How to Make an Accurate Three-Dimensional Model of Any Crystal from its Stereogram

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ABSTRACT
To make an accurate three-dimensional model of any crystal, plot partial stereograms of one face from each form on the crystal and all the faces with which it shares edges. Rotate each partial stereogram until the chosen pole is on the W radius of the stereonet. Label the reoriented poles. For any edge, draw a zone circle containing the poles of the chosen face and its edge neighbor, and the zone pole line. The orientation of this zone pole line is also that of the common edge of the two faces, so an edge orientation line may be drawn parallel to it. Then, draw this edge line on the stereogram at a convenient position and repeat for all edges of the face. Next, arrange the edges to make a face of chosen shape and size and repeat for all faces, keeping common edges constant in length. Finally, transfer multiple copies of each face drawing to a rigid material such as sheet balsa, cut them out, and glue the faces together with wood glue to make the model.

Keywords: Apparatus; mineralogy and crystallography.

INTRODUCTION
We have developed a simple, accurate, and inexpensive technique for making a geometrically accurate 3-D model of any crystal at any size. All interfacial angles on a carefully constructed model will be correct to about one degree. So far as we are aware, the technique has not been reported before. The first author is responsible for this paper except the section titled “A Different Type of Model,” which is the responsibility of the second author.

Klein and Hurlbut (1993, p. 56-63) or Bloss (1971, p.70-96) provide excellent treatments of stereonet/steregram fundamentals and a basic course on their use. One can find stereonets in both these references; the least distorted is given on page 75 of Bloss (1975), although it needs to be enlarged about 2X. (A stereonet from such a reference needs to be copied photographically for the best work, since photocopy machines may distort copied images slightly). A brief review of stereonet fundamentals important for the constructions in this article can be found at: http://www.sonoma.edu/geology. Instructions on such other topics as Miller Indices are provided in both the above references.

THE DRAWING AND MODEL-MAKING SETUP
Complete angular data on the faces of the crystal for which one wishes to make a model (The section titled “Obtaining Angular Data on Crystals” discusses data sources and data types) are necessary to make a unique stereogram for it. If possible, one should have an illustration of the crystal or perhaps a specimen. First, it is necessary to decide on the size of the model (the authors’ models are about fifteen centimeters in maximum dimension). It is best to have a large open area on a flat table in a comfortable working situation. Set up the stereonet glued to a rigid backing and with a tack through its center (Klein and Hurlbut, 1993, p. 59). Tape down the stereonet. Leave an area on the table for laying out, gluing, and assembling the model. You will need a pack of page-sized tracing paper for stereograms. Use transparent tape to reinforce the tracing paper where the tack shaft goes through, to prevent wearing or tearing of the hole.

For drawing tools, you will need a metal straight-edge at least 1.5 feet long, a large triangle, and a very sharp pencil. Colored pens and pencils are often useful. You will also need a can of artist’s spray adhesive to fasten paper patterns to the construction material.

To build the model, one or more sheets of 1/16” balsa wood or soft card stock, a pack of several single-edge razor blades, and a tube of quick-drying wood glue for model making should be at hand. A sanding stick will be useful for final finishing, and perhaps lacquer if desired.

AN EXAMPLE: CONSTRUCTION OF A CRYSTAL MODEL OF VESUVIANITE
Figure 1 is an illustration of a crystal of vesuvianite (idocrase), a common metamorphic mineral, taken from Ford (1955, #904, p. 608), together with its standard stereogram. Note that the crystal is composed of only three different face forms. The eight p faces are in (111) and the four m are in (100), while the front a face is (100), related to the side a face (010) by a 4-fold rotational symmetry axis. Sufficient data to plot (111) is that p'(angle) p = Ill (angle) (111) = 50° 39' (Ford, 1955, p. 608). All other faces of the crystal’s forms can be plotted from the mineral’s 4/m 2/m 2/m tetragonal symmetry and the rule that (010) plots at the E point on the stereogram.

Drawing Face (111)
We will first demonstrate the technique by drawing the first of the three faces whose outlines need to
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be constructed, face (111). There are
two main steps in the process for
each edge of the face: (1) reorienting
the stereogram and (2) drawing
draw edge lines. We strongly recommend
that the following operations be
plotted on a stereogram.

1. Reorientation of the Stereogram. The first major task is to
move the pole of (111) to the cen-
ter of the stereogram so face (111)
is horizontal in the plane of the
paper. This operation is accom-
plished in five steps. (It is impor-
tant to be as precise and accurate
as possible in these steps; the ac-
curacy of the model depends on it.)

1) Draw an initial stereogram for
the vesuvianite crystal (Figure
1). This will provide data for
the construction of all the faces
for the model. Locate all
poles to the nearest 0.5 degree.

2) Prepare a second tracing paper
sheet and put it down over the
first stereogram. On this over-
lay copy a partial stereogram
from the first one, displaying just (111) and the faces that
intersect it; (010), (100), (110),
(111), and (111) (Figure 2A).
Make an E index mark. Using
this relatively simple partial
stereogram will make it much
easier to keep track of the face
poles during reorientation and
drawing.

3) Remove both stereograms and
remount the partial one. Ro-
tate this partial stereogram
around the tack clockwise un-
til (111) lies on the W radius of
the net (Figure 2B). This takes
135° in this case. Tape the
stereogram in place. (Use these
steps for any face).

4) With the stereogram held in
position, move the (111) point
east along the W radius to the
center of the stereogram. This
causes face (111) to lie in the
plane of the net with no fore-
shortening. Count the number
of degrees (111) has moved (36°
in this case) to get to the cen-
ter. Move all other face poles
congruently (also 36° in this
case) with the same sense of
motion along the small circles

Figure 2. A) partial stereogram in standard orientation showing (111) and the five faces which contact it; B) partial stereogram rotated 135° clockwise to put (111) on the W radius of the stereonet; C) poles moved 36° along the small circles of the net to put (111) in the center and move all other poles congruently; D) The partial stereogram rotated 135° counterclockwise to re-
turn to the original position and match the E index.

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on which they are located (See Bloss, 1971, p. 91-92). On Figure 2C the rotation paths that the migrating face poles follow are shown as dashed lines. Label all the new face-pole positions with their Miller indices using a new color to clearly differentiate them from the index labels for the initial face-pole positions. The stereogram and its face poles are now reoriented. (Use these same steps for any face). Note that in Figure 2D and subsequent figures the original locations of the face poles have been removed and only the reoriented poles are shown.

Not in this case, but in many other crystals, one or more face poles which must be used will plot on the lower hemisphere and be labeled on the stereogram with open circles. Such poles will move in the opposite direction from those in the upper hemisphere in the rotation just described. Poles may also cross from one hemisphere to another (cross the primitive) as they move, and reverse direction of movement when they do.

5) Remove the tape holding the stereogram in position and rotate it 135° counterclockwise to its original position; the E index mark will be in its original place but the face poles will not (Figure 2D). Tape the stereogram in place again. Drawing of the (111) face can now begin.

2. Drawing Appropriate Zones, Zone Poles, and Edge Lines.
The second major task is to draw the face. Face (111) on the crystal has five contacting faces: (111), (111), (110), (100), and (010). Consequently, five edges need to be drawn to define the face. Recall that two or more faces that intersect along parallel edges define a zone. The smallest possible zone has two faces, with one common intersecting edge, which is the setup we use. On the stereogram, recall that a zone plots as a great circle, the zone circle, through the face poles of the zone. The zone pole is a line normal to the plane of this zone circle, and has the key characteristic of being parallel to the edges of intersection of the faces in the zone.

In the technique presented here, where one face pole plots at the center of the stereogram, any zone circle which contains it is vertical and therefore plots edge on as a single straight line on the stereogram. In Figure 3A, for example, (111) and (110) have a common zone circle that is vertical. Also, in this construction, the zone pole is horizontal and lies in the plane of the paper and so does the intersecting edge of the faces in the zone, that is, the edge between (111) and (110).

We next define a line that we call an edge line, which is parallel to the zone pole and the interfacial edge, normal to the zone circle, and lies in the plane of the paper.

We draw it on the stereogram itself (Figure 3A). We arbitrarily choose a convenient length for this first edge as in Figure 3B, and this determines the size of the face and of the model. Next, we will draw the complete face, as shown in Figure 3B.

1) To draw the complete face, we must draw five zone circles in succession, each pairing (111) with one of its bordering faces, find the right orientation for each of the five edges of the face, and then draw these edges. We have located the first zone and edge, of (111) and (110), in the preceding paragraph.

2) The second zone is of (111) and (111). An edge line normal to
its zone circle marks the edge between (111) and (111), as shown on Figure 3B.

3) The third zone is of (111) and (111). An edge line normal to their zone circle marks the edge between (111) and (111), also shown on Figure 3B. These first three edges form an isosceles triangle, which is the main outline of (111). (111) has, however, in addition to its three main edges, two short edges against small (100) faces that must be added, as follows.

4) The fourth zone is of (111) and (100) and turns out to be cozonal with the third zone, (Figure 3B), as the three face poles lie on the same great circle. The edge of (111) against (111) is then parallel to the edge of (111) against (100), which is perhaps surprising. Draw the latter edge to an arbitrary length (Figure 3B), which should be chosen so the model will look approximately like the illustration in Figure 1. (A good practice with drawing complex faces is to draw the main shape, as was done here, and then add smaller modifying edges).

5) The fifth zone is of (111) and (010) and is cozonal with the second. Draw the edge the same length as the edge of (111) with (100).

Face (111) has now been drawn (Figure 3B). Eight identical copies will be needed to make the model. Note that the fundamental isosceles triangle of the face is invariant in shape but not in size. The secondary edges against the (100) faces are quite variable in length, and the overall (111) faces may have any of an infinite number of shapes, defined by the modeler. Note that one can make nonideal crystals by making various edges of (111) against particular (100) faces different in length.

Drawing Face (110)

All four $m$ faces ($(110)$) for the example vesuvianite are the same shape and size, so we can make a pattern for one from a new stereogram and copy it four times. In the case of (110), the contacting faces are (111), (111), (100), and (010). The technique for drawing (110) is the same as for drawing (111). Make a second partial stereogram for vesuvianite on a new overlay of the primary stereogram of Figure 1, plotting just these five faces. Reorient the partial stereogram, draw appropriate zone circles and edge lines, and block out and draw face (110) in the same exact sequence of steps taken earlier in drawing face (111). Figure 3C shows the reoriented face poles, zone circles, and edge lines and the (110) face drawn from them. To make these new faces the same scale as the $p$ or (111) face set above, make the common edge between (111) and (110) the same exact length on both drawings. Use a divider or a scrap of paper for measuring. Be very careful to be accurate here.

Drawing Face (100)
The four $a$ faces ($(100)$) are identical, and again, one construction drawing will suffice. Plot a third partial stereogram for (100) and its neighboring faces (111), (111), (111), (111), (110) from the main stereogram of Figure 1. Reorient the partial stereogram as before, draw zone circles and edge lines, and construct the face. Figure 3D shows the reoriented stereogram, the zone circles, the edge lines, and the (100) face. Make the edges on (100) the same length as those which match them on the (111) and (110) faces previously drawn for a precise fit.

Cutting Out the Faces
One face from each of the three forms composing the crystal has been drawn. Now, go over the patterns carefully and make sure that all the matching edges are the exact same length. Make sure that symmetrically related edges and internal angles match exactly. Move edges where necessary. This careful study of the quality of the three face patterns will ensure an accurate model.

The next step is to transfer sufficient copies of these drawings to the material from which the model is to be made. The most precise way to copy the face patterns onto the material is as follows. Tape the original pattern to a light table and put a blank sheet of paper over it. Then, with a very sharp pencil and a straightedge, exactly copy the face onto the overlying sheet. Repeat this as many times as needed. Then, copy the other faces in the same way. Try to end up with a compact group, which in this case comprises eight (111), four (110), and four (100) faces. Take this group of faces and cut out the area of paper on which they lie. Then, spray its backside with an artist’s adhesive spray and let it dry until tacky (follow the directions on the container) but removable; then, press it down onto the construction material. We use 1/16-inch sheet balsa wood as the material for our models, although this method will work with a variety of materials. The faces can be cut out immediately.

A second way to mark the face outlines is to take the paper with the face sets drawn on it, hold it down with tape, and push a common pin through all the corners of the faces into the material below. Then, remove the paper and draw the edges of the faces between the pinpricks. This method is not quite as accurate as the first but avoids the use of the spray, which may be inadvisable in a group or where someone finds it unpleasant.

The next step is to cut out all the faces. For this, use single-edged razor blades rather than an Exacto type knife blade, because they are much thinner and allow a more accurate cut. Take a metal straightedge and lay it exactly along a face edge. Cut along the edge with the razor blade tilted about 45° back under the metal straightedge, to bevel the face edge. This will allow fitting the faces against each other to sharp edges. Do your best to cut exactly along the line of the pattern. Cut each edge until the face is free, and repeat for all the faces. Last, remove the paper pattern from the faces.

When these eight $p$, four $a$, and four $m$ faces have been cut out, the components of a model vesuvianite crystal will be ready to assemble.
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Figure 4. Incomplete model of vesuvianite lying on the angle jig. The remaining faces needed for completion lie beside it, along with four internal braces to hold {111} faces against each other at the proper angle.

Assembling the Model

Two things are the most important when gluing two faces together: (1) matching the faces to a tight, sharp edge, and (2) getting the interfacial angle right. In the early stages of construction, to do these things we use a simple jig to hold the two faces in proper alignment and augment that with an internal brace. Figure 4 shows our jig; it is a slab of balsa with a slot cut into it, into which we insert a piece of cardboard cut to the correct interfacial angle for each case. (Recall that one can measure the interfacial angle between any two faces on a stereogram by lining their poles up on a great circle). To get the edge aligned just right, we glue the two faces together, and hold them together for one minute. By then the glue has begun to stiffen. We then put the pair of faces on the angle jig, with the glued edge lying on the balsa slab at a right angle to the cardboard angle guide and the two faces fitted against the jig parts so they lie at the correct interfacial angle (Figure 4). For two faces of form {111}, for example, the interfacial angle is 50° (Figure 1). Figure 4 shows an incomplete model of vesuvianite, set down so that it is clear that the interfacial angle on the model matches the cardboard guide. We press the edges together against the jig and look at the joined edge from all directions for fit. After about two minutes, when the glue is quite stiff, we lift the face pair up off the jig and visually check for perfect alignment. We then replace the faces on the jig in the correct orientation and let the glue set for a few more minutes. In this step, we have mated the two faces perfectly and established the correct interfacial angle between them.

To further assure a correct interfacial angle, and to strengthen the model in the early stages of construction, we use an internal brace across the edge. We cut out a small piece of balsa with the correct interfacial angle and glue it to the inside of the edge being glued. This helps assure that the correct interfacial angle is obtained and increases the strength of the model. Figure 4 shows several of these braces in place in a partial model of vesuvianite and a set lying loose as well.

When the model is assembled, a good technique is to build it in parts and fit the parts together. In Figure 4, for example, the base of the vesuvianite model is complete; we would next assemble the last four (111) faces in a separate set and glue that "top" onto the part shown. Last, we would glue the four (100) a faces into their openings, while holding them with a pin or knife tip. No braces or jigs are necessary for this last step as the parts can only fit one way. The exact gluing plan for each model will vary. The model, once made, is surprisingly strong. Figure 5 shows five wood models of various levels of complexity made using the above technique.

A special case arises with very small faces. It is best to construct these after the model is made using the larger faces. A good technique is to mark the edges of the small face on the paper pattern for each of the larger faces it contacts and leave the paper on these faces while the model is constructed. Then, trim

Figure 5. Six complete models. All but one are replicas of particular drawings in Ford (1955). Left rear is olivine, balsa, #888, p. 597, on a stand; left center is calcite, balsa, #775, p. 512; left front is barite, balsa, partial copy of #1036, p. 749; right rear, vesuvianite, card foldup, #904, p. 608; right center, corundum, balsa, #730, p. 461; right front, parahgilgardite, balsa, data from Hurlbut (1938). This last species is the only representative of triclinic class 1.
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Figure 6. Fold-up model for vesuvianite.

done for the olivine model in Figure 5.

A DIFFERENT TYPE OF MODEL

For student use, the above technique of model assembly can be greatly simplified by drawing all the faces of the crystal on a single sheet of light card stock in such a manner that the card can be folded up into the crystal (Figure 6) as follows.

1) After the model's faces are drawn, as in the section titled “An Example: Construction of a Crystal Model of Vesuvianite,” tape the papers with the faces onto a light table. Then, overlay a second sheet of paper on the first and carefully copy the faces, one by one, onto the overlay in such a manner that they are joined along common edges. The goal is to copy them, joined together, in such a way that the completed drawing will have all the faces needed for the crystal and can be cut out and folded up to make the crystal model (Figure 6).

2) Make a photocopy of the paper overlay. Spray its back with artist’s adhesive spray, wait until it is tacky (see directions), and press it down smoothly onto a sheet of light card stock. Then, using a single-edged razor blade and the metal straightedge, cut out all the free edges of the pattern. You may want to bevel the edges of the faces by tilting the razor blade back under the edge about 45° when cutting. Peel off the pattern.

3) Turn the cutout card over and use the edge of the razor blade or the tip of a dead ball-point pen to scribe lightly cut lines along the traces of the edges of the crystal, on what will be the inside of the model. This will allow smooth folding of the card along edge lines.

4) Fold up the cutout model, carefully bending the card along each edge. To get an edge to bend along a straight line, again be sure to scribe the back of the card first and use a wood or
metal strip pressed down along the edge line as a guide for the bend. Check faces that adjoin along an edge to be sure they fit well. Bend all the edges and check the quality of fit along all the edges to be glued.

5) Begin to glue the model. Fold any two adjoining faces together and glue them, again using quick-setting wood-model glue. Hold the edges together temporarily with drafting tape. Keep checking the alignment of the joint while the glue sets. When one edge has set, move onto the next. When the last edge has been glued, the crystal model is complete. The process of pulling the faces together to fit together along common edges will automatically force them into the correct interfacial angles. The vesuvianite model in Figure 5 was made this way.

6) Paint the model with clear or colored model paint if desired.

With this technique, crystal models of many types can be mass-produced for class use. The copying and gluing technique is well within the abilities of students and allows them each to have several personal models showing properties of symmetry, axis placement, and so on, which they can study at their leisure. A set of overlays, ready for transfer to card stock, can be photocopied for each student, and in a few hours they can prepare all the models needed for a course.

This technique is not suitable for very complex models with many forms, especially if the faces are small. Reasonably simple forms representing all the classes and all symmetry styles can certainly be made quickly, however.

**OBTAINING ANGULAR DATA ON CRYSTALS**

Modern mineralogy books, such as Klein and Hurlbut (1993), do not generally contain interfacial angular data on the minerals they describe. Ford (1955), however, provides a great many complete descriptions and is widely available in libraries. In addition, the Georef indexing service allows rapid location of articles on any mineral, some of which usually have interfacial angular data (as in the reference by Hurlbut (1938) for parahilgardite used to make the model in Figure 5). These data may be in one of two formats.

The first format is that used by Ford (1955) and in this article; faces are located by using their angular relationships to other faces that plot in known positions on stereograms, such as (010). The second format, derived from studies with reflecting goniometers, locates faces independently by using angles made by a beam of light reflected from the face. In this second case, faces are located by a pair of angles, phi and rho; a face position table for the mineral includes a list of these values. Klein and Hurlbut (1993, p. 58) and Blos (1971, p. 74) show how to plot face poles on the stereogram using these latter angular data.

**ACKNOWLEDGMENTS**

The senior author dedicates this paper to Dr. John Mandarino, retired from the University of Toronto, who was his instructor in crystallography at Michigan Technological University and who first interested him in stereonets and their applications. He also expresses his appreciation for the efforts of an anonymous reviewer, whose comments improved the manuscript and who provided the drawing technique used in Figure 3.

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**Food for Thought**

If we think that scientific laws are flexible enough to be affected by the social setting of their discovery, then some may be tempted to press scientists to discover laws that are more proletarian or feminine or American or religious or Aryan or whatever else it is they want. This is a dangerous path, and more is at stake in the controversy over it than just the health of science....our civilization has been powerfully affected by the discovery that nature is strictly governed by impersonal laws. As an example I like to quote the remark of Hugh Trevor-Roper that one of the early effects of this discovery was to reduce the enthusiasm for burning witches. We will need to confirm and strengthen the vision of a rationally understandable world if we are to protect ourselves from the irrational tendencies that still beset humanity.
