Chapter 1
Measurement: What and How

Introduction

The purpose of the laboratory portion of most structural geology courses is to learn how to define quantitatively the geometry of deformed rocks. Furthermore, we would like to develop the tools to allow us to convert, easily and precisely, between the geometries of rock bodies at two different times in their history. These times may be the present, deformed, state and the initial, undeformed state or the two times may capture only a small part of the rock's history. Finally, the lab should lay the groundwork for at least a basic understanding of mechanics. All of these goals require that the structural geologist be very precise about geometry and the coordinate systems used to define the geometry, so that is where we will start.

Primitive Geometric Objects

Rocks are composed of linear and planar elements: bedding and secondary foliations such as cleavage can be defined, at least locally, by planes whereas things
like fold axes, mineral lineations, and paleocurrent directions are **lines**. It turns out that, because there is one line oriented perpendicular to any particular plane, all planes can also be represented by their corresponding perpendicular line which is known as the **normal** or the **pole** to a plane.

The previous paragraph is an oversimplification because, in the vast majority of cases, all of these lines have a direction in which they point. The paleocurrent, for example, flowed towards a particular direction. The pole to bedding can point in either the direction in which strata become younger or become older. The direction matters and thus our geological lines commonly have an arrowhead and tail; that is, they are a geometric and mathematical quantity known as a **vector**. In some cases, we care about the length, or **magnitude**, of our vector as in the case of the displacement of a fault or the thickness of a stratigraphic unit. But in many other cases, we only care about its **orientation** in space. We will use vectors extensively in subsequent chapters but before we can do that there are some more basic things to address: how do we measure lines and planes and what coordinate systems do we use, because it is impossible to talk about vectors without reference to a coordinate systems.

**Data Collection**

*Instruments Used in the Field*

Traditionally, a structural geologist used a geological compass/clinometer to measure the orientation of features of interest. These are precision analog instruments that enable the geologist to measure the orientation of a feature of interest to within a degree or less. The Brunton Pocket Transit (Fig. 1.1), most commonly used in North America, excels at taking checking **bearings** — horizontal angles measured with respect to North — and **inclinations** — angles in a vertical plane measured with respect to the horizontal — over long distances; thus the word "transit" in its formal name, though most people just refer to it as a "Brunton compass". In Europe and other parts of the world, a Freiberg compass is more common. This type of instrument is less suitable for sighting bearings over long distances but is very efficient at measuring planar and linear features by placing the top or edge of the compass flush against the rock.
Precision analog compasses have been around for centuries but it is likely that, within a few years, they will largely be replaced by digital devices, most commonly in the form of smart phone programs or apps. Most smart phones contain accelerometers, gyroscopes, and electronic magnetometers which enable apps to determine the exact orientation in space. Additionally, such devices also keep accurate track of the time and date and can determine their position every accurately using the Global Positioning System (GPS) as well as triangulation on cell phone towers and wireless networks. Thus, one can hypothetically capture a large number of measurements quickly using a compass app on a smart phone. Several such apps are already available for iOS and Android operating systems and, with proper calibration, can yield excellent results. To date, most smart phone compass apps for geological use have taken to mimicking analog compasses and thus use the same terminology and coordinate system. There is a great deal of room for innovation in this space and it is likely that future apps will provide substantially more information. As a simple example, it is not possible to measure directly the pole to a plane with a traditional analog compass; the geologist must do a simple calculation in the field or more likely back in the office to get this value. A smart phone app, however can instantaneously calculate, record, and display this value in the field. The approach that this manual takes to structural geology lab will enable you to take advantage of data from this new digital world.

*Measuring Lines and Planes*

Both types of compasses and most smart phone compass apps measure bearings or azimuths clockwise with respect to the rotation axis of the Earth, i.e., north, and the angle downward or upward from the horizontal. The previous sentence has several important assumptions built in that are seldom explicitly stated: what is our coordinate system and what are the conventions used to indicate whether a number...
is positive or negative? Traditionally in structural geology, horizontal angles are positive measured clockwise from North and vertical angles are measured positive downwards. If you think about it for a minute, this is just the opposite of the convention that you use when you make a graph or plot data on a map. Graphs follow an engineering convention where angles are measured positive up from the x-axis (i.e., counterclockwise) and on maps, elevations are positive upward and depths are negative! The point is, it doesn't matter what convention you choose as long as you are clear and consistent. In a subsequent chapter, we will learn how to change from one convention and corresponding coordinate system to another, an operation that will help us solve lots of interesting problems.

A plane can be defined by the azimuth of a horizontal line contained within it, known as the **strike** and the maximum angle measured downward from the horizontal to the plane, a quantity known as the **dip** (Fig. 1.2). The azimuth of the dip — that is, the projection of the dip onto the horizontal — is known as the **dip direction** or **dip azimuth**. The true dip direction is always 90° from the strike. The most convenient way to think of the strike line is to imagine the plane half-submerged in a body of water. Because the surface of the water is necessarily horizontal, the waterline on the plane is a horizontal line in the plane (Fig. 1.3).
The dip deserves further consideration. Let’s say that you are studying a vertical road cut in a region where the rocks have a uniform strike and dip. The orientation of the road cut will determine what you see: if the road cut is parallel to the strike, then the strata will appear to be flat because the strike is a horizontal line in the plane of bedding (Fig. 1.4, left block). If the road cut is perpendicular to strike, then you will see the true dip of bedding. At any other orientation of the road cut, you will see an apparent dip of bedding, which is always less than the true dip (Fig. 1.4, right block). Problems involving apparent dips are extremely common in structural geology. In subsequent chapters, we will learn quantitative methods for...
calculation of true dip from two apparent dips or apparent dip given true dip and apparent dip direction but for now a little practice in visualization is in order.

The specification of a strike and dip for a plane is subject to a number of potential ambiguities that do not plague the dip direction and dip format. Which direction of the strike line do you use? How do you make sure that the plane dips in the correct direction? Because in the past structural geologists have tried to accommodate all possible combinations of strike direction and dip direction — that is they did not settle upon a standard and stick to it — a number of inefficient and potentially error-prone formats have sprung up (Fig. 1.5). The “quadrant” format is perhaps the worst offender: one must write down (correctly!) a combination of five numbers and letters such as “N 47 W, 22 S”. The student is strongly encouraged not to use this format even though you will need to know how to read it. On can eliminate two letters simply by using the azimuth of the horizontal bearing: 313, 22 S. In this book, we will use either dip direction/dip or more commonly a format known as the right hand rule (RHR). Using the RHR, one gives the strike direction such that the dip is to the right when looking in the direction of the strike az-

Figure 1.5 Conventions for how to specify the orientations of two planes that share the same strike line. Specifying the rake of a line is also given. Stick figure is looking away from the reader and holding out his/her right hand. Avoid using the quadrant format!
imuth (Fig. 1.5). Thus, we can further reduce the plane orientation given previously to: 133, 22.

The orientation of a line is also specified by a horizontal azimuth, or trend, defined by the projection of the line onto the horizontal plane and the plunge, a vertical angle measured from the horizontal downwards to the line (Fig. 1.2). Note that for lines, or vectors, where the arrowhead points upwards, their plunge has a negative value. There are many times in geology when we are interested in lines that are contained within planes: for example, a paleocurrent direction in sedimentary bedding or slickensides on a fault plane. In these cases, it is often most convenient to measure the angle between the strike of the plane and the line of interest, which is known as the rake or pitch (Figs. 1.2, 1.5). Although strikes and trends are measured in horizontal planes and dips and plunges in vertical planes, the rake is commonly measured in an inclined plane. Traditionally, the rake has been measured from either end of the strike line, yielding two possible values, with the correct value identified by giving the general quadrant direction. This is a recipe for confusion! The convention followed here is that the rake is always measured from the given strike azimuth and thus varies between 0 and 180°.

There are several ways to measure the orientations of lines and planes. The two most common have their origins in the unique capabilities of the two types of compasses mentioned earlier: Freiberg compasses, as well as certain modern versions of the Brunton compass, can measure dip and dip direction in a single operation. To measure a plane, the top cover of the compass is rotated so that it is flush against the rock layer. An air bubble is brought to the center of the bullseye level on the face of the compass, ensuring that the compass face defines a horizontal plane. The geologist can then read the dip azimuth of the plane from the number that the North needle points at on the face of the compass. The vertical angle that represents the dip is read directly off a scale on the side of the compass.

If one is using a traditional Brunton compass, a different approach is used: First, the side edge of the main part of the compass is placed on the rock and ad-

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1 Two other reasons for using the RHR will be seen in a later chapter: (a) the strike, true dip, and pole (SDP) define a right-handed cartesian coordinate system that is convenient for solving problems related to bedding; and (b) double couple focal mechanisms of earthquakes are commonly given using the Aki-Richards convention where the plane is specified using RHR and the sign of the rake gives the sense of slip (positive for thrust faulting and negative for normal faulting.)
justed by rotating it until the bullseye level is level. One can then read the strike of
the plane as the number to which the north arrow points. It takes a second opera-
tion to measure the dip angle: the side edge of the compass is placed flush on the
rock so that the brass arm of the compass points either up or down dip. The lever
on the back side of the compass is then rotated until the bar level is horizontal and
the dip value (or apparent dip value) read off of the clinometer scale on the face of
the compass.

**Uncertainties**

Of course, rocks seldom define perfectly smooth planes or exactly straight
tables. They have irregularities that can be quite significant. Several field methods
have been developed for dealing with this fact. Students are commonly admonished
to place a field book or other non-magnetic planar object on the surface of the
plane to be measured to smooth out the irregularities. Using a more advanced field
technique, the geologist positions themselves so that their eye is in the plane of
bedding and they see the plane “edge-on”. They then set the clinometer of a Brun-
ton-style compass to horizontal and sight through the hole in the mirror to located
a horizontal line in the plane. Finally, they take a bearing on the horizontal line in
the plane to get the strike. This method does a better job of smoothing out the ir-
regularities at the scale of the entire outcrop and can also be used to measure a
plane’s orientation where one cannot physically access the plane (e.g., across a roaring river or a busy six lane highway). It does, however, take considerable practice to master!

Without knowing why one is measuring the plane in the first place, it is im-
possible to know which is the best method to use. For a regional mapping job, one
commonly wants the best orientation at the scale of the entire outcrop. On the oth-
er hand, the variations, themselves, maybe the subject of study as for example
where one is trying to define asperities on a fault plane. However, the scale-invari-
ant nature of irregularities in any natural surface or linear feature means that,
whatever the scale of the problem being addressed, the measurement of its orienta-
tion will not be perfect.
In addition to natural irregularities, there are other reasons why it is impossible to define the “correct” strike and dip of the plane. Two different geologists may use slightly different methods for measuring a line or plane and even the same geologist who makes multiple measurements of the same plane at the same location will come up with a range of values because of seemingly trivial changes in measurement methodology. Thus, ideally one would make multiple measurements of a plane or a line and average them. That way, although we cannot state with certainty what the “correct” orientation is, we could at very least come up with the best estimate of the orientation and even use standard statistical techniques to calculate the uncertainty (standard deviation) in the orientation. We will do exactly that in a following chapter.

The uncertainties we have discussed so far are of the type known as random, uncorrelated errors (Fig. 1.6a, b). There is no way to predict whether the next measurement will be higher or lower than the previous one or, within some range, by how much. They result from stochastic variations in natural features and our own inability to measure them accurately. These errors are amenable to calculation of a mean and a standard deviation (which we will do in the next chapter). The smaller the uncertainty, for these types of errors, the more reliable the result. Non-random or correlated errors are an entirely different beast (Fig. 1.6c, d). Take for example, the geologist who unwittingly measured a bunch of strikes and dips near a large magnetic body or with the declination set incorrectly on his or her compass. In the case of nonrandom errors, even though the statistics might be good (e.g., Fig. 1.6c), the results will be crummy.

This discussion brings up two important terms: accuracy and precision. Accurate means that our measurements are a reasonably good representation of the
true value, even if we can never know exactly what the true value is. **Precise**, on the other hand, means that a measurement has been made with instruments that record the observation to a large number of significant figures. Ideally, our measurements should be both accurate and precise (Fig. 1.6a). Even experienced scientists, however, often fall into the trap of thinking that because a measurement is precise, it must also be accurate; that is a fallacy. In the case of nonrandom errors, our measurement can be very precise but not very accurate (Fig. 1.6c). Earlier in this chapter, we mentioned the advent of data collection via digital devices such as smartphones. With any digital device, however, one must be careful to acknowledge that, although the answer produced is precise, its accuracy must not be assumed but proven. Digital sampling systems are highly subject to nonrandom errors!

**Graphical Representation of Orientation Data**

There are two fundamental ways that structural geologists display their orientation data with quantitative rigor. In **maps**, we are concerned about both orientation and the spatial relation of one feature to another. In the second type, stereo-
graphic projections, commonly called stereonets, we are just concerned with orientations, alone.

Maps

Geological maps are one of the most fundamental, original data sources in our profession. They show the distribution, known and inferred, of rock units on the surface of the earth, the nature of contacts separating them (e.g., stratigraphic, unconformities, intrusive contacts, faults), and are the basic way that we evaluate the distribution and geometry of deformed rock layers. Maps commonly show strike and dip symbols in the layered units, and may show the orientations of secondary structures such as cleavage, lineations, and joints. A map is a formal scientific document and should be treated as such.

All maps are a projection of features that lie on the irregular, but approximately spherical, surface of the earth onto a horizontal plane (Fig. 1.7). This has an immediate practical implication: when you measure a distance on a map (i.e., a map distance), it is a horizontal distance not the longer distance that you actually
travel along a slope (i.e., the *slope distance*; Fig. 1.8). The *slope angle* is measured between the slope and the horizontal and is usually calculated by:

\[
\text{slope angle} = \tan^{-1}\left( \frac{\Delta \text{ elevation}}{\text{map distance}} \right)
\]

where $\Delta$ means “change in”. A related measure of steepness of slope is the percent grade, which you are likely to have seen on highway signs in mountainous terrain:

\[
\text{percent grade} = \left( \frac{\Delta \text{ elevation}}{\text{map distance}} \right) \times 100.
\]

Humans are notoriously poor at estimating slopes. On a road over a steep mountain pass, you are likely to see a sign reporting “8% Grade Ahead”. If you take the arctangent of 0.08, that “steep” grade has a slope angle of just 4.6°!

Beyond this practical implication, there is a more profound aspect to the fact that maps represent projections: Although the Earth is approximately spherical, the piece of paper or computer screen that displays the map is flat. There is inevitably some distortion that occurs when we project a spherical surface onto a flat medium. There are a myriad of *map projections* that accomplish this task depending on the size of the map area and the purpose for which the map is needed (Snyder, 1987). For now, you mostly need to know that all maps represent tradeoffs of the following factors:

- *Conformal* — preserves the same scale in every direction, locally, thus maintaining the correct shape of the features
• **Equal Area** — preserves the area throughout, but distorts the shape

• **Equidistant** — depicts the correct distance between a point at the center of the projection and points in any direction away from the center

• **Equal Angle** — Shows true angles or bearings, locally

You cannot have all of the above in a single map! For example, a map that is both conformal and equal area is impossible, as is a map that is equidistant and equal angle. As we shall see below, stereonets have exactly the same limitations because they are fundamentally the same thing: a projection of spherical data onto a flat screen or paper.

Map coordinates are usually given in terms of **longitude** and **latitude**. You are, of course, familiar with a globe with its lines of longitude running from pole to pole and lines of latitude running around the globe perpendicular to its rotation axis (Fig. 1.9). Lines of longitude are known as **great circles**; if you slice the globe

![Figure 1.9 — Left: the globe with lines of longitude and latitude. Right: a cut-away view of the earth showing how the position of New York City is defined by a vector from the center of the Earth that pierces the surface of the sphere in a point](image_url)
through the middle, the intersection on the surface is a great circle. A more concrete way of visualizing great circles is to think of a peeled orange or grapefruit: the lines made by the segments of the fruit are great circles because all of the segments meet in the middle. You have probably heard people speak of “great circle routes” as the shortest distance between two points. That is true because that line is an arc or segment of a great circle. The lines of latitude are small circles because they do not cut through the center of the globe. The complete coordinates of any point on a globe, say New York City, are given by its longitude — the angle between the great circle that goes through Greenwich, England and that which goes through New York — and the latitude — the angle between the equator and a line drawn from the center of the Earth to New York (Fig. 1.9 right). Lines through the center of a sphere intersect the surface at a point (e.g., New York City). Finally, you can see that if you were to rotate the vector from the center to New York City about the rotation axis of the Earth, it would sweep out a cone and the intersection of the cone with the sphere produces a small circle (Fig. 1.9), which is why they are sometimes called conic sections.

Mapping has been revolutionized in the last decade or two by three trends: (1) the advent of geographic information systems (GIS) of varying complexity, (2) the availability of large digital data sets, especially digital topography and ubiquitous satellite imagery with resolutions of a few meters, and (3) small portable devices like tablets, smart phones, and ruggedized laptops equipped with GPS receivers for accurate positioning. Mapping has gone digital and with it, the need for geologists who know how to manipulate and extract information from large collections of numbers has increased dramatically.

Ironically, as the power of the tools and data sets we use has increased, the number of geologists creating new maps has plummeted. Many students in structural geology today will never get a chance to make a geologic map beyond whatever they experience in field camp. Even so, today’s geologists need to know how to extract quantitative information from the reams of paper maps published by state and federal geological surveys for more than 100 years. A few years ago, this would have meant spreading the map out on a drafting table with scale, compass, and protractor in hand and carefully carrying out graphical constructions. Today, we have a variety of software tools available to do these tasks and many government
entities have made raster images of maps available online at little or no cost. We will work with these scanned maps extensively in this course.

The way we represent the orientation of a planar feature on a map is with a strike and dip symbol (Fig. 1.10). The exact nature of the symbol varies with the feature that it represents, but they all have the same basic design: a long line drawn parallel to the strike of the planar feature and a short tick mark indicating the dip direction. The magnitude of the dip is commonly shown whereas the strike value is not. Linear features, like paleocurrent directions, are shown with a lineation symbol which is an arrow with the value of the plunge shown at the arrowhead (Fig. 1.10).

In addition to strike and dip symbols on maps, there is another way to extract orientation data: because surface of the Earth is irregular — that is, it has topography — the way planar units cross the surface of earth reflects their orientation. We call this the rule of V’s because, when seen in map view, contacts that represent planar surfaces make the form of the letter “V” when they cross topography. Where a bed crosses a valley, the tip of the “V” points downstream when the bed is inclined or dips downstream (Fig. 1.11) and it points upstream when the bed dips upstream, is horizontal, or dips downstream at an angle less than the stream.

Figure 1.10 — Strike and dip symbol for bedding dipping 30° to the east-south-east and a lineation symbol showing the trend and plunge of a linear feature in the plane of bedding in map view (left) and visualized as a block diagram (right).
Of course, to interpret correctly the orientation of beds using the rule of V’s, one has to be able to determine hills, valleys, and which way the rivers flow. Most geologic maps published by geological surveys contain topographic contours, lines of equal elevation. If you were to walk exactly along a contour line, you would go neither up nor down hill; walk perpendicular to the contours and you are going in the direction of maximum slope. Modern mapping increasingly uses shaded digital elevation models (DEM) to portray topography but for quantitative analysis students still need to know how to use topographic contour maps.
Structural geologists use stereographic projections to display orientation data when the spatial relation of the individual observations with respect to each other is not important. A stereonet can also be used to do complex calculations such as rotations, calculating lines of intersection, etc. by placing a sheet of tracing paper over the grid of lines and rotating it about the center. That function has been largely re-

**Stereonets**

Figure 1.12 — Classical three point construction to determine the dip of bed Js in Figure 1.11. The diagram is a vertical plane oriented in the true dip direction (parallel to the line labeled “1025.5” in Figure 1.11. Note that maps are a projection onto a horizontal plane.

Figure 1.13 — Two types of stereonets: (a) the equal angle, or Wulff, net; and (b) the equal area, or Schmidt, net. All of the blue shaded small circles are the same size and shape on the surface of the sphere (they all have a 10° radius). You can see that the equal angle net in (a) is conformal (shape is preserved, that is they are all circles) but is not equal area or equidistant (the 10° spacing gets bigger as you go from the center to the edge of the net). Conversely, in the equal area net (b) the circles are distorted except at the center but they all have the same area and the 10° spacing from the center outward is constant (equidistant).
placed by computer stereonet programs that are far more powerful, accurate, and precise in terms of computation and provide publication quality graphics automatically. Here, we emphasize only the use of stereonets to display orientation data.

One’s first view of a stereonet is instantly familiar: it looks like a globe or a map of the entire Earth (Fig. 1.9 left). There are great circles, just like lines of longitude, running from pole to pole, and small circles, similar to lines of latitude, that run across the globe from east to west. Of course, our picture of a stereonet, just like the globe, on the screen is a projection of a sphere onto a flat surface and, as shown in Figure 1.9, left, can only display half of the sphere. As with any mapping, depicting a sphere on a flat surface inevitably involves distortion. Two types of stereonets are commonly in use: the equal area (Schmidt) net and the equal angle (Wulff) net (Fig. 1.13).

Stereonets used in mineralogy, structural geology, geophysics embody all of the same concepts as our globe. Planar features are plotted as great circles and linear features plot as points and there are different types of distortion depending on the type of projection used. In a similar fashion to our example of a globe, miner-

Figure 1.14 — The lower hemisphere projection (a) oblique view, and (b) top view. Planes intersect the hemisphere as great circles and lines plot as points. δ is the true dip, α is the apparent dip, and β is the angle between the strike and the trend of the apparent dip. Note similarity of (b) with Figure 1.15b.
alogists use an upper hemisphere projection whereas in structural geology and geophysics we use a lower hemisphere projection (Fig. 1.14). The latter projection means that we are looking down into a cereal bowl and seeing the inside of the bowl projected onto the horizontal plane through the center of the sphere (Fig. 1.14). Visualizing this geometry is fundamental to understanding how stereonets display data.

Plotting stereonets by hand is tedious and imprecise. The basic idea is shown in Figure 1.15. An equal angle, or more likely equal area, grid is mounted on a piece of cardboard or some other firm but thin surface. The geologist then places a sheet of tracing paper over the grid and put a push pin or thumbtack through the tracing paper into a hole in the center of the firm backing to which the grid is mounted. The tracing paper can now rotate about the center of the grid. After marking North on the tracing paper, the geologist is ready to begin plotting. To plot
a plane, rotate the tracing paper by an amount equal and opposite to the strike of the plane. For example, in Figure 1.15, the plane has a strike of 056° so the geologist rotates the tracing paper by 56° counterclockwise. Once this rotation is accomplished, one counts in on the east axis of the grid an amount equal to the dip value and then traces by hand the corresponding great circle. Rotating the tracing paper back to alignment with the grid — so that north on the tracing paper is aligned with north on the grid puts the great circle that represents the plane in its correct position (Fig. 1.15b).

The great circles and small circles on the stereonet grid are read in degrees, just like longitude and latitude are marked off in degrees on the globe. In Figure 1.15, the grid is drawn in 10° increments, whereas most paper stereonets are in 2° increments (most computer programs allow you to adjust the grid increment). If you read in along the EW grid line (Fig. 1.15), you’ll see that you can measure from 0° at the edge of the net (known as the primitive or horizontal) to 90° at the center; a vertical line will plot as a point exactly at the center of the net (a plunge of 90°).

Angles measured in the plane (e.g., rakes) can be determined by counting off the number of degrees along the great circle. For example, in Figure 1.15a, you can see that the rake of the apparent dip line (that has a plunge of \( \alpha \)) is 40°; likewise, the angle in the plane between the apparent dip line and the true dip line is 50°.

If all that sounds complicated, it is but nonetheless the procedure is a skill that can be learned with a small amount of practice. The problems with this approach, however, are two-fold: first, several of the operations have nothing to do with learning how to interpret these displays. Programs like this can help if you are having trouble relating a stereonet plot to the three dimensional objects it represents.
but only with the limitations of drawing great circles by hand. How does rotating
the tracing paper in a direction opposite to the rotation of the strike with respect to
north make this process clearer? Hint: it doesn’t! Second and more importantly, few
structural geologists use paper stereonets now, anyway, as there are a number of
good programs available for Mac, Windows, Android, and iOS. The computer cer-
tainly isn’t virtually rotating a piece of paper with respect to a grid; it is using sim-
ple but powerful mathematical algorithms and displaying the results on a stereonet
because that’s what structural geologists are used to! Thus, in most of this book, we
are going to learn how to do structural calculations the way the computer does and
only use stereographic projects to visualize our results (Fig. 1.16).

Computing

Structural geologists use a large number of computer programs to speed up
their work. These programs may be written in a variety of languages: a few
decades ago the language was likely to be Fortran, Pascal, or Basic; today it is more
likely to written in some flavor of C, Python, Java, or Matlab. What is important,
however, is not the language but the algorithm behind the language. In this book,
we will use a very simple computing environment, the humble spreadsheet pro-
gram, usually exemplified by Microsoft Excel®. There are several advantages to
this approach:

1. You have probably used spreadsheets before so they are familiar.
   That means that you can just focus on the algorithm and not worry
   about language syntax, development environment, etc.

2. It is quite likely that you already have Microsoft Office® installed
   on your computer and thus you already have Excel®. No addition-
al purchase necessary!

3. A spreadsheet is naturally in the form of a table, or matrix, and
   many of the things we would like to calculate in structural geology
   are best thought of as tables of numbers.

Computers have a couple of traits that you will probably find either exhilarating or
frustrating: they are dumb and they are logical. Because computers are dumb ma-
chines, they are extremely literal: they will do exactly what you tell them to do, even
if it is not really what you wanted! Second, because they are logical, you have to understand the logic of your calculation before you can tell the computer what to do. Nonetheless, computing is a profoundly powerful skill for a scientist to possess, and it is in that spirit that this book emphasizes simple computing via spreadsheets to solve structural geology problems. Once you understand the power of the calculation, that is the algorithm, you will have greater motivation to learn a programming environment much more powerful than a spreadsheet program.

A spreadsheet, like any program, has certain rules that one must follow. For those of you who have never used a spreadsheet for anything more than making a table, we offer the following abbreviated set of rules:

- To fill a cell with a computed value, the first character in the cell must be the equals sign, “=”. Following the equals sign is the formula that you want to compute.

- In formulas, one refers to the input data, whether a number or another computed value, via its cell address. The cell address is composed of a letter that indicates the column of the cell followed by a number that indicates the row. For example, “C3” refers to the value in column C, row 3. When entering a formula, after the equals sign you can usually enter the cell address by just clicking on the cell that you want.

- When you copy a formula from one part of the spreadsheet to another, the cell addresses are adjusted automatically — that is, the cell addresses are relative. If you have a formula in C3 that uses the value in A1, when you copy the formula to D4 (one column over and one row down from the original), it will automatically adjust to

Those of you who already know a programming language should, by all means, do the exercises in this book using that language rather than in a spreadsheet. More advanced programming languages have many features that simplify the overall task of implementing an algorithm. For example, a simple do/for loop in a programming language is more cumbersonely implemented in a spreadsheet by manually copying and pasting rows containing formulae and nested loops are even more difficult.
use the value in B2 (one over and one down from A1). Relative cell addresses are one of the reasons why spreadsheets are so powerful.

- Sometimes, however, you want to keep using the original value even though you have copied the formula. For this you need an absolute cell address which is indicated with a “$” in front of the column and/or row letter/number. If, in the above example, you wanted to keep using the value in A1 when the formula was copied to a different cell, you would type the address as “$A$1” in the formula.

- Finally, for now, all computer languages, including spreadsheets, do trigonometric calculations using radians rather than degrees. Useful formulae for converting from radians to degrees are:

\[
\begin{align*}
1 \text{ radian} &= \frac{180^\circ}{\pi} = 57.2958^\circ; \\
90^\circ &= \frac{\pi}{2}; \quad 180^\circ = \pi; \quad 270^\circ = \frac{3\pi}{2}; \quad 360^\circ = 2\pi
\end{align*}
\]

Say you want to calculate the sine of the angle in cell A3. In the cell where you want the answer to appear (e.g., A4) you would type:

=\text{SIN}(\text{RADIANS}(A3))

To convert the value in A4 back to degrees you would enter

=\text{DEGREES}(\text{ASIN}(A4))
Exercises—Chapter 1

1. For the following block diagrams, fill in the bed geometry on each exposed side of the block. For each side, indicate whether one would see a true dip or an apparent dip of the bed if you observed that side of the block head on (looking perpendicular to that face of the block).

(a)  

(b)  

(c)  

(d)
2. For each of the map snippets below, state qualitatively which way the bedding dips. Start by using the topographic contours to identify ridges and valleys and then determine which way the creeks in the valley flow (i.e., the up- and down-stream directions). Then, use the way that the stratigraphic contacts cross the valley to determine the dip direction. For each map, it is sufficient to state that “the bedding dips to the east” or “the bedding dips to the SW”.
3. Below are five orientations of planes. Convert them into right-hand rule format:
   a. Convert from Quadrant to RHR format: (i) W 15 S, 61 S; (ii) N 56 E, 20 NW; (iii) S 30 E, 33 W;
   b. Convert from Dip direction and dip to RHR format: (i) 237, 74; (ii) 099, 48

4. The instructor will set up a tilted layer or rock in the lab or will take you out to a place where you can measure strikes and dips of a natural planar surface. Each person in the class, including the instructor or other experienced geologist, should measure the plane the same number of times, at least 10 or 15 times would be good.
   a. Describe the variation in your answers: How much variation in strike is there? In dip? Does it appear easier to measure the strike or the dip more accurately? What factors might determine which is easier?
   b. Now compare your answers to those of your classmates and instructor. Can you tell which answers are more precise or whose are more accurate? How?

5. Plot your results from Question 4 in a stereonet program as (a) great circles, and (b) poles to the planes.
6. The following stereonet plots show planes and or lines. Describe the orientations in each and answer any additional questions written next under the plot.

what is the approximate orientation of the line of intersection of the black and blue planes?
All of the questions below apply to the following table. Each row in the table is a single datum, i.e. a single plane with one or more lines in it. Planes are given in azimuth format and lines in trend, plunge format. Asterisks show missing values; *** is a missing azimuth or bearing, and ** is a missing plunge or dip. Some of the values are redundant: for example, once you know the true dip and dip direction, you also know the strike and dip.

<table>
<thead>
<tr>
<th>Datum</th>
<th>Strike &amp; Dip of Plane</th>
<th>True Dip (T&amp;P)</th>
<th>Apparent Dip(s) (T&amp;P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>050, **, *</td>
<td>*** , **</td>
<td>090, 25</td>
</tr>
<tr>
<td>2</td>
<td>*** , ** , *</td>
<td>*** , **</td>
<td>159, 34 and 270, 43</td>
</tr>
<tr>
<td>3</td>
<td>*** , ** , *</td>
<td>010, 48</td>
<td>321, ** and 090, **</td>
</tr>
</tbody>
</table>

7. Solve for the missing values for each of the three datums using a stereonet to solve for each of the missing values in each row.

(a) In the second datum, above, you are given two apparent dips. Use a stereonet to determine the angle between those to apparent dips, measured in the plane that contains them.

(b) Assume that the plane in datum three is a bedding plane. Restore the plane to horizontal. What were the original bearings of the two apparent dip directions prior to the tilt of the bedding?

Rotate the plane in row 1 by returning the plane in row 2 back to its original horizontal position. What is the orientation of the plane in row one after you have performed this rotation?