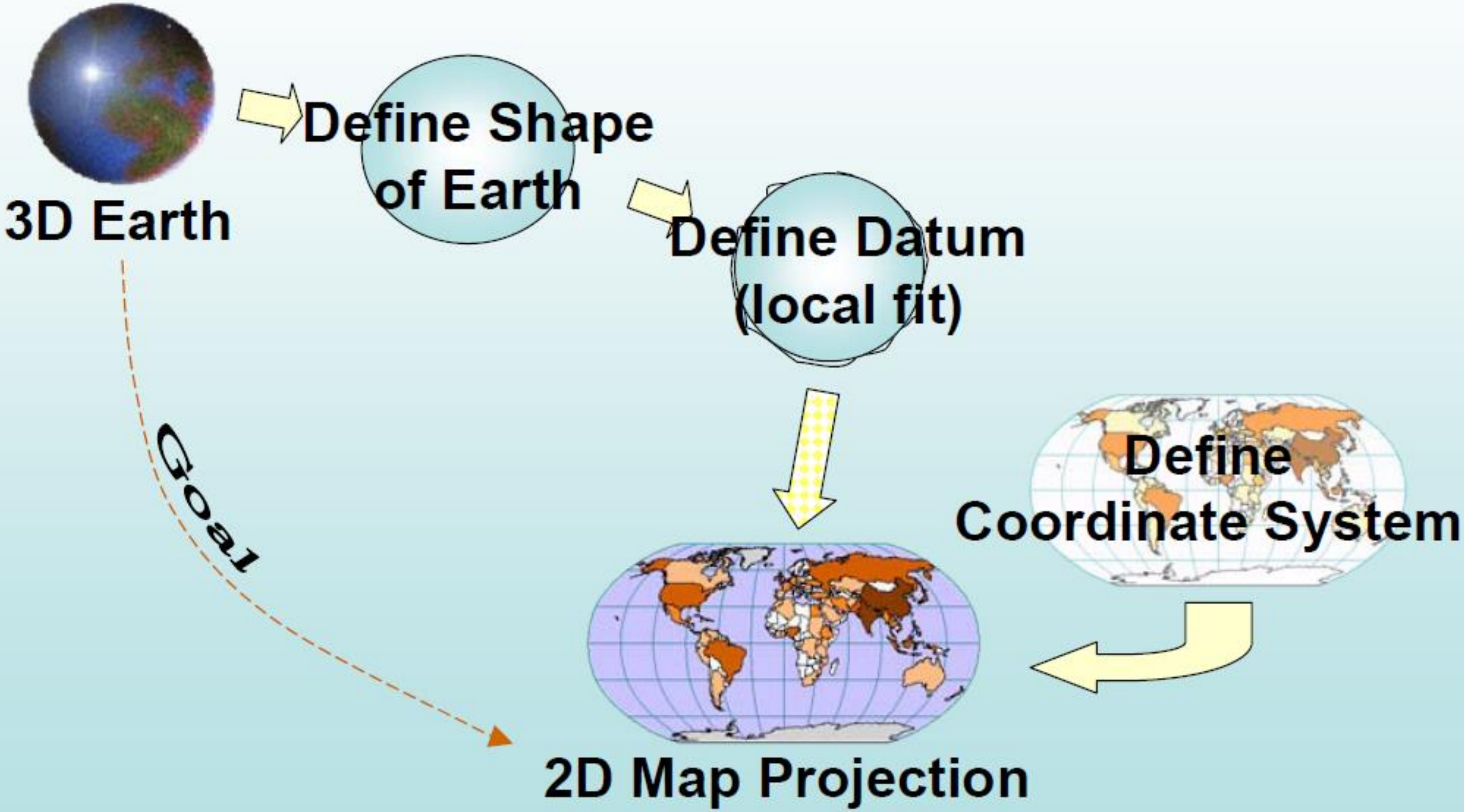
Map Projections

Introduction

Map Projection

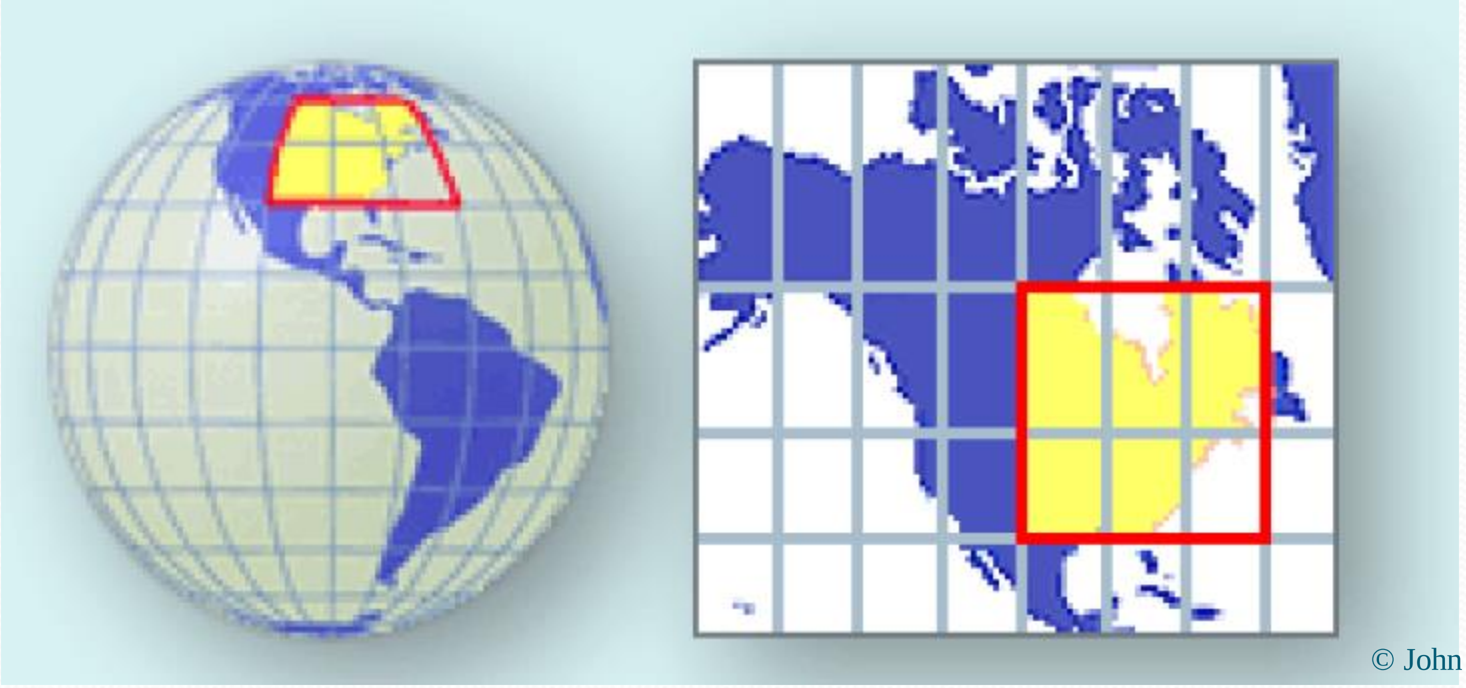


Slide courtesy of Leslie Morrissey

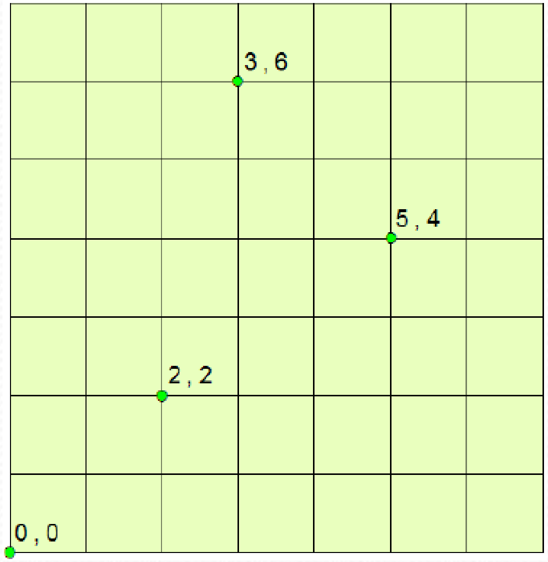
Terminology

- **Projection (Map Projection)** – A method by which the curved surface of the earth is portrayed on a flat surface.

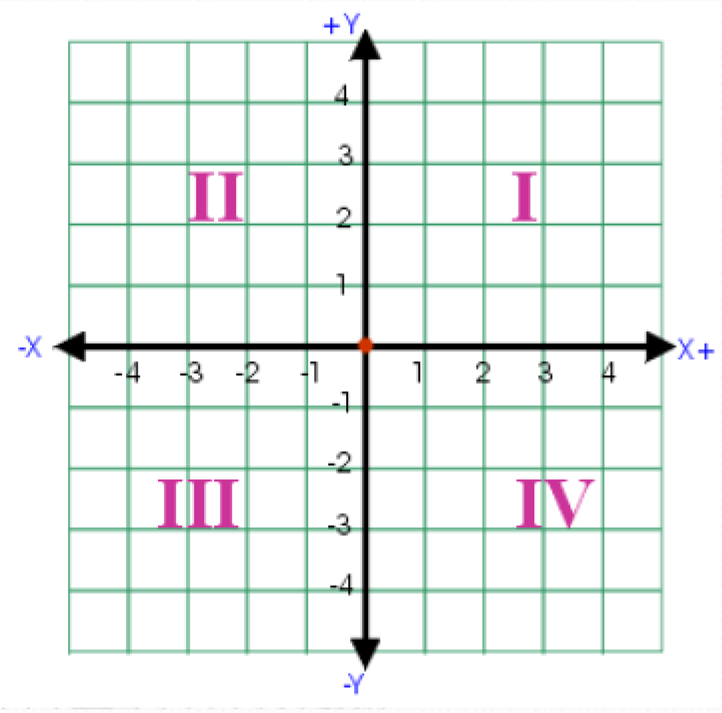
This requires a systematic mathematical transformation of the earth's graticule of lines of longitude and latitude onto a plane.



- **Coordinate System** – A reference framework consisting of a set of points, Lines and/or surfaces, and a set of rules, used to define the positions of points in space in either two or three dimensions.
- **Planar Coordinate System** – A two-dimensional measurement system that locates features on a plane based on their distance from an origin (0,0) long two perpendicular axes.



- **Cartesian Coordinate System** – A two-dimensional, planar coordinate system in which horizontal distance is measured along an x-axis and vertical distance is measured along a y-axis. Each point on the plane is defined by an x,y coordinate. Relative measures of distance, area, and direction are constant.

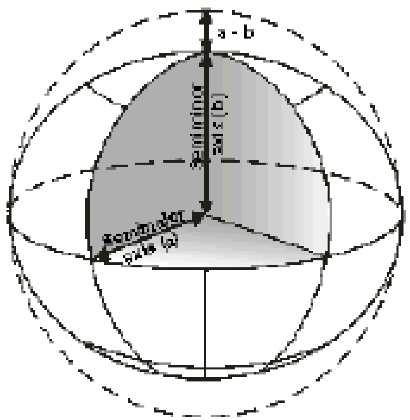


Terminology

Ellipsoid/Spheriod – A three-dimensional, closed geometric shape, all planar sections of which are ellipses or circles.

A three-dimensional shape obtained by rotating an ellipse about its minor axis, with dimensions that either approximate the earth as a whole, or with a part that approximates the corresponding portion of the geoid.

A mathematical figure that approximates the shape of the Earth in form and size, and which is used as a reference surface for geodetic surveys. Used interchangeably with Spheriod. (From Nationalatlas.gov)



Ellipsoid	a (m)	b (m)	*1/f
Airy	6,377,563.396	6,356,256.910	
Australian national	6,378,160		298.25
Bessel	6,377,397.155		299.1528128
Clarke 1866	6,378,206.4	6,356,583.8	
Clarke 1880	6,378,249.145		293.465
Everest	6,377,276.345		300.8017
Hough	6,378,270		297
International	6,378,388		297
Modified Airy	6,377,340.189		
Modified Everest	6,377,304.063		300.8017
South American 1969	6,378,160		298.25
WGS 72	6,378,135		298.26

*Flattening is the ratio of the difference between the semimajor axis and the semiminor axis of the spheroid and its major axis $\frac{(a-b)}{a}$ and may be stated by the numerical value of the reciprocal of the flattening (1/f).

- Common ellipsoids used now are Clarke 1866, the Geodetic Reference System of 1980(GRS80) and more recently the WGS84 ellipsoid.
- …And then there's the Geoid

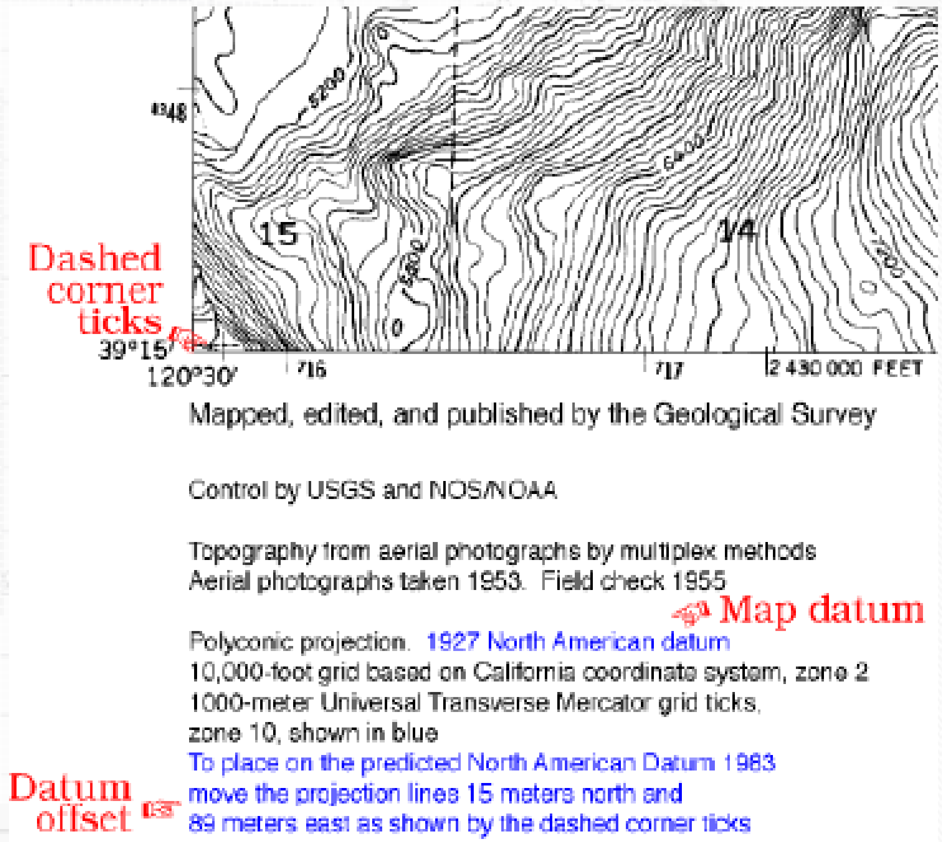
  This is a hypothetical figure of the earth that represents the surface as being at mean sea level, but still influenced by gravitational pull, density of earth's materials, and hydrostatic forces.

Terminology

Datum – The reference specifications of a measurement system, usually a system of coordinate positions on a surface (a horizontal datum) or heights above or below a surface (a vertical datum).

Geodetic Datum – A datum that is the basis for calculating positions on the earth's surface or heights above or below the earth's surface.

Datums are based on specific Ellipsoids and sometimes have the same name as the ellipsoid.



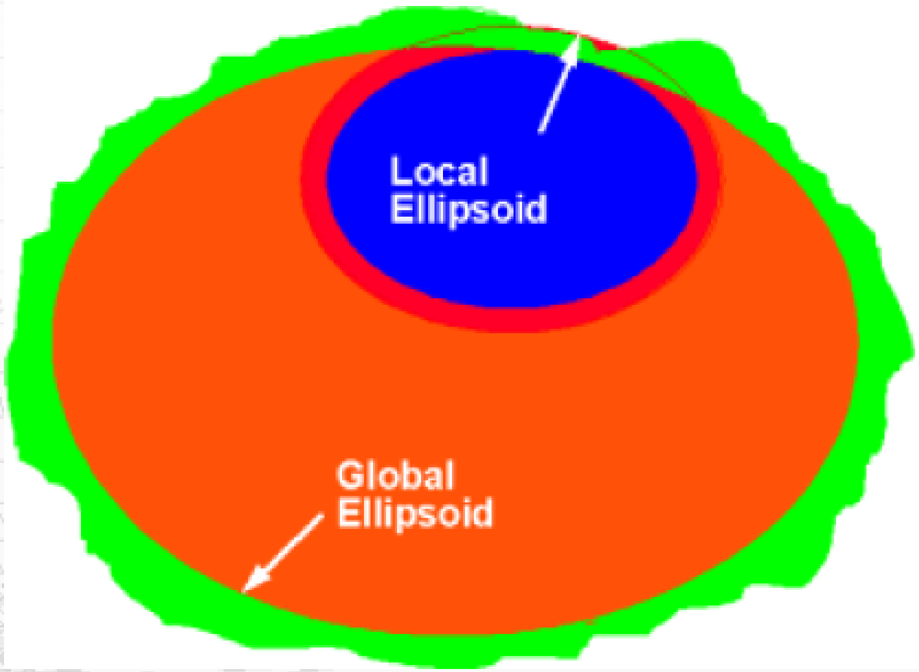
Terminology

Geocentric Datum – A horizontal geodetic datum based on an ellipsoid that has its origin at the earth's center of mass.

Examples are the World Geodetic System of 1984, the North American Datum of 1983, and the Geodetic Datum of Australia of 1994. The first uses the WGS84 ellipsoid; the latter two use the GRS80 ellipsoid.

Geocentric datums are more compatible with GPS.

Local Datum – A horizontal Geodetic datum based on an ellipsoid that has its origin on the surface of the earth, such as the North American Datum of 1927.



Terminology

Transformation – The process of converting the coordinates of a map or an image from one system to another, typically by shifting, rotating, scaling, skewing, or projecting them.

Geographic Transformation – A systematic conversion of the latitude-longitude values for a set of points from one geographic coordinate system to equivalent values in another geographic coordinate system.

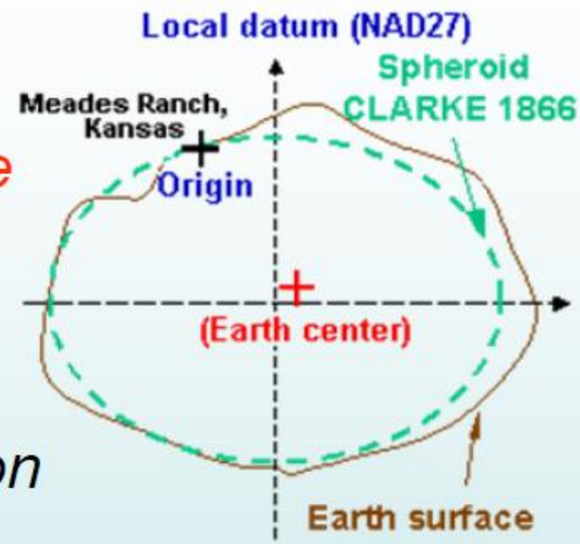
Sometimes called the "**Datum Shift**"

$$\Delta\phi'' = [-\Delta X \sin\phi \cos\lambda - \Delta Y \sin\phi \sin\lambda + \Delta Z \cos\phi + (a\Delta f + f\Delta a)\sin 2\phi]/[R_M \sin 1'']$$

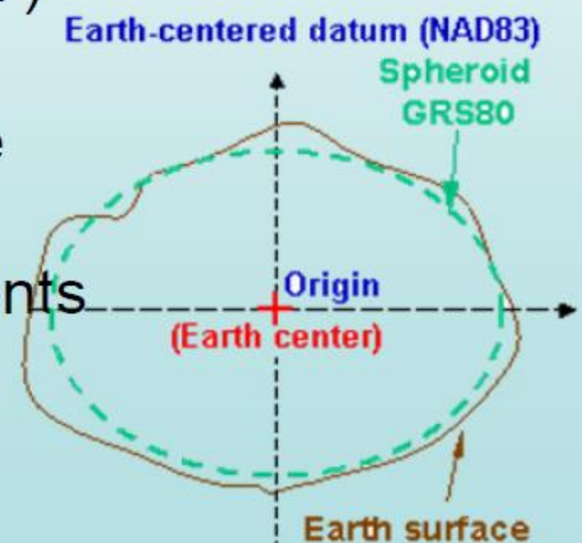
$$\Delta\lambda'' = [-\Delta X \sin\lambda + \Delta Y \cos\lambda]/[R_N \cos\phi \sin 1'']$$

$$\Delta H = \Delta X \cos\phi \cos\lambda + \Delta Y \cos\phi \sin\lambda + \Delta Z \sin\phi + (a\Delta f + f\Delta a)\sin^2\phi - \Delta a$$

- **Datum**
  - *a set of control points used to define 3D Earth locations on a sphere, ellipsoid, or geoid*
  - *best local fit* for a region
  - *each datum favors a particular region*



- North American Datum of 1927 (**NAD27**) used Clarke 1866 ellipsoid
- **NAD83** based on Geodetic Reference System 1980 (GRS80) ellipsoid
  - developed from satellite measurements
  - North American Datum 1983
  - *NAD83 is more accurate!*



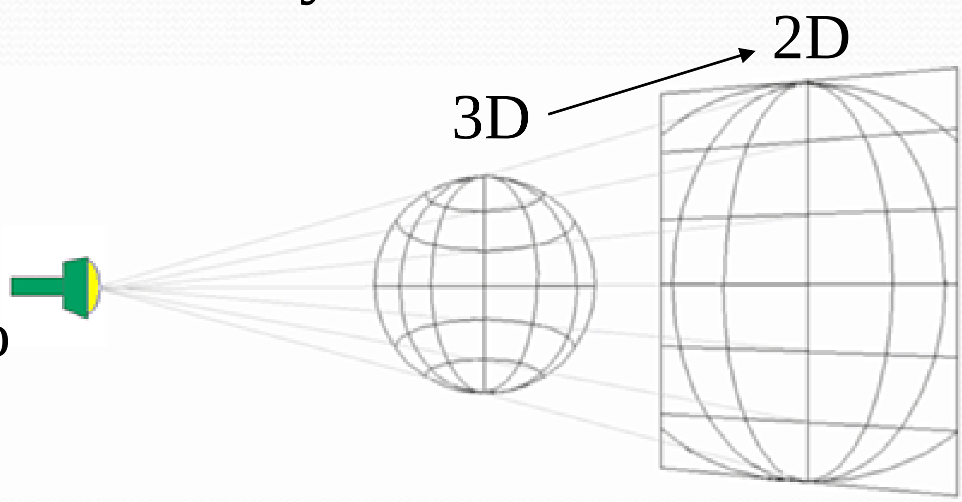
- *GPS data are based on WGS84 (geoid)*

Slide courtesy of Leslie Morrissey

Map Projection

- This is the method by which we transform the earth's spheroid (real world) to a flat surface (abstraction), either on paper or digitally
- Because we can't take our globe everywhere with us!
- Remember: most GIS layers are 2-D

Think about projecting a see-through globe onto a wall

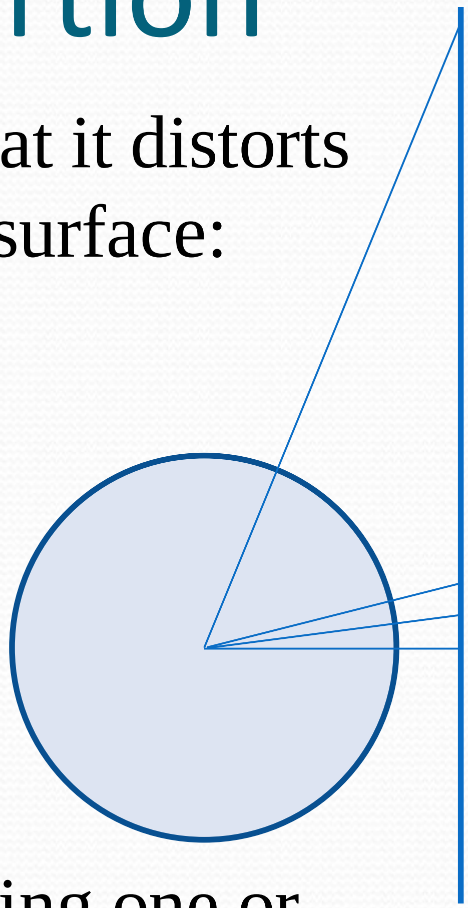


Developable surface, a.k.a. *Projection surface*

Source: ESRI

Map Projection-distortion

- The problem with map projection is that it distorts one or several of these properties of a surface:
  - Shape
  - Area
  - Distance
  - Direction
- Some projections specialize in preserving one or several of these features, but none preserve all



Map Projection-distortion

- **Shape:** projection can distort the shape of a feature. *Conformal* maps preserve the shape of smaller, local geographic features, while general shapes of larger features are distorted. That is, they preserve local angles; angle on map will be same as angle on globe. Conformal maps also preserve constant scale locally

Map Projection-distortion

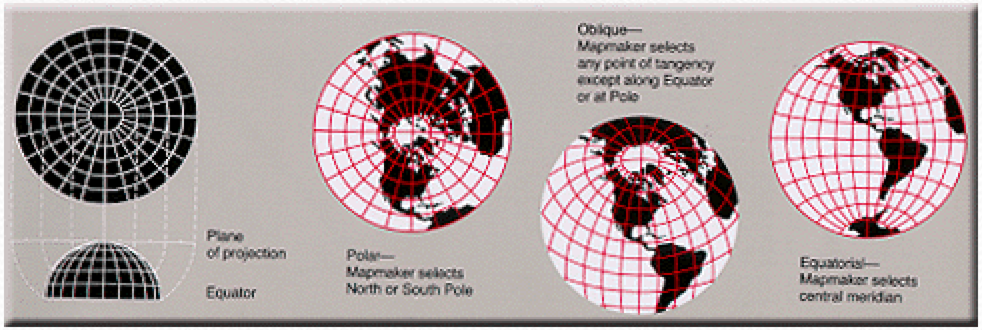
- **Area:** projection can distort *area*, meaning that features do not have the correct area relative to one another. Map projections that maintain this property are often called *equal area map projections*.
- For instance, if S America is 8x larger than Greenland on the globe, it will be 8x larger on map
- <u>No map projection can be conformal and equal area</u>; sacrifice shape to preserve area and vice versa.

Map Projection-distortion

- **Distance**: Projection can distort measures of true distance. Accurate distance is maintained for only certain parallels or meridians unless the map is very localized. Maps are said to be *equidistant* if distance from the map projection's center to all points is accurate.

Map Projection-distortion

- **Direction:** Projection can distort true directions (angle or *azimuth*) between locations; *azimuthal* projections maintain true direction with respect to the center point. Some azimuthal map projections maintain direction between any two points, so that the angle of a line drawn between any two locations on the projection gives the correct direction with respect to true north.



Map Projection-distortion

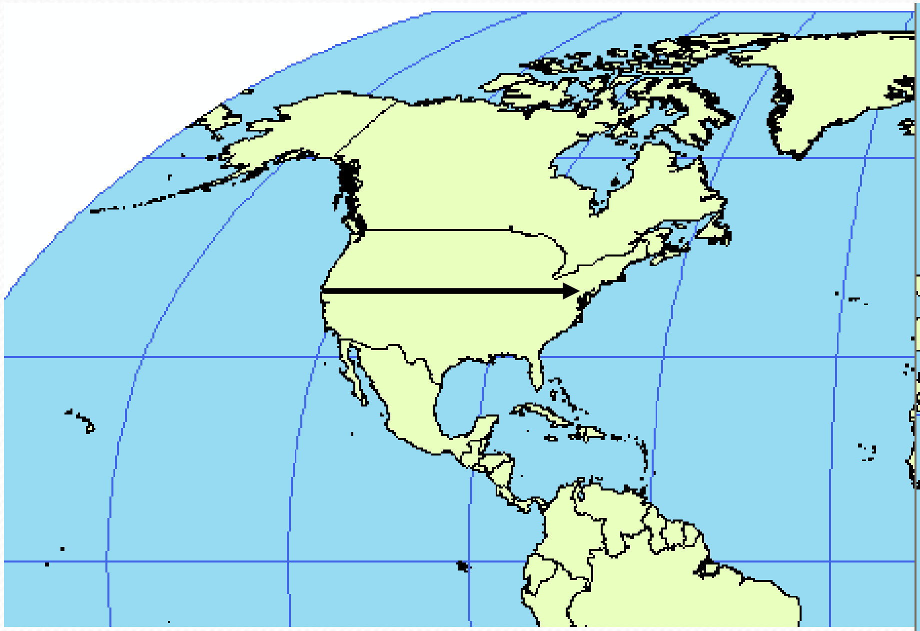
- Hence, when choosing a projection, one must take into account what it is that matters in your analysis and what properties you need to preserve
- Conformal and equal area properties are mutually exclusive but some map projections can have more than one preserved property. For instance a map can be conformal and azimuthal
- Conformal and equal area properties are **global** (apply to whole map) while equidistant and azimuthal properties are **local** and may be true only from or to the center of map

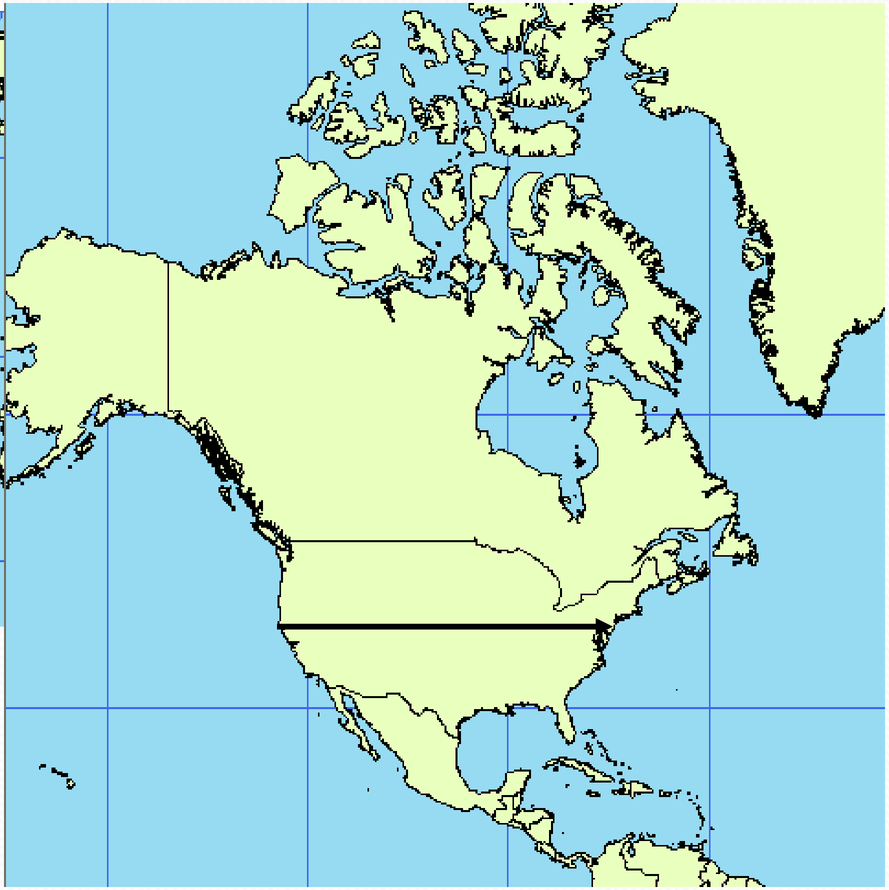
Area Distortion

Mercator Projection

- 827,000 square miles
- 6.8 million square miles

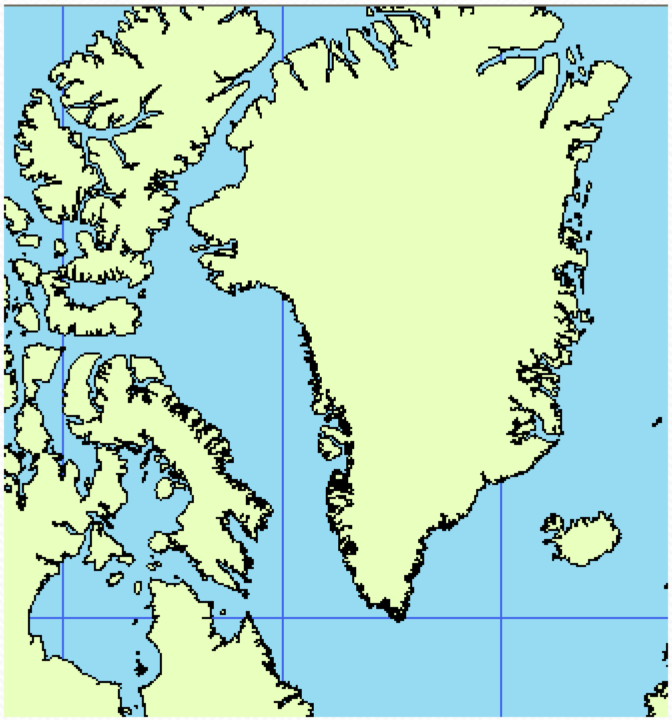
Distance distortion





- 4,300 km: Robinson
- 5,400 km: Mercator

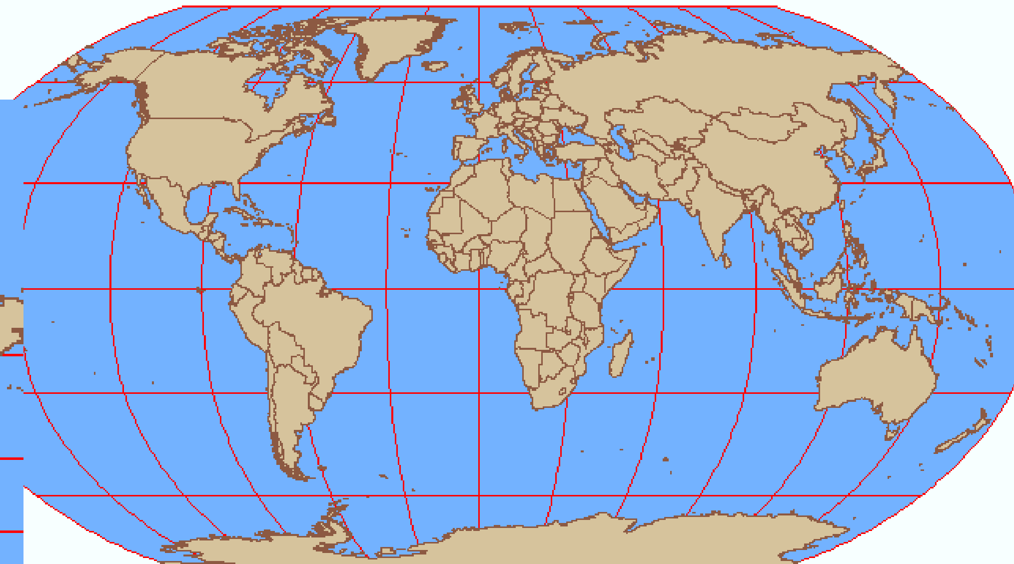
Shape distortion



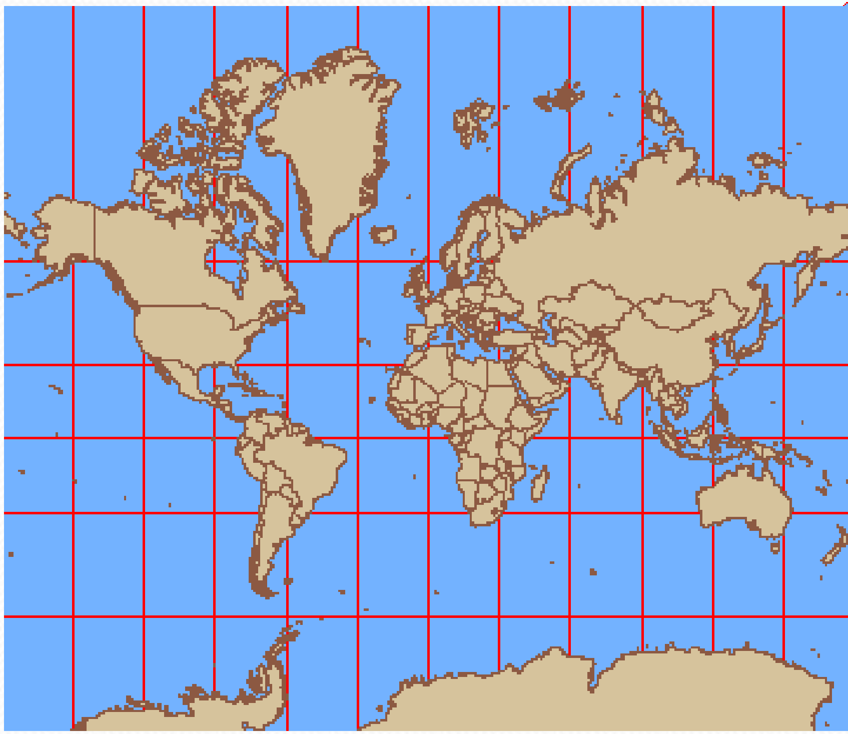
- Mercator (left)
- World Cylindrical Equal Area (above)
- The distortion in shape above is necessary to get Greenland to have the correct area
- The Mercator map looks good but Greenland is many times too big

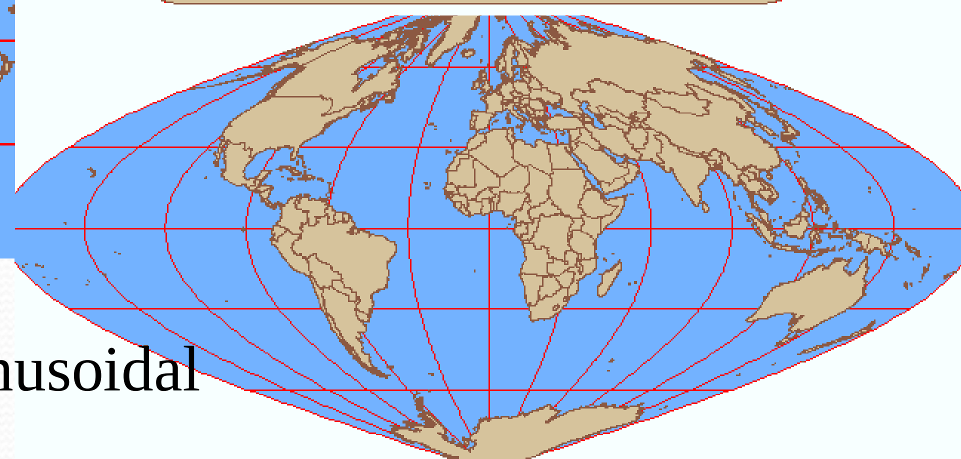
Some Examples of distortion

Robinson



Mercator—goes on forever

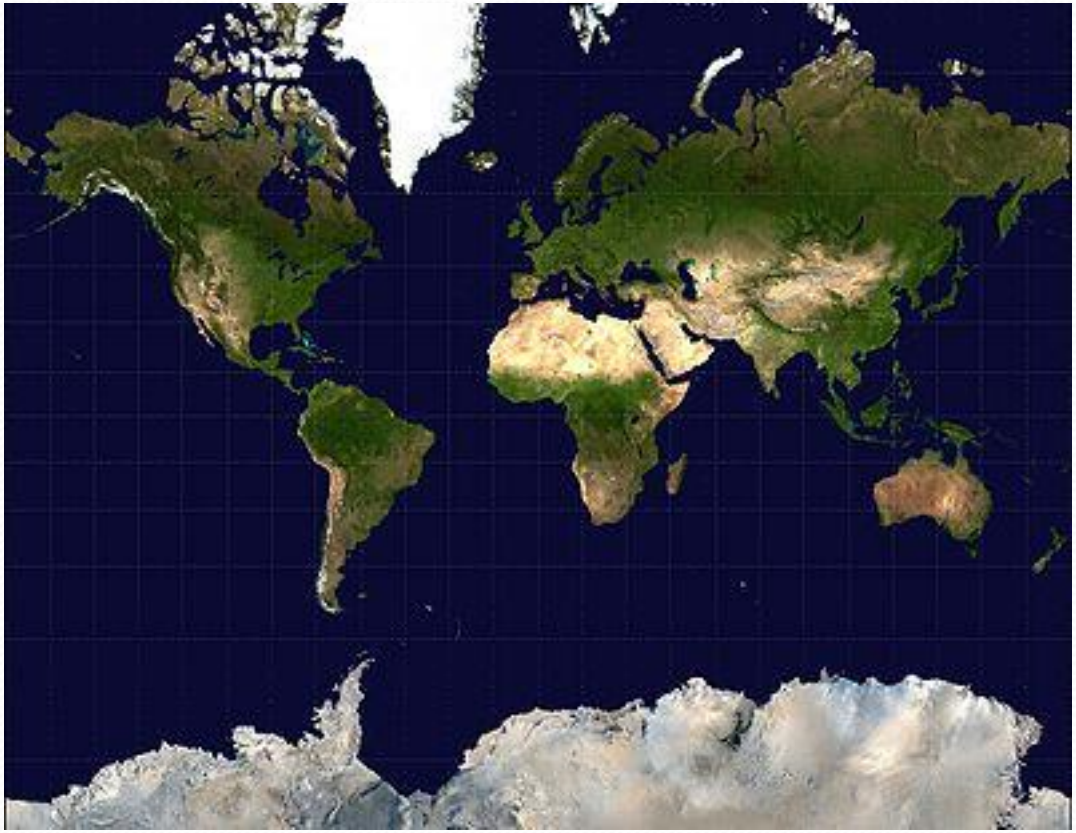




sinusoidal

Some examples of distortion

- Mercator maintains shape and direction, but sacrifices area



Some examples of distortion

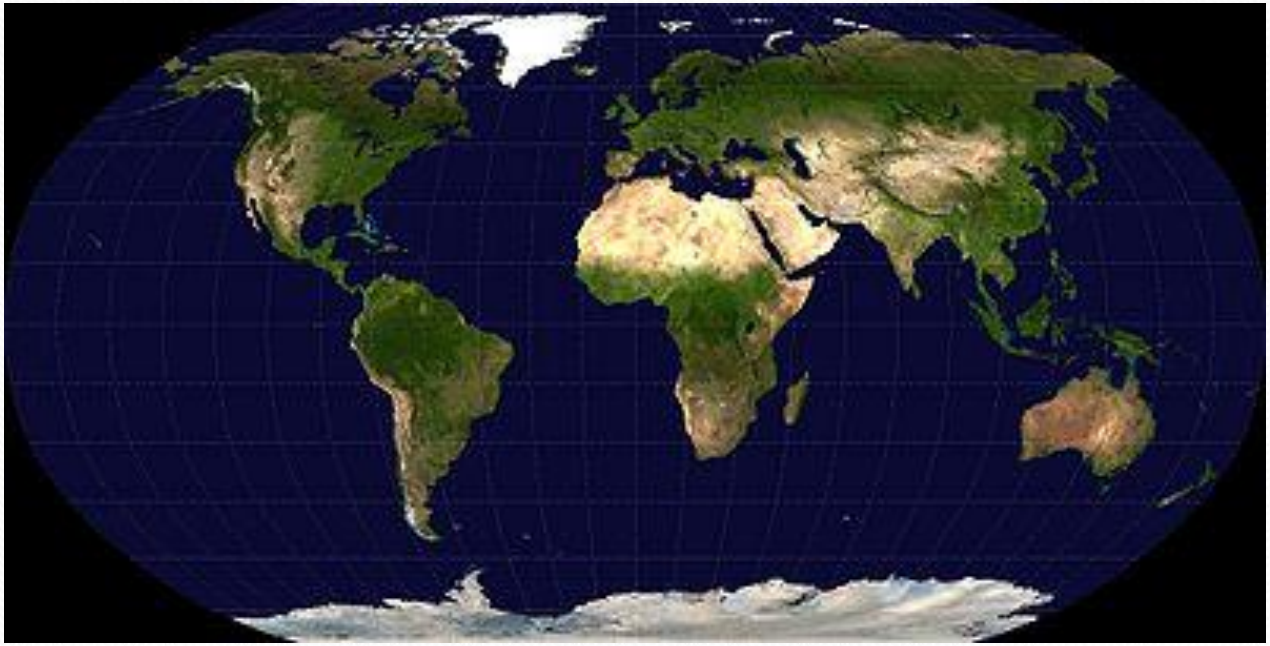
- The Sinusoidal and Equal-Area Cylindrical projections both maintain **area**, but look quite different from each other. The latter distorts shape

Lambert Equal-area Cylindrical

Sinusoidal

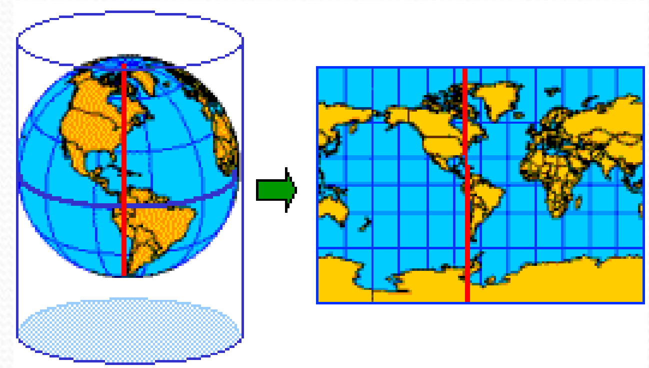
Some examples of distortion

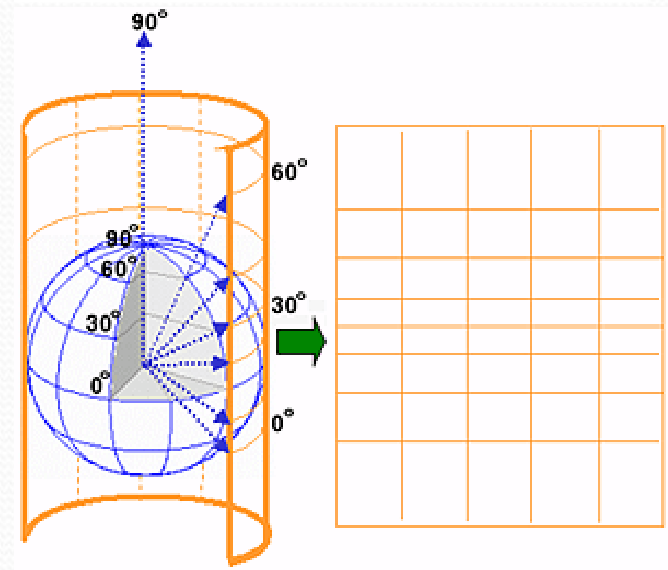
- The Robinson projection does not enforce any specific properties but is widely used because it makes the earth's surface and its features look somewhat accurate



General Map Projection: Cylindrical

- Created by wrapping a cylinder around a globe and, in theory, projecting light out of that globe
- Meridians in cylindrical projections are equally spaced, while the spacing between parallel lines of latitude increases toward the poles
- Meridians never converge so poles can't be shown
- Does not distort local **shape** (*conformal*) or direction



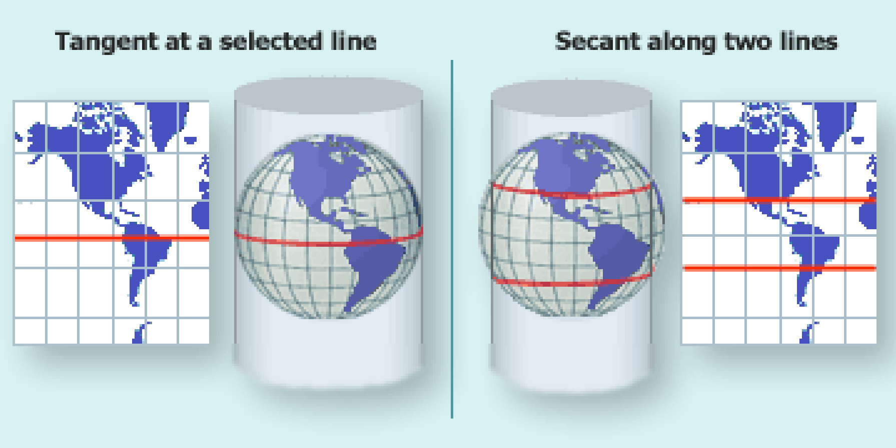


Source: ESRI

Cylindrical Map Types

1. Tangent to great circle: in the simplest case, the cylinder is North-South, so it is tangent (touching) at the equator; this is called the *standard parallel* and represents where the projection is most accurate

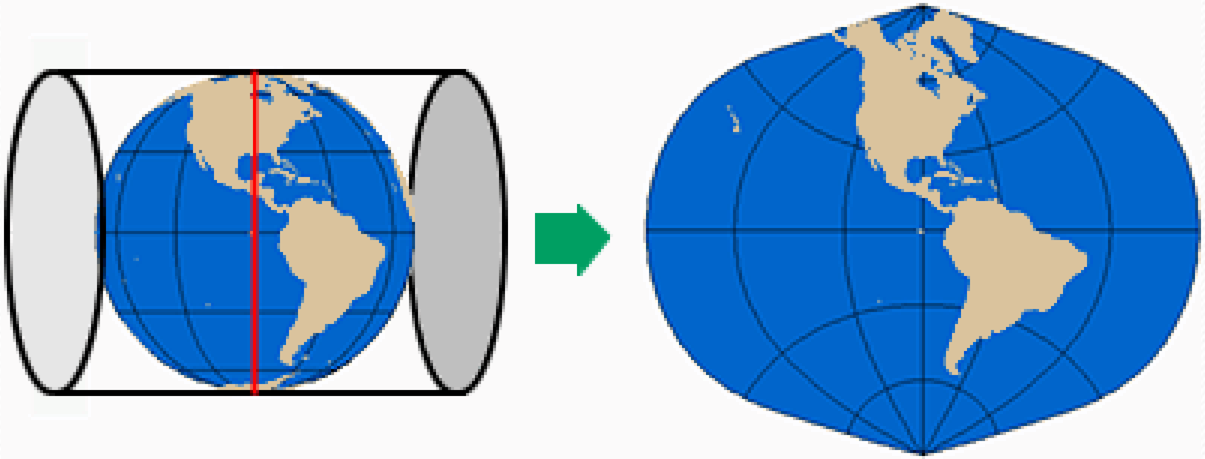
2. If the cylinder is smaller than the circumference of the earth, then it intersects as a *secant* in two places



Source: http://nationalatlas.gov/articles/mapping/a_projections.html

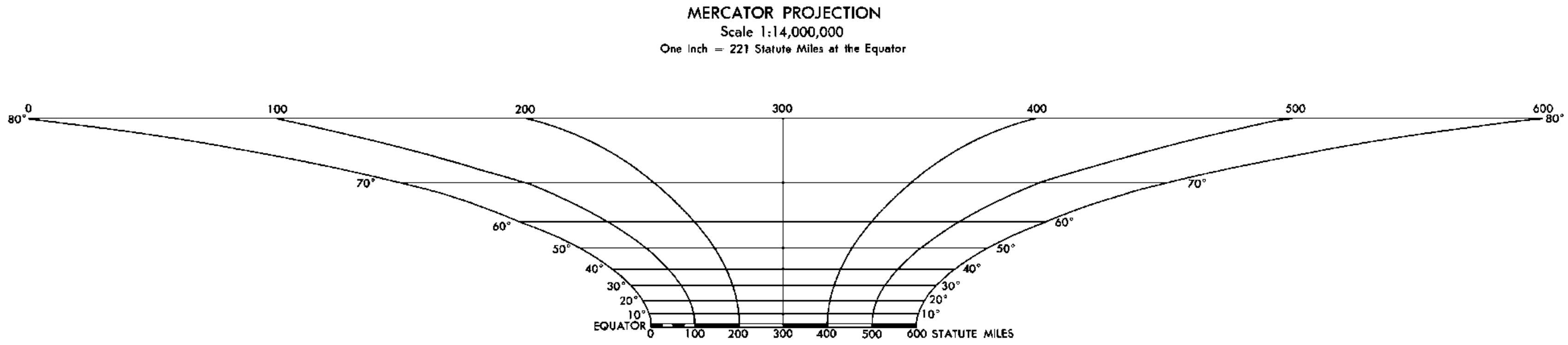
Cylindrical Map Types

3. Transverse cylindrical projections: in this type the cylinder is turned on its side so it touches a line of longitude; these can also be tangent

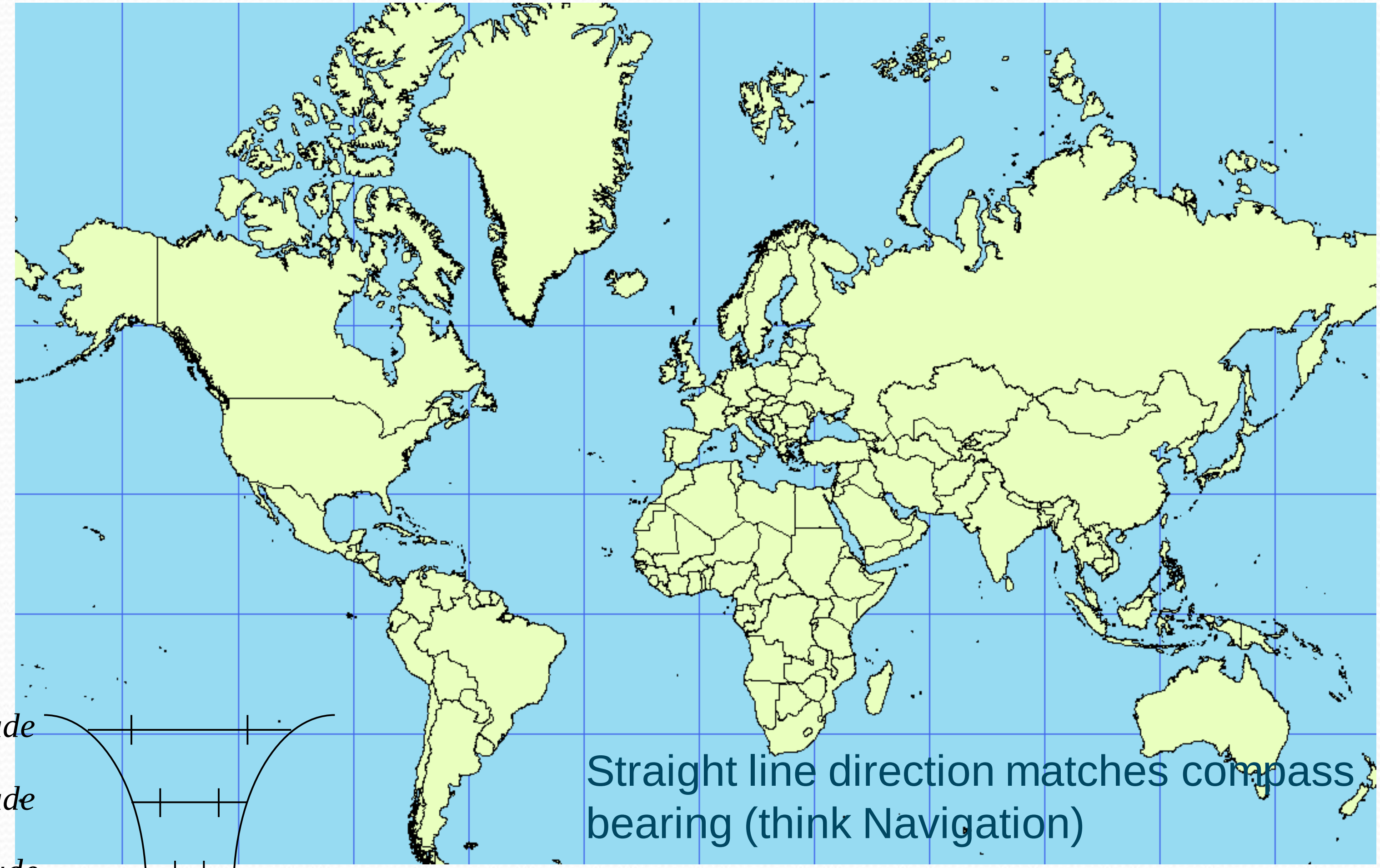


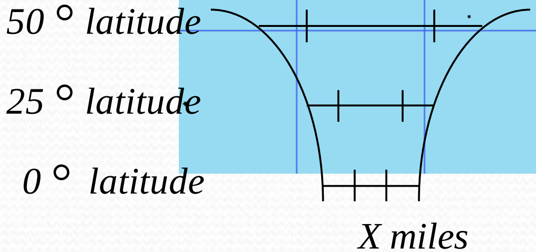
Cylindrical map distortion

- North-south (equatorial) cylindrical projections cause major distortions at higher latitudes because points on the cylinder are further away from the corresponding point on the globe
- East-west distances are true along the equator but not as distance from the equator (latitude) changes
- Requires alternating scale bar based on latitude



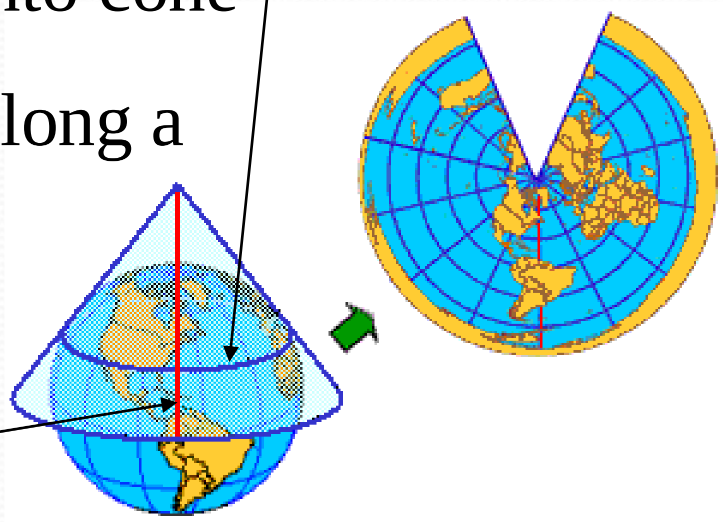
Cylindrical Map Distortion





General Projection Types: Conic

- Projects a globe onto a cone
- In simplest case, globe touches cone along a single latitude line, or tangent, called *standard parallel*
- Other latitude lines are projected onto cone
- To flatten the cone, it must be cut along a line of longitude (see image)
- The opposite line of longitude is called the *central meridian*



Source: ESRI

Map Projection-General Types

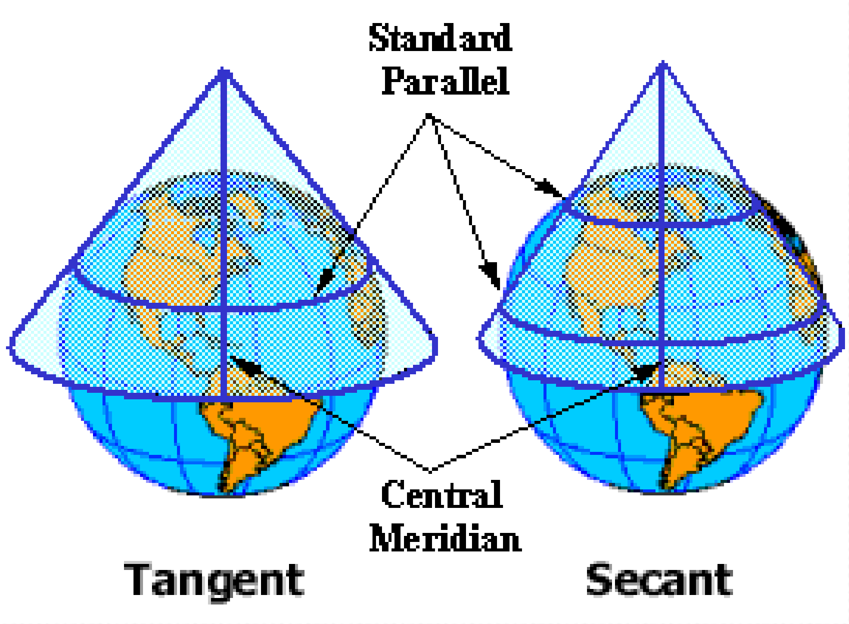
Conic Projections:

- Projection is most accurate where globe and cone meet—at the *standard parallel*
- Distortion generally increases north or south of it, so poles are often not included
- Conic projections are typically used for mid-latitude zones with east-to-west orientation. They are normally applied only to portions of a hemisphere (e.g. North America)

Map Projection-General Types

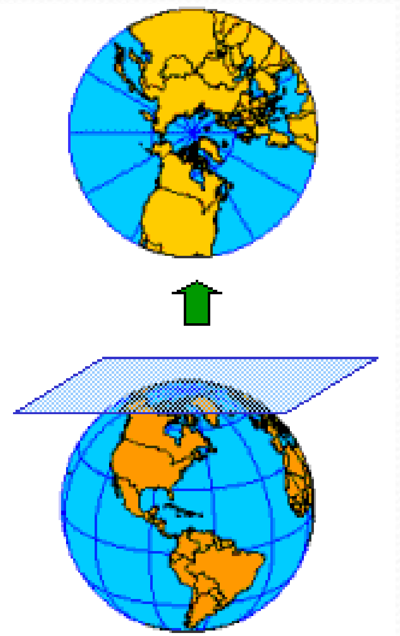
Conic projections:

- Can be tangent or secant
- Secant are more accurate for reasons given earlier



Map Projection-General Types

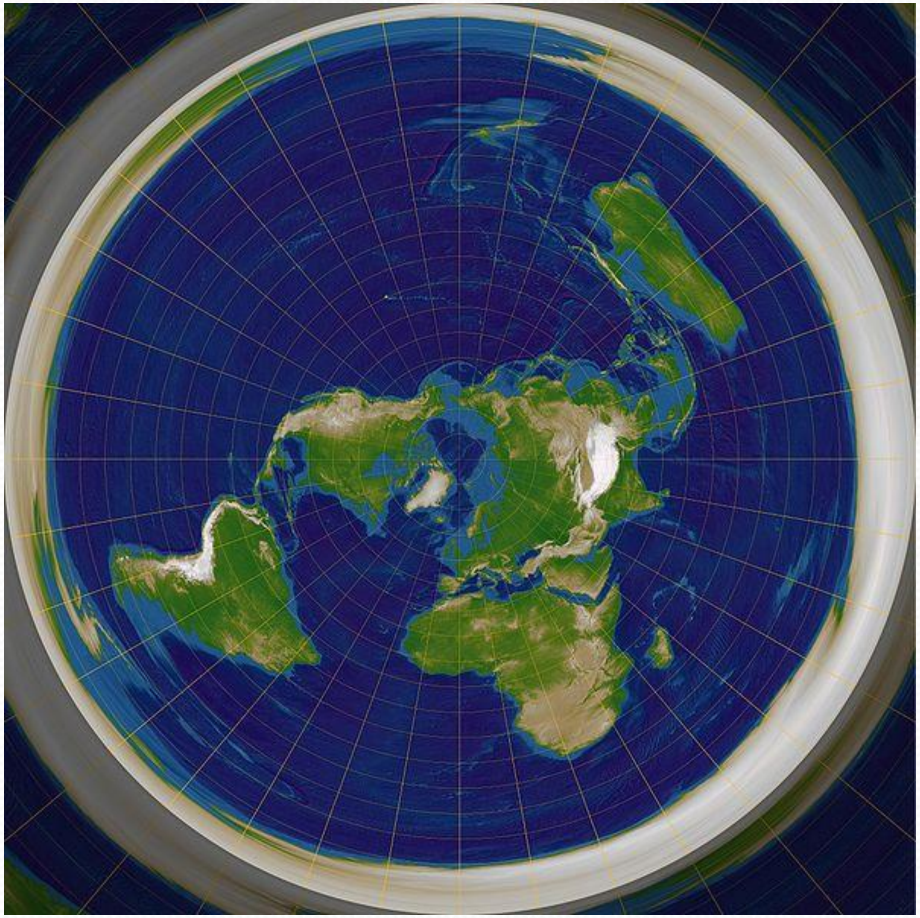
- **Planar** or **Azimuthal Projections:** simply project a globe onto a flat plane
- The simplest form is only tangent at one point
- Any point of contact may be used but the poles are most commonly used
- When another location is used, it is generally to make a small map of a specific area
- When the poles are used, longitude lines look like hub and spokes



Source: ESRI

Map Projection-General Types

- **Planar** or **Azimuthal Projections:**
- Because the area of distortion is circular around the point of contact, they are best for mapping roughly circular regions, and hence the poles



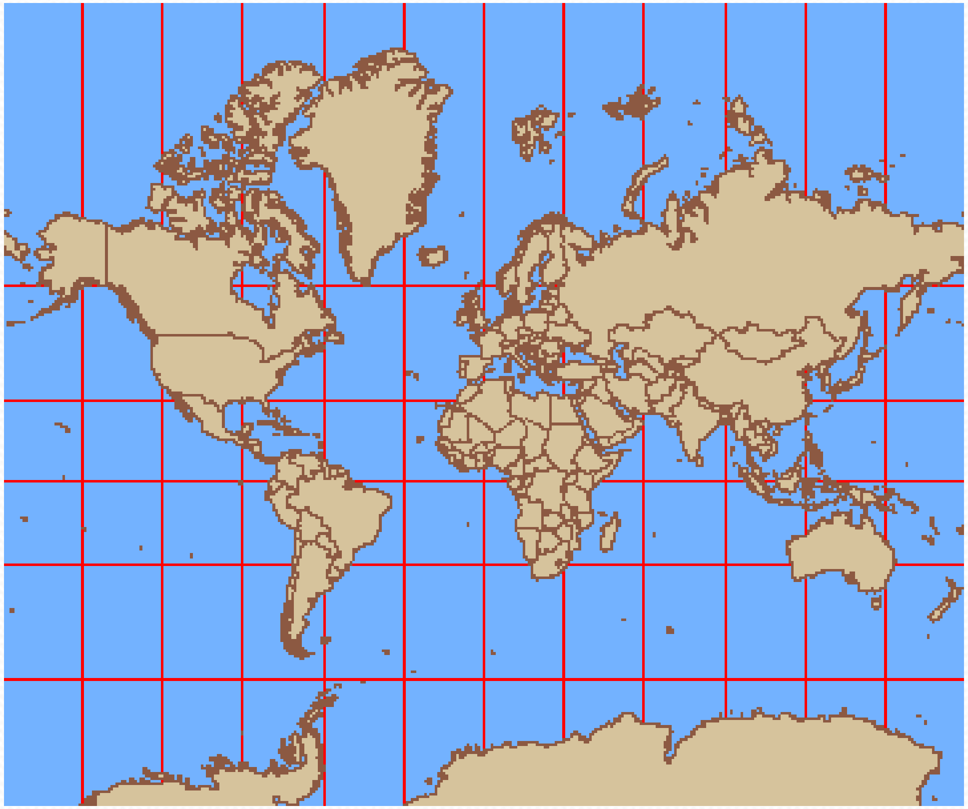
Map Projection-Specific Types

- **Mercator**: This is a specific type of cylindrical projection
- Invented by Gerardus Mercator during the 16th Century
- It was invented for navigation because it **preserves azimuthal accuracy**—that is, if you draw a straight line between two points on a map created with Mercator projection, the angle of that line represents the actual bearing you need to sail to travel between the two points

Source: ESRI

Map Projection-Specific Types

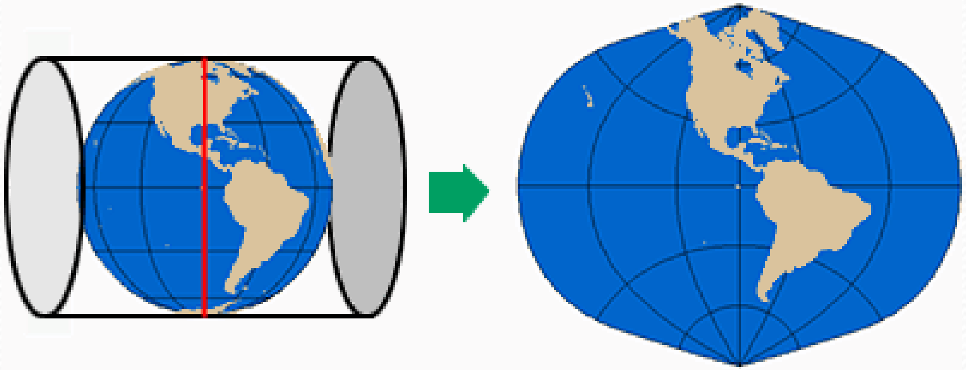
- **Mercator**: Of course the Mercator projection is not so good for preserving area.



Notice how it enlarges high latitude features like Greenland and Antarctica relative to mid-latitude features

Map Projection-Specific Types

- **Transverse Mercator**: Invented by Johann Lambert in 1772, this projection is cylindrical, but the axis of the cylinder is rotated 90°, so the tangent line is longitudinal, rather than equatorial
- In this case, only the central longitudinal meridian and the equator are straight lines



All other lines are represented by complex curves: that is they can't be represented by single section of a circle

Source: ESRI

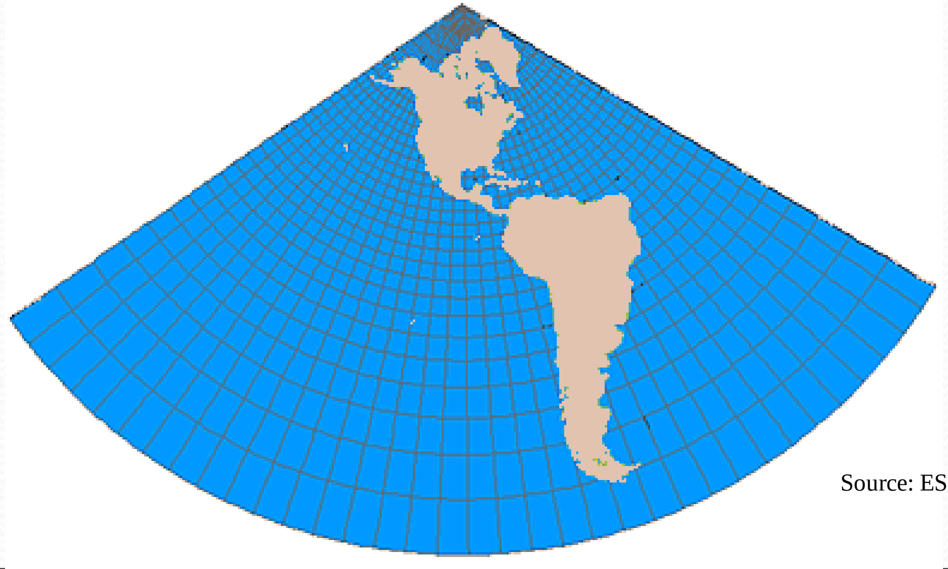
Map Projection-Specific Types

Transverse Mercator:

- Not used on a global scale but applied to regions that have a general north-south orientation, while Mercator tends to be used more for geographic features with east-west axis.
- It is used commonly in the US with the State Plane Coordinate system, for north-south features

Map Projection-Specific Types

- **Lambert Conformal Conic**: invented in 1772, this is a type of conic projection
- Latitude lines are unequally spaced arcs that are portions of concentric circles. Longitude lines are actually radii of the same circles that define the latitude lines.



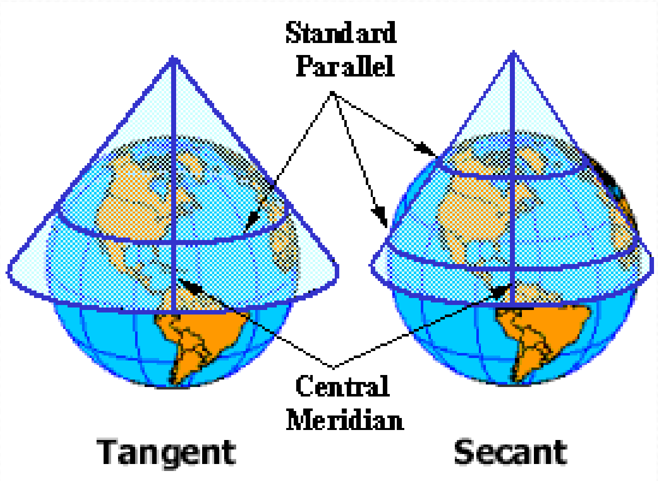
Source: ESRI

Map Projection-Specific Types

- **The Lambert Conformal Conic** projection is very good for middle latitudes with **east-west orientation**.
- It portrays the pole as a point
- It portrays **shape** more accurately than area and is commonly used for North America.
- <u>The State Plane coordinate system uses it for east-west oriented features</u>

Map Projection-Specific Types

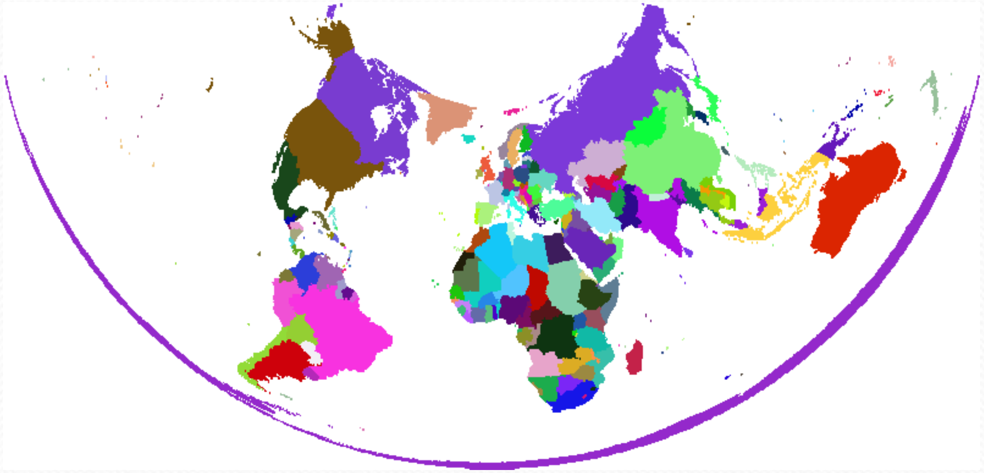
- **The Lambert Conformal Conic** projection is a slightly more complex form of conic projection because it intersects the globe along two lines, called secants, rather than along one, which would be called a tangent
- There is no distortion along those two lines
- Distortion increases with distance from the secants



Source: ESRI

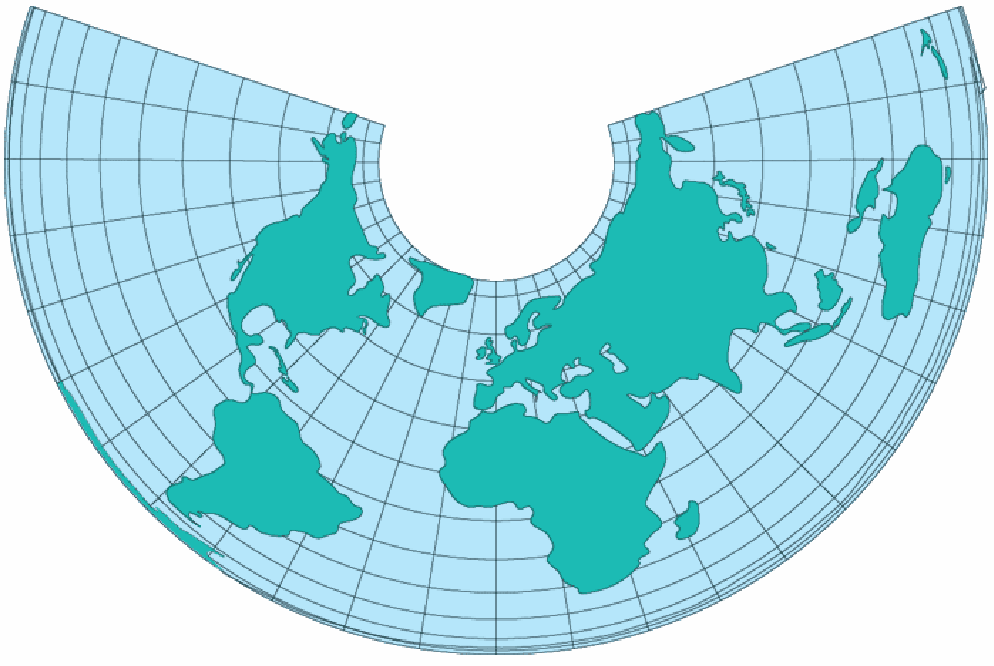
Map Projection-Specific Types

- **Albers Equal Area Conic** projection: Another conic projection (like Lambert)
- Developed by Heinrich Christian Albers in 1805
- What property does it preserve?



Map Projection-Specific Types

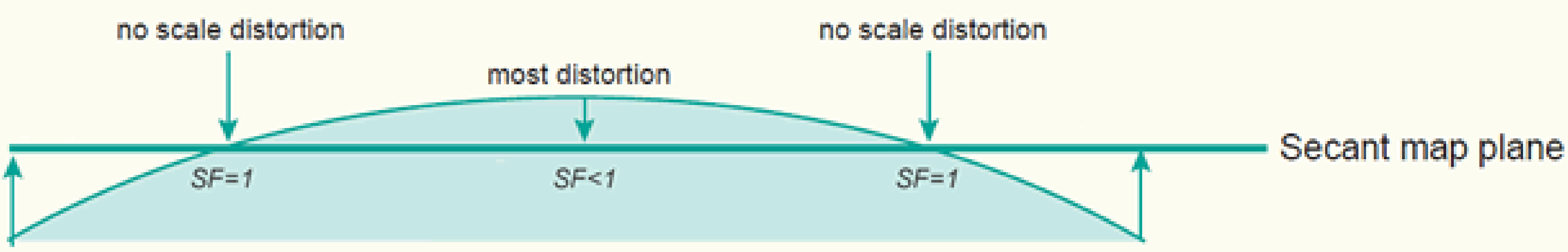
- **Albers Equal Area Conic** preserves **area** while Lambert preserves *shape*
- Albers also differs in that poles are represented as arcs, not as points (meridians don't meet)
- Latitude lines are unequally spaced concentric circles, whose spacing decreases toward the poles.



Map Projection-Specific Types

- **Albers Equal Area Conic:** It preserves area by making the scale factor along meridians the reciprocal of the scale factor along parallels.

- **Scale factor** is the ratio of local scale of a point on the projection to the reference scale of the globe; 1 means the two are touching and values <> 1 means the projection surfaceis at a distance



Plane Coordinate Systems

- Map **projections**, provide the means for viewing small-scale maps, such as maps of the world or a continent or country (1:1,000,000 or smaller)
- Plane **coordinate systems** are typically used for much larger-scale mapping (1:100,000 or bigger)
- Very large scale (local) maps have distortions that are not measurable … effectively non-existent

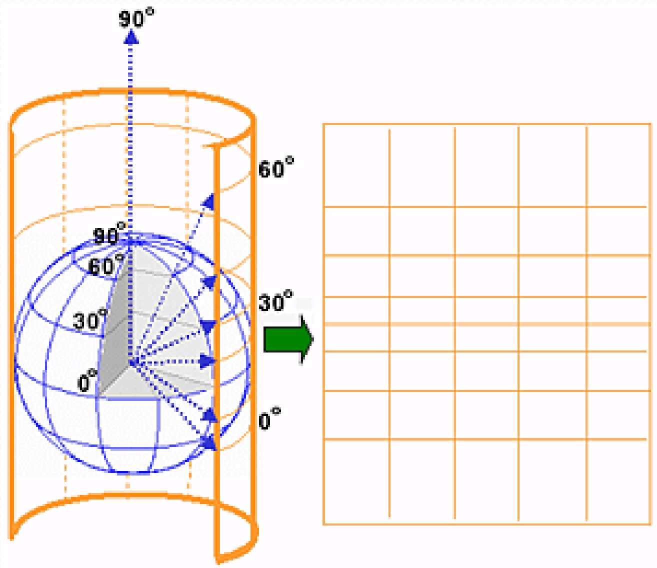
Plane Coordinate Systems

- Projections are designed to **minimize distortions** of the four properties we talked about, because as scale decreases, error increases
- Coordinate systems are more about **accurate positioning** (relative and absolute positioning)
- To maintain their accuracy, coordinate systems are generally divided into **zones** where each zone is based on a separate map projection that is optimized for each zone ⟹ Group of projections!

Reason for PCSs

- Remember that projections are most accurate where the projection surface is close to the earth surface. The further away it gets, the more distorted it gets

- Hence a global or even continental projection is bad for accuracy because it's only touching along one (tangent) or two (secant) lines and gets increasingly distorted



Reason for PCSs

- Plane coordinate systems get around this by breaking the earth up into **zones** where each zone has its own projection center and projection.
- <u>The more zones</u> there are and the smaller each zone, <u>the more accurate</u> the resulting projections
- This serves to minimize the <u>scale factor</u>, or distance between projection surface and earth surface to an acceptable level

Coordinate Systems

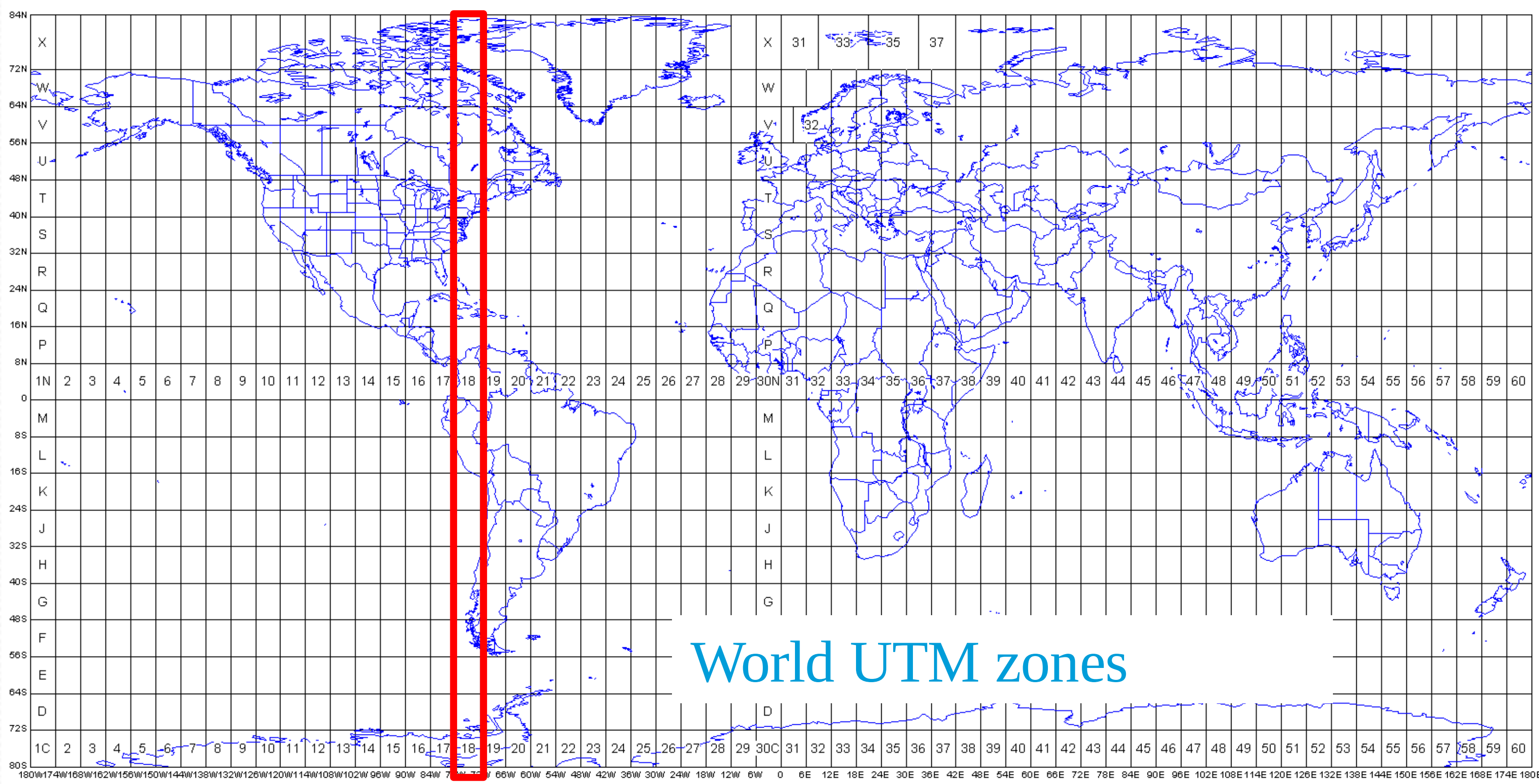
- The four most commonly used coordinate systems in the US:
  - **Universal Transverse Mercator (UTM) grid system**
  - The Universal Polar Stereographic (UPS) grid system
  - **State Plane Coordinate System (SPC)**
  - And the Public Land Survey System (PLSS)

UTM

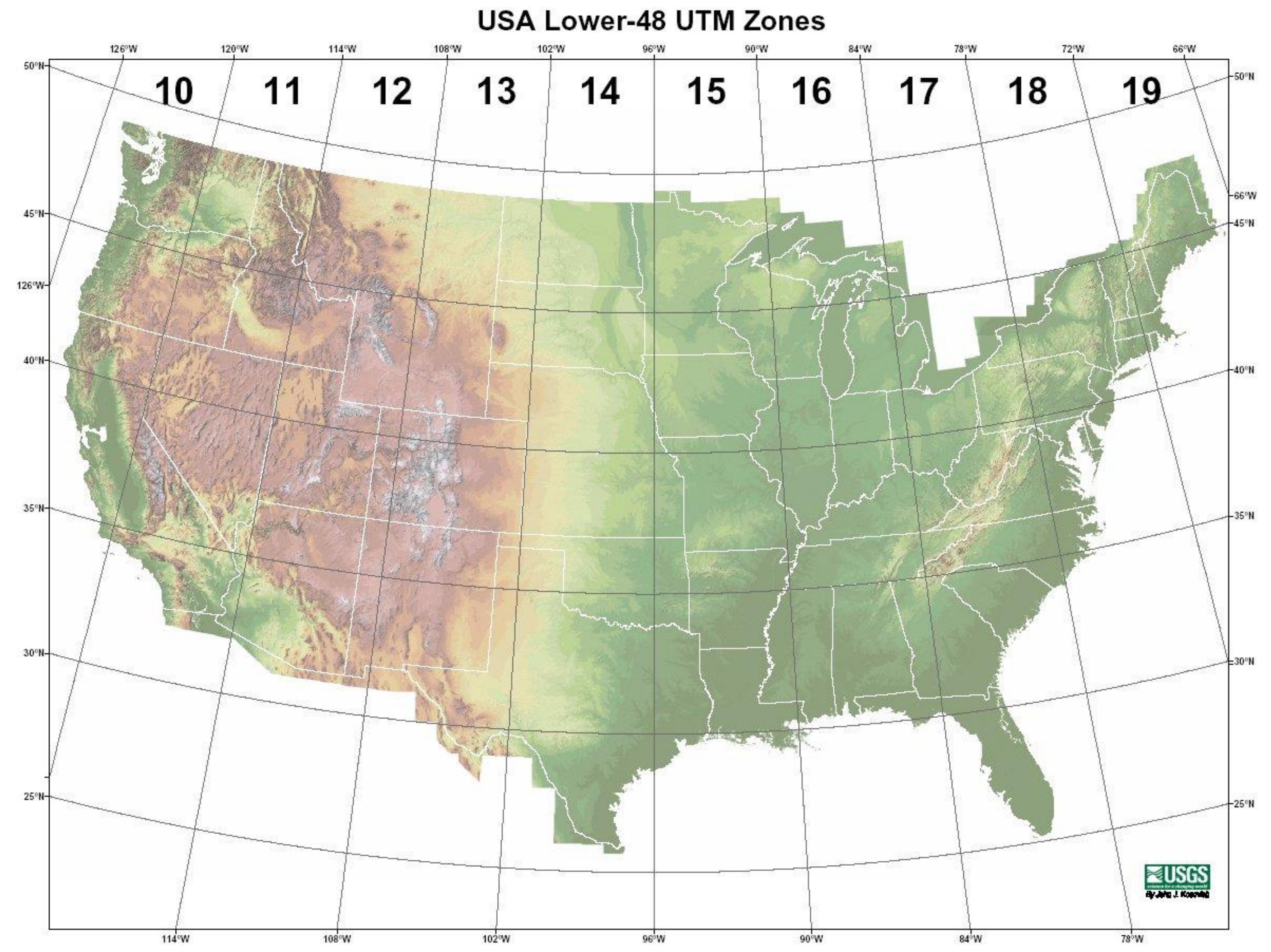
- Universal Transverse Mercator is a very common coordinate system
- UTM is based on the Transverse Mercator projection (remember, that's using a cylinder turned on its side)
- It generally uses either the NAD27 or NAD83 datum, so you will often see a layer as projected in "UTM83" or "UTM27"
- U.S. Federal agency data format

UTM

- UTM divides the earth between 84°N and 80°S into **60 zones**, each of which covers 6 degrees of longitude


World UTM zones

United States UTM Zones

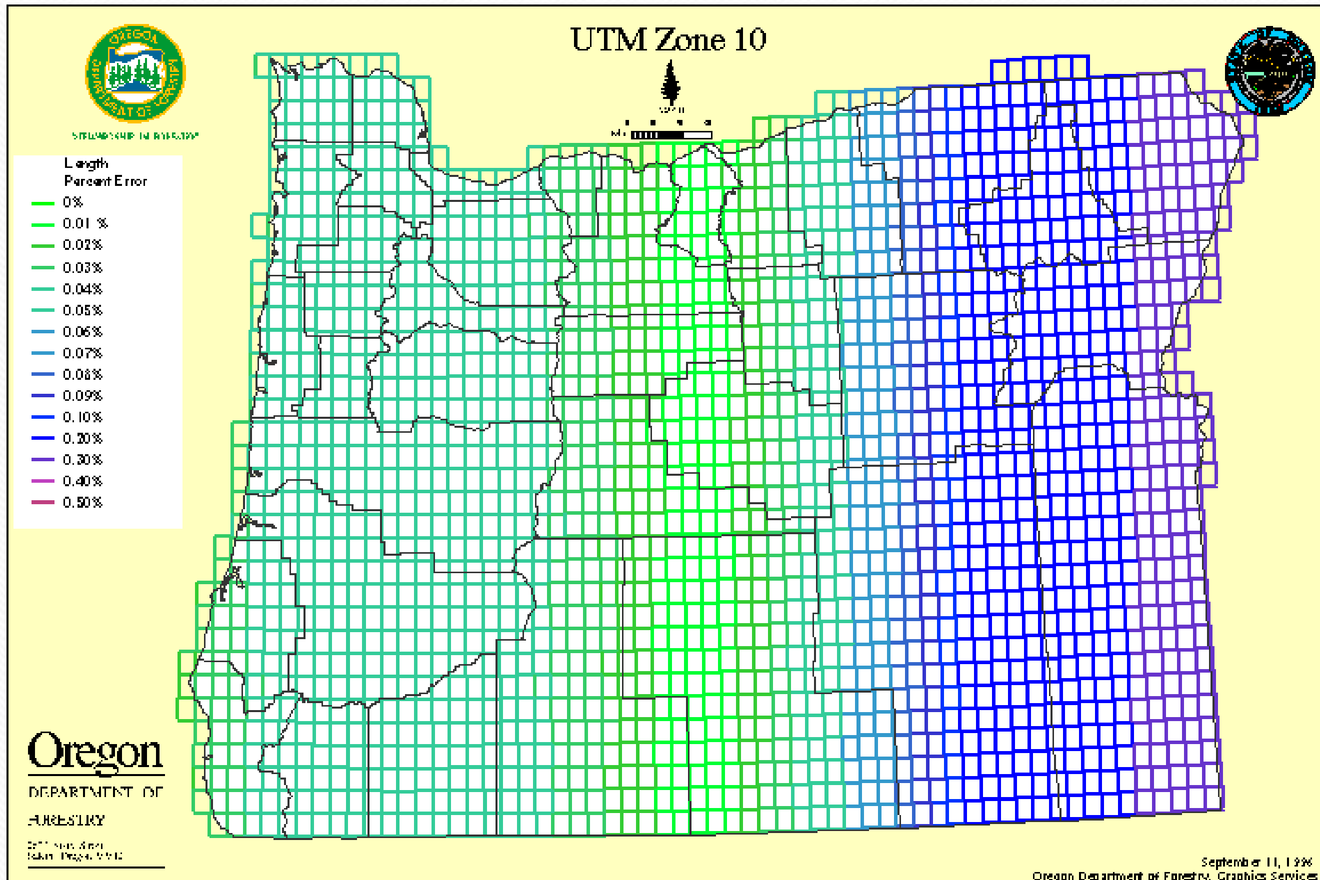


UTM

- Each UTM zone is projected separately
- There is a false origin (zero point) in each zone
- In the transverse Mercator projection, the “cylinder” touches at two secants, so there is a slight bulge in the middle, at the *central meridian*. This bulge is very very slight, so the scale factor is only .9996
- The *standard meridians* are where the cylinder touches

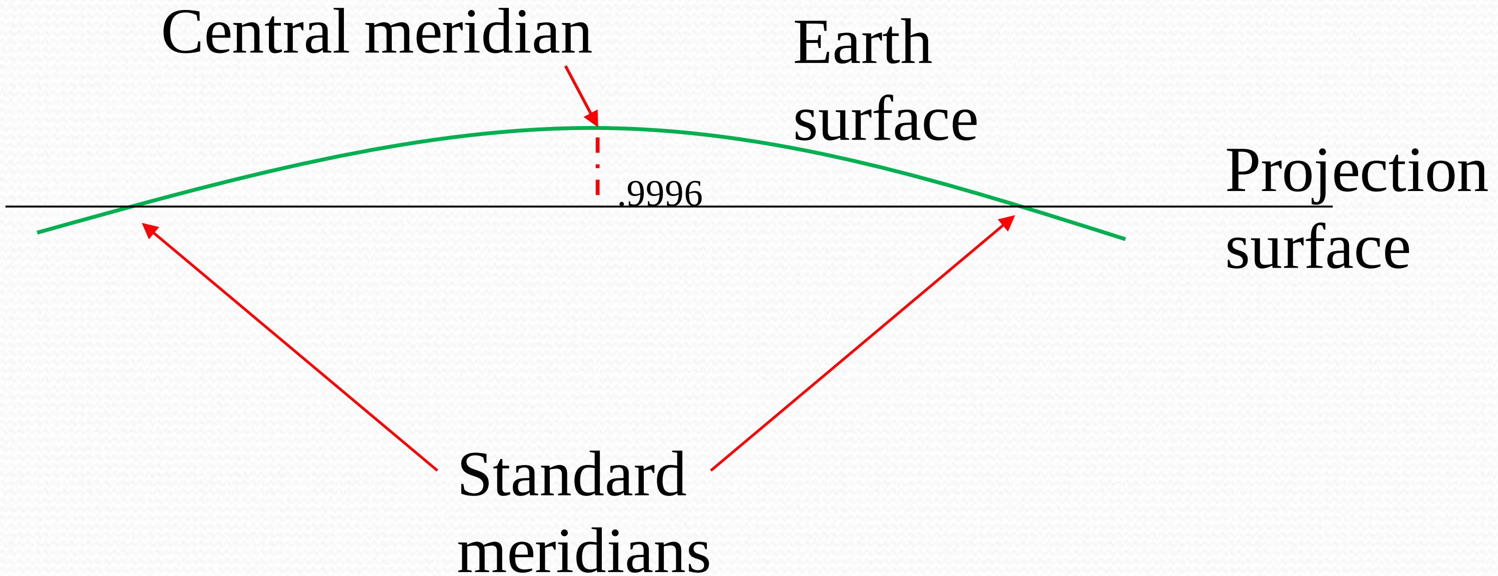
UTM

- Because each zone is big, UTM can result in significant errors further away from the center of a zone, corresponding to the central and standard meridians



UTM

- Scale factors are 0.9996 in the middle and 1 at the two secants (Transverse Mercator projection)
- The "cylinder" touches at two secants. The bulge at the central meridian is very, very slight



UTM

- UTM is used for large scale mapping applications the world over, when the unit of analysis is fairly small, like a state
- Good choice for multi-state projects, but its best to stay within a single zone
- Its accuracy is 1 in 2,500
- For portraying very large land units, like Alaska or the 48 states, a projection is usually used, like Albers Equal Area Conic

Projection in GIS software

1. **Define Projection**
   a) Defines a map projection for a layer (.prj file)
      - *does not reproject* data
      - *does not change data*

2. **Project** (i.e. reproject)
   a) *Projects data from one map projection to a different map projection (changes data)*
   b) Data must have a defined projection to start
   c) Give new reprojected output file a new name

Slide courtesy of Leslie Morrissey