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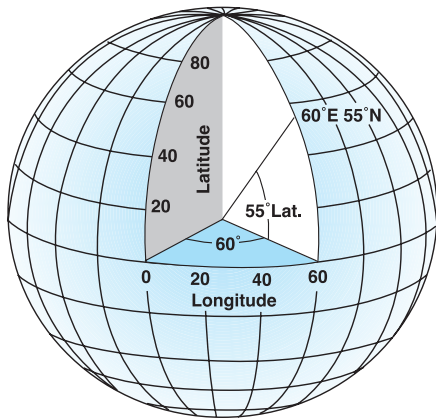
Geographic coordinate systems

In this chapter you'll learn about longitude and latitude. You'll also learn about the parts that comprise a geographic coordinate system including

- *Spheres and spheroids*
- *Datums*
- *Prime meridians*

A *geographic coordinate system* (GCS) defines locations on the earth using a three-dimensional spherical surface. A GCS is often incorrectly called a datum, but a datum is only one part of a GCS. A GCS includes an angular unit of measure, a prime meridian, and a datum (based on a spheroid).

A feature is referenced by its *longitude* and *latitude* values. Longitude and latitude are angles measured from the earth's center to a point on the earth's surface. The angles are measured in degrees (or in grads).



The world as a globe showing the longitude and latitude values.

In the spherical system, 'horizontal' or east-west lines are lines of equal latitude or *parallels*. 'Vertical' or north-south lines are lines of equal longitude or

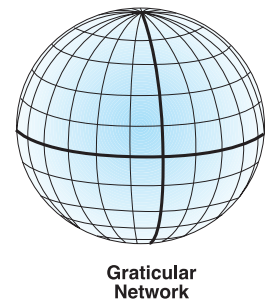
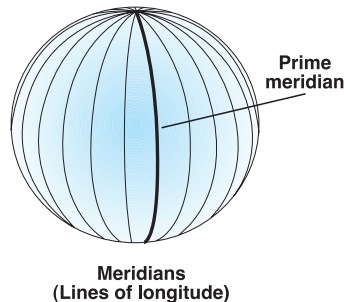
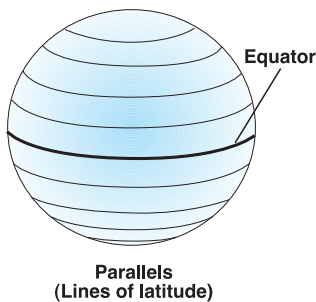
meridians. These lines encompass the globe and form a gridded network called a *graticule*.

The line of latitude midway between the poles, the horizontal axis, is called the equator and defines the line of zero latitude. The vertical axis, which defines the line of zero longitude, is called the prime meridian. For most geographic coordinate systems, the prime meridian is the longitude that passes through Greenwich, England. Other countries use as prime meridians longitude lines that pass through Bern, Bogota, and Paris.

Where the equator and prime meridian intersect defines the origin (0,0). The globe is then divided into four geographical quadrants based on compass bearings from the origin. Above and below the equator are north and south, and to the left and right of the prime meridian are west and east.

Latitude and longitude values are traditionally measured in decimal degrees or in degrees, minutes, and seconds (DMS). Latitudes are measured relative to the equator and range from -90° at the South Pole to $+90^\circ$ at the North Pole. Longitude is measured relative to the prime meridian positively, up to 180° , when traveling east and measured negatively up to -180° , when traveling west. If the prime meridian is at Greenwich, then Australia, which is south of the equator and east of Greenwich, has positive longitude values and negative latitude values.

Although longitude and latitude can locate exact positions on the surface of the globe, they are not uniform units of measure. Only along the equator does the distance represented by one degree of

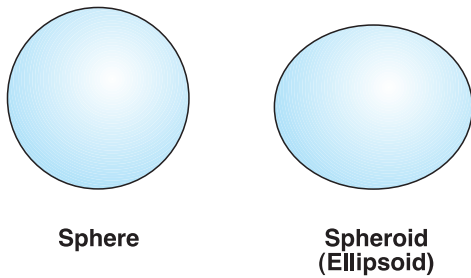


The parallels and meridians that form a graticule.

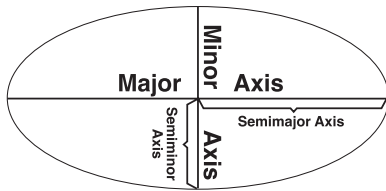
longitude approximate the distance represented by one degree of latitude. This is because the equator is the only parallel as large as a meridian. (Circles with the same radius as the spherical earth are called *great circles*. All meridians and the equator are *great circles*.)

Above and below the equator, the circles defining the parallels of latitude get gradually smaller until they become a single point at the North and South Poles where the meridians converge. As the meridians converge toward the poles, the distance represented by one degree of longitude decreases to zero. On the Clarke 1866 spheroid, one degree of longitude at the equator equals 111.321 km, while at 60° latitude it is only 55.802 km. Since degrees of latitude and longitude don't have a standard length, you can't measure distances or areas accurately or display the data easily on a flat map or computer screen.

The shape and size of a geographic coordinate system's surface is defined by a sphere or spheroid. Although the earth is best represented by a spheroid, the earth is sometimes treated as a sphere to make mathematical calculations easier. The assumption that the earth is a sphere is possible for small-scale maps, those smaller than 1:5,000,000. At this scale, the difference between a sphere and a spheroid is not detectable on a map. However, to maintain accuracy for larger-scale maps (scales of 1:1,000,000 or larger), a spheroid is necessary to represent the shape of the earth.

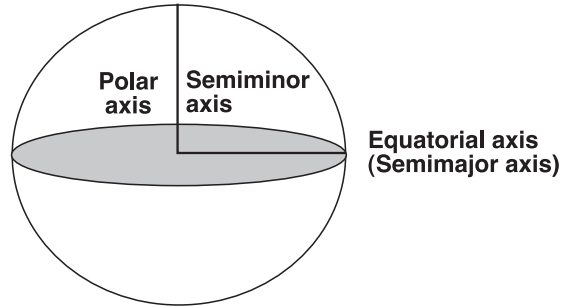


A sphere is based on a circle, while a spheroid (or ellipsoid) is based on an ellipse. The shape of an ellipse is defined by two radii. The longer radius is called the semimajor axis, and the shorter radius is called the semiminor axis.



The major and minor axes of an ellipse.

Rotating the ellipse around the semiminor axis creates a spheroid.



The semimajor axis and semiminor axis of a spheroid.

A spheroid is defined by either the semimajor axis, a , and the semiminor axis, b , or by a and the *flattening*. The flattening is the difference in length between the two axes expressed as a fraction or a decimal. The flattening, f , is

$$f = (a - b) / a$$

The flattening is a small value, so usually the quantity $1/f$ is used instead. Sample values are

$$a = 6378137.0 \text{ meters}$$

$$1/f = 298.257223563$$

The flattening ranges between zero and one. A flattening value of zero means the two axes are equal, resulting in a sphere. The flattening of the earth is approximately 0.003353.

Another quantity is the square of the eccentricity, e , that, like the flattening, describes the shape of a spheroid.

$$e^2 = \frac{a^2 - b^2}{a^2}$$

DEFINING DIFFERENT SPHEROIDS FOR ACCURATE MAPPING

The earth has been surveyed many times to better understand its surface features and their peculiar irregularities. The surveys have resulted in many spheroids that represent the earth. Generally, a spheroid is chosen to fit one country or a particular area. A spheroid that best fits one region is not

necessarily the same one that fits another region. Until recently, North American data used a spheroid determined by Clarke in 1866. The semimajor axis of the Clarke 1866 spheroid is 6,378,206.4 meters, and the semiminor axis is 6,356,583.8 meters.

Because of gravitational and surface feature variations, the earth is neither a perfect sphere nor a perfect spheroid. Satellite technology has revealed several elliptical deviations; for example, the South Pole is closer to the equator than the North Pole. Satellite-determined spheroids are replacing the older ground-measured spheroids. For example, the new standard spheroid for North America is GRS 1980, whose radii are 6,378,137.0 and 6,356,752.31414 meters.

Because changing a coordinate system's spheroid changes all previously measured values, many organizations don't switch to newer (and more accurate) spheroids.

DATUMS

While a spheroid approximates the shape of the earth, a datum defines the position of the spheroid relative to the center of the earth. A datum provides a frame of reference for measuring locations on the surface of the earth. It defines the origin and orientation of latitude and longitude lines.

Whenever you change the datum, or more correctly, the geographic coordinate system, the coordinate values of your data will change. Here's the coordinates in DMS of a control point in Redlands on NAD 1983.

-117 12 57.75961 34 01 43.77884

Here's the same point on NAD 1927.

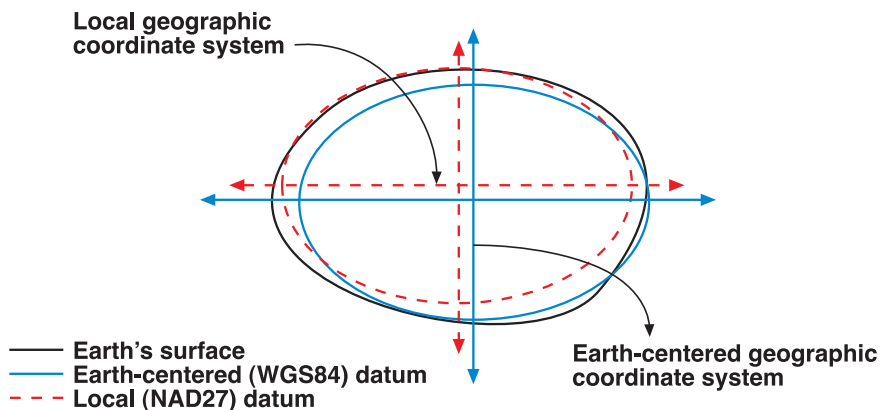
-117 12 54.61539 34 01 43.72995

The longitude value differs by about a second while the latitude value is around 500th of a second.

In the last 15 years, satellite data has provided geodesists with new measurements to define the best earth-fitting spheroid, which relates coordinates to the earth's center of mass. An earth-centered, or geocentric, datum uses the earth's center of mass as the origin. The most recently developed and widely used datum is the World Geodetic System of 1984 (WGS84). It serves as the framework for locational measurement worldwide.

A local datum aligns its spheroid to closely fit the earth's surface in a particular area. A point on the surface of the spheroid is matched to a particular

position on the surface of the earth. This point is known as the 'origin point' of the datum. The coordinates of the origin point are fixed, and all other points are calculated from it. The coordinate system origin of a local datum is not at the center of the earth. The center of the spheroid of a local datum is offset from the earth's center. The North American Datum of 1927 (NAD27) and the European Datum of 1950 are local datums. NAD27 is designed to fit North America reasonably well, while ED50 was created for use in Europe. A local datum is not suited for use outside the area for which it was designed.



There are two horizontal datums used almost exclusively in North America. These are the North American Datum of 1927 (NAD 1927) and the North American Datum of 1983 (NAD 1983).

NAD 1927

The North American Datum of 1927 uses the Clarke 1866 spheroid to represent the shape of the earth. The origin of this datum is a point on the earth referred to as Meades Ranch in Kansas. Many NAD 1927 control points were calculated from observations taken in the 1800s. These calculations were done manually and in sections over many years. Therefore, errors varied from station to station.

NAD 1983

Many technological advances in surveying and geodesy since the establishment of NAD 1927—electronic theodolites, GPS satellites, Very Long Baseline Interferometry, and Doppler systems—revealed weaknesses in the existing network of control points. Differences became particularly noticeable when linking existing control with newly established surveys. The establishment of a new datum would allow for a single datum to cover consistently North America and surrounding areas.

The North American Datum of 1983 is based upon both earth and satellite observations, using the GRS80 spheroid. The origin for this datum is the earth's center of mass. This affects the surface location of all longitude–latitude values enough to cause locations of previous control points in North America to shift, sometimes as much as 500 feet. A 10 year multinational effort tied together a network of control points for the United States, Canada, Mexico, Greenland, Central America, and the Caribbean.

Because NAD 1983 is an earth-centered coordinate system, it is compatible with global positioning system (GPS) data. The raw GPS data is actually reported in the World Geodetic System 1984 (WGS 1984) coordinate system.

HARN OR HPGN

There is an ongoing effort at the state level to readjust the NAD 1983 datum to a higher level of accuracy using state-of-the-art surveying techniques

that were not widely available when the NAD 1983 datum was being developed. This project, known as the High Accuracy Reference Network (HARN), or High Precision GPS Network (HPGN), is a cooperative project between the National Geodetic Survey and the individual states.

Currently all states have been resurveyed, but not all of the data has been released to the public yet. Thirty-three states are published as of November 1999.

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Projected coordinate systems

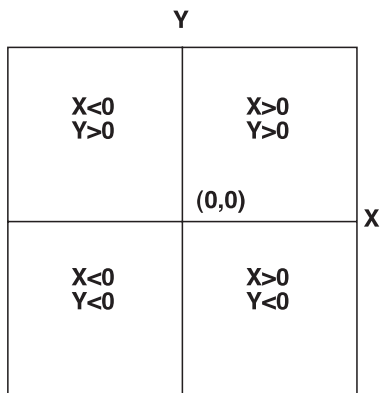
Projected coordinate systems are any coordinate system designed for a flat surface such as a printed map or a computer screen. Topics in this chapter include

- *Characteristics and types of map projection*
- *Different parameter types*
- *Customizing a map projection through its parameters*
- *Common projected coordinate systems*

A projected coordinate system is defined on a flat, two-dimensional surface. A projected coordinate system, unlike a geographic one, has the advantage that lengths, angles, and areas are constant across the two dimensions. This is not true when working in a geographic coordinate system. A projected coordinate system is always based on a geographic coordinate system that can use a sphere or spheroid.

In a projected coordinate system, locations are identified by x,y coordinates on a grid, with the origin at the center of the grid. Each position has two values referencing it to that central location. One specifies its horizontal position and the other its vertical position. The two values are called the x -coordinate and y -coordinate. Using this notation, the coordinates at the origin are $x = 0$ and $y = 0$.

On a gridded network of equally spaced horizontal and vertical lines, the horizontal line in the center is called the x -axis and the central vertical line is called the y -axis. Units are consistent and equally spaced across the full range of x and y . Horizontal lines above the origin and vertical lines to the right of the origin have positive values; those below or to the left are negative. The four quadrants represent the four possible combinations of positive and negative x - and y -coordinates.



The signs of x - and y -coordinates in a projected coordinate system.

WHAT IS A MAP PROJECTION?

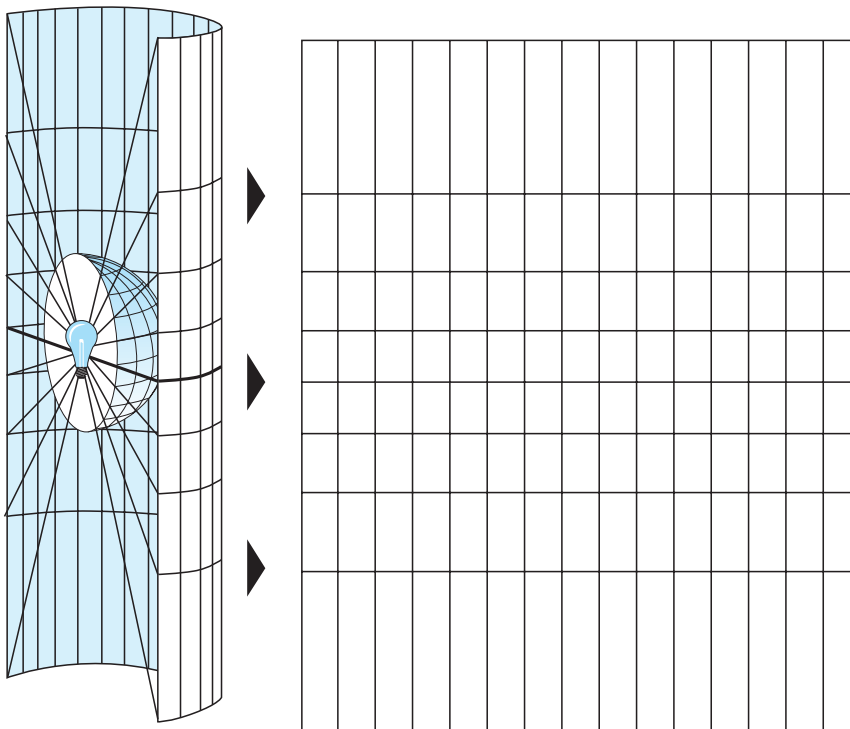
Whether you treat the earth as a sphere or as a spheroid, you must transform its three-dimensional surface to create a flat map sheet. This mathematical transformation is commonly referred to as a *map projection*. One easy way to understand how map projections alter spatial properties is to visualize shining a light through the earth onto a surface, called the projection surface.

A spheroid can't be flattened to a plane any easier than flattening a piece of orange peel—it will rip. Representing the earth's surface in two dimensions causes distortion in the shape, area, distance, or direction of the data.

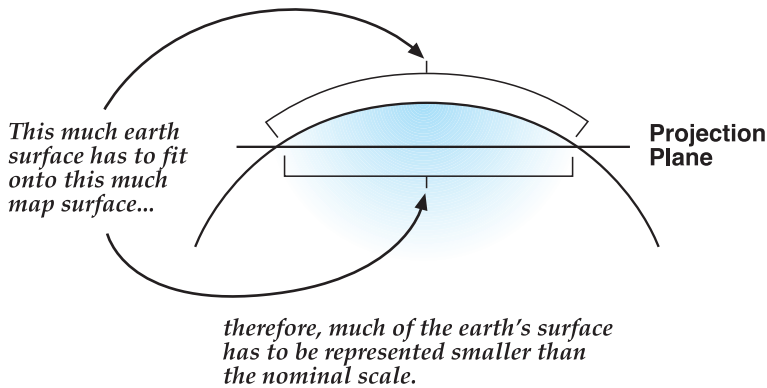
A map projection uses mathematical formulas to relate spherical coordinates on the globe to flat, planar coordinates.

$$(\lambda, \varphi) \ll (x, y)$$

Different projections cause different types of distortions. Some projections are designed to minimize the distortion of one or two of the data's characteristics. A projection could maintain the area of a feature but alter its shape. In the above graphic, data near the poles is stretched. The diagram on the next page shows how three-dimensional features are compressed to fit onto a flat surface.



The graticule of a geographic coordinate system is projected onto a cylindrical projection surface.



Map projections are designed for specific purposes. A map projection might be used for large-scale data in a limited area, while another is used for a small-scale map of the world. Map projections designed for small-scale data are usually based on spherical rather than spheroidal geographic coordinate systems.

Conformal projections

Conformal projections preserve local shape. Graticule lines on the globe are perpendicular. To preserve individual angles describing the spatial relationships, a conformal projection must show graticule lines intersecting at 90-degree angles on the map. This is accomplished by maintaining all angles. The drawback is that the area enclosed by a series of arcs may be greatly distorted in the process. No map projection can preserve shapes of larger regions.

Equal area projections

Equal area projections preserve the area of displayed features. To do this, the other properties of shape, angle, and scale are distorted. In equal area projections, the meridians and parallels may not intersect at right angles. In some instances, especially maps of smaller regions, shapes are not obviously distorted, and distinguishing an equal area projection from a conformal projection may prove difficult unless documented or measured.

Equidistant projections

Equidistant maps preserve the distances between certain points. Scale is not maintained correctly by any projection throughout an entire map; however, there are, in most cases, one or more lines on a map along which scale is maintained correctly. Most projections have one or more lines for which the length of the line on a map is the same length (at map scale) as the same line on the globe, regardless of whether it is a great or small circle or straight or curved. Such distances are said to be *true*. For example, in the Sinusoidal projection, the equator and all parallels are their true lengths. In other equidistant projections, the equator and all meridians are true. Still others (e.g., Two-Point Equidistant) show true scale between one or two points and every other point on the map. Keep in mind that no projection is equidistant to and from all points on a map.

True-direction projections

The shortest route between two points on a curved surface such as the earth is along the spherical equivalent of a straight line on a flat surface. That is the great circle on which the two points lie. True-direction or *azimuthal* projections maintain some of the great circle arcs, giving the directions or azimuths of all points on the map correctly with respect to the center. Some true-direction projections are also conformal, equal area, or equidistant.

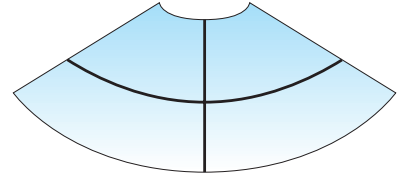
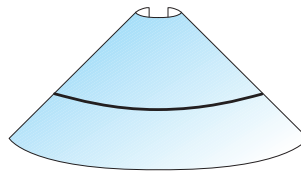
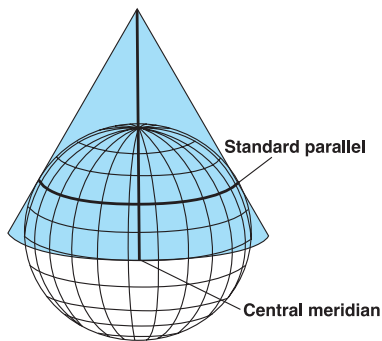
Because maps are flat, some of the simplest projections are made onto geometric shapes that can be flattened without stretching their surfaces. Common examples are cones, cylinders, and planes. A mathematical expression that systematically projects locations from the surface of a spheroid to representative positions on a planar surface is called a *map projection*.

The first step in projecting from one surface to another is to create one or more points of contact. Each contact is called a *point (or line) of tangency*. As illustrated in the section below about 'Planar projections', a planar projection is tangential to the globe at one point. Tangential cones and cylinders touch the globe along a line. If the projection surface intersects the globe instead of merely touching its surface, the resulting projection is a secant rather than a tangent case. Whether the contact is tangent or secant, the contact point or lines are significant because they define locations of zero distortion. Lines of true scale are often referred to as *standard lines*. In general, distortion increases with the distance from the point of contact.

Many common map projections are classified according to the projection surface used: conic, cylindrical, and planar.

Conic projections

The most simple conic projection is tangent to the globe along a line of latitude. This line is called the *standard parallel*. The meridians are projected onto the conical surface, meeting at the apex, or point, of the cone. Parallel lines of latitude are projected onto the cone as rings. The cone is then 'cut' along any meridian to produce the final conic projection, which has straight converging lines for meridians and concentric circular arcs for parallels. The meridian opposite the cut line becomes the *central meridian*.

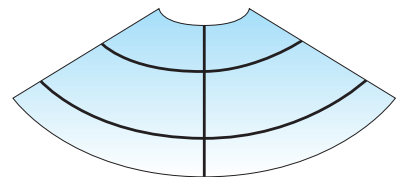
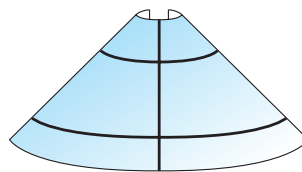
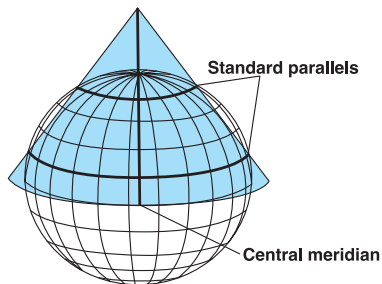


In general, distortion increases away from the standard parallel. Thus, cutting off the top of the cone produces a more accurate projection. This is accomplished by not using the polar region of the projected data. Conic projections are used for mid-latitude zones that have an east-to-west orientation.

by two standard parallels. It is also possible to define a secant projection by one standard parallel and a scale factor. The distortion pattern for secant projections is different between the standard parallels than beyond them. Generally, a secant projection has less overall distortion than a tangent case. On still more complex conic projections, the axis of the cone does not line up with the polar axis of the globe. These are called *oblique*.

The representation of geographic features depends on the spacing of the parallels. When equally

spaced, the projection is equidistant in the north-south direction but neither conformal nor equal area such as the Equidistant Conic projection. For small areas, the overall distortion is minimal. On the Lambert Conic Conformal projection, the central parallels are spaced more closely than the parallels



Somewhat more complex conic projections contact the global surface at two locations. These projections are called *secant* conic projections and are defined

near the border, and small geographic shapes are maintained for both small-scale and large-scale maps. Finally, on the Albers Equal Area Conic

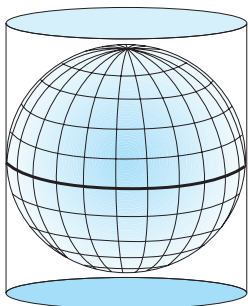
projection, the parallels near the northern and southern edges are closer together than the central parallels, and the projection displays equivalent areas.

Cylindrical projections

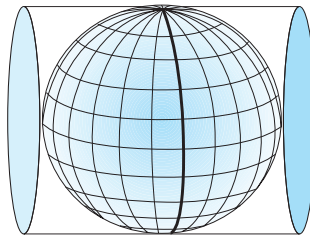
Cylindrical projections can also have tangent or secant cases. The Mercator projection is one of the most common cylindrical projections, and the equator is usually its line of tangency. Meridians are geometrically projected onto the cylindrical surface, and parallels are mathematically projected, producing graticular angles of 90 degrees. The cylinder is 'cut' along any meridian to produce the final cylindrical projection. The meridians are equally spaced, while the spacing between parallel lines of latitude increases toward the poles. This projection is conformal and displays true direction along straight lines. *Rhumb lines*, lines of constant bearing, but not most great circles, are straight lines on a Mercator projection.

For more complex cylindrical projections the cylinder is rotated, thus changing the tangent or secant lines. Transverse cylindrical projections such as the Transverse Mercator use a meridian as the tangential contact or lines parallel to meridians as lines of secancy. The standard lines then run north and south, along which the scale is true. Oblique cylinders are rotated around a great circle line located anywhere between the equator and the meridians. In these more complex projections, most meridians and lines of latitude are no longer straight.

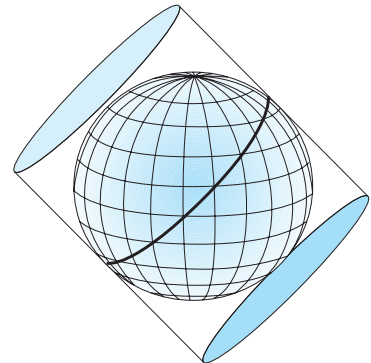
of equidistance. Other geographical properties vary according to the specific projection.



Normal



Transverse



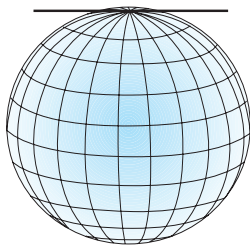
Oblique

In all cylindrical projections, the line of tangency or lines of secancy have no distortion and thus are lines

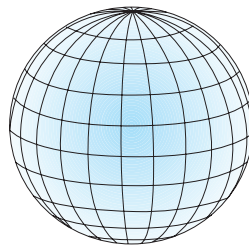
Planar projections

Planar projections project map data onto a flat surface touching the globe. A planar projection is also known as an azimuthal projection or a zenithal projection. This type of projection is usually tangent to the globe at one point but may be secant. The point of contact may be the North Pole, the South Pole, a point on the equator, or any point in between. This point specifies the *aspect* and is the focus of the projection. The focus is identified by a central longitude and a central latitude. Possible aspects are *polar*, *equatorial*, and *oblique*.

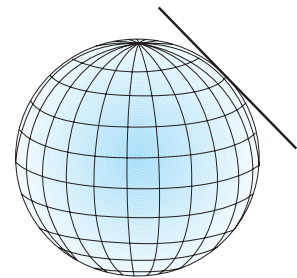
projections. Perspective points may be the center of the earth, a surface point directly opposite from the focus, or a point external to the globe, as if seen from a satellite or another planet.



Polar



Equatorial



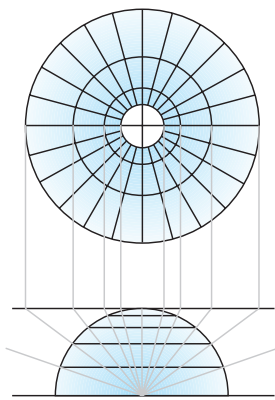
Oblique

Polar aspects are the simplest form. Parallels of latitude are concentric circles centered on the pole, and meridians are straight lines that intersect at the pole with their true angles of orientation. In other aspects, planar projections will have graticular angles of 90 degrees at the focus. Directions from the focus are accurate.

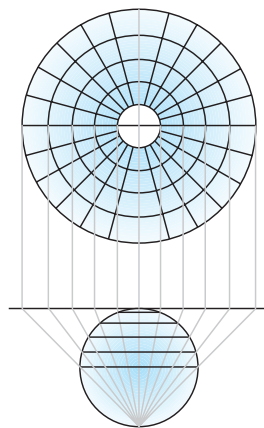
Great circles passing through the focus are represented by straight lines; thus the shortest distance from the center to any other point on the map is a straight line. Patterns of area and shape distortion are circular about the focus. For this reason, azimuthal projections accommodate circular regions better than rectangular regions. Planar projections are used most often to map polar regions.

Some planar projections view surface data from a specific point in space. The point of view determines how the spherical data is projected onto the flat surface. The perspective from which all locations are viewed varies between the different azimuthal

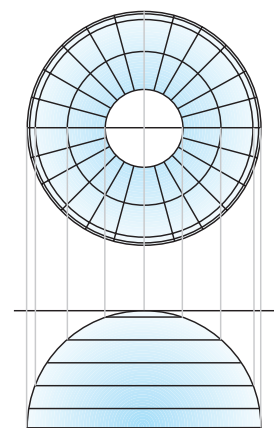
Azimuthal projections are classified in part by the focus and, if applicable, by the perspective point. The graphic below compares three planar projections with polar aspects but different perspectives. The Gnomonic projection views the surface data from the center of the earth, whereas the Stereographic projection views it from pole to pole. The Orthographic projection views the earth from an infinite point, as if viewed from deep space. Note how the differences in perspective determine the amount of distortion toward the equator.



Gnomonic



Stereographic



Orthographic

The projections discussed previously are conceptually created by projecting from one geometric shape (a sphere) onto another (a cone, cylinder, or plane). Many projections are not related as easily to one of these three surfaces.

Modified projections are altered versions of other projections (e.g., the Space Oblique Mercator is a modification of the Mercator projection). These modifications are made to reduce distortion, often by including additional standard lines or changing the distortion pattern.

Pseudo projections have some of the characteristics of another class of projection. For example, the Sinusoidal is called a pseudocylindrical projection because all lines of latitude are straight and parallel and all meridians are equally spaced. However, it is not truly a cylindrical projection because all meridians except the central meridian are curved. This results in a map of the earth having an oval shape instead of a rectangular shape.

Other projections are assigned to special groups such as circular, star, and so on.