AN OVERVIEW OF SPATIAL INDEXING WITHIN RDBMS

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OUTLINE

- Motivation
- GIS Primer
- Spatial Indexing
  - Naïve Approaches
  - Data-driven Strategies
  - Space-driven Strategies
- Spatial Support in SQL Anywhere 12
- Advanced GIS: Indexing Round-Earth Data

MOTIVATION

What's the point?

- Common Application Domains
  - CAD/CAM
  - GIS

  Low Dimensionality

  - Multimedia
  - OLAP

  High Dimensionality

- Common Queries
  - Point Data:
    - Polygon Range
    - Nearest Neighbour

  High Dimensionality

  Low Dimensionality

  - Polygon Data:
    - Point Stabbing
    - Polygon Range (Intersection or Containment)

GIS PRIMER

DATA REPRESENTATION

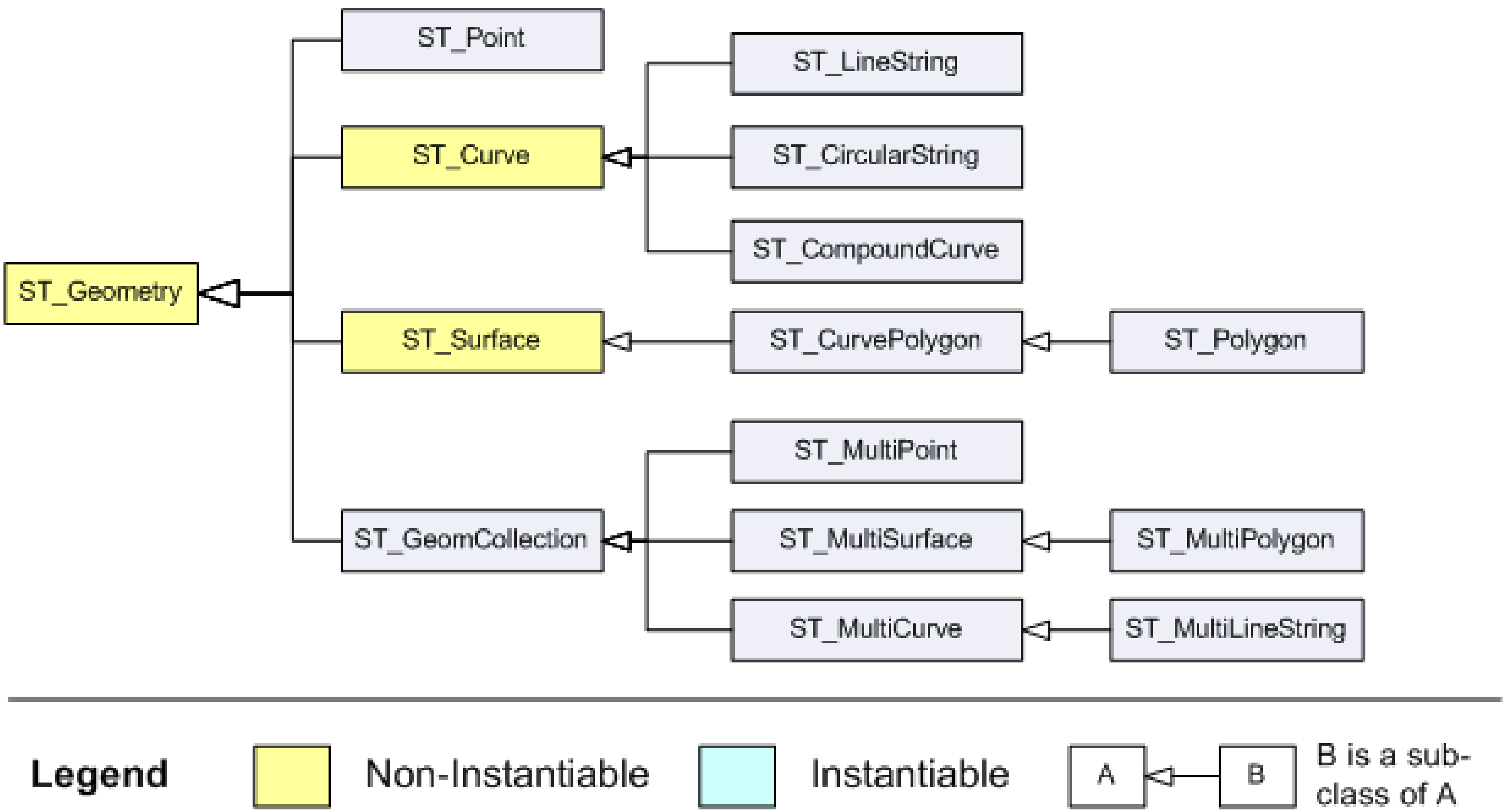
Two fundamental representations used in GIS (and graphics in general).

- Raster
  - Data stored as (one or more) pixelated images
  - Granularity fixed by pre-defined grid
  - Single pixel blends information from multiple objects
  - Storage size depends upon canvas size & granularity
- Vector
  - Each spatial object stored/rendered separately
  - Fundamental feature types:
    - Points (0-dim)
    - Lines (1-dim)
    - Polygons (2-dim)
  - Granularity limited only by precision of coordinates
  - Storage size depends upon number & complexity of objects

SQL/MM

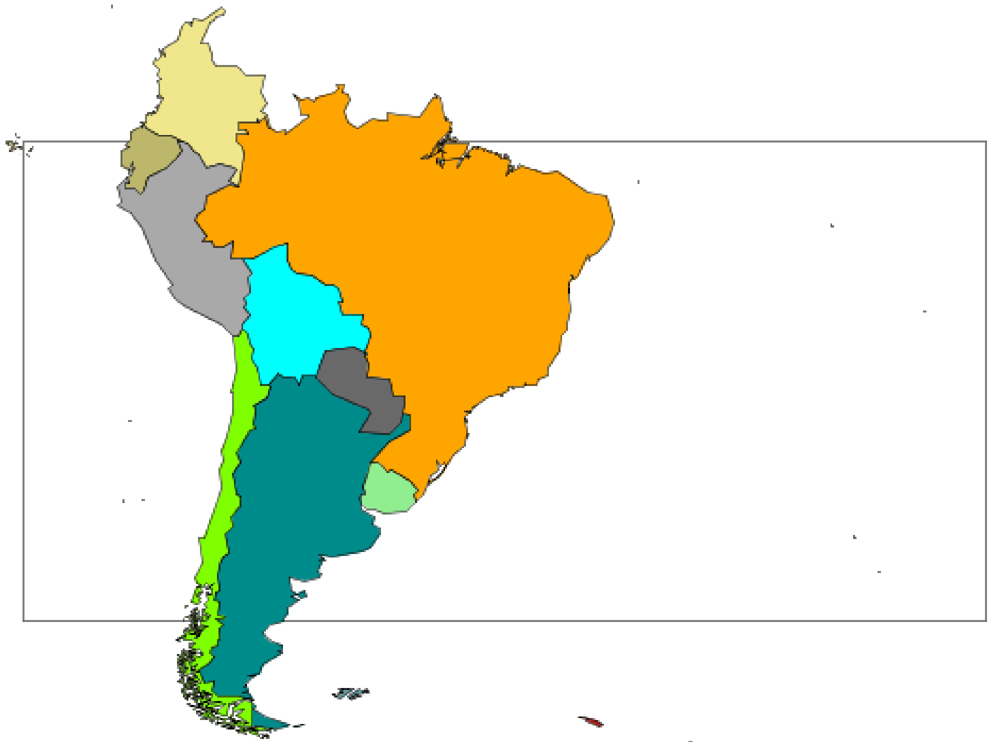
SQL/MM DATA MODEL

Also the Open Geospatial Consortium standard for SQL access to spatial data.



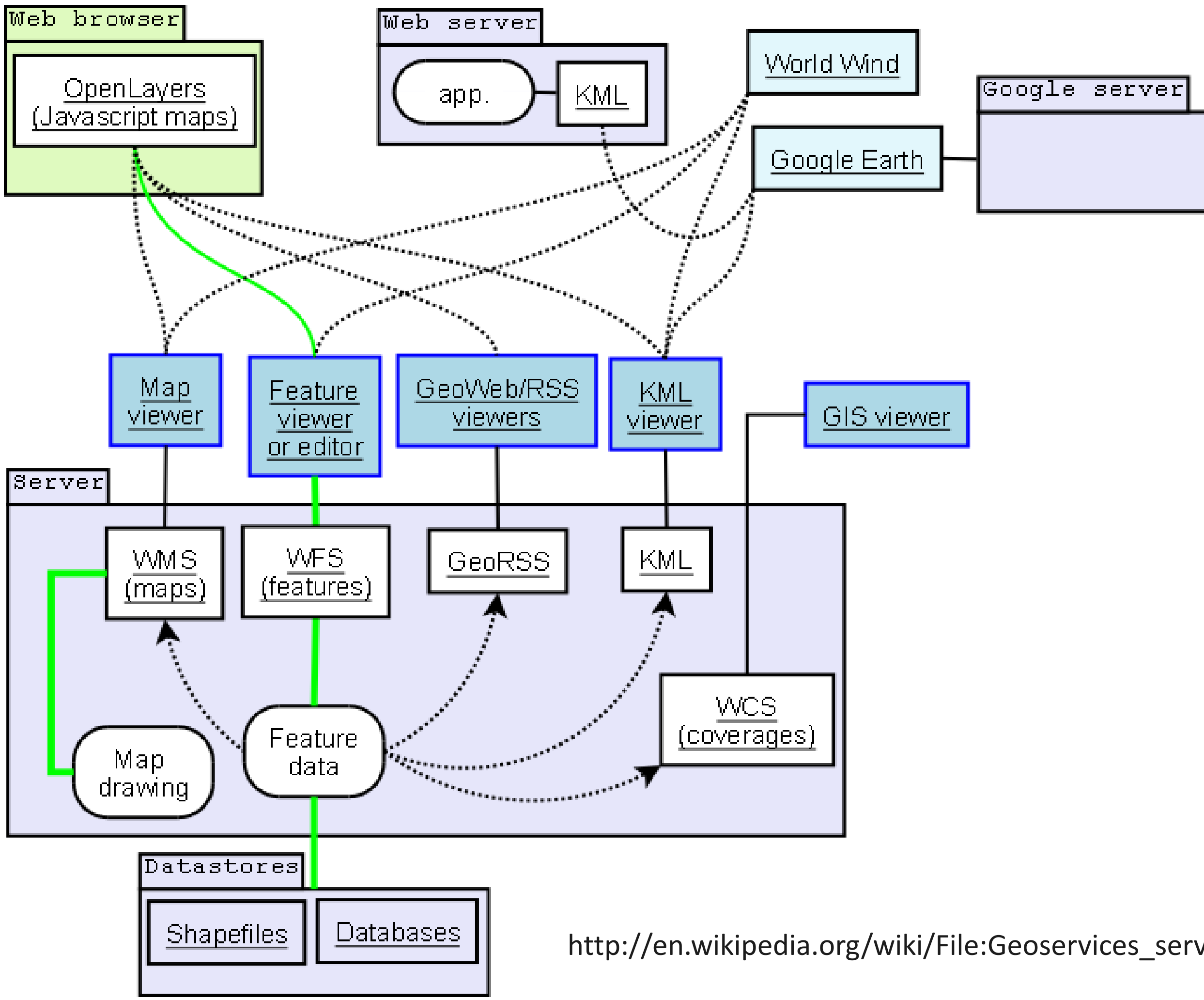
SQL/MM SAMPLE QUERY

```
SELECT geometry
FROM countries
WHERE geometry.ST_Intersects( new ST_Polygon(
    'POLYGON((-90 0, -90 -45, 0 -45, 0 0, -90 0))'
    , 4326 ) = 1
```



OGC STANDARDS WITHIN WEB SERVICES

Modern GIS applications integrate spatial data from a rich collection of sources.



http://en.wikipedia.org/wiki/File:Geoservices_server_with_apps.png

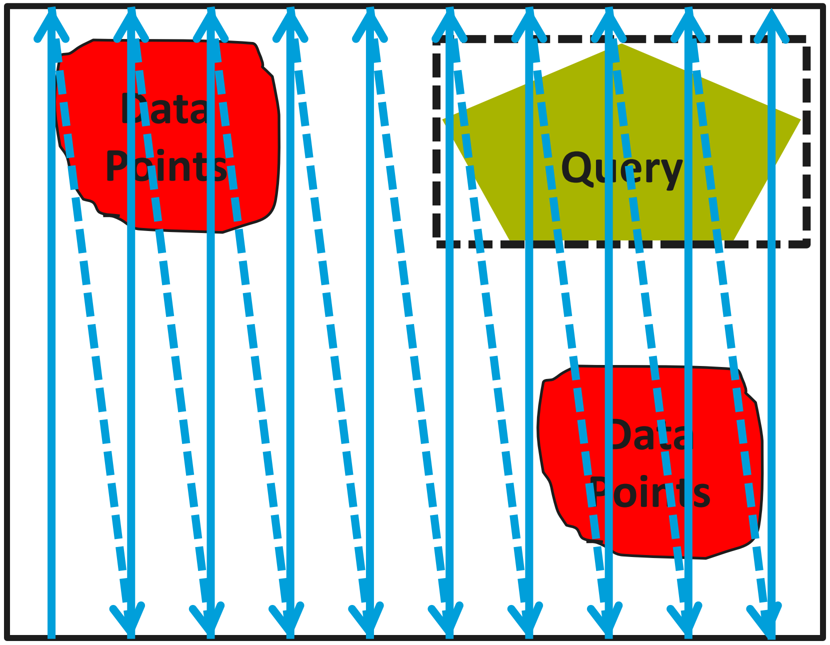
SPATIAL INDEXING

NAÏVE APPROACHES

COMPOSITE KEY B-TREES

Main Idea: **Compose index keys from multi-dimensional points**

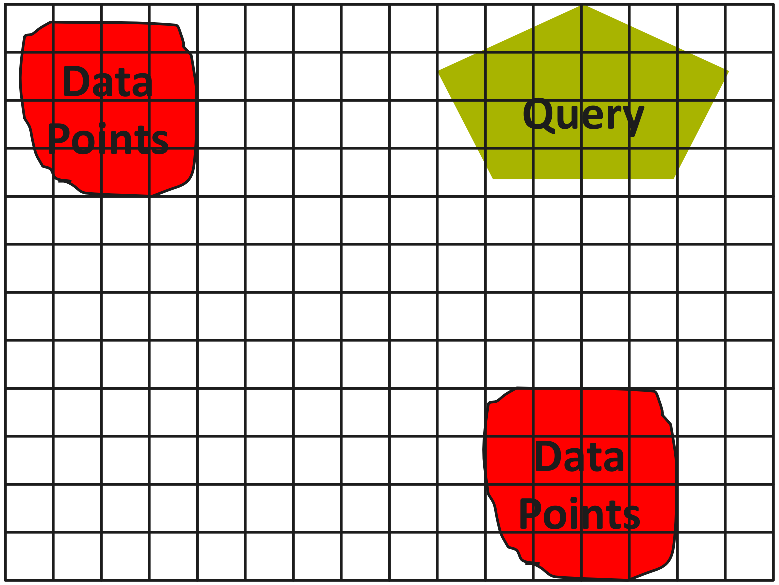
- Point data only
- Index key formed by fixing an ordering of dimensions
- Query processing:
  - Scan entire key range between min/max key values touched by query object
    - *Poor performance if leading attributes are not equality predicates*
- Fundamental weakness:
  - Spatial co-locality substantially different from index co-locality



FIXED GRIDS

Main Idea: **Divide space into even partitions**

- Point or polygon data
- Partitions store lists of data objects that intersect the cell
- Query processing:
  - Scan list for each partition touched by query object
    - *Performance depends heavily on range size relative to grid granularity*
- Fundamental weakness:
  - Fixed granularity does not adapt to data distribution or query workload



SPATIAL INDEXING

DATA-DRIVEN STRATEGIES

DATA-DRIVEN INDEXING STRATEGIES

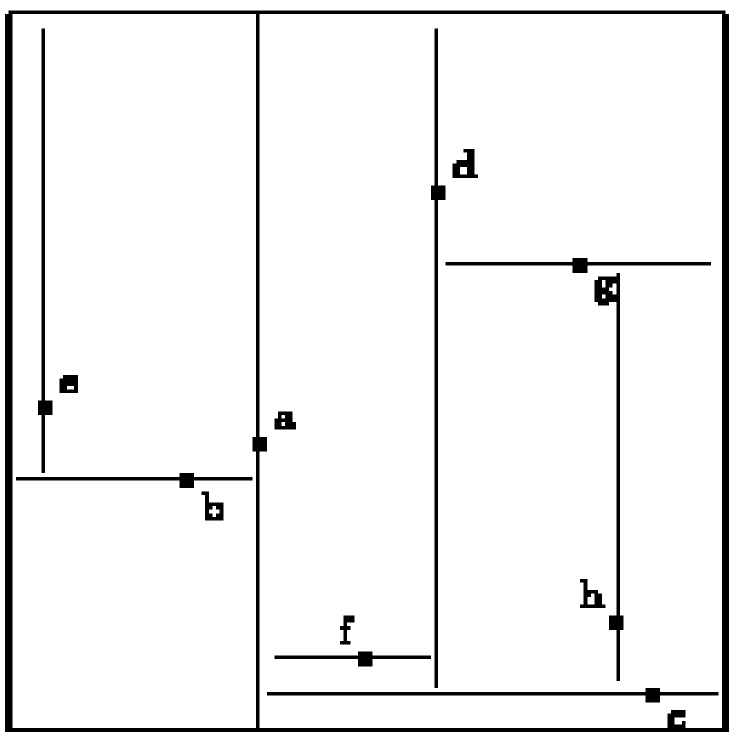
- ***Distinguishing Characteristics:***
  - Index key *composed from* values of indexed attribute(s)
  - Index layout/organization adjusts to distribution of inserted index keys

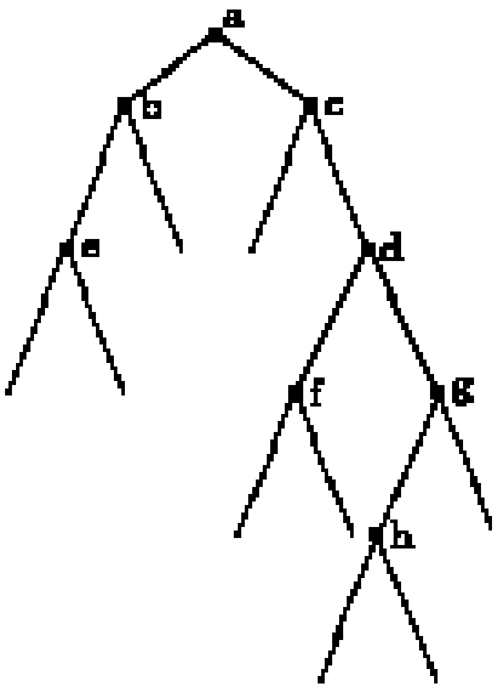
- Representative Index Types:
  - Single-dimensional
    - Balanced binary trees
    - B-trees
  - Multi-dimensional
    - *kd*-trees
    - Point quadtrees
    - R-trees

KD-TREES

Main Idea: **Generalize BSTs by splitting on alternating dimensions**

- Point data only
- Not designed for secondary storage

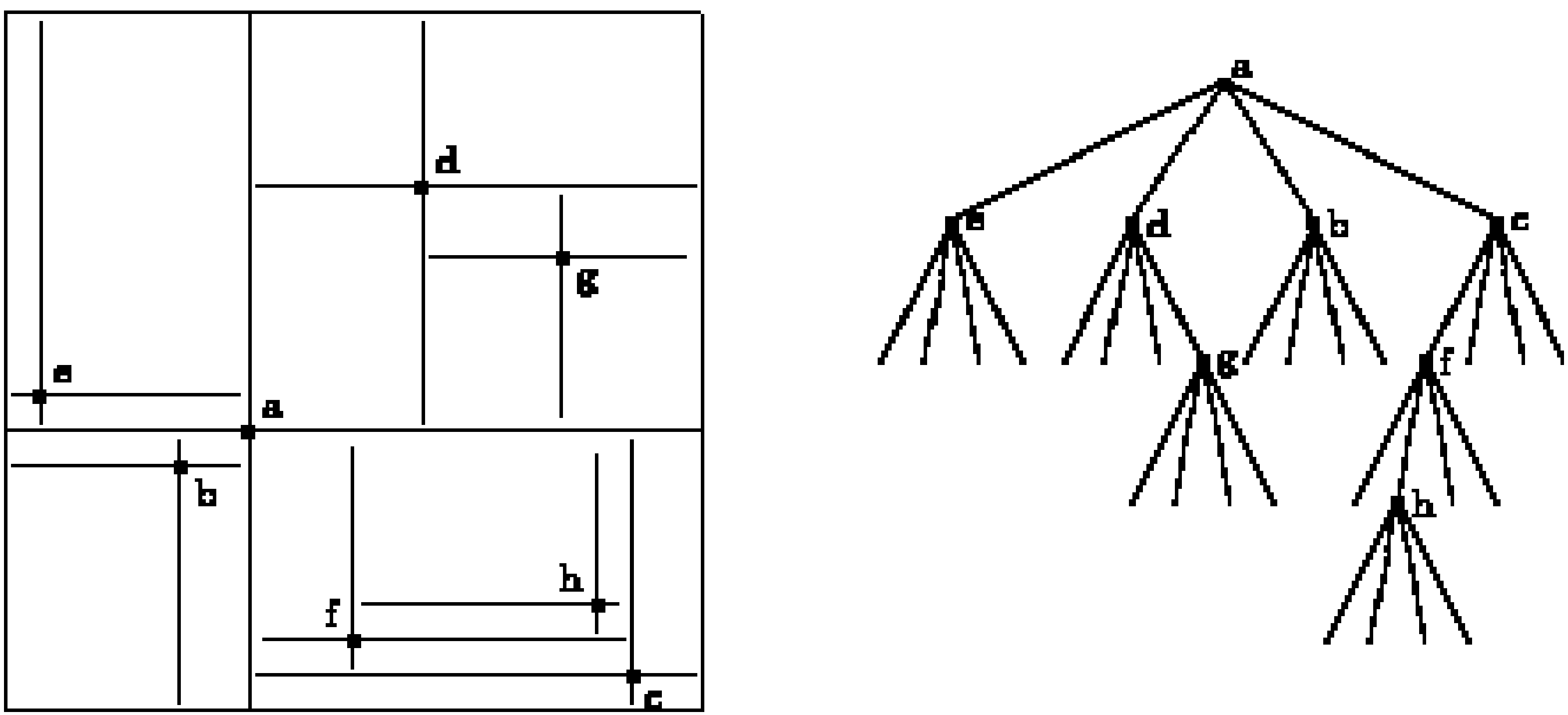




POINT QUADTREES

Main Idea: **Variation of *kd*-trees that splits on all dimensions simultaneously**

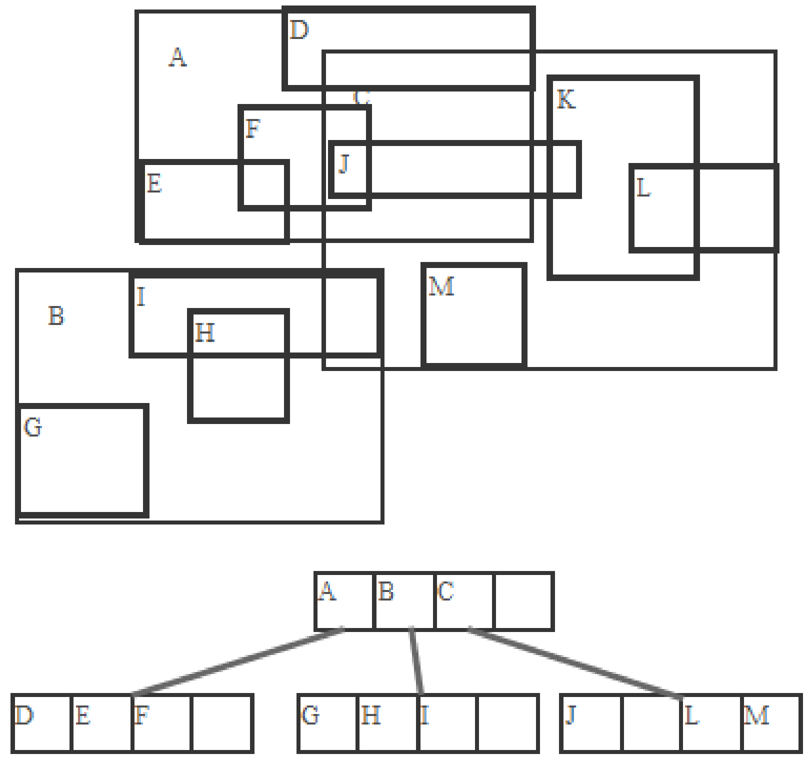
- Point data only
- Not designed for secondary storage



R-TREES

Main idea: **Generalize B-trees to rectangular keys**

- Polygon data
- Optimized for secondary storage
- Query processing:
  - Recursively descend into **all** subtrees that intersect the query object
- Insertion:
  - Recursively descend into and extend **any** subtree intersecting the object
  - Node splitting like B-tree



R-TREES CONT'D

Main idea: **Generalize B-trees to rectangular keys**

- Tree structure can vary widely depending upon
  - Insertion order
  - Heuristic for breaking ties
- Degree of overlap heavily impacts query performance
  - No worst-case guarantees
- Plethora of variations:
  - Various insert heuristics
  - Partition data objects to avoid overlap (R+ tree)
  - Total ordering of leaves (Hilbert R-tree)

- Widely implemented:
  - Oracle
  - IBM Informix
  - Ingres
  - Postgres (PostGIS)
  - MySQL
  - SQLite (SpatiaLite)
  - …

SPATIAL INDEXING

SPACE-DRIVEN STRATEGIES

SPACE-DRIVEN INDEXING STRATEGIES

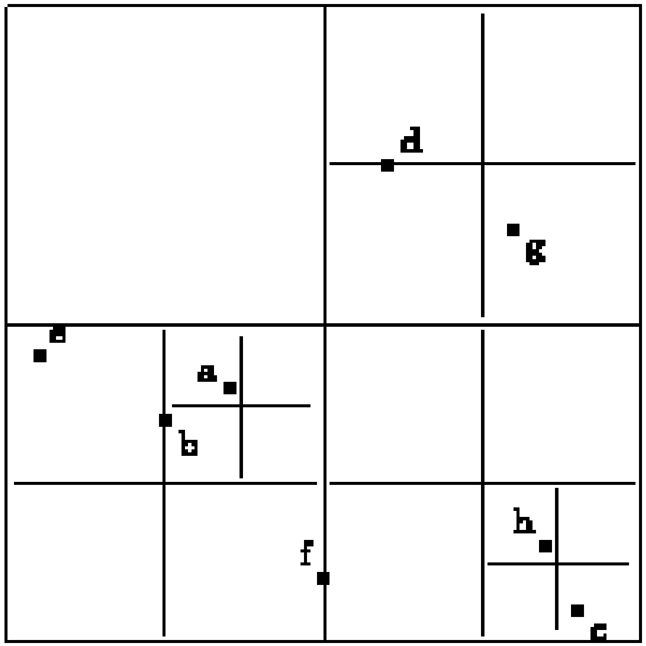
- ***Distinguishing Characteristics:***
  - Index key *a function of* values of indexed attribute(s)
    - Design of function pre-supposes knowledge of domain
  - Index layout dictated by structure of key domain

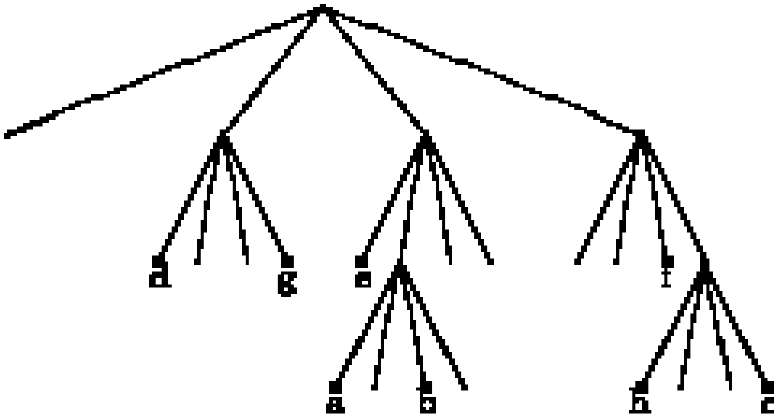
- Representative Index Types:
  - Single-dimensional
    - Various hash-based indexes
  - Multi-dimensional
    - Fixed grids
    - Region quadtrees
    - Linearized (region) quadtrees (hybrid of space-driven & data-driven)

REGION QUADTREES

Main Idea: **Variation of Point Quadtree that always splits into uniform quadrants**

- Point or polygon data
- Not designed for secondary storage



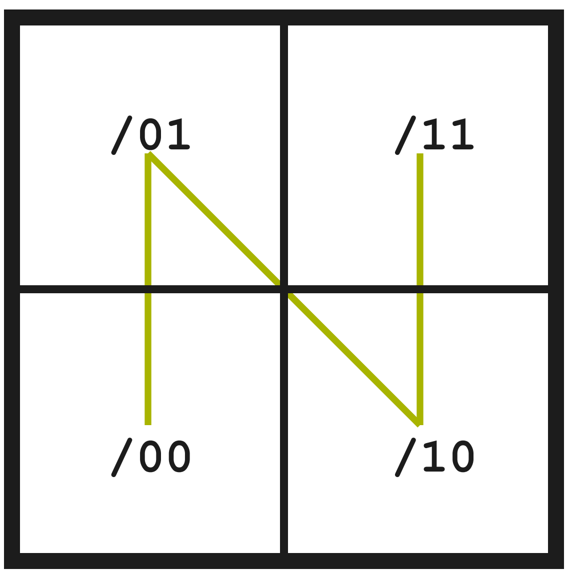


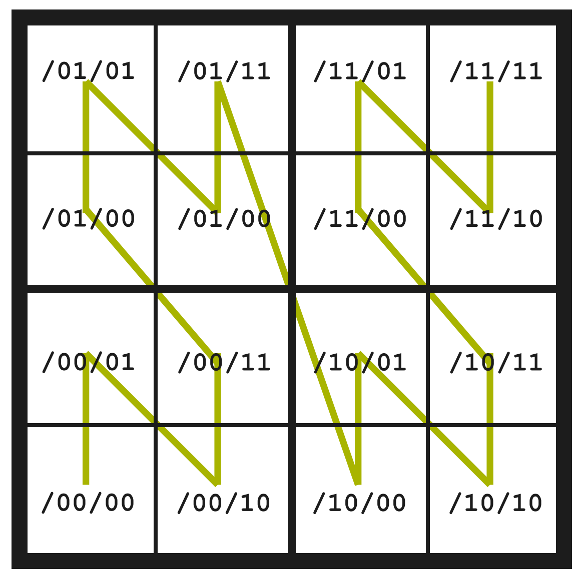
LINEARIZED QUADTREES

Main Idea: **Logical region quadtree physically stored within a B+-tree**

- Key domain *logically* corresponds to uniform recursive partition of space
- Keys *physically* stored in B-tree (presumes total order)

- *Space-filling curve* translates spatial co-locality into index co-locality
  - Logical subtrees form contiguous key ranges



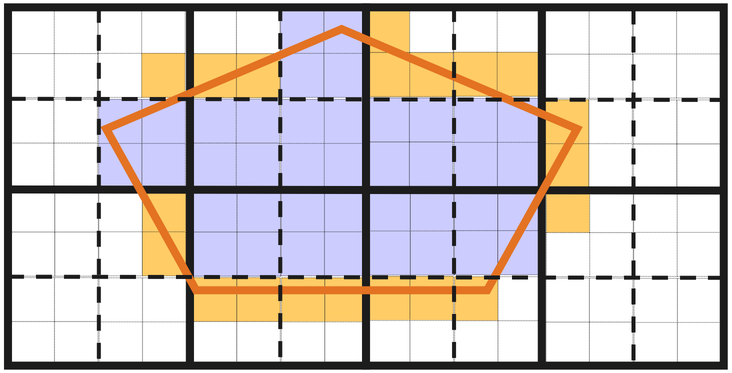


LINEARIZED QUADTREES CONT'D

Main Idea: **Logical region quadtree physically stored within a B+-tree**

- Point or polygon data
- Optimized for secondary storage
- Relies on object *tesselation*
- Insertion:
  - Tesselate data into tiles
  - Insert entry for each tile
- Query processing:
  - Tesselate query into tiles
  - Retrieve corresponding key ranges

- Widely implemented:
  - Oracle
  - IBM DB2
  - Microsoft SQL Server
  - Teradata
  - Sybase SQL Anywhere



SUMMARY: RDBMS SPATIAL INDEXES

Comparison of two widely-implemented indexes in general-purpose RDBMS

R-tree

- Domain agnostic
- Objects approximated as single rectangle
  - *More precise filtering for (nearly) rectangular data*
  - *Smaller index*
- Index structure/quality depends on insertion order
  - *Degrades under updates*
- Single forking index traversal
  - *Complicates locking*
  - *Parallelism opportunities revealed during traversal*

Linearized Quadtrees

- Domain fixed at index creation
- Objects approximated as multiple tiles
  - *More precise filtering for non-rectangular data*
  - *More expensive scanning*
- Index structure/quality independent of insertion order
  - *Predictable performance*
- Set of B+-tree ranges
  - *Well studied/tuned locking*
  - *Parallelism opportunities revealed during tessellation*

SPATIAL SUPPORT IN SYBASE SQL ANYWHERE 12

WHAT IS SQL ANYWHERE?

RDBMS component of the Sybase iAnywhere product suite.

- SQL Anywhere
  - Full-function, small-footprint relational DBMS with support for triggers, stored procedures, materialized views, intra-query parallelism, hot failover, OLAP queries, multidatabase capability, spatial data, …
- Mobilink/SQL Remote
  - Two-way data replication/synchronization technologies for replicating data through different mechanisms to support occasionally-connected devices
- Ultralite
  - “fingerprint” database supports ad-hoc SQL on very small devices
- UltraliteJ
  - 100% Java fingerprint database for Blackberry and iPhone

DESIGN GOALS OF SQL ANYWHERE

- Ease of administration
  - Comprehensive yet comprehensible tools
- Good out-of-the-box performance
  - "Embeddability" features → self-tuning
  - Many environments have no DBA's
- Cross-platform support
  - 32- and 64-bit Windows (7, Vista, XP, Server, 2000, 9x), Windows CE/Pocket PC, Linux 32- and 64-bit, HP-UX, AIX, Solaris (SPARC and Intel), Mac OS/X, Compaq Tru-64
- Interoperability

LINEAR QUADTREE TUNING ISSUES

How do you configure indexes if you haven’t seen the data or workload?

- Performance of linear quadtrees greatly affected by tessellation granularity
- Other systems:
  - Same algorithm used for both *data* and *query* objects
  - Parameters specified at *index creation*
    - Number of subdivisions constituting a “level” (2, 4, 8, 16, 32, 64)
    - Maximum number of levels in logical quadtree
    - Maximum number of levels to descend within an object
    - Maximum number of tessellation blocks per object
- Not obvious:
  - How to choose these parameters
  - How DBA can know that index is mis-configured

DECOUPLING DATA/QUERY TESSELLATION

Why should data and query objects be tessellated by the same algorithm?

- Data and query objects have competing priorities for tessellation granularity
- Data object tessellation
  - Optimal granularity depends upon **query window**
  - Small queries → granular data (minimize false positives)
  - Large queries → coarse data (minimize duplicates)
- Query object tessellation
  - Optimal granularity depends upon **data density**
  - Dense data → granular queries (minimize false positives)
  - Sparse data → coarse queries (minimize B-tree probes)

DATA-DRIVEN QUERY TESSELLATION

Defer tessellation decisions until query execution time.

- Data objects not tessellated
  - Single index entry per geometry (smallest containing block)

- Query objects tessellated dynamically
  - Candidate tessellation → index range plan
  - Plan cost estimated using DBMS cost model (histograms)
  - Top-down branch-and-bound algorithm finds tessellation with optimal cost
  - Cost-based fallback to sequential table scan
  - *Run-time per-tuple (query geometry) plan optimization*

ADVANCED GIS CONCEPTS

INDEXING ROUND-EARTH DATA

SPATIAL REFERENCE SYSTEMS

What is the length of this line?

`LINESTRING( 0 0, 1 1 )`

- Cartesian coordinate system: **1.4142 units**
- Polar coordinate system: **1 unit**
- World Geodetic System (WGS) 84: **156899.568 m**

- SRS provides semantic context:
  - Coordinate system unit of measure (degrees, meters, etc.)
  - Coordinate bounds
  - Linear unit of measure
  - Planar vs spheroid data
  - Projection information for transforming between SRSs
  - Specified tolerance (SQL Anywhere)

ROUND EARTH COORDINATE SYSTEMS

Unfortunately, "as the crow flies" depends upon the breed of crow…

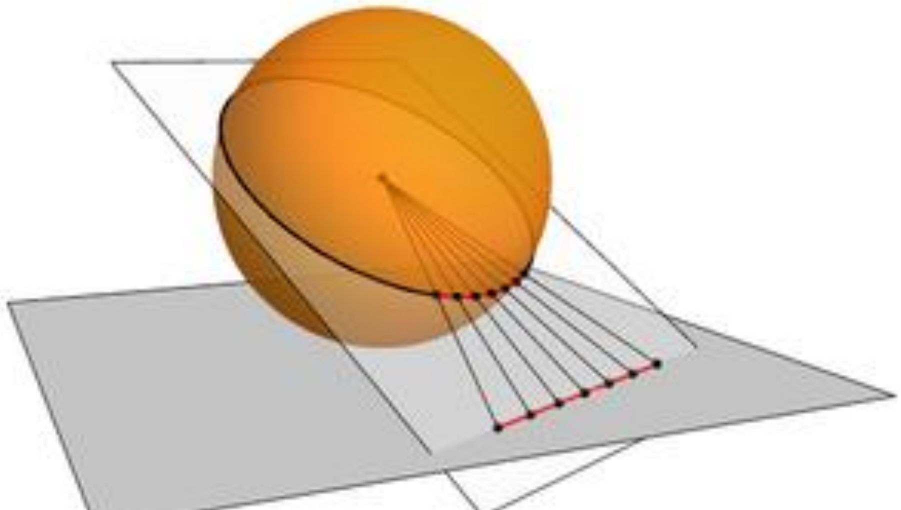
Multiple interpretations of lines on ellipsoidal earth:

1. Geodesic
   - Shortest path along true surface (ellipsoidal earth)
   - Widely used, but complex to compute and reason about
   - Used by Oracle, DB2

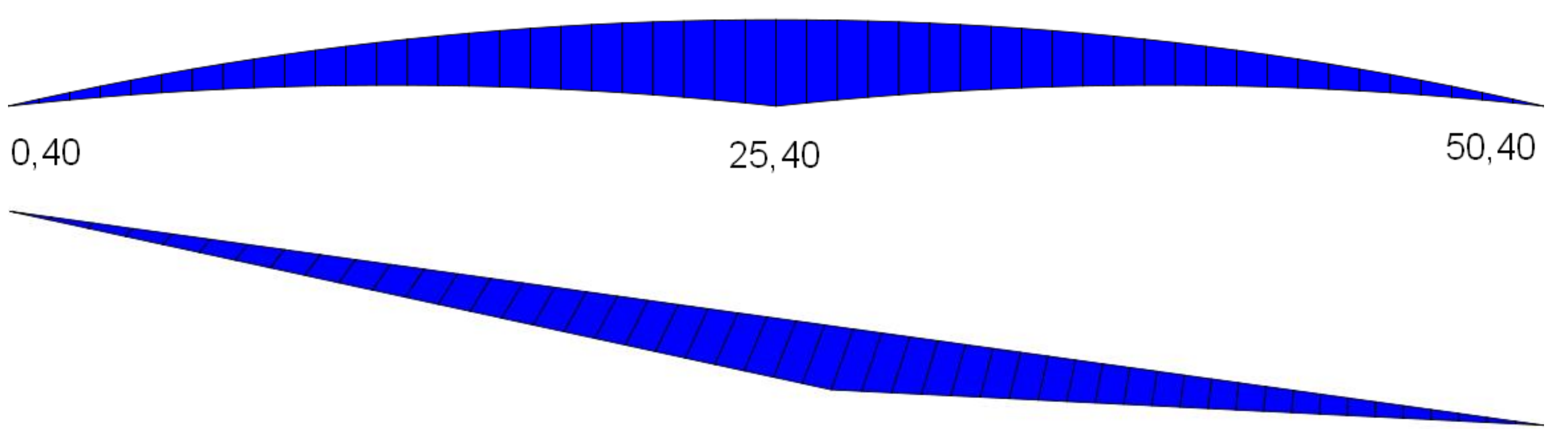
2. Great Elliptic Arc
   - Shortest path along circular earth (great circular arc), projected down to true surface
   - Simpler to compute and reason about
   - Used by Microsoft, Sybase

GNOMONIC PROJECTIONS

Great circular arcs project as straight lines onto any plane.

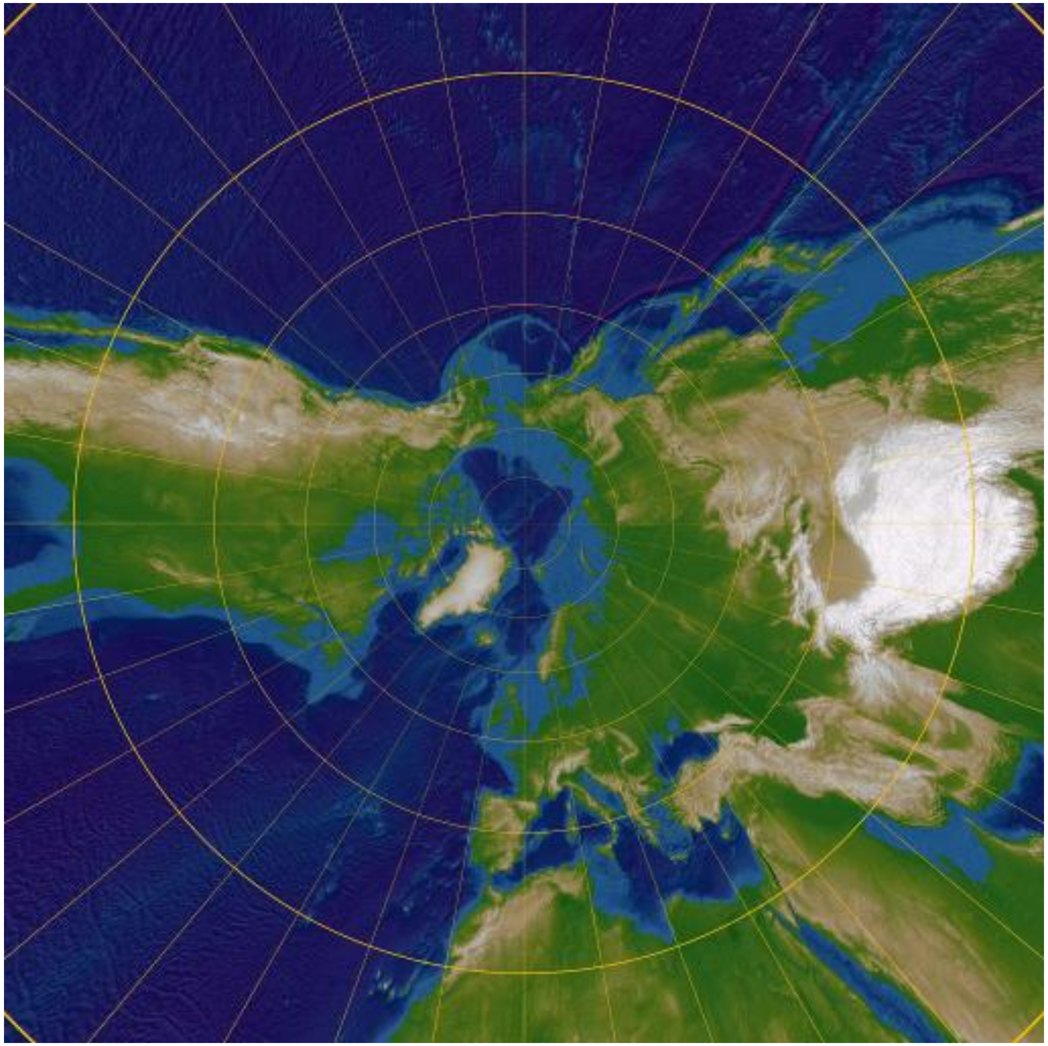


http://en.wikipedia.org/wiki/File:Gnomonic.png



PROJECTING ROUND EARTH

Limitations of a single gnomonic projection.



http://en.wikipedia.org/wiki/File:Gnomonic_Projection_Polar.jpg

PROJECTING ROUND EARTH

Project globe onto a regular octahedral; cut/unfold along equator; flatten.

http://www.progonos.com/furuti/MapProj/Dither/ProjPoly/Foldout/Octahedron/octahedron.html