

Projections and Coordinate Systems

Discussion

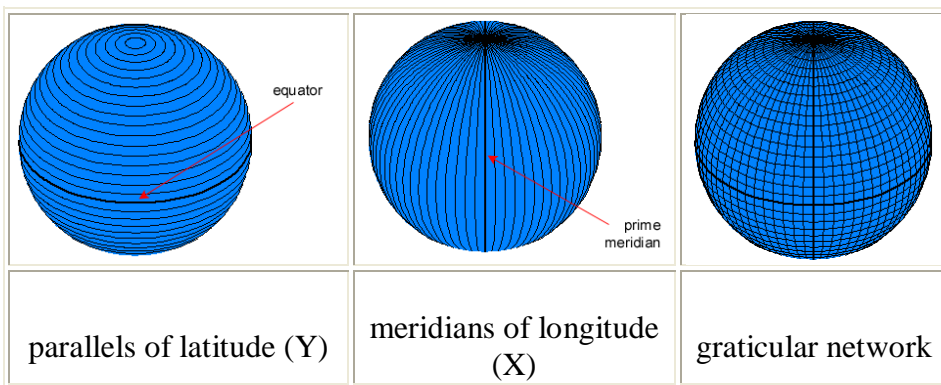
Projections and coordinate systems are a complicated topic in GIS, but they form the basis for how GIS can store, analyze, and display spatial data. Understanding projections and coordinate systems is important knowledge to have, especially if you deal with many different sets of data that come from different sources.

Projections

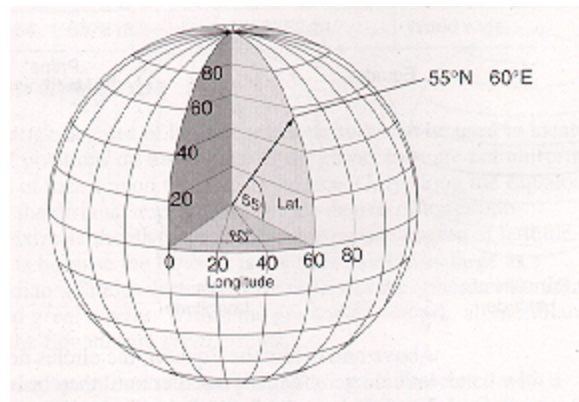
The best model of the earth would be a 3-dimensional solid in the same shape as the earth. Spherical globes are often used for this purpose. However, globes have several drawbacks.

- Globes are large and cumbersome.
- They are generally of a scale unsuitable to the purposes for which most maps are used. Usually we want to see more detail than is possible to be shown on a globe.
- Standard measurement equipment (rulers, protractors, planimeters, dot grids, etc.) cannot be used to measure distance, angle, area, or shape on a sphere, as these tools have been constructed for use in planar models.
- The latitude-longitude spherical coordinate system can only be used to measure angles, not distances or areas.

Here is an image of a globe, displaying lines of reference. These lines can only be used for measurement of angles on a sphere. They cannot be used for making linear or areal measurements.



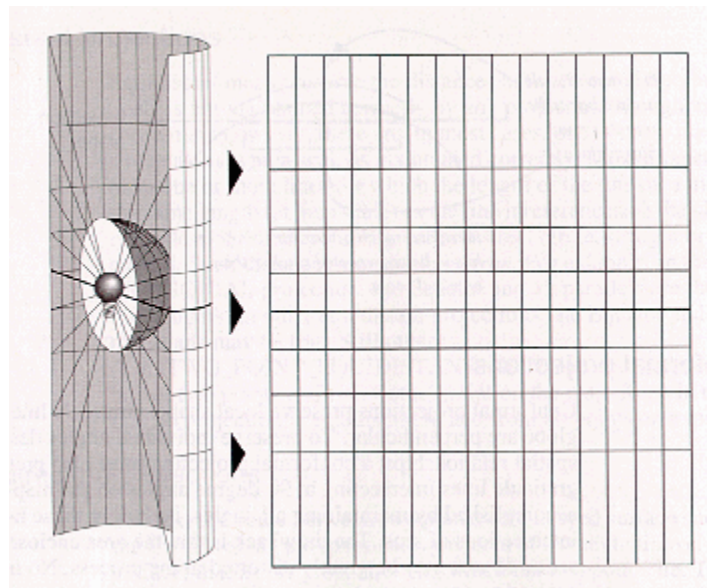
Positions on a globe are measured by angles rather than X, Y (Cartesian planar) coordinates. In the image below, the specific point on the surface of the earth is specified by the coordinate (60 °. E longitude, 55 den. N latitude). The longitude is measured as the number of degrees from the prime meridian, and the latitude is measured as the number of degrees from the equator.



[Image from ESRI]

For this reason, projection systems have been developed. Map projections are sets of mathematical models which transform spherical coordinates (such as latitude and longitude) to planar coordinates (x and y). In the process, data which actually lie on a sphere are projected onto a flat plane or a surface. That surface can be converted to a planar section without stretching.

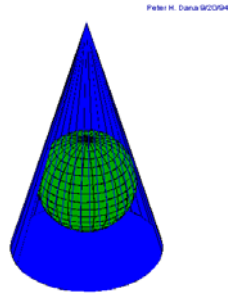
Here is a simple schematic designed to show how a projection works. Imagine a glass sphere marked with grid lines or geographic features. A light positioned in the center of the sphere shines (“projects”) outward, casting shadows from the lines. A plane, cone, or cylinder (known as a *developable surface*) is placed outside the sphere. Shadows are cast upon the surface. The surface is opened flat, and the geographic features are displayed on a flat plane. As soon as a projection is applied, a Cartesian coordinate system (regular measurement in X and Y dimensions) is implied. The user gets to choose the details of the coordinate system (e.g., units, origin, and offsets).



[Image from ESRI]

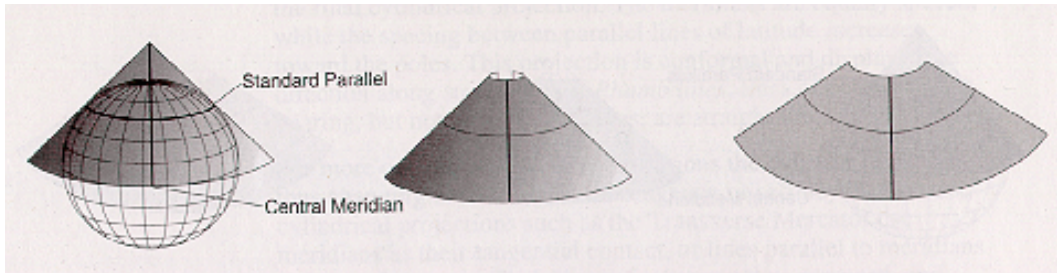
The projection surfaces (i.e., cylinders, cones, and planes) form the basic types of projections:

Conic

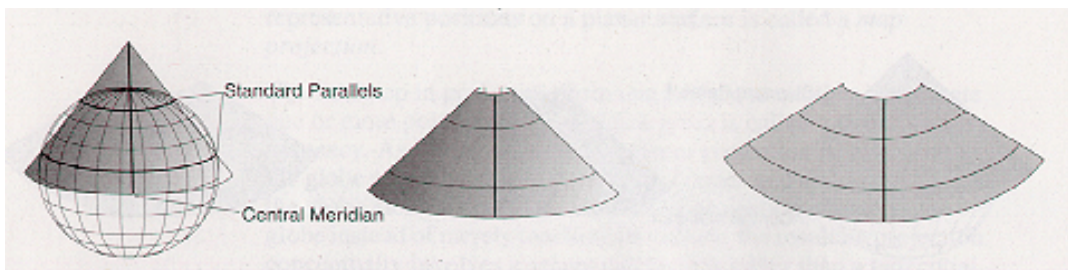


Conical Projection Surface

The conic tangent case:



The conic secant case:

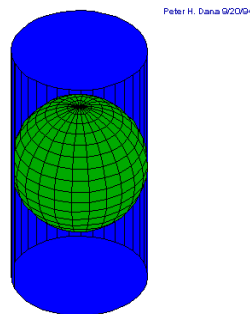


Standard parallels are where the cone touches or slices through the globe.

The central meridian is opposite the edge where the cone is sliced open.

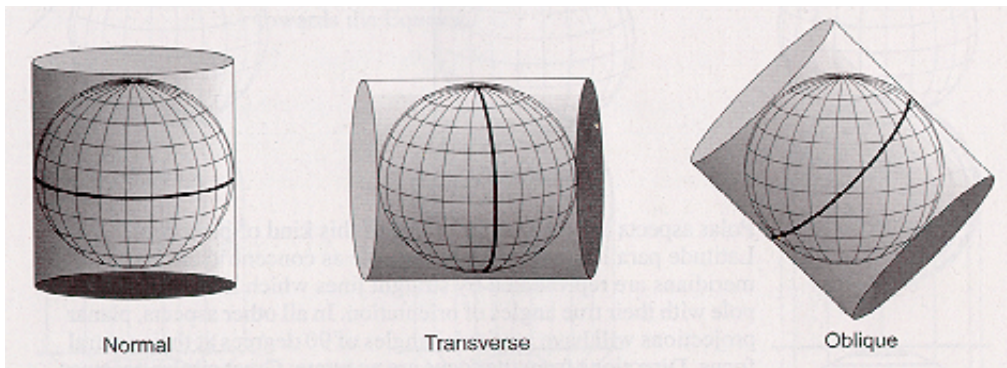
Conic projections are used frequently for mapping large areas (e.g., states, large countries, or continents).

Cylindrical



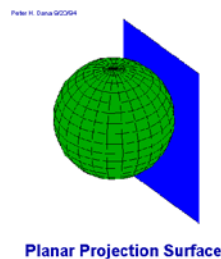
Cylindrical Projection Surface

Different cylindrical projection orientations:

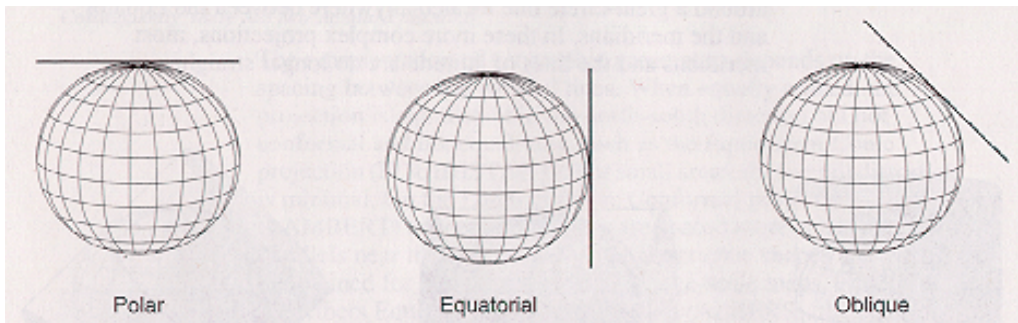


The most common cylindrical projection is the Mercator projection, which is the basis of the UTM (Universal Transverse Mercator) system.

Planar (Orthographic)



Different orthographic projection parameters:



[Images placed with permission of [Peter Dana](#)]

Distortion

Notice in these images how distortion in distance is minimized at the place on the surface that is closest to the sphere. Distortion increases as you travel along the surface farther from the light source. This distortion is an unavoidable property of map projection. Although many different map projections exist, they all introduce distortion in one or more of the following measurement properties:

- Shape
- Distance
- True Direction
- Area

Distortion will vary in at least one of each of the above properties depending on the projection used, as well as the scale of the map, or the spatial extent that is mapped. Whenever one type of distortion is minimized, there will be corresponding increases in the distortion of one or more of the other properties.

There are names for the different classes of projections that minimize distortion.

- Those that minimize distortion in shape are called **conformal**.
- Those that minimize distortion in distance are known as **equidistant**.
- Those that minimize distortion in area are known as **equal-area**.
- Those minimizing distortion in direction are called **true-direction** projections.

It is appropriate to choose a projection based on which measurement properties are most important to your work. For example, if it is very important to obtain accurate area measurements (e.g., for determining the home range of an animal species), you will select an equal-area projection.

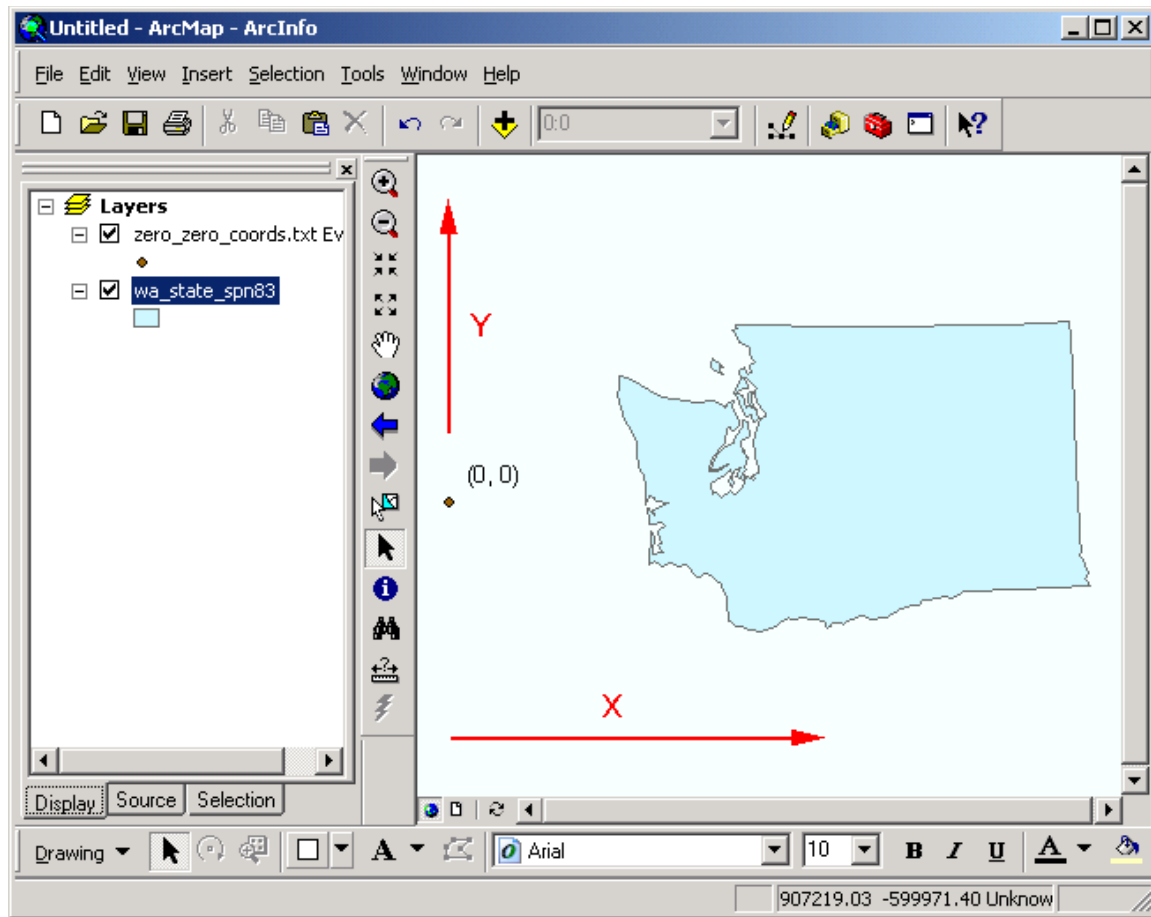
Coordinate Systems

Once map data are projected onto a planar surface, features must be referenced by a planar coordinate system. The geographic system (latitude-longitude), which is based on angles measured on a sphere, is not valid for measurements on a plane. Therefore, a Cartesian coordinate system is used, where the origin (0, 0) is toward the lower left of the planar section. The true origin point (0, 0) may or may not be in the proximity of the map data you are using.

Coordinates in the GIS are measured from the origin point. However, **false eastings** and **false northings** are frequently used, which effectively offset the origin to a different place on the coordinate plane. This is done in order to achieve several purposes:

- Minimize the possibility of using negative coordinate values (to make calculations of distance and area easier).
- Lower the absolute value of the coordinates (to make the values easier to read, transcribe, calculate, etc.).

In this image, Washington state is projected to State Plane North (NAD83). All of the locations on the map are now referenced in Cartesian coordinates, where the origin lies several hundred miles off the Pacific coast.



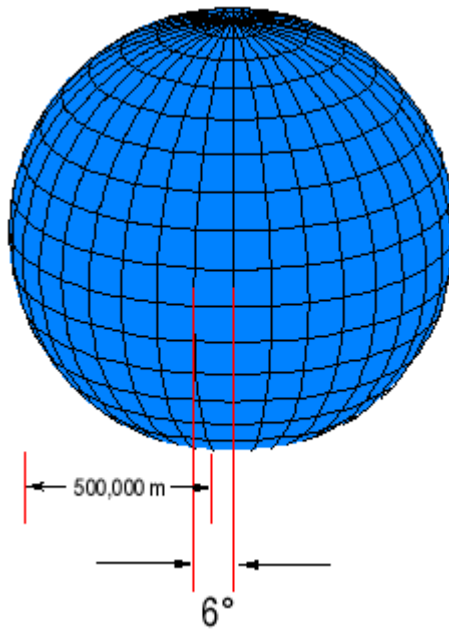
Some measurement framework systems define both projections and coordinate systems. For example, the Universal Transverse Mercator (UTM) system, commonly used by scientists and Federal organizations, is based on a series of 60 transverse Mercator projections, in which different areas of the earth fall into different 6-degree zones. Within each zone, a local coordinate system is defined, in which the X-origin is located 500,000 m west of the central meridian, and the Y-origin is the south pole or the equator, depending on the hemisphere. The State Plane system also defines both projection and coordinate system.

The two most common coordinate/projection systems you will encounter in the USA are:

- State Plane - The state plane system includes different projections for each state, and frequently different projections for different areas *within* each state. The State Plane system was developed in the 1930s to simplify and codify the different coordinate and projection systems for different states within the USA. Three conformal projections were chosen: the Lambert Conformal Conic for states that are longer in the east-west direction, such as Washington, Tennessee, and Kentucky, the Transverse Mercator projection for states that are longer in the north-south direction, such as Illinois and Vermont, and the Oblique Mercator projection for the panhandle of Alaska, because it is neither predominantly north nor south, but at an oblique angle. To maintain an accuracy of 1 part in 10,000, it was necessary to divide many states into multiple zones. Each zone has its own central meridian and standard parallels to maintain the desired level of accuracy. The origin is located south of the zone boundary, and false eastings are applied so that all coordinates within the zone will have positive X and Y values. The boundaries of these zones follow county boundaries. Smaller states such as Connecticut require only one zone, whereas Alaska is composed of ten zones and uses all three projections. Washington is divided into 2 zones, a north zone and a south zone. Here are the projection parameters for each zone:

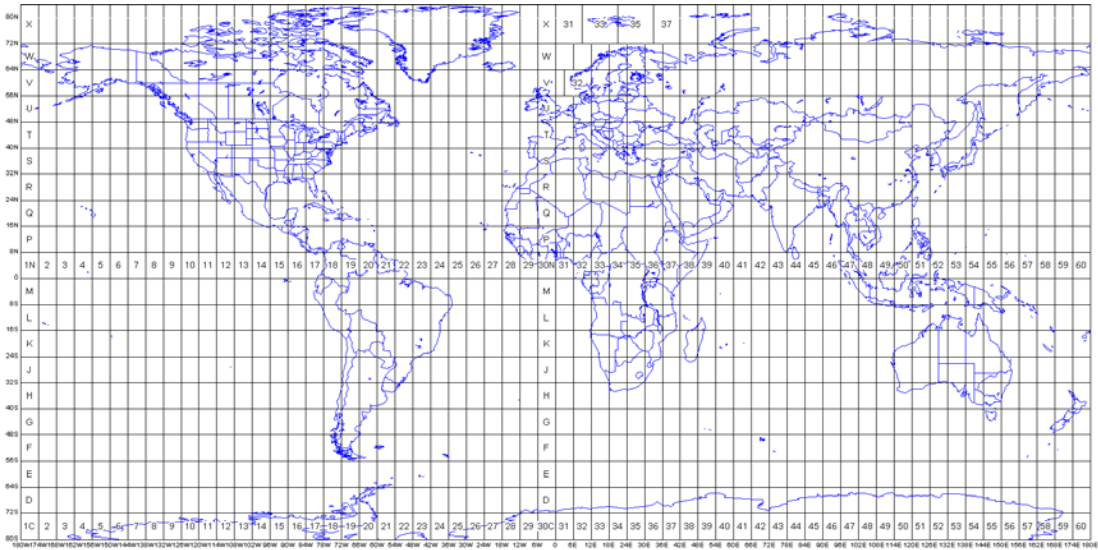
Zone	SPCS Zone #	FIPS Zone #	Projection	1st Std. Parallel Latitude (D M S)	2nd Std. Parallel Latitude (D M S)	Central Meridian Longitude (D M S)	Origin Latitude (D M S)	False Easting (m)	False Northing (m)
WA_N	5601	4601	Lambert Conformal Conic	47 30 00	48 44 00	-120 50 00	47 00 00	609601.21920	0
WA_S	5626	4602	Lambert Conformal Conic	45 50 00	47 20 00	-120 30 00	45 20 00	609601.21920	0

- Universal Transverse Mercator (UTM) - A particular subset of the transverse Mercator is the Universal Transverse Mercator (UTM) which was adopted originally by the US Army for large-scale military maps. In the UTM system, the globe is divided into 60 zones between 84° S and 84° N, most of which are 6° wide. Each UTM zone has its own central meridian and spans 3° west and 3° east from the center of the zone. Note that the position of the cylinder developable surface is positioned at a different place around the globe for each zone. X- and Y-coordinates are in meters by convention. For zones in the northern hemisphere, the X-origin is a place 500,000 m west of the central meridian, and the Y-origin is the Equator. The false easting is used to eliminate negative coordinates. For zones in the southern hemisphere, the X origin is also 500,000 m west of the central meridian, but the Y-origin is the South



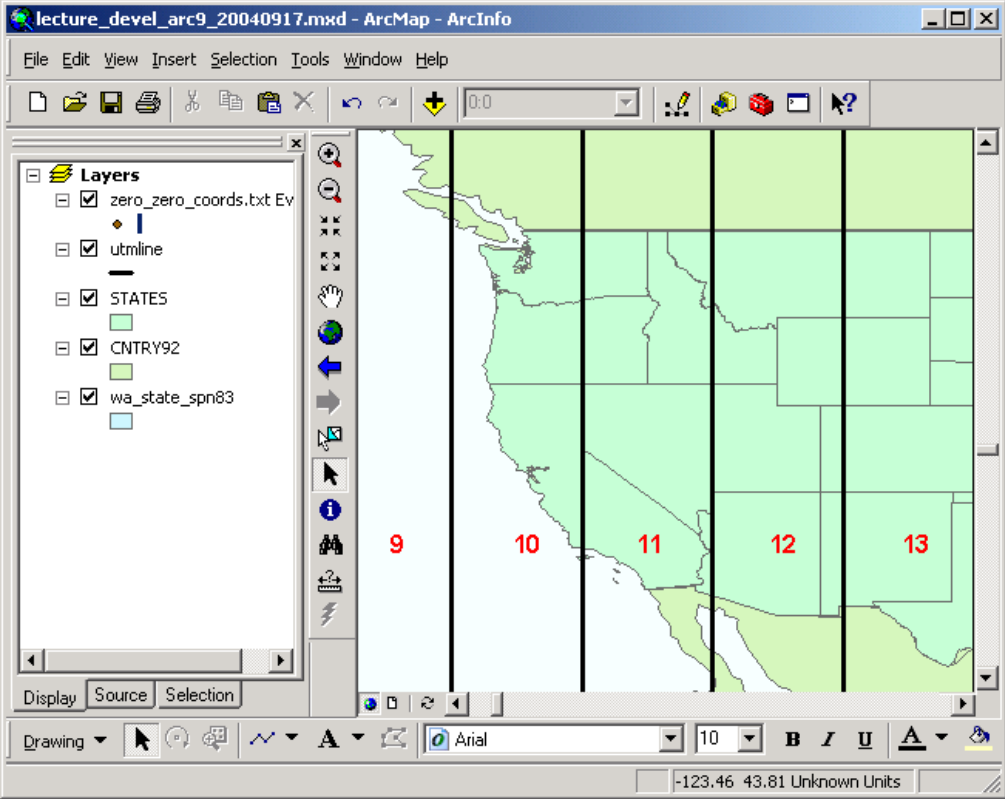
Pole.UTM Zone layout:

UTM Zone locations and grid designations:

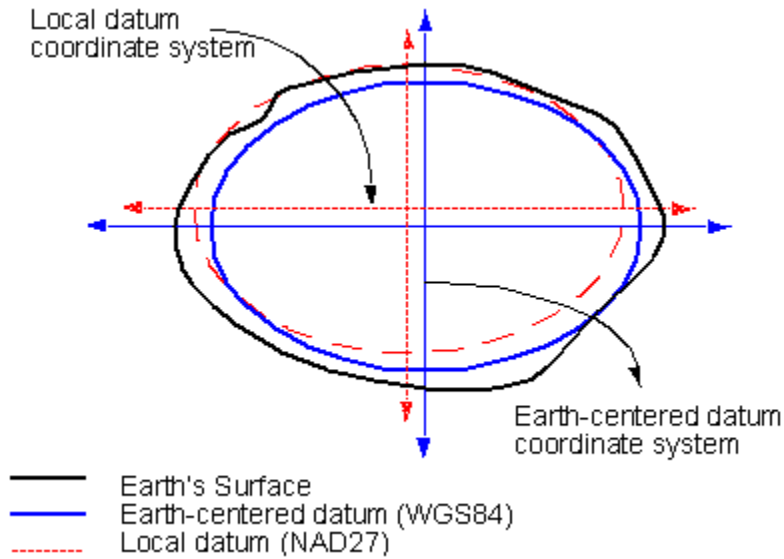


By convention, areas in Washington are mapped in Zone 10 of the UTM system, even though eastern Washington lies in Zone 11. Zone 10 has its central meridian at 123° W longitude, and covers the range 126° W -120° W. The Zone's origin is 500,000 m west of 123° W.

Here are the UTM Zones for the Western USA:



Datums are sets of parameters and ground control points defining local coordinate systems. Because the earth is not a perfect sphere, but is somewhat “egg-shaped,” geodesists use **spheroids** and **ellipsoids** to model the 3-dimensional shape of the earth. Although the earth can be modeled by an egg-shaped solid, local variations still exist, due to differential thickness of the earth’s crust, or differential gravitation due to density of the crustal material. A datum is created to account for these local variations in establishing a coordinate system.



[image from ESRI]

In the image above, the earth is shown as the irregular surface (thick black line). A generalized earth-centered coordinate system (WGS84, in blue) provides a good overall mean solution for all places on the earth. However, for specific local measurements, WGS84 cannot account for local variations. Instead, local datums have been developed. In this example, the local North American Datum of 1927 (NAD27, in dashed red line) more closely fits the earth’s surface in the upper-left quadrant of the earth’s cross-section. NAD27 only fits this quadrant, so to use it in another part of the earth will result in serious errors in measurement. For mapping North America, in order to obtain the most accurate locations and measurements, NAD27 or NAD83/91 are used.

Projection Storage vs. Definition

All spatial datasets are stored with one projection/coordinate system or another. Even the so-called “unprojected” datasets, which have their coordinates stored in decimal degrees of latitude and longitude, are using a spatial reference system that is managed by the computer. This is what is meant by “storage.” Every dataset is stored with a spatial reference, regardless of if the spatial referencing system is documented with the dataset.

If a dataset has been built with documentation about its spatial referencing, then it is said to have a projection or coordinate system “defined.” If a dataset has no projection defined, it is possible to use the software to define the projection, that is, to add extra data that describe the projection and coordinate system of the dataset.

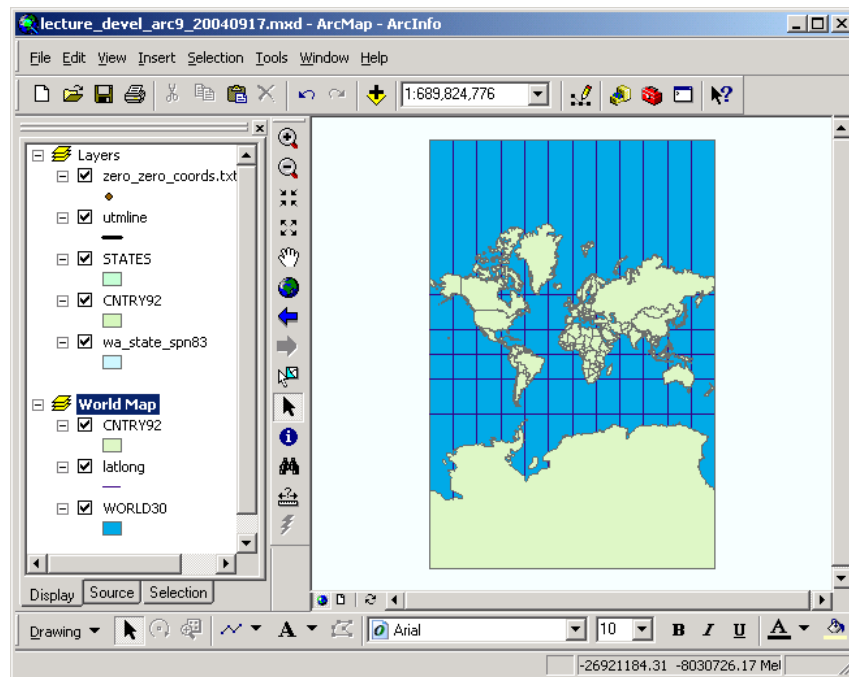
In any case, it is extremely important, as a user, to know the projection and coordinate system of all the data you use. Sometimes datasets will appear to be incompatible; if this happens, sometimes the only step necessary to

allow the datasets to be used together is to define the projection. Once the projection is defined, ArcGIS will be able to manage the datasets and, if necessary, project one of the datasets on the fly to match the other.

Examples of different projections

Here is a view of the world in several different projections, along with brief descriptions of their properties (descriptions copied from the on-line documentation):

Mercator (cylindrical)



Properties:

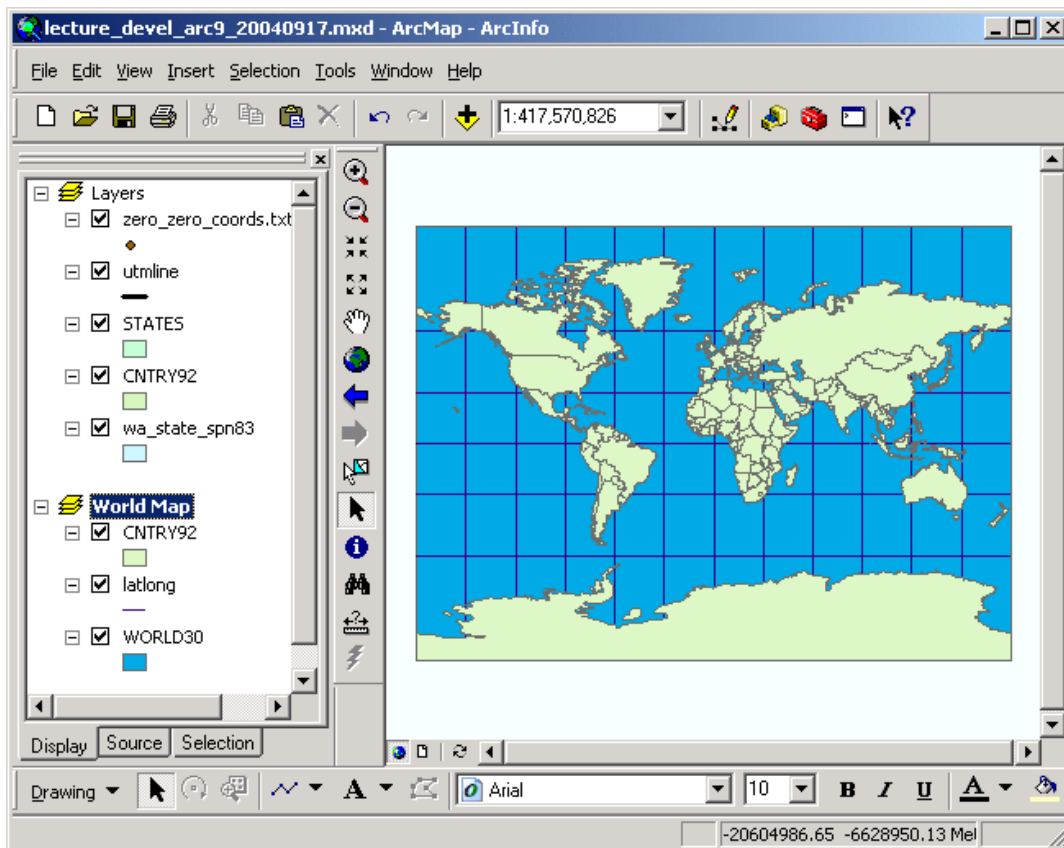
Shape: Conformal. Small shapes are well represented because this projection maintains the local angular relationships.

Area: Increasingly distorted toward the polar regions. For example, in the Mercator projection, although Greenland is only one-eighth the size of South America, Greenland appears to be larger.

Direction: Any straight line drawn on this projection represents an actual compass bearing. These true direction lines are rhumb lines, and generally do not describe the shortest distance between points.

Distance: Scale is true along the Equator, or along the secant latitudes.

Miller (cylindrical)



Properties:

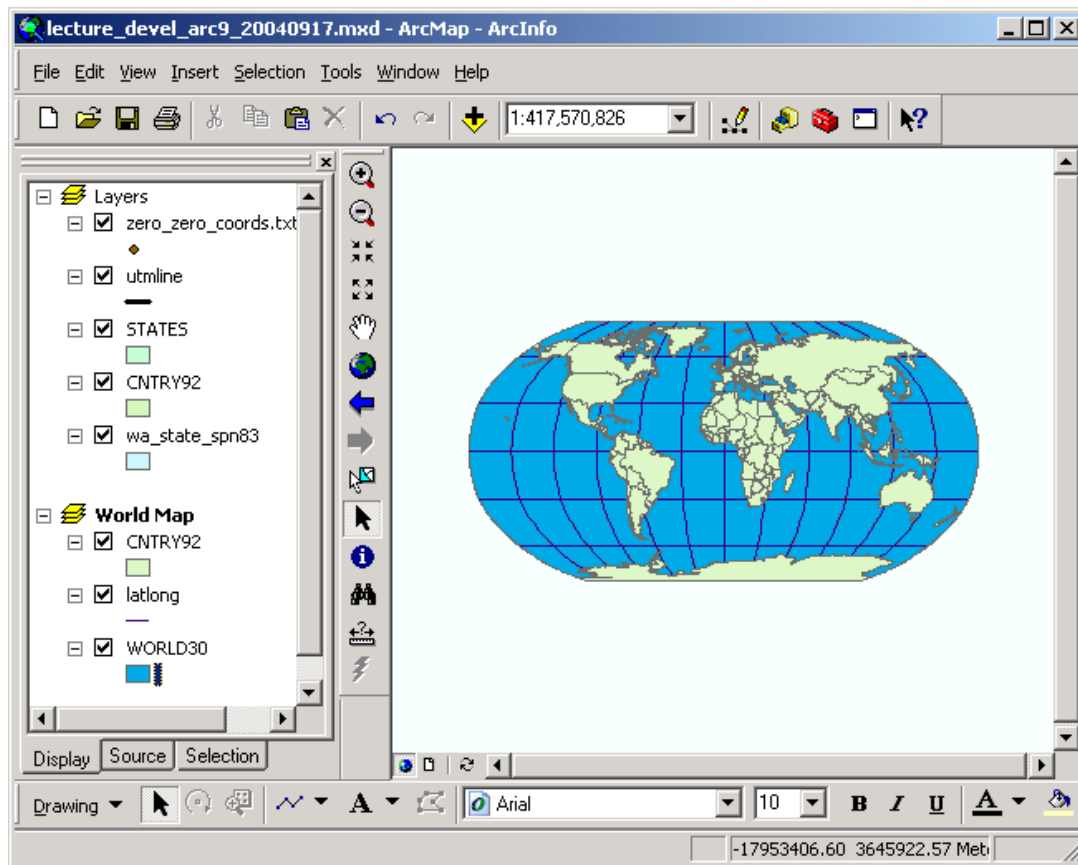
Shape: Minimally distorted between 45th parallels, increasingly toward the poles. Land masses are stretched more east to west than they are north to south.

Area: Distortion increases from the Equator toward the poles.

Direction: Local angles are correct only along the Equator.

Distance: Correct distance is measured along the Equator.

Robinson (pseudo-cylindrical)



Properties:

Shape: Shape distortion is very low within 45° of the origin and along the Equator.

Area: Distortion is very low within 45° of the origin and along the Equator.

Direction: Generally distorted.

Distance: Generally, scale is made true along latitudes 38° N and S. Scale is constant along any given latitude, and for the latitude of opposite sign.

Lambert (planar)



Properties:

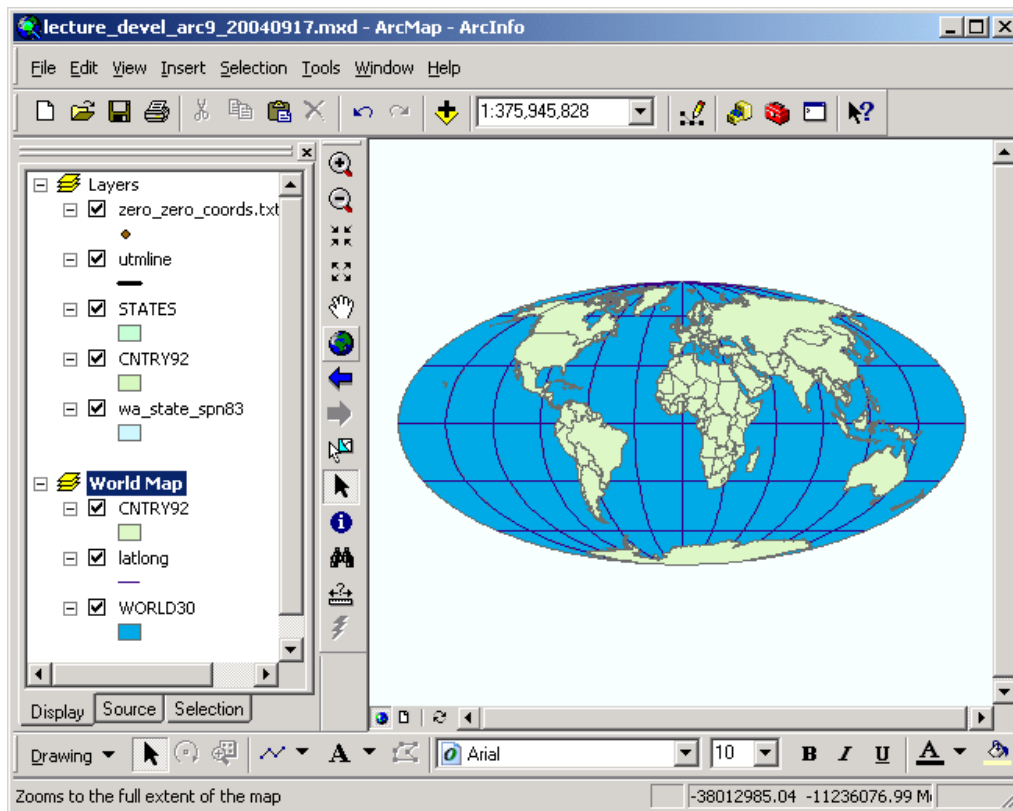
Shape: Shape is minimally distorted, less than 2 percent, within 15° from the focal point. Beyond that, angular distortion is more significant; small shapes are compressed radially from the center and elongated perpendicularly.

Area: Equal-area.

Direction: True direction radiating from the central point.

Distance: True at center. Scale decreases with distance from the center along radii and increases from the center perpendicular to the radii.

Mollweide



Properties:

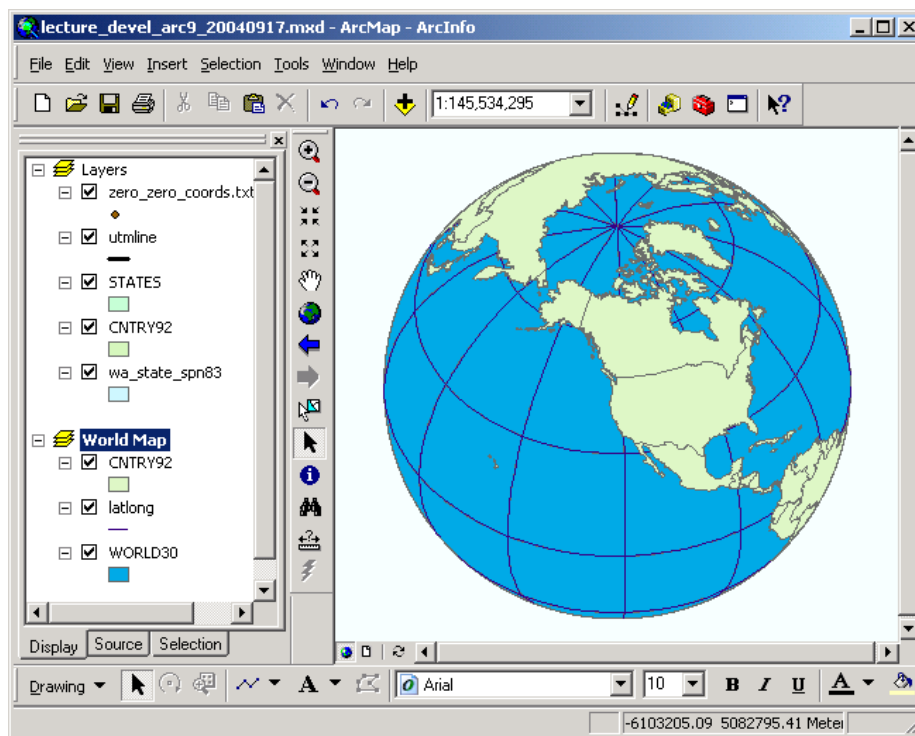
Shape: Shape is not distorted at the intersection of the central meridian and latitudes $40^{\circ} 44' N$ and S . Distortion increases outward from these points and becomes severe at the edges of the projection.

Area: Equal-area.

Direction: Local angles are true only at the intersection of the central meridian and latitudes $40^{\circ} 44' N$ and S . Direction is distorted elsewhere.

Distance: Scale is true along latitudes $40^{\circ} 44' N$ and S . Distortion increases with distance from these lines and becomes severe at the edges of the projection.

Orthographic



Properties:

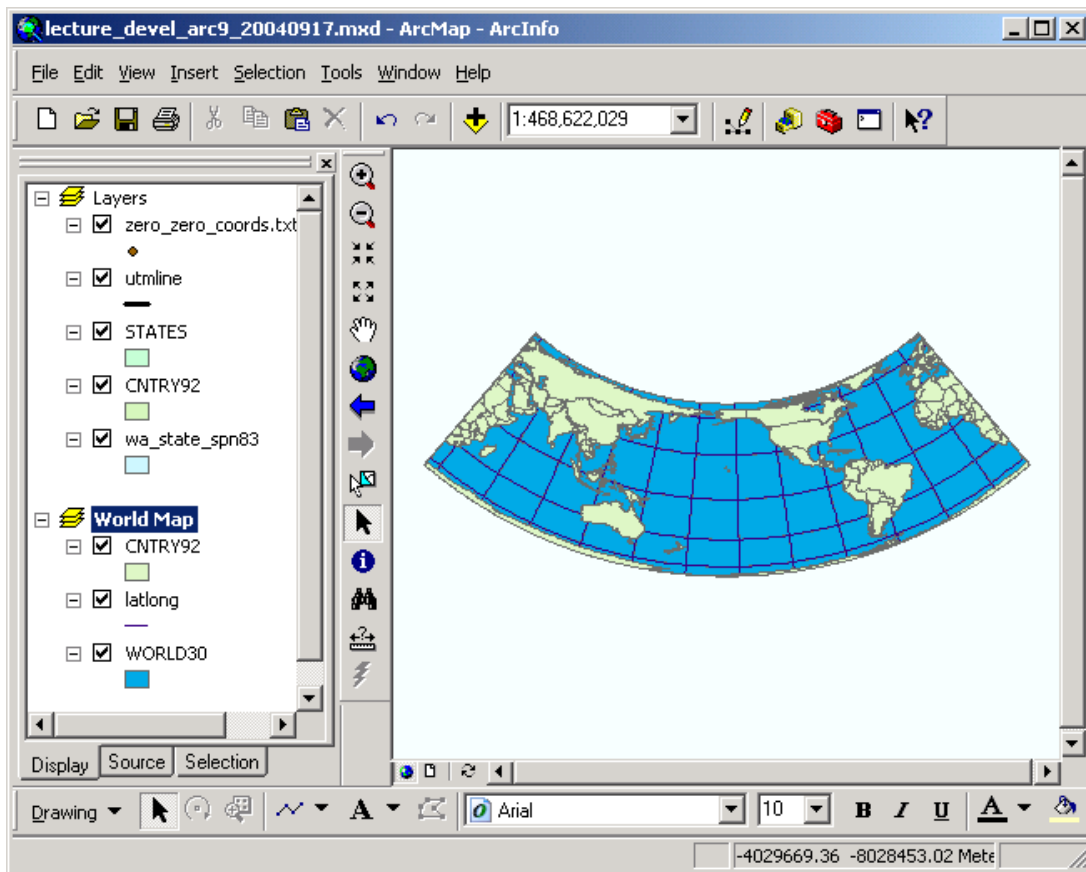
Shape: Minimal distortion near the center; maximal distortion near the edge.

Area: The areal scale decreases with distance from the center. Areal scale is zero at the edge of the hemisphere.

Direction: True direction from the central point.

Distance: The radial scale decreases with distance from the center and becomes zero on the edges. The scale perpendicular to the radii, along the parallels of the polar aspect, is accurate.

Albers (conic)



Properties:

Shape: Shape is true along the standard parallels of the normal aspect (Type 1), or the standard lines of the transverse and oblique aspects (Types 2 and 3). Distortion is severe near the poles of the normal aspect or 90° from the central line in the transverse and oblique aspects.

Area: There is no area distortion on any of the projections.

Direction: Local angles are correct along standard parallels or standard lines. Direction is distorted elsewhere.

Distance: Scale is true along the Equator (Type 1), or the standard lines of the transverse and oblique aspects (Types 2 and 3). Scale distortion is severe near the poles of the normal aspect or 90° from the central line in the transverse and oblique aspects.

For more complete discussions of map projections and related topics, see these resources, or perform a web search:

- [Karen Mulcahy's Map Projection Home Page](#)
- [Geodetic Datum Overview, Department of Geography, University of Colorado at Boulder](#)
- [Global Positioning System Overview, Department of Geography, University of Colorado at Boulder](#)
- [Coordinate Systems Overview, Department of Geography, University of Colorado at Boulder](#)
- ArcGIS Help

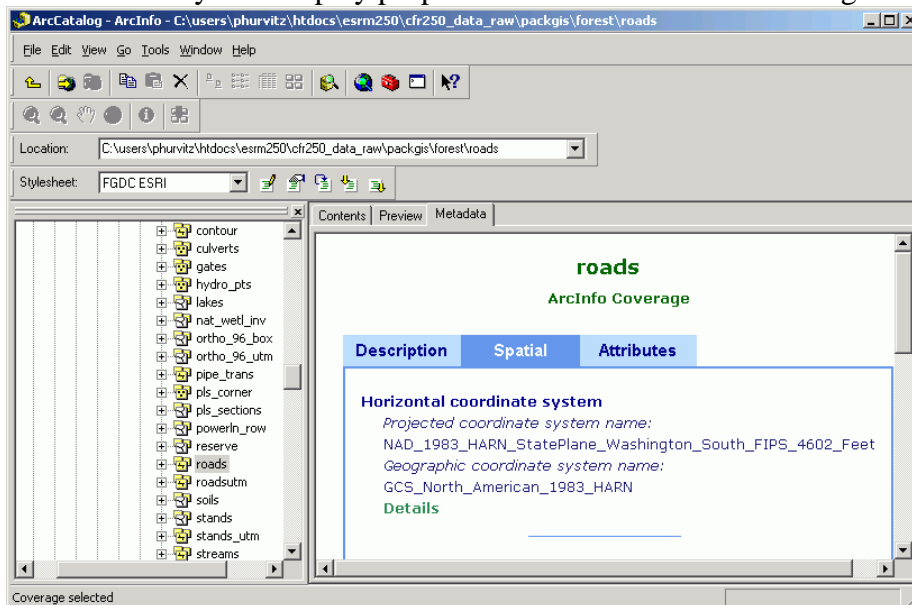
Projecting spatial datasets

ArcGIS at version 10 supports projection transformations of both vector and raster data.

You may have data that are stored unprojected (i.e., the data have internal coordinates representing latitude and longitude measurements); other data may be stored in a projection/coordinate system such as State Plane or UTM. There are several possible options for projection transformations, based on how your data are stored:

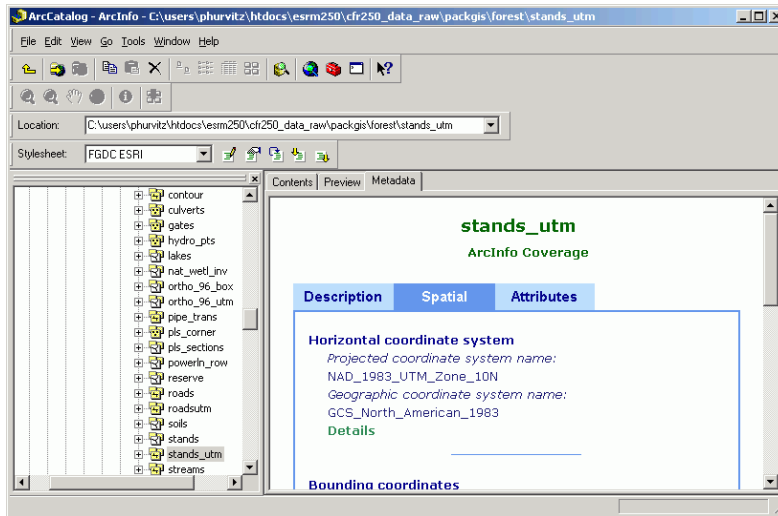
1. Different datasets stored in different projections.

1. If projection is defined for each file. You can tell this is the case because each dataset will show its projection in ArcCatalog (Metadata > Spatial). There will be a description for **Horizontal coordinate system**. In this case, ArcMap should have no problem displaying these datasets at the same time. If ArcMap can read the projection parameters for both datasets, it will project one of them “on the fly” for display purposes. Here is an ArcInfo coverage stored in State Plane:

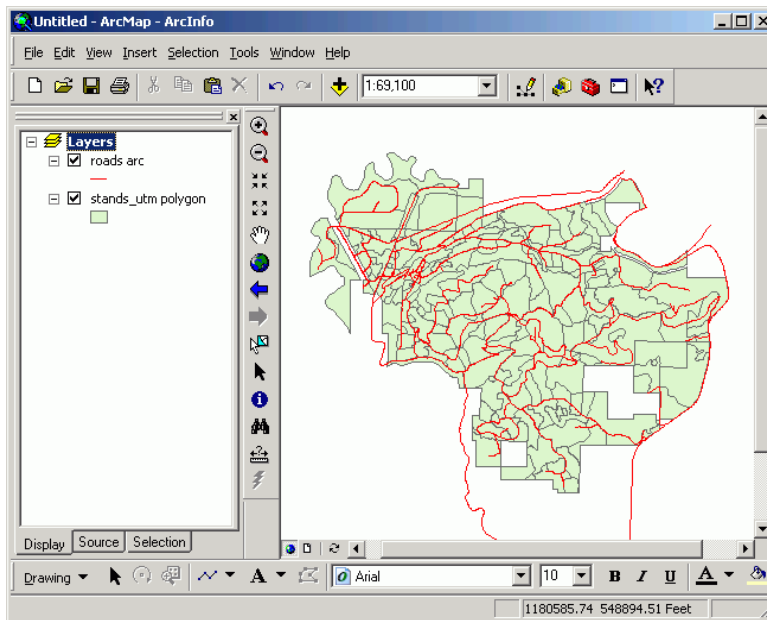


2. And a coverage stored in UTM:

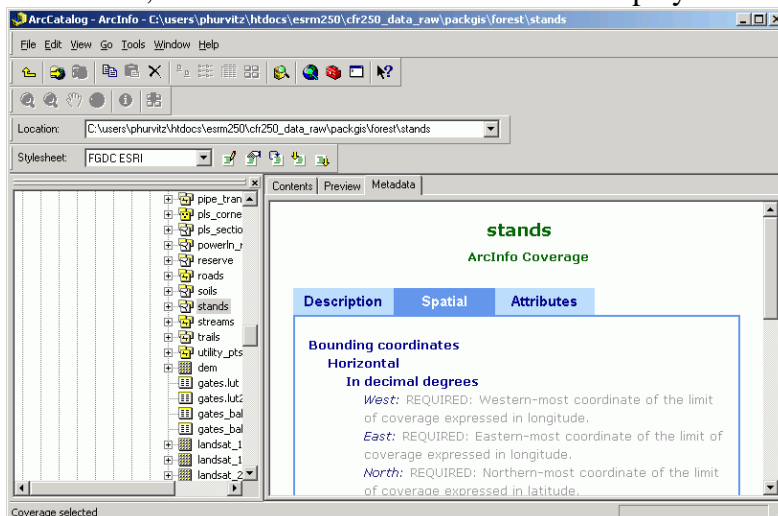
3.

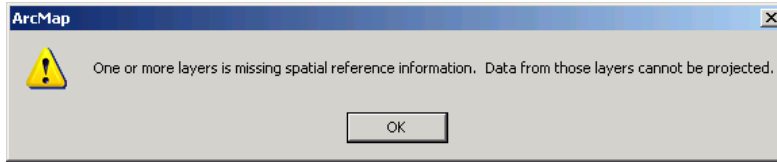


Both displayed at the same time:

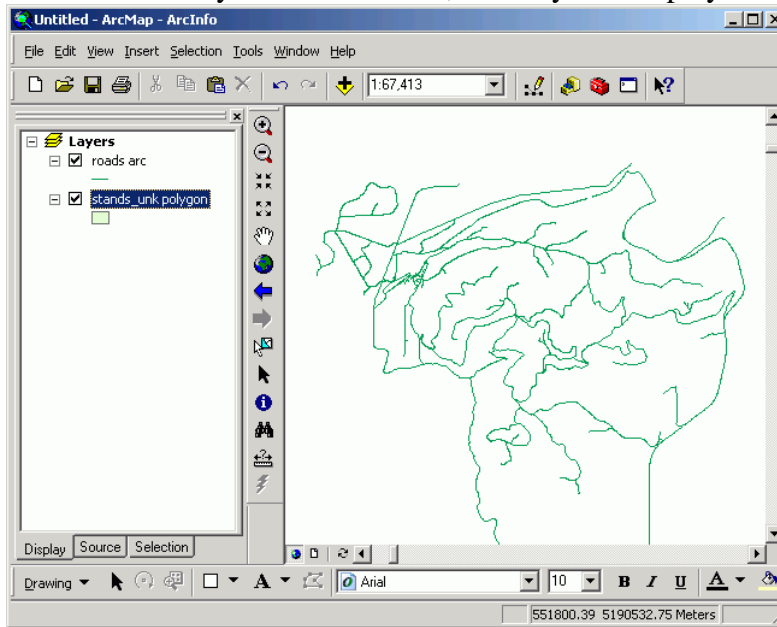


4. If projection is undefined for one or more of the files. You can tell this from ArcCatalog as well. If there is no projection defined, there will be no description for **Horizontal coordinate system**. In this case, the datasets will not be able to be displayed simultaneously.





Note that both layers are turned on, but only one displays.



2. *Different datasets stored in the same projection.*

1. If datasets share the same projection, they will display simultaneously if the projection is defined.
2. If datasets share the same projection, they will display simultaneously even the projection is undefined for one or more of the datasets.

ArcGIS will always attempt to project the view of data on the fly. A data frame's properties can be changed to match any supported projection/coordinate system. In this case, new datasets are not created, but only the view is changed. You can think of this as putting on different pairs of glasses, each one of which is a different projection. When you "view" unprojected or State Plane data with the UTM "glasses," your data will appear to be projected to UTM. If you view unprojected or UTM data with the State Plane "glasses," your data will appear to be projected to State Plane. However, you have not actually changed the data in any way, you have only changed the way you are looking at the data. When unprojected data are displayed in a view, they are by default shown in a display that appears similar to the **Plate Carée** projection.

If you are only displaying data together, it is fine to mix datasets that are stored with different projection parameters. However, if you are doing any analytical work, it is always suggested to make sure your datasets are **stored** in the same projection.

Also, it is always recommended to make sure your datasets have projections defined. That way, if there is any confusion, either for the developer or another user, one can always view the projection information.

A number of these situations will be covered in lab.

How projections work on a programmatic level

Each different projection is a mathematical function that takes coordinate pairs as inputs [(x, y)], and generates new coordinate pairs as output [f(x, y)], as shown in the generic function below. The projection function is symbolized by *f*.

$$(X, Y) \xrightarrow{f} f(X, Y)$$

input	output
angles	Cartesian coordinates
State Plane	UTM
Miller Cylindrical	Lambert Azimuthal

Here is an example of how a projection changes a set of coordinates. The original longitude/latitude coordinate is somewhere within Seattle.

Projection, zone, datum (units)	X	Y
geographic, NAD27 (decimal degrees)	-122.35°	47.62°
UTM, Zone 10, NAD27 (meters)	548843.5049	5274052.0957
State Plane, WA-N, NAD83 (feet)	1266092.5471	229783.3093

Each of the projections in this example (UTM, State Plane), are governed by a different set of projection functions, and therefore result in different output values from the same input value.

If you consider the vector data model, every point has a coordinate; every line's nodes and vertices have coordinates; and every polygon's outlines have coordinates. Projection of a dataset from one system to another is simply the process of applying the projection function to each coordinate in the dataset. The larger and more complex a dataset, the longer it will take to perform the projection.

You should be aware of a key difference between projecting a dataset and simply applying a projection to a data frame. In the former case, each pair of input coordinates has a new output coordinate location calculated. In the latter case, some generalization of data is used in order to speed display. When accurate and precise measurements are needed, always project the datasets themselves, rather than just projecting the data frame.