The University of Pretoria  
Department of Geology

An introduction to Stereographic Projection for Geologists  
and Mining Engineers

GLY 254  
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Introduction:
This booklet is designed to accompany the course in stereographic projection, which forms the bulk of the practical component for GLY 254 (and GLY 410) presented at the University of Pretoria. It contains a number of geometrical problems which consider the attitude of geological planes and lines in three dimensional (3D) space, and as such is very useful for solving problems and illustrating data relating to both structural geology and mining engineering. Certain pages in the booklet contain questions which must be completed, neatly removed from the booklet and submitted for assessment. In addition to this continuous assessment, a practical test based on stereographic projection will be given during one of the lecture times. Questions on stereographic projection may also be included in the final exam.

Measurement of data:
Much of field geology (whether on the surface of the planet or down a mine) is concerned with the recognition, measurement and description of the orientation of geological features (usually planes or lines) in 3D space. It is often easy to identify a bedding plane, for example, which has been tilted away from its initial horizontal orientation (remember the ‘Law of Original Horizontlity’ from GLY 152?). But if you wanted to describe, or even illustrate the orientation of the plane to someone who has not been to the outcrop, how can you accurately give an indication of the attitude of the bedding plane? If you think about it, it’s rather a problem, as there are an infinite number of planes which can exist in 3D space. We need to use a convention so that we can accurately describe any of these infinite planes. There are two common ways of describing the orientation of planes in 3D, and one convention for lines.

The types of plane and lines that you may want to measure whilst in the field will be covered in detail in lectures, but the planes that a structural geologist is often interested in are bedding, cleavage, foliation, fault planes, joints and fold axial planes. Lineations (lines) which may be measured include ripple crest or palaeocurrent directions, fold hinges, slickenside lineations and a variety of linear fabrics in tectonites.
Planes and lineations are measured using a compass-clinometer specially designed for geologists. Common types used by geologists are the Silva, the Brunton and the Freiberg compasses. The method for the description of planes is the ‘STRIKE, DIP and DIP DIRECTION’ method. There is also a second method of defining planes, using only dip and dip direction values, but this will not be covered in these notes. Which of these two methods you use is largely governed by the type of compass you use (Silva and Brunton compasses measure planes by strike, dip and dip direction; the Freiberg compass can measure by both methods). Most text books utilise the strike, dip and dip direction method, so that is what is followed here.

The strike can be defined as ‘the orientation, relative to true north, of a line formed by the intersection of a horizontal plane and the plane being measured’. This is measured numerically, using the 360° intervals around the cardinal points of the compass. During measurement of strike, the horizontal plane is defined by the compass body (many compasses have a spirit level incorporated into the body for exactly this purpose), and the line of interception is defined by the long edge of the compass body which is held along the plane being measured. The dip can be defined as ‘the maximum angle between the plane and horizontal’. It is important to note that the dip is always measured perpendicular (i.e. at right angles) to the strike line, in order to achieve the maximum angle. If a dip is measured less than 90° from the strike line, an apparent dip is measured, which is always less than the true dip. See figure 1 for clarification. Dip is measured using the inclinometer incorporated into the geological compass.

**Figure 1:**

In the diagram above, the orientation of the strike line is parallel with true north. Therefore the strike is either 000° or 180°, depending on which end of the strike line you measure the orientation. This is true for ALL strike lines…they have two ends, and therefore you can measure either one of two directions, but note that each measurement must differs from its pair by 180° (e.g. a line which strikes 045° would also strike 225°). The angle of dip in the diagram above is about 50°. However, it is vital to note that strike and dip alone do not define the orientation of a plane. The diagram below (Figure 2) illustrates why this is the case:
Figure 2:

Note that both planes illustrated here have exactly the same strike value (000° or 180°), and exactly the same dip value (about 45°), and yet they are different planes, i.e. a given set of strike and dip values is identical for two of the infinite number of planes. In order to separate these two possibilities, we need to add a third modifier, which is known as the ‘dip direction’. Note that the two possible planes with matching sets of strike and dip values dip in opposite directions; in figure 2, the dark grey plane dips towards the east, and the light grey plane dips towards the west.

Therefore, if we were to describe the dark grey plane above, we would write the following: 180°/45° E.

Note that when we are listing the strike value (which may vary between zero and 360°) we always use three digits. When we list a dip value (which may vary between zero and 90°), we use two digits. An eastward-dipping plane which has a strike just east of north (i.e. less than 10°), and a shallow dip (also less than 10°) might be written: 008°/06°E

Note that zeros are added in order to bring the number up to three digits (for strike) and two digits (for dip). The reason why this is done is so that it is impossible to confuse strike values with dip values even if hastily written down in a field notebook. Dip-directions need only be vague; remember that in our use of dip directions, we are discriminating between two planes which are 180° apart. Use the cardinal points of the compass at 45° intervals (i.e. the letters N, NE, E, SE, S, SW, W, NW) to indicate the approximate direction towards which the plane dips. The use of dip direction is not an optional extra for a minor point of clarification. It is a vital part of your description of a plane and must always be included.

Using all the possible strike directions (values 000° through to 180° [which also includes all the strike directions from 180° to 360°]) and all the possible dip values (00° [horizontal] through to 90°[vertical]), plus the fact that each strike value can accommodate two possible dip directions, we can resolve the infinite number of planes into 180 x 90 x 2 = 32400 different planes that we can measure using this
convention. Of all the other infinite number of planes in 3D space, they are $\frac{1}{2}^\circ$ or less away from the planes we can measure.

Please note that you will lose marks on assessed work if you do not remember to use three digits for strike values, two digits for dip values, or forget to add the dip direction modifier.

So, now we can accurately measure and describe the orientation of any plane in 3D space to within $\frac{1}{2}^\circ$ of accuracy. But there is still a problem concerning the presentation of these figures. If you went out into the field or down a mine, and collected the strikes, dips and dip directions of hundreds of bedding planes, it would be useful to be able to somehow illustrate the orientations of these beds graphically, rather than having rows of numbers, which is very difficult to visualise. This is rather difficult to perform, as the planes which you measured occupy 3D space, and therefore any graphical way of representing this data set would also have to be in three dimensions, which seems very difficult to achieve in a report written on a 2D piece of paper.

**Projection of 3D data:**
In fact you are probably very familiar with the method of dealing with the problem of accurately representing 3D phenomenon on 2D paper. The planet earth is a 3D object, and yet most atlases and geography/geology textbooks contain a map of the Earth. A 3D object is *projected* onto a 2D page in a book. Often a hemisphere of the earth (usually the eastern and western hemispheres, but sometimes the northern and southern hemispheres too) is projected within a circular map. The lines of latitude and longitude are distorted during the projection, so that the 3D hemisphere is squashed onto a page. This same procedure is undertaken in stereographic projection.

The next thing to think about is a glass sphere, with an equator marked on it. The equator is thus dividing the upper and lower hemispheres. Now think about a plane passing through the sphere (grey plane in Figure 3), so that the plane passes right through the centre. In the case of Figures 3, 4 and 5, the plane has an orientation of $020^\circ/55^\circ$ SE.

**Figure 3:**
Don’t think of this as a direct analogy with a globe of the Earth. If this were the case, then north would be at the top of the glass sphere. In this globe, north (and all the other cardinal points of the compass) lie on the plane of the equator. When we look down on the glass sphere from above, it’s as if we are looking down on a map. Look again at the grey plane which passes through the sphere. Look at where the plane passes through the lower hemisphere, and notice that where the edge of the sphere and the plane intersect, a long arc is formed. In geometry, this arc is termed a ‘great circle’ (on a globe of the Earth, or on a projection of the Earth in an atlas, the lines of longitude are also ‘great circles’. The lines of latitude on a globe are termed ‘small circles’ because they are smaller diameter than great circles). For the purposes of this, and all other stereographic projections in structural geology, we will only be looking at the lower hemisphere (forget about the upper hemisphere, unless you are studying mineralogy). Imagine that you are looking vertically down through the glass sphere from the very top-most point (known as the zenith), so that you can see the great circle formed by the intersection of the plane and the edge of the sphere beneath. If you were to sketch what you saw, it would look like this:

**Figure 4:**

![Figure 4](image)

The vertical view which is sketched above is, in fact, an approximate stereographic projection from a 3D object (the lower hemisphere) onto a 2D piece of paper. In stereographic projection, you are performing a projection as follows:

**Figure 5:**

![Figure 5](image)

Figure 5 shows how a plane in 3D passes through an imaginary sphere, and the trace formed by the intersection of the plane with the sphere is projected towards the zenith. The arc which is projected onto a plane passing through the primate circle is the stereographic projection of the plane. Each of the 32400 planes that we can measure
with a compass-clinometer will define its own unique great circle on a stereographic projection.

In a similar fashion, lineations can also be plotted on a stereographic projection. Lineations can be measured with a compass clinometer, and are defined by a TREND and PLUNGE. A trend can be defined as the orientation relative to north (measured in a horizontal plane) of the line measured in the down-plunge direction. The plunge is the angle between the lineation and the horizontal. There are therefore a range of 359 different values of trend, and 89 different values of plunge which can be measured with a compass-clinometer (that’s 31952 lineations). See Figure 6 for an example.

Figure 6:

In Figure 6, the lineation has a trend of about $330^\circ$, and a plunge of $30^\circ$ (written $30^\circ \Rightarrow 330^\circ$). Note that, unlike a strike, a trend can only have one possible value, as the direction is defined by the down-plunge direction. In 3D, a lineation would plot within a sphere, and on a steronet as shown in Figure 7:

Figure 7:

Once again, the vast numbers of lineations can be defined by the projection of the unique point that each line makes when it intercepts the sphere.

So far we have considered how planes and lineations would look if they intercept a sphere, and then how a projection of this would look. Obviously we cannot walk around in the field carrying big transparent spheres. We need a method by which we can directly plot a measured plane or lineation onto a projection. This is accomplished
by means of a ‘Stereonet’. There are two types of net commonly in use; the Schmidt net and the Wulf net, each of which uses a slightly different projection. In structural geology we use the Schmidt net, which preserves the angular relationships between plotted planes. The Schmidt net is shown in Figure 8. Cut out the net and mount it on stiff cardboard so that it can be re-used, and so that it doesn’t get crumpled. Rips, crumples and holes in the net greatly reduce its accuracy!

**Figure 8:**

The net shown above shows a number of great circles for planes which strike 000º-180º. Each of the great circles represents different dip values at 2º intervals (the bolder great circles are at 10º intervals). Thus planes with shallow angles of dip plot as great circles closer to the perimeter of the net, and steeper angles of dip are reflected by great circles with less curvature towards the centre of the net. See Figure 9.
As Figure 9 illustrates, the dip value can be altered simply by counting from the edge of the net inwards along the E-W line. If the planes in Figures 9a and b had a westerly rather than easterly dip-direction, then the planes would be plotted by counting inwards from the opposite (western) edge of the net.

It is therefore easy to plot planes on a stereonet. BUT, the net only shows great circles for planes which happen to strike due North/South. What about all the planes with other strikes? Obviously a full set of great circles for all strike values cannot be incorporated into a single diagram (imagine another 179 sets of great circles added to Figure 8!). In stereographic projection we overcome this problem by plotting our great circles on a sheet of tracing paper mounted on top of the stereonet, by a drawing pin (thumb tack), which passes through the centrepoint of the net. By rotating the tracing paper clockwise or anticlockwise, different strike directions can be temporarily lined up with the North-South line on the net beneath, so that a great circle with suitable dip value can be plotted, before rotating the tracing paper back to its original position. It’s best to mark the original north position on the tracing paper, to assist with rotation back to the correct orientation. An example of plotting planes is given in Figure 10, where a plane with an orientation of 045°/55° SE is plotted.
Once you have rotated the tracing paper back to its original position, always check that the dip direction indicated by the great circle on your stereonet reflects the dip direction recorded for the plane. It’s very easy to plot the wrong dip direction!

Lineations can similarly be plotted on a stereonet, although there is an important difference; Because the trend is measured in the direction of plunge, instead of rotating the trend direction to the N-S line, rotate it instead to the E-W line, and count the correct plunge from either the E or W point on the net inwards, depending on the plunge direction. See Figure 11, which shows the method of plotting a lineation with a plunge of 38°, and a trend of 229° (38°⇒229°).

It is important that the hole punched in both the stereonet and the tracing paper by the drawing pin do not become enlarged by successive rotations. If this happens, the tracing paper does not rotate about the same axis, which can lead to inaccuracy when plotting. It is often a good idea to reinforce the hole in the tracing paper with transparent tape.

Now try the questions on the following page.
**Question Sheet 1.**

Fill in your answers on this page, remove the page carefully (use scissors!), and submit it for marking.

**Name:**_______________________________ **Student Number:**_________________

In the diagrams below on the left plot the approximate orientation of the given plane/lineation on the stereographic projection. Also draw a map in each box using standard bedding plane or lineation symbols for the given plane/lineation. Remember to include the dip/plunge value. In the diagrams on the right, where the stereonet has been completed with planes or lineations, estimate the orientation of the plane/lineation, and complete the map.

<table>
<thead>
<tr>
<th>Standard map symbols:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal bedding plane</td>
</tr>
<tr>
<td>Vertical bedding plane</td>
</tr>
<tr>
<td>Bedding plane strike and dip value</td>
</tr>
<tr>
<td>Lineation trend and plunge value</td>
</tr>
</tbody>
</table>

180/45 W

205/05 SE

008/90

30=330
**Poles to planes:**
Very often in structural geology, we have gone out into the field and collected many (literally hundreds) of orientations of (e.g.) bedding planes. If we want to see how the orientation of bedding planes varies, it is obviously important to plot all the planes on the same stereographic projection. However, if hundreds of planes are plotted as great circles, the stereographic projection soon looks very complicated, and rather like a plate of spaghetti. With the complexity of numerous superimposed great circles it becomes very difficult to visualise any patterns in variation in the orientation of planes. It is therefore necessary to reduce our data on the stereonet to smaller symbols, which will not interfere with each other, and yet show exactly the same information about the orientation of planes as great circles do.

The **pole** to a plane is a convenient way of overcoming this problem. A pole to a plane is the point where a lineation which is perpendicular to a plane intersects the edge of the lower hemisphere. Geographical examples are both the North and South poles. These are poles to the plane of the equator, with the South Pole being the interception of the lineation in the southern (lower) hemisphere (See Figure 13a). The 3D orientation of any given plane that you happen to measure can be represented not only by its great circle, but also by the pole to that circle; each individual plane has its own dedicated pole. Obviously, as a pole is a lineation, it is represented on the stereonet by a single point. It is therefore much easier to plot large numbers of planes by plotting poles rather than the great circles. See Figure 13b.

**Figure 13:**

![Diagram a) showing the relationship between pole, equator, and lineation](image1)

![Diagram b) showing a plane with its pole](image2)
Figure 14 illustrates the method of plotting poles to bedding. It involves rotating the plane so that it lies on a great circle (and is therefore orientated N-S). The pole (which is perpendicular, i.e. 90º to the plane) can be plotted by counting 90º through the centre point. As a shortcut, simply count the dip value of the plane (55º in this case) away from the centrepoint. In the example in Figure 14, the plane has an orientation of 045/55 SW, and the pole an orientation of 35º⇒315º. Note that the strike of the plane and the trend of the pole are 90º apart, and the plunge of the pole can be calculated by subtracting the dip value of plane from 90 (90º-55º=35º):

**Intersection lineations:**
Imagine that underground there is a fault that intercepts an inclined bed of limestone. Where these two planar features intersect, an ore deposit forms (hydrothermal, ore-bearing fluids may have circulated along the fault plane). Any two planes which are not parallel with each other will intercept, and where they intersect they form a line (you can try this with two hardback books). This is known as an intersection lineation. By plotting the orientation of the two planes as great circles together on the same projection, you get a point at which the two great circles cross. This point represents the orientation of the intersection lineation, and therefore the orientation of the ore body. There are questions on this in question sheet 2.

Closely related to this is a type of stereographic projection known as a β (beta) diagram. β diagrams are concerned with defining the orientation of a fold axis, based upon the orientation of the limbs of the fold. The line along which the two limbs of a fold intersect is called the hinge line, and is parallel to the fold axis. Defining the hinge line and fold axis can therefore be performed by plotting the planes of the two lines of the fold.

**Figure 15:**
**Question Sheet 2.**

Most of these questions involve the use of the stereonet and tracing paper. Cut out the stereonet on page 7, mount it on cardboard, and add bearings at 10° intervals around the edge of the stereonet. On the tracing paper, trace the edge of the net (the primitive circle) and mark on the North position. Remove the tracing paper sheets from the net and submit them along with your answers.

1. a.) Using the stereonet plot the following planes as great circles
   i.) 345°/67° NE
   ii.) 303°/20° SW
   iii.) 073°/45° NW

b.) On the same sheet of tracing paper, plot the poles to the above planes. Use colours to indicate which pole corresponds to which plane

2.) Plot the following lineations on a separate sheet of tracing paper:
   (a.) 34°⇒267° (b.) 67°⇒359° (c.) 05°⇒135° (d.) 85°⇒035° (e.) 00°⇒140°

Questions 3, and 4 concern lineations and their relationship to planes. Look again at Figure 6, and note that if a lineation is lying on a plane, then on a stereonet, the point where the lineation plots must lie on the great circle of the plane on which the lineation is found. Bear this in mind when answering the following questions. You will have to use your stereonet and tracing paper to solve them:

3.) A bed which is exposed in a vertical cutting has an apparent dip of 68°⇒310° and a strike of 045°. What is the true dip?

4.) A dolerite dyke in a mine has an apparent dip of 34°⇒014° in one tunnel and 78°⇒254° in the other. What is the strike and dip of the dyke?

5.) A fault has orientation 035°/60° NW and it intersects a limestone bed with orientation 152°/35° NE. Hydrothermal alteration along the fault plane has resulted in an ore shoot forming along the intersection of the two planes.
   a.) What is the orientation of the ore shoot?
   b.) What is the pitch of the ore shoot in the plane of the fault?
   c.) What is the pitch of the ore shoot in the plane of the limestone bed?

6.) One limb of a fold has orientation 234°/67° SE and the other limb 348°/31° NE. What is the orientation of the hinge line?

7.) Two intersecting shear zones have orientations: 035°/54° NW and 312°/30° NE
   a.) What is the orientation of the line of intersection?
   b.) What is the orientation of the plane perpendicular to the line of intersection?
   c.) What is the obtuse angle between the shear zones in this plane?
   d.) What is the orientation of the plane that bisects the obtuse angle?
   e.) A tunnel must be developed to the line of intersection between the shear zones. For maximum stability the tunnel must bisect the obtuse angle between the shear zones and be perpendicular to the line of intersection. What should the trend and plunge of the adit be?
   f.) If the tunnel approaches the line of intersection from the south, will the full ore carts be going uphill or downhill as they come out of the mine?
**Rotations:**
As you are hopefully beginning to realize, stereographic projections allow the geologist or engineer an easy, convenient graphical way to calculate some horrendous 3D geometrical problems. Another example of such a tough problem, which would otherwise be a nightmare to try and calculate, concerns the rotation of planes and lineations. As you know, stratified rocks were originally horizontal (‘Law of Original Horizontality’) and are very often tilted away from horizontal during subsequent tectonism. Any original planes and lineations preserved in the rock are thus rotated too, and it is often necessary to ‘rotate the rocks back’ to their original position using a stereonet, so that we can find the original (pre-tilting) orientation of these structures.

In order to perform rotations we need to make use of the small circles mentioned on page 5. The lines of latitude on a globe are examples of small circles, and they are also included on a stereonet, getting larger in length (i.e. circumference) towards the E-W line. Again small circles are drawn on the stereonet at $2^\circ$ intervals (except where the lines converge towards the North and South, where there isn’t enough space). We can perform rotations by shifting *poles of planes* or *lineations* along small circles by the required number of degrees.

An example: consider the following sketch cross-section (Figure 16).

**Figure 16:**

In Figure 16, beds developed beneath an angular unconformity have an orientation of $040^\circ/55^\circ$E, and the beds above the angular unconformity (and the angular unconformity itself) have an orientation of $190^\circ/20^\circ$W. What was the orientation of the lower beds during the erosion of the unconformity and deposition of the upper beds? In order to calculate this, we need to effectively rotate the upper beds to horizontal (after all, they *must* have been horizontal when they were initially deposited). A horizontal bed has a vertical pole, so we need to rotate the pole of the $190^\circ/20^\circ$W plane to vertical. This is accomplished by placing the pole on the E-W line, and rotating the pole a suitable number of degrees until it is vertical (in this case the pole must be rotated $20^\circ$). During this rotation, we are using the E-W small circle. The pole of the lower beds must also be rotated in the *same direction* by the *same*
amount along its own small circle. How this is achieved is illustrated below in Figure 17.

Figure 17:

1. Plot planes and poles of upper and lower beds.
2. Rotate net until pole of upper bed lies on E-W small circle. Pole rotates 20° along small circle towards the west. Pole of lower beds also rotates 20° along its small circle towards the west.
3. Plot plane relating to original orientation of pole of lower beds.
4. Return to net north position. Lower beds were originally orientated 030°/71°SE.

Note that sometimes bedding planes can be overturned. This means that to return beds to their original horizontal orientation, they (and their poles) will need to be tilted more than 90° (i.e. back to vertically-inclined planes, and then an extra 90° to horizontal). During such a rotation, the pole will leave one side of the stereonet (at the stage when the plane is vertical), and immediately return to the net on the opposite side (i.e. 180° away). Using the principles above, try answering question sheet 3 on the next page. Again, remember to add the primitive circle (outer edge of net) to your tracing paper, which makes it easier to mark.
**Question Sheet 3.**

1.) Layers below an angular unconformity have orientation 331° 76° SW and those above 112°/25° N. What was the orientation of the older beds while the younger were being deposited?

2.) Planar cross-bedding with orientation 042°/34° SE are developed between bedding planes with orientation 154°/20° SW. What was the original orientation of the cross-beds?

3.) Ripple-marks (i.e. lineations) with orientation 39°⇒272° occur in a sandstone layer with orientation 280°/80° SW. What was the orientation of the ripple-marks during deposition of the sandstone?

4.) On opposite limbs of a fold, developed beneath an unconformity (150°/22° SW), the following observations were made: eastern limb has orientation of 042°/23° SE and western limb 160°/46° SW. Investigate the nature of the original folding, before the unconformity was tilted. Your answer should include the original orientation of each limb, and the original orientation of the hinge line.

5.) **Bonus question (this one is tough!)**
The orientation of asymmetric ripplemarks in sandstone can be used to determine the direction that the current was flowing when the sand was deposited. If ripplemarks indicating a current direction of 142° occur within an overturned sandstone bed whose attitude is 344°/77 W, what direction did the current flow?
Dealing with large/regional-scale folding, and the construction of $\pi$ (pi) diagrams:

Very often when we are mapping in the field, we come across folded strata that is simply too large to measure directly, or even too big to see directly. When the orientation of bedding planes is plotted on a map (e.g. Figure 20), it is easier to see the presence of a fold, but we still need to analyse the folding stereographically in order to determine the 3D geometry. Another possibility is that an area has been mapped regionally, and is underlain by lots of small-scale folds (i.e. a sequence of anticlines/antiforms and synclines/synforms). It is important to note that if data from lots of small-scale folds, and data from a single large-scale fold would produce an identical plot on a stereonet; stereographic projections take no account of the geographical location at which a plane was recorded. If we are mapping on a large scale, then it is likely that we will have recorded many hundreds of orientations of bedding planes, which would need to be shown on a stereonet. Obviously we cannot plot hundreds of great circles on a single stereonet (it would look very confusing, and effectively show nothing), so poles to planes must be plotted instead. The plotting of poles of planar data to illustrate the presence of folding is known as a $\pi$ diagram. The basis of a $\pi$ diagram is the idea that poles to bedding from a single cylindrical fold sequence would project as lineations onto a single plane (the $\pi$ circle), as shown in Figure 19. Therefore, by plotting all the poles recorded throughout a fold sequence, the scatter of poles will define (or approximately define) a single great circle on the stereonet. The $\pi$ circle can be plotted simply by plotting the great circle which has the best fit through the scatter of poles. The fold axis is perpendicular to the $\pi$ circle, and so on the stereonet it can be plotted as the pole to the $\pi$ circle.

Figure 19:

Most folds in examples like that shown above are rather contrived, perfectly cylindrical folds, which will perfectly define a single $\pi$ circle. In naturally deformed strata, however, folds are not so perfectly cylindrical, and therefore there is a certain amount of scatter way from the $\pi$ circle. The greater the degree of scatter, the less cylindrical the fold.

The limbs of a fold, which are characterised by subparallel bedding planes, will plot as a number poles which are very close to each other on the stereonet. The average
(central) point in each cluster of poles is thus the average orientation of the pole of each of the fold limbs. The interlimb angle can be measured by counting the angle between each limb within the plane of the π circle. There are two conjugate angles which can be measured on the π circle (one is acute, one is obtuse, and together the angles add to 180°), so you need to be very careful that the one you measure is the correct interlimb angle. The point half way along the interlimb angle is the pole of the axial plane. Note that the fold axis should lie on, or close to the axial plane. In most naturally formed folds, the axial plane is curved (so it isn’t really a plane at all). It is often therefore better to describe it geometrically as an ‘axial surface’.

**Plotting fold axial planes for a variety of folds:**

Bedding planes within a limb of a fold tend to be orientation parallel or sub-parallel to each other, so it follows that poles from a single limb of a fold will plot fairly close to each other on a π diagram. Limbs of a fold are therefore represented by a small scatter of sub-parallel pole plots. The approximate centre of the scatter can be considered to be the pole of the average plane of each limb. The π diagram allows for the axial plane of the fold to be calculated, based on the average orientation of each limb. The axial plane can be defined as the plane which bisects the interlimb angle of the fold. The hingeline of the fold is therefore a linear element of the axial plane, and the average axial plane can be plotted by identifying the plane which passes through the hingeline of the fold (found either by plotting a β diagram, or by finding the fold axis from the pole of the π circle), and passes through a line which bisects the interlimb angle. However, it is very important to consider that the intersecting planes of the two limbs create two angles; one of the angles is the interlimb angle, and the other is 180°- interlimb angle. When you plot the axial plane, you must think about which of the two angles developed along the π circle is the true interlimb angle. To illustrate this, examine Figures 20 and 21 on the next pages.
Figure 20:

How axial planes will plot on a pi-diagram for a variety of folds

As Figure 20 illustrates, progressive tightening of the fold is represented on the stereonet by the poles of bedding becoming increasing parallel with the pole of the axial plane. Ultimately, an isoclinal fold (whether upright or overturned) has poles to bedding superimposed on the pole of the fold axial plane.

The other element required to plot the pole is the interlimb angle, which can be most conveniently measured by counting the angle between the average poles for each limb in the plane of the $\pi$ circle (the angle between the average planes of the limbs is the
same as the angle between the poles of each limb). Remember that open folds will have an obtuse interlimb angle, and tight to isoclinal folds will have increasingly acute interlimb angles. Which of the two angles you measure in the plane of the $\pi$ circle should reflect this. See Figure 21 for further clarification.

**Figure 21:**

*Measurement of interlimb angles for various folds:*

- **Open, upright fold:**
  - Axial plane
  - ½ interlimb angle (wide)
  - Pole to axial plane

- **Tight, upright fold:**
  - Axial plane
  - ½ interlimb angle (narrow)

- **Isoclinal, upright fold:**
  - Tiny/no interlimb angle (parallel sides)

- **Reasonably isoclinal, overturned fold:**
  - Overturned limb
Bearing all this information in mind, now try question sheet 4, which relates to Figure 23, which is a map of folded strata in an area of Scotland affected by the Caledonian Orogeny, and subsequent Tertiary-aged igneous activity associated with the initial opening of the North Atlantic Ocean. It shows the strike and dip of bedding planes (strike is the upper digit, dip is the lower digit), and the dip direction is indicated by the bedding symbol. The axial plane and hinge line orientation for some of the small-scale folds in the area are also indicated, and also the outcrop of vertically-dipping dolerite dykes (thick black lines).

Figure 22:
**Question Sheet 4:**

**GENERAL GEOMETRIC CHARACTERISTICS OF A FOLD**

You need to ensure that you are familiar with the following terminology, which describes the geometry of a fold or folded areas:

- Syncline; synform; synclinorium; anticline; antiform; anticlinorium; fold axis; hinge line; axial plane/axial surface; axial planar trace; crest; trough; fold limbs

**QUESTIONS:**

1. Figure 22 is a geological field map of a part of the Caledonian mountain range in NW Scotland. Strikes and dips of bedding are indicated. Small-scale folds are also present and the orientations of their hinge lines and axial planes are indicated at a few localities. Inspect the map and classify the type of structure and determine the major geometrical characteristics (orientations) of the structure.

2. Plot the poles to bedding on a Schmidt net (π - diagram). Is the fold cylindrical? Determine the orientation of the fold-axis.

3. Determine the general direction of the axial planar trace on the map. Use the π - diagram to determine the orientation of the axial plane. What are the angles between the axial plane and the fold limbs?

4. What is the relationship, if any, between the fold-axis you have plotted on the π diagram and the hinge lines of the small-scale folds on the map? What is the relationship between the axial plane that you calculated on the π diagram, and the axial planes of the small-scale folds?

5. Indicate on the π diagram the orientations of the σ₁, the σ₂ and the σ₃ axes of the stress field that might have been responsible for the folding developed on the map.

6. What is the relationship between the vertically-dipping dykes (thick black lines on Figure 22) and the fold structure? What is the likely orientation of the σ₃ axis of the stress field into which the dykes intruded. How does this orientation compare with the orientation of the σ₃ axis associated with folding?
Stereographic Projection using Spheristat 2.2 Software:

Having now learned the principles of stereographic projection by hand, this exercise (Practical 5) concerns the use of computer-aided plotting of stereographic projections. We will use SpheriStat 2.2 software.

1. Click on the Spheristat icon on the desktop. It will either be labelled ‘Spheristat’ or ‘SSWIN’. When the program opens, you will be asked to enter a project code. Just click OK, and a fresh project opens with default settings. If you subsequently find that the program hangs, restart the program, and enter any number (e.g. 123) for a project code.

2. 6 icons appear at the top of the screen. The third icon from the left opens a new editor. Click on this and we can start to enter data. 10 columns are present in the spreadsheet. Station (Stn), X, Y, and Z coordinates, Structure, Group, Weight, Azimuth, Inclination and Additional Information. Many of these columns are not used often (e.g. station number, which is a reference to an outcrop number that you might have recorded in a field notebook, X,Y, and Z coordinates, which are used to allow Spheristat to plot maps, weight and Information, which can be used to make any notes on the spread sheet). As these are used infrequently (and will not be used in this exercise) they can be switched off so that they do not appear on the spreadsheet. To do this, click on the spreadsheet editor icon (far right icon) and un-tick all these parameters. Click OK to return to your customised spread sheet.

3. Now we need to set up our data types and conventions to be used throughout this project. Click on the second icon from the right (it has ‘90’ and a picture of a spanner on it), and a dialogue box opens through which we can set the conventions. Firstly, we must set the orientation convention. We have become used to plotting planes as strike, dip and dip direction, and lineations as trends and plunges. There are other conventions too, and Spheristat allows for a total of four different conventions….the 360º left-hand rule, the 360º right hand rule, the quadrant classification and Inclination defined (our convention). Click on Inclination defined. In the planar data box, click on Strike/Dip (some geologists prefer to measure planes using dip and dip-direction as it is faster with certain types of compasses). Set the data type as axial (default). Click OK and return to your spreadsheet. You are now ready to enter your data.

4. The computer needs to be prompted as to whether you are entering data for planes or lineations. Different types of data (i.e. different structures) require different codes to be entered in the ‘structure’ column of the spreadsheet. Bedding planes have a code of 33 (see Figure 23 for other codes of other structures). As we are only dealing with bedding orientations in this exercise, we will only fill the value of 33 in the structure column (after a few entries, 33 appears by default, so simply press ‘Enter’ to speed up your data entries). The ‘Group’ column controls two things regarding the symbol used to show your data on the net. A positive group value prompts the computer to plot a pole to the plane. A negative value prompts the computer to plot a plane. The value of positive numbers denotes different symbols for poles (or lineations). Use a value of 1.0 for large dots and 2.0 for small dots (2.0 best if you have lots of data- it prevents overlapping of symbols). For this initial example, where we will plot planes, enter a group value of –1.0. Enter an azimuth of 180º (that’s the strike), and an inclination of 45º W (that’s the dip) and press Enter to start the next data entry. On the second entry, Structure (33) and Group (-1.0)
should appear automatically, and can simply be entered. Add in a different plane of your own choice. After the second plane has been entered, let’s now look at the resultant stereonet.

5. Click on the net icon (5th from left). Your stereonet appears.

6. Now let’s plot all the data from question sheet 4 (the folded strata in Scotland in Figure 23). There is too much data here to allow us to plot planes, so plot poles instead. Therefore your group must be +2.0 (+ = plot poles, 2.0 = small symbols). As you plot in azimuths and inclinations (i.e. strikes and dips) don’t be concerned if your azimuth data automatically switches 180° when you enter the dip direction. This is just the computer arranging your data, and it prefers to use one strike direction rather than another. Also if you type in a dip-direction that is not suitable for the strike value you have entered, the program automatically chooses a more suitable dip-direction. For the first few minutes, keep checking the net to see that poles are plotting where you expect them to. When you have plotted all the data, examine your resultant net.

7. The vast number of poles that you have plotted seem very confusing. It is much easier to see what’s going on if we can see contoured data rather than raw data. Spheristat will very quickly contour your data based on the number of poles which plot within a given portion of the net. Click on ‘Analysis/Density distribution’ and click on ‘Count’. In the window, the contoured data appears, and click on ‘Done’ to add this to your net. However, the raw data is still there. Click on the Net setup icon (right hand icon), and in the show dialogue box, off-tick ‘data points’, and click OK.

8. How can we determine the π circle and the fold axis? Go back into the Net Setup box, and tick on the 1st principle direction (fold axis) and 1st principle plane (π circle). Tick off the 2nd and 3rd Principle directions and planes. Click OK to return to your finished net, and print it out. You can save your work prior to closing in a suitable directory on the C-drive.

Spheristat is also capable of performing rotations easily. Use some examples from question sheet 3, e.g. Problem 1: Layers below an angular unconformity have orientation 331°/76°SW and those above 112°/25°N. What was the orientation of the older beds while the younger were being deposited? Plot in the poles of the two bedding planes. However, this time, don’t remove the ‘station’ column in the spreadsheet. Give station numbers 1 and 2 to data below and above the unconformity respectively.

We now need to rotate the pole of the bed above the unconformity to vertical (thus giving us a horizontal plane). But which of the two poles represents the bedding orientation above the unconformity? Remember that we assigned station 2 to the layers above. Click on ‘Search/Find stations, and enter ‘2’ in the dialogue box. Station 2, which we are looking for, turns red. Now we know which pole to rotate.

Go to ‘Edit/Rotate data’. A new box appears, with station 2 remaining highlighted. Click and drag station 2 to a vertical position (in the centre of the net). The other pole (the bed beneath the unconformity) rotates to a new position. Click on ‘Save’ to record your rotated data as a new net. One source of possible inaccuracy here is the fact that your pointer might not be exactly on the pole when you start the rotation or quite at vertical when you finish the rotation. Note that at the bottom of the net during the rotation, the trend and plunge of the pole are listed. Use these to help guide your pointer, to indicate when to start and finish rotating.
FEEL FREE TO EXPLORE THE OTHER FUNCTIONS OF SPHERISTAT. YOU WILL FIND SPHERISTAT (OR OTHER SIMILAR PROGRAMS) OF GREAT USE DURING FIELD MAPPING.

**Figure 23:**

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**Integrated structural analysis:**

Unfortunately we cannot travel into a suitable field area within the time period of a single 3 hour practical session. The aim of the final practical class is to simulate a field area composed of deformed rock inside a room. Around the lab, there are samples of rocks which show secondary and, in some cases, primary structures too. During the course of this practical, you are effectively in the field, and you have three hours to undertake a structural analysis of the ‘field’ area. During this practical, examine the rocks and describe what structures you see. Give as full a description as possible, including a description of the processes which were involved in the deformation (e.g. brittle, ductile, brittle-ductile?). It is also important that you determine as well as possible the orientation of the strain and stress ellipses or ellipsoids for each sample.

The rocks are mounted on sheets of paper in such a way that they are orientated. If you need to move the orientated samples, ensure that they go back on the paper in exactly the same position and orientation, ready for the next student. Your task for these samples is to measure the orientation of planes and lineations with a compass-clinometer, describe the samples and identify strain and stress axes (and ellipsoids) in true 3D space.

For example, a fold with limbs orientated $180^\circ/45^\circ$ W and $180^\circ/45^\circ$E, with a hinge line plunging $20^\circ\Rightarrow000^\circ$, would have an $00^\circ\Rightarrow270^\circ$ orientated $S_3/\sigma_1$ axis, an $S_1/\sigma_3$ orientated $80^\circ\Rightarrow180^\circ$, and an $S_2/\sigma_2$ axis orientated $20^\circ\Rightarrow000^\circ$ (all three strain/stress axes being mutually perpendicular). Remember- some samples show brittle deformation and others ductile. Some show both! (Remember the law of cross-cutting relationships; is brittle older or younger than the ductile structure?). Is it likely that brittle and ductile structures form in the same environment? Is it likely that they form under the same stress regime, with the same orientation of the strain/stress axes?

Go through each of the orientated samples and determine the orientations of strain ellipses (or ellipsoids where possible). What do you find regarding the orientation of the ellipses/ellipsoids for each of the samples? If you find that all these are orientated approximately parallel, then consider the possibility that all the various structures that you have measured might be related to each other.

This is illustrating the theory that a range of structures can form in a predictable orientation as a result of a single deformational event (integrated structural analysis). We should not consider joints, faults or folds as isolated structures, but rather, potentially, as different responses to the same brittle deformational event, with all structures forming within the same stress/strain ellipsoid. Similarly, in a ductile environment, foliation, lineation, shear zones and folding can all be considered as being potentially related, provided that they fit the same orientations of strain/stress axes.
Figure 24:

Examine the Figure 24 above. It shows strain ellipses, though the axes have been labelled as stress axes. Within the ellipses are drawn some of the possible structures that might be expected to form as a result of the strain and stress given the directions of the principle axes.