GIS's Roots in Cartography

- Earth models
- Datum
- Geographic coordinates
- Map projections
- Coordinate systems
- Basic properties of geographic features

Organizing Data and Information

- Information can be **organized** as lists, numbers, tables, text, pictures, maps, or indexes.
- Clusters of information called **data** can be stored together as a database.
- A database is stored in a computer as **files**.

The Elements of GIS

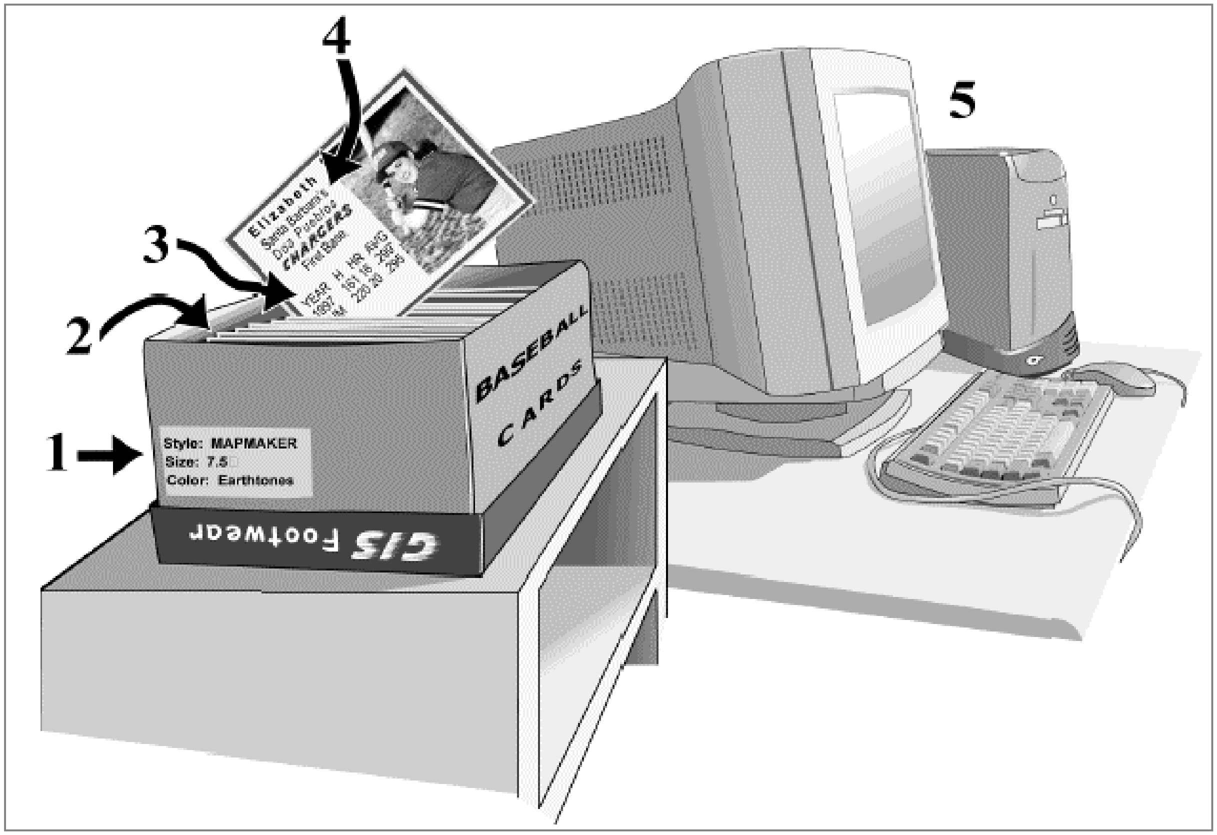


Figure 2.1 The elements of a GIS. (1) The database (shoebox); (2) the records (baseball cards); (3) the attributes (the categories on the cards, such as batting average, (4) the geographic information (locations of the team's stadium in latitude and longitude); (5) a means to use the information (the computer).

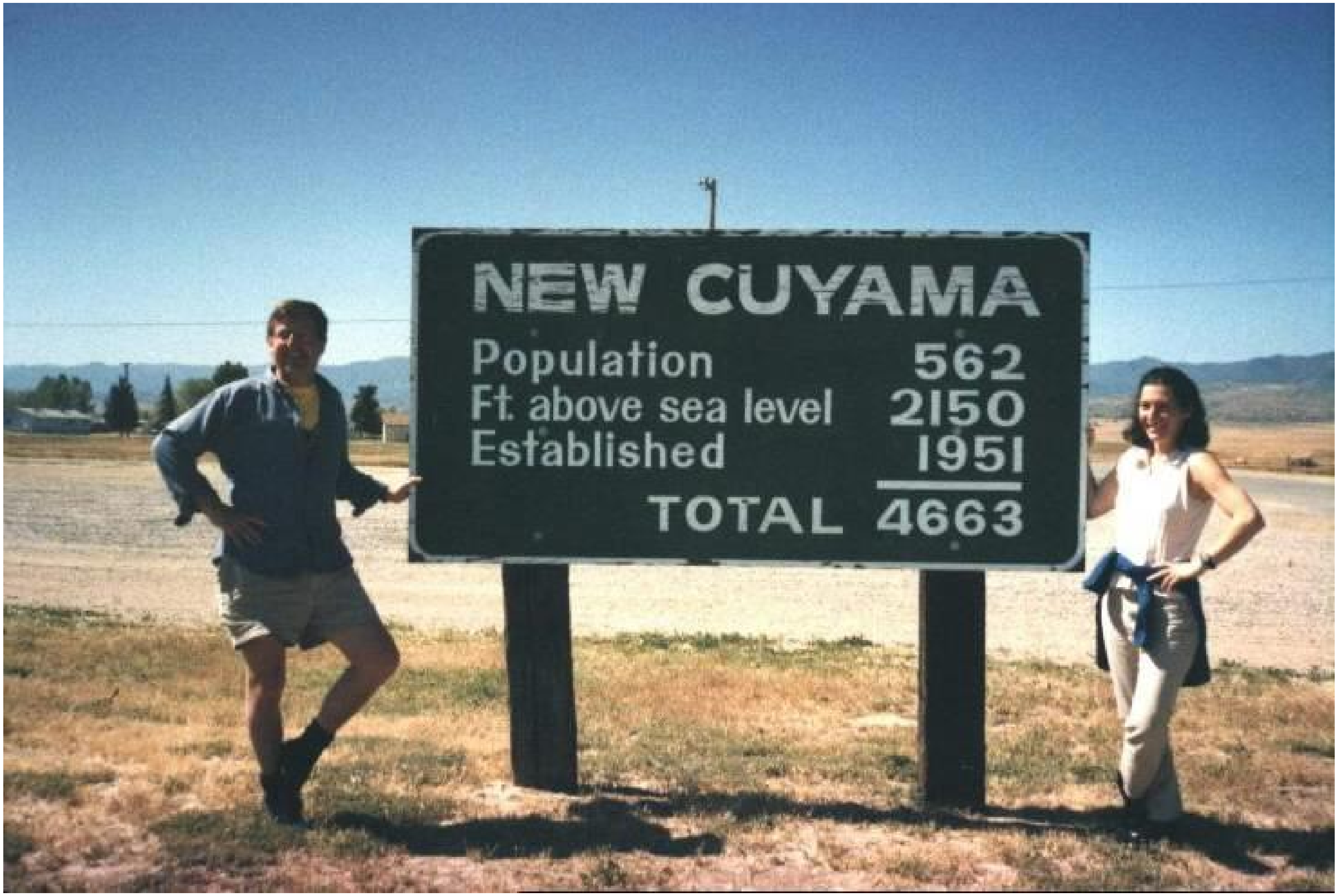
The GIS Database

- In a database, we store **attributes as column headers** and **records as rows**.
- The contents of an attribute for one record is a **value**.
- A value can be **numerical or text**.

Flat File Database

	Attribute	Attribute	Attribute
Record	Value	Value	Value
Record	Value	Value	Value
Record	Value	Value	Value

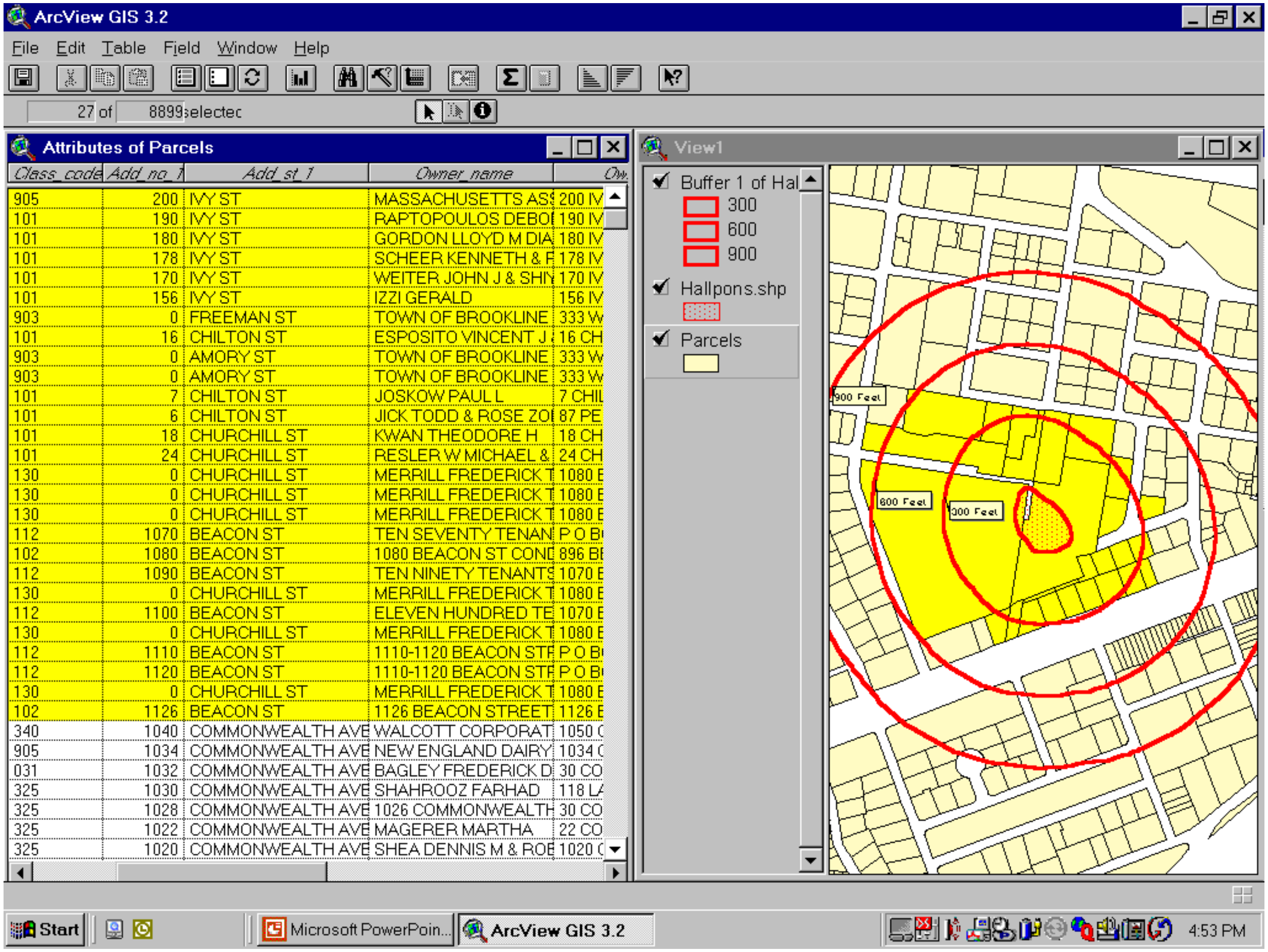
Attributes have Units



The GIS Database (continued)

- Data in a GIS must contain a **geographic reference** to a map, such as latitude and longitude.
- The GIS cross-references **the attribute data with the map data**, allowing searches based on either or both.
- The **cross-reference is a link**.

The GIS Database (continued)



Class_code	Add_no_1	Add_st_1	Owner_name	Ow
905	200	IVY ST	MASSACHUSETTS AS	200 IV
101	190	IVY ST	RAPTOPOULOS DEBO	190 IV
101	180	IVY ST	GORDON LLOYD M DIA	180 IV
101	178	IVY ST	SCHEER KENNETH & F	178 IV
101	170	IVY ST	WEITER JOHN J & SHIN	170 IV
101	156	IVY ST	IZZI GERALD	156 IV
903	0	FREEMAN ST	TOWN OF BROOKLINE	333 W
101	16	CHILTON ST	ESPOSITO VINCENT J	16 CH
903	0	AMORY ST	TOWN OF BROOKLINE	333 W
903	0	AMORY ST	TOWN OF BROOKLINE	333 W
101	7	CHILTON ST	JOSKOW PAUL L	7 CHIL
101	6	CHILTON ST	JICK TODD & ROSE ZO	87 PE
101	18	CHURCHILL ST	KWAN THEODORE H	18 CH
101	24	CHURCHILL ST	RESLER W MICHAEL &	24 CH
130	0	CHURCHILL ST	MERRILL FREDERICK T	1080 E
130	0	CHURCHILL ST	MERRILL FREDERICK T	1080 E
130	0	CHURCHILL ST	MERRILL FREDERICK T	1080 E
112	1070	BEACON ST	TEN SEVENTY TENAN	P O B
102	1080	BEACON ST	1080 BEACON ST COND	896 BE
112	1090	BEACON ST	TEN NINETY TENANTS	1070 E
130	0	CHURCHILL ST	MERRILL FREDERICK T	1080 E
112	1100	BEACON ST	ELEVEN HUNDRED TE	1070 E
130	0	CHURCHILL ST	MERRILL FREDERICK T	1080 E
112	1110	BEACON ST	1110-1120 BEACON STR	P O B
112	1120	BEACON ST	1110-1120 BEACON STR	P O B
130	0	CHURCHILL ST	MERRILL FREDERICK T	1080 E
102	1126	BEACON ST	1126 BEACON STREET	1126 E
340	1040	COMMONWEALTH AVE	WALCOTT CORPORAT	1050 C
905	1034	COMMONWEALTH AVE	NEW ENGLAND DAIRY	1034 C
031	1032	COMMONWEALTH AVE	BAGLEY FREDERICK D	30 CO
325	1030	COMMONWEALTH AVE	SHAHROOZ FARHAD	118 LA
325	1028	COMMONWEALTH AVE	1026 COMMONWEALTH	30 CO
325	1022	COMMONWEALTH AVE	MAGERER MARTHA	22 CO
325	1020	COMMONWEALTH AVE	SHEA DENNIS M & ROE	1020 C

Cartography and GIS

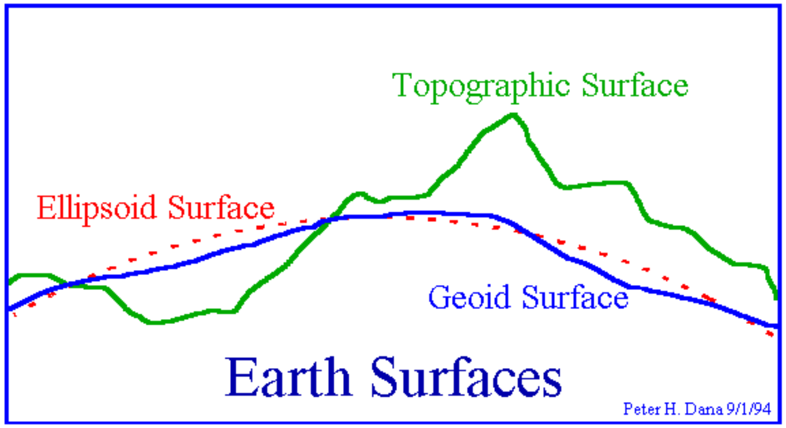
- Understanding the way maps are **encoded** to be used in GIS requires knowledge of **cartography**
- Cartography is the **science** that deals with the **construction, use, and principles** behind maps
- A map is a **depiction** of all or part of the earth or other geographic phenomenon as a set of symbols and at a scale whose **representative fraction** is less than one to one

Models of the Earth

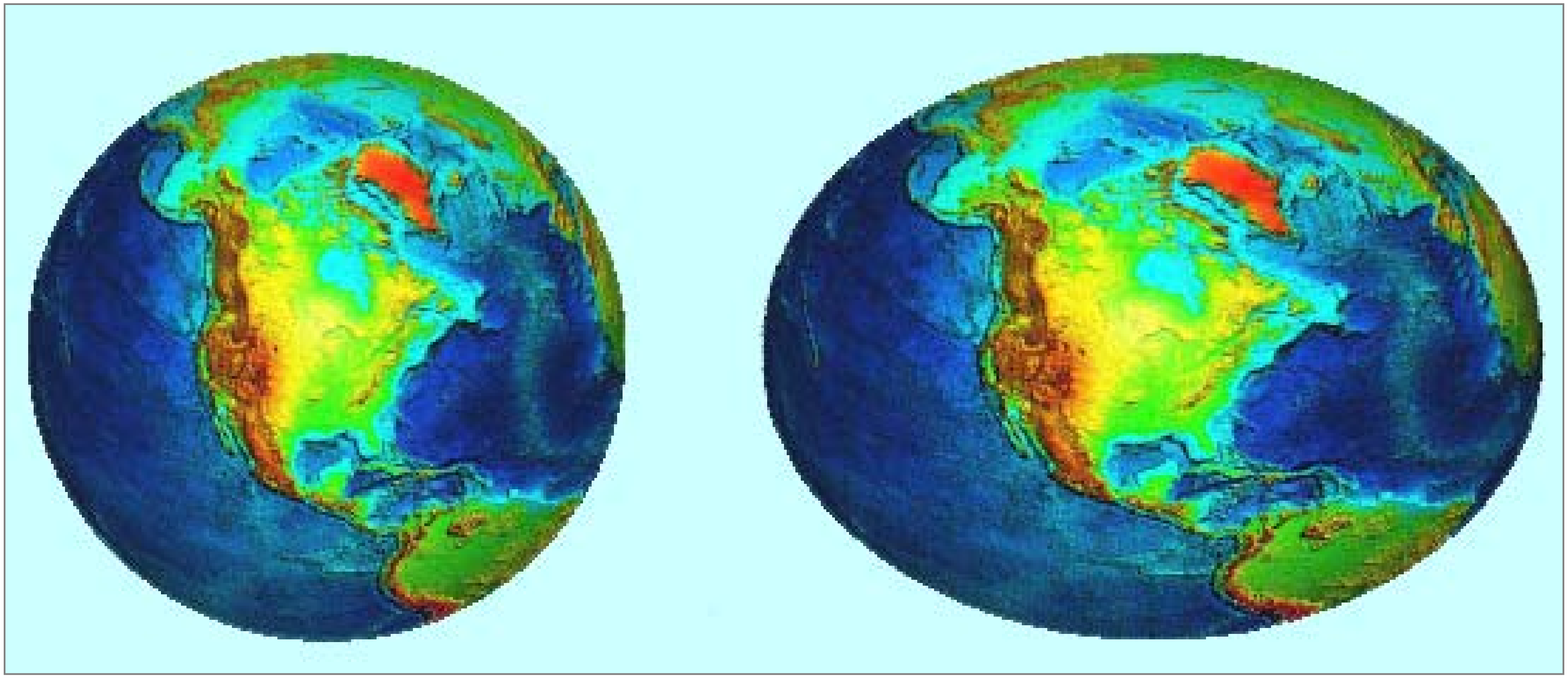
A Sphere

An Ellipsoid

A Geoid



Earth Shape: Sphere and Ellipsoid



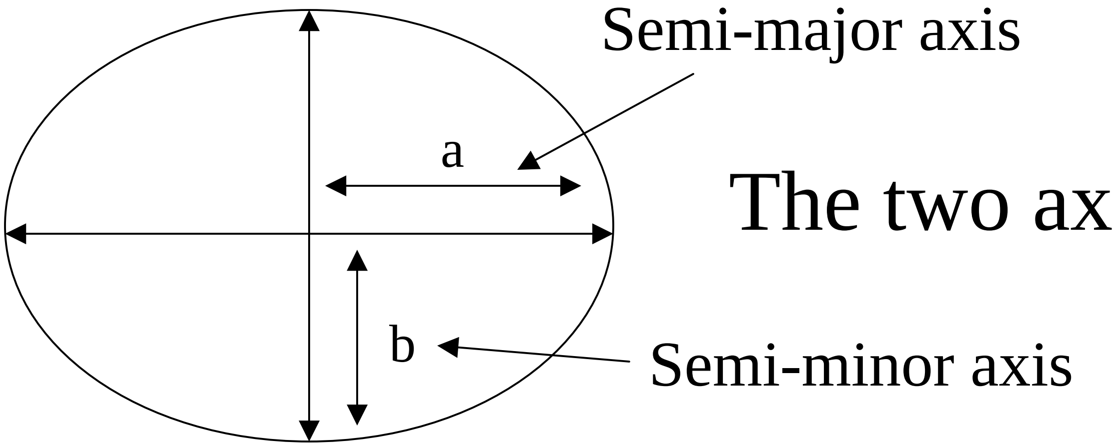
Pole to pole distance: 39,939,593.9 meters
Around the Equator distance: 40,075,452.7 meters

Earth Shape: Sphere and Ellipsoid

- The sphere is about **40 million meters** in circumference.
- An **ellipsoid** is an ellipse rotated in three dimensions about its shorter axis.
- The earth's ellipsoid is only **1/297** off from a sphere.
- Many ellipsoids have been **measured**, and **maps based on each**. Examples are WGS84 and GRS80.

Ellipticity of the Earth

- **How far** is the **Earth** from being a perfect sphere?



Semi-major axis

a

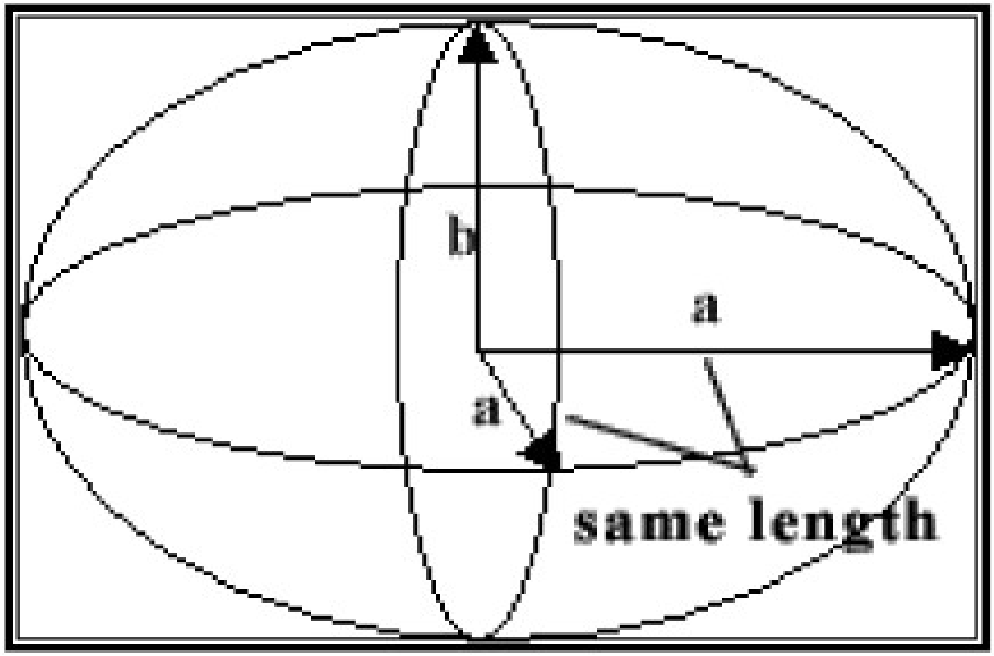
b

Semi-minor axis

The two axes of an ellipsoid

- Using these two axes’ lengths we can calculate the **ellipticity** (flattening) of an ellipsoid, with $f = 0$ being a perfect sphere and $f = 1$ being a straight line

Ellipticity of the Earth

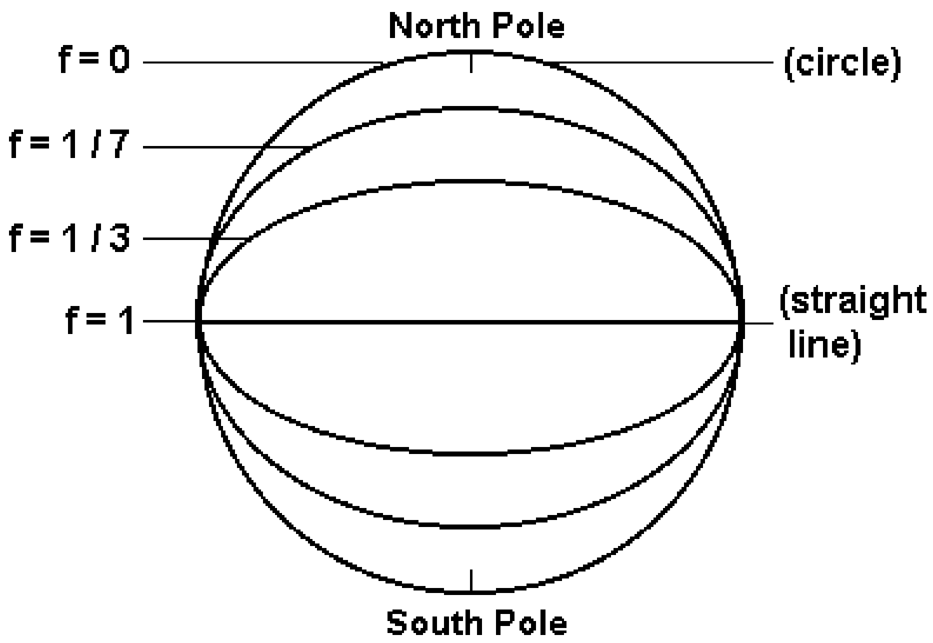


- a = semi-major axis
- b = semi-minor axis
- *f* = [(a - b) / a] = flattening

Ellipticity of the Earth

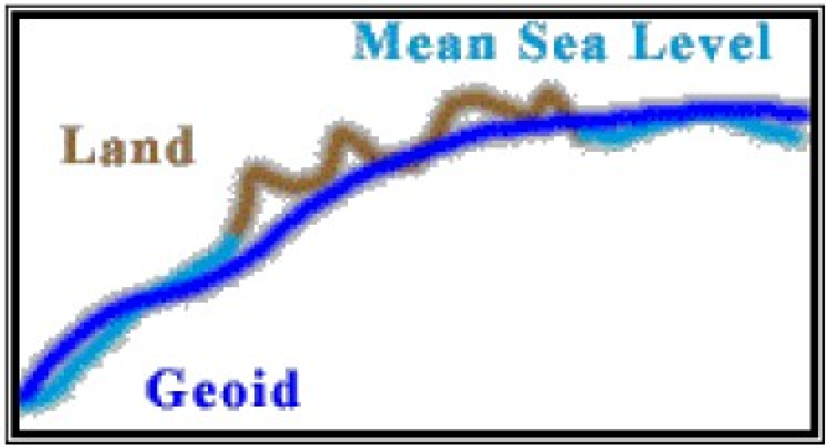
- **Newton** estimated the Earth's ellipticity to be about *f* = 1/300
- **Modern satellite technology** gives an *f* = 1/298 (~0.003357)

These small values of *f* tell us that the Earth is very close to being a sphere, but not close enough to ignore its ellipticity if we want to accurately locate features on the Earth


Examples of ellipsoid flattening (f)

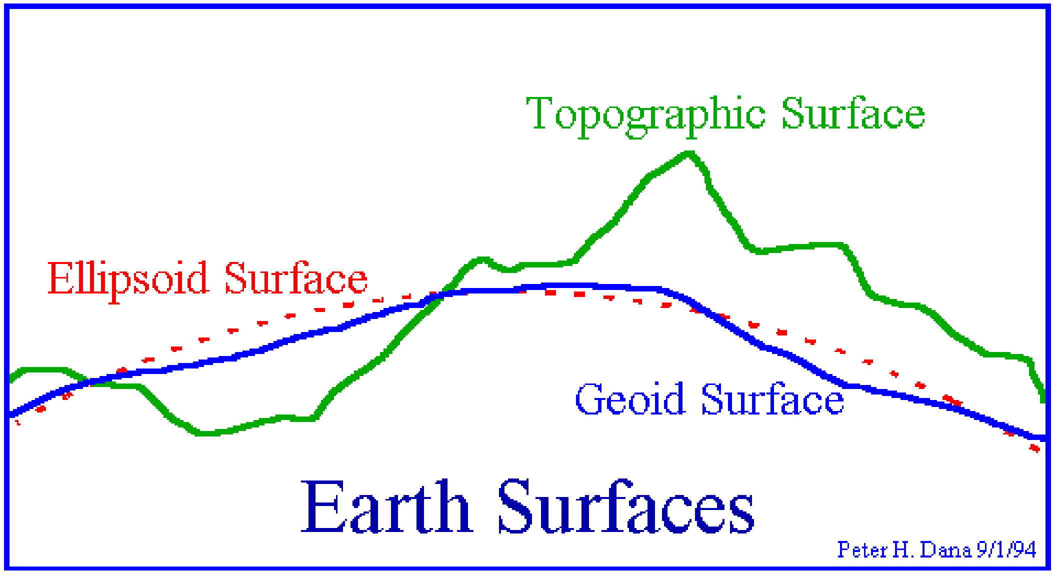
The Earth as a Geoid

- Rather than using a regular shape like an ellipsoid, we can create a **more complex** model that takes into account the **Earth's irregularities**
- The only thing shaped like the Earth is the Earth itself, thus the term **Geoid**, meaning "Earth like"
- Its **shape** is based on the Earth's gravity field, correcting for the centrifugal force of the earth's rotation.



The Earth as Geoid

- **Geoid** → The surface on which gravity is the same as its strength at mean sea level
- **Geodesy** is the science of measuring the size and shape of the earth and its gravitational and magnetic fields.



Geodetic Datum

- In order to manage the complexities of the shape of a geoid model of the Earth, we use something called a **geodetic datum**
- **Datum** -- *n.* (dat -ə m) \ any numerical or geometric quantity which serves as a reference or base for other quantities
- A geodetic datum is used as a **reference base** for mapping
- It can be **horizontal or vertical**
- It is always tied to a **reference ellipsoid**

The Datum

- An ellipsoid gives the **base elevation** for mapping, called a **datum**.
  - North American Datum 1927 (NAD27)
  - North American Datum 1983 (NAD83)

Earth Models and Datums

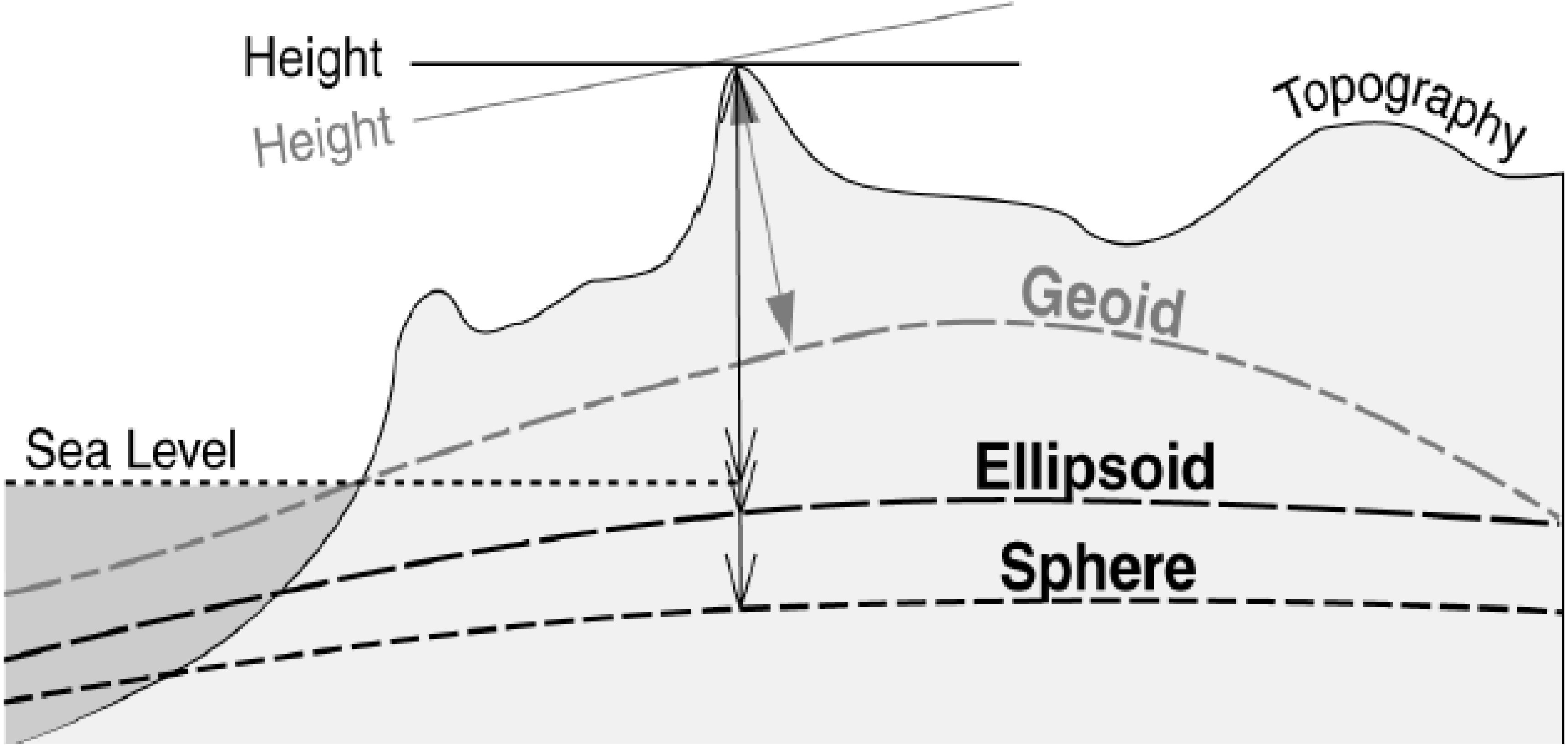
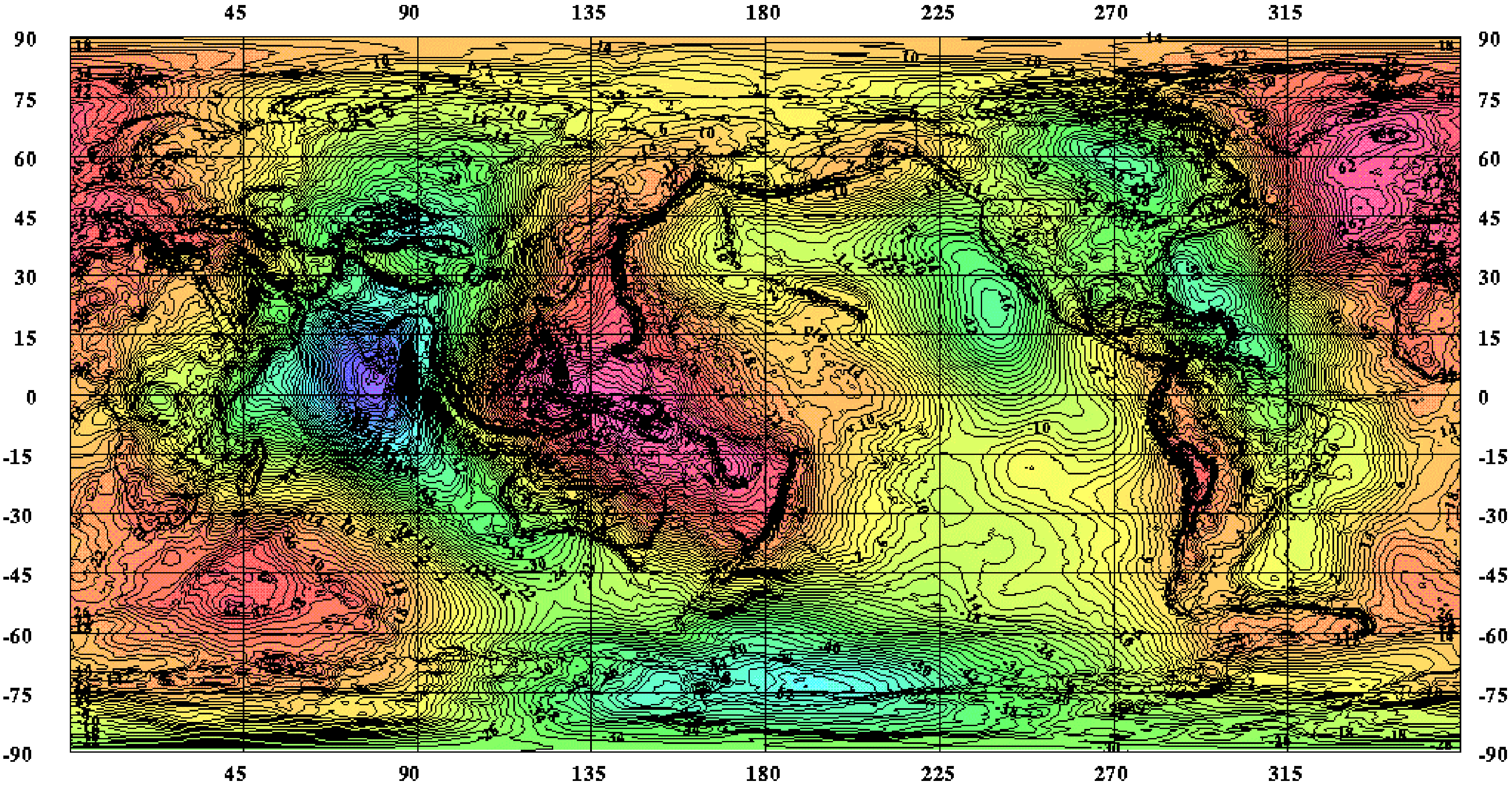


Figure 2.4 Elevations defined with reference to a sphere, ellipsoid, geoid, or local sea level will all be different. Even locations as latitude and longitude will vary somewhat. When linking field data such as GPS with a GIS, the user must know what base to use.

Geoid



EGM96 15 MINUTE GEOID CI = 2 Meters

-105.0 85.0 **Meter**

Map Scale

- Map scale is based on the **representative fraction**, the **ratio** of a **distance on the map** to the **same distance on the ground**.
- Most maps in GIS fall between **1:1 million and 1:1000**.
- A GIS is **scaleless** because maps can be enlarged and reduced and plotted at many scales other than that of the original data.
- To **compare** maps in a GIS, **both** maps **MUST** be at the **same scale** and have the **same extent**.

Scale of a Baseball Earth

- **Baseball** circumference = 226 mm = 0.226 m
- **Earth** circumference approx 40 million meters
- **Representative Fraction** is : 1:177 million

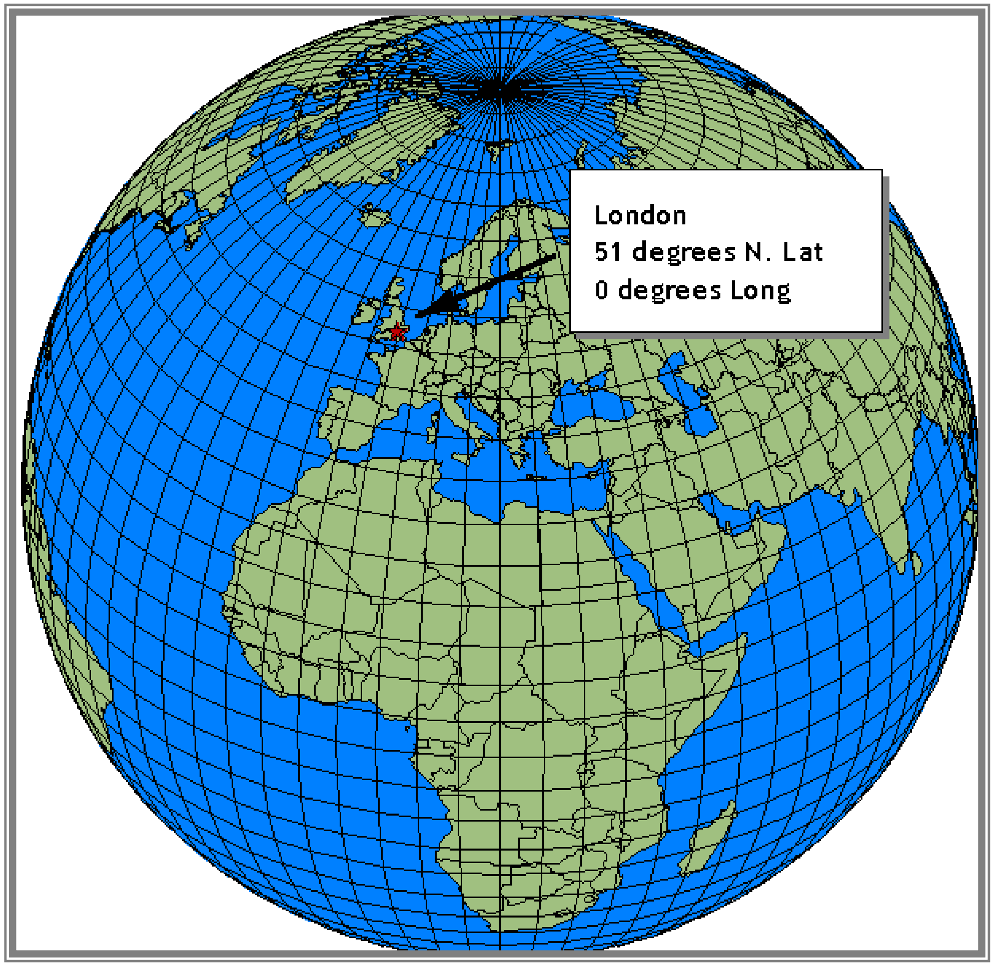
0.226 Meters = 40 million
40million/0.226 = 1:177 million

Geographic Coordinates

- We can use **geographic coordinates** (i.e. latitude & longitude) to specify locations
- Treating the Earth as a sphere is accurate enough for small maps of large areas of the Earth (i.e. **very small scale maps**)

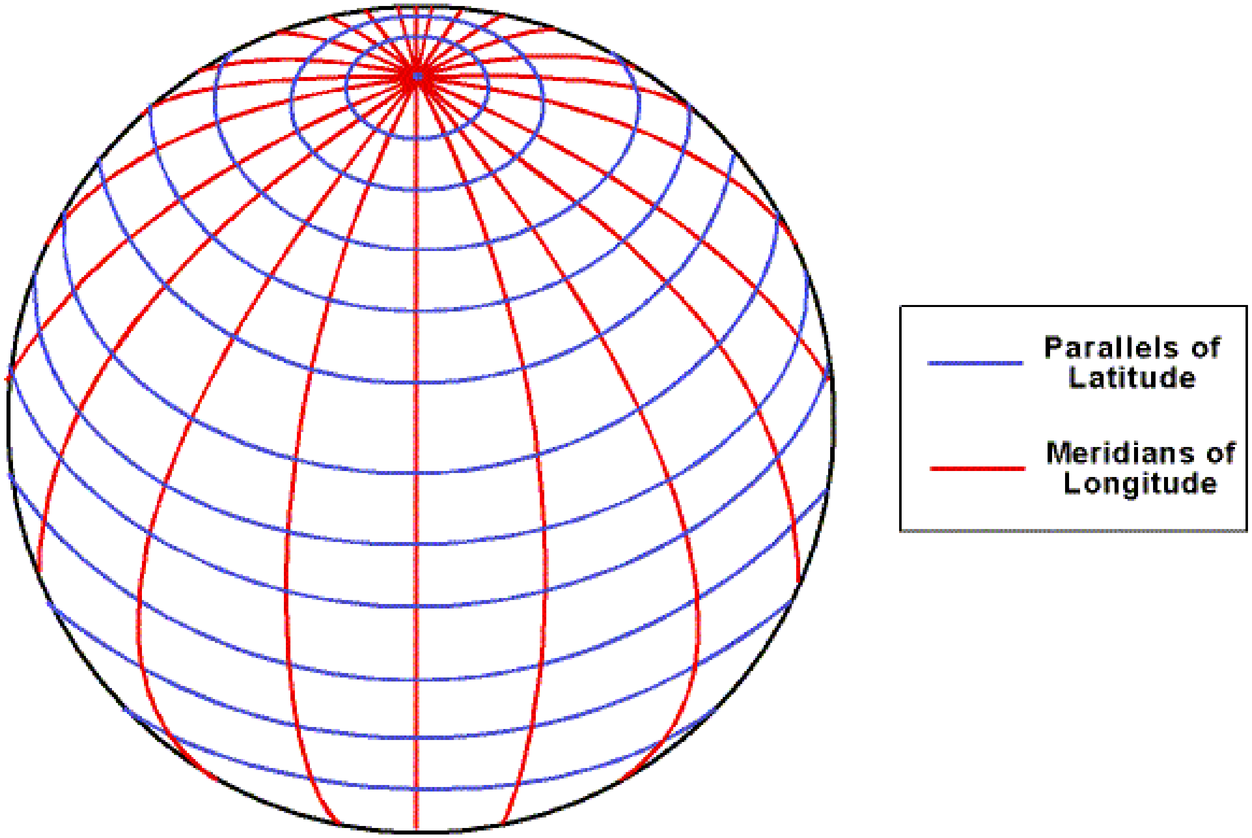
Geographic Coordinates

- Latitude and longitude are based on the **spherical** model of the Earth
- This is the **most commonly-used** coordinate system (i.e. you will have seen it on globes or large-scale maps)



Geographic Coordinates

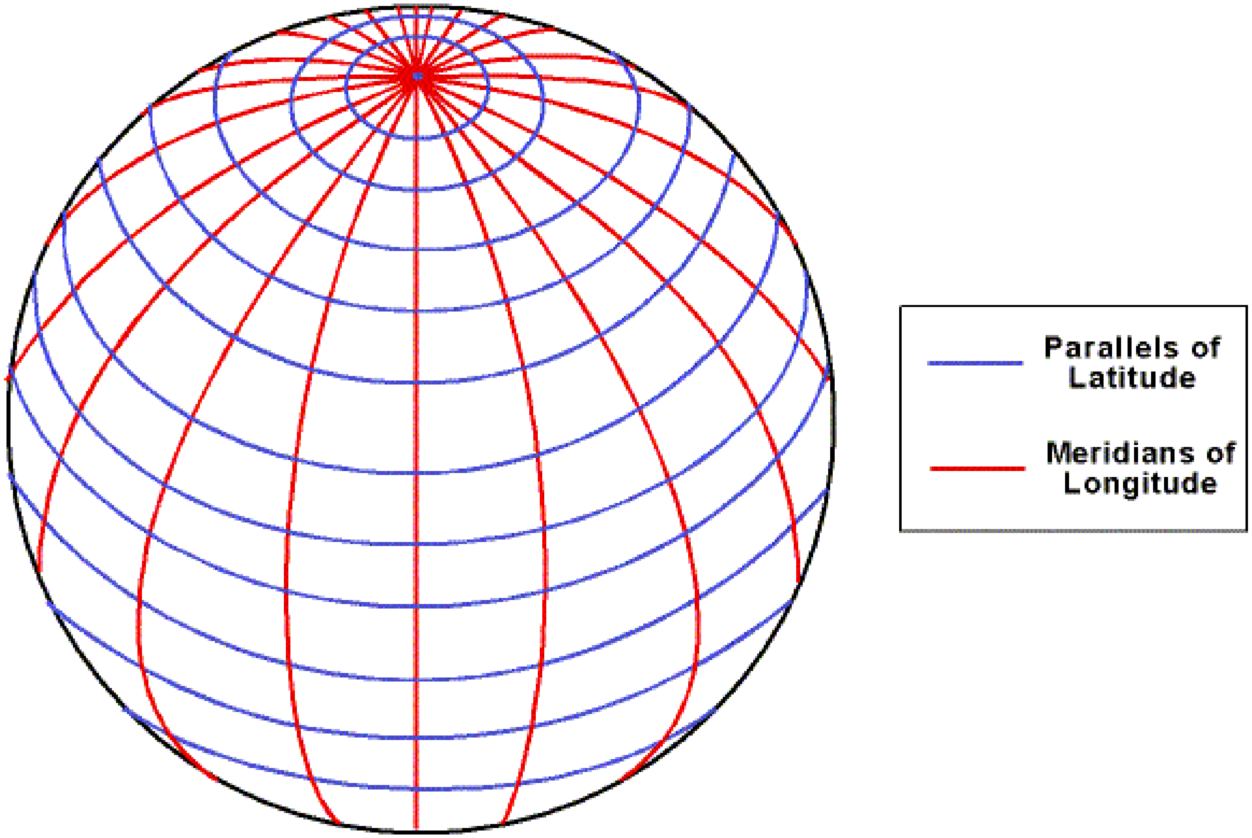
- Lines of latitude are called **parallels**
- Lines of longitude are called **meridians**



Tony Kirvan 11/8/97

The Graticule

- The **parallels and meridians** of latitude and longitude form a **graticule** on a globe, a grid of orthogonal lines



Tony Kirvan 11/8/97

Geographic Coordinates

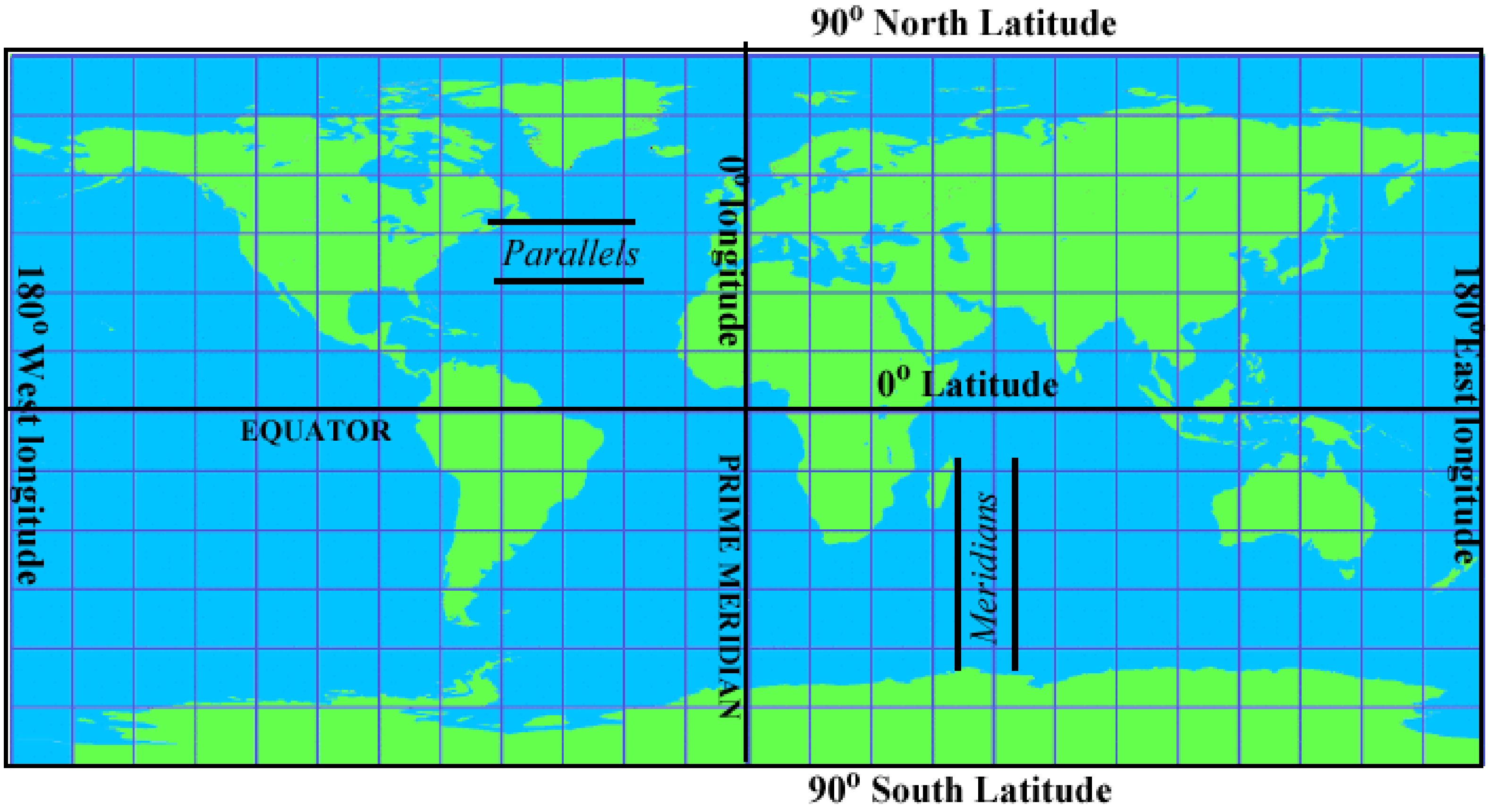
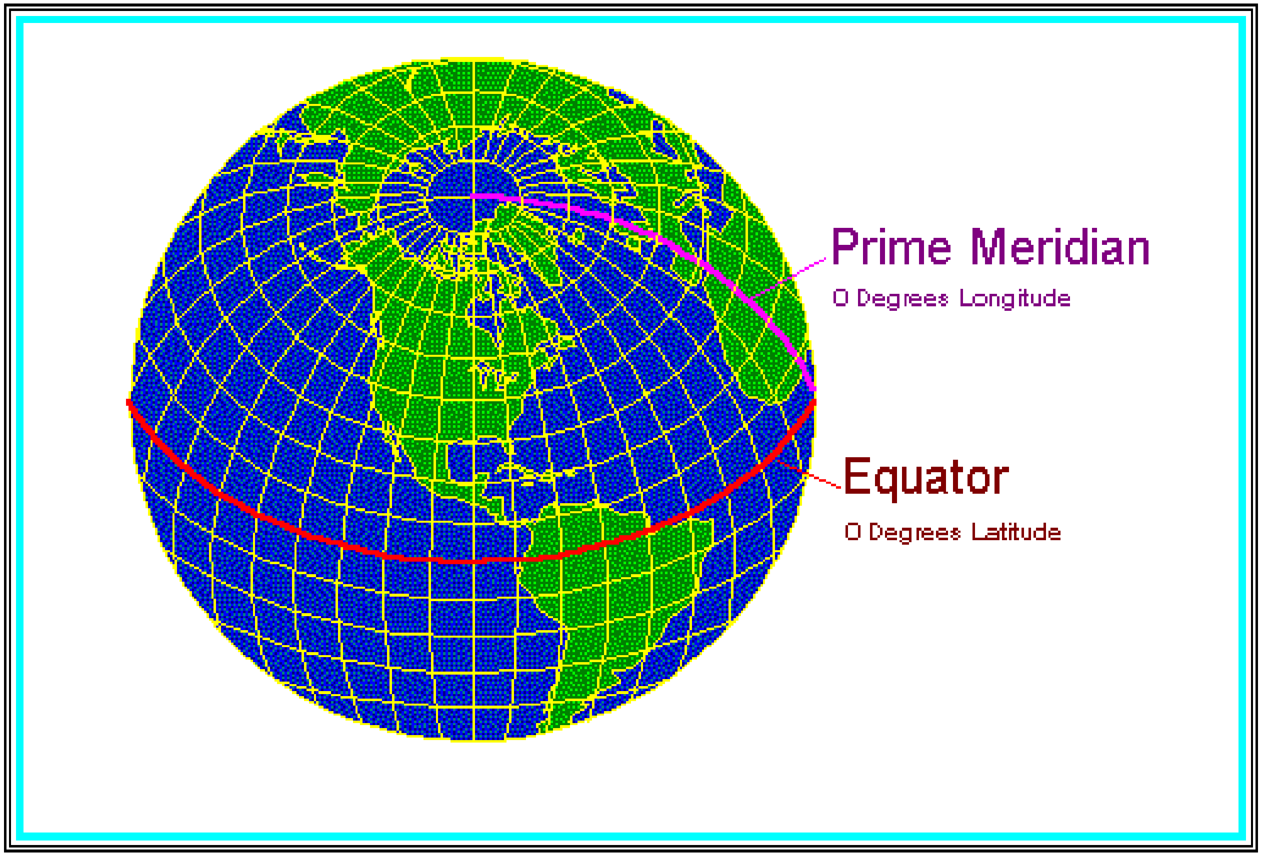


Figure 2.6 Geographic coordinates. The familiar latitude and longitude system, simply converting the angles at the earth's center to coordinates, gives the basic equirectangular projection. The map is twice as wide as high (360° east-west, 180° north-south).

Geographic Coordinates

- The **Prime Meridian** and the **Equator** are the origin lines used to define latitude and longitude



The Prime Meridian (1884)

The International Meridian Conference (1884: Washington DC)

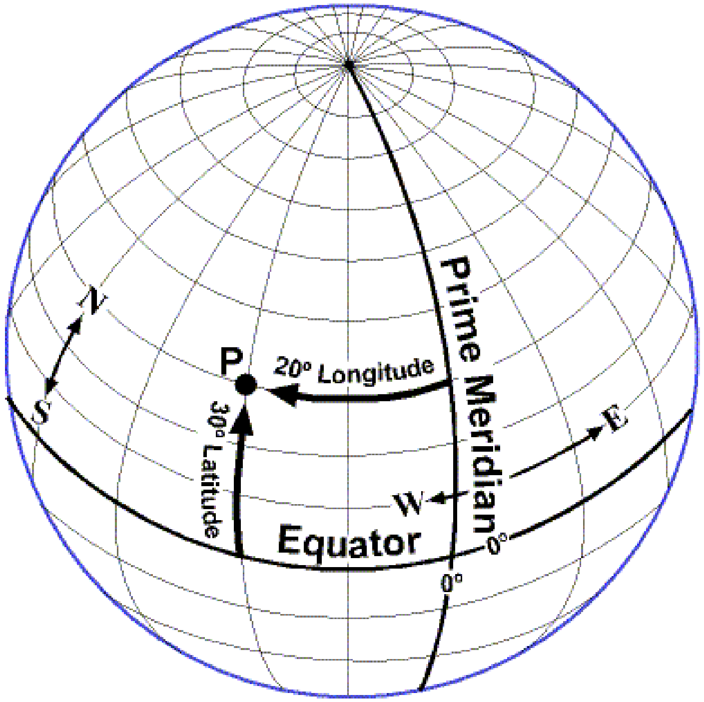
“That it is the opinion of this Congress that it is desirable to adopt a single prime meridian for all nations, in place of the multiplicity of initial meridians which now exist.”

“That the Conference proposes to the Governments here represented the adoption of the meridian passing through the center of the transit instrument at the Observatory of Greenwich as the initial meridian for longitude.”

“That from this meridian longitude shall be counted in two directions up to 180 degrees, east longitude being plus and west longitude minus.”

Geographic Coordinates

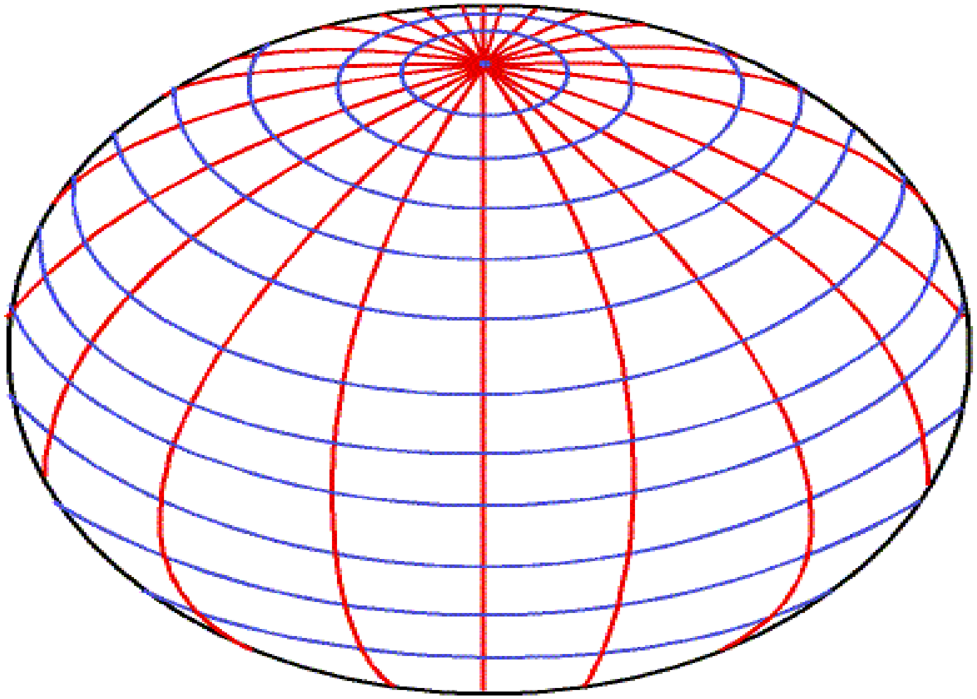
- Geographic coordinates are calculated using **angles**
- **Units** are in degrees, minutes, and seconds
- **Any location** on the planet can be specified with a **unique pair** of geographic coordinates



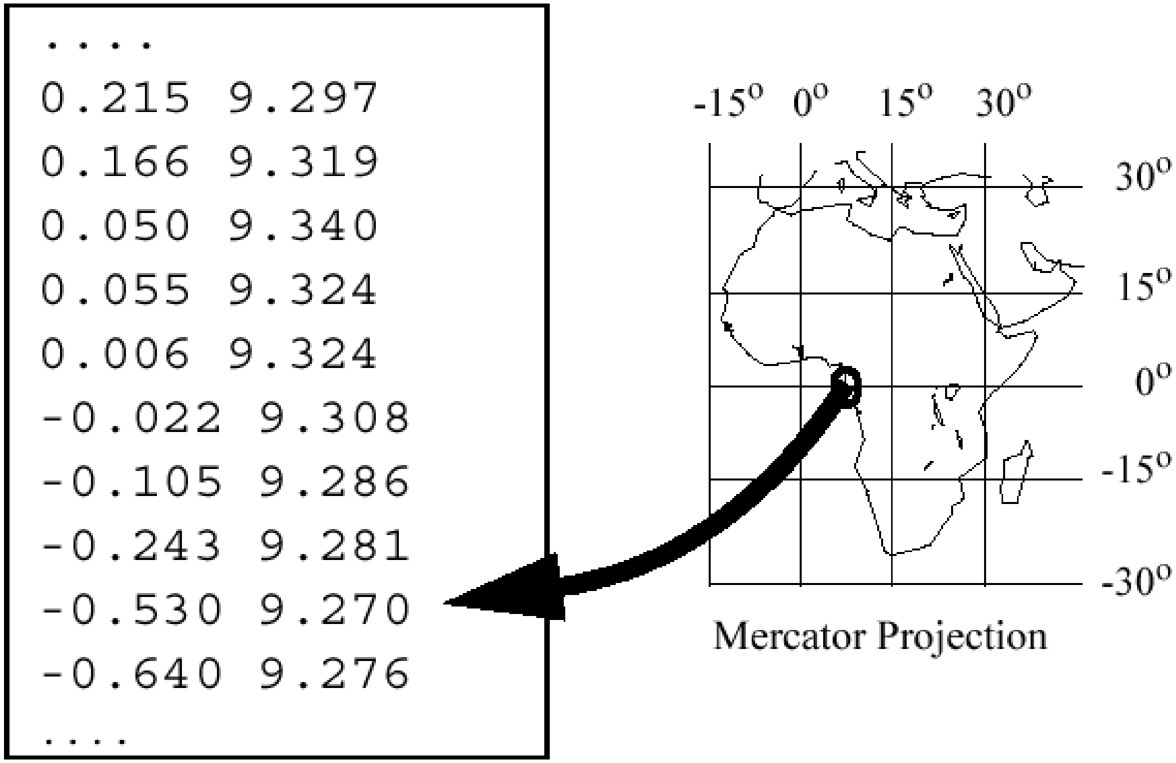
Tony Kirvan 11-8-97

Latitude & Longitude on an Ellipsoid

- On a sphere, lines of latitude (parallels) are an **equal distance** apart everywhere
- On an ellipsoid, the distance between parallels **increases slightly** as the latitude increases



Geographic Coordinates as Data



....	
0.215	9.297
0.166	9.319
0.050	9.340
0.055	9.324
0.006	9.324
-0.022	9.308
-0.105	9.286
-0.243	9.281
-0.530	9.270
-0.640	9.276
....	

Figure 2.12 Part of the World Data Bank I listing of the coordinates of the coastline of Africa. Format is geographic coordinates in decimal degrees.

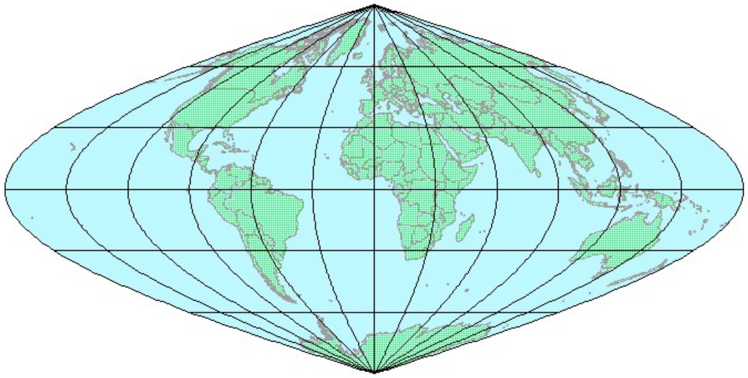
Using Projections to Map the Earth

- We have discussed **geodesy**, and we now know about modeling the shape of Earth as an ellipsoid and geoid
- We are ready to tackle the problem of transforming the **3-dimensional Earth → 2-dimensional representation** that suits our purposes:

Earth surface

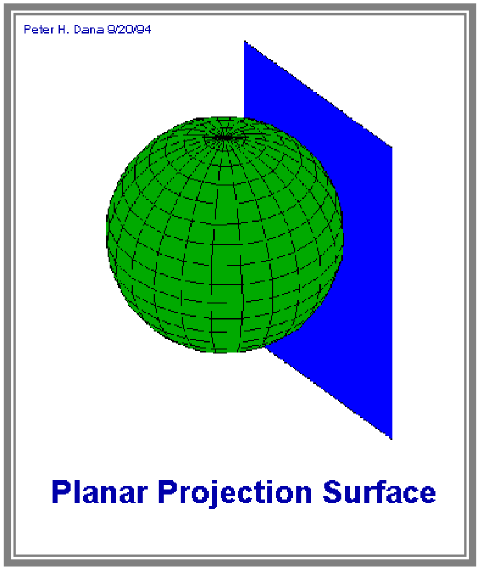
map →

Paper map or GIS

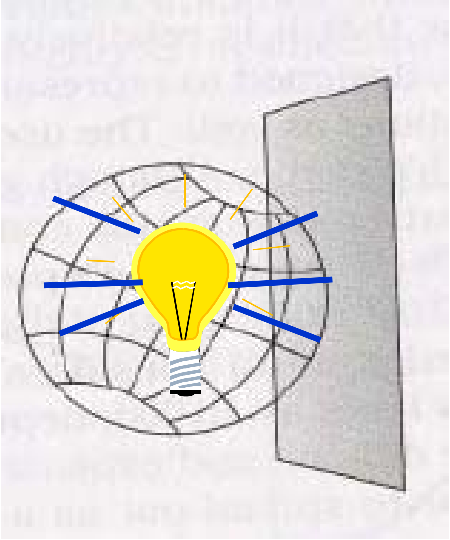


What is a Projection?

- **Map projection** - The systematic transformation of points on the **Earth's surface** to corresponding points on a **planar surface**

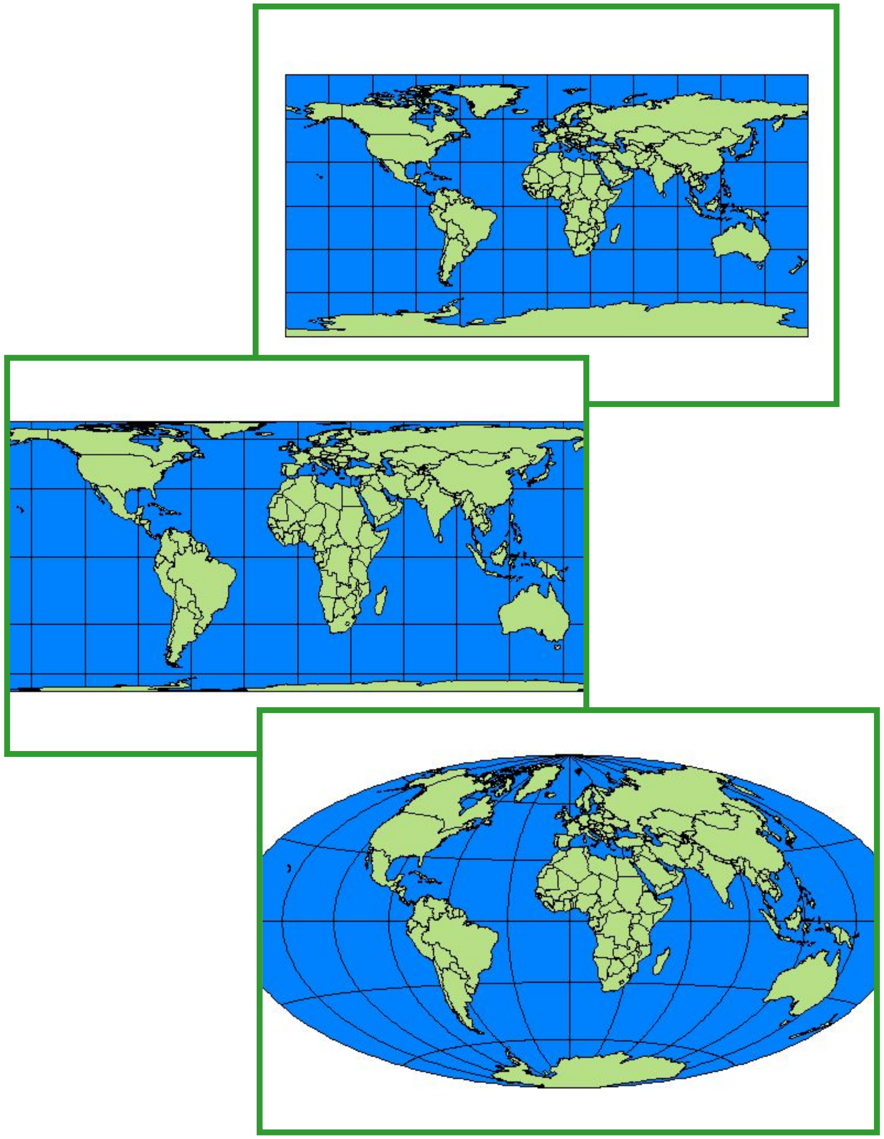


- The easiest way to imagine this is to think of a **light bulb** inside of a semi-transparent globe, shining features from the **Earth's surface** onto the **planar surface**



Projections Distort

- Because we are going from the 3D Earth → 2D planar surface, projections **always** introduce some type of **distortion**
- When we select a map projection, we choose a particular projection to **minimize the distortions** that are important to a **particular application**



Three Families of Projections

- There are **three major families** of projections, each tends to introduce **certain kinds of distortions**, or conversely each has certain **properties** that it used to **preserve** (i.e. spatial characteristics that it does not distort):
- **Three families:**
    1. Cylindrical projections
    2. Conical projections
    3. Planar projections

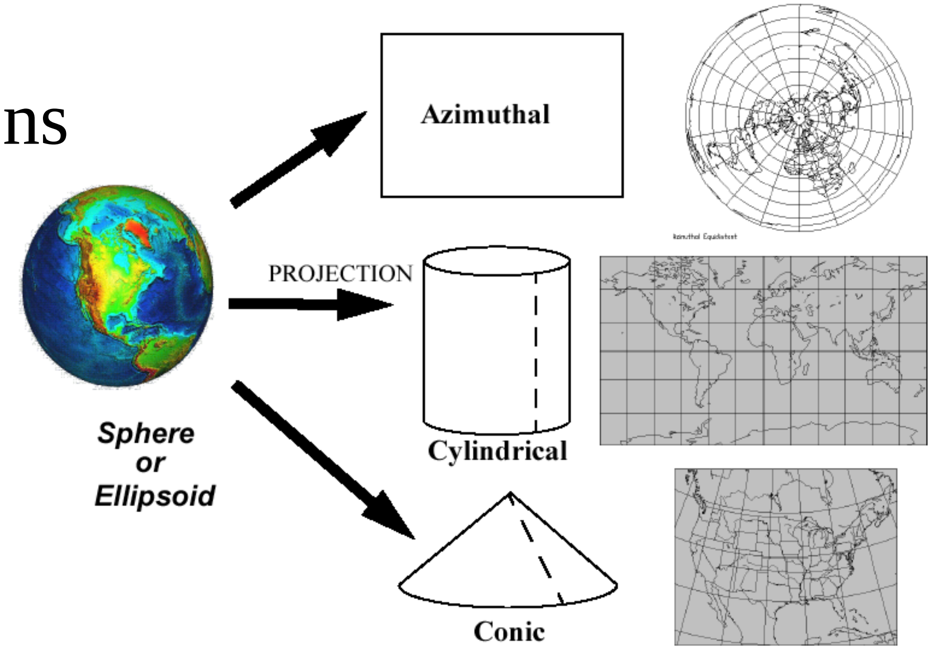
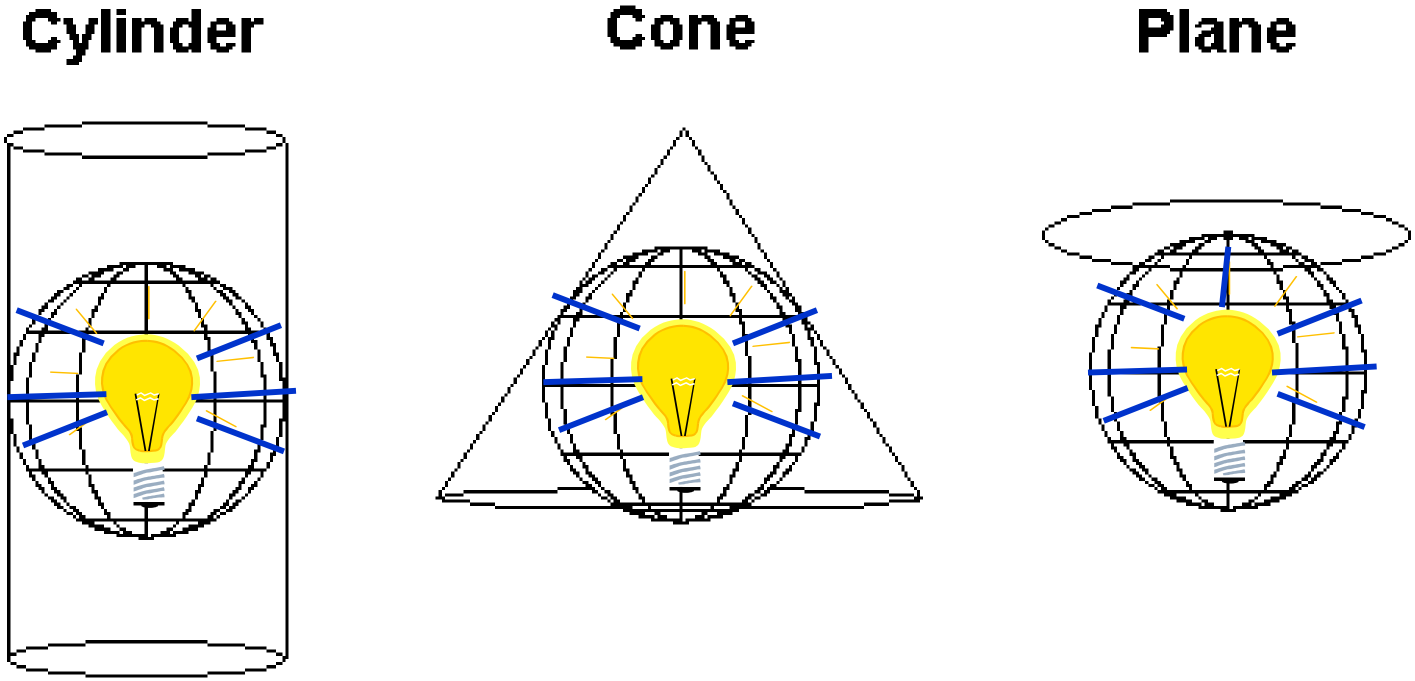


Figure 2.7 The earth can be projected in many ways, but basically onto three shapes that can be unrolled into a flat map: a flat plane, a cylinder, and a cone.

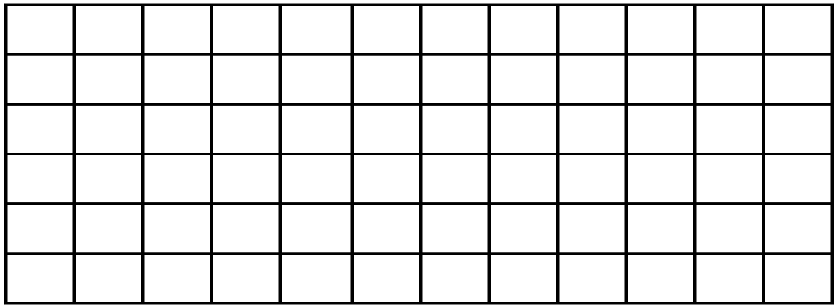
The Graticule

- Picture a light source **projecting** the shadows of the graticule lines on the surface of a transparent globe onto the developable surface …

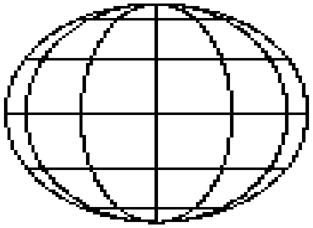


The Graticule, Projected

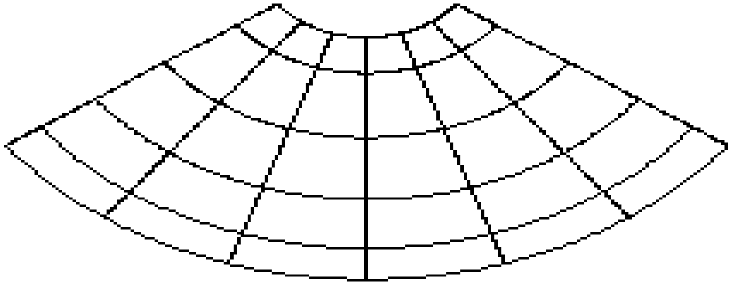
CYLINDRICAL GRATICULE



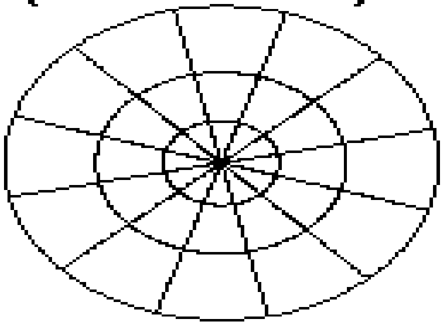
GLOBE GRATICULE



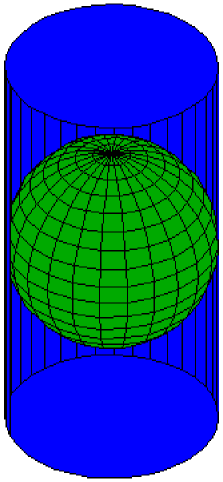
CONIC GRATICULE



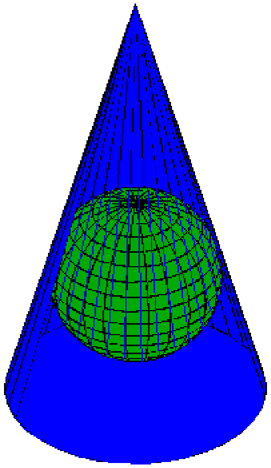
PLANAR (AZIMUTHAL) GRATICULE



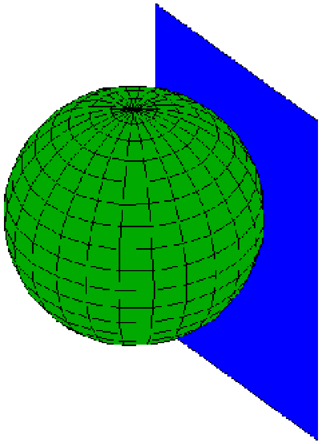
Tangent Projections


Peter H. Dana 9/20/94

Cylindrical Projection Surface


Peter H. Dana 9/20/94

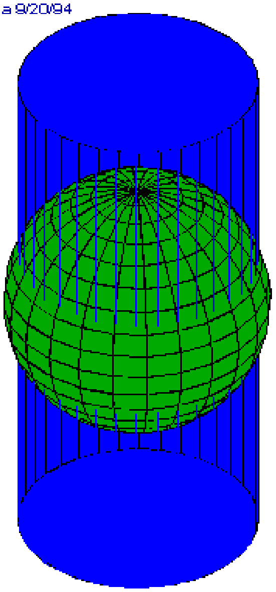
Conical Projection Surface


Peter H. Dana 9/20/94

Planar Projection Surface

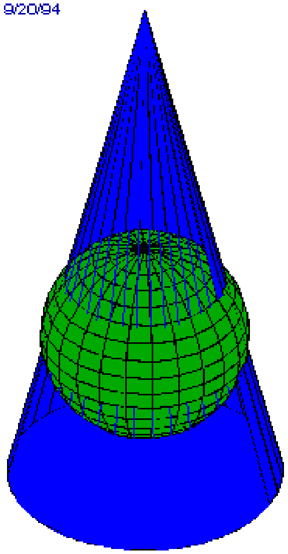
- Tangent projections have a **single standard point** (in the case of planar projection surfaces) or a **standard line** (for conical and cylindrical projection surfaces) of contact between the developable surface and globe

Secant Projections



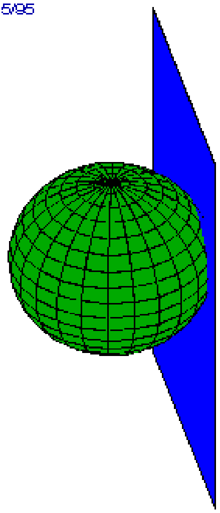
Peter H. Dana 9/20/94

Secant Cylindrical Projection



Peter H. Dana 9/20/94

Secant Conic Projection



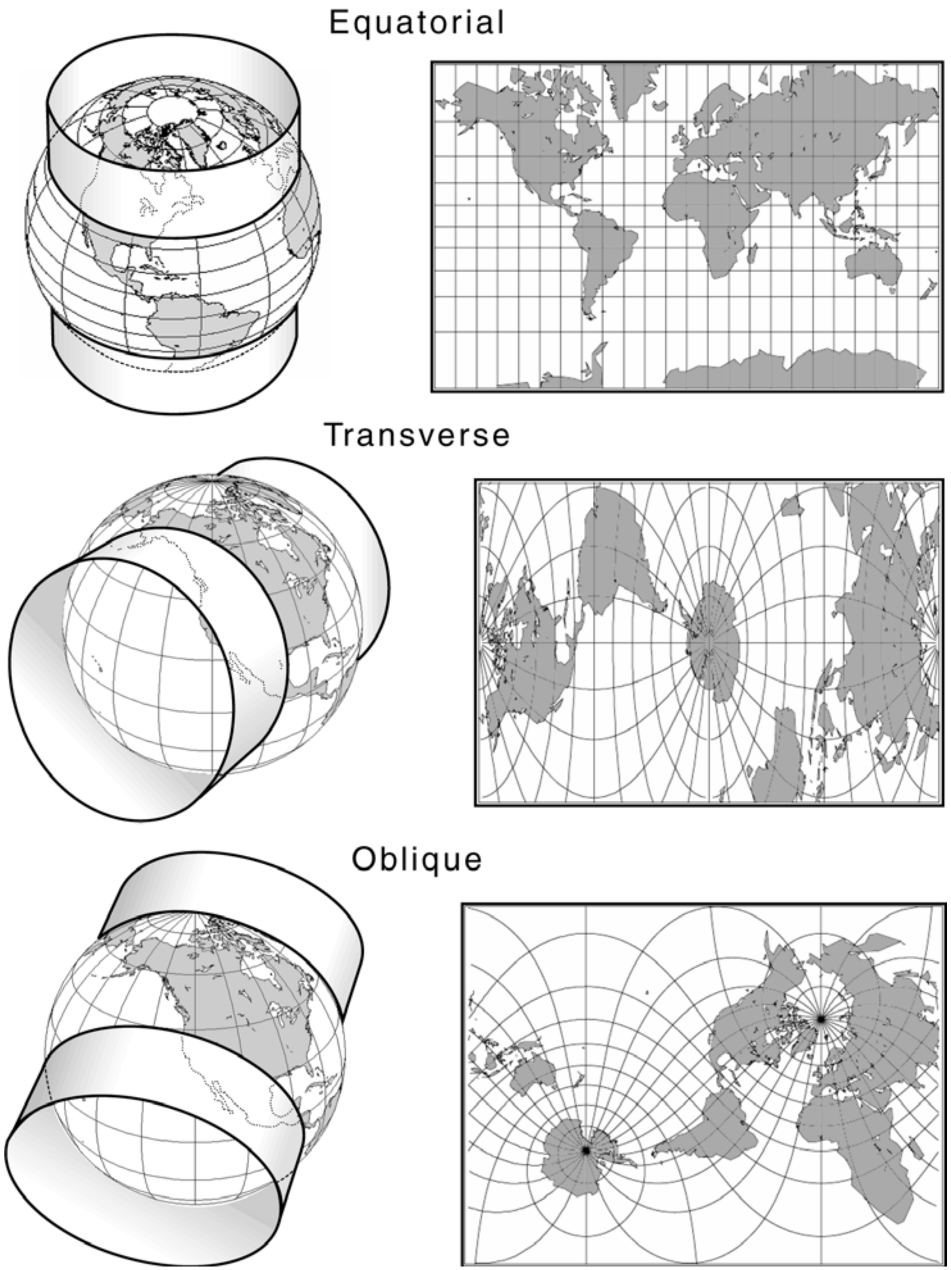
Peter H. Dana 4/25/95

Secant Planar Projection

- Secant projections have a **single standard line** (in the case of planar projection surfaces) or **multiple standard lines** (for conical and cylindrical projection surfaces) of contact between the developable surface and the globe

Secant Map Projections

Figure 2.9
Variations on the Mercator (pseudocylindrical) projection shown as secant



Standard Parallels

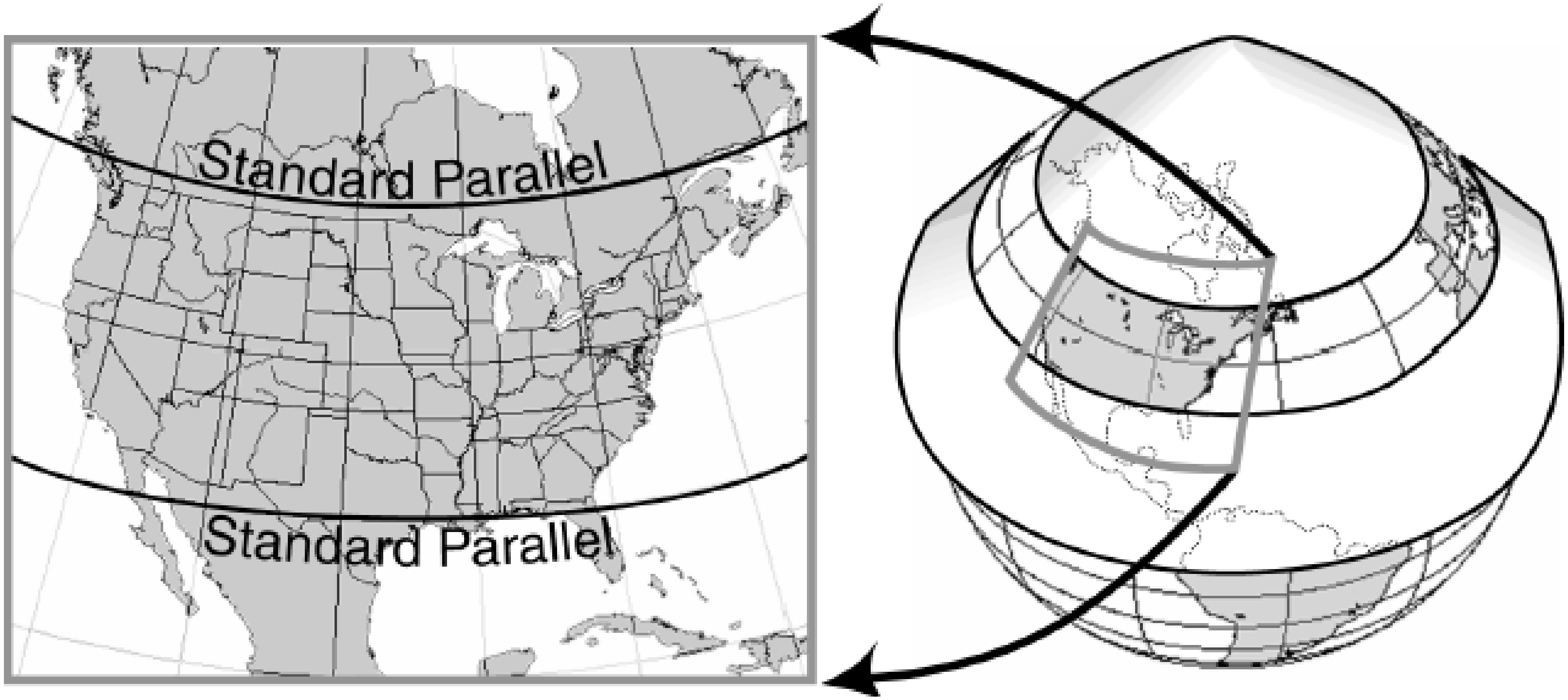


Figure 2.8 Standard parallels. The conic projection cuts through the globe, and the earth is projected both in and out onto it. This is a secant conic projection. Lines of true scale, where the cylinder and sphere touch, become standard parallels. If the touching is along one line, the projection is tangent and has one standard parallel.

Map Projections (continued)

- Projections can be based on axes **parallel** to the earth's rotation axis (equatorial), at **90 degrees to it** (transverse), or at **any other angle** (oblique).
- A projection that **preserves the shape** of features across the map is called **conformal**.
- A projection that **preserves the area** of a feature across the map is called **equal area or equivalent**.
- No flat map can be both equivalent and conformal. Most fall between the two as **compromises**.
- To **compare** maps in a GIS, both maps **MUST** be in the **same projection**.

No flat map can be both equivalent & conformal.

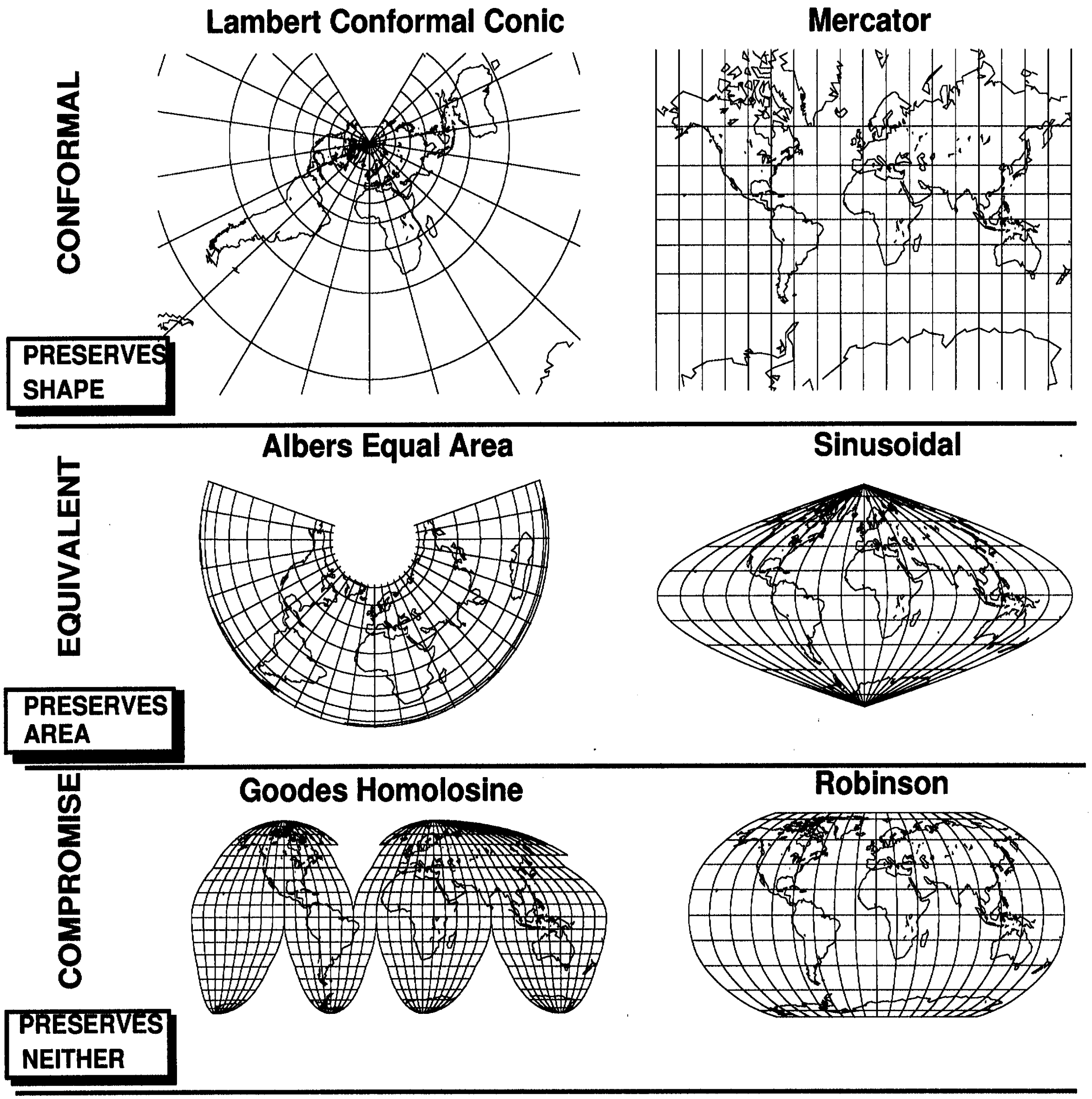


Figure 2.9 Examples of projections classified by their distortions. Conformal projections preserve local shape, equivalent projections preserve area, while compromise projections lie between the two. No projection can be equivalent and conformal.

Preservation of Properties

- Every map projection introduces some sort of **distortion** because there is always distortion when reducing our 3-dimensional reality to a 2-dimensional representation

- **Q:** How should we **choose** which projections to use?

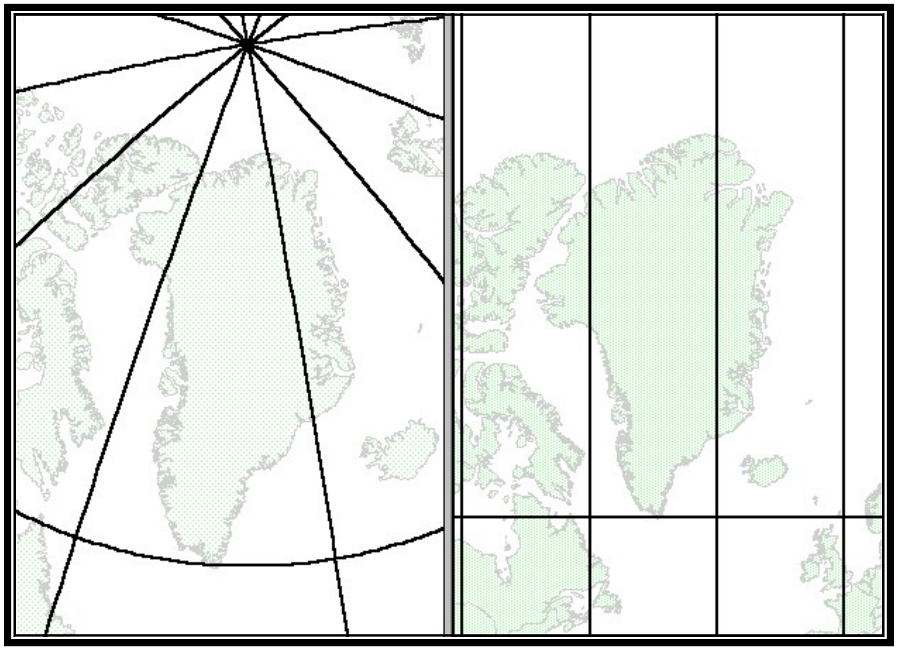
  A: We should choose a map projection that **preserves the properties** appropriate for the application, choosing from the following properties:

  1. Shape
  2. Area
  3. Distance
  4. Direction

Note: It may be more useful to classify map projections by the **properties they preserve**, rather than by the shape of their surfaces

Preservation of Properties - Shape

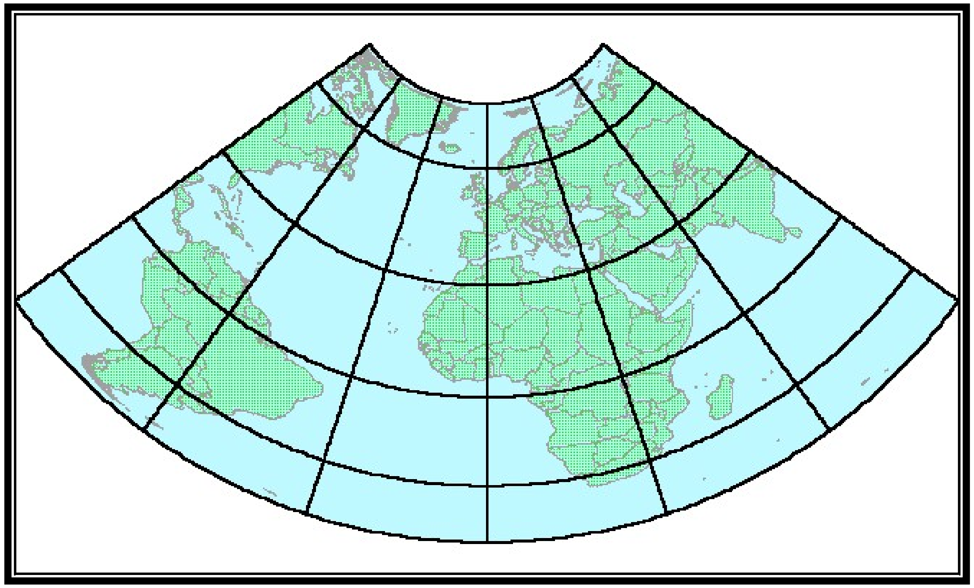
- If a projection preserves shape, it is known as a **conformal** projection
  - – preserves **local shape** (i.e. angles of features)
  - – graticule lines have **90°** intersection
  - – **distortion** of shape, area **over longer distances**
  - – **rhumb lines**
    - lines of constant direction



Greenland (Globe) Greenland (Mercator)

Preservation of Properties - Area

- **Equal Area Projections**
  - **preserve** the **area** of displayed features
  - however, shape, distance, direction, or any combination of these may be **distorted**
  - on large-scale maps, the distortion can be quite difficult to notice

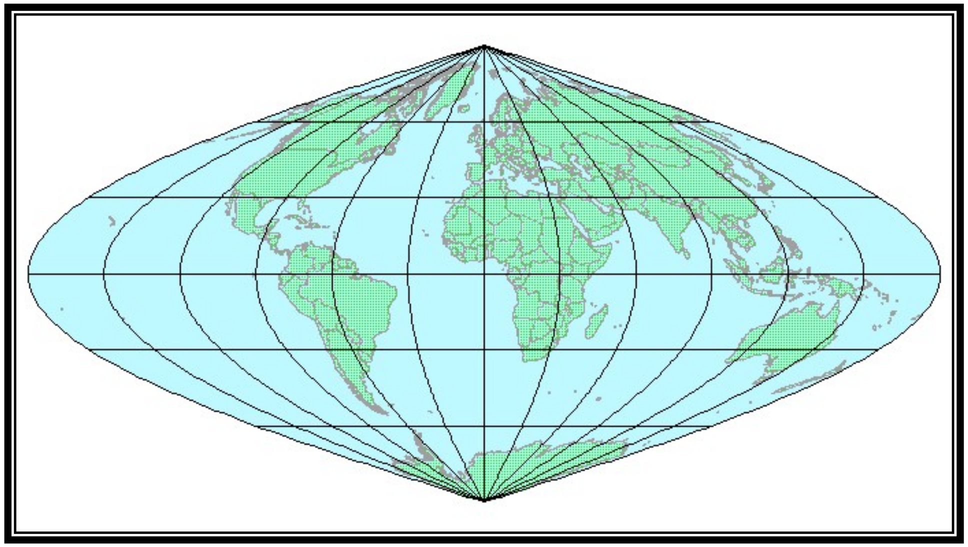


Albers Equal-Area Conic

A projection **cannot preserve both** shape and area!

Preservation Properties - Distance

- **Equidistant Projections**
  - **preserve** the **distance** between certain points
  - they maintain scale along one or more lines
  - display true distances

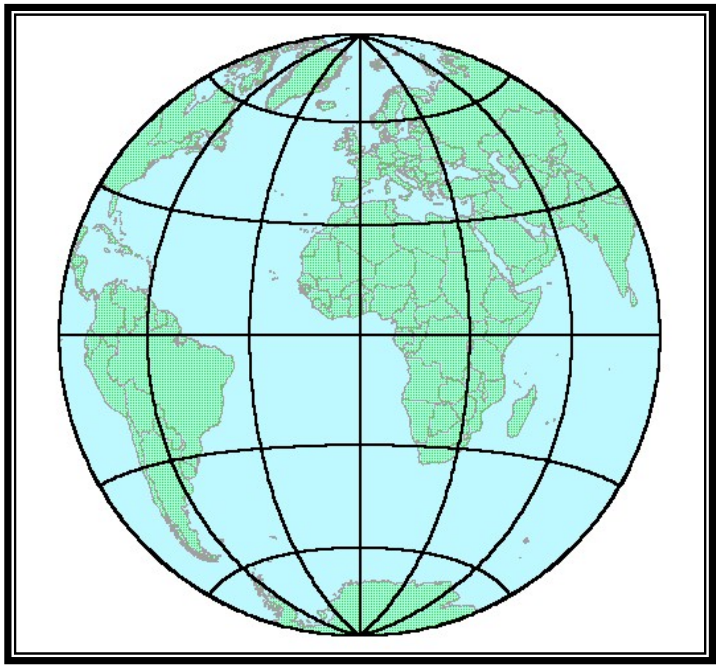


Sinusoidal

A projection **cannot preserve distance** everywhere!

Preservation Properties - Direction

- **Azimuthal Projections**
  - preserve **directions**, or azimuths, of all points on the map with respect to the center
  - They can also be
    - conformal
    - equal-area
    - equidistant



Lambert Equal-Area Azimuthal

A projection **cannot preserve direction** everywhere!

Coordinate Systems

- We have addressed both the issue of how to model the shape of the 3-dimensional Earth as an **ellipsoid/geoid**, and how to transform spatial information from the Earth’s surface to a 2-dimensional representation using the **projection** process

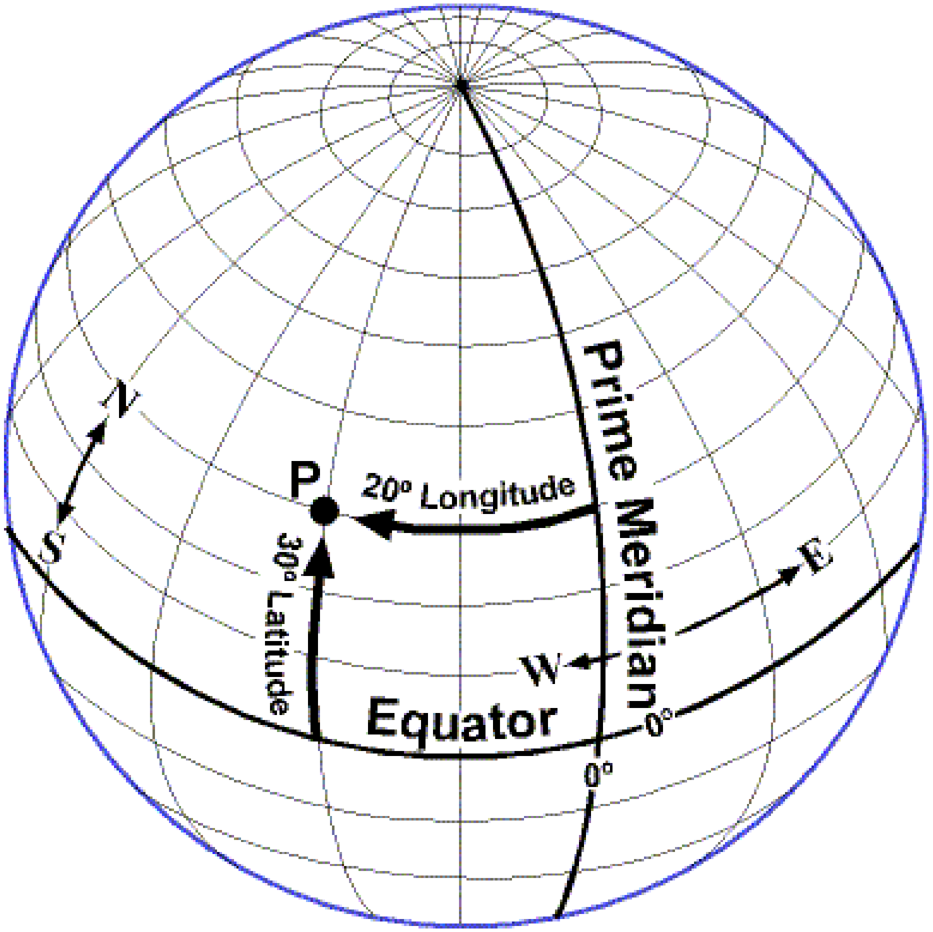
- Our remaining task is to conceive of some system by which we can precisely **specify locations** on a projected map that correspond to actual locations on the surface of the Earth → For this, we need to use some **coordinate system**

Coordinate Systems

- A coordinate system is a **standardized method** for **assigning codes to locations** so that locations can be found **using the codes alone**.
- Standardized coordinate systems use **absolute locations**.
- In a coordinate system, the x-direction value is the **easting** and the y-direction value is the **northing**. Most systems make both values positive.

The Geographic Coordinate System

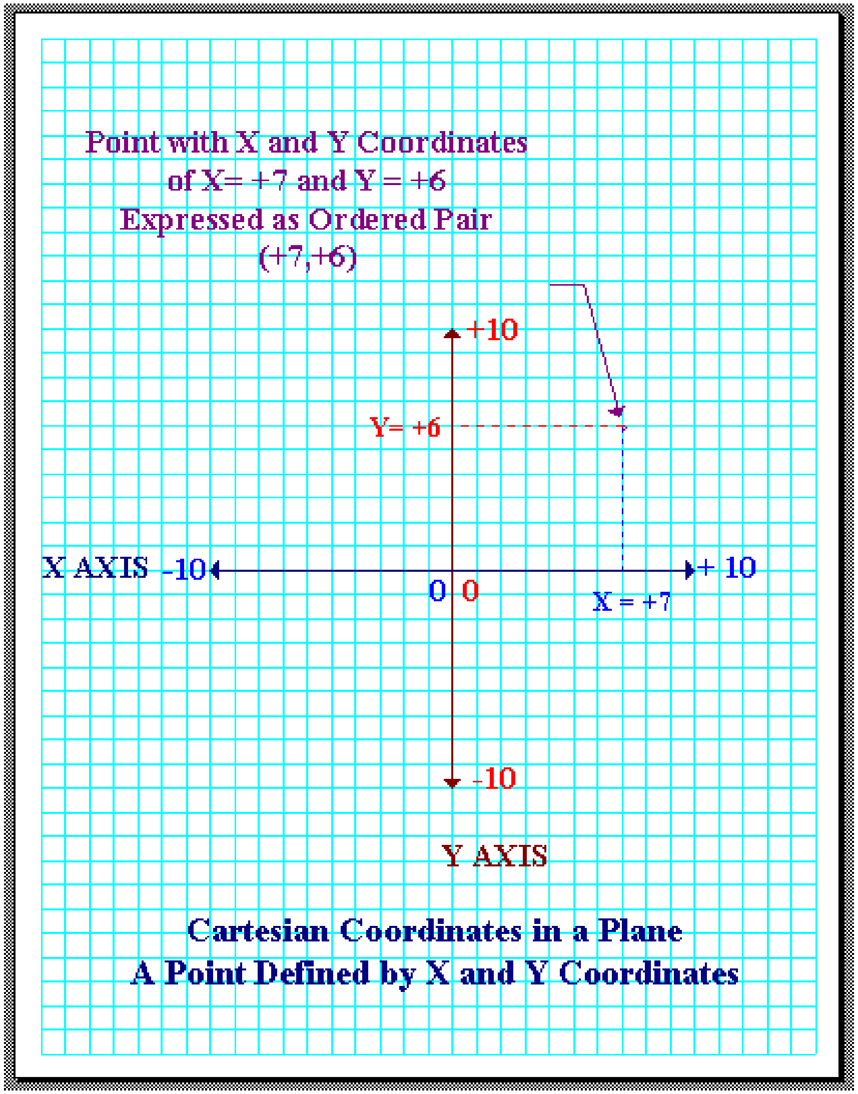
Viewing latitude and longitude angles from a 3D perspective:



Tony Kirvan 11-8-97

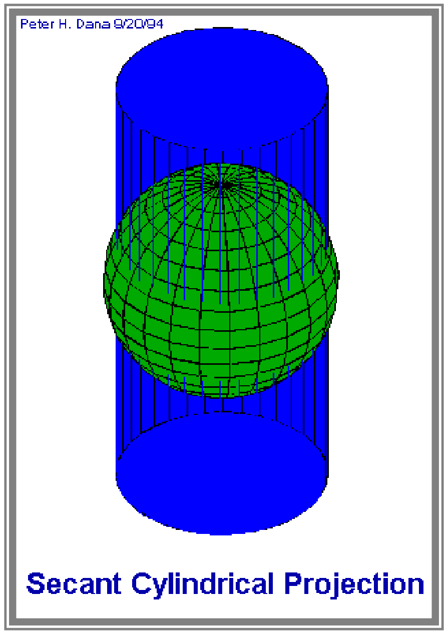
Planar Coordinate Systems

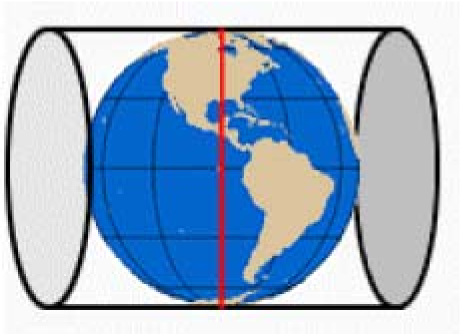
- Once we start working with **projected** spatial information, using latitude and longitude becomes **less convenient**
- We can instead use a **planar coordinate system** that has *x* and *y* axes, an arbitrary origin (a Cartesian plane), and some convenient units (e.g. ft. or m.)
- When applied in a geographic context:
  - **Eastings** are ***x*** values
  - **Northings** are ***y*** values



Universal Transverse Mercator

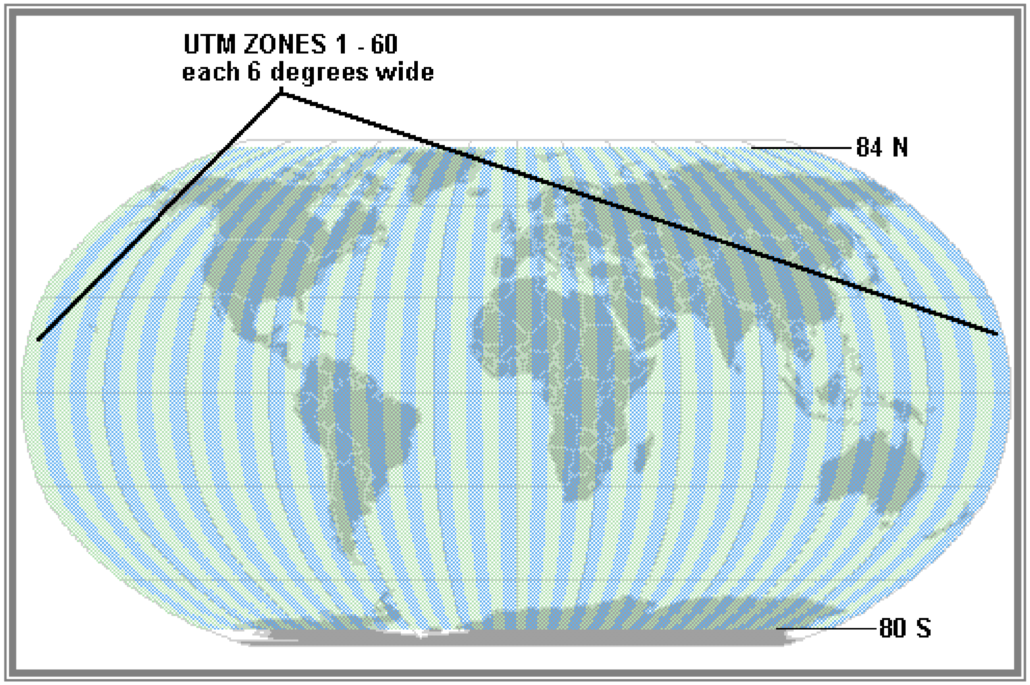
- Earlier, you were introduced to the Transverse Mercator **projection**
- That projection is used as the **basis** of the UTM **coordinate system**, which is widely used for topographical maps, satellite images, and many other uses
- The projection is based on a **secant transverse cylindrical projection**
- Recall that this projection uses a **transverse cylinder** that has **standard lines** that run **north-south**, and **distortion** increases as we move further **east or west**



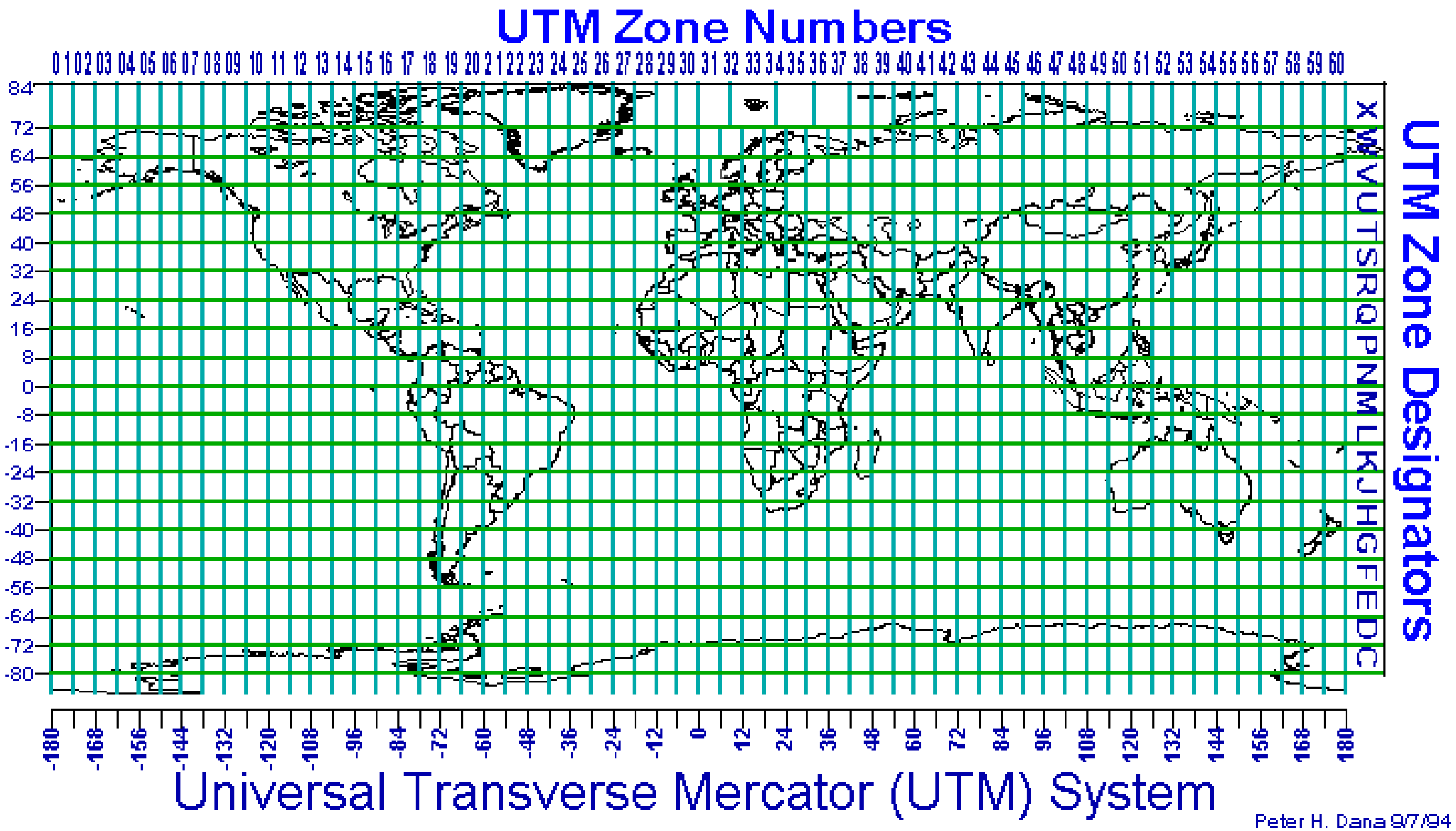


Universal Transverse Mercator

- In order to **minimize** the **distortion** associated with the projection, the UTM coordinate system uses a **separate Transverse Mercator projection** for every **6 degrees** of longitude → the world is divided into **60 zones**, each 6 degrees of longitude in width, each with its own UTM projection:

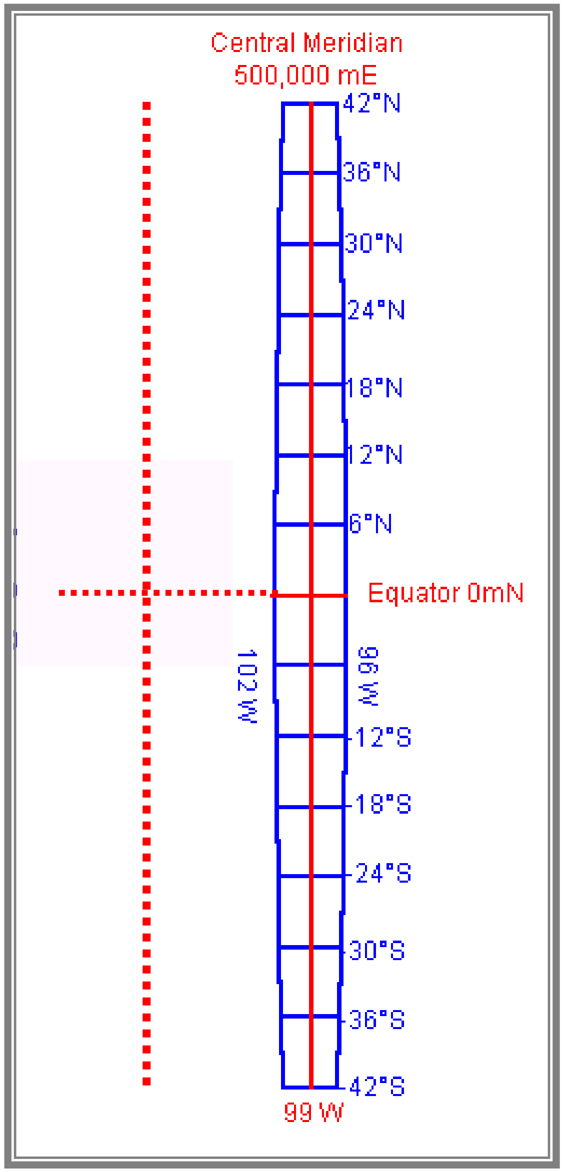


Universal Transverse Mercator



Universal Transverse Mercator

- The **central meridian**, which runs down the middle of the zone, is used to define the position of the origin
- **Distance units** in UTM are defined to be in **meters**, and distance from the origin is measured as an **Easting** (in the x-direction) and a **Northing** (in the y-direction)
- The x-origin is west of the zone (a false easting), and is placed such that the central meridian has an Easting of **500,000 meters**



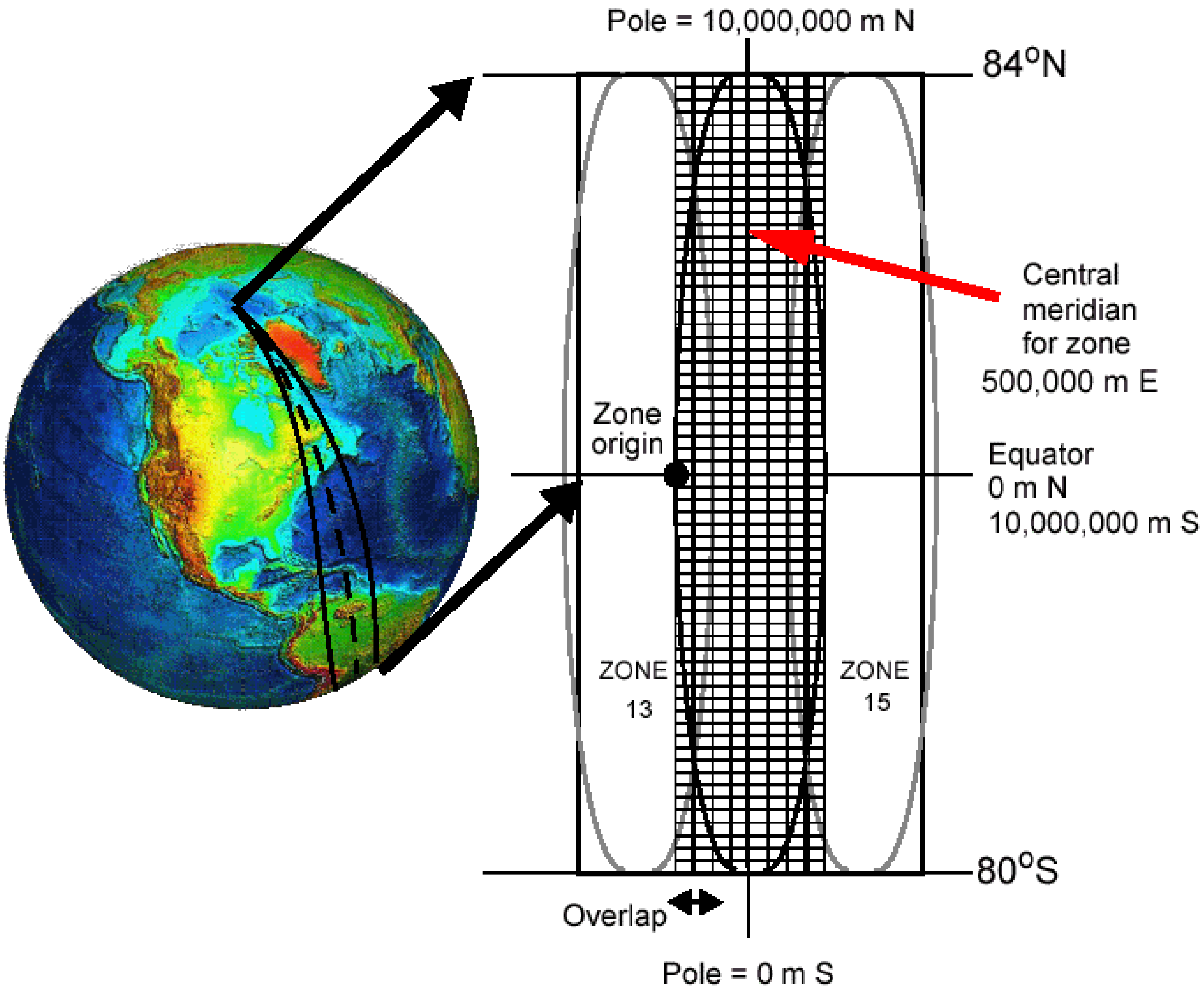


Figure 2.14 The universal transverse Mercator coordinate system.

UTM Zones in the Lower 48

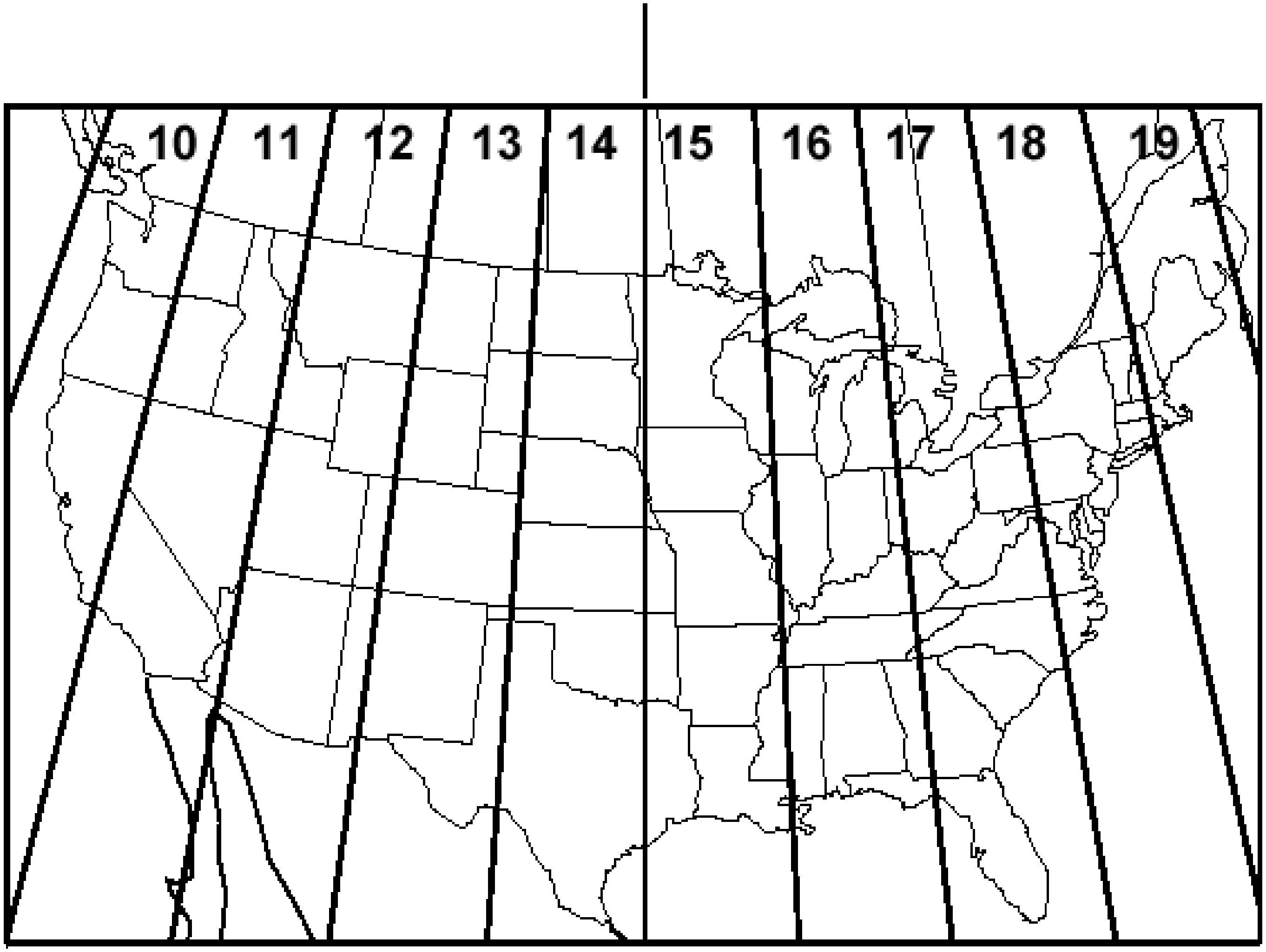


Figure 2.13 Universal transverse Mercator zones in the 48 contiguous states.

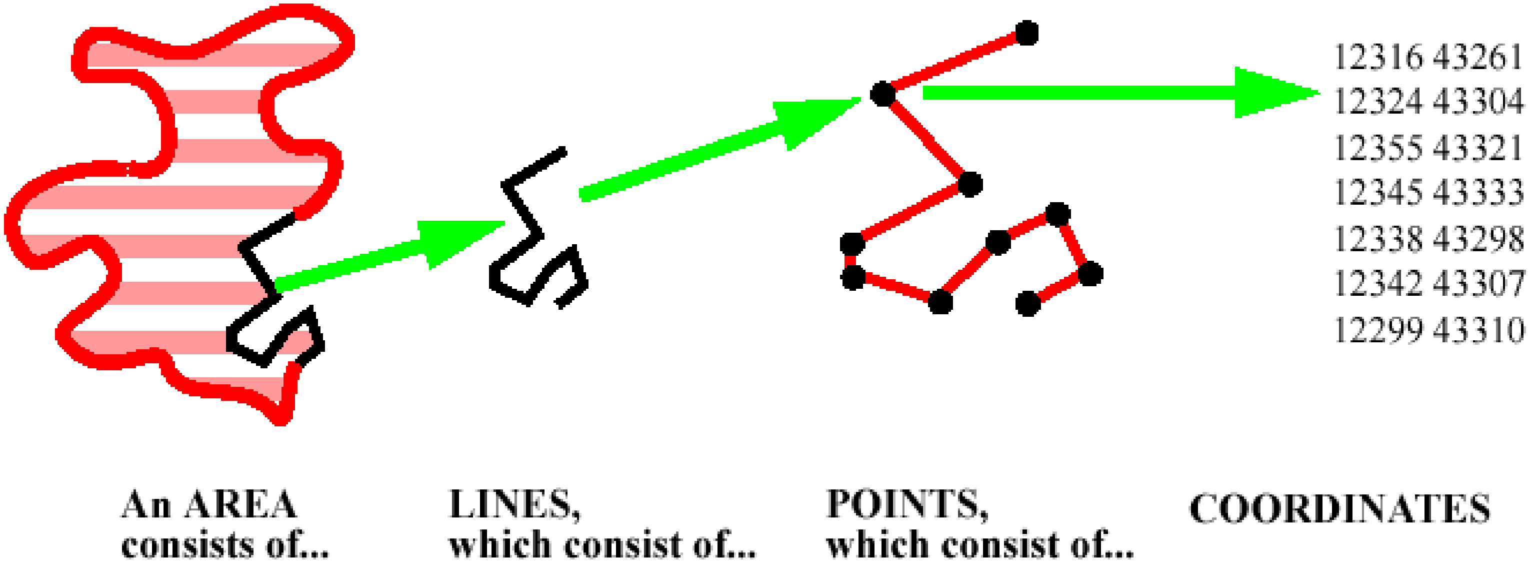
GIS Capability

- A GIS package should be able to **move between**
  - map projections,
  - coordinate systems,
  - datums, and
  - ellipsoids.

Building complex features

- **Simple** geographic features can be used to **build** more **complex** ones.
- **Areas** are **made up of lines** which are **made up of points** represented by their **coordinates**.
- Areas = {Lines} = {Points}

Areas are Lines are Points are Coordinates

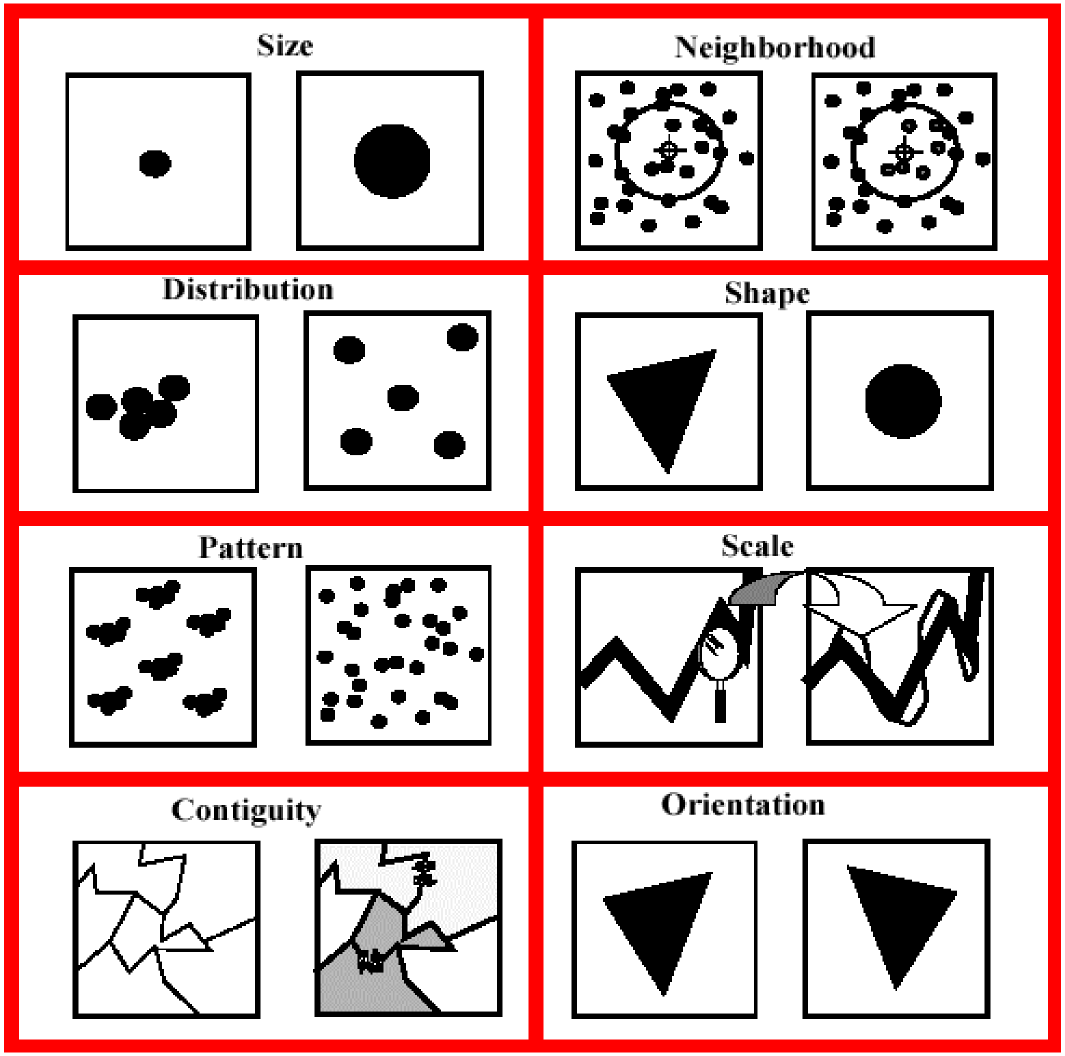


12316	43261
12324	43304
12355	43321
12345	43333
12338	43298
12342	43307
12299	43310

Figure 2.19 Geographic information has *dimension.* Areas are two-dimensional and consist of lines, which are one-dimensional and consist of points, which are zero-dimensional and consist of a coordinate pair.

Basic Properties of Geographic Features

- size
- distribution
- pattern
- contiguity
- neighborhood
- shape
- scale
- orientation.



GIS Analysis

- Much of GIS analysis and description consists of **investigating the properties** of geographic features and **determining the relationships** between them.

GIS's Roots in Cartography

- Earth models
- Datum
- Geographic coordinates
- Map projections
- Coordinate systems
- Basic properties of geographic features

Next Topic:

Maps as Numbers