Spatial DBs

Objectives/TOC

- spatial DBs: definition, characteristics, need, creation..
- spatial datatypes
- spatial operators
- spatial indices
- implementations
- miscellany

What is a spatial database?

"A spatial database is a database that is optimized to store and query data related to objects in space, including points, lines and polygons."

In other words, it includes objects that have a SPATIAL location (and extent). A chief category of spatial data is geospatial data - derived from the geography of our earth.

Characteristics of geographic data

- has location
- has size
- is auto-correlated
- scale dependent
- might be temporally dependent too

Geographic data is NOT 'business as usual'!

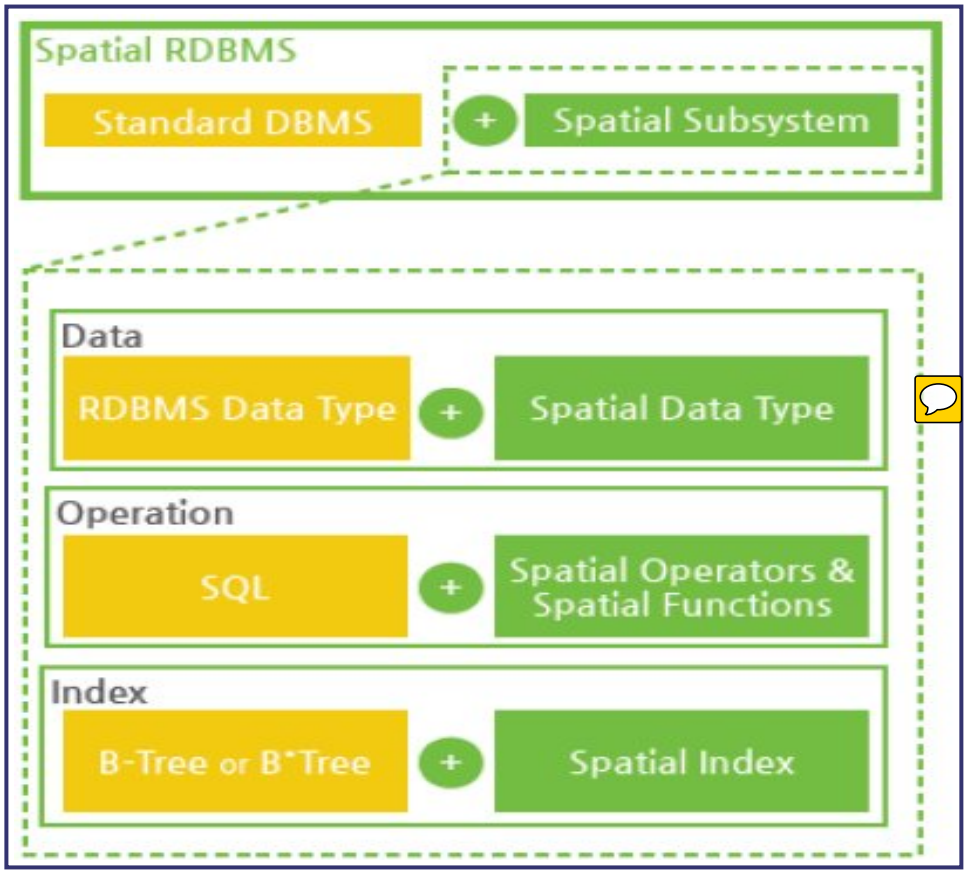
Entity view vs field view

In spatial data analysis, we distinguish between two conceptions of space:

- entity view: space as an area filled with a set of discrete objects
- field view: space as an area covered with essentially continuous surfaces

For our purposes, we will adopt the 'entity' view, where space is populated by discrete objects (roads, buildings, rivers..).

Components



So a spatial DB is a collection of the following, specifically built to handle spatial data:

- **types**
- **operators**

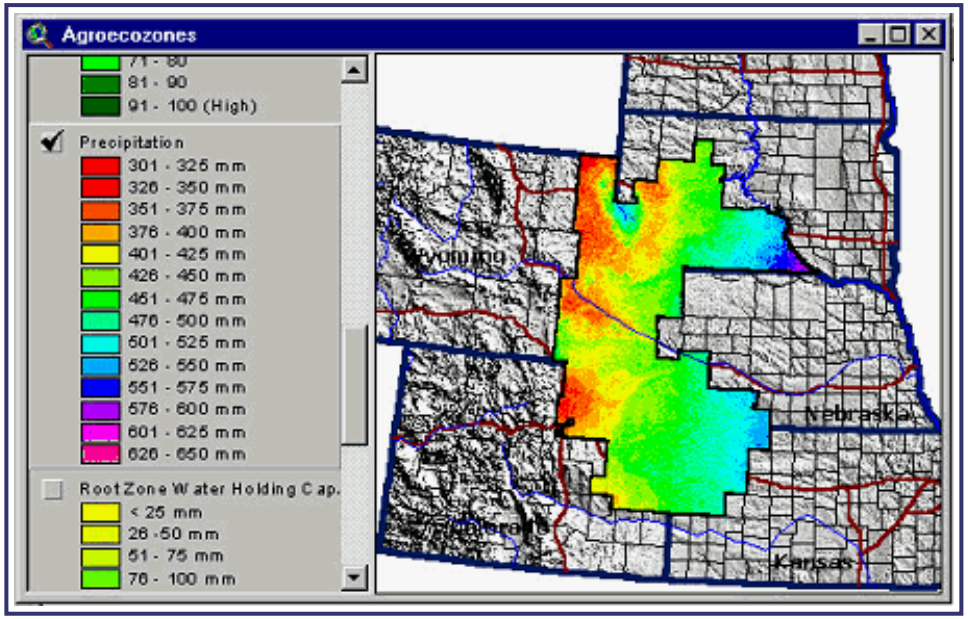
- indices 

Soon, we will explore what types, operators and indices mean.

Examples of spatial data

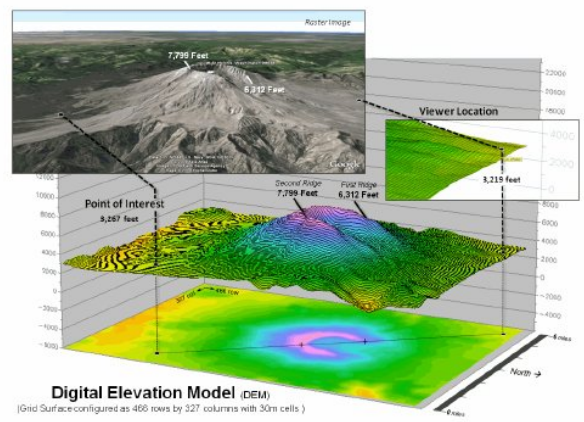
CAD data:

Agricultural data:



3D data:

- Three-dimensional data examples
  - Weather
  - Cartesian coordinates (3-D)
  - Topological
  - Satellite images



What can be plotted on to a map?

- crime data
- spread of disease, risk of disease [look at this too]
- drug overdoses - over time
- census data
- income distribution, home prices
- locations of Starbucks (!)
- (real-time) traffic
- agricultural land use, deforestation

Who uses spatial data?

- **Army Field Commander**: Has there been any significant enemy troop movement since last night?
- **Insurance Risk Manager**: Which homes are most likely to be affected in the next great flood on the Mississippi?
- **Medical Doctor**: Based on this patient's MRI, have we treated somebody with a similar condition ?
- **Molecular Biologist**: Is the topology of the amino acid biosynthesis gene in the genome found in any other sequence feature map in the database ?
- **Astronomer**:Find all blue galaxies within 2 arcmin of quasars.

Government agencies

Various government agencies routinely coordinate spatial data collection and use, operating in effect, a national spatial data infrastructure (NSDI) - these include federal, state and local agencies. At the federal level, participating agencies include:

- Department of Commerce
  - Bureau of the Census
  - NIST
  - NOAA
- Department of Defense
  - Army Corps of Engineers
  - Defense Mapping Agency
- Department of the Interior
  - Bureau of Land Management

  - Fish and Wildlife Service
  - U.S Geological Survey
- Department of Agriculture
  - Agricultural Stabilization and Conservation Service
  - Economic Research Service
  - Forest Service
  - National Agriculture Statistical Service
  - Soil Conservation Service
- Department of Transportation
  - Federal Highway Administration
- Environmental Protection Agency
- NASA 

As you can see, spatial data is a SERIOUS resource, vital to national interests.

Where does spatial data come from?

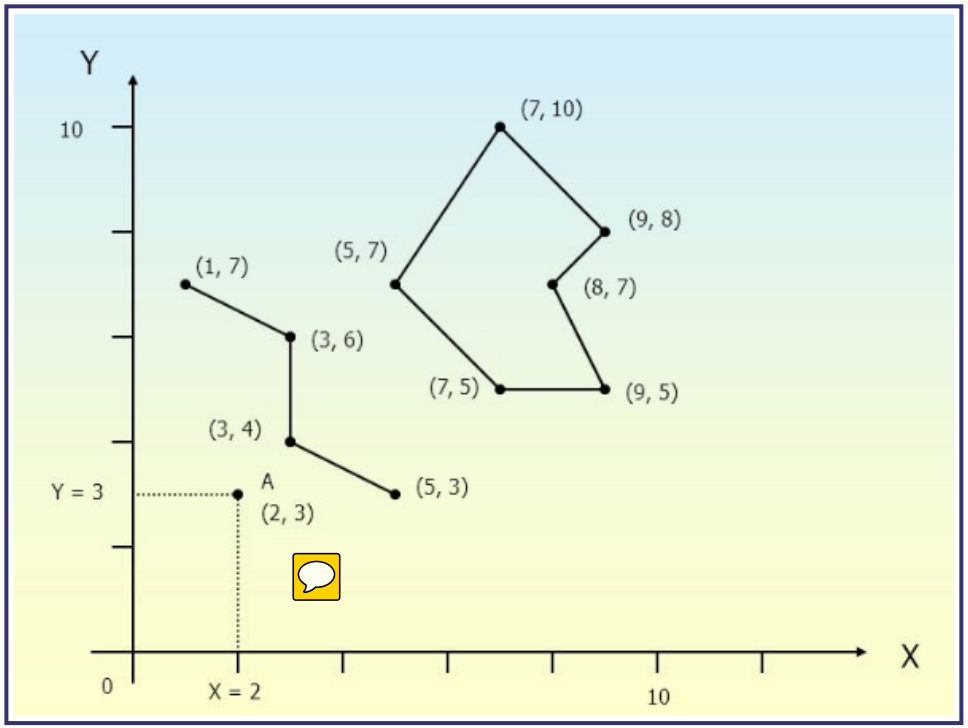
Spatial data is created in a variety of ways:

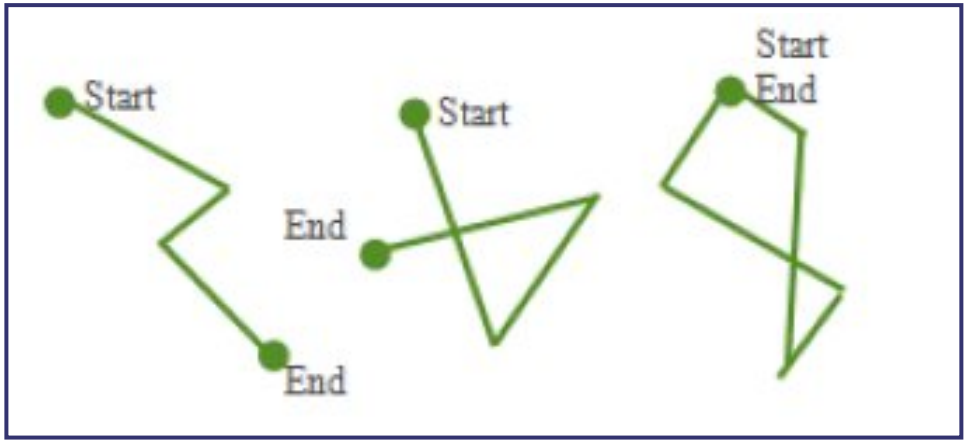
- CAD: user creation
- CAD: reverse engineering
- maps: cartography (surveying, plotting)
- maps: satellite imagery
- maps: 'copter, drone imagery
- maps: driving around
- maps: walking around

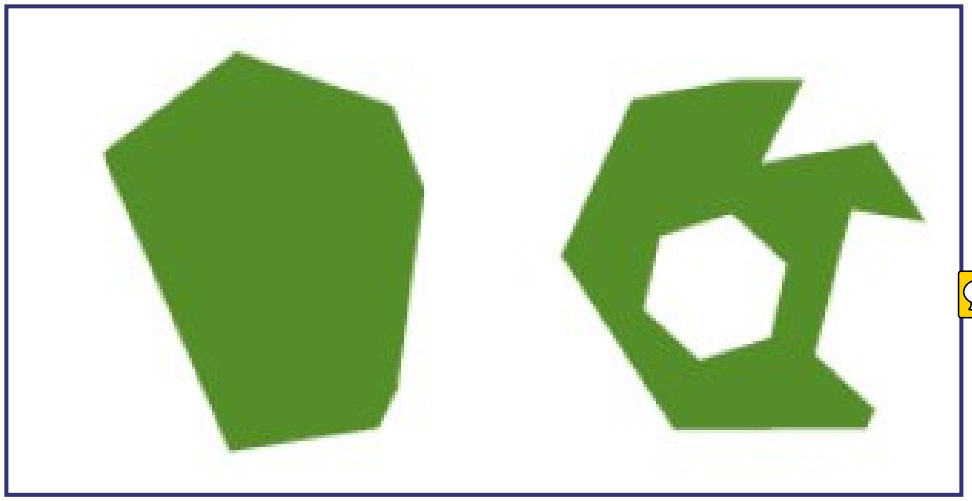
What to store?

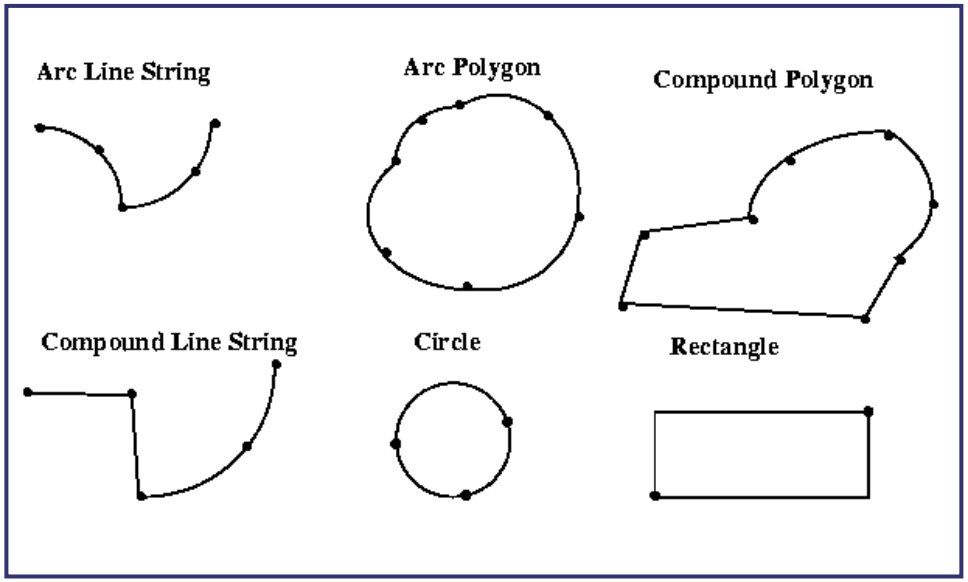
All spatial data can be described via the following entities/types:

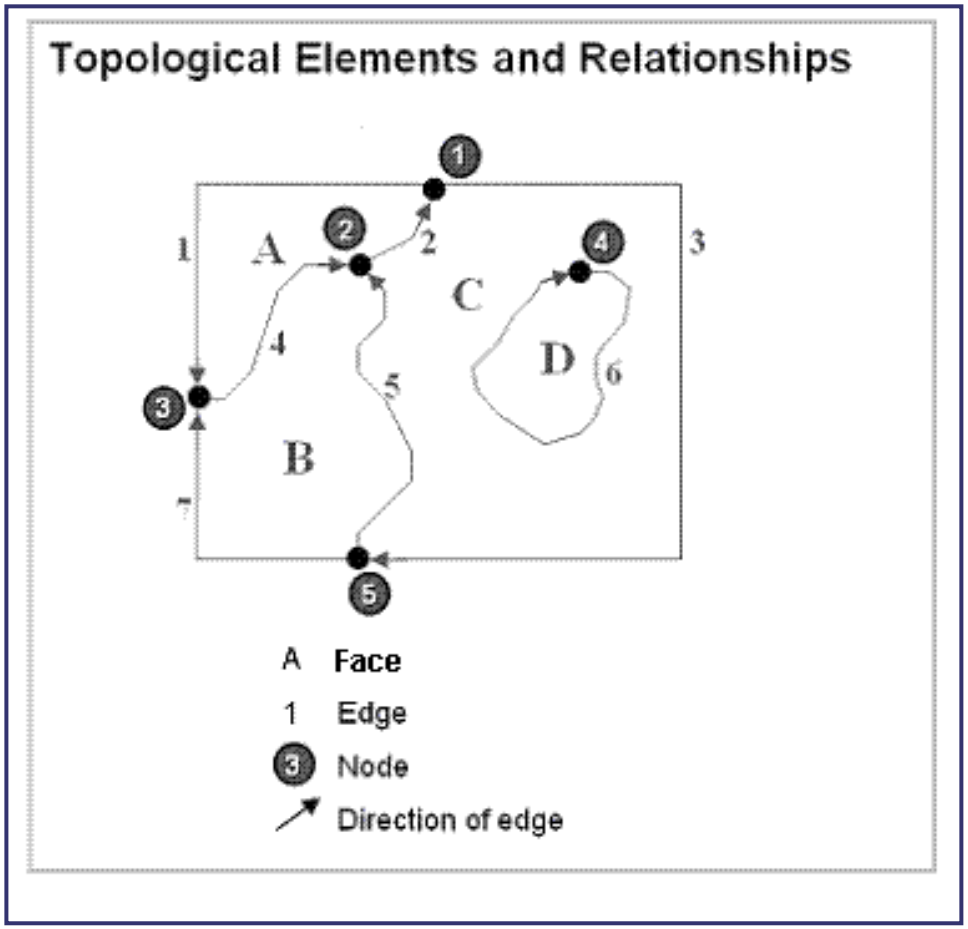
- points/vertices/nodes
- polylines/arcs/linestrings
- polygons/regions
- pixels/raster

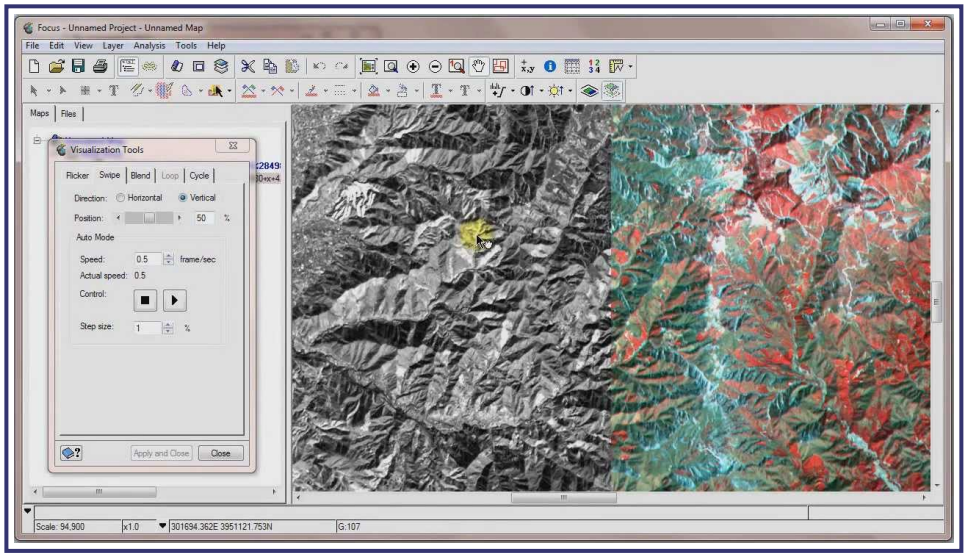

Y
10
(7, 10)
(9, 8)
(5, 7)
(1, 7)
(8, 7)
(3, 6)
(7, 5)
(9, 5)
(3, 4)
Y = 3
A
(2, 3)
(5, 3)
X
0
X = 2
10


Start
Start
Start
End
End
End




Arc Line String
Arc Polygon
Compound Polygon
Compound Line String
Circle
Rectangle

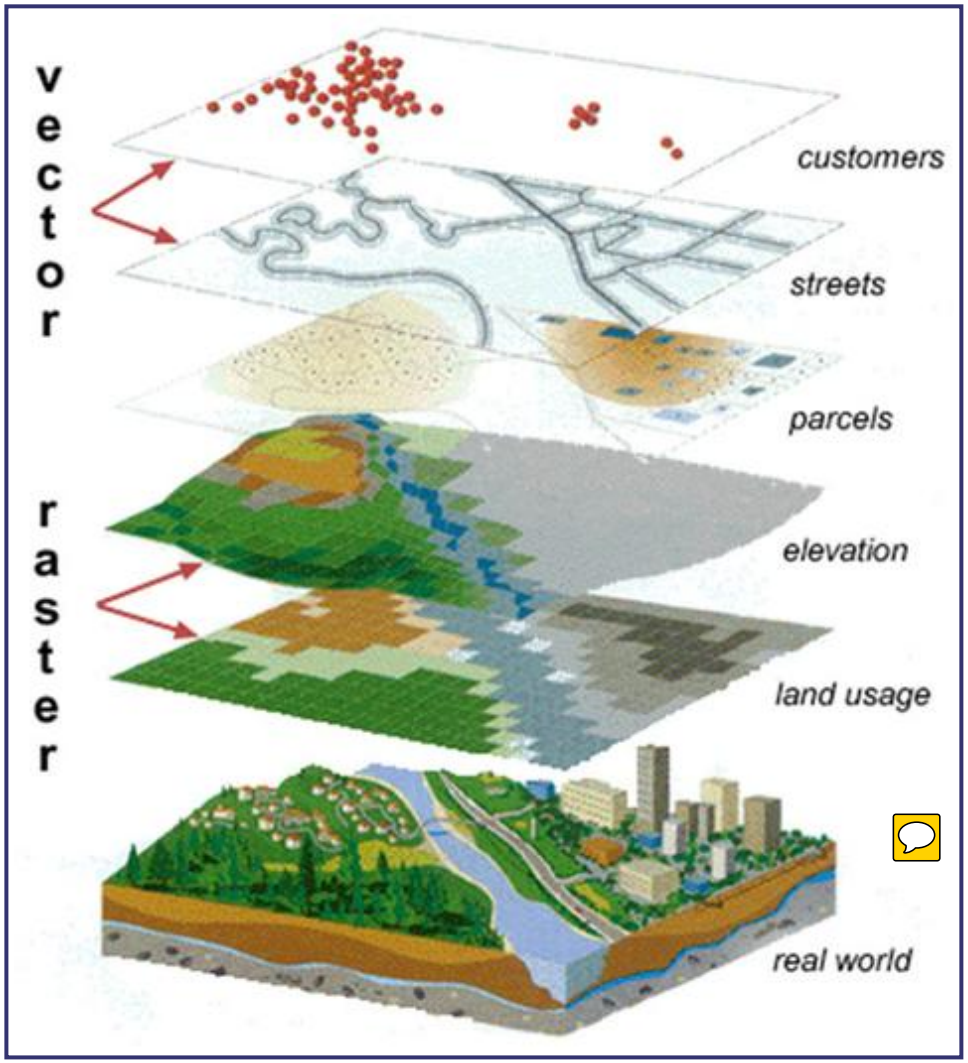

Topological Elements and Relationships
1
2
3
4
5
A
B
C
D
1
2
3
4
5
6
7
A Face
1 Edge
3 Node
Direction of edge

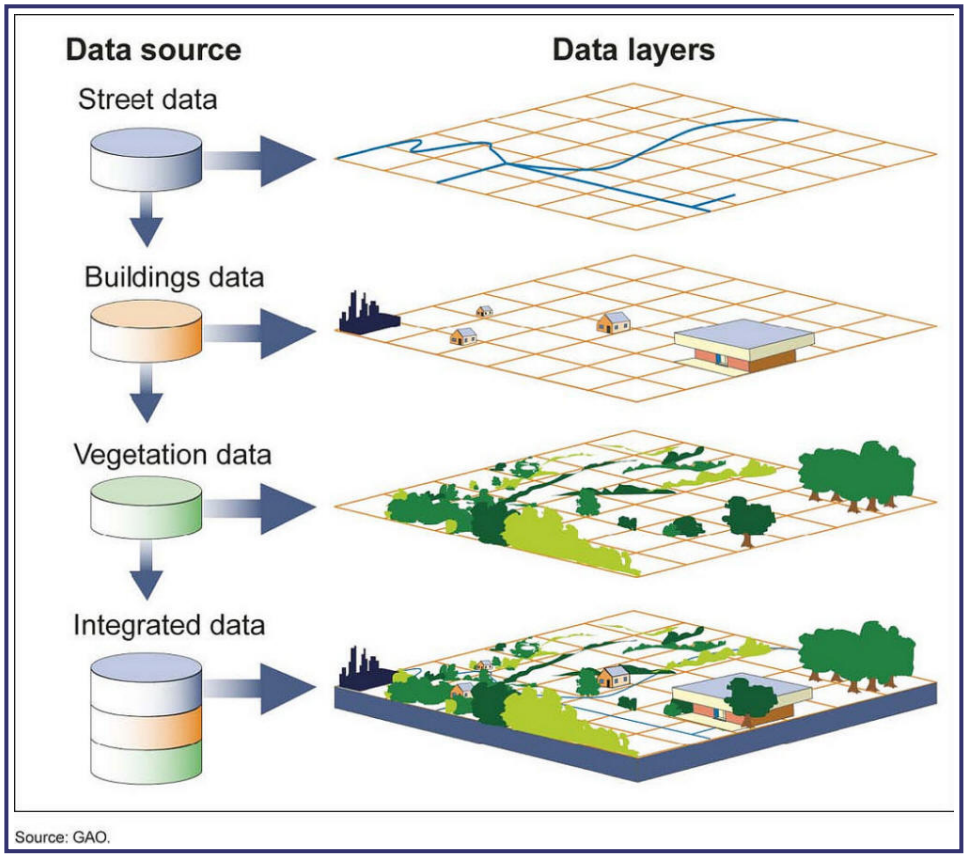

Focus - Unnamed Project - Unnamed Map
File Edit View Layer Analysis Tools Help
Maps Files
Visualization Tools
Flicker Swipe Blend Loop Cycle
Direction: Horizontal Vertical
Position: 50 %
Auto Mode
Speed: 0.5 frame/sec
Actual speed: 0.5
Control:
Step size: 1 %
Apply and Close
Close
Scale: 94,900
x1.0
301694.362E 3951121.753N
G:107

Points, lines, polys => models and non-spatial attrs

Once we have spatial data (points, lines, polygons), we can:

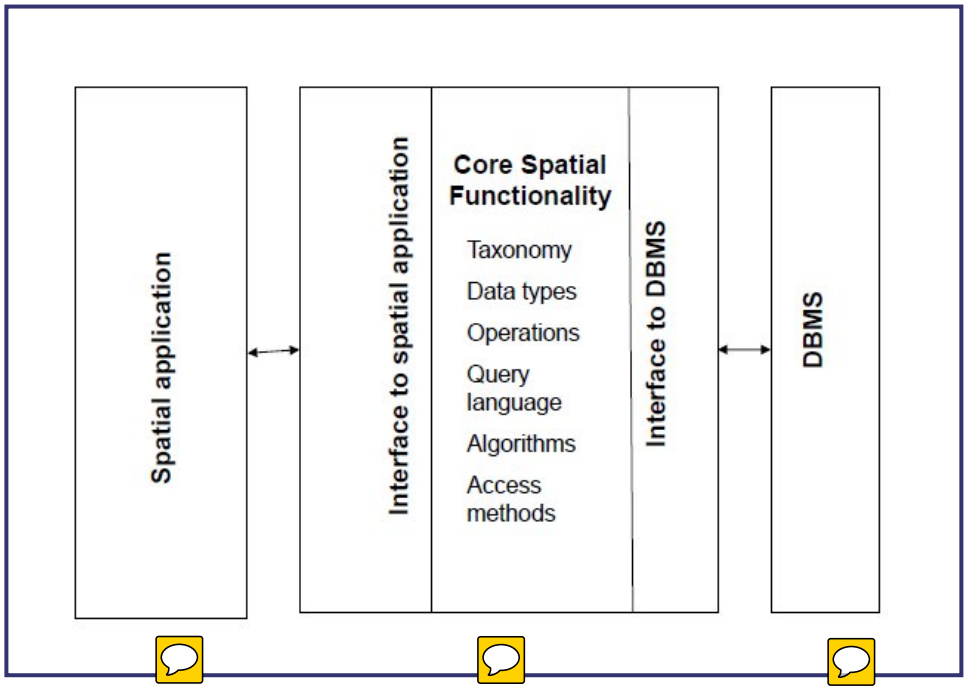
- 'model' features such as lakes, soil type, highways, buildings etc, using the geometric primitives as underlying types
- add 'extra', non-spatial attributes/features to the underlying spatial data

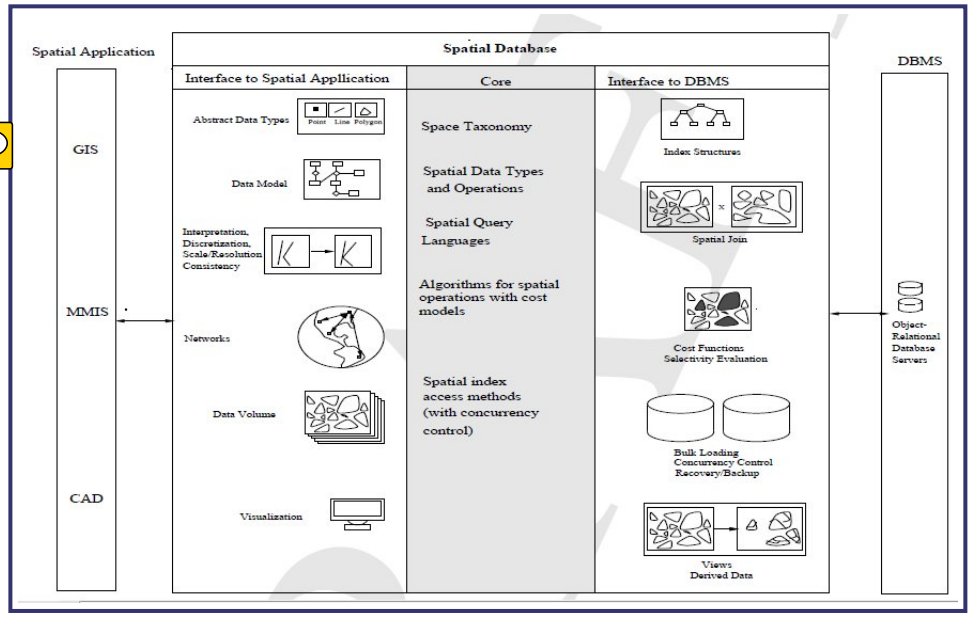

vector
raster
customers
streets
parcels
elevation
land usage
real world



Look at this map, overlaid with scary data..

SDBMS architecture




Spatial Application
Spatial Database
DBMS
Interface to Spatial Applliication
Core
Interface to DBMS
GIS
MMIS
CAD
Abstract Data Types
Point Line Polygon
Data Model
Interpretation, Discretization, Scale/Resolution Consistency
Networks
Data Volume
Visualization
Space Taxonomy
Spatial Data Types and Operations
Spatial Query Languages
Algorithms for spatial operations with cost models
Spatial index access methods (with concurrency control)
Index Structures
Spatial Join
Cost Functions Selectivity Evaluation
Bulk Loading Concurrency Control Recovery/Backup
Views Derived Data
Object-Relational Database Servers

GIS vs SDBMS

GIS is a specific application architecture built on top of a [more general purpose] SDBMS.

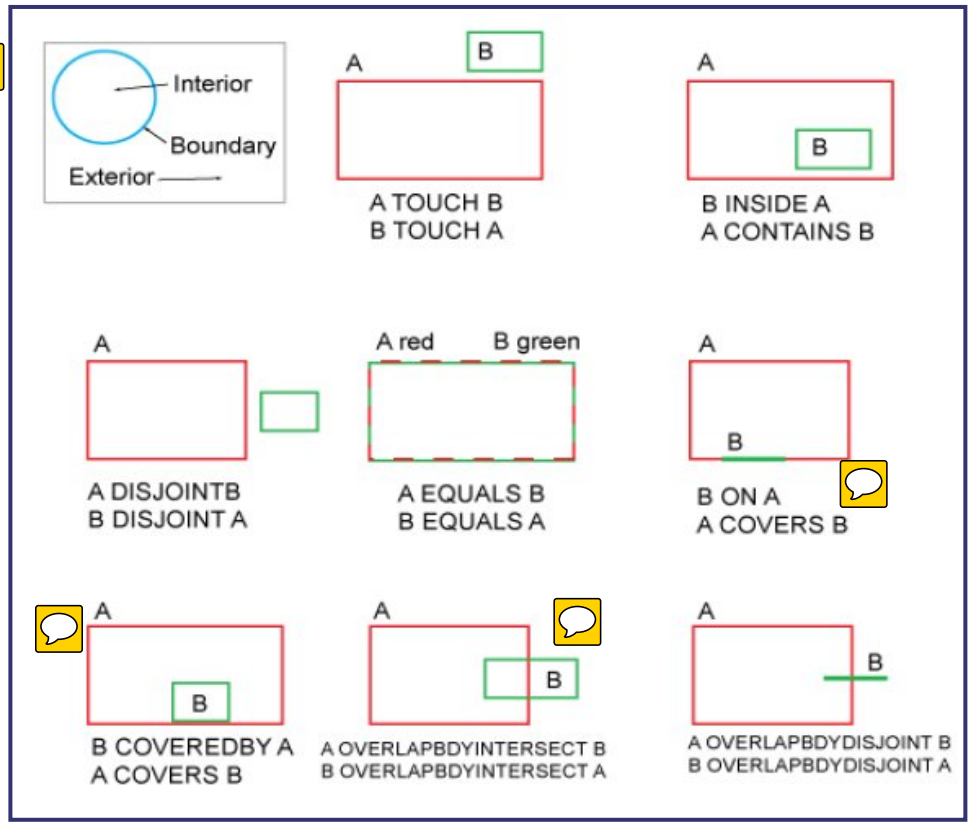
GIS typically tend to be used for:

Search	Thematic search, search by region, (re-)classification
Location analysis	Buffer, corridor, overlay
Terrain analysis	Slope/aspect, catchment, drainage network
Flow analysis	Connectivity, shortest path
Distribution	Change detection, proximity, nearest neighbor
Spatial analysis/Statistics	Pattern, centrality, autocorrelation, indices of similarity, topology: hole description
Measurements	Distance, perimeter, shape, adjacency, direction

Spatial relationships

In 1D (and higher), spatial relationships can be expressed using 'intersects', 'crosses', 'within', 'touches' (these are T/F predicates).

Here is a sampling of spatial relationships in 2D:



Another diagram showing the [binary] operations:

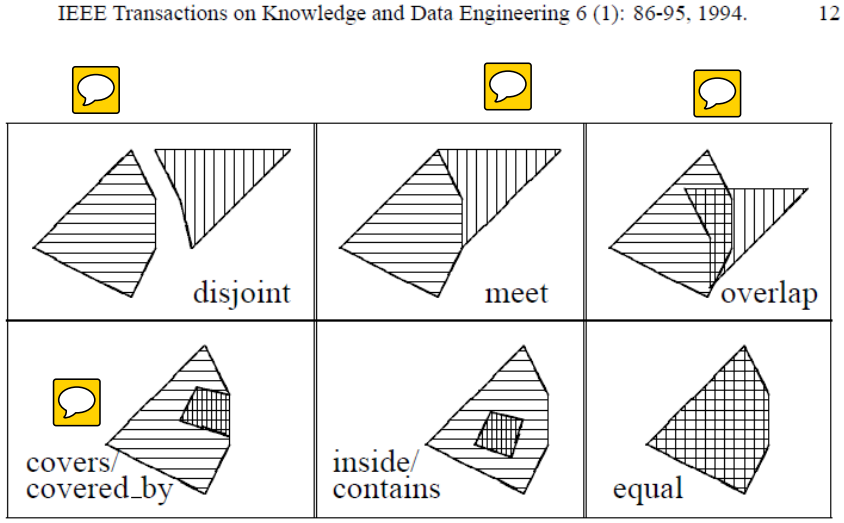
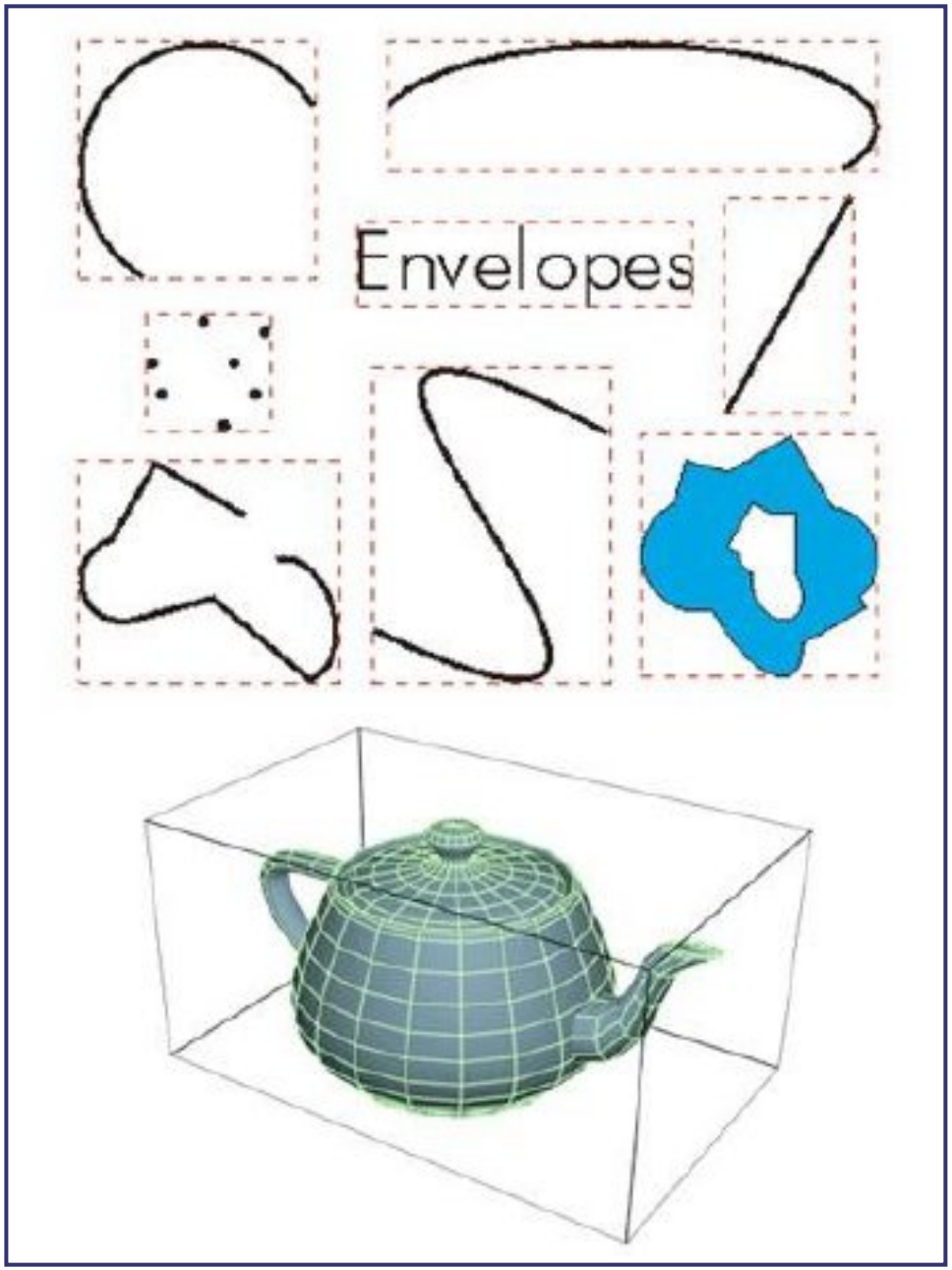


Figure 2. Examples of the binary topological relationships (a) disjoint, (b) meet, (c) overlap, (d) covers/covered_by, (e) inside/contains, and (f) equal [24].

Minimum Bounding Rectangles (MBRs) are what are used to compute the results of operations shown above:


Envelopes

Spatial relations - categories

Spatial relationships can be:

- **topology**-based [using defns of boundary, interior, exterior]
- **metric**-based [**distance**/Euclidian, **angle** measures]
- **direction**-based
- **network**-based [eg. **shortest path**]

Topological relationships could be further grouped like so:

- **proximity**
- **overlap**
- **containment**

How can we put these relations to use?

We can perform the following, on spatial data:

- spatial measurements: find the distance between points, find polygon area..
- spatial functions: find nearest neighbors..
- spatial predicates: test for proximity, containment..

Spatial Data Entity Creation

- Form an entity to hold county names, states, populations, and geographies

```
CREATE TABLE County(
    Name        varchar(30),
    State       varchar(30),
    Pop         Integer,
    Shape       Polygon);
```

Spatial Data Entity Creation (Cont.)

- Form an entity to hold river names, sources, lengths, and geographies

```
CREATE TABLE River(
    Name        varchar(30),
    Source      varchar(30),
    Distance    Integer,
    Shape       LineString);
```

Example Spatial Query

- Find all the counties that border on Contra Costa county

```
SELECT      C1.Name
FROM        County C1, County C2
WHERE       Touch(C1.Shape, C2.Shape) = 1
            AND C2.Name = 'Contra Costa';
```

Example Spatial Query (Cont.)

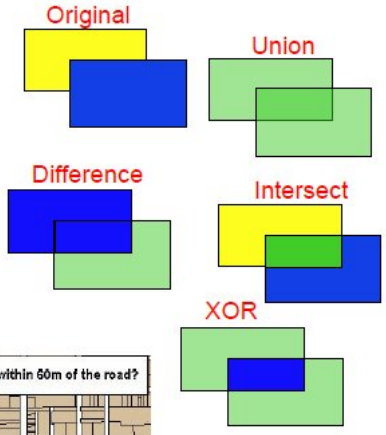
- Find all the counties through which the Merced river runs

```
SELECT      C.Name, R.Name
FROM        County C, River R
WHERE       Intersect(C.Shape, R.Shape) = 1
            AND R.Name = 'Merced';
```

Spatial operators, functions

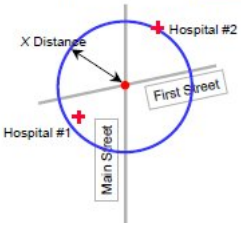
Spatial Functions

- Returns a geometry
  - Union
  - Difference
  - Intersect
  - XOR
  - Buffer
  - CenterPoint
  - ConvexHull
- Returns a number
  - LENGTH
  - AREA
  - Distance



Spatial Operators

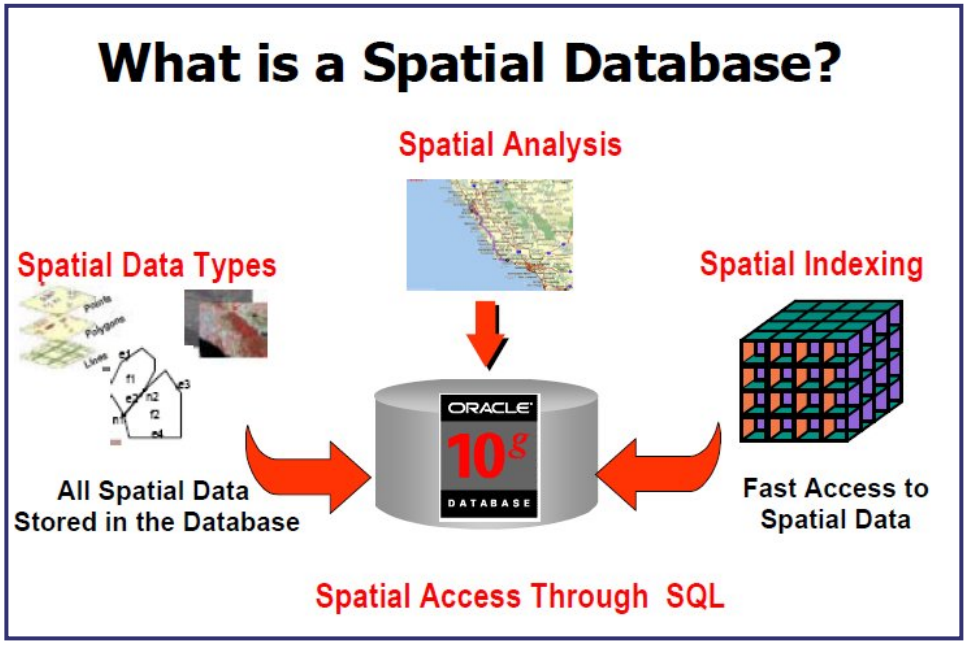
- Full range of spatial operators
  - Implemented as functional extensions in SQL
  - Topological Operators
    - Inside Contains
    - Touch Disjoint
    - Covers Covered By
    - Equal Overlap Boundary
  - Distance Operators
    - Within Distance
    - Nearest Neighbor

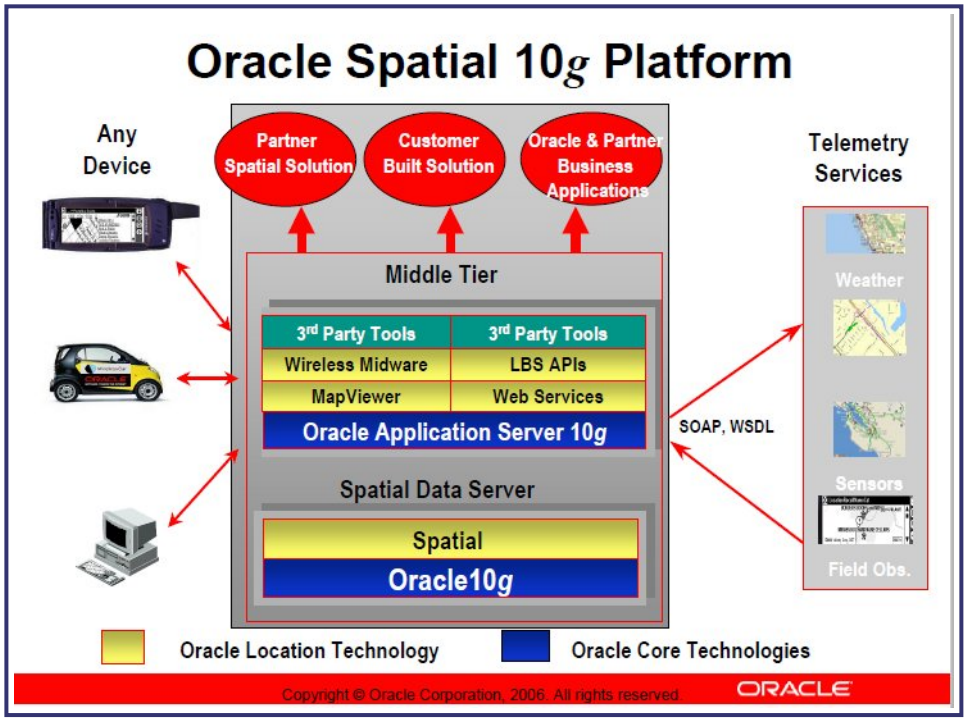


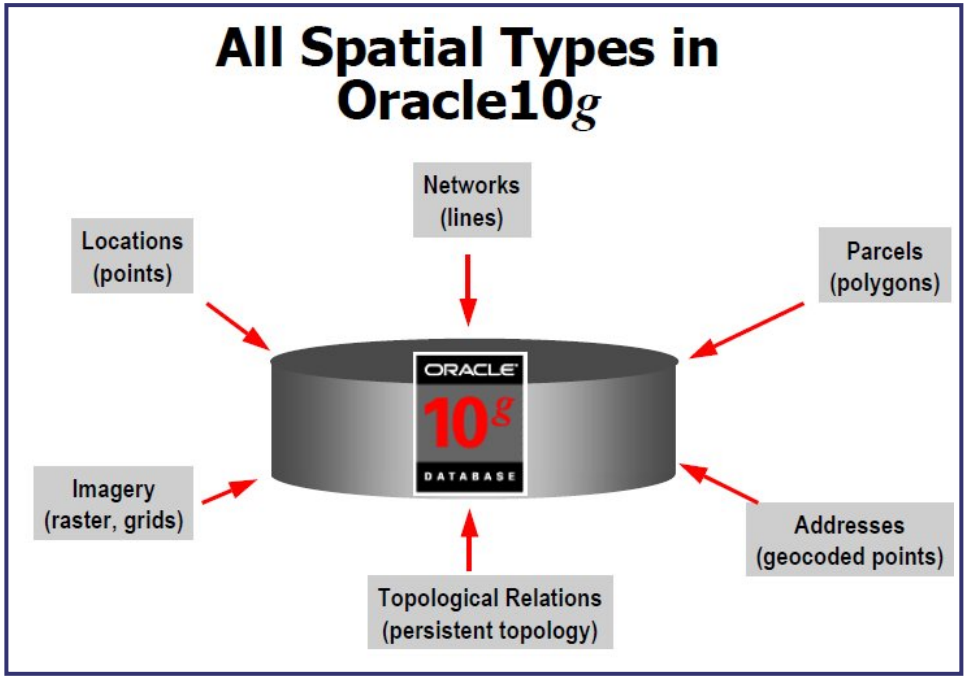

```
#query

+ equals(another :Geometry) : Boolean
+ disjoint(another :Geometry) : Boolean
+ intersects(another :Geometry) : Boolean
+ touches(another :Geometry) : Boolean
+ crosses(another :Geometry) : Boolean
+ within(another :Geometry) : Boolean
+ contains(another :Geometry) : Boolean
...

#analysis

+ distance(another : Geometry) : Distance
+ buffer(another : Distance) : Geometry
+ convexHull() : Geometry
...
```

Oracle Spatial

Oracle offers a 'Spatial' library for spatial queries - this includes UDTs and custom functions to process them.




Oracle Spatial 10g Platform
Any Device
Partner Spatial Solution
Customer Built Solution
Oracle & Partner Business Applications
Telemetry Services
Middle Tier
3rd Party Tools
3rd Party Tools
Wireless Midware
LBS APIs
MapViewer
Web Services
Oracle Application Server 10g
SOAP, WSDL
Weather
Sensors
Field Obs.
Spatial Data Server
Spatial
Oracle10g
Oracle Location Technology
Oracle Core Technologies
Copyright © Oracle Corporation, 2006. All rights reserved.
ORACLE


All Spatial Types in Oracle10g
Networks (lines)
Locations (points)
Parcels (polygons)
ORACLE
10g
DATABASE
Imagery (raster, grids)
Addresses (geocoded points)
Topological Relations (persistent topology)

SDO_GEOMETRY Object

- SDO_GEOMETRY Object

```
SDO_GTYPE          NUMBER
SDO_SRID           NUMBER
SDO_POINT          SDO_POINT_TYPE
SDO_ELEM_INFO      SDO_ELEM_INFO_ARRAY
SDO_ORDINATES      SDO_ORDINATE_ARRAY
```

- Example

```
SQL> CREATE TABLE states (
  2     state        VARCHAR2(30),
  3     totpop       NUMBER(9),
  4     geom         SDO_GEOMETRY);
```

SDO_GEOMETRY Object

- SDO_GTYPE – Defines the type of geometry stored in the object

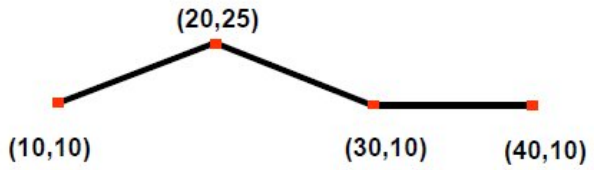
GTYPE	Explanation
1 POINT	Geometry contains one point
2 LINESTRING	Geometry contains one line string
3 POLYGON	Geometry contains one polygon
4 HETEROGENEOUS COLLECTION	Geometry is a collection of elements of different types: points, lines, polygons
5 MULTIPOINT	Geometry has multiple points
6 MULTILINESTRING	Geometry has multiple line strings
7 MULTIPOLYGON	Geometry has multiple polygons

SDO_GTYPE

SDO_GTYPE	Four digit GTYPEs - Include dimensionality		
	2D	3D	4D
1 POINT	2001	3001	4001
2 LINESTRING	2002	3002	4002
3 POLYGON	2003	3003	4003
4 COLLECTION	2004	3004	4004
5 MULTIPOINT	2005	3005	4005
6 MULTILINESTRING	2006	3006	4006
7 MULTIPOLYGON	2007	3007	4007

Constructing Geometries

```
SQL> INSERT INTO LINES VALUES (
  2>     attribute_1, …. attribute_n,
  3>     SDO_GEOMETRY (
  4>       2002, null, null,
  5>       SDO_ELEM_INFO_ARRAY (1,2,1),
  6>       SDO_ORDINATE_ARRAY (
  7>         10,10, 20,25, 30,10, 40,10))
  8>     );
```



Spatial Operators

- Operators
  - SDO_FILTER
    - Performs a primary filter only
  - SDO_RELATE and SDO_<relationship>
    - Performs a primary and secondary filter
  - SDO_WITHIN_DISTANCE
    - Generates a buffer around a geometry and performs a primary and optionally a secondary filter
  - SDO_NN
    - Returns nearest neighbors

SDO_FILTER Example

- Find all the cities in a selected rectangular area
- Result is approximate

```
SELECT c.city, c.pop90
FROM proj_cities c
WHERE sdo_filter (
        c.location,
        sdo_geometry (2003, 32775, null,
          sdo_elem_info_array (1,1003,3),
          sdo_ordinate_array (1720300,1805461,
                              1831559, 2207250))
      ) = 'TRUE';
```

Hint 1: All Spatial operators return `TRUE` or `FALSE`. When writing spatial queries always test with = `'TRUE'`, never <> `'FALSE'` or = `'true'`.

SDO_RELATE Example

- Find all counties in the state of New Hampshire

```
SELECT c.county, c.state_abrv
FROM geod_counties c,
     geod_states s
WHERE s.state = 'New Hampshire'
 AND sdo_relate (c.geom,
                 s.geom,
                 'mask=INSIDE+COVEREDBY')
                    ='TRUE';
```

Note: For optimal performance, don't forget to index `GEOD_STATES(state)`

Relationship Operators Example

- Find all the counties around Passaic county in New Jersey:

```
SELECT /*+ ordered */ a.county
FROM geod_counties b,
     geod_counties a
WHERE b.county = 'Passaic'
    AND b.state = 'New Jersey'
    AND SDO_TOUCH(a.geom,b.geom) = 'TRUE';
```

- Previously:

```
. . .
AND SDO_RELATE(a.geom,b.geom,
     'MASK=TOUCH') = 'TRUE';
```

SDO_NN Example

- Find the five cities nearest to Interstate I170, ordered by distance

```
SELECT /*+ ordered */
       c.city, c.state_abrv,
       sdo_nn_distance (1) distance_in_miles
FROM geod_interstates i,
     geod_cities c
WHERE i.highway = 'I170'
  AND sdo_nn(c.location, i.geom,
             'sdo_num_res=5 unit=mile', 1) = 'TRUE'
ORDER by distance_in_miles;
```

- Note: Make sure you have an index on `GEOD_INTERSTATES (HIGHWAY)`.

SDO_WITHIN_DISTANCE Examples

- Find all cities within a distance from an interstate

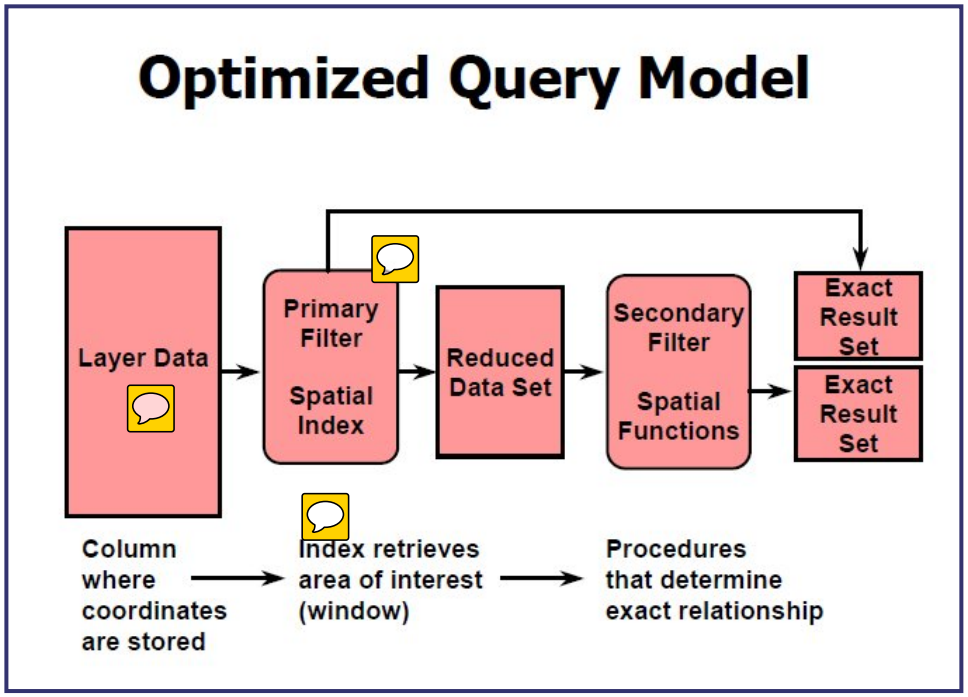
```
SELECT /*+ ordered */ c.city
FROM geod_interstates i, geod_cities c
WHERE i.highway = 'I170'
   AND sdo_within_distance (
        c.location, i.geom,
       'distance=15 unit=mile') = 'TRUE';
```

- Find interstates within a distance from a city

```
SELECT /*+ ordered */ i.highway
FROM geod_cities c, geod_interstates i
WHERE c.city = 'Tampa'
   AND sdo_within_distance (
        i.geom, c.location,
        'distance=15 unit=mile') = 'TRUE';
```

Spatial Indexing

- Used to optimize spatial query performance
- R-tree Indexing
  - Based on minimum bounding rectangles (MBRs) for 2D data or minimum bounding volumes (MBVs) for 3D data
  - Indexes two, three, or four dimensions
- Provides an exclusive and exhaustive coverage of spatial objects
- Indexes all elements within a geometry including points, lines, and polygons


Optimized Query Model
Layer Data
Primary Filter
Spatial Index
Reduced Data Set
Secondary Filter
Spatial Functions
Exact Result Set
Exact Result Set
Column where coordinates are stored
Index retrieves area of interest (window)
Procedures that determine exact relationship

Postgres PostGIS

Types of queries - PostGIS

The function names for queries differ across geodatabases. The following list contains commonly used functions built into PostGIS, a free geodatabase which is a PostgreSQL extension (the term 'geometry' refers to a point, line, box or other two or three dimensional shape):

Types of queries - PostGIS (Cont.)

1. Distance(geometry, geometry) : number
2. Equals(geometry, geometry) : boolean
3. Disjoint(geometry, geometry) : boolean
4. Intersects(geometry, geometry) : boolean
5. Touches(geometry, geometry) : boolean
6. Crosses(geometry, geometry) : boolean

Types of queries - PostGIS (Cont.)

7. Overlaps(geometry, geometry) : boolean
8. Contains(geometry, geometry) : boolean
9. Intersects(geometry, geometry) : boolean
10. Length(geometry) : number
11. Area(geometry) : number
12. Centroid(geometry) : geometry

Here is an example - table creation, and polygon insertion:

```
Create Table County (
name VARCHAR(30),
shape geometry);
CREATE TABLE


Insert into County values ('Lynn', ST_Polygon(ST_GeomFromText('LINESTRING(75.15 29.53 1,77 29 1,77.6 29.5 1,
 75.15 29.53 1)'),4326));
INSERT 0 1

SELECT *
FROM County;
 name |
          shape

------+----------------------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------------------
------------------
 Lynn | 01030000A0E61000000100000004000000A99999999C9524048E17A14AE873D4000000000000F03F000000000040534000
0000000000003D4000000000000F03F666666666666534000000000000803D4000000000000F03F9A99999999C9524048E17A14AE873D
4000000000000F03F
(1 row)


Saty@Satys_USC_PC ~
$
```

To do the above, here are the steps on a PC (similar steps on a Mac):

- install Postgres (v.9.5, not 9.6 beta!)
- bring up 'Application Stack Builder' (an add-on that gets installed when Postgres v9.5 is installed), from the available installation options that come up, pick Spatial Extensions -> 'PostGIS 2.2 for Postgres 9.5', install
- bring up a shell (I use 'cygwin'); note - if you want to use cygwin, be sure to use the shell that comes up when you run cygwin.bat, *not* the 'mintty' shell that you get when you double-click on the cygwin icon; Mac users would use the built-in shell
- 9.5/bin/initdb (on a Mac the path would be different)
- 9.5/bin/pg_ctl start - this starts the Postgres server
- 9.5/bin/createdb mydb - a new db for us to create tables in
- 9.5/bin/psql.exe -d mydb -c "CREATE EXTENSION postgis;" - this adds spatial types to our db; note: 'psql' is the program that lets us communicate with the db server, via the shell

- 9.5/bin/psql.exe -d mydb -a -f county.sql - this is how you can execute SQL commands that you store in a .sql file
- edit the .sql file (eg add more data [including spatial data], create new tables, write SQL queries [including spatial ones]..), run the file (as shown above), edit, run.....
- 9.5/bin/pg_ctl stop - optionally you can stop the server and restart it later
- ...

You can learn a lot about spatial queries from this page.

Creating spatial indexes

As (more so than) with non-spatial data, the creation and use of spatial indexes VASTLY speed up processing!

Can B Trees index spatial data?

In short, YES, if we pair it up with a 'z curve' indexing scheme (using a space-filling curve):

Organizing spatial data with space filling curves

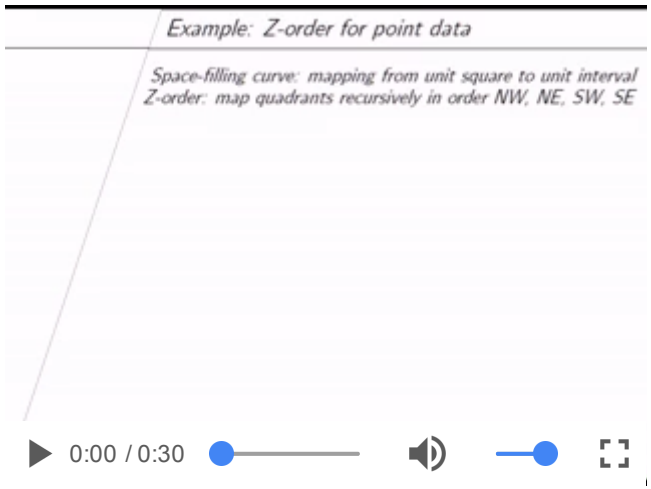
- Issue:
  - Sorting is not naturally defined on spatial data
  - Many efficient search methods are based on sorting datasets
- Space filling curves
  - Impose an ordering on the locations in a multi-dimensional space
    - Examples: row-order (Fig. 1.11(a), z-order (Fig 1.11(b))
  - Allow use of traditional efficient search methods on spatial data

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

(a)

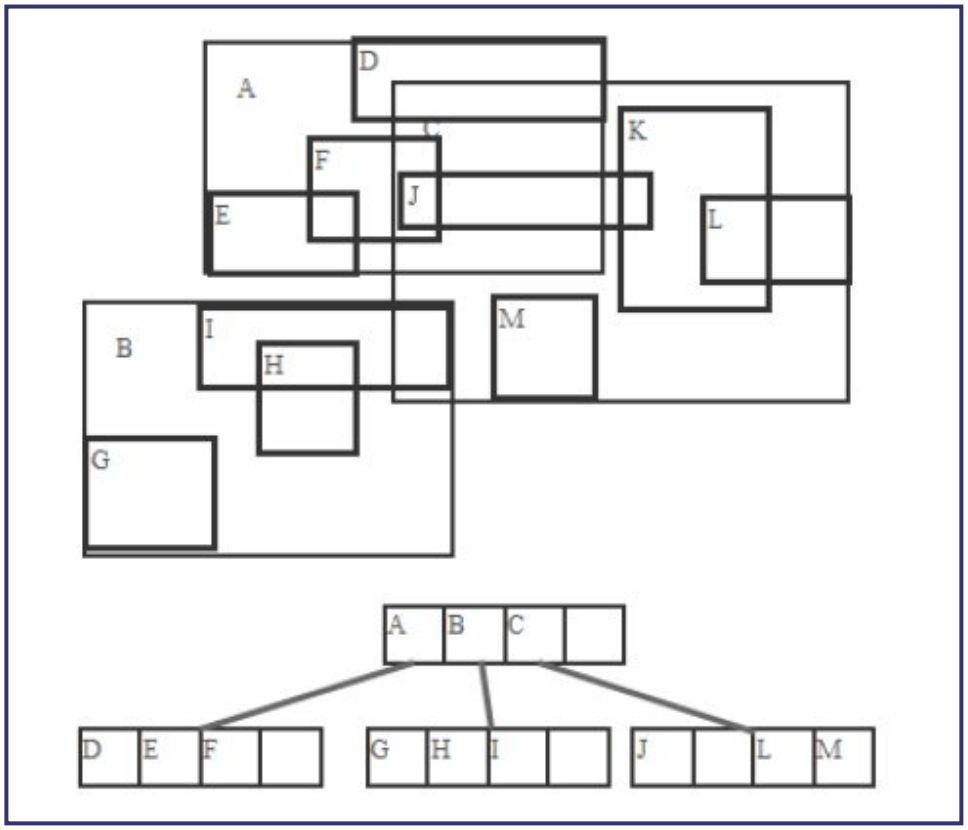
7	8	14	16
5	6	13	15
2	4	10	12
1	3	9	11

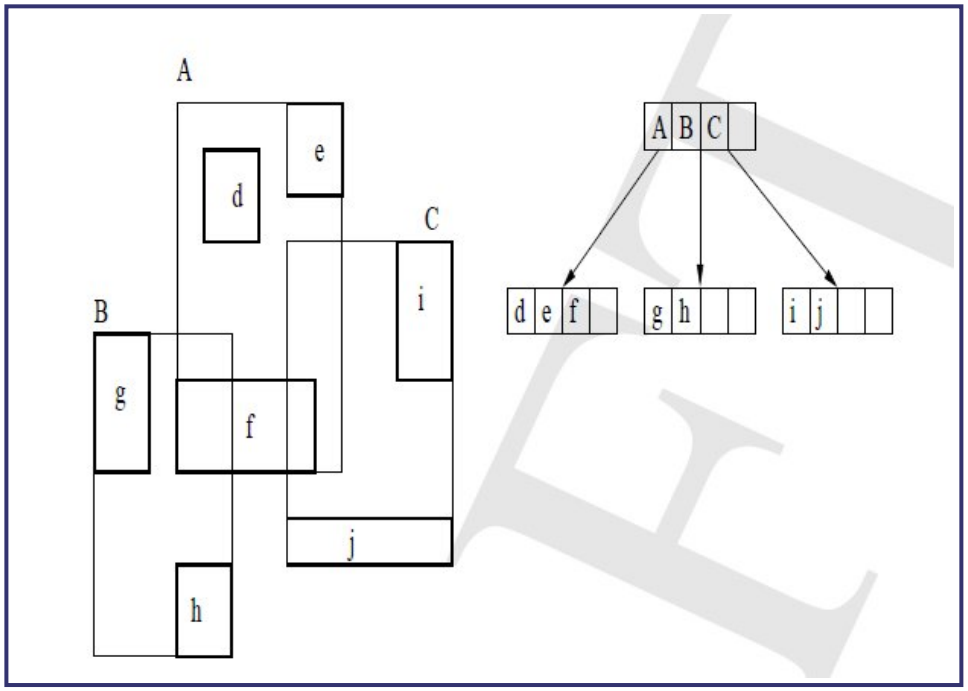
(b)



But, this is of academic interest mostly, not commonly practiced in industry.

R trees



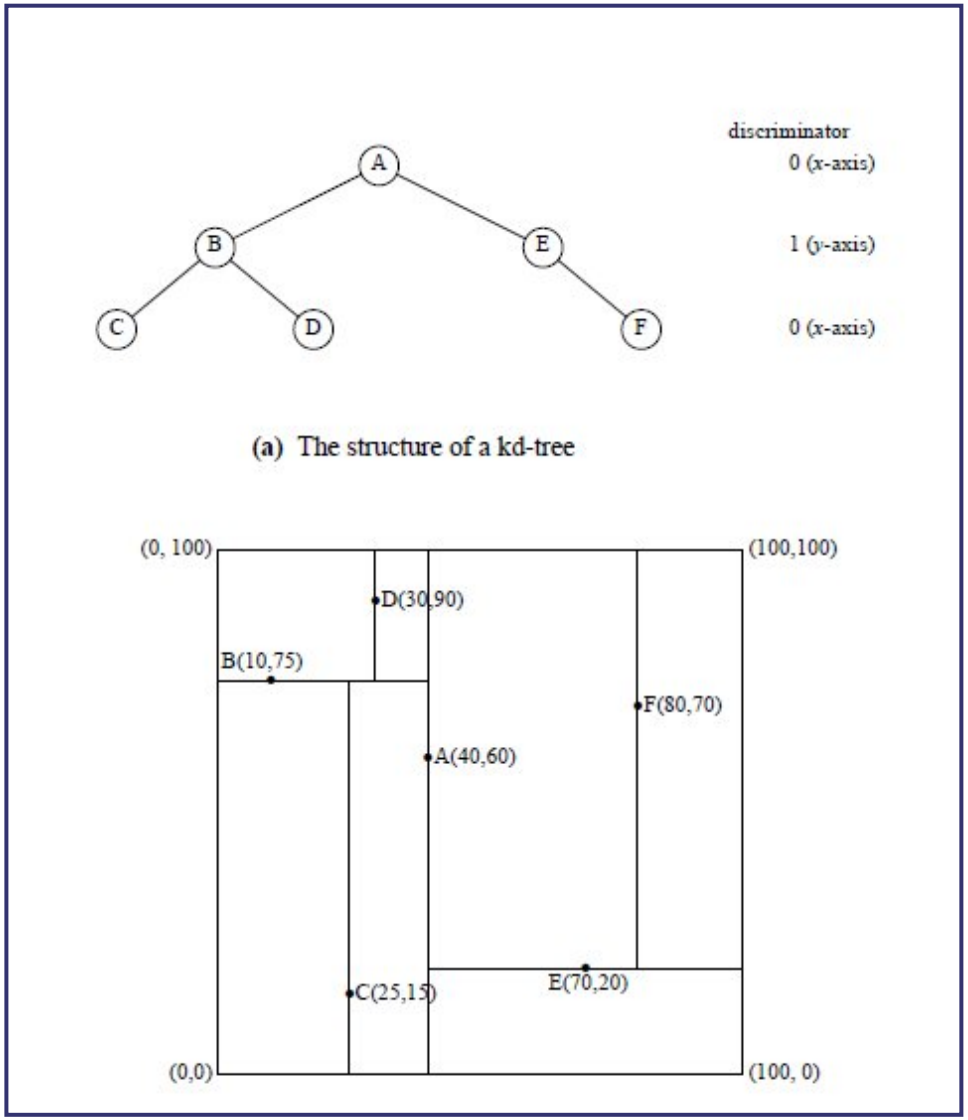


R trees use MBRs to create a hierarchy of bounds.

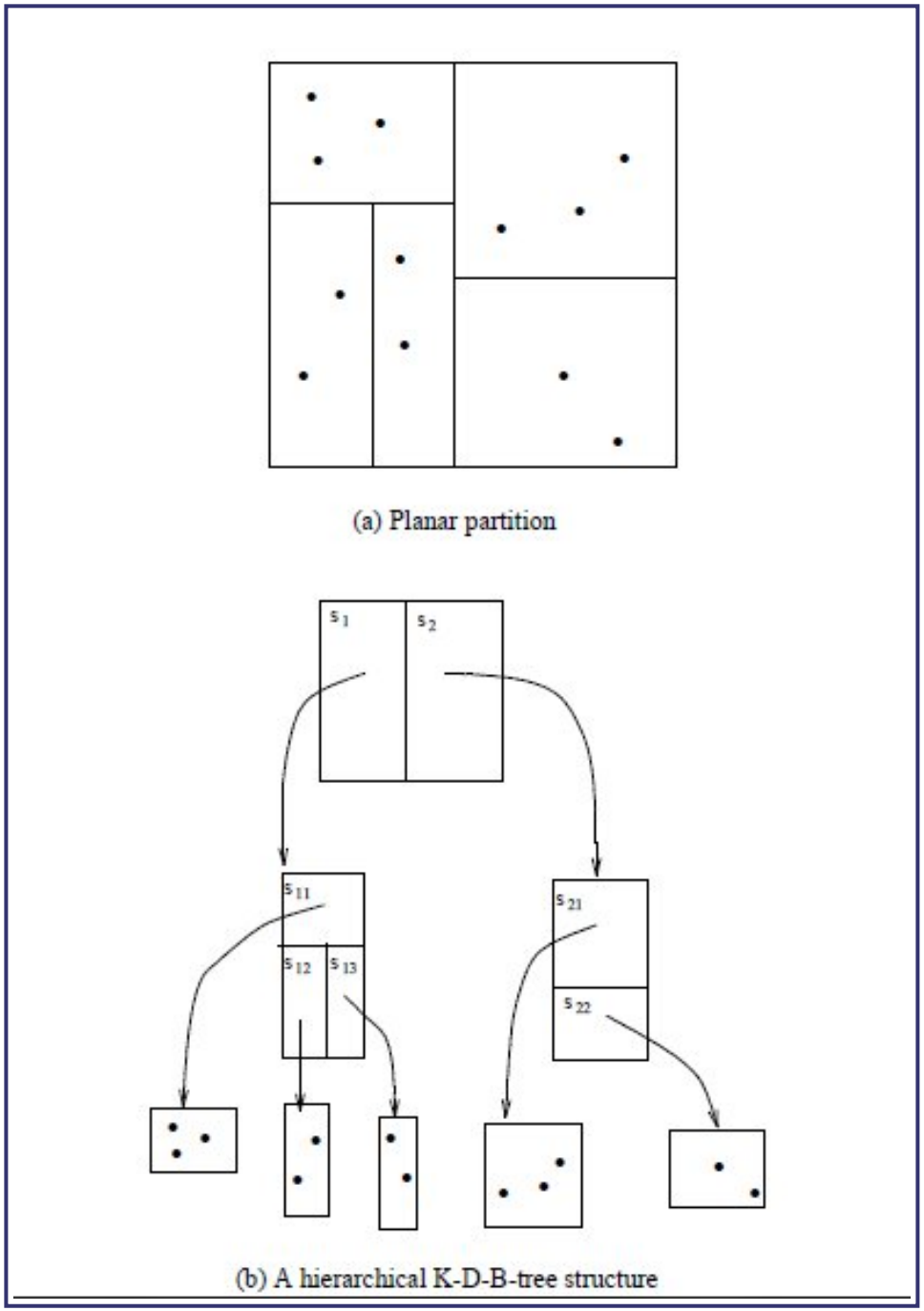
Variations, FYI: R+ tree, R* tree, Buddy trees, Packed R trees..

k-d trees, K-D-B trees

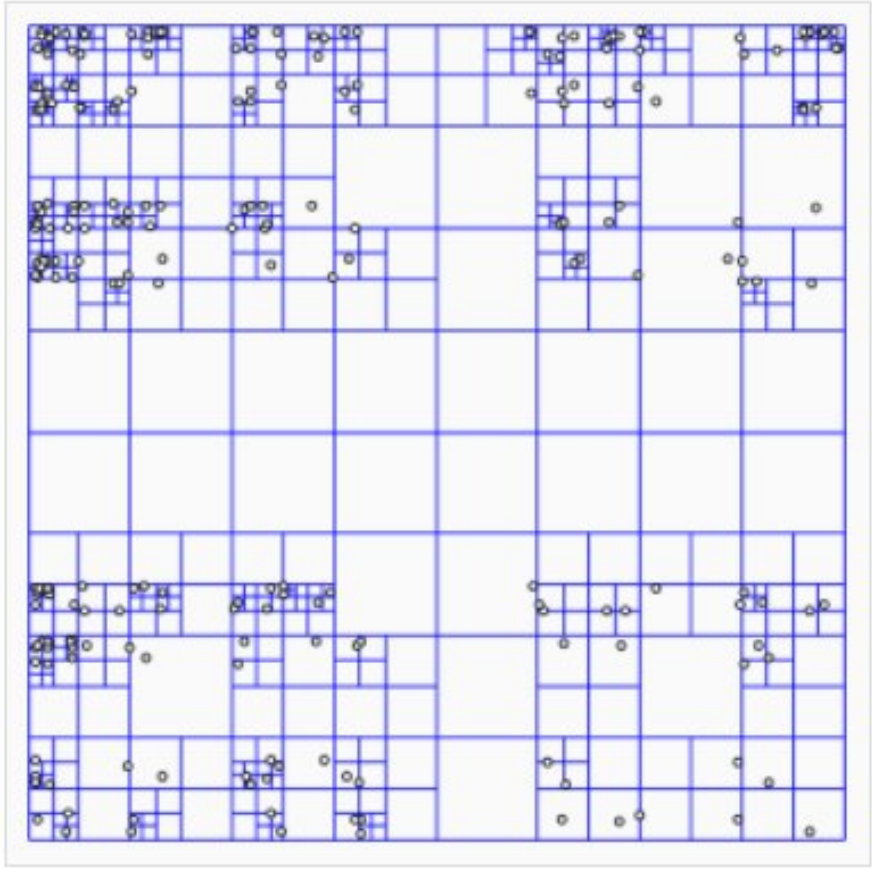
k-d tree



Alternate: K-D-B tree:


(a) Planar partition
s_1
s_2
s_{11}
s_{12}
s_{13}
s_{21}
s_{22}
(b) A hierarchical K-D-B-tree structure

Quadtrees (and octrees)

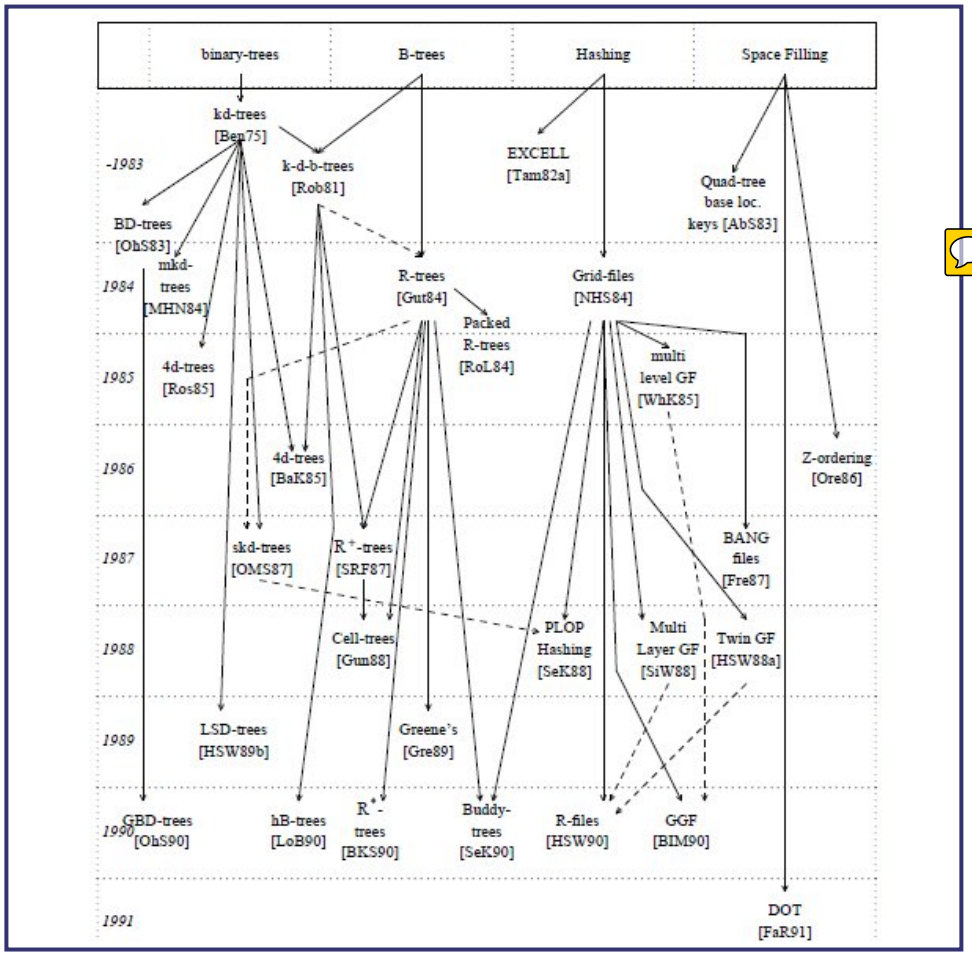


A representation of how a quadtree divides an indexed area. Source: Wikipedia

Each node is either a leaf node, with indexed points or null, or an internal (non-leaf) node that has exactly 4

children. The hierarchy of such nodes forms the quadtree.

Indexing evolution



Indexing schemes continue to evolve.

Query processing: filter, refine

Query Processing

- Efficient algorithms to answer spatial queries
- Common Strategy - filter and refine
  - Filter Step: Query Region overlaps with MBRs of B,C and D
  - Refine Step: Query Region overlaps with B and C

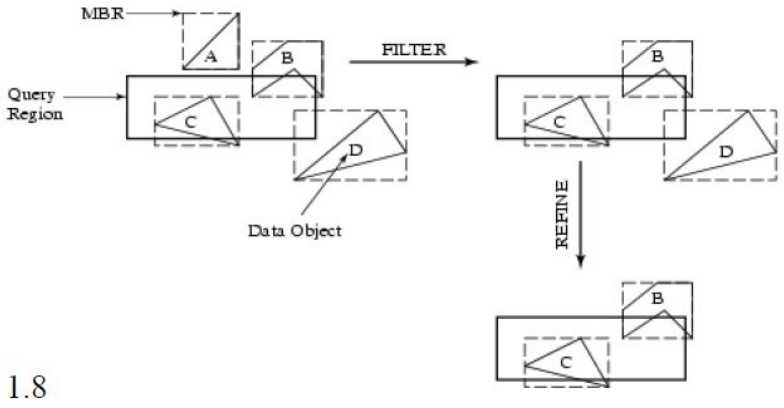
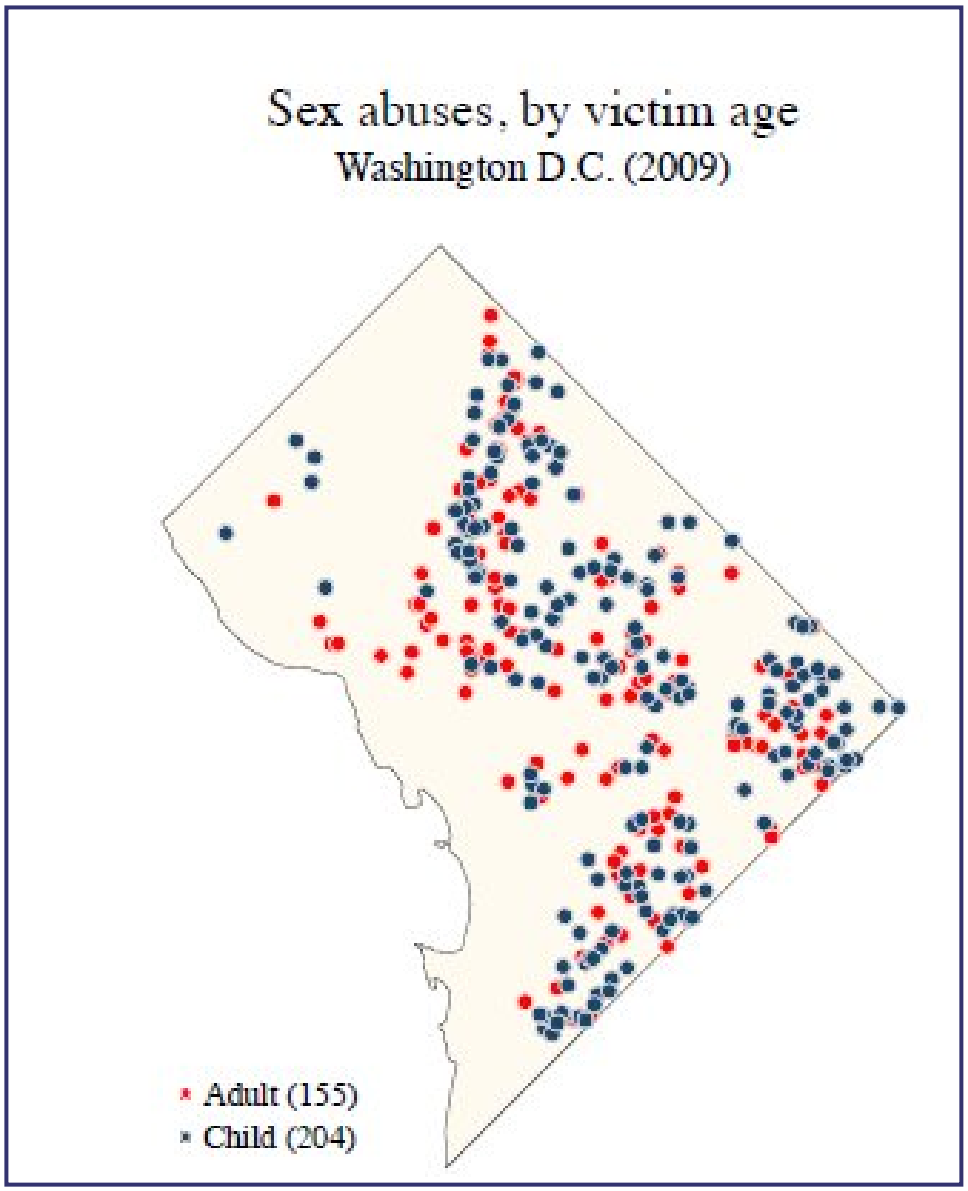


Fig 1.8

Visualizing spatial data

A variety of non-spatial attrs can be mapped on to spatial data, providing an intuitive grasp of patterns, trends and abnormalities. Following are some examples.

Dot map:


Sex abuses, by victim age
Washington D.C. (2009)
Adult (155)
Child (204)

Proportional symbol map:

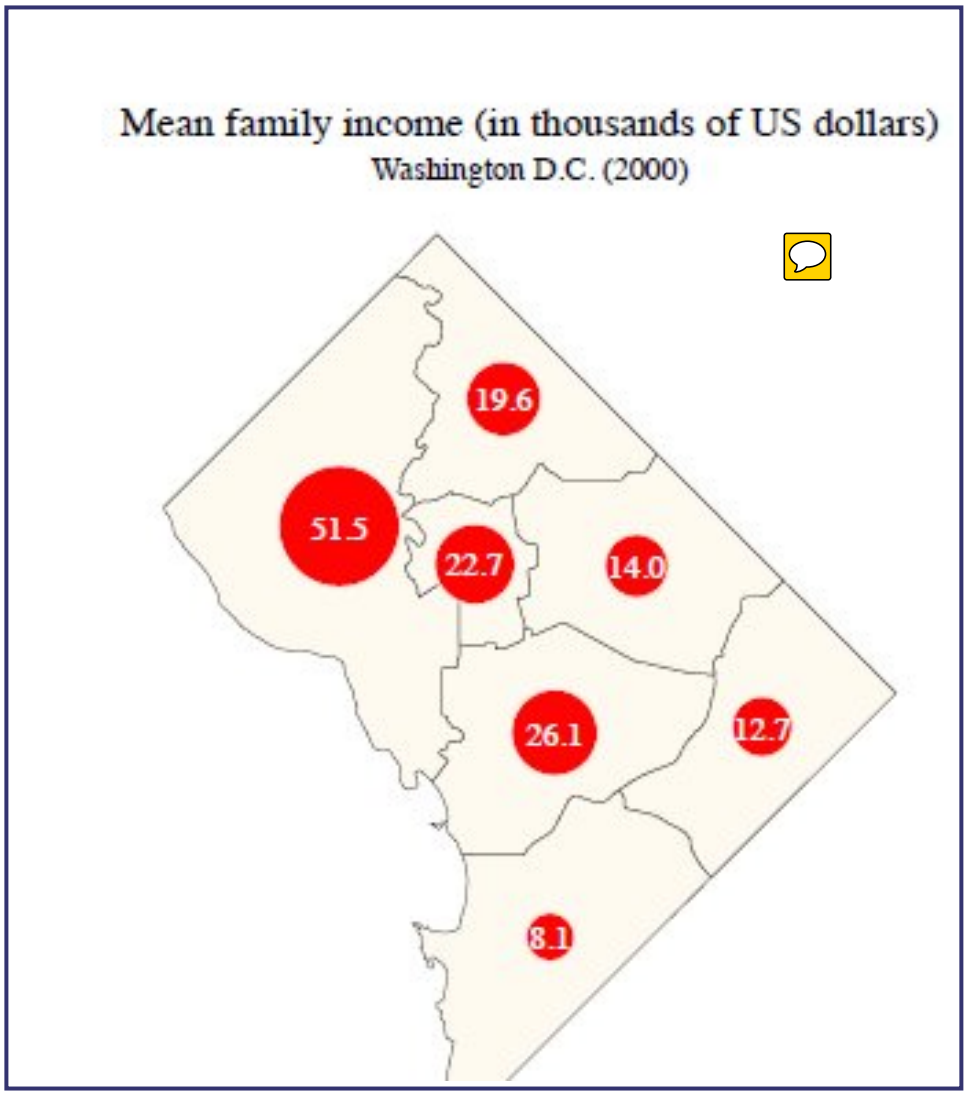
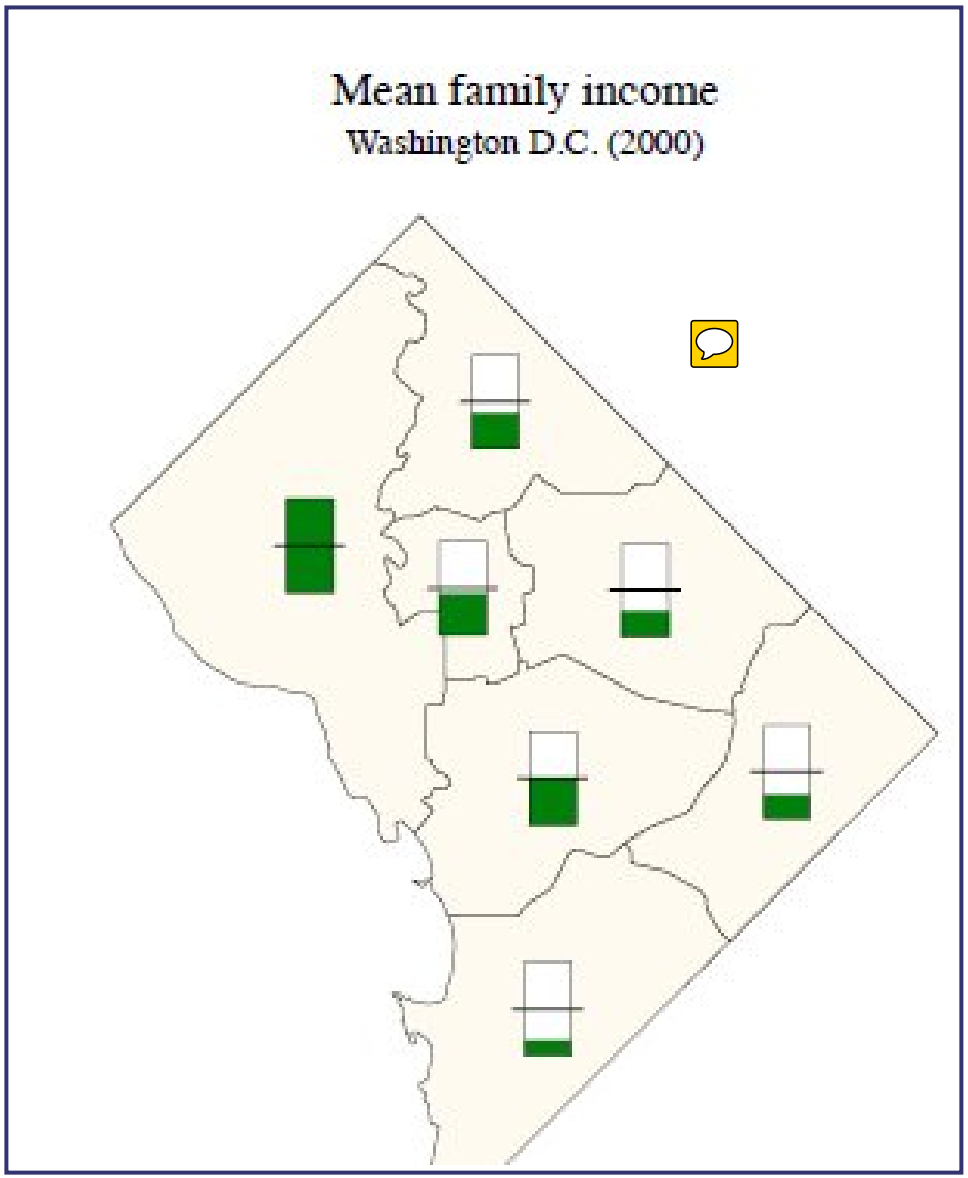
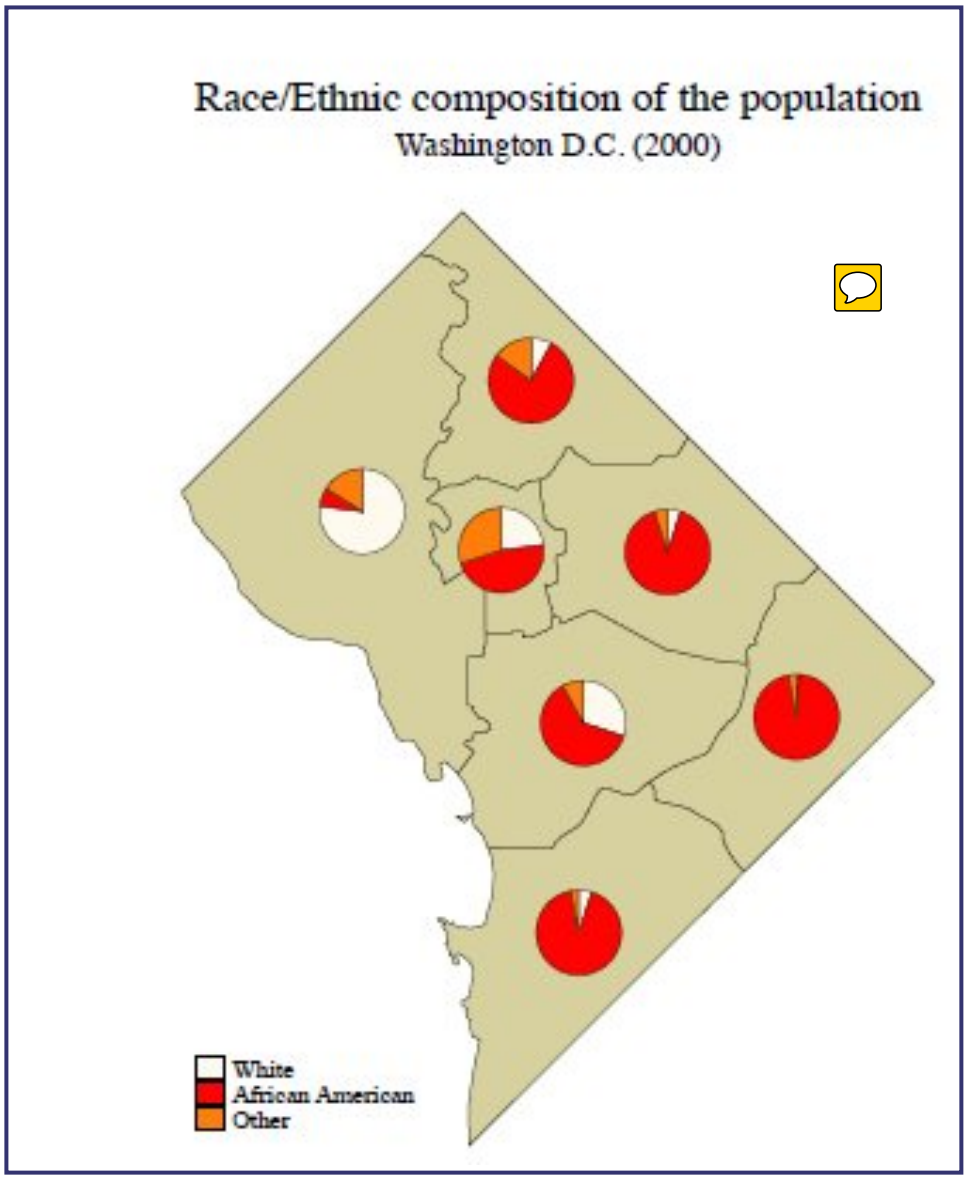


Diagram map:

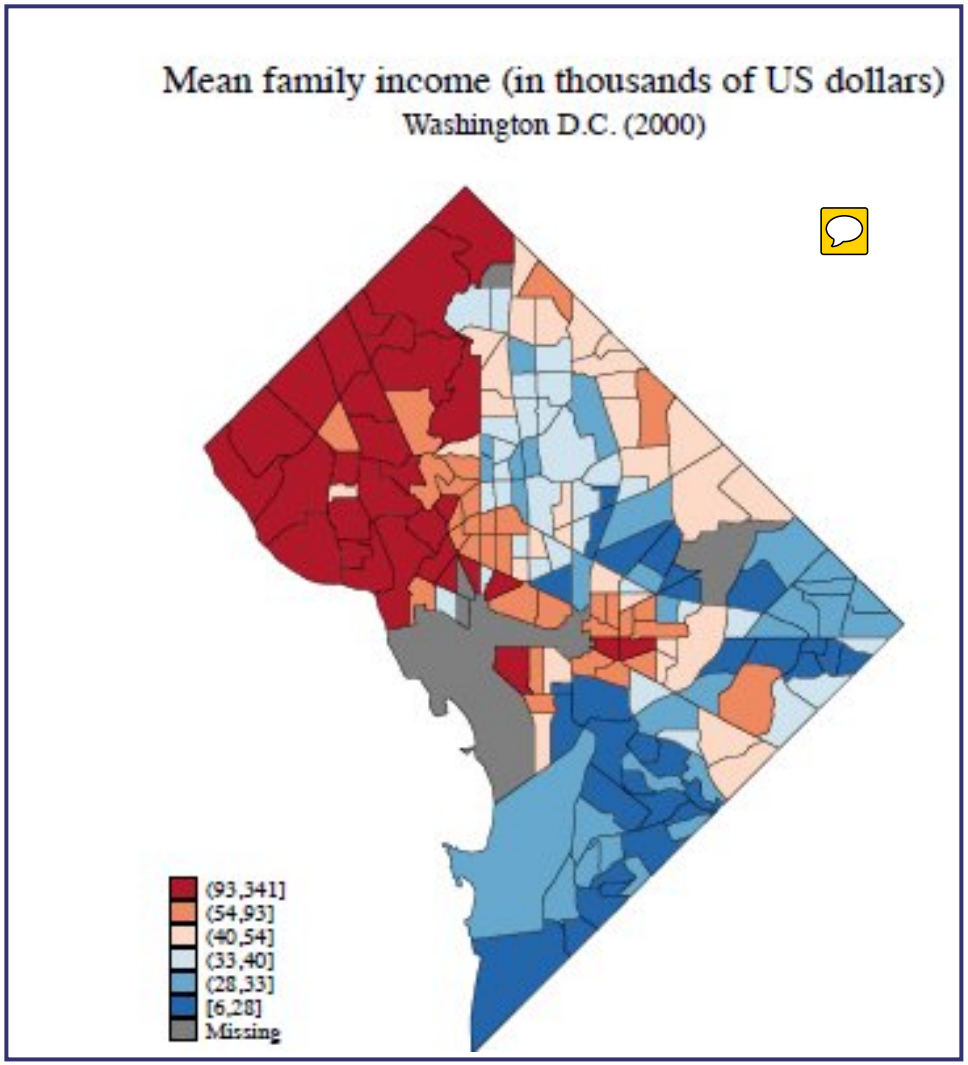


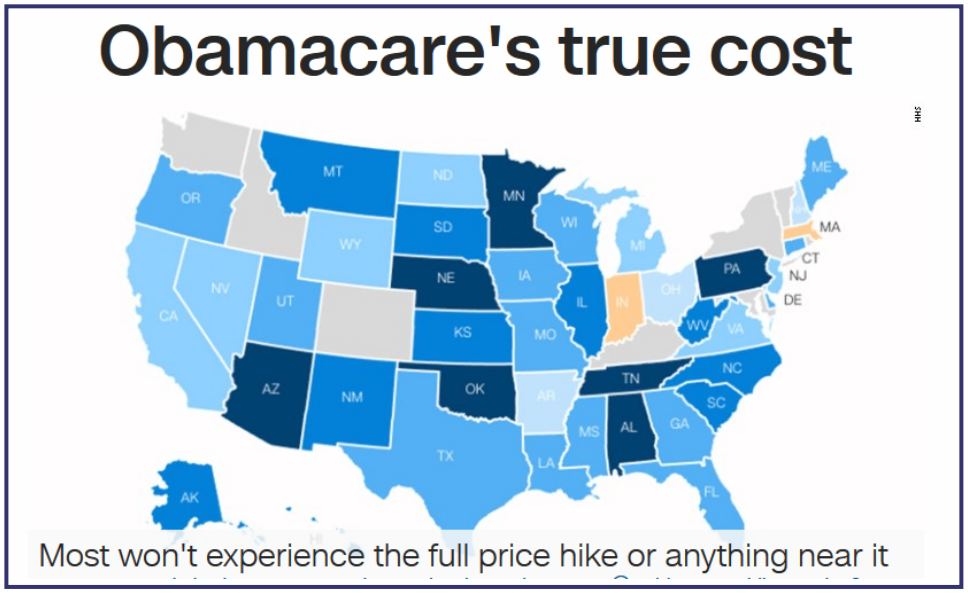
Another diagram map:



Also possible to plot multivariate data this way.

Choropleth maps (plotting of a variable of interest, to cover an entire region of a map):


Mean family income (in thousands of US dollars)
Washington D.C. (2000)
(93,341]
(54,93]
(40,54]
(33,40]
(28,33]
[6,28]
Missing


Obamacare's true cost
MT
ND
MN
OR
SD
WI
MI
WY
NY
VT
NH
ME
MA
CT
NJ
DE
PA
NE
IA
IL
IN
OH
WV
VA
NV
UT
CA
KS
MO
NC
AZ
NM
OK
AR
TN
SC
MS
AL
GA
TX
LA
FL
AK
Most won't experience the full price hike or anything near it

So who (else) has spatial extensions?

Everyone!

Thanks to SQL's facility for custom datatype ('UDT') and function creation ('functional extension'), "spatial" has been implemented for every major DB out there:

- Oracle: Locator, Spatial, SDO
- Postgres: PostGIS
- DB2: Spatial Datablade
- Informix: Geodetic Datablade
- SQL Server: Geometric and Geodetic Geography types
- SQLite: SpatiaLite
- ..

Google KML

Google's KML format is used to encode spatial data for Google Earth, etc. Here is a page on importing other geospatial dataset formats into Google Earth.

OpenLayers

OpenLayers is an open GIS platform. 

ESRI: Arc*

ESRI is the home of the powerful, flexible family of ArcGIS products - and they are local!

QGIS

QGIS is another open source GIS platform..