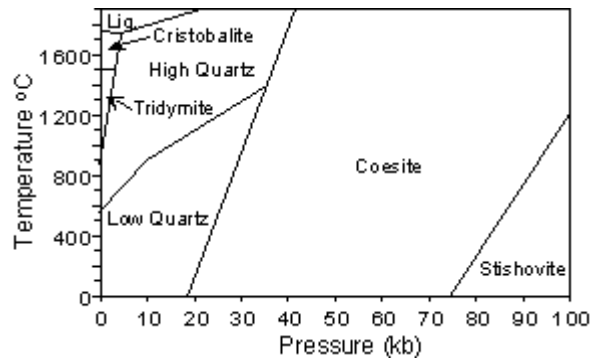
reconstructive transformation to the hexagonal structure of graphite. Because this transformation involves a drastic rearrangement of atoms on the crystal structure, as evidenced by the fact that diamond is the hardest naturally occurring substance and graphite is one of the softest) diamond is found at the T & P conditions present at the Earth's surface, where it is therefore only metastable.

- Al_2SiO_5 - has three polymorphs. The high pressure form is kyanite (Triclinic), the high temperature form is sillimanite (orthorhombic), and the low temperature, low pressure form is andalusite (orthorhombic). Transformations between all three polymorphs are reconstructive, thus all three forms can metastably exist at the Earth's surface. Transformation rates are somewhat faster, however, at higher temperatures in the Earth.



- CaCO_3 - has two polymorphs. The high pressure form is aragonite (orthorhombic) and the low pressure form is calcite (hexagonal). The transformation between the two polymorphs is reconstructive, so metastable polymorphs can exist.

- SiO_2 - has 6 polymorphs. With decreasing temperature at low pressure, cristobalite (isometric) undergoes a reconstructive transformation to tridymite (hexagonal). Further lowering of temperature results in tridymite undergoing a reconstructive transformation to high quartz (also hexagonal). Lowering temperature further results in high quartz undergoing a displacive transformation to low quartz.



Cristobalite and tridymite can exist metastably at the low temperatures near the Earth's surface, and thus are found in rocks. But high quartz will also transform to low quartz before it reaches temperatures present at the Earth's surface, so it is never found in rocks.

With increasing pressure, at low temperature low quartz undergoes a displacive transformation to coesite (Monoclinic), and coesite undergoes a reconstructive transformation to stishovite (tetragonal) at even higher pressures. Thus, coesite and stishovite have metastable polymorphs that can be found in rocks.

- KAlSi_3O_8 - As discussed above, this compound has three polymorphs that undergo order-disorder transformations with lowering of temperature. The high temperature polymorph is sanidine (monoclinic). It is usually only found in volcanic rocks that have cooled very rapidly so that a higher state of order is not achieved. With slower cooling, sanidine eventually undergoes a

transformation to orthoclase (also monoclinic), and orthoclase eventually transforms to microcline (triclinic) with further slow cooling.

Polytypism

Polytypism is a type of polymorphism wherein different polymorphs exist in different domains of the same crystal. It has to do with the way that individual layers are stacked within a crystal structure. Polytypism has little geologic consequence, and will thus not be discussed further here.

Metamict Minerals

Metamict minerals are minerals whose crystal structure has been partially destroyed by radiation from contained radioactive elements. The breakdown of the crystal structure results from bombardment of a particles emitted by the decay of U and Th radioactive isotopes.

The mineral zircon (ZrSiO_4) often has U and Th atoms substituting for Zr in the crystals structure. Since U and Th have radioactive isotopes, Zircon is often seen to occur in various stages of metamictization.

Mineraloids

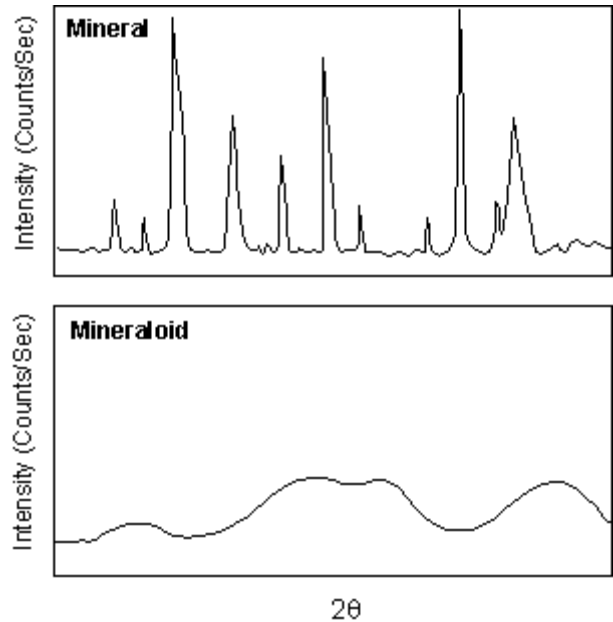
By definition, a mineral has to have an ordered atomic arrangement, or crystalline structure. There are some Earth materials that fit all other parts of the definition of a mineral, yet do not have a crystalline structure. Such compounds are termed *amorphous* (without form).

Some of these amorphous compounds are called mineraloids. These usually form at low temperatures and pressures during the process of chemical weathering and form mammillary, botryoidal, and stalactitic masses with widely varying chemical compositions. Limonite

[FeO(OH)·nH₂O] and allophane (a hydrous aluminum silicate) are good examples.

Others like volcanic glass and opal (SiO₂·nH₂O) have short-range order or domains wherein some crystalline-like order exists.

Unlike crystalline minerals that show sharp, well defined x-ray diffraction peaks, these mineraloids with short-range order show broad diffraction peaks that give evidence of the short-range order.



Pseudomorphism

Pseudomorphism is the existence of a mineral that has the appearance of another mineral. Pseudomorph means false form. Pseudomorphism occurs when a mineral is altered in such a way that its internal structure and chemical composition is changed but its external form is preserved. Three mechanisms of pseudomorphism can be defined:

1. Substitution. In this mechanism chemical constituents are simultaneously removed and replaced by other chemical constituents during alteration. An example is the replacement of wood fibers by quartz to form petrified wood that has the outward appearance of the original wood, but is composed of quartz. Another example is the alteration of fluorite which forms isometric crystals and is sometimes replaced by quartz during alteration. The resulting quartz crystals look isometric, and are said to be pseudomorphed after fluorite.
2. Encrustation. If during the alteration process a thin crust of a new

mineral forms on the surface of a preexisting mineral, then the preexisting mineral is removed, leaving the crust behind, we say that pseudomorphism has resulted from encrustation. In this case the thin crust of the new mineral will have casts of the form of the original mineral.

3. Alteration. If only partial removal of the original mineral and only partial replacement by the new mineral has taken place, then it is possible to have a the space once occupied entirely by the original mineral be partially composed of the new mineral. This results for example in serpentine pseudomorphed after olivine or pyroxene, anhydrite (CaSO_4) pseudomorphed after gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), limonite [$\text{FeO} \cdot (\text{OH}) \cdot n\text{H}_2\text{O}$] after pyrite (FeS_2), and anglesite (PbSO_4) after galena (PbS).

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LECTURE NOTES

1ST SEMESTER

UNIT 4

Introduction to Uniaxial Minerals

Uniaxial minerals are a class of anisotropic minerals that include all minerals that crystallize in the tetragonal and hexagonal crystal systems. They are called uniaxial because they have a single optic axis. Light traveling along the direction of this single optic axis exhibits the same properties as isotropic materials in the sense that the polarization direction of the light is not changed by passage through the crystal. Similarly, if the optic axis is oriented perpendicular to the microscope stage with the analyzer inserted, the grain will remain extinct throughout a 360° rotation of the stage. The single optic axis is coincident with the c-crystallographic axis in tetragonal and hexagonal minerals. Thus, light traveling parallel to the c-axis will behave as if it were traveling in an isotropic substance because, looking down the c-axis of tetragonal or hexagonal minerals one sees only equal length a-axes, just like in isometric minerals.

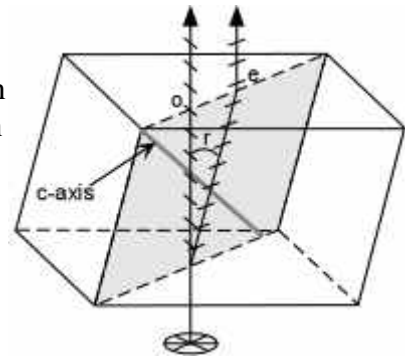
- Like all anisotropic substances, the refractive indices of uniaxial crystals varies between two extreme values. For uniaxial minerals these two extreme values of refractive index are defined as ω (or N_o) and ϵ (or N_e). Values between ω and ϵ are referred to as ϵ' .
- Uniaxial minerals can be further divided into two classes. If $\omega > \epsilon$ the mineral is said have a **negative optic sign** or is **uniaxial negative**. In the opposite case, where $\epsilon > \omega$ the mineral is said to have a **positive optic sign** or is **uniaxial positive**.
- The absolute **birefringence** of a uniaxial minerals is defined as $|\omega - \epsilon|$ (the absolute value of the difference between the extreme refractive indices).

Double Refraction

All anisotropic minerals exhibit the phenomenon of double refraction. Only when the birefringence is very high, however, is it apparent to the human eye. Such a case exists for the hexagonal (and therefore uniaxial) mineral calcite. Calcite has rhombohedral cleavage which means it breaks into blocks with parallelogram - shaped faces. If a clear rhombic cleavage block is placed over a point and observed from the top, two images of the point are seen through the calcite crystal. This is known as double refraction.

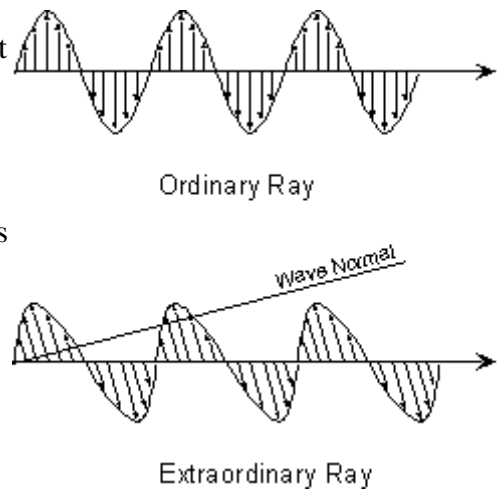
What happens is that when unpolarized light enters the crystal from below, it is broken into two polarized rays that vibrate perpendicular to each other within the crystal.

One ray, labeled o in the figure shown here, follows Snell's Law, and is called the **ordinary ray**, or **o-ray**. It has a vibration direction that is perpendicular to the plane containing the c-axis and the path of the ray. The other ray, labeled e in the figure shown here, does not follow Snell's Law, and is therefore referred to as the **extraordinary ray**, or **e-ray**. The e ray is polarized with light vibrating within the plane containing the c-axis and the propagation path of the ray.



Since the angle of incidence of the light is 0° , both rays should not be refracted when entering the crystal according to Snell's Law, but the e-ray violates this law because its angle of refraction is not 0° , but is r , as shown in the figure. Note that the vibration directions of the e-ray and the o-ray are perpendicular to each other. These directions are referred to as the **privileged directions** in the crystal.

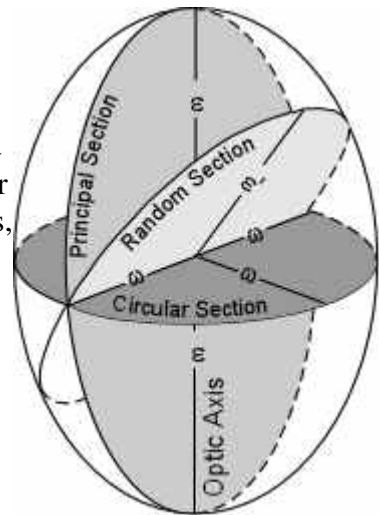
If one separates out the e-ray and the o-ray as shown here, it can be seen that the o-ray has a vibration direction that is perpendicular to the propagation direction. On the other hand, the vibration direction of the e-ray is not perpendicular to the propagation direction. A line drawn that is perpendicular to the vibration direction of the e-ray is called the **wave normal** direction. It turns out the wave normal direction does obey Snell's Law, as can be seen by examining the diagram of the calcite crystal shown above. In the case shown, the wave normal direction would be parallel to the o-ray propagation direction, which is following Snell's Law.



Uniaxial Indicatrix

Just like in isotropic minerals, we can construct an indicatrix for uniaxial minerals. The uniaxial indicatrix is constructed by first orienting a crystal with its c-axis vertical. Since the c-axis is also the optic axis in uniaxial crystals, light traveling along the c-axis will vibrate perpendicular to the c-axis and parallel to the ω refractive index direction. Light vibrating perpendicular to the c-axis is associated with the o-ray as discussed above. Thus, if vectors are drawn with lengths proportional to the refractive index for light vibrating in that direction, such vectors would define a circle with radius ω . This circle is referred to as the **circular section** of the uniaxial indicatrix.

Light propagating along directions perpendicular to the c-axis or optic axis is broken into two rays that vibrate perpendicular to each other. One of these rays, the e-ray vibrates parallel to the c-axis or optic axis and thus vibrates parallel to the ϵ refractive index. Thus, a vector with length proportional to the ϵ refractive index will be larger than or smaller than the vectors drawn perpendicular to the optic axis, and will define one axis of an ellipse. Such an ellipse with the ϵ direction as one of its axes and the ω direction as its other axis is called the **Principal Section** of the uniaxial indicatrix.



After Bloss, 1981

Light vibrating parallel to any direction associated with a refractive index intermediate between ϵ and ω will have vector lengths intermediate between those of ϵ and ω and are referred to as ϵ' directions.

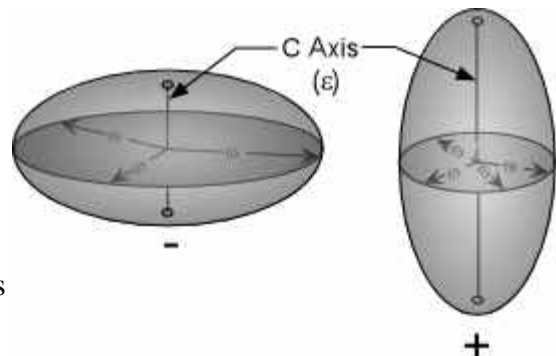
Thus, the uniaxial indicatrix is seen to be an ellipsoid of revolution. Such an ellipsoid of revolution would be swept out by rotating the ellipse of the principal section by 180° . Note that there are an infinite number of principal sections that would cut the indicatrix vertically.

Light propagating along one of the ϵ' directions is broken into two rays, one vibrates parallel to an ϵ' direction and the other vibrates parallel to the ω direction. An ellipse that has an ϵ' direction and a ω direction as its axes is referred to as a random section of the indicatrix.

Optic Sign

Recall that uniaxial minerals can be divided into 2 classes based on the optic sign of the mineral.

- If $\omega > \epsilon$, the optic sign is negative and the uniaxial indicatrix would take the form of an oblate spheroid. Note that such an indicatrix is elongated in the direction of the stroke of a minus sign.
- If $\epsilon > \omega$, the optic sign is positive and the uniaxial indicatrix would take the form of a prolate spheroid. Note that such an indicatrix is elongated in the direction of the vertical stroke of a plus sign.

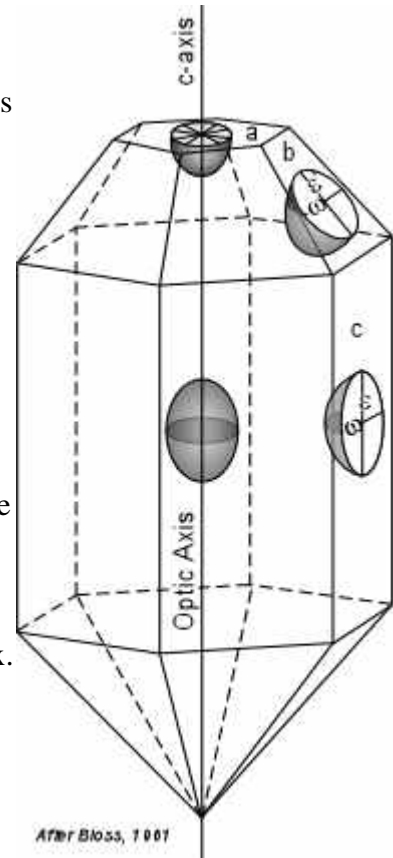


Application of the Uniaxial Indicatrix

The uniaxial indicatrix provides a useful tool for thinking about the vibration directions of light as it passes through a uniaxial crystal. Just like crystallographic axes, we can move the indicatrix anywhere in a crystal so long it is moved parallel to itself.

This is shown here for an imaginary tetragonal crystal. In this case the optic sign of the mineral is positive, and the uniaxial indicatrix is shown at the center of the crystal.

- If the crystal is mounted on the microscope stage such that the c-axis or optic axis is perpendicular to the stage, we can move the indicatrix up to the top face of the crystal (face a) and see that such light will be vibrating in the ω direction even if we rotate the stage. Thus we will see the circular section of the indicatrix.
- If the crystal is mounted on the stage such that the c-axis is parallel to the stage, we can move the indicatrix to one of the side faces of the crystal (such as face c) and see that light will be broken up into two rays, one vibrating parallel to the ϵ direction and one vibrating parallel to the ω direction. Thus we will see one of the principal planes of the indicatrix.



- If the crystal is mounted on the stage such that the c-axis or optic axis is neither parallel to or perpendicular to the stage, we can move the indicatrix to some random face that is not parallel to or perpendicular to the c-axis (such as face b) and see that the light will be broken into two perpendicular rays, one vibrating parallel to the ω direction and the other vibrating perpendicular to an ϵ' direction. Thus we will see one of the random sections of the indicatrix.

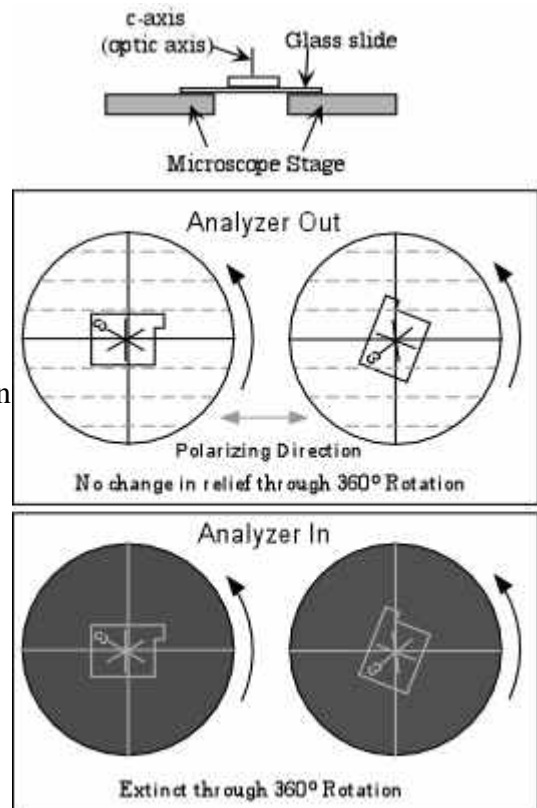
We will next look at what we could observe for crystals oriented on the microscope stage for each of the general orientations described above, beginning with the unique circular section.

Circular Section

If a crystal is mounted on the microscope stage with its optic axis oriented exactly perpendicular to the stage, the circular section of the indicatrix can be imagined to be on the upper surface of the crystal such as for the crystal face labeled a in the diagram above.

In this orientation the crystal behaves just like an isotropic mineral.

- Light polarized in an E-W direction entering the crystal from below remains polarized in an E-W direction as it passes through the crystal.
- Since light is vibrating parallel to an ω direction for all orientations of the grain, no change in relief would be observed as we rotate the microscope stage.
- A comparison of the refractive index of the grain to that of the oil using the Becke line method would allow for the determination of the ω refractive index of the mineral.
- With the analyzer inserted the grain would go extinct and would remain extinct throughout a 360° rotation of the microscope stage, because the light exiting the crystal will still be polarized in an E-W direction.

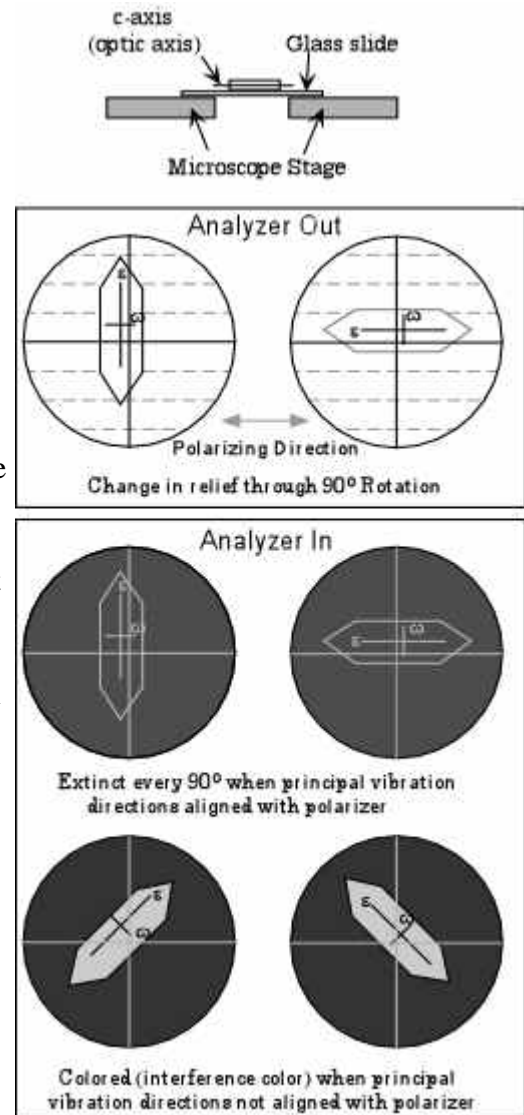


Principal Section

If the mineral grain is oriented such that the optic axis is oriented parallel to the microscope stage, then we can imagine the principal section of the indicatrix as being parallel to the top of the grain such as would be the case for a crystal lying on face c in the diagram above.

In this case, the mineral will show birefringence for most orientations, unless one of the privileged directions in the crystal is lined up with the E-W polarizing direction of the incident light entering from below.

- If the ω direction in the crystal is parallel to the polarizing direction of the microscope, the light will continue to vibrate in the same direction (E-W) as it passes through the crystal. In this position, one could use the Becke Line test to measure the ω refractive index.
- If the ε direction in the crystal is parallel to the polarizing direction, again, light will continue to vibrate parallel to the polarizing direction as it passes through the crystal. In this position one could use the Becke Line method to determine the ε refractive index.
- Since the refractive index will be different for the ω direction and the ε direction, there will be some change in relief of the grain as it is rotated 90° between the two positions. How much change in relief would also depend on the birefringence of the mineral ($|\omega - \varepsilon|$).
- If the analyzer is inserted when the ω direction or the ε direction is parallel to the polarizing direction of the microscope, the grain will be extinct, because the light will still be vibrating parallel to the polarizer as it emerges from the grain.
- If the ω and ε privileged directions in the crystal are at any other angle besides 0° and 90° to the polarizing direction, some light of the light will be vibrating at an angle to the polarizer on emergence from the crystal and some of this light will be transmitted through the analyzer. This will be seen as color, called the *interference color*.



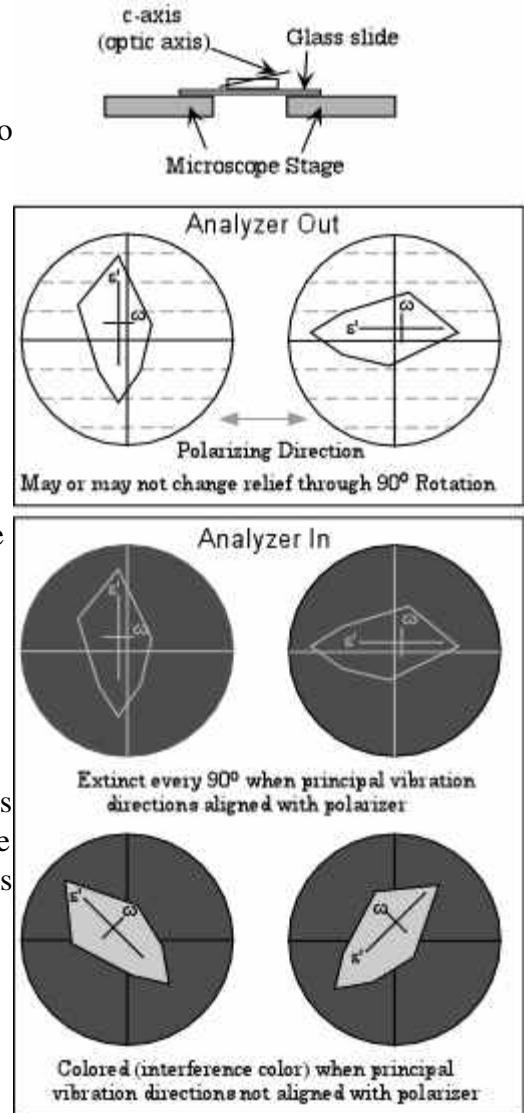
- Thus, as one rotates the stage with the analyzer inserted, the grain will go extinct every 90° , and will show an interference color between these extinction positions. The origin and significance of the interference colors will be discussed in the next lecture.

Random Section

If the mineral grain is oriented such that the optic axis is oriented at an angle to the microscope stage, then we can imagine a random section of the indicatrix as being parallel to the top of the grain such as would be the case for a crystal lying on face b in the crystal diagram above.

In this case, the mineral will also show birefringence for most orientations, unless one of the privileged directions in the crystal is lined up with the E-W polarizing direction of the incident light entering from below. But this time, one of the privileged directions corresponds to the ω direction and the other to an ε' direction in the crystal.

- Again, if the ω direction in the crystal is parallel to the polarizing direction of the microscope, the light will continue to vibrate in the same direction (E-W) as it passes through the crystal. In this position, one could use the Becke Line test to measure the ω refractive index.
- If the ε' direction in the crystal is parallel to the polarizing direction, again, light will continue to vibrate parallel to the polarizing direction as it passes through the crystal. In this position one could use the Becke Line method to determine the ε' refractive index, but this would be of little value, since ε' could have values anywhere between ω and ε .
- Since the refractive index will be different for the ω direction and the ε' direction, there may or may not be a change in relief of the grain as it is rotated 90° between the two positions. If ε' is close to ω , there will be little change in relief, and if ε' is close to ε , then there could be a large change in relief.



- If the analyzer is inserted when the ω direction or the ε' direction is parallel to the polarizing direction of the microscope, the grain will be extinct, because the light will still be vibrating parallel to the polarizer as it emerges from the grain.
- If the ω and ε' privileged directions in the crystal are at any other angle besides 0° and 90° to the polarizing direction, some of the light will be vibrating at an angle to the polarizer on emergence from the crystal and some of this light will be transmitted through the analyzer. This will be seen as color, called the *interference color*.
- Thus, just as in the case of the principal section, as one rotates the stage with the analyzer inserted, the grain will go extinct every 90° , and will show an interference color between these extinction positions.

Note that by using the Becke Line method and mounting grains of the same mineral in oils with a variety of refractive indices, we could determine the ω and ε refractive indices of the mineral. Once these are known we could determine the optic sign (if $\omega > \varepsilon$ the mineral is uniaxial negative

or if $\varepsilon > \omega$, the mineral is uniaxial positive), and the birefringence of the mineral ($|\omega - \varepsilon|$). But, this would be a time consuming operation and would be difficult.

It would be less difficult in the case where the grain is either elongated in the direction of the c-axis or has a cleavage parallel to the c-axis (such as $\{110\}$, $\{100\}$, $\{010\}$, or $\{10\bar{1}0\}$). In these cases one could more easily keep track of which direction is associated with ω (the direction perpendicular to the c-axis) and which direction is associated with ε (the direction parallel to the c-axis).

Fortunately, there are other means to determine optic sign and birefringence that are less time consuming. We will learn about these other means in the next lecture. Nevertheless, in lab you will have to determine both refractive indices on a uniaxial mineral as an aid to learning the concepts involved.

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LECTURE NOTES
1ST SEMESTER
UNIT 4

Biaxial Minerals

All minerals that crystallize in the orthorhombic, monoclinic, or triclinic crystal systems are biaxial. Biaxial crystals have 2 optic axes, and this distinguishes biaxial crystals from uniaxial crystals. Like uniaxial crystals, biaxial crystals have refractive indices that vary between two extremes, but also have a unique intermediate refractive index. Biaxial refractive indices are as follows:

- The smallest refractive index is given the symbol α (or X).
- The intermediate refractive index is given the symbol β (or Y).
- The largest refractive index is given the symbol γ (or Z)

All biaxial minerals have optical symmetry equivalent to $2/m2/m2/m$. But, in each of the crystal systems, the optical directions have different correspondence to the crystallographic directions.

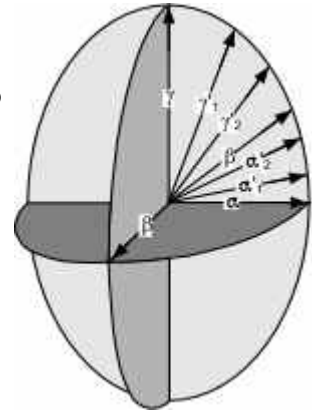
- In orthorhombic crystals the optical directions correspond to the crystallographic axes, i.e. the X direction and its corresponding refractive index, α can be either the a, b, or c crystallographic axes, the Y direction and β can be parallel to either a, b, or c, and the Z direction or γ , can be parallel to either a, b, or c.
- In monoclinic crystals, one of the X (α), Y (β), or Z (γ) directions or indices is parallel to the b crystallographic axis, and the other two do not coincide with crystallographic directions.
- In triclinic crystals none of the optical directions or indices coincide with crystallographic directions, although in some rare case one of the indices might coincide with one of the crystallographic directions.

The Biaxial Indicatrix

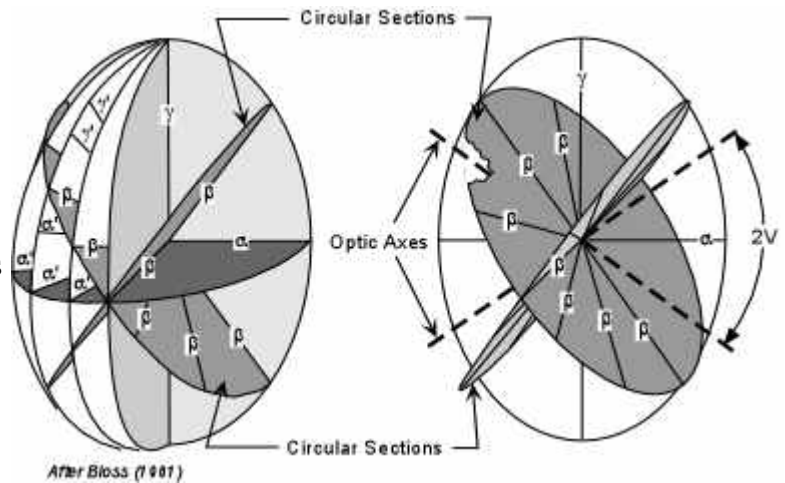
The biaxial indicatrix, like the isotropic and uniaxial indicatrices, diagrammatically illustrates

the refractive index for vibration directions of light. It is shown in the diagram below.

The biaxial indicatrix has three principle axes, labeled α , β , and γ . Directions that have refractive indices between α and β , are referred to as α' . Directions with refractive indices between γ and β are referred to as γ' . Note that the β direction also must occur in the plane that includes α and γ . Similarly, if we were to draw all other possible planes that include the γ direction, β would have to occur in each of these as well. This results in two sections that would be circular with a radius equivalent to the β refractive index. These two sections are referred to as the circular sections. In the diagrams below we see the two circular sections, each having a radius equal to the β refractive index.



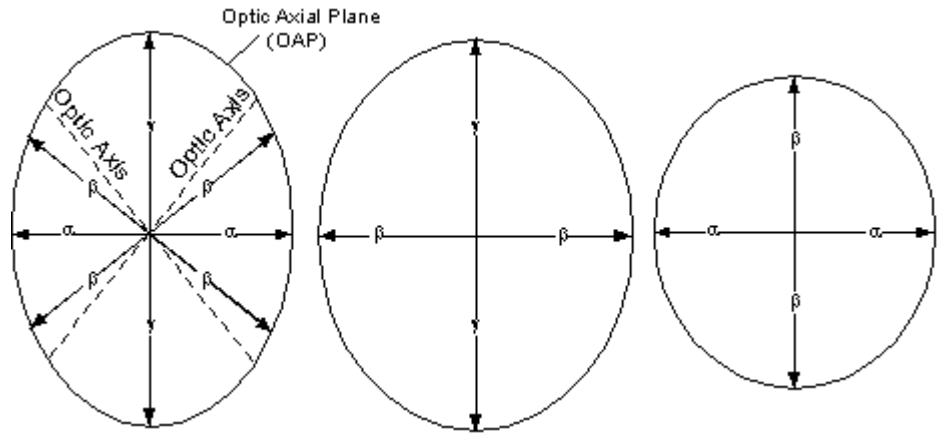
In the left-hand diagram some of the other possible planes that include γ are shown. In the right-hand diagram these planes are removed to show only the circular sections. Lines drawn perpendicular to the circular sections are the optic axes. This is why minerals that exhibit these optical properties are called biaxial.



The acute angle between the optic axes is called the $2V$ angle.

Just like in uniaxial minerals, if one is looking down one of the optic axes, light traveling along the optic axis will be vibrating in the β direction, and thus the mineral would be extinct for all rotation positions.

The three principal planes of the biaxial indicatrix are shown here. The plane containing the α and γ directions also contains the optic axes, which are perpendicular to the β directions. This plane is called the *optic axial plane* or *OAP*.



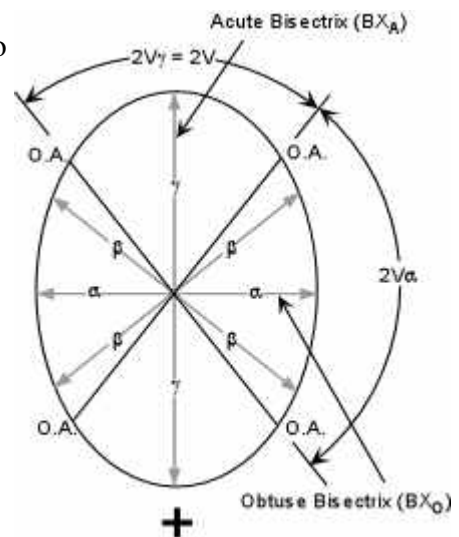
The other two principal planes contain the γ and β directions and the α and β directions, respectively.

Optic Sign of Biaxial Minerals

The optic sign of biaxial minerals depends on whether the β refractive index is closer to that of α or to γ . There are several ways that this can be stated, so we will look at all of them.

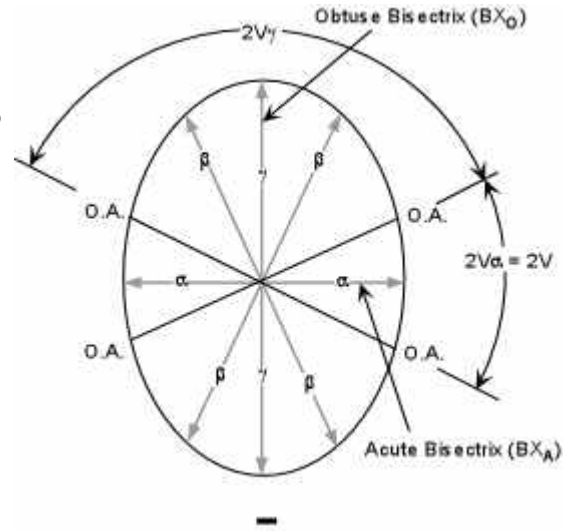
Biaxial Positive

- A mineral is biaxial positive if β is closer to α than to γ .
- In this case the acute angle, $2V$, between the optic axes is bisected by the γ refractive index direction. Thus we say that γ is the *acute bisectrix* (BX_A), because it bisects this angle.
- If a table of optical properties of minerals reports the $2V$ angle, it usually refers to this acute angle. But some tables report the $2V$ as $2V_\gamma$ or $2V_\alpha$. Note that in the case of a biaxial positive mineral, $2V_\gamma$ is the acute bisectrix, while $2V_\alpha$ bisects the obtuse angle between the optic axes (called the *obtuse bisectrix* (BX_O)).



Biaxial Negative

- A mineral is biaxial negative if β is closer to γ than to α .
- In this case the acute angle, $2V$, between the optic axes is bisected by the α refractive index direction. Thus we say that α is the acute bisectrix.
- In the case of a biaxial negative mineral, $2V_\alpha$ is the acute bisectrix, while $2V_\gamma$ is the obtuse bisectrix.

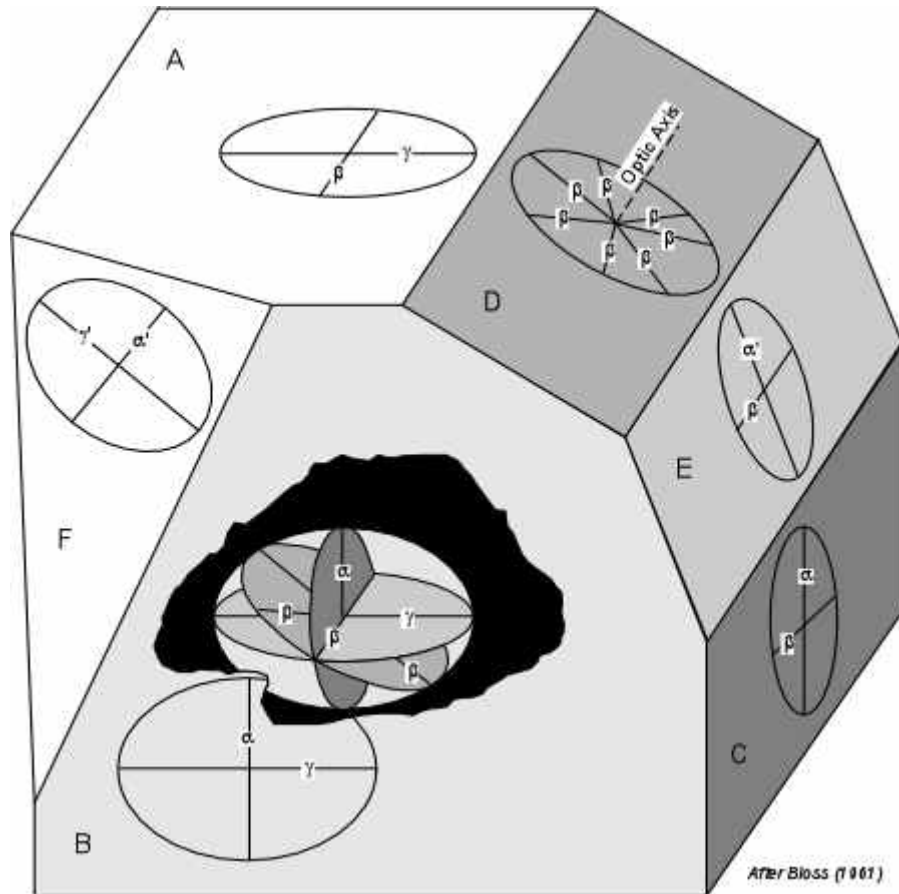


- Note that $2V_\alpha + 2V_\gamma = 180^\circ$.
- If $2V = 90^\circ$ the mineral has no optic sign.
- If $2V = 0^\circ$ the mineral is uniaxial.

Optical Orientations of Biaxial Crystals

Just like in uniaxial crystals, we can move the indicatrix around in a crystal so long as the indicatrix is kept parallel to the optical directions, and use this as an aid to determining the optical directions in the crystal. Several orientations are possible, the most general are shown in the diagram below. Note that in this diagram we have not shown the crystallographic axes, because different minerals will show different relationships between optical directions and crystallographic directions as discussed above.

- If a crystal oriented on the microscope stage with its α vibration direction perpendicular to the stage, then the β and γ vibration directions will be the two privileged directions in the crystal, as for the face labeled A in the diagram below. With such a face it would be possible to determine the β and γ refractive indices by using the Becke line method and various oils when either of these privileged directions is oriented parallel to the polarizer. Just as in uniaxial minerals, the crystal would be extinct with the analyzer inserted when either of the privileged directions are parallel to the polarizer. At any other orientation of the two principal vibration directions the crystal would exhibit an interference color that reflects the thickness of the crystal and the birefringence for this orientation ($\gamma - \beta$). Note that this would **not** be the maximum interference color for this crystal.



- If a crystal face such as B in the diagram above is parallel to the microscope stage, one would be looking down the β direction in the crystal. In this orientation the optic axial plane (OAP) would be parallel to the stage, and the α and γ refractive indices could be determined using the Becke line method and various oils. Because the β direction in this orientation is perpendicular to or normal to the OAP, the β direction is often referred to as the optic normal direction (O.N.).

In this orientation the interference color exhibited by positions off of extinction would again reflect the thickness of the crystal and the birefringence. But the birefringence for this orientation would be the absolute or maximum birefringence possible for this crystal ($\gamma - \alpha$).

- If a face like C were lying parallel to the stage, it would show another of the principal planes of the indicatrix, this time showing the α and β vibration directions of the crystal. Again, the refractive indices corresponding the α and β could be determined in this orientation. Note that for crystal faces A or C, we would be looking down either the BX_A or BX_O depending on the optic sign of the mineral. The interference color seen with the analyzer inserted will reflect an intermediate birefringence for the crystal ($\beta - \alpha$).
- If a face like D were lying parallel to the stage, it would show the circular section and

one of the optic axes would be orientated perpendicular to the stage. For this orientation the crystal would show no change in relief on rotation of the stage with the analyzer not inserted, and would remain extinct through a 360° rotation with crossed polarizers. For any rotation position the β refractive index could be determined.

- Faces like E and F, if lying parallel to the stage, would have privileged directions corresponding to random vibration directions. α' , γ' and β could be measured, but this would be of little use because all of these refractive indices are intermediate.

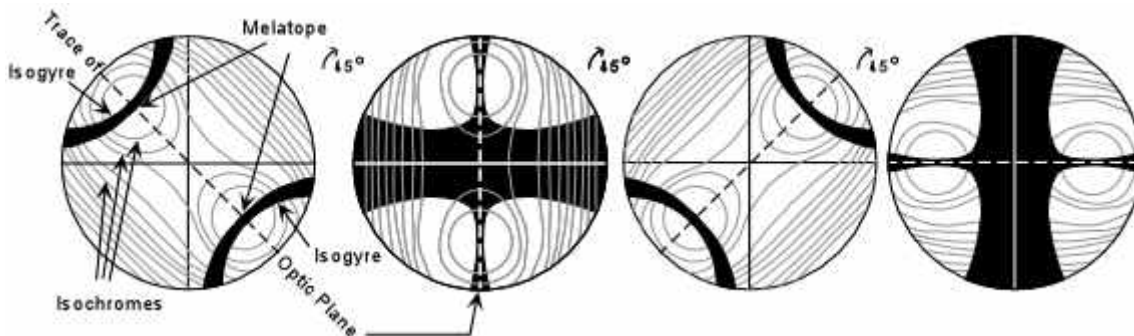
While knowledge of the optical directions can provide a means to measure the principle refractive indices, this is not often done because much of the information necessary to identify a biaxial mineral can be obtained from interference figures.

Biaxial Interference Figures

Four primary types of biaxial interference are seen. Only two of these are commonly used, but it is essential to discuss all four so that you can recognize each.

Acute Bisectrix Figure (BX_A)

Looking down the acute bisectrix, (the γ direction perpendicular to the stage if the crystal is optically positive, or the α direction perpendicular to the stage if the crystal is negative), at 45° off extinction in conosccope mode, one would see the interference figure shown in the left-hand diagram below.



- The dark isogyres mark the positions where light vibrating parallel to the polarizer has passed through the crystal.
- At the points of maximum curvature of the isogyres are the two melatopes that mark the positions where rays that traveled along the optic axis emerge from the field of view.
- Note that the distance between the two melatopes is proportional to the angle $2V$ between the optic axes.
- Also seen are isochromes, which show increasing interference colors in all directions away from the melatopes. The number of isochromes and maximum order of the interference colors seen will increase with increasing thickness and absolute

birefringence of the crystal.

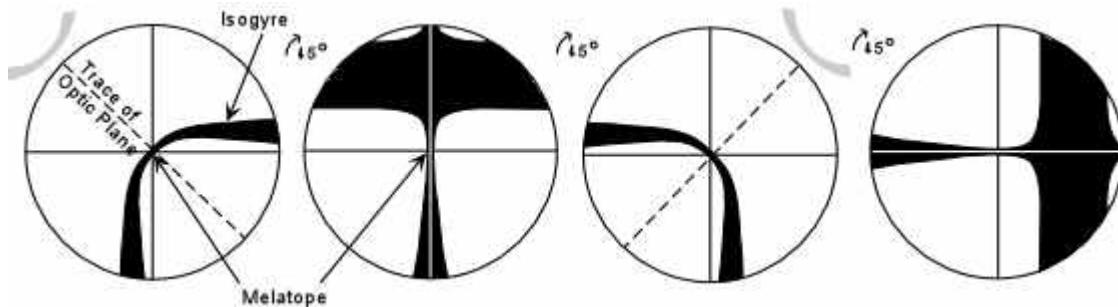
- Shown in the figure is the trace of the optic axial plane which includes the two optic axes.

As the stage is rotated 45° from this initial position, the isogyres will close to produce a cross. In this position the crystal would be extinct in orthoscope mode. The melatopes will be rotated so that both lie along the N-S cross hair.

Rotation by an additional 45° will result in the isogyres then separating again to show the interference figure in the third diagram. Another 45° rotation will again cause the isogyres to close into a cross, this time with the OAP lying parallel to the polarizing direction of the microscope. The crystal would again be extinct in orthoscope mode. Another 45° rotation would return the view to the first diagram in the series.

Optic Axis Figure (OA)

If one of the optic axes is oriented perpendicular to the stage, placing the microscope in conoscope mode will result in an optic axis interference figure. This is similar to the BX_A figure, except one of the isogyres and melatopes will be outside of the field of view (unless the $2V$ angle is very small).



During rotation of the stage, the melatope will remain at the cross-hair intersection and the isogyres will close to form an off-centered cross and then separate to show the curved isogyre in the adjacent quadrant of the field of view.

OA figures are easiest to find among randomly oriented grains, because a grain that shows such a figure will show no change in relief on a 360° rotation (analyzer out), and will remain extinct through a 360° rotation (analyzer inserted).

Obtuse Bisectrix Figure (BX_O)

A BX_O figure will be similar to the BX_A figure, except that the melatopes will be outside of the field of view most of the time during a 360° rotation. Still, every 90° the broad cross will form as the OAP becomes parallel to one of the cross hairs.

Optic Normal Figure (O.N.)

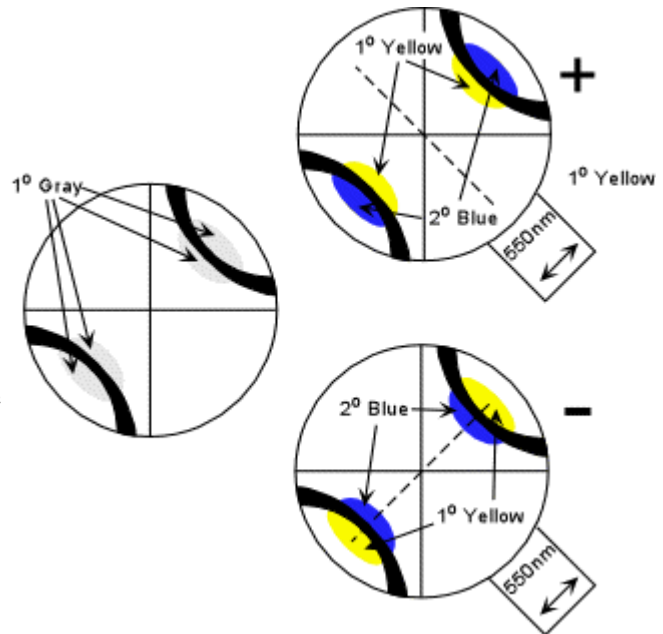
If the principal β direction of the indicatrix is oriented perpendicular to the stage, such that the crystal's privileged directions are α and γ , then changing to conosccope mode will produce an optic normal figure, also called a *flash figure*. In this figure, when one of the two privileged directions lines up with the polarizer, a broad cross covering almost the entire field of view will be observed. This cross, however will quickly disappear after just a slight rotation of the stage (this is why it is often called a flash figure). If one sees an optic normal figure, then the interference colors observed in orthoscope mode will reflect the absolute or maximum birefringence of the mineral, as discussed above.

Determination of Optic Sign

Biaxial interference figures are most useful for the determination of optic sign and estimation of the $2V$ angle, both of which are useful diagnostic properties of biaxial minerals. The two most useful are the BX_A figure and OA figure.

Acute Bisectrix Figure

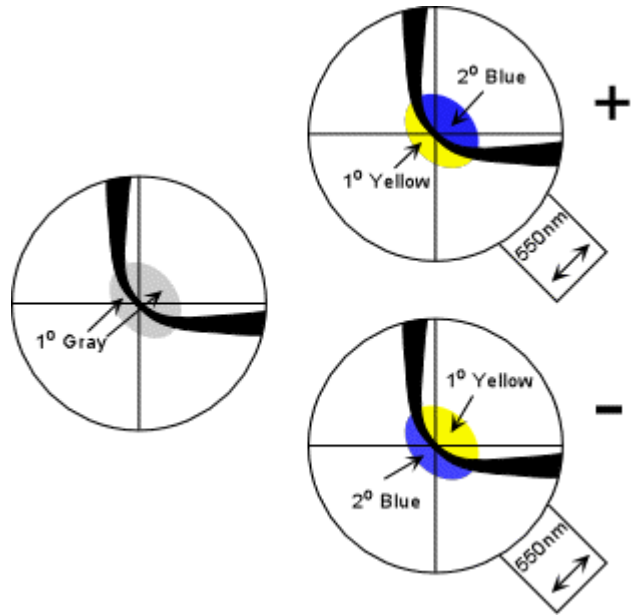
To determine the optic sign of a biaxial mineral from a BX_A figure, position the isogyres so that the melatopes are in the NE and SW quadrants. There should be an area near the melatopes that shows a 1° gray interference color. Observe this area as you insert the 550nm or 1° red compensator. If the 1° gray area in region between the two isogyres turns yellow, the mineral is biaxial positive. If the 1° gray area inside of both the isogyres turns yellow the mineral is biaxial negative. Note that it is easiest to remember this if you imagine the area inside the isogyres turns yellow and a line drawn inside the isogyres crosses the slow direction of the compensator like the vertical stroke on a plus sign. For a negative mineral, the line connecting the two yellow areas is parallel to the slow direction in the compensator, forming the minus sign.



Centered Optic Axis Figure

Optic axis figures probably provide the easiest method for determination of optic sign because grains with an orientation that would produce an OA figure are perhaps the easiest to find.

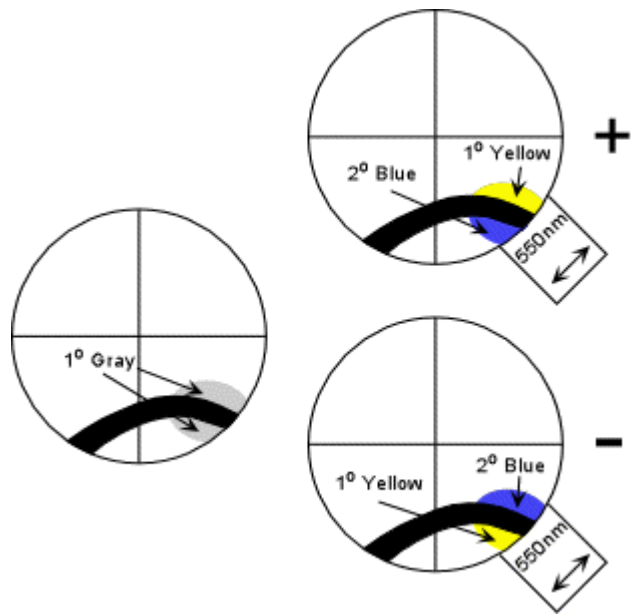
The method is similar to the B_{XA} figure, except you will be looking at only one of the isogyres. Again place the isogyre so that the inside of the isogyre is in the NW quadrant. Find the area that shows 1° gray close to the melatope. Observe this area as the 550 nm compensator plate is inserted. If the area outside of the isogyre turns yellow, the mineral is biaxial positive. If the area inside the isogyre turns yellow, the mineral is biaxial negative.



Off-centered Figures

Probably even easier to locate are off-centered OA or B_{XA} interference figures.

The method for optic sign determination in off-centered figures is essentially the same as for B_{XA} and OA figures. Position the isogyres so that it fits best in either the NE or SW quadrant. Observe the gray area near the melatopes and note the color change on insertion of the 550 nm compensator. If the gray area outside the isogyre turns yellow, the mineral is biaxial positive. If the gray area outside isogyre turns blue and the gray area inside the isogyre turns yellow, the mineral is biaxial negative.



How to Locate Different types of Biaxial Interference Figures

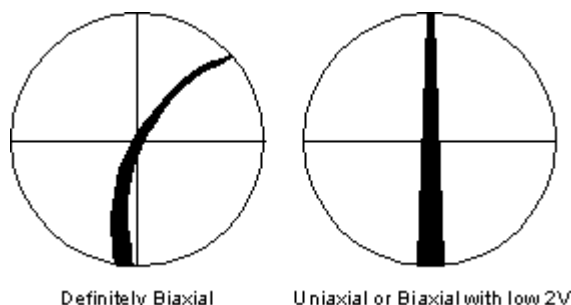
The best indicator of the type of interference figure a given grain will produce is the level of interference colors exhibited by the grain in orthoscope mode. Note that the O.N. figure will occur on grains that show the maximum interference colors. Such a grain will give the best indicator of the absolute birefringence of the mineral. OA. figures and Off-centered OA figures will be easiest to locate because the grain will either be completely extinct on a 360° rotation (OA figure) or will show very low birefringence (off-centered OA).

Type of Interference Figure	Level of Interference Colors
O.N.	Maximum
B _{XO}	Relatively High
B _{XA}	Relatively Low
O.A.	None
Off-centered O.A.	Very Low

How to Distinguish Biaxial from Uniaxial Interference Figures

Biaxial minerals can often be distinguished from uniaxial minerals on the basis of an interference figure.

To do so, rotate the stage until the isogyre rests on intersection of the cross hairs. If there is any curvature to the isogyre, the mineral is biaxial. If the isogyre is straight, then the mineral is either biaxial with a low 2V or is uniaxial. In the latter case further tests will have to be made on other grains to make the distinction.



Estimation of 2V

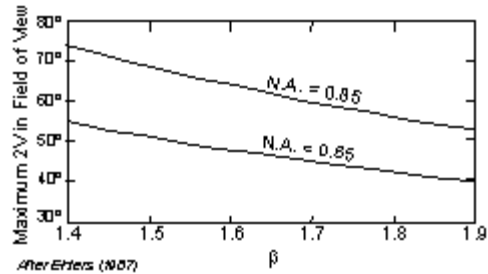
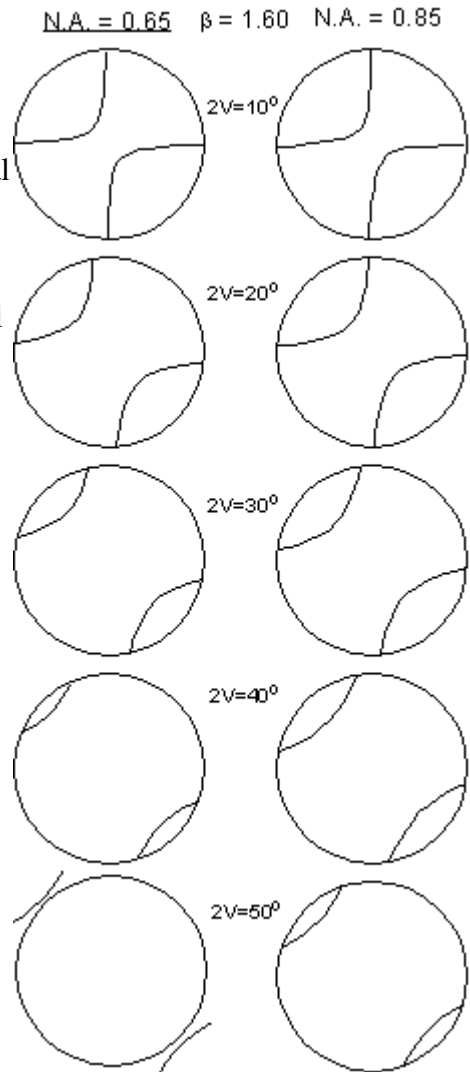
Precise determination of 2V can only be made by determining the 3 principal refractive indices of the mineral. But, 2V can be estimated from Acute Bisectrix figures and Optic Axis figures using the diagrams shown here.

Acute Bisectrix Figure

Recall that for a BX_A figure the distance between the melatopes is proportional to the $2V$ angle. To estimate the $2V$ from a BX_A figure, one first needs to know the numerical aperture (N.A.) of the objective lens used to observe the interference figure. The microscopes in our labs have an N.A. of 0.65, while research microscopes generally have a higher N.A. of 0.85. The diagram shown here gives a visual estimate of the $2V$ angle for objective lenses with these two values of N.A. for a mineral with a β refractive index of 1.6.

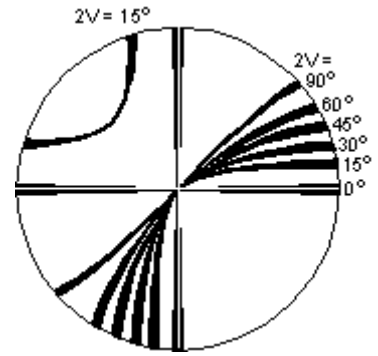
Remember that if the $2V$ is 0° the mineral is uniaxial, and would thus show the uniaxial interference figure. The separation of the isogyres or melatopes increases with $2V$ and the isogyres eventually go outside of the field of view for a $2V$ of 50° with the smaller N.A., and about 60° for the larger N.A.

Since the maximum $2V$ that can be observed for a BX_A figure depends on the β refractive index, the chart shown here may be useful to obtain more precise estimates if the β refractive index is known or can be measured.



Optic Axis Figure

2V estimates can be made on an optic axis figure by noting the curvature of the isogyres and referring to the diagram shown here. Note that the curvature is most for low values of 2V and decreases to where the isogyre essentially forms a straight line across the field of view for a 2V of 90°. For a 2V of 0° the mineral is uniaxial and the isogyres form a cross with straight isogyres.



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